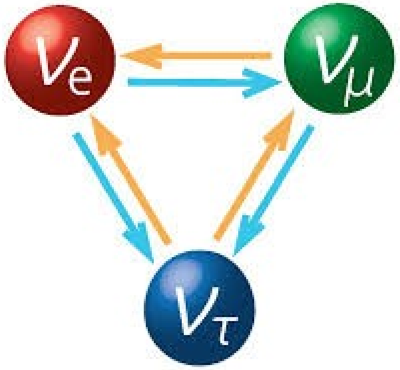
International Workshop on
the Origin of Matter-Antimatter Asymmetry

CP2023

12–17 févr. 2023
École de Physique des Houches
Fuseau horaire Europe/Paris

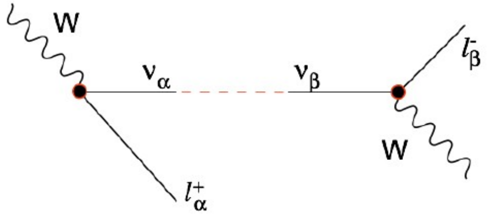
CPV in neutrino oscillations:
introduction to T2K and NOVA



S.Bolognesi (CEA, IRFU)

Neutrino oscillations in long-baseline experiments: how do they happen?

Neutrino oscillations



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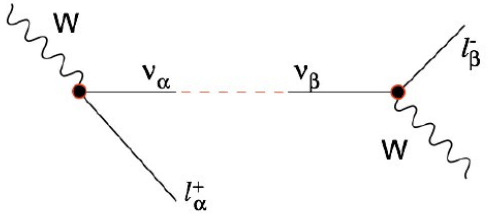
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1}^* & U_{e2}^* & U_{e3}^* \\ U_{\mu 1}^* & U_{\mu 2}^* & U_{\mu 3}^* \\ U_{\tau 1}^* & U_{\tau 2}^* & U_{\tau 3}^* \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Neutrino oscillations



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$U_{\alpha i}$ are expressed in terms of 3 mixing angles (θ_{13}, θ_{23}, θ_{12}) and a phase δ_{CP}

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\rm CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\rm CP}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{\rm CP}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{\rm CP}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{\rm CP}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{\rm CP}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{\rm CP}} & c_{23}c_{13} \end{bmatrix}$$

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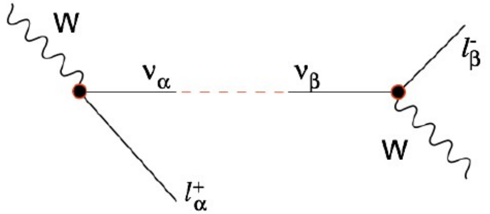

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Time evolution of the mass state $|\nu_k(t)\rangle = \exp(-iE_k t)\,|\nu_k\rangle$

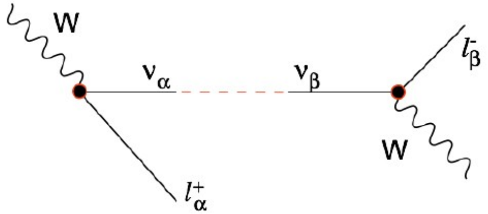
$$P_{\alpha\to\beta} = |\langle\nu_\beta(t)|\nu_\alpha\rangle|^2 = \left|\sum_i U^*_{\alpha i}U_{\beta i}e^{-im_i^2 L/2E}\right|^2 . = \delta_{\alpha\beta} - 4\sum_{i>j}\mathrm{Re}(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin^2\left(\frac{\Delta m^2_{ij}L}{4E}\right)$$
$$+2\sum_{i>j}\mathrm{Im}(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin\left(\frac{\Delta m^2_{ij}L}{2E}\right),$$

neutrino oscillation probability also depends on mass differences: Δm^2_{ij}

$$1.27 \times \frac{\Delta m^2}{\mathrm{eV}^2}\frac{L}{\mathrm{km}}\frac{\mathrm{GeV}}{E}$$

Δm^2 fixes the energy and baseline of experiments:
maximal sensitivity when sin~1 this phase ~ $\pi/2$ (and $3\pi/2$, ...)

Neutrino oscillations



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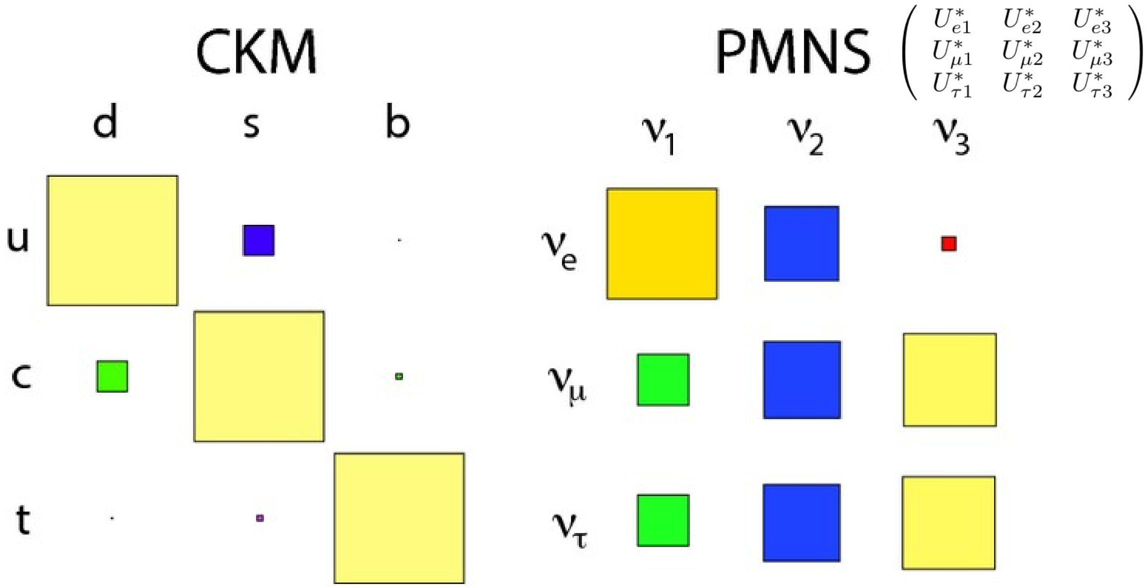
3 mass eigenstate → two Δm^2

$|\Delta m^2_{32}| \sim 2.4\text{x}10^{-3}$ → Long baseline accelerator experiments (~300-1300 km, ~0.5-3 GeV)
(atmospheric experiments integrate many oscillations)

$\Delta m^2_{12} \sim 7.4\text{x}10^{-5}$ → KamLAND (~180 km, ~4 MeV)
(solar ν experiments like SNO actually rely on matter effect)

$|\Delta m^2_{ee}| = |\Delta m^2_{32}| \pm \cos^2\theta_{12}\,\Delta m^2_{21} \sim 2.6\text{x}10^{-3}$ → Reactor experiments (~1-1.5km, ~3MeV)

Status and open questions

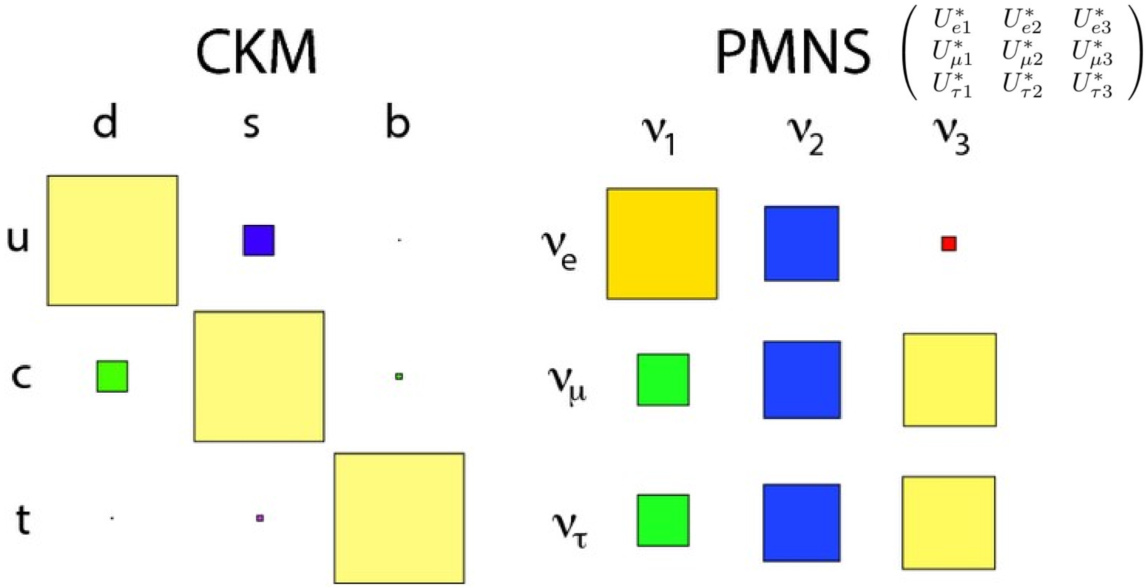


- **Precision measurements of flavour mixing pattern:**

  - very large mixing (θ_{23} ~$\pi/4$ would imply maximal mixing, ie $U_{\mu i}$~$U_{\tau i}$, if not which octant?)

  - θ_{13} smaller but not so small (U_{e3}) → access to δ_{CP} phase

Status and open questions



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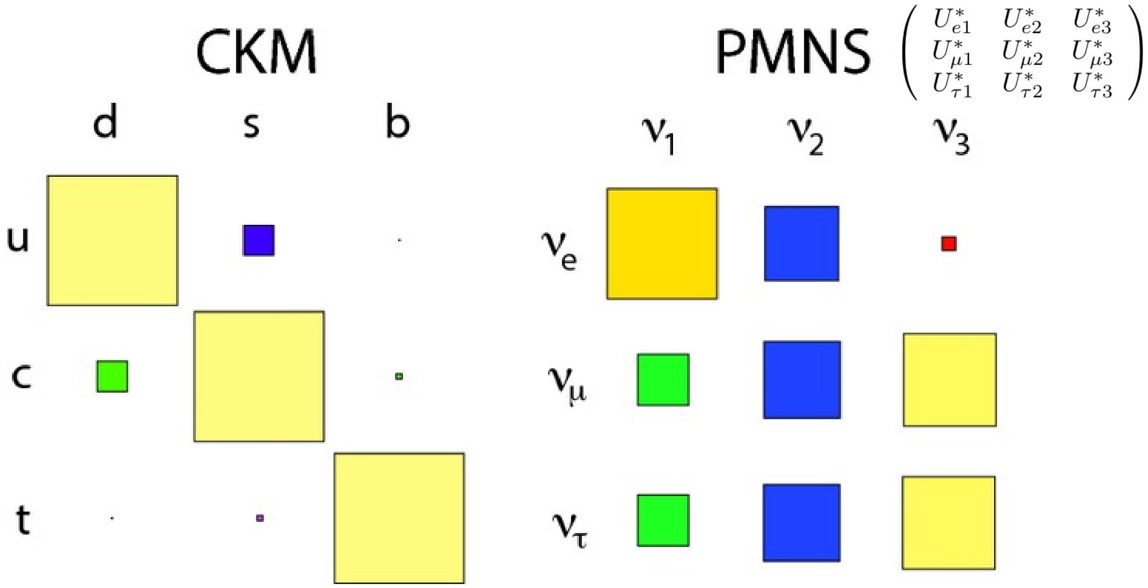
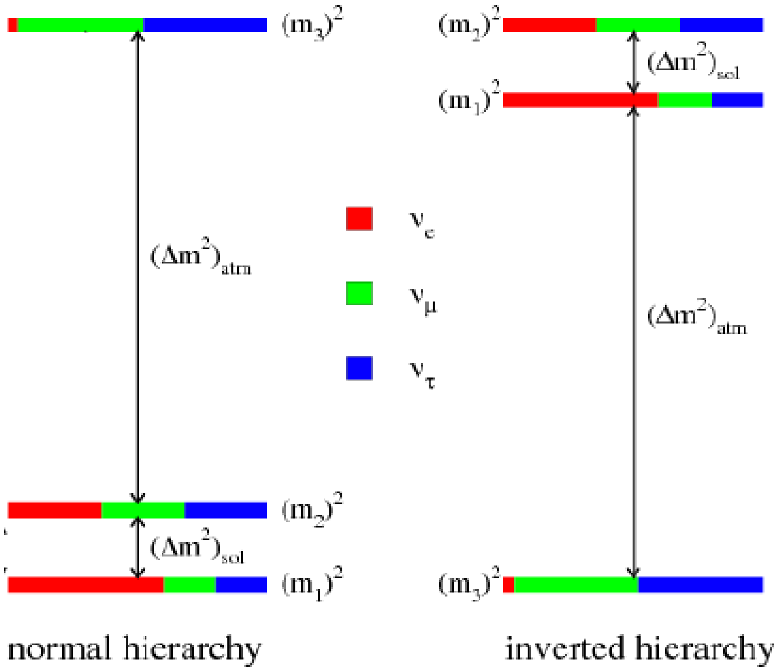
- δ_{CP} parametrizes different oscillations for ν and $\bar{\nu}$ what is its value? If not 0,π then **new fundamental source of CP violation (and first in leptonic sector!)**

Status and open questions





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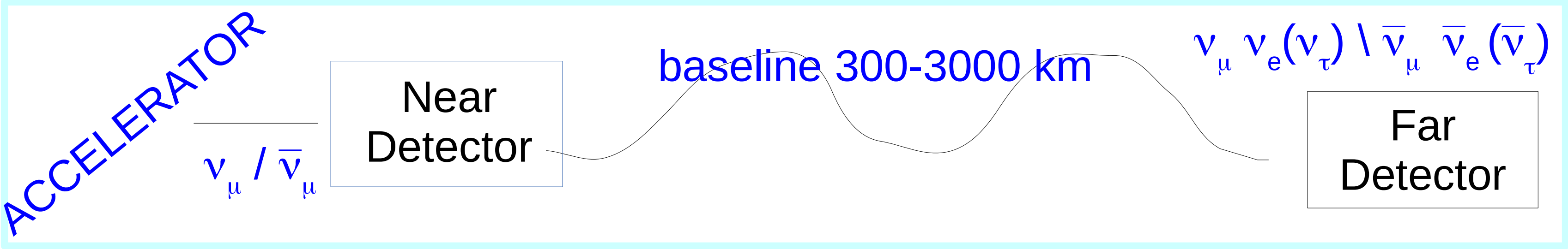
- **Mass Hierachy :** is the mass ordering the same for charged and neutral leptons?

  - in combination with cosmological measurements can constrain the neutrino mass

  - important input to $0\nu\beta\beta$ measurement

Long-baseline experiments

- Oscillation probability estimated by **comparing ν (and $\bar{\nu}$) rate by flavor between source (near detectors) and far detectors:**



ACCELERATOR

ν_μ / $\bar{\nu}_\mu$

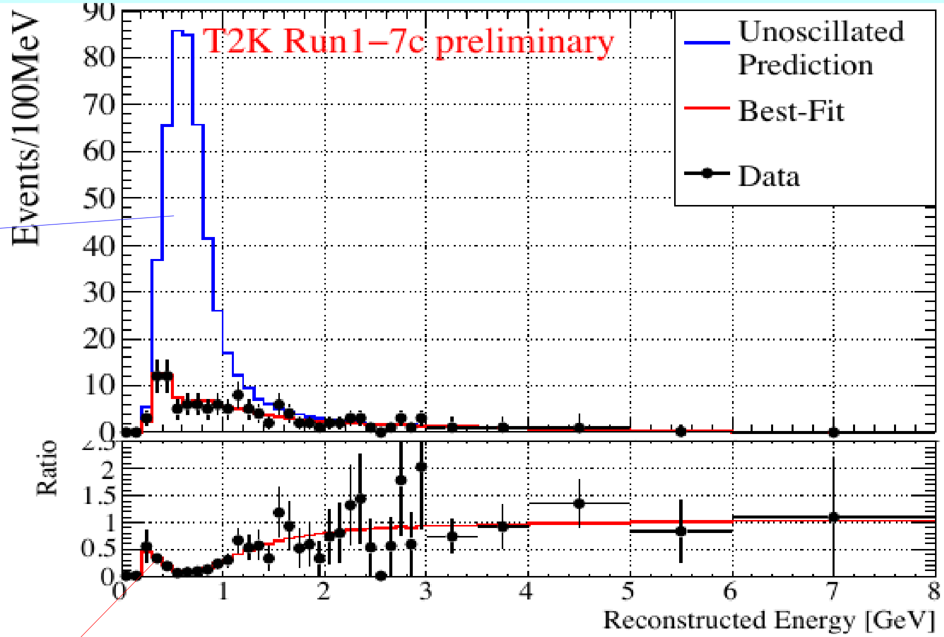
Near Detector

baseline 300-3000 km

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

Far Detector

Flux of produced neutrinos
x
cross-section of neutrino interaction in our detectors



Oscillation in two flavour approximation

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

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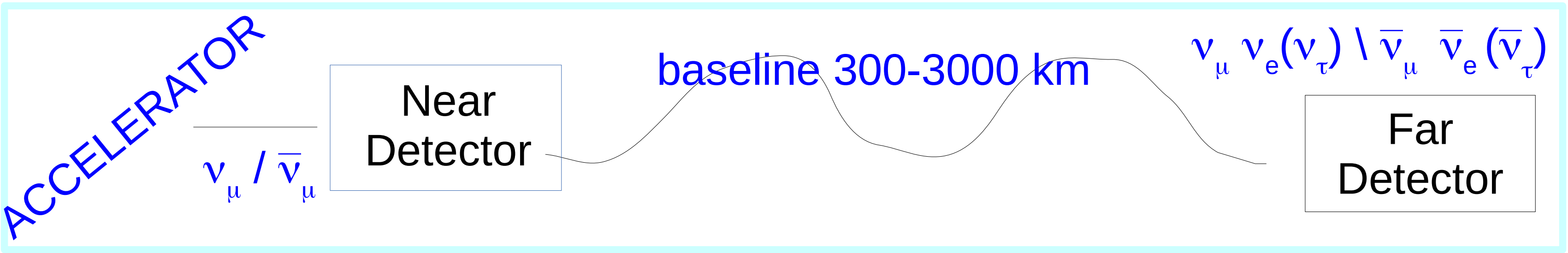


ACCELERATOR

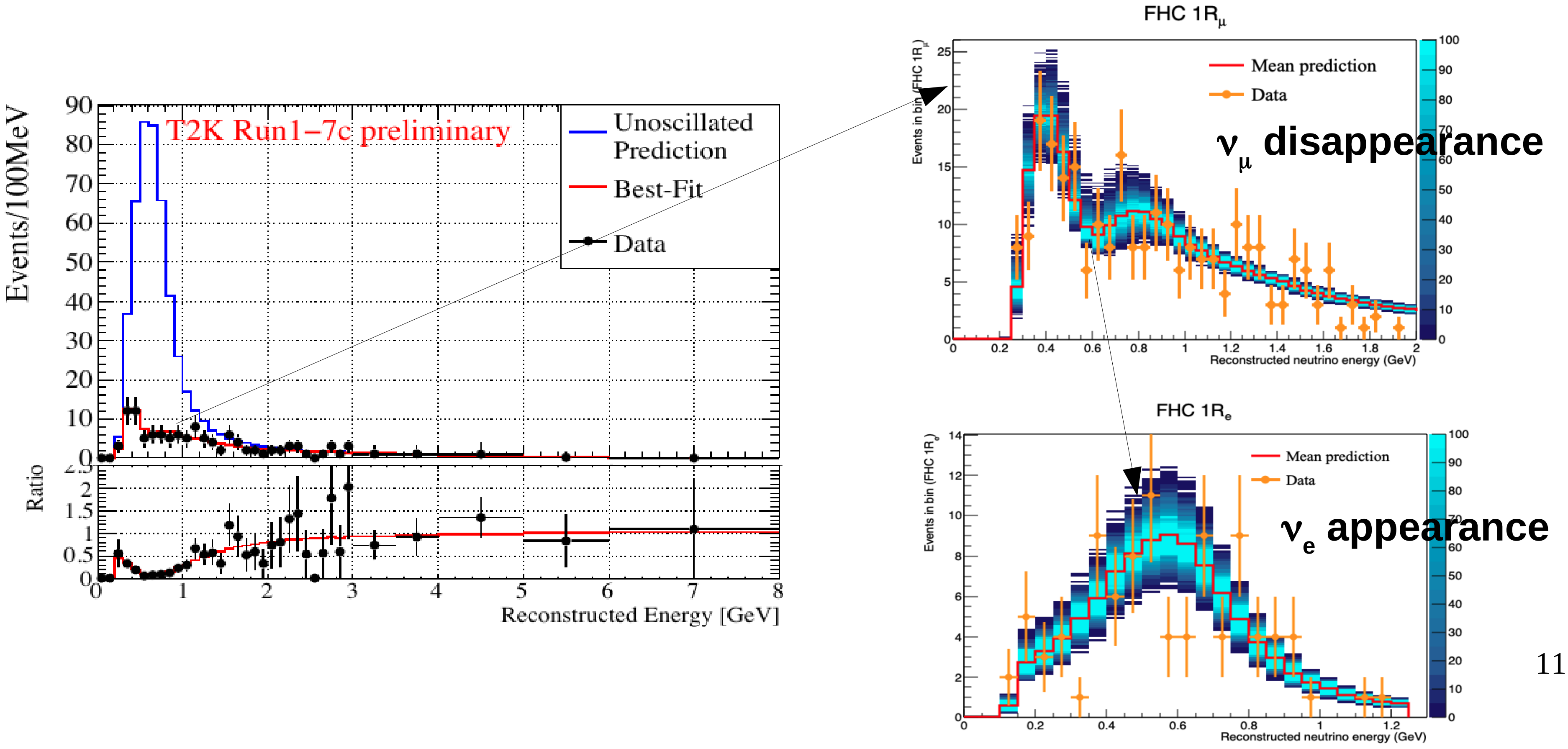
ν_μ / $\bar{\nu}_\mu$

Near Detector

baseline 300-3000 km

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

Far Detector



T2K preliminary Run1-10

ν_μ disappearance: $\sin^2 2\theta_{23}$, $|\Delta m^2_{32}|$

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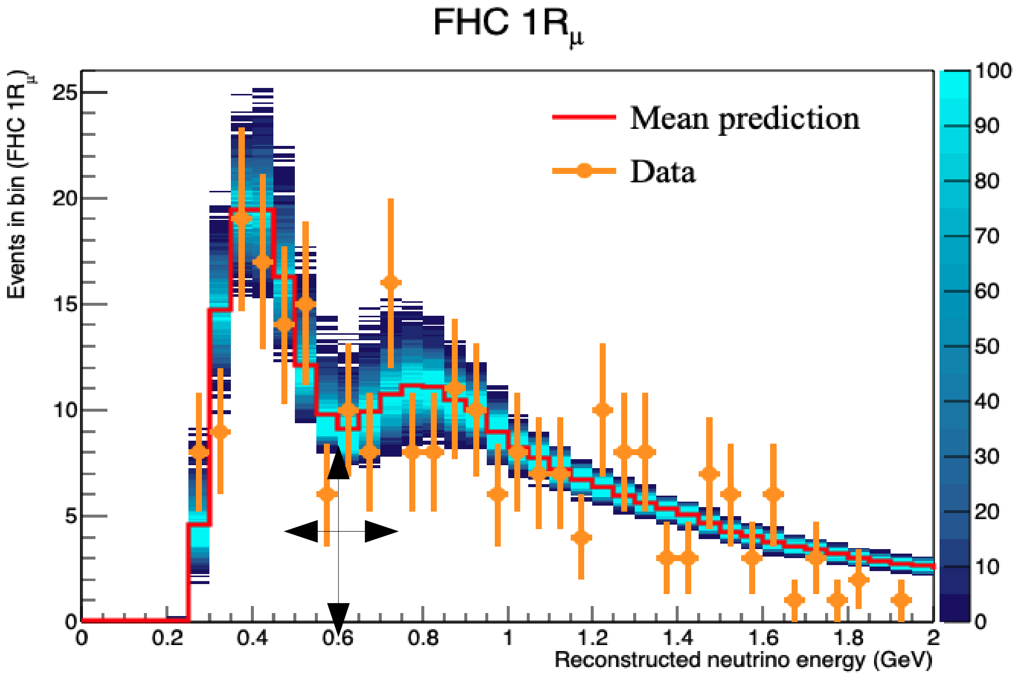
(simplified 2-flavors approximation)

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

→ need to control rate of neutrinos (flux x cross-section)

- **$\Delta m^2_{31(32)}$ ~ frequency of the disappearance** (position of spectrum minimum)

→ need to control energy spectrum (energy resolution and scale)

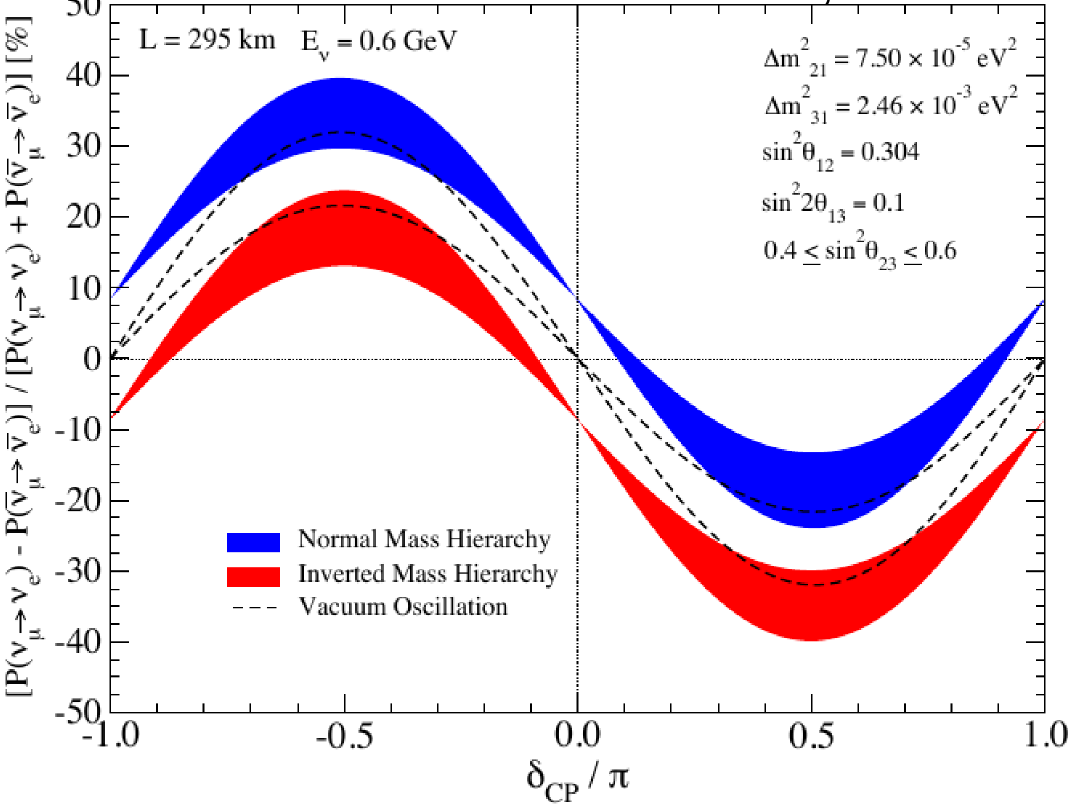


$\nu_e/\overline{\nu}_e$ appearance: δ_{CP} and MH

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

T2K baseline and energy

~30% CPV, 10% MO



Matter effects are different between neutrinos and antineutrinos, since they rise effectively from the charged-current interaction with the Earth matter

- All neutrinos (ν_e, ν_μ, ν_τ) interact with matter (e,p,n) through Z0 exchange (Neutral Current) → overall phase in mass eigenstate evolution which can be subtracted.

- ν_e also makes charged current interactions (W+-) with electrons in matter
→ additional potential in matter of opposite sign for $\nu_e/\overline{\nu}_e$ $\quad A = \pm 2\sqrt{2} G_F N_e E\,,$

- larger neutrino energy and longer baseline → larger the matter effect
(Earth crust~constant density and at LBL below MSW effect)

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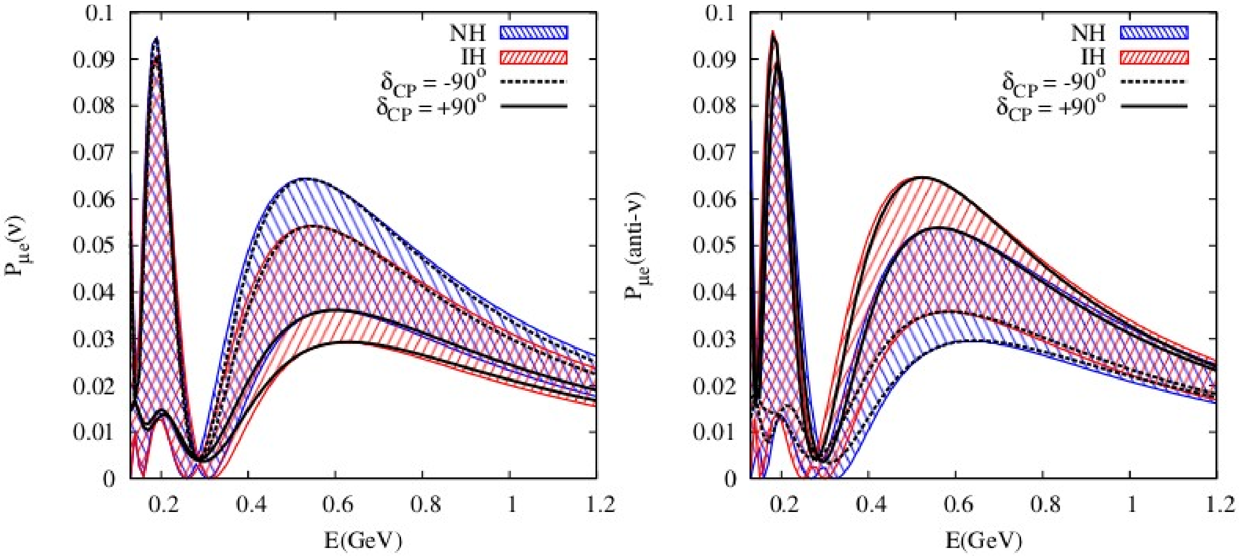


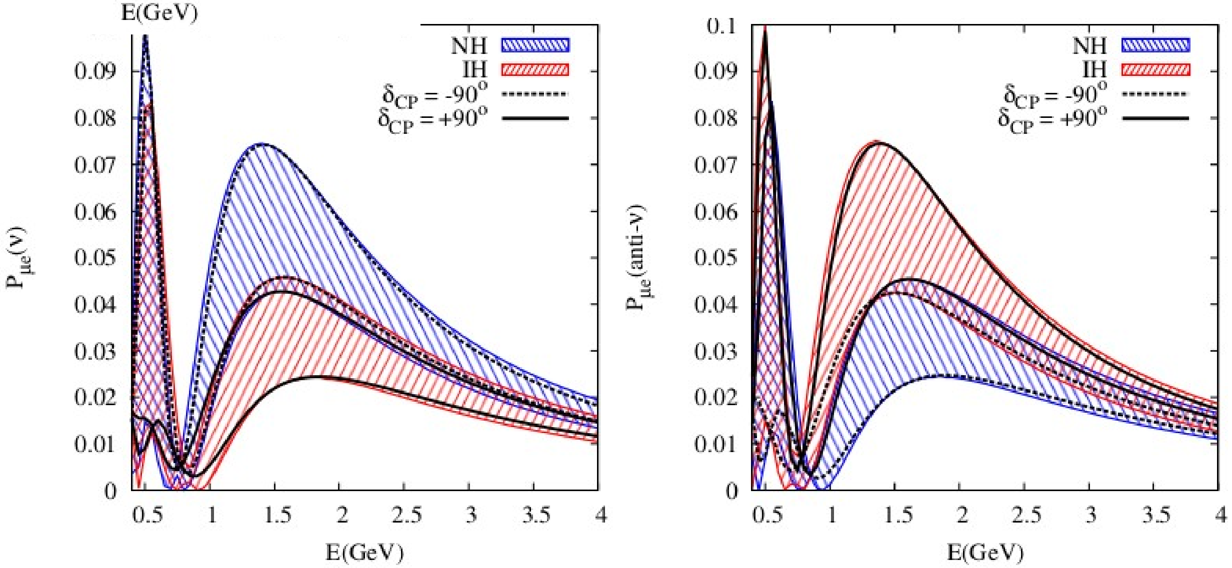
Adv.High Energy Phys. 2014 (2014) 457803

$\sin^2 2\theta_{13} = 0.089$, $\sin^2\theta_{23} = 0.5$

L=295km
(T2K)

L=810km
(NOVA)

30% CPV,
30% MH
(degeneracy)



$\nu_e \leftrightarrow \nu_\mu$

So **can we just focus on $\nu_e/\bar{\nu}_e$ counting** (CPV discovery is mostly a counting experiment) and forget about all the complications of precision physics on ν_μ (relatively high statistics already now) ?

