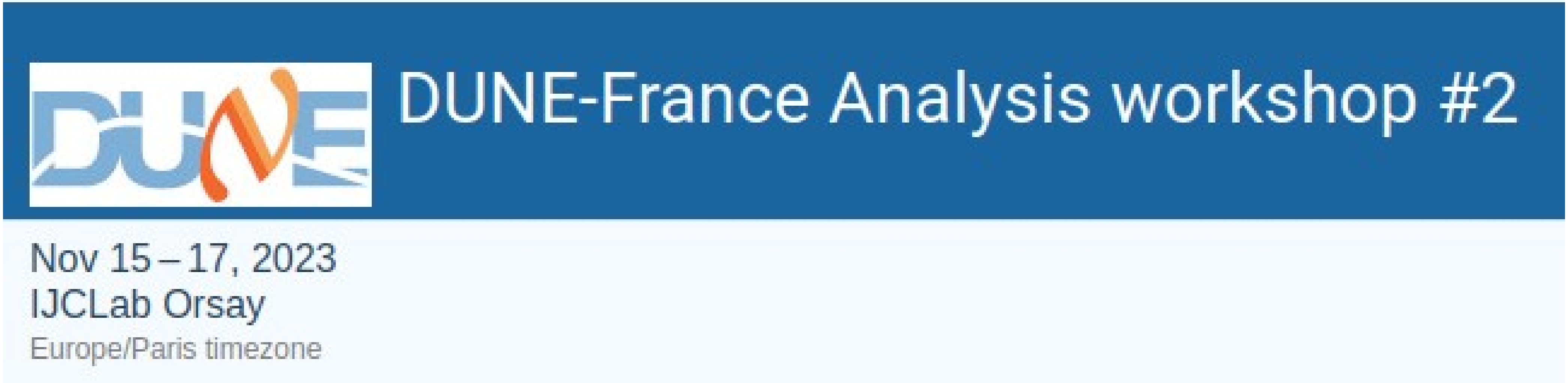


DUNE-France Analysis workshop #2

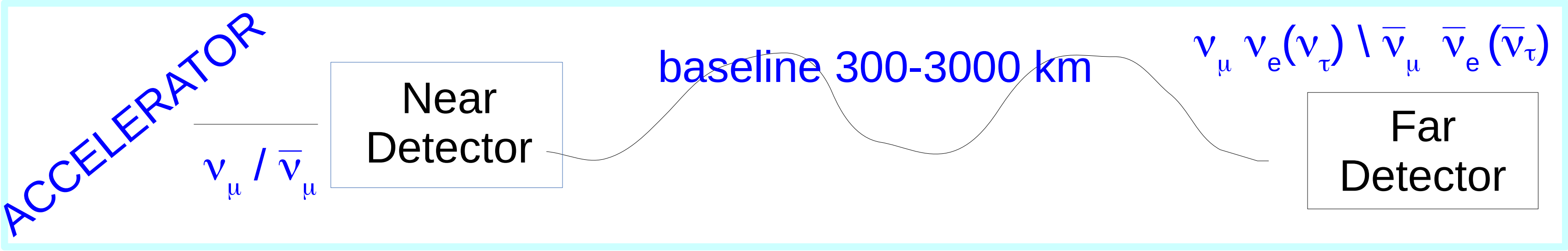
Nov 15 – 17, 2023
IJCLab Orsay
Europe/Paris timezone

Impact on Oscillation Measurement of Neutrino xsec models

→ focus on next steps: aka, how to get the neutrino energy right

S.Bolognesi (CEA, IRFU)

Oscillation analysis: the basics



ACCELERATOR

ν_μ / $\bar{\nu}_\mu$

Near Detector

baseline 300-3000 km

ν_μ $\nu_e(\nu_\tau)$ \ $\bar{\nu}_\mu$ $\bar{\nu}_e(\bar{\nu}_\tau)$

Far Detector

$$N^{FD}_{\nu_{\alpha'}} \approx P_{\nu_\alpha \to \nu_{\alpha'}} \times N^{ND}_{\nu_\alpha}$$

Number of neutrinos at the Far Detector (FD) of a given flavour α' (α=e,μ,τ)

Number of neutrinos at the Near detector (ND)

The **oscillation probability** $\nu_\alpha \to \nu_{\alpha'}$ which you want to estimate: it depends on the parameters you want to measure (long baseline experiments: θ_{13}, θ_{23} Δm^2_{32} δ_{CP})

Dependence on neutrino energy

To extract the oscillation parameters, the oscillation probability must be evaluated **as a function of neutrino energy,** since the neutrino beams are not monochromatic:

$$P_{\nu_\alpha \to \nu_{\alpha'}}(E_\nu) = \sin^2 2\theta \sin^2\left(\frac{1.27\,\Delta m^2_{21} L}{4E_\nu}\right)$$

→ we need to know the **number of neutrinos as a function of E$_\nu$** at near and far detectors

$$\boxed{N_{\nu_\alpha}(E_\nu) = \phi(E_\nu) \times \sigma(E_\nu)\, dE_\nu}$$

flux= number of neutrinos produced by the accelerator per cm^2, per bin of energy, for a given number of protons on target

$$[\int \phi(E_\nu)\, dE_\nu] \equiv [\Phi] = [cm^{-2}\, POT^{-1}]$$

cross-section = probability of interaction of the neutrinos in the material of the detector

$$[\sigma] = [cm^2]$$

Flux and cross-section

- So the oscillation probability becomes:

predicted number of neutrino interactions at the FD (w/o oscillations)

$$\frac{N^{FD}_{\nu_{\alpha'}}(E_\nu)}{N^{ND}_{\nu_\alpha}(E_\nu)} \approx P_{\nu_\alpha \to \nu_{\alpha'}}(E_\nu) \times \frac{\phi^{FD}_{\nu_{\alpha'}}(E_\nu)}{\phi^{ND}_{\nu_\alpha}(E_\nu)} \times \frac{\sigma^{FD}_{\nu_{\alpha'}}(E_\nu)}{\sigma^{ND}_{\nu_\alpha}(E_\nu)}$$

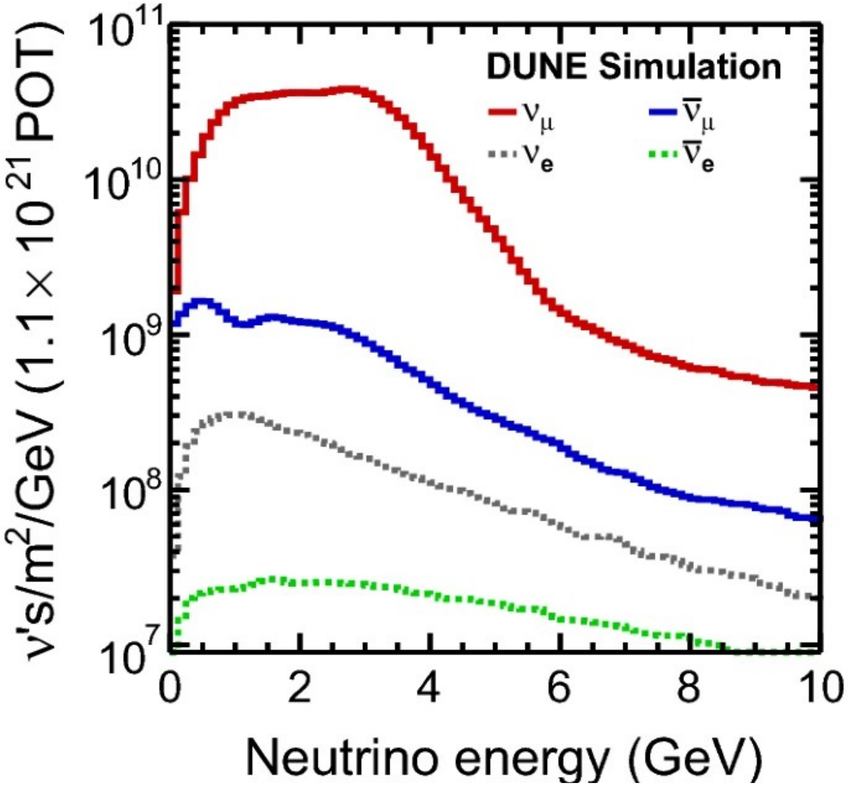
measured number of neutrino interactions at the ND

We measure flux and xsec for ν_α (and $\nu_{\alpha'}$) at the ND and *we use our models to extrapolate* at the far detector

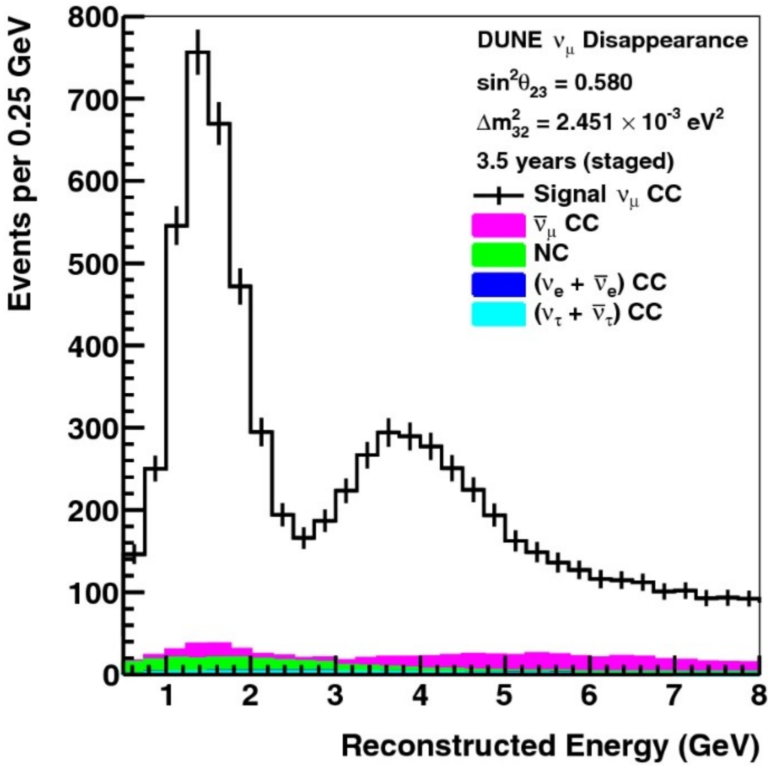
→ systematic minimized if same flux (eg, same off-axis angle) and same target material. But even in that case there are **intrinsic differences / problems which induce model dependency**

ND → FD: different energy

$$\frac{N^{FD}_{\nu_{\alpha'}}(E_\nu)}{N^{ND}_{\nu_\alpha}(E_\nu)} \approx P_{\nu_\alpha \to \nu_{\alpha'}}(E_\nu) \times \frac{\phi^{FD}_{\nu_{\alpha'}}(E_\nu)}{\phi^{ND}_{\nu_\alpha}(E_\nu)} \times \frac{\sigma^{FD}_{\nu_{\alpha'}}(E_\nu)}{\sigma^{ND}_{\nu_\alpha}(E_\nu)}$$

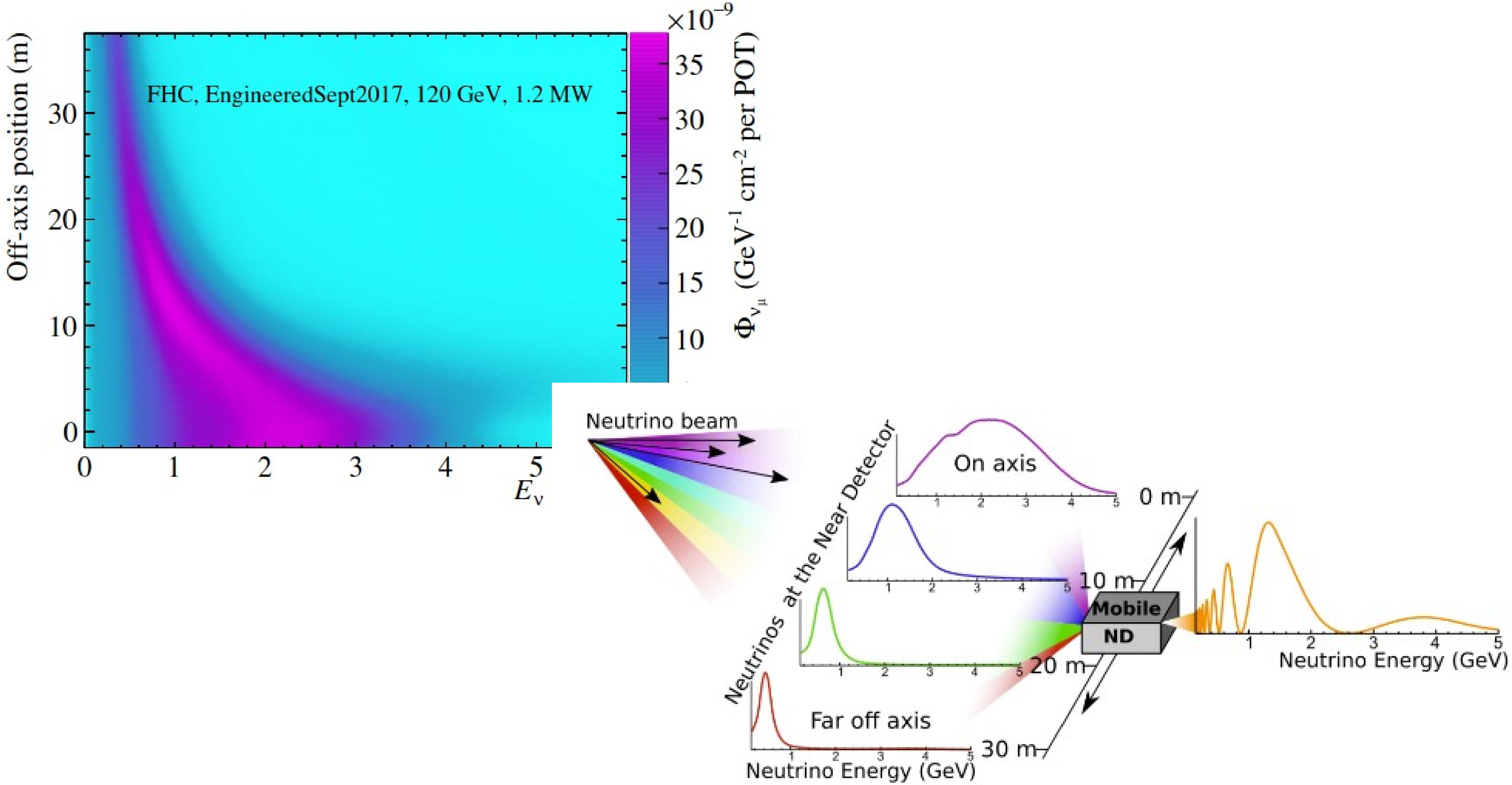


oscillation



ND → FD: different energy: PRISM!

Reproduce the ‘oscillated’ spectrum at ND by combining different the flux at different off-axis angles



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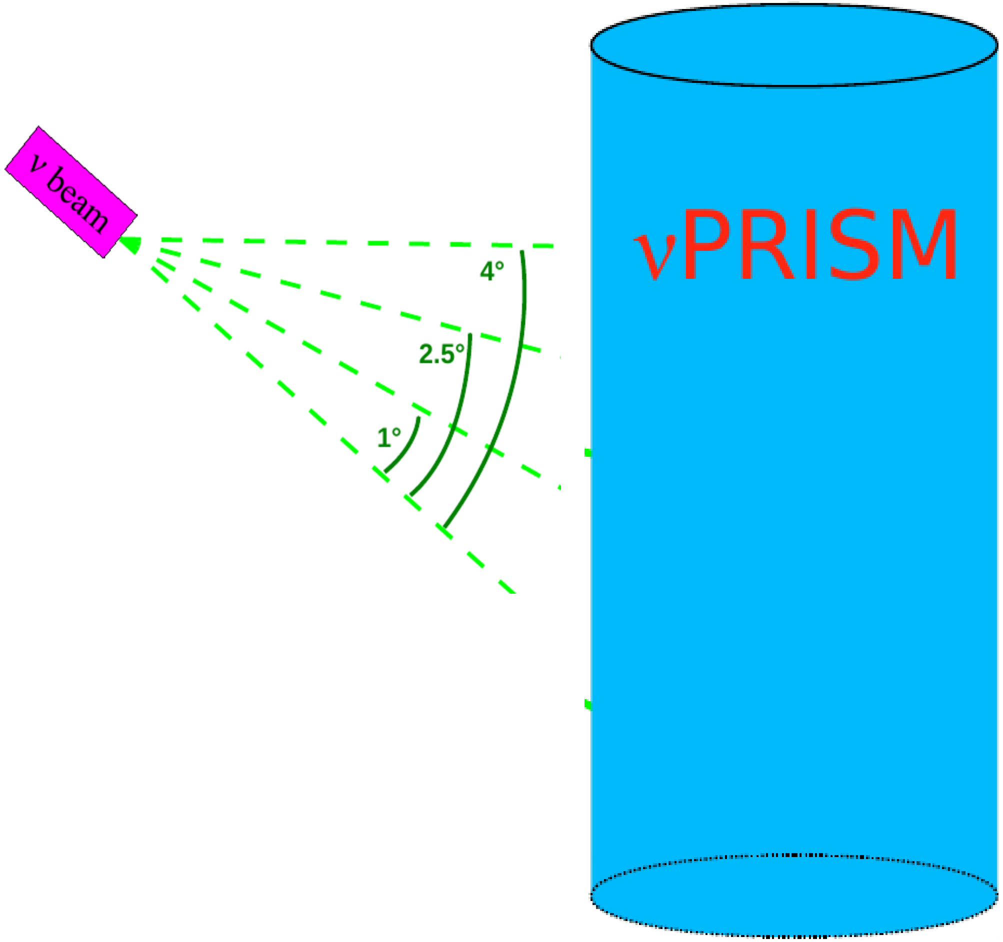
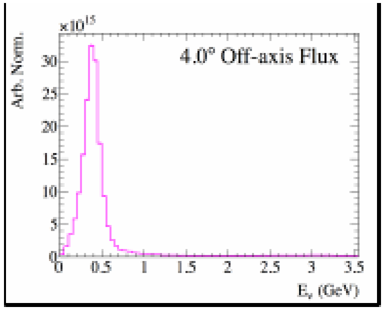
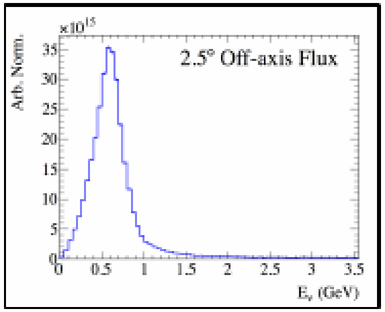
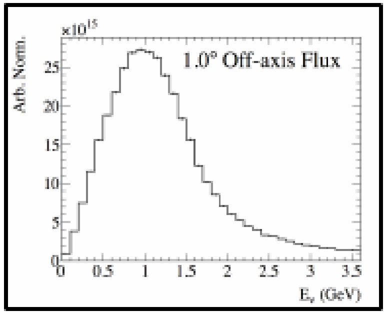






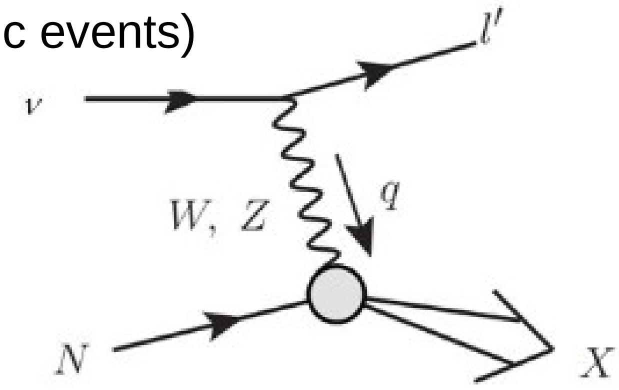


ND → FD: acceptance

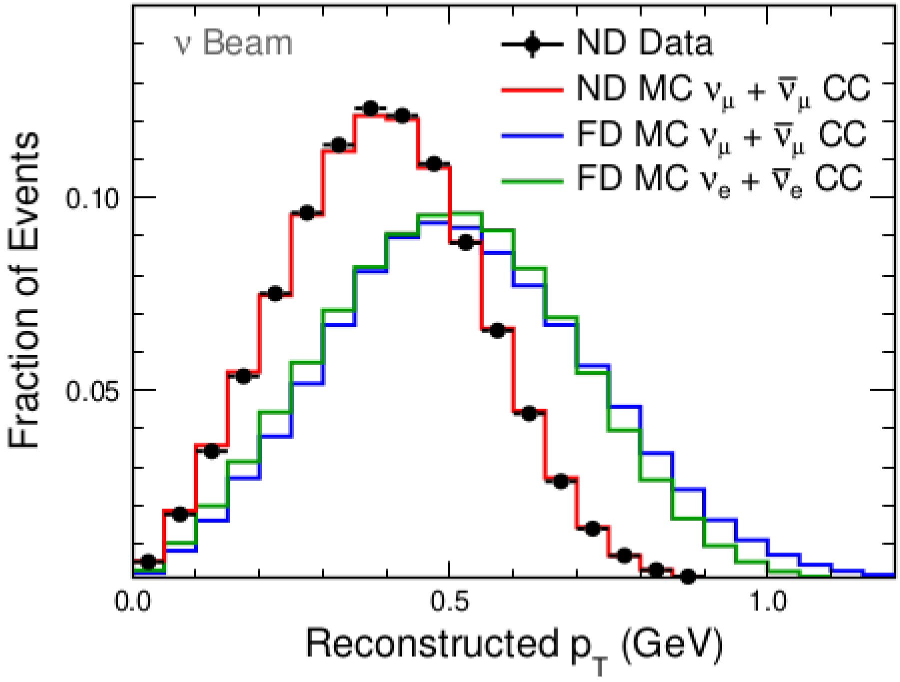
$$\frac{N^{FD}_{\nu_{\alpha'}}(E_\nu)}{N^{ND}_{\nu_\alpha}(E_\nu)} \approx P_{\nu_\alpha \rightarrow \nu_{\alpha'}}(E_\nu) \times \frac{\phi^{FD}_{\nu_{\alpha'}}(E_\nu)}{\phi^{ND}_{\nu_\alpha}(E_\nu)} \times \frac{\sigma^{FD}_{\nu_{\alpha'}}(E_\nu)}{\sigma^{ND}_{\nu_\alpha}(E_\nu)}$$

Recent example from NOVA:

- Due to different detector size, the acceptance of ND and FD is different: transverse momentum of the muon is larger when larger energy/momentum transferred to the nucleus (more inelastic events)



Recent example from NOVA:



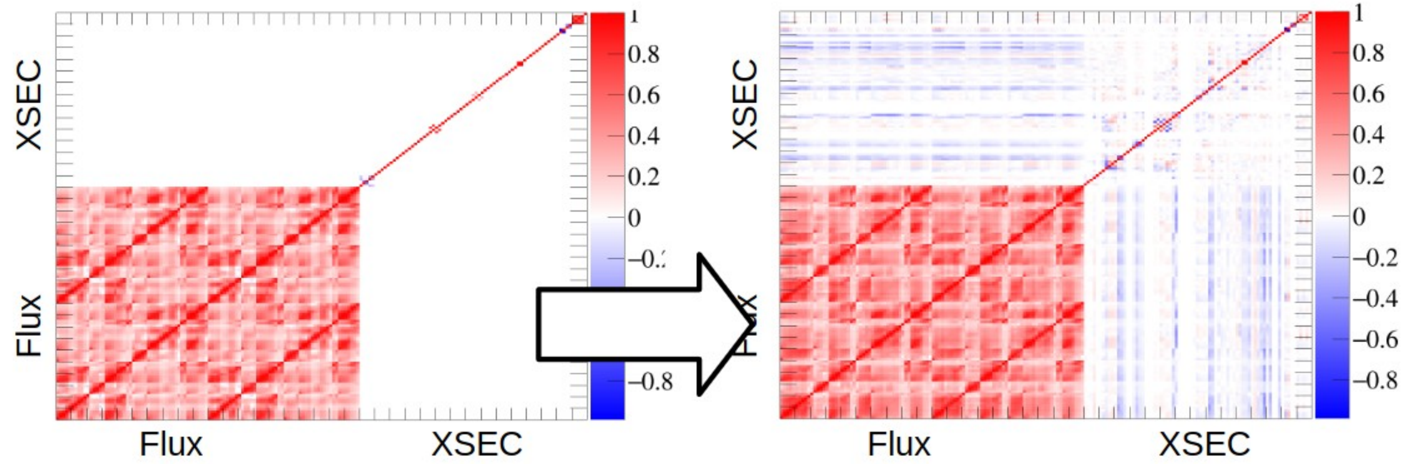
Need model-dependent efficiency corrections to extrapolate ND xsec to FD xsec

ND → FD: flux-xsec anticorrelation

Flux and xsec extrapolation from ND to FD are different → we need to separately estimate flux and xsec at the ND

But we measure only the product of the two (strong anti-correlation between them)

Recent example from T2K:



T2K Run1-10, 2022 Preliminary

T2K Run1-10, 2022 Preliminary

	Pre- ND fit	Post- ND fit
flux	~5%	~2.8-3.0%
cross-section	~10-15%	~3.5-3.8%
flux*xsec		~2.6-2.8%
Total (+ xsec not accessible at ND, SK detector)	~17%	~3.5-5%

- Today xsec uncertainties dominate before the fit
- strong anticorrelation between flux and xsec (would be ~5% if uncorrelated)
- flux*xsec constitutes ~50% of the final systematic error budget

Energy reconstruction

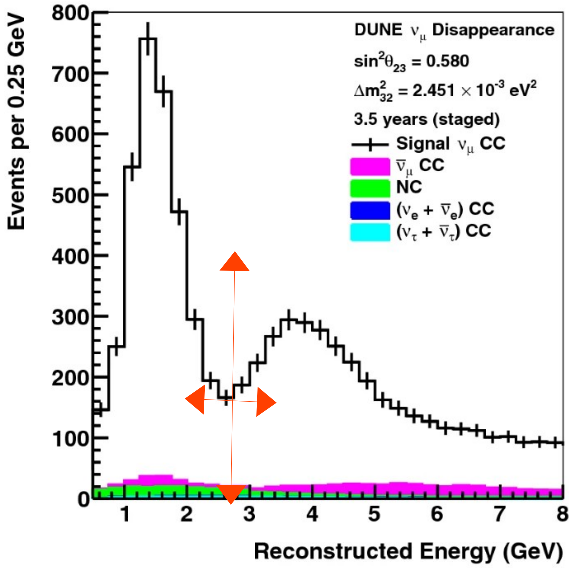
$$\frac{N^{FD}_{\nu_{\alpha'}}(E_\nu)}{N^{ND}_{\nu_\alpha}(E_\nu)} \approx \int \boxed{P_{\nu_\alpha \to \nu_{\alpha'}}(E^{true}_\nu)} \times \frac{\phi^{FD}_{\nu_{\alpha'}}(E_\nu)}{\phi^{ND}_{\nu_\alpha}(E_\nu)} \times \frac{\sigma^{FD}_{\nu_{\alpha'}}(E_\nu)}{\sigma^{ND}_{\nu_\alpha}(E_\nu)} \boxed{R(E^{true}_\nu - E_\nu)} dE_\nu$$

From the detector observables (E_{rec}=“all” particles in the final state), we need to ‘unfold’ back to the true neutrino energy, to extract the oscillation parameters

$$P(\nu_\alpha \to \nu_\beta) = \underbrace{\sin^2(2\theta)}_{\textbf{amplitude}} \sin^2 \left(\underbrace{1.27 \frac{\Delta m^2_{ji}[\mathrm{eV}^2] L[\mathrm{km}]}{E_\nu[\mathrm{GeV}]}}_{\textbf{frequency}} \right)$$

(simplified 2-flavors approximation)

- **$\sin\theta_{23}$ ~ amplitude of the ν_μ ($\bar{\nu}_\mu$) disappearance (height of spectrum minimum)**
- **$\Delta m^2_{31(32)}$ ~ frequency of the disappearance (position of spectrum minimum)**



Target: ~2% precision on normalization, ~1% precision on energy scale

$\nu_e/\bar{\nu}_e$ appearance: δ_{CP} measurement

Search for CPV and measuring dCP are two very different experimental targets.
Prospects for dCP precision ~10-15 degrees from each experiment of next generation

$$\mathcal{A}_{\mathrm{CP}} \equiv \frac{P(\nu_\mu \to \nu_e) - P(\overline{\nu}_\mu \to \overline{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\overline{\nu}_\mu \to \overline{\nu}_e)} \simeq -\frac{\sin 2\theta_{12}\boxed{\sin\delta}}{\sin\theta_{13}\tan\theta_{23}}\Delta_{21} + \text{matter effects},$$

Actually at second order:

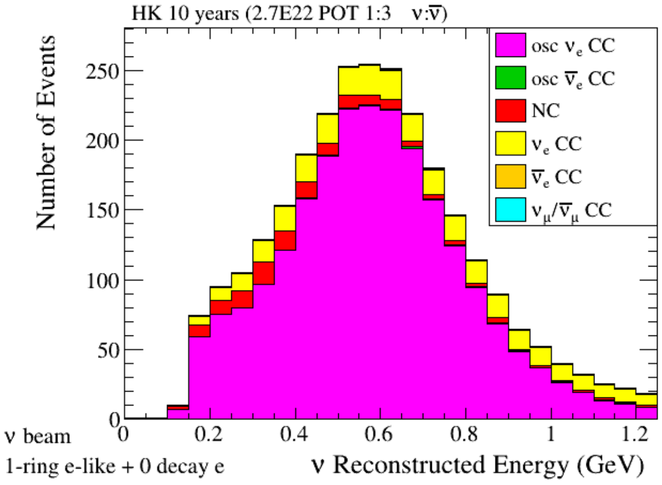
$P_{apperarance}$ ~ +/- A sinδ + Bcosδ + ...

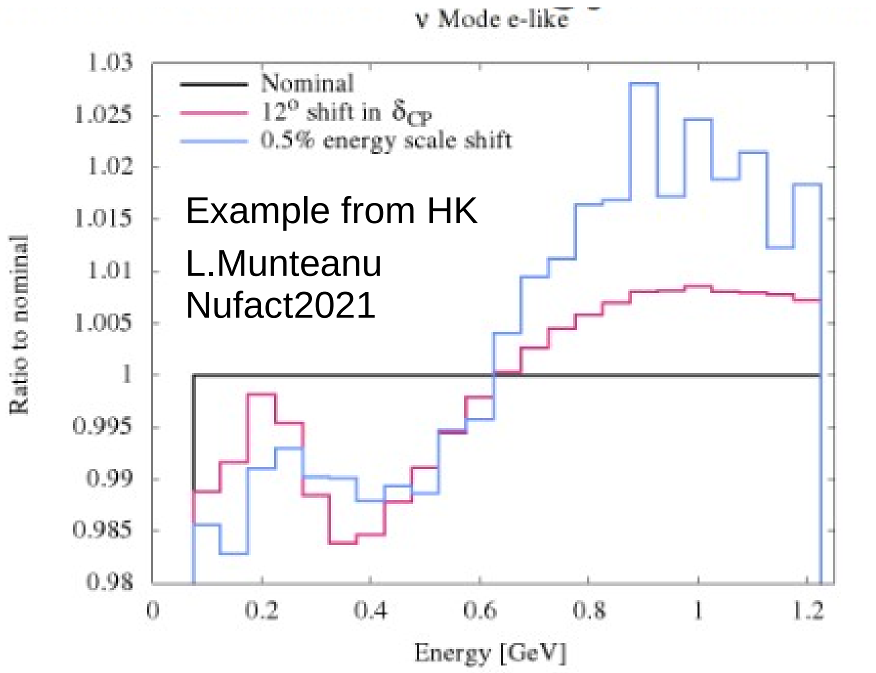
detailed formula →

$$\begin{aligned} P_{long-baseline} \simeq\ & \boxed{\sin^2 2\theta_{13}}\boxed{\sin^2\theta_{23}}\sin^2\Delta \\ & \mp\ \alpha\ \sin 2\theta_{13}\boxed{\sin\delta_{CP}}\cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{23}\sin^3\Delta \\ & +\ \alpha\ \sin 2\theta_{13}\boxed{\cos\delta_{CP}}\cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{23}\cos\Delta\sin^2\Delta \\ & +\ \alpha^2\ \cos^2\theta_{23}\sin^2 2\theta_{12}\sin^2\Delta \end{aligned}$$

with $\alpha \equiv \Delta m^2_{21}/\Delta m^2_{23}$ and $\Delta \equiv \Delta m^2_{31}L/(4E_\nu)$.

- **At δ_{CP}~ +/-π/2** the precision on δ_{CP} (~P_{app} derivative vs δ_{CP}) is dominated by the second term: **precise energy spectrum measurement ($\cos\delta_{CP}$ dependance) dominate the resolution**





Example from HK
L.Munteanu
Nufact2021

Model dependency

Even if the PRISM approach minimize the impact of important systematic uncertainties (notably, obtaining a virtually identical ND and FD energy spectrum)

There are still **intrinsic model-dependent systematics** due to

- difference between ND and FD (eg, acceptance)
(and it is impossible to separate flux and xsec from ND data)

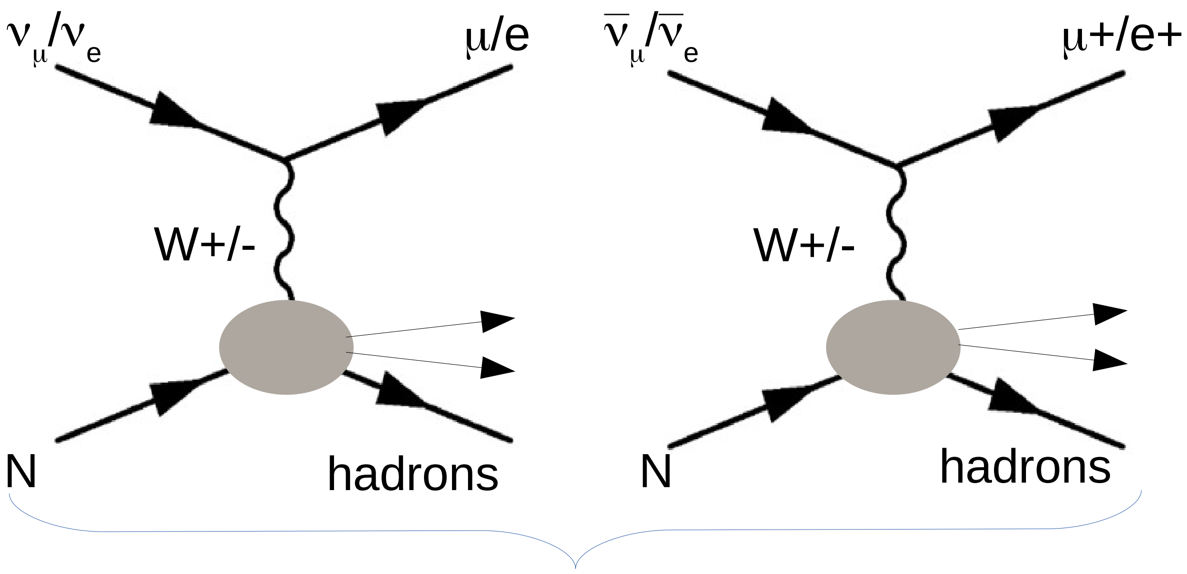
- neutrino energy ‘unfolding’
(I will mostly focus on this aspect on the following...)

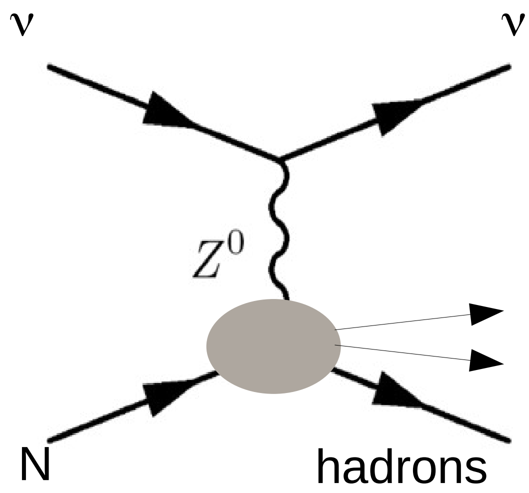
Need of a good model of xsec and flux to minimize these residual systematics

Neutrino cross-section and neutrino energy reconstruction

Neutrino “signal” and “background”

Neutrino can interact with target nucleons in our detector materials





Charged Current (CC) main signal:

- outgoing lepton well visible in the detector to tag interactions → allow to **identify the incoming neutrino flavour and 'charge'**
- full final state can be reconstructed in the detector → allow to **estimate the incoming neutrino energy**

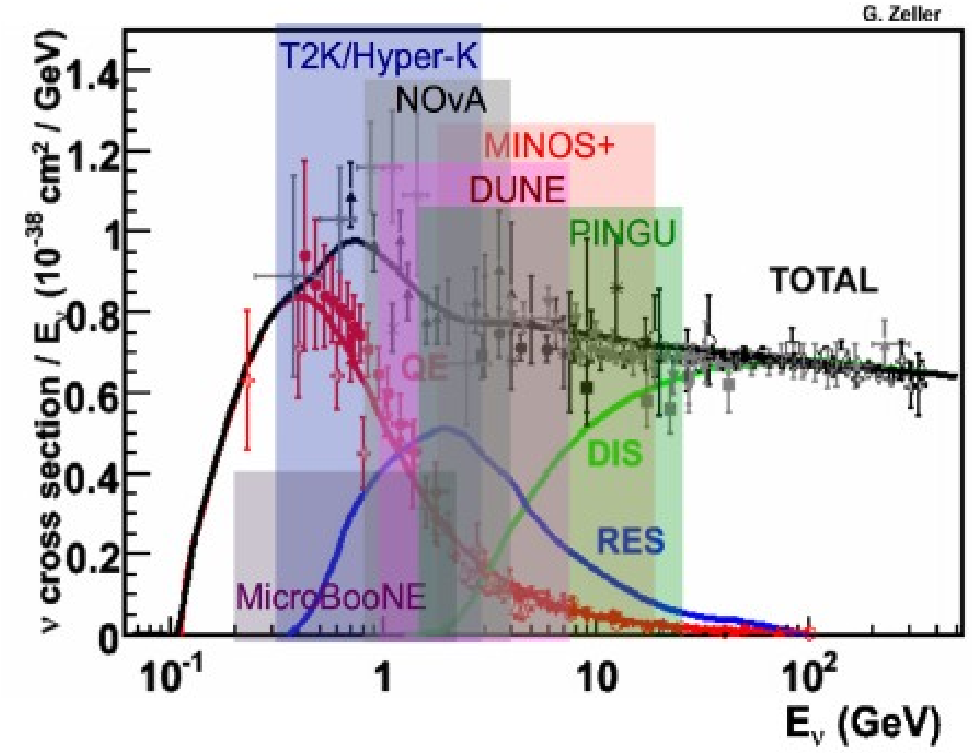
(in realistic detectors this actually relies on various approximations)

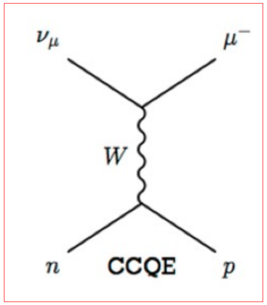
Neutral Current (NC) background

Sometimes the outgoing hadrons can be misidentified as lepton in the detector → background that need to be estimated and subtracted from data distributions

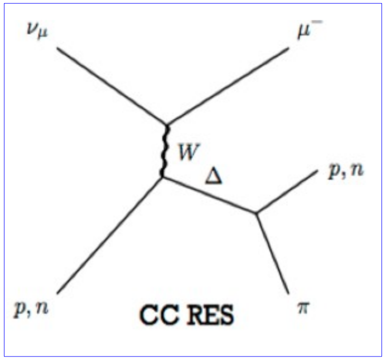
(I will discuss CC but everything can be 'easily' extended to NC)

σ vs E_ν for different processes

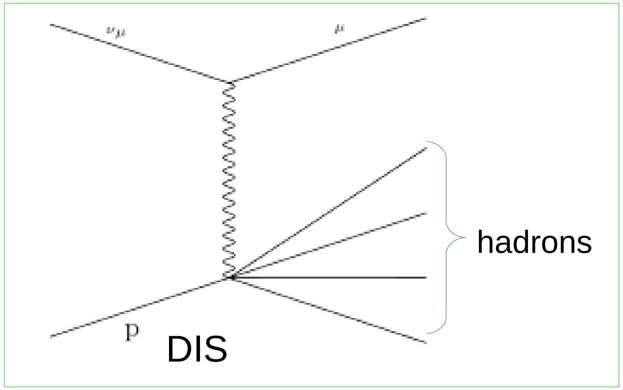




- **QE** = Quasi-Elastic



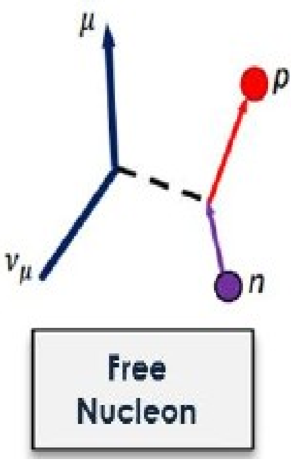
- **RES** = Pion production in the final state through excitation of the nucleon to a resonant state
- **DIS** (Deep Inelastic Scattering) = the nucleon is broken → probing the quark structure of the nucleons → shower of hadrons



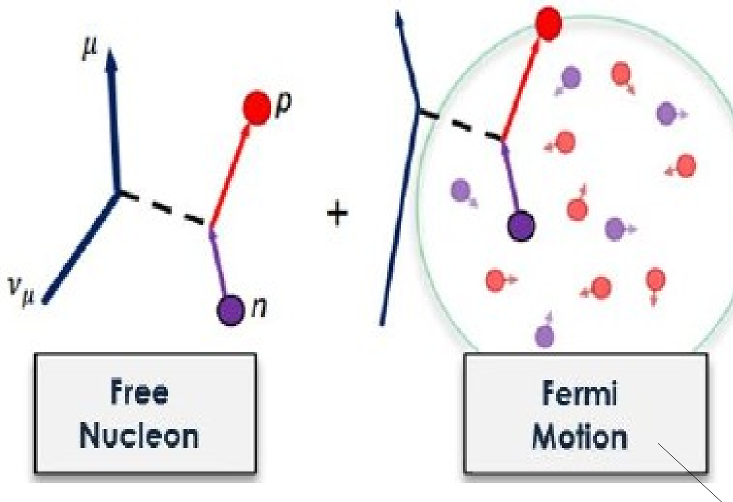
$$N_{FD}^{\nu'} = \int \boxed{\Phi^{\nu}(E_\nu)}\,\boxed{P_{osc}^{\nu\to\nu'}(E_\nu)}\,\boxed{\frac{d\sigma^{\nu'}}{dE_\nu}}\,dE_\nu$$

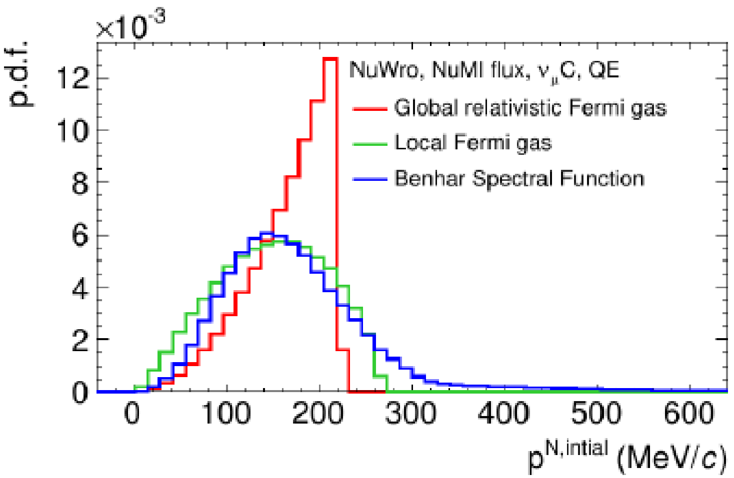
Need to propagate the xsec from ND to FD: **each process has a different E_ν dependence, different resolution and acceptance effects** → need to know the xsec of each process separately

Nuclear effects

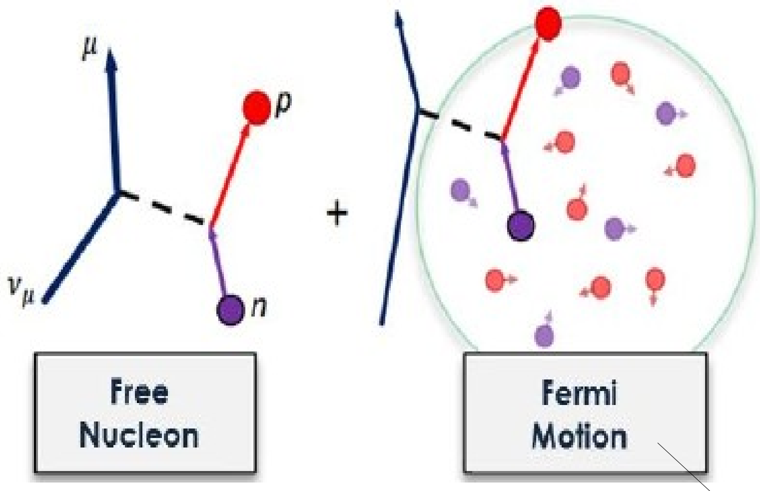


Nuclear effects

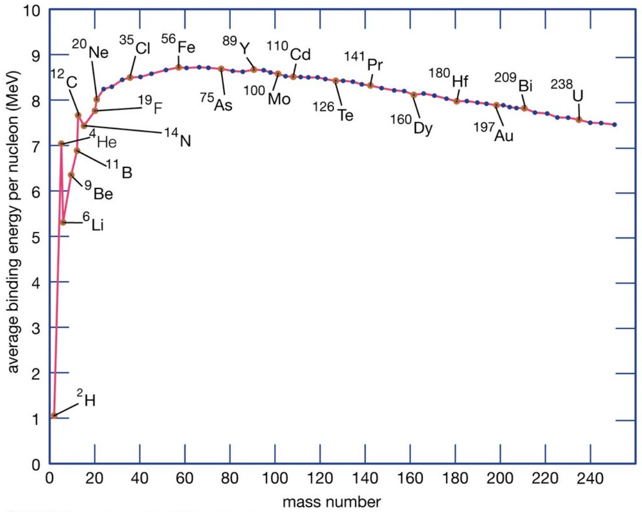




Nuclear effects



and binding energy



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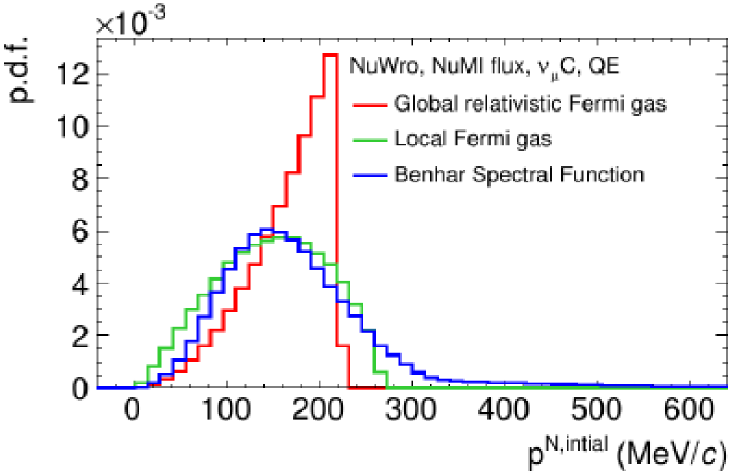
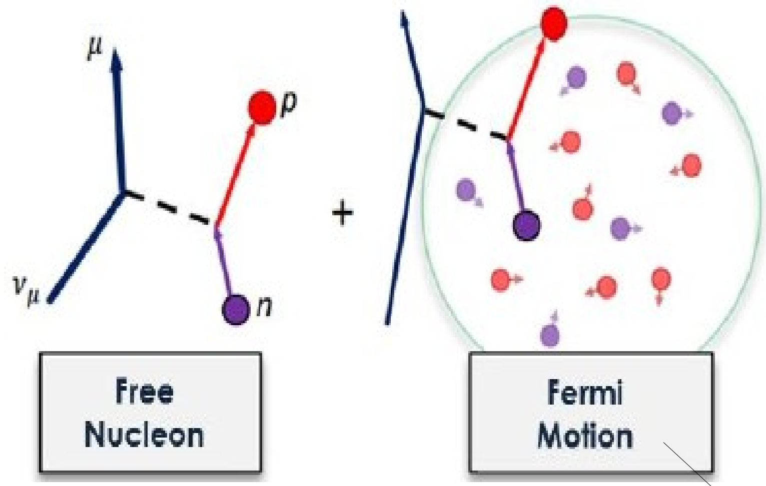
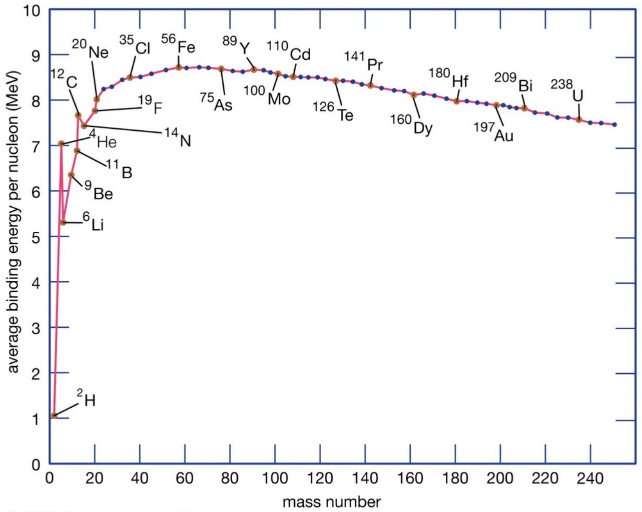


Nuclear effects



and binding energy



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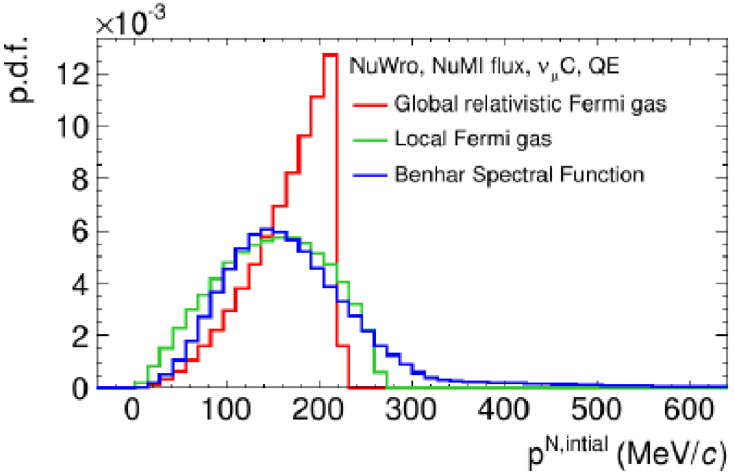
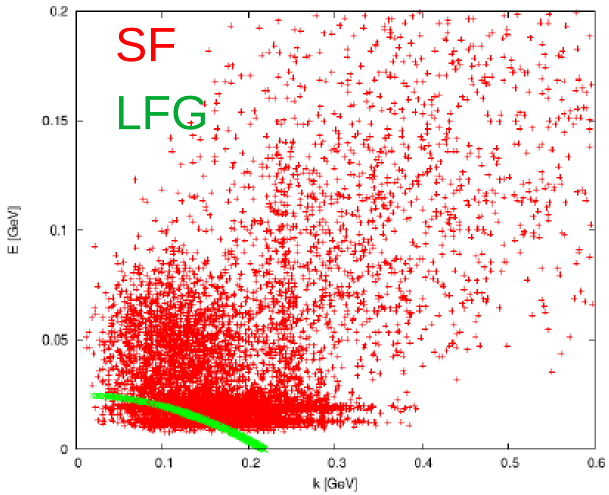
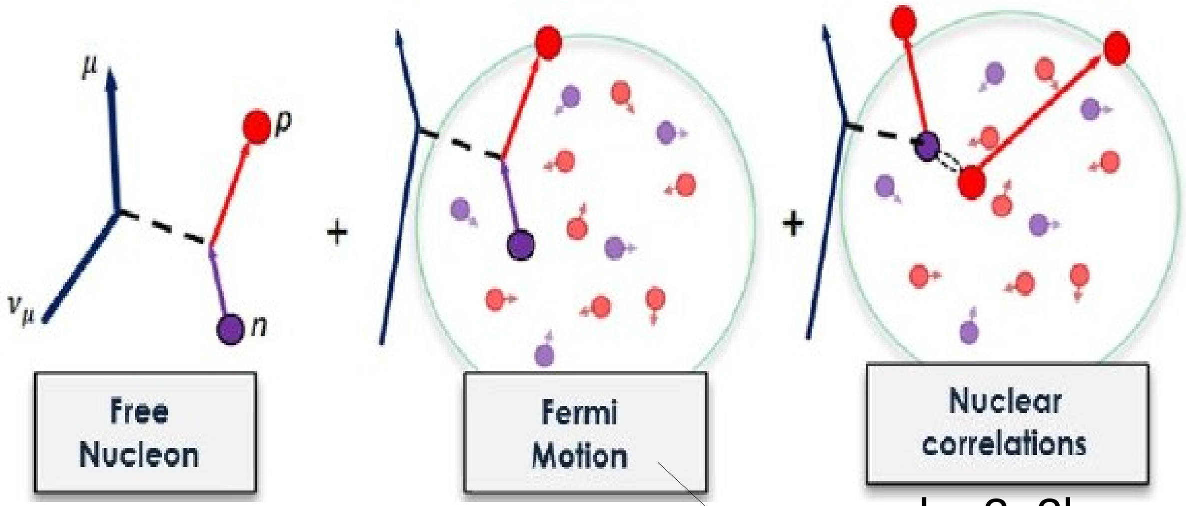


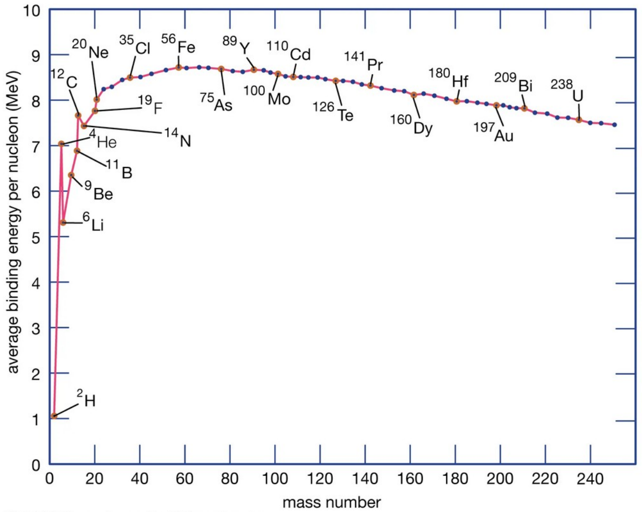


Nuclear effects



aka 2p2h, SRC, RPA, ...

and binding energy



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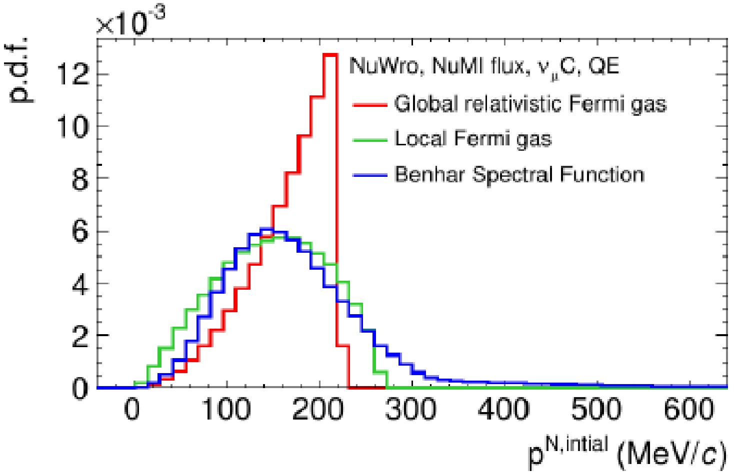
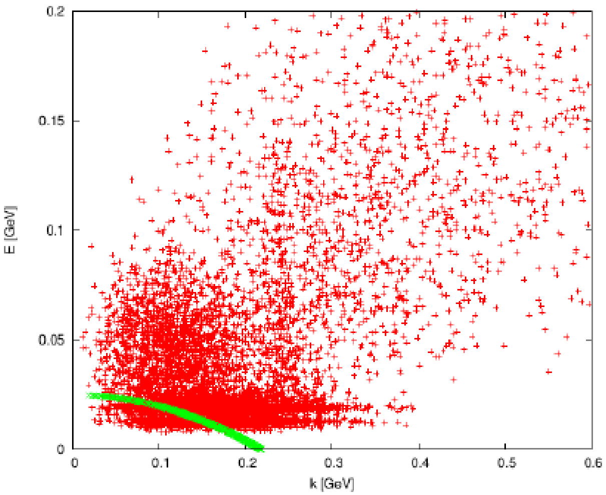
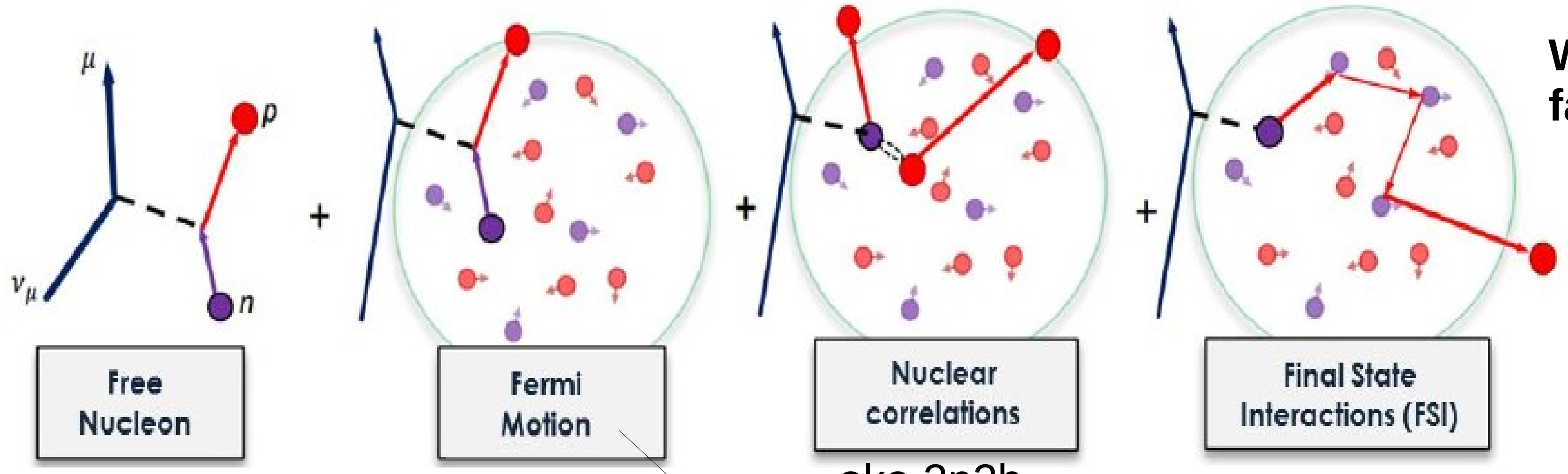




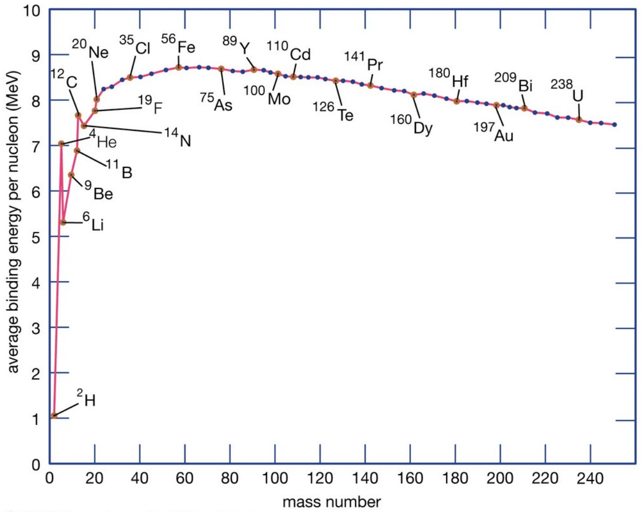
Nuclear effects



We assume factorization!

and binding energy

aka 2p2h,
SRC, RPA, ...



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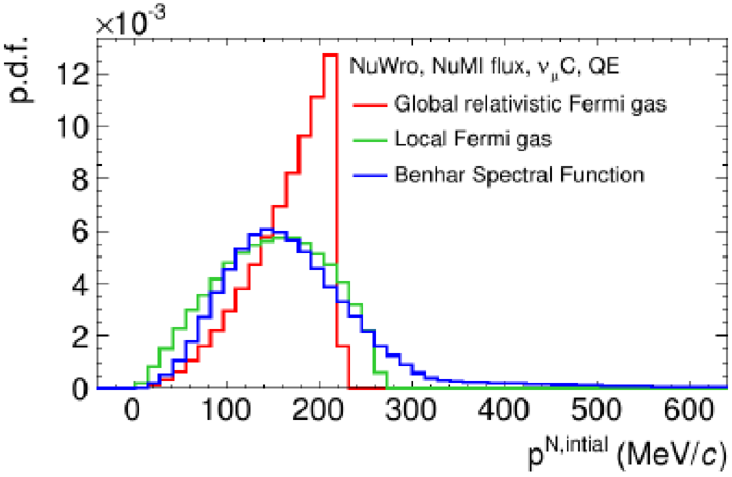
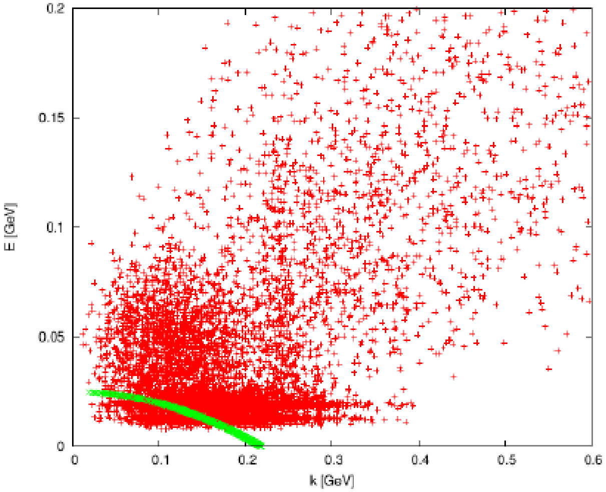
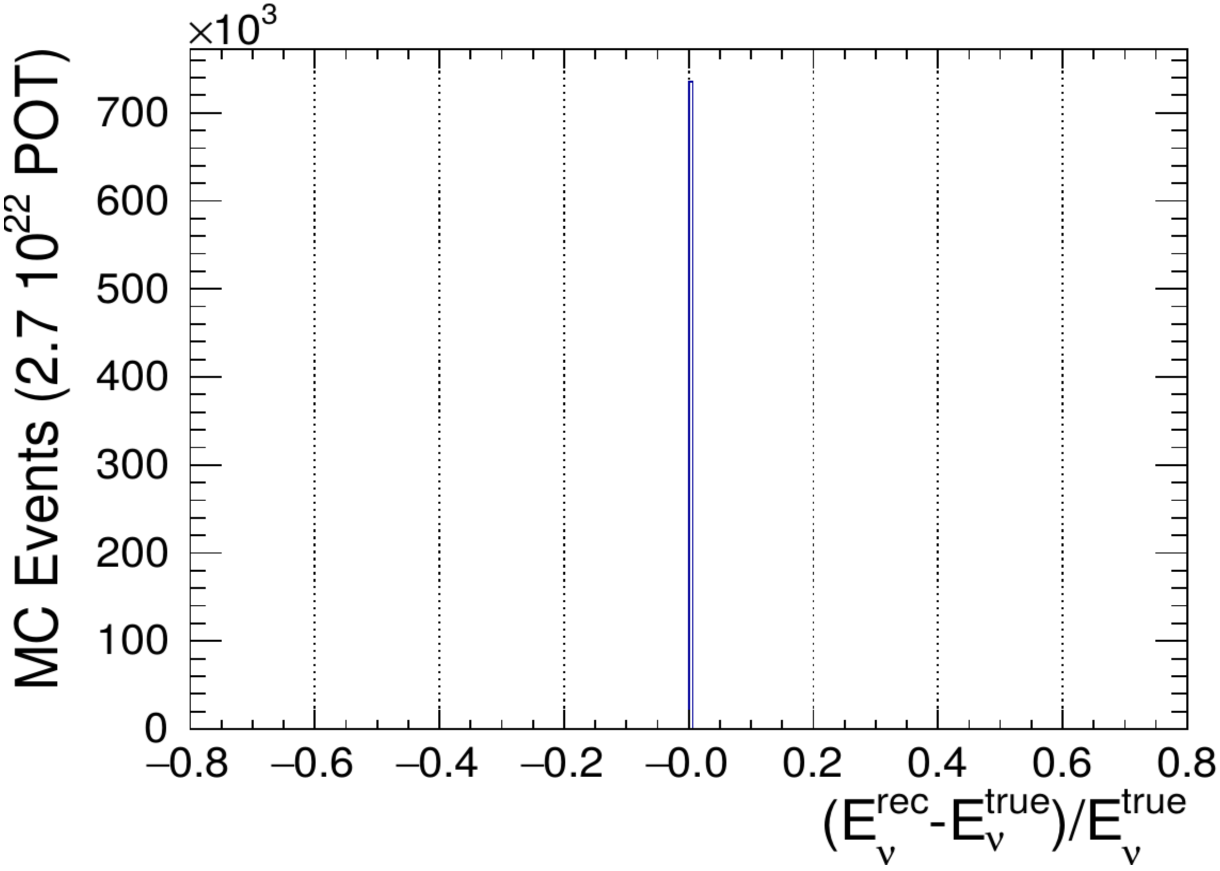




Inclusive energy reconstruction: lepton only

$$\overline{E_\nu} = \frac{m_p^2 - (m_n - E_b)^2 - m_\mu^2 + 2(m_n - E_b)E_\mu}{2(m_n - E_b - E_\mu + p_\mu cos\,\theta_\mu)}$$

CCQE formula:
Eν calculated from muon only kinematics is a perfect estimator for **elastic scattering on a free nucleon at rest**



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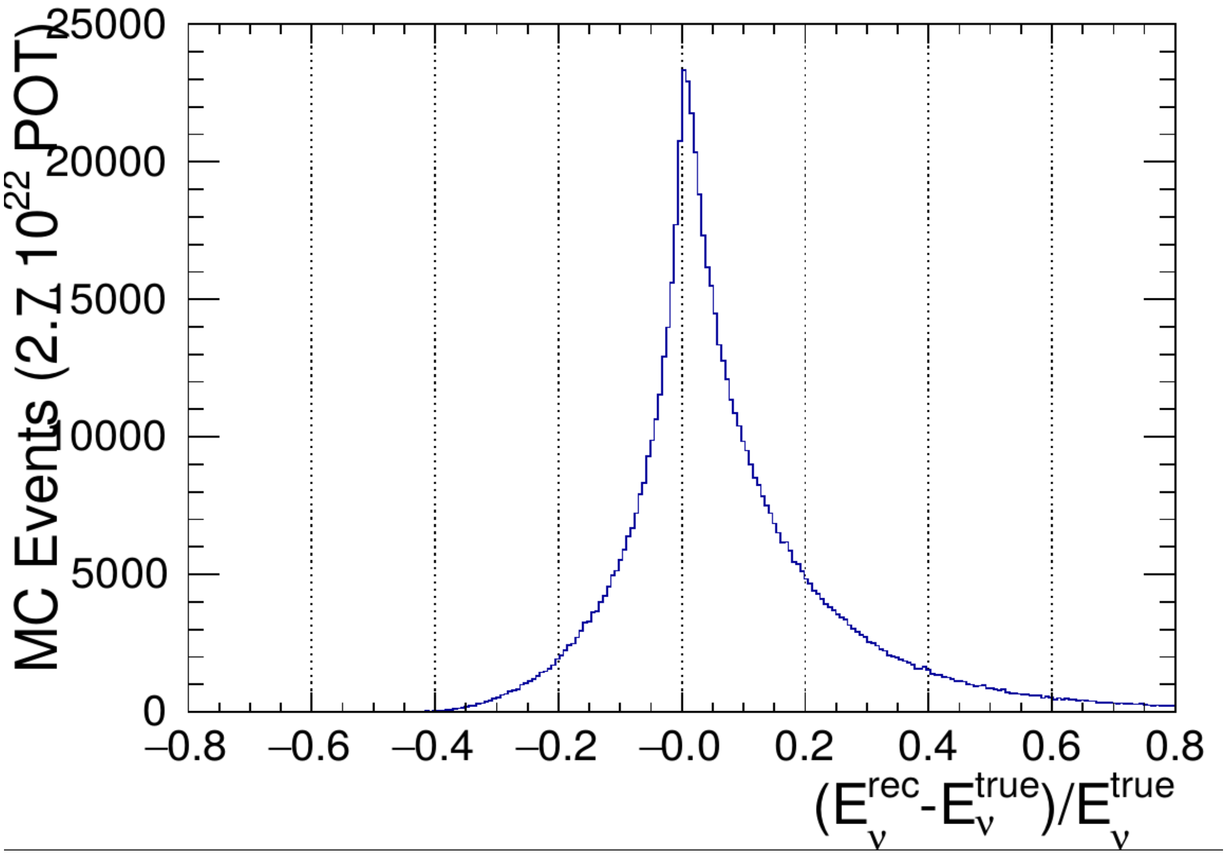
The motion of nucleons inside the nucleus **(Fermi momentum) cause a smearing on E_ν^{rec}**

The energy needed to extract the nucleon from its shell **(removal or binding energy) induces a bias on E_ν^{rec}**



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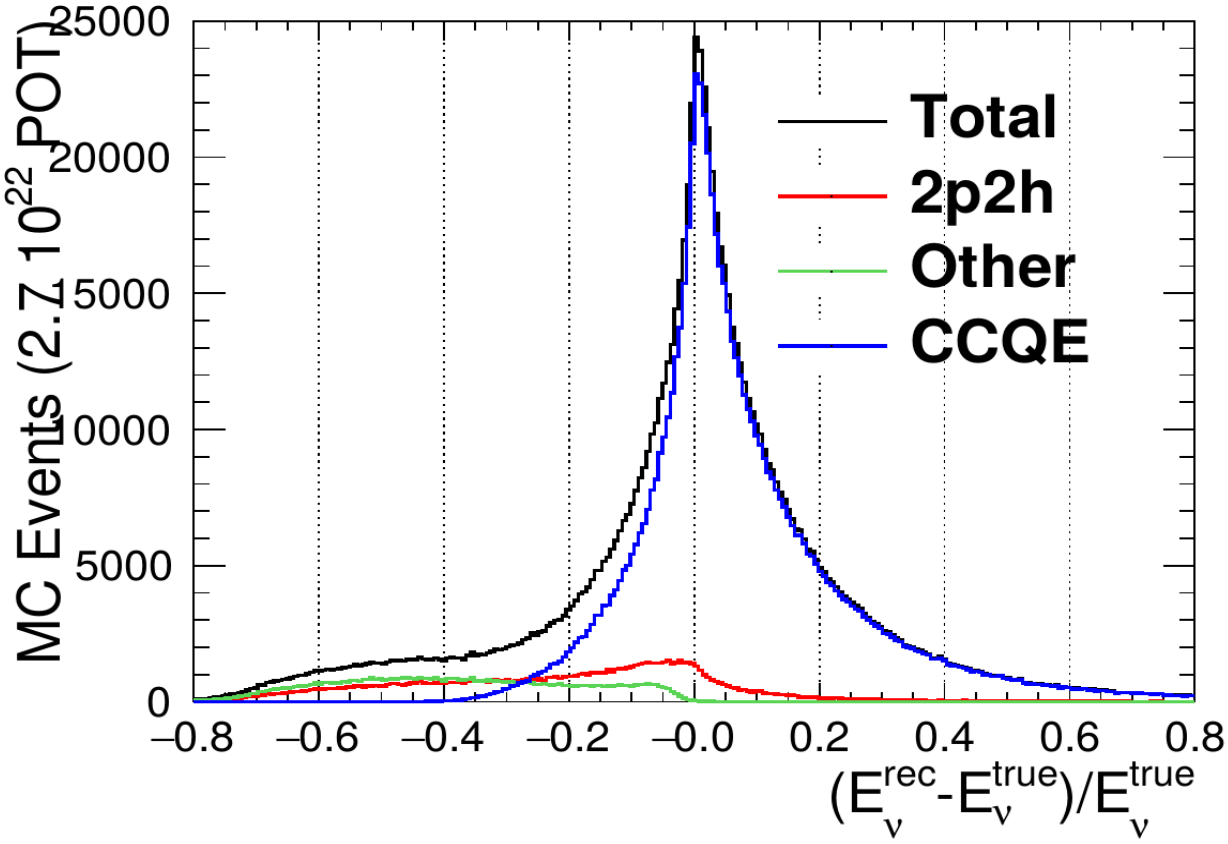
CCQE formula is **not a good estimator of true E_ν for non-CCQE events: eg, 2p2h where the <u>second nucleon goes undetected (eg neutron, or proton below threshold)</u> and CC1pi with <u>pion absorbed in nucleus by FSI</u>**



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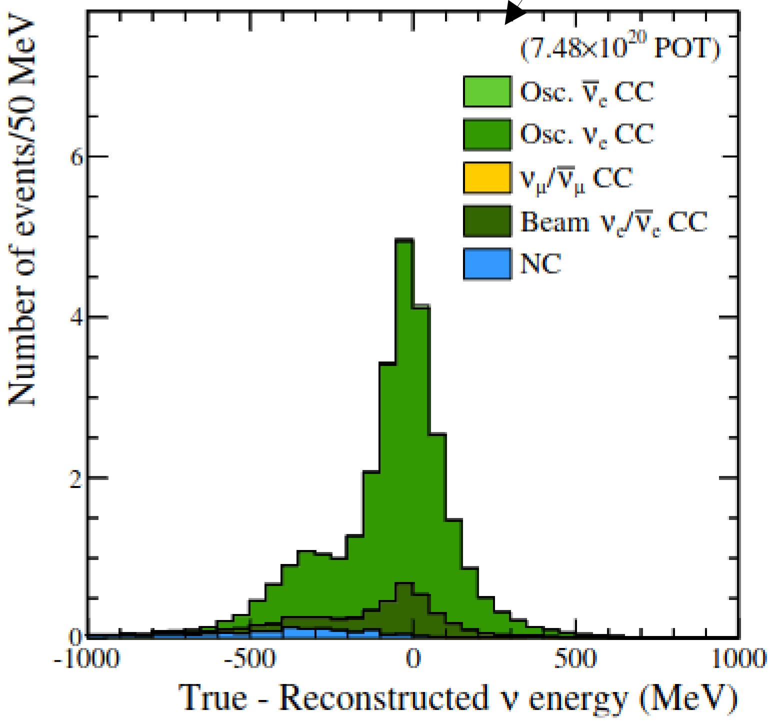
CCQE formula

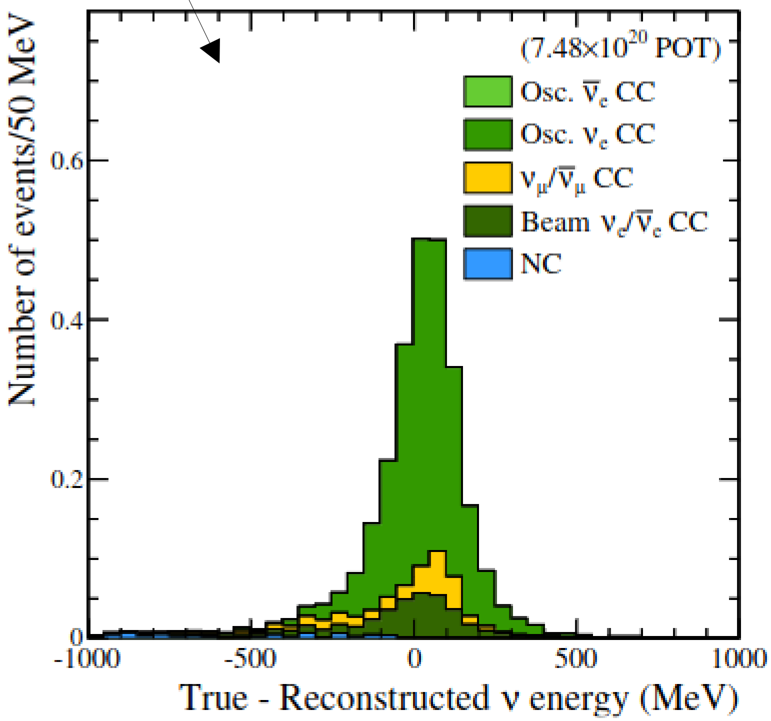
Notice that similar formulas could be built also in case of pion production:

Reconstruct neutrino energy from lepton kinematics only, assuming Δ++ resonance (mostly true in FHC at T2K energy)

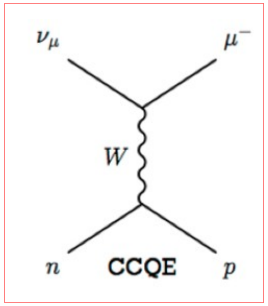
$$E_\nu^{\text{rec}} = \frac{m_{\Delta^{++}}^2 - m_p^2 - m_l^2 + 2m_pE_l}{2(m_p - E_l + p_l\cos\theta_l)}$$

Resolutions at SK with detector effects:
Phys.Rev.D 96 (2017) 9, 092006





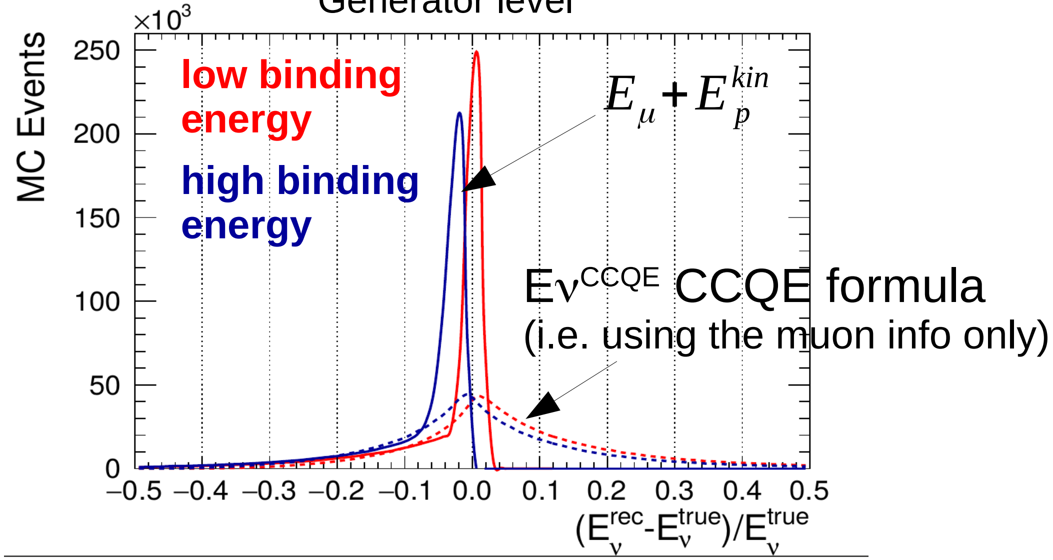
Energy reconstruction with exclusive analysis



Energy reconstruction using **muon and kinetic energy of the nucleon** (proton for ν_μ interaction or neutron for $\bar{\nu}_\mu$ interactions)

$$E_\nu^{rec} = E_\mu + E_N^{kin}$$

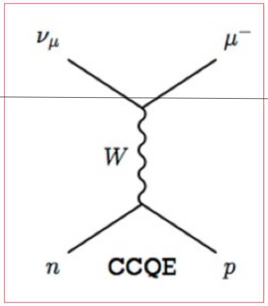
Generator level



$E\nu^{CCQE}$ CCQE formula
(i.e. using the muon info only)

Great improvement on the resolution of neutrino energy reconstruction

Energy reconstruction with exclusive analysis



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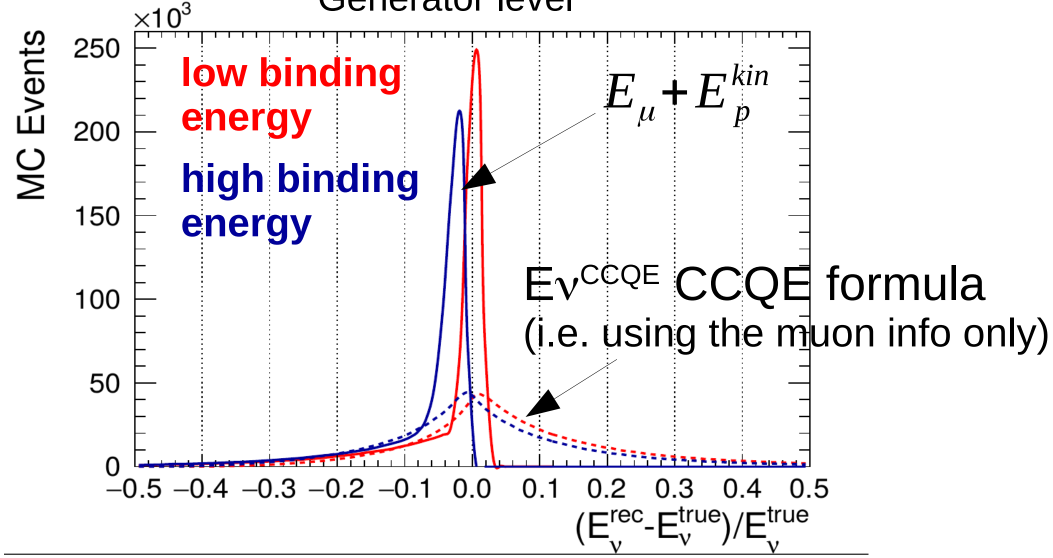
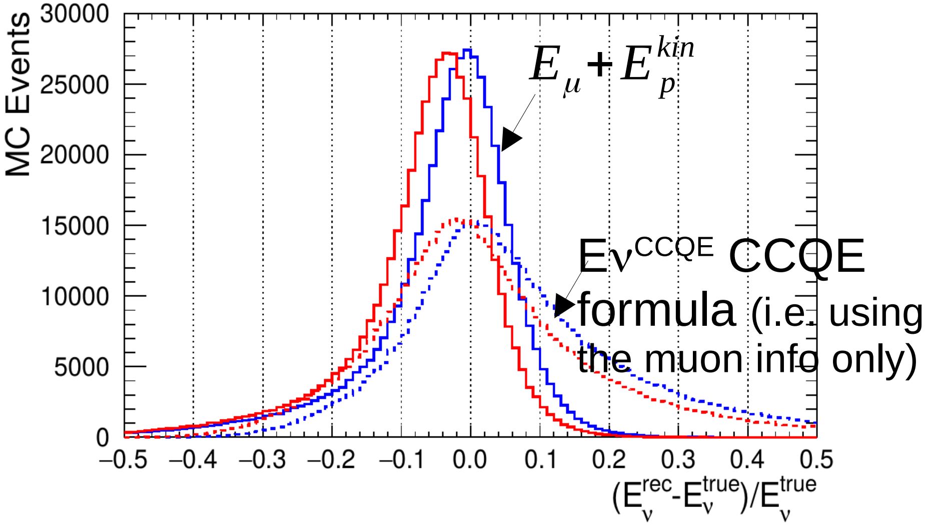


With ND280-upgrade **detector efficiency and resolution**



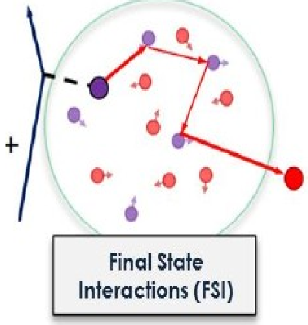
Great improvement on the resolution of neutrino energy reconstruction

- **A new generation of analysis** is being developed at T2K, with ND280 upgrade, which fully exploits the proton/neutron measurement.

→ This is also the way DUNE will recontruct energy: v**ery good exclusive reconstruction + large xsec at high energy (multipion)**

New challenges

“Missing energy”:



- **neutrons**
- **protons and pions which are re-absorbed by Final State Interactions**
- the **energy which is below tracking threshold**

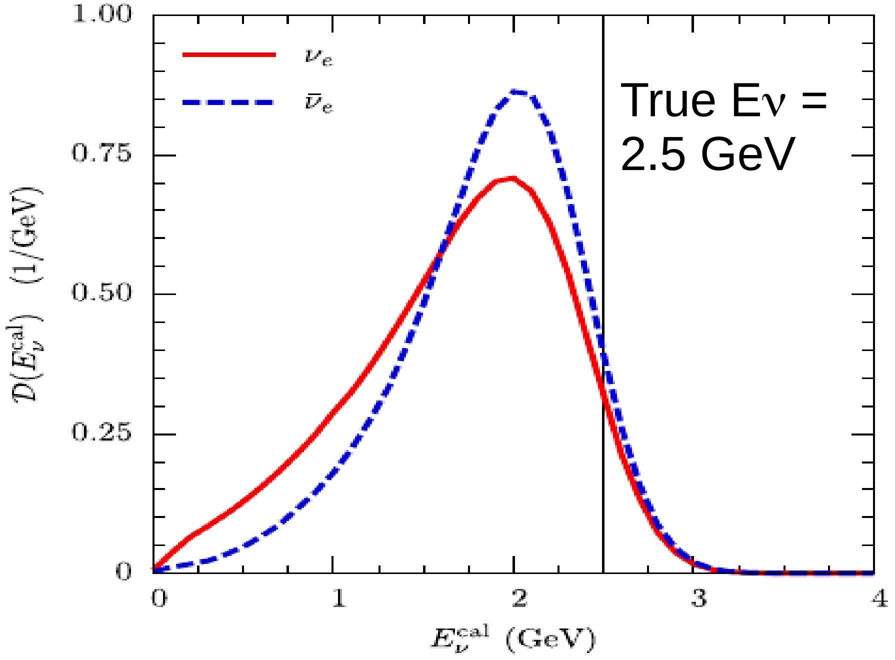
- Part of this ‘missing’ energy could be detected **‘calorimetrically’ (aka vertex activity): all energy is ultimately emitted as low energy hadrons (π+,π-,π0,p,n) and nuclear clusters (eg α, d, t...) through FSI and nuclear de-excitation**
→ need to control the response of the detector to such different particles to ‘unfold’ to their kinetic energy and, ultimately sum it up to get the true Eν

From model point of view we will need to control:

- **pion, proton, neutron FSI**
- **nuclear de-excitation**

Impact of missing energy: neutrons

J. Phys. G: Nucl. Part. Phys. **44** (2017) 054001

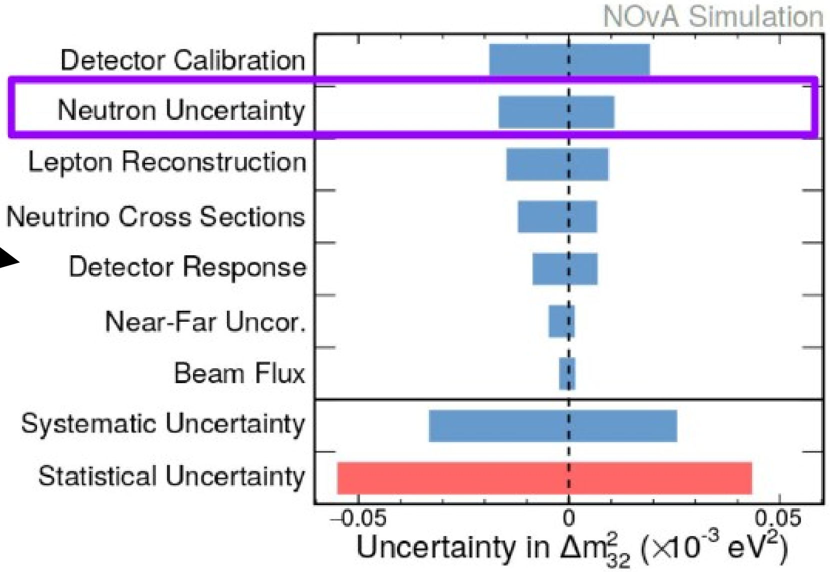


- Impact of missing energy on DUNE-like calorimetric energy reconstruction (phenomenological study)

- Large contribution from nuclear effects (neutrons! Hadrons below tracking) and entangled with detector calibration

- Neutrons can bias $\nu/\bar{\nu}$ Eν reconstruction since different neutron rate for $\nu/\bar{\nu}$ interactions

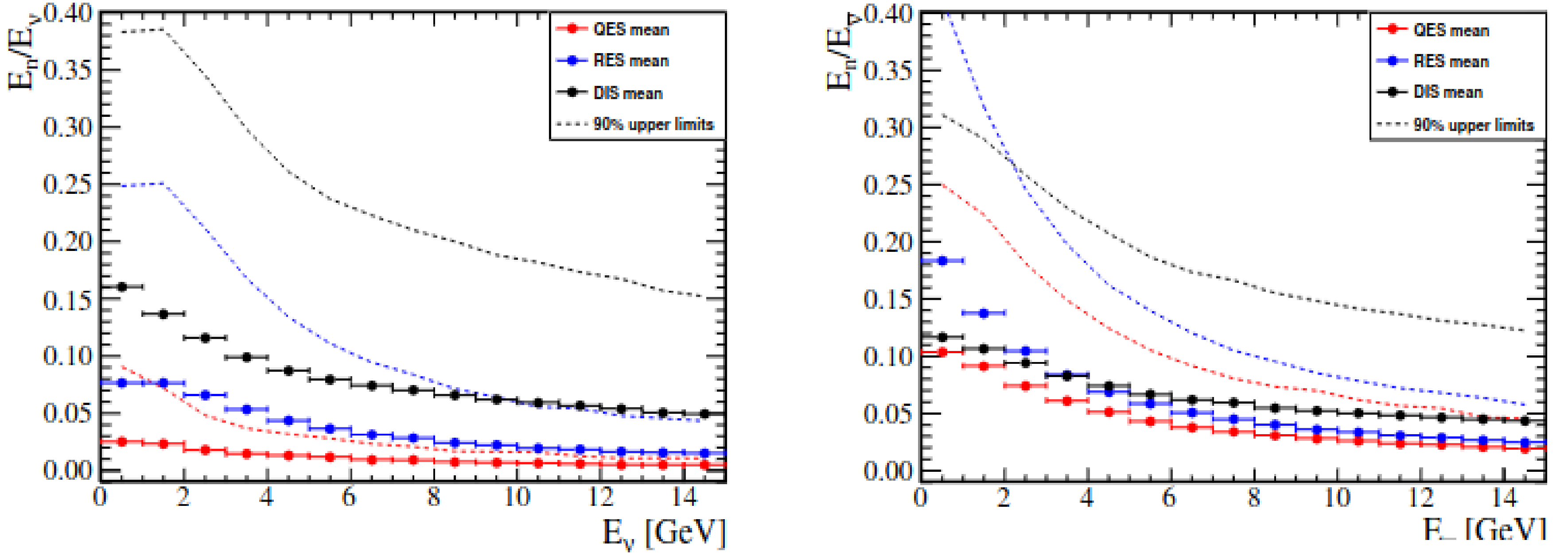
Not a surprise to the LBL community:
see NOVA systematics



Phys.Rev.D 107 (2023) 3, 032012

Neutrons@DUNE

Crucial next step: measurement of fraction of Eν which goes to neutrons: **need to measure the neutron multiplicity and kinematics for different neutrino interaction processes**



Average energy fraction transferred to the primary neutrons relative to the neutrino energy (left) and the antineutrino energy (right).

ND280 Upgrade will measure neutrons for the first time in neutrino interactions!

Study of impact of neutrons on E_ν^{rec} in DUNE

Study of ND280-upgrade like detector in DUNE flux at near detectors: just looked at CCQE for now….