My personal opinion: NO!

- would a claim of 5σ discovery on CPV be trusted if we cannot describe the ν_μ oscillated spectra? Most of systematics (both for detector and for flux and cross-section model) are correlated between ν_e and ν_μ

- flux and cross-section of ν_e cannot be precisely constrained by near detector because very few ν_e in the flux before oscillation → use ν_μ to constrain ν_e and this could be done only if we trust the model enough to extrapolate from one flavour to another

- in the CPV-MH degeneracy regions, precise ν_e energy spectrum helps disentangling the two effects

- on the long term, the measurement of δ_{CP} requires good precision in ν_e energy spectrum

ν_e systematic uncertainties are important and will be constrained mostly by ν_μ precision measurements

From CPV discovery to δ_{CP} measurement

Asking if $\delta_{CP} \neq 0,\pi$ or asking what is its value are two different questions:

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

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

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

Actually at second order:

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

detailed formula →

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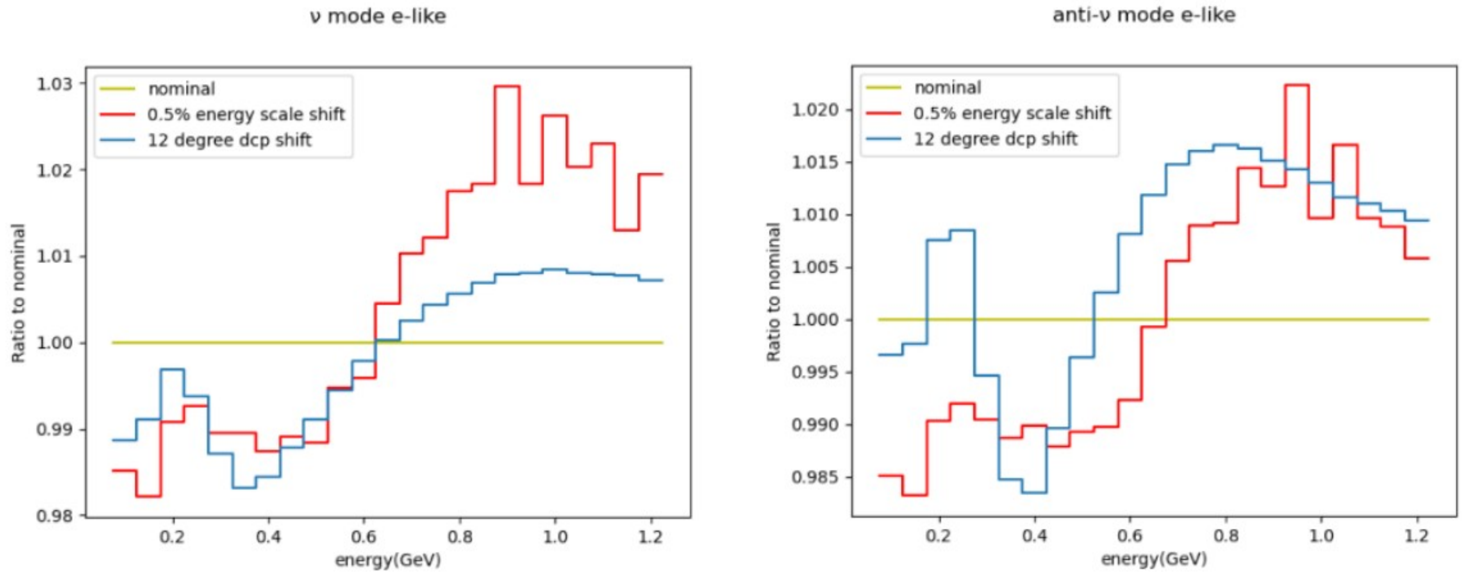
At δ_{CP}~ +/-π/2 the precision on δ_{CP} (~P_{app} derivative on δ_{CP}) is dominated by the second term: **precise energy spectrum measurement (cosδ_{CP} dependance) dominate the resolution**

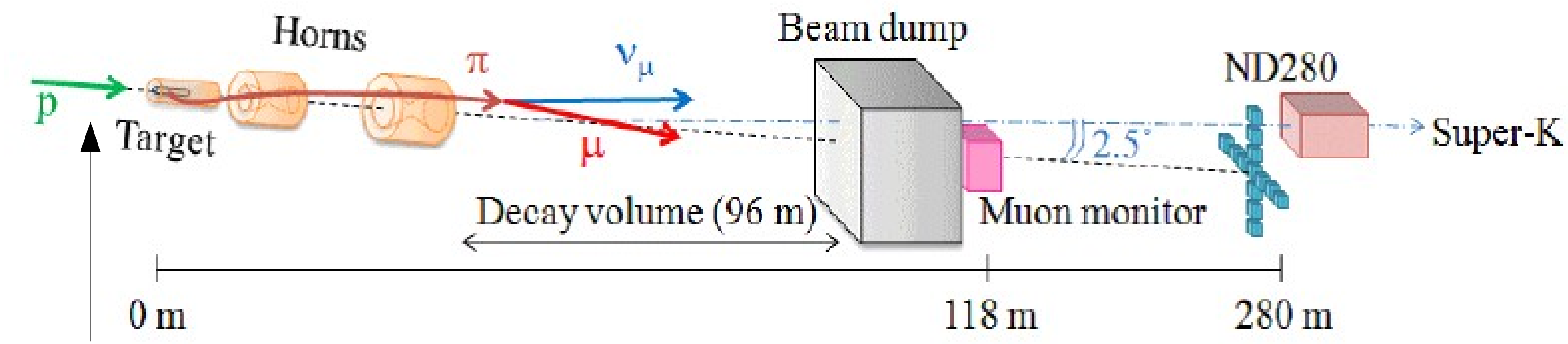


L.Munteanu
Nufact 2021

Neutrino oscillations in long-baseline experiments: how do we measure them?

Neutrino ‘beam’

Beam: protons → pions

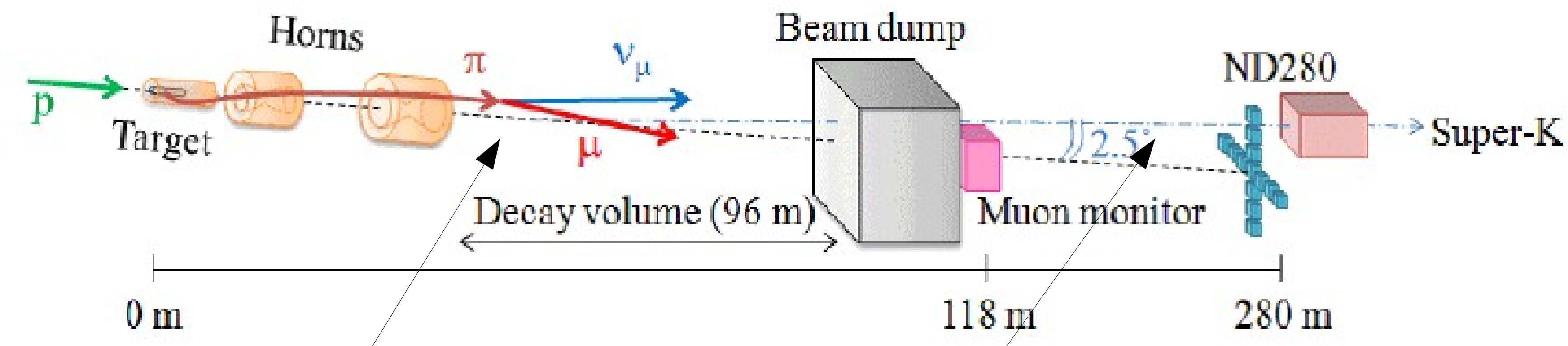


- Proton beam:
30 GeV JPARC, 120 GeV NuMi FNAL → 500 kW and above (next generation 1-2MW)

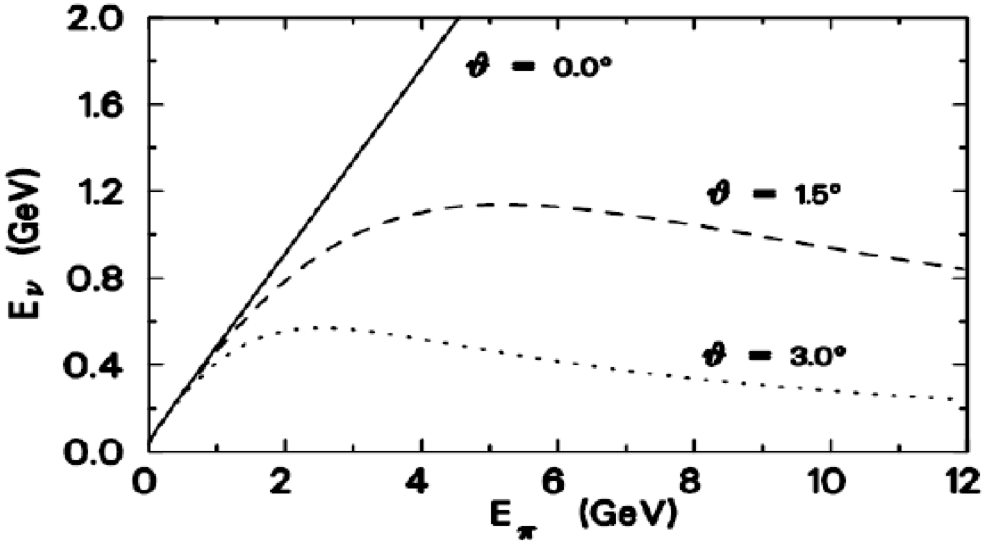
$$P(kW) \propto POT\ (10^{20}) \times E_p\ (GeV)/T\ (10^7\ s)$$

- Horns to focus all pions (kaons) of the right sign
  - $\pi^+ \rightarrow \mu^+\nu_\mu$ Forward Horn Current (FHC) → ν_μ flux
  - $\pi^- \rightarrow \mu^-\bar{\nu}_\mu$ Reverse Horn Current (RHC) → $\bar{\nu}_\mu$ flux

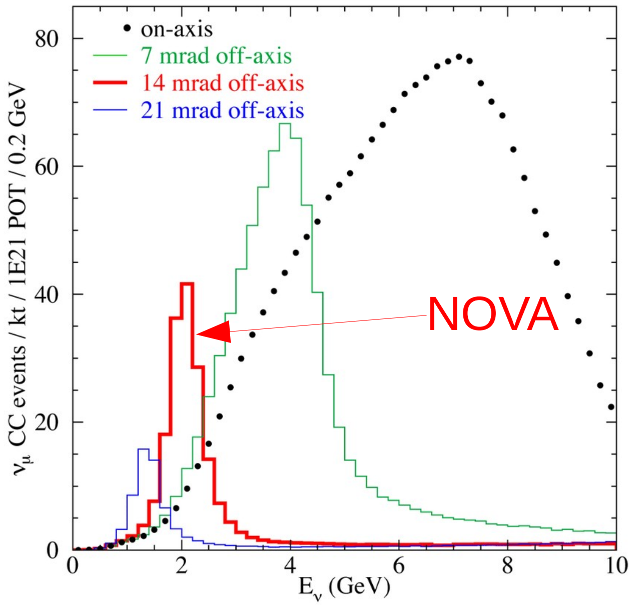
Beam: off-axis



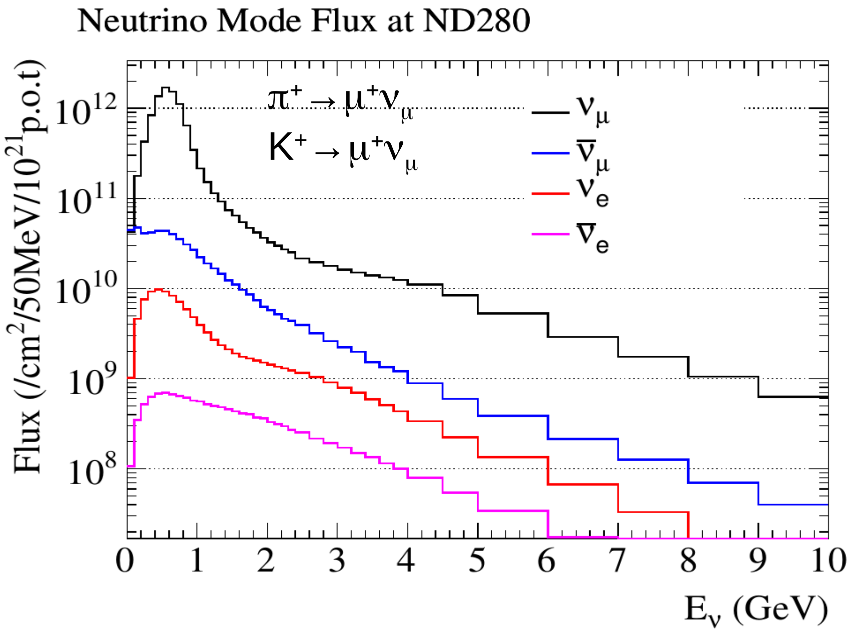
Energy of ν emitted in 2-body decay at an angle relative to π direction is only weakly dependent on parent's momentum

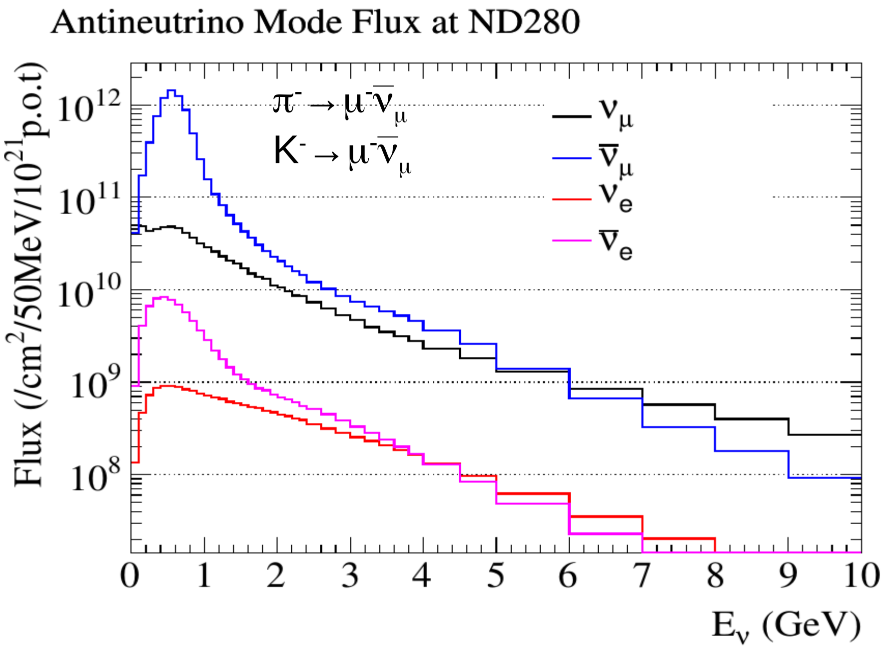


Tune the angle → tune the energy to be at the peak of ν_μ disappearance (~E/L)



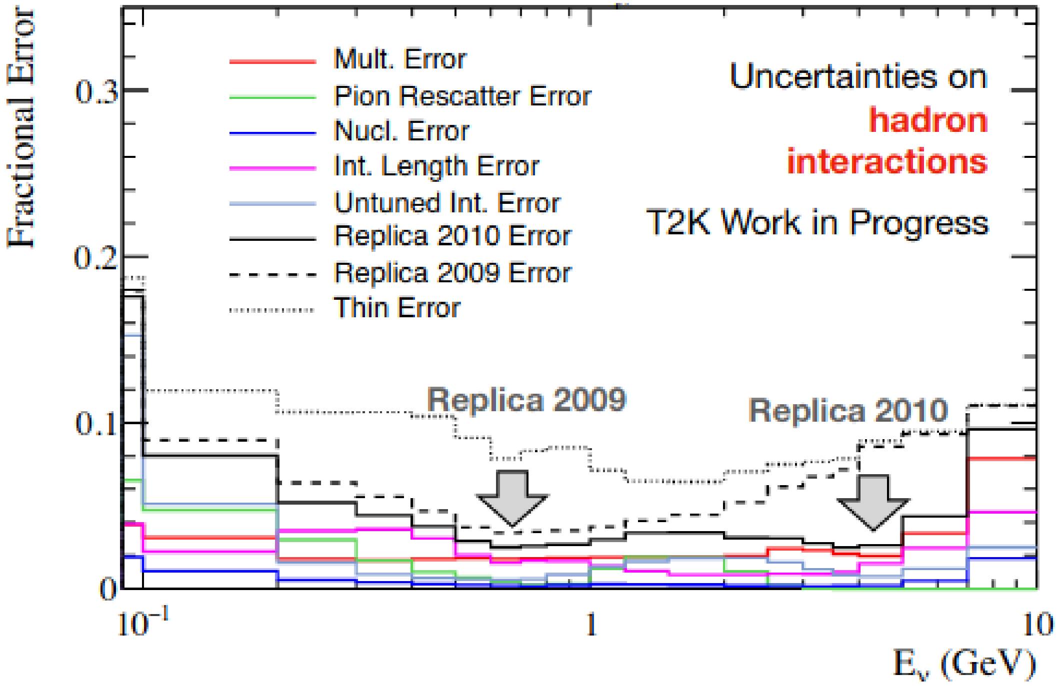
Flux


Neutrino Mode Flux at ND280


Antineutrino Mode Flux at ND280

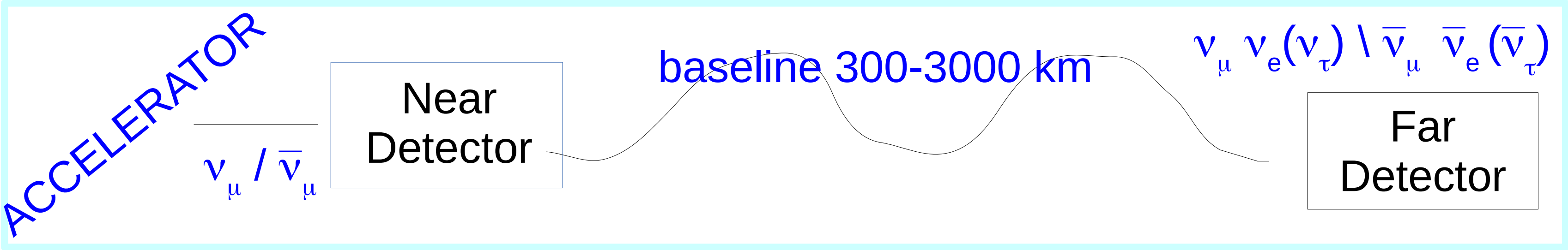
- ν_e intrinsic background
- Wrong sign background
(ν in $\bar{\nu}$ beam)

- Flux tuning with hadroproduction measurements at dedicated experiments.
Example from NA61 with replica-target of T2K



From near to far detector

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:

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

→ 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

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

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

measured number of neutrino interactions at the ND

→ systematic minimized if same flux (eg, same off-axis angle) and same target material
(same acceptance is not possible due to different size of ND and FD)

But the most complicated part is :

1) the neutrino energy spectrum is different at ND (before oscillation) and at the FD (after oscillation)
→ so we measure the xsec and flux at a given energy and we need to extrapolate to a different energy

2) 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)

The difficult part ...

The following issues induce an ***unavoidable model dependency in any oscillation analysis*** and make the evaluation of systematics in oscillation measurements a difficult task:

- how to reconstruct energy from the final state of neutrino interactions
- extrapolation of xsec and flux to different energy spectrum
- separate flux and xsec evaluation from ND data

Need reliable models of flux and neutrino-nucleus cross-section models

Specifics of $\nu_e/\bar{\nu}_e$ (→ CPV)

Due to low statistics $\nu_e/\bar{\nu}_e$ at the near detector, we use $\nu_\mu/\bar{\nu}_\mu$ to constrain all systematics which are correlated between ν_e and ν_μ

→ main remaining systematics are:

- difference in cross-section between $\boldsymbol{\nu_e/\bar{\nu}_e}$ and $\boldsymbol{\nu_\mu/\bar{\nu}_\mu}$
  - lepton universality holds! In any given model of ν-nucleus interaction the $\boldsymbol{\nu_e}$ → $\boldsymbol{\nu_\mu}$ extrapolation is straightforward (different mass)
  - we do not control well ν-nucleus interaction even in $\boldsymbol{\nu_\mu}$: a lot of work on-going to improved the models and have good tuning of them from near detector
- difference in flux: $\boldsymbol{\nu_e}$ at oscillation peak energy mostly from muons → strong correlation with $\boldsymbol{\nu_\mu}$

$\pi^+ \rightarrow \mu^+\nu_\mu$

$K^+ \rightarrow \mu^+\nu_\mu$

$\mu^+ \rightarrow e^+\nu_e\nu_\mu$

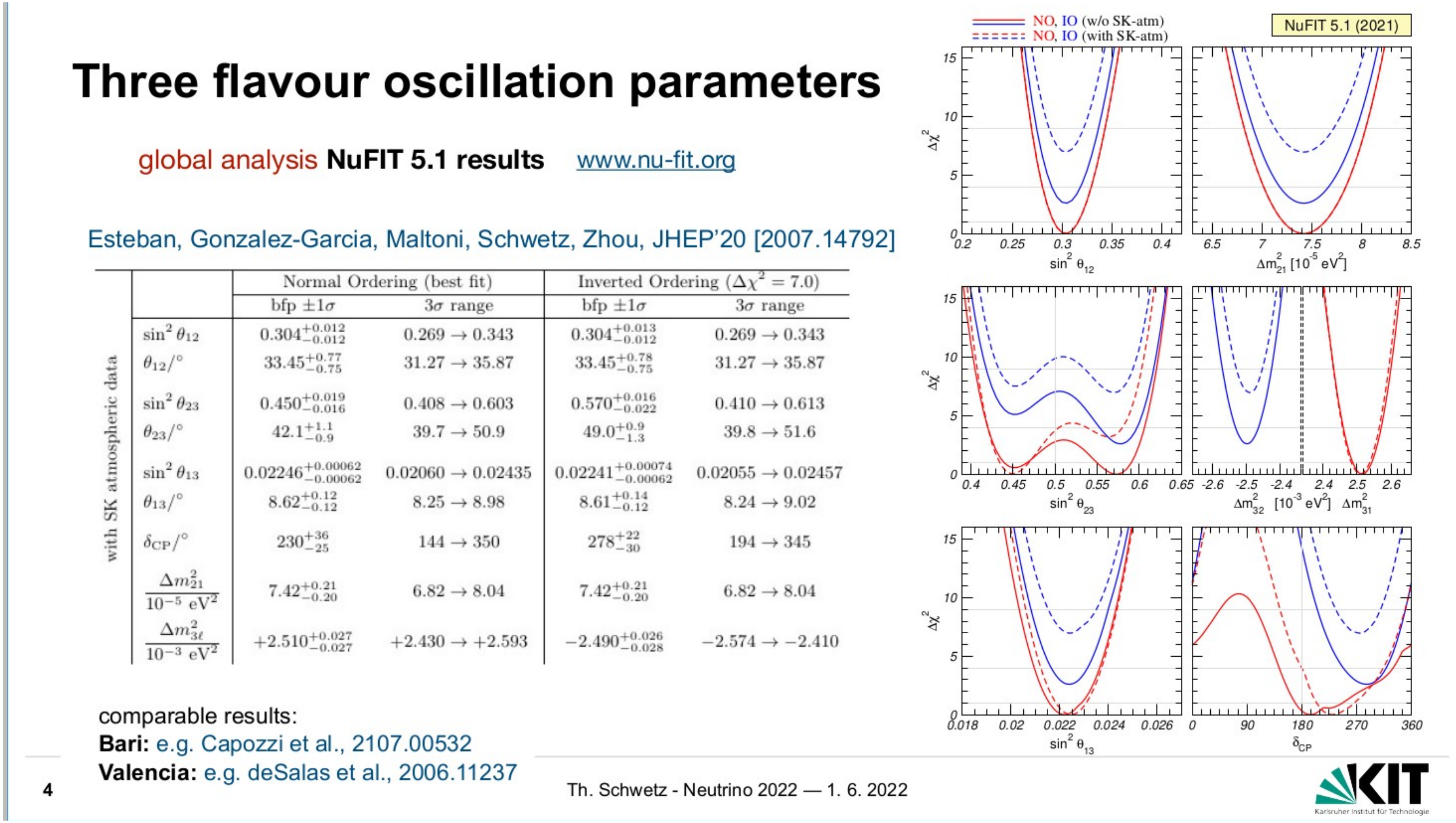
→ **solution: very precise measurements of at near detector $\nu_\mu/\bar{\nu}_\mu$**

- **difference in far detector systematics between ν_e and ν_μ** (in general, having very different reconstruction/resolution/efficiency for e and μ is a weak point)

Present status of oscillation parameters

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]

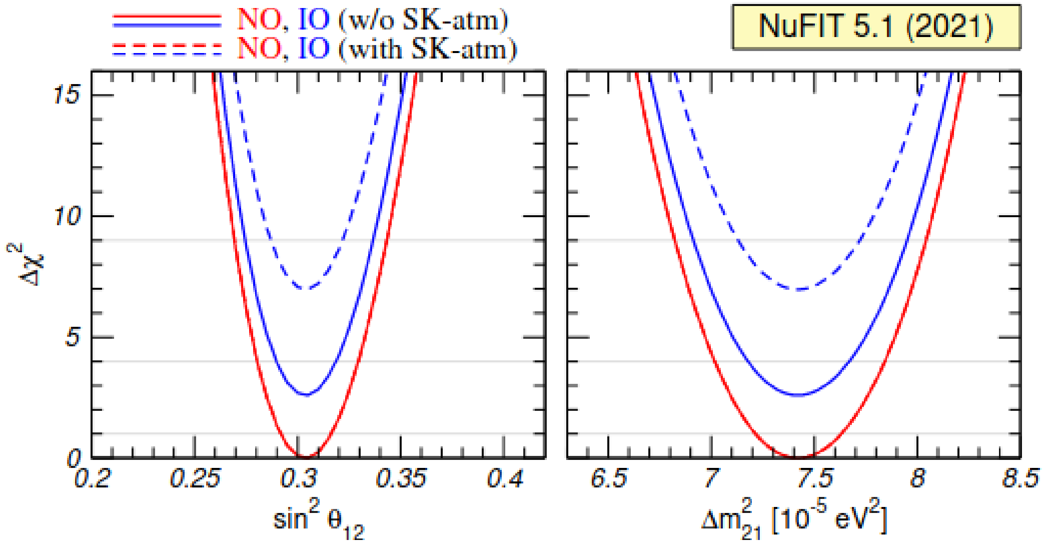
		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 7.0$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
with SK atmospheric data	$\sin^2\theta_{12}$	$0.304^{+0.012}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$
	$\theta_{12}/^\circ$	$33.45^{+0.77}_{-0.75}$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

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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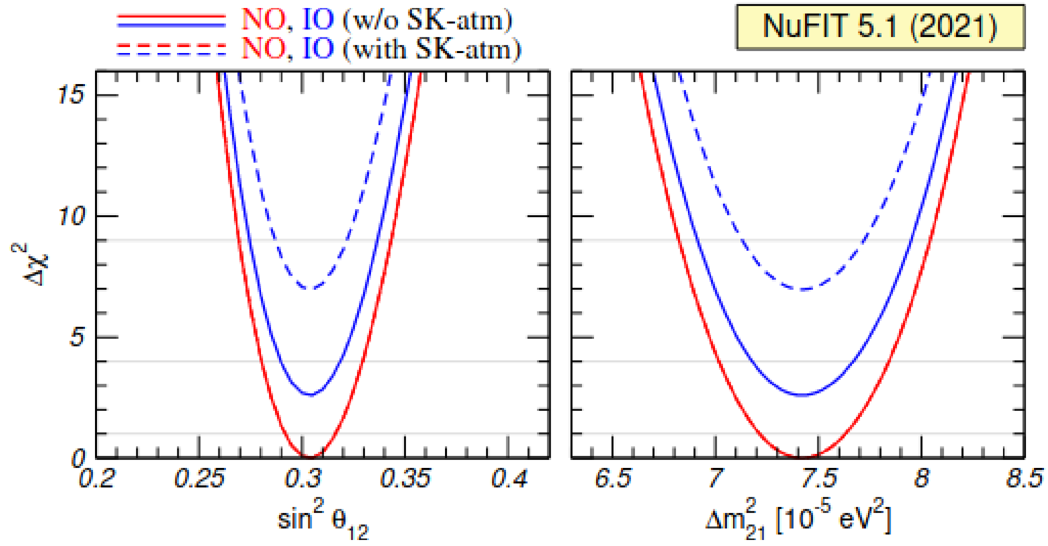

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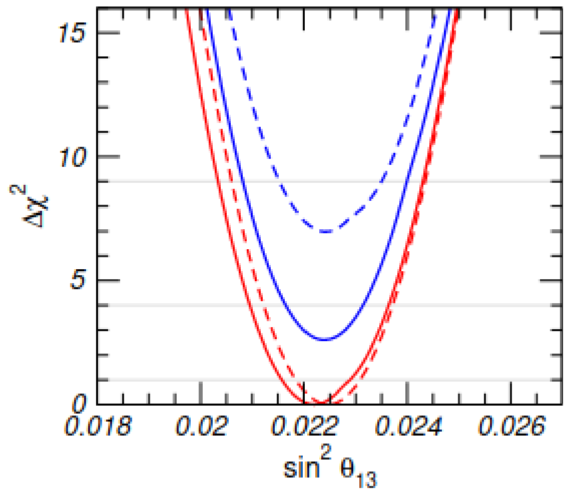

θ_{13} measured with reactor experiments at ~1% precision

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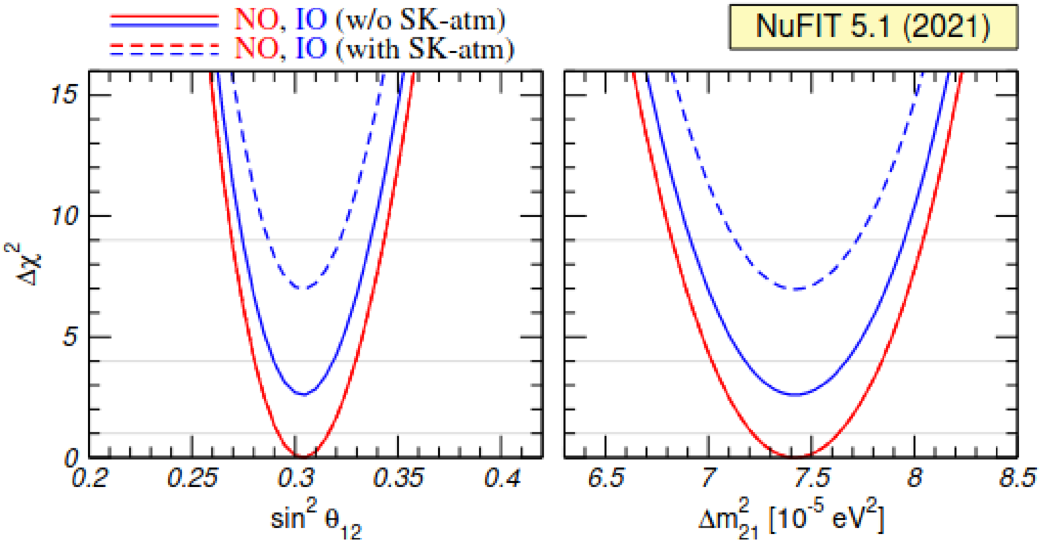

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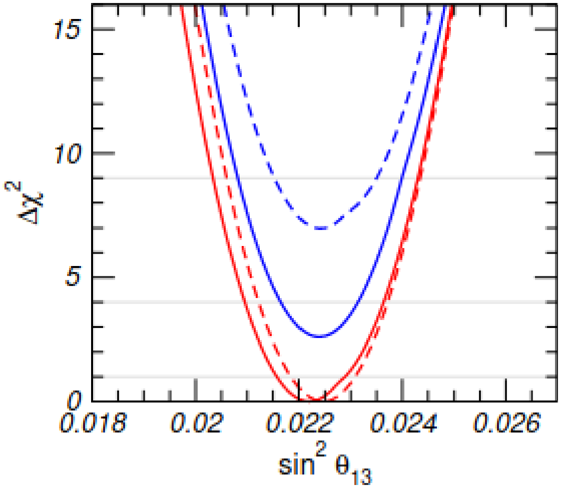

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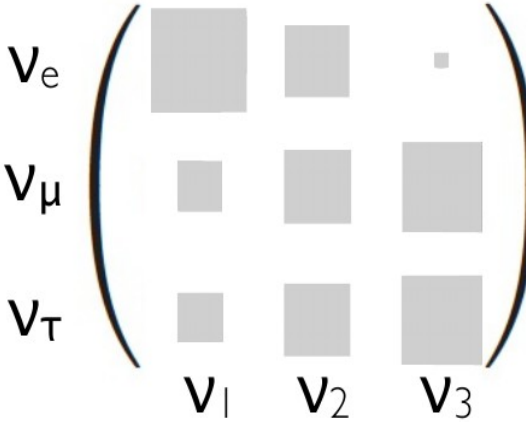
Best avenue for PMNS unitarity test:



⇒ **best precision**

⇒ **OK precision**

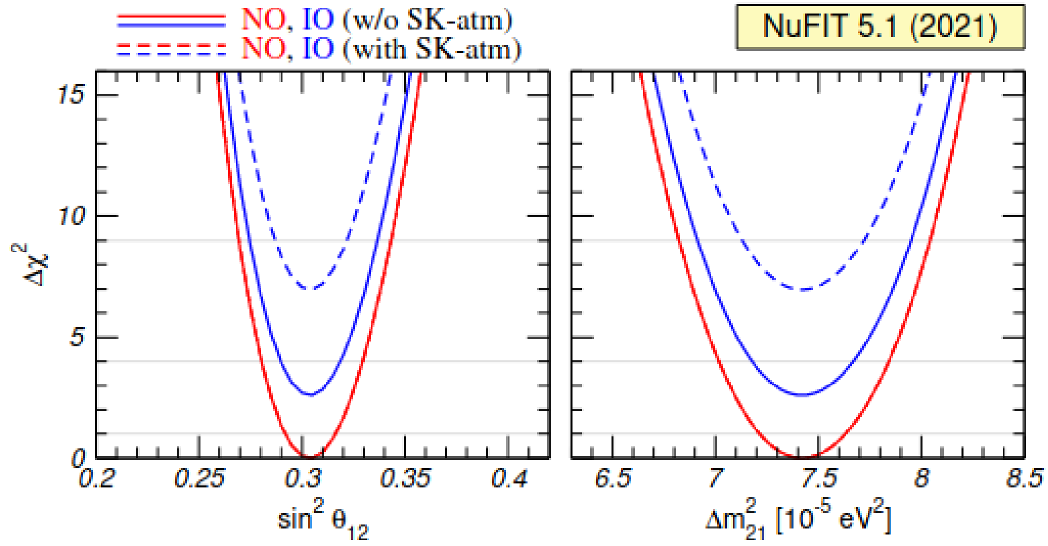
⇒ **poorest precision**

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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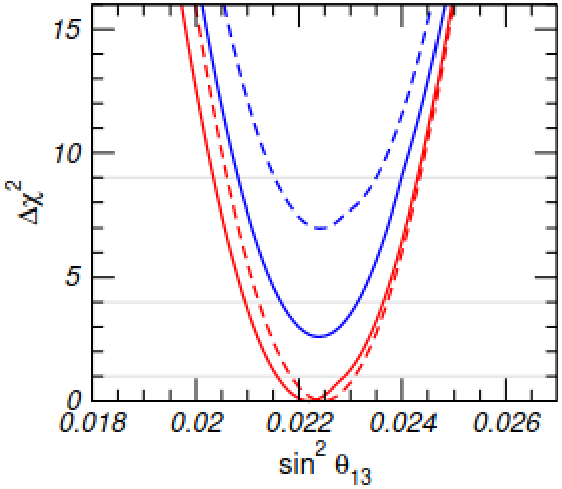

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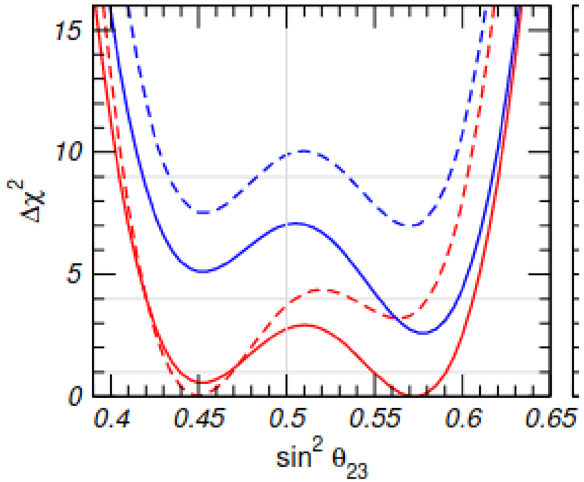

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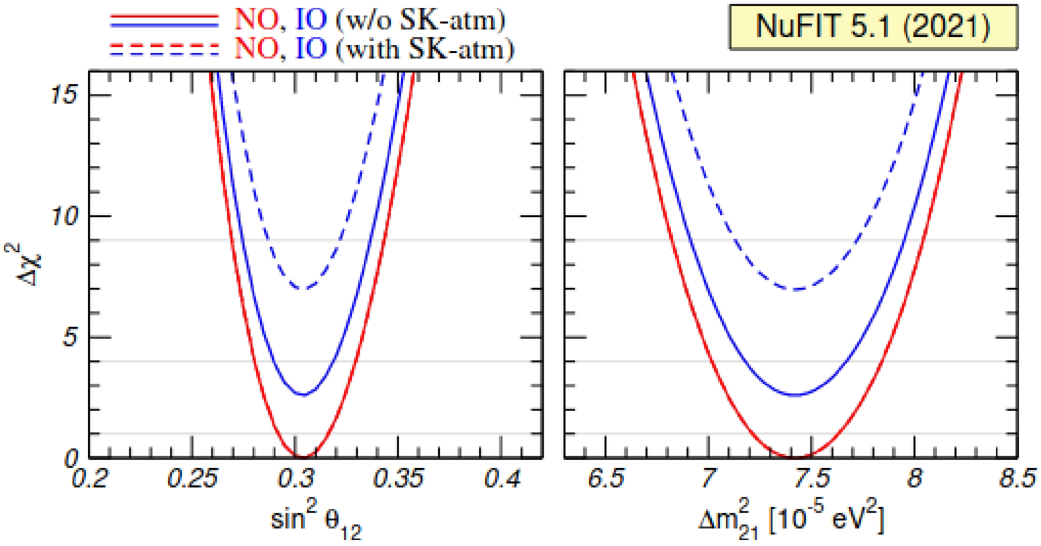

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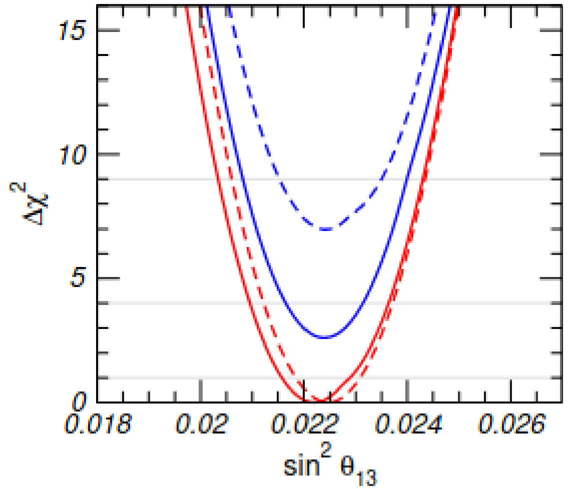

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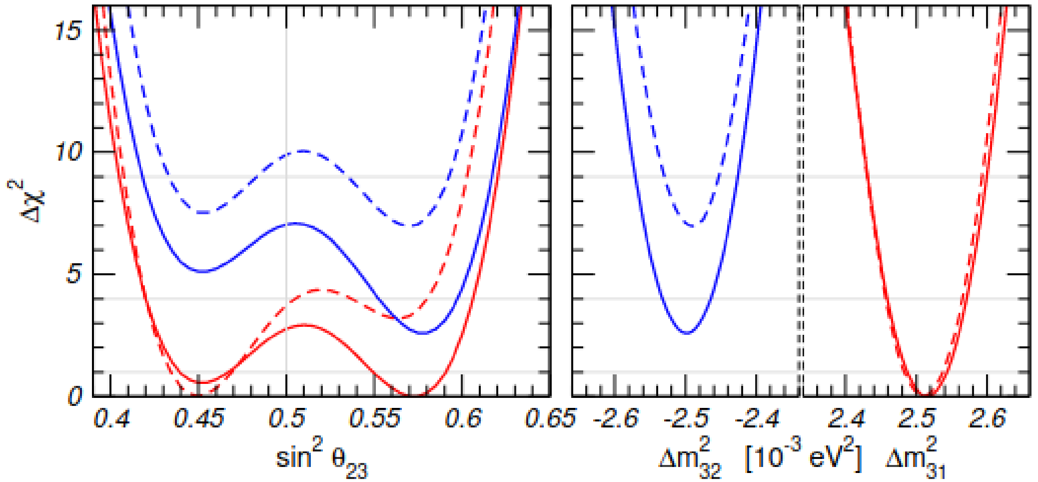
- **$|\Delta m^2_{31(32)}|$ ~1%** (not so robust...) → important to get <1% (see later) challenging to control systematics uncertainties

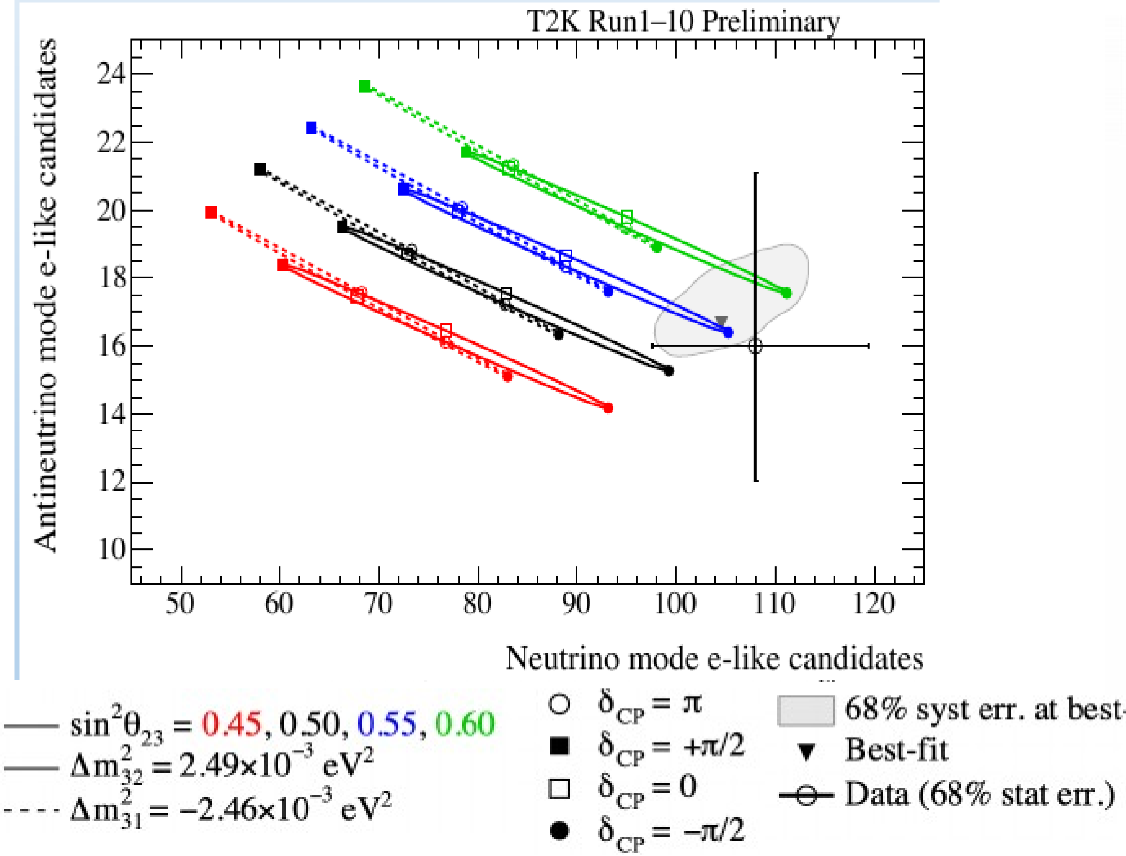


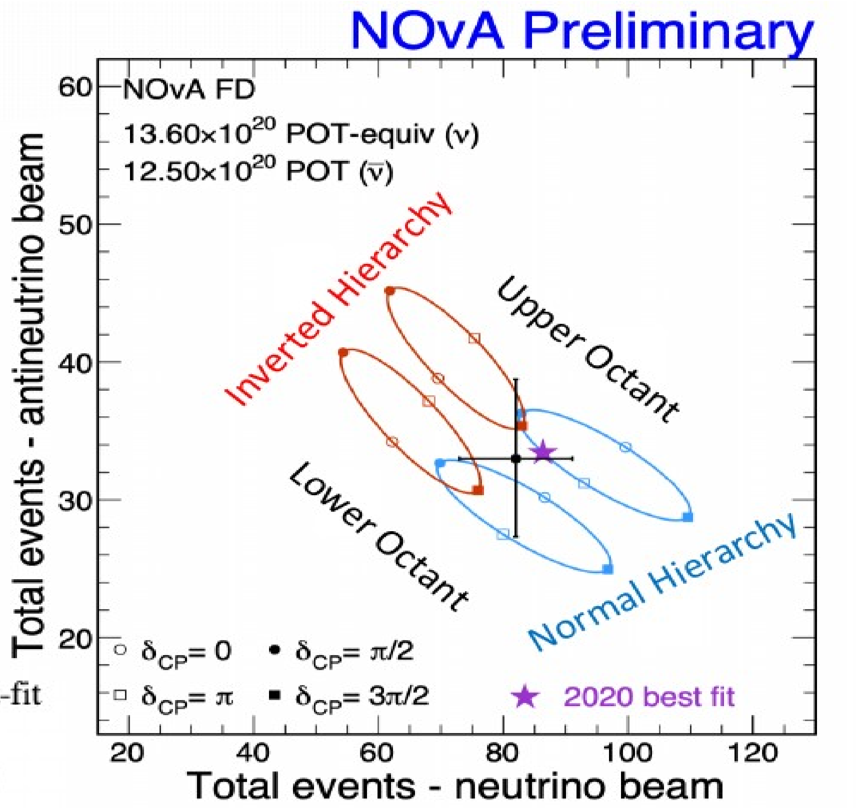
$\nu_e/\bar{\nu}_e$ apperance: MH, δ_{CP}

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

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

- **NOVA: δ_{CP} and MH with degeneracies**
((δ_{CP} $3\pi/2$ and IH = δ_{CP} $\pi/2$ and NH)

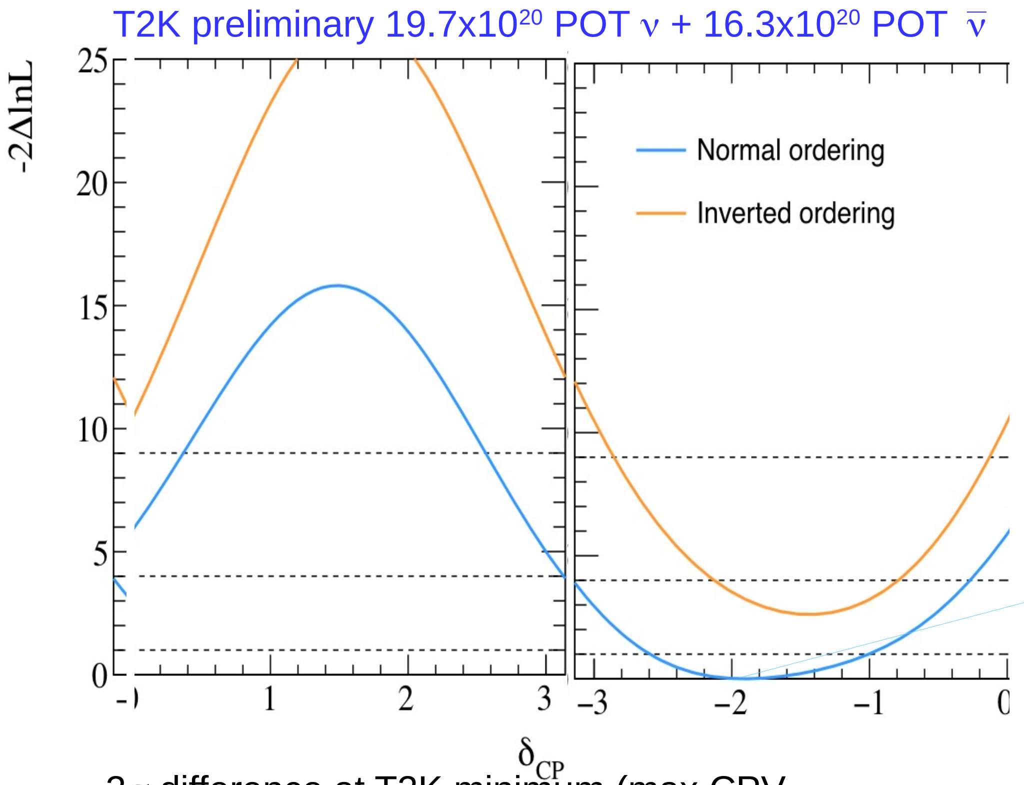


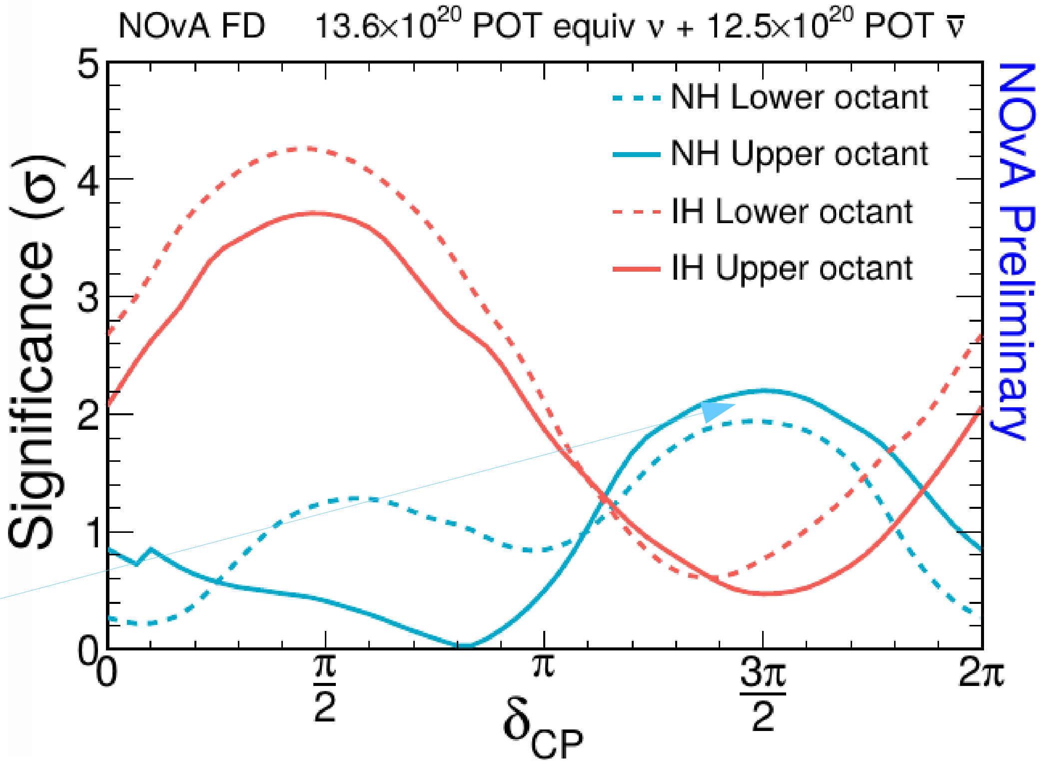


Using 2020 results in the following (2022 in next talks!)

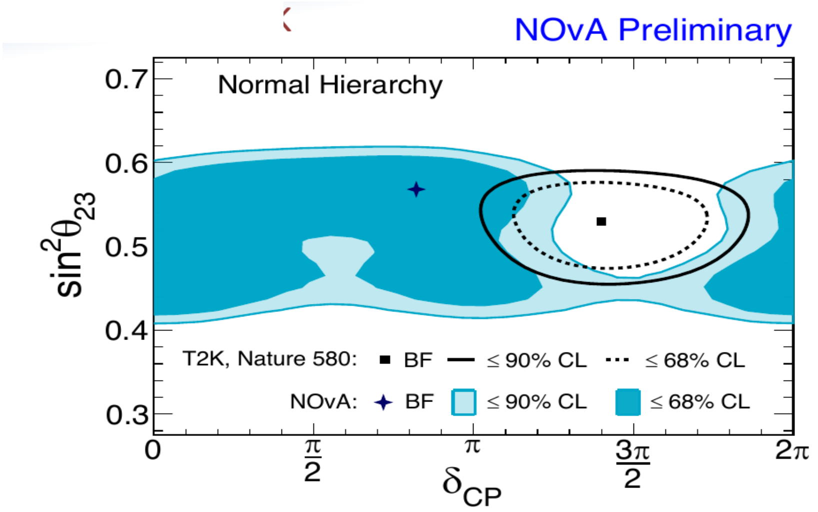
δ_{CP}

Using 2020 results
(2022 results in next talks!)



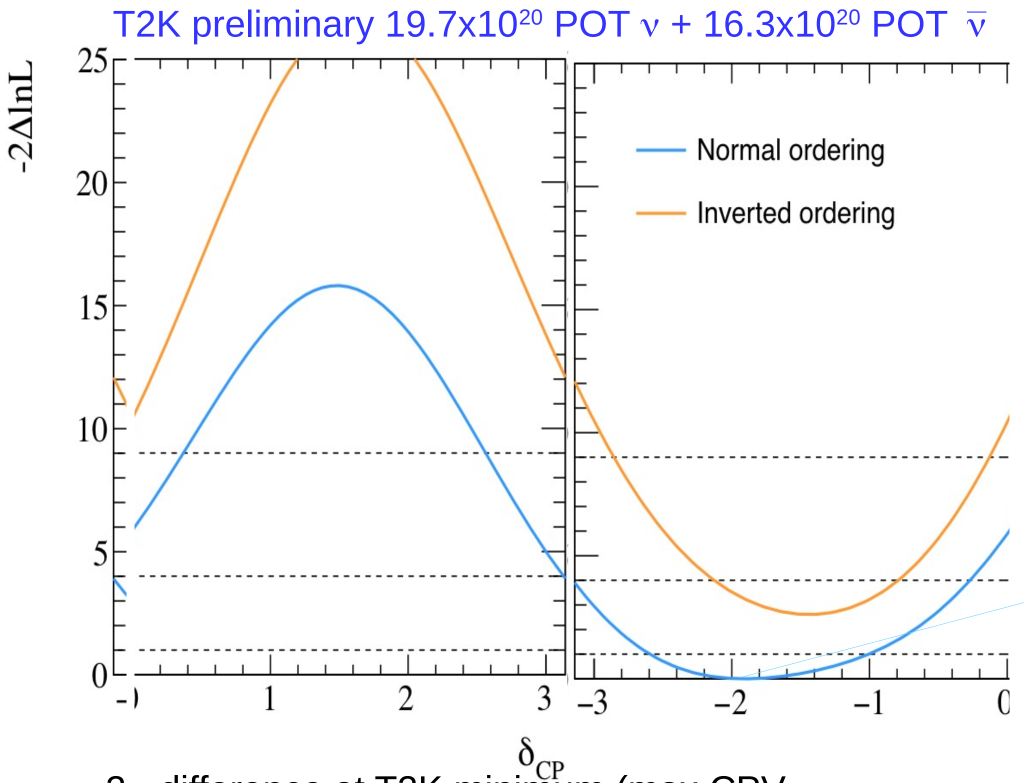


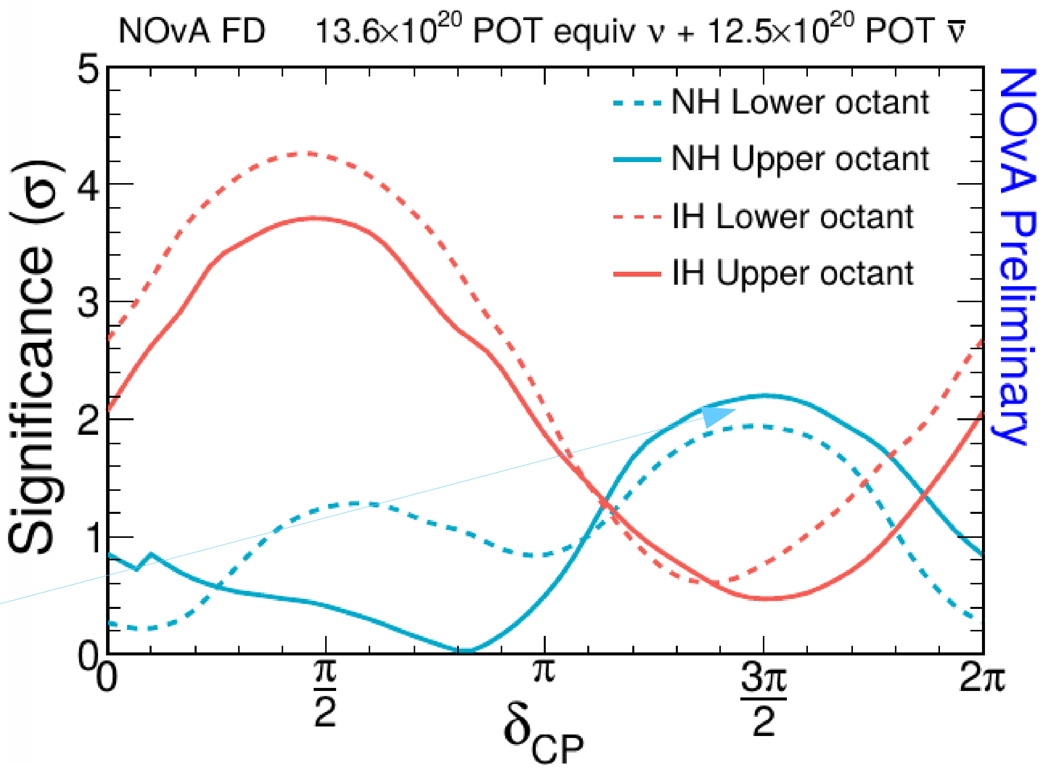
2σ difference at T2K minimum (max CPV, NH) but still common regions at 1σ



δ_{CP}

Using 2020 results (2022 results in next talks!)