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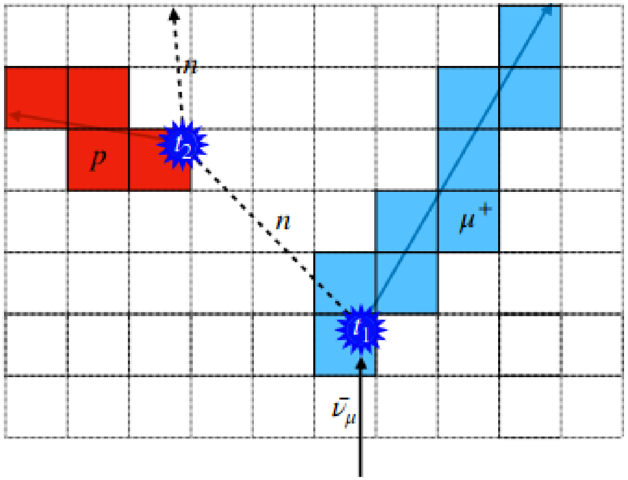
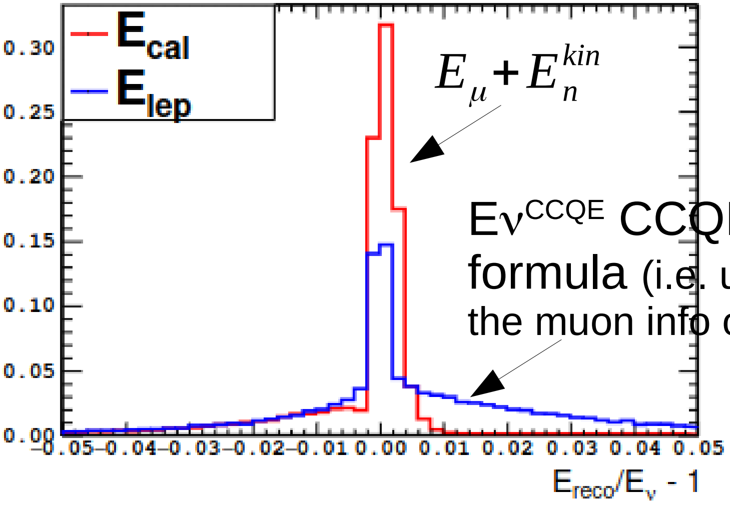


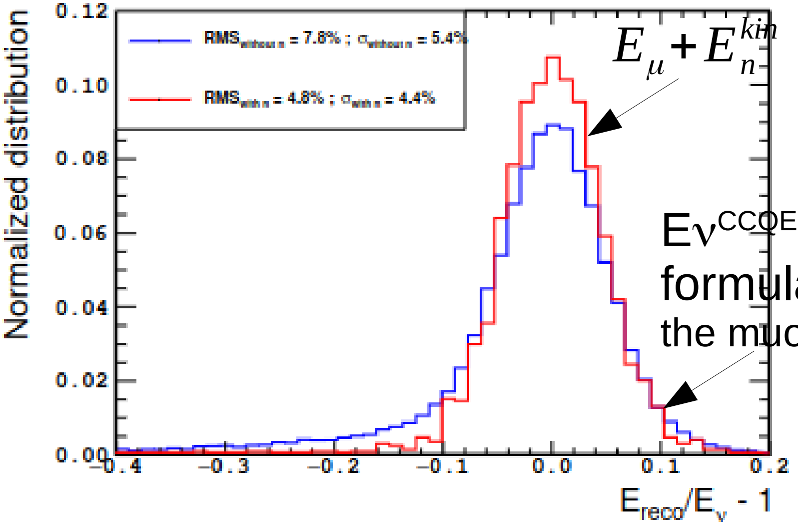
Generator level



$E_\mu + E_n^{kin}$

$E\nu^{CCQE}$ CCQE formula (i.e. using the muon info only)

With detector effects and realistic background

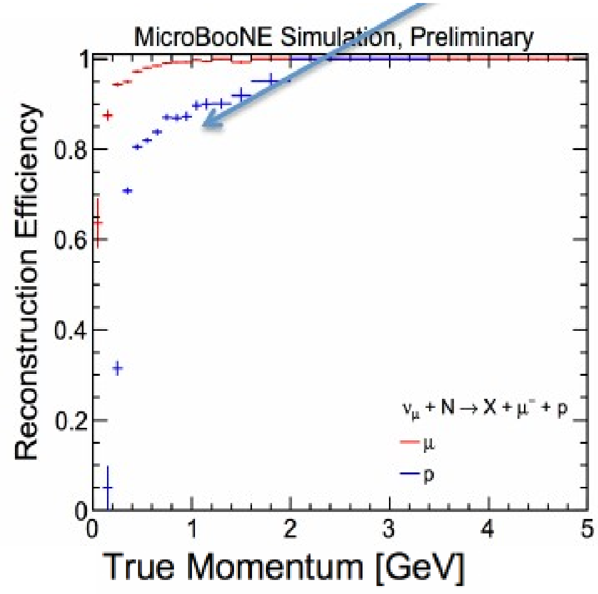


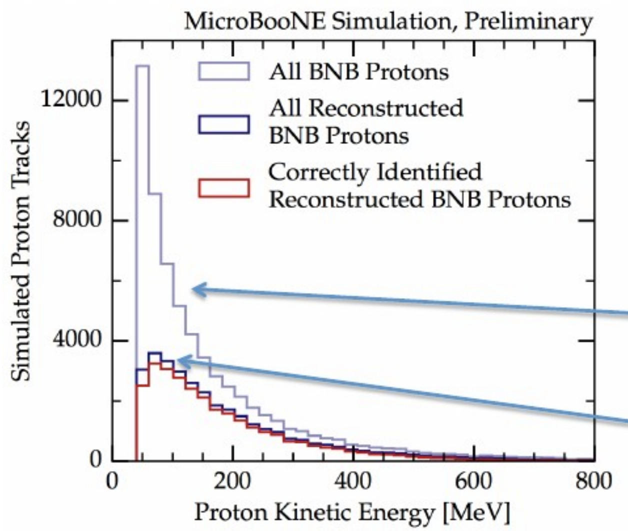
$E_\mu + E_n^{kin}$

$E\nu^{CCQE}$ CCQE formula (i.e. using the muon info only)

Protons below tracking

The capability of tracking protons (and pions) depends on their momenta: **to correct for un-tracked particles we need to know the 'missing' protons (below tracking)**



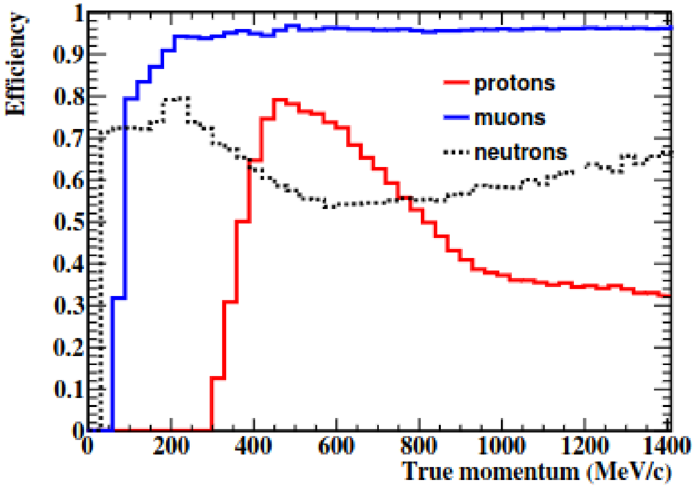


MicroBooNE proton momentum efficiency

Uncertainties:

- MC needed to correct for these lost protons
- mis-ID protons counted as pions – energy wrong, or muons – event topology wrong

ND280 upgrade proton momentum efficiency



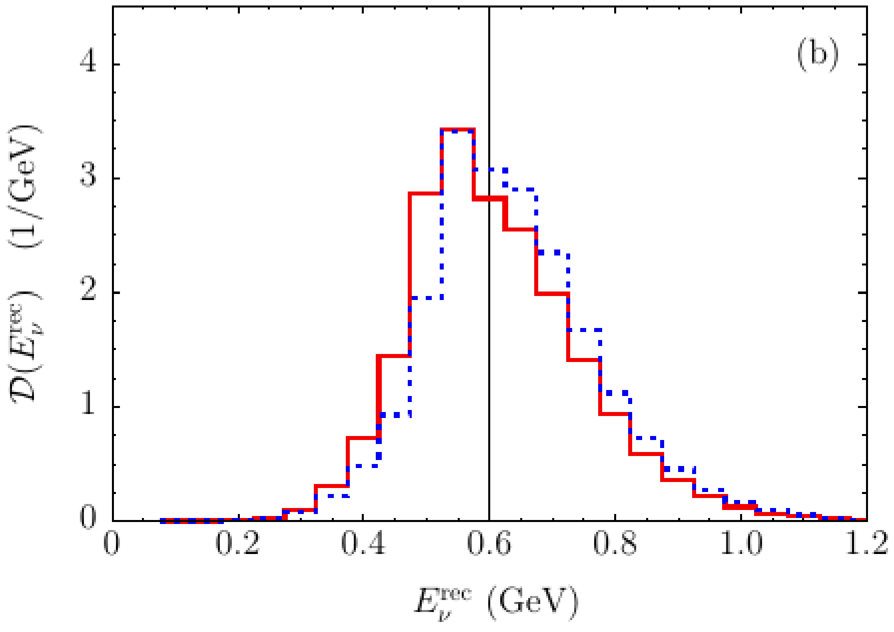
Need good FSI model to know how many protons loose energy in the nucleus and go below detecting threshold

FSI effects on calorimetric energy

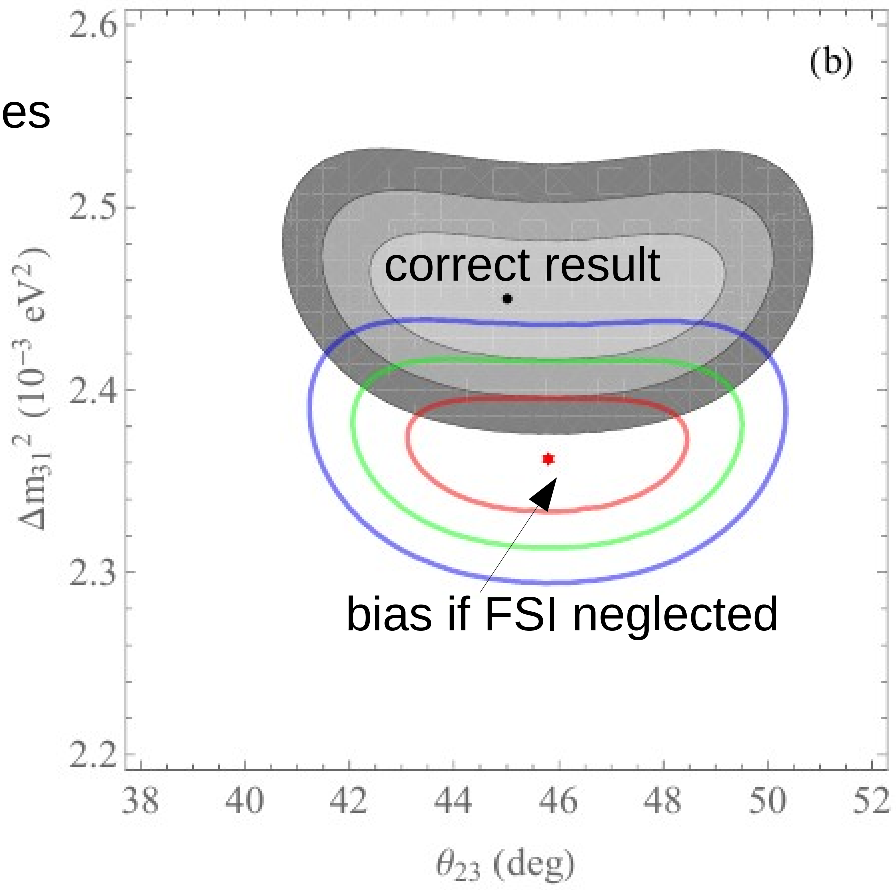
→ **Effects on neutrino calorimetric energy reconstruction for oscillation analysis:**

- some energy get lost in the rescattering in the nucleus and cannot be reconstructed
- efficiency corrections for low momentum particles from MC need reliable model of charge, multiplicity and kinematics of outgoing hadrons

Bias in the reconstructed energy if FSI are neglected with 'realistic' detector performances (phenomenological study)

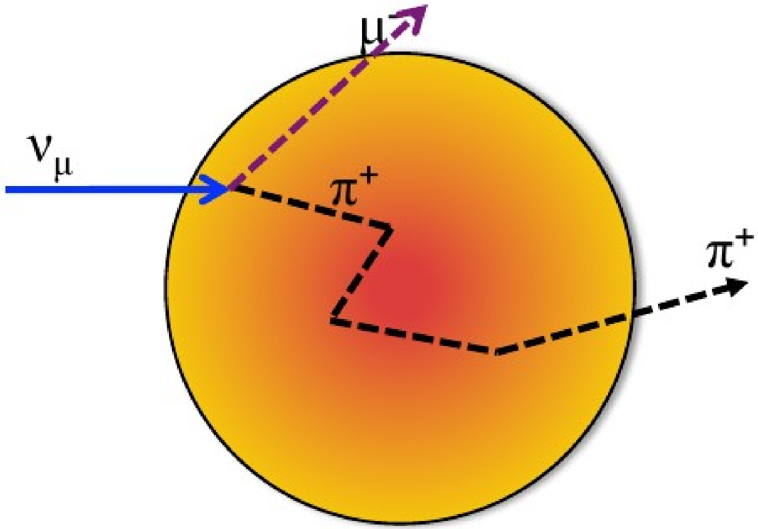


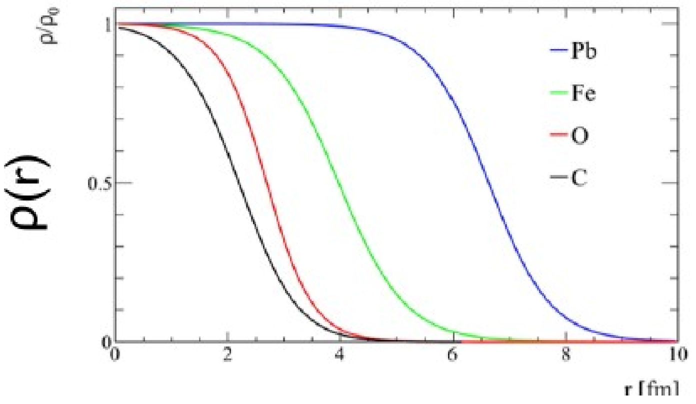
arXiv:1704.07835



FSI

- NEUT, NuWro, GENIE hN, FLUKA, Geant4 use Intra-Nuclear **Cascade Models**





- Particles are stepped within the nucleus
- At each step within the nuclear radius the mean free path is calculated:
  - $\lambda_{\text{step}}(r) = [\sigma_{\text{microsopic}}\rho(r)]^{-1}$
  - Using Monte Carlo method decide if interaction takes place
  - If not, continue to next step

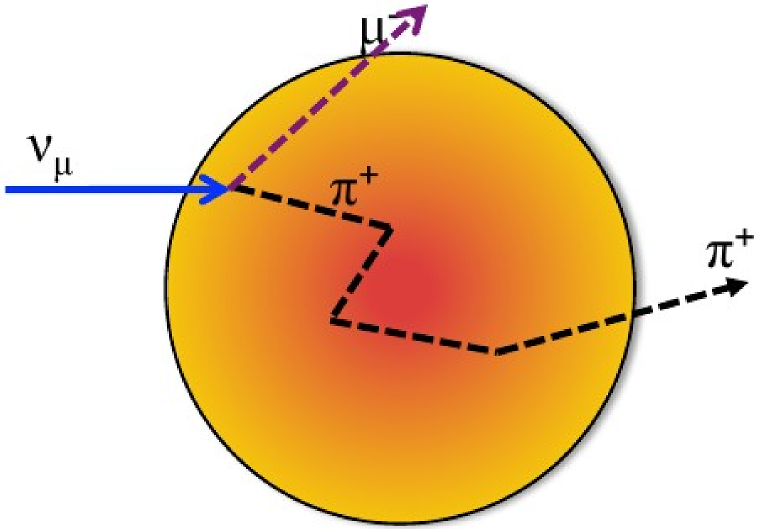
- A-dependence introduced through $\rho(r)$
  - Three-parameter Fermi model for Oxygen,
  - Two-parameter Fermi model for other nuclei

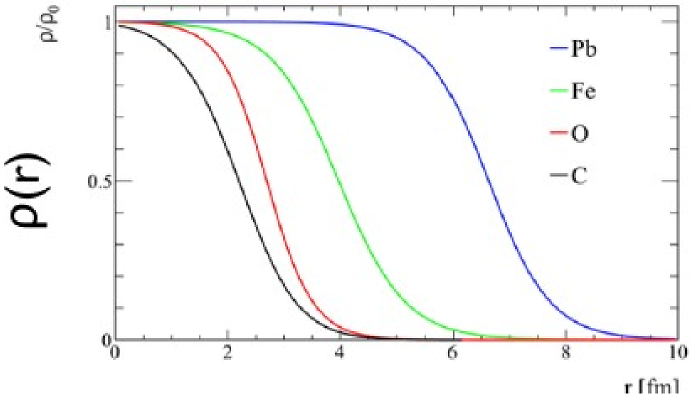
$$\frac{\rho(r)}{\rho_0} = \frac{1 + w\frac{r^2}{c^2}}{1 + \exp\left(\frac{r-c}{\alpha}\right)}$$

FSI

Elder Pinzon (York U.) – NuINT 2017

❖ NEUT, NuWro, GENIE hN, FLUKA, Geant4 use Intra-Nuclear **Cascade Models**





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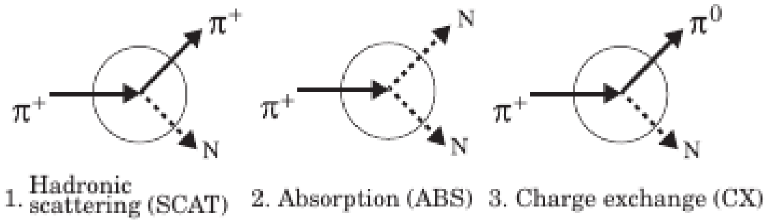
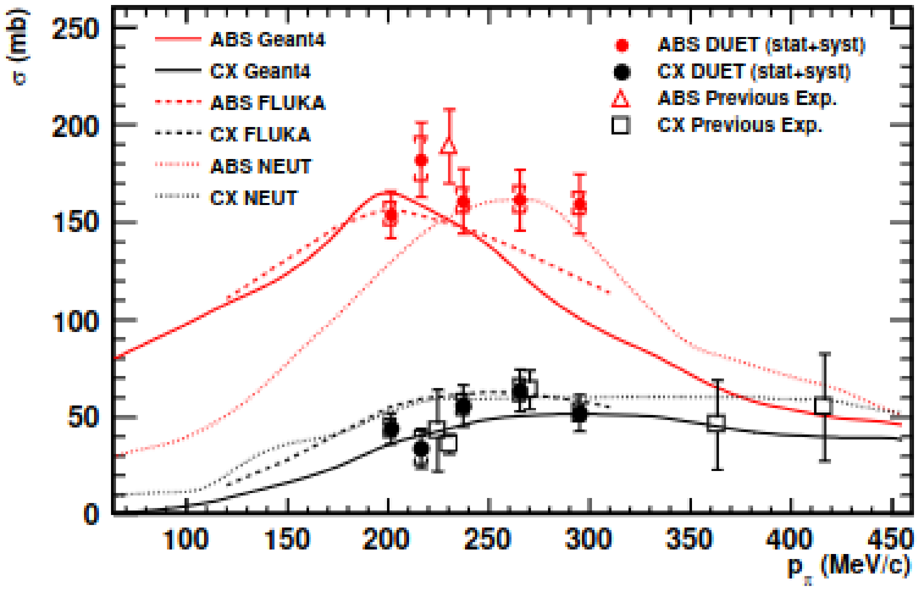
FSI model is tuned to external data: pion-Nucleus and proton-Nucleus cross-section.

Pions data

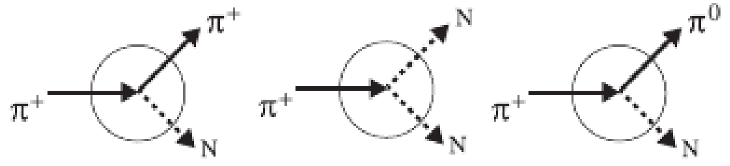


- Pion-nucleus cross-section: **very sparse data available**
- Recent (2017) measurement from **DUET** experiment at TRIUMF used for improved tuning

Phys.Rev.D 99 (2019) 5, 052007



Pions data



1. Hadronic scattering (SCAT) 2. Absorption (ABS) 3. Charge exchange (CX)

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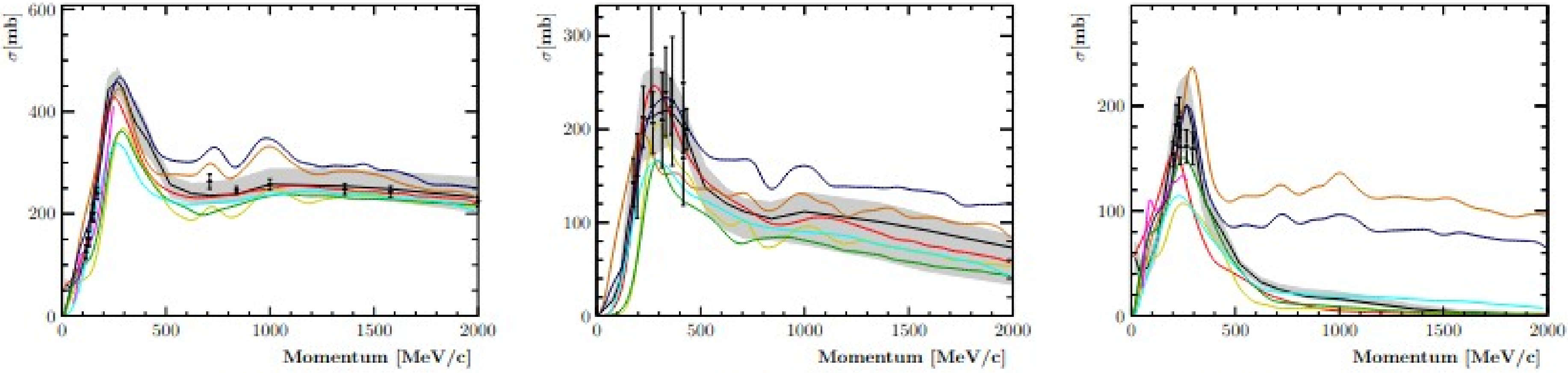
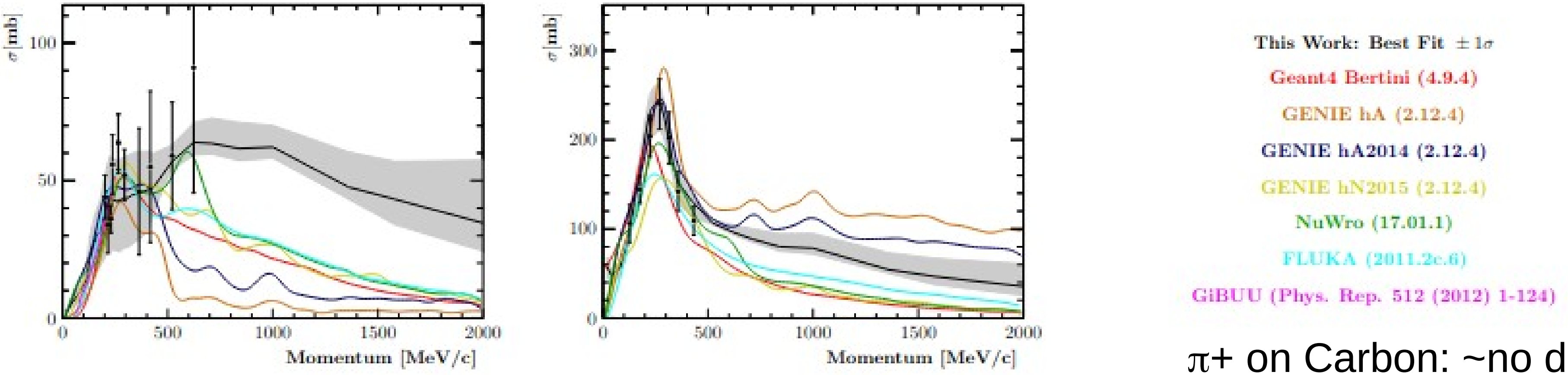


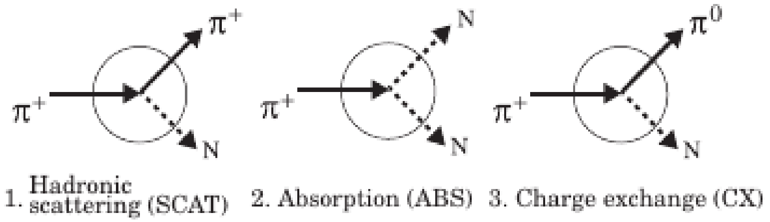
(a) Reactive (b) Quasi-elastic (c) Absorption (ABS)



(d) Charge exchange (CX) (e) ABS+CX

π+ on Carbon: ~no data above 500 MeV

Pions data



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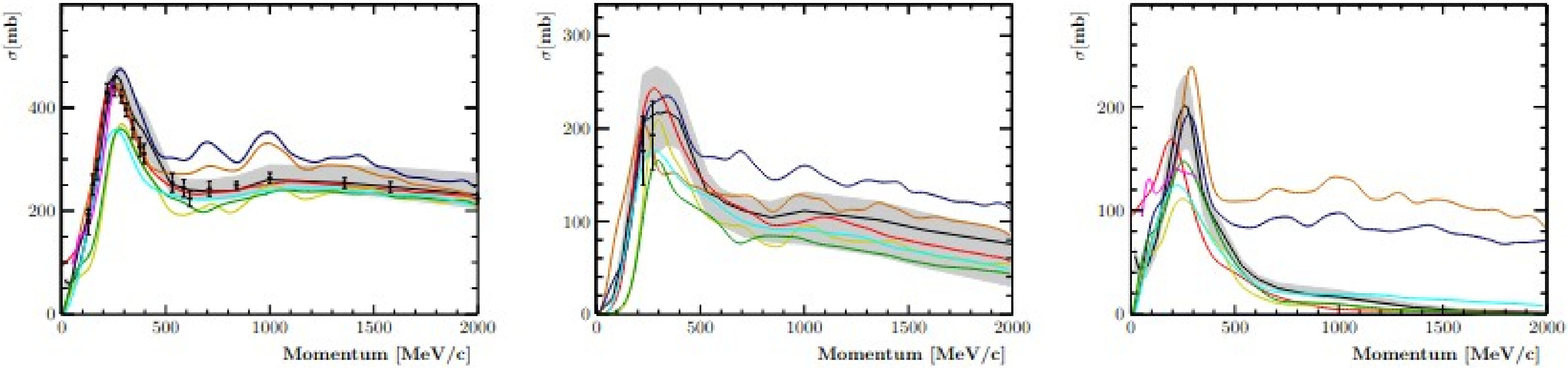

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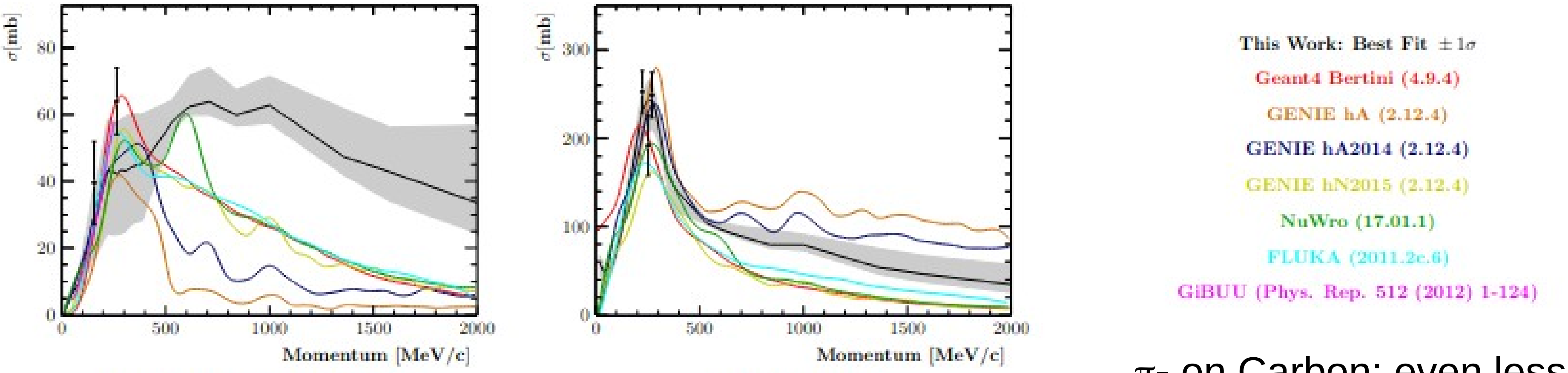
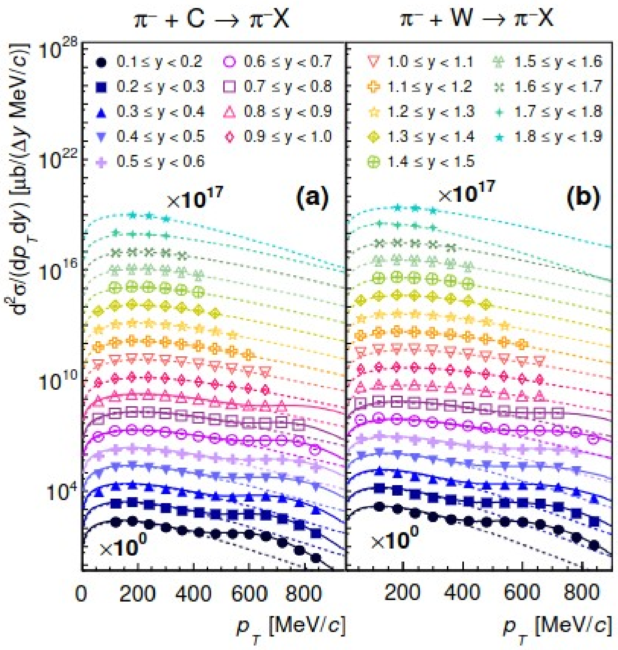


(d) Charge exchange (CX) (e) ABS+CX

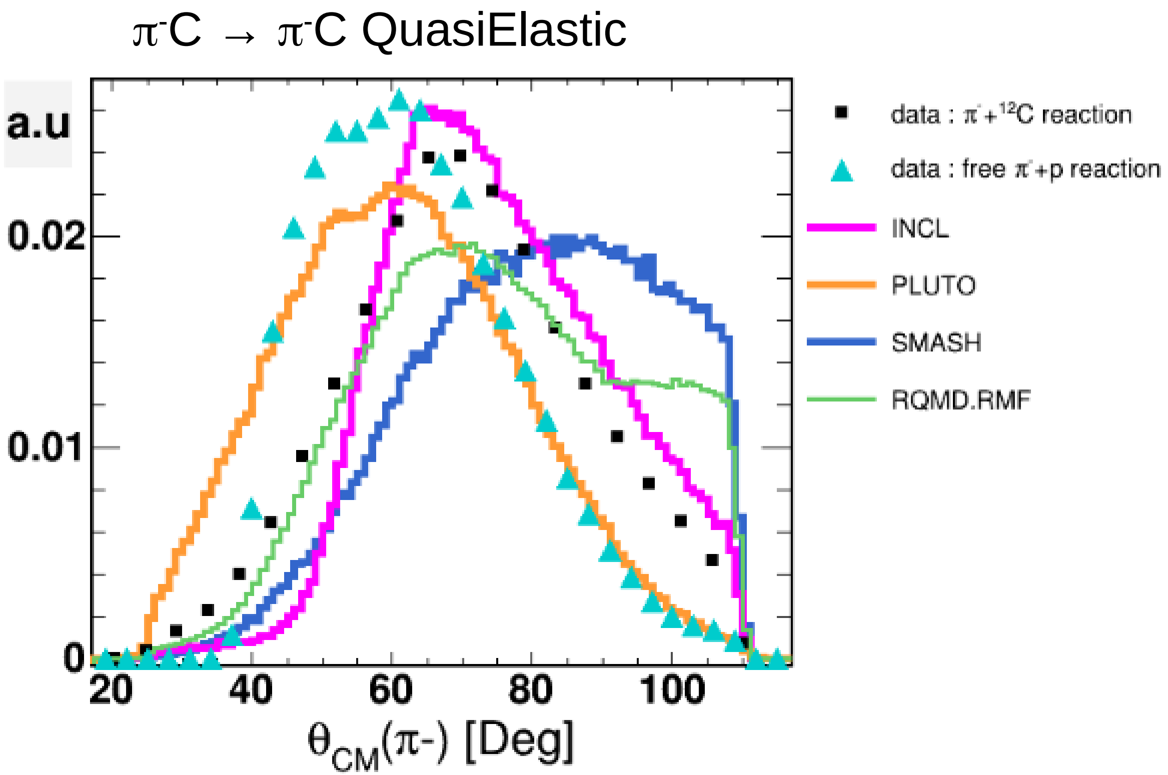
π- on Carbon: even less data!

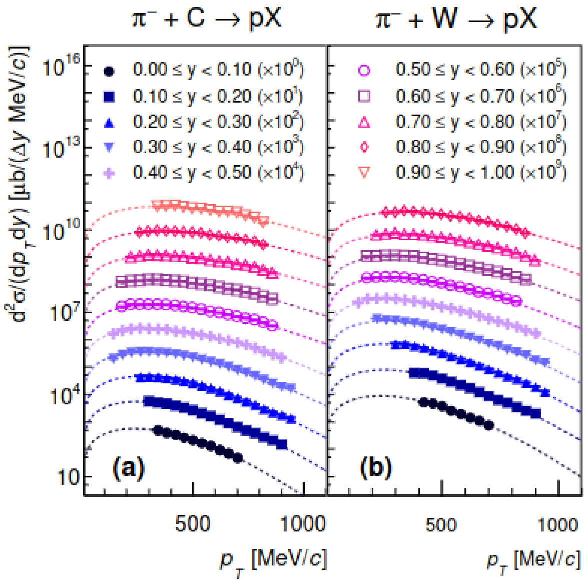
New HADES data!!

New HADES data:
π- + C/W @ 0.7GeV exclusive analysis



A gold mine of new data to tune our FSI models!





PoS FAIRness2022 (2023) 023

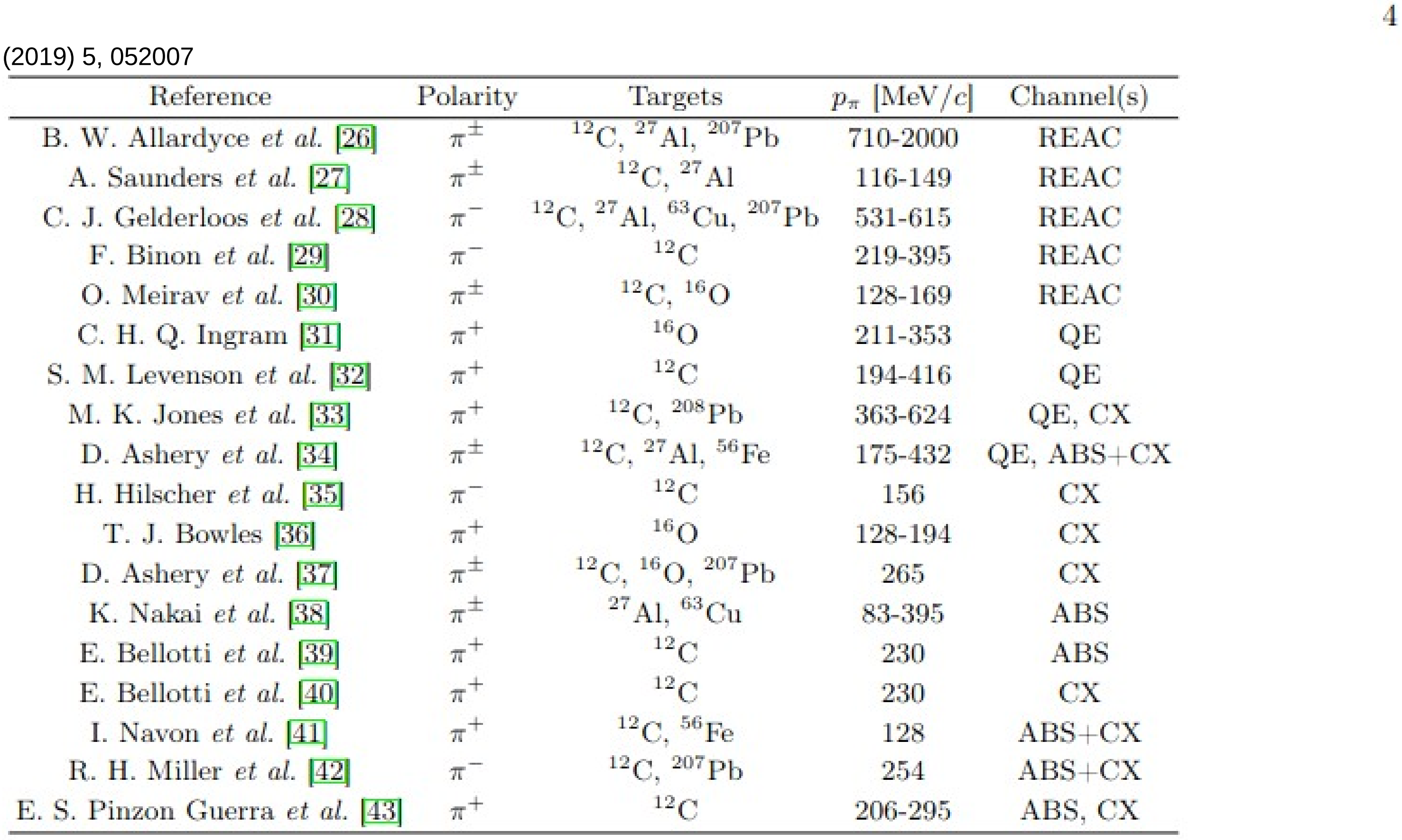
Thesis of F.Hojeij @ICJLab

e-Print:2301.03940

Pions data: A-dependence

- Pion-nucleus cross-section: **sparse data available for various nuclei**

Phys.Rev.D 99 (2019) 5, 052007



Reference	Polarity	Targets	p_π [MeV/c]	Channel(s)
B. W. Allardyce *et al.* [26]	$\pi^\pm$	^{12}C, ^{27}Al, ^{207}Pb	710-2000	REAC
A. Saunders *et al.* [27]	$\pi^\pm$	^{12}C, ^{27}Al	116-149	REAC
C. J. Gelderloos *et al.* [28]	π^-	^{12}C, ^{27}Al, ^{63}Cu, ^{207}Pb	531-615	REAC
F. Binon *et al.* [29]	π^-	^{12}C	219-395	REAC
O. Meirav *et al.* [30]	$\pi^\pm$	^{12}C, ^{16}O	128-169	REAC
C. H. Q. Ingram [31]	π^+	^{16}O	211-353	QE
S. M. Levenson *et al.* [32]	π^+	^{12}C	194-416	QE
M. K. Jones *et al.* [33]	π^+	^{12}C, ^{208}Pb	363-624	QE, CX
D. Ashery *et al.* [34]	$\pi^\pm$	^{12}C, ^{27}Al, ^{56}Fe	175-432	QE, ABS+CX
H. Hilscher *et al.* [35]	π^-	^{12}C	156	CX
T. J. Bowles [36]	π^+	^{16}O	128-194	CX
D. Ashery *et al.* [37]	$\pi^\pm$	^{12}C, ^{16}O, ^{207}Pb	265	CX
K. Nakai *et al.* [38]	$\pi^\pm$	^{27}Al, ^{63}Cu	83-395	ABS
E. Bellotti *et al.* [39]	π^+	^{12}C	230	ABS
E. Bellotti *et al.* [40]	π^+	^{12}C	230	CX
I. Navon *et al.* [41]	π^+	^{12}C, ^{56}Fe	128	ABS+CX
R. H. Miller *et al.* [42]	π^-	^{12}C, ^{207}Pb	254	ABS+CX
E. S. Pinzon Guerra *et al.* [43]	π^+	^{12}C	206-295	ABS, CX

Pions data: A-dependence

- Pion-nucleus cross-section: sparse data available for various nuclei → **the best way to tune FSI properly is to fit to all nuclei together: important info on FSI dynamic could be extracted from A-dependence**

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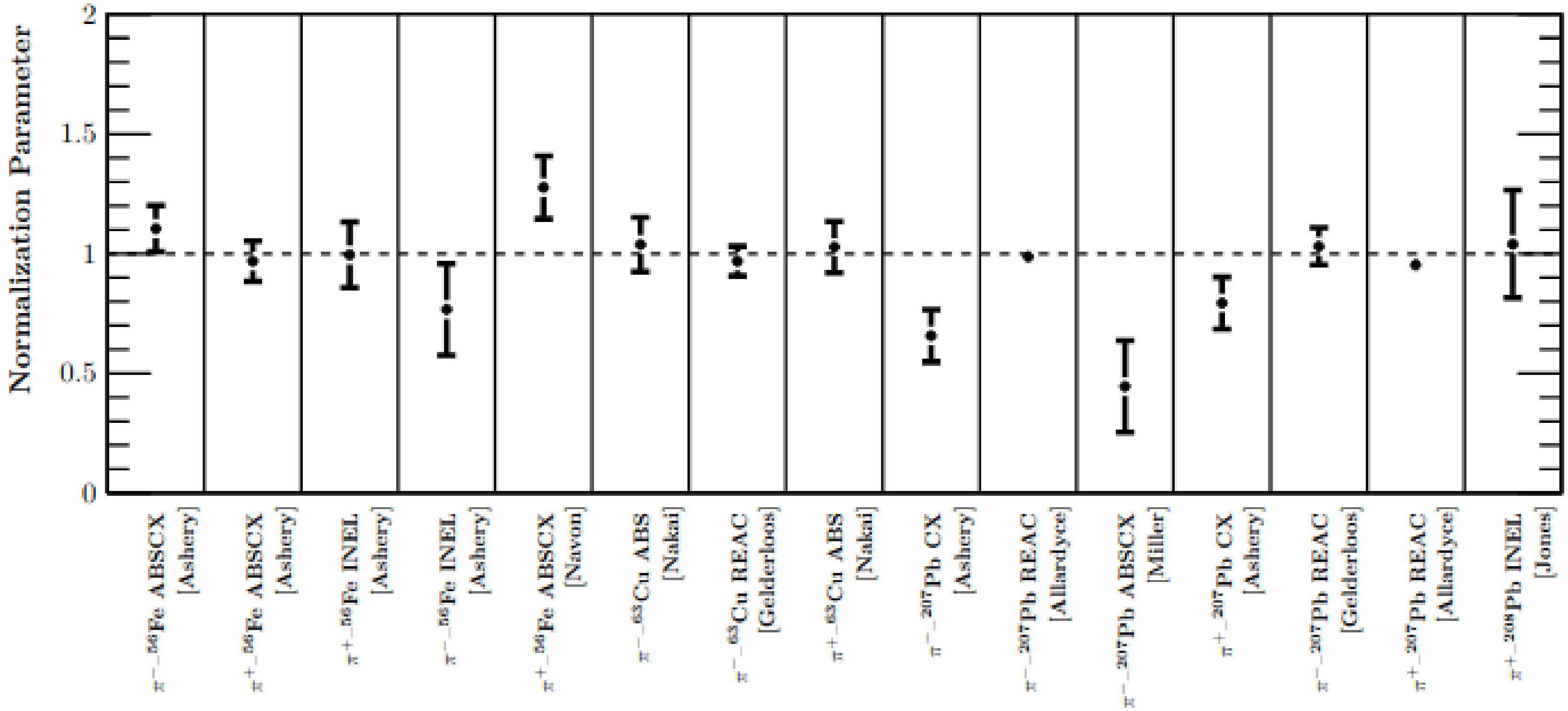
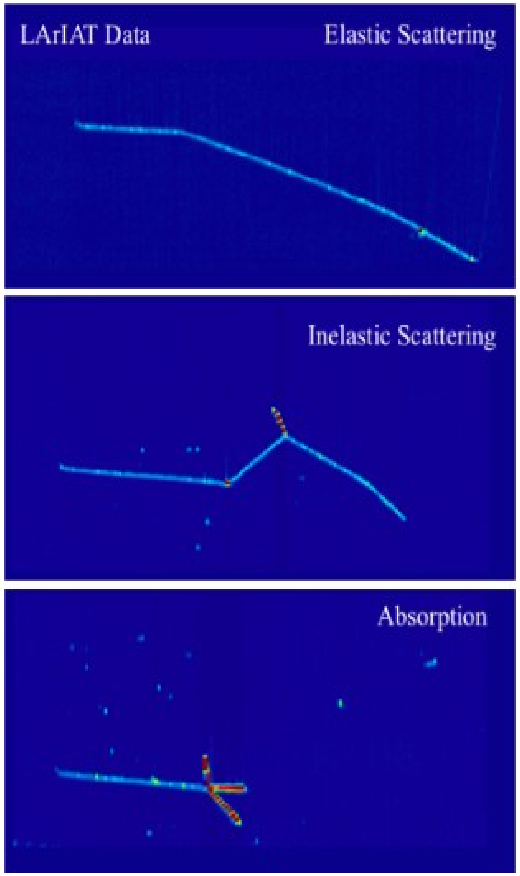
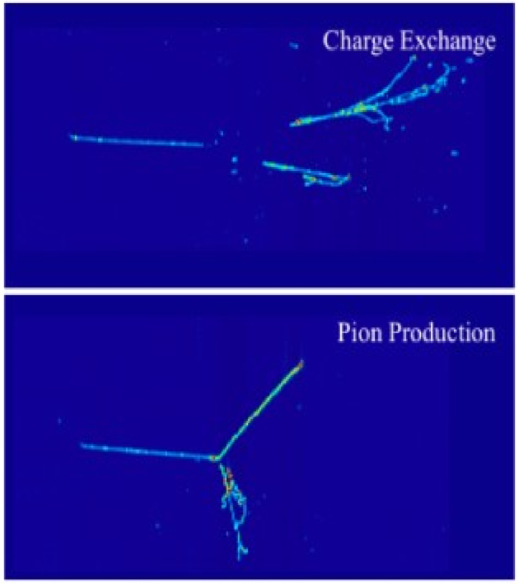


(c) Heavy nuclei

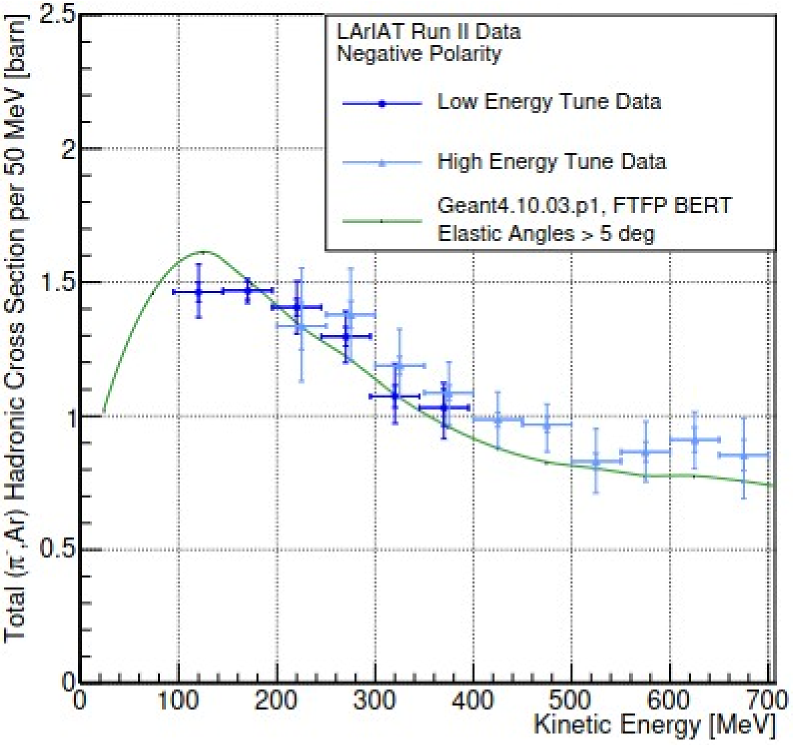
Pions data on Argon

- **LArIAT:** FNAL LAr on π- beam





Phys.Rev.D 106 (2022) 5, 052009

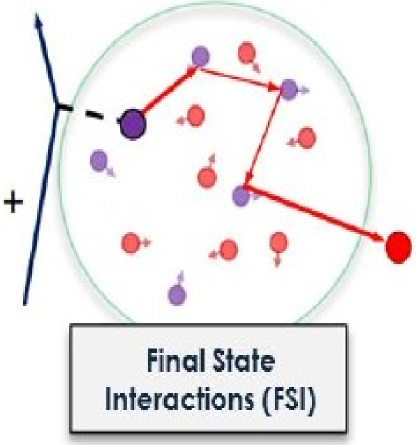


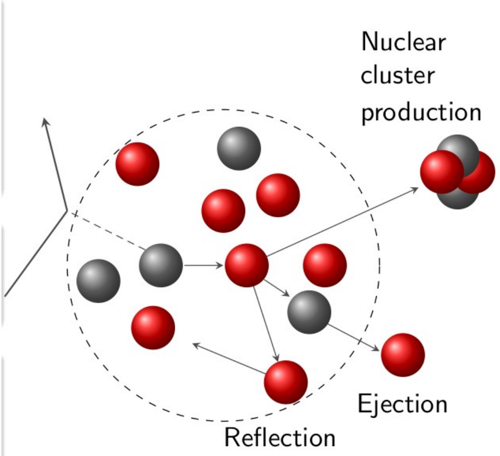
- **Large potential from DUNE prototypes on CERN test beam!**

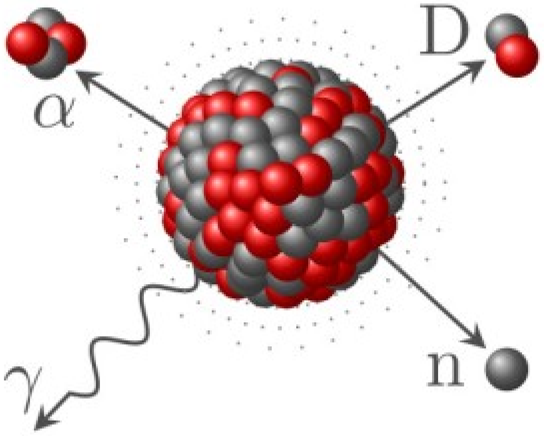
Phys.Rev.D 106 (2022) 3, 032009
e-Print: 2309.05410 [hep-ph]

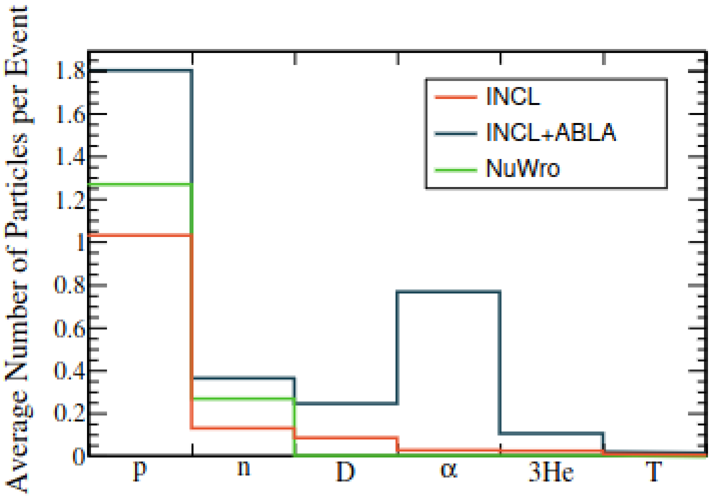
More sophisticated FSI models

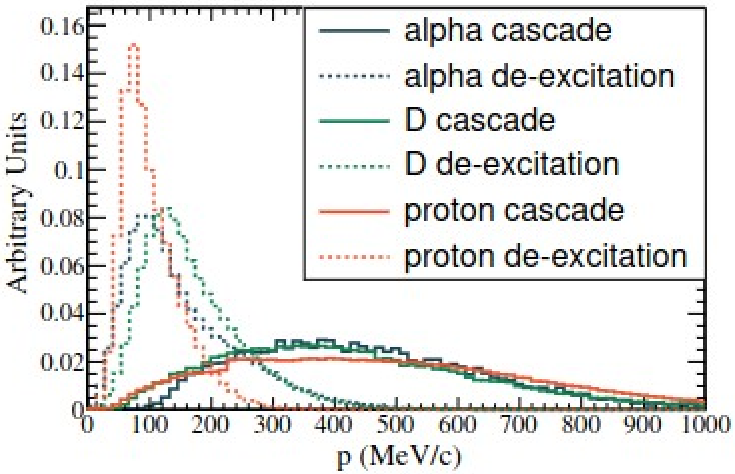
Recent study on proton FSI with more sophisticated model (INCL) put in evidence new effects: production of nuclear clusters!











Phys.Rev.D 106 (2022) 3, 032009
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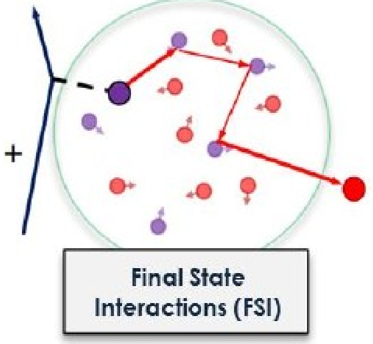
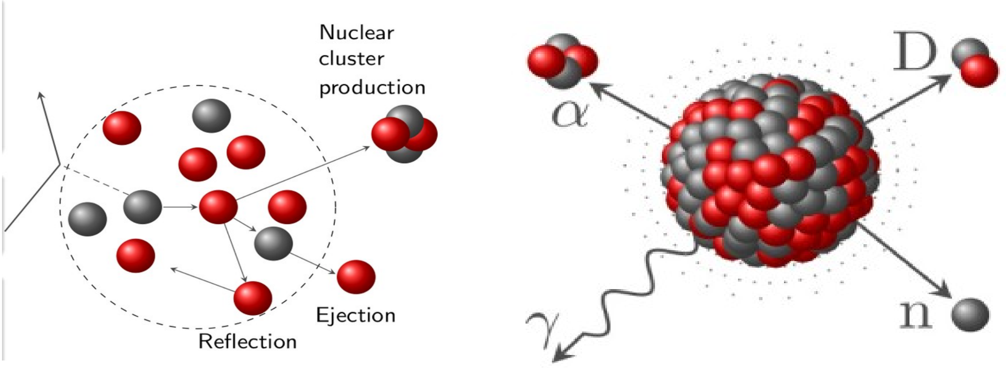
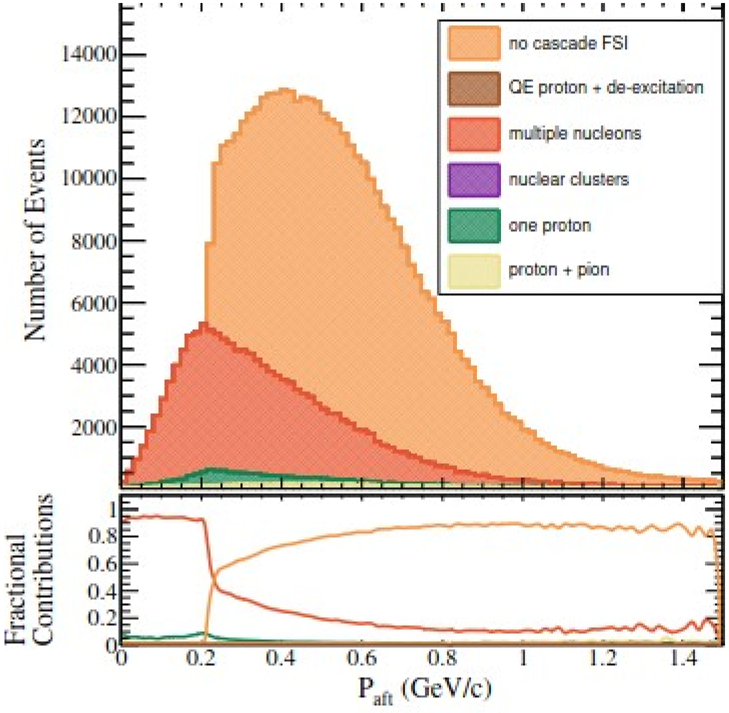
More sophisticated FSI models

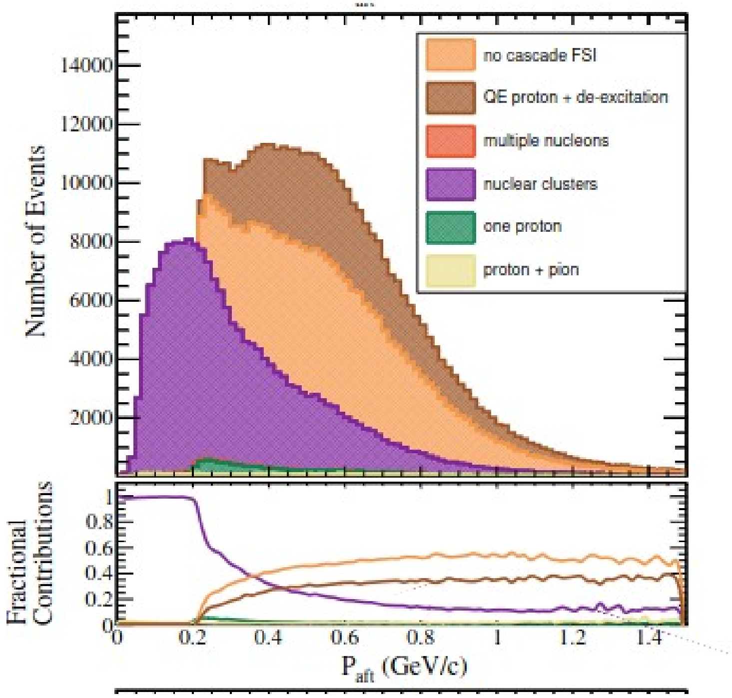
Recent study on proton FSI with more sophisticated model put in evidence new effects: production of nuclear clusters!





Impact also on leading order variables: eg, leading proton momentum

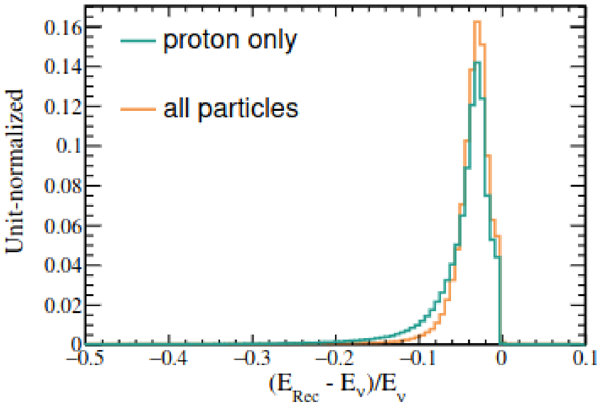




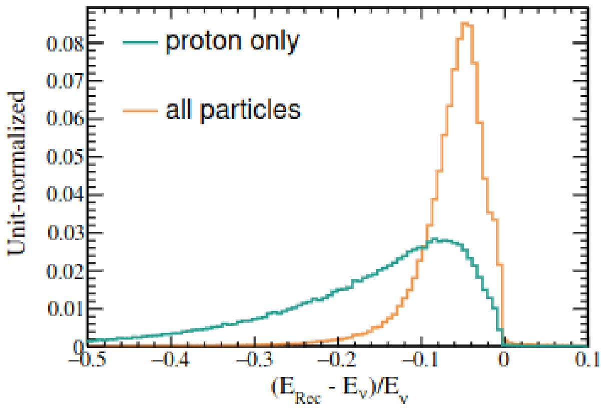
Vertex activity / calorimetric energy

For events with FSI, using only the leading outgoing nucleon is not enough: **need to reconstruct multiple nucleons and clusters for good neutrino energy reconstruction**

No FSI events



FSI events

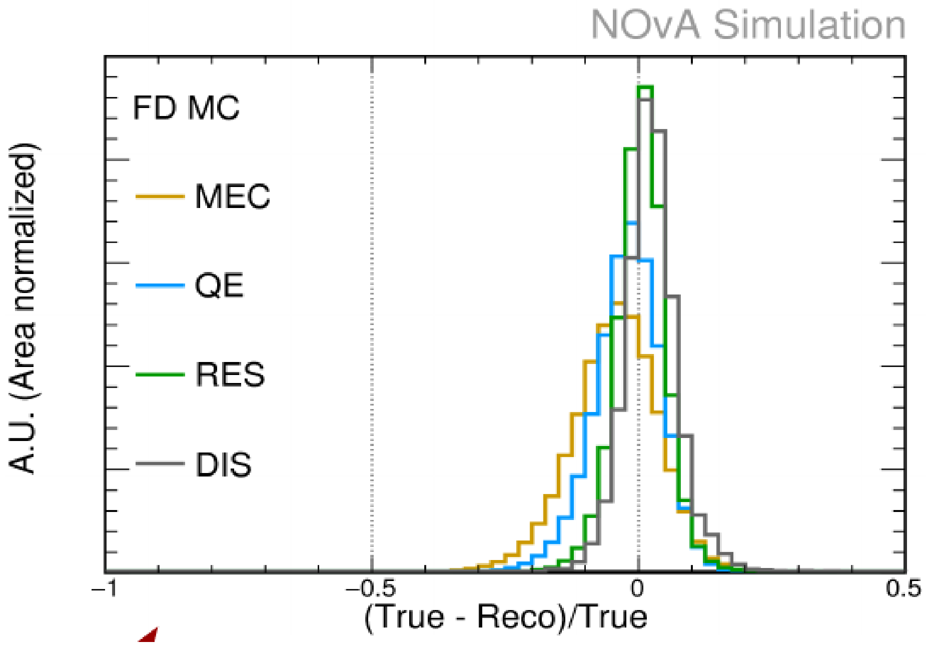


Generator level → detector effects very difficult to control for such low momentum/high mass particles (quenching, secondary interactions...)

An ‘inclusive’/’calorimetric’ energy reconstruction is never really inclusive!

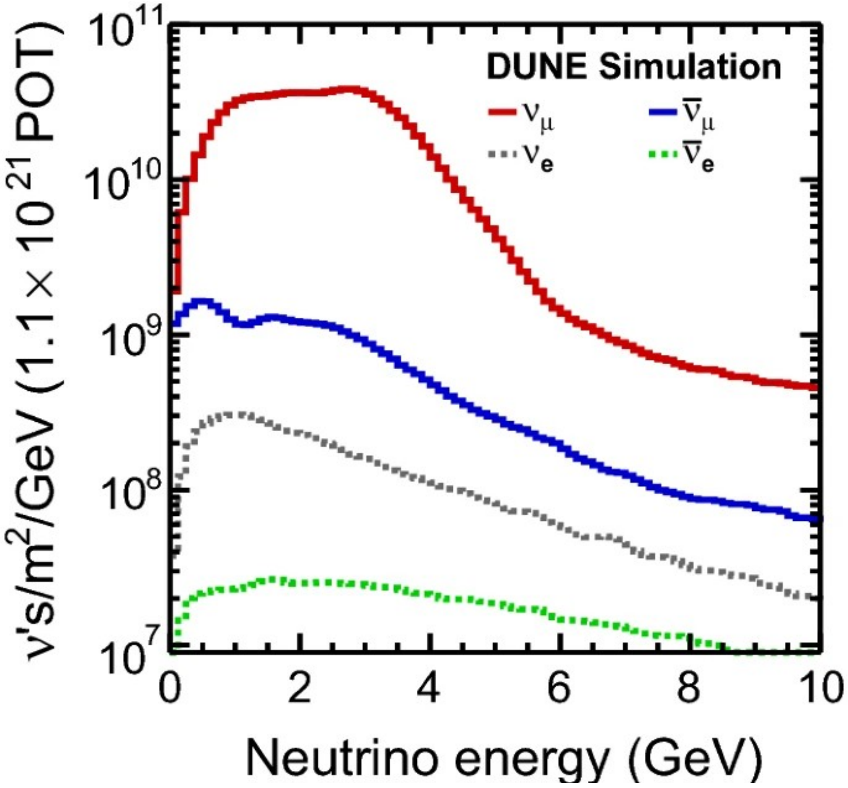
The response of the detector depends on the type of particle → need to have exclusive analysis/models to correct for detector effects

Example from NOVA:
different response of detector depending on the particle
→ different Eν resolution and bias depending on the final state
Need models to untangle detector response and get back to actual released energy

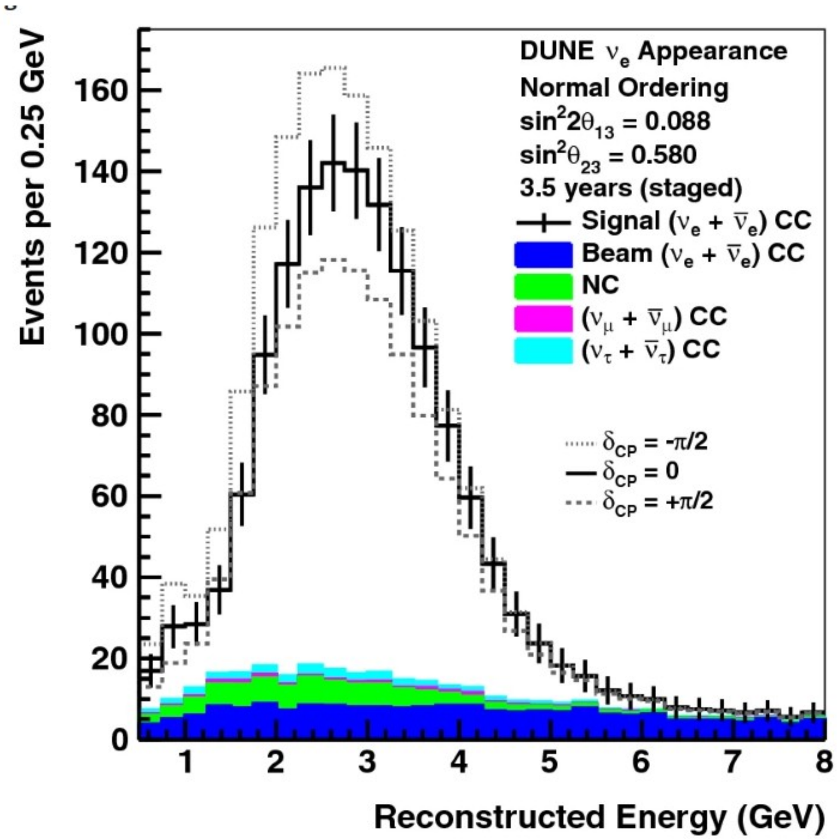


ND → FD: ν_e/ν_μ

Appearance of ν_e in ν_μ dominated flux: useful for θ_{23} octant determination + δ_{CP} measurement



oscillation



First order systematics on CPV

$$\mathcal{A}_{\rm CP} \equiv \frac{P(\nu_\mu \to \nu_e) - P(\overline{\nu}_\mu \to \overline{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\overline{\nu}_\mu \to \overline{\nu}_e)} \simeq -\frac{\sin 2\theta_{12} \boxed{\sin\delta}}{\sin\theta_{13}\tan\theta_{23}}\Delta_{21} + \text{matter effects} \, ,$$

$\delta_{CP} \neq 0, \pi$ means to demonstrate ν_e / $\bar{\nu}_e$ asymmetry ≠ 0

Most important systematics is ν_e / $\bar{\nu}_e$ rate prediction (xsec*flux*det)

What matter is the ANTICORRELATED uncertainty between ν_e and $\bar{\nu}_e$

- We use $\nu_\mu/\bar{\nu}_\mu$ at ND to constrain the ν_e / $\bar{\nu}_e$ model. So the relevant uncertainty for δ_{CP} is on the ratio $\nu_e/\nu_\mu/\bar{\nu}_e/\bar{\nu}_\mu$

ν_e uncertainties

- Flavor universality holds: the ν_e/ν_μ uncertainties fully comes from **dependence of the cross-section on the lepton mass (m_{lep})**

- Two main effects:

  - **dependence on m_{lep} of the ν-nucleus cross-section at leading order**

  - **dependence of the radiative corrections: the correction itself is expected to be small (NLO) but the dependence on mass can be enhanced**

- In both cases if the ν-nucleus cross-section is correctly modeled, the proper mass dependency can be calculated without uncertainties.
There is no “intrinsic” uncertainty in extrapolating from ν_μ to ν_e

- In reality the model of the cross-section has uncertainties and these uncertainties may affect differently ν_e and ν_μ due to the m_{lep} dependency of the part of the cross-section that is mis-modeled.
→ we express this in terms of uncorrelated uncertainty between ν_e and ν_μ
(but there is no “uncorrelation” in any single specific model of cross-section, it is just a way to say that we do not know the proper model both for ν_e and ν_μ)

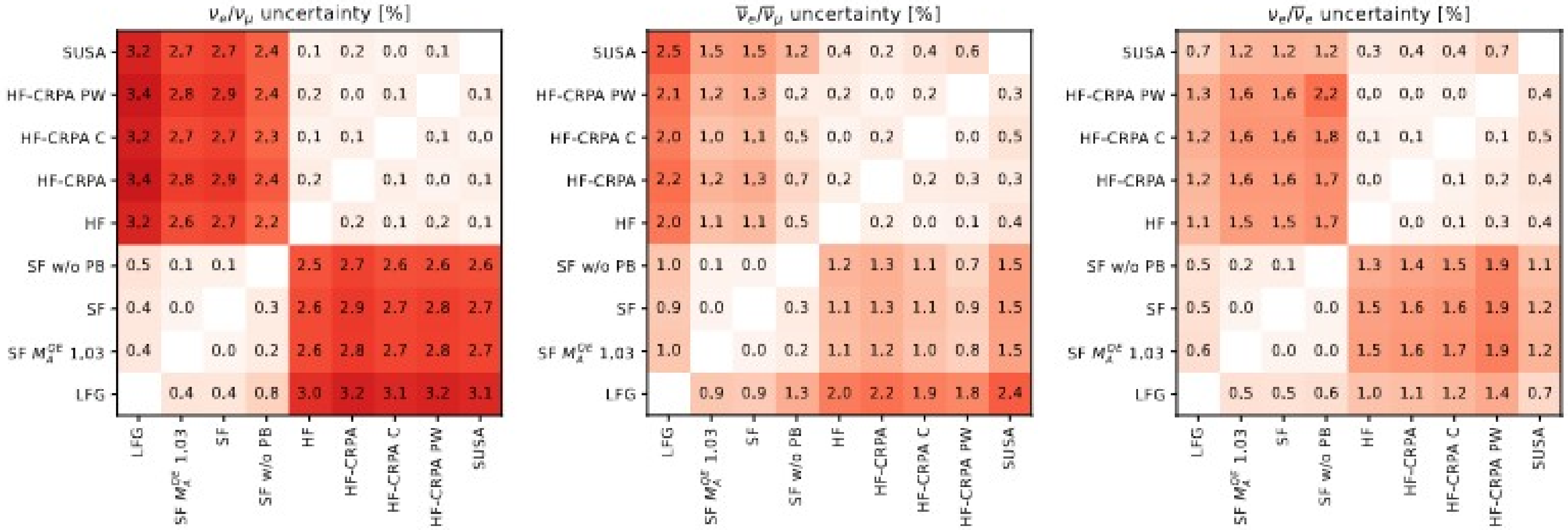
ν_e, ν_μ, $\bar{\nu}_e$, $\bar{\nu}_\mu$ uncertainties

- Both for radiative corrections and for nuclear effects, the mass dependency is the same for ν_e and $\bar{\nu}_e$ so the uncertainty is expected to be mostly correlated between ν_e and $\bar{\nu}_e$

- All the theoretical uncertainties which may have anticorrelated effects between ν and $\bar{\nu}$ (Coulomb corrections, 2p2h) are mostly correlated between ν_μ and ν_e

- So *<u>in our present understanding</u>* of the **theory: uncertainty on $\nu_e/\nu_\mu/\bar{\nu}_e/\bar{\nu}_\mu$ should be very small except in specific regions of the phase space** (where $\nu_\mu/\bar{\nu}_\mu$ uncertainty become relevant for ν_e/ν_μ differences)

Recent results: nuclear effects



ν_e/ν_μ uncertainty [%]

	LFG	SF M_A^{QE} 1.03	SF	SF w/o PB	HF	HF-CRPA	HF-CRPA C	HF-CRPA PW	SUSA
SUSA	3.2	2.7	2.7	2.4	0.1	0.2	0.0	0.1	
HF-CRPA PW	3.4	2.8	2.9	2.4	0.2	0.0	0.1		0.1
HF-CRPA C	3.2	2.7	2.7	2.3	0.1	0.1		0.1	0.0
HF-CRPA	3.4	2.8	2.9	2.4	0.2		0.1	0.0	0.1
HF	3.2	2.6	2.7	2.2		0.2	0.1	0.2	0.1
SF w/o PB	0.5	0.1	0.1		2.5	2.7	2.6	2.6	2.6
SF	0.4	0.0		0.3	2.6	2.9	2.7	2.8	2.7
SF M_A^{QE} 1.03	0.4		0.0	0.2	2.6	2.8	2.7	2.8	2.7
LFG		0.4	0.4	0.8	3.0	3.2	3.1	3.2	3.1

$\overline{\nu}_e/\overline{\nu}_\mu$ uncertainty [%]

	LFG	SF M_A^{QE} 1.03	SF	SF w/o PB	HF	HF-CRPA	HF-CRPA C	HF-CRPA PW	SUSA
SUSA	2.5	1.5	1.5	1.2	0.4	0.2	0.4	0.6	
HF-CRPA PW	2.1	1.2	1.3	0.2	0.2	0.0	0.2		0.3
HF-CRPA C	2.0	1.0	1.1	0.5	0.0	0.2		0.0	0.5
HF-CRPA	2.2	1.2	1.3	0.7	0.2		0.2	0.3	0.3
HF	2.0	1.1	1.1	0.5		0.2	0.0	0.1	0.4
SF w/o PB	1.0	0.1	0.0		1.2	1.3	1.1	0.7	1.5
SF	0.9	0.0		0.3	1.1	1.3	1.1	0.9	1.5
SF M_A^{QE} 1.03	1.0		0.0	0.2	1.1	1.2	1.0	0.8	1.5
LFG		0.9	0.9	1.3	2.0	2.2	1.9	1.8	2.4

$\nu_e/\overline{\nu}_e$ uncertainty [%]

	LFG	SF M_A^{QE} 1.03	SF	SF w/o PB	HF	HF-CRPA	HF-CRPA C	HF-CRPA PW	SUSA
SUSA	0.7	1.2	1.2	1.2	0.3	0.4	0.4	0.7	
HF-CRPA PW	1.3	1.6	1.6	2.2	0.0	0.0	0.0		0.4
HF-CRPA C	1.2	1.6	1.6	1.8	0.1	0.1		0.1	0.5
HF-CRPA	1.2	1.6	1.6	1.7	0.0		0.1	0.2	0.4
HF	1.1	1.5	1.5	1.7		0.0	0.1	0.3	0.4
SF w/o PB	0.5	0.2	0.1		1.3	1.4	1.5	1.9	1.1
SF	0.5	0.0		0.0	1.5	1.6	1.6	1.9	1.2
SF M_A^{QE} 1.03	0.6		0.0	0.0	1.5	1.6	1.7	1.9	1.2
LFG		0.5	0.5	0.6	1.0	1.1	1.2	1.4	0.7

FIG. 3: The flux-averaged uncertainties in percent obtained by comparing the different cross section models shown in table I: Δ_{ν_e/ν_μ} (left), $\Delta_{\bar{\nu}_e/\bar{\nu}_\mu}$ (centre), $\Delta_{\nu_e/\bar{\nu}_e}$ (right). The lower triangle is averaged over the event rate distribution predicted by the model given on the horizontal-axis, while the upper triangle contains the resulting values from the averaging over the model on the vertical-axis, resulting in an asymmetric matrix.

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Radiative corrections

- Electrons and muons tend to emit **soft and collinear gammas with different probabilities depending on m_{lep} (small electron mass gives more emission)**

This is a small effect (at NLO level) on the total cross-section but can get enhanced in specific kinematics regions (when gammas very soft and very collinear)

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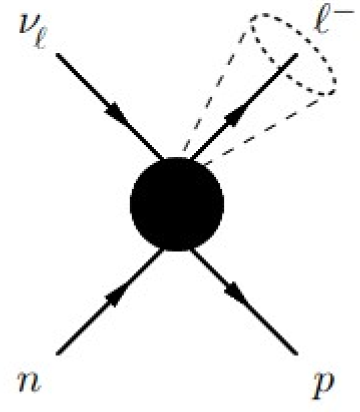
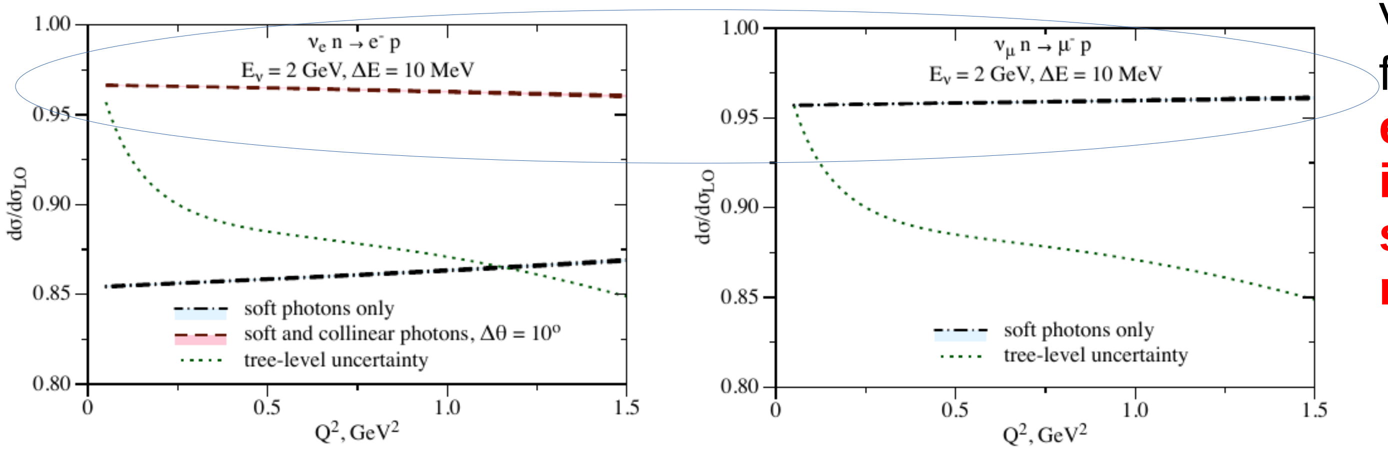


- **NLO/LO Xsec** for ‘realistic’ flavour selection
  - muons including soft gammas and vetoing hard gammas
  - electrons including soft and collinear gammas and vetoing hard gammas
  - should reproduce what we measure in detectors



Very similar NLO correction for ν_e and ν_μ: **radiative effect on ν_e/ν_μ <5% if we make proper cuts to simulate detector lepton reconstruction**

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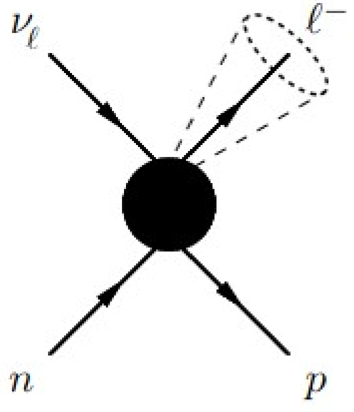
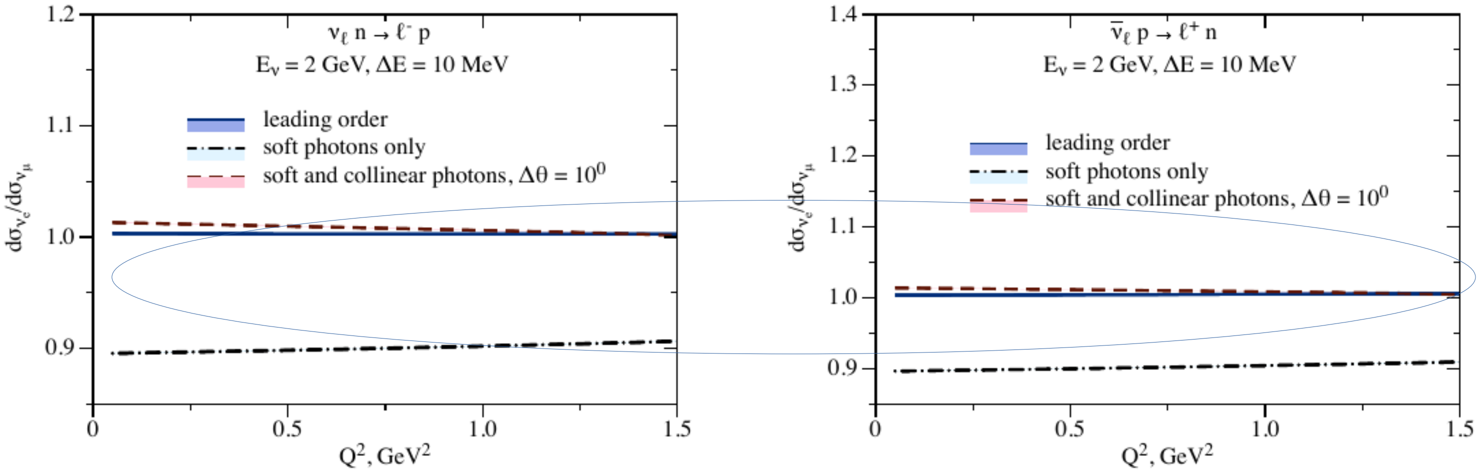
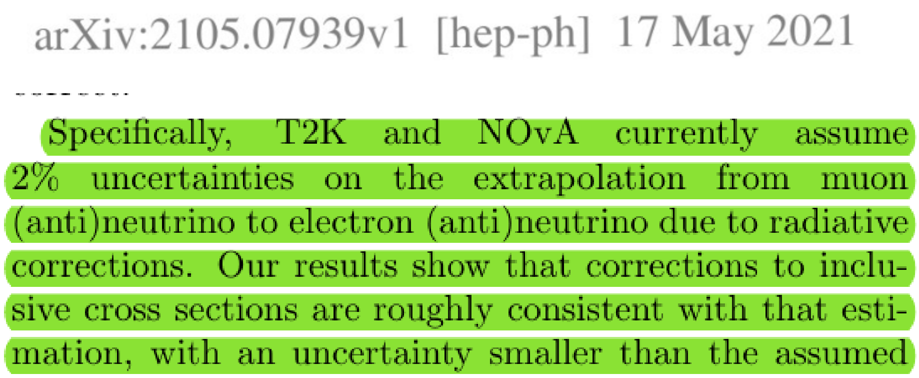




Very similar between ν and $\bar\nu$

radiative effects on $\nu_e/\nu_\mu/\bar\nu_e/\bar\nu_\mu$ <1-2%

Conclusions for radiative corrections



arXiv:2105.07939v1 [hep-ph] 17 May 2021

Specifically, T2K and NOvA currently assume 2% uncertainties on the extrapolation from muon (anti)neutrino to electron (anti)neutrino due to radiative corrections. Our results show that corrections to inclusive cross sections are roughly consistent with that estimation, with an uncertainty smaller than the assumed

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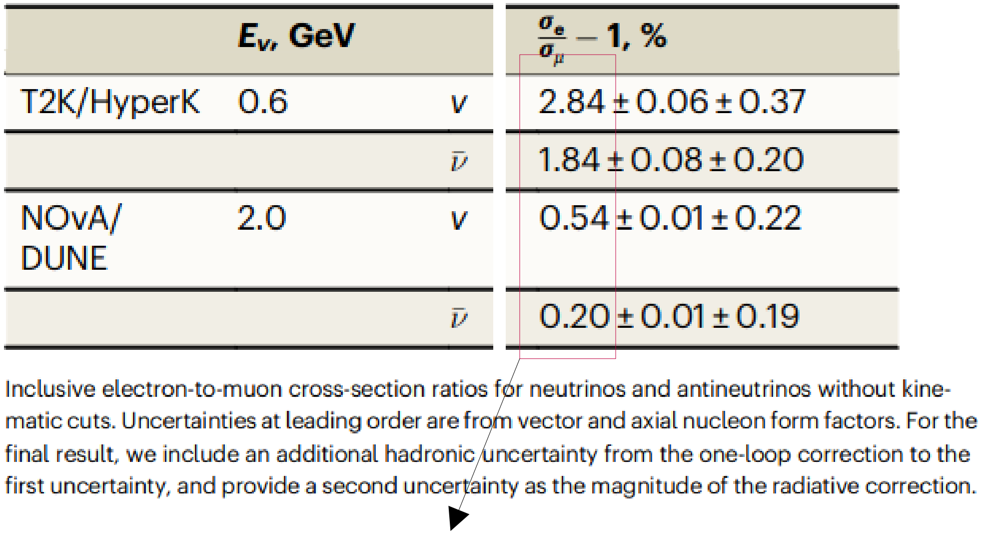
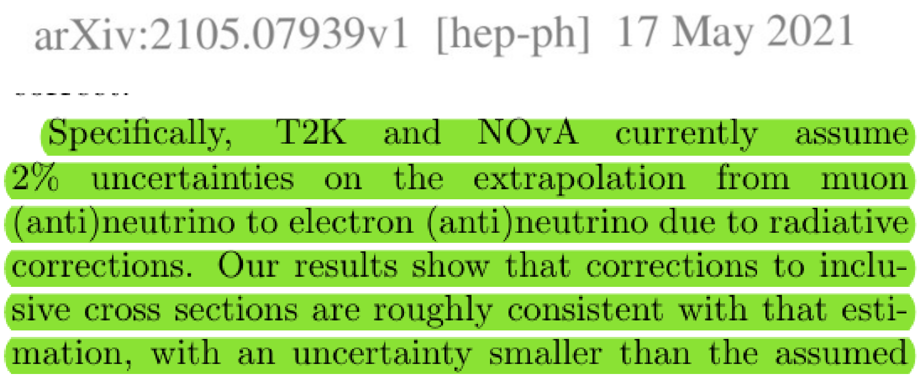


	E_ν, GeV		$\frac{\sigma_e}{\sigma_\mu}-1$, %
T2K/HyperK	0.6	ν	2.84 ± 0.06 ± 0.37
		$\bar{\nu}$	1.84 ± 0.08 ± 0.20
NOvA/ DUNE	2.0	ν	0.54 ± 0.01 ± 0.22
		$\bar{\nu}$	0.20 ± 0.01 ± 0.19

Inclusive electron-to-muon cross-section ratios for neutrinos and antineutrinos without kinematic cuts. Uncertainties at leading order are from vector and axial nucleon form factors. For the final result, we include an additional hadronic uncertainty from the one-loop correction to the first uncertainty, and provide a second uncertainty as the magnitude of the radiative correction.

Difference between ν_e/ν_μ xsec is small (<3%)

Conclusions for radiative corrections



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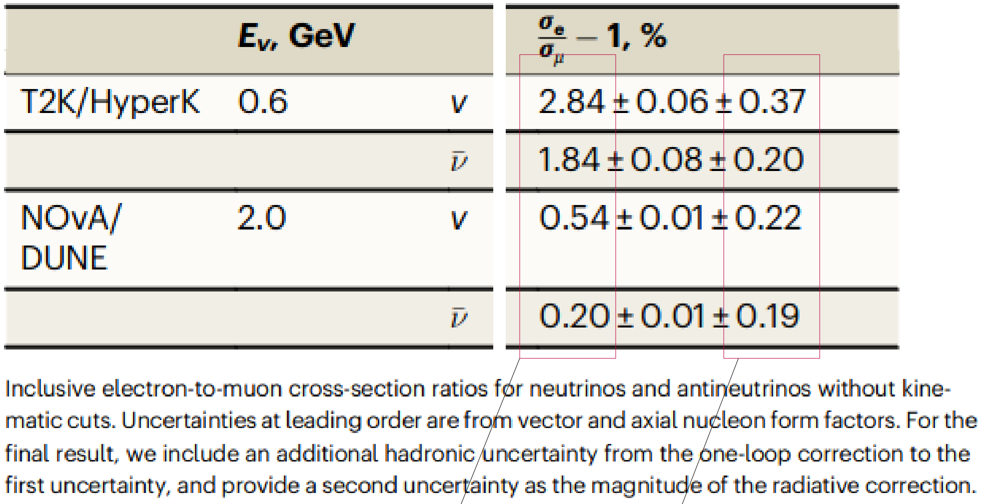

E_ν, GeV			$\frac{\sigma_e}{\sigma_\mu} - 1$, %
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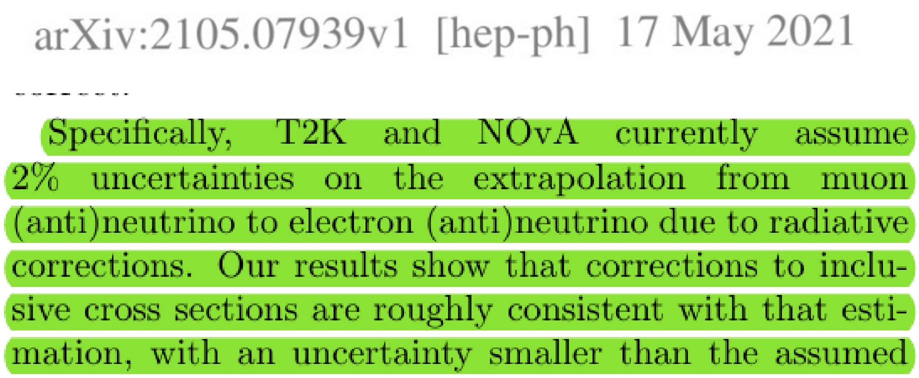
Difference between ν_e/ν_μ xsec is small (<3%)

Size of the radiative effect is small (<1%)

Conclusions for radiative corrections



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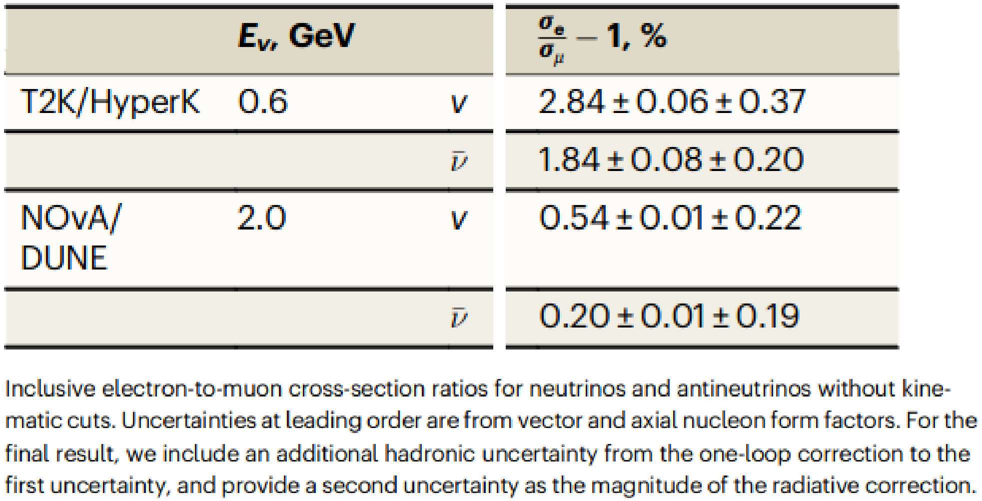

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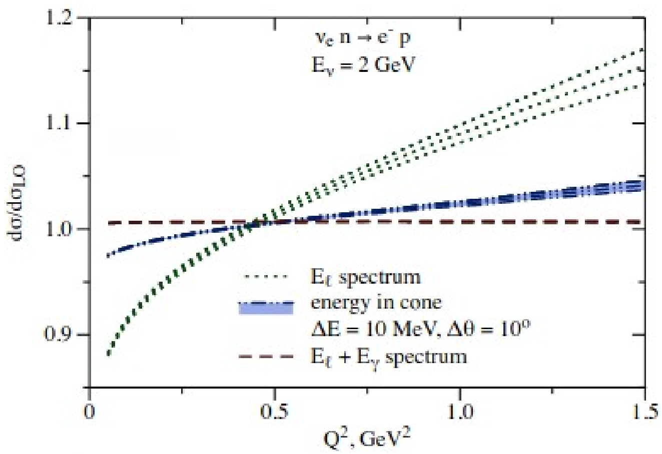
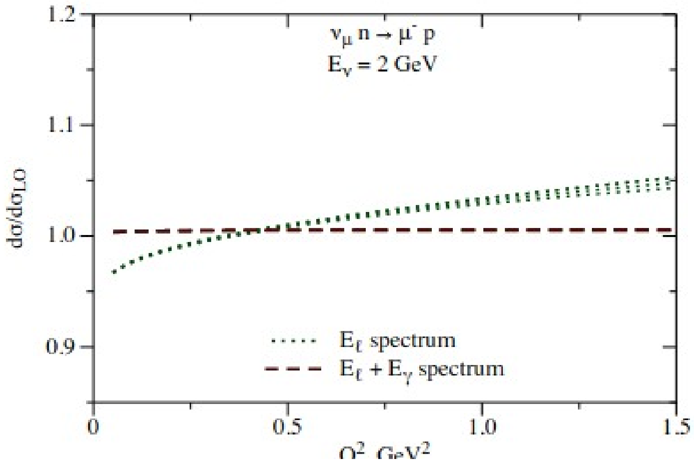
We will need to use this theory calculation to get the kinematics right (but not so important, to first order, for CPV but important for precision measurement of δCP)





And again ν and $\bar{\nu}$ behave in the same way (correlated uncertainties)

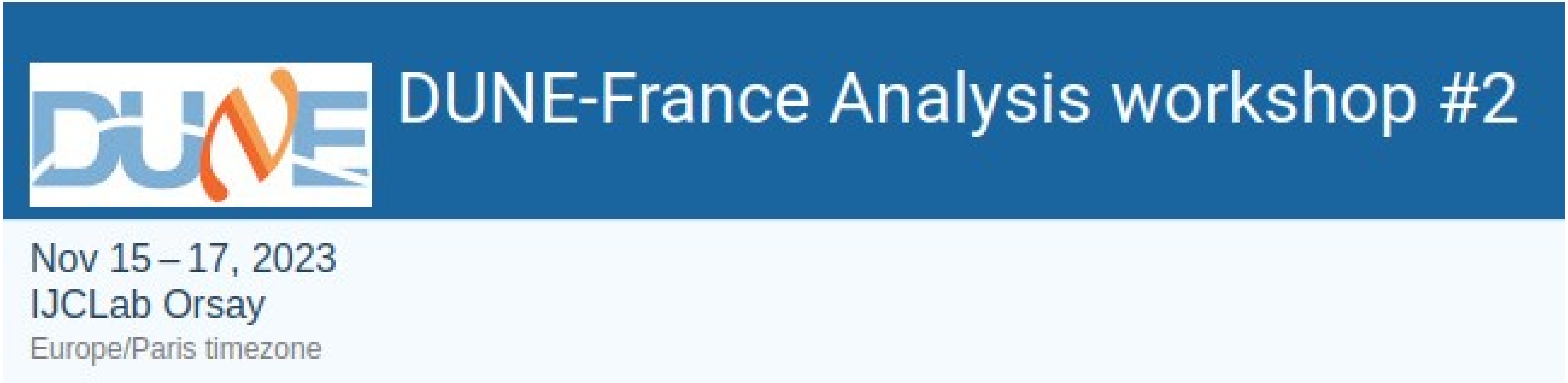
Summary

The LBL domain is moving from inclusive (lepton-only) to exclusive analysis (lepton+hadrons) analysis to improve the **resolution of neutrino energy reconstruction.**
Actually, compulsory at energy higher than CCQE as in DUNE.

Need to control new effects: **'missing energy'**
→ important input from **ND280 upgrade neutron measurements**
→ important to **tune FSI models to external data (HADES!)** to correct for hadrons below threshold
(A joint effort of the LBL domain on FSI tuning would be welcome!)

A **'calorimetric' energy** reconstruction is not really inclusive given to the different response of detector to different particles: need to model exclusive final states to 'unfold' detector effects properly
(Recent FSI studies shows production of much more different particles: eg, nuclear clusters)

ν_e/ν_μ is the leading systematics on CP-violation discover (and MH determination) but theory/phenomenological studies keep confirming small effects for xsec differences
(except in very specific phase space regions)



DUNE-France Analysis workshop #2

Nov 15 – 17, 2023
IJCLab Orsay
Europe/Paris timezone

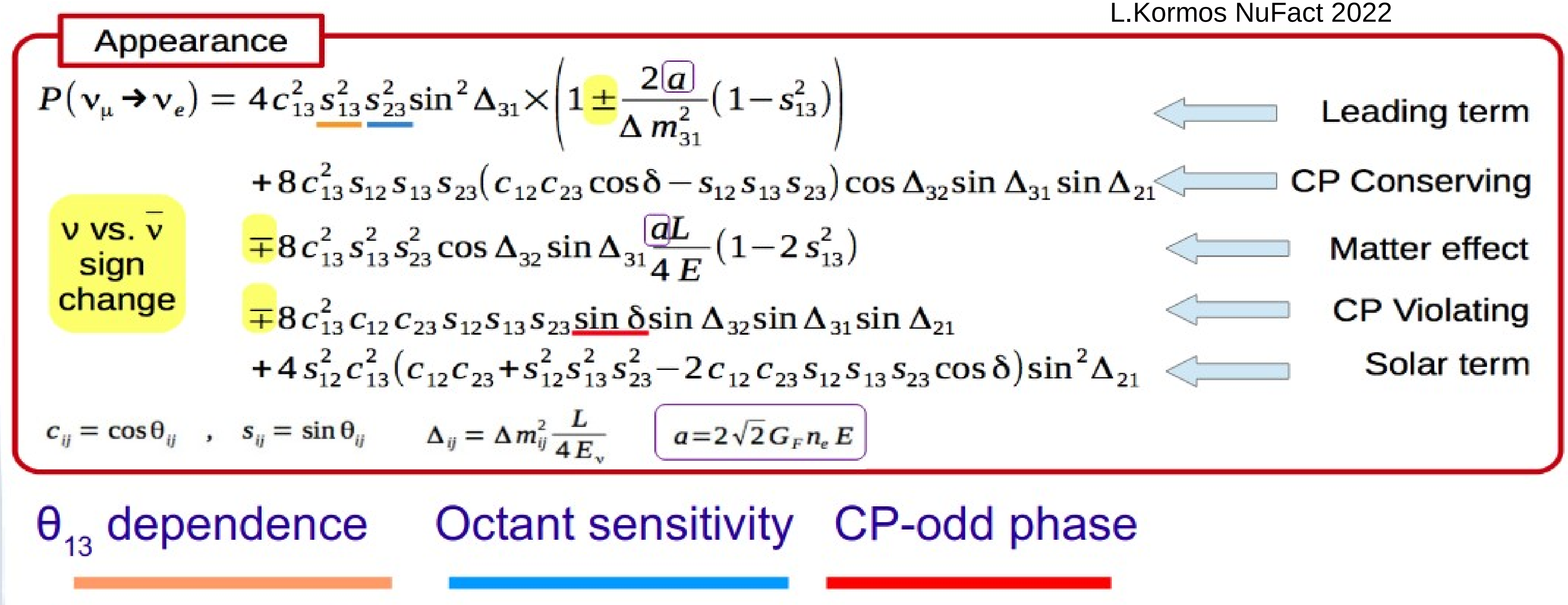
Oscillation measurements at high statistics:

statistical challenges and beyond

S.Bolognesi (CEA, IRFU)

Oscillation probability

L.Kormos NuFact 2022



Appearance

$$P(\nu_\mu \rightarrow \nu_e) = 4c_{13}^2 \underline{s_{13}^2} \underline{s_{23}^2} \sin^2\Delta_{31} \times \left(1 \pm \frac{2\boxed{a}}{\Delta m_{31}^2}(1-s_{13}^2)\right)$$ Leading term

$$+8c_{13}^2 s_{12} s_{13} s_{23}(c_{12}c_{23}\cos\delta - s_{12}s_{13}s_{23})\cos\Delta_{32}\sin\Delta_{31}\sin\Delta_{21}$$ CP Conserving

$$\mp 8c_{13}^2 s_{13}^2 s_{23}^2 \cos\Delta_{32}\sin\Delta_{31}\frac{\boxed{a}L}{4E}(1-2s_{13}^2)$$ Matter effect

$$\mp 8c_{13}^2 c_{12} c_{23} s_{12} s_{13} s_{23} \underline{\sin\delta} \sin\Delta_{32}\sin\Delta_{31}\sin\Delta_{21}$$ CP Violating

$$+4s_{12}^2 c_{13}^2 (c_{12}c_{23} + s_{12}^2 s_{13}^2 s_{23}^2 - 2c_{12}c_{23}s_{12}s_{13}s_{23}\cos\delta)\sin^2\Delta_{21}$$ Solar term

ν vs. $\bar{\nu}$ sign change

$c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$ $\Delta_{ij} = \Delta m_{ij}^2 \frac{L}{4E_\nu}$ $\boxed{a = 2\sqrt{2}G_F n_e E}$

θ_{13} dependence Octant sensitivity CP-odd phase

- leading dependence on δ_{CP} and MO (prop. to L), changing sign for ν and $\bar{\nu}$

- need large θ_{13} to access sinδ_{CP} (sensitivity to δ_{CP} from ν only if θ_{13} well known)

- subleading dependence on cosδ_{CP} → important for δ_{CP} precision measurement

Likelihood

$\mathbf{x}_{\mathbf{obs}}$ = main observable E^{ν}_{rec}
+ others: θ^{μ} (δp_T, …) to constrain systematics and separate Sig/Backgr

o = oscillation parameters (θ_{ij}, δ_{CP}, δm^2_{ij})
f = systematic parameters (xsec, flux, detector model)

$$\mathcal{L}(\{N_s^{\text{obs.}}, \boldsymbol{x}_s^{\text{obs.}}\}_{\forall s}, \boldsymbol{o}, \boldsymbol{f}) = \prod_{s \in \text{samples}} \left[\mathcal{L}_s(N_s^{\text{obs.}}, \boldsymbol{x}_s^{\text{obs.}}, \boldsymbol{o}, \boldsymbol{f})\right] \times \mathcal{L}_{\text{syst.}}(\boldsymbol{f})$$

$$\sum_{i \in \text{bins}} \left[\left(N_{s,i}^{\text{exp.}} - N_{s,i}^{\text{obs.}}\right) + N_{s,i}^{\text{obs.}} \times \ln\left(N_{s,i}^{\text{obs.}} / N_{s,i}^{\text{exp.}}\right)\right]$$

$$\mathcal{L}_{\text{syst}} = \exp\left(-0.5 \sum_{i,j} v_i M_{ij} v_j\right),$$

Covariance matrix of the systematics (constrained from ND fit + external measurements)

$$N_{s,i}^{\text{exp.}} = N_{s,i}^{\text{exp.}}(\boldsymbol{o}, \boldsymbol{f})$$

$$N_b^{\text{exp.}}(\boldsymbol{o}) = \sum_{\nu,e} T(\nu, e, b) \times P_{\text{osc}}(\nu, e, \boldsymbol{o})$$

Maximize the likelihood over **o** and **f** (ie, for N_{exp} =~ N_{obs}).
How to treat the ‘nuisances’ = parameters which are not of direct interest (systematics but also other oscillation parameters when we project on 1-dimensional results)

Profiling versus marginalization

- **Profiling** (‘frequentist’) is ‘easy’… = minimize over all parameters

$$(\boldsymbol{o}, \boldsymbol{f})_{\text{Bestfit}} = \underset{\boldsymbol{o},\boldsymbol{f}}{\arg\max}\ \mathcal{L}(N^{\text{obs.}}, \boldsymbol{x}^{\text{obs.}}, \boldsymbol{o}, \boldsymbol{f})$$

… actually, difficult to cover ‘discrete’ options: different MH, different octants due to local minima → multiple fits and then chose the lower chi2

- ‘Bayesian’ approach = **marginalization** (better take into account non-gaussianity?)

$$\mathcal{L}_{\text{marg}}(N^{\text{obs.}}, \boldsymbol{x}^{\text{obs.}}, \boldsymbol{o}) = \int \mathrm{d}\boldsymbol{f}\, \mathcal{L}(N^{\text{obs.}}, \boldsymbol{x}^{\text{obs.}}, \boldsymbol{o}, \boldsymbol{f}).$$

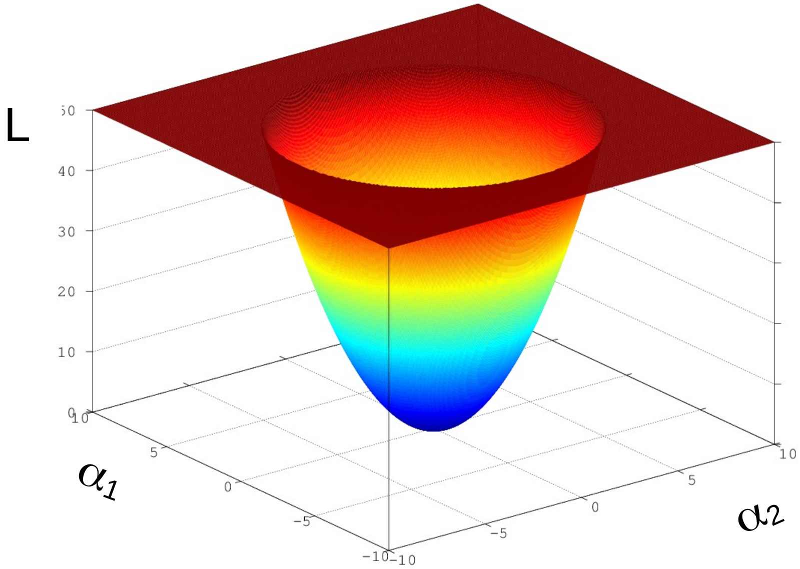
$$\int \mathrm{d}\boldsymbol{f}\, \mathcal{L}_{\text{syst.}}(\boldsymbol{f}) \rightarrow \frac{1}{N}\sum_{i=1}^{N}$$

Throw N toys over nuisances distribution: N could be *really* large for high statistics (= N fits)

→ Distribution of (marginalized) likelihood versus the parameter of interest

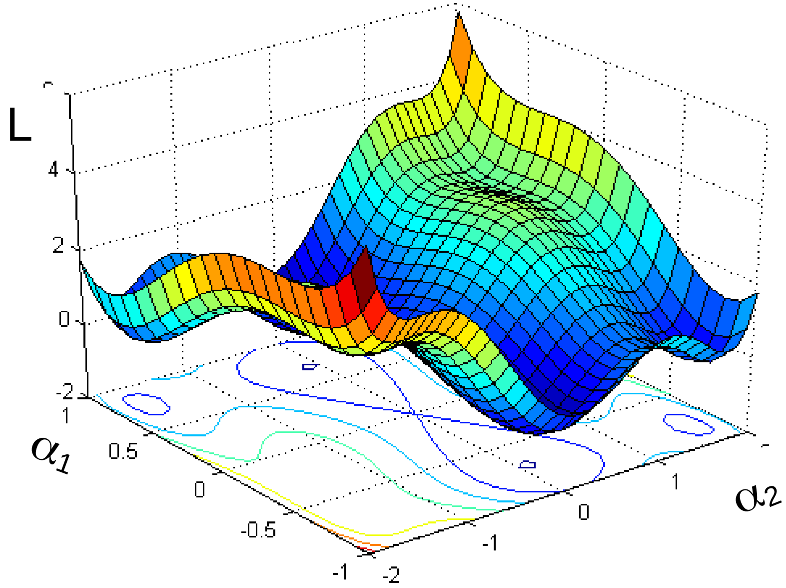
Complex likelihood surface!