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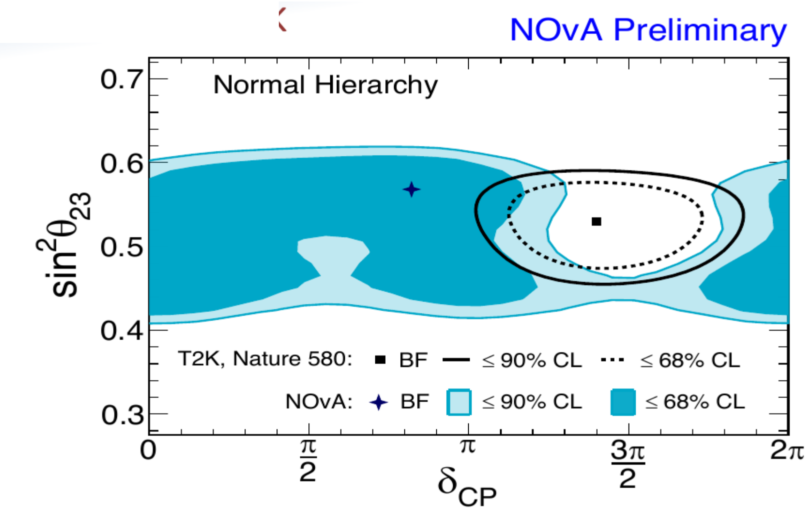
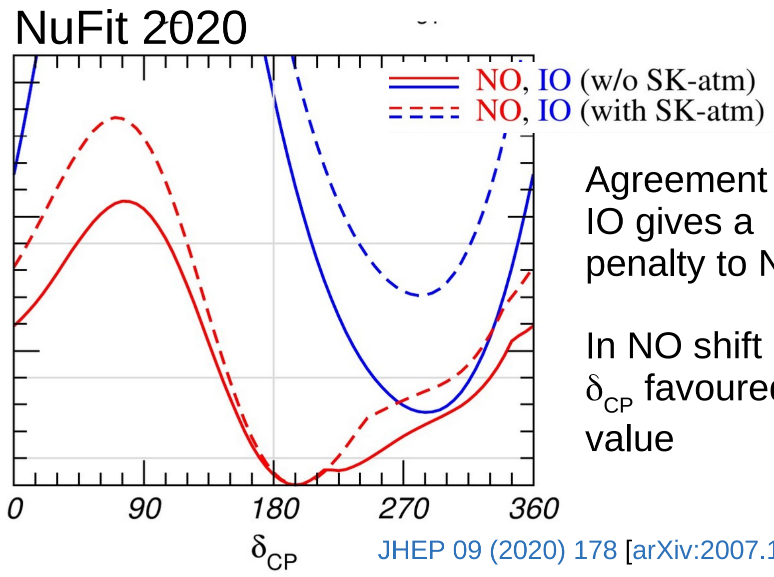


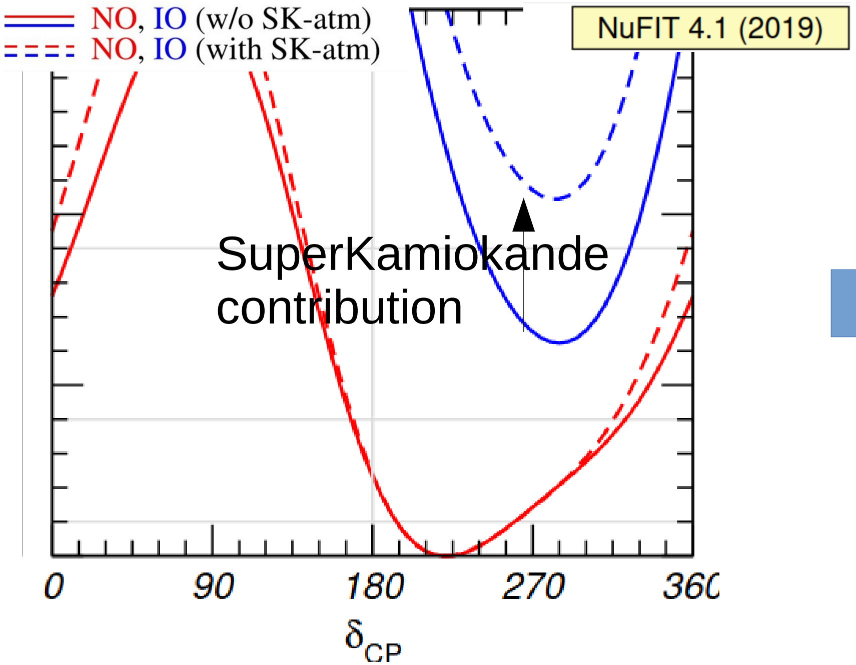


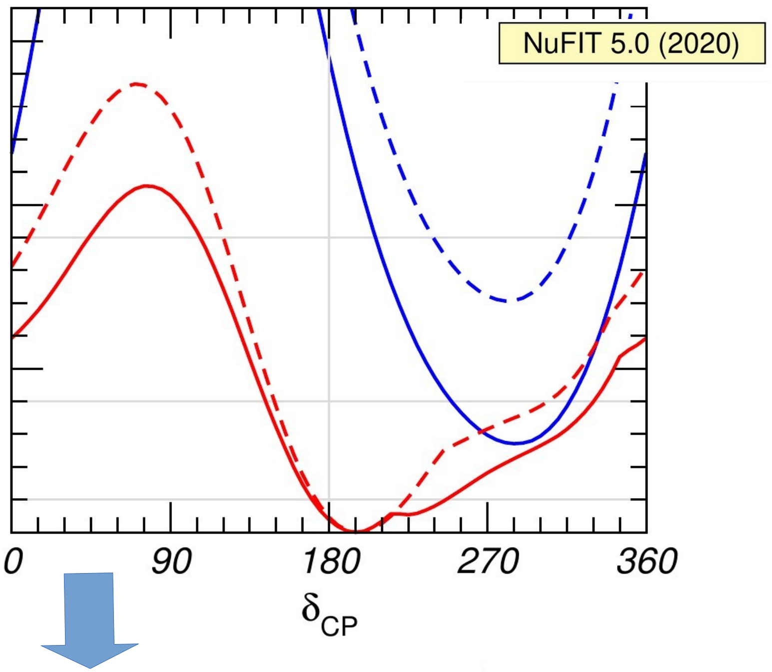
Agreement in IO gives a penalty to NO

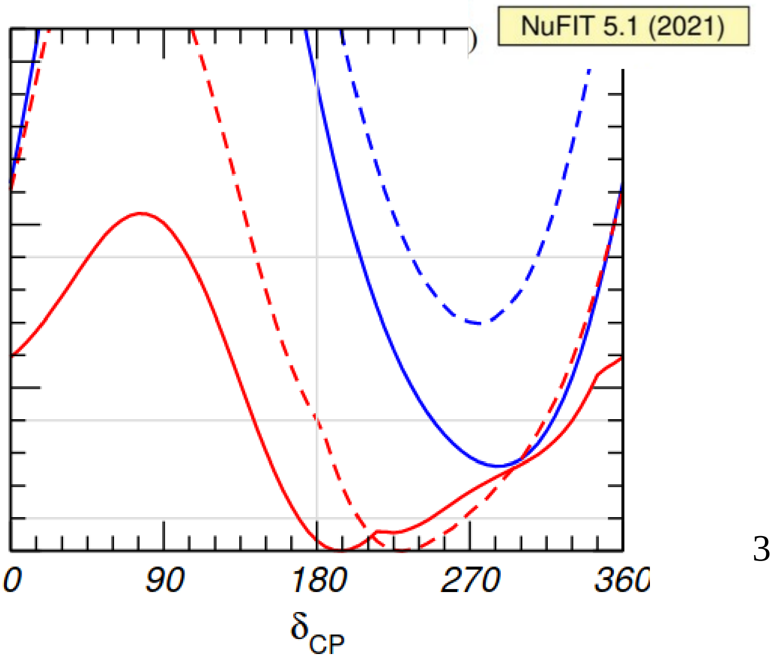
In NO shift on δ_{CP} favoured value

JHEP 09 (2020) 178 [arXiv:2007.14792]

Mass Hierarchy: 2019 → 2022







- MO sensitivity dominated by SuperKamioande

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

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

- NuFit 5.0 updated with SK I-IV analysis presented at Neutrino 2020
→ shift best δ_{CP} in combination with T2K+NOVA

→ NO favoured at 2.7σ
→ CP conservation disfavoured at ~2σ

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
- standard neutrino interactions for production and detection
- standard matter effects along propagation

- 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

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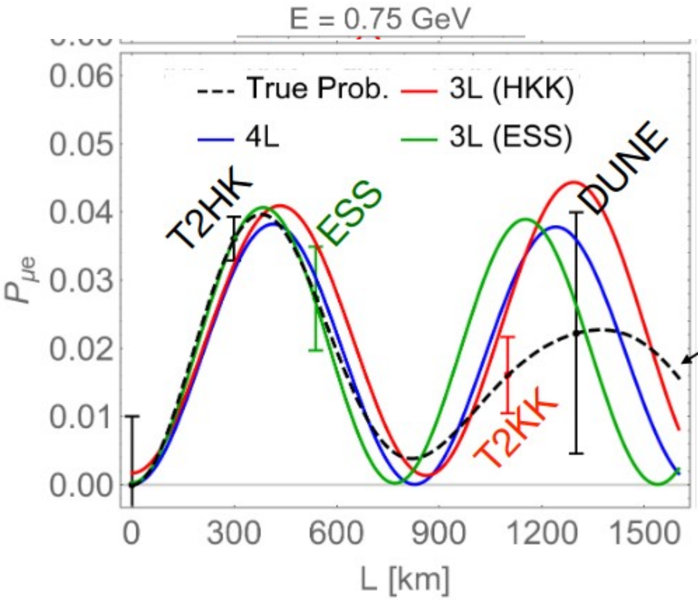
arXiv:2106.16099 [hep-ph]

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**



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

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

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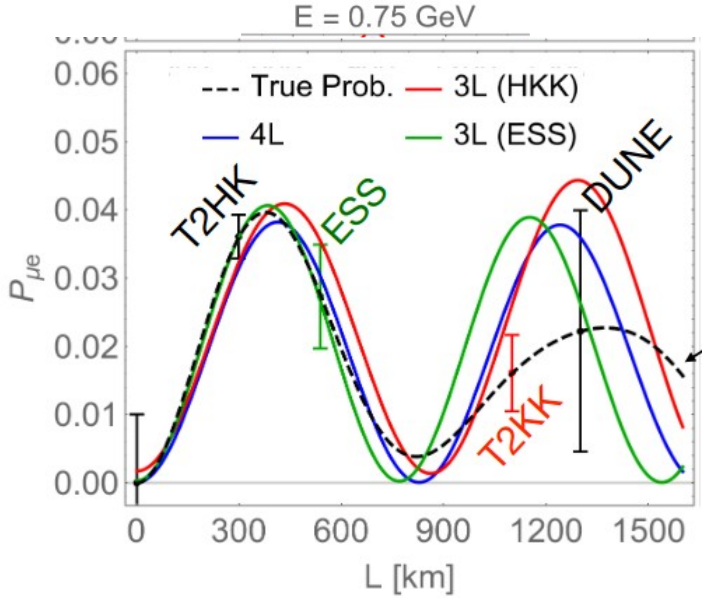


No good fit with L-even terms only → T-Violation !

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

- Combination of experiments will be needed for a **comprehensive, precise 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, ...

Stay tuned!

- **Neutrino oscillation in long-baseline experiments is entering the precision era:**

  - atmospheric parameters from ν_μ disappearance ($\sin^2 2\theta_{23}$, $|\Delta m^2_{31(32)}|$), as well as future δ_{CP} precision measurement needs good control of systematics

  → new generation of near detectors, improved flux tuning from dedicated hadro-production experiments, improved models of neutrino-nucleus interactions
  → increased analysis sophistication

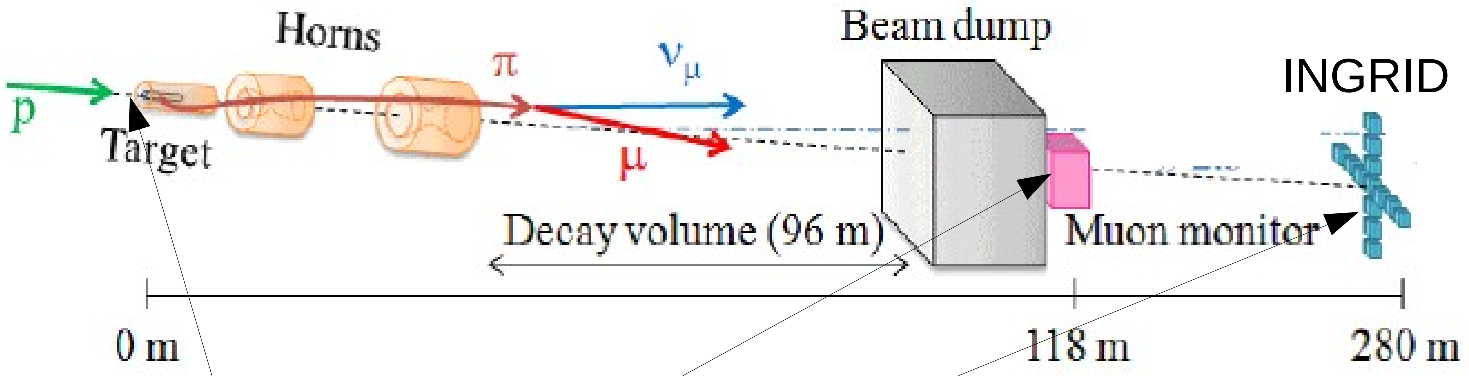
- ν_e ($\bar{\nu}_e$) **appearance is today statistically limited** → interesting prospects in the next future to get to 3σ on CPV and MH already with T2K, NOVA, Superkamiokande and their combinations (→ lifting degeneracies!)

- **Next: 5σ generation experiments (HyperKamiokande, DUNE)**
→ next-to-next: oscillation measurements beyond present (strict) assumptions requires a joint effort between experiments
(today combination of T2K, NOVA, SuperKamiokande is a good ‘reharsal’)

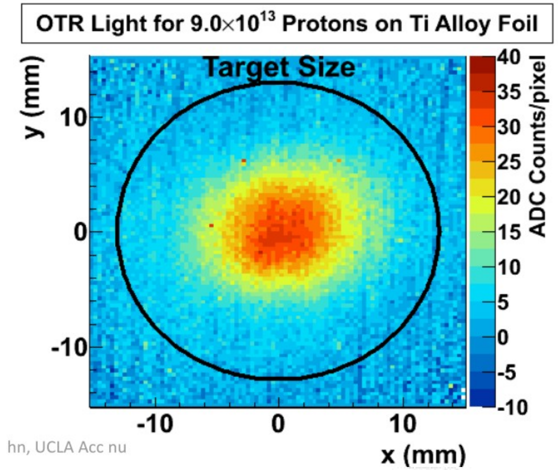
BACKUP

Beam: monitoring

- **Monitoring of the beam:** intensity, position, direction

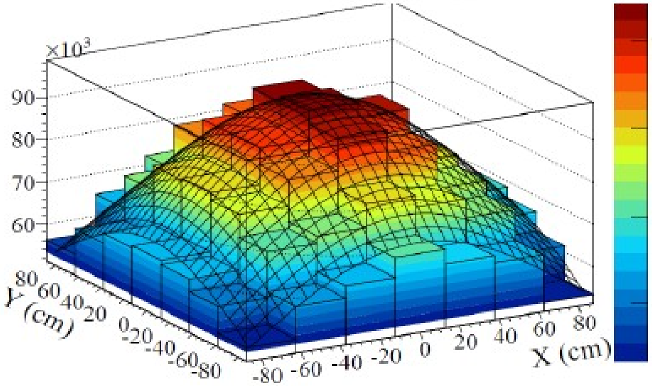


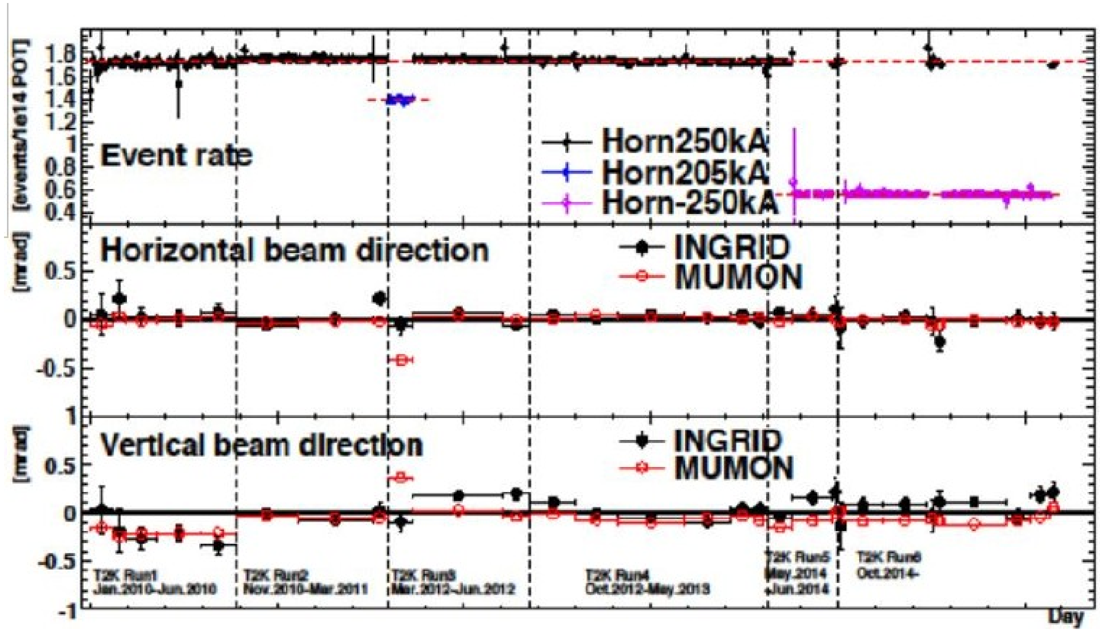
- looking at **protons**
- looking at **muons**
- looking at **neutrinos**



Protons

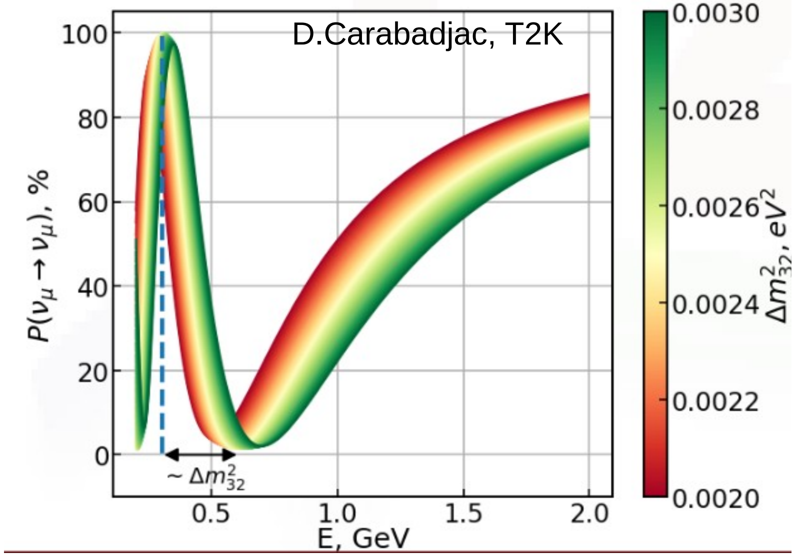
Muons





Atmospheric parameters: ν_μ disapp

$$P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \cos^4\theta_{13} \sin^2 \boxed{\frac{\Delta m^2_{32} L}{4E}}$$


D.Carabadjac, T2K

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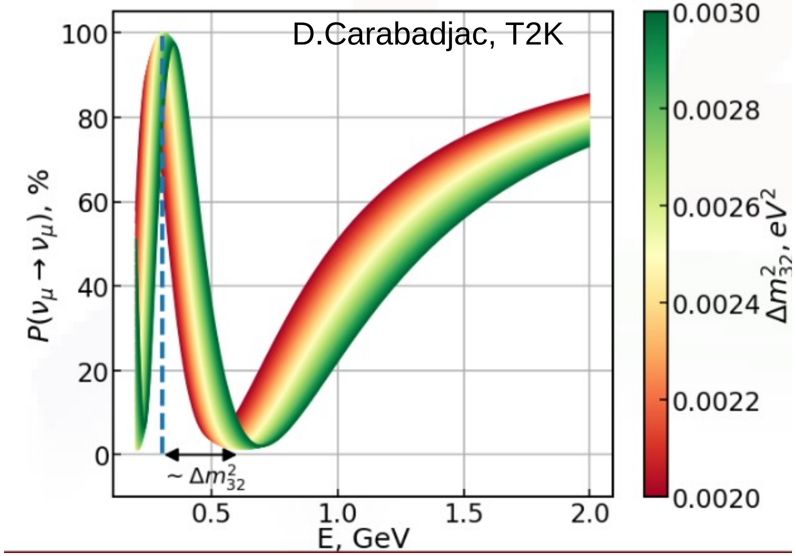
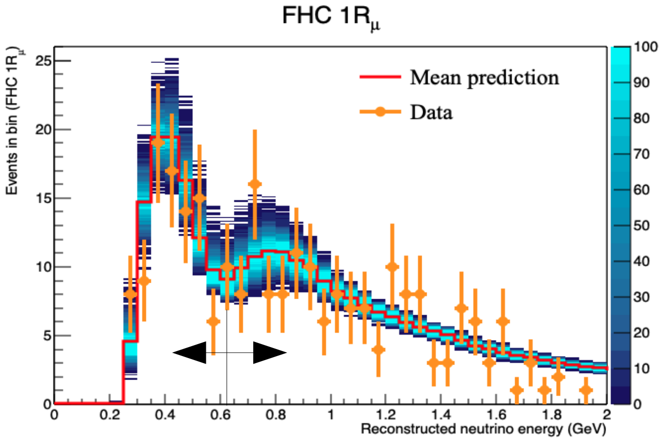


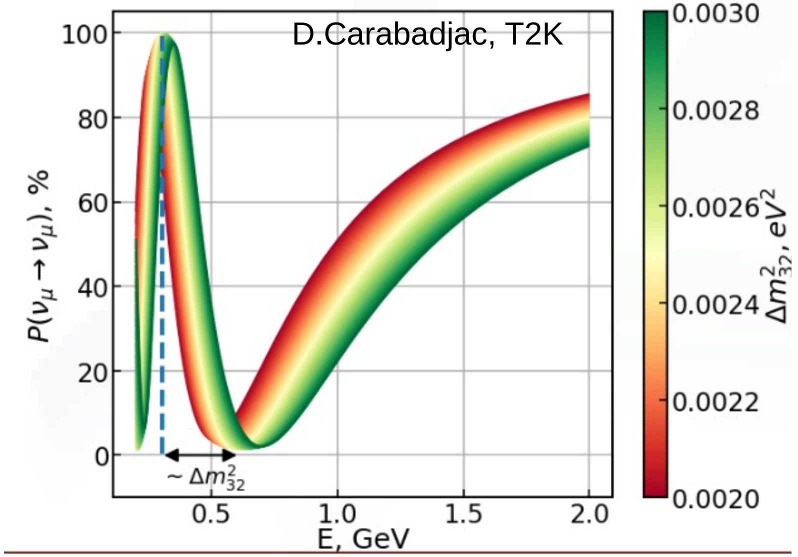


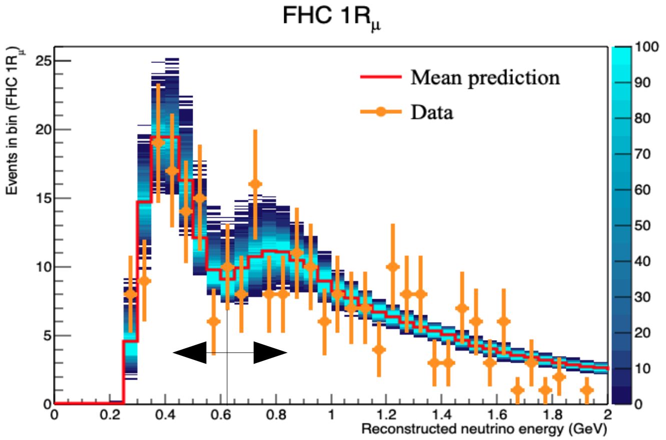
- Precise measurement of neutrino energy event by event is crucial: good resolution on neutrino energy reconstruction + avoid bias in energy scale

Precision at few % level (→ few MeV)

Atmospheric parameters: ν_μ disapp

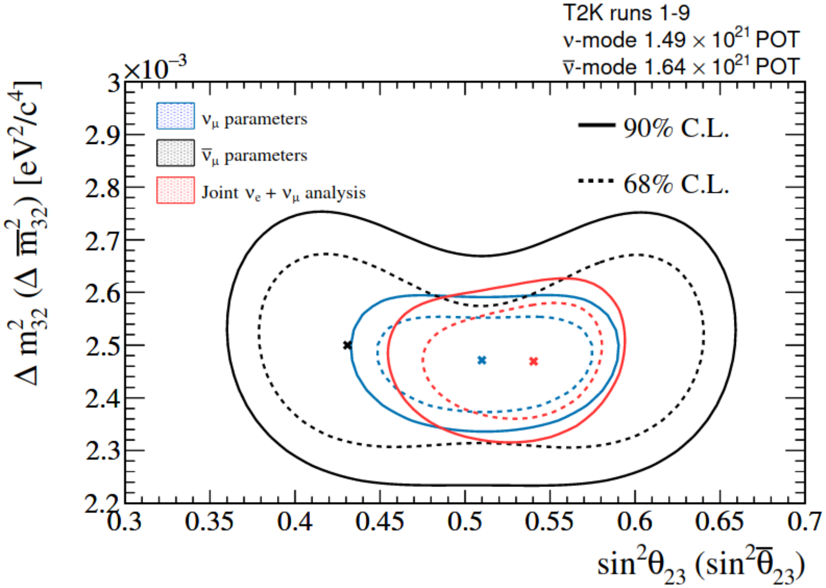
$$P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \cos^4 \theta_{13} \sin^2 \boxed{\frac{\Delta m^2_{32} L}{4E}}$$





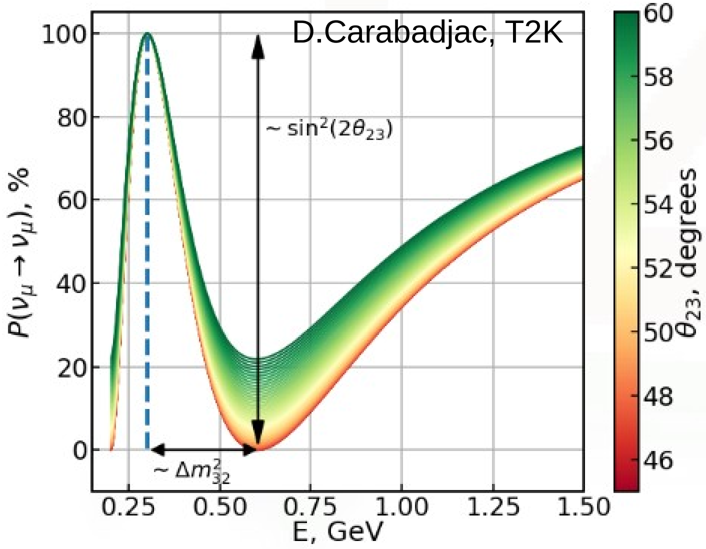
- Precise measurement of neutrino energy event by event is crucial: good resolution on neutrino energy reconstruction + avoid bias in energy scale
Precision at few % level (→ few MeV)

- Correlated effects in ν and $\bar{\nu}$ (assuming CPT invariance)

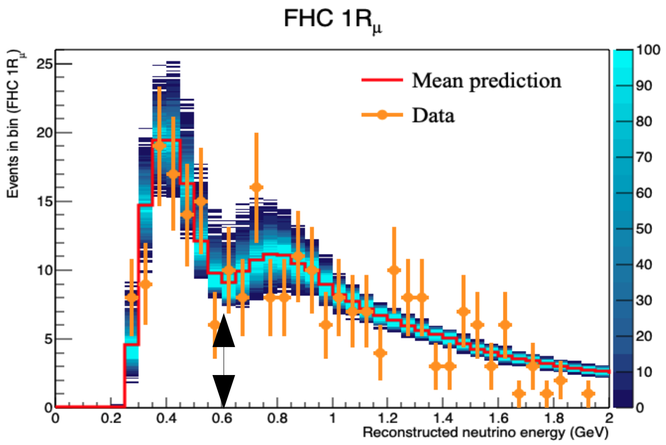


Atmospheric parameters: ν_μ disapp

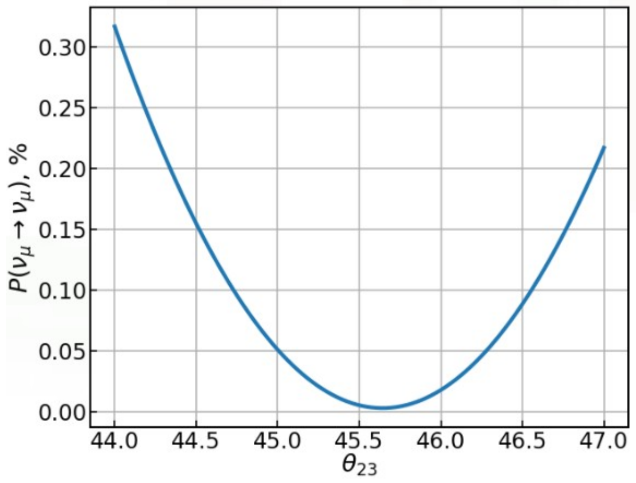
$$P(\nu_\mu \to \nu_\mu) \approx 1 - \boxed{\sin^2 2\theta_{23}}\, \cos^4\theta_{13} \sin^2 \frac{\Delta m^2_{32} L}{4E}$$



D.Carabadjac, T2K



D.Carabadjac, T2K



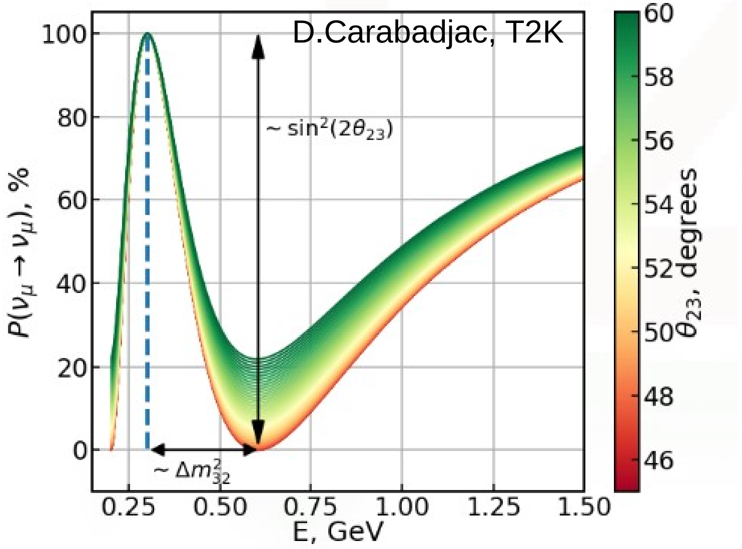
- Measurement proportional to number of observed muon neutrino at oscillation maximum

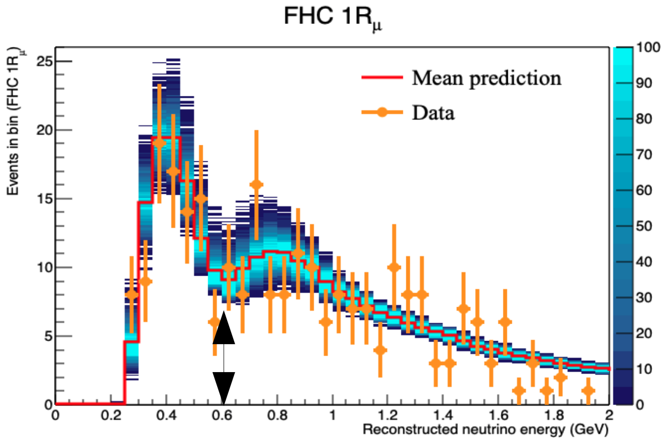
→ need control of ν_μ overall normalization at few %

(again correlated between ν and $\bar{\nu}$)

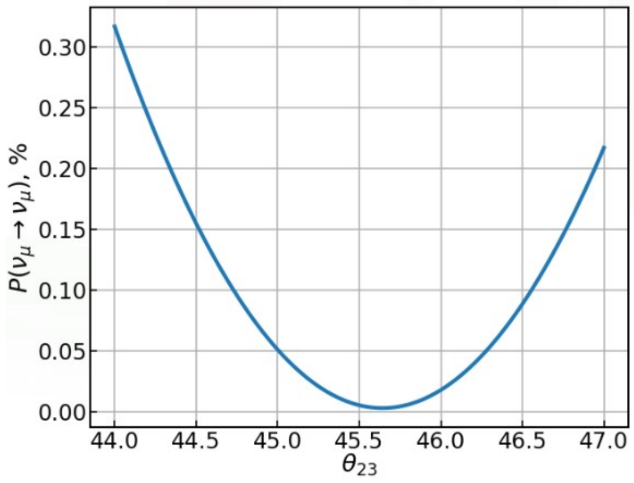
Atmospheric parameters: ν_μ disapp

$$P(\nu_\mu \to \nu_\mu) \approx 1 - \boxed{\sin^2 2\theta_{23}}\, \cos^4\theta_{13} \sin^2 \frac{\Delta m^2_{32} L}{4E}$$



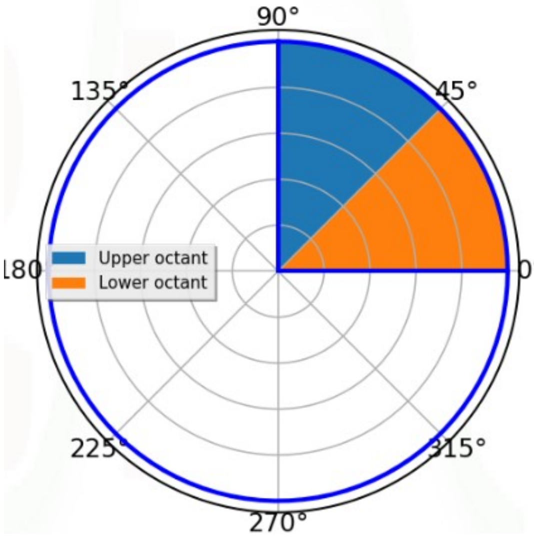


D.Carabadjac, T2K



- Measurement proportional to number of observed muon neutrino at oscillation maximum
→ need control of ν_μ overall normalization at few %
(again correlated between ν and $\bar{\nu}$)

- Maximal mixing **$\theta_{23}\sim\pi/4$** would be a very interesting symmetry.
Away from that, octant degeneracy due to quadratic dependence on $\sin^2 2\theta$

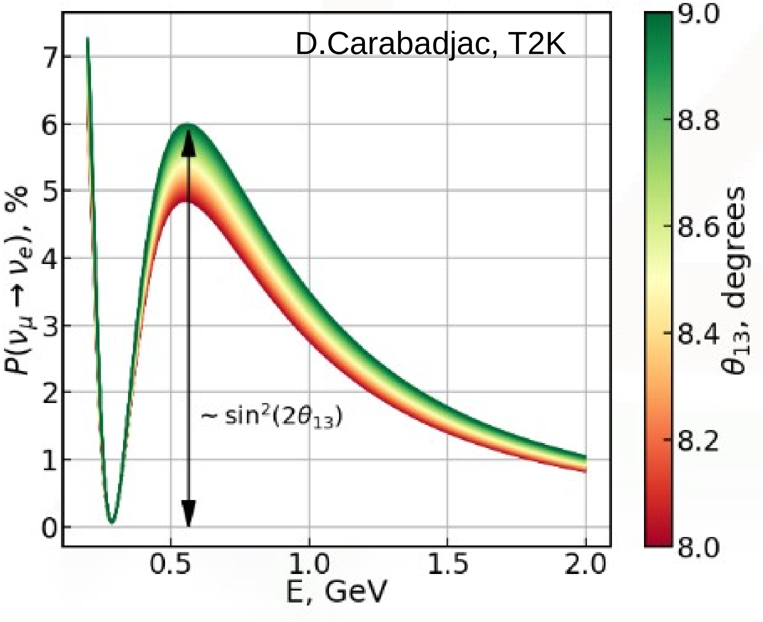


① $\theta_{23} \in [0\,;\,\pi/4]$ - lower octant

② $\theta_{23} \in [\pi/4,\ \pi/2]$ - upper octant

ν_e appearance

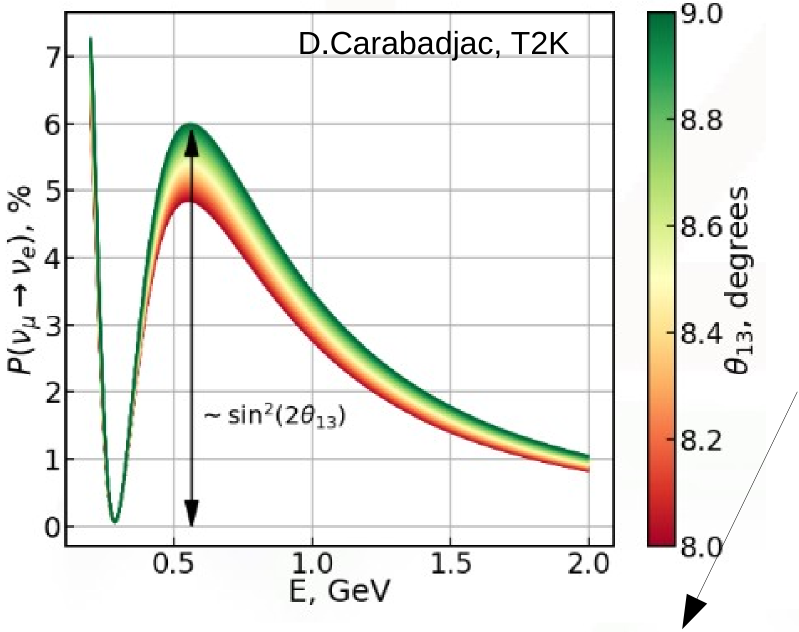
$$P(\nu_\mu \to \nu_e) \approx \boxed{\sin^2 2\theta_{13}} \sin^2\theta_{23} \sin^2 \frac{\Delta m^2_{32} L}{4E}$$



- **θ_{13}** well measured by reactor experiments (~1.5%)

ν_e appearance

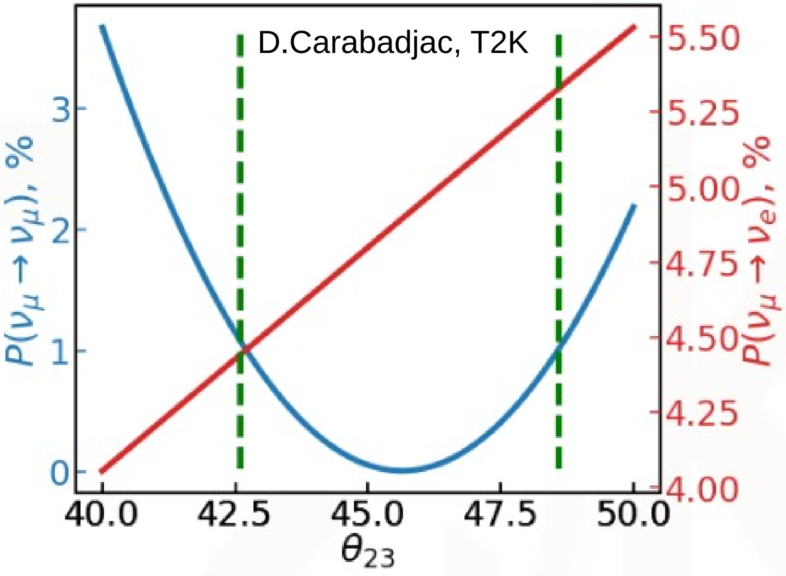
$$P(\nu_\mu \to \nu_e) \approx \boxed{\sin^2 2\theta_{13}}\,\boxed{\sin^2 \theta_{23}}\,\sin^2 \frac{\Delta m^2_{32} L}{4E}$$



- θ_{13} well measured by reactor experiments (~1.5%)

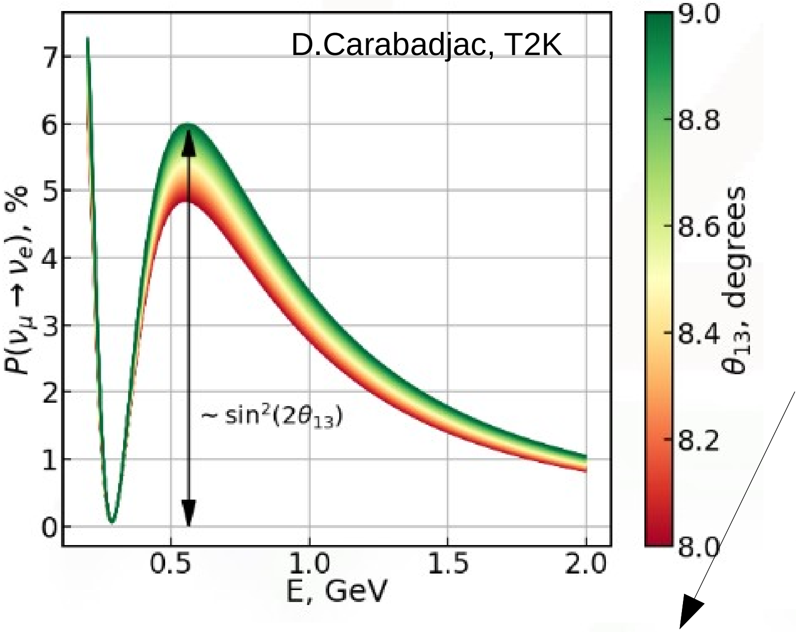
- sensitivity to θ_{23}

→ break degeneracy on θ_{23} octant (~1% effect)



ν_e appearance

$$P(\nu_\mu \to \nu_e) \approx \boxed{\sin^2 2\theta_{13}}\,\boxed{\sin^2 \theta_{23}}\,\sin^2 \frac{\Delta m^2_{32} L}{4E} + \boxed{\sim\sin\theta_{13} \text{ x } \sin\delta\sim}$$

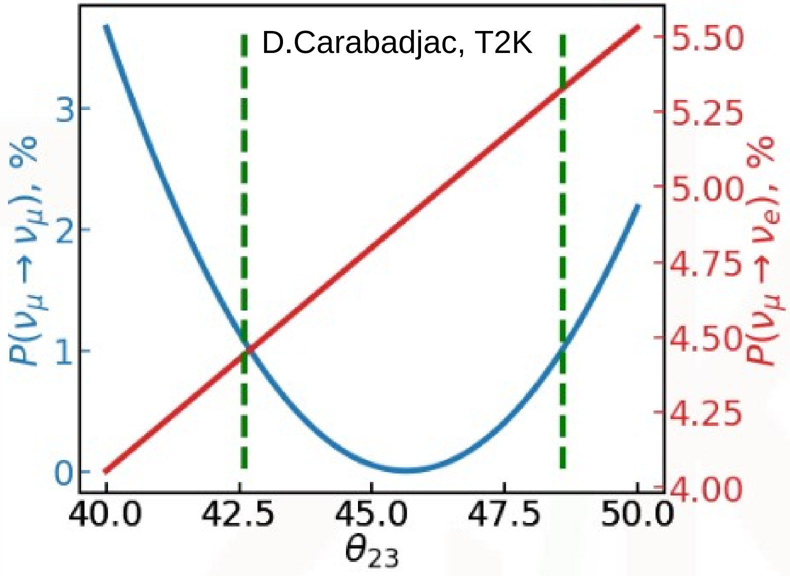


- θ_{13} well measured by reactor experiments (~1.5%)

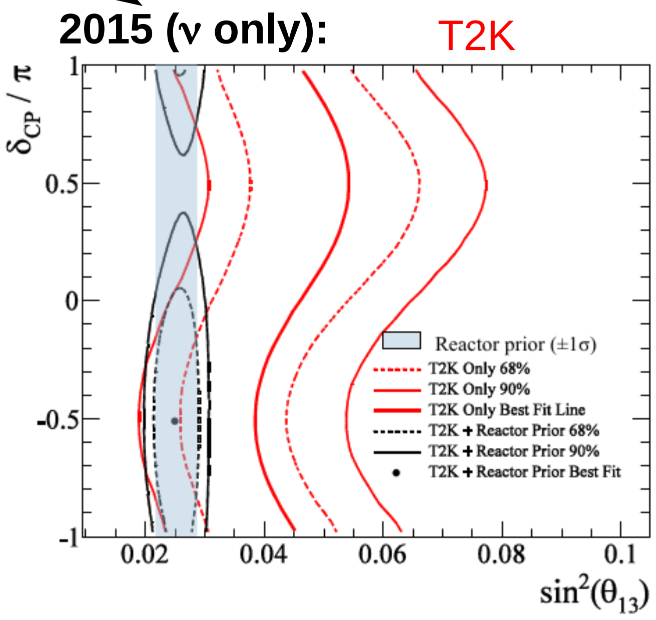
- sensitivity to θ_{23}

→ break degeneracy on θ_{23} octant (~1% effect)

→ with θ_{13} from reactor, some sensitivity to δ_{CP}



2015 (ν only):



T2K+ θ_{13} from reactors

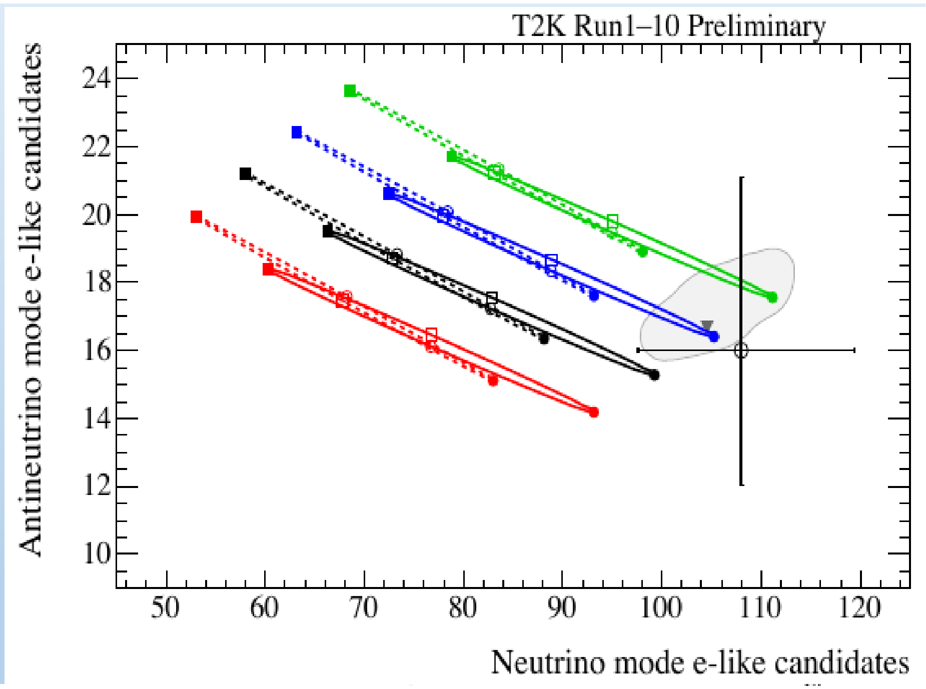
$\nu_e/\bar{\nu}_e$ apperance: MH, δ_{CP}

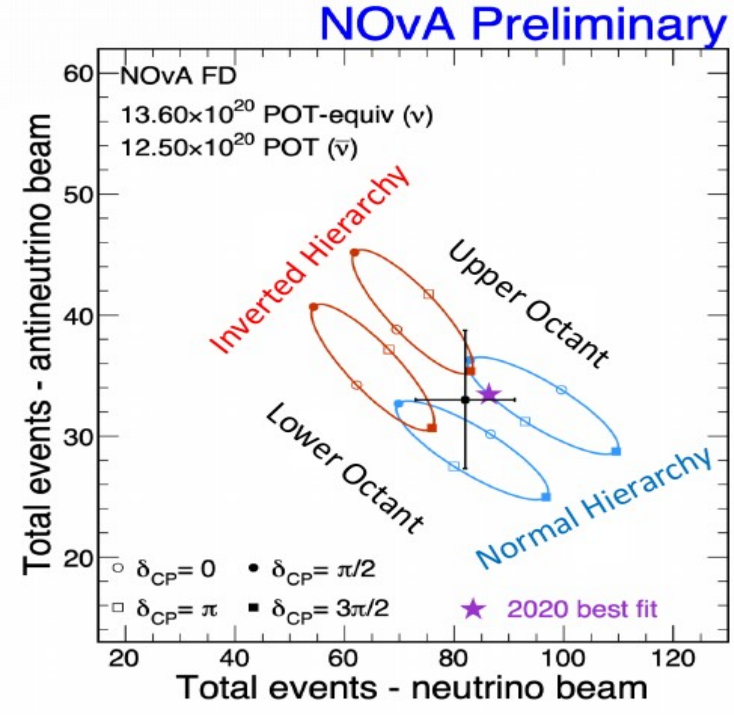
Experiment	CP asymmetry	Mass Hierarchy
T2K (T2HK)	~30%	~10%
Nova	~30%	~30%

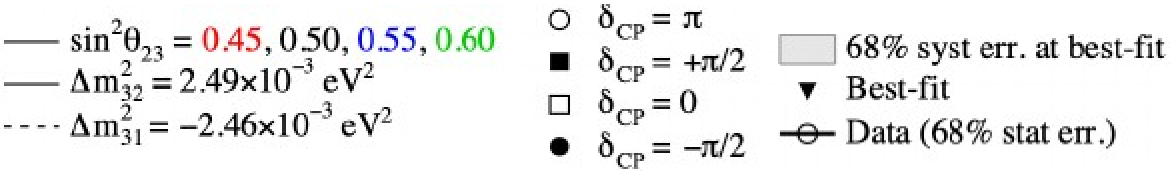
- **T2K: clean δ_{CP} measurement with small MH sensitivity**

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

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







A bit of (recent) history...

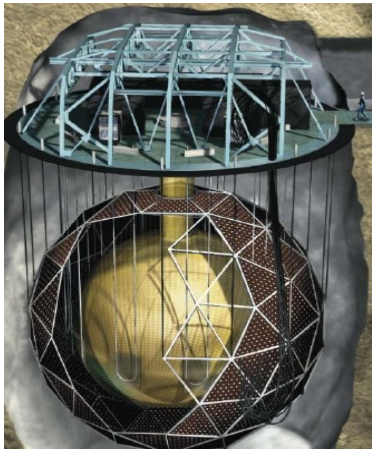
SuperKamiokande
1996 – today!

1998 Discovery of ν oscillation

from zenith angle dependence of atmospheric ν_μ rate

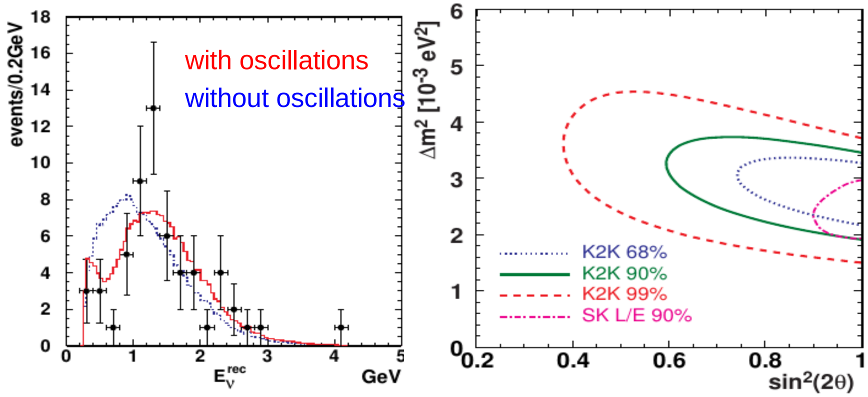
Sudbury Neutrino Observatory (SNO)
1999 – 2006

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

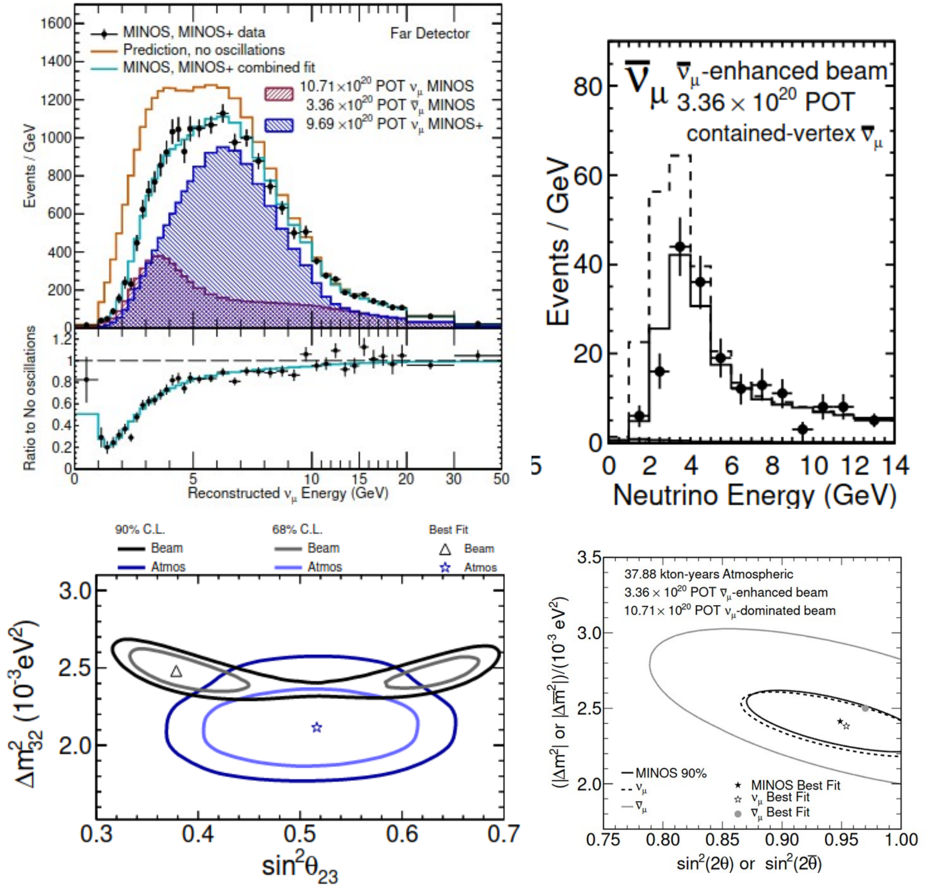


Precision from accelerator experiment:
high purity and tunable neutrino flux

(1999-2006) K2K



2003 – 2015 MINOS (→ - 2016 MINOS+)



(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

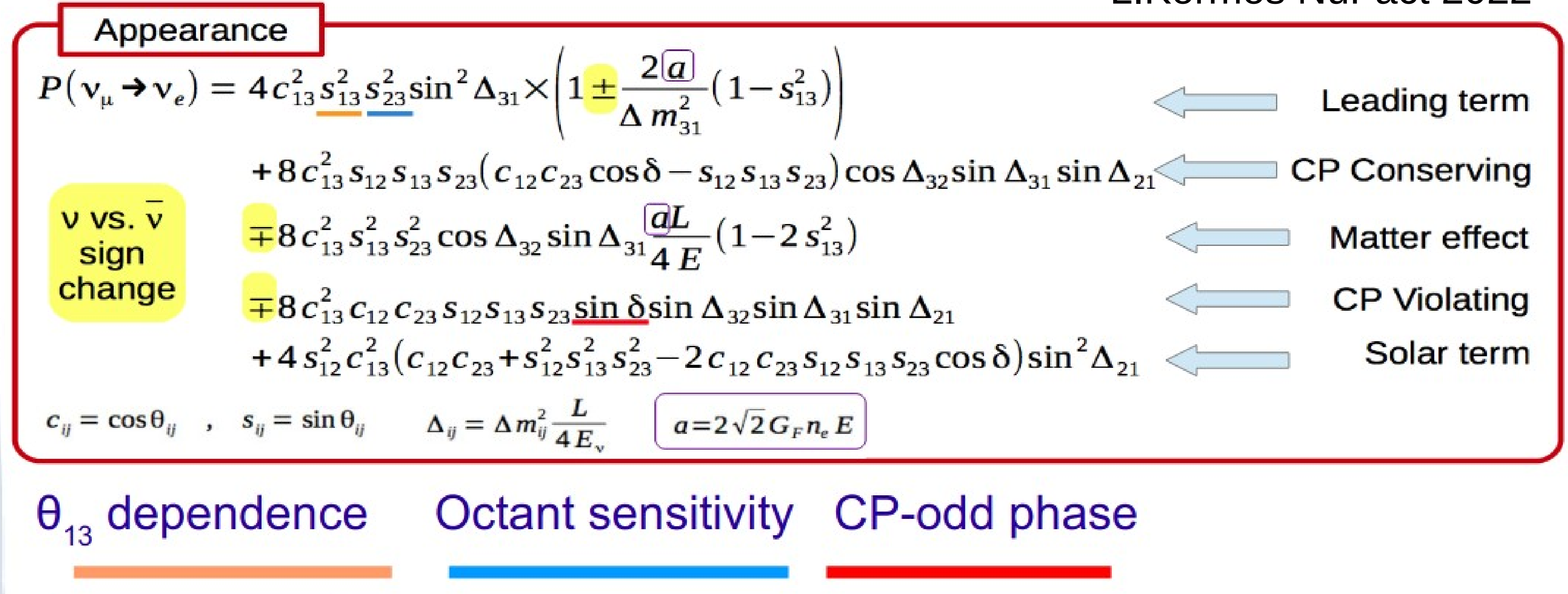
→ observation of ν_e apperance
T2K (2010 - today)

→ to measure MH, longer baseline:
NOVA started 2014

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

ν_e appearance full formula

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

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

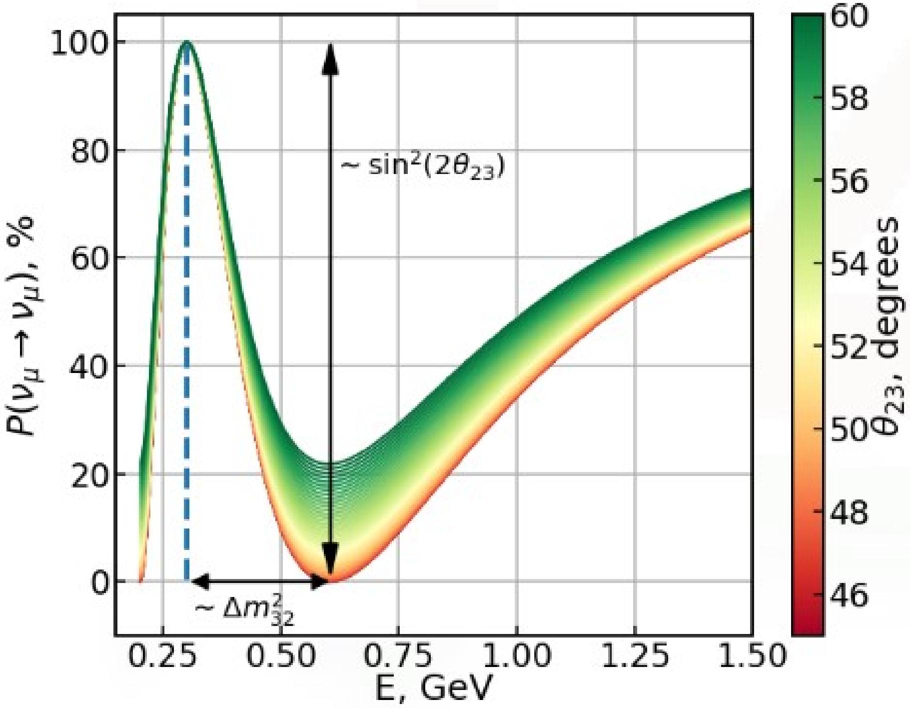
θ_{13} dependence Octant sensitivity CP-odd phase

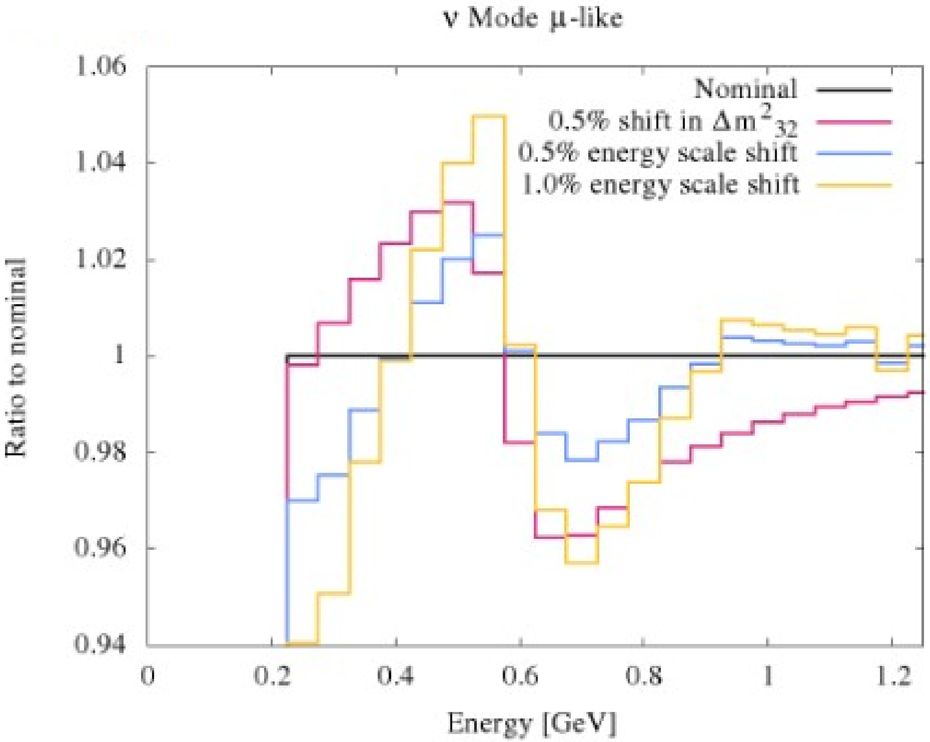
- leading dependence on δ_{CP} and MO (prop. to L), changing sign for ν and $\bar{\nu}$
- need large θ_{13} to access $\sin\delta_{CP}$ (sensitivity to δ_{CP} from ν only if θ_{13} well known)
- subleading dependence on $\cos\delta_{CP}$ → important for δ_{CP} precision measurement