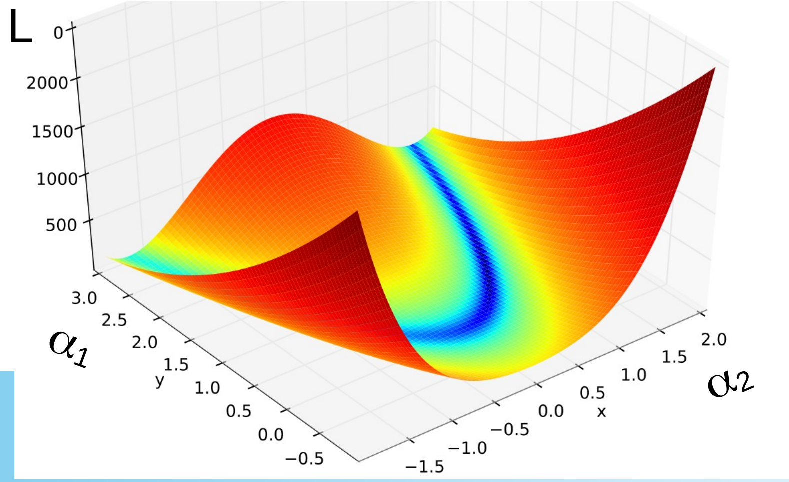
The likelihood may have multiple minima
+ you can have complex functional inter-dependency of the parameters
(certainly true for oscillation parameters in PMNS paradigm: see oscillation formula)



Ideal world

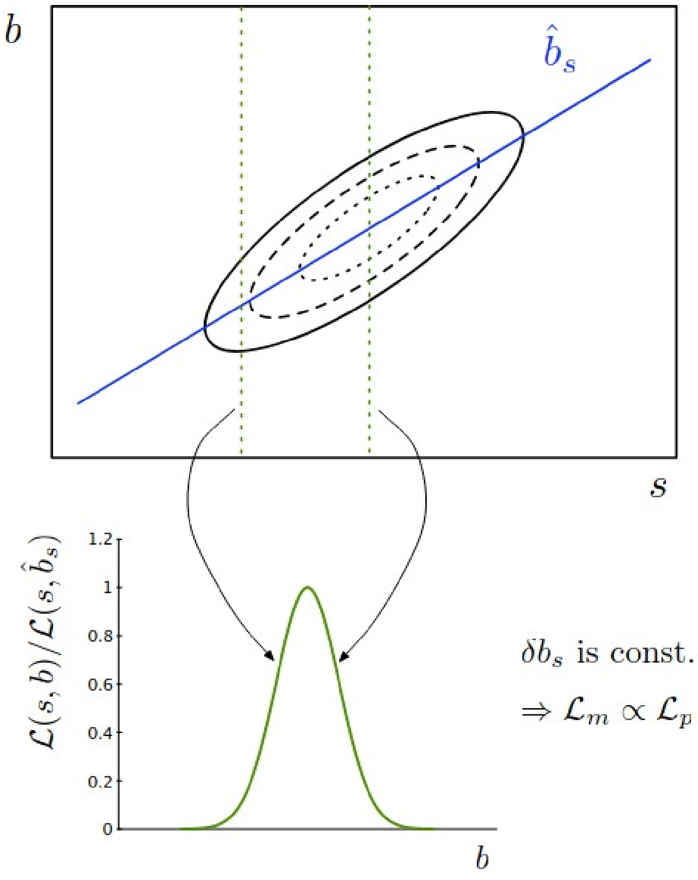
Real life in oscillation measurements!





Profiling vs marginalization?

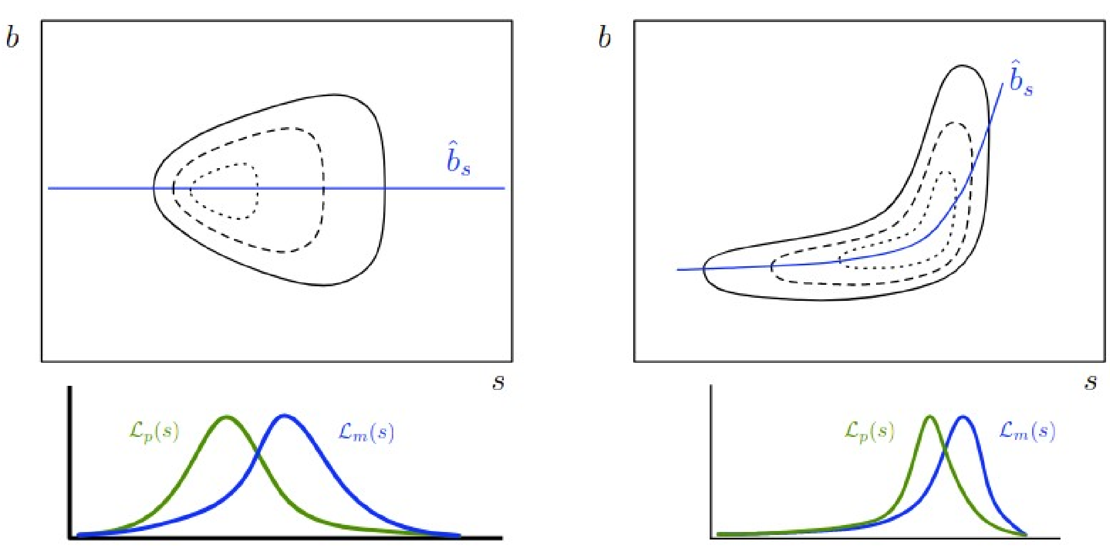
Profiling ~ marginalization, if error on POI s ~ constant over b nuisances



δb_s is const. vs. s

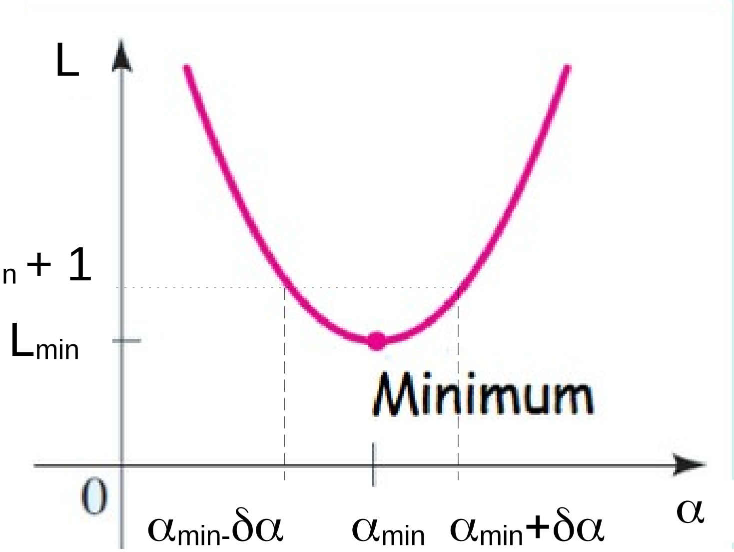
$\Rightarrow \mathcal{L}_m \propto \mathcal{L}_p$

If error on POI s changes with nuisance b values and/or non linear correlation then **results can be widely different!**



Non Gaussianity

MINUIT (or any other algorithm) will find the minimum for you



How to define "1 sigma" error on α?

If the likelihood is a χ2, ie all your uncertainties have a Gaussian distribution then you have the simple χ2 rules

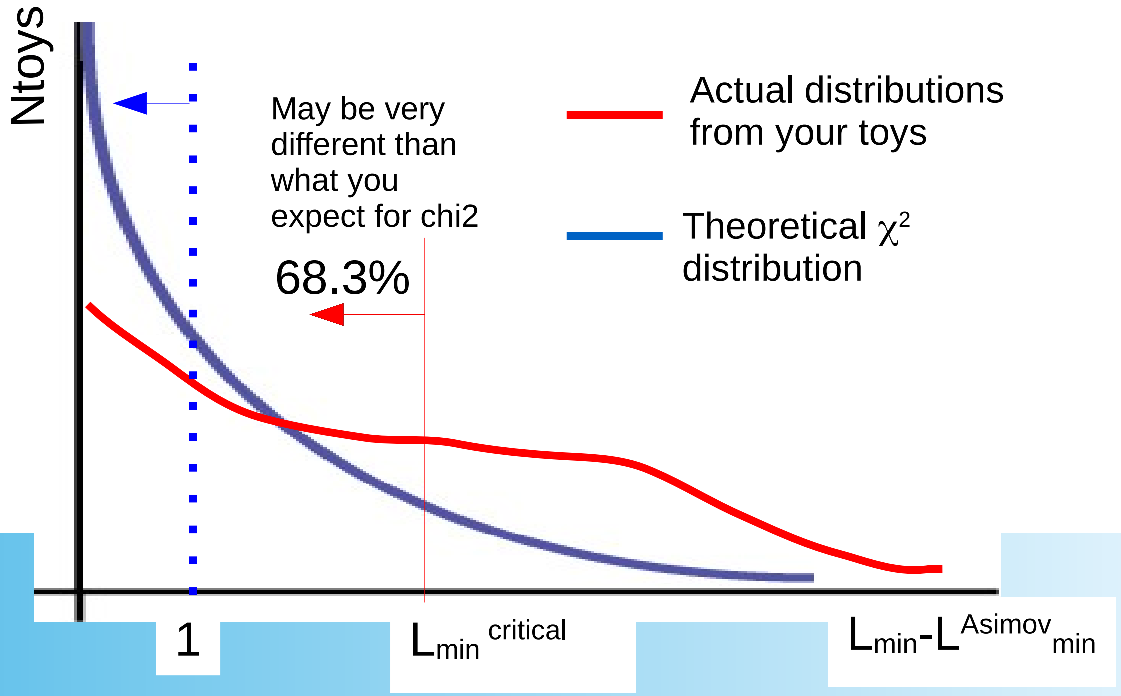
L_{min} + 1 → α_{min} +/- $\delta\alpha$

Typically real world is never perfectly Gaussian

→ **toys: run many fits sampling the nuisances parameters around 'true' values**

→ **look at distribution of L-L_{true}**

e.g. integrate over 68% of your results to know the ΔL~'1σ' error



May be very different than what you expect for chi2

68.3%

Actual distributions from your toys

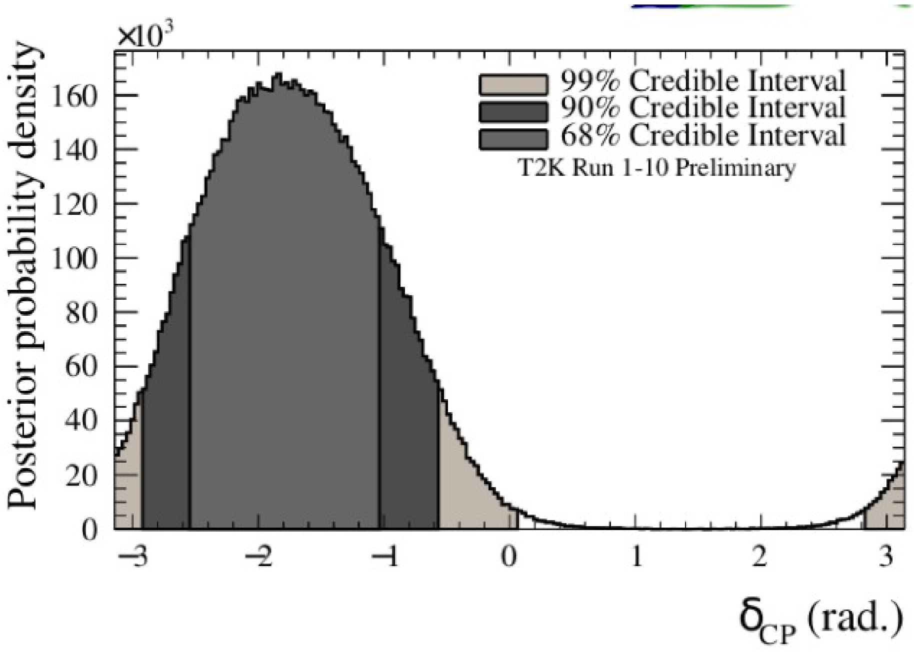
Theoretical χ^2 distribution

Credible vs confidence intervals

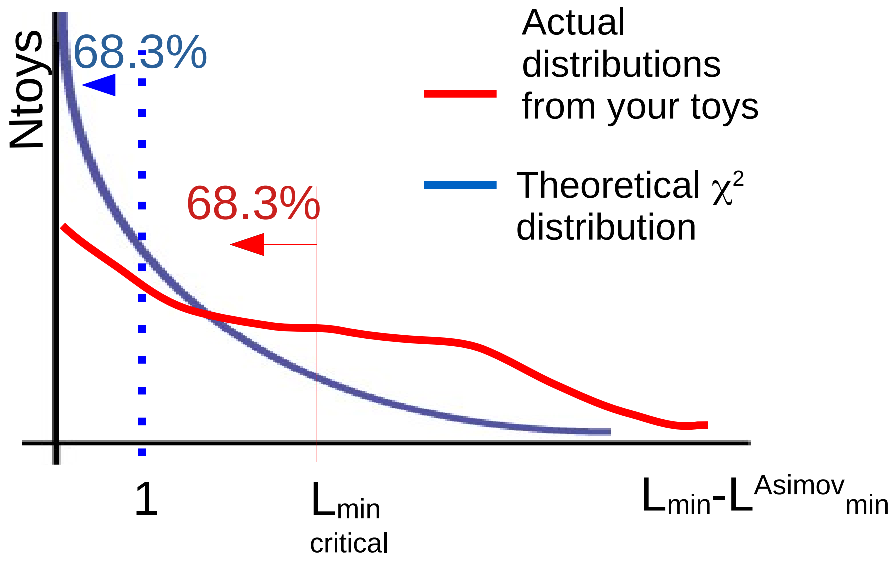
Credible intervals: evaluate the data likelihood for different values of the parameter of interest **o**

$$p(\boldsymbol{o}\,|\,N^{\text{obs.}}, \boldsymbol{x}^{\text{obs.}}) = \frac{\mathcal{L}_{\text{marg}}(N^{\text{obs.}}, \boldsymbol{x}^{\text{obs.}}, \boldsymbol{o}) \times p(\boldsymbol{o})}{\int \mathrm{d}\boldsymbol{o}' \, \mathcal{L}_{\text{marg}}(N^{\text{obs.}}, \boldsymbol{x}^{\text{obs.}}, \boldsymbol{o}') \times p(\boldsymbol{o}')},$$

This is the (in-)famous 'prior'



Confidence intervals (Fieldman Cousin): throw toys over the MC likelihood around best fit value → build distribution of likelihood values and define critical values which correspond to 1/2/3 σ looking at the % of toys (68.3, 95.45, 99.73)



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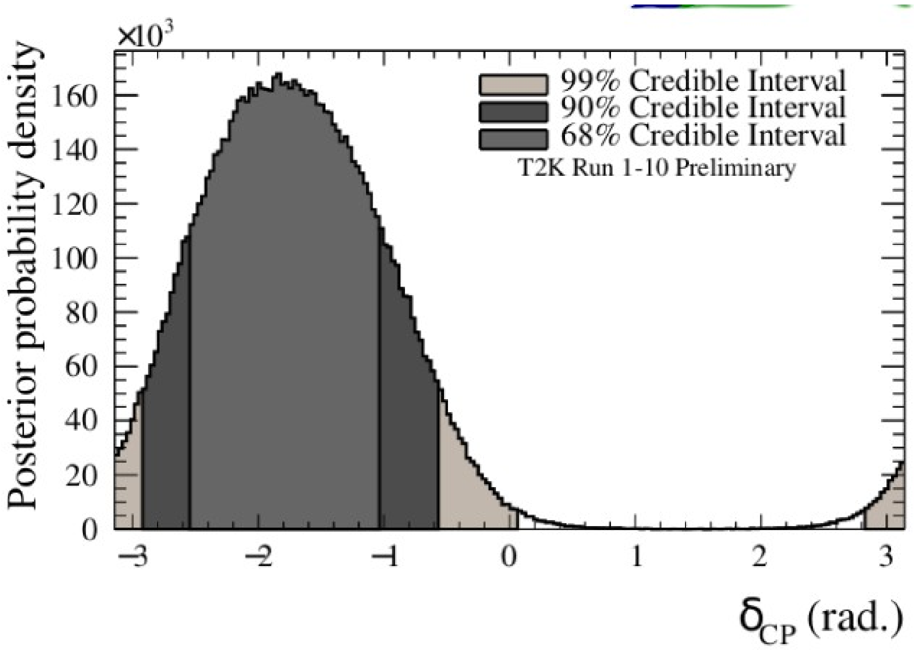

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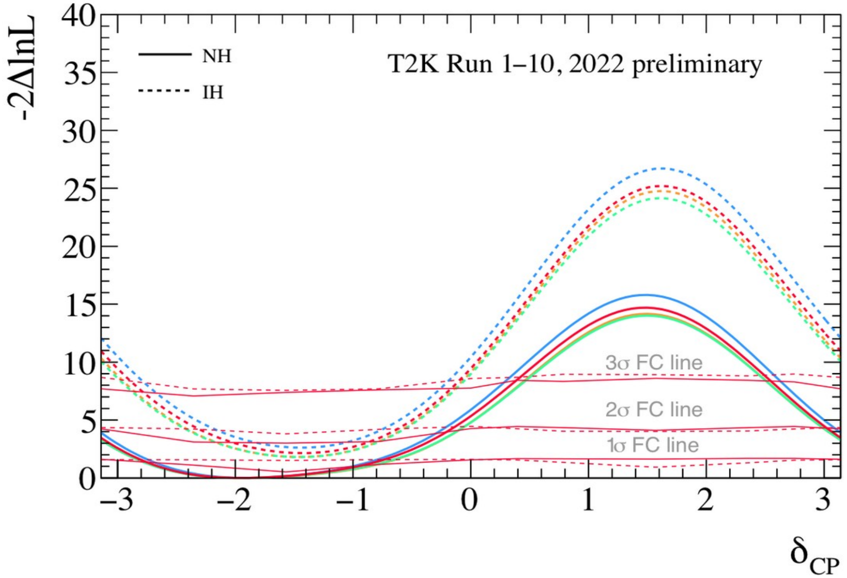
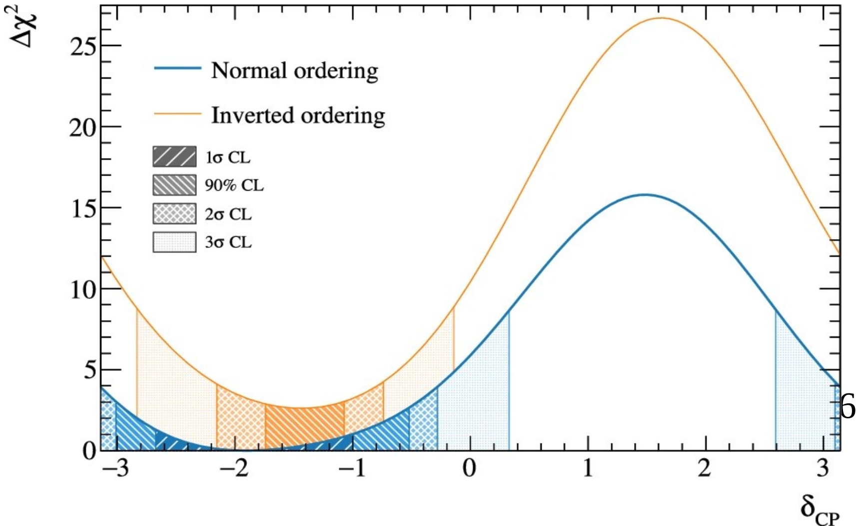
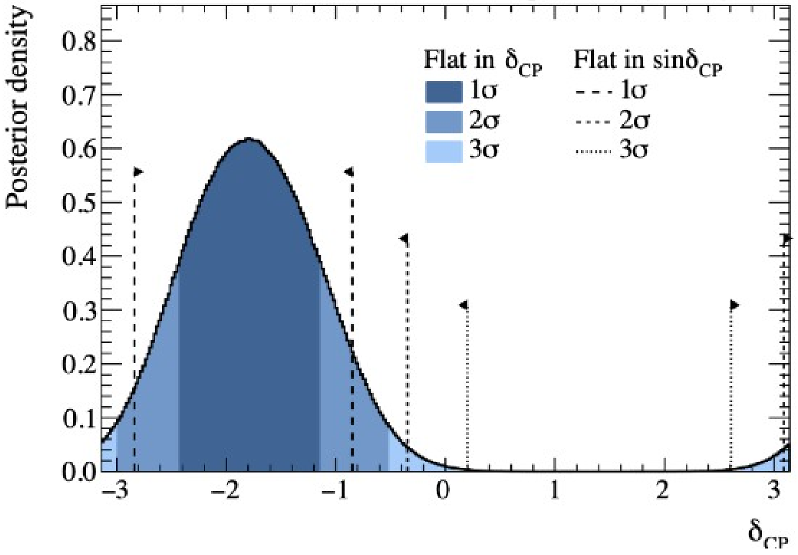




Priors / sampling

Bayesian results depends on prior:
Eg, how to sample δ_{CP}? Flat in δ_{CP} or flat in $\sin\delta_{CP}$?
The result is different!

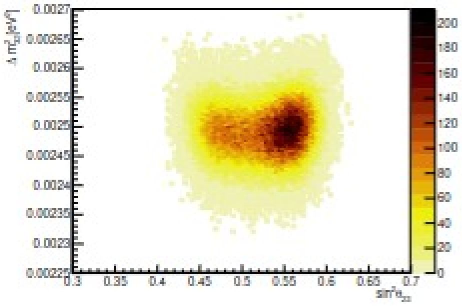


A 'practically similar' dependency is present in Feldman Cousin confidence intervals: **how you sample the nuisances in Feldman Cousin toys?**

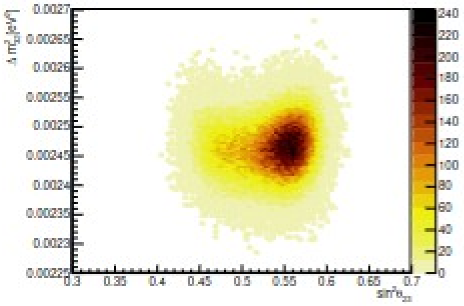
T2K choice for δ_{CP}: the $\sin\theta_{23}$, δm^2_{23} parameters are generated according to the result of an Asimov fit corresponding to the best-fit point

→ we do have seen sizable difference on critical values expected at high statistics by changing the sampling distribution of $\sin\theta_{23}$, δm^2_{23}

(Another interesting problem: sample the systematic nuisance over priors or posterios?)



(b) Δm^2_{32} vs. $\sin^2\theta_{23}$ (NH)

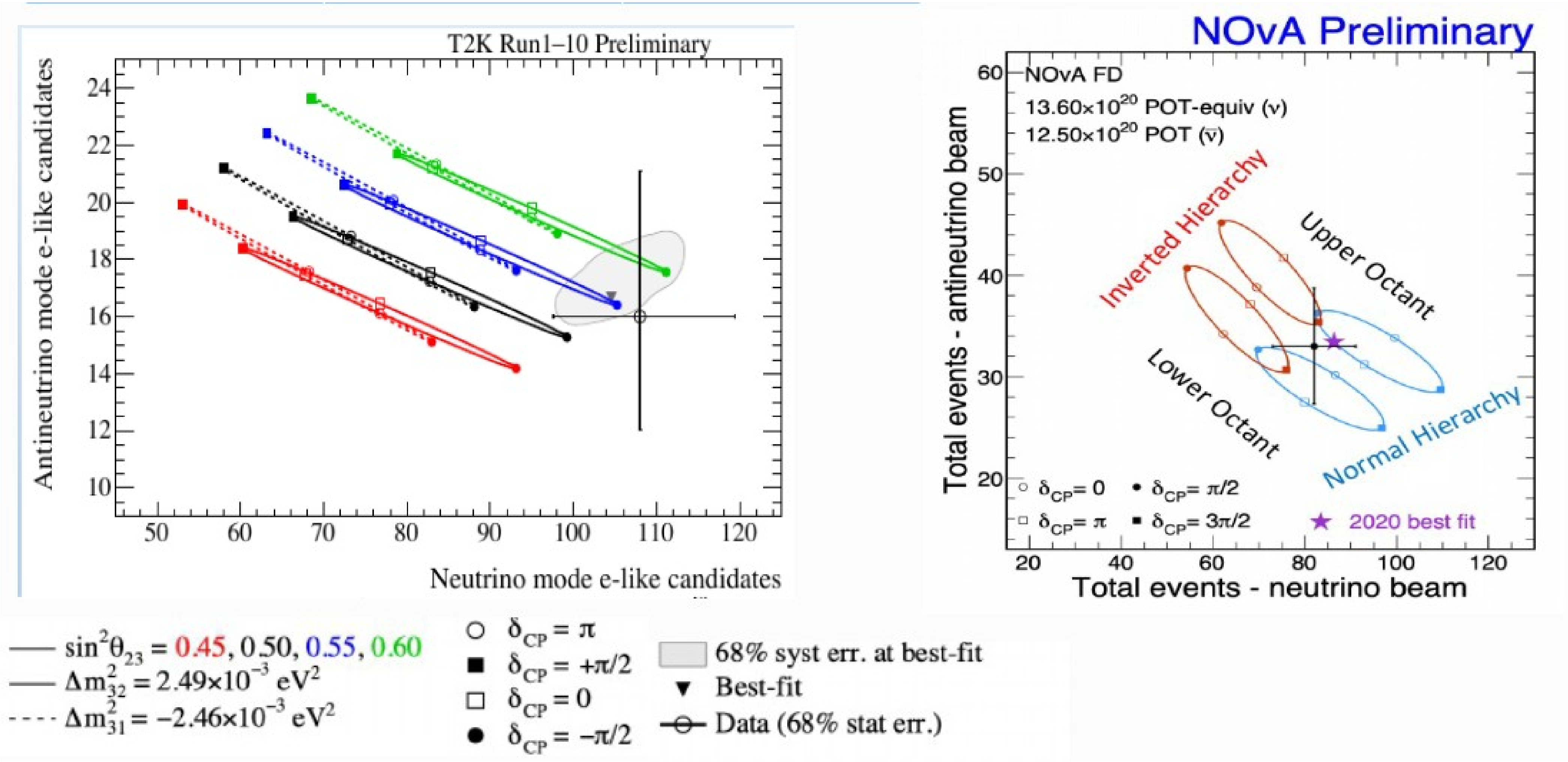


(c) $|\Delta m^2_{31}|$ vs. $\sin^2\theta_{23}$ (IH)

Very nice paper from NOVA: 2207.14353 [hep-ex]

At the core of the problem...

Non gaussianity is due to cyclic nature of parameters (eg angles between 0,π) + degeneracies (δ_{CP} vs MH) + boundary conditions (PMNS limits)

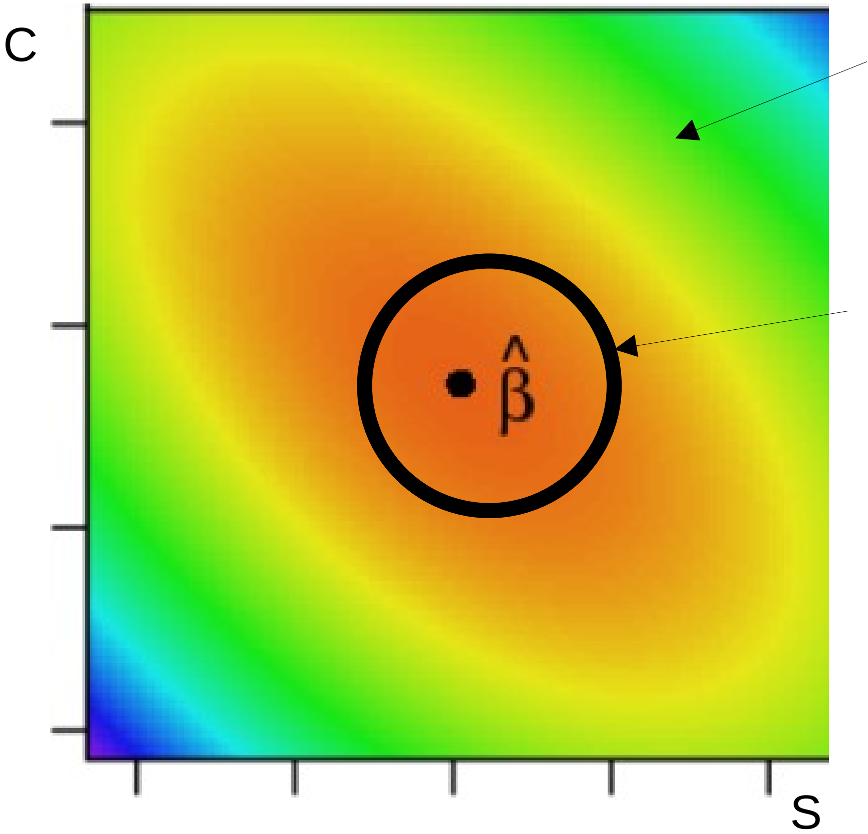


Better parametrizations?

Phys.Lett. B544 (2002) 286-294

$$P(\nu_\alpha \rightarrow \nu_\beta) \sim A_{\alpha\beta}\sin\delta + B_{\alpha\beta}\cos\delta + C_{\alpha\beta} = A_{\alpha\beta}S + B_{\alpha\beta}C + C_{\alpha\beta}$$

Where we can take **S and C to be free parameters between -inf, +inf** and projected back into whatever parametrization (eg PMNS) we wish (after the fit!) → much more 'Gaussian' fit



Results from fit to 'linearized' model

sinδ vs cosδ unitarity constrain: likelihood profile could be projected ('sampled') on this smaller parameter space

Probably possible also for $\sin^2\theta_{23}$ (normalization) but more difficult for δm^2...

Beyond PMNS

- **The ‘standard’ oscillation paradigm (PMNS-based) is very strict and not motivated by fundamental symmetries** (mixing angles and neutrino masses are ‘accidental’ numbers).

In particular it assumes

- minimal 3-flavour scenario (unitarity!)
- standard neutrino interactions for production and detection
- standard matter effects along propagation

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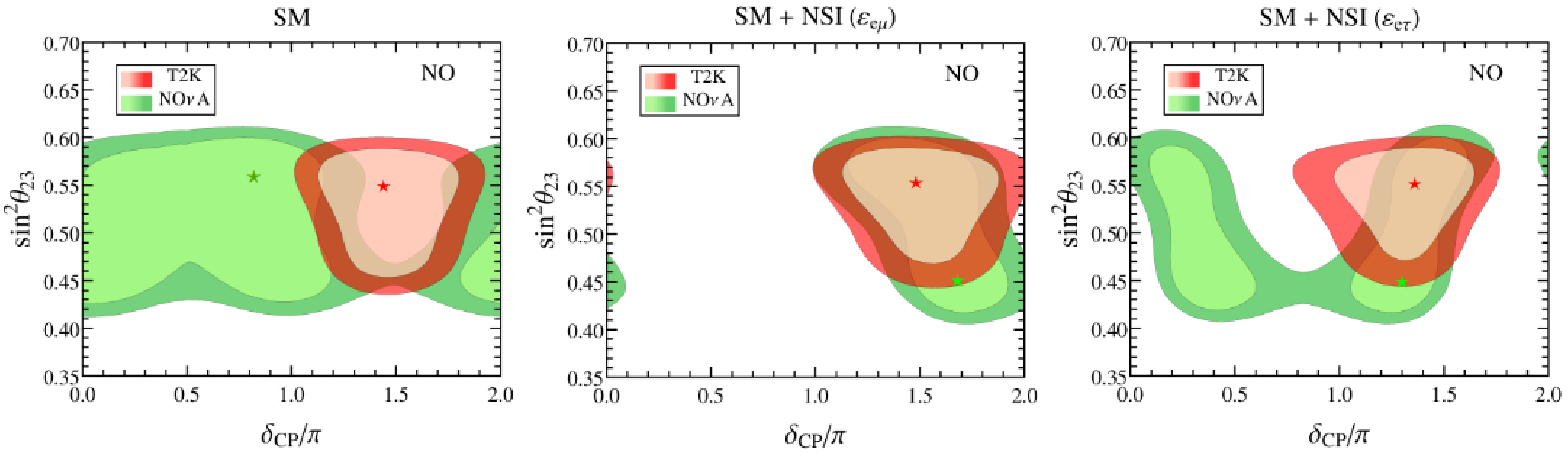
- **Combination of HK and DUNE beyond the PMNS paradigm useful for**
  - bounds on New Physics in specific models (eg, Non Standard Interactions)

- A reharsal: T2K+NOVA combination (already showing tension, but limited by statistics)



Phys.Rev.Lett. 126 (2021) 5, 051802

Beyond PMNS

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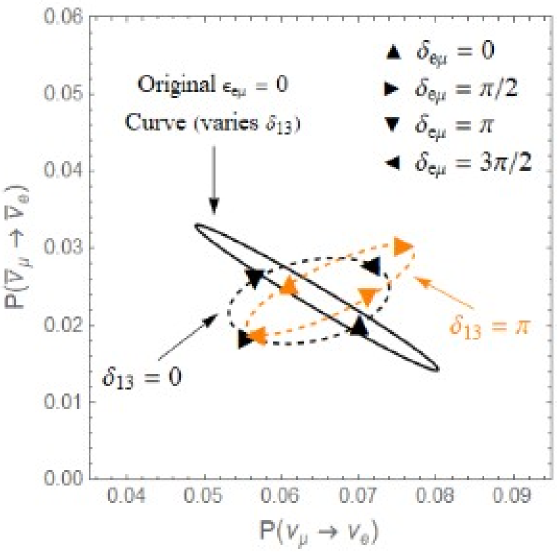
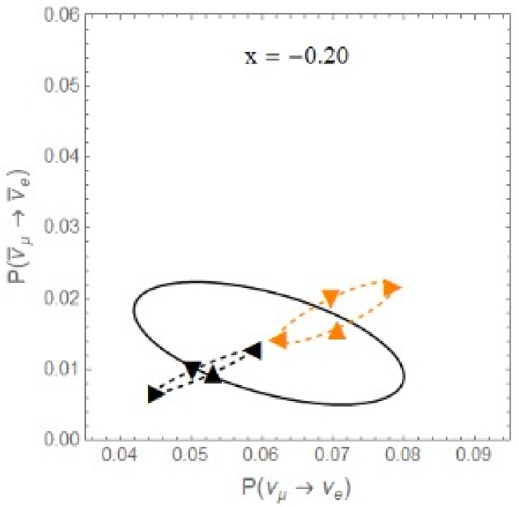
- **Combination of HK and DUNE beyond the PMNS paradigm useful for**
  - bounds on New Physics in specific models (eg, Non Standard Interactions)
  - more than the sum of sensitivities: effects of New Physics can obfuscate ‘standard’ PMNS interpretation and induce degeneracies: comparison between experiments at different L/E solve them

Eg: new sources of **CP-violation in Non Standard Interactions** from non-diagonal terms in matter potential



moving to different (L/)E



CIPANP 2018, Print:1809.11128 [hep-ph]

Study of L

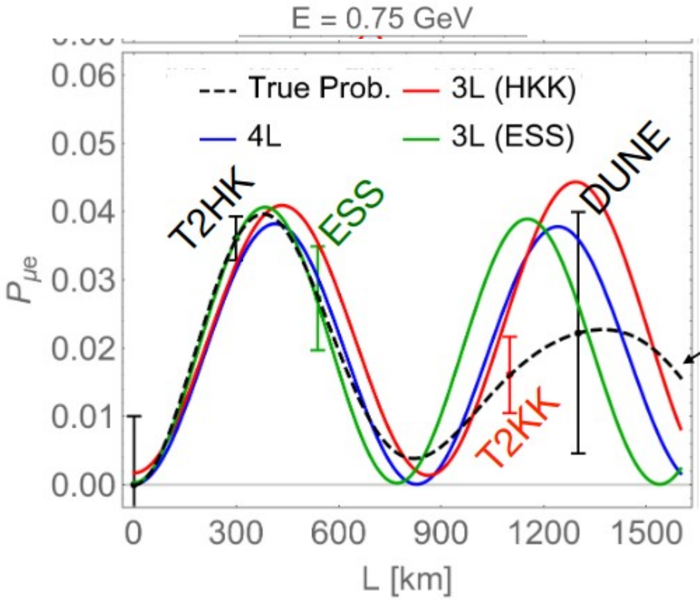
- Expand the oscillation study with a **more general paradigm: with next generation of experiments we will look at oscillations with a much more open-mind approach:** we want to characterize the L/E dependency of flavour mixing

Eg: can we search for **fundamental CP violation in a more model-independent way?**

- allow for arbitrary (non-standard) matter effect -
- allow for arbitrary (non-unitary) mixing between flavour and energy eigenstates (even different for production and detection)

→ **search for T-violation → look for L dependency of oscillations at fixed energy**

Phys. Rev. Lett. 128, 091801 –



No good fit with L-even terms only → T-Violation !

3nu probability with $\delta_{\rm CP} = 90^\circ$

Study of L

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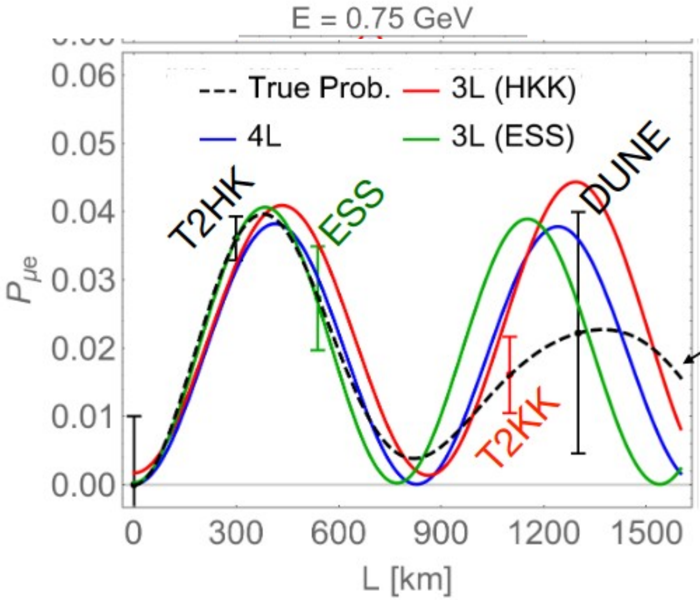
arXiv:2106.16099 [hep-ph]



No good fit with L-even terms only → T-Violation !

3nu probability with $\delta_{CP} = 90^\circ$

- Combination of experiments will be crucial for a **comprehensive and open-minded** characterization of ν oscillations
Crucial to have a coherent program of Near Detectors + establish a common language in terms of nuclear models, …

A reharsal: T2K+NOVA combination (really though!!)
It is difficult! → Start to plan for it well in advance!

Summary

- Correct **statistical treatment of oscillation measurements at high statistics** is challenging.
There is a lot of (possibly arbitrary) choices which needs to be made
→ important to have detailed and wide discussion inside the LBL community
(eg PHYSTAT workshops: T2K and NOVA are opening the road!)
The target is not necessarily to use the same approach but to understand each other!
Especially important in view of future joint fits

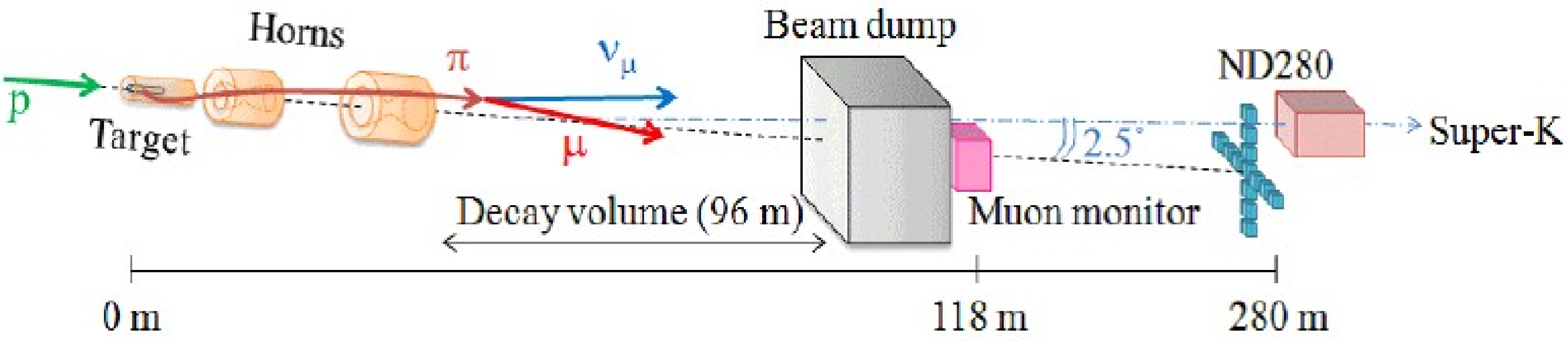
- Generic but ‘clever’ **beyond PMNS parametrizations** are common in phenomenology studies: we should also start to investigate them in the experimental community (T2K is moving in that direction)
→ joint fits are absolutely crucial for beyond-PMNS characterization of oscillation behavior

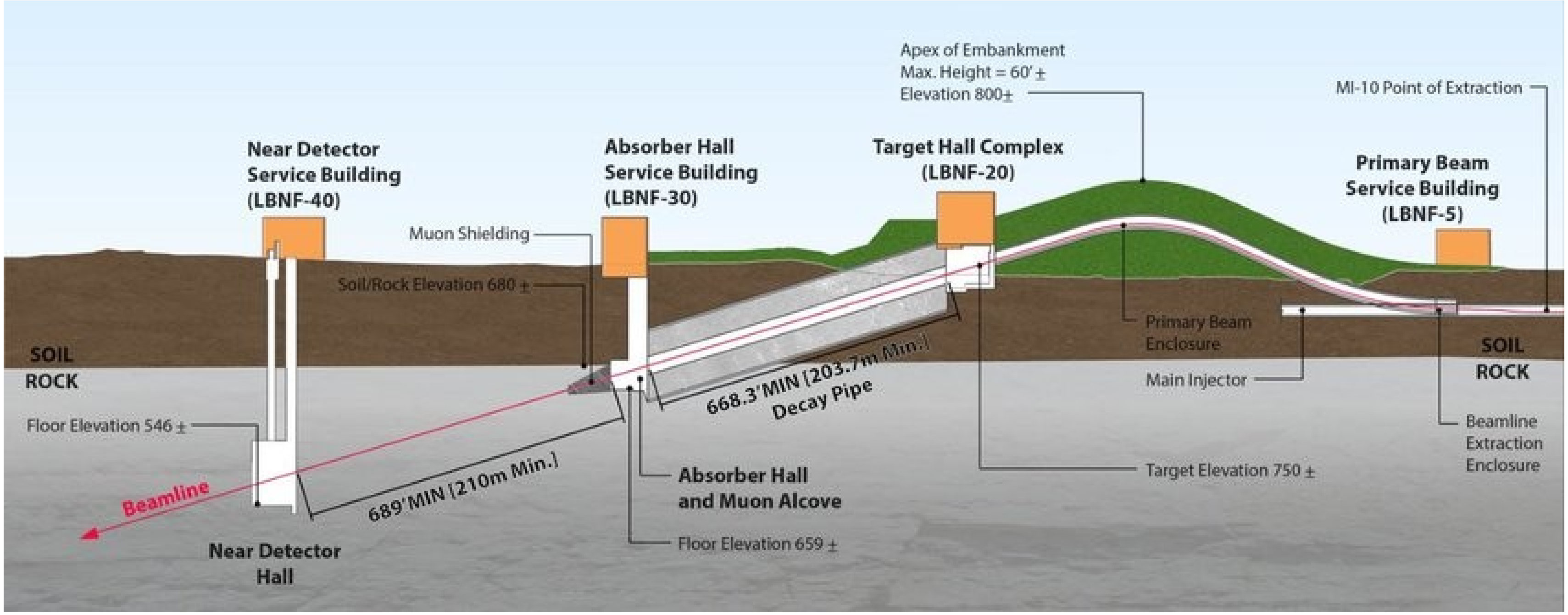
- **Joint fits are incredibly difficult in LBL domain: a lot of (partial) correlation in the xsec and flux modeling → need to discuss and plan for it well in advance!**
Today is not too early!

BACKUP

Flux tuning

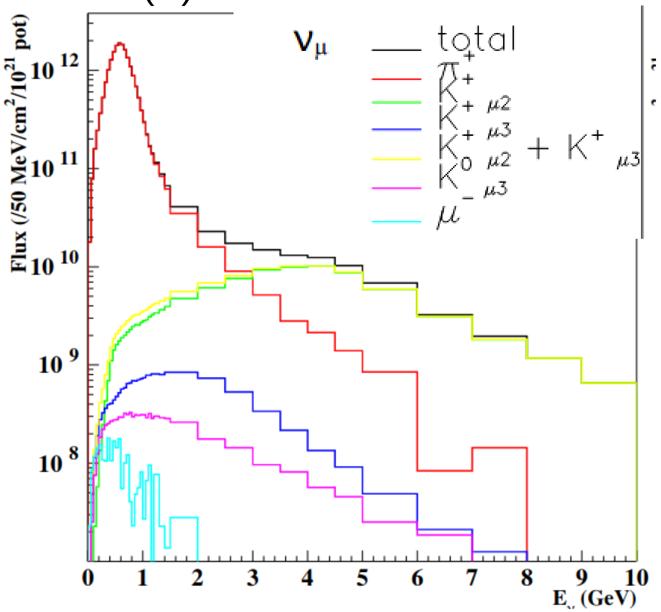
Neutrino 'beams':
T2(H)K and DUNE examples



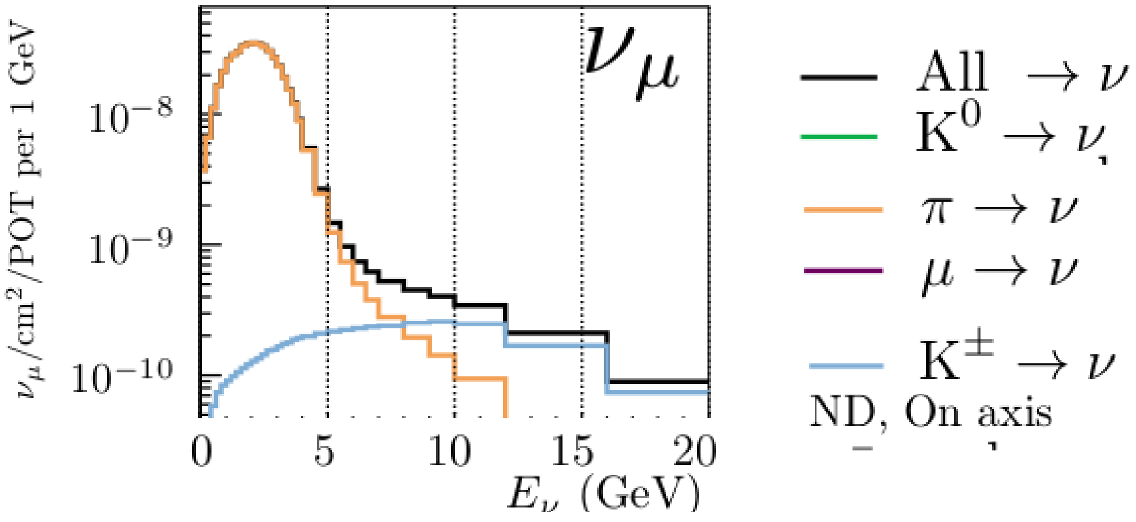


ν_μ flux

T2(H)K



DUNE



ν_μ flux

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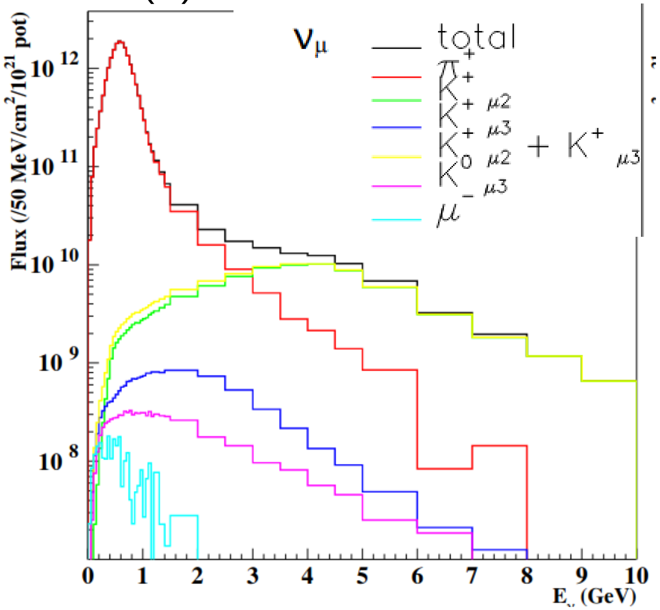
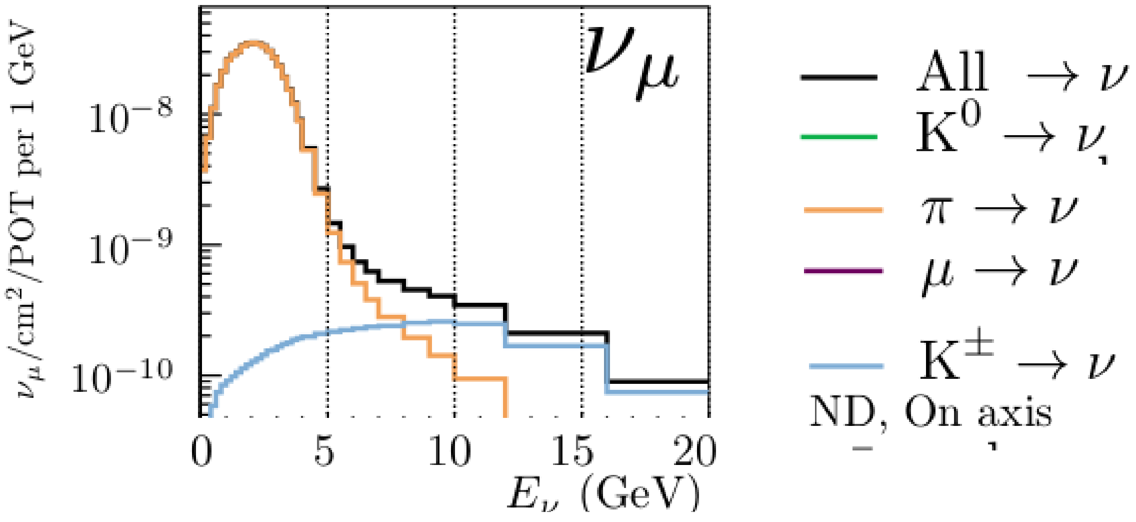
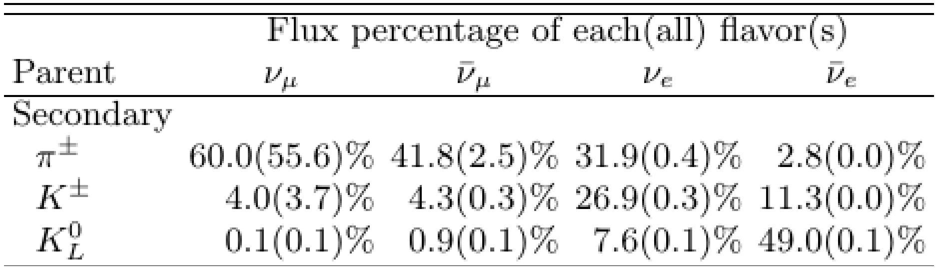


DUNE



T2K

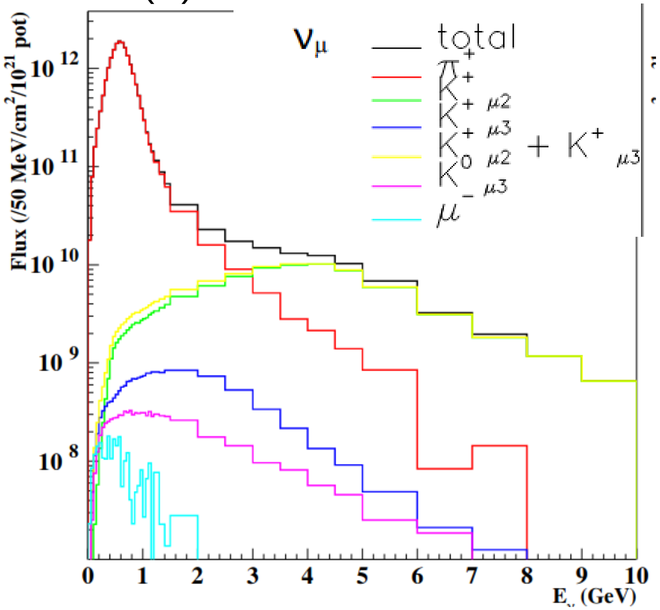


Parent	Flux percentage of each(all) flavor(s) ν_μ	$\bar{\nu}_\mu$	ν_e	$\bar{\nu}_e$
Secondary				
$\pi^\pm$	60.0(55.6)%	41.8(2.5)%	31.9(0.4)%	2.8(0.0)%
$K^\pm$	4.0(3.7)%	4.3(0.3)%	26.9(0.3)%	11.3(0.0)%
K^0_L	0.1(0.1)%	0.9(0.1)%	7.6(0.1)%	49.0(0.1)%

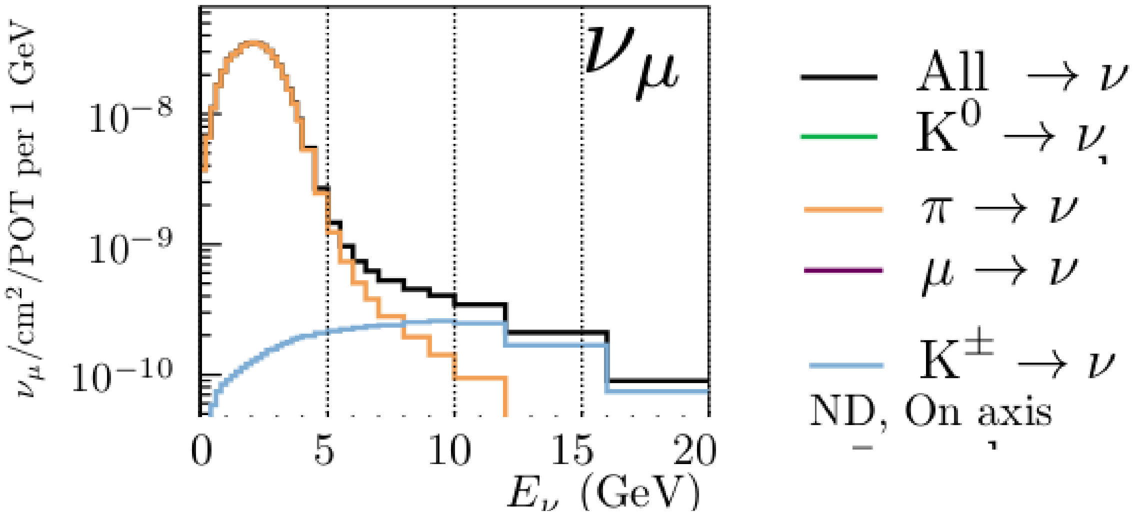
Proton interactions in the target → production of **'secondary' hadrons on Carbon**

ν_μ flux

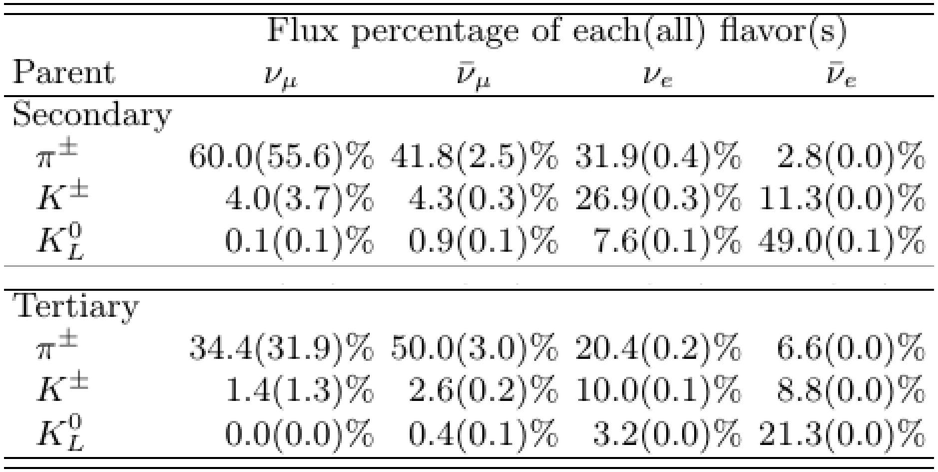
T2(H)K



DUNE



T2K



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Tertiary				
$\pi^\pm$	34.4(31.9)%	50.0(3.0)%	20.4(0.2)%	6.6(0.0)%
$K^\pm$	1.4(1.3)%	2.6(0.2)%	10.0(0.1)%	8.8(0.0)%
K^0_L	0.0(0.0)%	0.4(0.1)%	3.2(0.0)%	21.3(0.0)%

Proton interactions in the target → production of **'secondary' hadrons on Carbon**

Re-interactions of hadrons with target, horns, vessel, beam dump... → production of **'tertiary hadrons' on C (or other materials)**

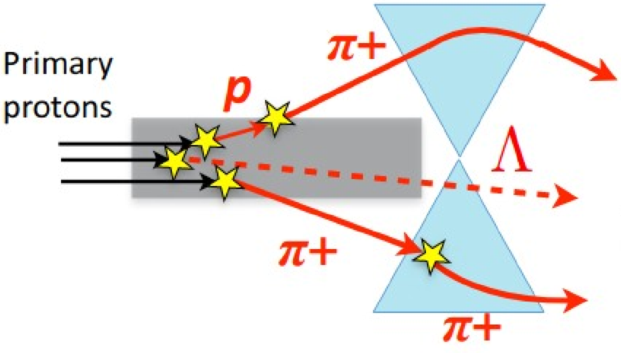
Flux tuning

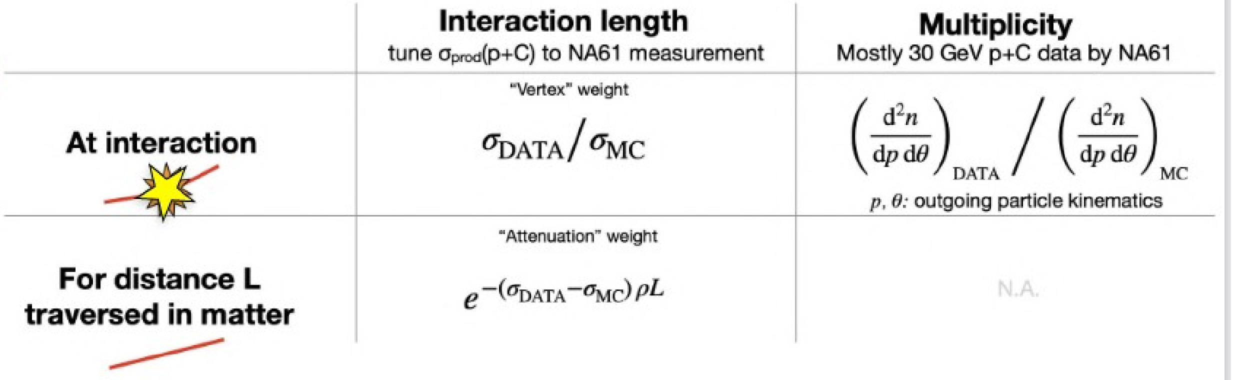
Simulation of hadron interactions with the target and all the beamline with **GEANT and FLUKA**

The simulations are tuned using external measurement from hadro-production experiments (NA61/SHINE and more...)

Total probability of hadron interactions and outgoing hadron multiplicity as a function of **incoming proton momentum and outgoing hadron momentum and angle** are tuned to match the hadro-production measurements:

Yoshikazu Nagai
WANP 2022 @Nagoya, Japan



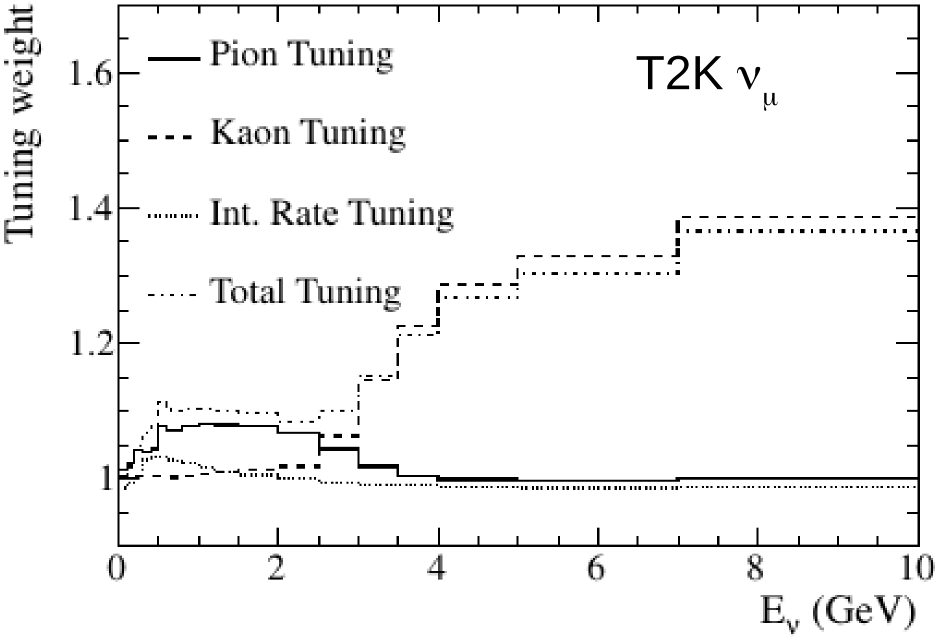


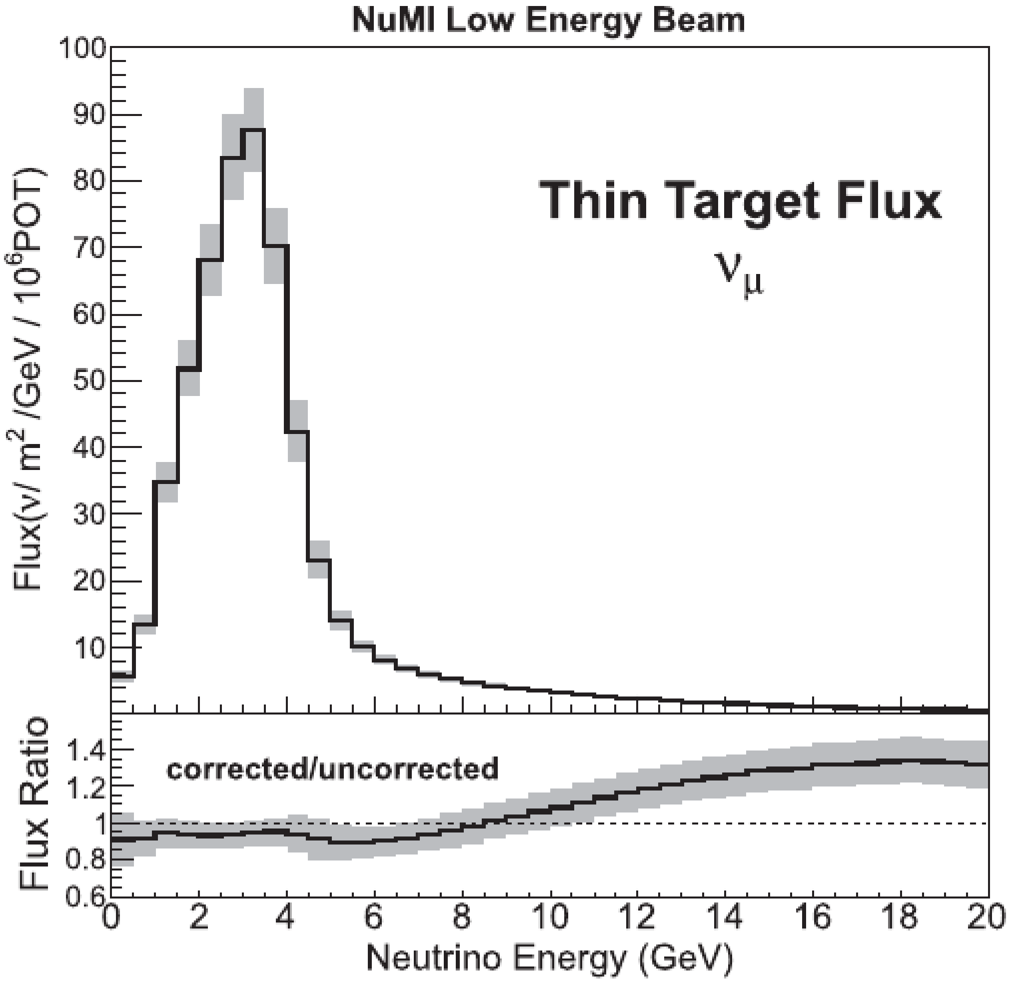
	Interaction length tune σ_{prod}(p+C) to NA61 measurement	**Multiplicity** Mostly 30 GeV p+C data by NA61
At interaction	"Vertex" weight $\sigma_{DATA}/\sigma_{MC}$	$\left(\frac{d^2n}{dp\,d\theta}\right)_{DATA} \Big/ \left(\frac{d^2n}{dp\,d\theta}\right)_{MC}$ p, θ: outgoing particle kinematics
For distance L traversed in matter	"Attenuation" weight $e^{-(\sigma_{DATA}-\sigma_{MC})\rho L}$	N.A.

Important point: **due to pion rescattering (in target and in beamline material) need data for different targets + at different proton and hadron energy!**

Example of tuning factors

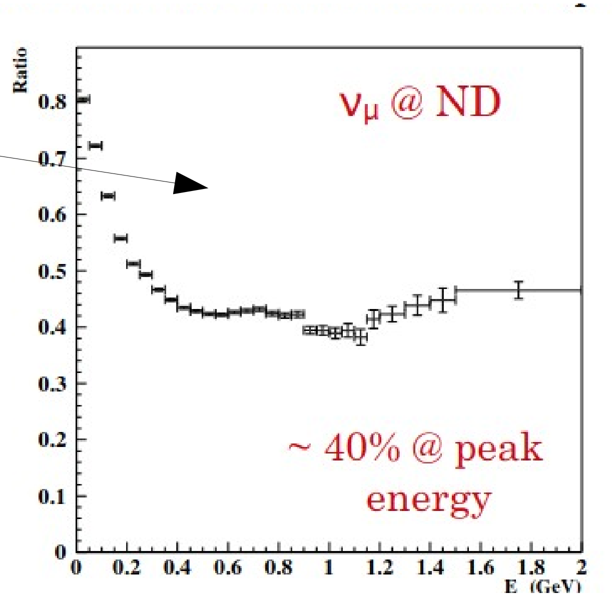
$$\frac{\text{flux tuned}}{\text{flux simulated}}$$



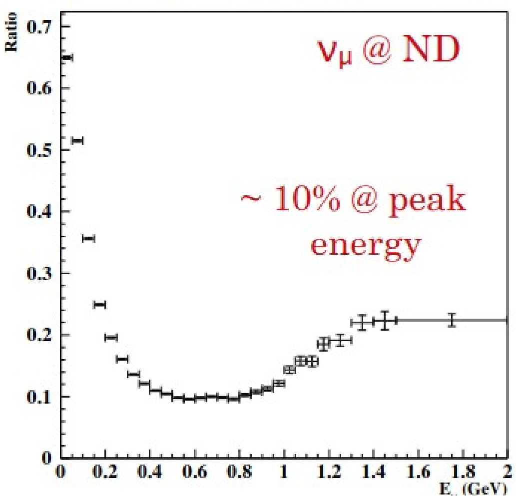


Need for replica target

Fraction of neutrinos from re-interactions in the target and in the beam line (~40%)

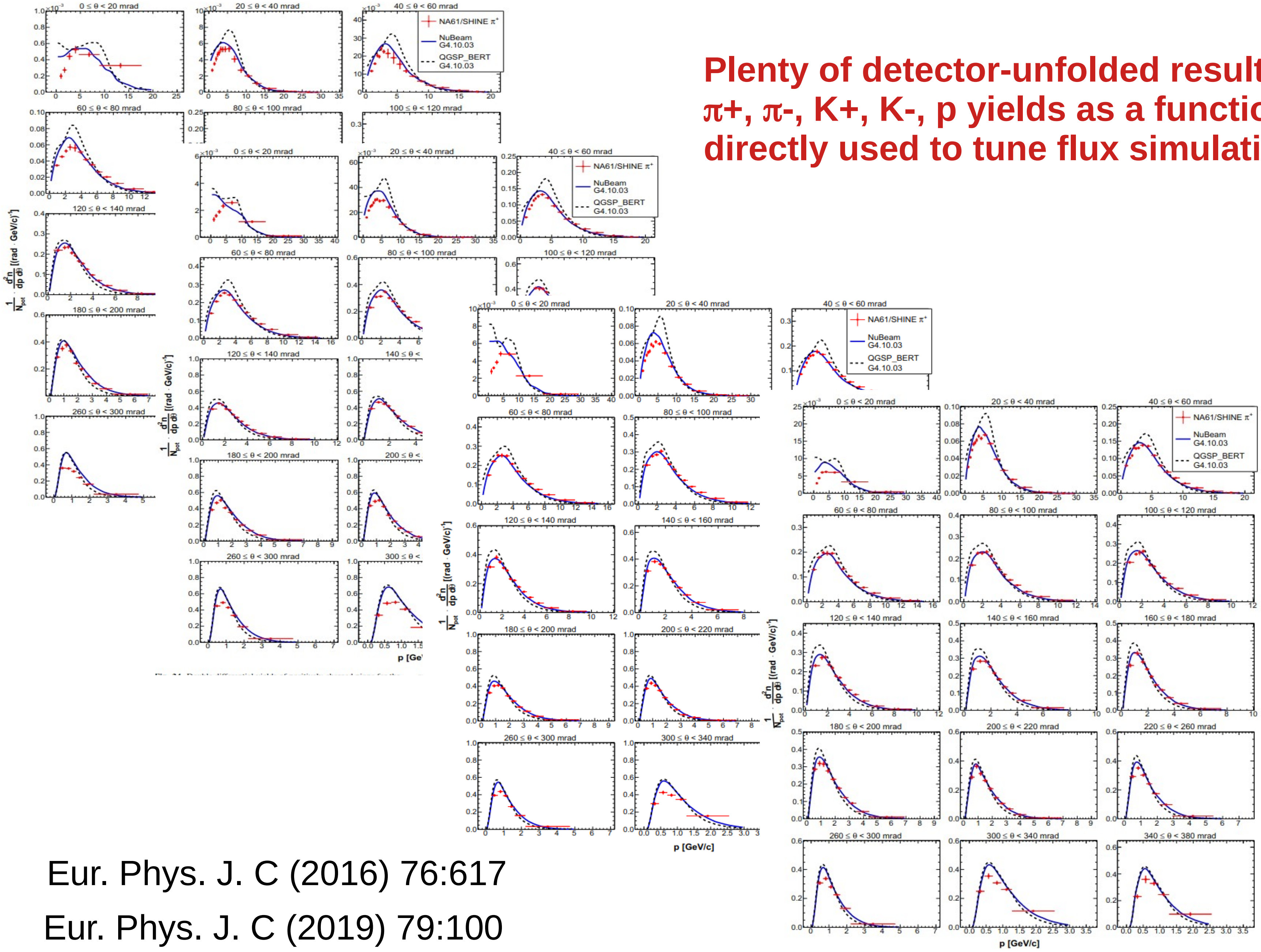


re-interactions in the beamline



→ **measurement of hadro-production with ‘replica target’** (= same target geometry as the neutrino experiment) allows to tune 90% of the flux (60% with thin target)

NA61 results with replica target

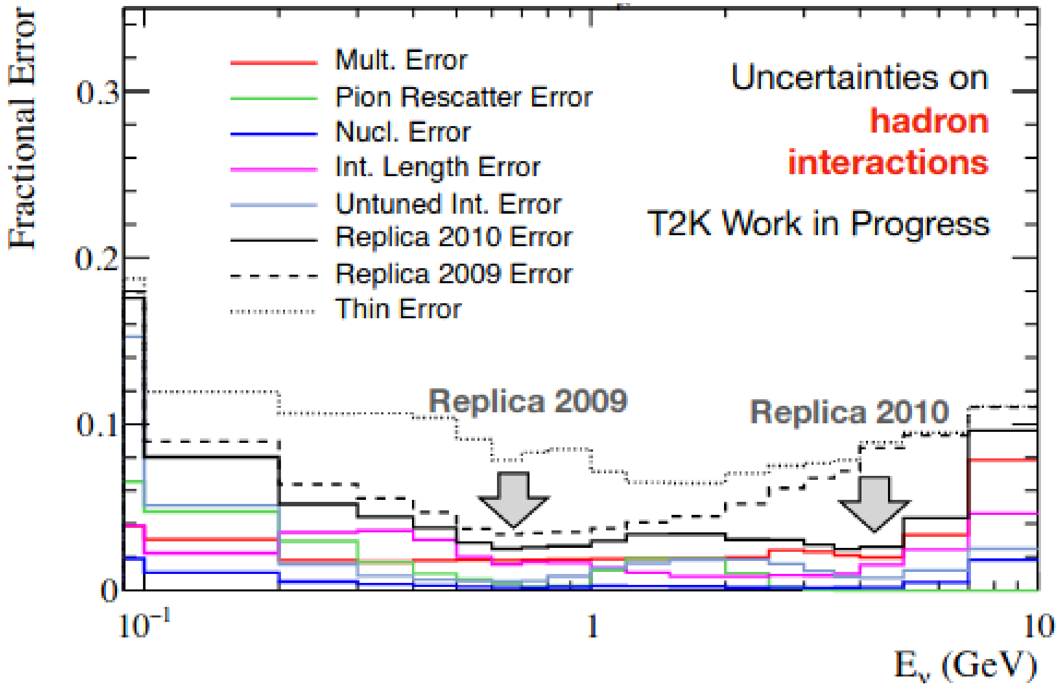


Plenty of detector-unfolded results:
π+, π-, K+, K-, p yields as a function of p, θ, z_{target}
directly used to tune flux simulation

Eur. Phys. J. C (2016) 76:617

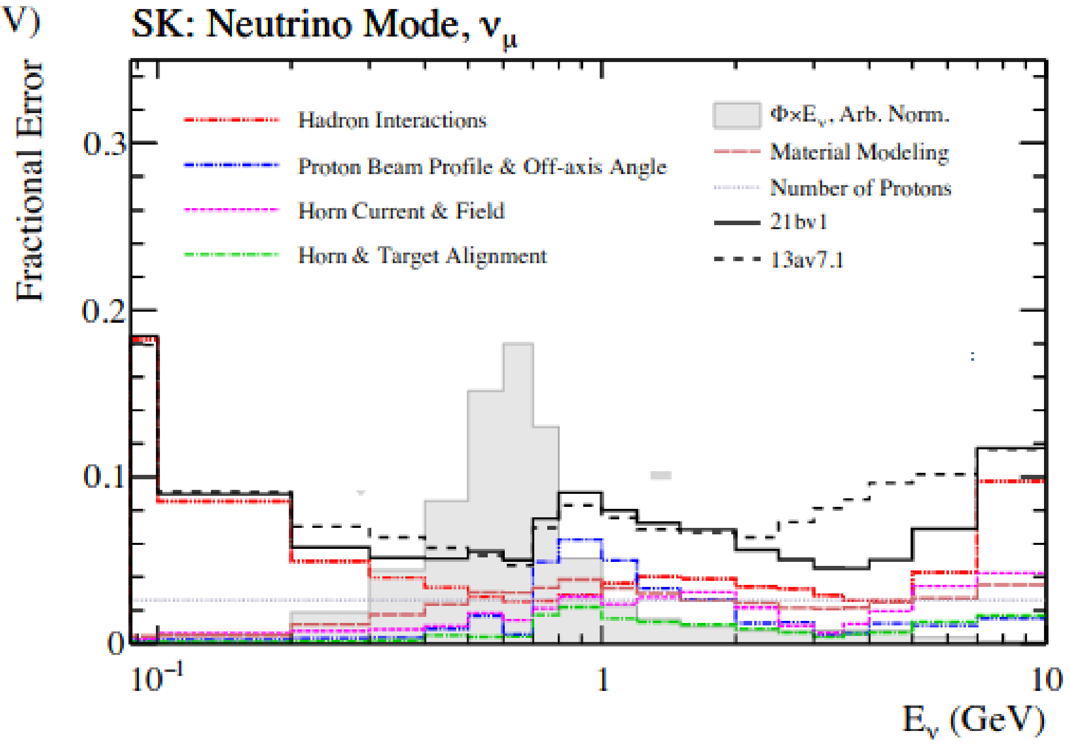
Eur. Phys. J. C (2019) 79:100

Flux uncertainties

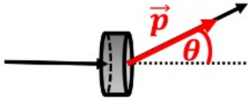


Huge improvement (~factor 2) of hadron-interaction uncertainties using NA61/SHINE replica target data (<5% in the flux peak)

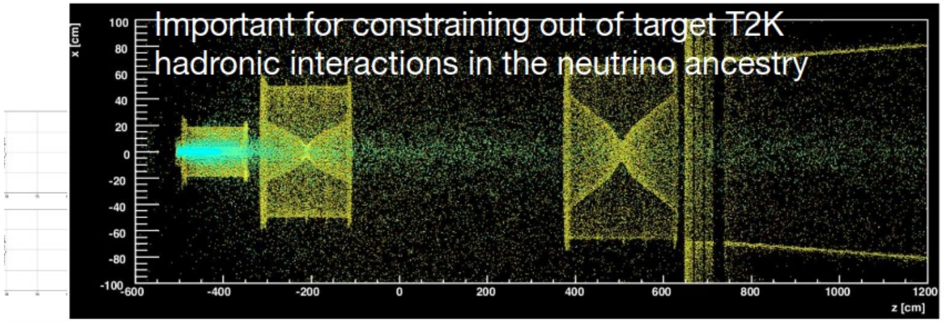
Total flux uncertainties today:
- low energy: hardon-interactions (especially total xsec evaluation)
- peak energy: modeling of (non-target) beamline material
- high energy: beam profile & off-axis angle



Future prospects

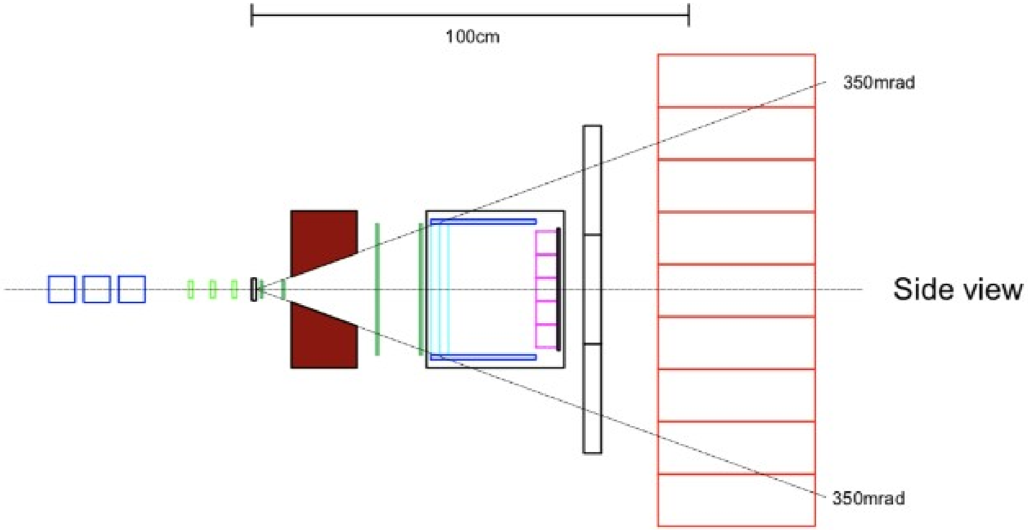


Thin targets from various materials (Al, Fe, Ti, H20 etc.), with different hadrons beam incident on them

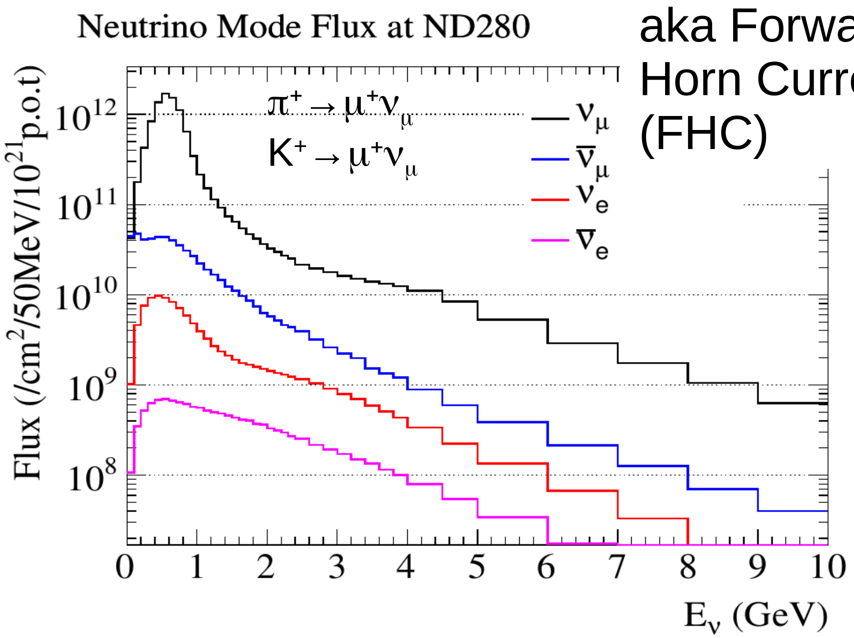

Important for constraining out of target T2K hadronic interactions in the neutrino ancestry

- New ‘table-top’ experiment at FNAL: **EMPHATIC** (targeting low energy especially interesting to cover the Booster beam for MicroBoone)

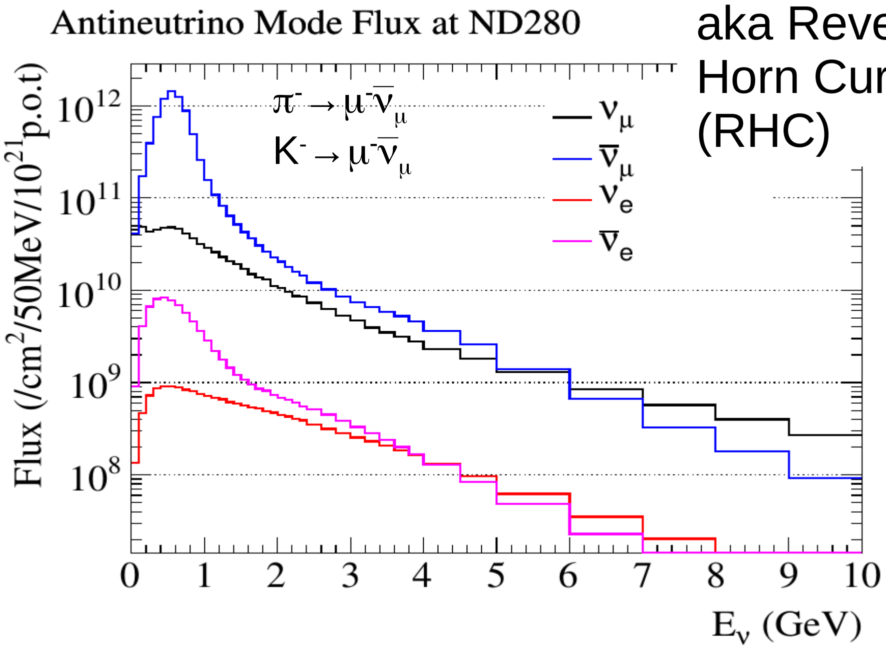
Particularly interesting to measure total proton cross-section (the other main left uncertainty) since both interacting and not-interacting events can be measured (fwd TPC in NA61 can also help for that!)



Flux in T2K: wrong sign

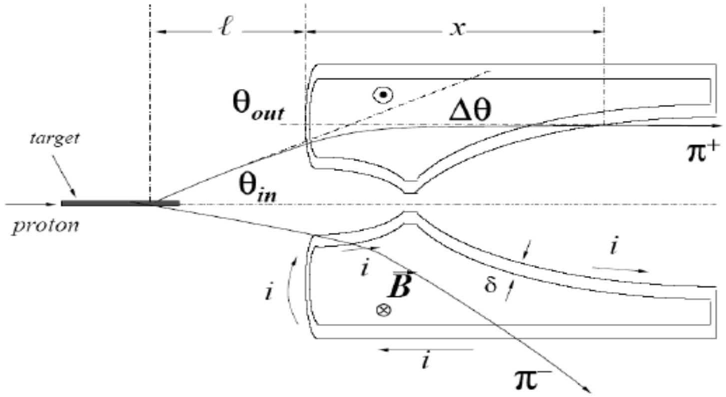


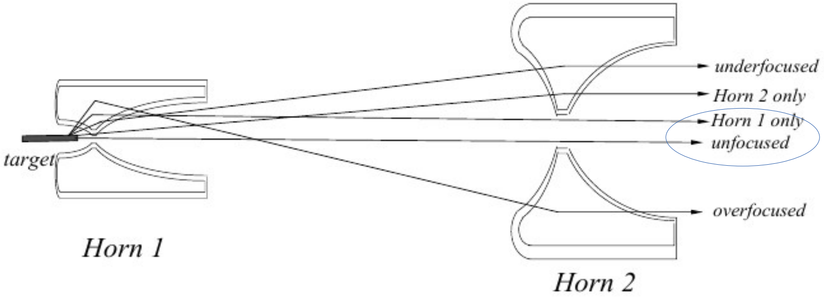
aka Forward Horn Current (FHC)



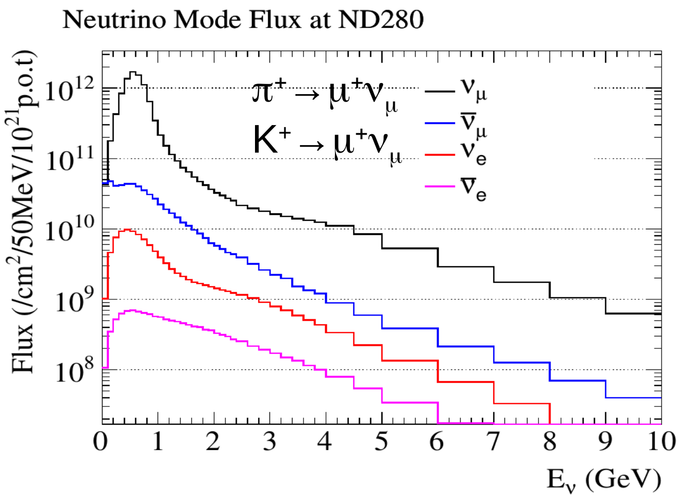
aka Reverse Horn Current (RHC)

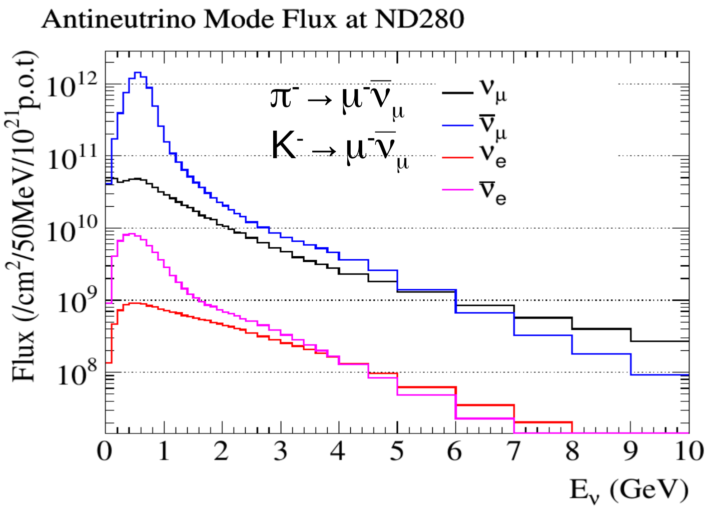
The 'wrong sign' background (important for δ_{CP} and MO) comes from high p_L pions (kaons) which cannot be defocused properly because they miss the horns → fractional contribution larger at high neutrino energies





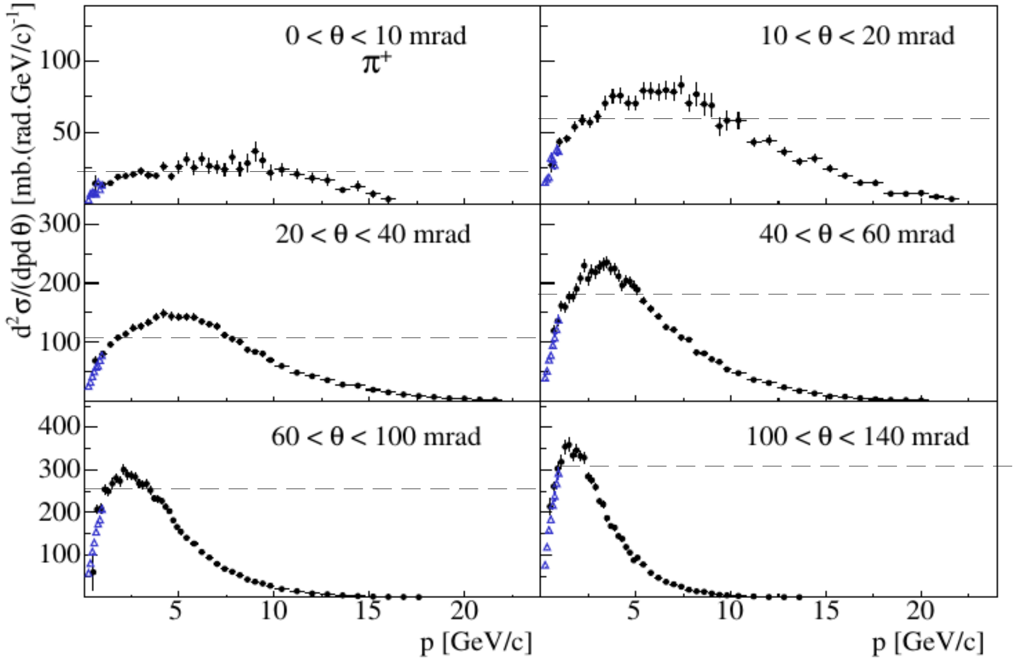
Flux in T2K: wrong sign

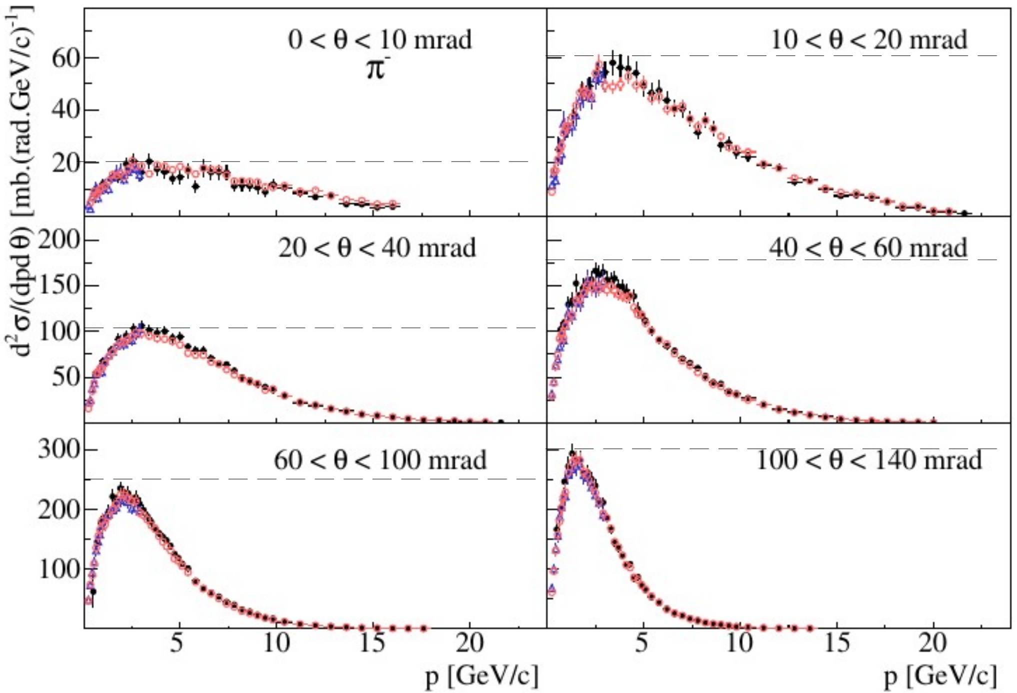




The 'wrong sign' background is larger in antineutrino mode since

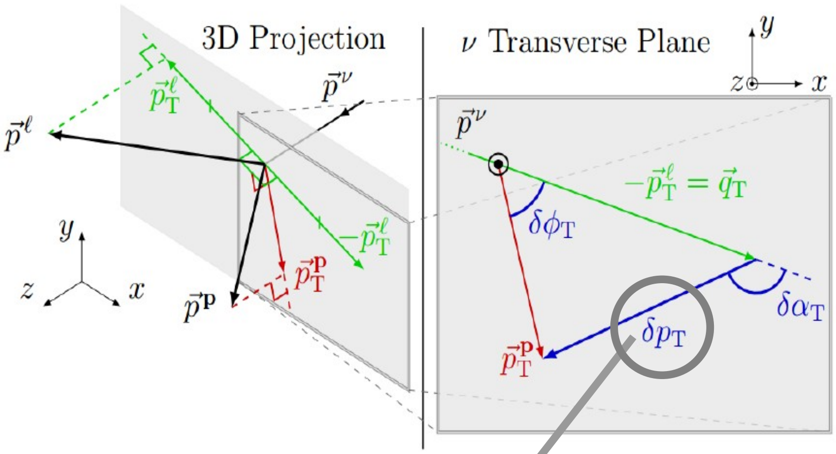
when proton hits the target it is more probable to create positive charged hadrons than negative ones





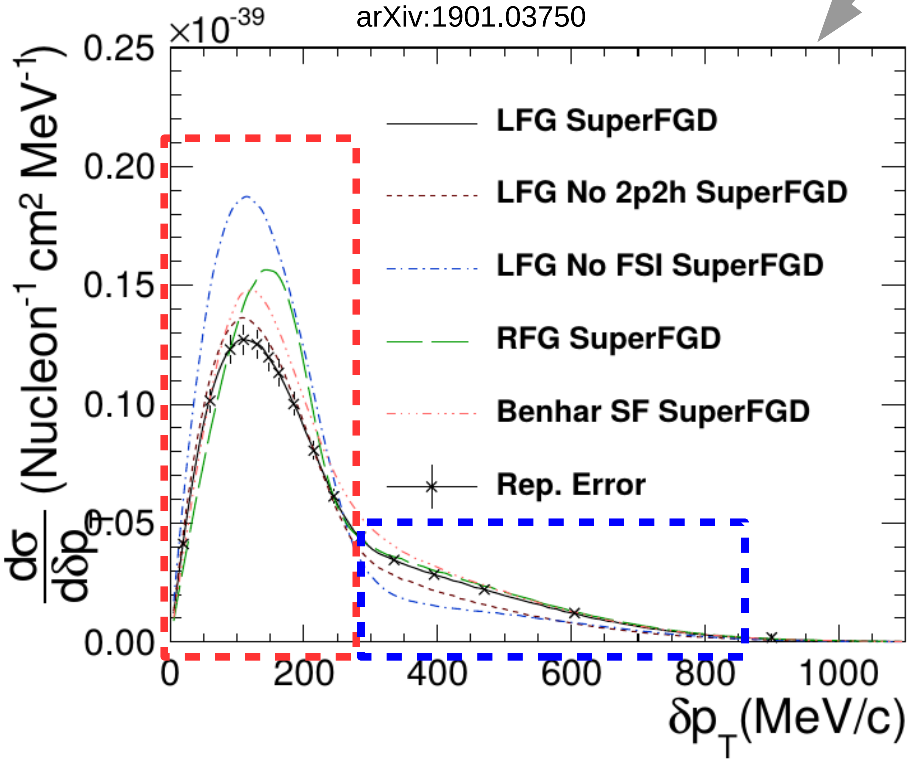
How to constrain IS/s/FSI

New kind of observables including the proton (neutron) information



I will use single transverse variables as a proxy: many more can be thought (p_n, Ehad, vertex activity...)

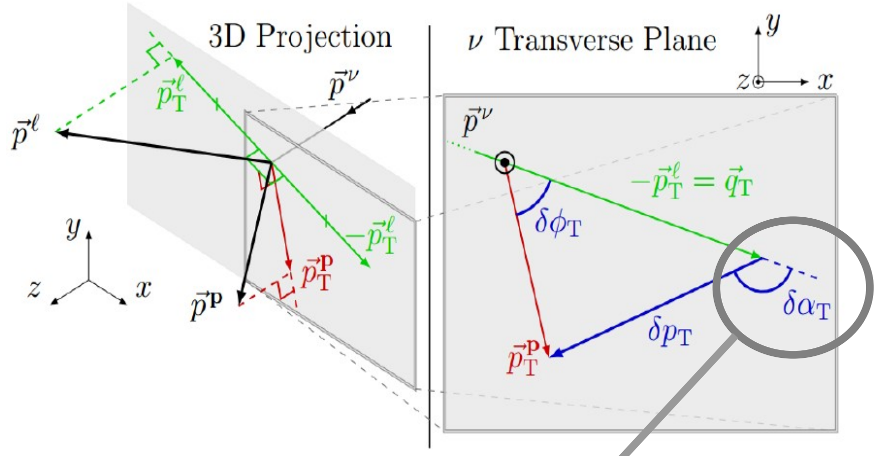
I will mostly discuss protons, neutrons, similar arguments holds for pions



- The bulk of dp_T is sensitive to **initial state effects:** Fermi momentum distribution
- **Fundamental interaction:** separate CCQE from 2p2h δp_T tail
- What about **FSI**?

How to constrain IS/□/FSI

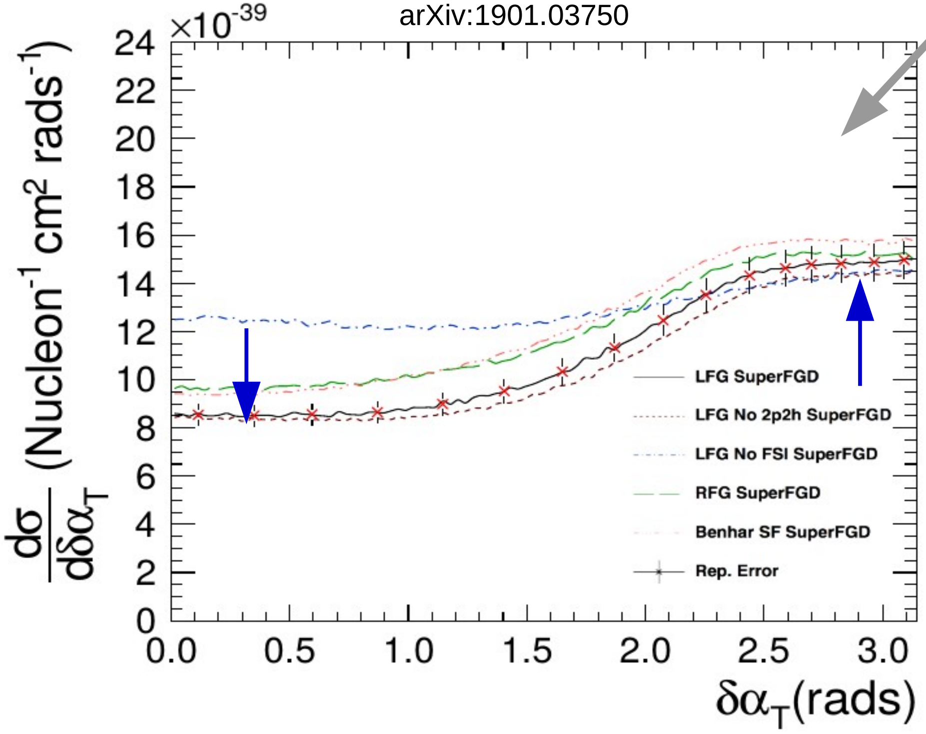
New kind of observables including the proton (neutron) information



I will use single transverse variables as a proxy: many more can be thought (pn, Ehad, vertex activity...)