Impact of systematics will hit first in ν_μ disappearance

As already discussed yesterday:

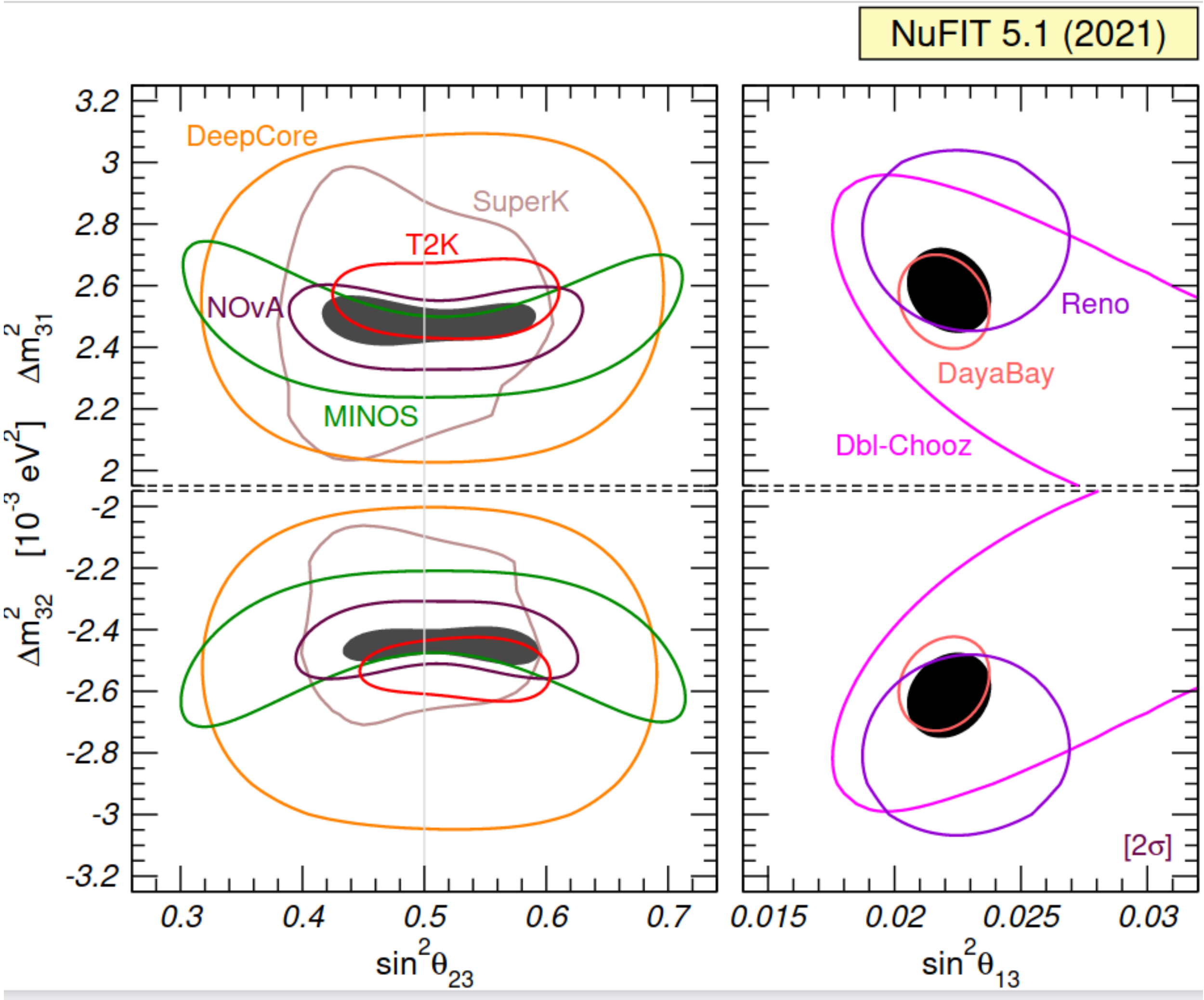
- precision $\sin\theta_{23}$ requires precision on neutrino rate at oscillation maximum
- precision on $|\Delta m^2_{31(32)}|$ requires precise neutrino energy reconstruction

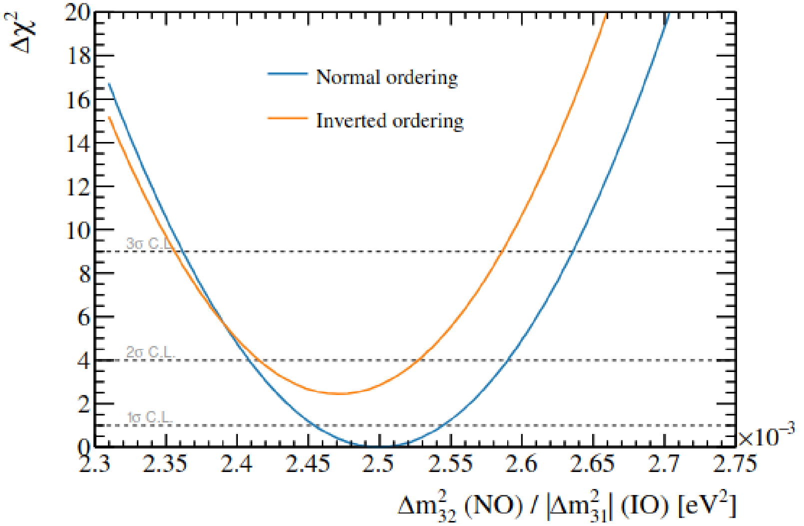




Need improved flux and xsec models (and tuning: NA61, Minerva, ...) and improved near detectors to better constrain model, notably for precise reconstruction of full final state
→ improved neutrino energy reconstruction

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





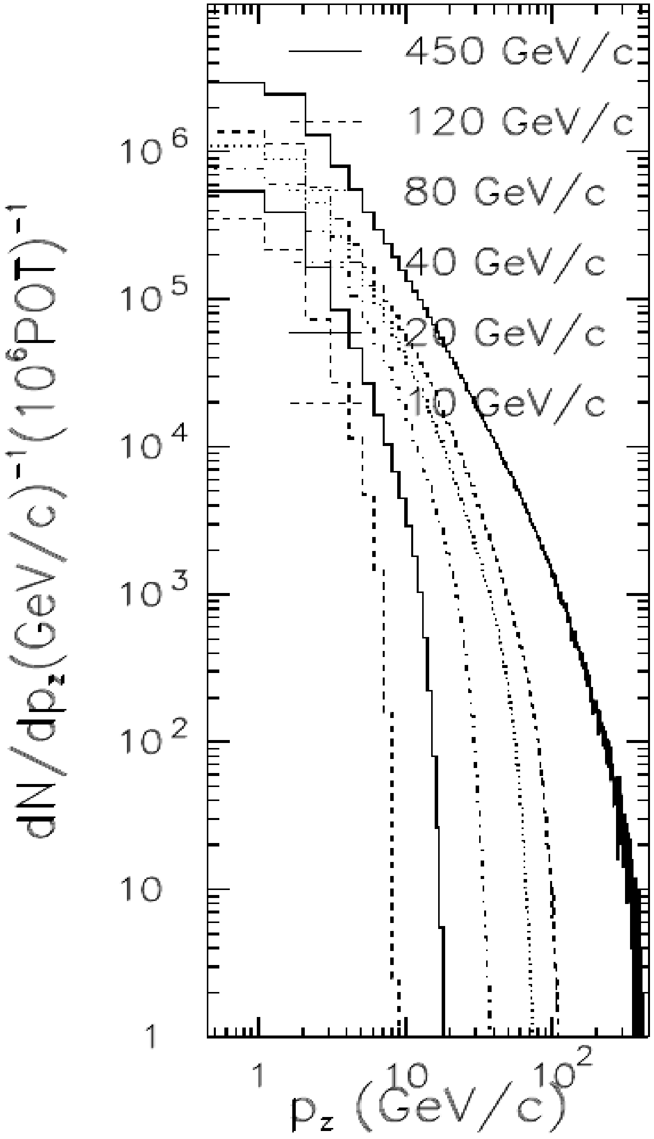
(b) T2K + reactor

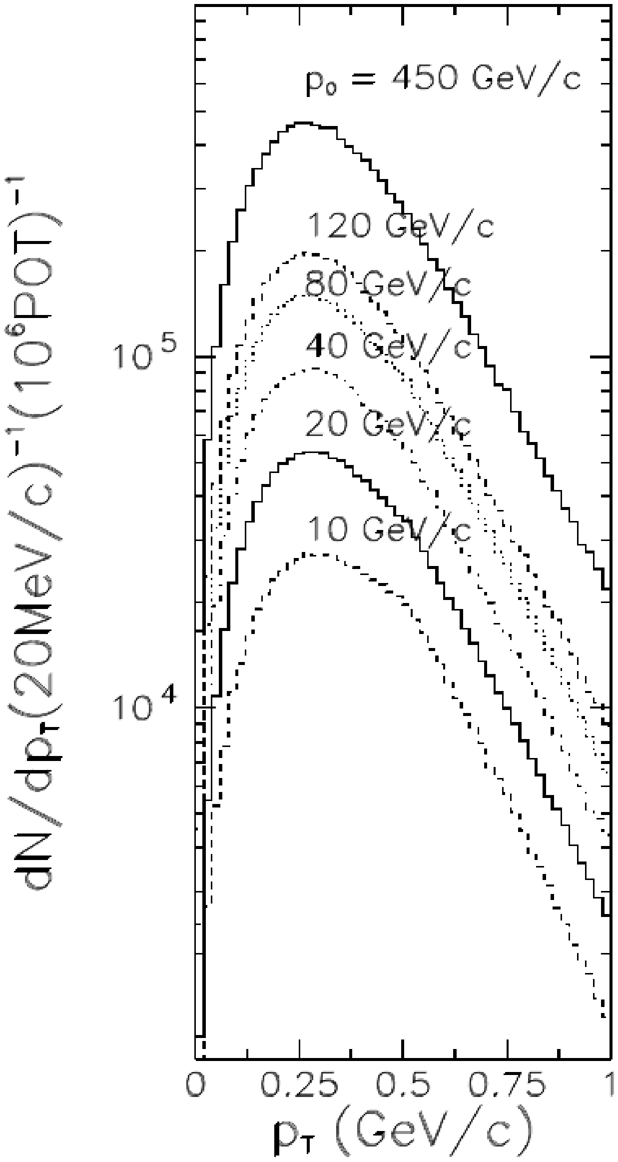
T2K: 2% precision with 1% shift between NO and IO

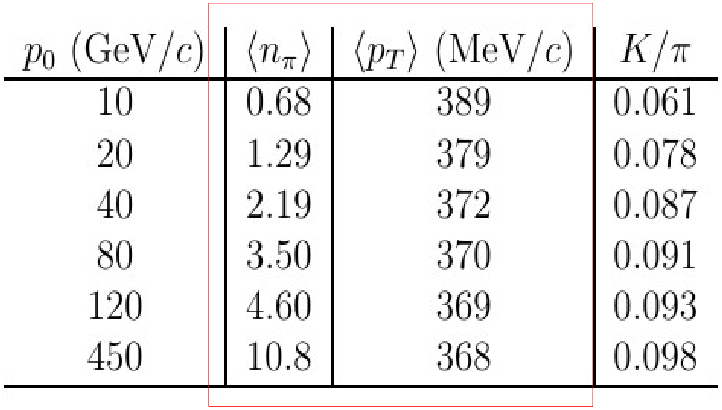
Similar resolution and shift in NOVA

Proton beam

Pion spectra for different proton momenta





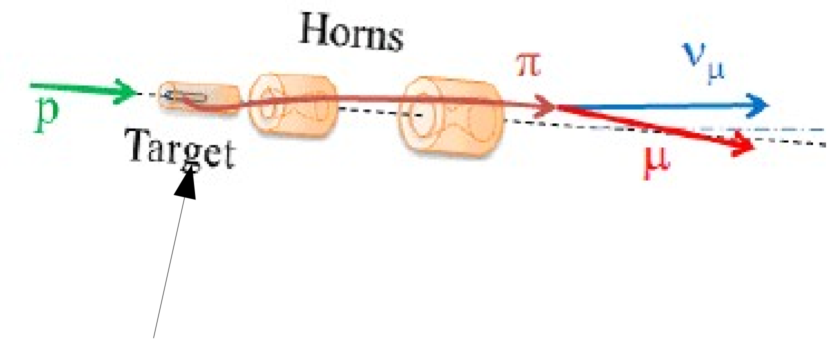


p_0 (GeV/c)	$\langle n_\pi \rangle$	$\langle p_T \rangle$ (MeV/c)	K/π
10	0.68	389	0.061
20	1.29	379	0.078
40	2.19	372	0.087
80	3.50	370	0.091
120	4.60	369	0.093
450	10.8	368	0.098

Roughly speaking: higher proton energy produce more pions without increasing much their transverse momentum

(but lower energy typically allows larger repetition rate)

Target



- **Shape**: cylindrical (or ruler) along proton beam direction to maximize the probability of protons to interact (~50-100cm)

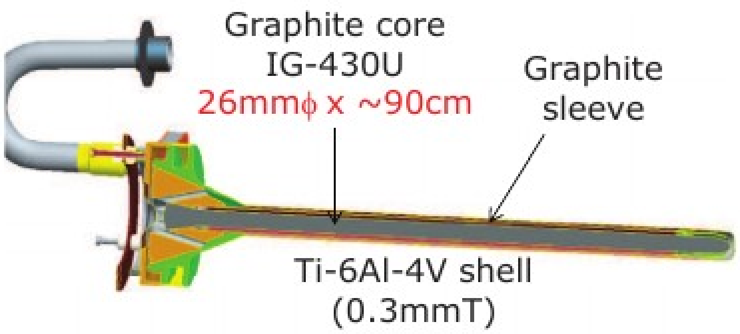
  (but re-interactions of hadrons inside the target are an additional complication)

  Transversal section should be ~3σ of proton beam width (~5-10mm)

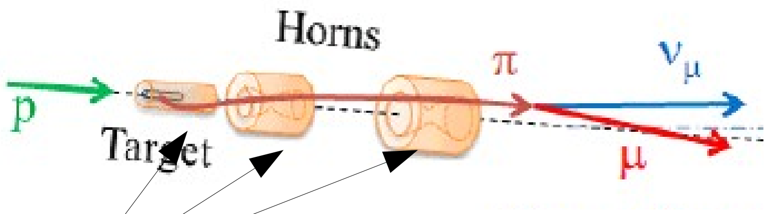
- **Low Z** (Aluminium, Berillium, Carbon, …) high probability of proton interacting and low probability of radiating (loosing energy in the target)

- **Need cooling** (air or water): larger the beam intensity → hotter the target

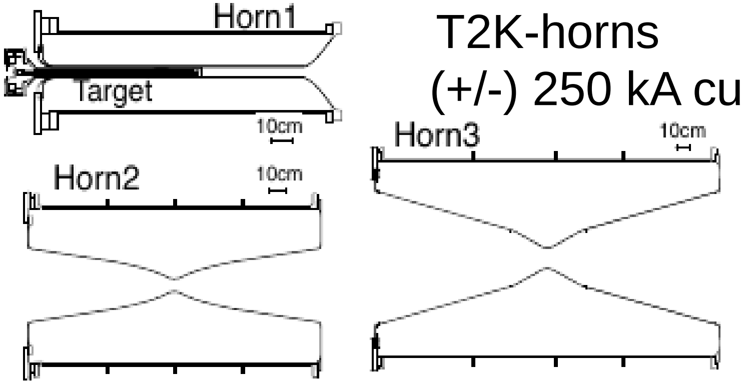
T2K



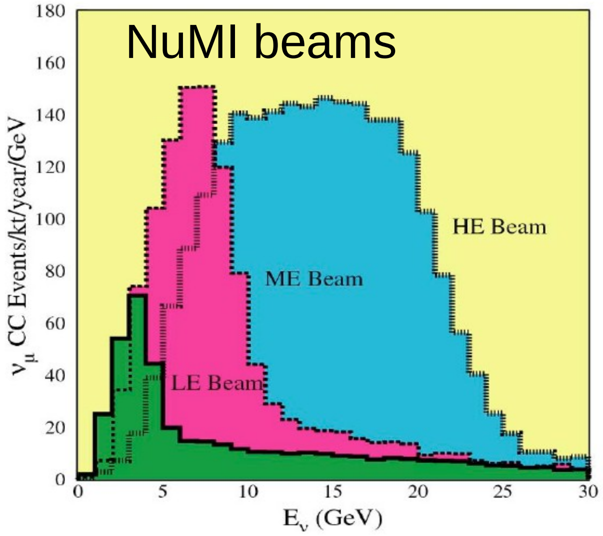
Horns



Horns to focus $\pi^{+/-}$ parallel to beam axis → ν_μ or $\bar{\nu}_\mu$ beam (aka Forward/Reverse Horn Current)

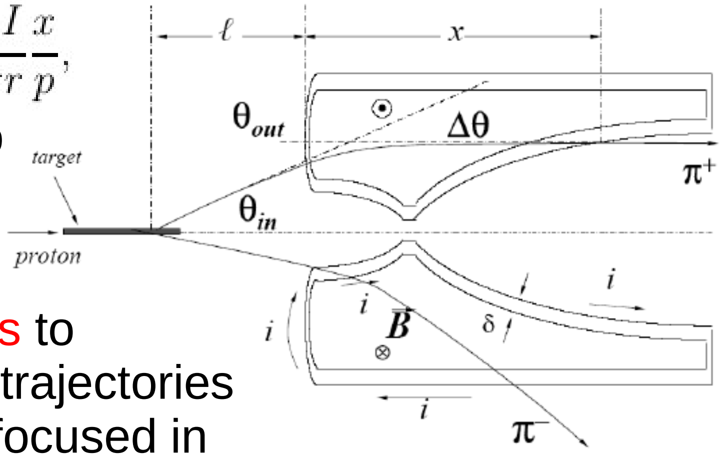


T2K-horns
(+/-) 250 kA current

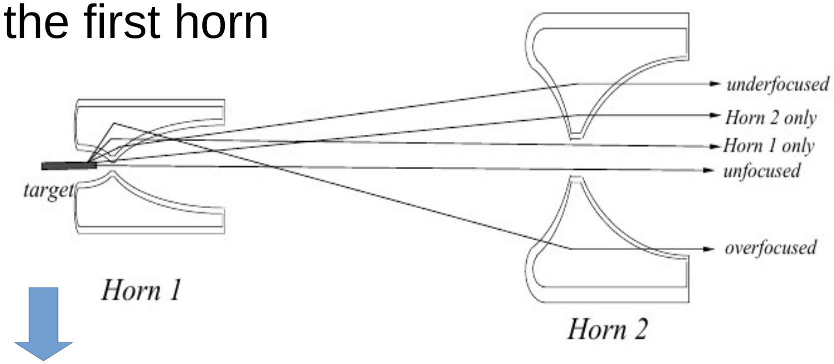


- $\Delta\theta = \frac{Bx}{p} = \frac{\mu_0 I}{2\pi r}\frac{x}{p}$,

(parabolic: same θ kink for all angles)

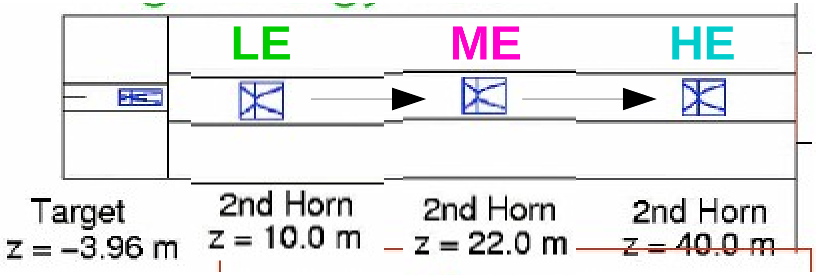


- multiple horns to recover pion trajectories not properly focused in the first horn



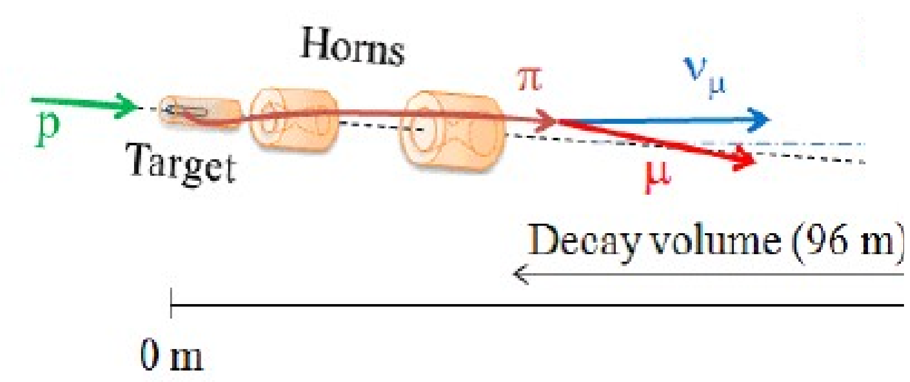
- the pions with smallest angle are the most energetic → to focus them need to move the horns

NuMI: 3 possible configurations → 3 beam energies



Decay volume

- **Let the hadrons to decay in (μ and) ν:**



Decay volume (T2K: He filled):

- Long to let most of the pion decaying
- not too long to avoid muon decay (ν_e pollution)

- most ν_μ's from 2-body decays:

$\pi^+ \rightarrow \mu^+\nu_\mu$

$K^+ \rightarrow \mu^+\nu_\mu$

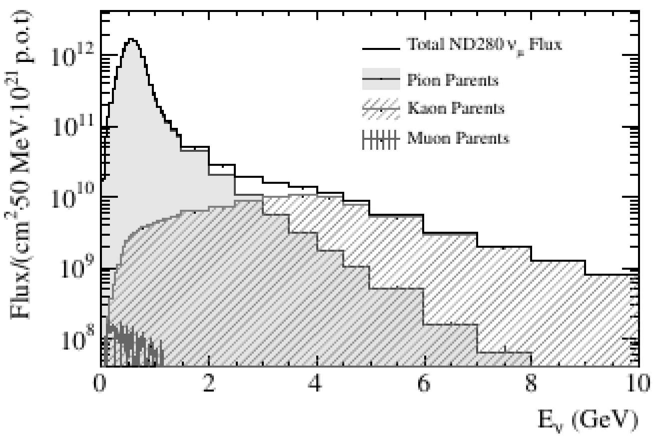
- most ν_e's from 3-body decays:

$\mu^+ \rightarrow e^+\nu_e\nu_\mu$

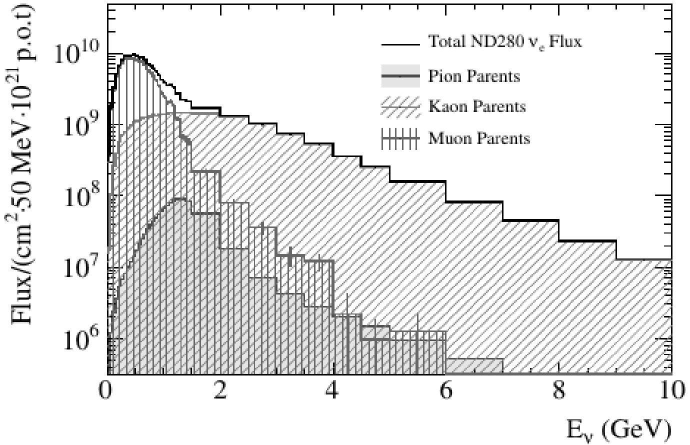
$K^+ \rightarrow \pi^0 e^+\nu_e$

- $\bar{\nu}_\mu$ / ν_μ larger at high energy due to high p_L π- which cannot be (de-) focused

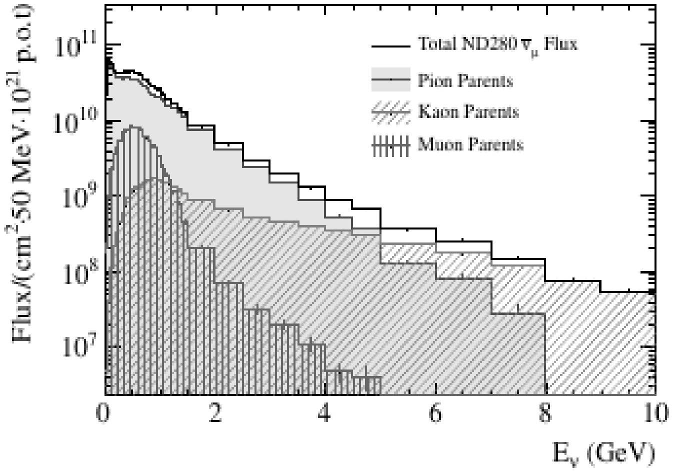
ν_μ T2K flux



ν_e background in T2K flux

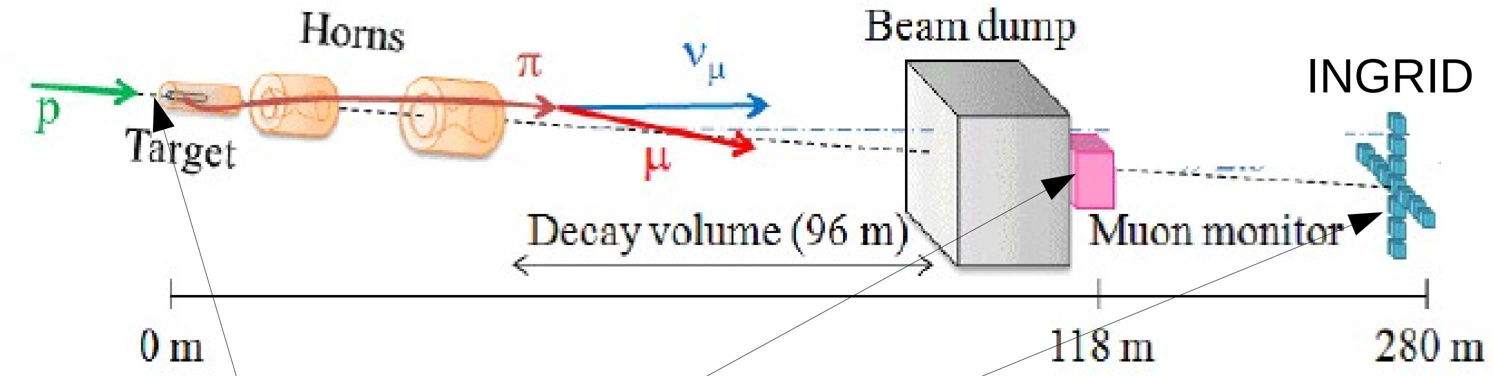


$\bar{\nu}_\mu$ background in T2K flux

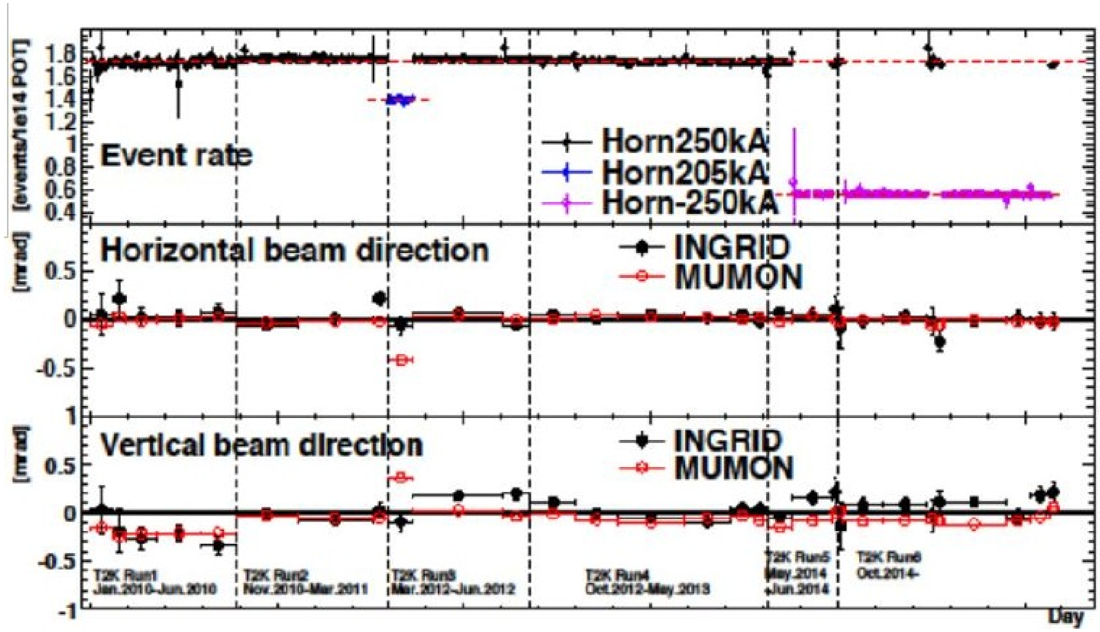


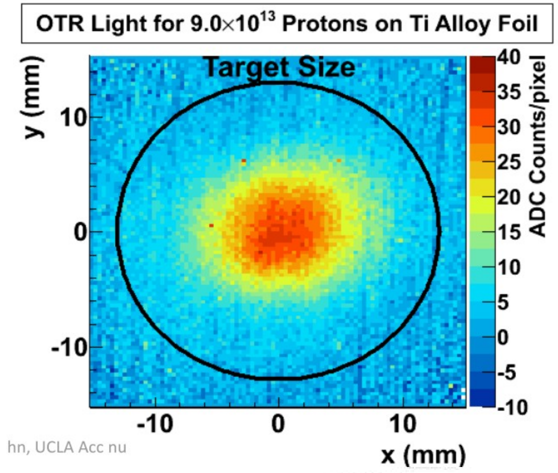
Beam monitoring

- **Monitoring of the beam:** intensity, position, direction



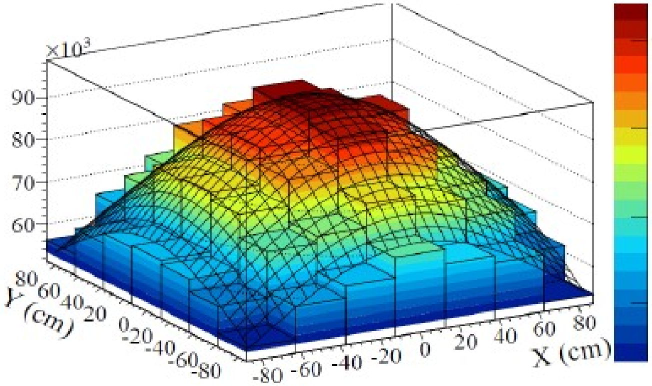
- looking at **protons**
- looking at **muons**
- looking at **neutrinos**