I will mostly discuss protons, neutrons, similar arguments holds for pions

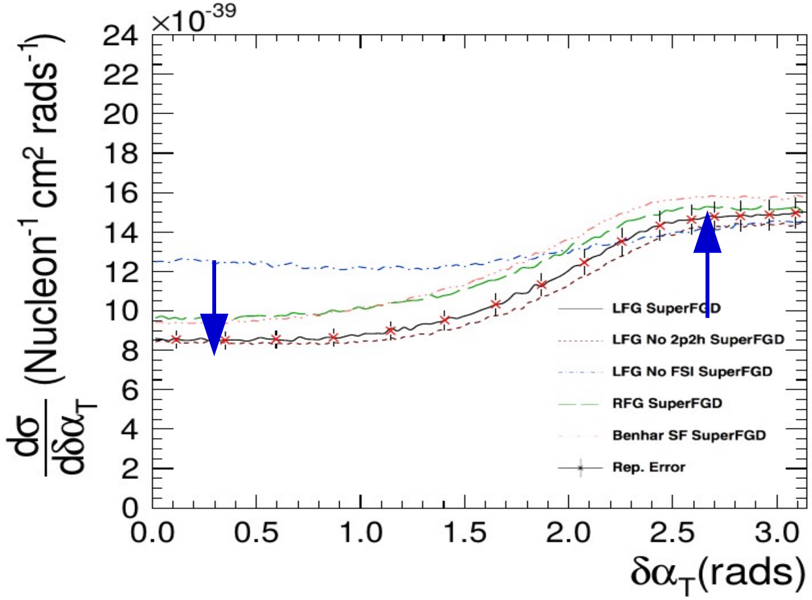
arXiv:1901.03750



da_T is sensitive to **FSI**:
how much acceleration/deceleration of the proton in the nucleus → □□$_T$ shape
(~flat without FSI)

Usefulness of Carbon

The capability of separating the different effects (IS/s/FSI) in these variable is only 'partial', there is always some degeneracy in the shapes between the different effects



Measurement of da$_T$/p$_T$ for different targets help disentangling IS/s/FSI effects!
Since they all have a different dependence on nucleus size A

Difference between C vs Ar give enough leverage for extracting A-depending effects separately

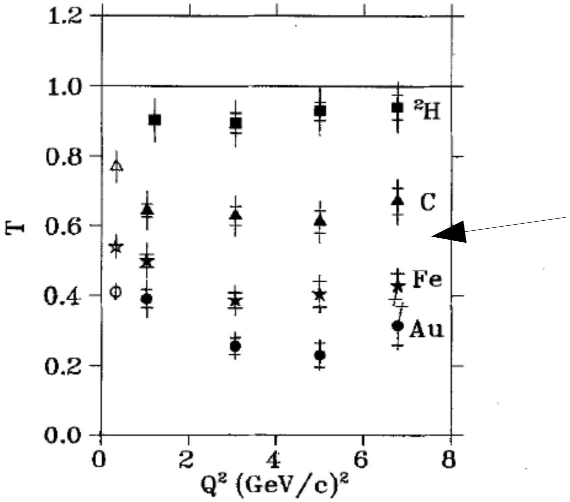


Fig. 1. Nuclear transparency for $A(e, e'p)$ as a function of Q^2. The inner error bars are the statistical uncertainty, and the outer error bars are the statistical and systematic uncertainties added in quadrature. The open points at $Q^2 = 0.33$ (GeV/c)^2 are from Ref. [27] for C, Ni, and Ta targets.

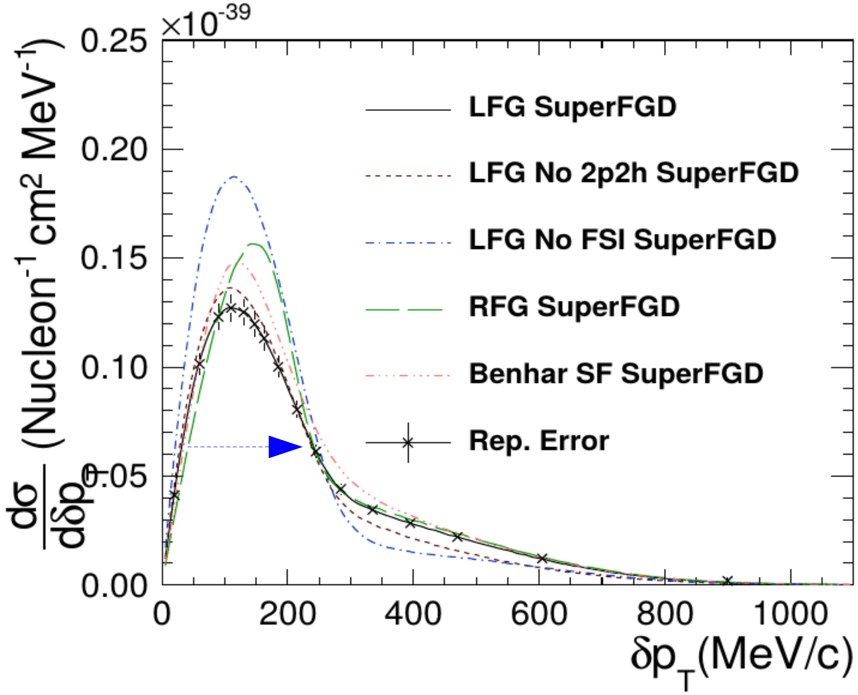
- FSI can be extracted from $_T$ shape:

preliminary parametrization of A-dependence can be extracted from electron scattering data and further tuned with ND data

Physics Letters B 351 (1995) 87–92

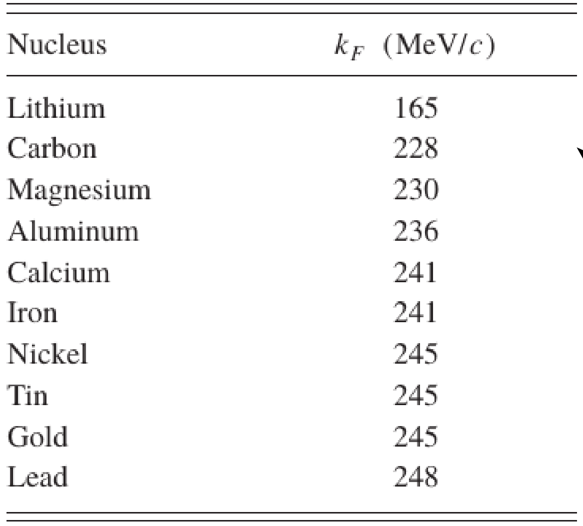
Usefulness of Carbon

The capability of separating the different effects (IS/□/FSI) in these variable is only 'partial', there is always some degeneracy in the shapes between the different effects



Measurement of □□$_T$/□p$_T$ for different targets help disentangling IS/□/FSI effects!
Since they all have a different dependence on nucleus size A

Difference between C vs Ar give enough leverage for extracting A-depending effects separately



Nucleus	k_F (MeV/c)
Lithium	165
Carbon	228
Magnesium	230
Aluminum	236
Calcium	241
Iron	241
Nickel	245
Tin	245
Gold	245
Lead	248

- Initial state effects (Fermi momentum) can be extracted from the width of the □p$_T$ distribution

(other variables are sensitive to binding energy)

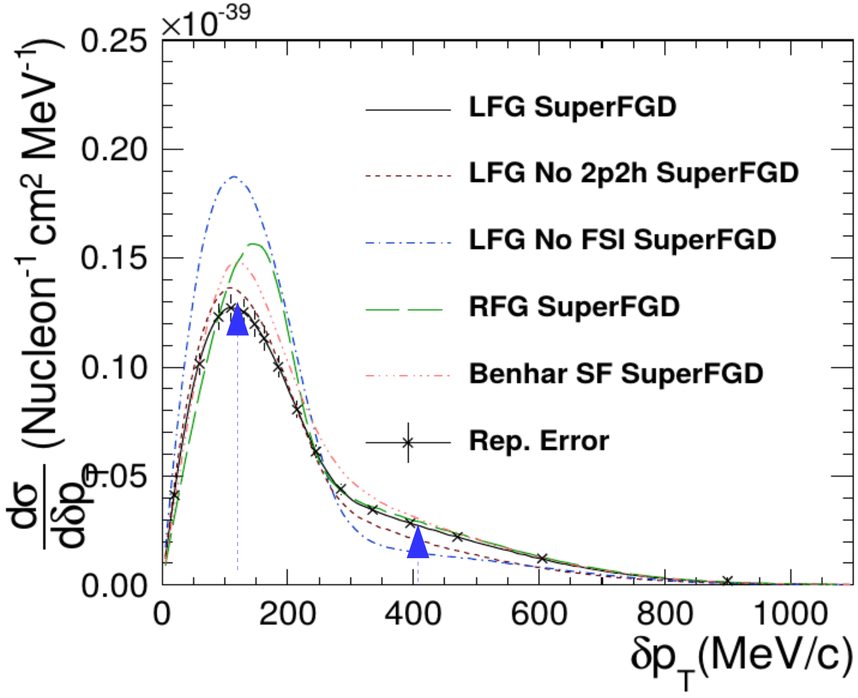
Fermi momentum dependence on A from electron scattering

PHYSICAL REVIEW C **65** 025502

SuSaV2 model: these values applied to Relativistic Mean Field model assure scaling of 2nd kind in the super-scaling functions for neutrino scattering
Phys. Rev. C 71, 065501

Usefulness of Carbon

The capability of separating the different effects (IS/□/FSI) in these variable is only 'partial', there is always some degeneracy in the shapes between the different effects



Measurement of □□$_T$/□p$_T$ for different targets help disentangling IS/□/FSI effects! Since they all have a different dependence on nucleus size A

Difference between C vs Ar give enough leverage for extracting A-depending effects separately

- Fundamental interaction, eg. 2p2h/CCQE, affect the height of peak/tail in □p$_T$

2p2h and CCQE cross-section have different A dependence
(e.g. SuSa model: 2p2h ~ A*k_F^2 , CCQE ~ A/k_F)

A-dependence of the cross-section is a powerful handle to evaluate CCQE and 2p2h separately (thus extrapolating properly the xsec from ND to FD)

Carbon to Argon

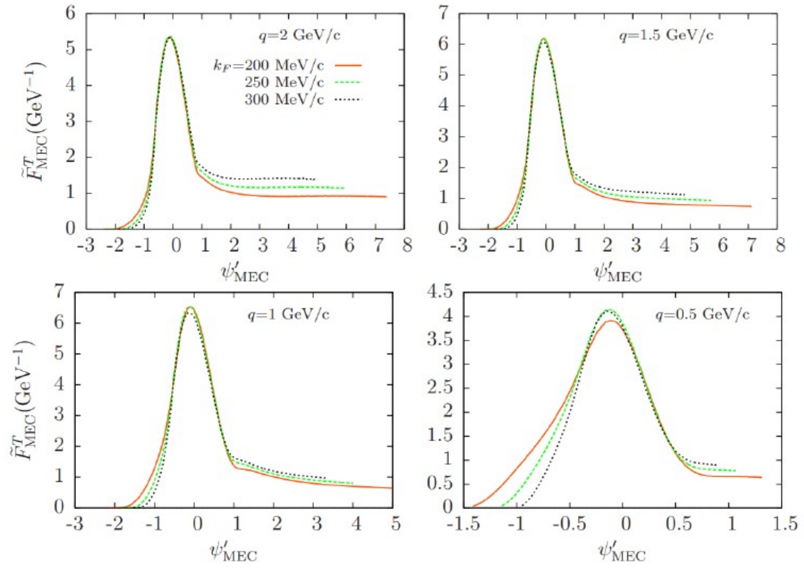
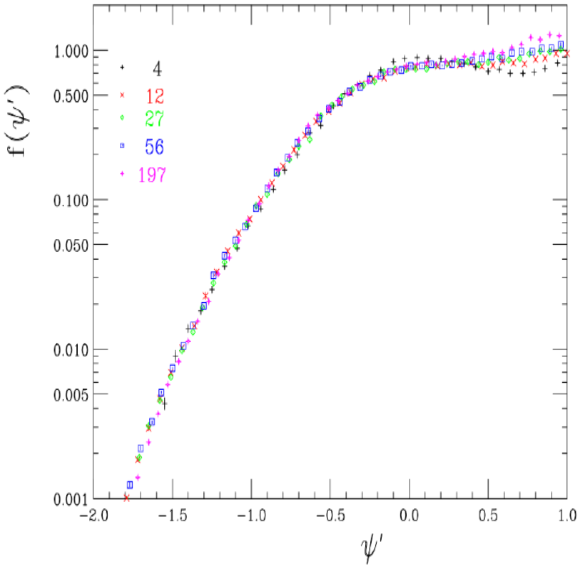


Figure 7: A demonstration of that the scaling behaviour of 2p2h interactions is broadly independent of nuclear target (given by the targets Fermi momentum, k_F) over a range



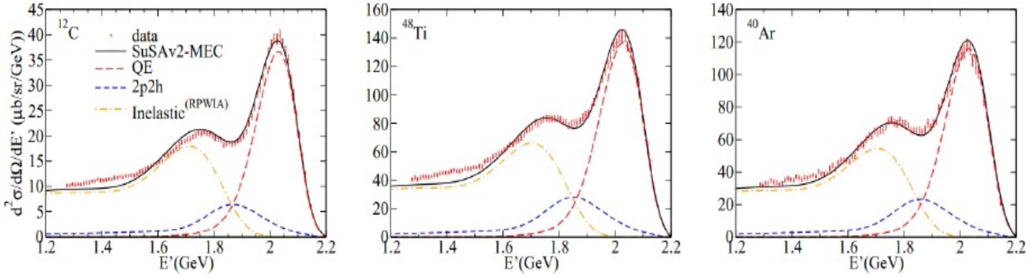
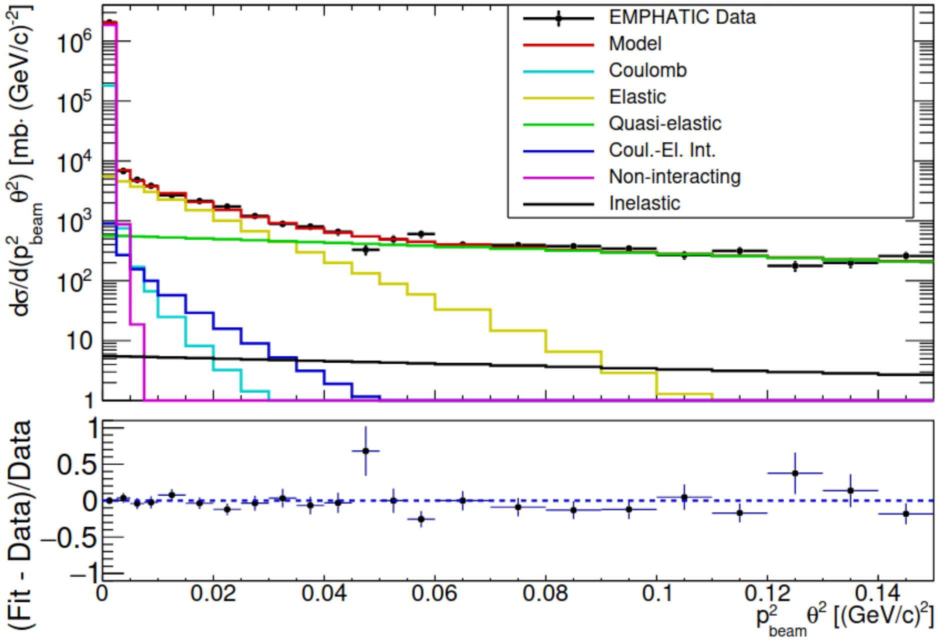


Figure 4: The scaling function (which characterises the difference between a nuclear cros section from a free-nucleon cross section) of as a function of the scaling variable fo different nuclear targets (the colours present different 'A' values). The main purpose o showing this plot here is to demonstrate that the scaling function is nearly identical i the 1p1h dominated region ($\Psi' < 0$). This figure is taken from reference [19].

Figure 3: A comparison of the SuSAv2 model (based on RMF) to inclusive electron scattering data on a variety of nuclear targets, including Argon. This figure is taken from reference [8]. This reference also shows how modifications to RMF (via and RMF-RPWIA blending function, described in section 2) motivated from electron-Carbon scattering data are necessary to describe this electron-Argon scattering data.

EMPHATIC first results



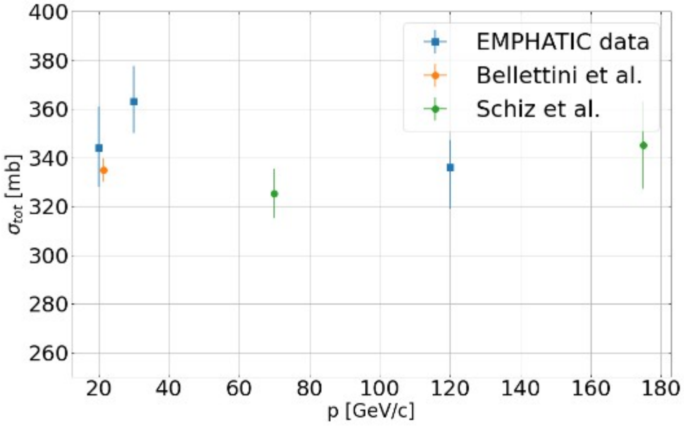
Total xsec can be measured by combination of

- transmission method $N_S = N_0 e^{-nd\sigma_{tot}}$
- optical theorem: Im part of limit at t^2=0 GeV^2 of scattering amplitude

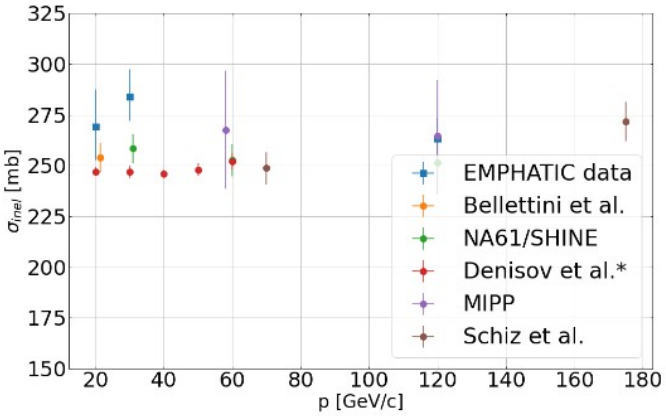
First pilot run for proof of principle

e-Print:2106.15723 [physics.ins-det]

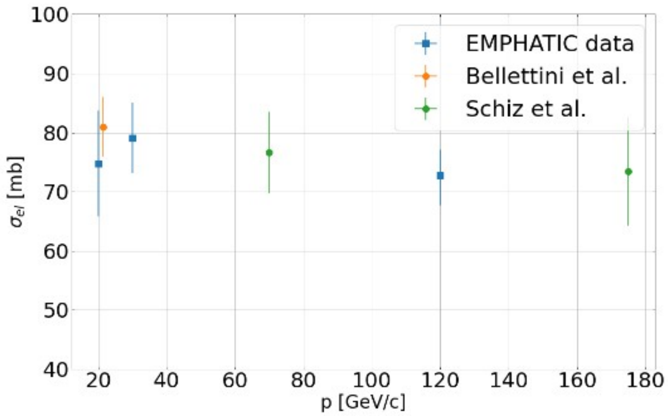
σ_{tot}



$\sigma_{inelastic}$



$\sigma_{elastic}$



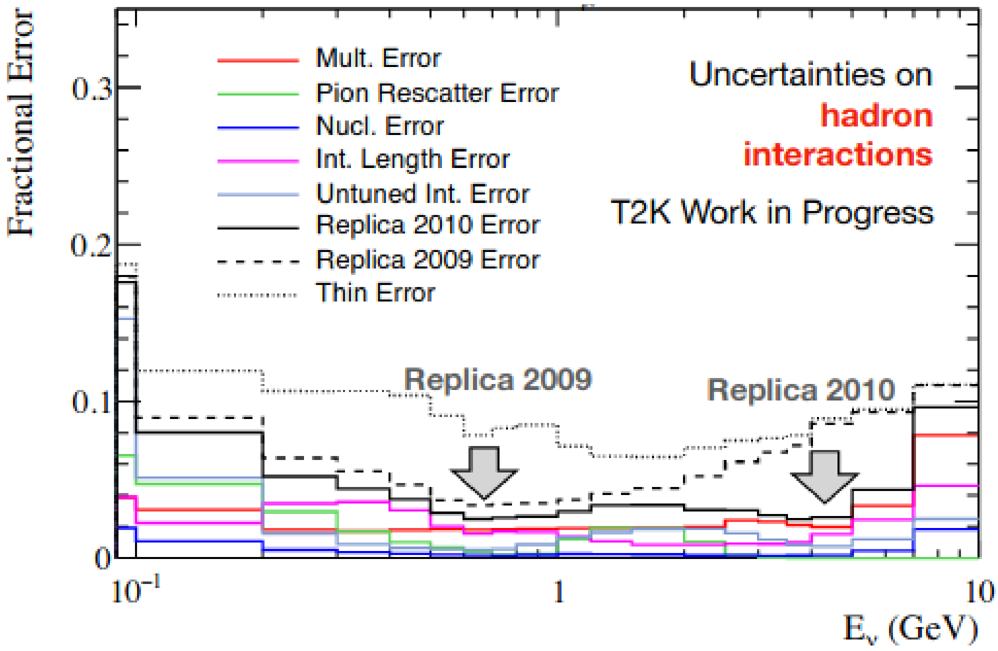
Lessons learned

- **First order:** pC→ π, K multiplicity and kinematics

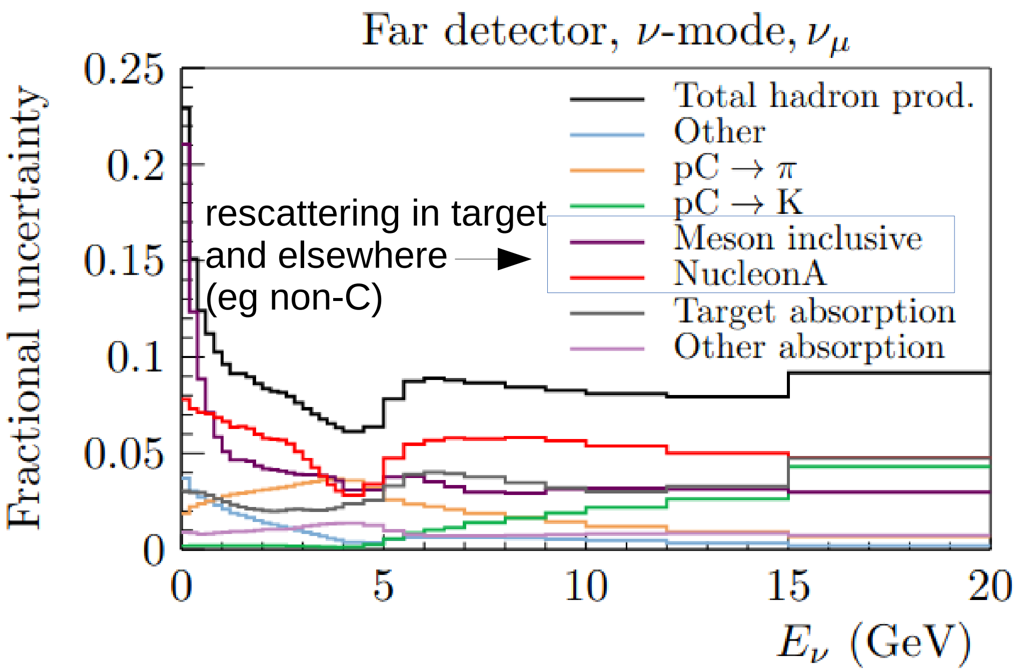
- With **replica target:** able to tune also re-interactions in target + minimize the impact of total proton cross-section uncertainty
(important to define exactly what do we measure for proton xsec: see Y.Nagai@WAMP)

- **Next:** re-interactions in the other elements of the beamline (not C) + hadrons outside the present NA61 acceptance

T2K (with intensive tuning from NA61 data-taking!)



Example for next LBL (DUNE): clear need of measurements on replica of future targets

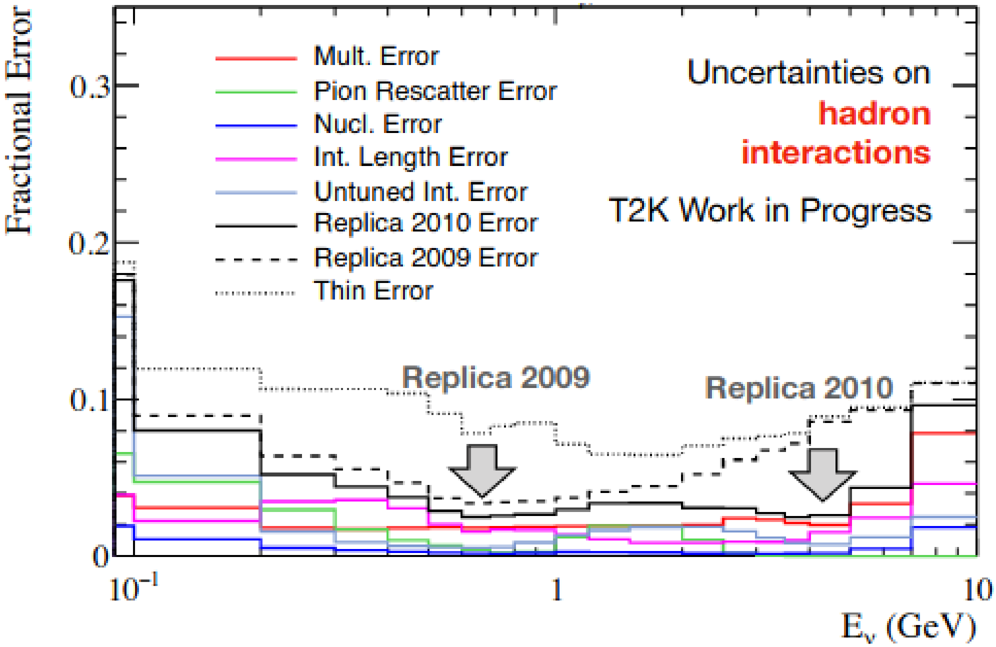


rescattering in target and elsewhere (eg non-C)

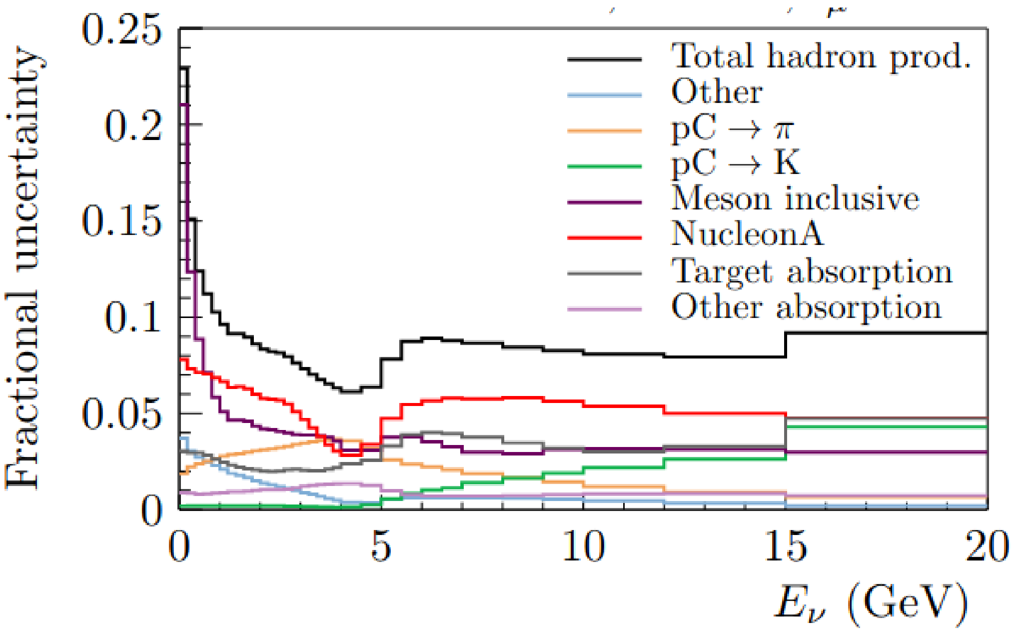
Prospects

Prospects for DUNE and HK: factor 2-3 better $\sin^2\theta_{23}$ measurement than today for each single experiment → **need control at ~<1% on flux normalization**

T2K (as an example for HK)



DUNE

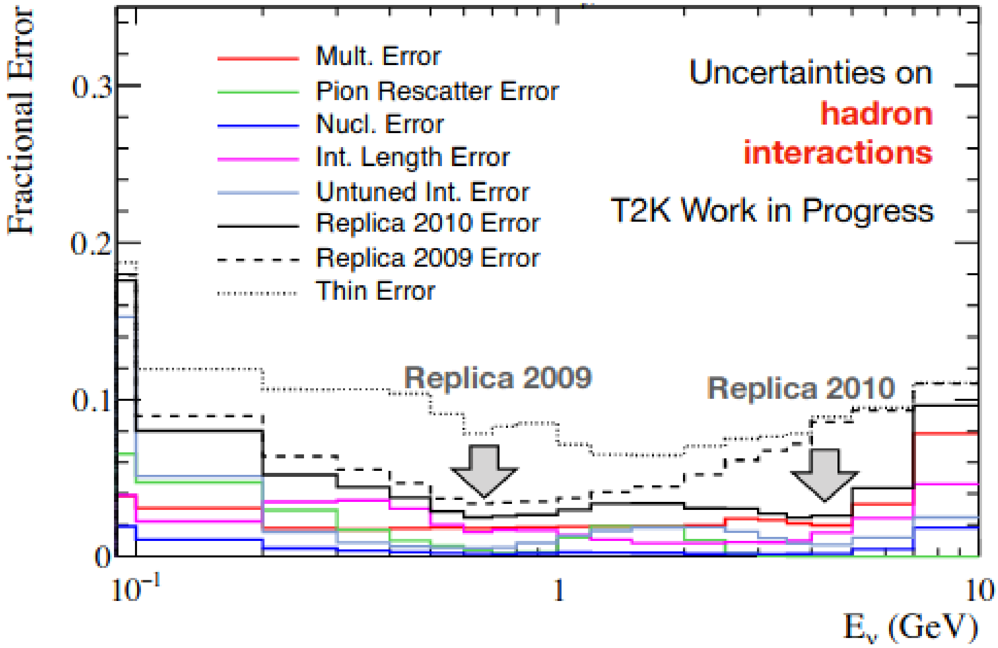


A systematics with leading impact on total flux rate is the total proton cross-section (aka interaction length): today ~2%

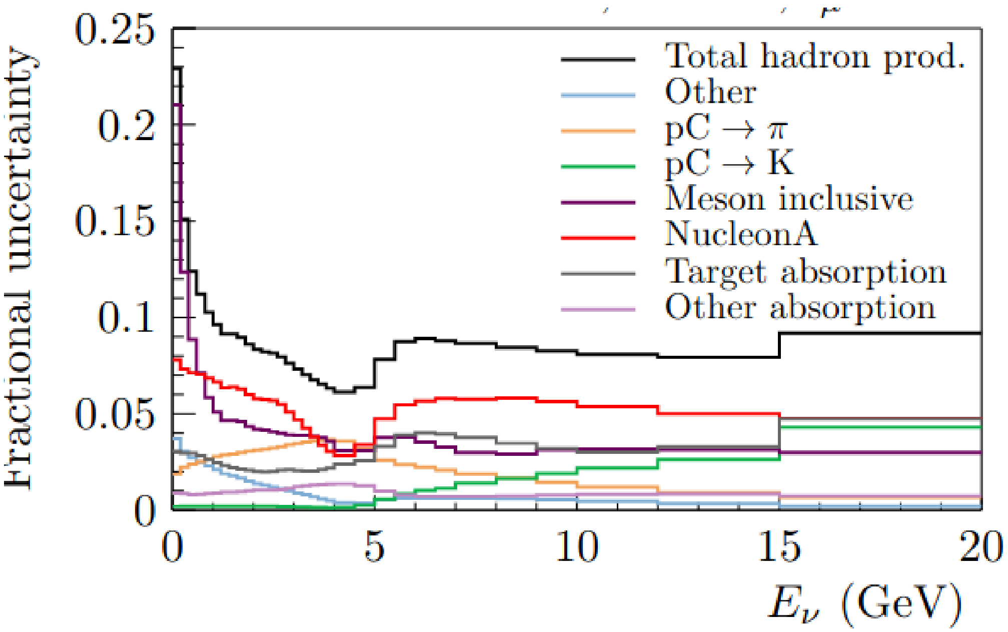
Prospects

Prospects for DUNE and HK: for each single experiment factor 2-3 better **Δ**m² measurement then global fit today and precise dCP → **control at ~<0.5% on “energy scale”**

T2K (as an example for HK)



DUNE

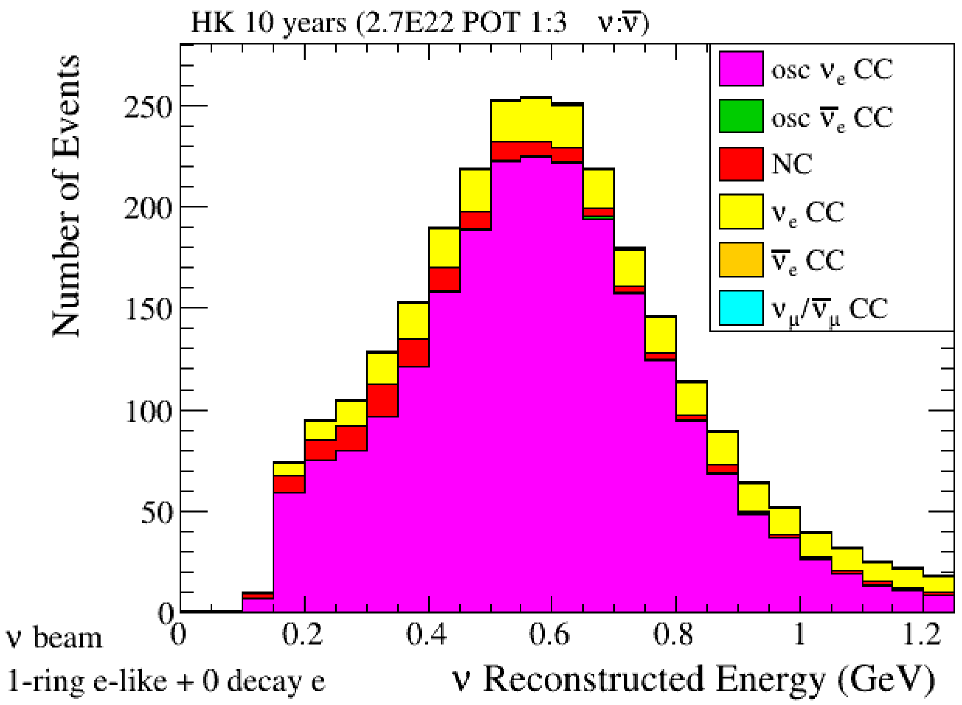


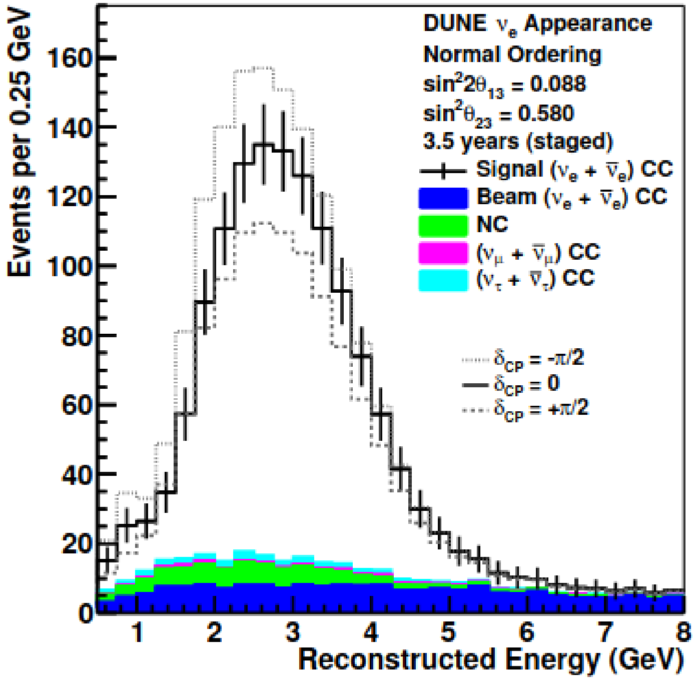
Most challenging systematics on flux shape comes from hadron rescattering error and untuned interactions (outside NA61 phase space)

Thanks to replica target in T2K: ~ 30% reinteractions in target now under control → still 10% of re-interactions in beamline. New measurements on other target material

Prospects

For today best fit values of θ_{23} we expect both HK and DUNE to reach ~4-5 sigma sensitivity to reject the wrong octant: huge increase in statistics of ν_e sample



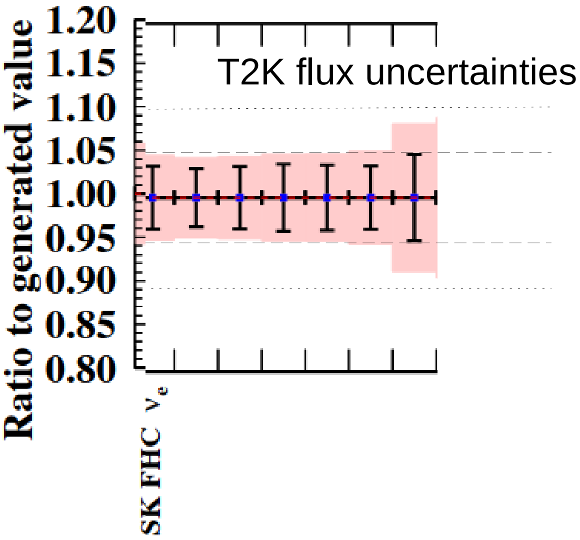


The most important background is the **intrinsic ν_e component inside the flux** (already present before oscillation): ~10%

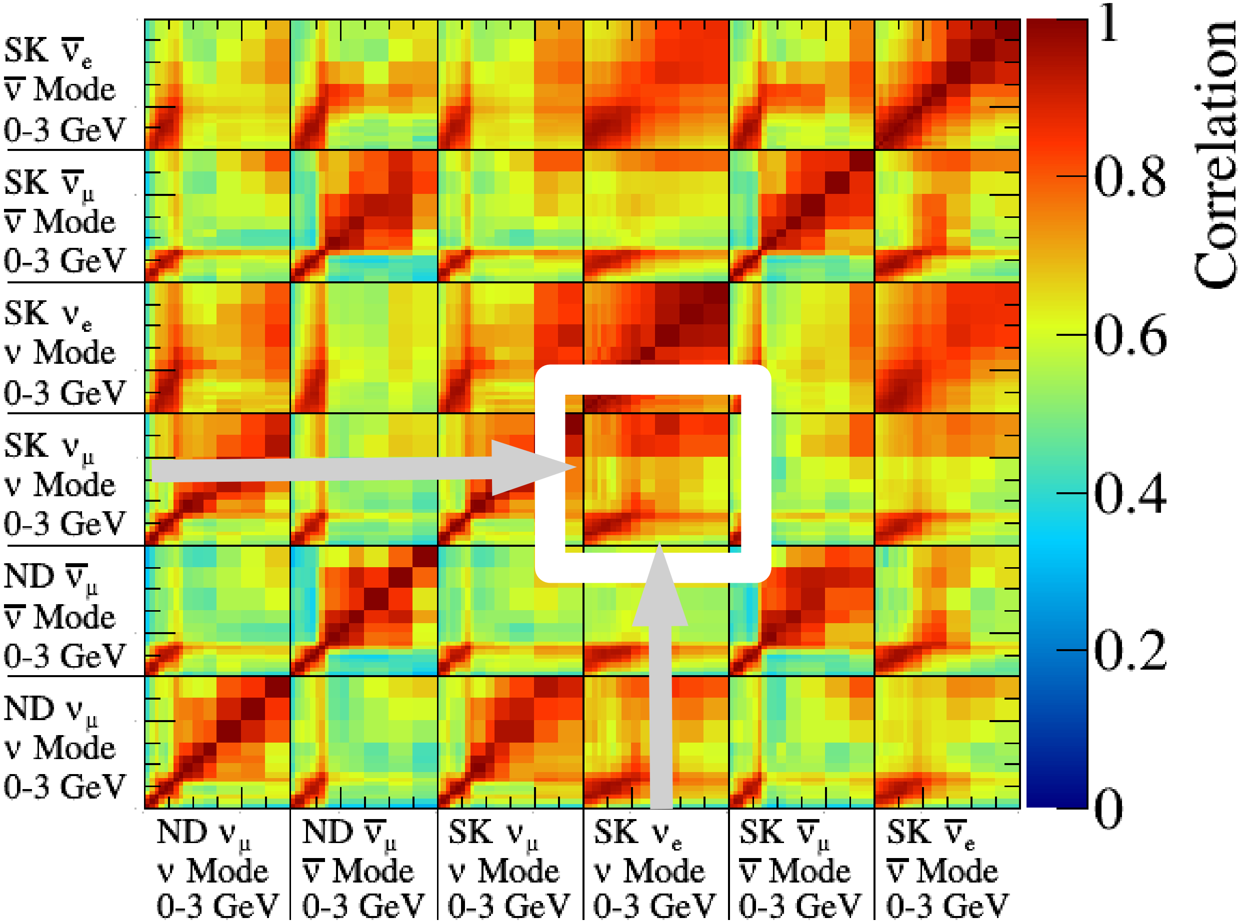
To measure ν_e oscillated signal normalization at ~1% (octant degeneracy breaking) need to have a **relative precision on the ν_e intrinsic background <5 %**

ν_e flux today

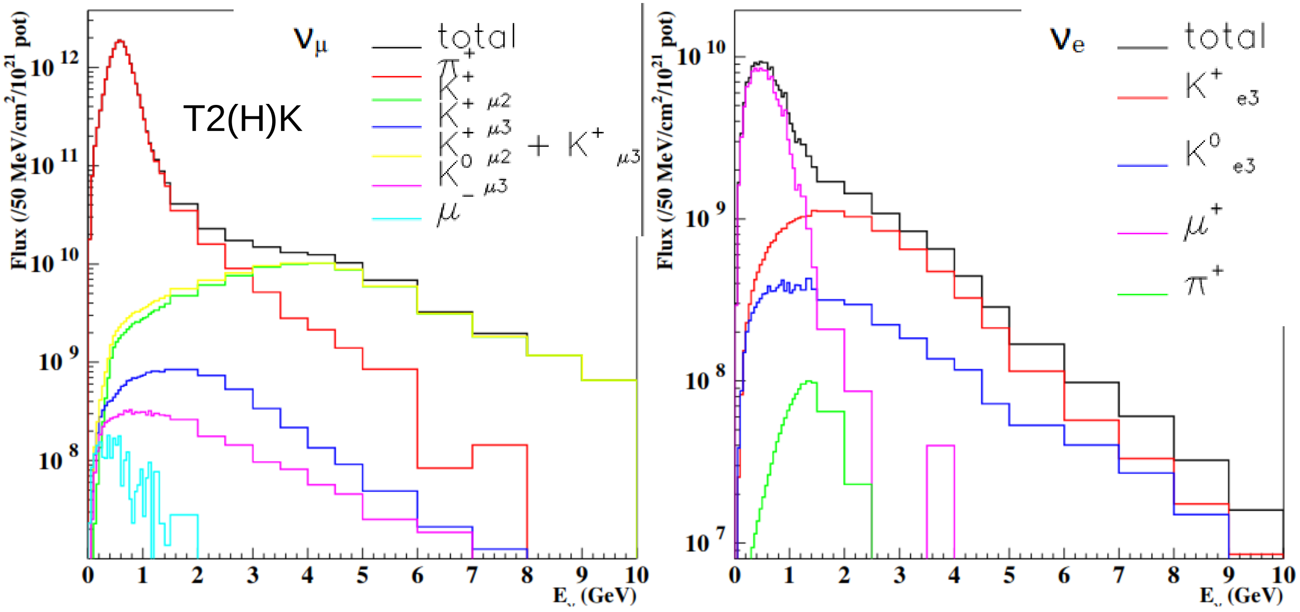
Today uncertainty on ν_e flux already at 5% level before ND constraints and **strong correlation between ν_μ and ν_e flux uncertainties:**



Correlations of T2K flux uncertainties

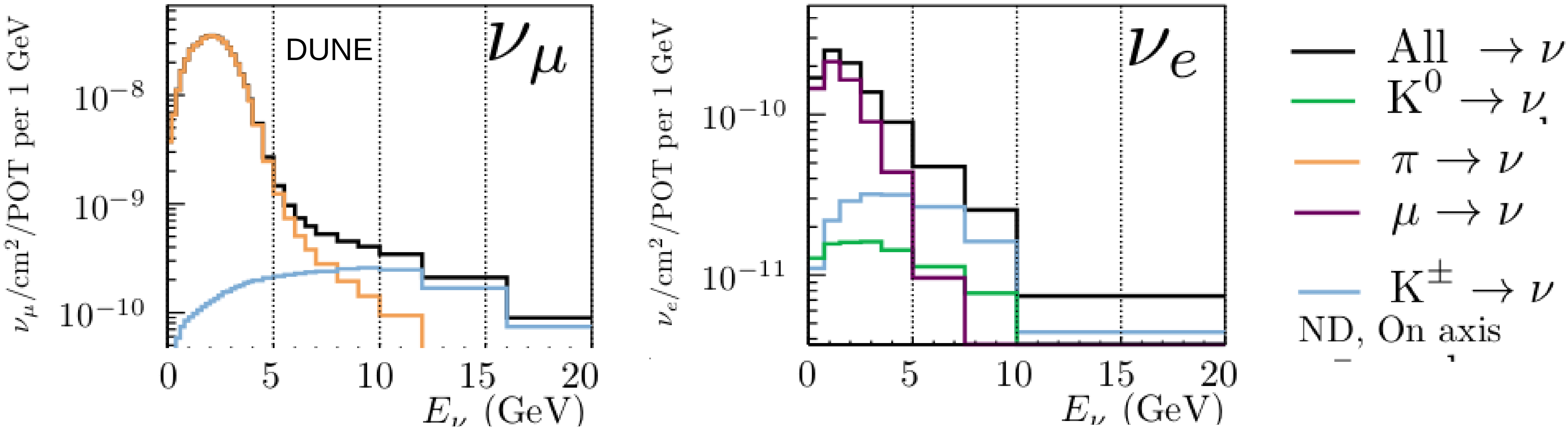


ν_e flux vs ν_μ flux

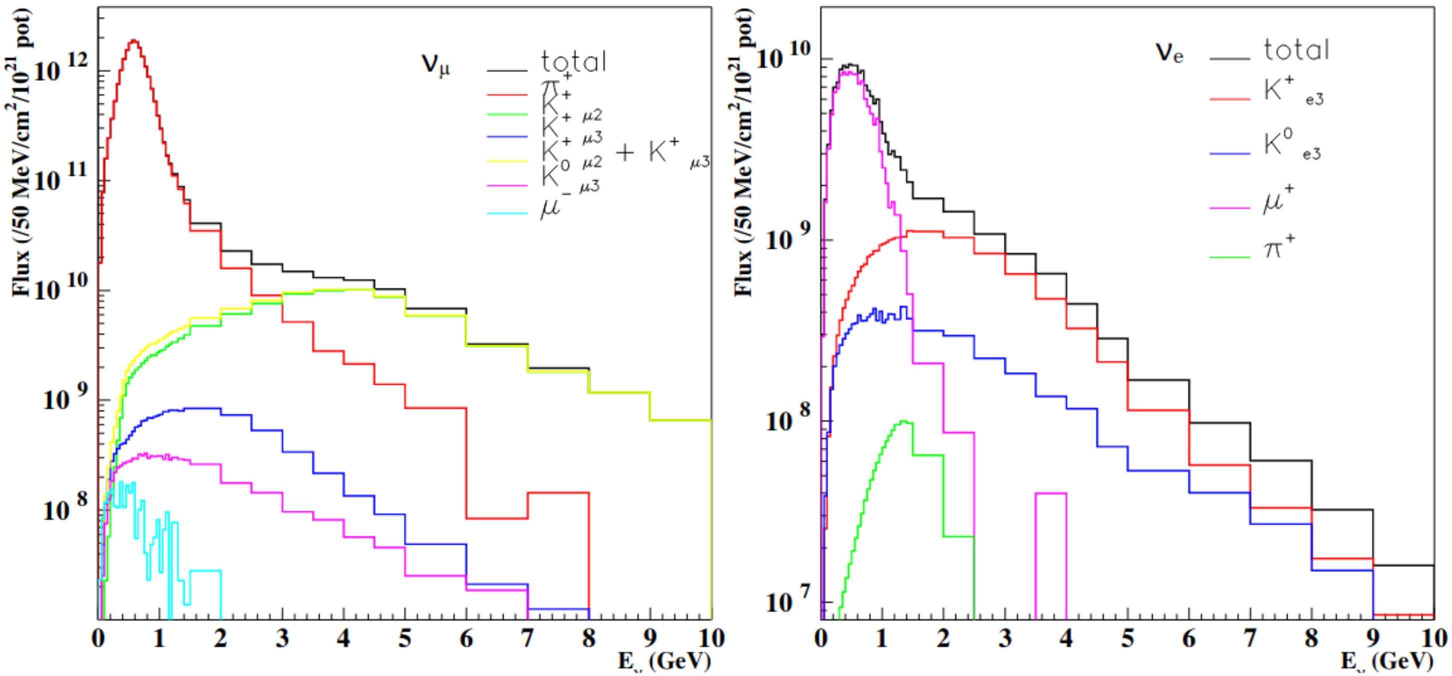


ν_e flux at the oscillation peak energy is dominated by μ decay coming from from π,K decays → correlation with **ν_μ**

(+ direct K decays into **ν_e** at
higher energy,
K0 subdominant)



Flux in T2K: intrinsic ν_e



ν species	Flux Abund.	Flux $\langle E_\nu \rangle$	Source: π^+ or π^- %	$\langle E_\nu \rangle$	K$^+$ or K$^-$ (K2) %	$\langle E_\nu \rangle$	K$^+$ or K$^-$ (K3) %	$\langle E_\nu \rangle$	K^0_L %	$\langle E_\nu \rangle$	μ^+ or μ^- %	$\langle E_\nu \rangle$
ν_μ	1.0	0.84	95.5	0.69	4.2	4.15	0.2	2.13	0.1	2.10	< 0.01	0.80
$\bar{\nu}_\mu$	0.0692	1.19	85.8	1.13	4.0	3.21	0.2	1.70	1.2	2.12	8.8	0.66
ν_e	0.0110	1.41	1.0	1.58	–	–	30.7	2.48	11.1	2.52	57.2	0.62
$\bar{\nu}_e$	0.0016	2.26	0.4	2.40	–	–	13.6	1.91	76.7	2.49	9.2	0.88

- Small intrinsic background to ν_e appearance measurements (important for δ_{CP} and MO).
- It can also be used to measure ν_e xsec at the near detector (with limited statistics)

One useful feature is that low-energy ν_e mostly come from muon and kaon (to pi0) decays so they do not follow the 3-body decay rule: different energy-angle dependence than ν_μ

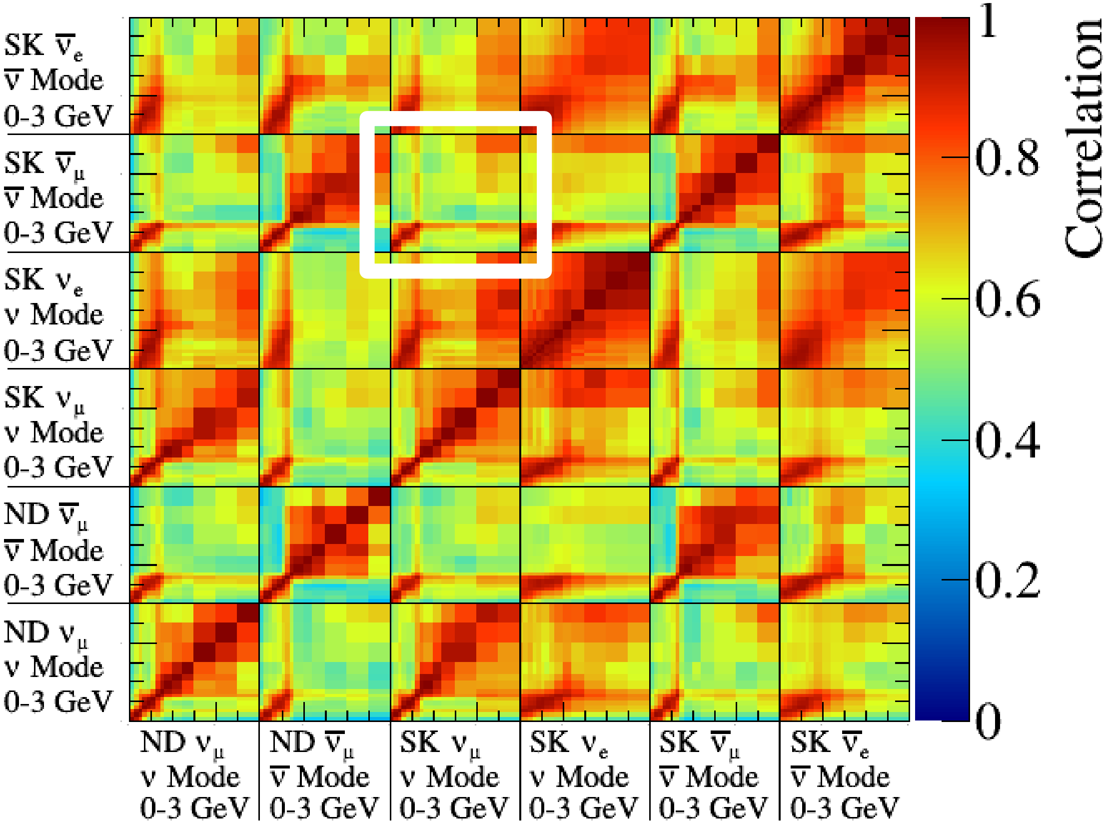
Prospects

Prospects for next generation: 5σ on CPV and MH

What is really important are $\nu_e/\bar{\nu}_e$ anticorrelations, they must be below 2% (the lower, the better → direct impact on sensitivity and ultimate limitation to it)

No direct anticorrelation from flux uncertainties (but need to constrain ν contamination into $\bar{\nu}$ [aka wrong sign])

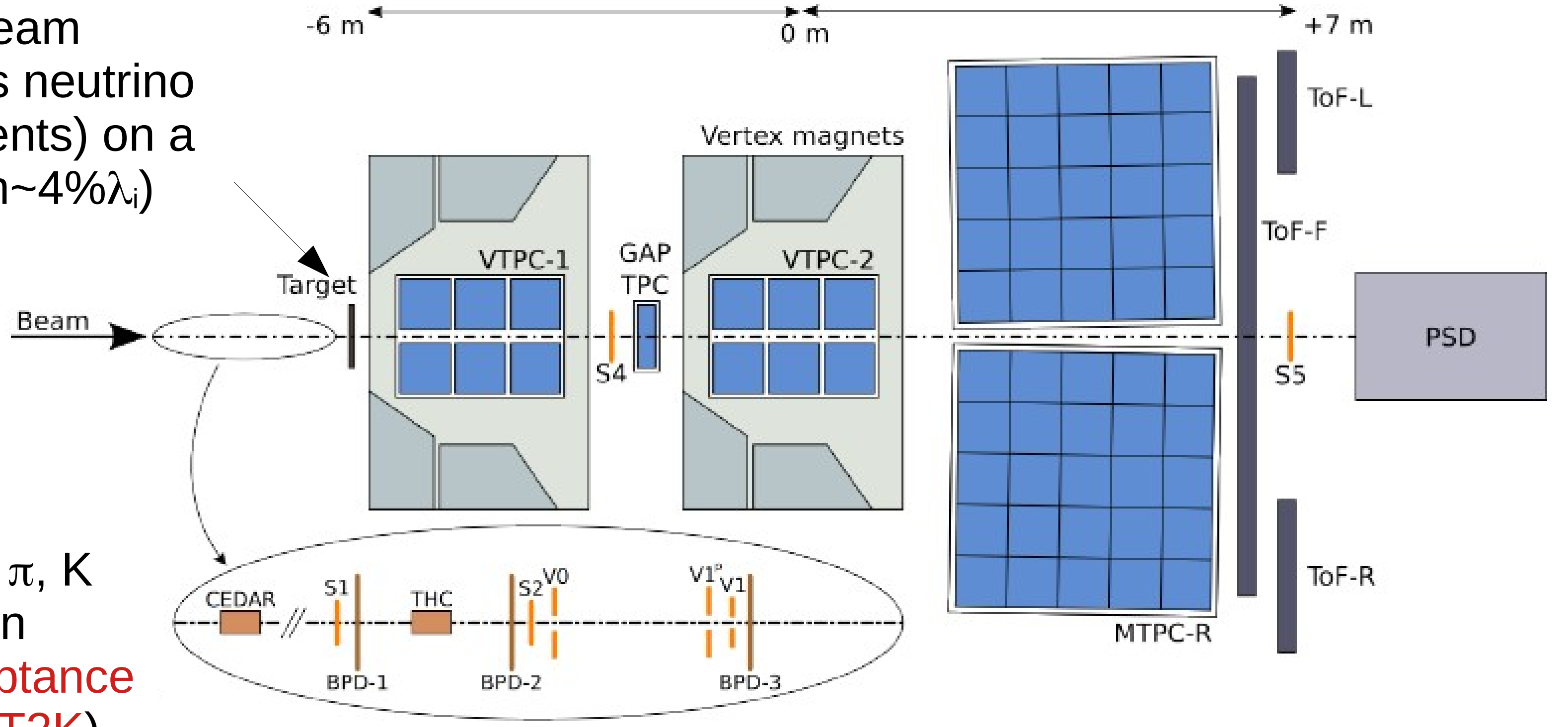
Correlations of T2K flux uncertainties



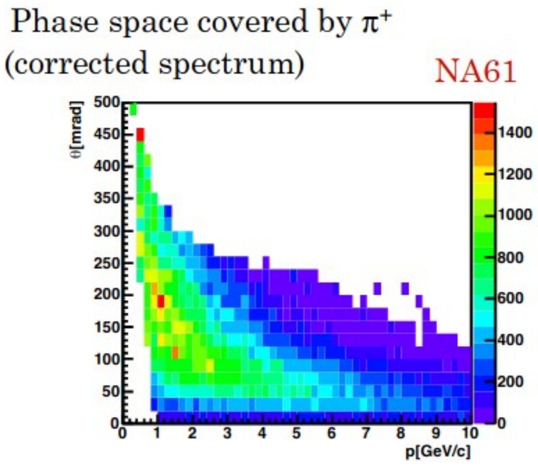
NA61/SHINE

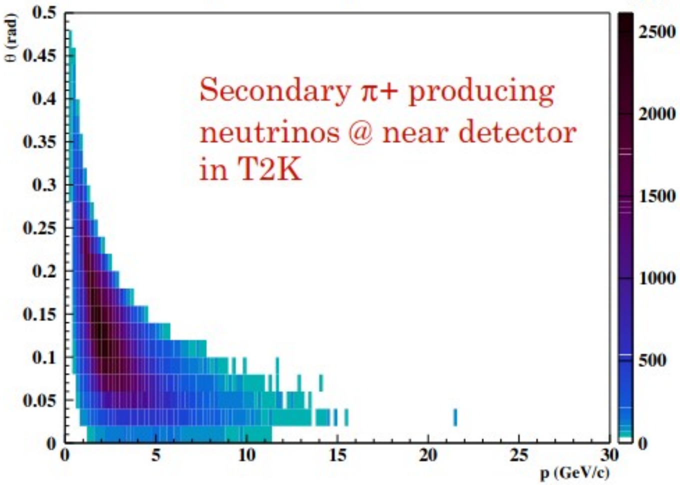
SPS Heavy Ion and Neutrino Experiment: Fixed target experiment using CERN SPS

proton beam (same as neutrino experiments) on a (thin 2cm~4%λ_i) target



Measure p, π, K in fwd region (good acceptance match with T2K)



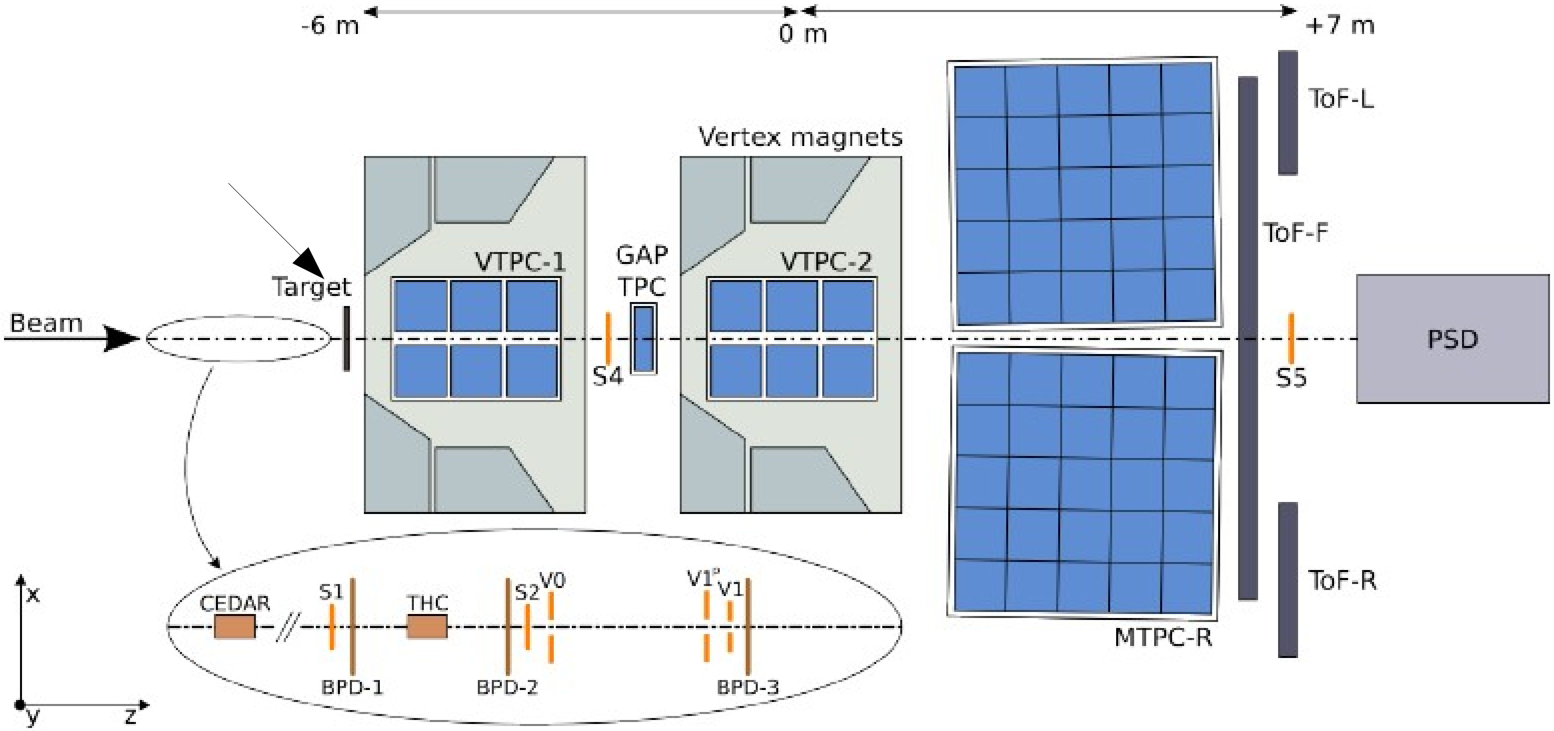


Momentum measurement with TPC in magnetic field (σ_p/p^2~0.005 GeV^{-1})

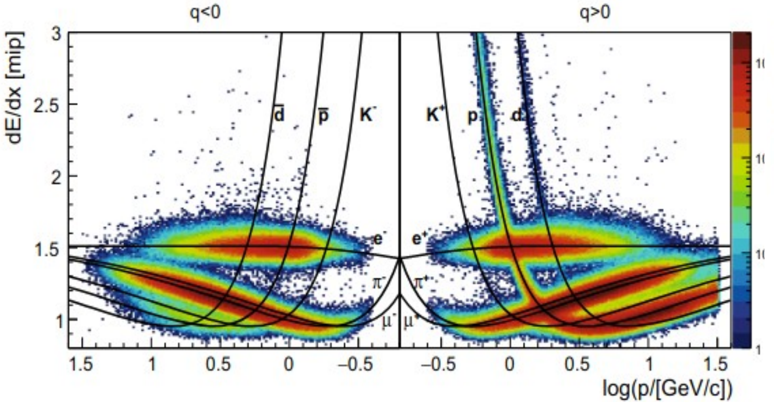
Angular measurement with 3-4 mrad resolution

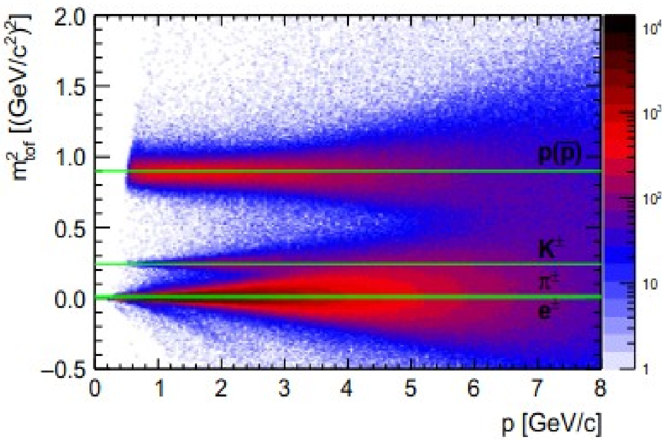
NA61/SHINE

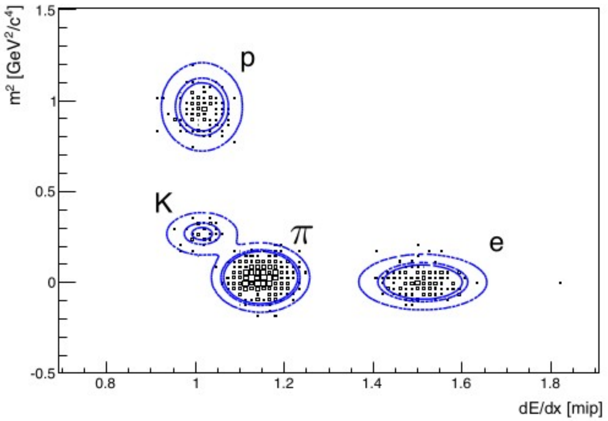
SPS Heavy Ion and Neutrino Experiment: Fixed target experiment using CERN SPS



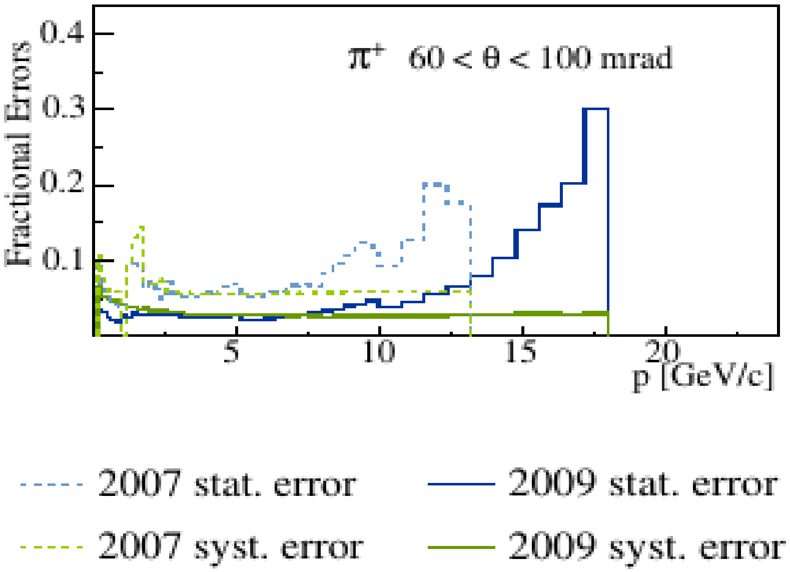
dE/dx + ToF measurement for clean PID

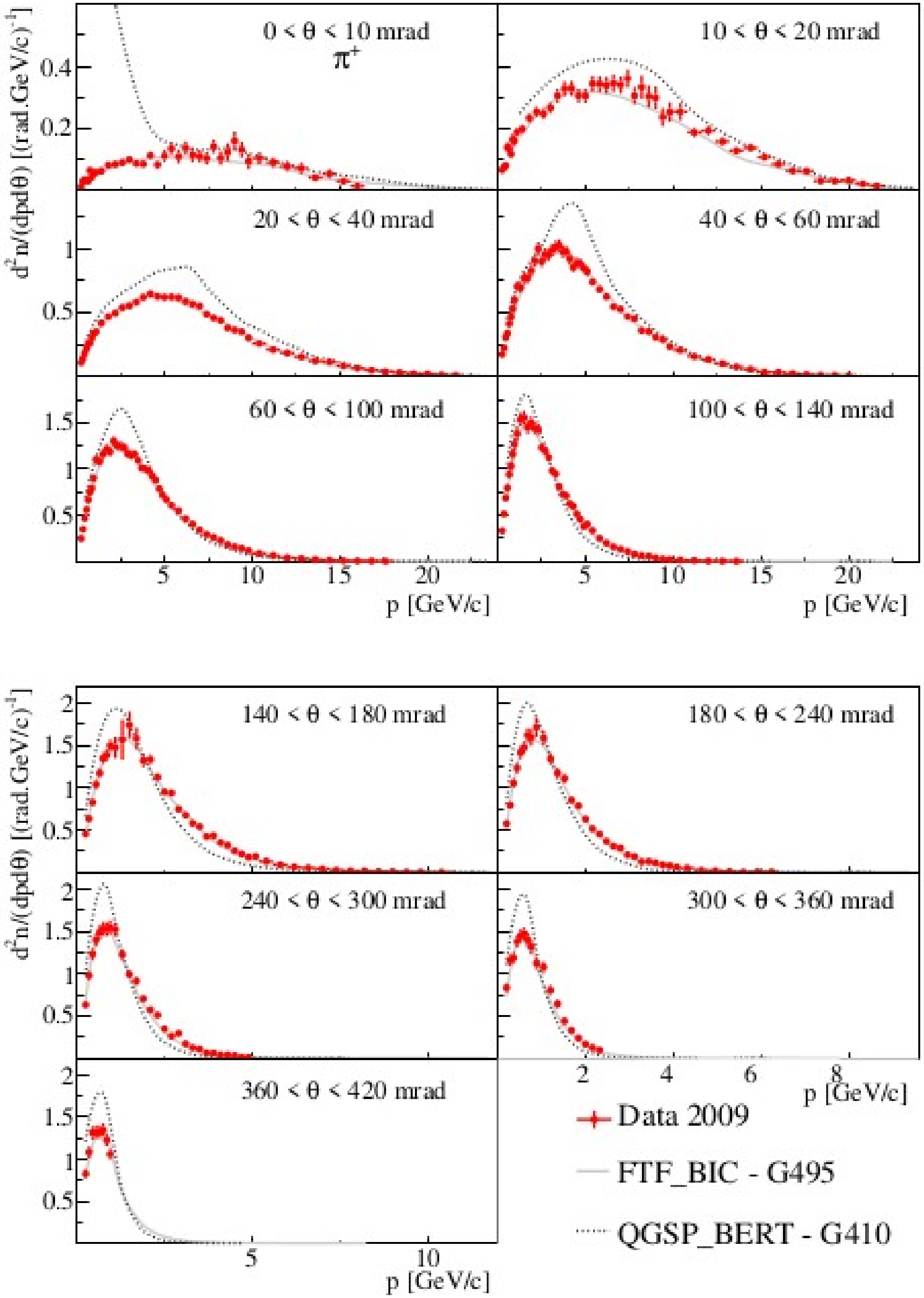






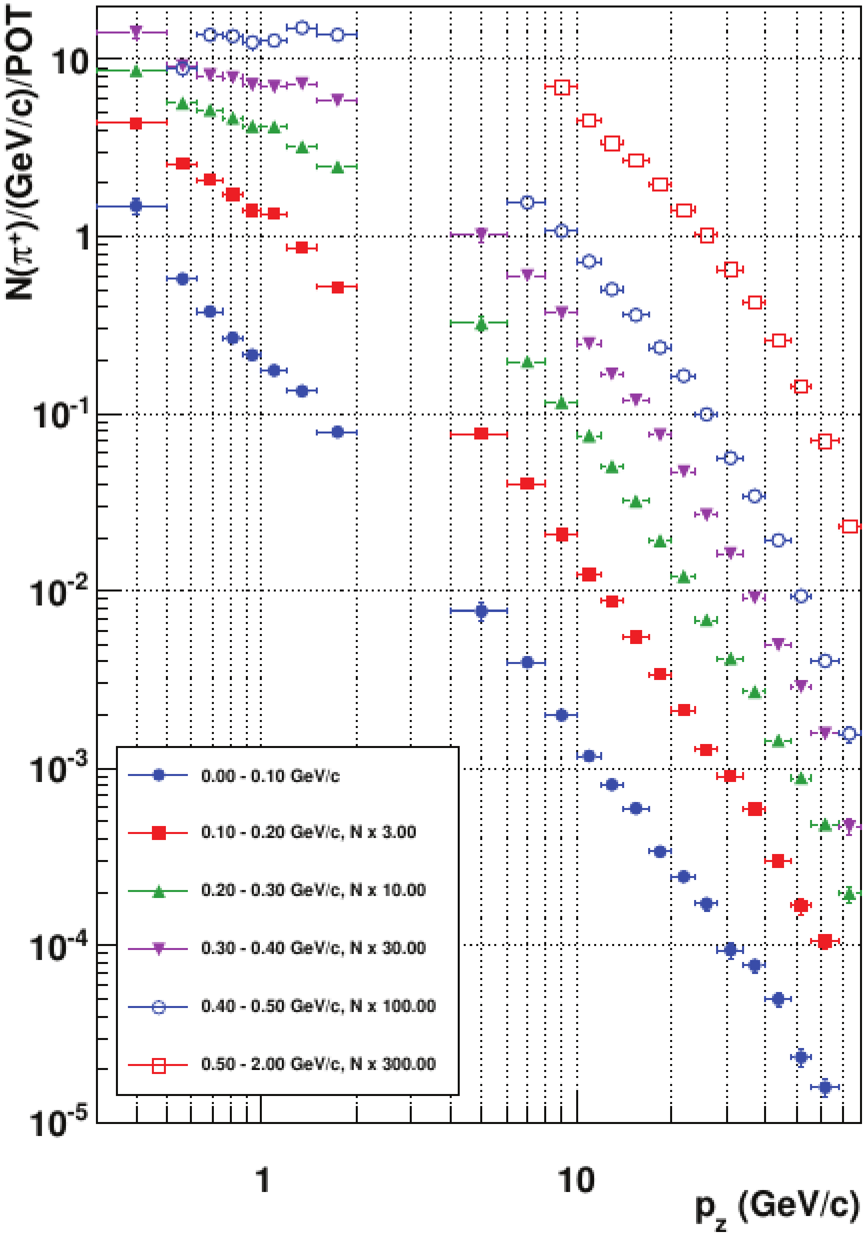
(Old) results

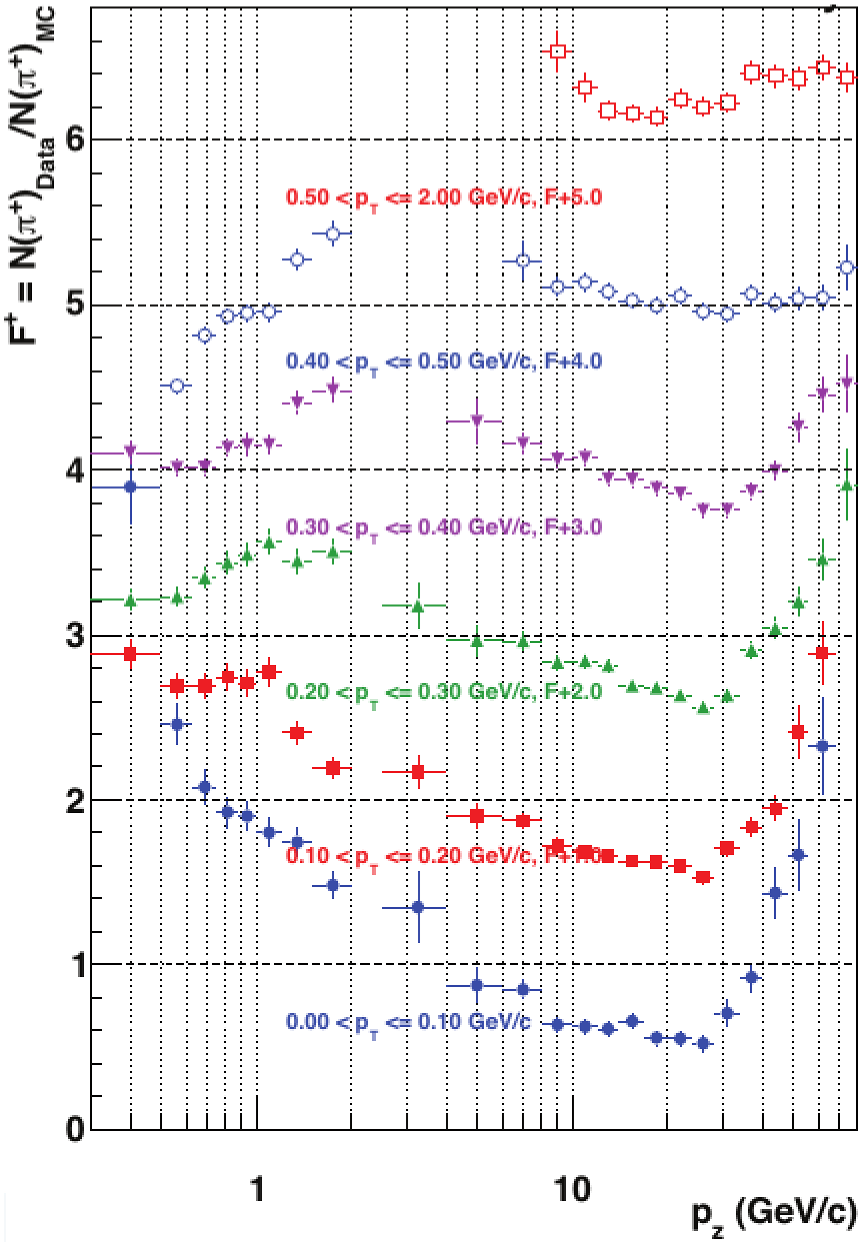




Full measurement of π+, π-, K+,K-

MIPP results for NuMI





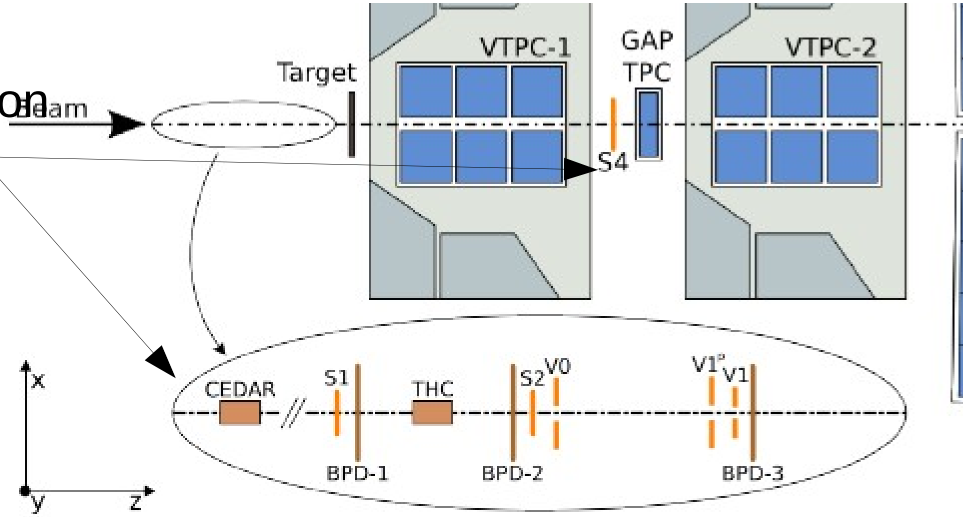
Cross-section normalization

$$\sigma_{hadroprod} = \sigma_{tot} - \sigma_{el} - \sigma_{qe}$$

σ_{tot} can be extracted from beam instrumentation in anti-coincidence with S4

(normalized to number of carbon nuclei in the target)

Need to correct for events with actual interactions in S4 using model



σ_{qe} quasi-elastic scattering on single nucleon in the carbon nucleus which get ejected (from GEANT)

σ_{el} elastic scattering on carbon nucleus (from previous measurements compared to GEANT → largest uncertainty)

$$\sigma_{\text{prod}} = 230.7 \pm 2.8(\text{stat}) \pm 1.2(\text{det})\,^{+6.3}_{-3.5}(\text{mod})\,\text{mb}$$

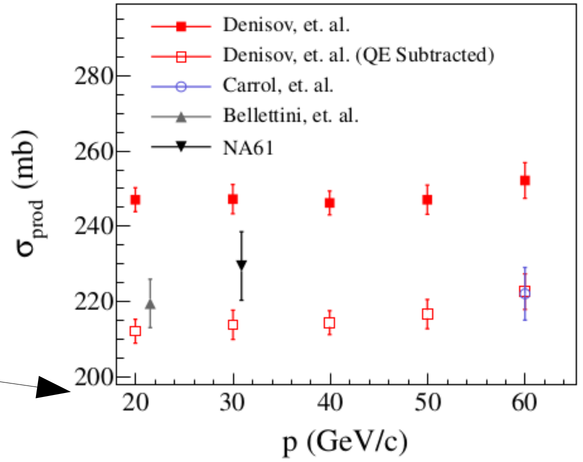
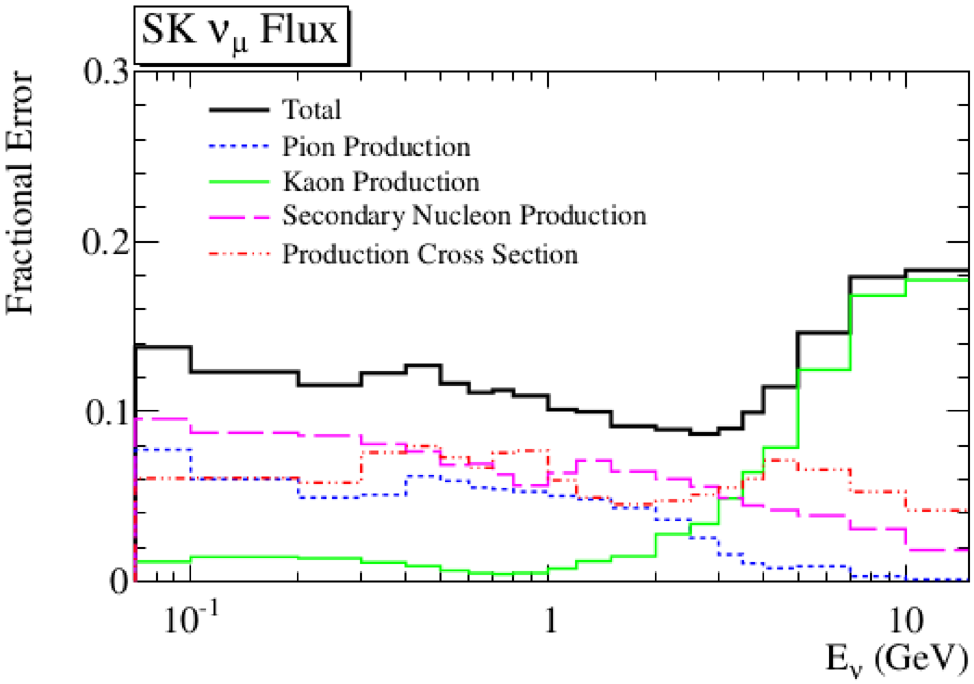


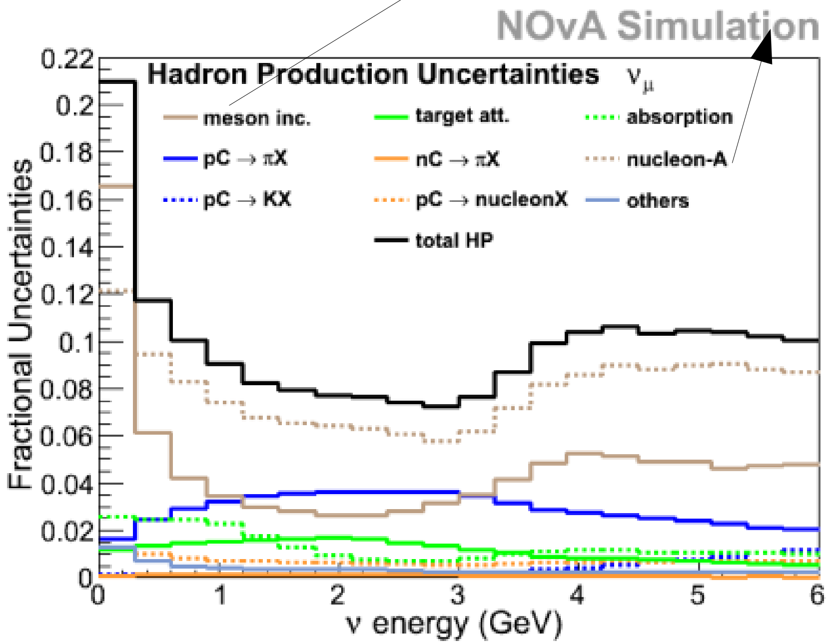
FIG. 37: Production cross-section measurements for protons on graphite targets for momenta 20–60 GeV/c. The data from Denisov *et al.* are shown with and without the quasi-elastic estimate subtracted since the quantity that is measured is ambiguous.

Flux uncertainties due to hadro-production using “thin targets” data (before ~2020)

These results improved greatly the flux uncertainty at LBL (~10%).

not C/target interactions

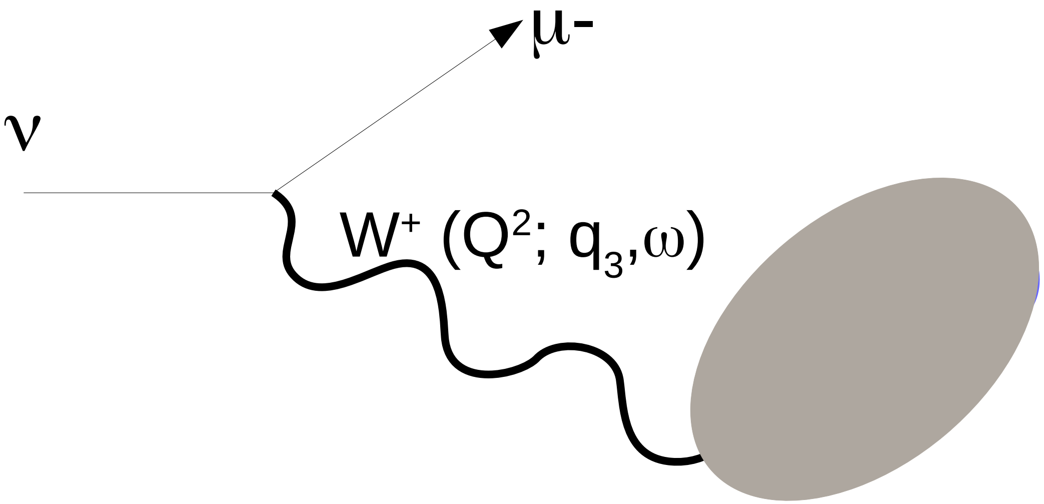




The remaining uncertainties were dominated by the total production cross-section and re-interactions in the horns

→ new NA61 measurement ‘more directly portable’ to T2K

The basic variables: q_3, ω



Only leptonic leg:

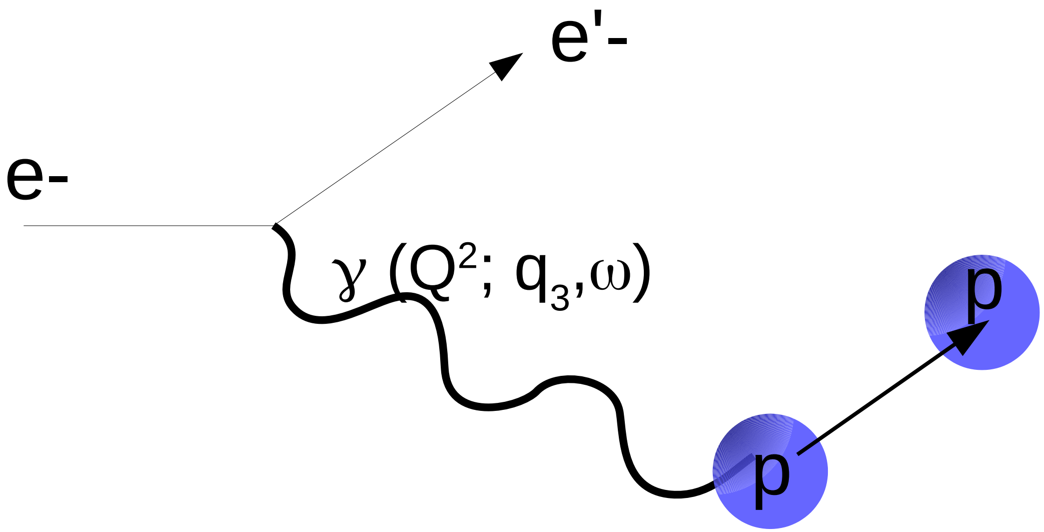
$q_3=\bar{p}_\nu-\bar{p}_\mu$

$\omega=E_\nu-E_\mu$

$Q^2 = (p_\nu-p_\mu)^2 \sim 2E_\mu E_\nu(1-\cos\theta)$

Cross-section can be parametrized as a function of E_ν, q_3,ω

The basic variables: e^-p scattering



$q_3=\overline{p}_e-\overline{p}_{e'}$

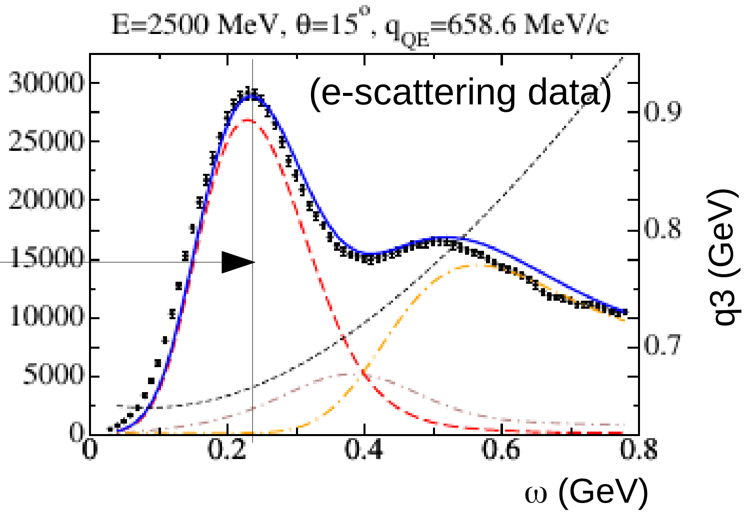
$\omega=E_e-E_{e'}$

$Q^2 = (p_e-p_{e'})^2 \sim 2E_eE_{e'}(1-\cos\theta)$

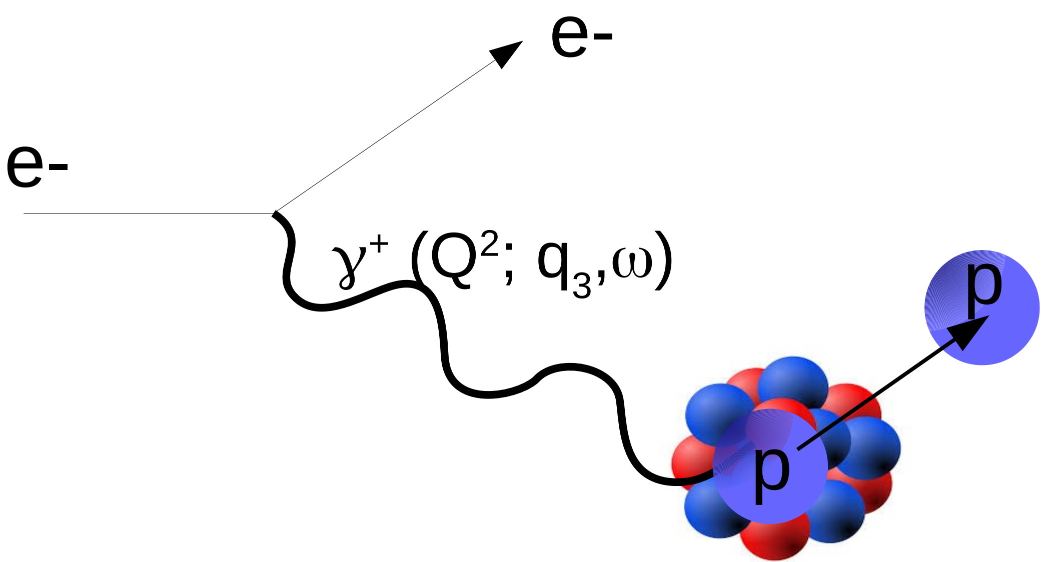
Only leptonic leg !

Cross-section can be parametrized as a function of E_e, q_3,ω

- Quasi-Elastic scattering on nucleon at rest



The basic variables: e^-p scattering



$q_3=\bar{p}_e-\bar{p}_{e'}$

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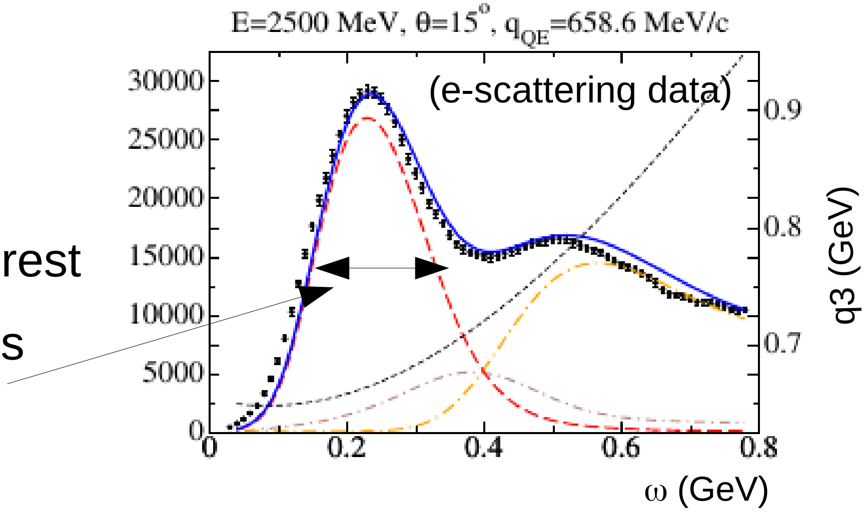
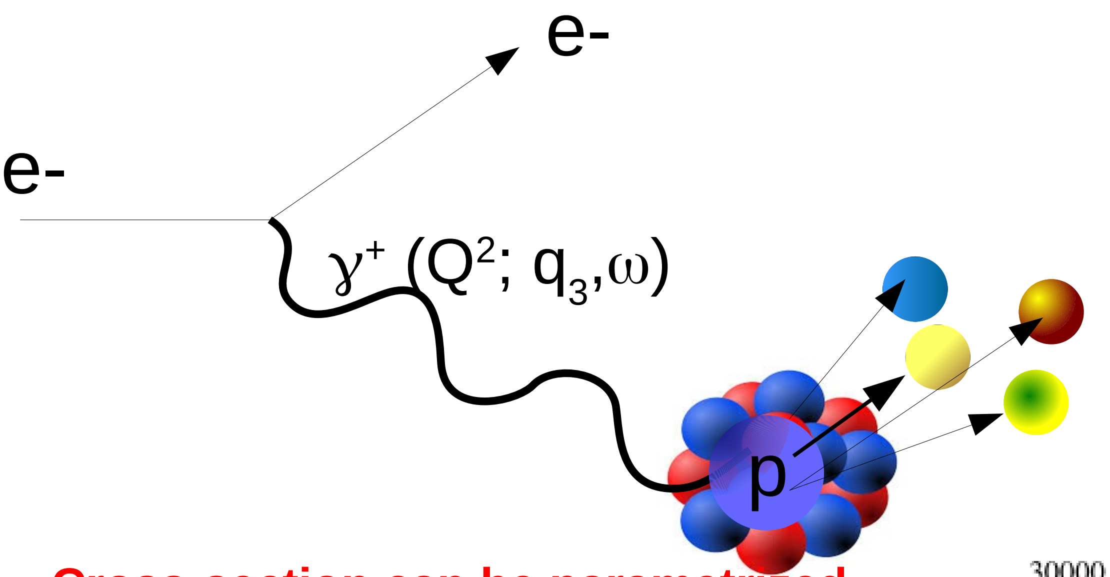
Cross-section can be parametrized as a function of E_e, q_3,ω

- Quasi-Elastic scattering on nucleon at rest

- Quasi-Elastic scattering: nuclear effects on initial state nucleon



The basic variables: $e^{-}p$ scattering



$q_3 = \overline{p}_e - \overline{p}_{e'}$

$\omega = E_e - E_{e'}$

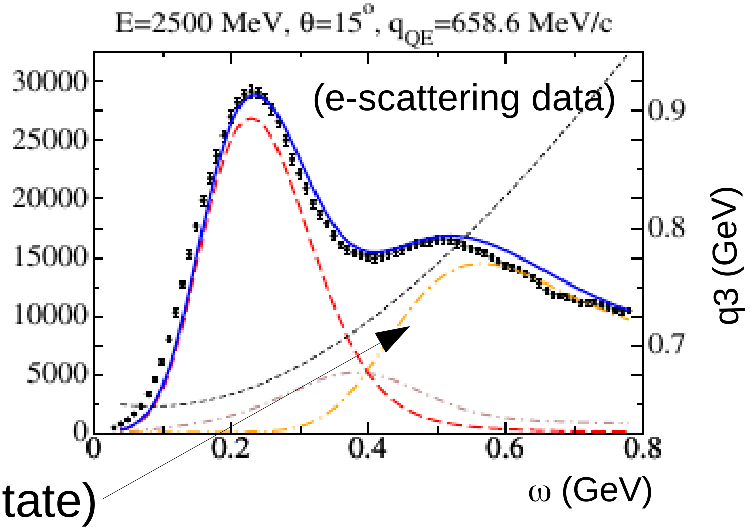
$Q^2 = (p_e - p_{e'})^2 \sim 2E_eE_{e'}(1-\cos\theta)$

Cross-section can be parametrized as a function of E_e, q_3,ω

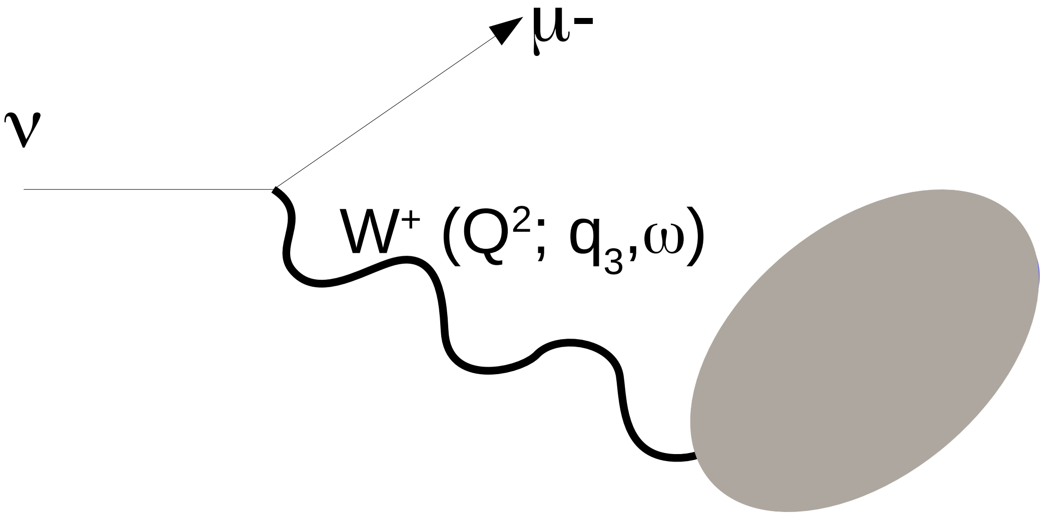
- QE scattering on nucleon at rest

- QE scattering: nuclear effects on initial state nucleon

- non-QE event (multiple particle in the final state)



Back to neutrinos...



$q_3=\bar{p}_\nu-\bar{p}_\mu$

$\omega=E_\nu-E_\mu$

$Q^2 = (p_\nu-p_\mu)^2 \sim 2E_\mu E_\nu(1-\cos\theta)$

Cross-section can be parametrized as a function of E_ν, q_3,ω

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- QE scattering: nuclear effects on initial state nucleon

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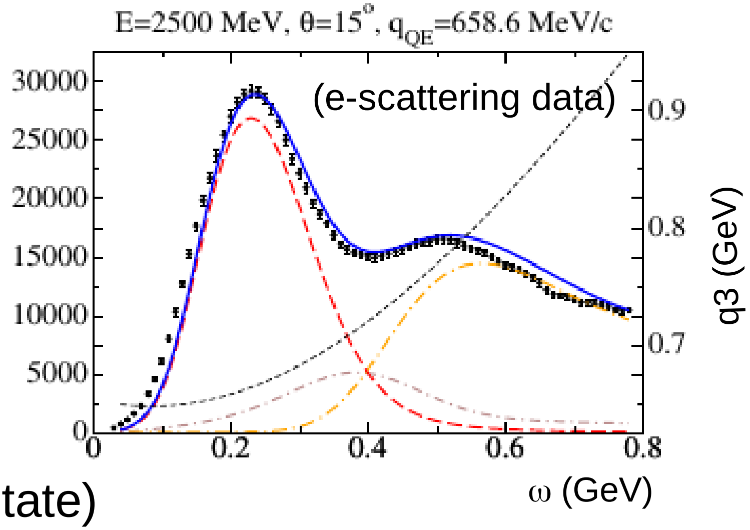
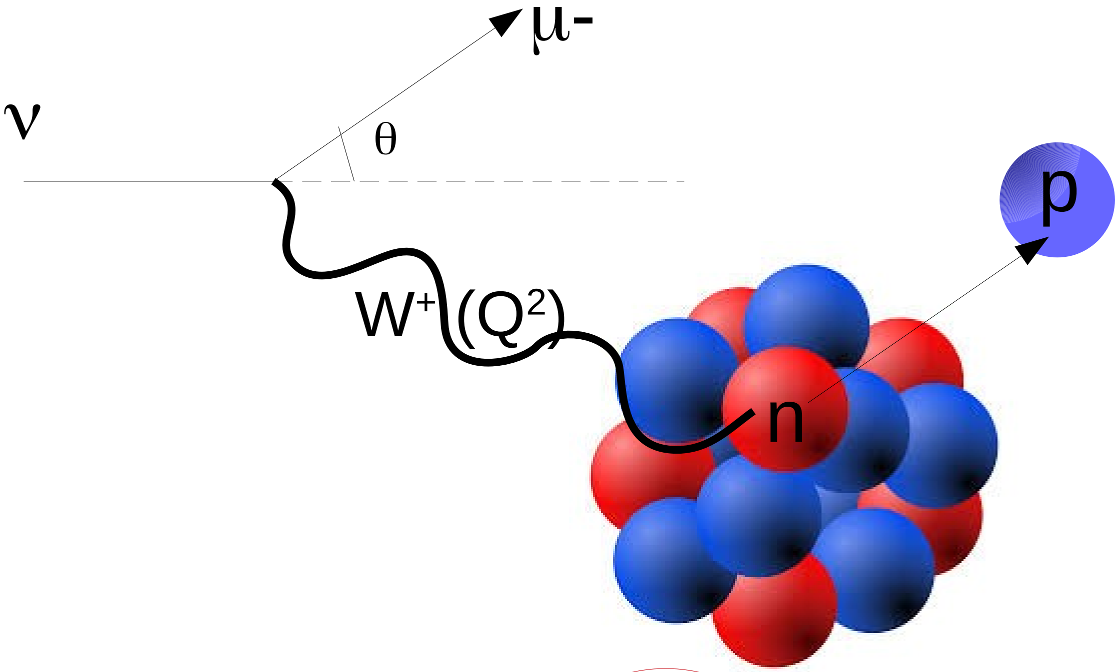


but the E_ν is only known on average (flux) → **q_3, ω are not known event by event from the leptonic leg only**

→ Need to consider the **hadronic leg to get Eν: strongly affected by nuclear effects** e.g intial nucleon momentum distribution, binding energy...

Neutrino cross-section: Q^2 dependence

The fundamental variable is the transferred 4-momentum to the nucleus (Q^2)



$$Q^2=(p_\mu-p_\nu)^2\approx$$

$$\approx 2E_\mu E_\nu(1-\cos\theta)$$

$$\sigma(\nu-Nucleus)\sim|F(Q^2)|^2\times\sigma_{point-like}(E_\nu,p_n,E_n)\times R(Q^2)$$ … and FSI!

Nucleon form factors

Nuclear effects on the initial state

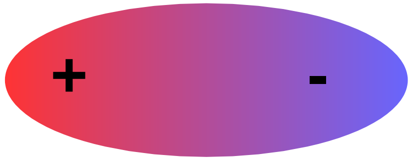
collective nuclear effects of xsec screening/enhancement (RPA)

Need to measure the muon in large phase space (high angle and backward) to measure the Q^2 dependence

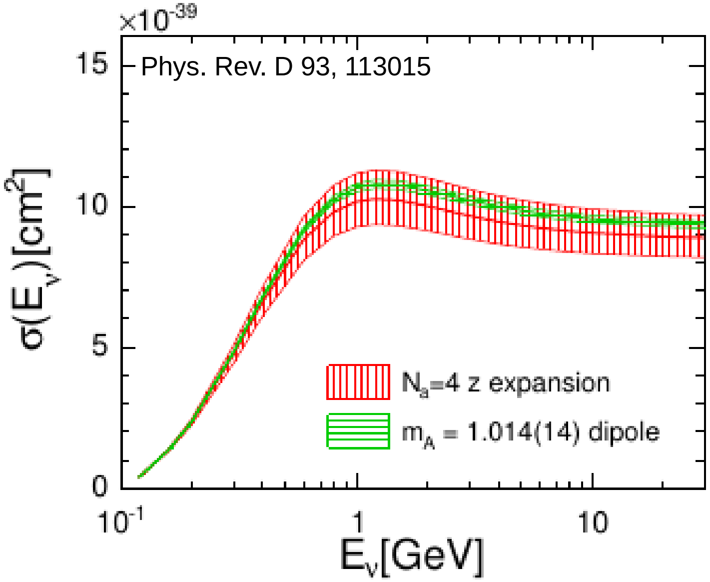
Nucleon form factors

- The vector form factors are well known from electron scattering data → but what about the **axial form factor?**
  Tuned from old bubble chamber data neutrino on deuterium (ANL, BNL, BEBC, FNAL, ...) and old data of pion photo-production

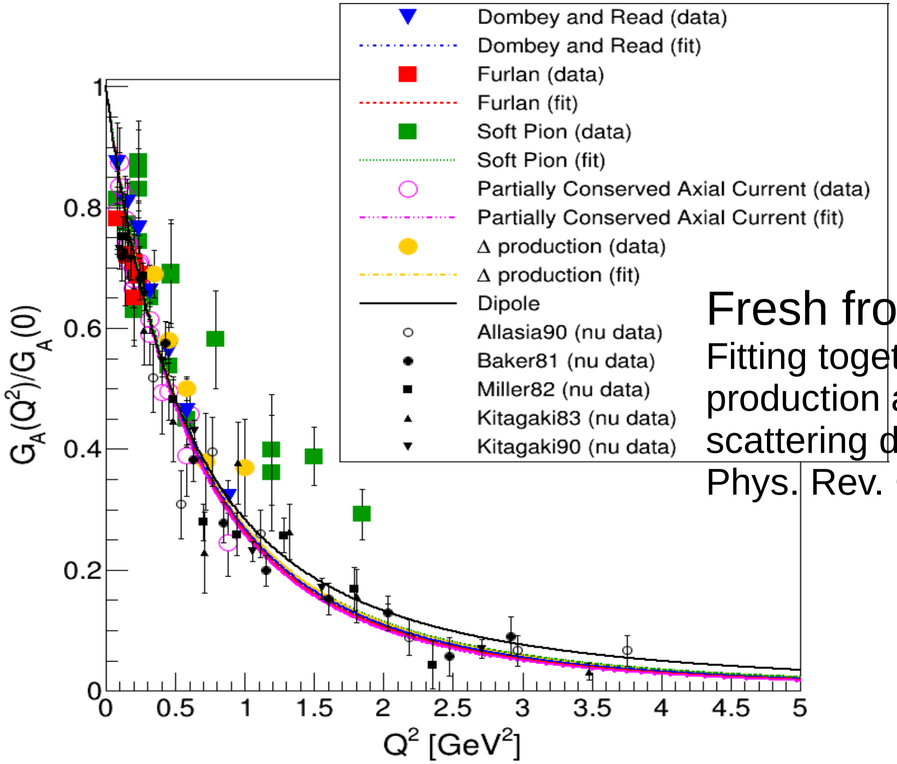
  Dipole function usually assumed:
  $$F_A(Q^2) = \frac{g_A}{(1+Q^2/M_A^{QE\,2})^2}$$



- Not well motivated! A lot of interest recently: fit to bubble chamber data repeated with other models based on QCD rules ('z expansion') or informed from pion photo-production



Neutrino-nucleon xsec uncertainties re-evaluated



Fresh from my laptop...
Fitting together pion photo-production and neutrino scattering data with model in Phys. Rev. C 78, 031201

Nuclear model

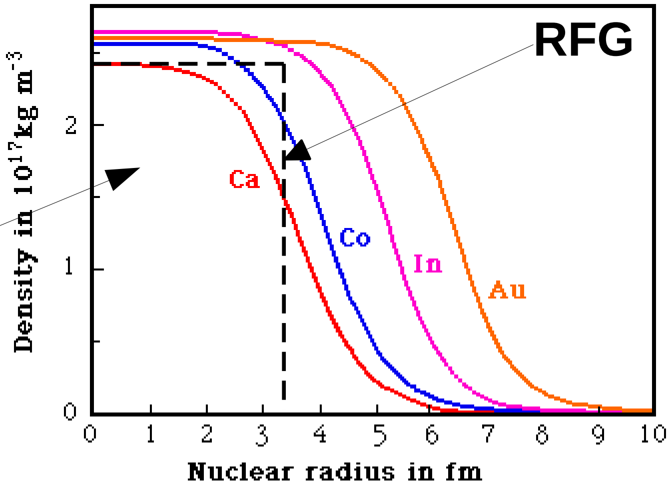
Various distributions of the momentum and energy of the nucleons in the nucleus

Relativistic Global Fermi Gas (RFG)

Fixed binding energy
Nucleus is a box of constant density

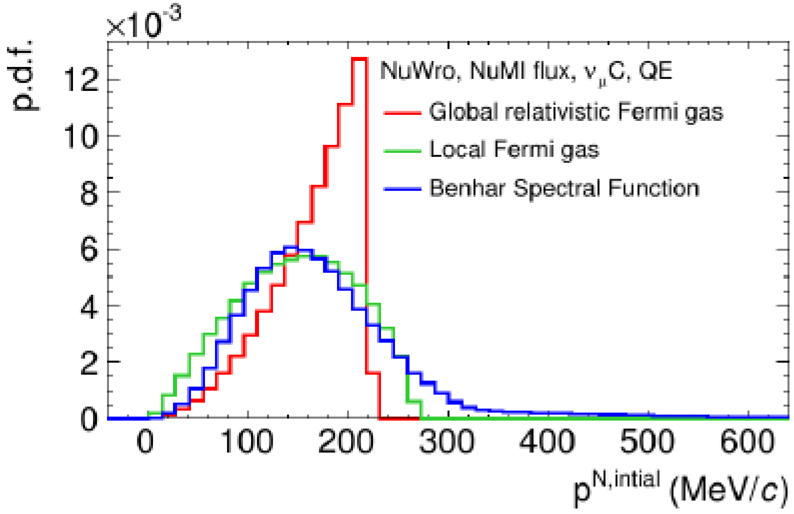
Local Fermi Gas (LFG)

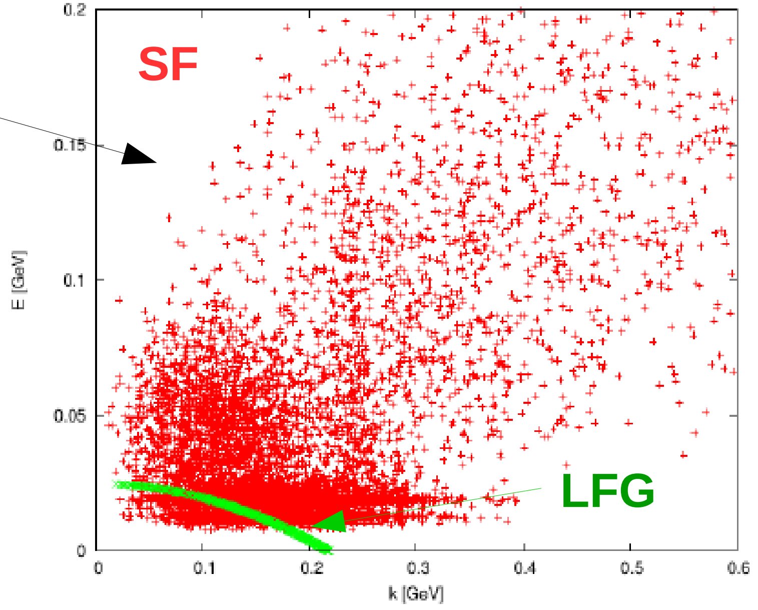
momentum (and binding energy) depends on the radial position in the nucleus, following the density profile of the nuclear matter



Spectral function

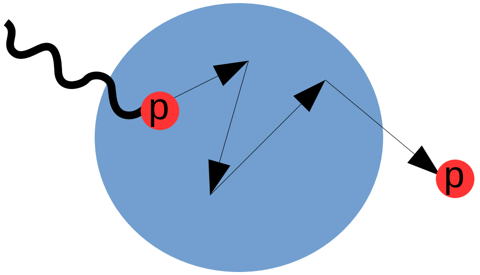
More sophisticated 2-dimensional distribution of momentum and binding energy





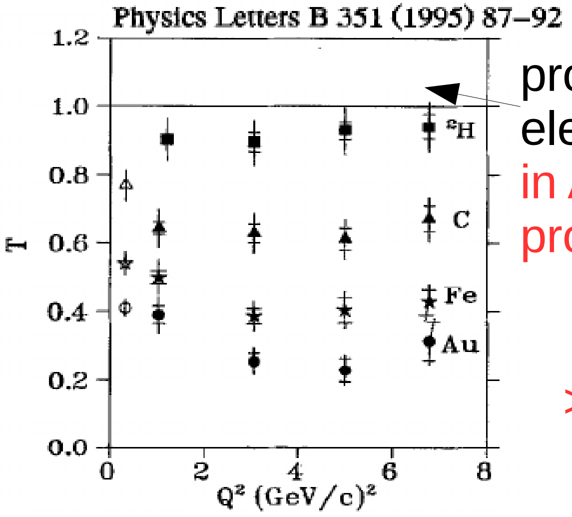
Final state interactions

- Both **pions and protons rescatter before exiting the nucleus:** this change the kinematics, multiplicity and charge of the hadrons in the final state



This process is simulated with approximated 'cascade' models tuned to pion-nucleus and proton-nucleus scattering cross-section

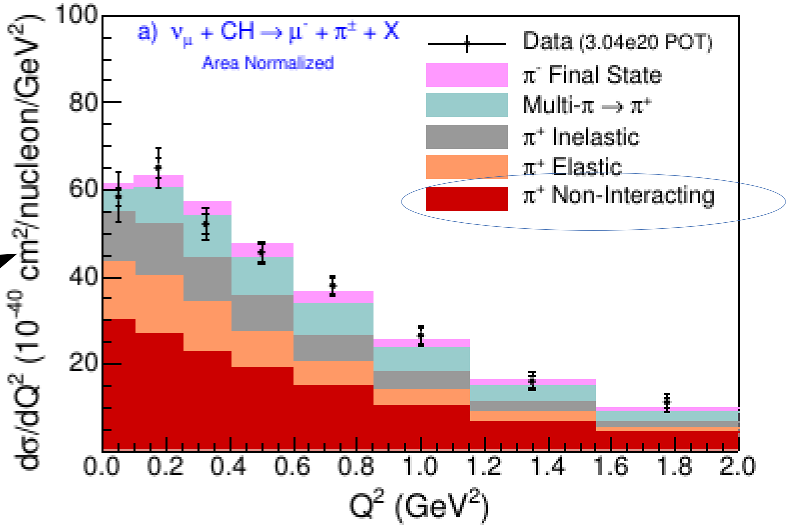
This is not a small effect!


Physics Letters B 351 (1995) 87–92

proton transparency in electron scattering:
in Ar FSI corrections for proton production is ~50%

Minerva CC1π sample:
>50% pions re-interacted in the nucleus

Phys.Rev. D94 (2016) no.5, 052005

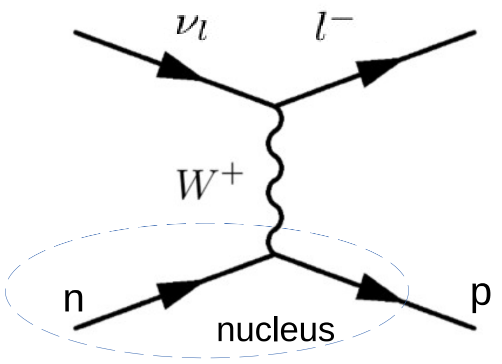


FSI effect on topology reconstruction

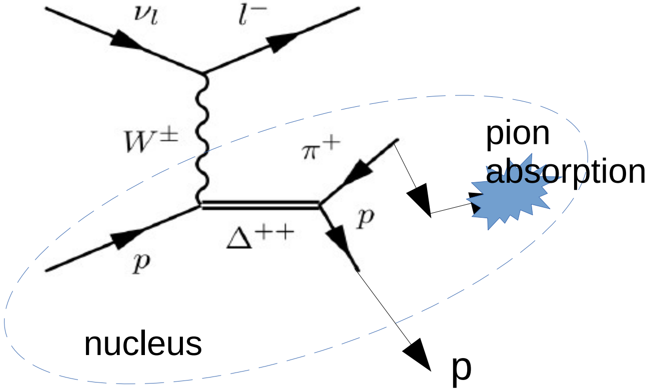
- CC-RES events move into CCQE-like signal (CC0π)

If we observe **a muon and proton in the final state and no pions**, we do not know if that event was:

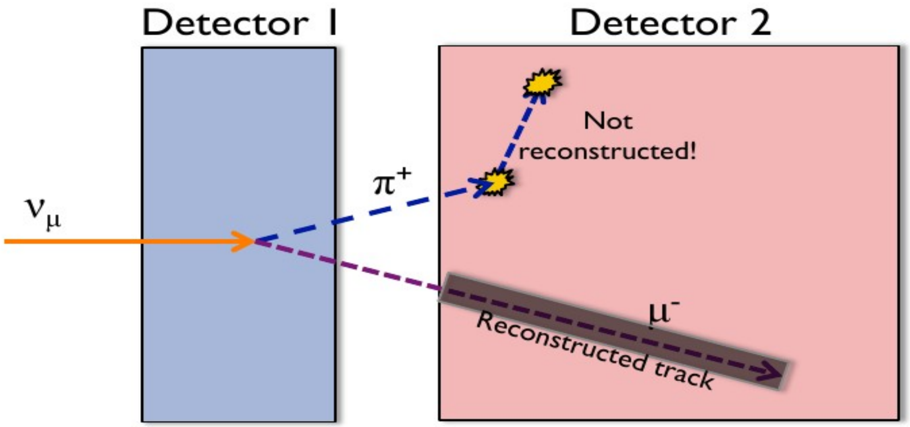
a 'real' CCQE event



or a RES event where the pion has been reabsorbed in the nucleus



The rescattering of the pion in the detector (outside) the original interacting nucleus is also relevant (**Secondary Interactions**)



Real measurement:

background subtraction and efficiency corrections

$$N^{FD}_{\nu_{\alpha'}} = \frac{N^{measured-at-FD}_{\nu_{\alpha'}} \times p^{FD}}{\epsilon^{FD}} \qquad N^{ND}_{\nu_{\alpha}} = \frac{N^{measured-at-ND}_{\nu_{\alpha}} \times p^{ND}}{\epsilon^{ND}}$$

$$\boxed{\epsilon = \frac{N^{signal-measured}_{\nu_\alpha}}{N^{signal}_{\nu_\alpha}}}$$

efficiency corrects for events which escape the detection (threshold, acceptance, containment...)

$$\boxed{p = \frac{N^{measured}_{\nu_\alpha} - N^{background}}{N^{measured}_{\nu_\alpha}} = \frac{N^{signal-measured}_{\nu_\alpha}}{N^{measured}_{\nu_\alpha}}}$$

purity corrects for background (events wrongly identified as ν_α)

Need to know efficiency and purity in order to correct for them → any possible mis-modeling of them causes a **systematic uncertainty in the oscillation analysis**

$$P_{\nu_\alpha \rightarrow \nu_{\alpha'}} \approx \frac{N^{measured-at-FD}_{\nu_{\alpha'}}}{N^{measured-at-ND}_{\nu_\alpha}} \times \frac{\epsilon^{ND}}{\epsilon^{FD}} \times \frac{p^{FD}}{p^{ND}}$$

What really matter is the difference between ND and FD (even when identical technology): eg, purity depends on ne/numu ratio, efficiency depends on size...

$\nu_e/\overline{\nu}_e$ appearance: δ_{CP} measurement

Search for CPV and measuring dCP are two very different experimental targets.
Prospects for dCP precision ~10-15 degrees from each experiment of next generation

$$\mathcal{A}_{\mathrm{CP}} \equiv \frac{P(\nu_\mu \to \nu_e) - P(\overline{\nu}_\mu \to \overline{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\overline{\nu}_\mu \to \overline{\nu}_e)} \simeq -\frac{\sin 2\theta_{12} \boxed{\sin\delta}}{\sin\theta_{13}\tan\theta_{23}}\Delta_{21} + \text{matter effects}\,,$$

Actually at second order:

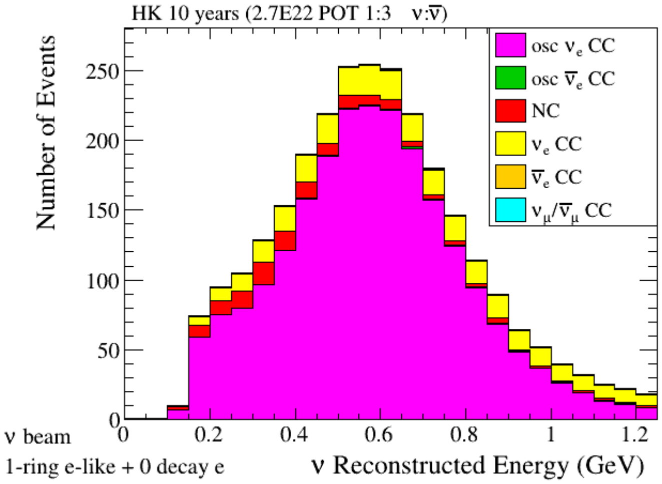
$P_{apperarance}$ ~ +/- A sinδ + Bcosδ + ...

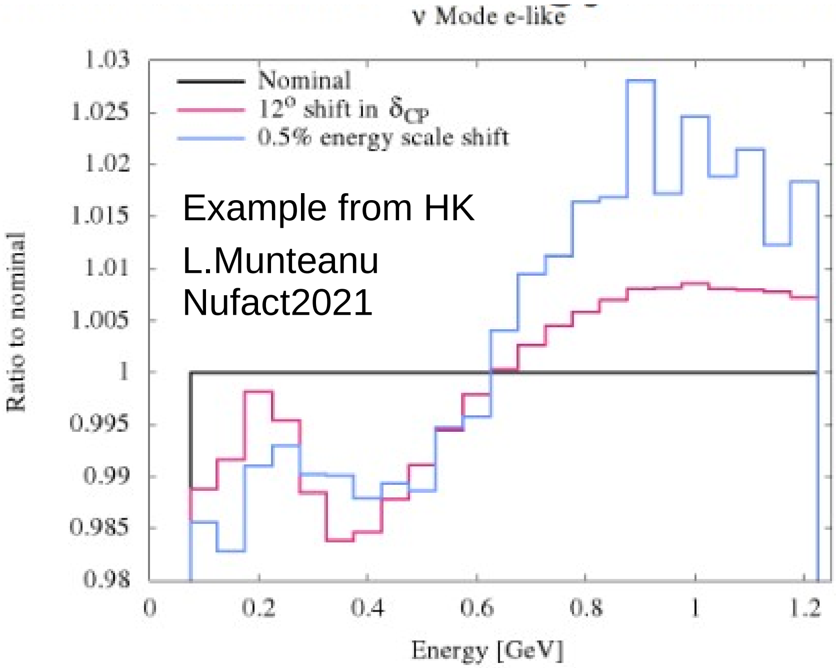
detailed formula $\longrightarrow$

$$\begin{aligned} P_{long-baseline} \simeq\ & \boxed{\sin^2 2\theta_{13}}\boxed{\sin^2\theta_{23}}\sin^2\Delta \\ & \mp\ \alpha\ \sin 2\theta_{13}\boxed{\sin\delta_{CP}}\cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{23}\sin^3\Delta \\ & +\ \alpha\ \sin 2\theta_{13}\boxed{\cos\delta_{CP}}\cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{23}\cos\Delta\sin^2\Delta \\ & +\ \alpha^2\ \cos^2\theta_{23}\sin^2 2\theta_{12}\sin^2\Delta \end{aligned}$$

with $\alpha \equiv \Delta m^2_{21}/\Delta m^2_{23}$ and $\Delta \equiv \Delta m^2_{31}L/(4E_\nu)$.

- **At δ_{CP}~ +/-π/2** the precision on δ_{CP} (~P_{app} derivative vs δ_{CP}) is dominated by the second term: **precise energy spectrum measurement ($\cos\delta_{CP}$ dependance) dominate the resolution**



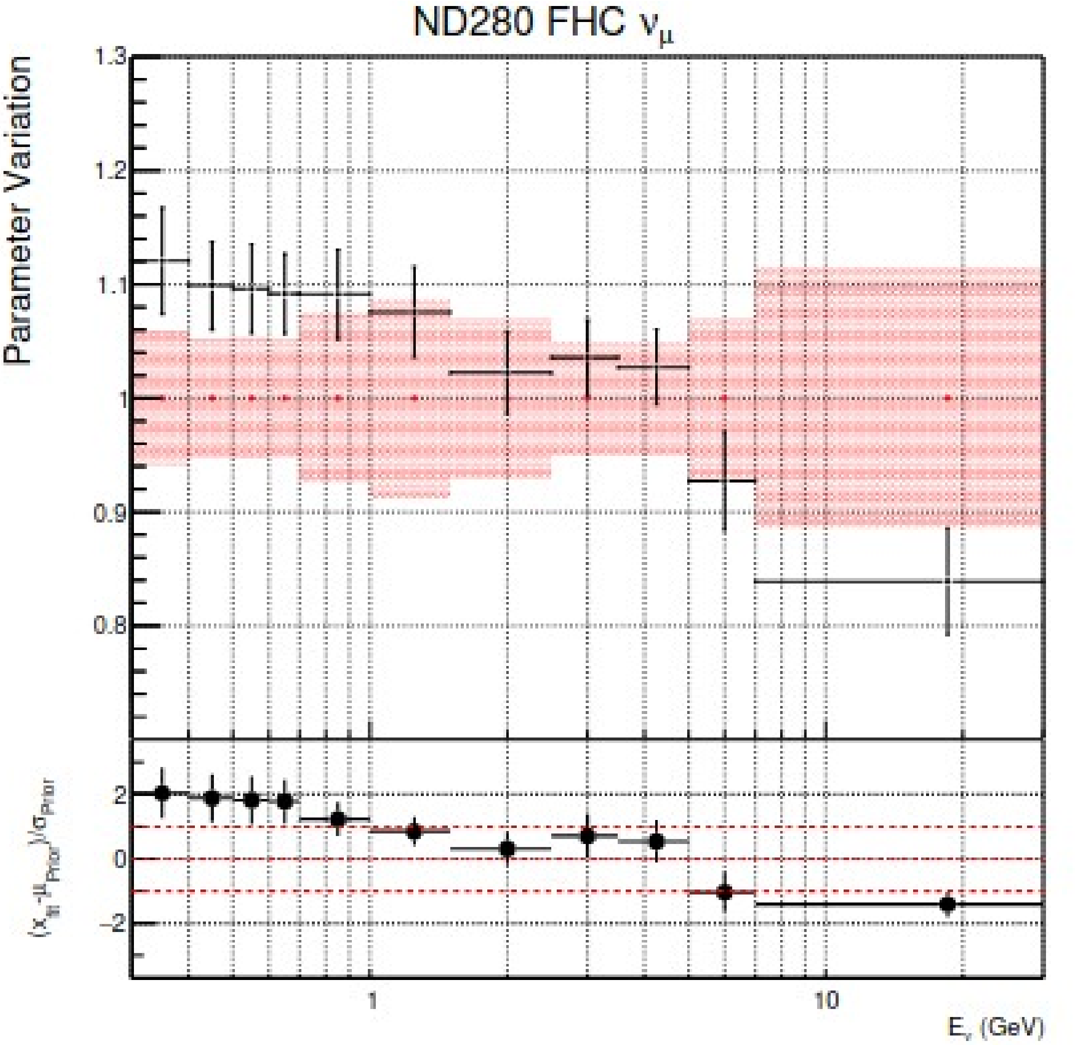


Example from HK
L.Munteanu
Nufact2021

Flux constraint from the ND

The ND measures the rate of neutrinos therefore it further constrain the flux

$$N_{\nu_\alpha}^{ND}(E_\nu)=\phi(E_\nu)\times\sigma(E_\nu)\,dE_\nu$$



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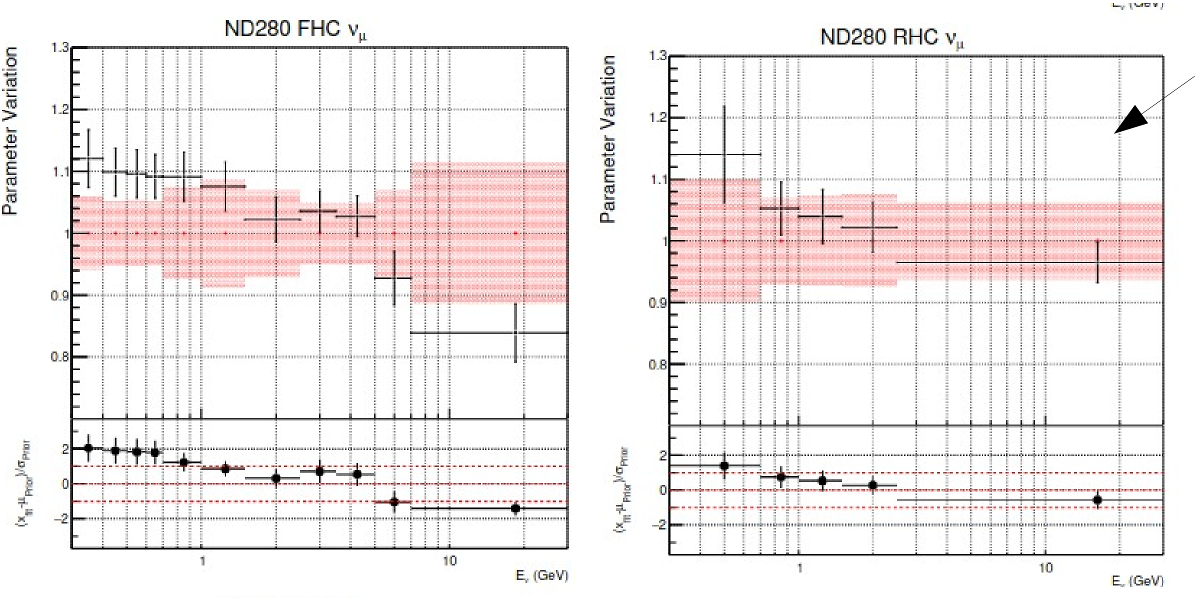

ND280 magnetized
→ measurement of wrong sign background

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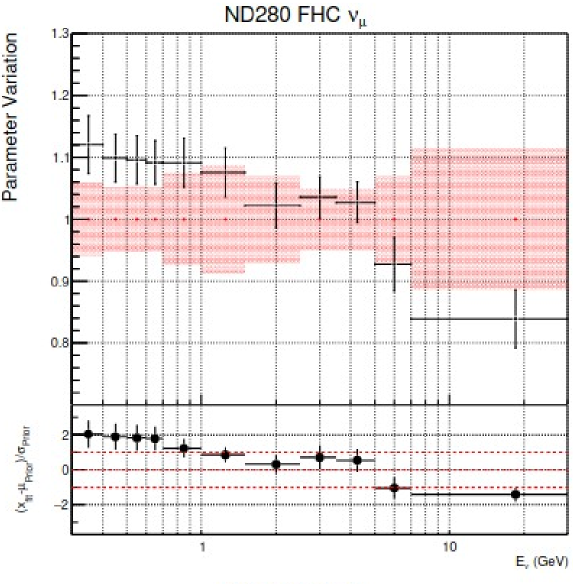

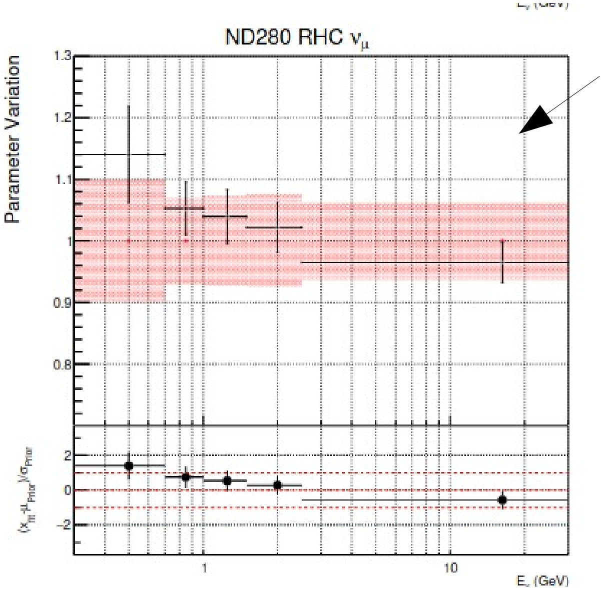

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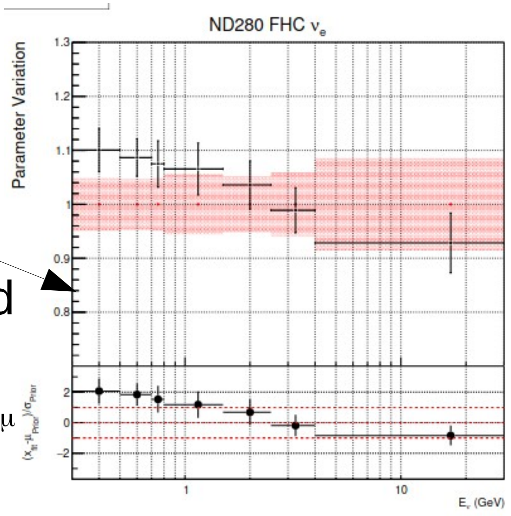

Low intrinsic ν_e stat → constrained only through correlations with ν_μ

Flux constraint from the ND

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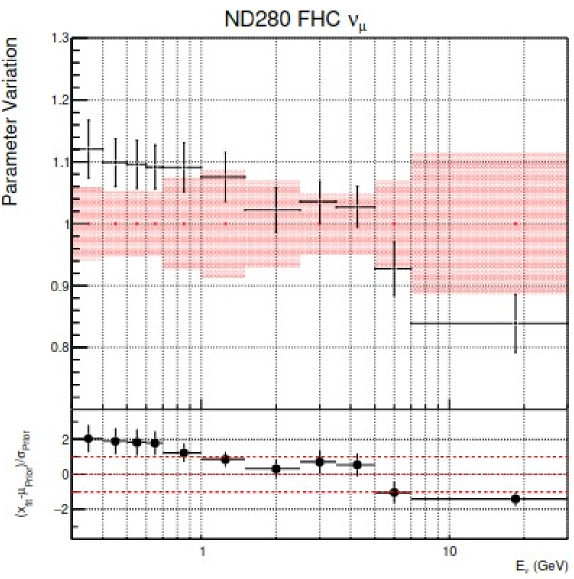
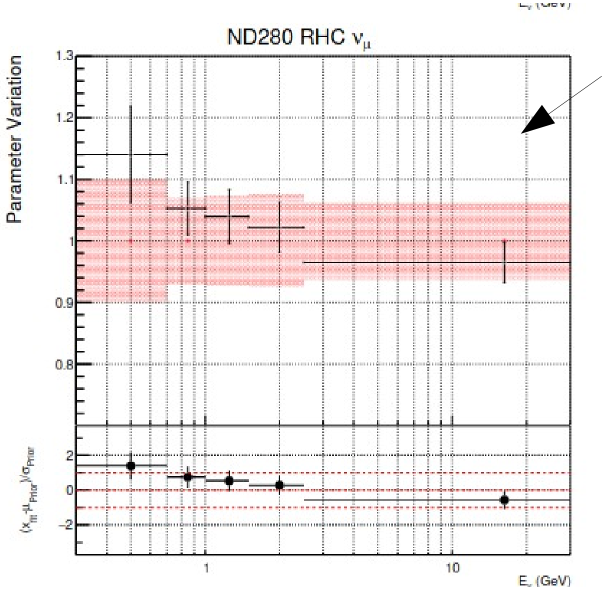
$$N_{\nu_\alpha}^{ND}(E_\nu) = \phi(E_\nu) \times \sigma(E_\nu)\, dE_\nu$$





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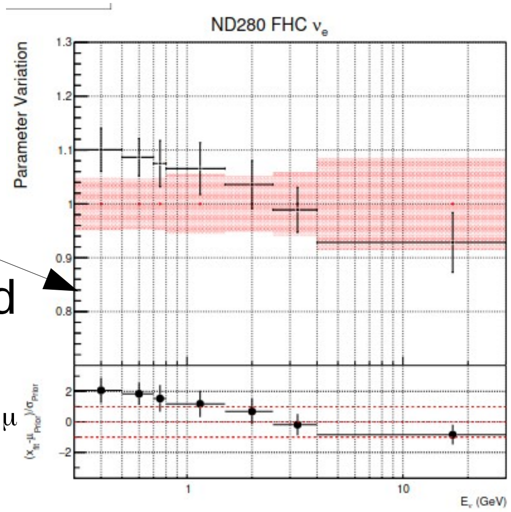


Low intrinsic ν_e stat → constrained only through correlations with ν_μ

	Pre- ND fit	Post- ND fit
flux	~5%	~2.8-3.0%
cross-section	~10-15%	~3.5-3.8%
flux+xsec		~2.6-2.8%
Total (+ xsec not accessible at ND, SK detector)	~17%	~3.5-5%

- Today xsec uncertainties dominate before the fit

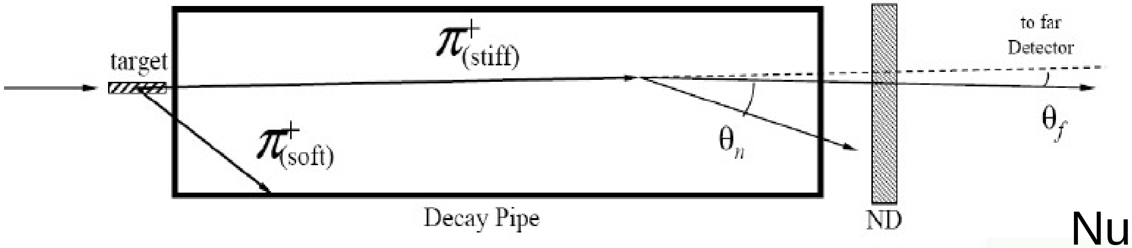
- strong anticorrelation between flux and xsec
(would be 5-10% if uncorrelated)

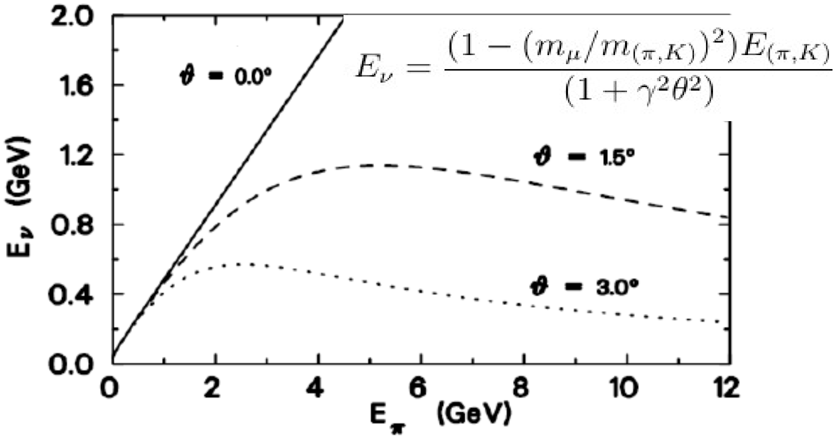
- flux*xsec constitutes ~50% of the final systematic error budget

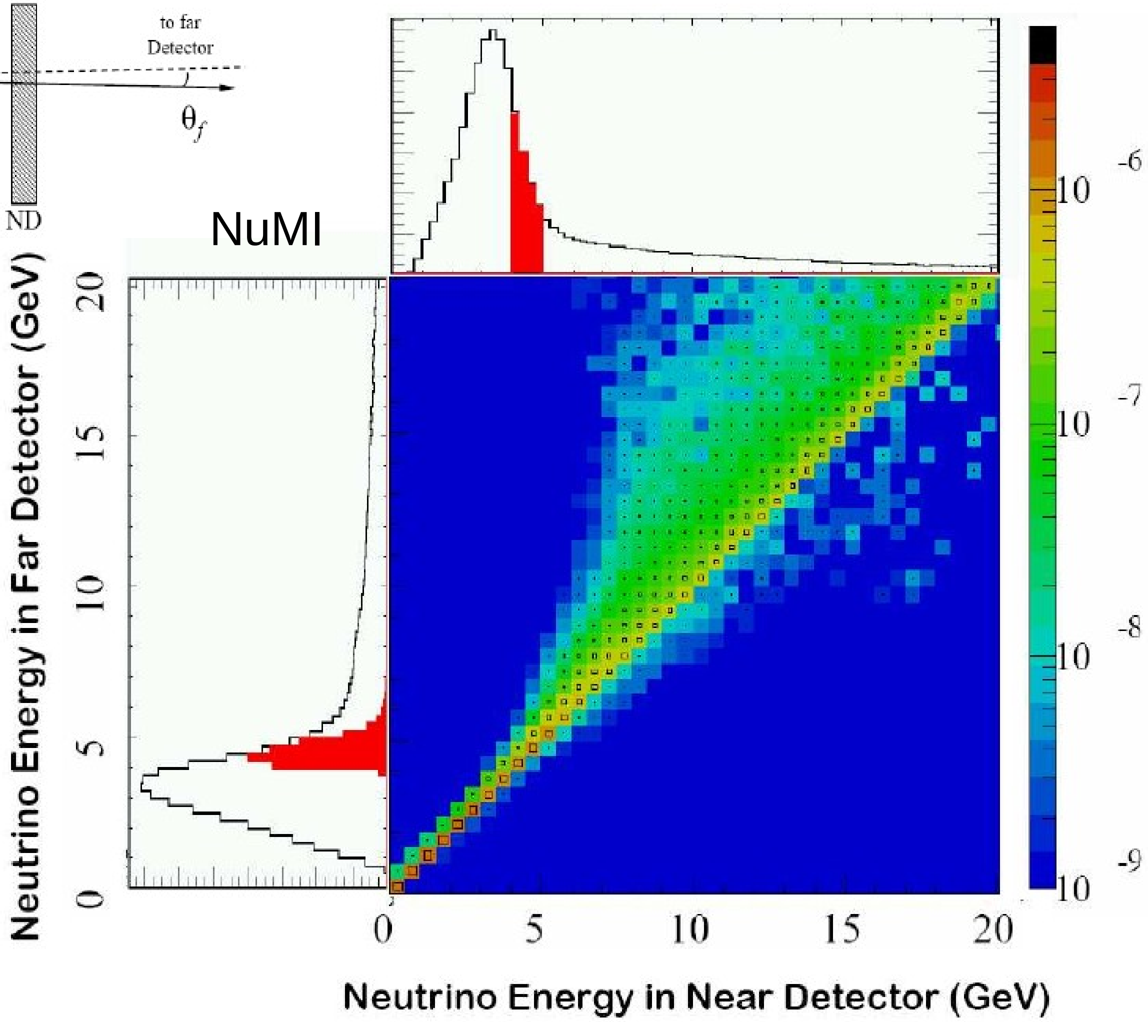
From ND to FD flux extrapolation

$$\frac{N^{FD}_{\nu_{\alpha'}}(E_\nu)}{N^{ND}_{\nu_\alpha}(E_\nu)} \approx P_{\nu_\alpha \rightarrow \nu_{\alpha'}}(E_\nu) \times \boxed{\frac{\phi^{FD}_{\nu_{\alpha'}}(E_\nu)}{\phi^{ND}_{\nu_\alpha}(E_\nu)}} \times \frac{\sigma^{FD}_{\nu_{\alpha'}}(E_\nu)}{\sigma^{ND}_{\nu_\alpha}(E_\nu)}$$

Different acceptance of pion angles → different neutrino energies for same pion kinematics



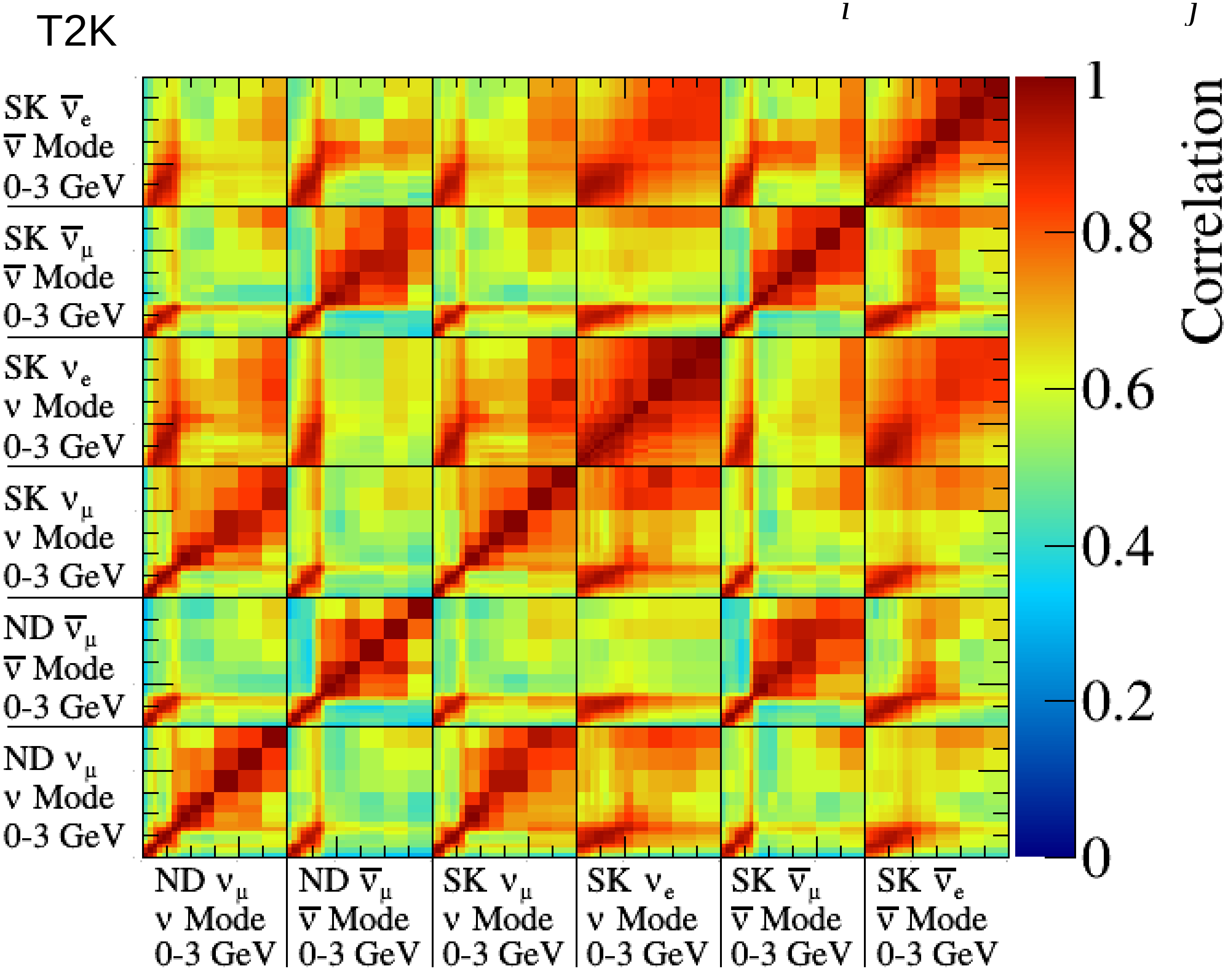




Extrapolation ND->FD uncertainties smaller (~1%) than overall flux uncertainties (10% → 5%)

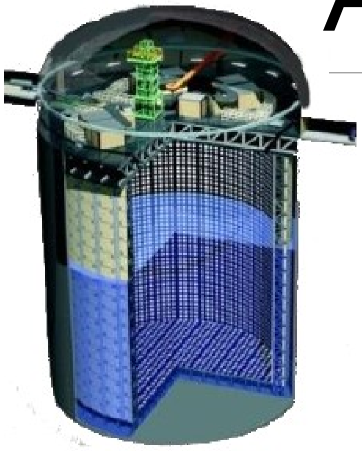
Flux correlations

Flux Correlations $$\rho = \frac{\sigma^2_{cov.ij}}{\sigma_i \sigma_j} = \frac{\sum_{i,j} (f_i - \langle f_i \rangle)(f_j - \langle f_j \rangle)}{\sqrt{\sum_i (f_i - \langle f_i \rangle)^2 \sum_j (f_j - \langle f_j \rangle)^2}}$$



- **large correlation between ND and SK fluxes**
- Large correlations between different bins in the same 'mode' → **flux uncertainty is to large extent an overall normalization** (shape uncertainties are smaller)
- **Correlations between different modes and neutrino flavors:** (to a certain extent) we can use ν_μ data to constrain $\bar{\nu}_\mu$ or ν_e fluxes

A bit of (recent) history...

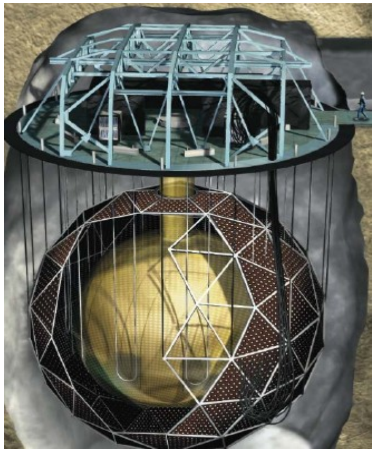


SuperKamiokande
1996 – today!

1998 Discovery of ν oscillation from zenith angle dependence of atmospheric ν_μ rate

Sudbury Neutrino Observatory (SNO)
1999 – 2006

2001 Solution of solar puzzle: $\nu_e / \Sigma\nu_\alpha \sim 1/3$



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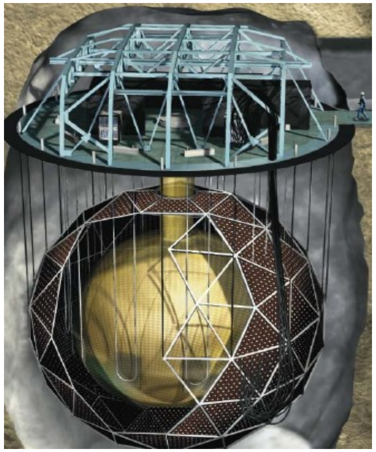

Precision from accelerator experiment:
high purity and tunable neutrino flux

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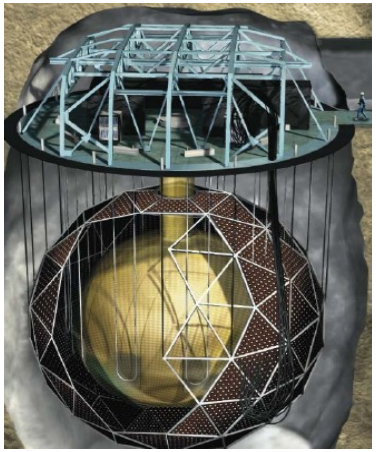
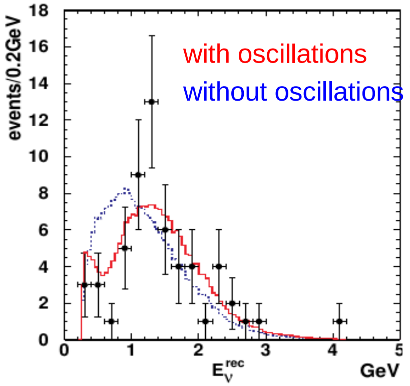
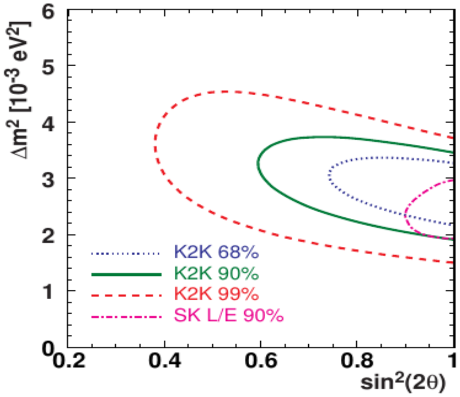


Precision from accelerator experiment: high purity and tunable neutrino flux

(1999-2006) K2K





A bit of (recent) history...

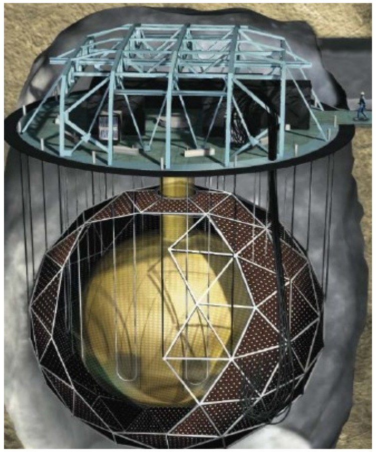
SuperKamiokande
1996 – today!

1998 Discovery of ν oscillation

from zenith angle dependence of atmospheric ν_μ rate

Sudbury Neutrino Observatory (SNO)
1999 – 2006

2001 Solution of solar puzzle: $\nu_e / \Sigma\nu_\alpha \sim 1/3$



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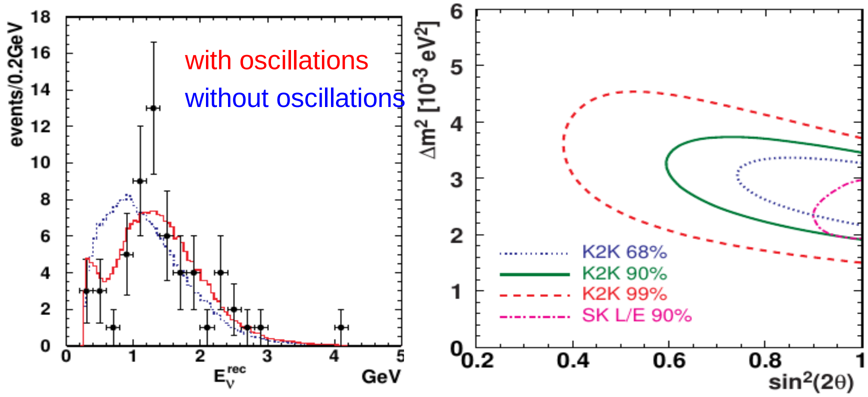
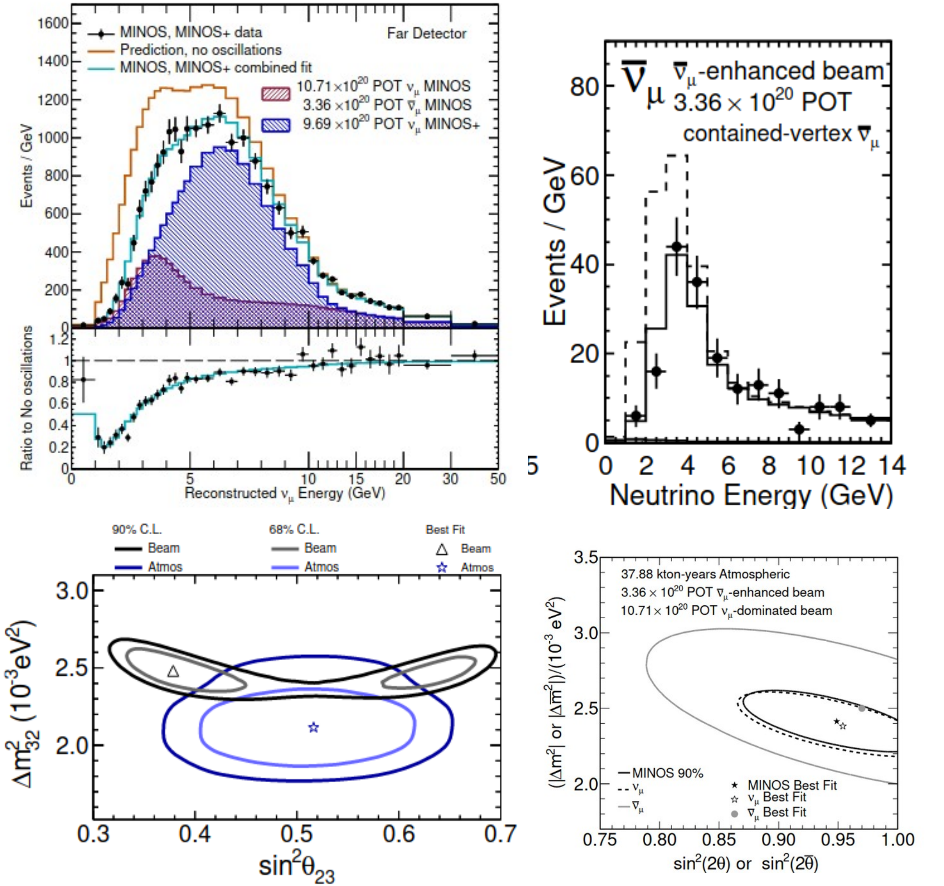


(2008-2012) OPERA : 5 $\nu_\mu \rightarrow \nu_\tau$ events obs.

2003 – 2015 MINOS (→ - 2016 MINOS+)



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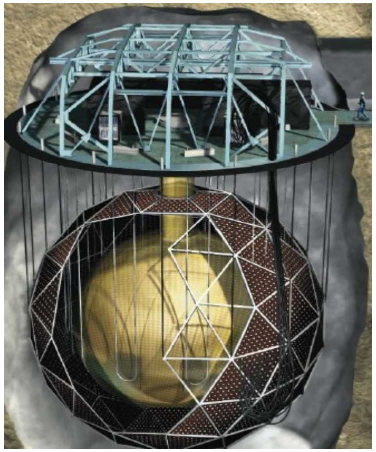

Precision from accelerator experiment: high purity and tunable neutrino flux

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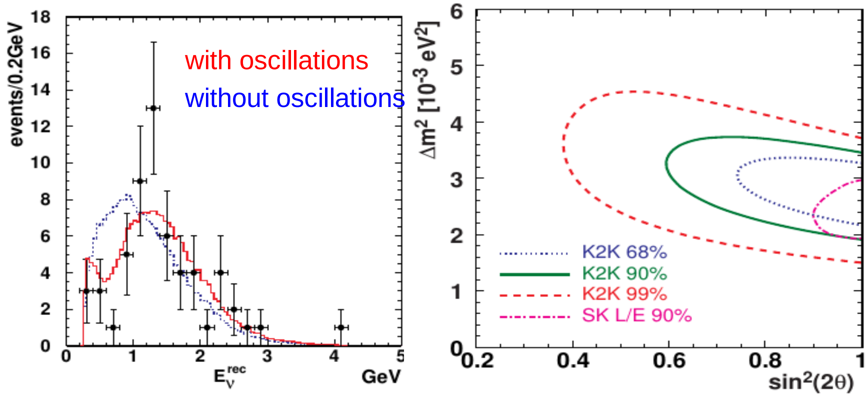

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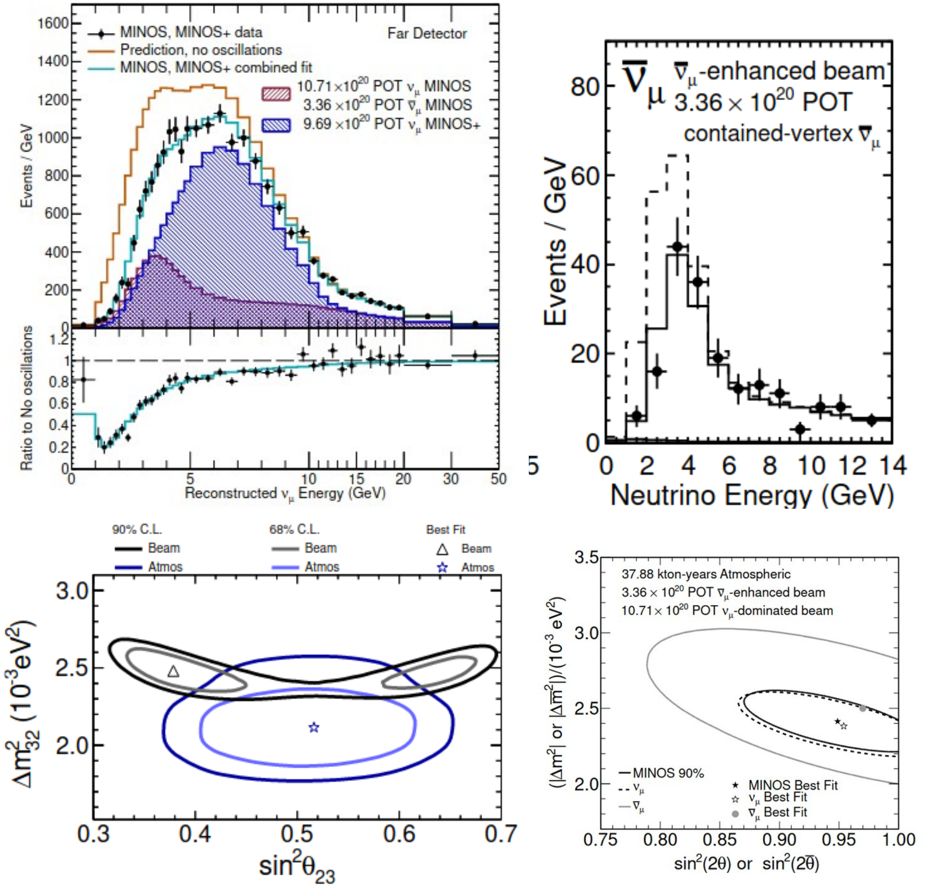


(2008-2012) OPERA : 5 $\nu_\mu \rightarrow \nu_\tau$ events obs.

Beyond ν_μ disappearance (θ_{23} and Δm_{32}): large statistics experiments looking for ν_e appearance

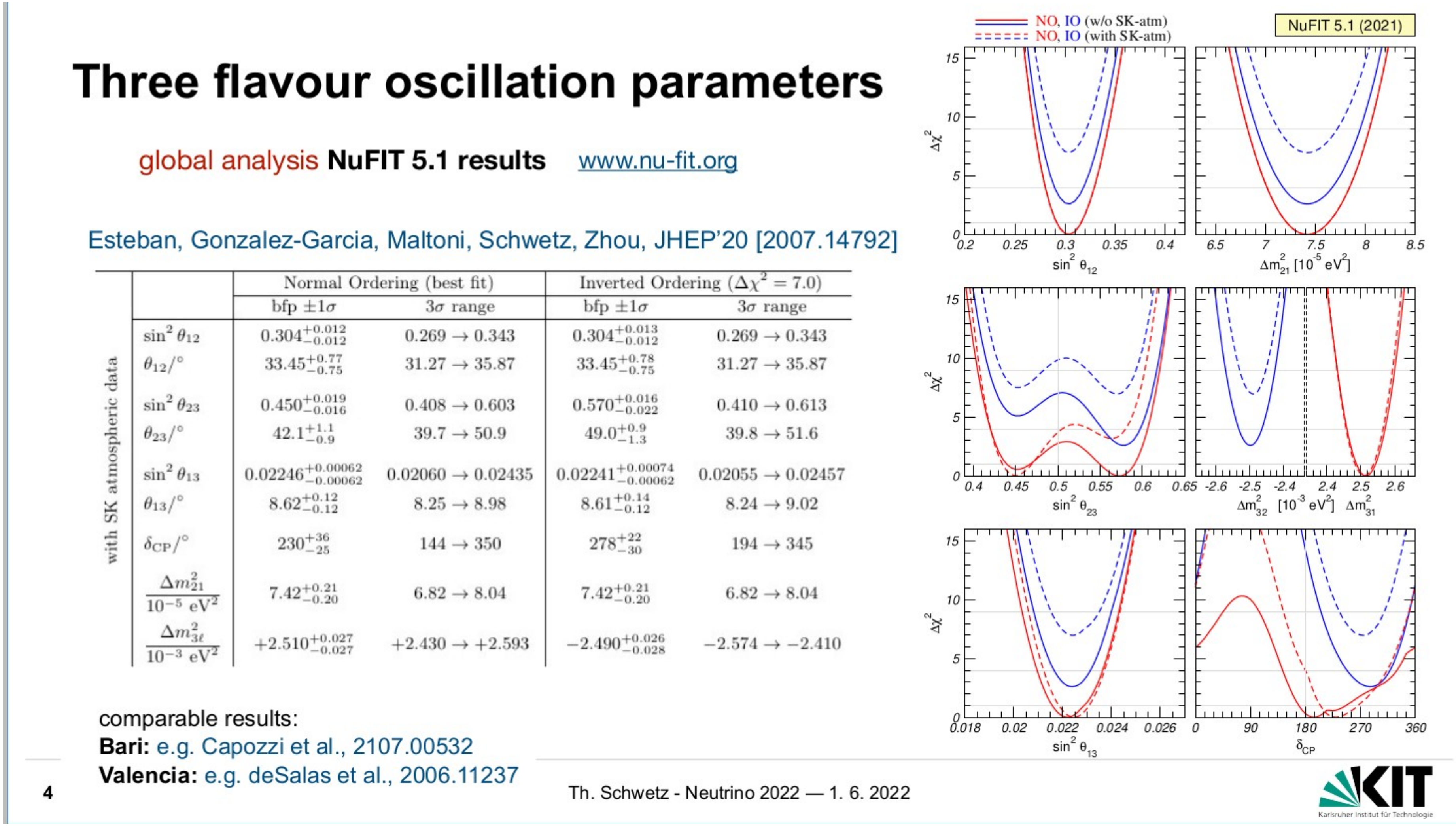
→ observation of ν_e apperance
T2K (2010 - today)

→ to measure MH, longer baseline:
NOVA started 2014

→ T2K Nature 2020 first results on δ_{CP} !

Status of PMNS measurements: joint fits

Recent reference with full details:



Three flavour oscillation parameters

global analysis **NuFIT 5.1 results** www.nu-fit.org

Esteban, Gonzalez-Garcia, Maltoni, Schwetz, Zhou, JHEP'20 [2007.14792]

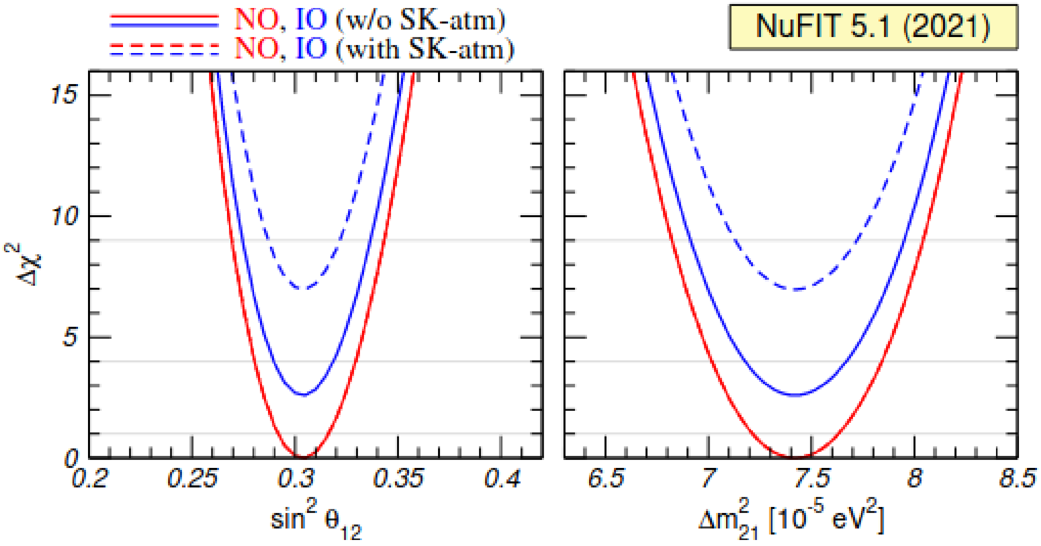
		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 7.0$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
with SK atmospheric data	$\sin^2\theta_{12}$	$0.304^{+0.012}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$
	$\theta_{12}/^\circ$	$33.45^{+0.77}_{-0.75}$	$31.27 \to 35.87$	$33.45^{+0.78}_{-0.75}$	$31.27 \to 35.87$
	$\sin^2\theta_{23}$	$0.450^{+0.019}_{-0.016}$	$0.408 \to 0.603$	$0.570^{+0.016}_{-0.022}$	$0.410 \to 0.613$
	$\theta_{23}/^\circ$	$42.1^{+1.1}_{-0.9}$	$39.7 \to 50.9$	$49.0^{+0.9}_{-1.3}$	$39.8 \to 51.6$
	$\sin^2\theta_{13}$	$0.02246^{+0.00062}_{-0.00062}$	$0.02060 \to 0.02435$	$0.02241^{+0.00074}_{-0.00062}$	$0.02055 \to 0.02457$
	$\theta_{13}/^\circ$	$8.62^{+0.12}_{-0.12}$	$8.25 \to 8.98$	$8.61^{+0.14}_{-0.12}$	$8.24 \to 9.02$
	$\delta_{\mathrm{CP}}/^\circ$	230^{+36}_{-25}	$144 \to 350$	278^{+22}_{-30}	$194 \to 345$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.510^{+0.027}_{-0.027}$	$+2.430 \to +2.593$	$-2.490^{+0.026}_{-0.028}$	$-2.574 \to -2.410$

comparable results:
Bari: e.g. Capozzi et al., 2107.00532
Valencia: e.g. deSalas et al., 2006.11237

4

Th. Schwetz - Neutrino 2022 — 1. 6. 2022

Status of PMNS measurements: joint fits



Solar parameters: θ_{12}, Δm^2_{21} known with **~few% precision** since KamLAND (no recent updates)
→ future prospects: JUNO <1%

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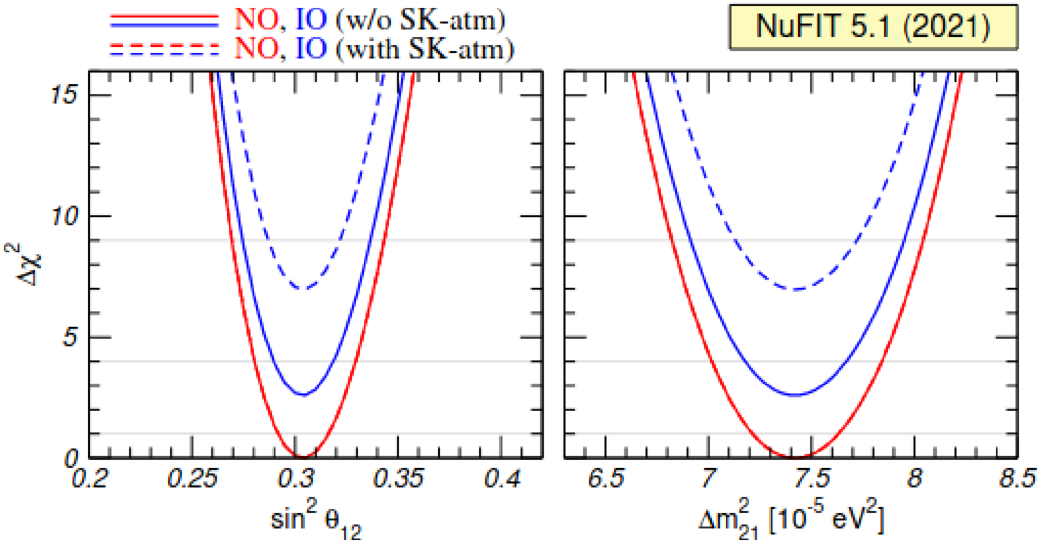

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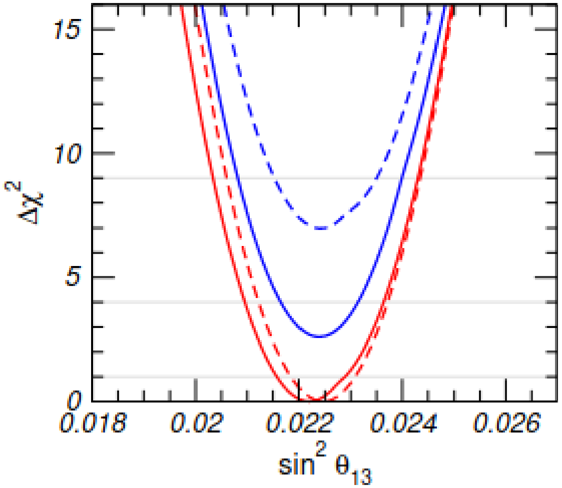

θ_{13} measured with reactor experiments at ~1% precision

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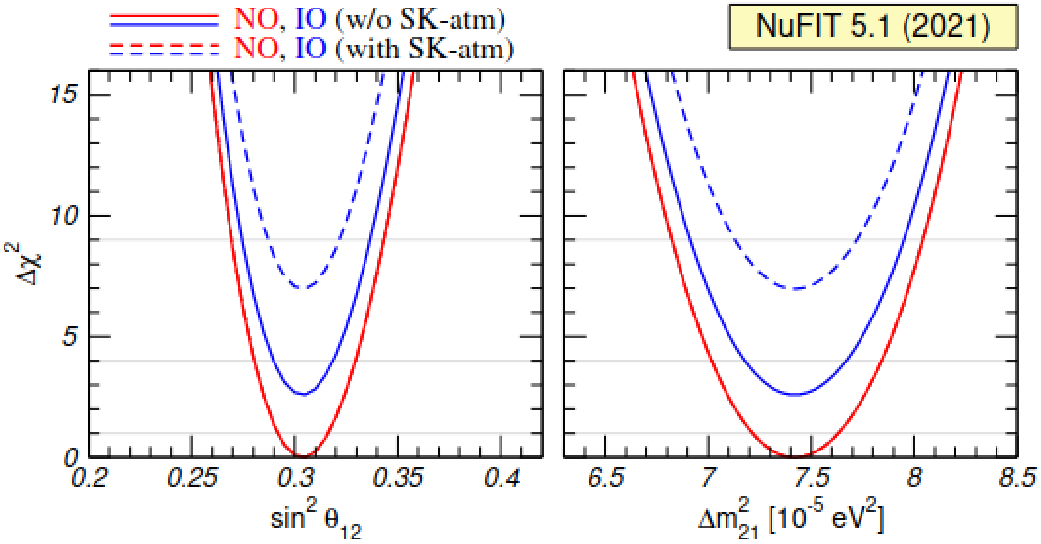

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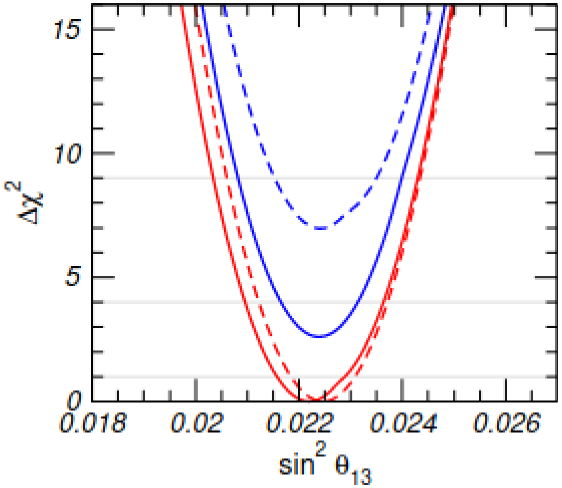

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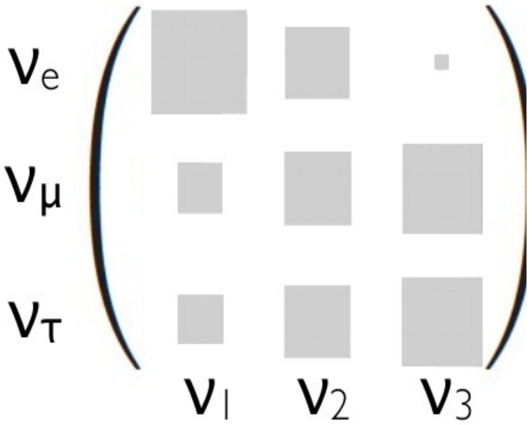
Best avenue for PMNS unitarity test:



⇒ **best precision**

⇒ **OK precision**

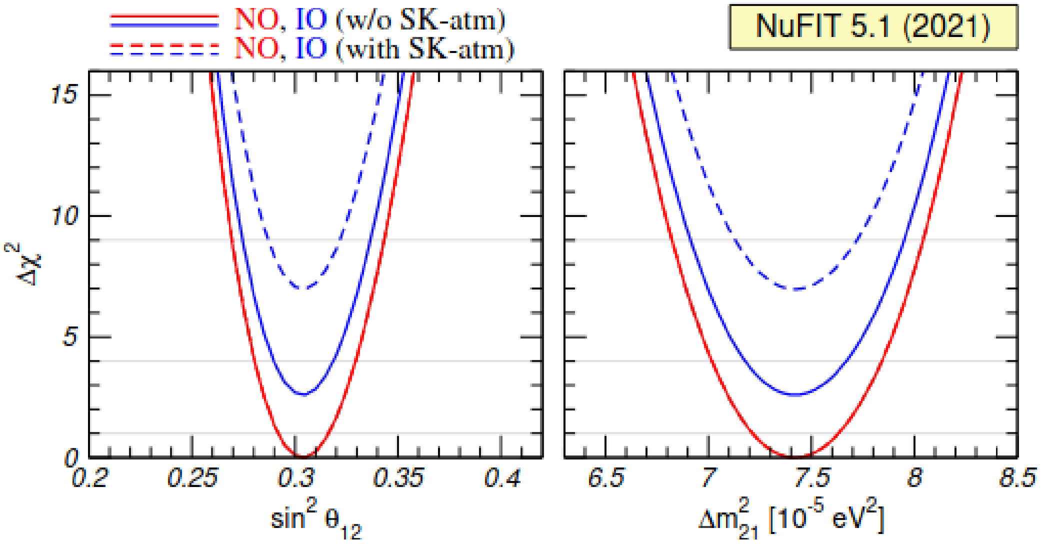
⇒ **poorest precision**

Exploring unitarity from different rows

$UU^\dagger = U^\dagger U = I$ ⇒ **many equations!!** $|U_{l1}|^2 + |U_{l2}|^2 + |U_{l3}|^2 = 1$

→ best limit expected from **electron top row**: θ_{13} from reactors and θ_{12} from JUNO

Status of PMNS measurements: joint fits



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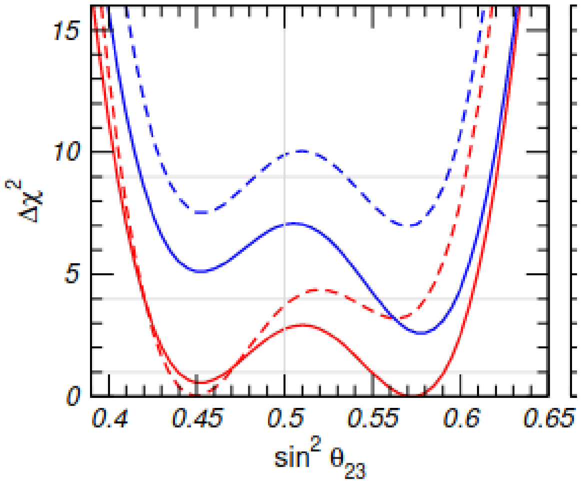
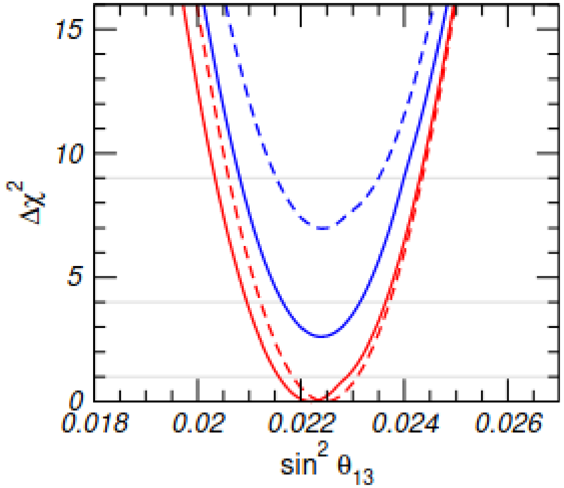
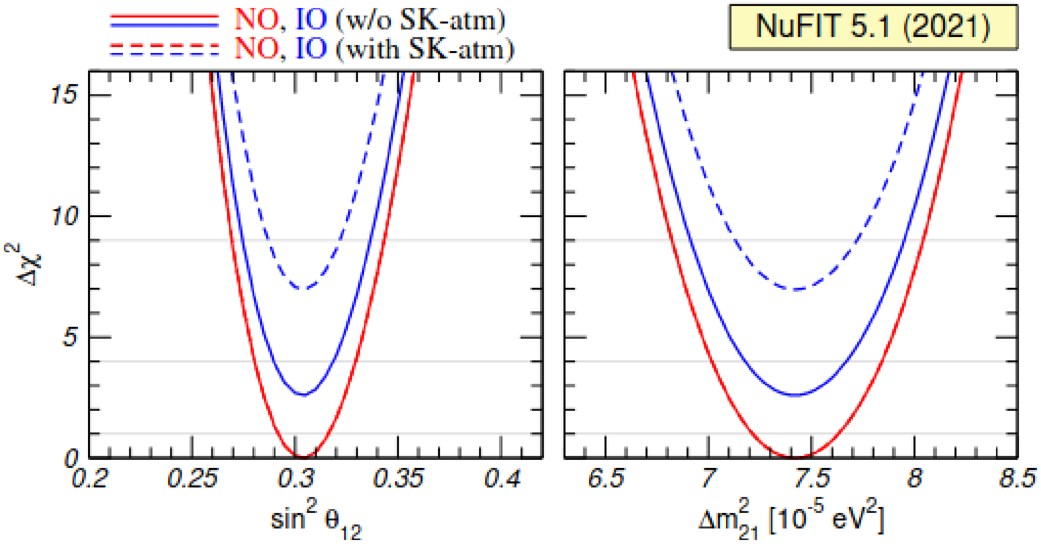
Atmospheric parameters:
- **θ_{23} ~few%** precision @1σ (improved by a factor of 2 in the last 10 years) but **~25%** precision @3σ: octant degeneracy, need high stat ν_e appearance





θ_{13} measured with reactor experiments at ~1% precision

Status of PMNS measurements: joint fits



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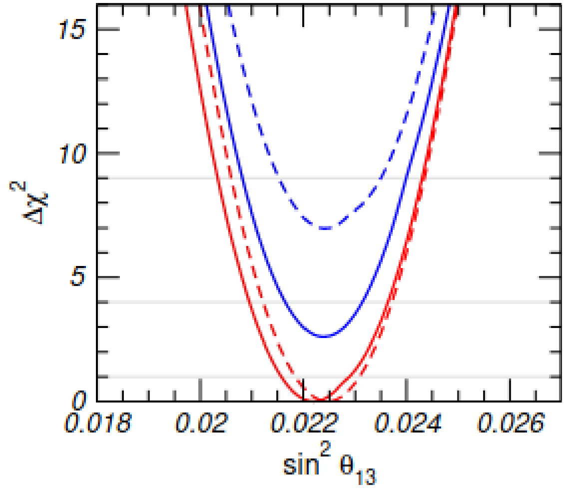

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Atmospheric parameters:

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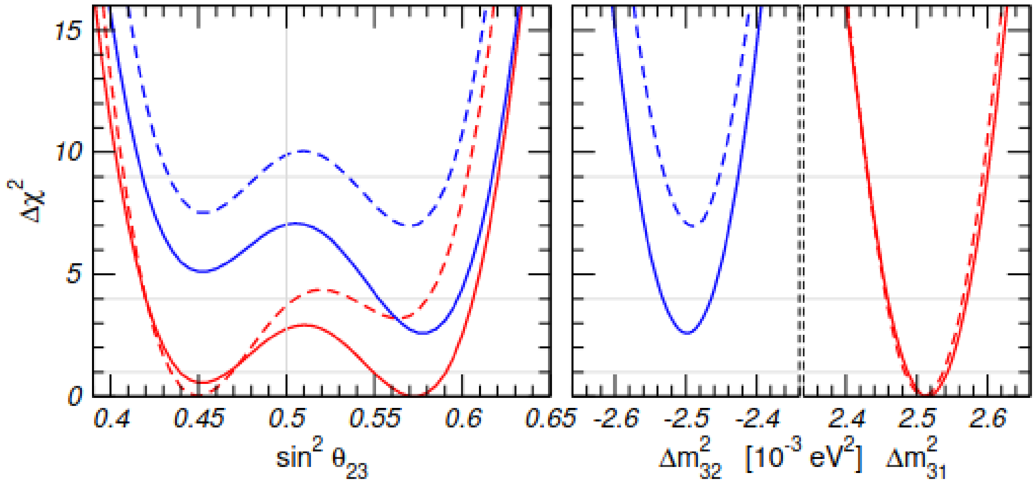
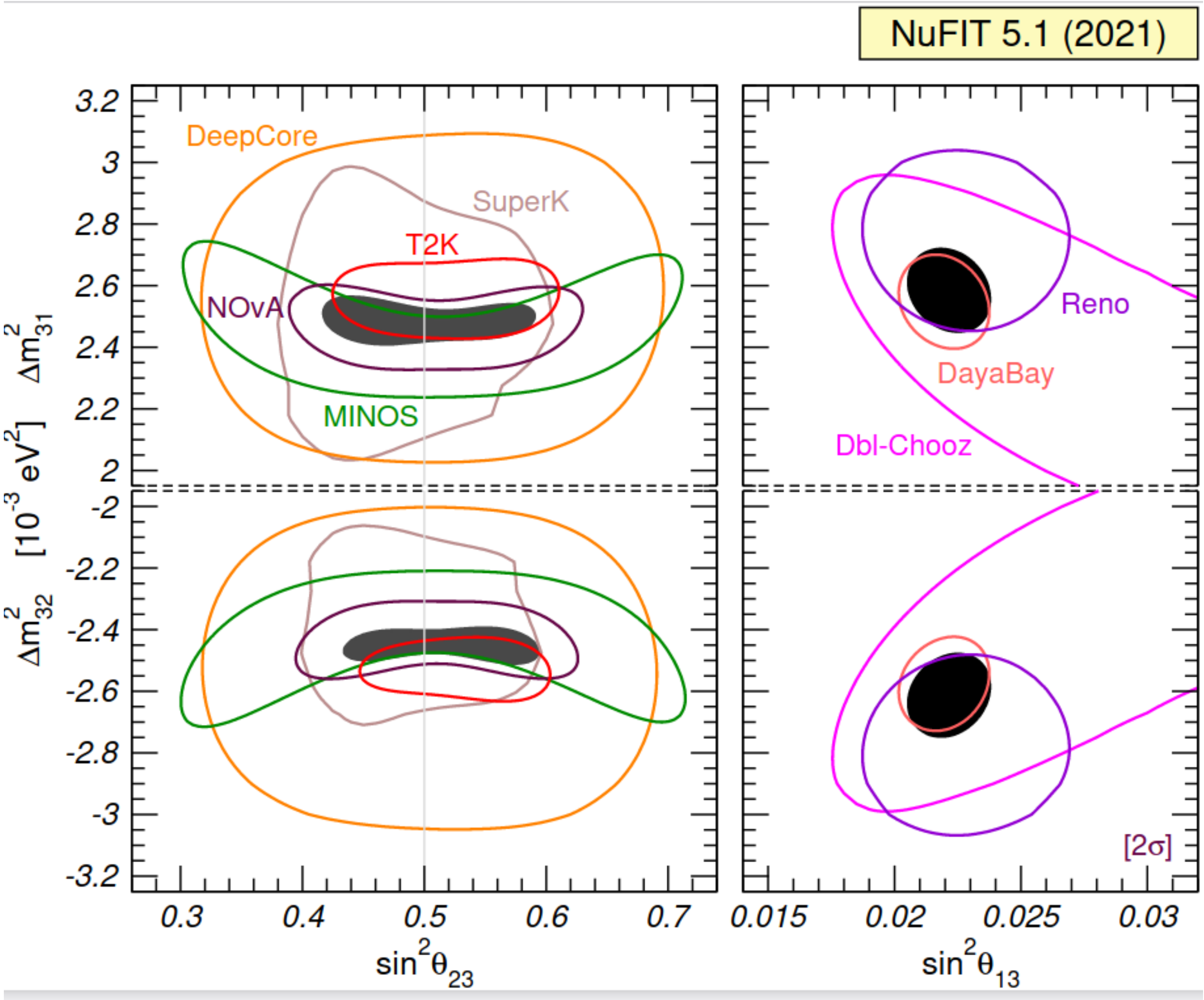
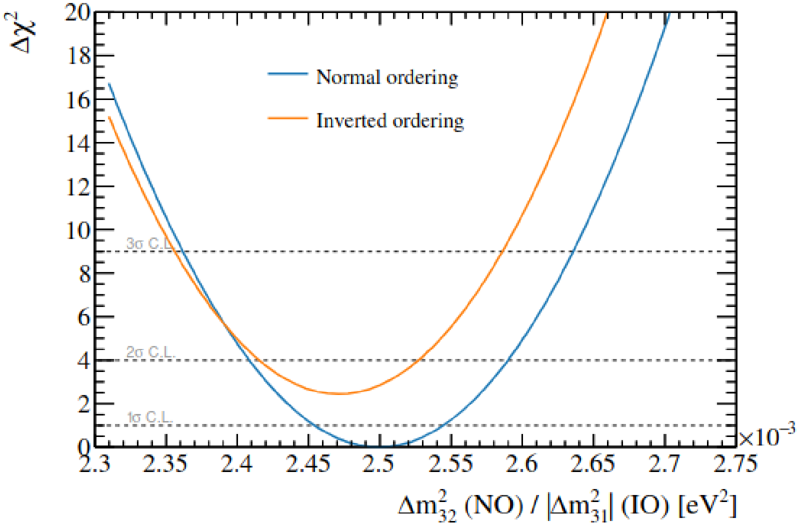
- **$|\Delta m^2_{31(32)}|$ ~1%** (not so robust...) → important to get <1% (see later) challenging to control systematics uncertainties



Status of PMNS measurements: zoom on $|\Delta m^2_{31(32)}|$





(b) T2K + reactor

T2K: 2% precision with 1% shift between NO and IO

Similar resolution and shift in NOVA

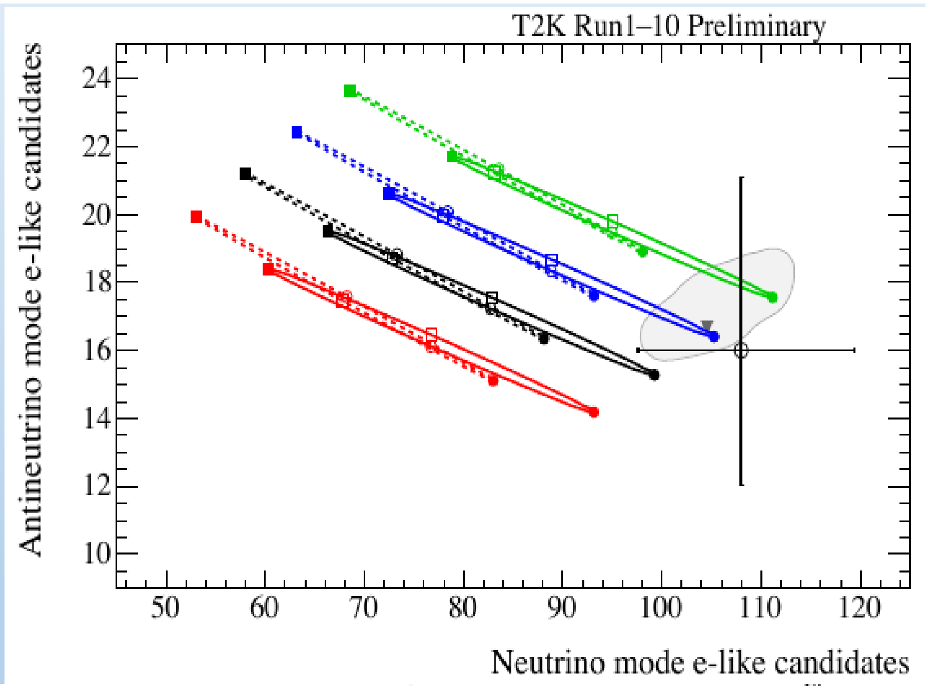
$\nu_e/\bar{\nu}_e$ apperance: MH, δ_{CP}

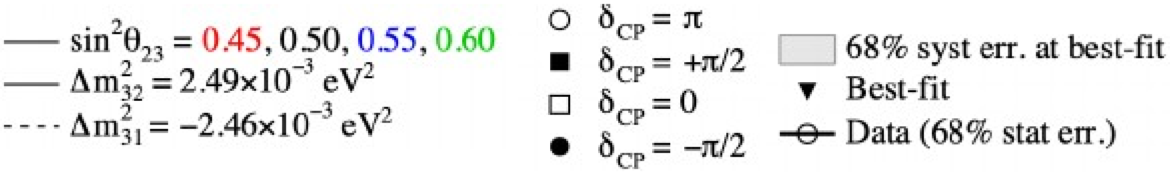
Experiment	CP asymmetry	Mass Hierarchy
T2K (T2HK)	~30%	~10%
Nova	~30%	~30%

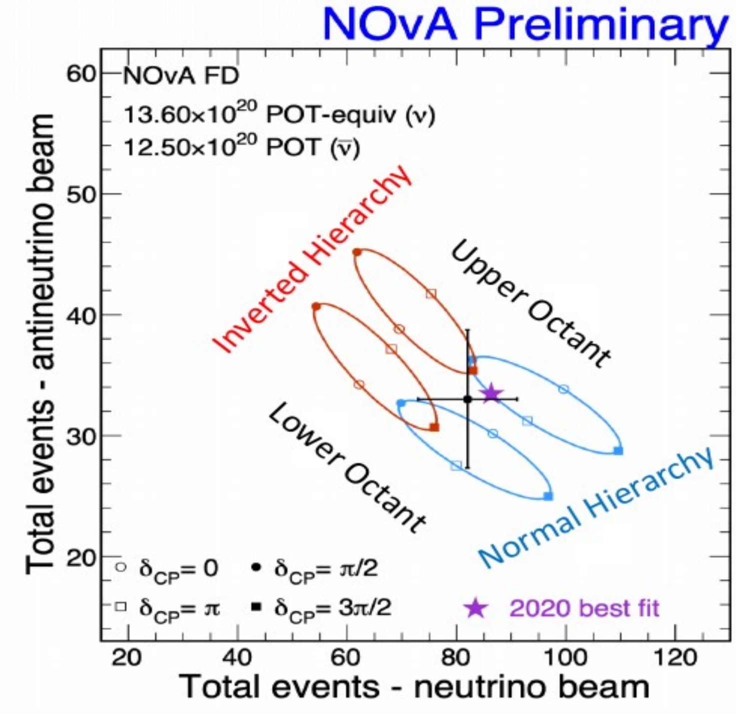
- **T2K: clean δ_{CP} measurement with small MH sensitivity**

- **NOVA: degenerate δ_{CP} and MH:**
(${\delta_{CP}}$ 3π/2 and IH = ${\delta_{CP}}$ π/2 and NH)

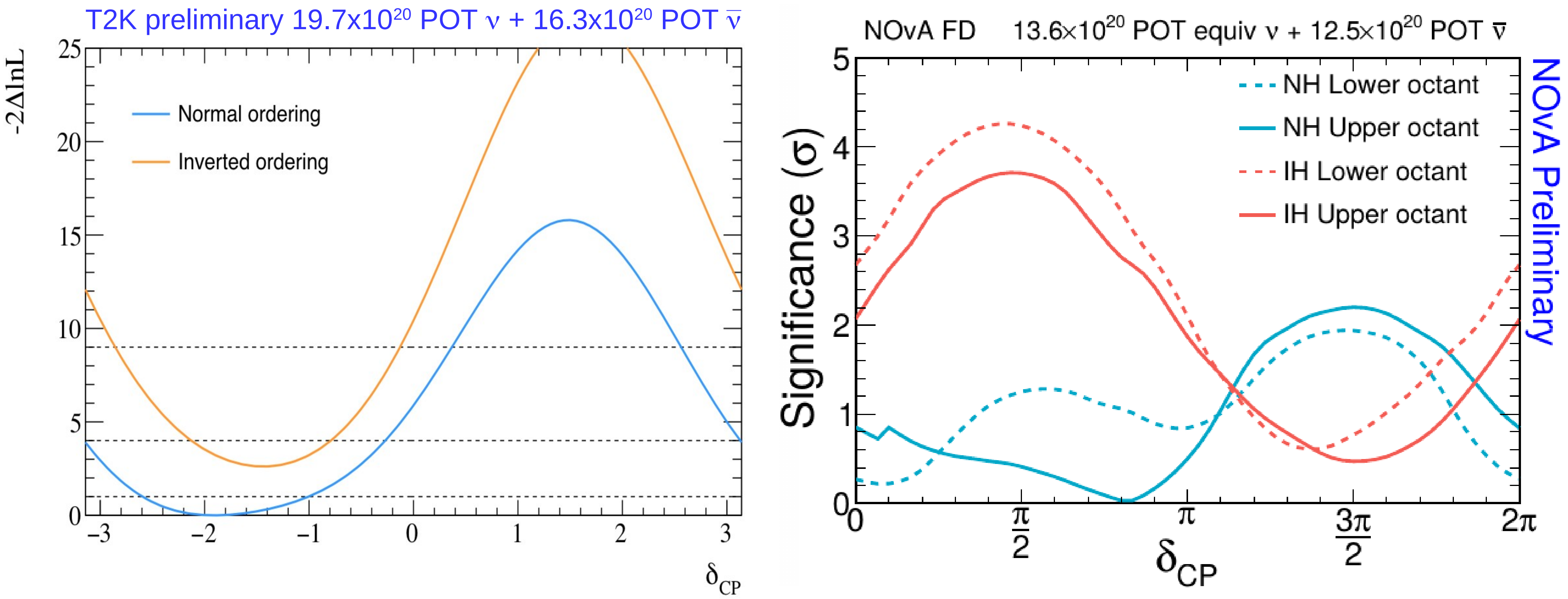
Using 2020 results in the following (2022 improved analyses confirmed the situation)







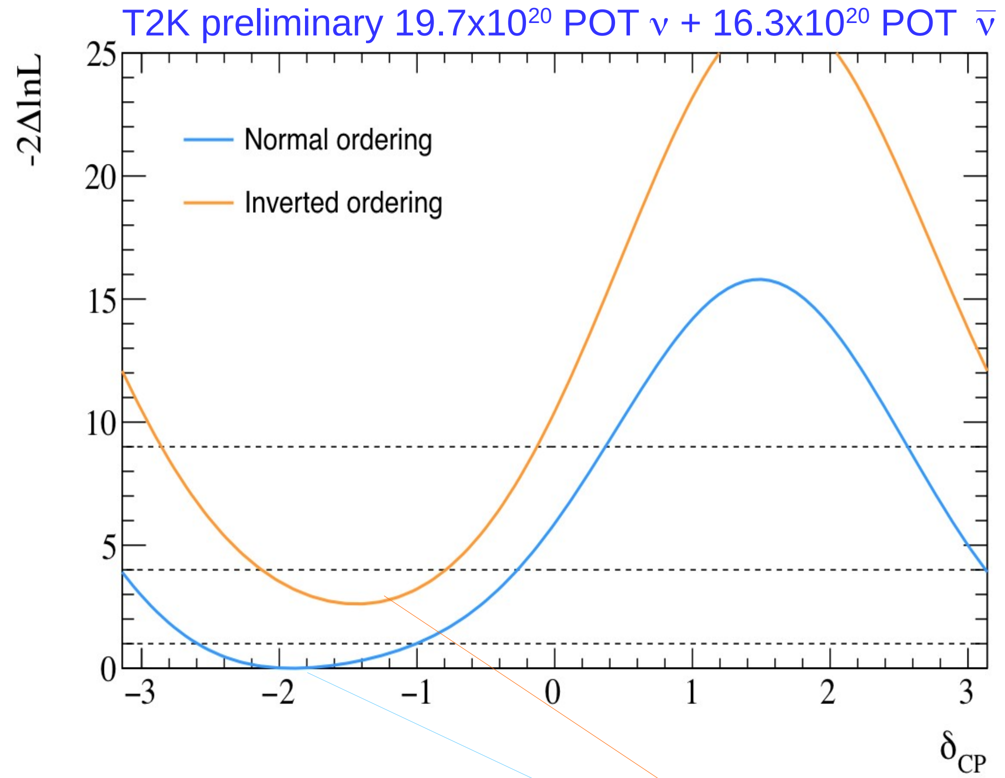
Results

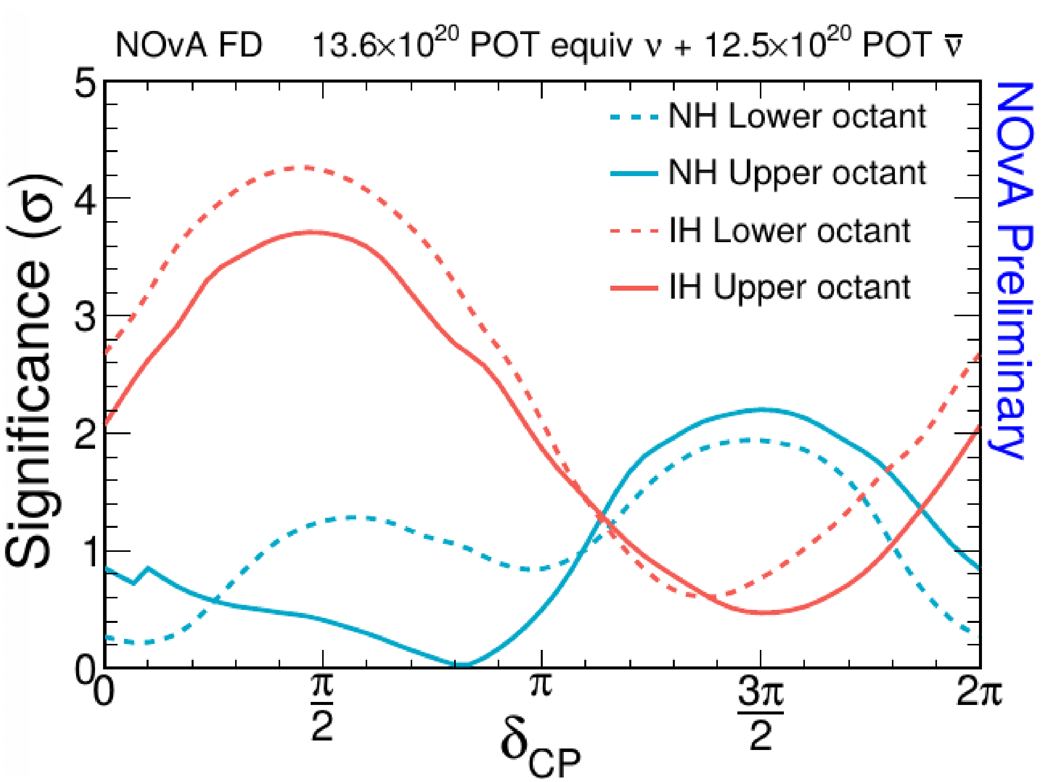


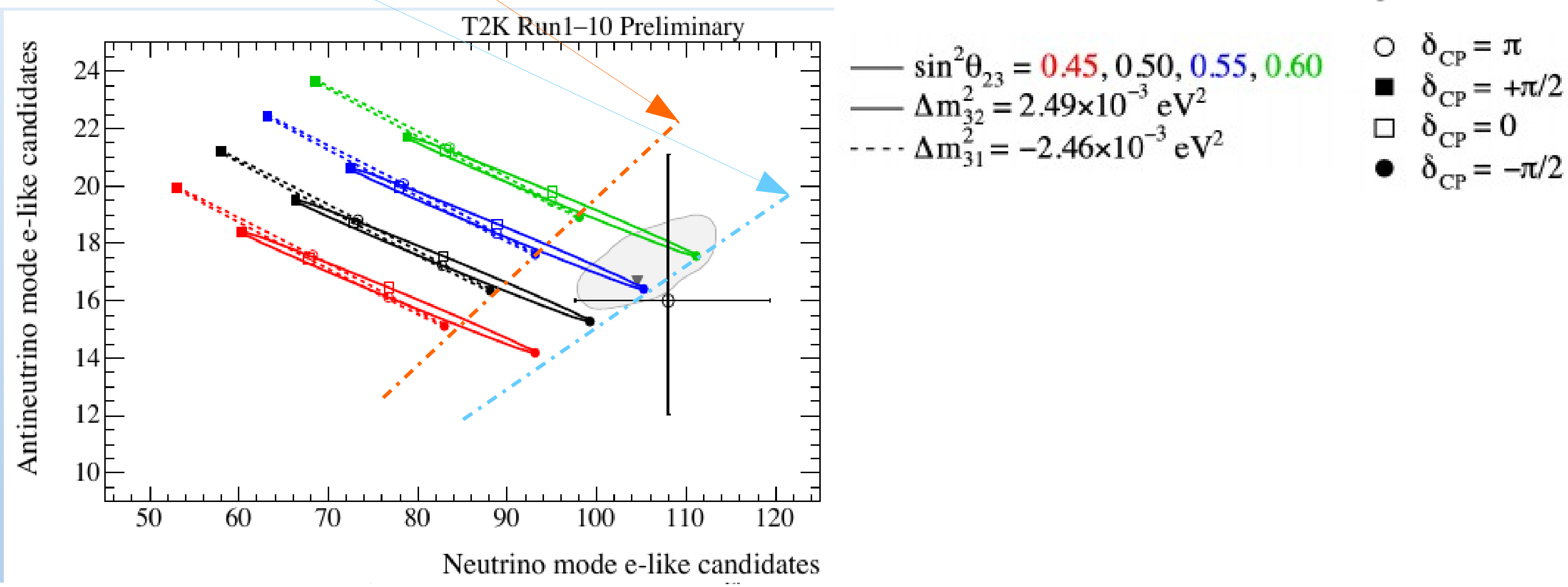
- Large **region disfavoured at 3σ** (T2K Nature cover in 2020). And for T2K even some region at 5σ but precision of statistical treatment will be discussed later.