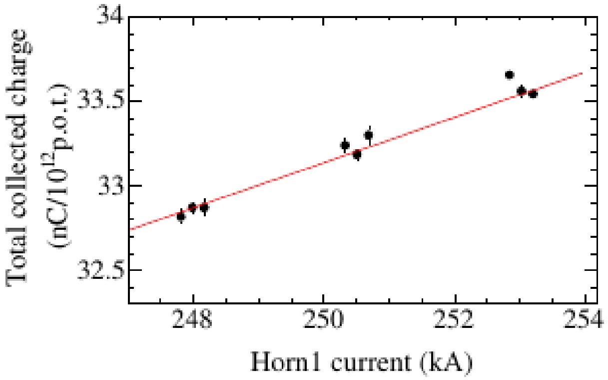
Protons

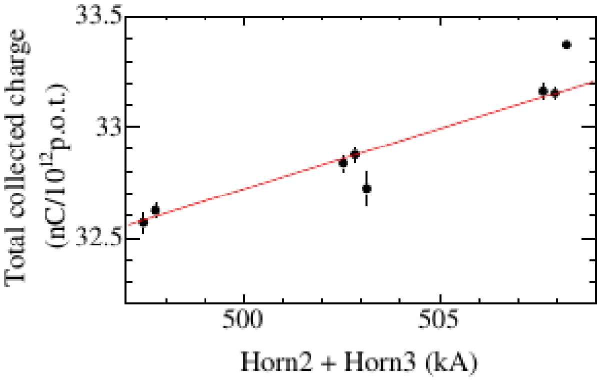
Muons

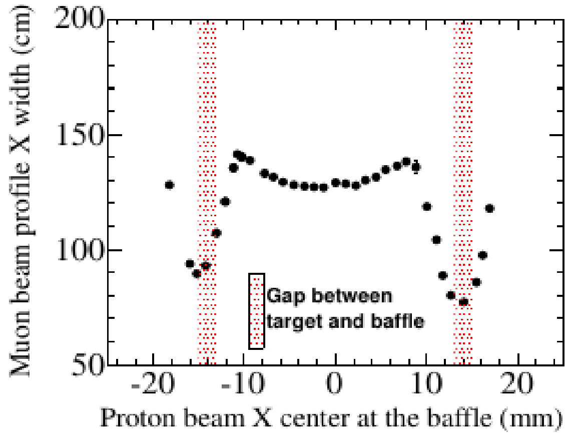


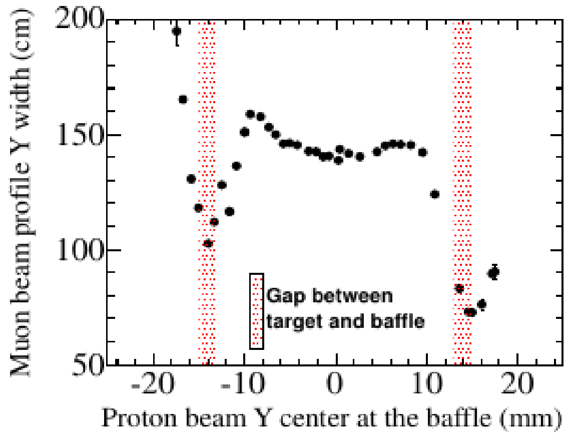
Playing around with the muon monitor

- Example from T2K: sensitivity to horn current and proton beam position

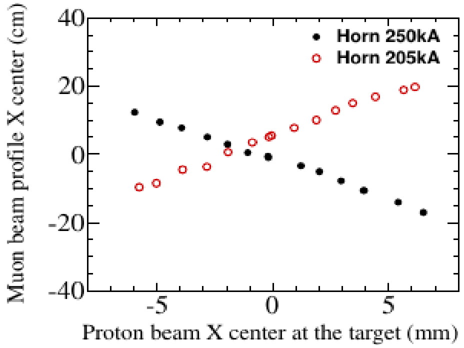


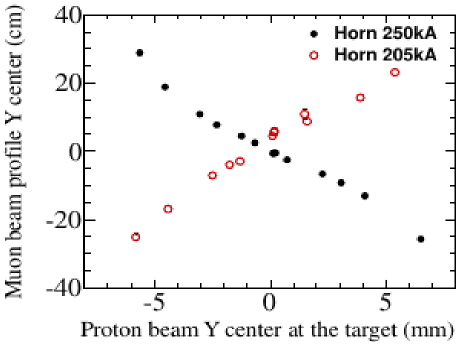


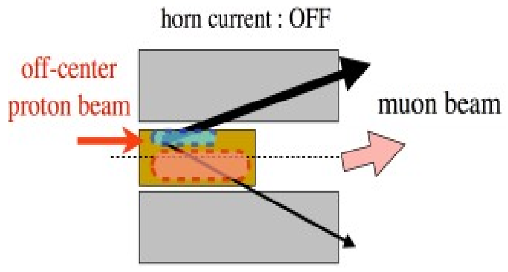


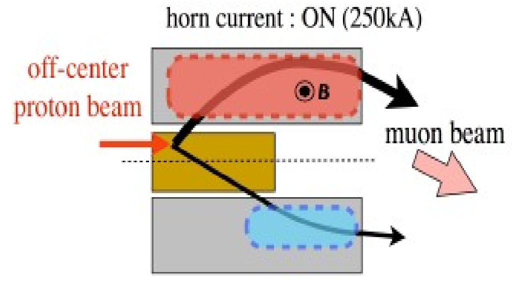


- Correlation between muon profile and proton beam position depends on the current

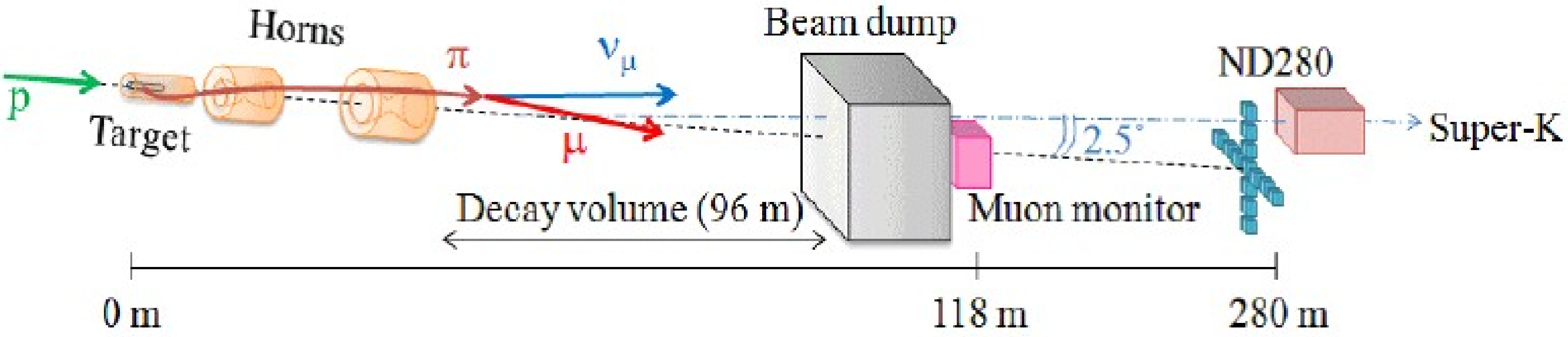






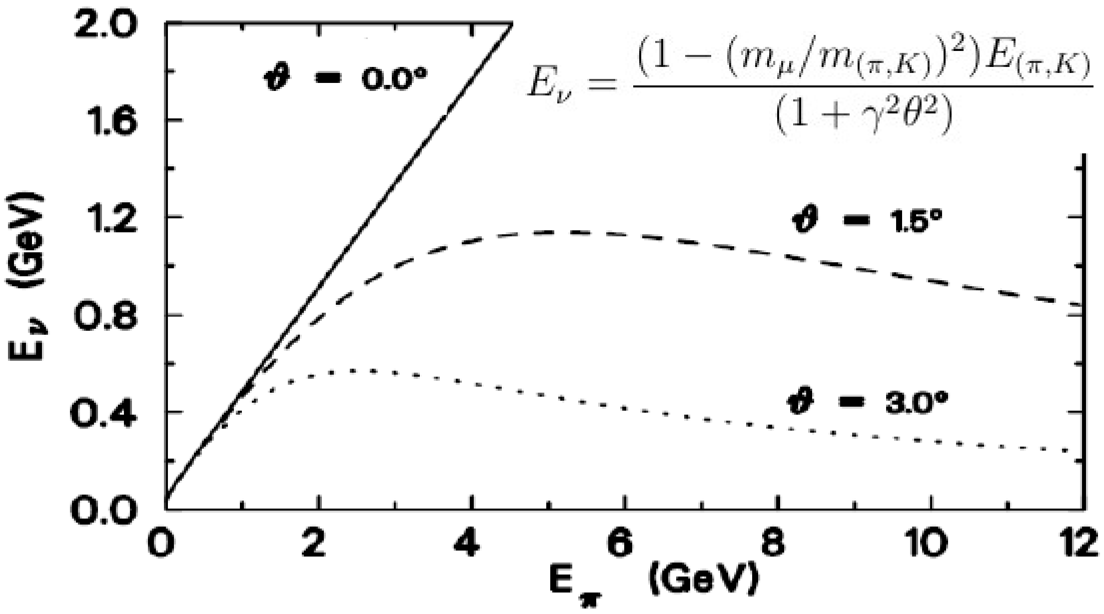


Tuning the neutrino energy

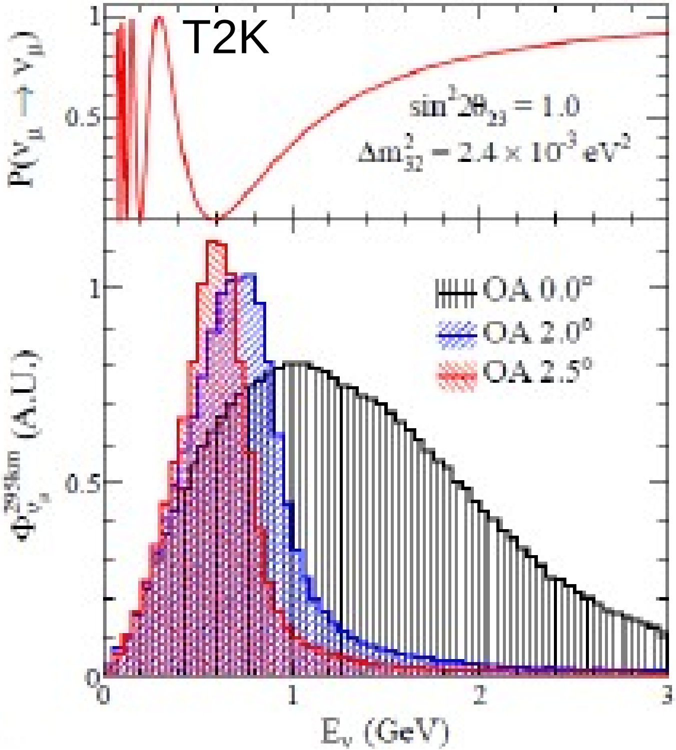


Energy of ν emitted in 2-body decay at an angle relative to π (K) direction is only weakly dependent on parent's momentum

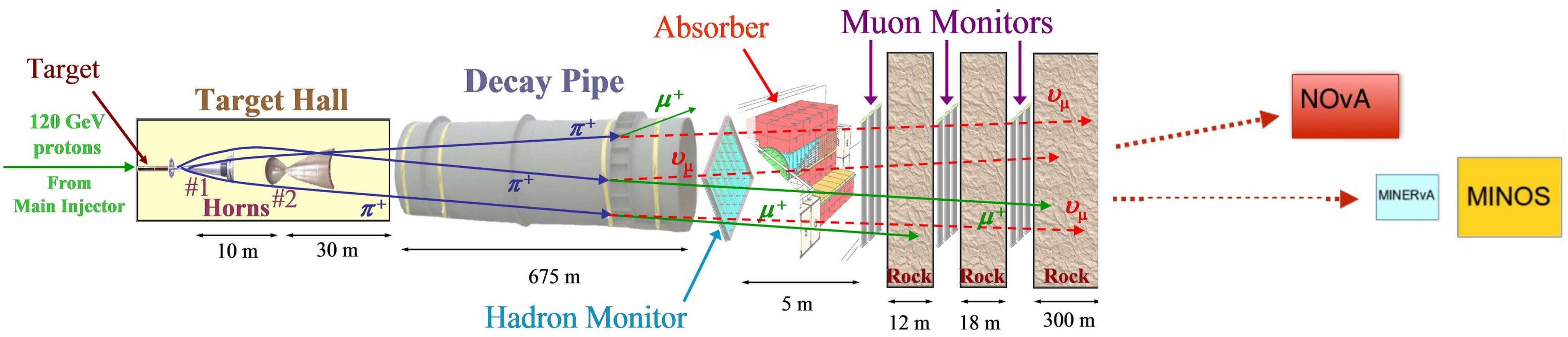
Off-axis → narrow flux at the maximum of the neutrino oscillation

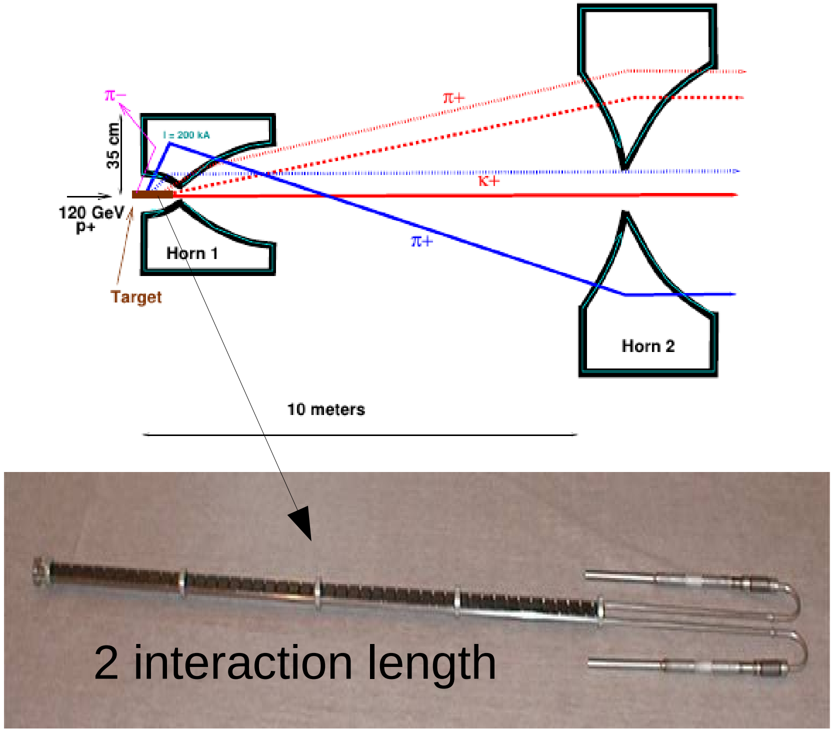


$$E_\nu = \frac{(1-(m_\mu/m_{(\pi,K)})^2)E_{(\pi,K)}}{(1+\gamma^2\theta^2)}$$



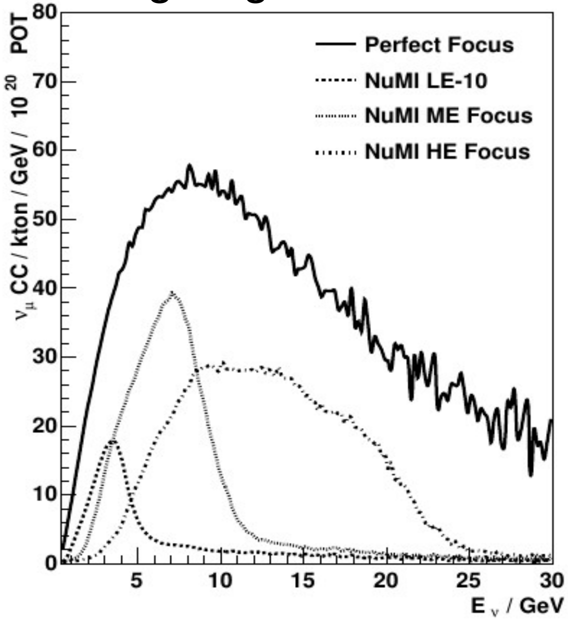
NuMI beam



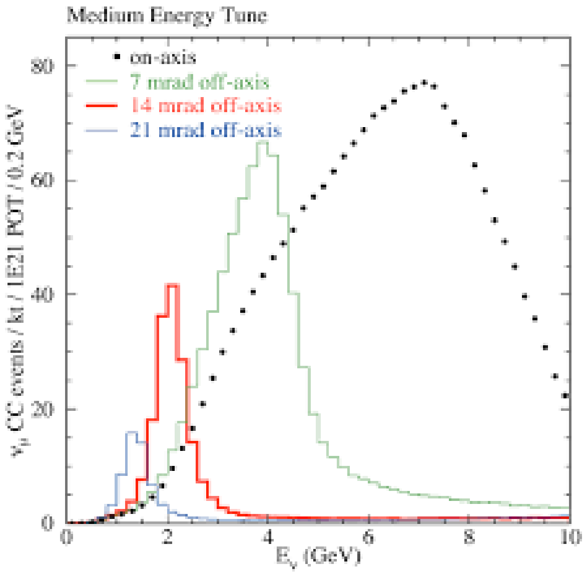


2 interaction length

Change energy by moving target and horns



Off-axis technique



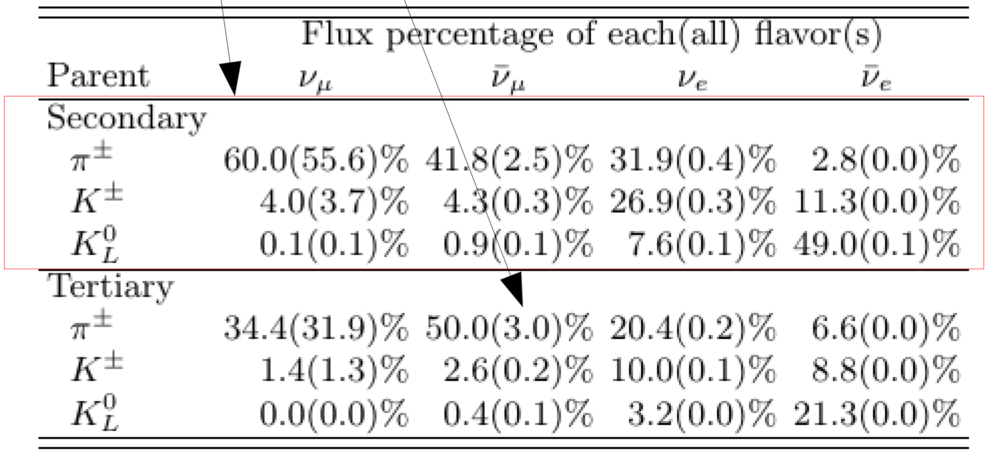
Flux tuning

Flux simulation

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

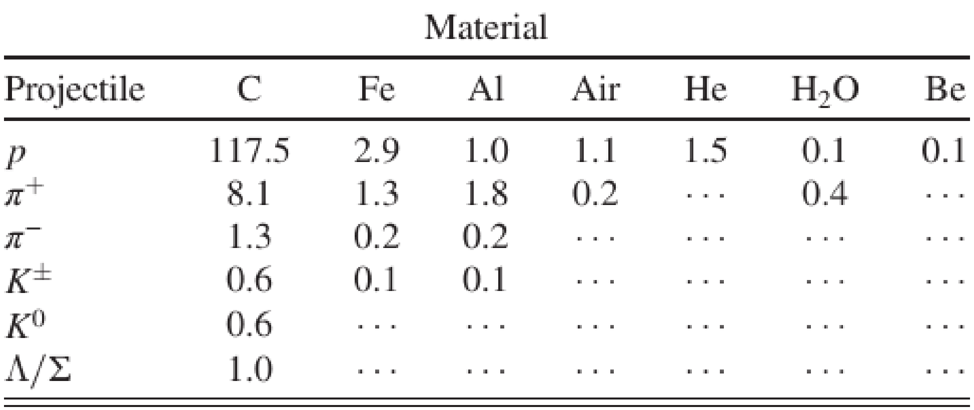
Re-interactions of hadrons with target, horns, vessel, beam dump... → production of **'tertiary hadrons' on C (or other materials)**

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_L^0	0.1(0.1)%	0.9(0.1)%	7.6(0.1)%	49.0(0.1)%
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_L^0	0.0(0.0)%	0.4(0.1)%	3.2(0.0)%	21.3(0.0)%

NuMI low energy



	Material						
Projectile	C	Fe	Al	Air	He	H_2O	Be
p	117.5	2.9	1.0	1.1	1.5	0.1	0.1
π^+	8.1	1.3	1.8	0.2	...	0.4	...
π^-	1.3	0.2	0.2	...	...	...	...
$K^\pm$	0.6	0.1	0.1	...	...	...	...
K^0	0.6	...	...	...	...	...	...
Λ/Σ	1.0	...	...	...	...	...	...

(average number of hadron interactions x 100 for each ν_μ)

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

Flux tuning

The simulations are tuned using external measurement from hadro-production experiments

T2K

Experiment	Beam Mom. (GeV/c)	Target	Particles
NA61/SHINE [11][12]	31	C	$\pi^\pm$, K^+
Eichten *et al.* [27]	24	Be, Al, ...	p, $\pi^\pm$, $K^\pm$
Allaby *et al.* [28]	19.2	Be, Al, ...	p, $\pi^\pm$, $K^\pm$
BNL-E910 [29]	6.4 – 17.5	Be	$\pi^\pm$

NuMI

NA49 pC @ 158 GeV (+HARP)
MIPP pC @ 120 GeV
Barton et Al *[Phys. Rev. D 27, 2580 (1983)]*

(need scaling to different targets, available at different proton energy)

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:

$$P(x;\sigma_{prod}) = \Delta x \sigma_{prod} \rho e^{-x\sigma_{prod}\rho}$$

$$W = \frac{P(x;\sigma'_{prod})}{P(x;\sigma_{prod})}$$

probability of proton to travel a path x in the target and interact in Δx

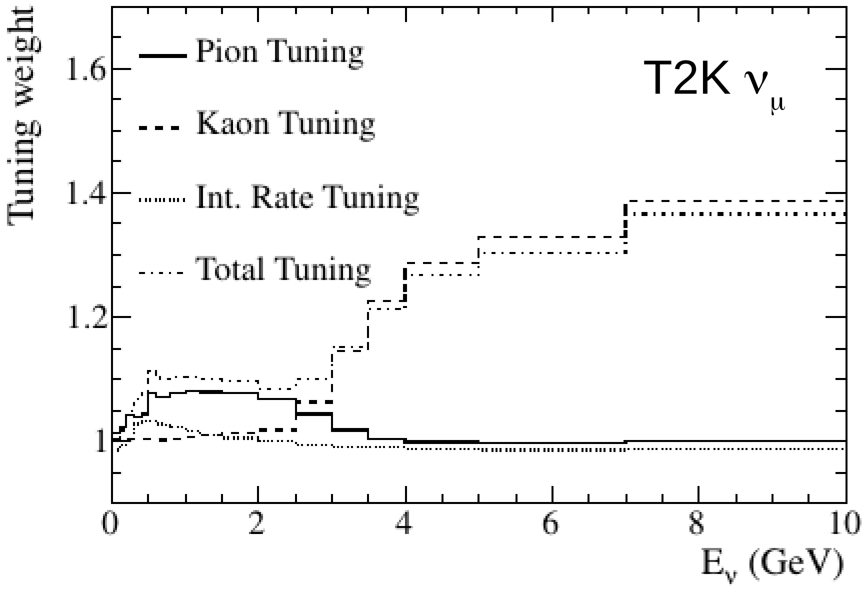
$$\frac{dn}{dp}(\theta, p_{in}, A) = \frac{1}{\sigma_{prod}(p_{in}, A)} \frac{d\sigma}{dp}(\theta, p_{in}, A).$$

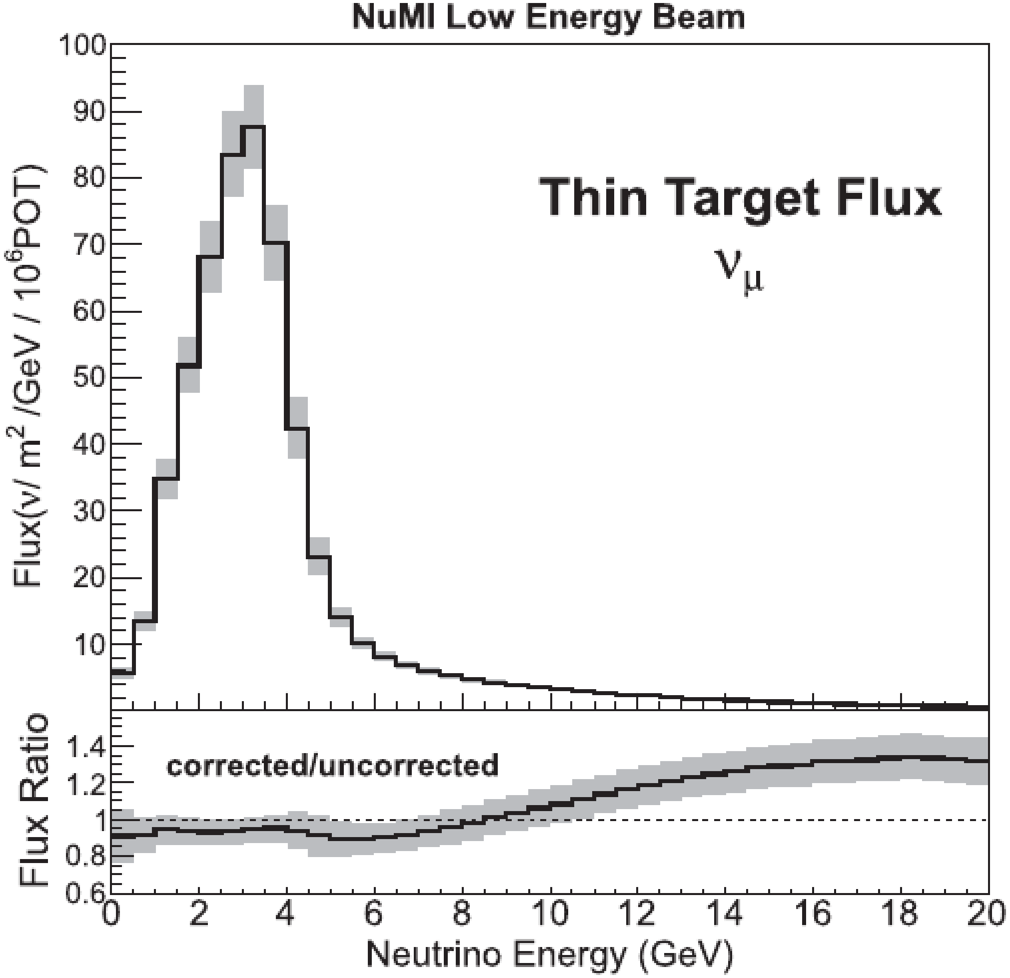
$$W(p_{in}, A) = \frac{[\frac{dn}{dp}(\theta, p_{in}, A)]_{data}}{[\frac{dn}{dp}(\theta, p_{in}, A)]_{MC}}$$

hadron multiplicity (with a certain angle and momentum) for each proton interaction

Tuning factors

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



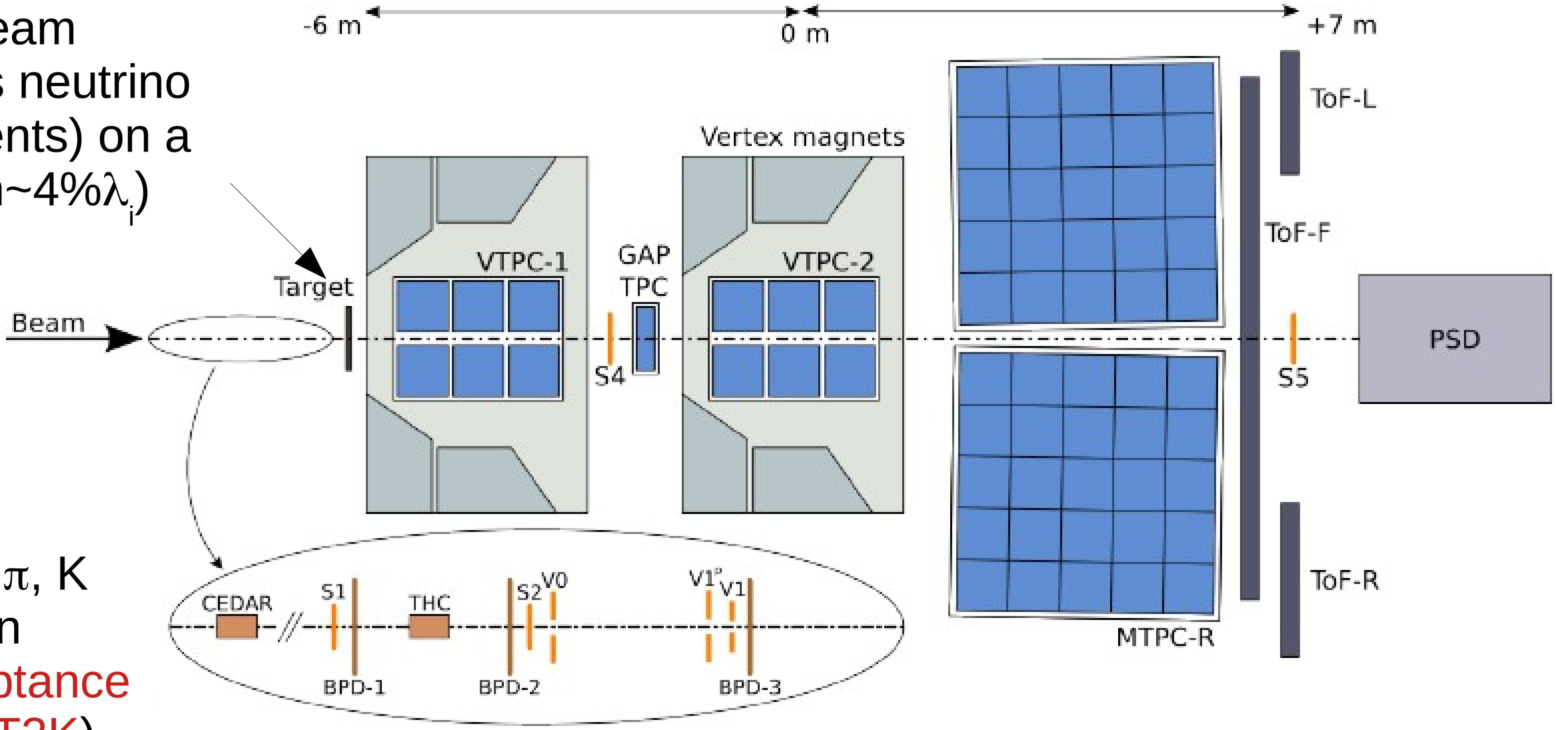


Uncertainties from theory corrections (scaling to different proton energies, targets, not covered phase space…) and from hadro-production data (statistics and systematics uncertainty)