Similar region disfavoured at T2K for NH and IH, while 3σ exclusion in NOVA only for IO

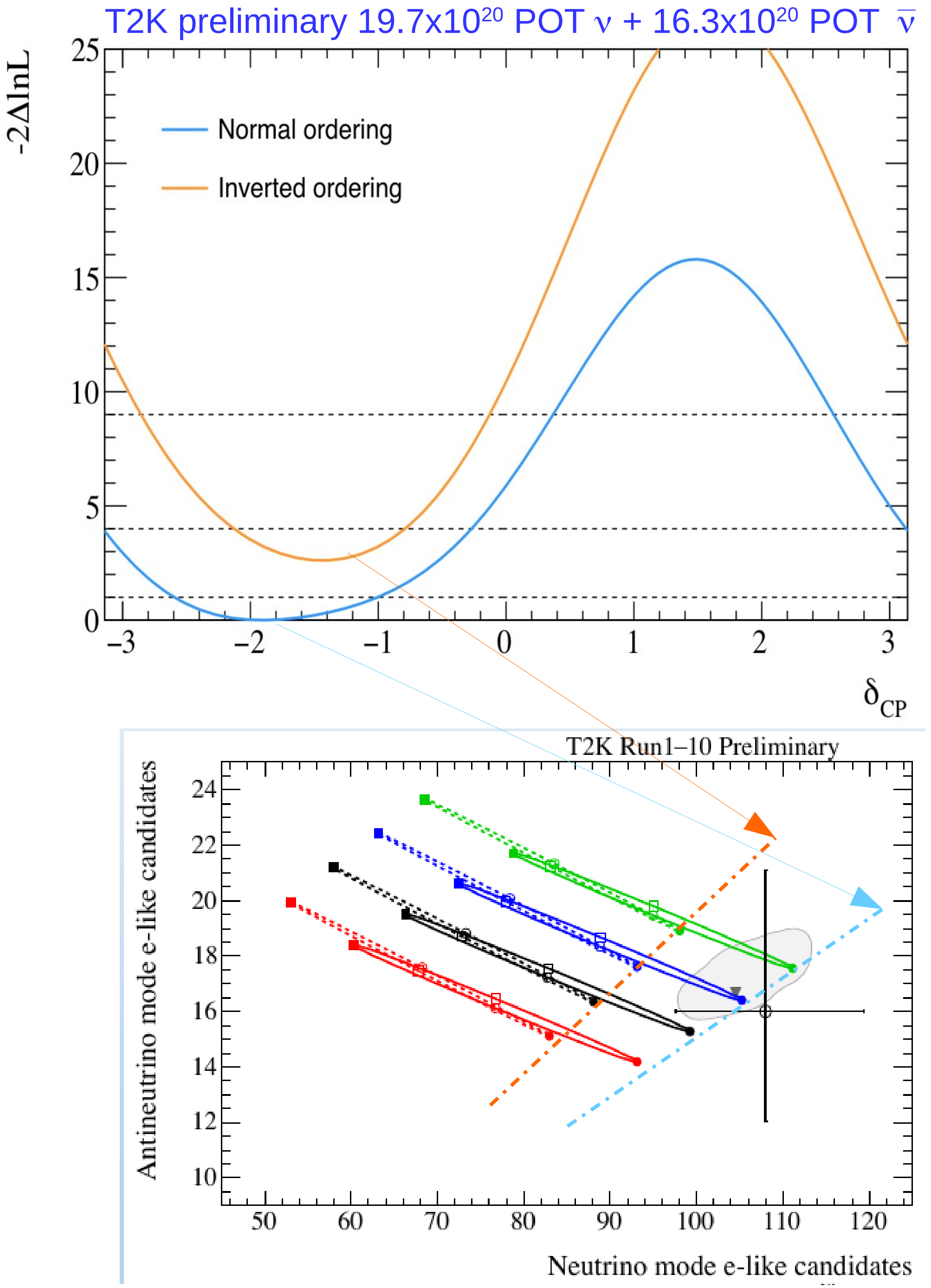
Results


T2K preliminary 19.7x10^20 POT ν + 16.3x10^20 POT ν̄
-2ΔlnL
Normal ordering
Inverted ordering
25
20
15
10
5
0
−3
−2
−1
0
1
2
3
δCP


NOvA FD 13.6×10^20 POT equiv ν + 12.5×10^20 POT ν̄
NOvA Preliminary
Significance (σ)
NH Lower octant
NH Upper octant
IH Lower octant
IH Upper octant
5
4
3
2
1
0
0
π/2
π
3π/2
2π
δCP


T2K Run1–10 Preliminary
Antineutrino mode e-like candidates
Neutrino mode e-like candidates
24
22
20
18
16
14
12
10
50
60
70
80
90
100
110
120
sin²θ23 = 0.45, 0.50, 0.55, 0.60
Δm²32 = 2.49×10⁻³ eV²
Δm²31 = −2.46×10⁻³ eV²
δCP = π
δCP = +π/2
δCP = 0
δCP = −π/2

Results



$\sin^2\theta_{23}$ = 0.45, 0.50, 0.55, 0.60

$\Delta m^2_{32} = 2.49\times10^{-3}$ eV^2

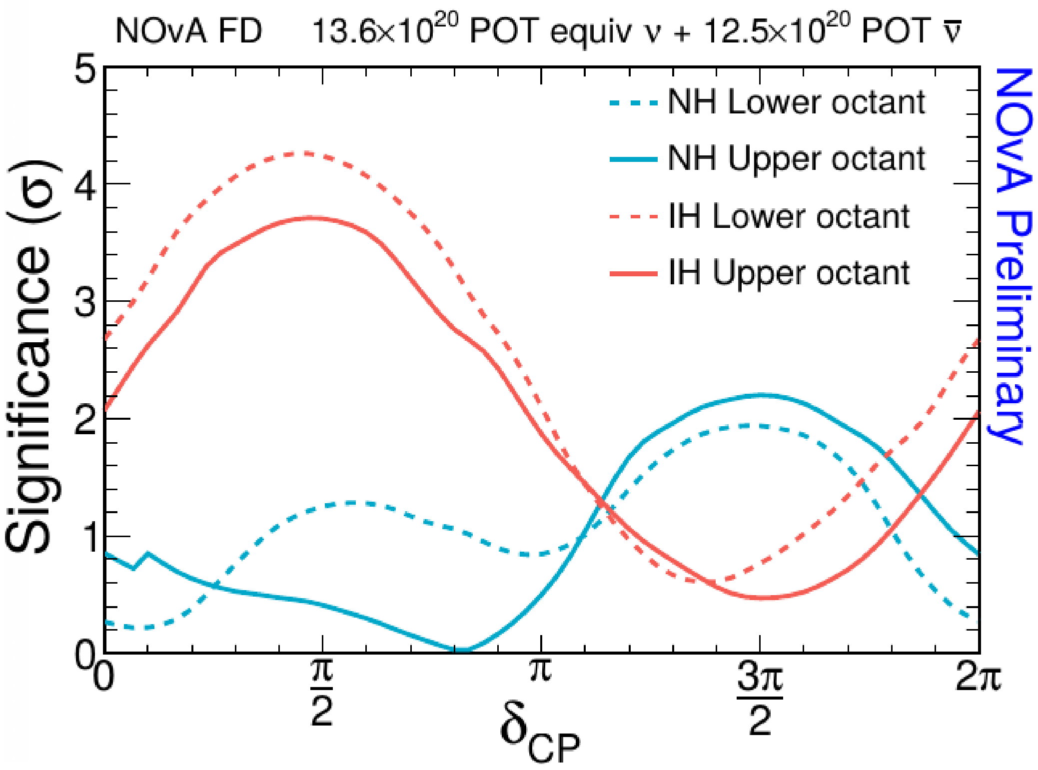
$\Delta m^2_{31} = -2.46\times10^{-3}$ eV^2

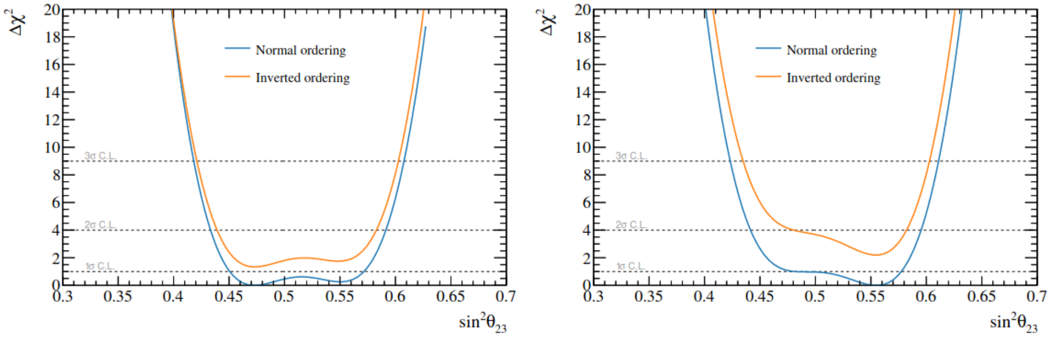
○ $\delta_{CP} = \pi$

■ $\delta_{CP} = +\pi/2$

☐ $\delta_{CP} = 0$

● $\delta_{CP} = -\pi/2$

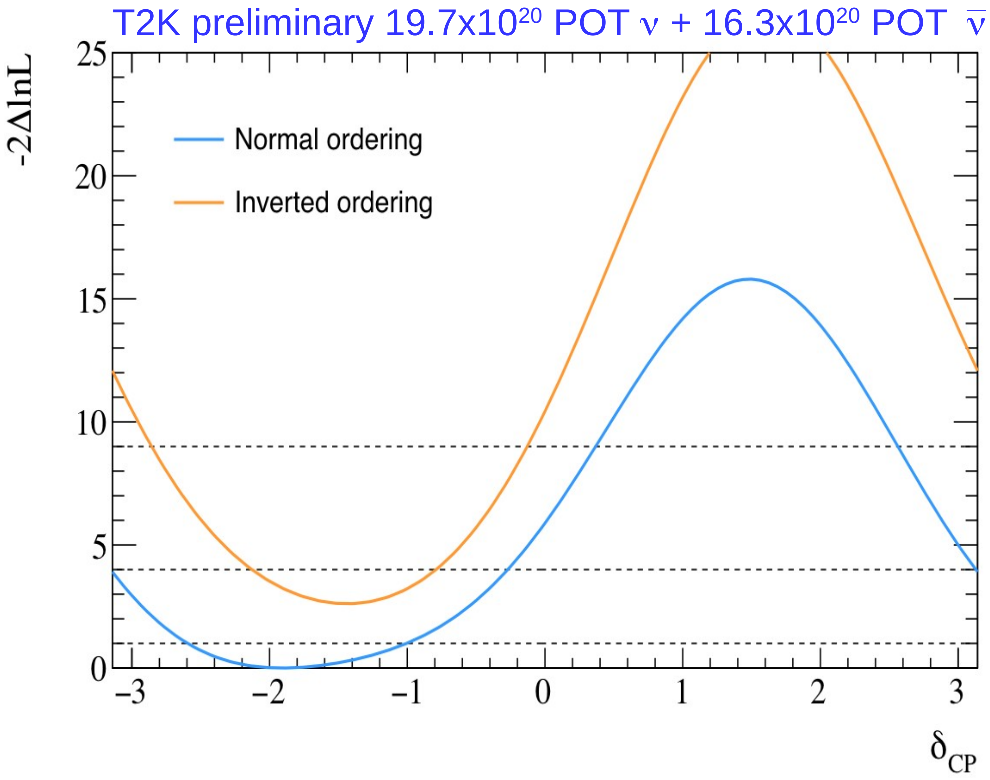


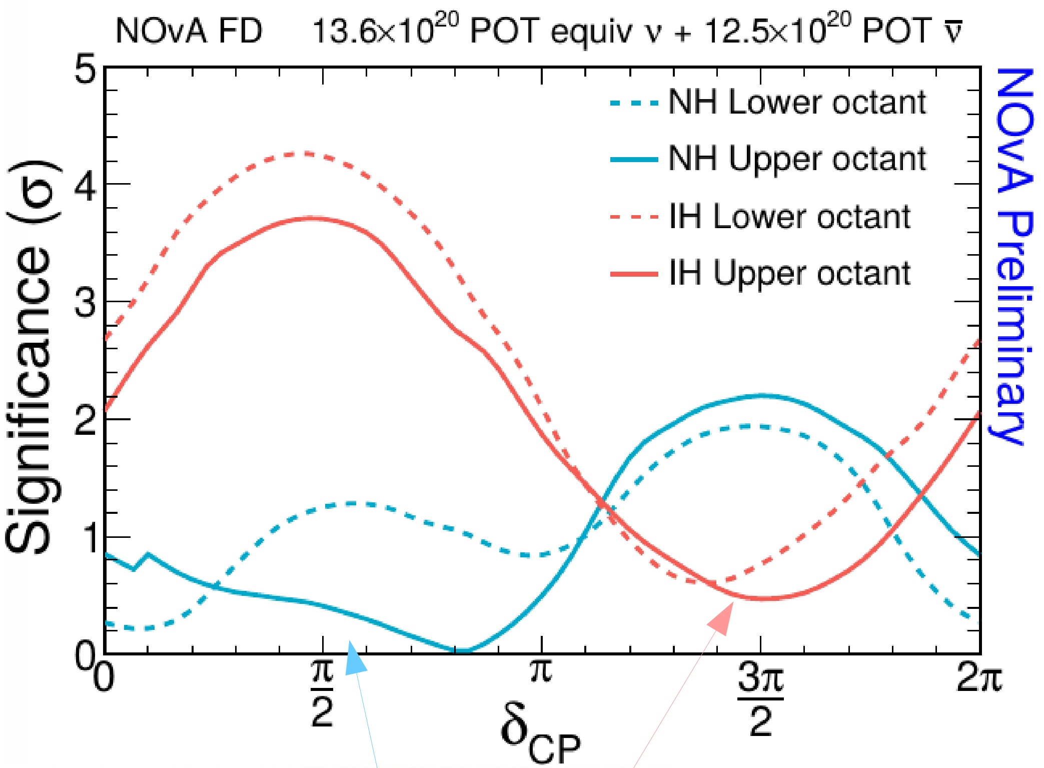


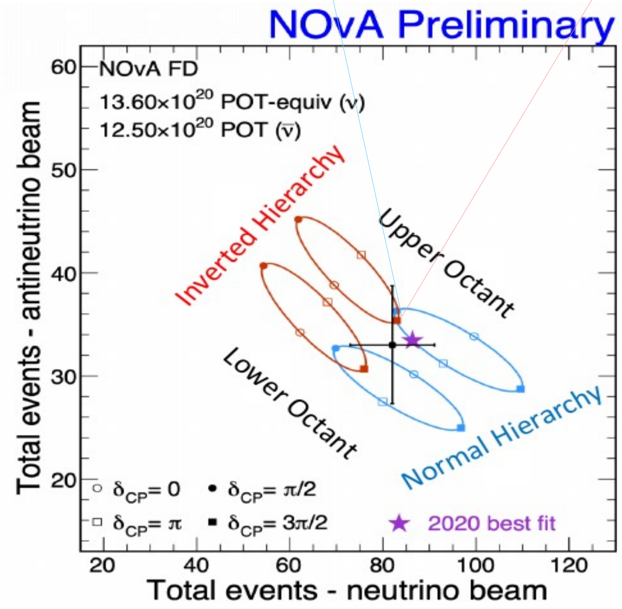
(a) T2K only

(b) T2K + reactor

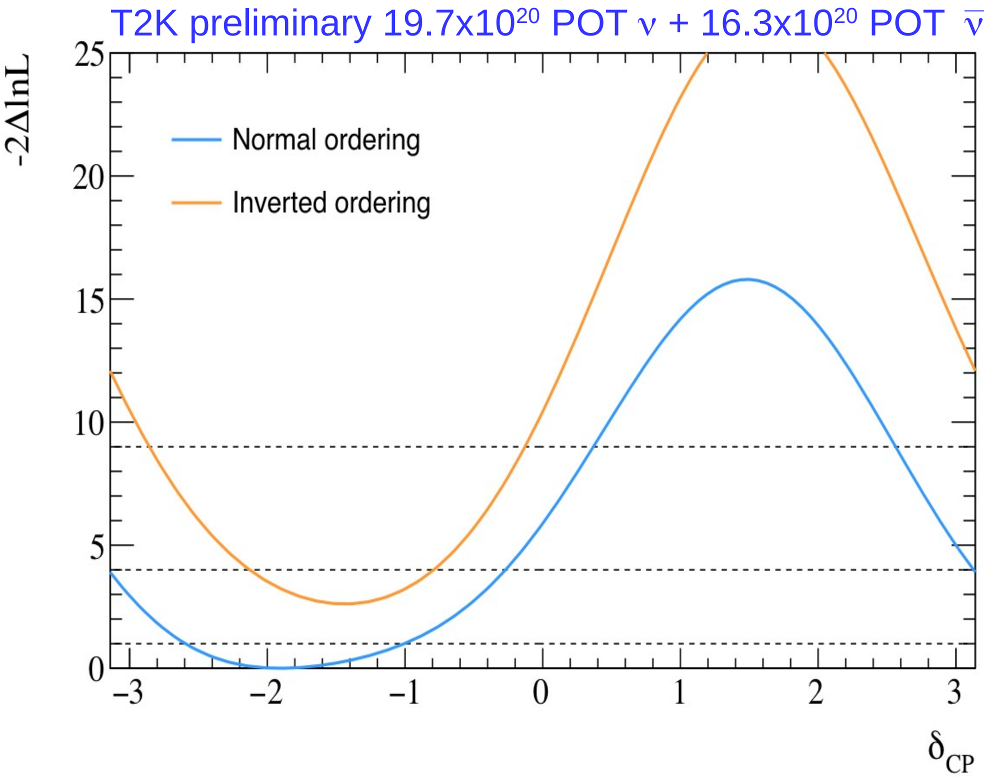
Results

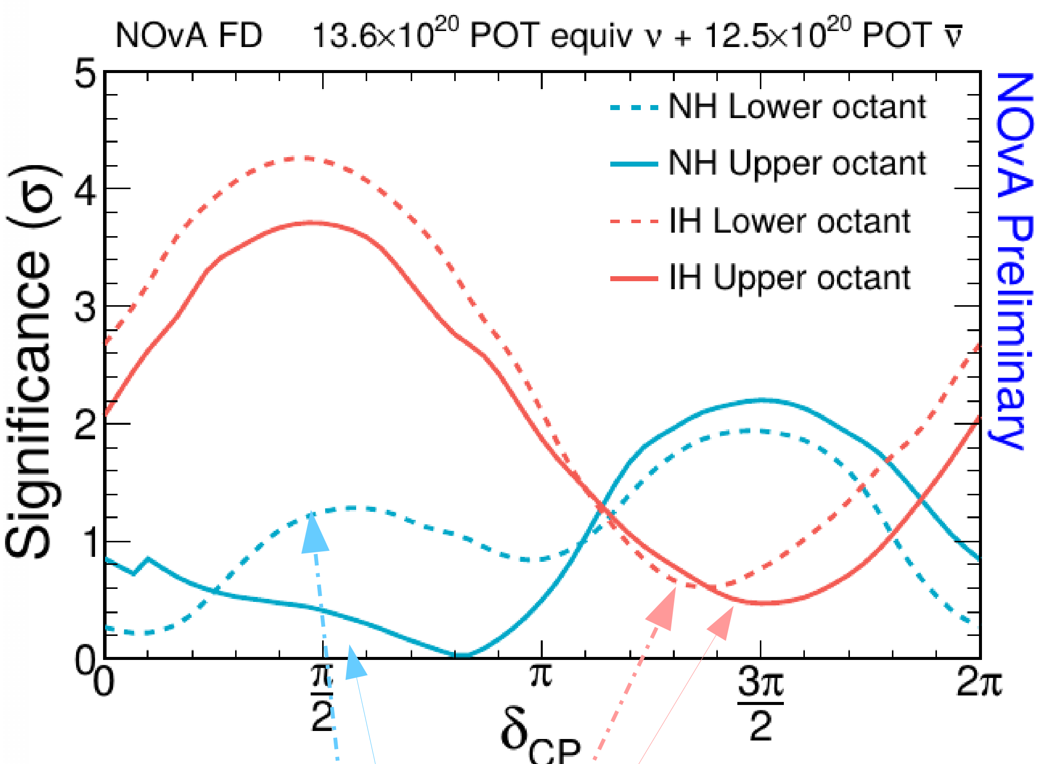

T2K preliminary 19.7x10^20 POT ν + 16.3x10^20 POT ν̄
-2ΔlnL
Normal ordering
Inverted ordering
δCP
0
5
10
15
20
25
–3
–2
–1
0
1
2
3

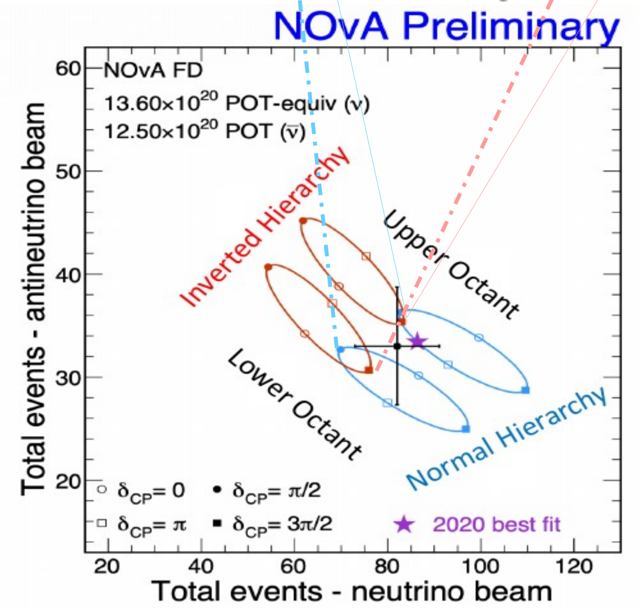

NOvA FD 13.6×10^20 POT equiv ν + 12.5×10^20 POT ν̄
Significance (σ)
NH Lower octant
NH Upper octant
IH Lower octant
IH Upper octant
NOvA Preliminary
δCP
0
π/2
π
3π/2
2π
0
1
2
3
4
5


NOvA Preliminary
NOvA FD
13.60×10^20 POT-equiv (ν)
12.50×10^20 POT (ν̄)
Inverted Hierarchy
Upper Octant
Lower Octant
Normal Hierarchy
δCP= 0
δCP= π/2
δCP= π
δCP= 3π/2
2020 best fit
Total events - antineutrino beam
Total events - neutrino beam
20
30
40
50
60
20
40
60
80
100
120

Results

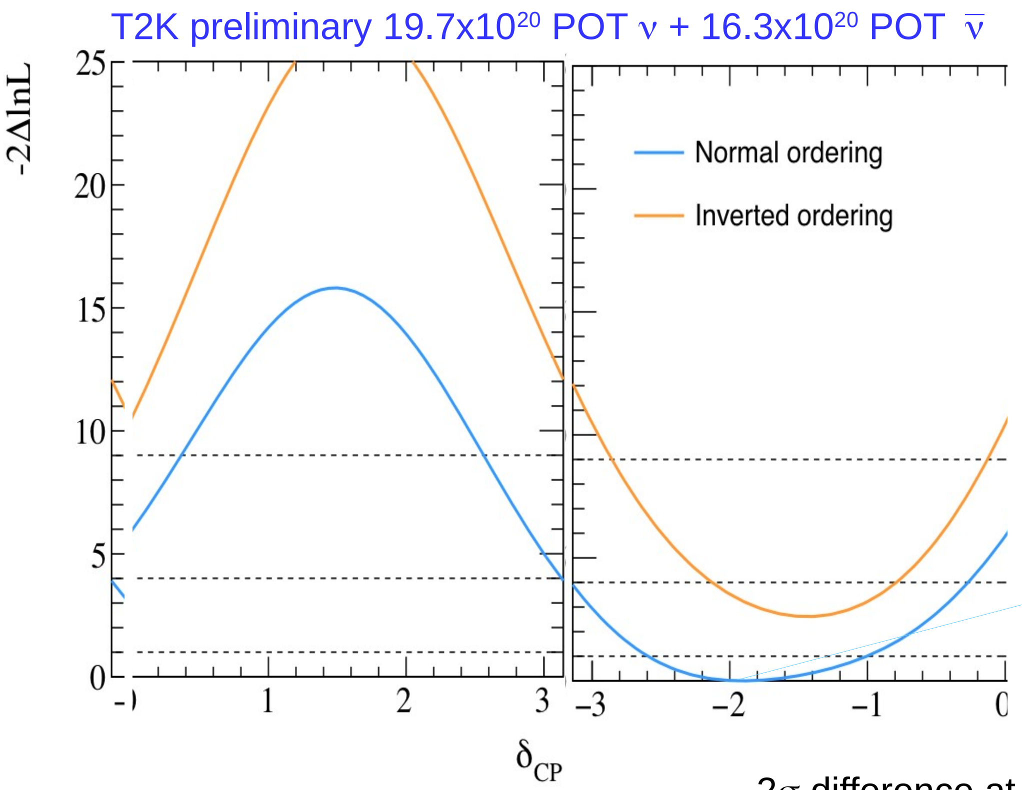


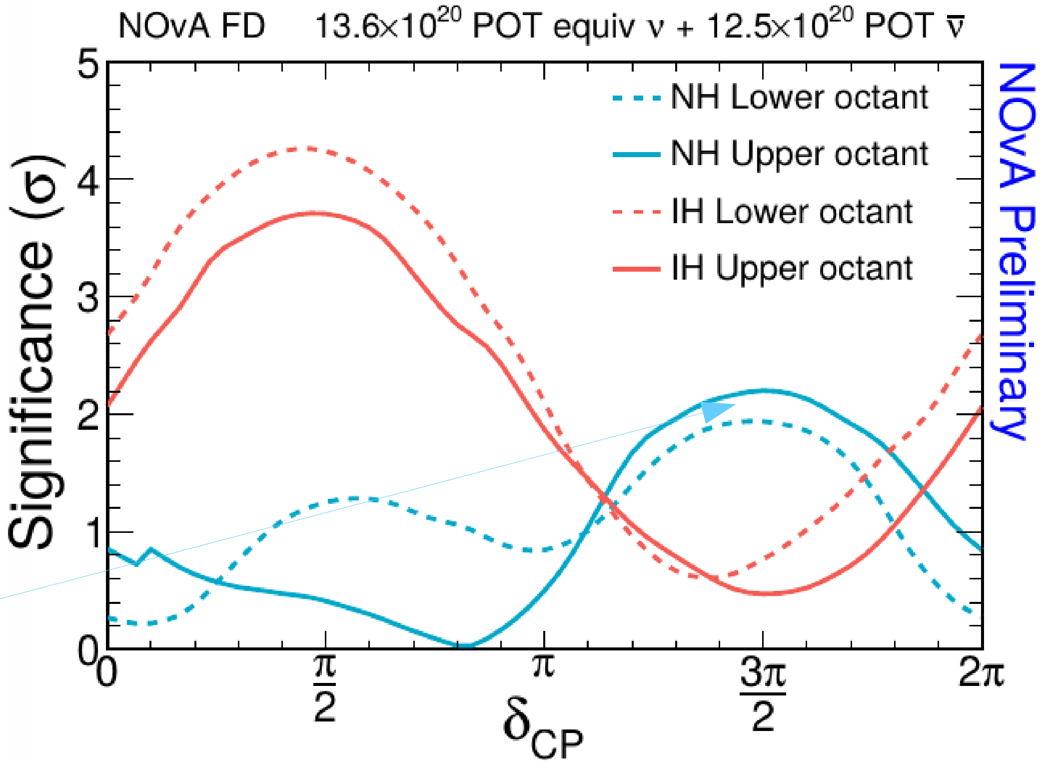




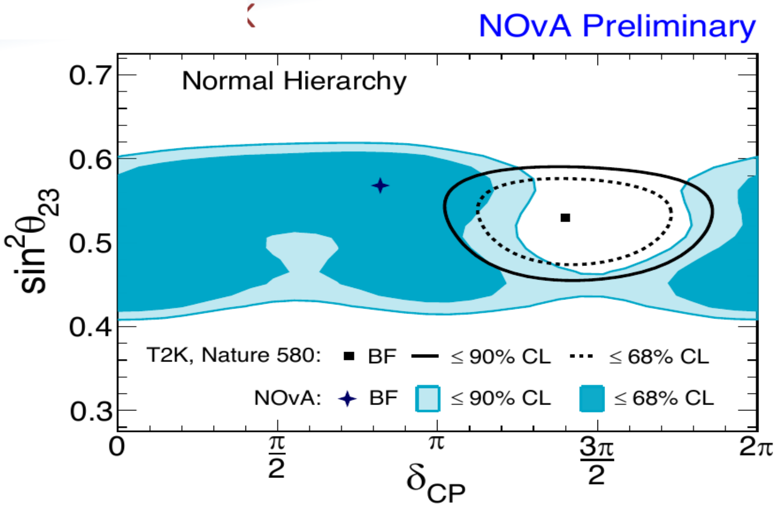
all these possibilities inside 1σ

Results

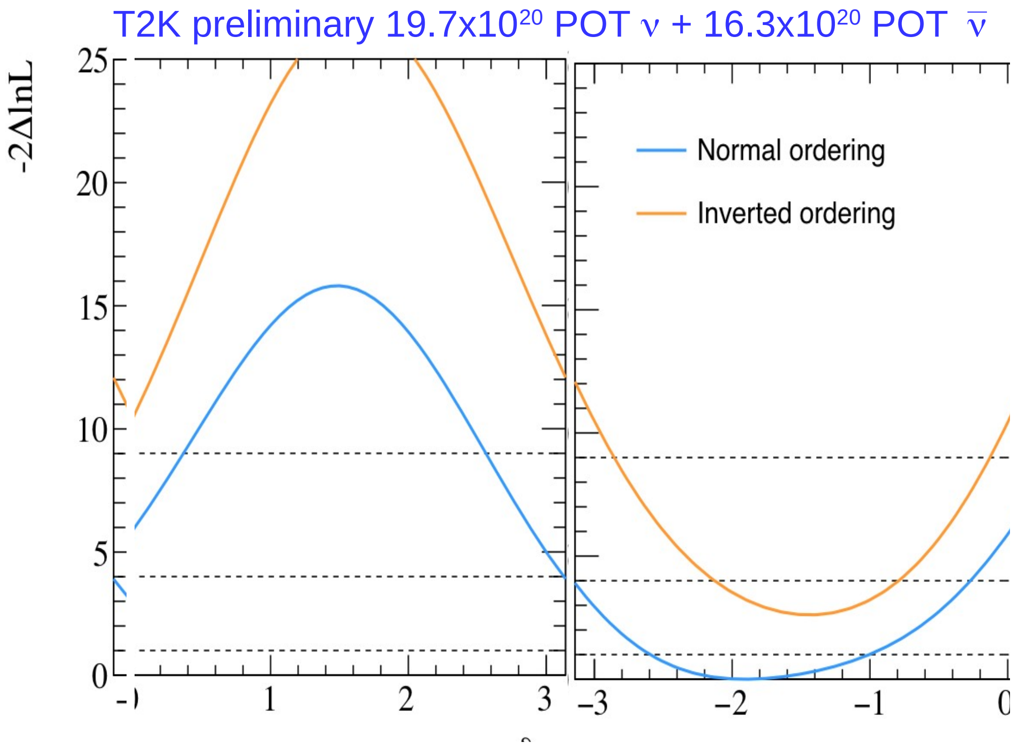

T2K preliminary 19.7x10^{20} POT ν + 16.3x10^{20} POT $\bar{\nu}$

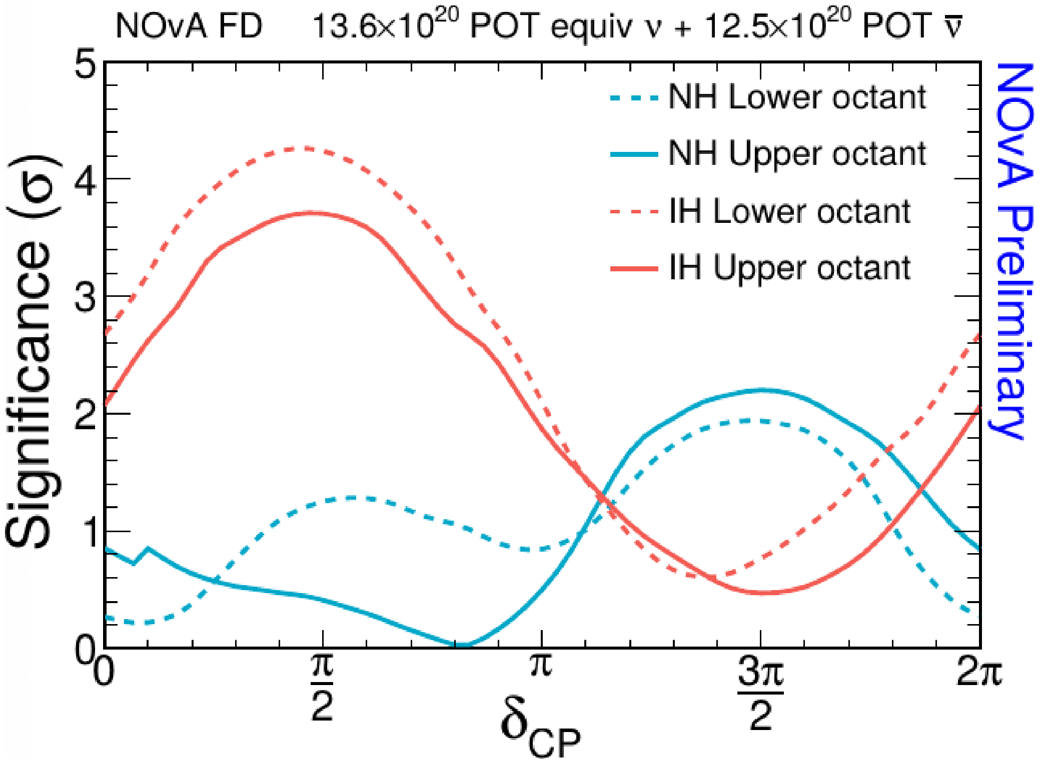

NOvA FD 13.6×10^{20} POT equiv ν + 12.5×10^{20} POT $\bar{\nu}$

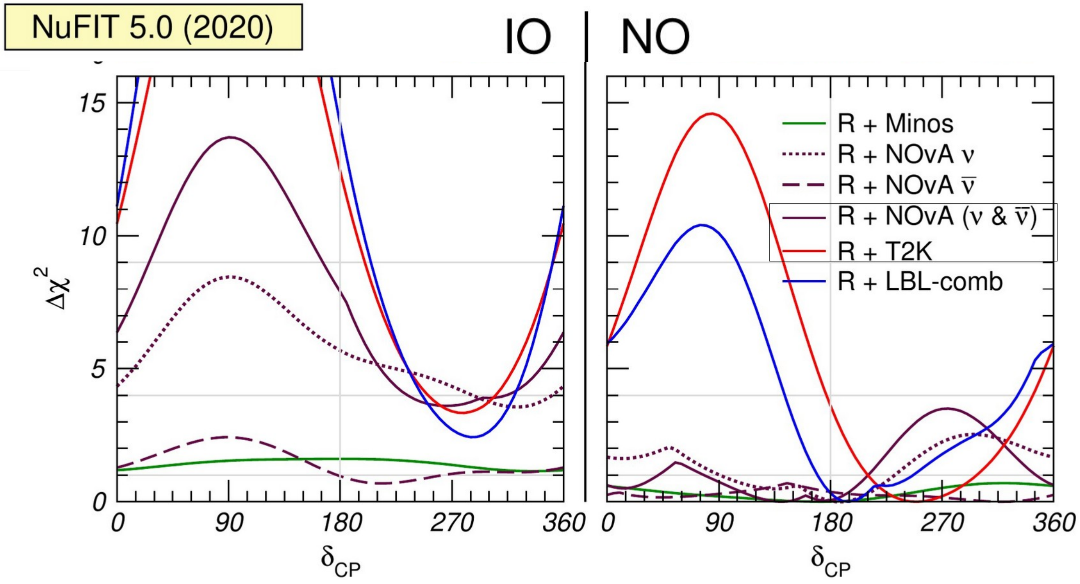
2σ difference at T2K minimum (max CPV, NH) but still common regions at 1σ

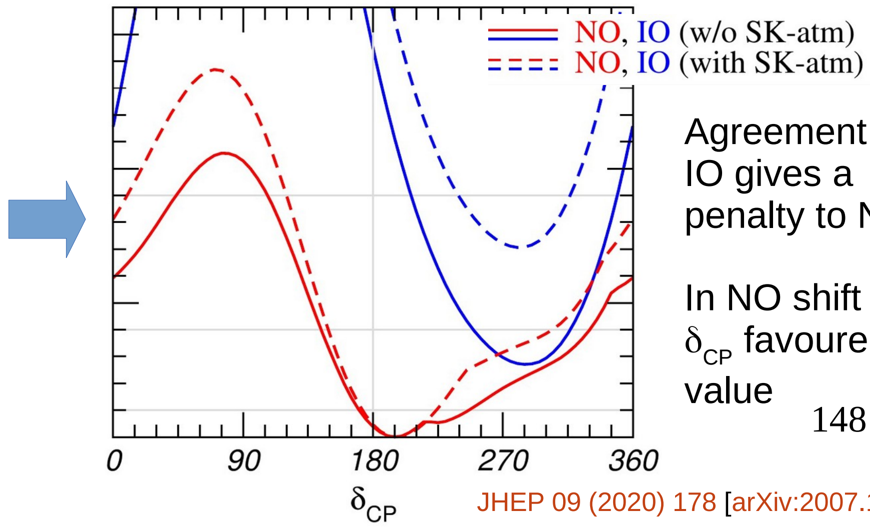


Results







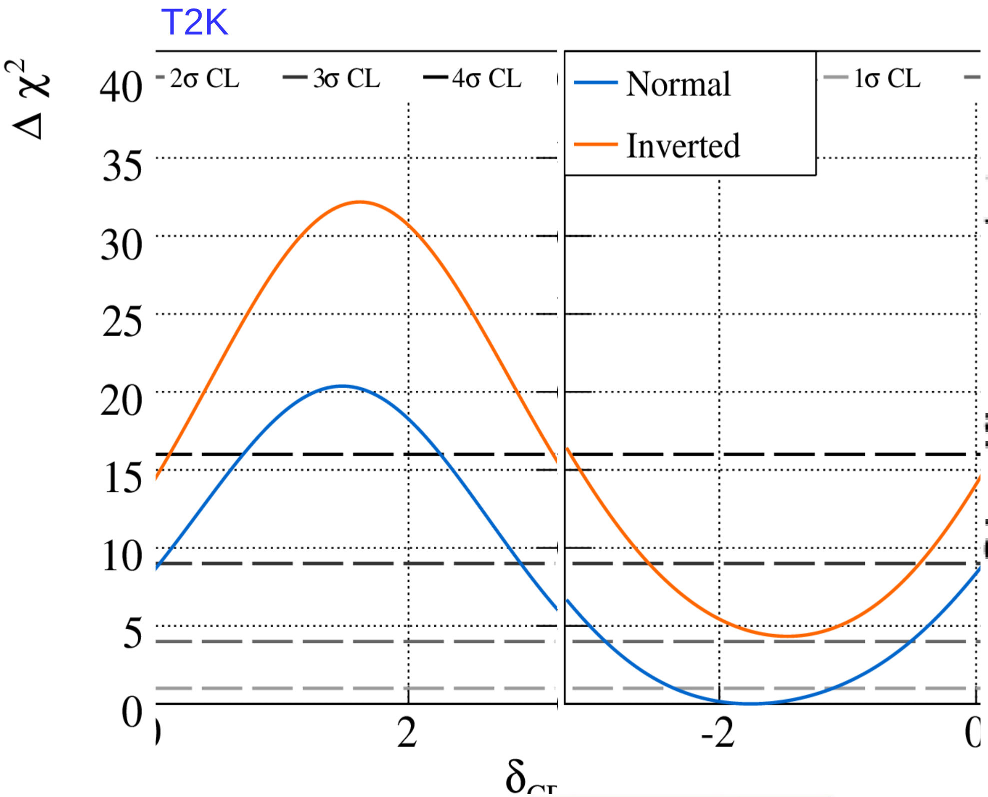


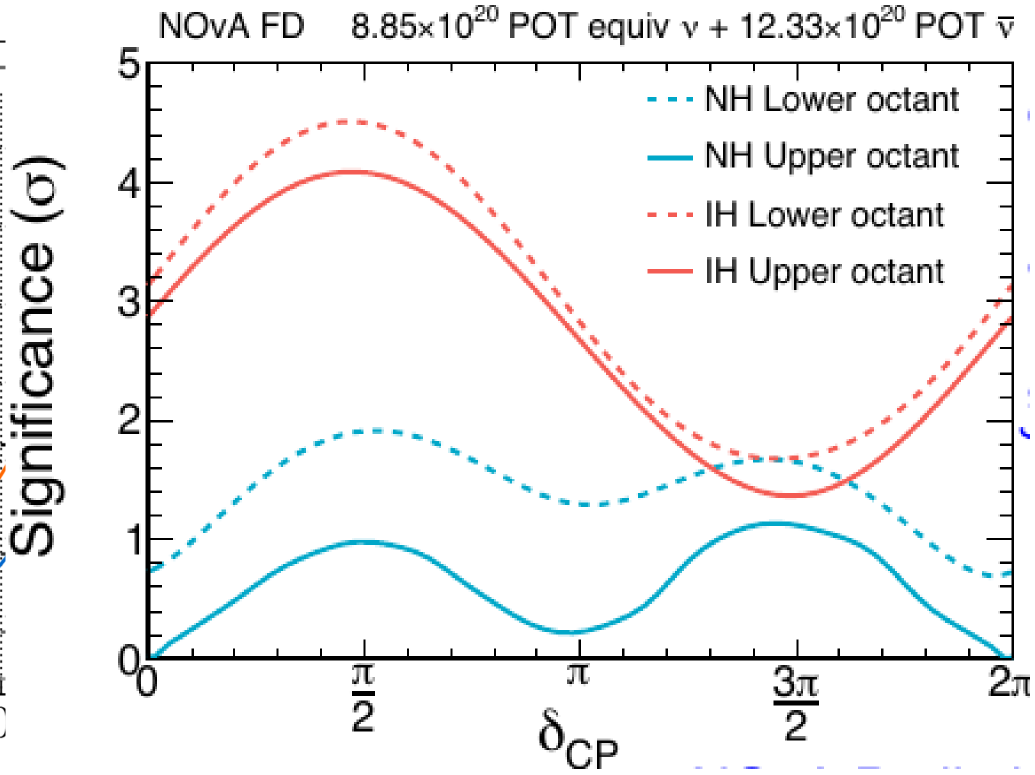
Agreement in IO gives a penalty to NO

In NO shift on δ_{CP} favoured value

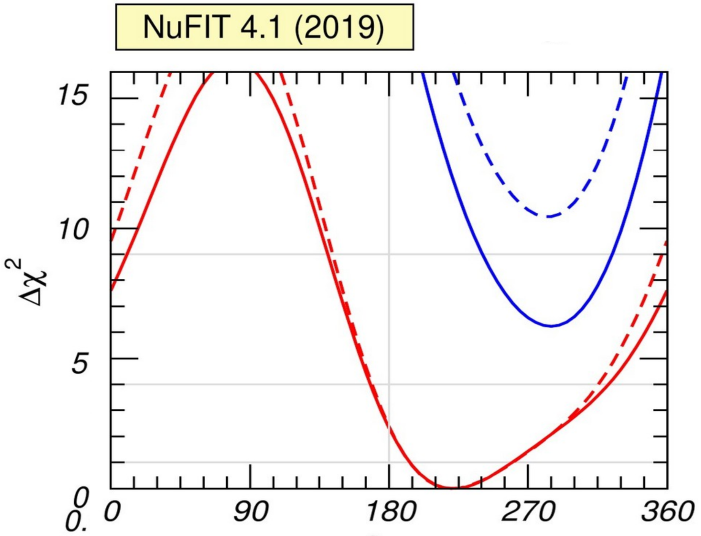
JHEP 09 (2020) 178 [arXiv:2007.14792]

Results ***2019 → 2020***

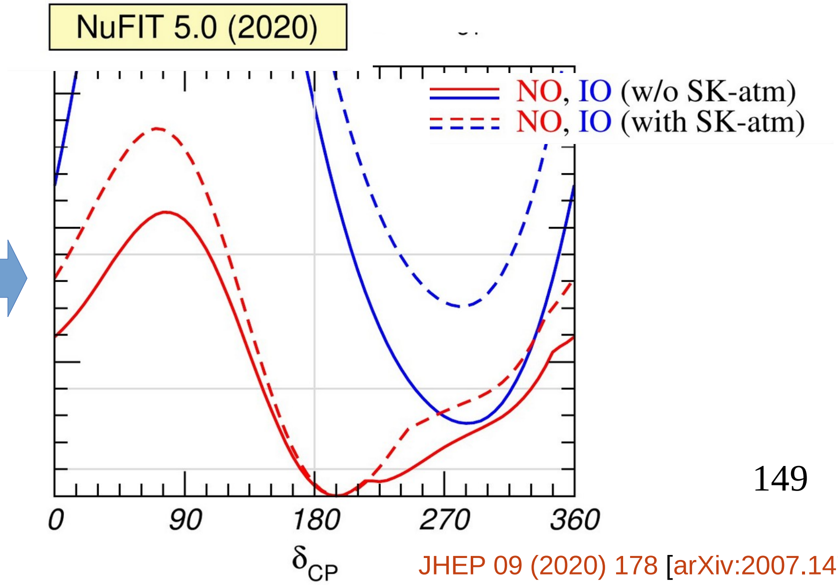




Something similar already visible in previous round of results

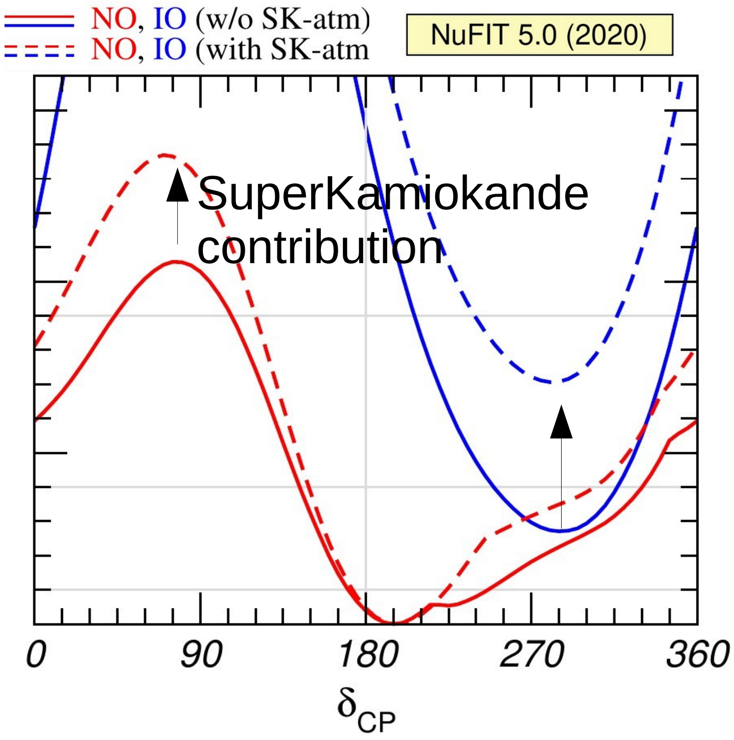


JHEP 01 (2019) 106 [arXiv:1811.05487]



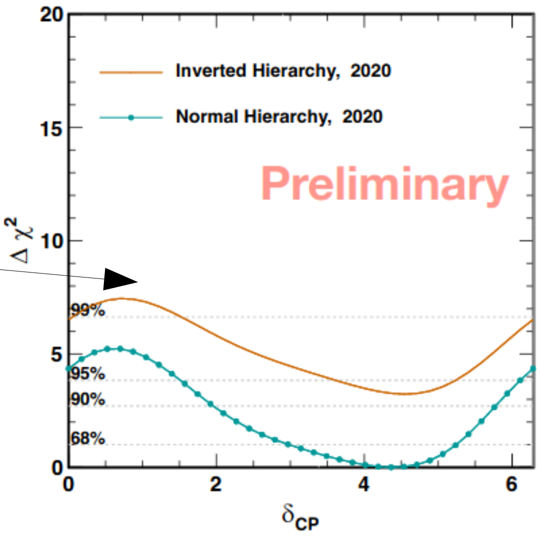
JHEP 09 (2020) 178 [arXiv:2007.14792]

Mass Hierarchy



SuperKamiokande contribution

NuFit 5.0 updated with SK I-IV analysis presented at Neutrino 2020



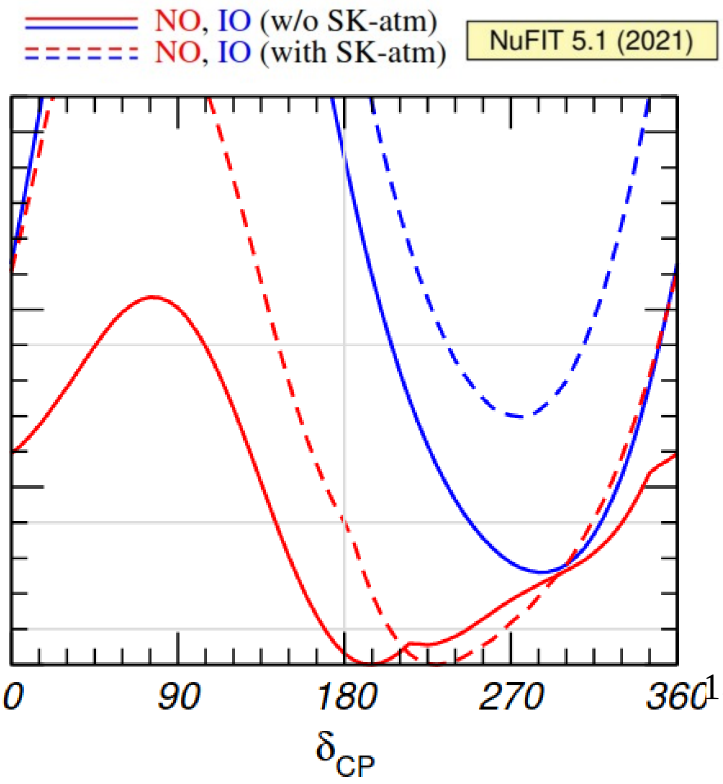
- Before 2020 NO favoured ($\Delta\chi^2$=10.4 >3σ!)

- Lost some NO significance due to T2K-NOVA mild tension in 2020 ($\Delta\chi^2$=7.1)

- **MO sensitivity dominated by SK**

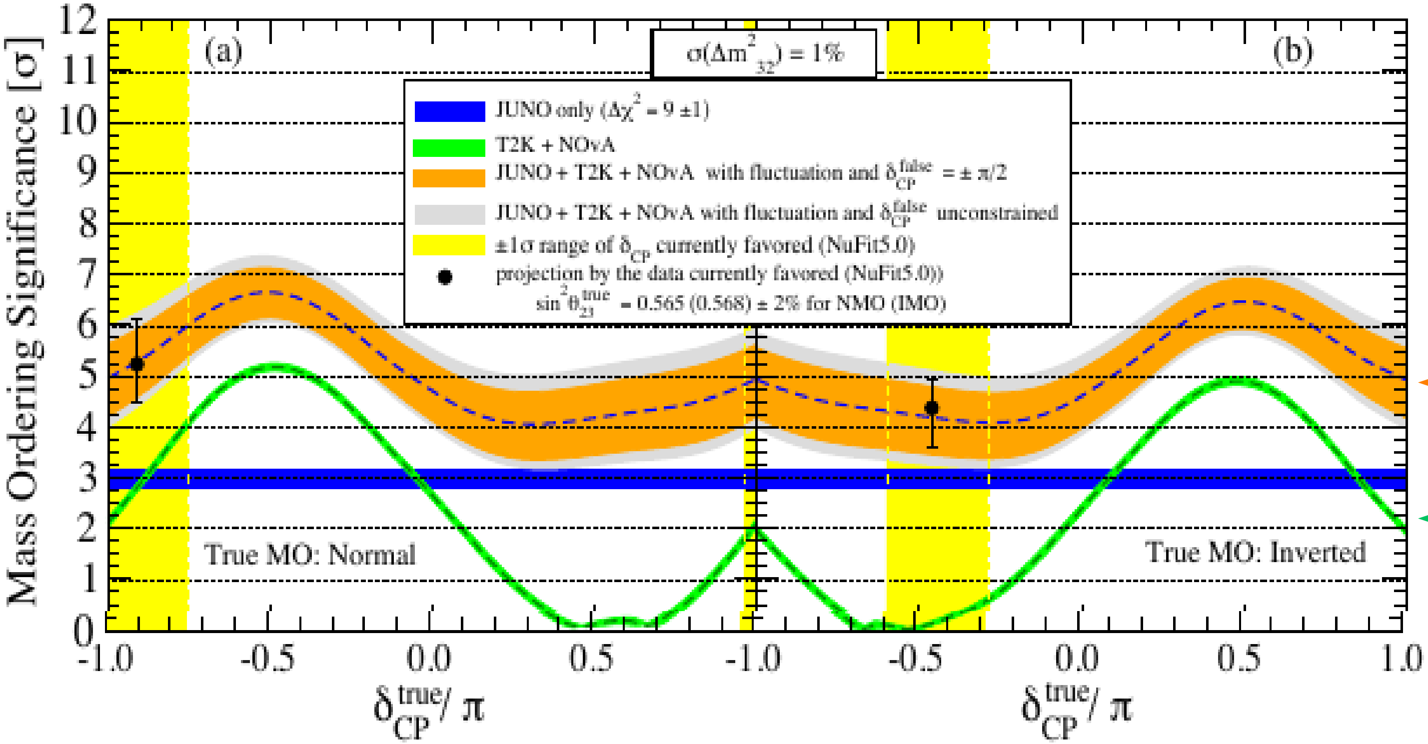
→ shift best δ_{CP} in combination with T2K+NOVA

→ CP conservation disfavoured at ~2σ



Combinations for MH: prospects

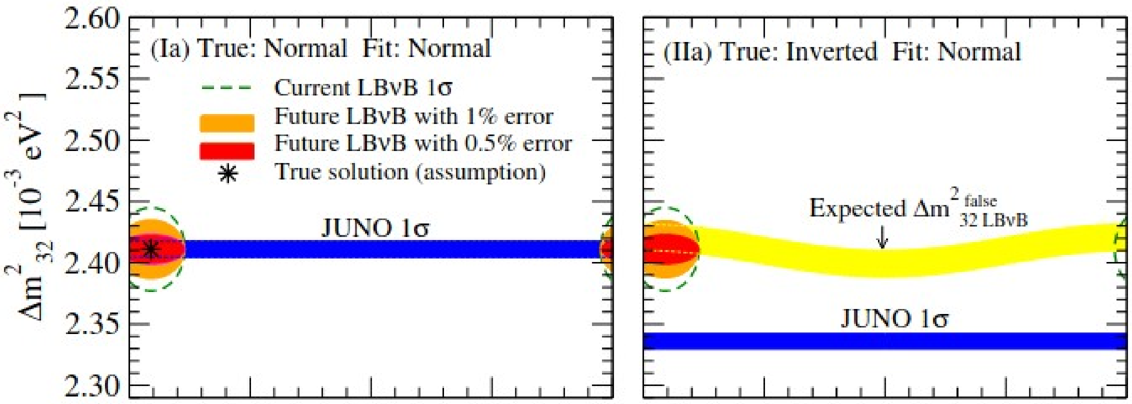
Very bright prospects for the future (and still not including SuperKamiokande!):



https://arxiv.org/pdf/2008.11280.pdf

T2K+NOVA+JUNO

T2K+NOVA

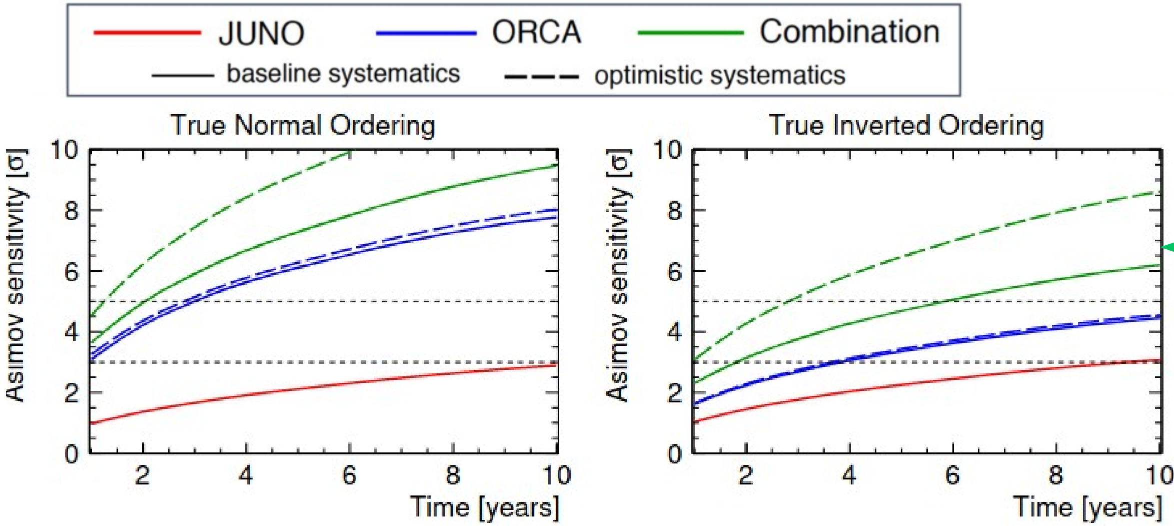


Boost of sensitivity from $\boldsymbol{|\Delta m^2_{31(32)}|}$ discrepancy (for wrong mass hierarchy) between ν_e (JUNO) and ν_μ (LBL) disappearance → ~2%

Importance of precise $\boldsymbol{|\Delta m^2_{31(32)}|}$ measurement in LBL experiments!
→ challenging target <1%

Combinations for MH: prospects

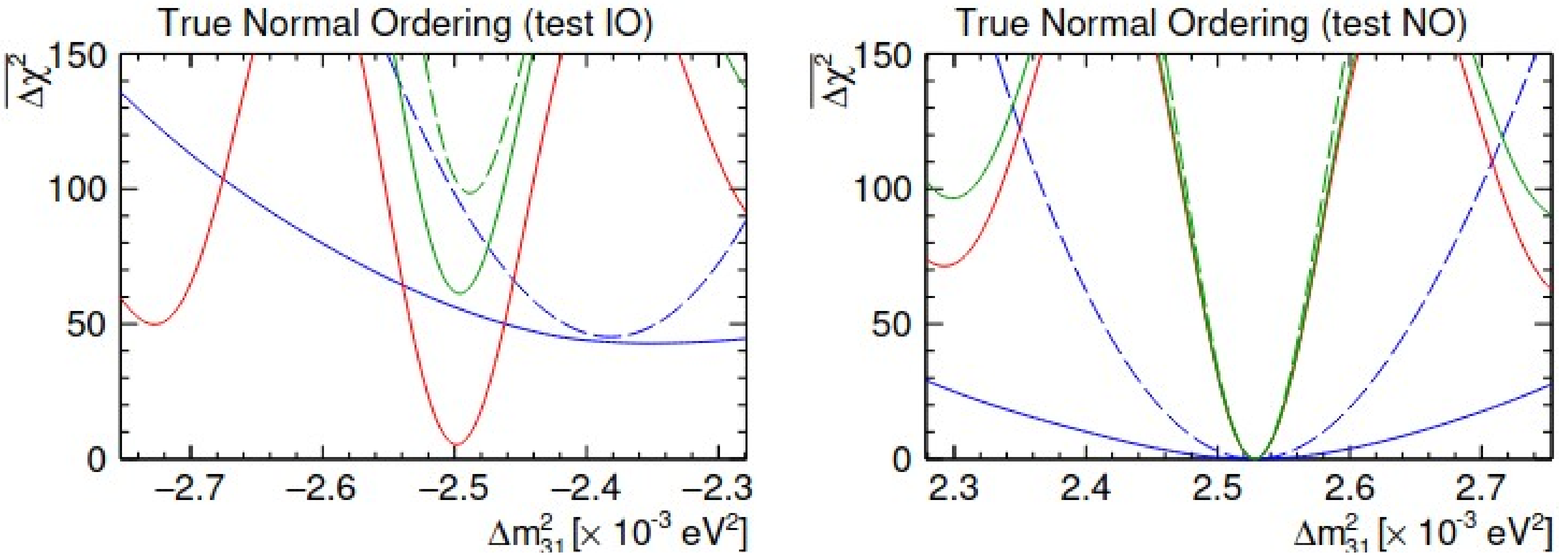
Further combination including ORCA (missing NOVA, T2K and SuperKamiokande):



JUNO+ORCA

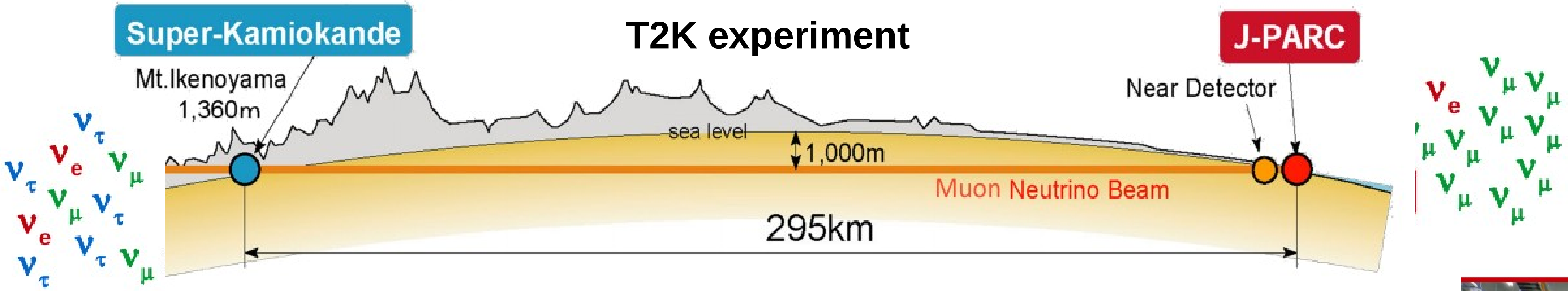
https://arxiv.org/pdf/2107.00344.pdf

Large boost of sensitivity from **$|\Delta m^2_{31(32)}|$** discrepancy (for wrong mass hierarchy) between ν_e (JUNO) and ν_μ (ORCA) disappearance

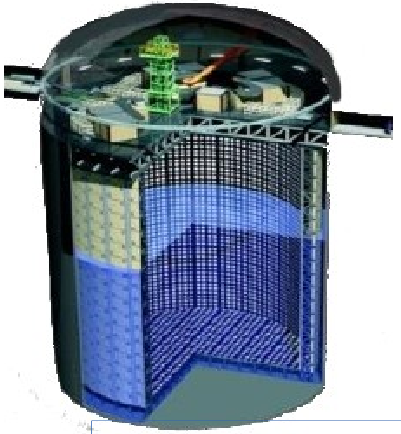


Anatomy of T2K and NOVA oscillation analysis

T2K

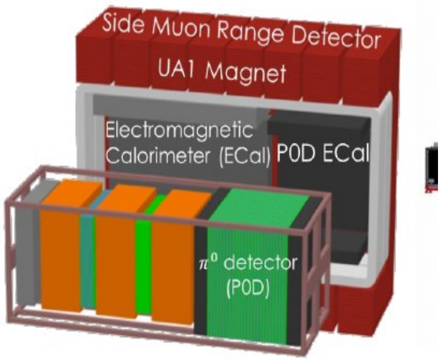


Super-Kamiokande

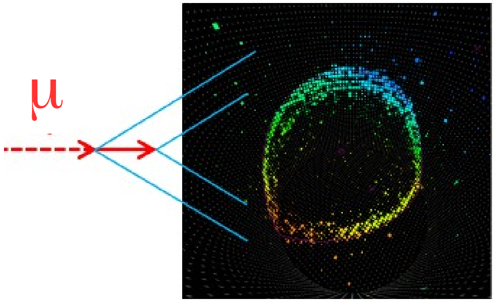


huge water cherenkov detector (50 kTon) with optimal μ/e identification to distinguish ν_e, ν_μ

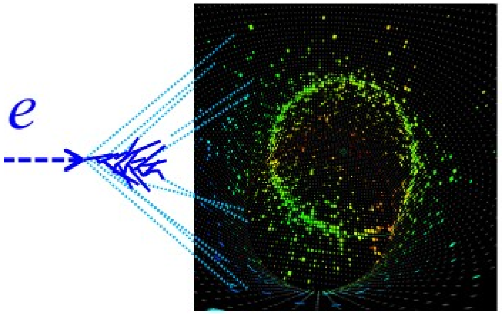
ND280 near detector



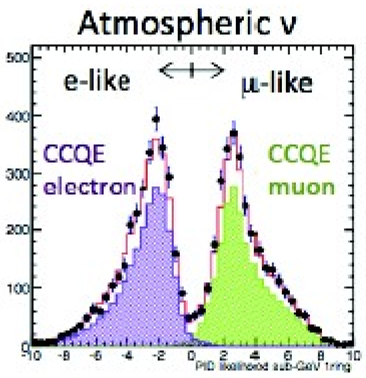
J-PARC facility: neutrino beam



clear ring

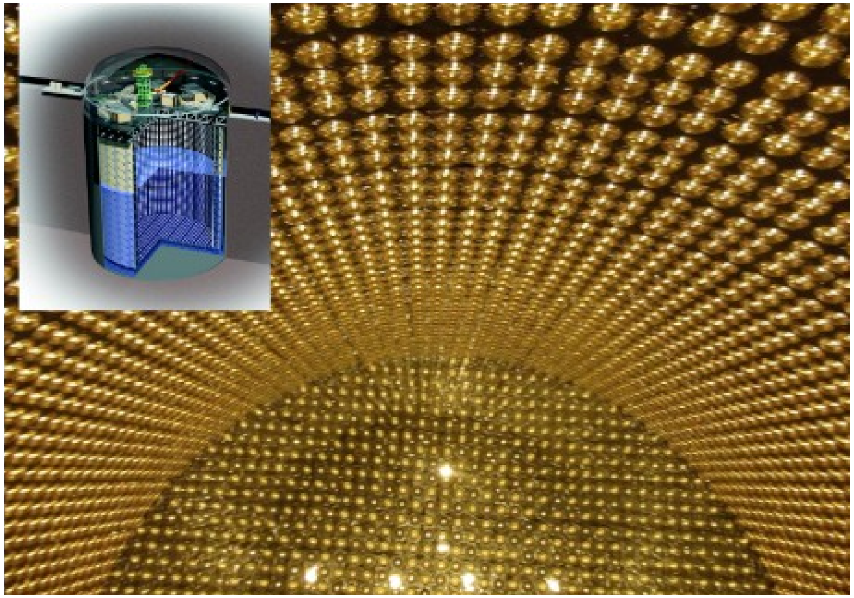


fuzzy ring



1% mis-id

SuperKamiokande samples

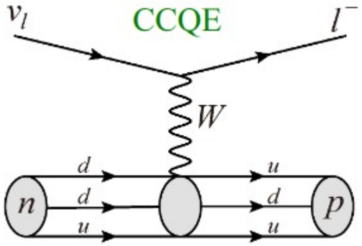


- Reconstruct Cherenkov ring from charged particles (above Cherenkov threshold)

- Use information of time, position and amount of light in the ring to estimate momentum and direction of particle (likelihood algo ‘fitqun’)

- ‘ring fuzzyness’ to distinguish e/μ (note: π~μ)

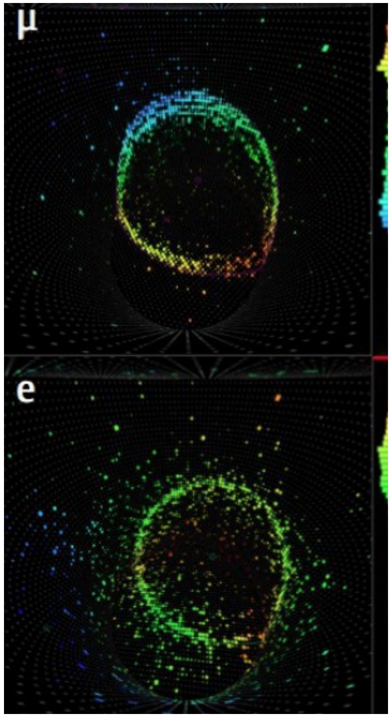
- Michel e- from muon (or π➔μ) decay: e- ring delayed in time



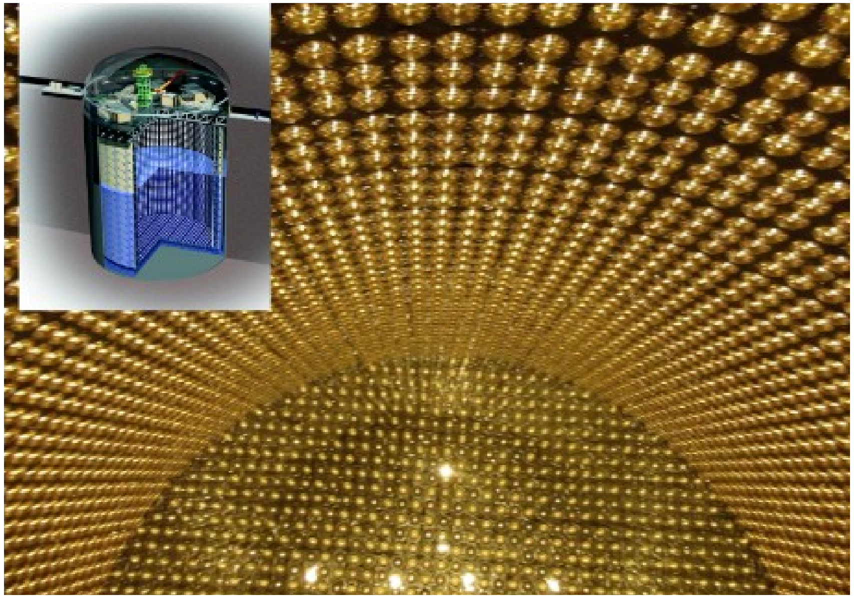
- Main channel at T2K energy:
single ring events (e or μ)
= Quasi-Elastic channel: can reconstruct neutrino energy from lepton kinematics only
[with nuclear physics uncertainty: see Martini lecture]

$$E_{\text{rec}}^{\text{CCQE}} = \frac{2\,(m_n - E_b)\,E_l + (2m_n - E_b)\,E_b + m_p^2 - m_n^2 - m_l^2}{2\,(m_n - E_b - E_l + |\boldsymbol{p}_l|\cos\theta_l)}$$

where m_n, m_p and m_μ are the masses of neutron, proton, and the charged lepton, $E_b = 27\,\text{MeV}$ is the nominal nucleon binding energy of oxygen, E_l and $\boldsymbol{p}_l$ are the reconstructed energy and three-momentum of the lepton, and θ_l is the reconstructed angle of the lepton with respect to the neutrino beam. The



SuperKamiokande samples

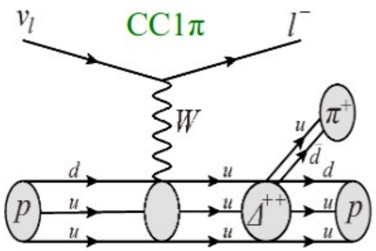


- Reconstruct Cherenkov ring from charged particles (above Cherenkov threshold)

- Use information of time, position and amount of light in the ring to estimate momentum and direction of particle (likelihood algo ‘fitqun’)

- ‘ring fuzzyness’ to distinguish e/μ (note: $\pi \sim \mu$)

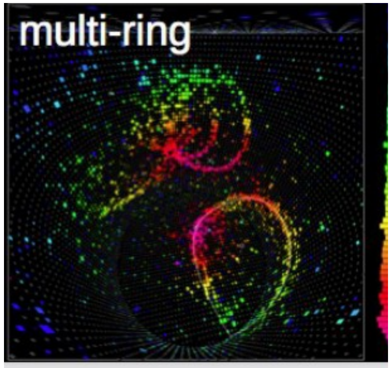
- Michel e- from muon (or $\pi \rightarrow \mu$) decay: e- ring delayed in time



- Additional channels with pion production (FHC), subleading and mostly at higher energy:

  - 1 ring electron (from ν_e) with 1 Michel electron
    → add statistics for ν_e sample

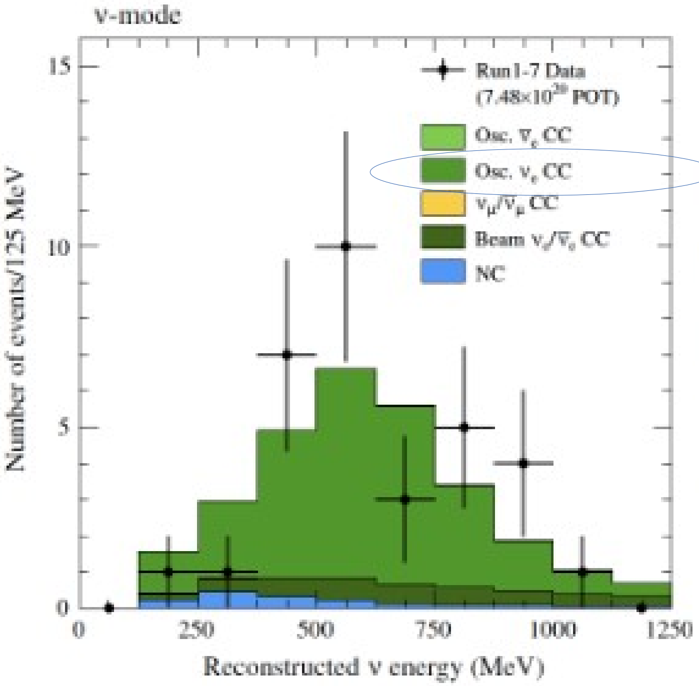
  - 1 ring muon (from ν_μ) + 1,2 Michel electron(s) and/or other ring from π
    → add high-energy ‘control sample’ for ν_μ

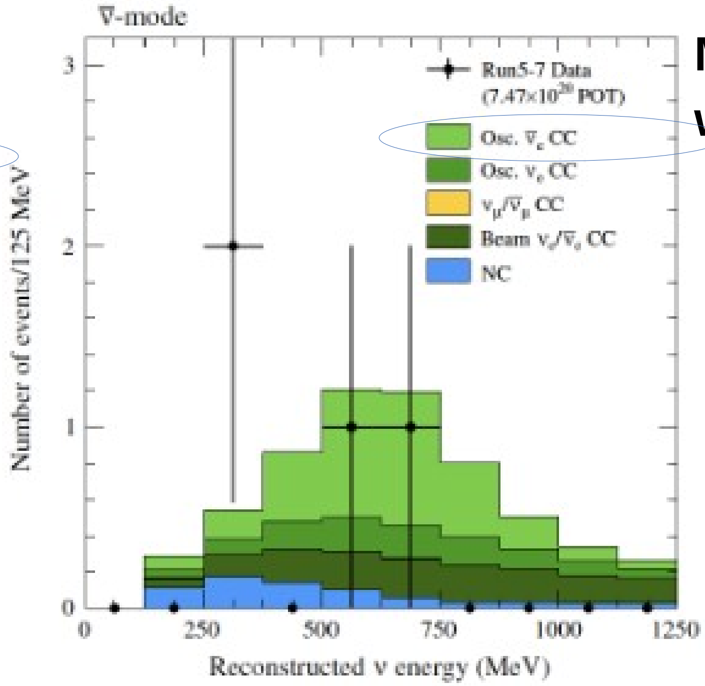


$$E_\nu^{\rm rec} = \frac{m_{\Delta^{++}}^2 - m_p^2 - m_l^2 + 2m_p E_l}{2(m_p - E_l + p_l \cos\theta_l)}$$

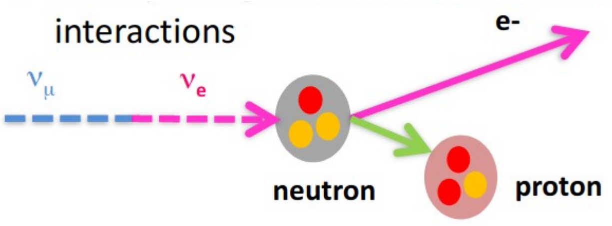
Reconstruct neutrino energy from lepton kinematics only, assuming Δ++ resonance (mostly true in FHC at T2K energy)

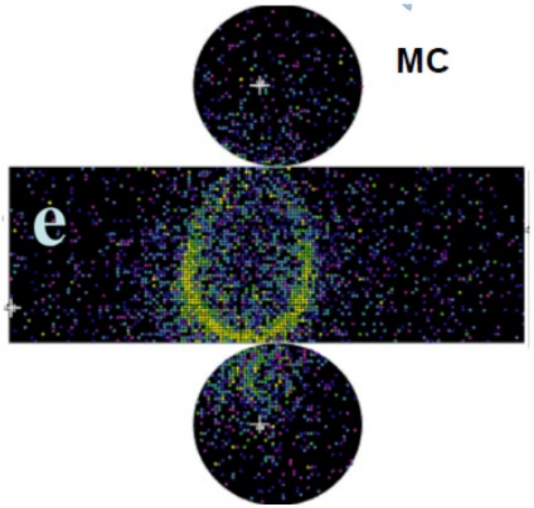
SuperKamiokande samples



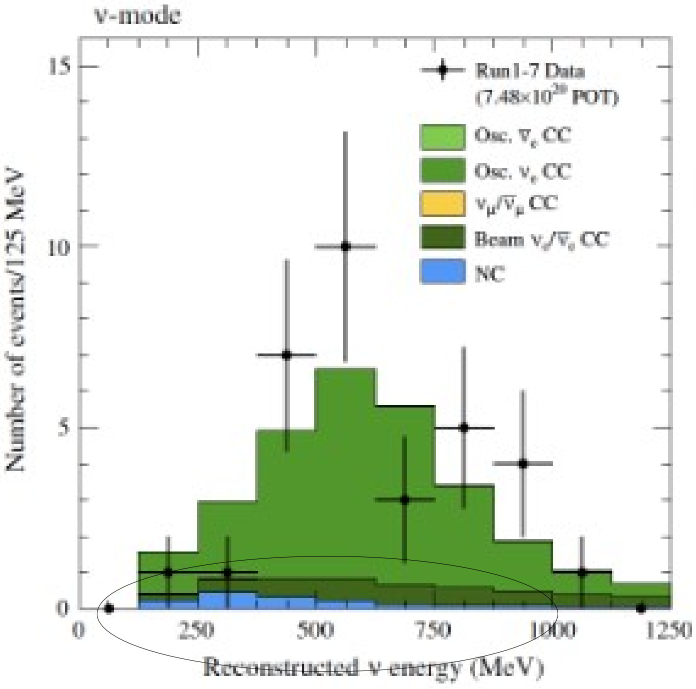


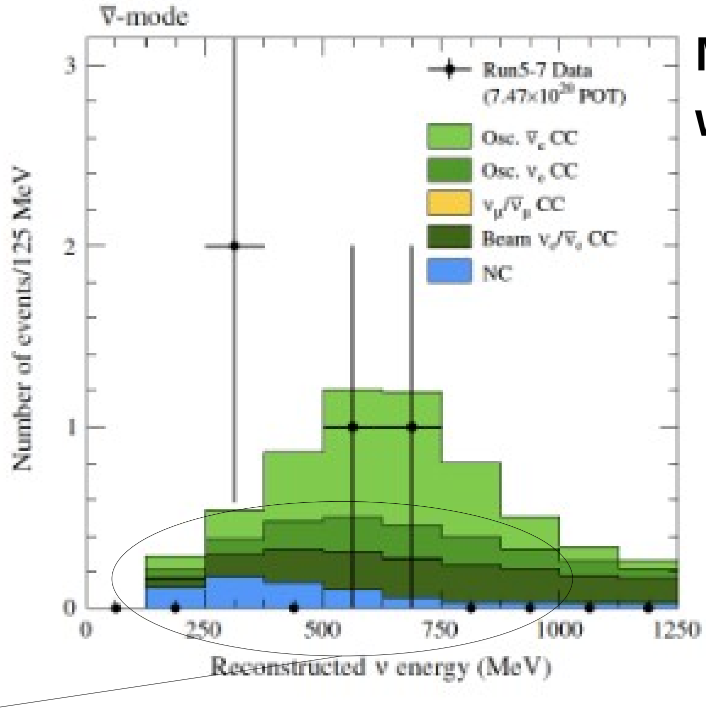
Main signal: ν_e ($\bar{\nu}_e$) appearance with single e-like ring



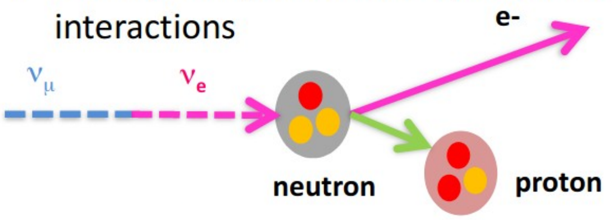


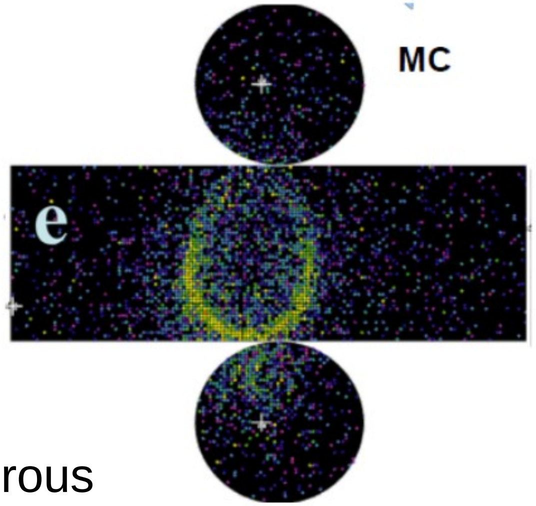
SuperKamiokande samples





Main signal: ν_e ($\overline{\nu}_e$) appearance with single e-like ring





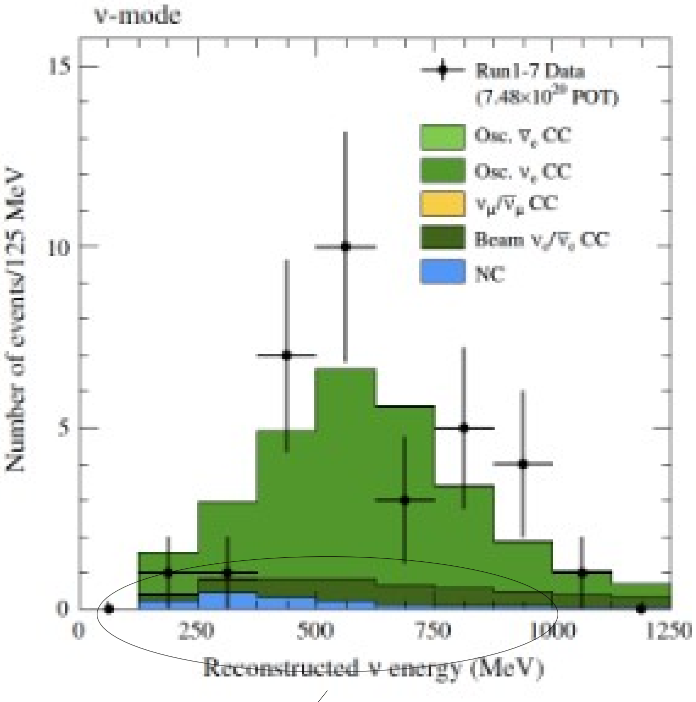
Backgrounds

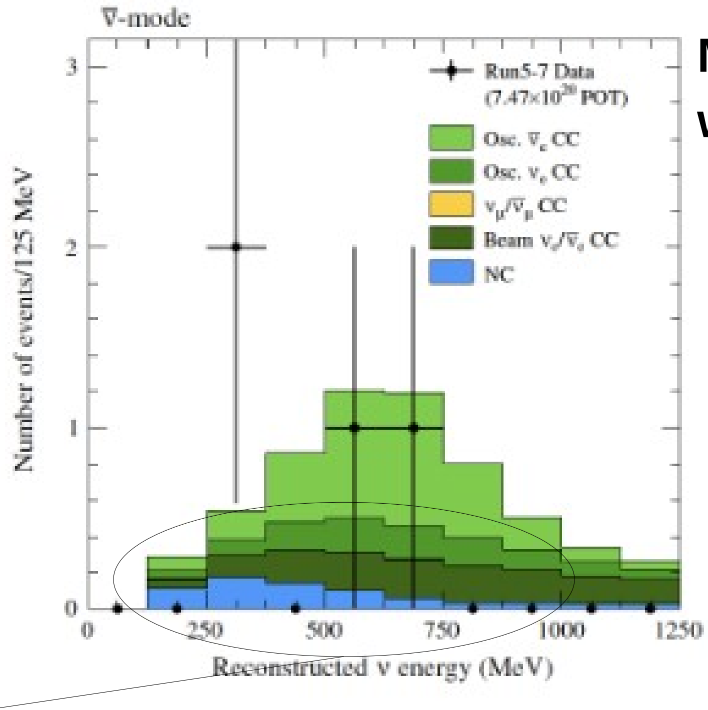
- Intrinsic ν_e from m,K decays ($\nu_e \rightarrow \nu_e$)

Especially $\boldsymbol{\nu_e}$ **wrong sign background** in $\overline{\nu}_e$ RHC sample dangerous for δ_{CP}: need to control $\nu_e/\overline{\nu}_e$ flux and xsec with near detector

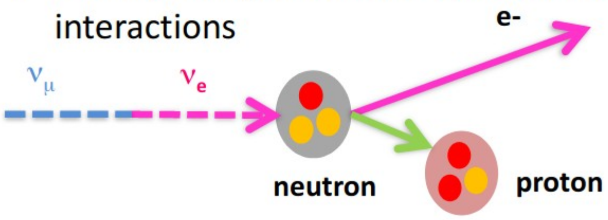
$$\sin\delta \sim \frac{P(\nu_\mu \to \nu_e) - P(\overline{\nu}_\mu \to \overline{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\overline{\nu}_\mu \to \overline{\nu}_e)}$$

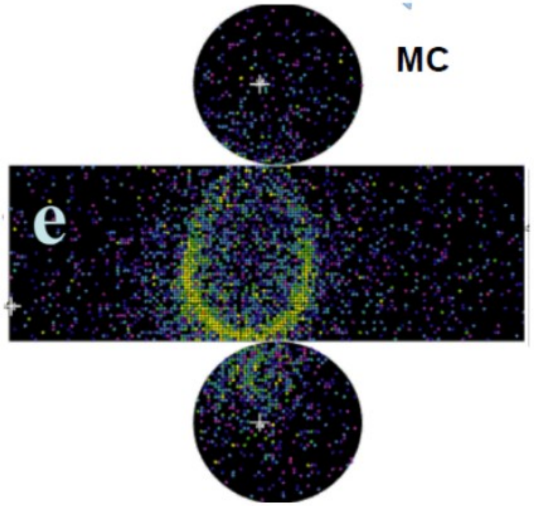
SuperKamiokande samples





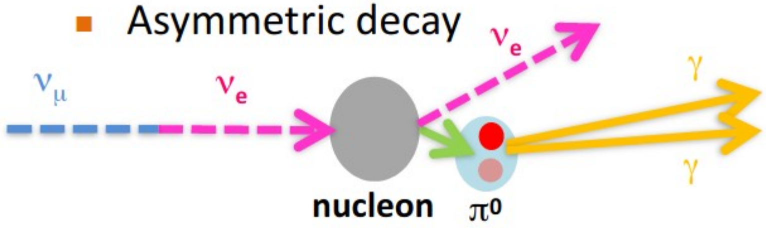
Main signal: ν_e ($\bar{\nu}_e$) appearance with single e-like ring

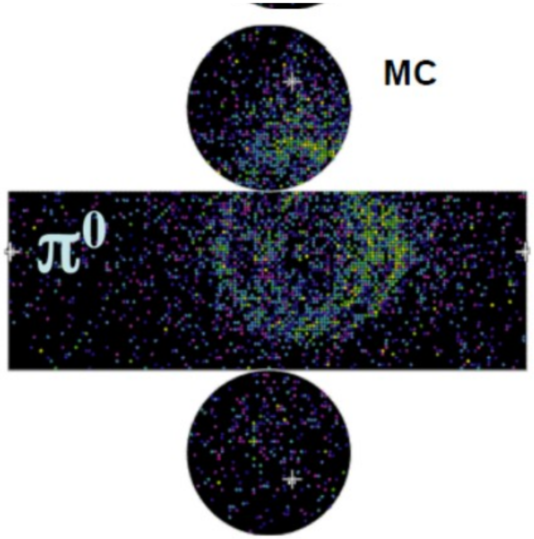




Backgrounds

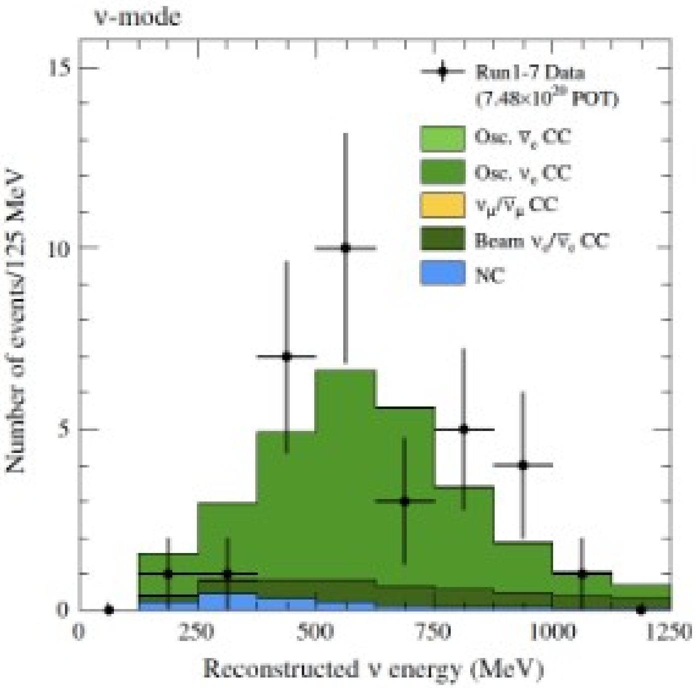
- Intrinsic ν_e from m,K decays ($\nu_e \rightarrow \nu_e$)
- NC single π^0 production
  - Overlap of gammas
  - Asymmetric decay

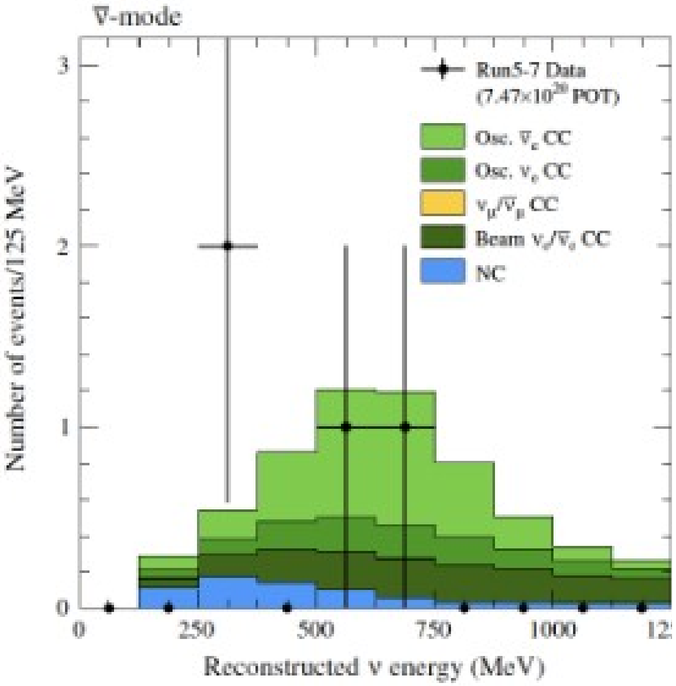


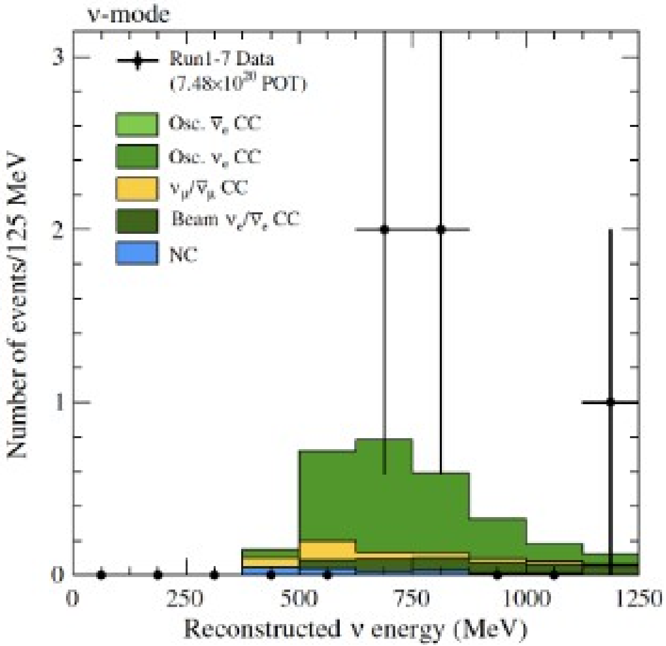


Roger Wendell

SuperKamiokande samples

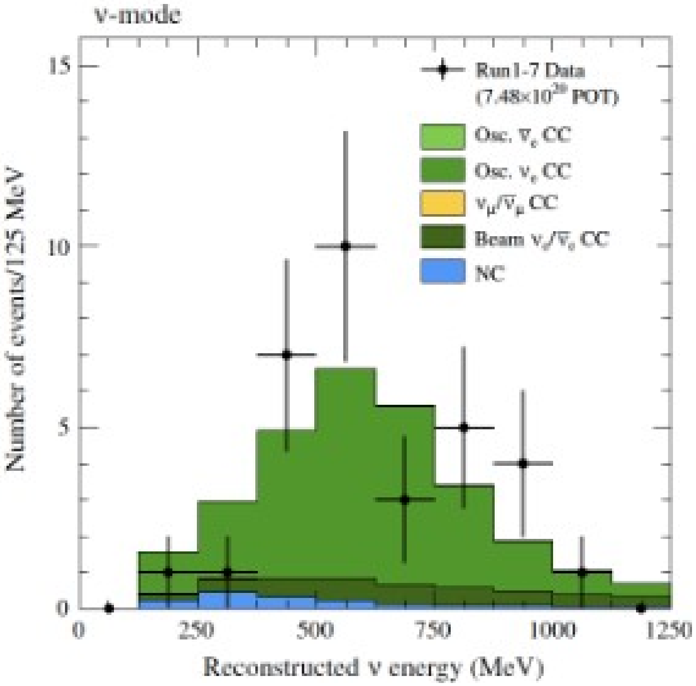


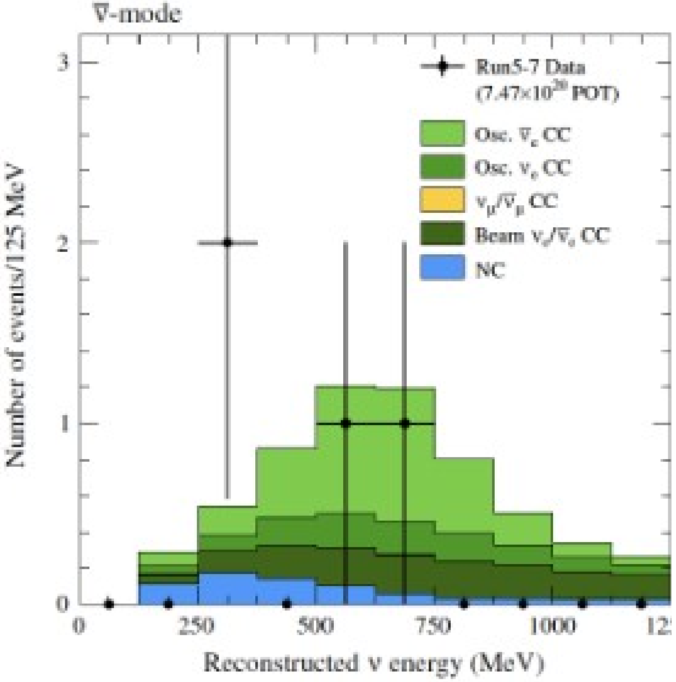


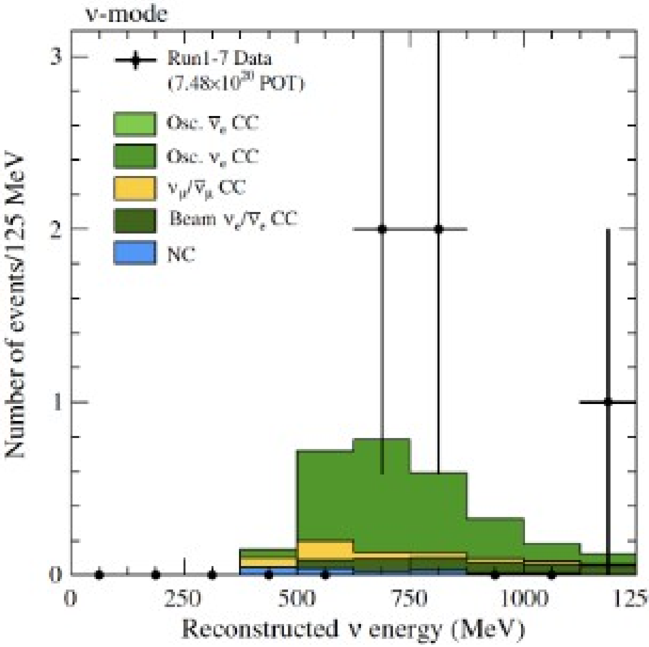


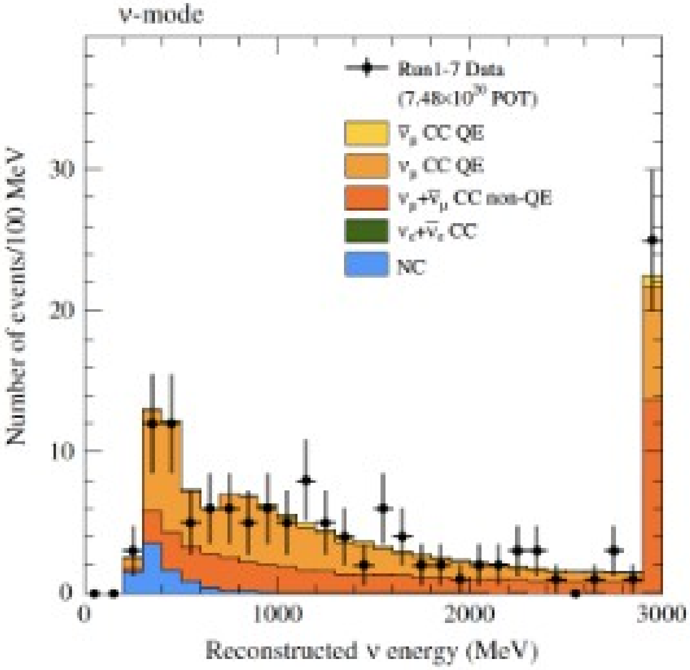
ν_e single ring + 1 Michel electron delayed

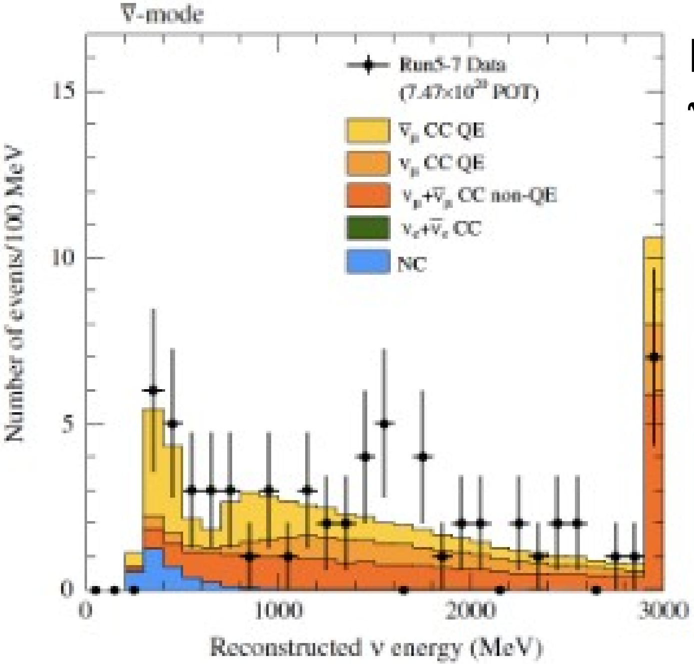
SuperKamiokande samples









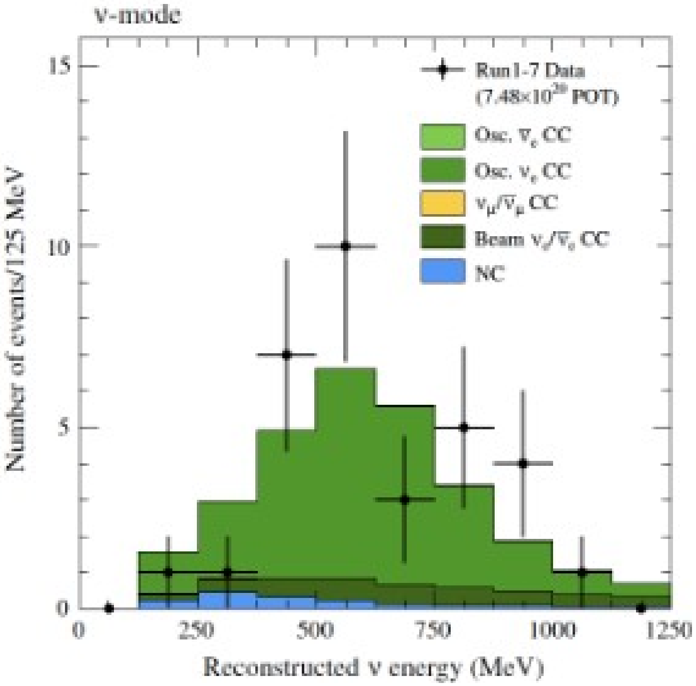


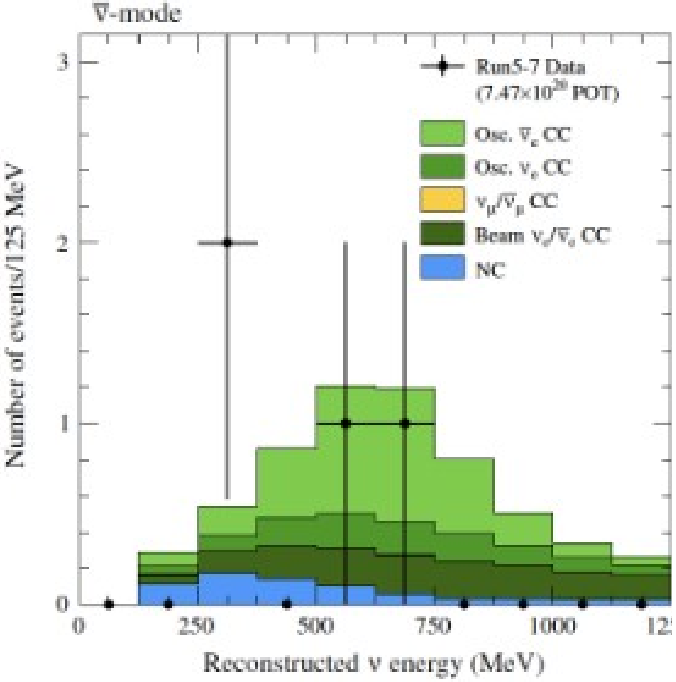
Main disappearance channel: ν_μ with 1 mu-like ring

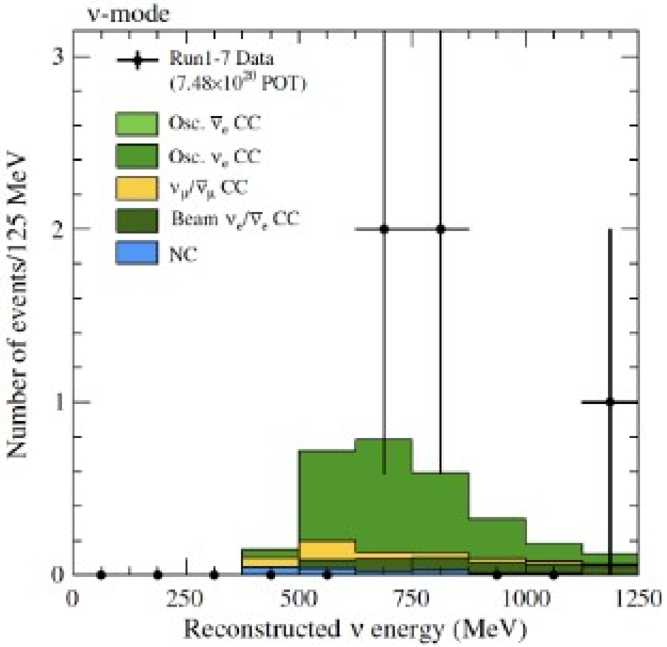
CC-nonQE does disappear but
- higher energy
→ not at oscillation maximum
- but much less precise E_ν^{rec}

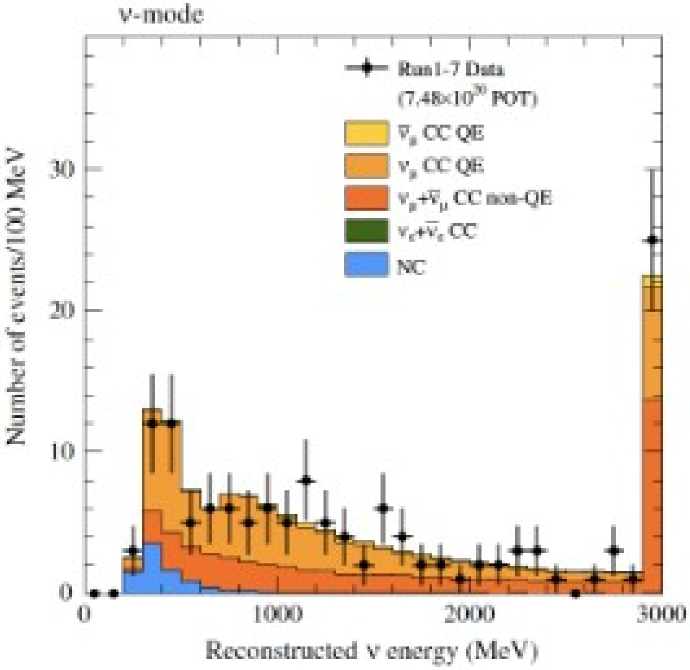
Important to have a dedicated CC-1π sample at far detector for x-check ‘feed-down’

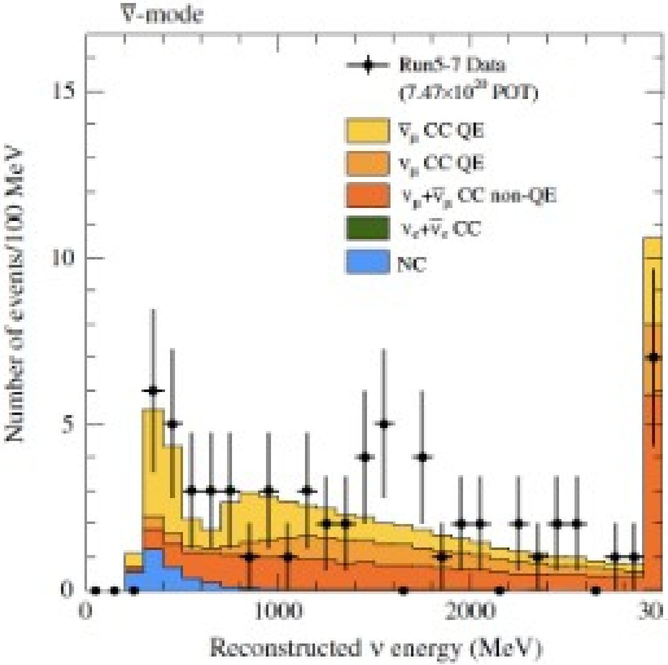
SuperKamiokande samples



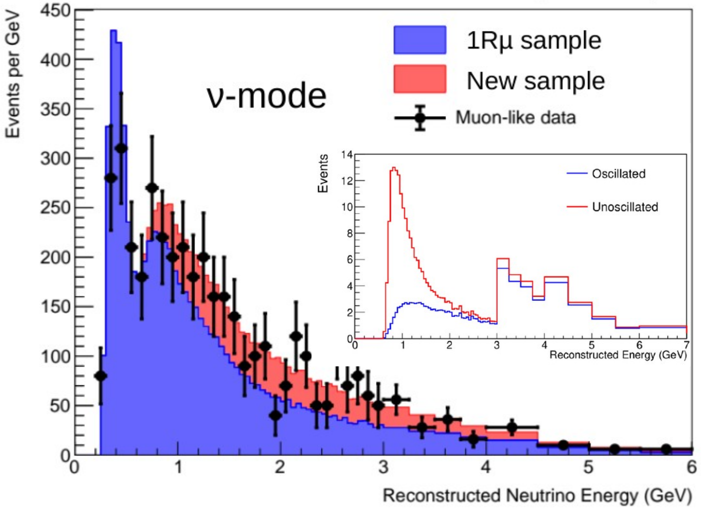




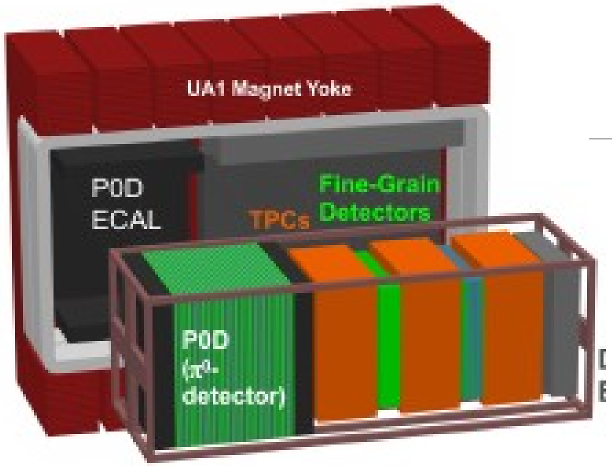


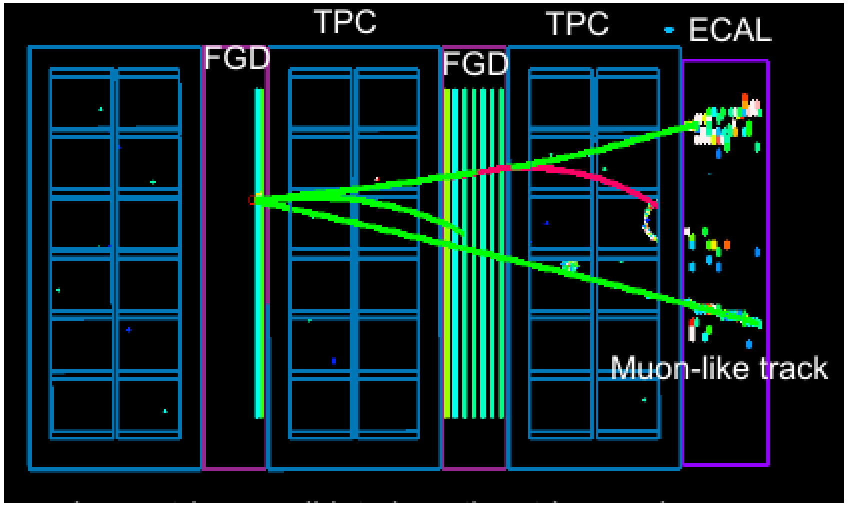


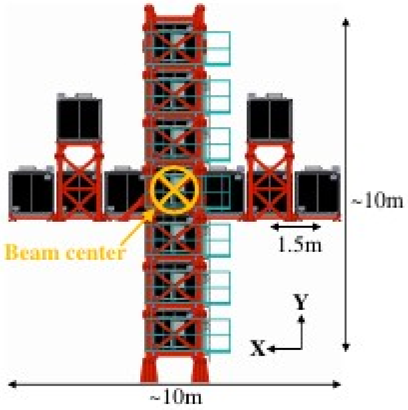
New multiring sample (2022)

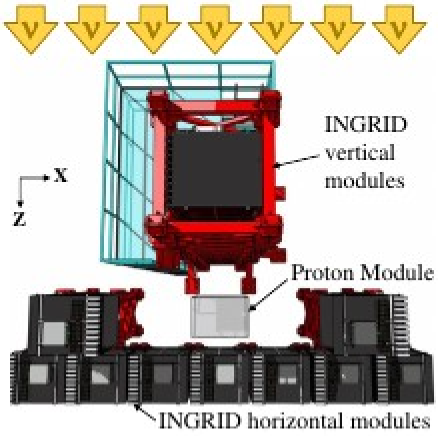


T2K near detectors









ND280 : off-axis (2.5º)

Measure flux and xsec for oscillation analysis

Full tracking and particle reconstruction (**magnetized!**): measure precisely neutrino and antineutrino rate before oscillation

- fully magnetized (0.2 T)
- FGD scintillators : x-y bars (C and passive water)
- TPC → **good tracking efficiency**, **resolution** (10% at p_T~1GeV) **and particle identification**
- P0D sampling scintillator for pi0 detection (water in/out)

INGRID : on-axis

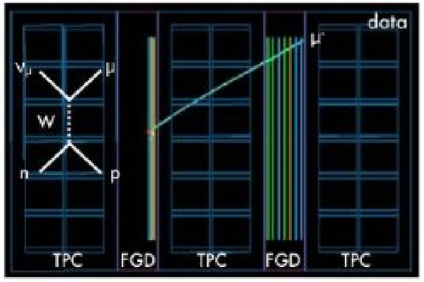
Beam stability monitoring: position and direction (off-axis: Eν depends on angle)

- iron plates alternated with CH scintillator (+ proton module : fully active scintillator)
- **coarser granularity, not magnetized but larger mass :** 2.5×10^{30} nucleons (Fe) + 1.8×10^{29} nucleons (CH)

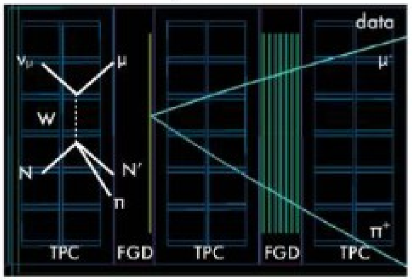
T2K ND selection

- Require one muon + separate sample based on proton, pion and γ multiplicity **(full exclusive final state reconstruction)**
- Until now, similar to SK: only lepton kinematics used for neutrino energy assessment

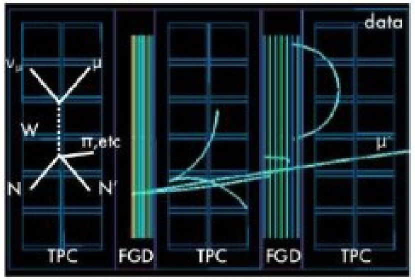
ν_μ CC0π



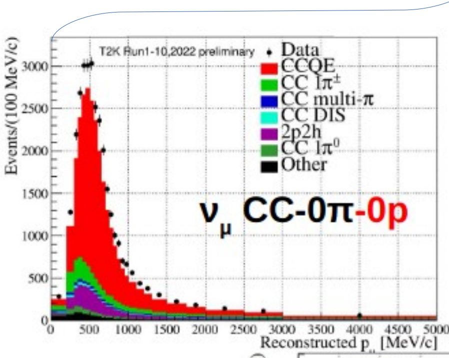
ν_μ CC1π^+

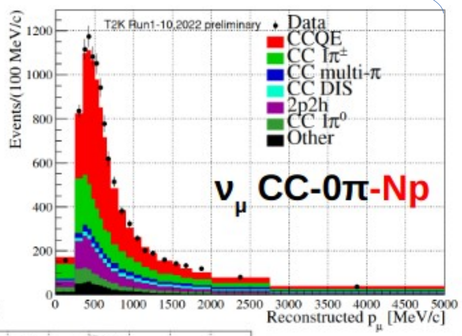


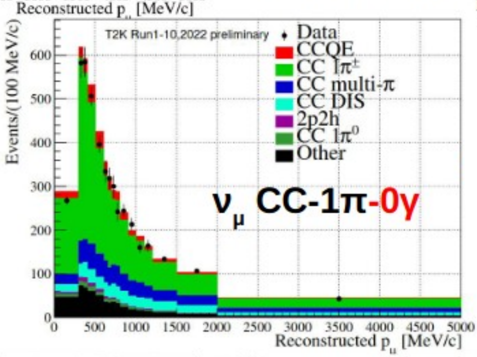
ν_μ CC other



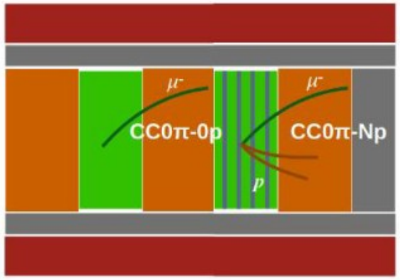
Main QE channel

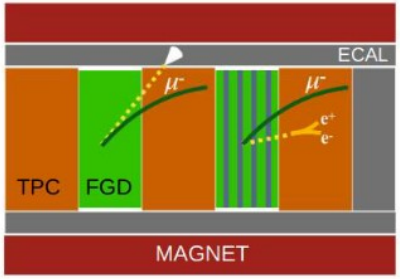


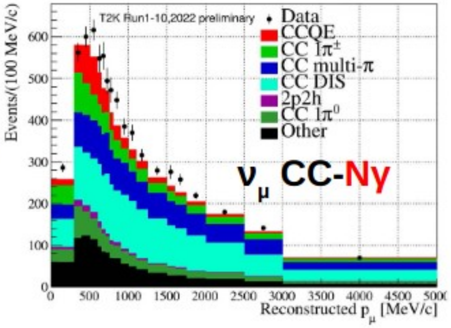


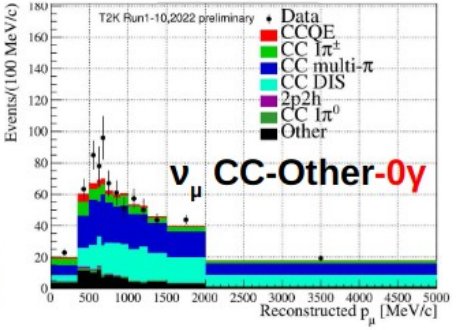


Proton and γ tagging: new in 2022









T2K ND selection

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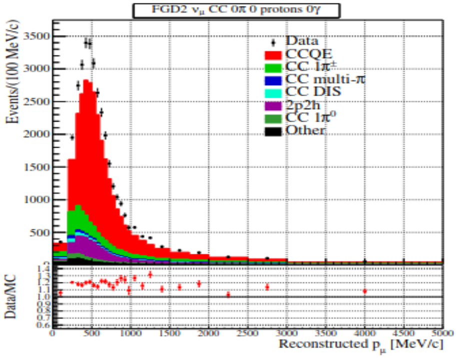
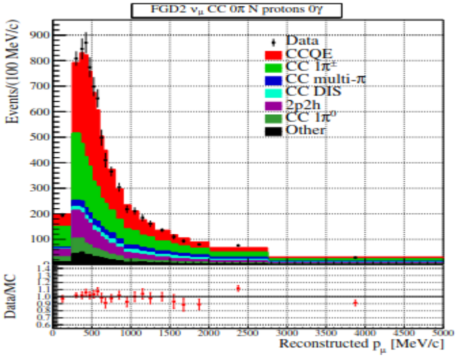
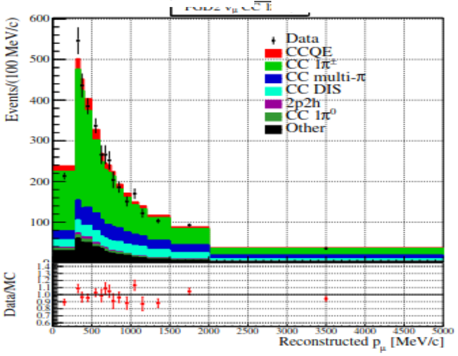
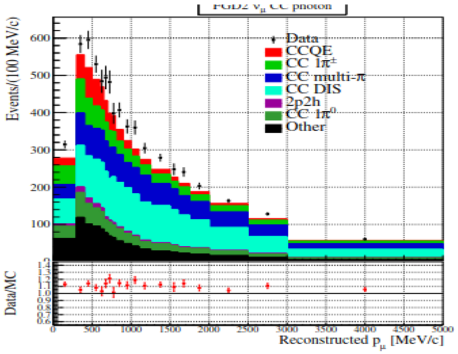
- Two sets of samples for **FGD1 (CH only) and FGD2 (CH+water)**

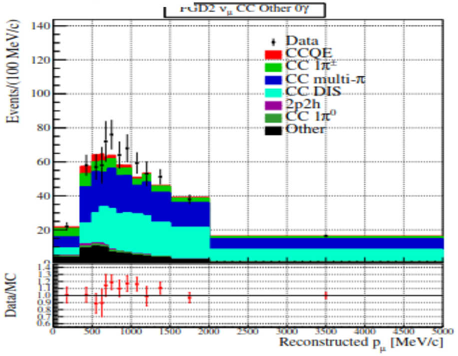


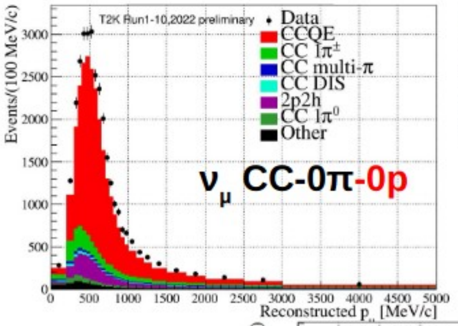


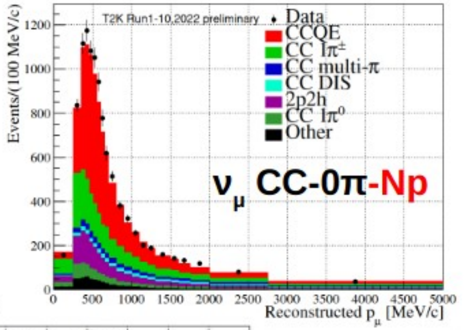


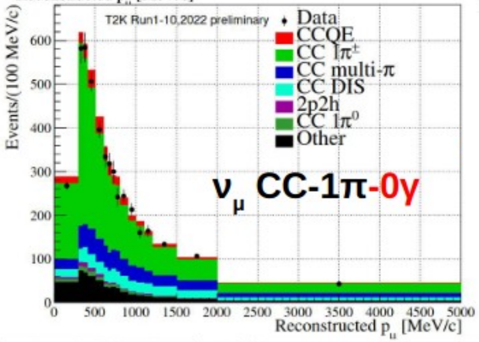
FGD2 **FGD1**

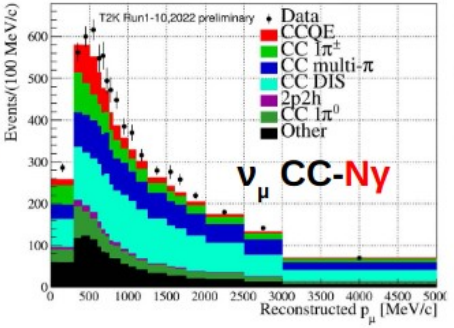


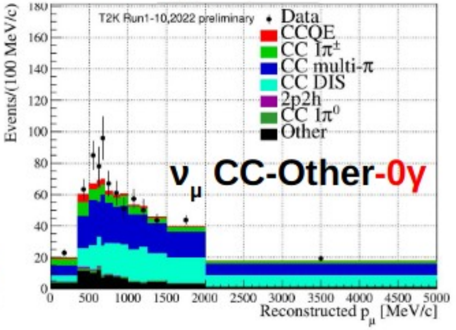












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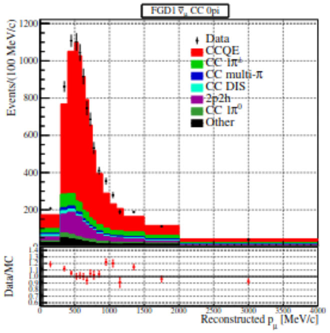
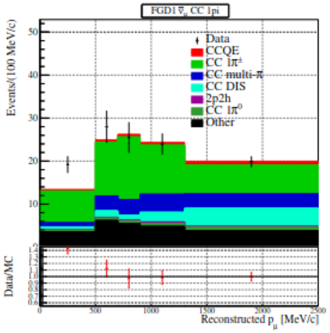
FGD1 RHC

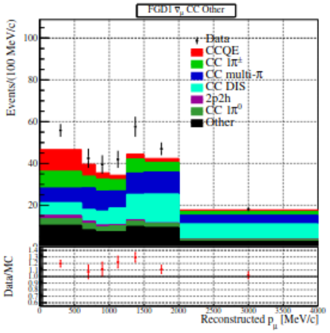
μ+ CC0π



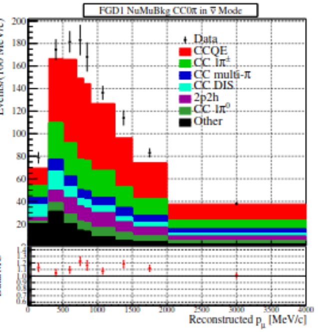
μ+ CC1π



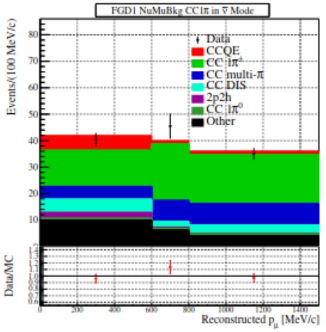
μ+ CC-Other



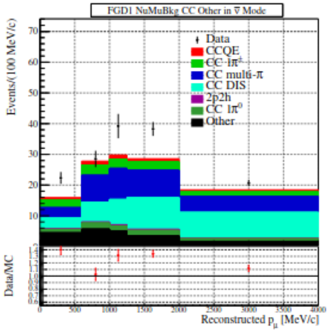
μ- CC0π



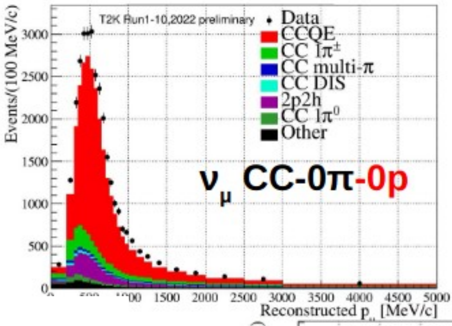
μ- CC1π

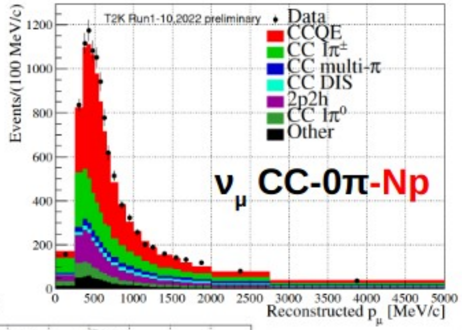


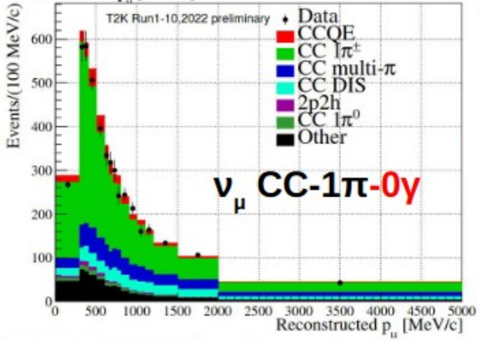
μ- CC-Other

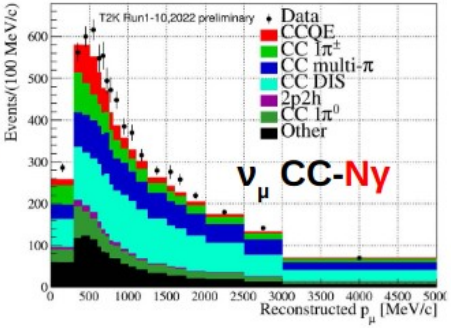


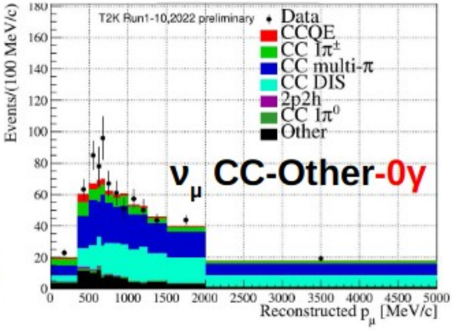
FGD1 FHC











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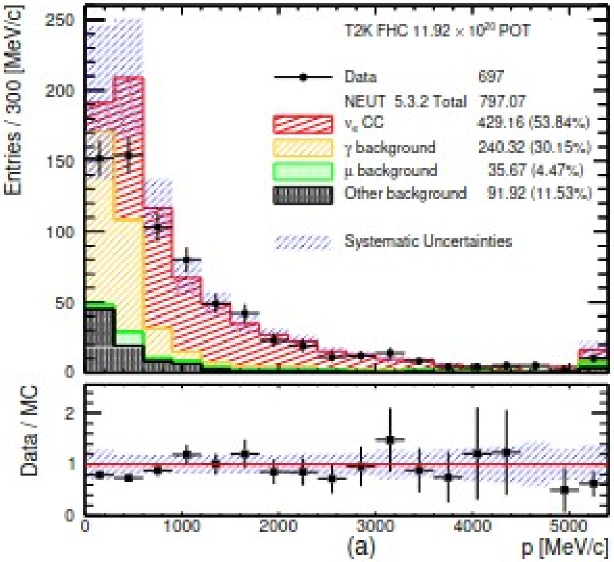
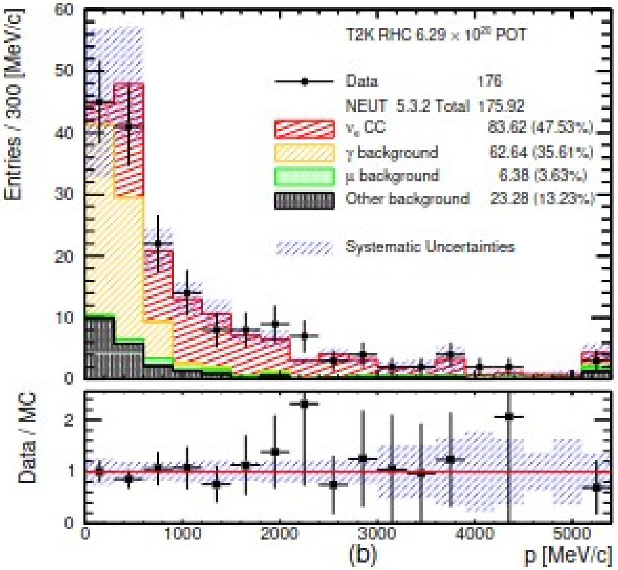
- **ν_e at ND: too low statistics (~8% precision)** due to the very good ν_μ/ν_e purity of the beam. What really matters for δ_{CP} in $\nu_e/\bar{\nu}_e$ flux and xsec (from nuclear theory ~<2%)
Dedicated ν_e cross-section measurement shows agreement with model but with large stat and systematics uncertainties.

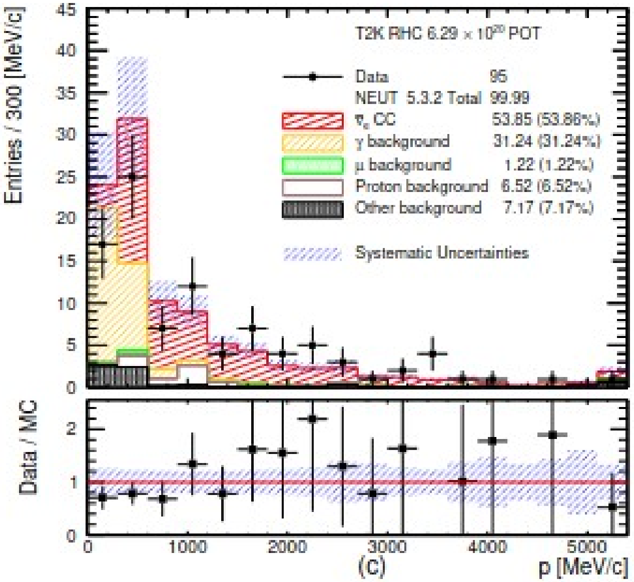
FHC: ν_e



RHC: $\bar{\nu}_e$



RHC: ν_e



T2K ND fit

- **ND measurement**

$$R_{ND}^{\nu'} = \int \boxed{\Phi^{\nu}(E_{\nu}) \frac{d\sigma^{\nu'}}{dE_{\nu}}} dE_{\nu}$$

$$R_{FD}^{\nu'} = \int \boxed{\Phi^{\nu}(E_{\nu})} \boxed{P_{osc}^{\nu\rightarrow\nu'}(E_{\nu})} \boxed{\frac{d\sigma^{\nu'}}{dE_{\nu}}} dE_{\nu}$$

~same flux at ND and FD

what we want to measure:
oscillation probability

- cross-section must be extrapolated from ND to FD (different neutrino energy distribution)
- flux and xsec must be disentangled

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- **Fit to ND observed distributions:**

$$R_{ND}^{\nu'}(E_{\nu}) = \Phi^{\nu}(E_{\nu}) \frac{d\sigma^{\nu'}}{dE_{\nu}} = F(\boxed{p_{\mu}, \cos\theta_{\mu}}; \alpha_{ND}, \alpha_{model})$$

nuisances = parametrization of (detector systematics), flux and nuclear physics uncertainties

T2K ND fit

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what we want to measure:
oscillation probability

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nuisances = parametrization of (detector systematics), flux and nuclear physics uncertainties

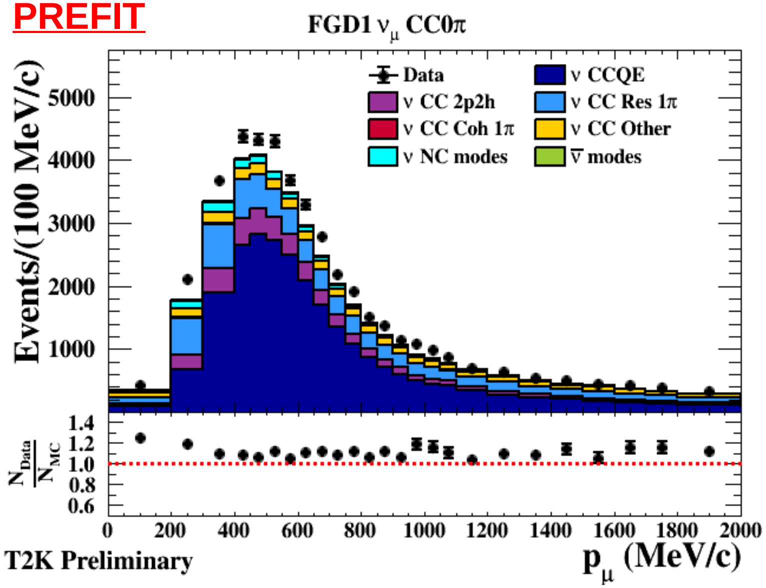
- **Tuned model** used for flux and cross-section disentagling and their extrapolation to FD
+correct reconstruction of energy at the far detector

$$E_\nu = R(p_\mu, \cos\theta_\mu; \alpha_{FD}, \alpha_{model})$$

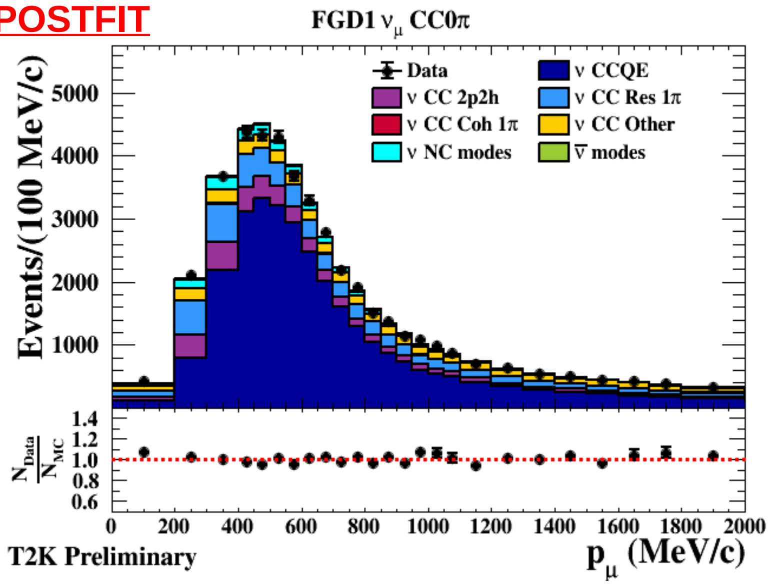
T2K ND: data fit

Simultaneous fit to all ND separate samples (only example of main channel shown)

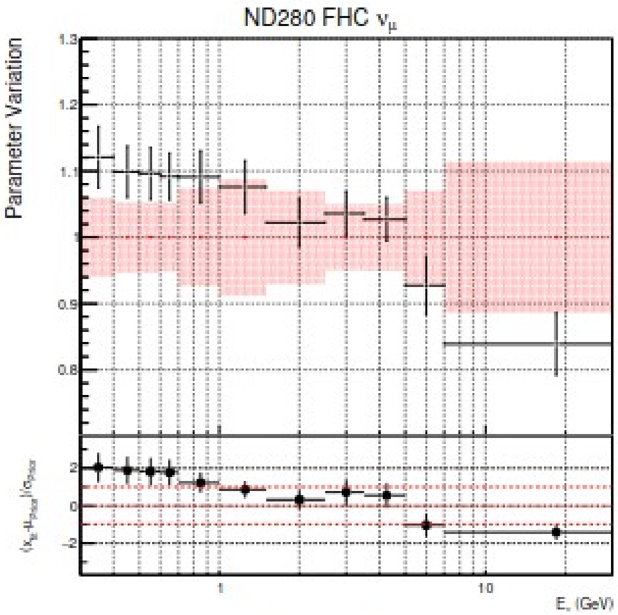
PREFIT

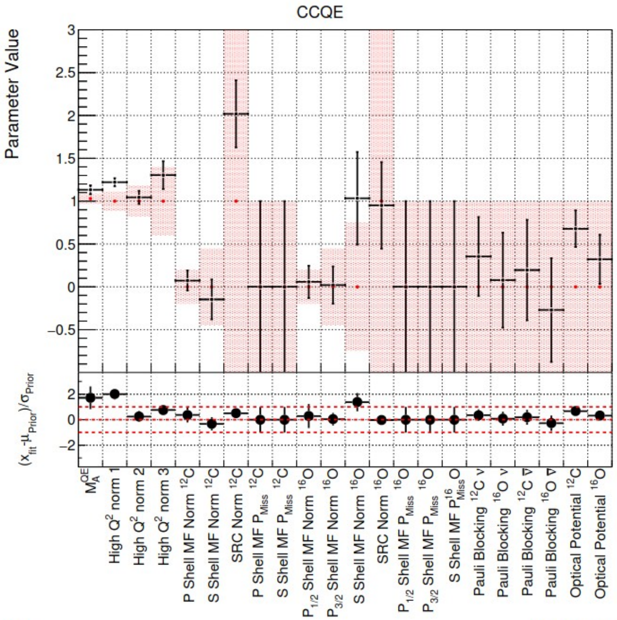


POSTFIT



Tuning of flux and xsec model





Actually hundreds of parameters (only main flux and xsec channel shown)

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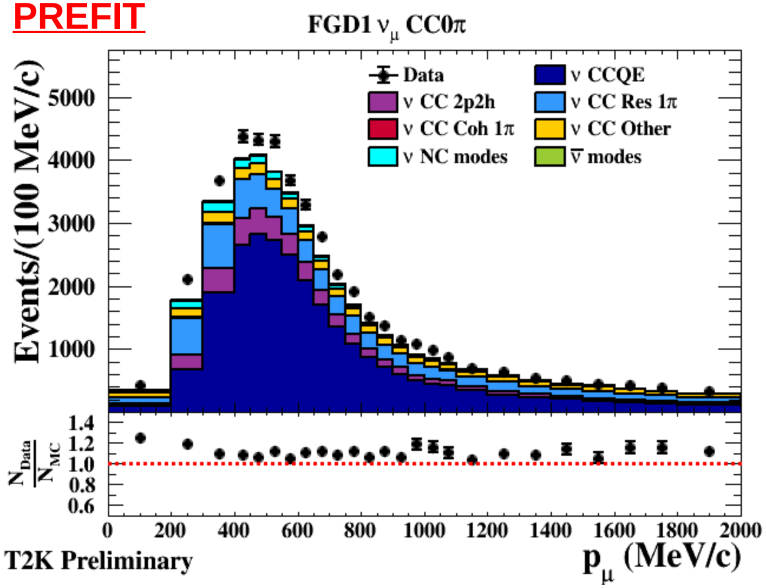

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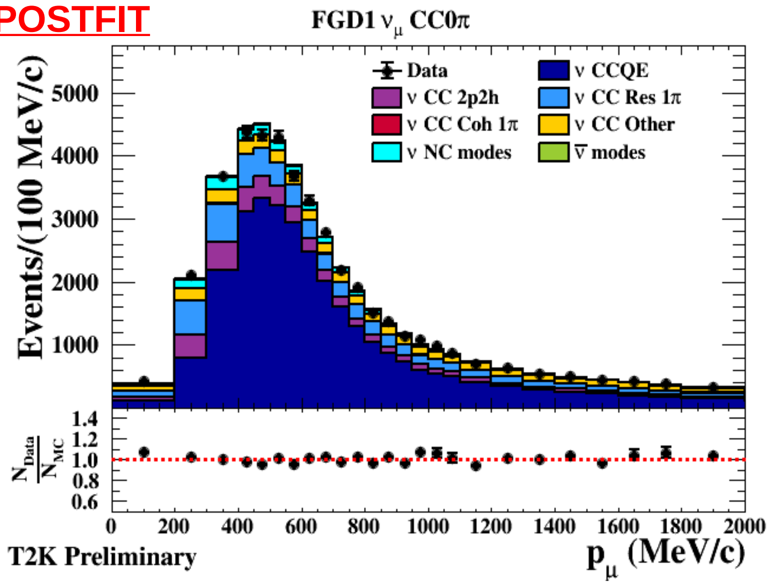

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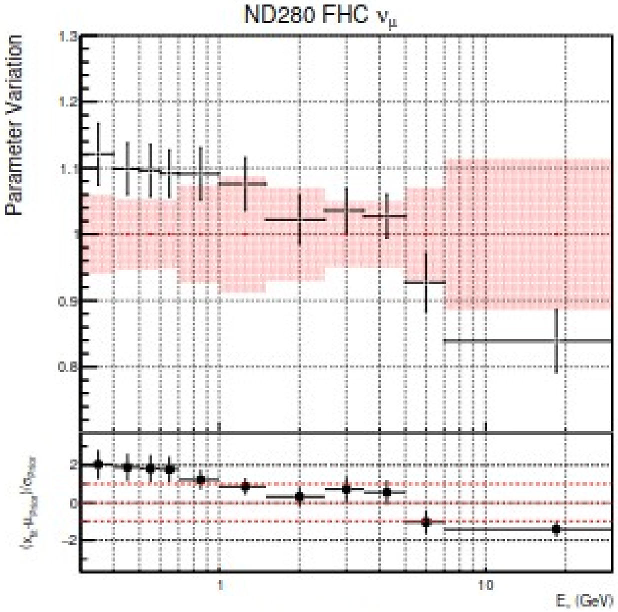

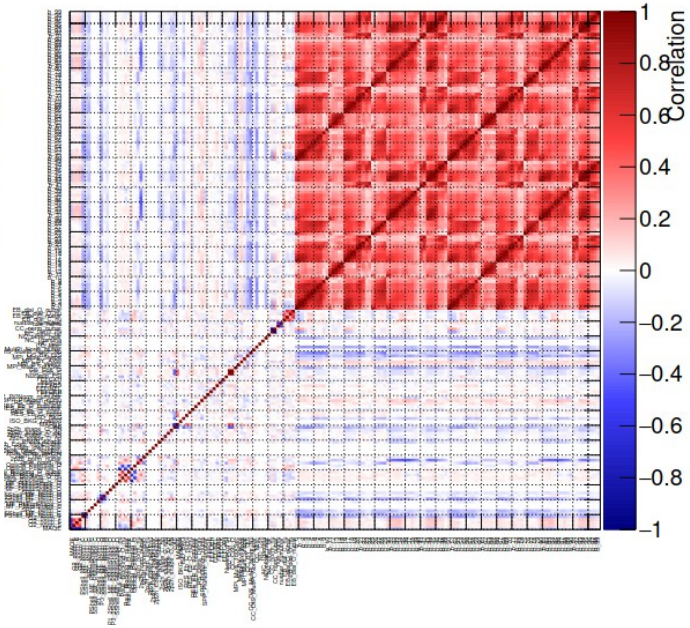

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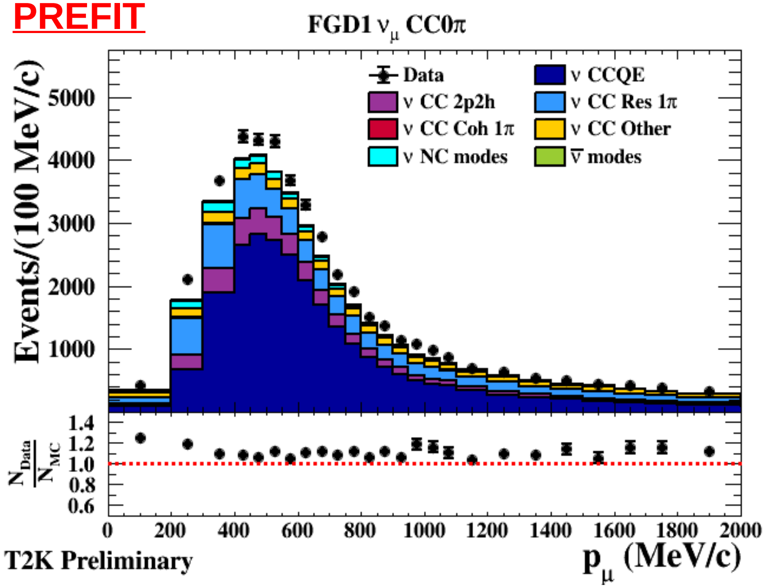
All parameters got correlated from the fit

T2K ND: data fit

Simultaneous fit to all ND separate samples (only example of main channel shown)

PREFIT



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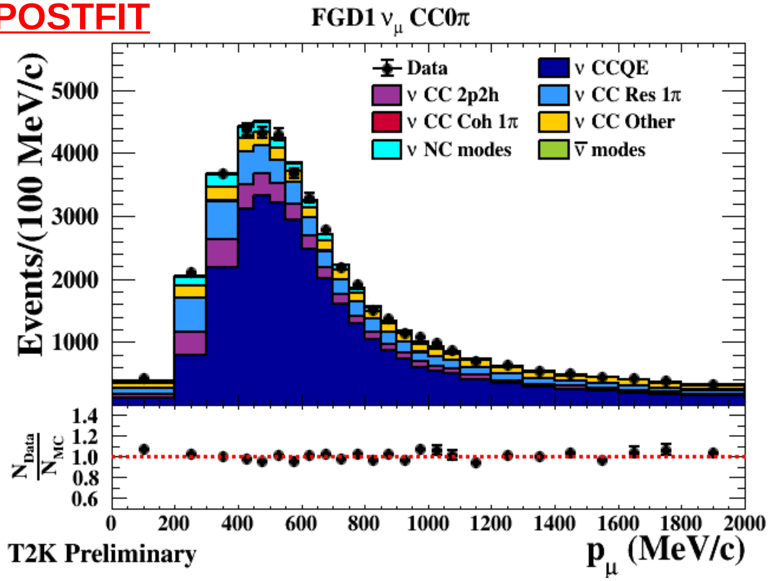
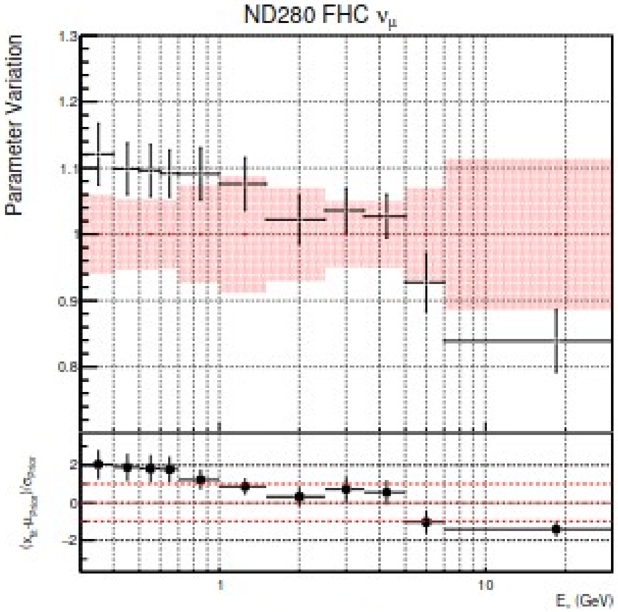
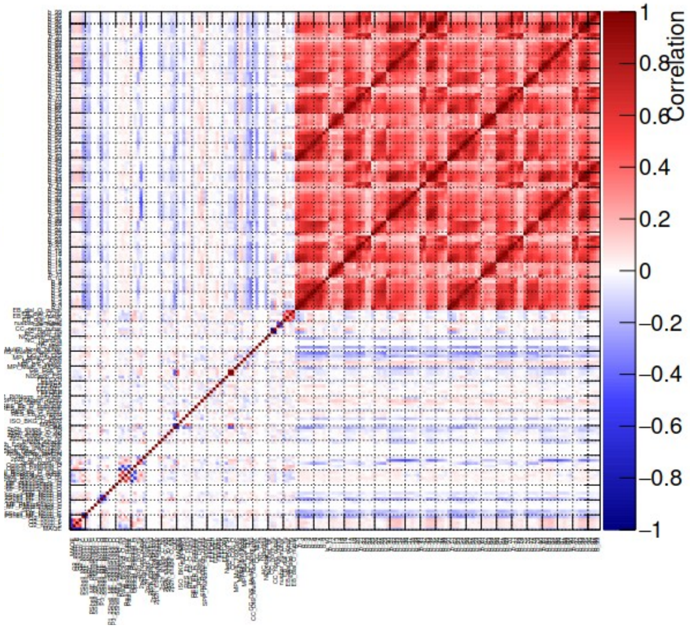


Tuning of flux and xsec model





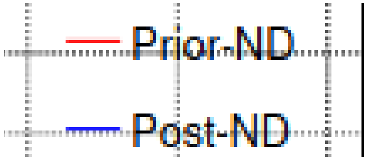
Actually hundreds of parameters (only main flux and xsec channel shown)

All parameters got correlated from the fit

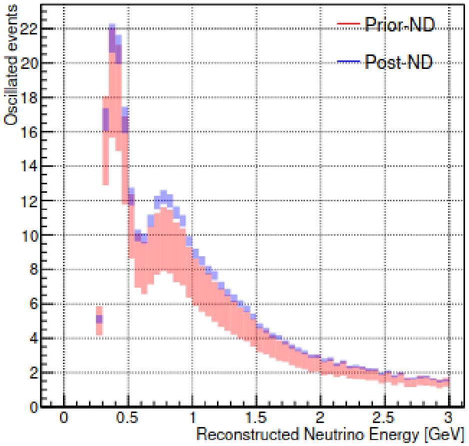
Tuned model used to estimate flux and xsec at far detector and tune Eν reconstruction at far detector

SuperKamiokande tuned distribution

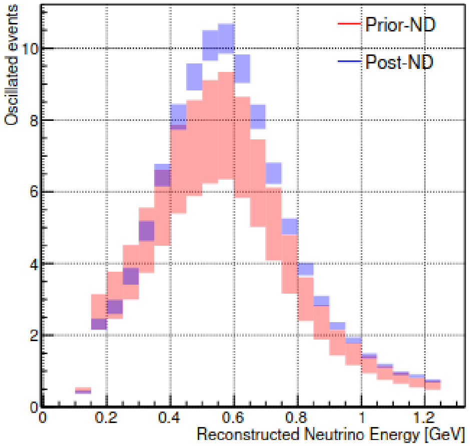
(Only main samples shown)



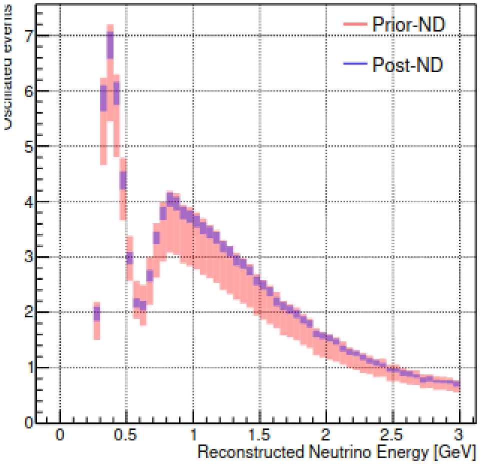
FHC 1ring μ



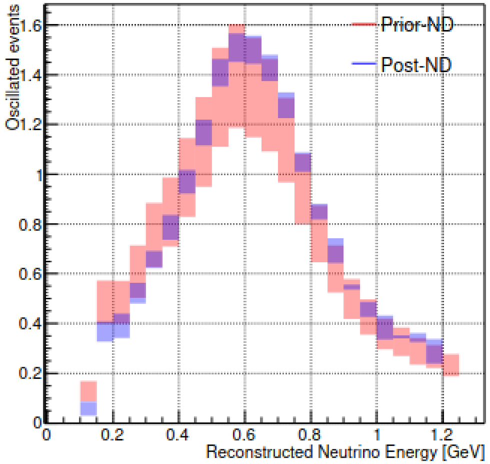
FHC 1ring e



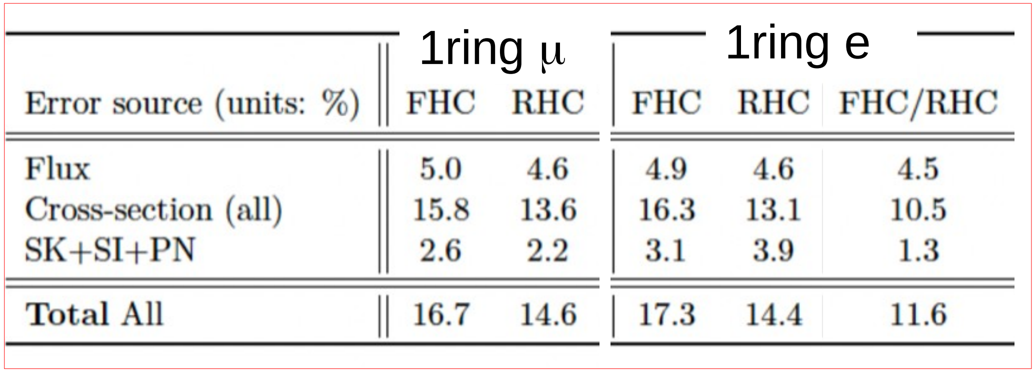
RHC 1ring μ



RHC 1ring e

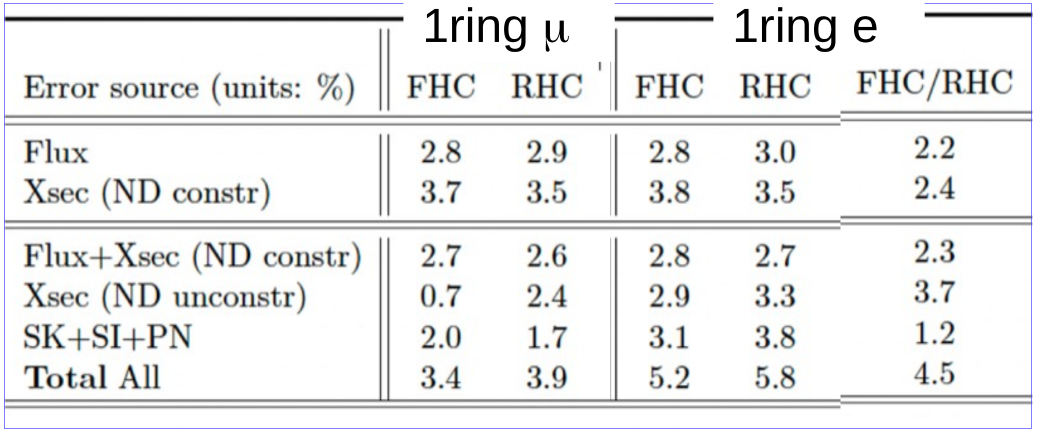


Before the ND fit



Error source (units: %)	1ring μ FHC	1ring μ RHC	1ring e FHC	1ring e RHC	1ring e FHC/RHC
Flux	5.0	4.6	4.9	4.6	4.5
Cross-section (all)	15.8	13.6	16.3	13.1	10.5
SK+SI+PN	2.6	2.2	3.1	3.9	1.3
Total All	16.7	14.6	17.3	14.4	11.6

After the ND fit

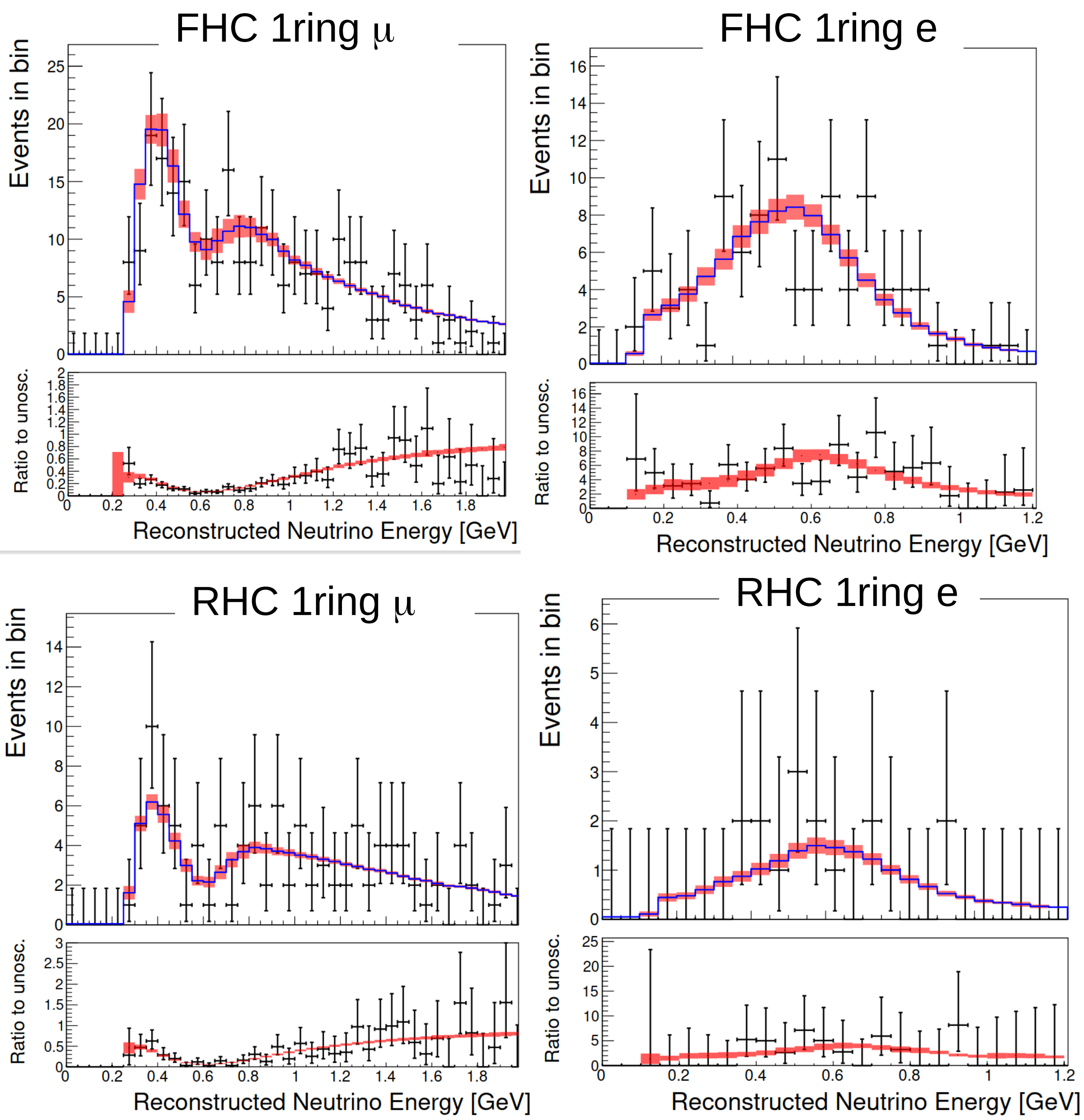


Error source (units: %)	1ring μ FHC	1ring μ RHC	1ring e FHC	1ring e RHC	FHC/RHC
Flux	2.8	2.9	2.8	3.0	2.2
Xsec (ND constr)	3.7	3.5	3.8	3.5	2.4
Flux+Xsec (ND constr)	2.7	2.6	2.8	2.7	2.3
Xsec (ND unconstr)	0.7	2.4	2.9	3.3	3.7
SK+SI+PN	2.0	1.7	3.1	3.8	1.2
Total All	3.4	3.9	5.2	5.8	4.5

SuperKamiokande fit

- The finally, SuperKamiokande expected distributions (ND-tuned) are fit to SK data to extract measurements of oscillation analysis parameters

(SuperKamiokande detector systematics are evaluated from atmospheric neutrinos and from dedicated control samples)



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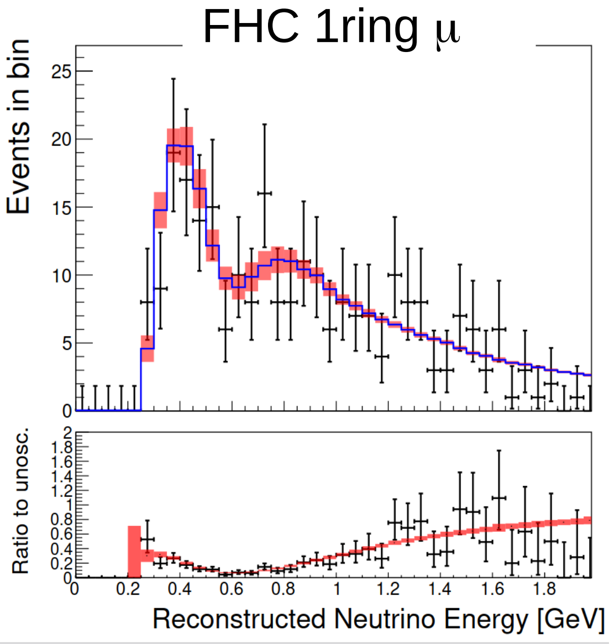
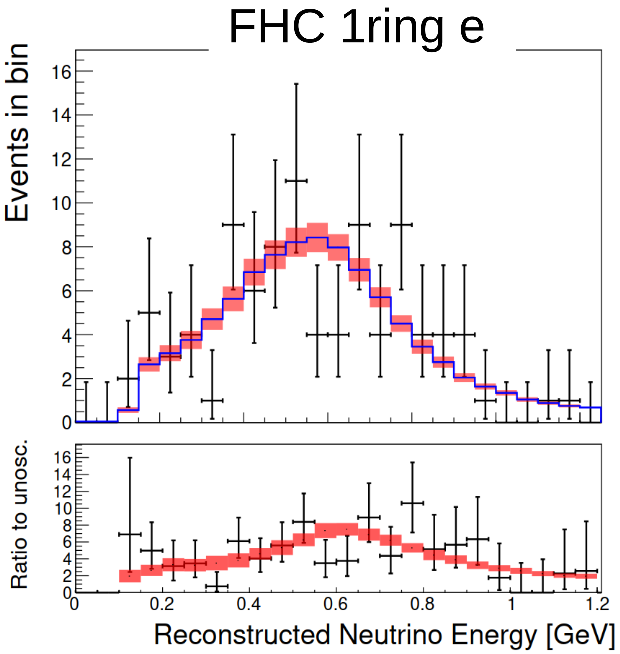
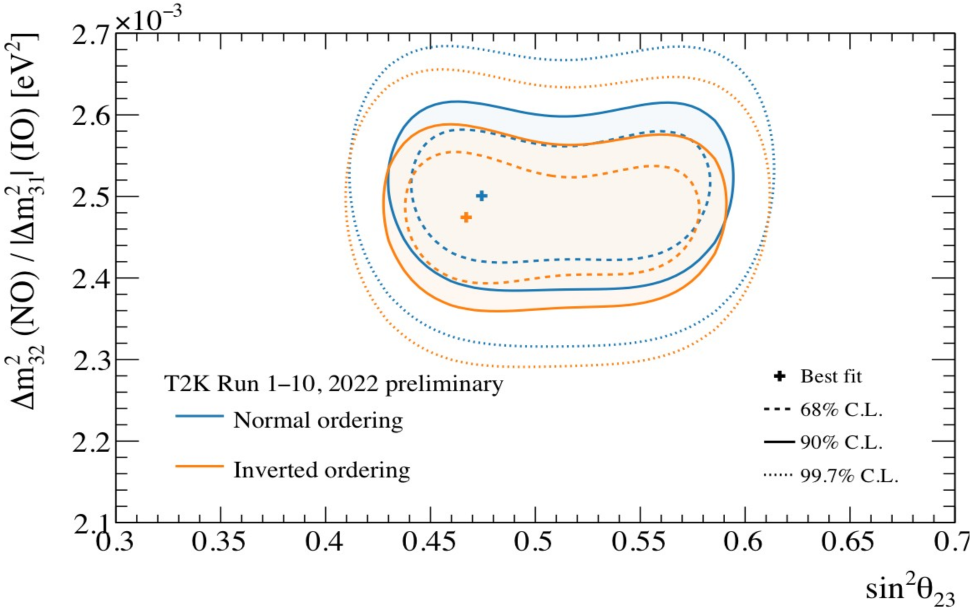
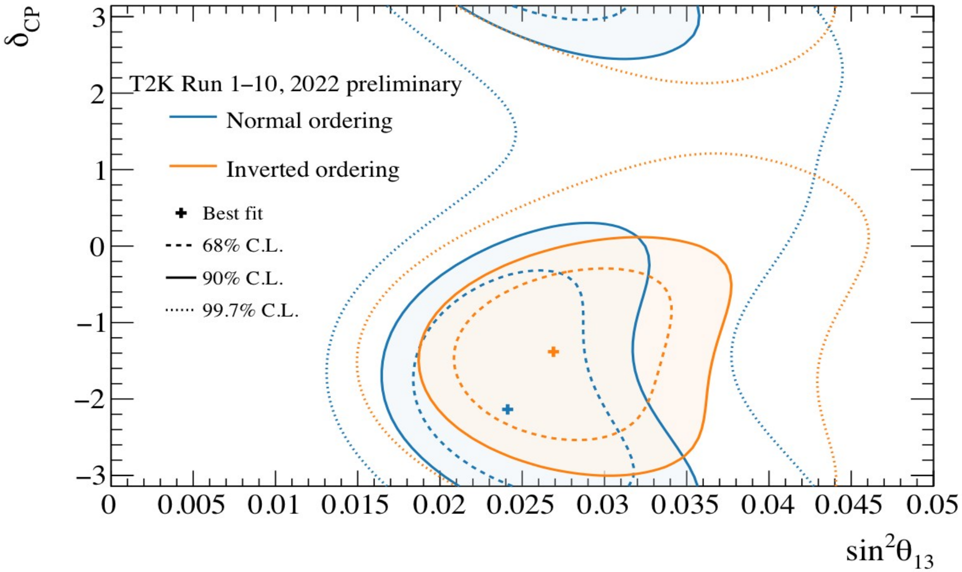




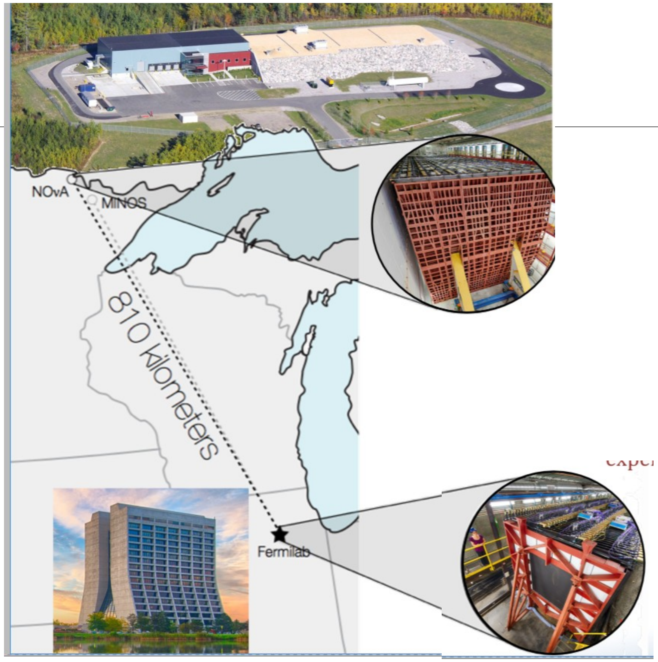
- Both a joint ND+FD fit and sequential ND → FD fit are done and compared.

Both frequentist and bayesian analysis are performed and compared





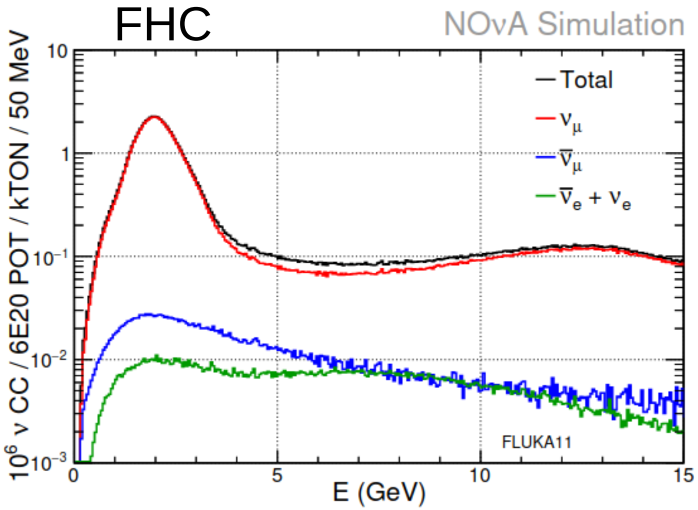
NOVA

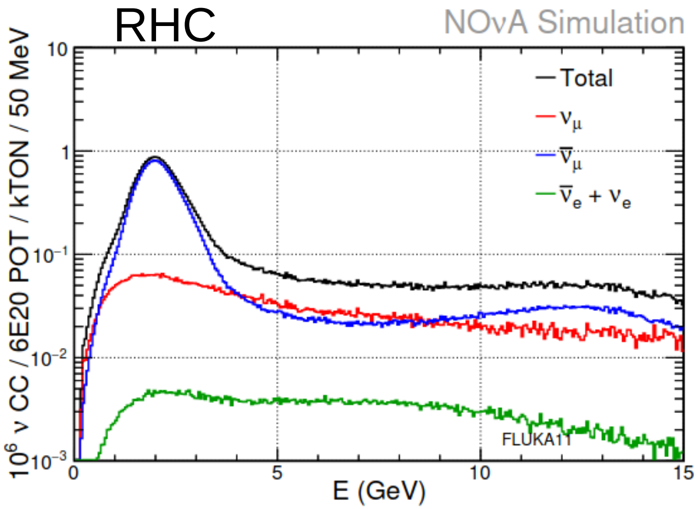


NUMI beam at FNAL

14mrad off-axis
(narrow-band spectrum)

Baseline: 810km





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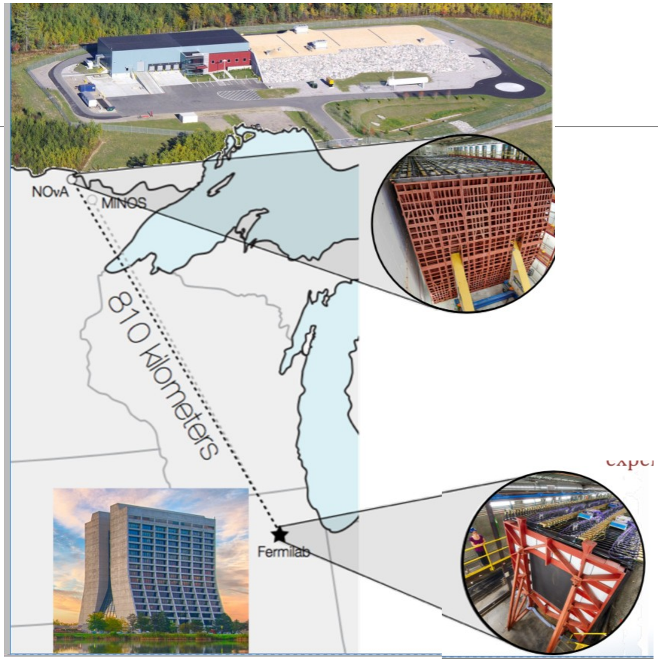

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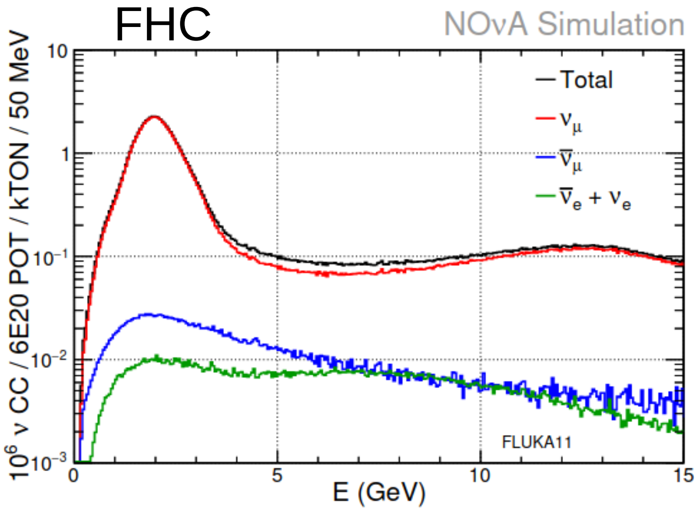
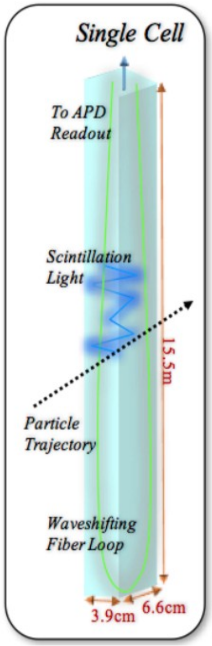
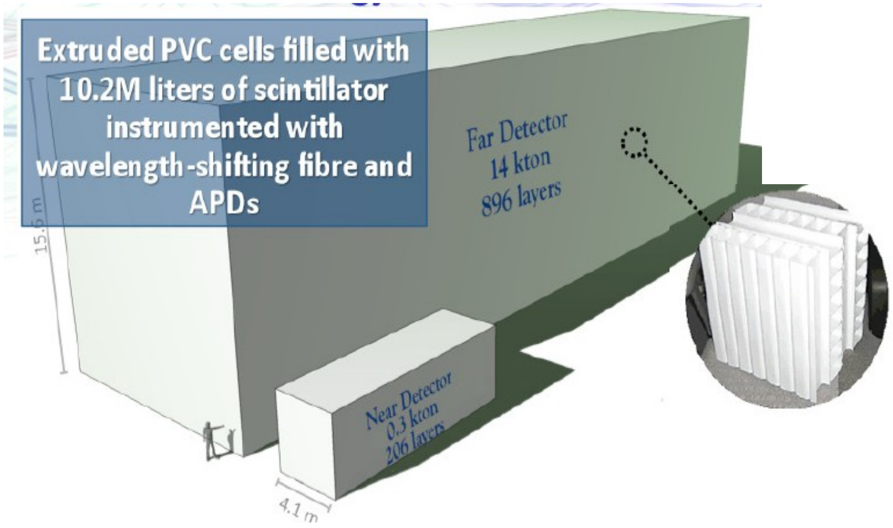


- **Same technology (liquid scintillator) for near and far detector**

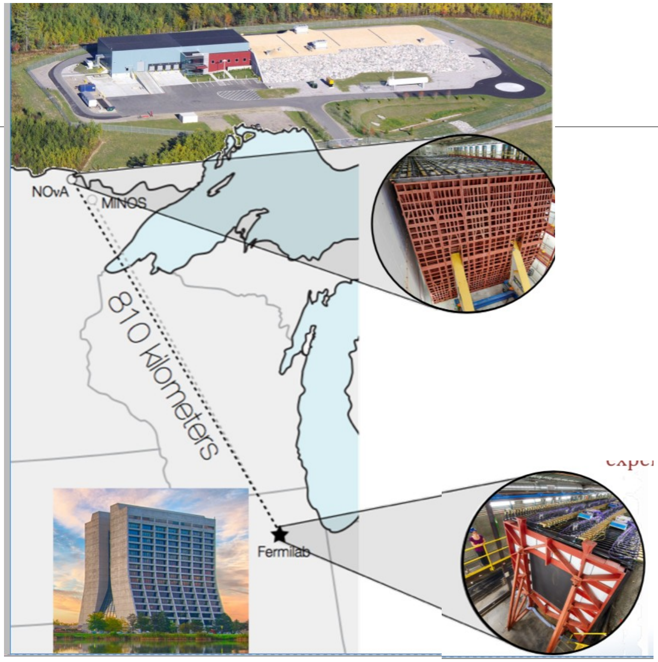
Near Detector: 300T underground
Far detector: 14 kT on the surface





Extruded PVC cells filled with 10.2M liters of scintillator instrumented with wavelength-shifting fibre and APDs

NOVA



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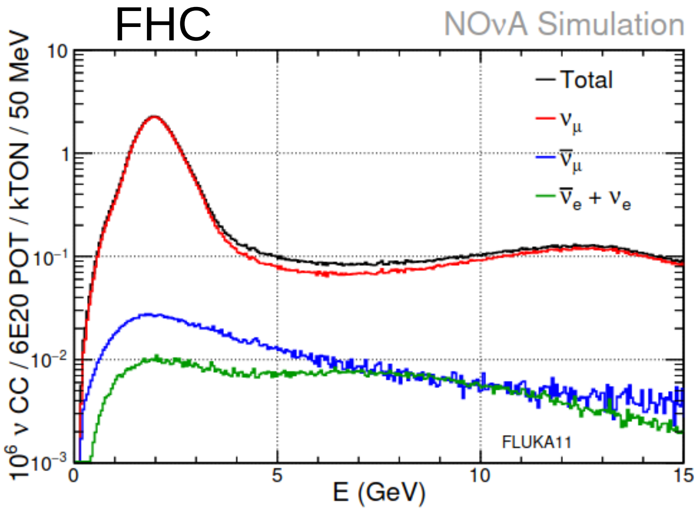

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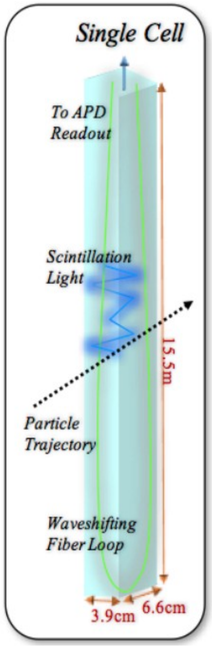
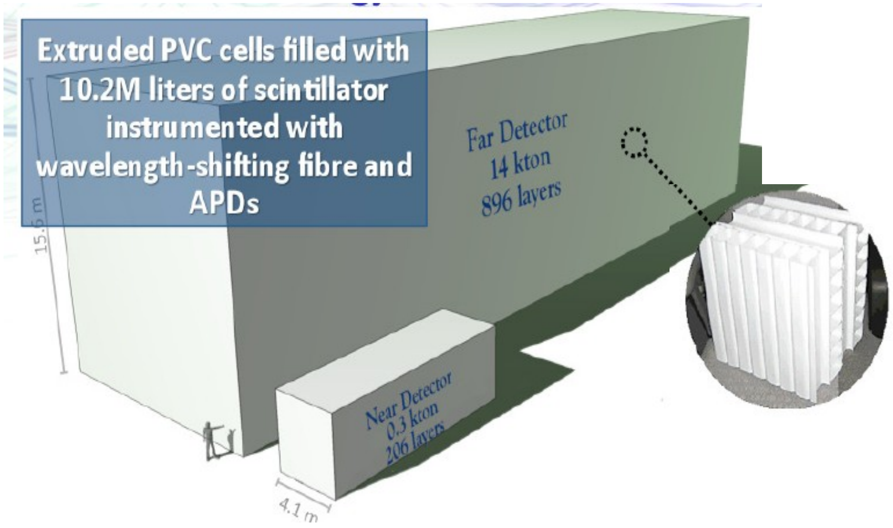
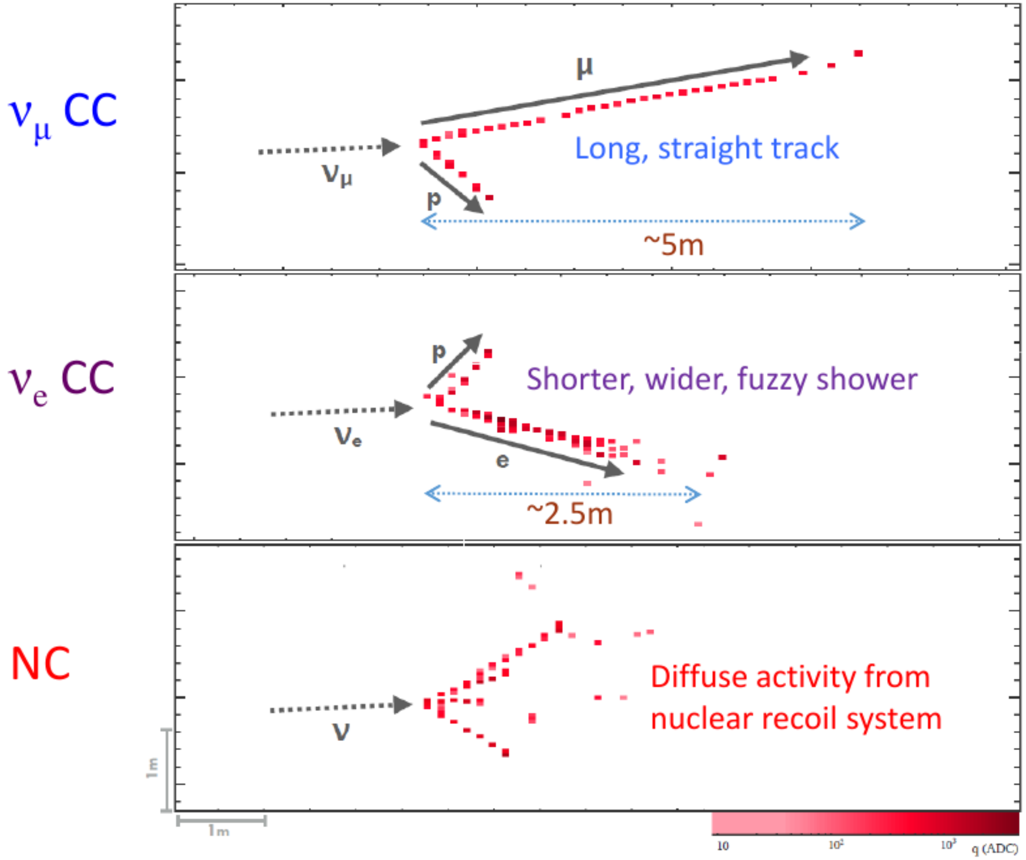




Extruded PVC cells filled with 10.2M liters of scintillator instrumented with wavelength-shifting fibre and APDs

- **How systematics on nuclear effects still affect ND to FD extrapolation:**
  - different $E\nu$ at ND and FD (before and after oscillation) → different $E_{had}/E\nu$, different resolution..
  - still need to disentangle flux and xsec since they depends on $E\nu$ differently
  - different acceptance (in p_T) at ND and FD due to different size

What do we measure?



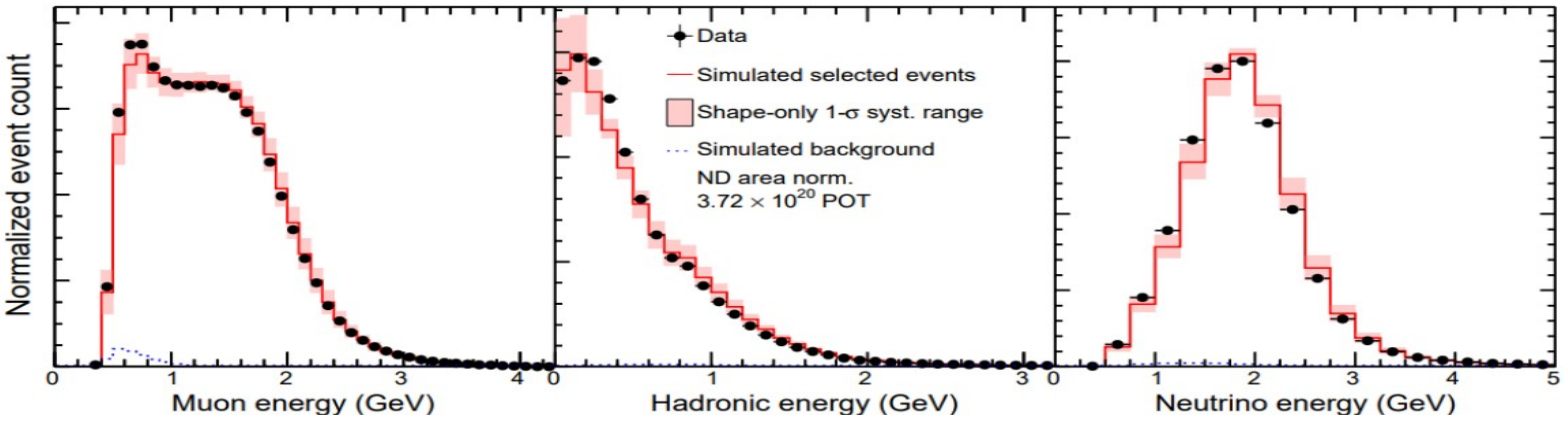
Muons (if contained)

Electrons as **shower**

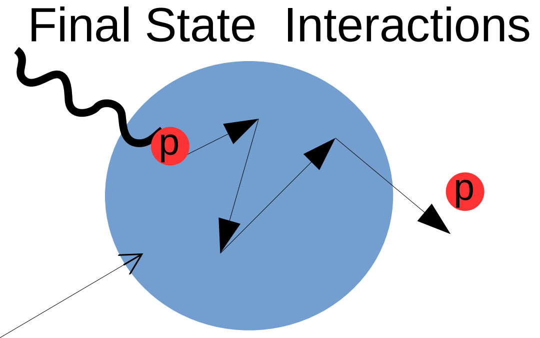
Hadrons (mostly as **diffuse activity + tracks)**

High energy flux: pion production and DIS → large fraction of Eν goes into hadrons

$$E_\nu = E_\mu + E_{had}$$

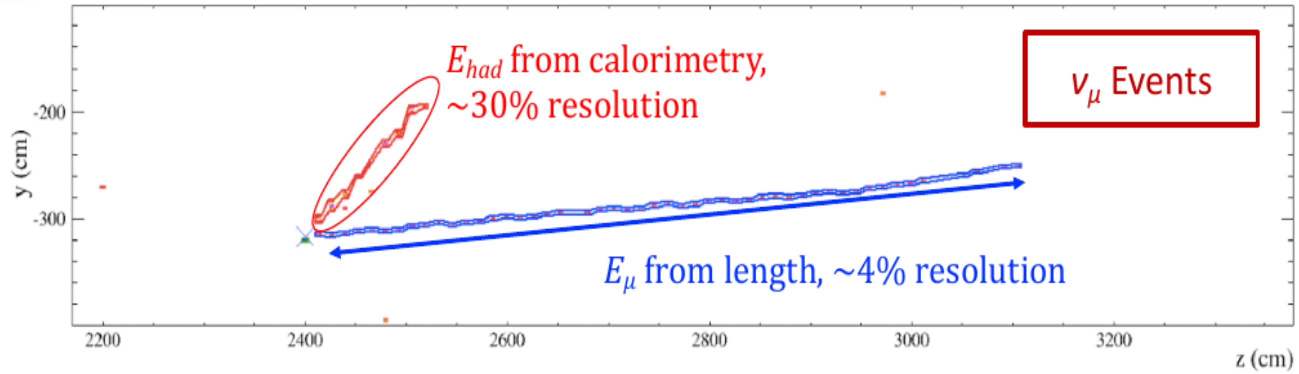


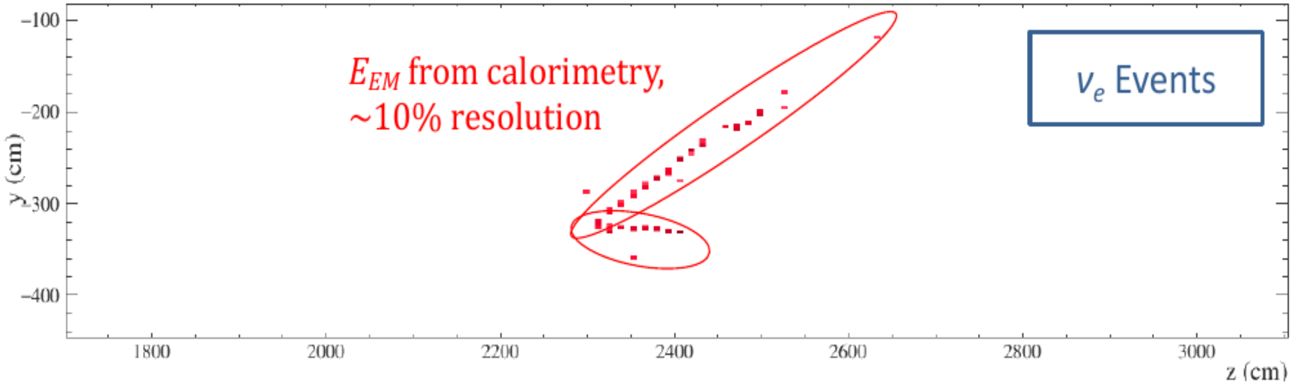
Eν reconstruction



- **Eν reconstructed with hadronic deposits:**
  - important difference $\nu - \bar{\nu}$: proton vs neutron (~undetected)
  - proton/pion energy smeared by Final State Interactions

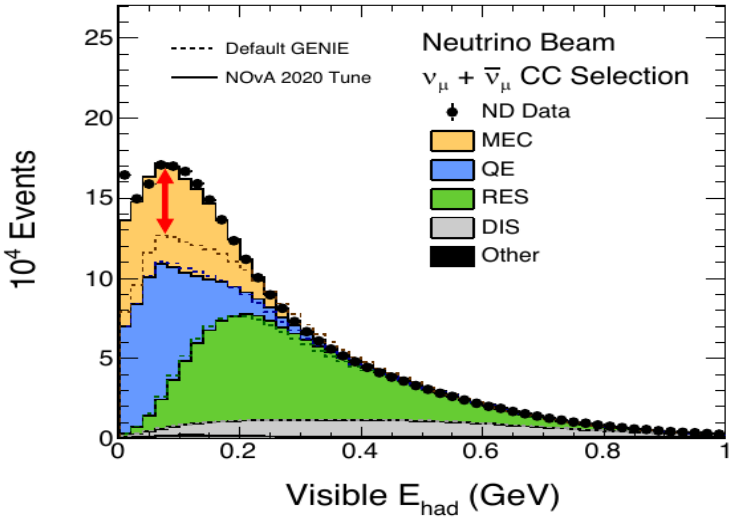
- Different reconstruction and energy resolution for ν_μ and ν_e



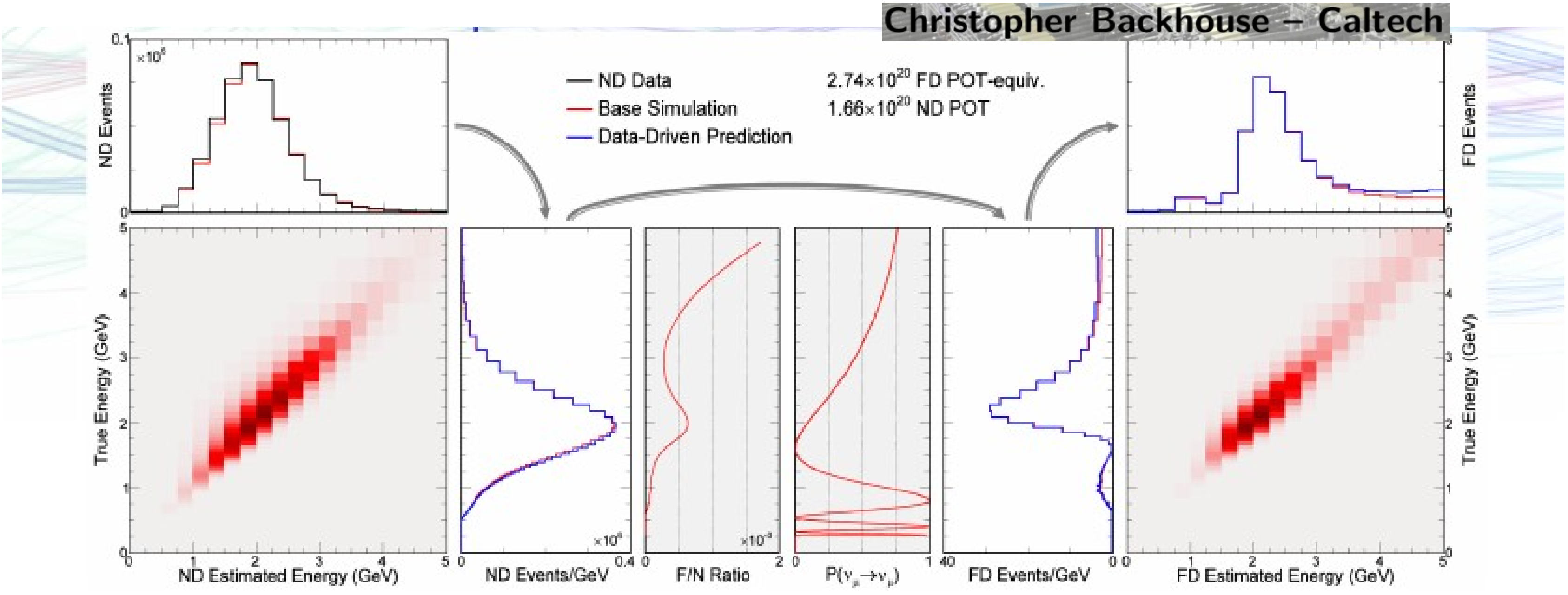


Important to tune model predictions for E_{had}

NOvA Preliminary



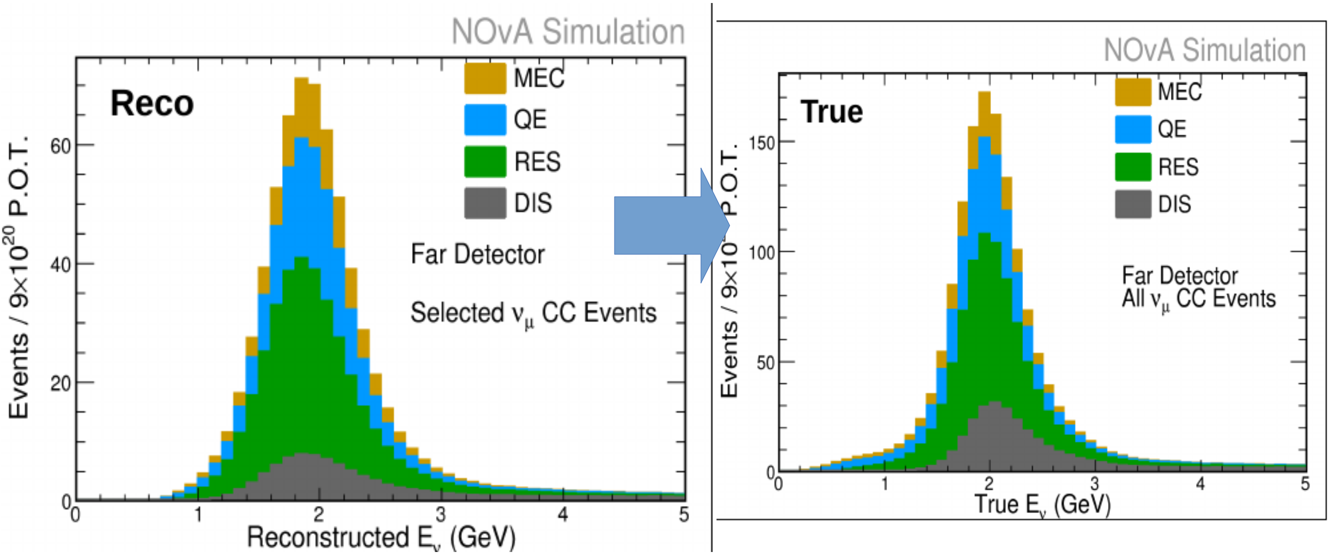
ND to FD extrapolation



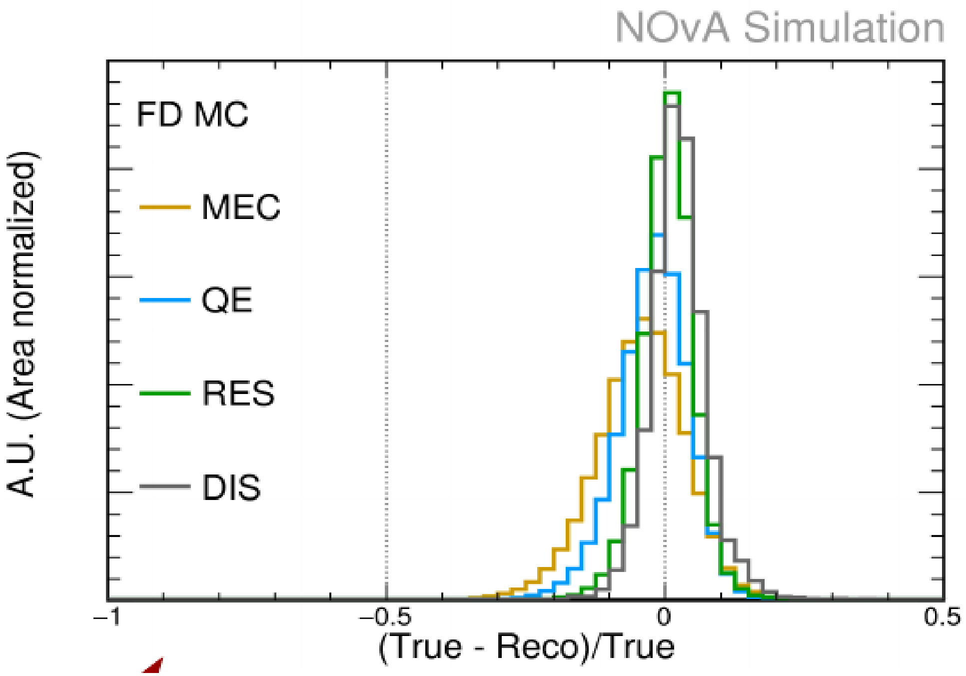
- Subtract NC expectation in ND, reweight MC in reco energy to match
- Transform to true energy, transport to FD with oscillations
- Transform to reco energy, add FD NC expectation back in
- Dependence on MC for background subtraction and true/reco matrix

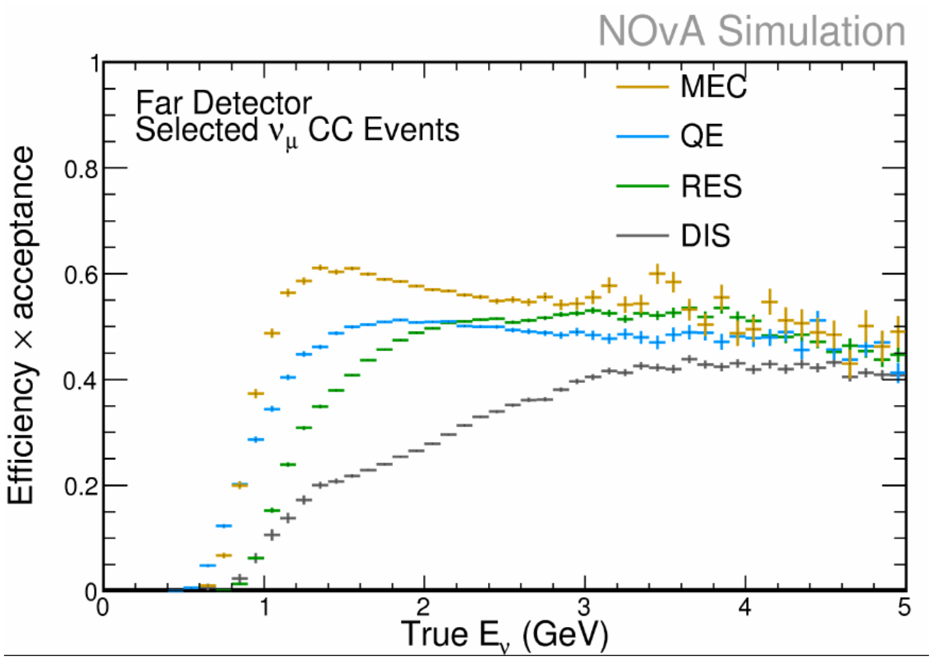
Not only detector systematics but also theoretical uncertainties (FSI, multiplicity in the final state, fraction of neutrons...) do affect the true ↔ reco correspondance

Resolution, efficiency, acceptance



Each process has different neutrino energy resolution and efficiency: dependence on hadron multiplicity, π^0 fraction, kinematics of leptons ...





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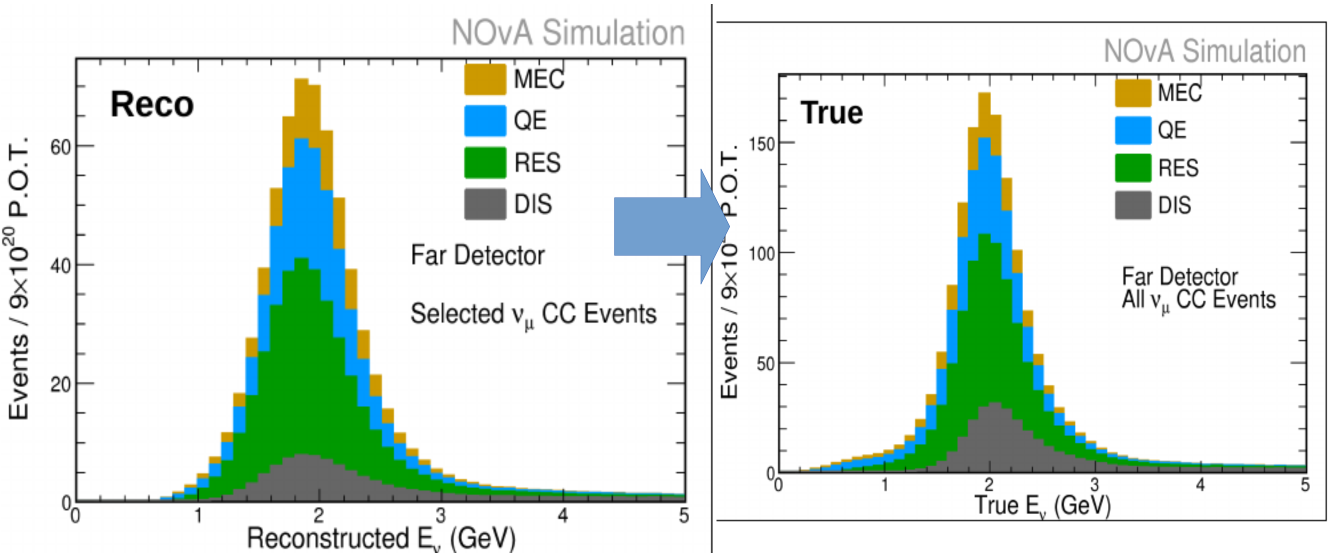
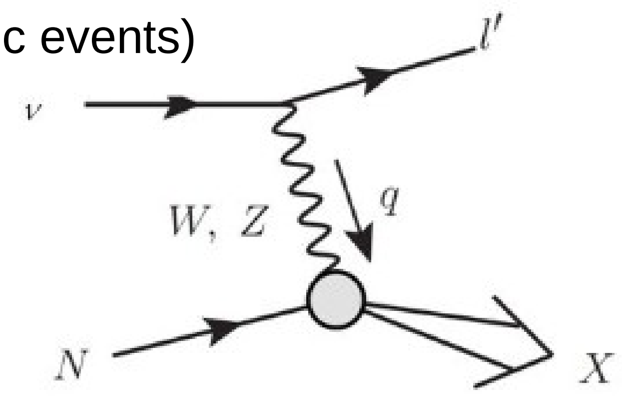
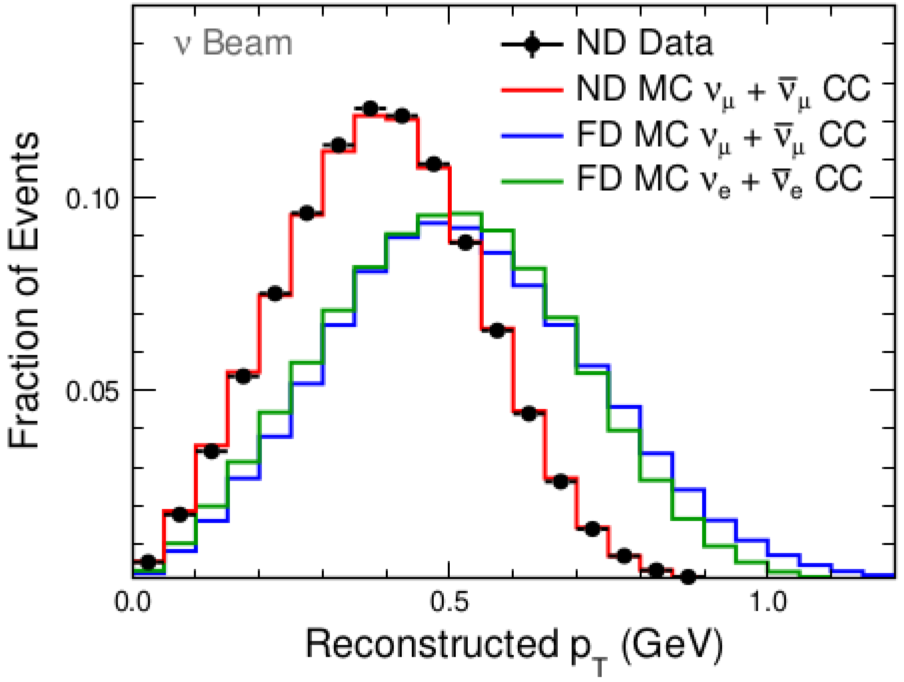


Each process has different neutrino energy resolution and efficiency: dependence on hadron multiplicity, π^0 fraction, kinematics of leptons ...

- Due to different detector size, the acceptance of ND and FD is different: transverse momentum of the muon is larger when larger energy/momentum transferred to the nucleus (more inelastic events)





Selection

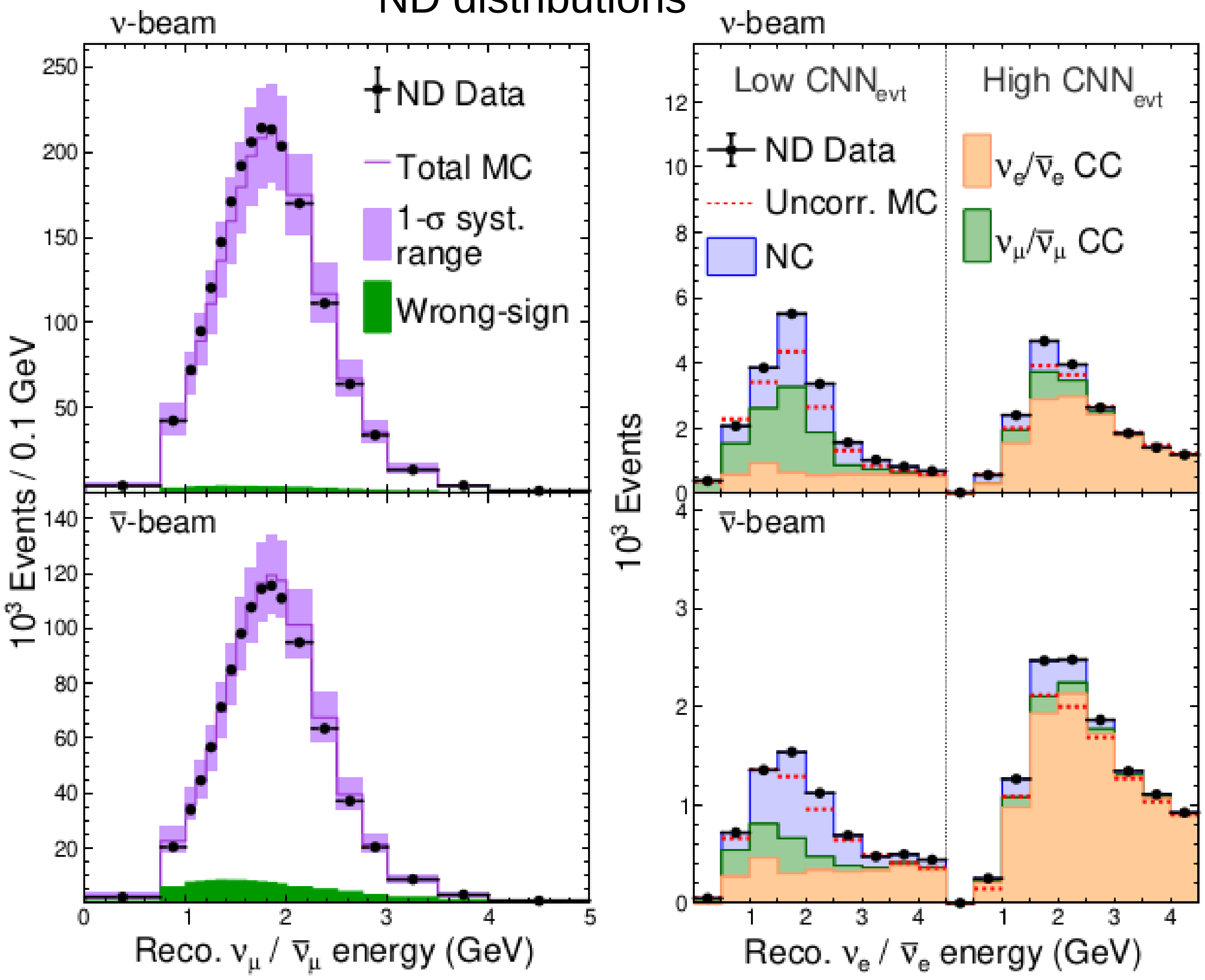
- Inclusive selection: require one muon/electron. Convolutional Neural Network (CNN to separate ν_μ, ν_e, NC, cosmogenic background)

  - Electron-like sample subdivided by CNN score (different purity)

  - Muon-like sample subdivided by fraction of hadronic energy (different resolution)

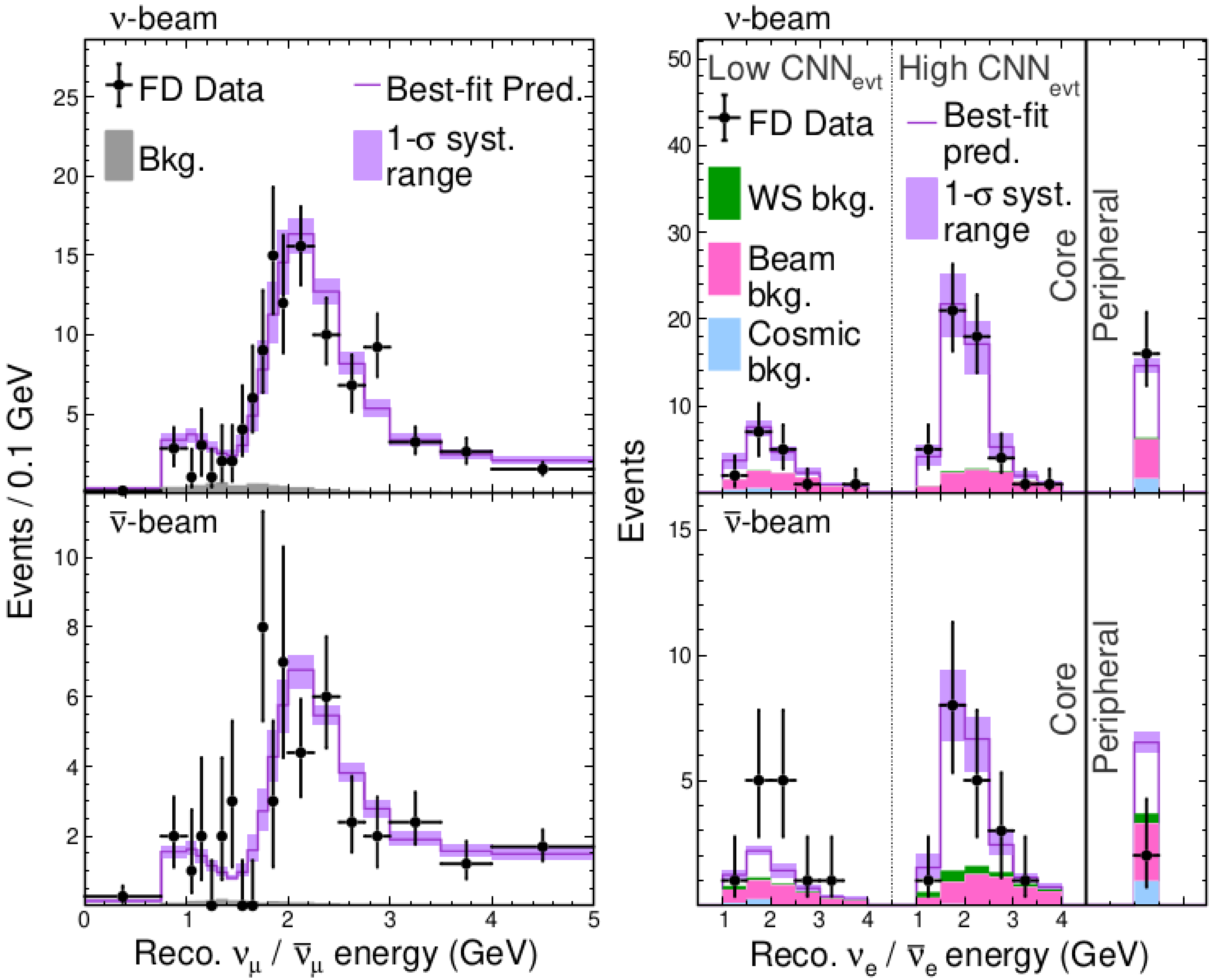
  - All samples subdivided in lepton transverse momentum to minimize impact of different acceptance at ND and FD

ND distributions



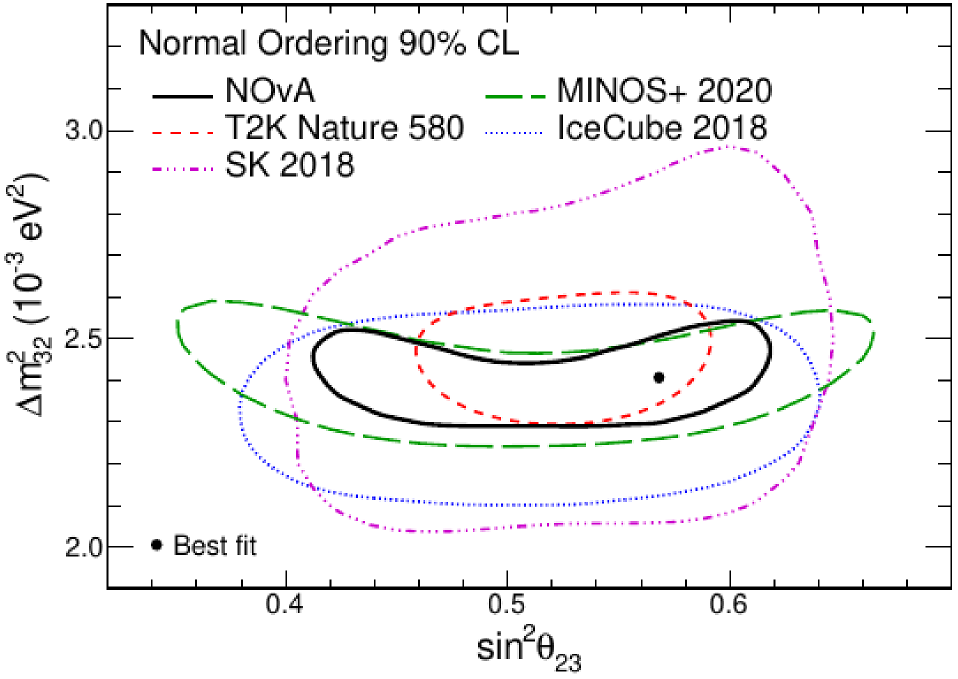
- Measurement of all the visible energy in the event to estimate the neutrino energy

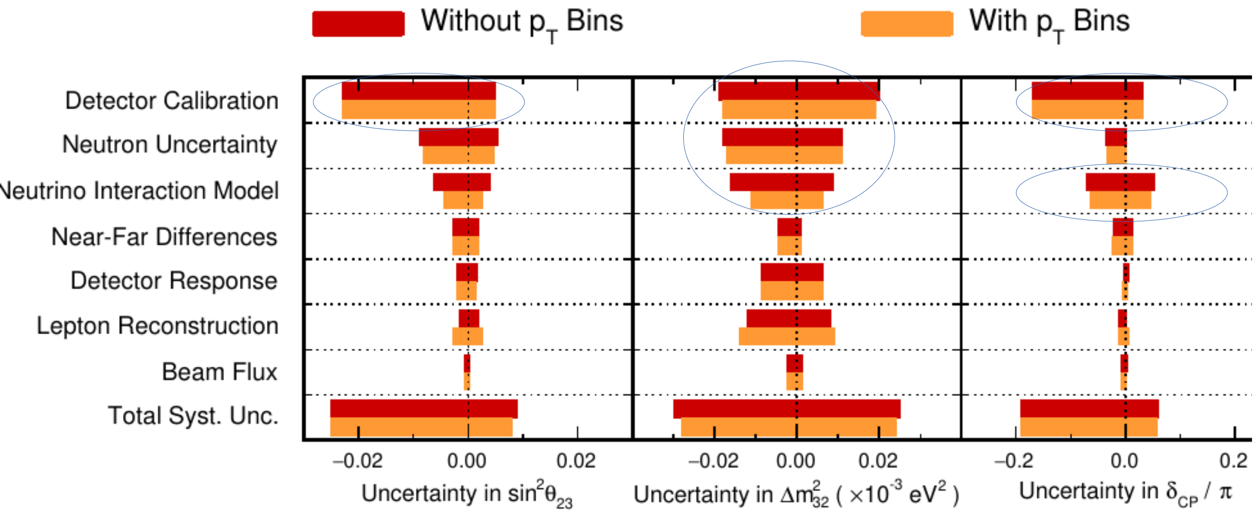
Far detector results

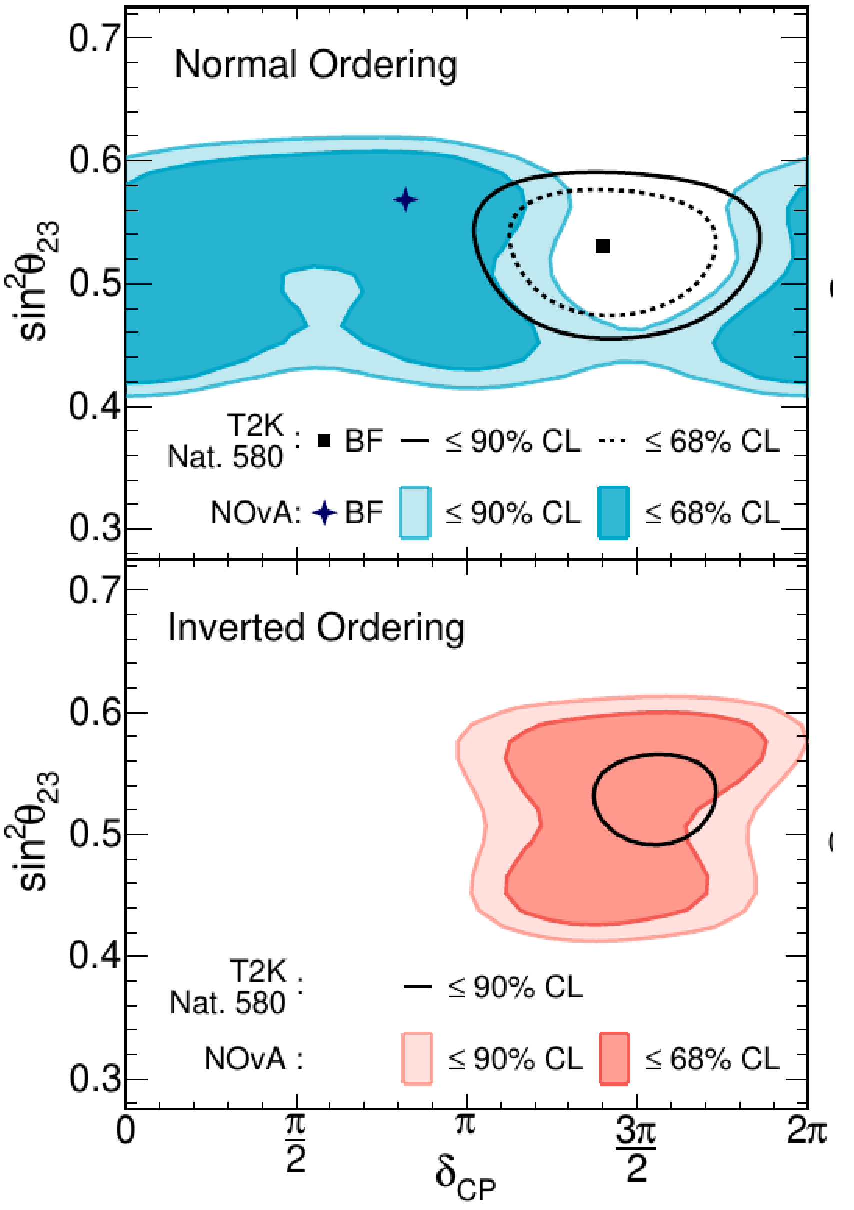


Fit to FD data with “ND-tuned” distribution
→ extract measurement of oscillation parameters

Far detector results





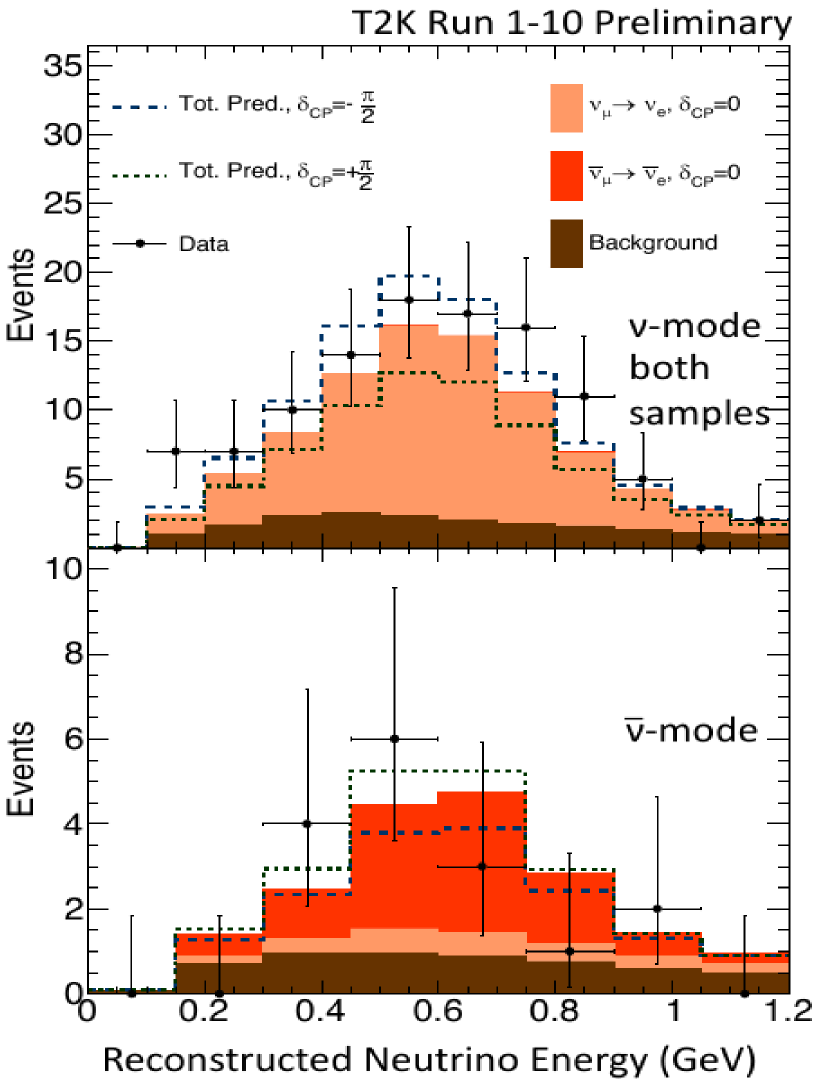


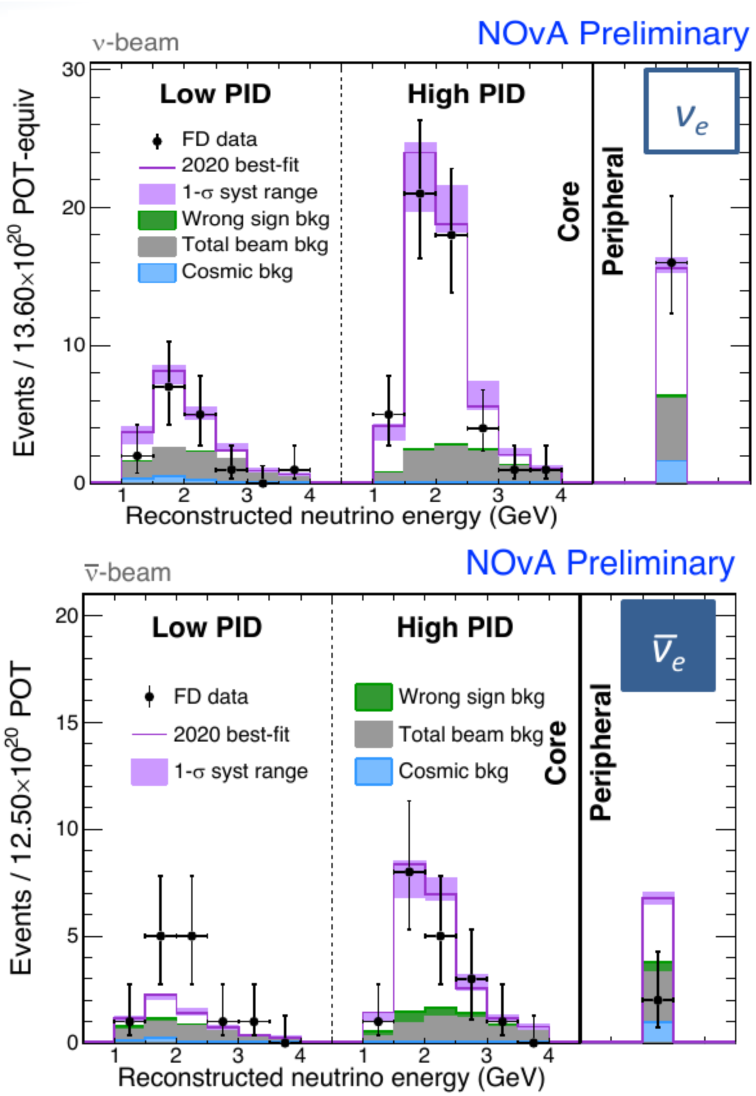
Limitations and future challenges

δ_{CP}: statistically limited

The δ_{CP} measurements are dominated by stat uncertainty (limited number of ν_e, $\bar{\nu}_e$ events)

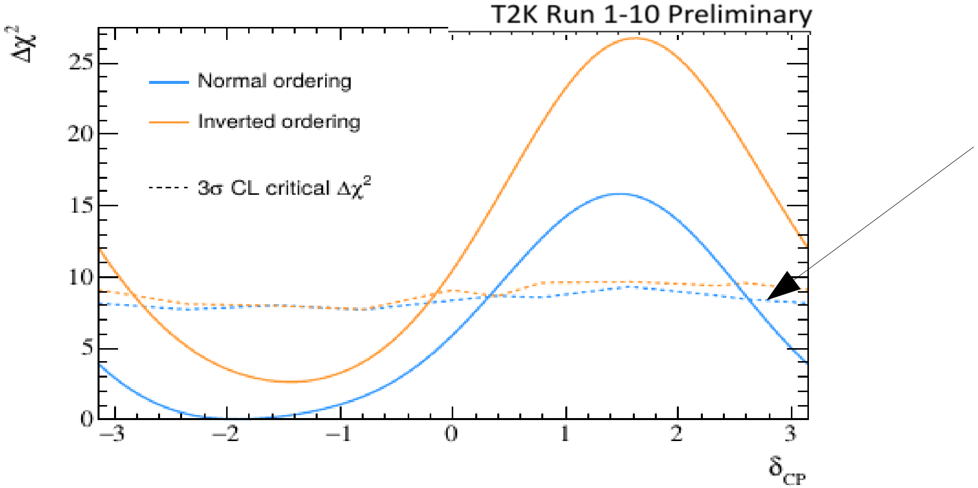
→ further data at T2K and NOVA (and next generation of experiments with more powerful beams and enlarged far detector mass)





Statistical treatment: Fieldman Cousin

When uncertainties are not Gaussian, you cannot simply calculate σ as units of $\Delta\chi^2$ (i.e. the test-statistic has not χ^2 distribution → need to run toys over all the parameters)



For each values of true δ_{CP} → look which χ^2 corresponds to 68%, 95% ...

How to sample nuisances?
[In Bayesian terms: which prior on nuisances?]

Treatment of 'nuisances' = parameters in the fit which are profiled or marginalized (e.g. θ_{23} and Δm^2 in plots of δ_{CP}, MO sensitivity)

- Near the δ_{CP} minimum, obvious way to sample the nuisances: from data results (Asimov at best fit)
  Far from minimum (or for parameters with low sensitivity from data) is less obvious:
  eg, sample over nuisances distribution for Asimov at that true δ_{CP} value?

  Safe at 3σ but what about >3σ? Studies on-going

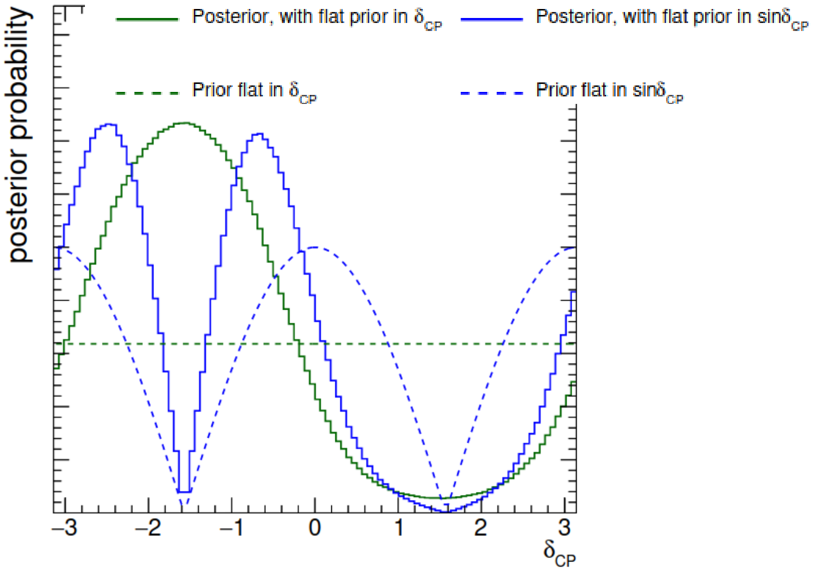
- Effect become important because of degeneracies and boundary effects

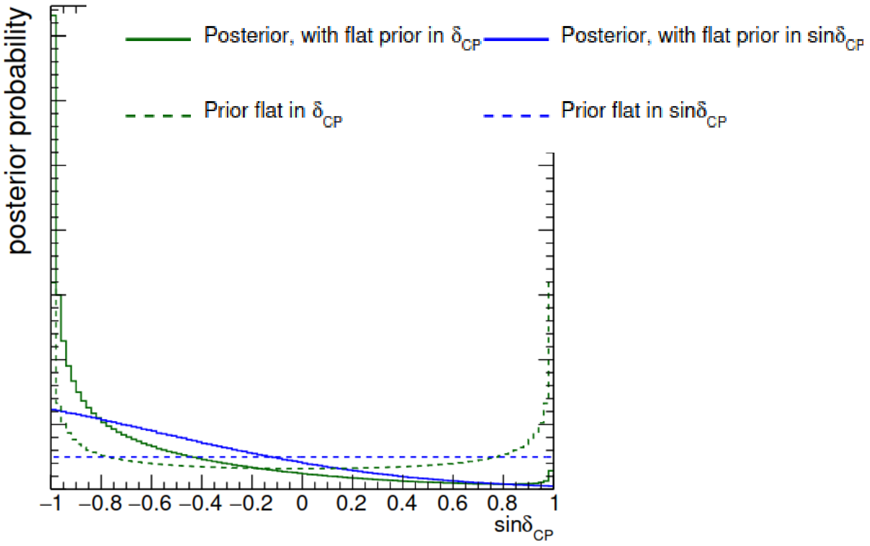
- Important effect for (future?) high stat results: in practice the region of 5σ exclusion may change and does not scale like 1/sqrt(N)!

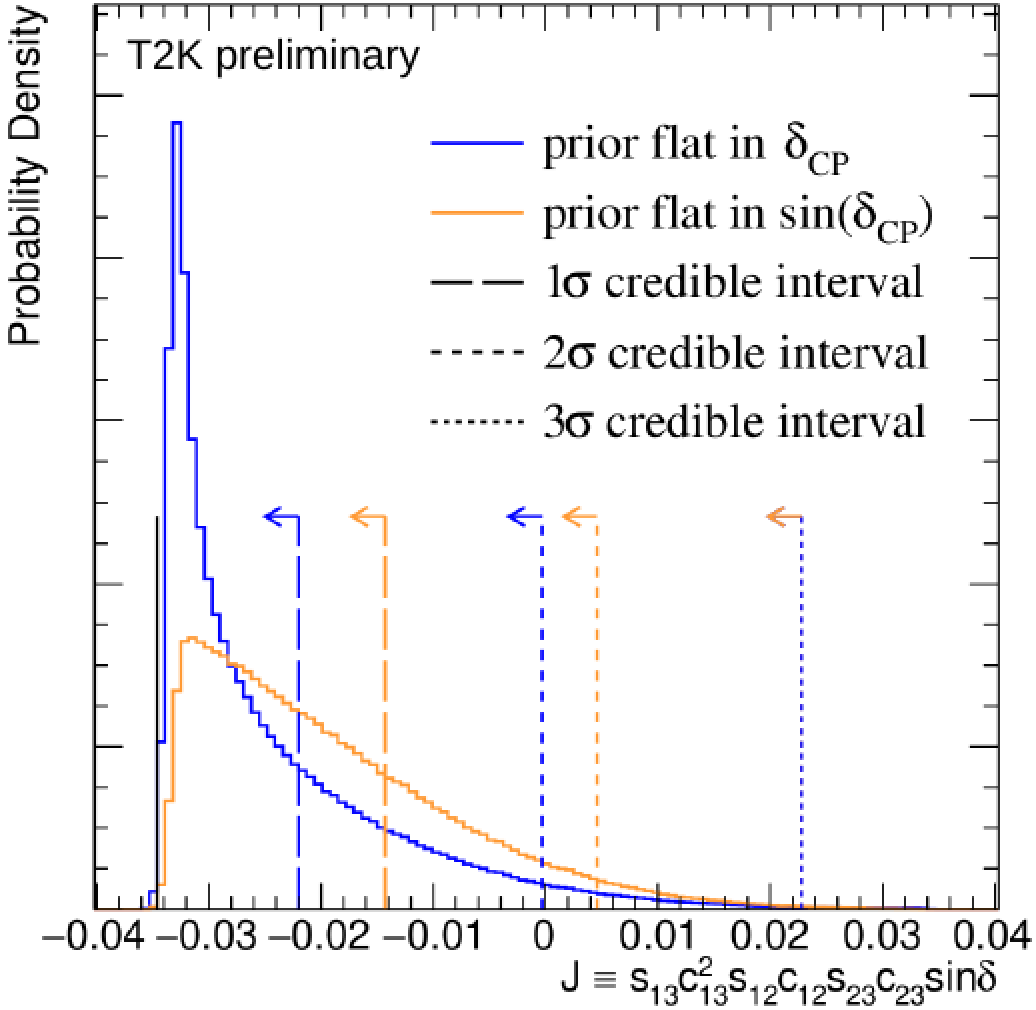
Statistical treatment: prior

What is the ‘physical parameter’:
δ_{CP} or $\sin\delta_{CP}$?
Is CPV δ_{CP} not $0,\pi$ or $\sin\delta_{CP}$ not 0?
Different priors are possible...

CPV = sign of Jarlskog invariant
(still impact from prior assumption:
flat on δ_{CP} or $\sin\delta_{CP}$?)



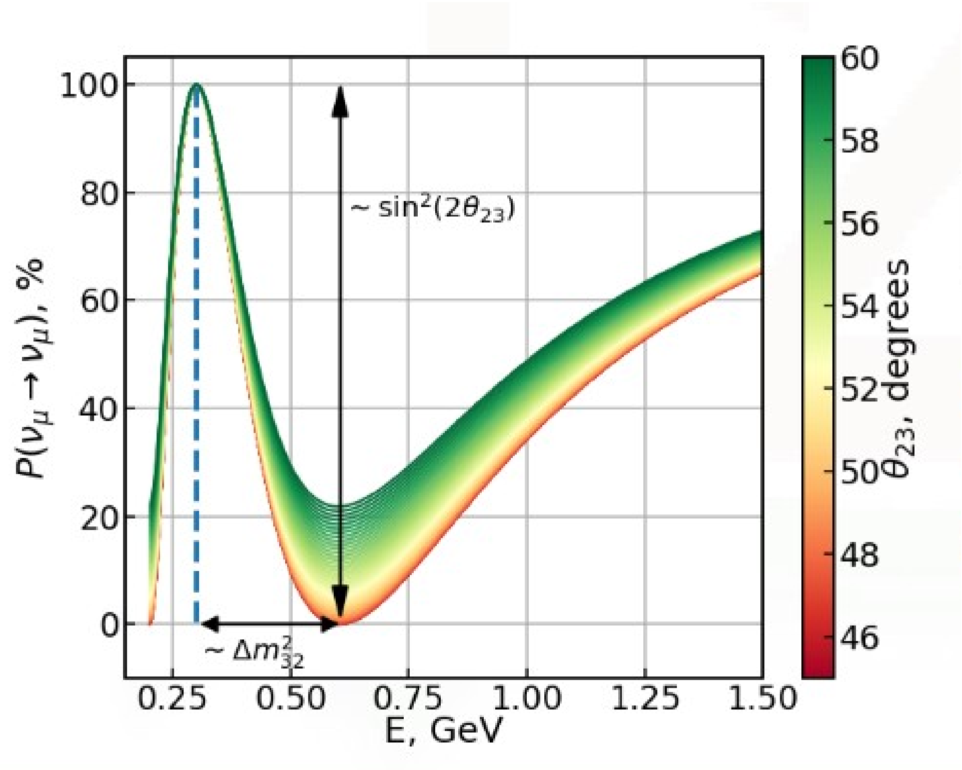


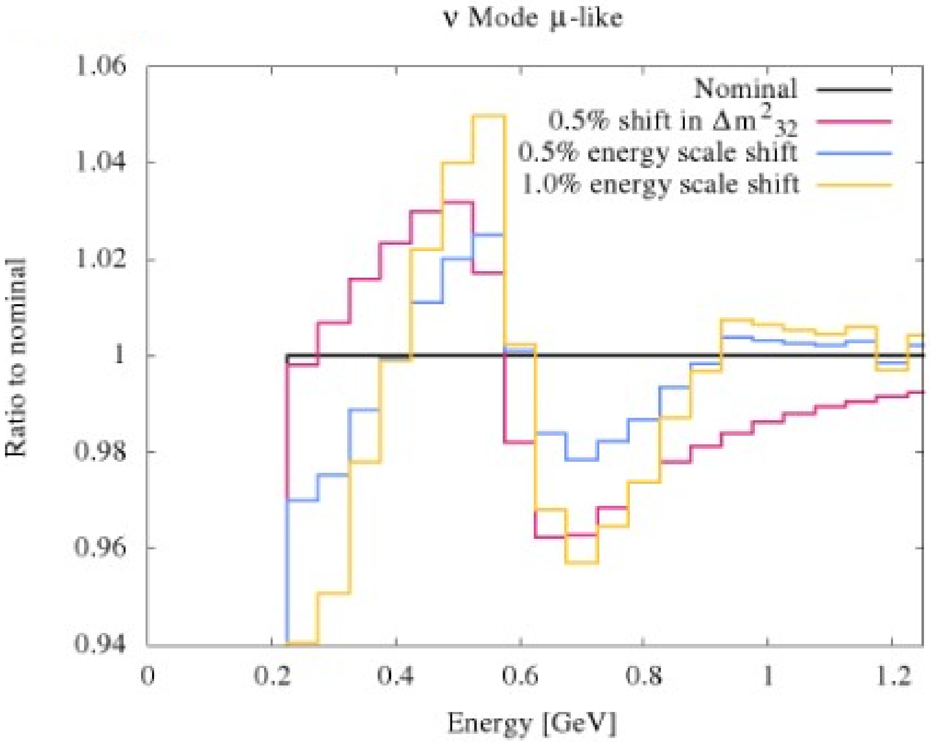


Impact of systematics will hit first in ν_μ disappearance

As already discussed yesterday:

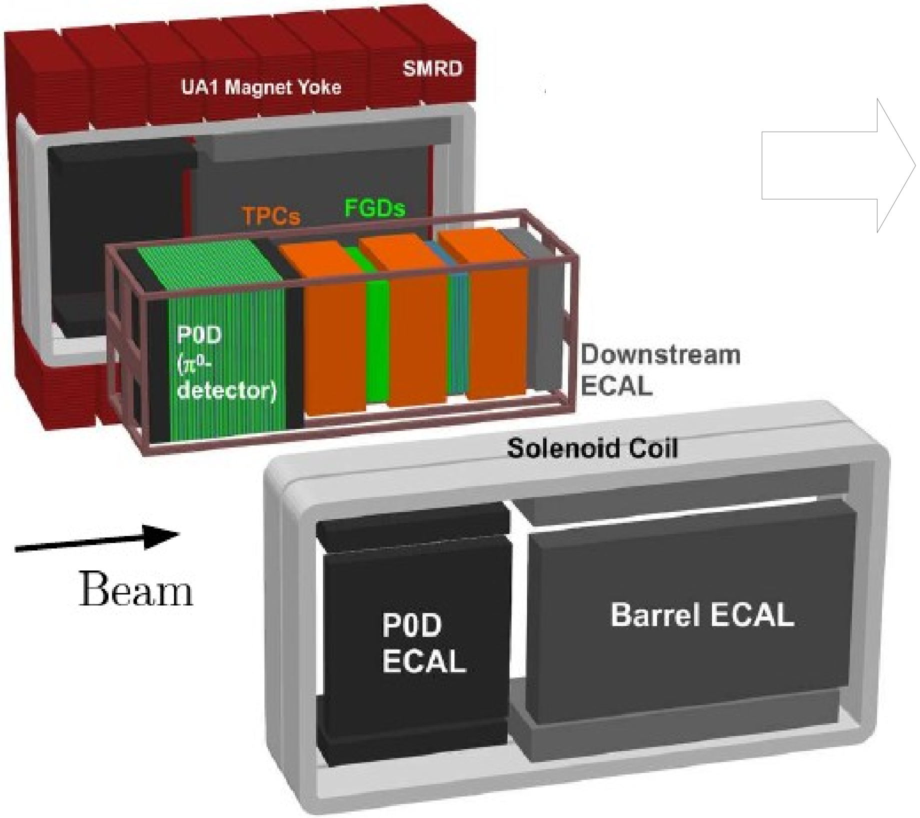
- precision $\sin\theta_{23}$ requires precision on neutrino rate at oscillation maximum
- precision on $|\Delta m^2_{31(32)}|$ requires precise neutrino energy reconstruction

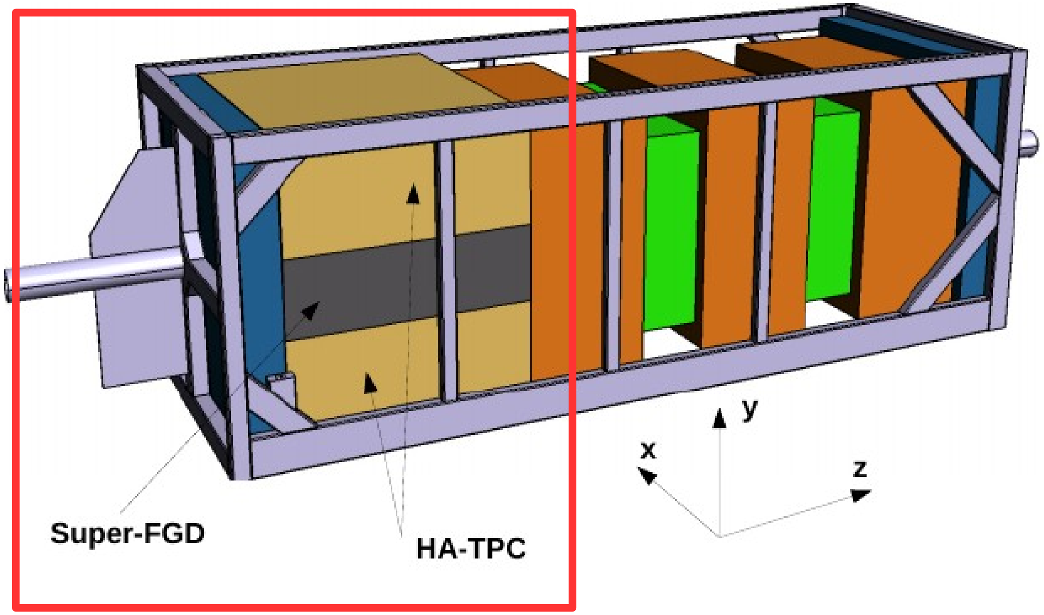




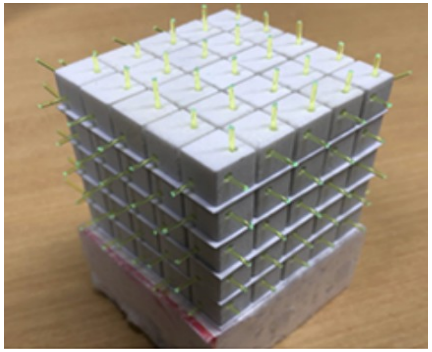
Need improved flux and xsec models (and tuning: NA61, Minerva, ...) and improved near detectors to better constrain model, notably for precise reconstruction of full final state → improved neutrino energy reconstruction

ND280 → ND280 upgrade





3D 'pixeled' scintillator
(1cm^3 cubes)



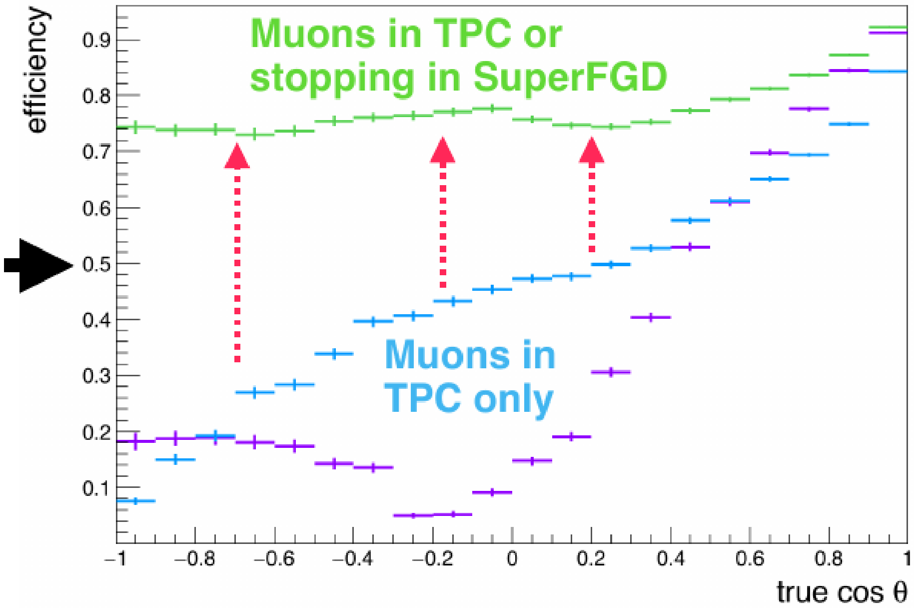
- **New target** with much lower threshold for track reconstruction (p,π)

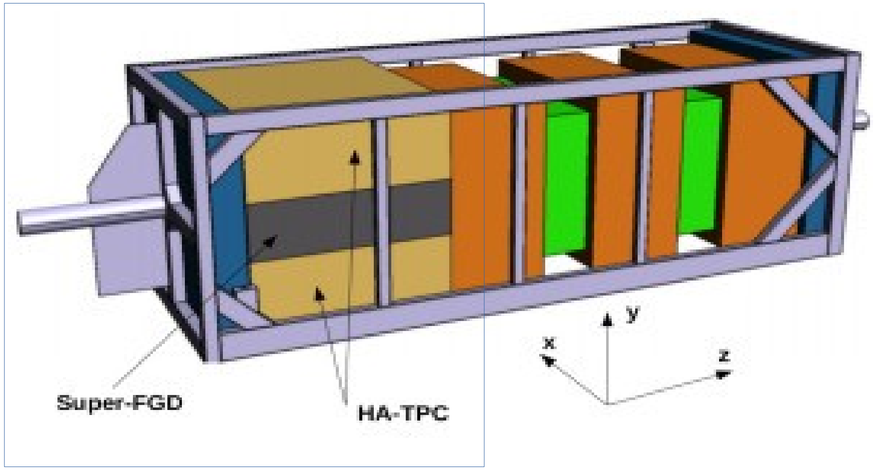
- **High angle TPCs with resistive Micromegas:** coverage at high angle and improved momentum resolution

- Scintillator planes all around the **new detectors for Time of Flight measurement of charged particles**

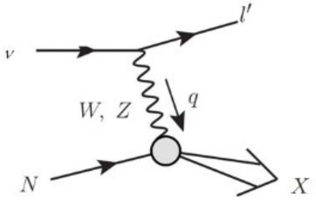
ND280 upgrade

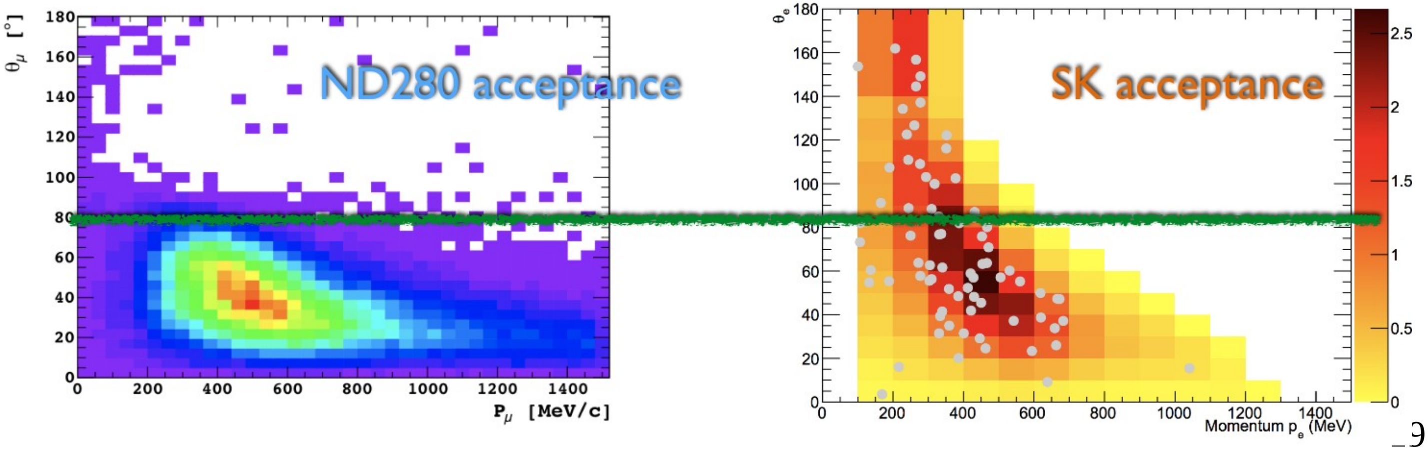
- larger statistics from new target + improved angular acceptance





Leptons at larger angle correspond to more inelastic events



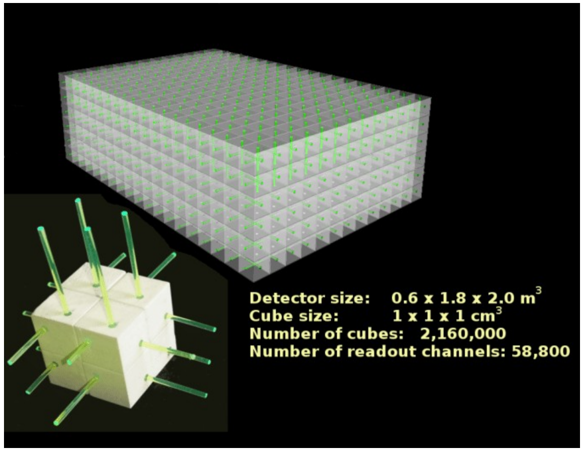


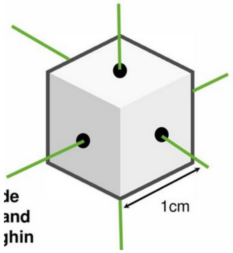
ND280 upgrade

T2K Work in Progress

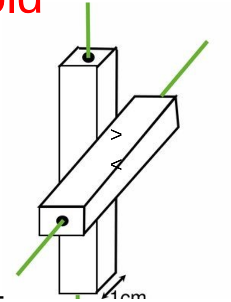
- larger statistics from new target + improved angulaire acceptance

- proton kinematics measurement down to low momentum threshold



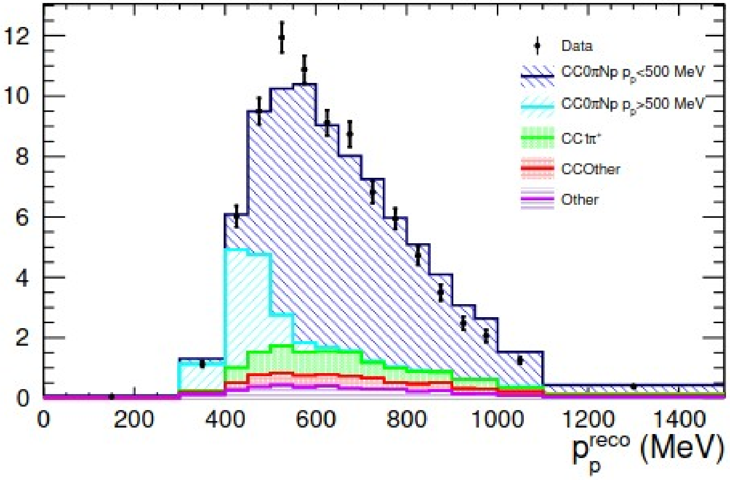


New '3D' scintillating detector

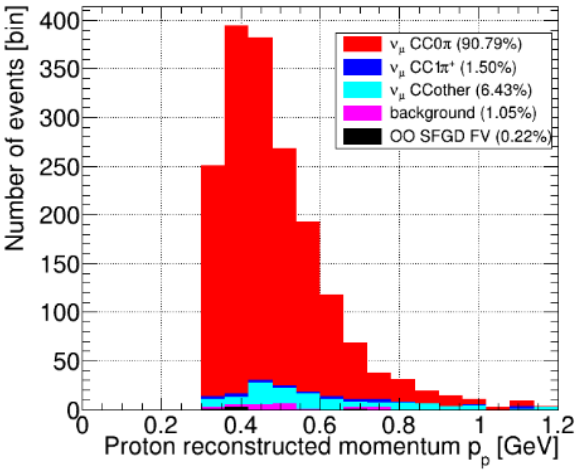


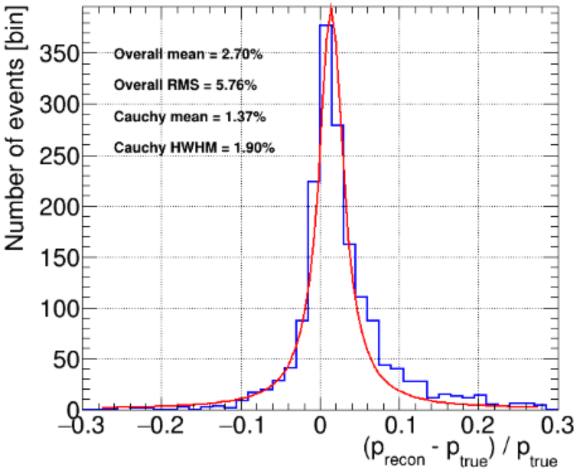
ND280 FGDs are '2D' scintillating detectors

ND280 measurement



ND280 upgrade (ν MC):





ND280 upgrade

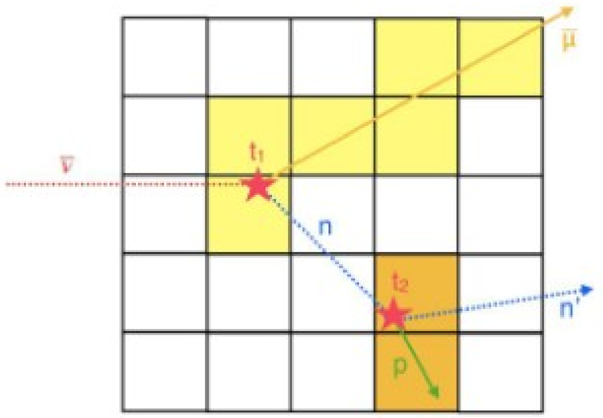
New analysis features are also preparing the road to the analysis of ND280 upgrade data:

- larger statistics from new target + improved angulaire acceptance

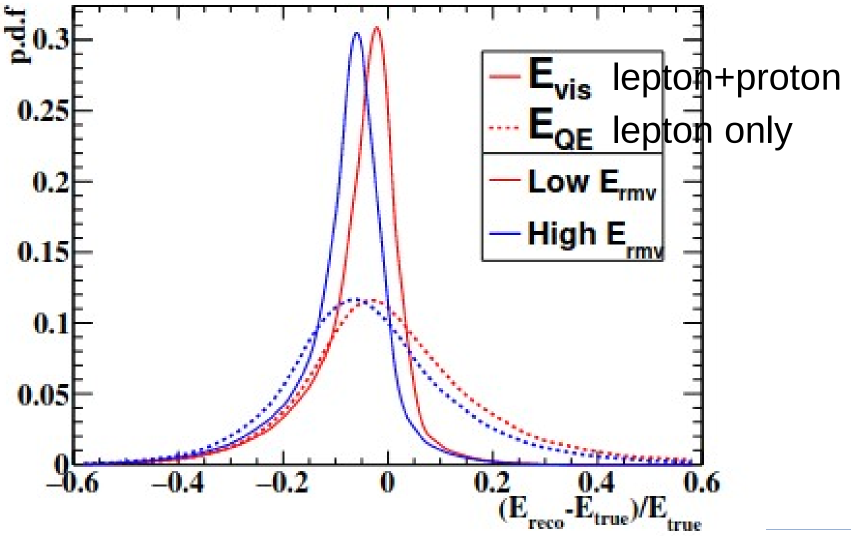
- proton kinematics measurement down to low momentum threshold

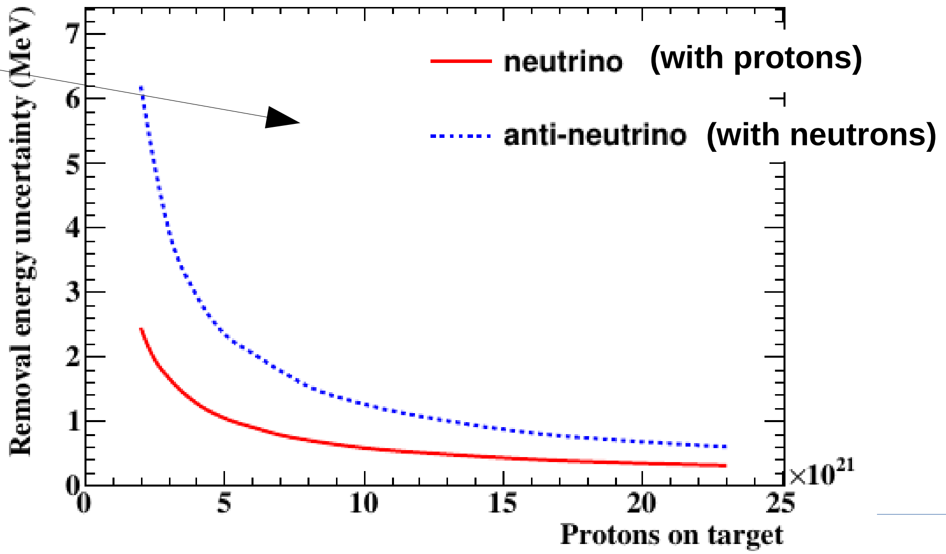
- neutron measurement event-by-event: NEW!!!

Time-of-flight technique



New generation of near detectors/analyses : full **exclusive reconstruction of final state for best neutrino energy 'reconstruction'** from outgoing interaction particles





Last remarks

Change of gear: from statistically dominated experiments to precision physics. Transition is happening in the next few years with T2K new runs (after beam and ND280 upgrade) and future NOVA runs.

The **role of T2K and NOVA** is similar to LEP to open the road to LHC:
- establish analysis strategies and best detector design (notably in terms of ND)
- some ~3σ (or more) indication for CPV and MH can already happen in next future from combination of experiments, including JUNO and ORCA

If we want to build a safe path to 5σ results for next generation of experiments (DUNE and HK), the work to do is still long:
we need to validating our model with better precisions with T2K and NOVA data.

If we had today the huge flow of data expected for next generation, we would be very soon limited by systematic uncertainty...

Systematics

- Crucial **role of Near Detectors:**

$$R_{ND}^{\nu'} = \int \boxed{\Phi^{\nu}(E_{\nu}) \frac{d\sigma^{\nu'}}{dE_{\nu}}} dE_{\nu}$$

ND measures rate vs neutrino energy

$$R_{FD}^{\nu'} = \int \boxed{\Phi^{\nu}(E_{\nu})} \boxed{P_{osc}^{\nu\rightarrow\nu'}(E_{\nu})} \boxed{\frac{d\sigma^{\nu'}}{dE_{\nu}}} dE_{\nu}$$

~same flux at ND and FD

what we want to measure: oscillation probability

cross-section must be extrapolated from ND to FD (different neutrino energy distribution) → need good neutrino energy reconstruction and good nuclear model

- Important systematics for d_{CP} (MH):
  - **difference between n and ▯ (xsec and flux)** Notably, **“wrong sign” background:** n in ▯ mode (p^+ focused beam)
  - **▯$_e$ intrinsic background:** ▯$_e$ produced in the beam by K / p->m decays

Near detectors and nuclear theory

ND measures rate vs neutrino energy before oscillation
→ characterize flux and xsec

$$R^{\nu'}_{ND} = \int \boxed{\Phi^{\nu}(E_\nu)\frac{d\sigma^{\nu'}}{dE_\nu}}\, dE_\nu$$

$$R^{\nu'}_{FD} = \int \boxed{\Phi^{\nu}(E_\nu)}\, \boxed{P^{\nu\rightarrow\nu'}_{osc}(E_\nu)}\, \boxed{\frac{d\sigma^{\nu'}}{dE_\nu}}\, dE_\nu$$

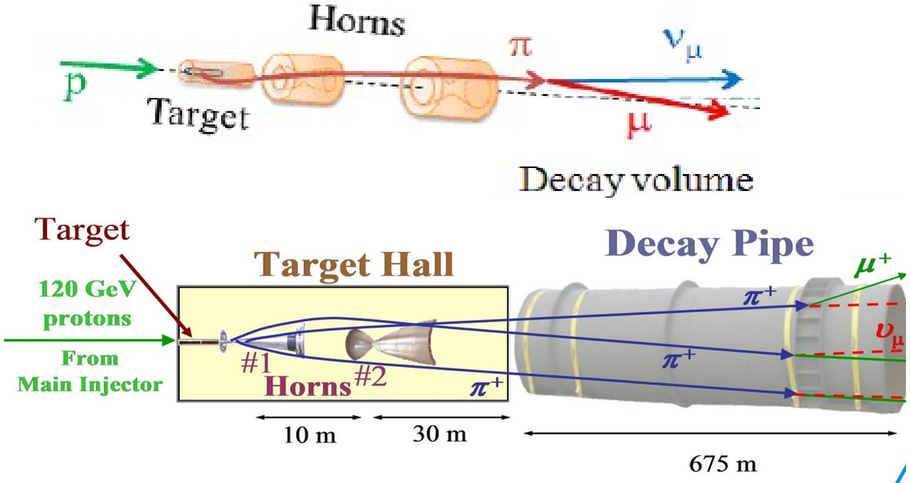
~same flux at ND and FD

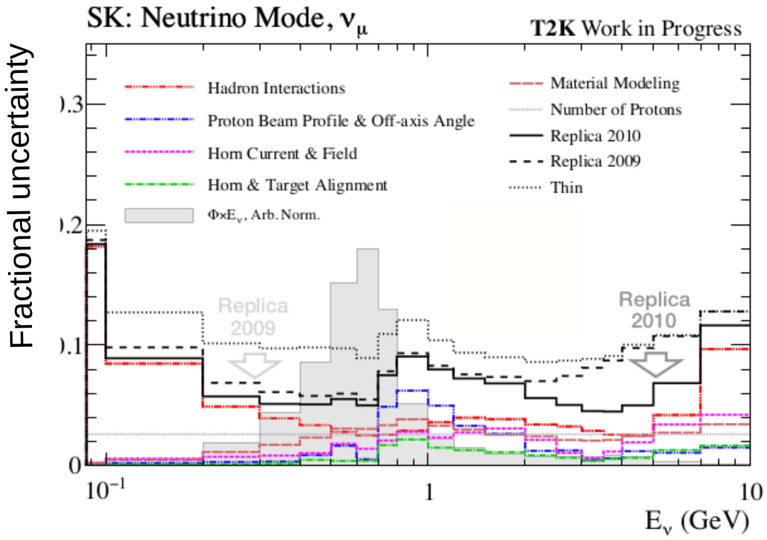
what we want to measure:
oscillation probability

cross-section must be extrapolated from ND to FD:
- different neutrino energy distribution
- ND measure flux times xsec

Need nuclear theory models!

Flux simulation and tuning (NA61/SHINE + MIPP)





Near detectors and nuclear theory

ND measures rate vs neutrino energy before oscillation
→ characterize flux and xsce

$$R_{ND}^{\nu'} = \int \boxed{\Phi^{\nu}(E_\nu)\frac{d\sigma^{\nu'}}{dE_\nu}} dE_\nu$$

$$R_{FD}^{\nu'} = \int \boxed{\Phi^{\nu}(E_\nu)} \boxed{P_{osc}^{\nu\rightarrow\nu'}(E_\nu)} \boxed{\frac{d\sigma^{\nu'}}{dE_\nu}} dE_\nu$$

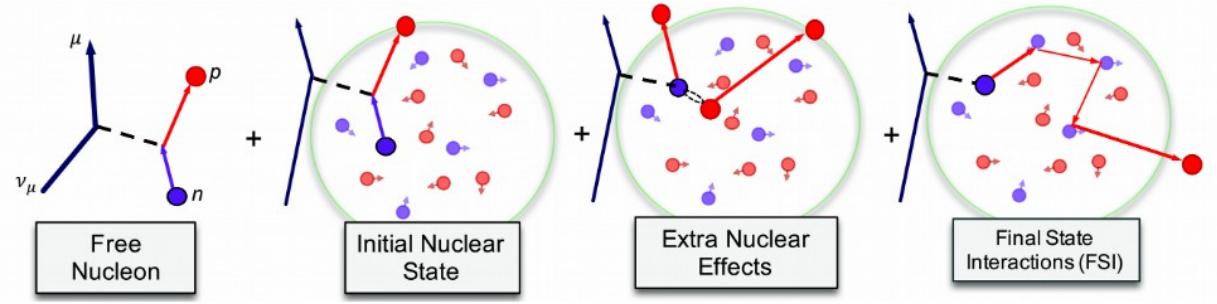
~same flux at ND and FD

what we want to measure:
oscillation probability

cross-section must be extrapolated from ND to FD:
- different neutrino energy distribution
- ND measure flux times xsec

Need nuclear theory models!

ν-nucleus interaction modeling and tuning

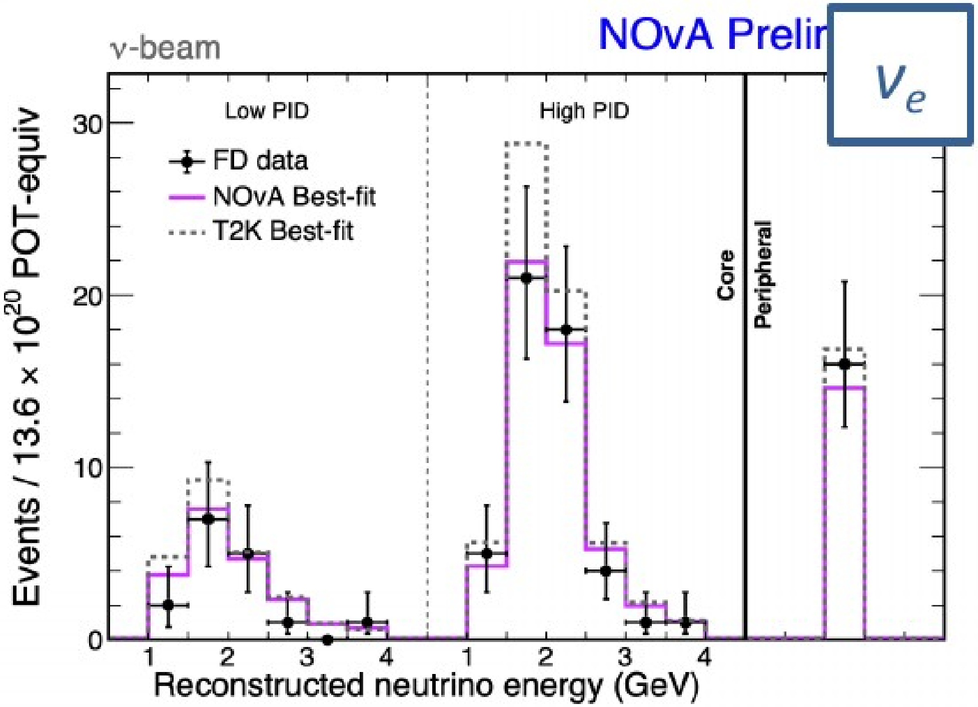


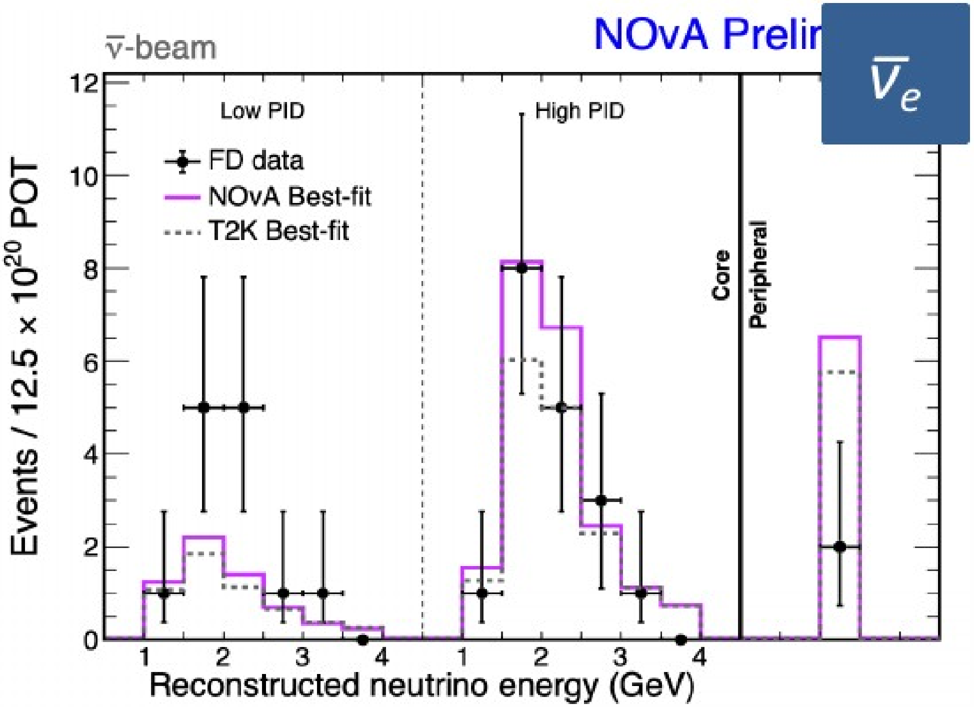
(and similarly for pion(s) production)

- Nuclear theory
- External data (eg e-scattering)
- ν-nucleus xsec measurements at near detectors and dedicated experiments (Minerva, ArgoNeuT, ..)

→ fundamentally the name of the game: precise Eν reconstruction

~~Conclusions~~ → Stay tuned for more data!





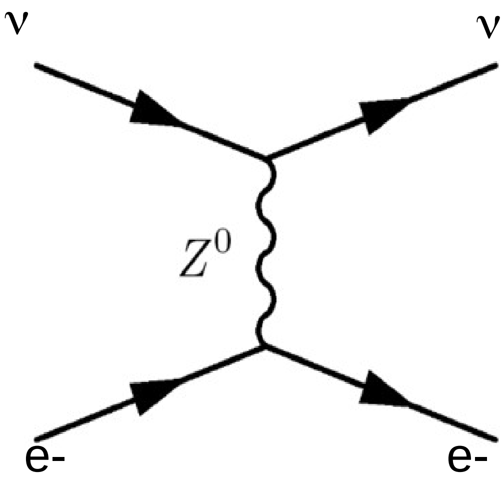
- Still in **ν_e / $\bar{\nu}_e$** (so δ_{CP} measurements) **the statistic uncertainties at the far detector is dominant over the systematics**

- The model of systematics is extremely different in T2K and NOVA and their impact and treatment is extremely different

- The evaluation of systematics is the big challenge for the next years: **T2K and NOVA are crucial to open the road to higher-statistics future LBL**

Further constraint from the ND (2)

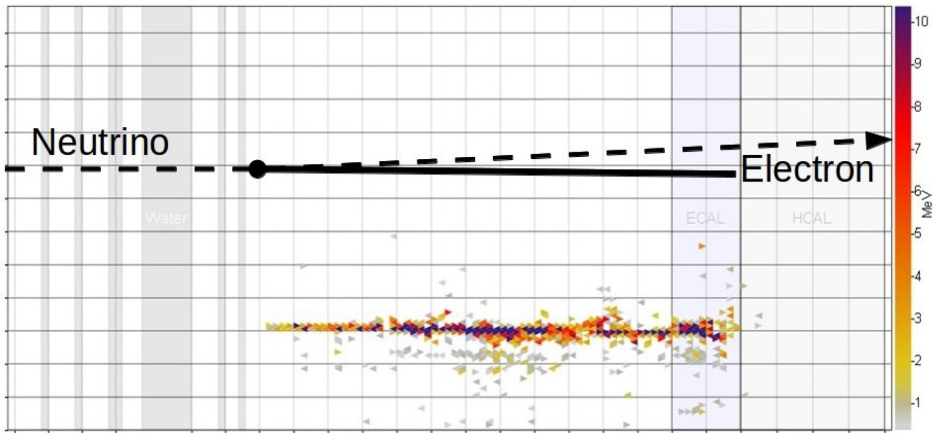
One nice exception: a cross-section which we know very well (no nuclear effects!)

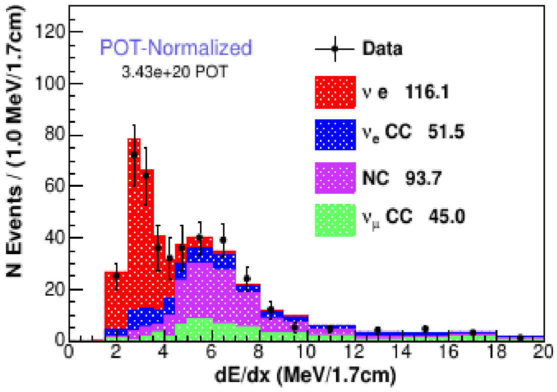


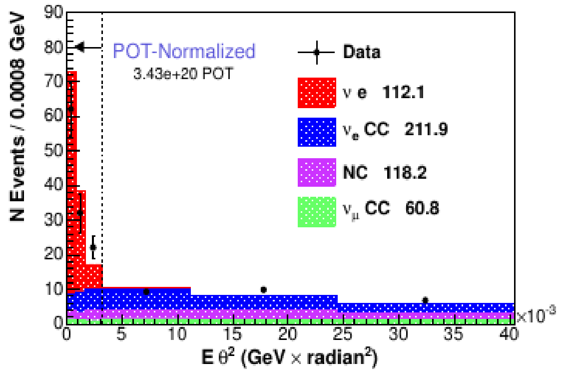
Neutrino scattering on electrons:
simple electroweak Neutral Current process for ν_μ and ν_τ,
(some Neutral Current – Charged Current interference for ν_e)

Difficulties: **very small xsec** (10^{-4} wrt to total CC ν interaction)
large backgrounds from $\pi^0 \to \gamma\gamma$ and ν_e CC

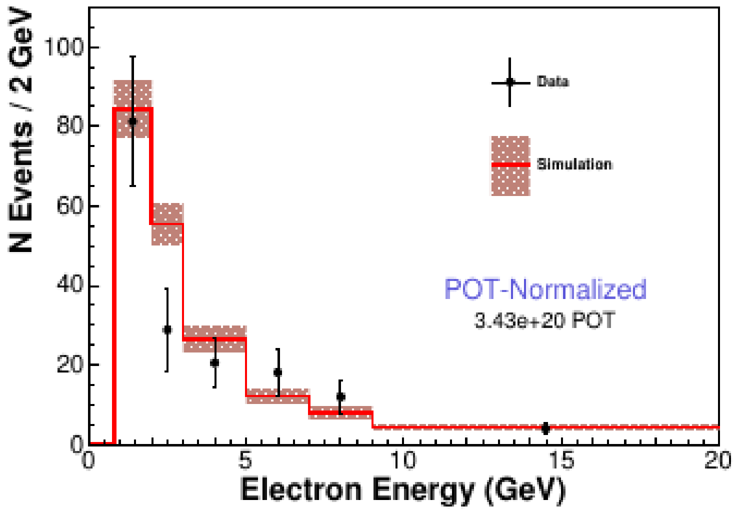
Minerva: clever cuts on electron ID and kinematics (forward electrons)





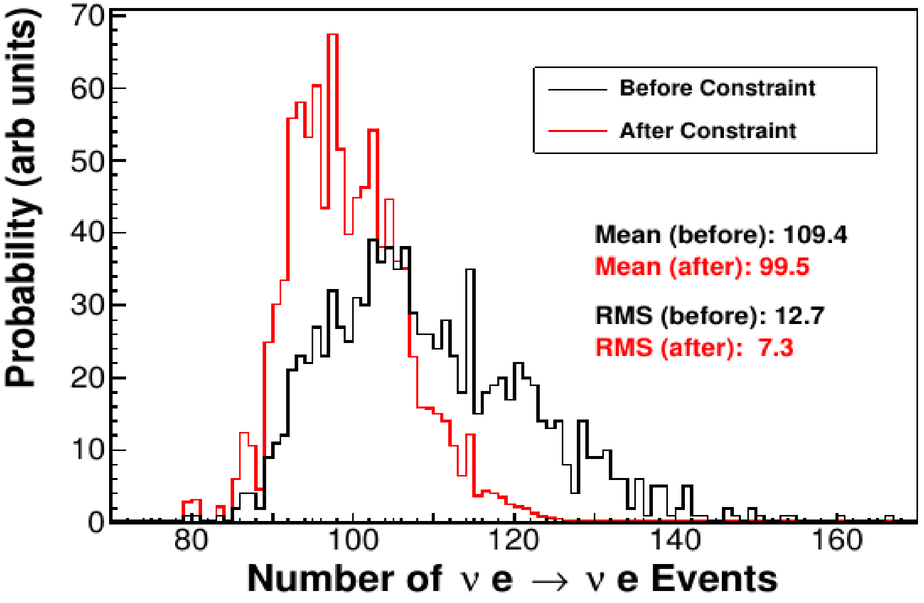


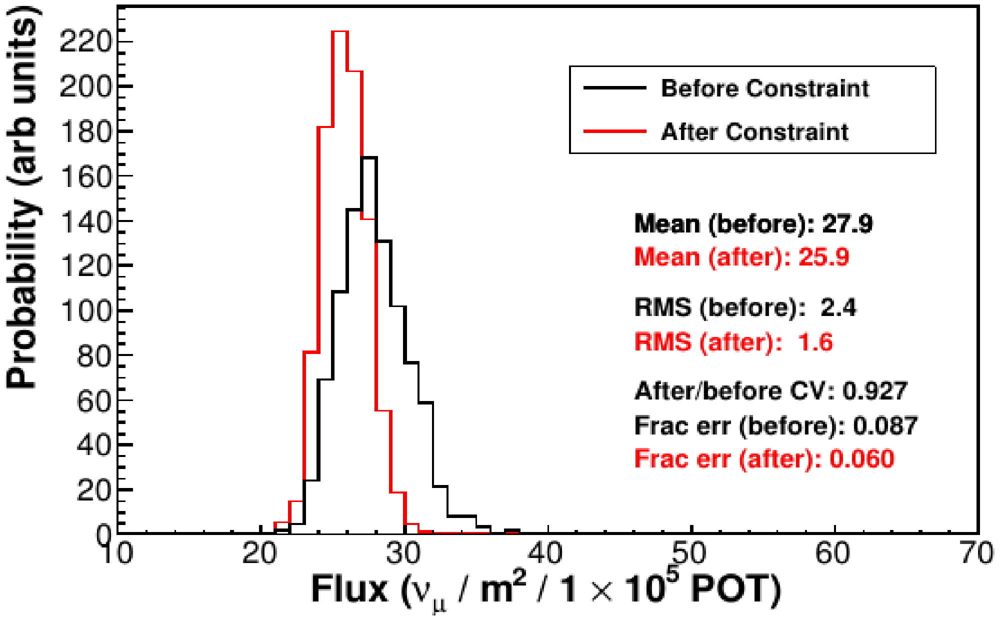
Constraints from ν-e scattering



Flux uncertainty is larger than the uncertainty on the measurement (stat.+syst) → can be used to constrain the flux

10% stat + 5-10% syst → prospects for high precision with future high intensity beams and large near detectors





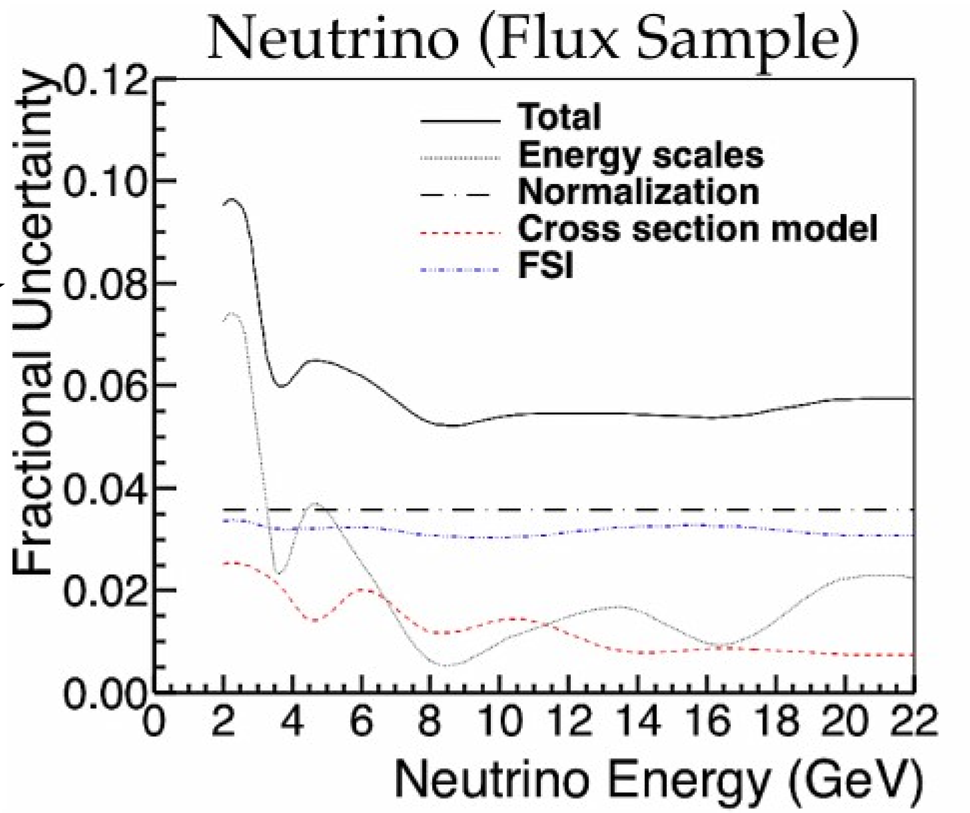
Constraints from low-ν method

$$\frac{d\sigma^{\nu,\bar{\nu}}}{d\nu} = A(1 + \frac{B^{\nu,\bar{\nu}}}{A}\frac{\nu}{E} - \frac{C^{\nu,\bar{\nu}}}{A}\frac{\nu^2}{2E^2})$$

ν= energy transferred to the nucleus

In the limit of ν->0 the xsec does not depend on Eν

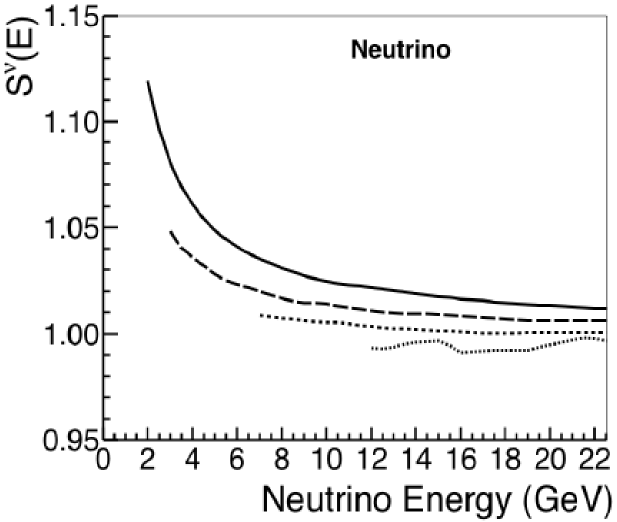
→ **event rate at low ν can be used to constraint the flux shape as a function of Eν**



Limitations:

- difficult to reconstruct the energy transferred to the nucleus: look at energy deposits around the vertex (vertex activity) → correct for neutrons and invisible energy (nuclear excitation, binding energy) below threshold
- flux normalization cannot be constrained
- independence on Eν is an approximation → need to correct with xsec models:

$$S^{\nu}(\bar{\nu})(\nu_0, E) = \frac{\sigma^{\nu}(\bar{\nu})(\nu < \nu_0, E)}{\sigma^{\nu}(\bar{\nu})(\nu < \nu_0, E \to \infty)}$$

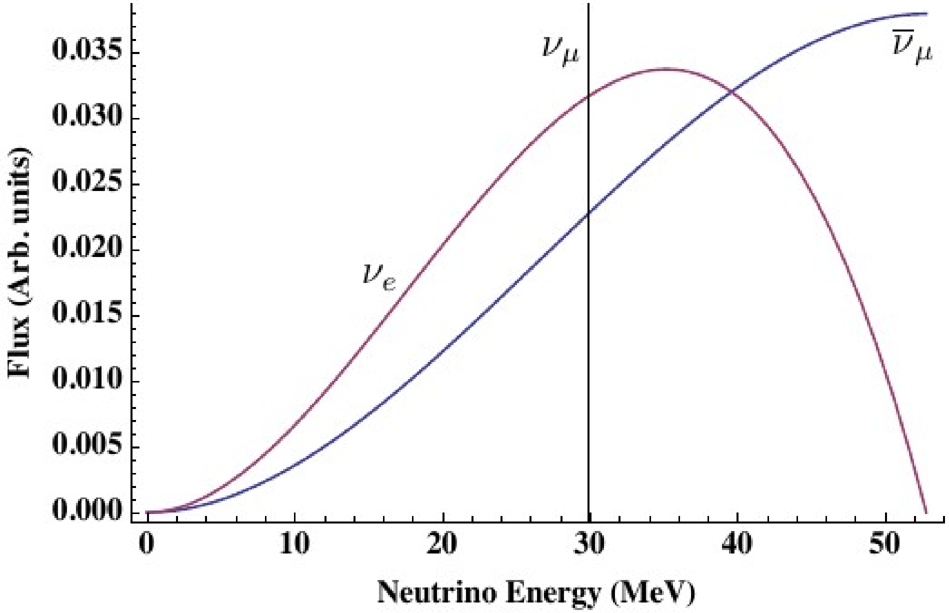


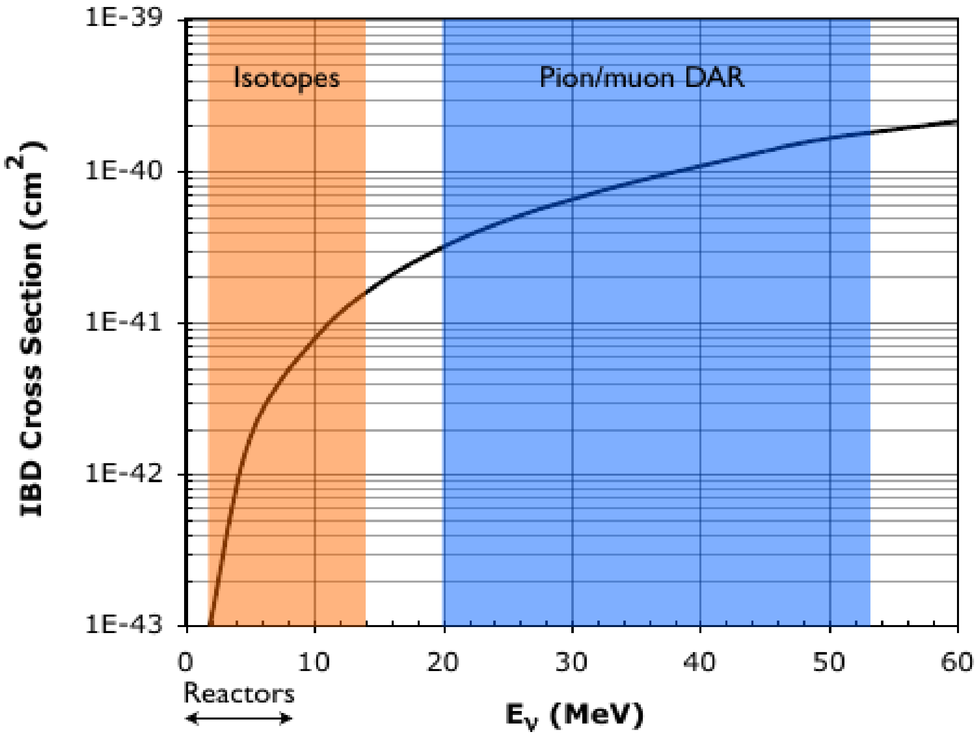
Non standard beams and fluxes

Pion decay at rest (DAR) in contrast to standard pion decay in flight (DIF)

- 😄 well known energy of neutrinos
- 😄 low energy → well known cross-section: IBD ($\bar{\nu}_e + p \rightarrow e^+ n$) and ν-e elastic scattering
- 😪 low energy → very low xsec need VERY intense sources

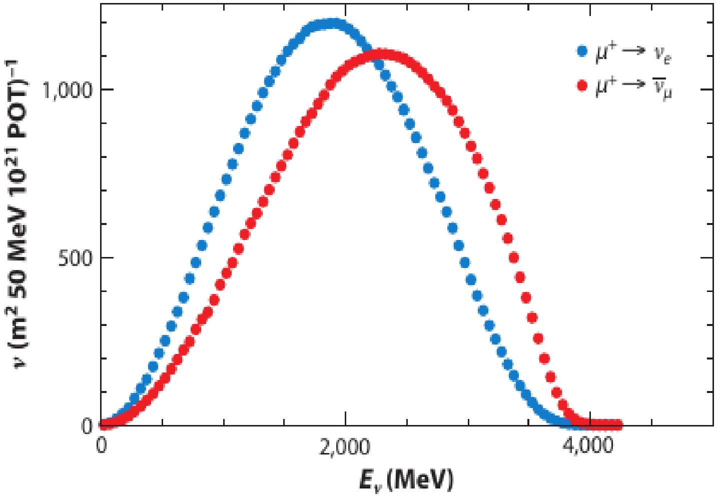
Low energy protons (eg from cyclotron) impinging on target surrounded by absorber to avoid DIF



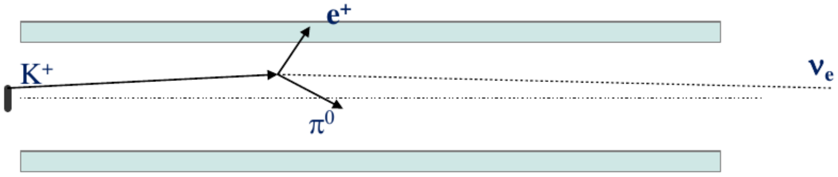


Non standard beams and fluxes

- Neutrinos from Stored Muons (**nuSTORM**): beams from the decay of 3.8 GeV muons confined within a storage ring
  - 😄 well known energy of neutrinos
  - 😄 large ν_e statistics



- Monitor the production of electrons in standard ν beam: uncertainty on ν_e flux improved by one order of magnitude



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$K^+ \to \pi^0 e^+ \nu_e$