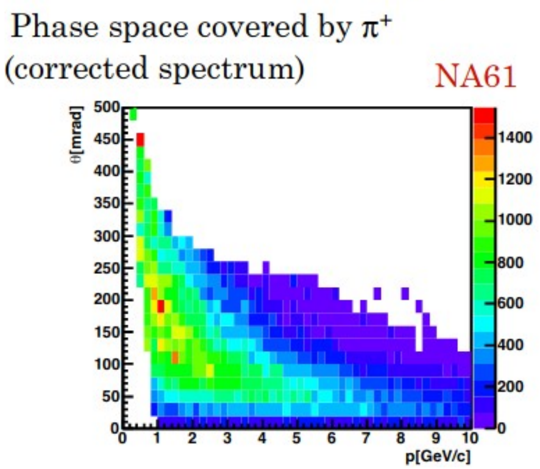
NA61/SHINE

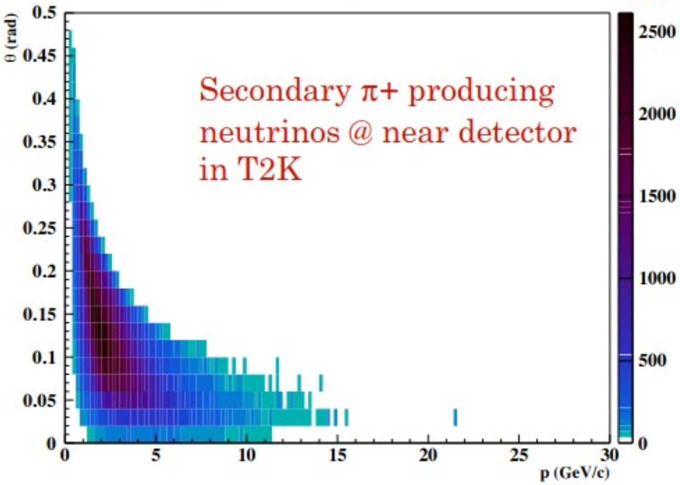
SPS Heavy Ion and Neutrino Experiment: Fixed target experiment using CERN SPS

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)



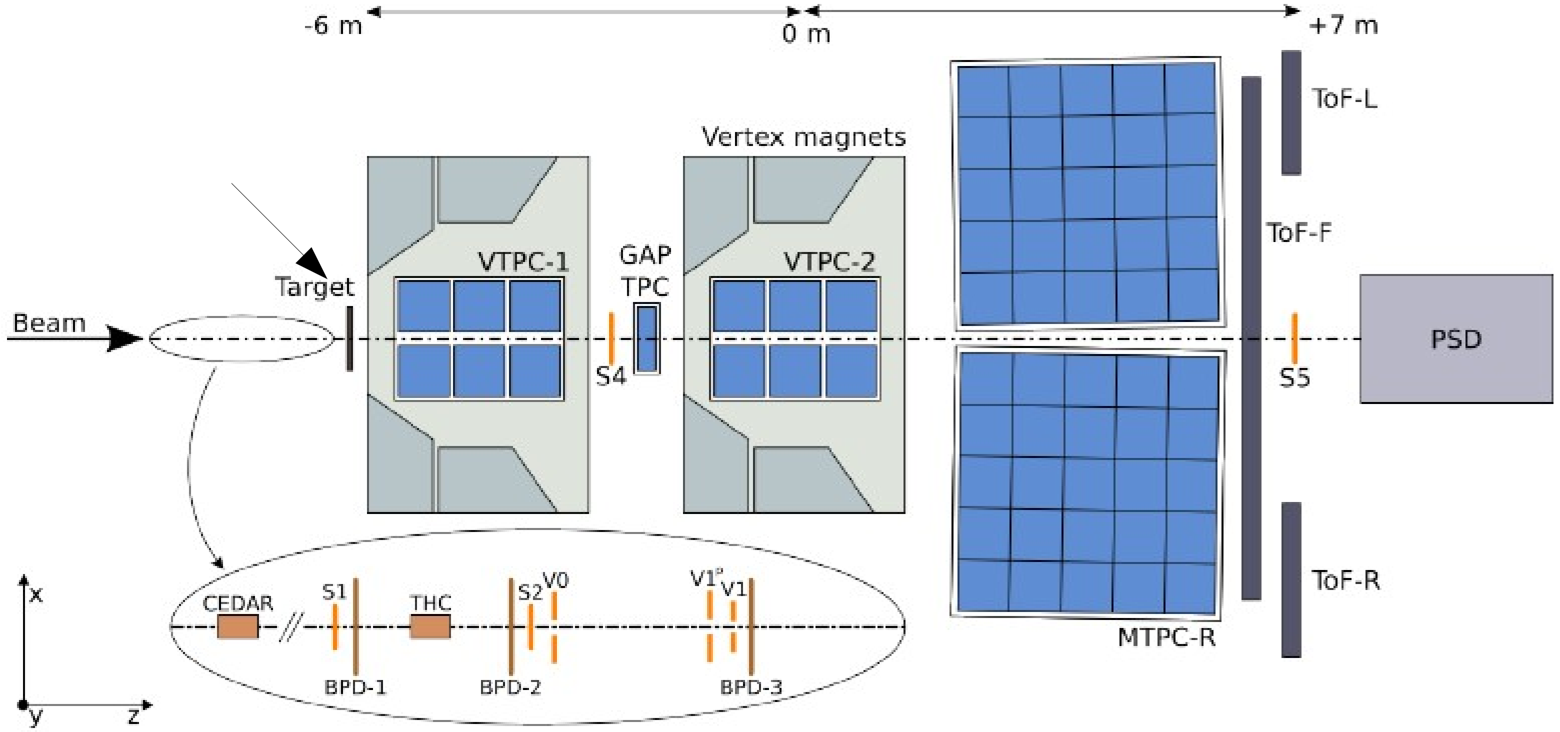


Momentum measurement with
TPC in magnetic field
($\sigma_p/p^2 \sim 0.005$ GeV^{-1})

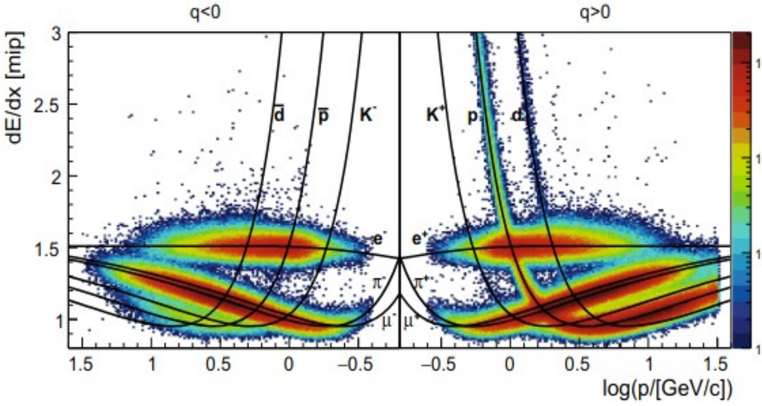
Angular measurement
with 3-4 mrad resolution

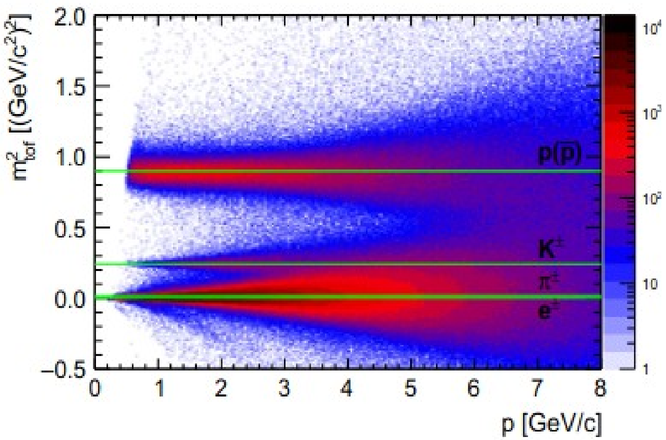
NA61/SHINE

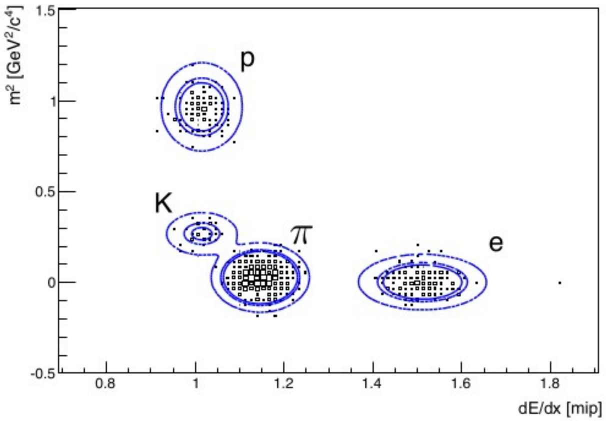
SPS Heavy Ion and Neutrino Experiment: Fixed target experiment using CERN SPS



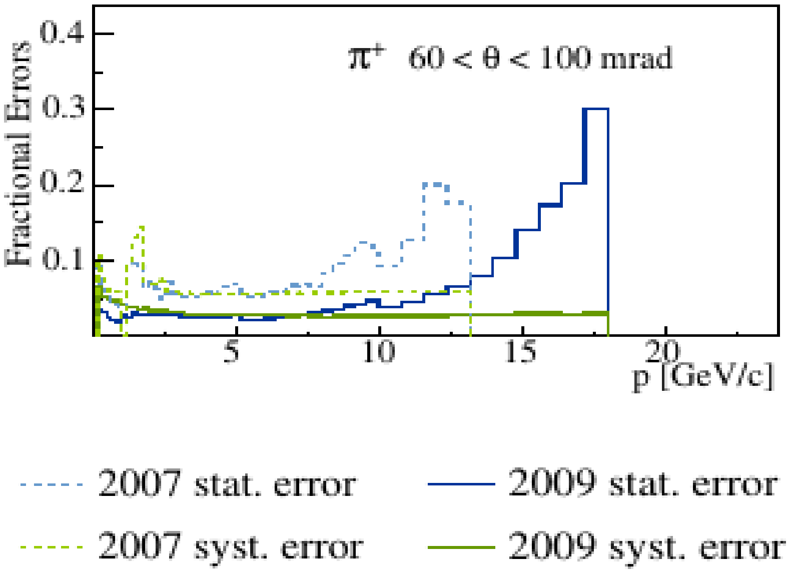
dE/dx + ToF measurement for clean PID



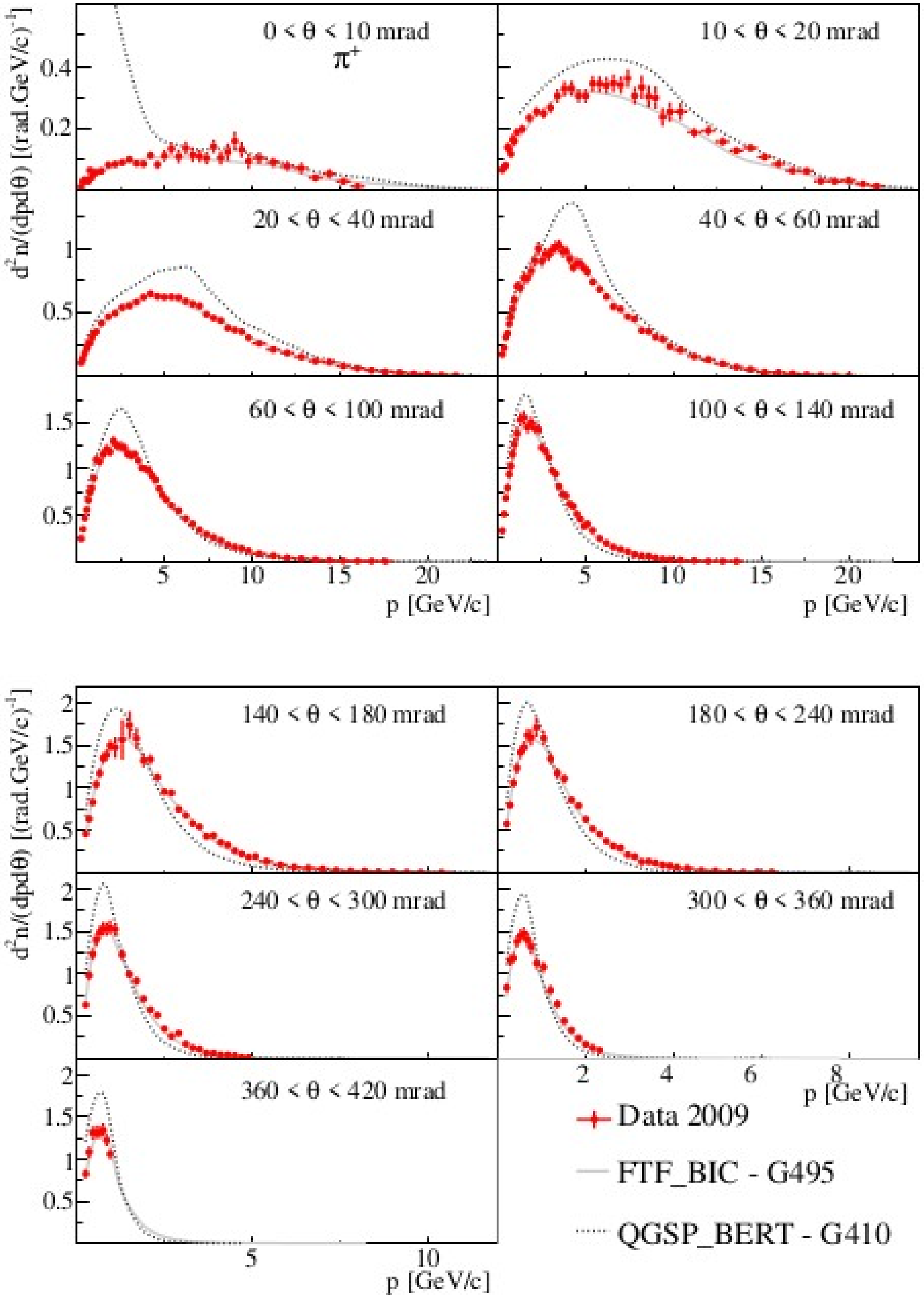




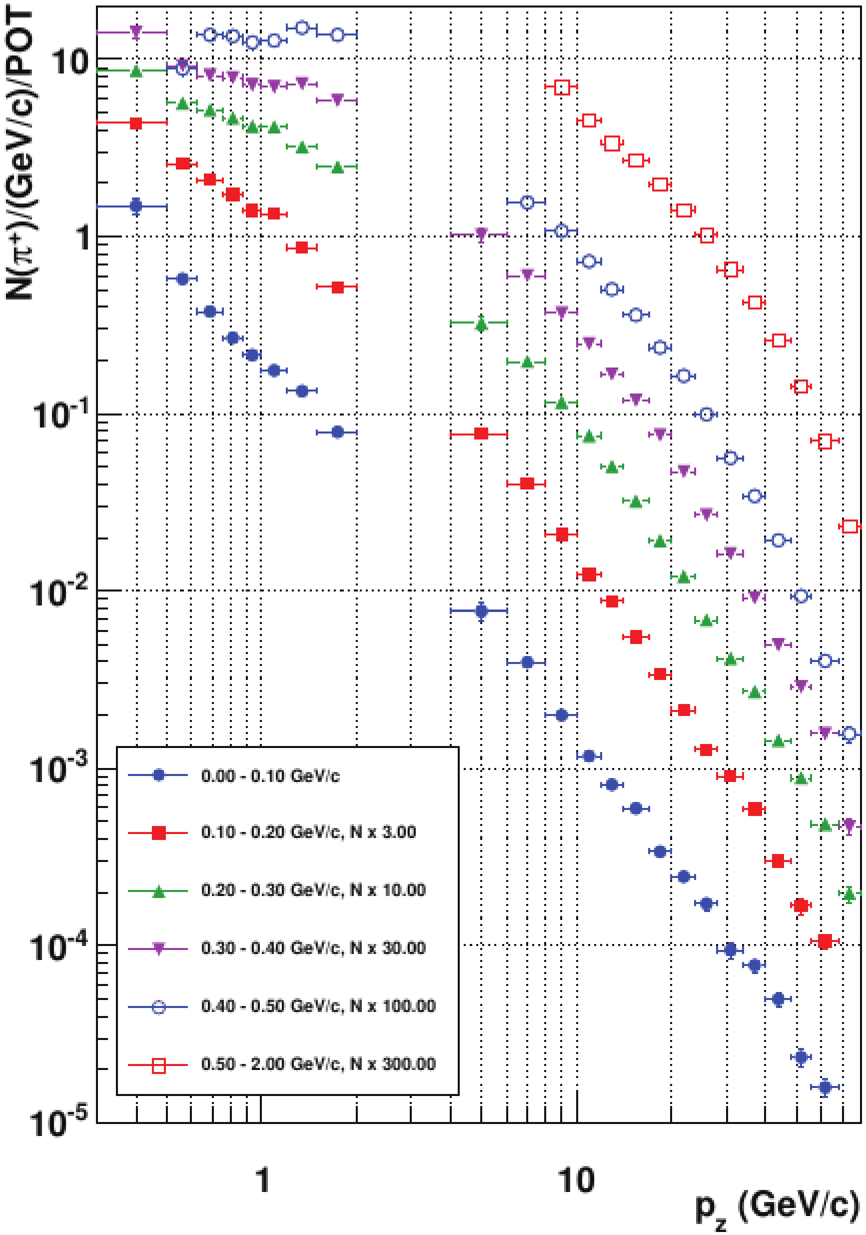
(Old) results

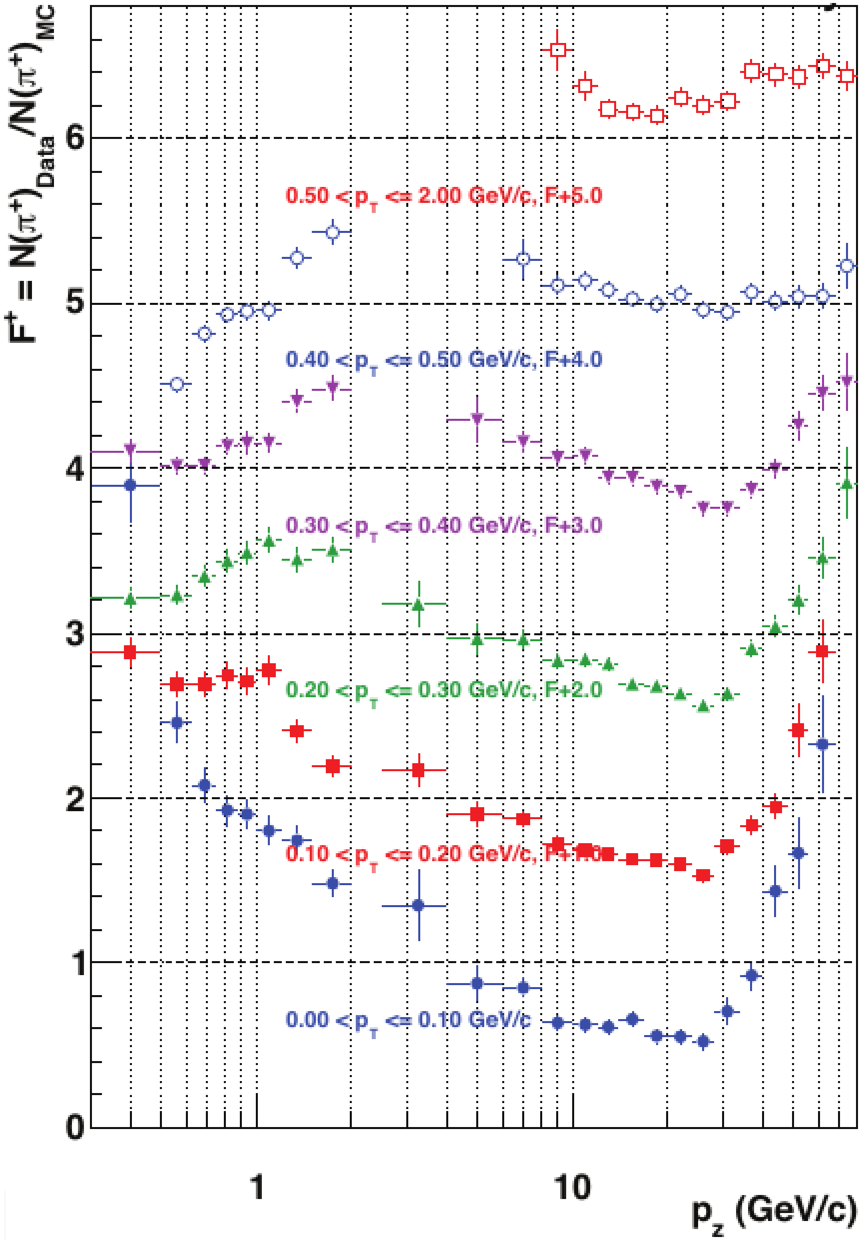


Full measurement of π+, π-, K+,K-



MIPP results for NuMI





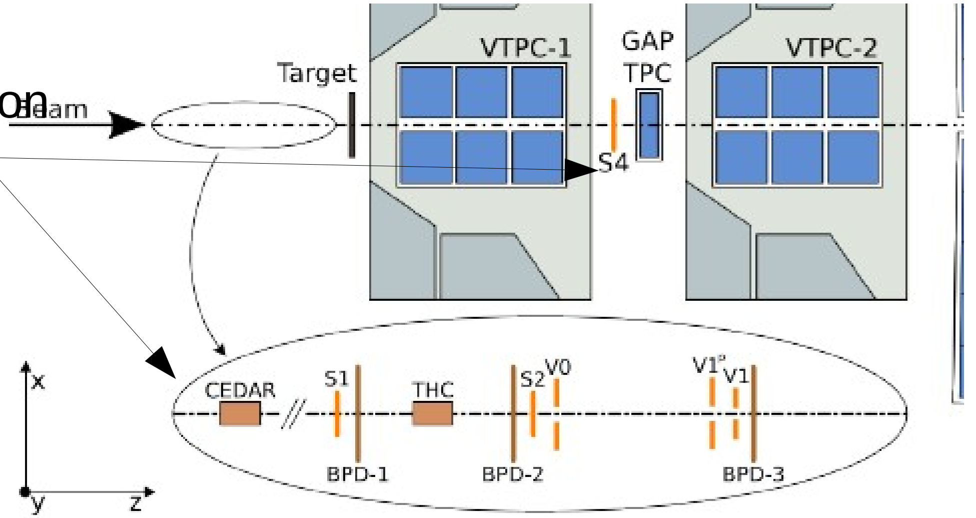
Cross-section normalization

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

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)

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

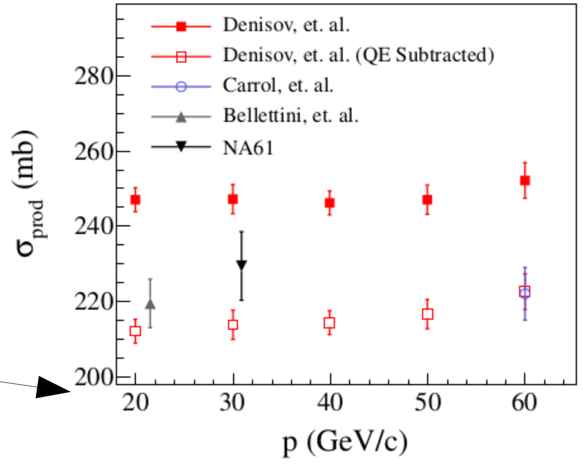
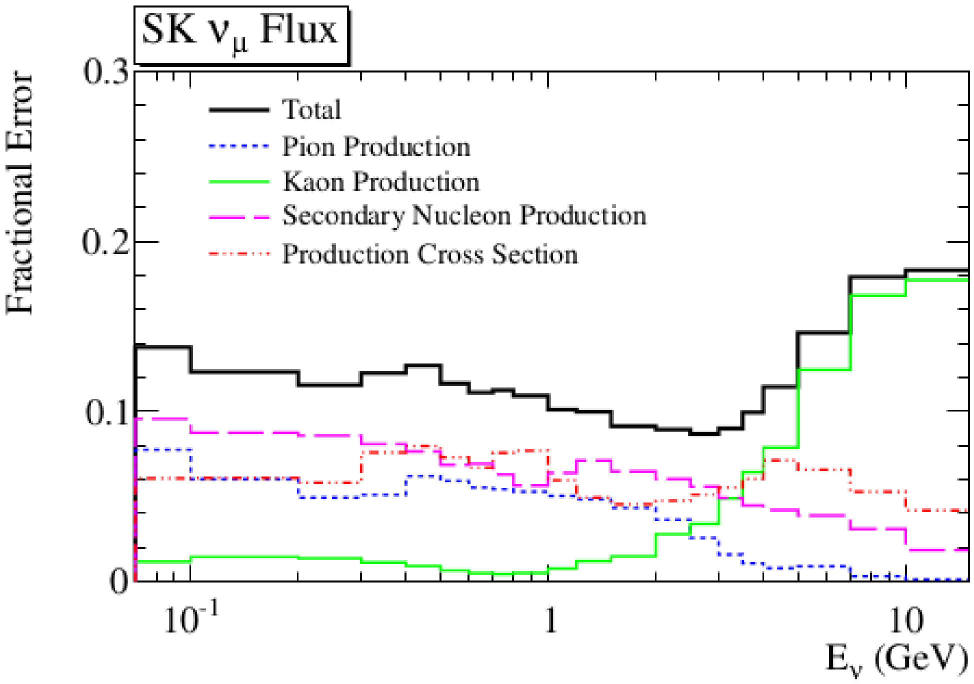


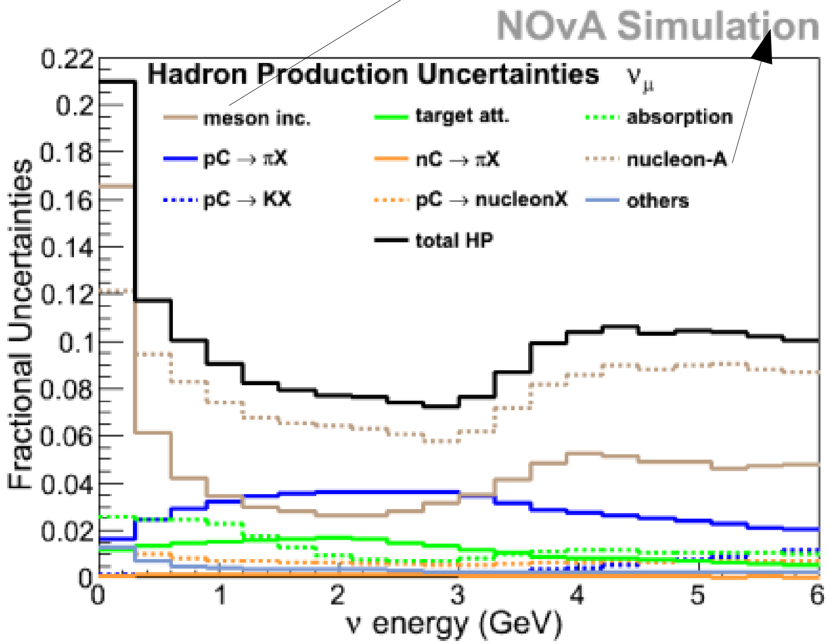
FIG. 37: Production cross-section measurements for protons on graphite targets for momenta 20–60 GeV/c. The data from Denisov *et al.* are shown with and without the quasi-elastic estimate subtracted since the quantity that is measured is ambiguous.

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



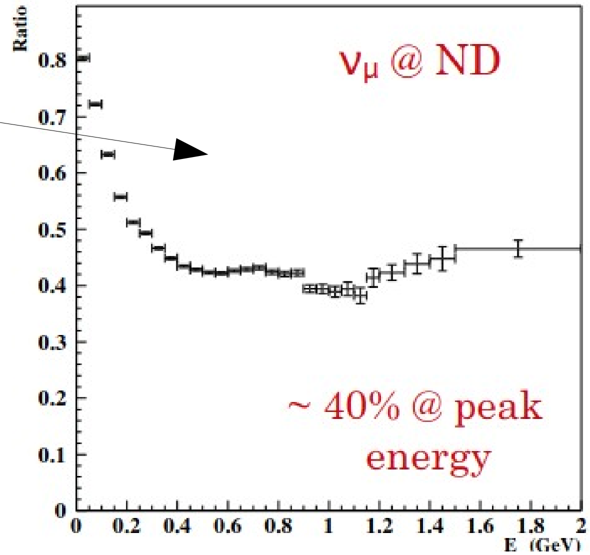


The remaining uncertainties were dominated by the total production cross-section and re-interactions in the horns

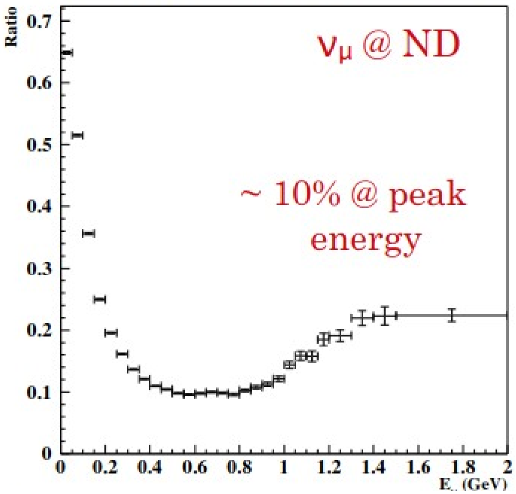
→ new NA61 measurement ‘more directly portable’ to T2K

Need for replica target: T2K example

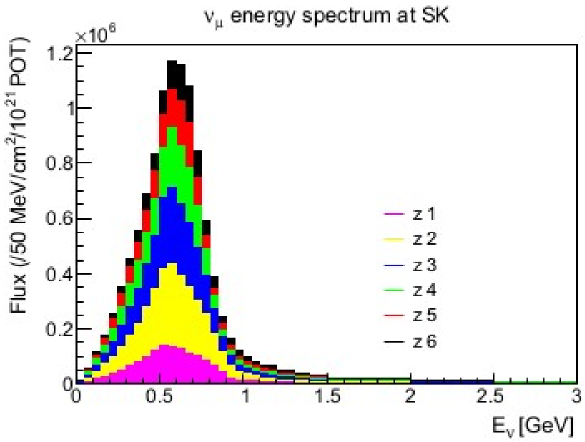
Fraction of neutrinos from re-interactions in the target and in the beam line (~40%)



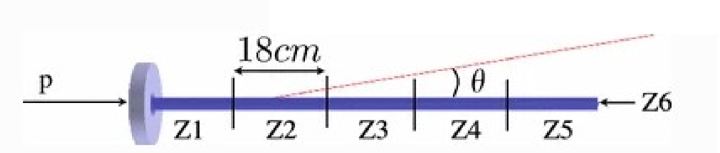
re-interactions in the beamline



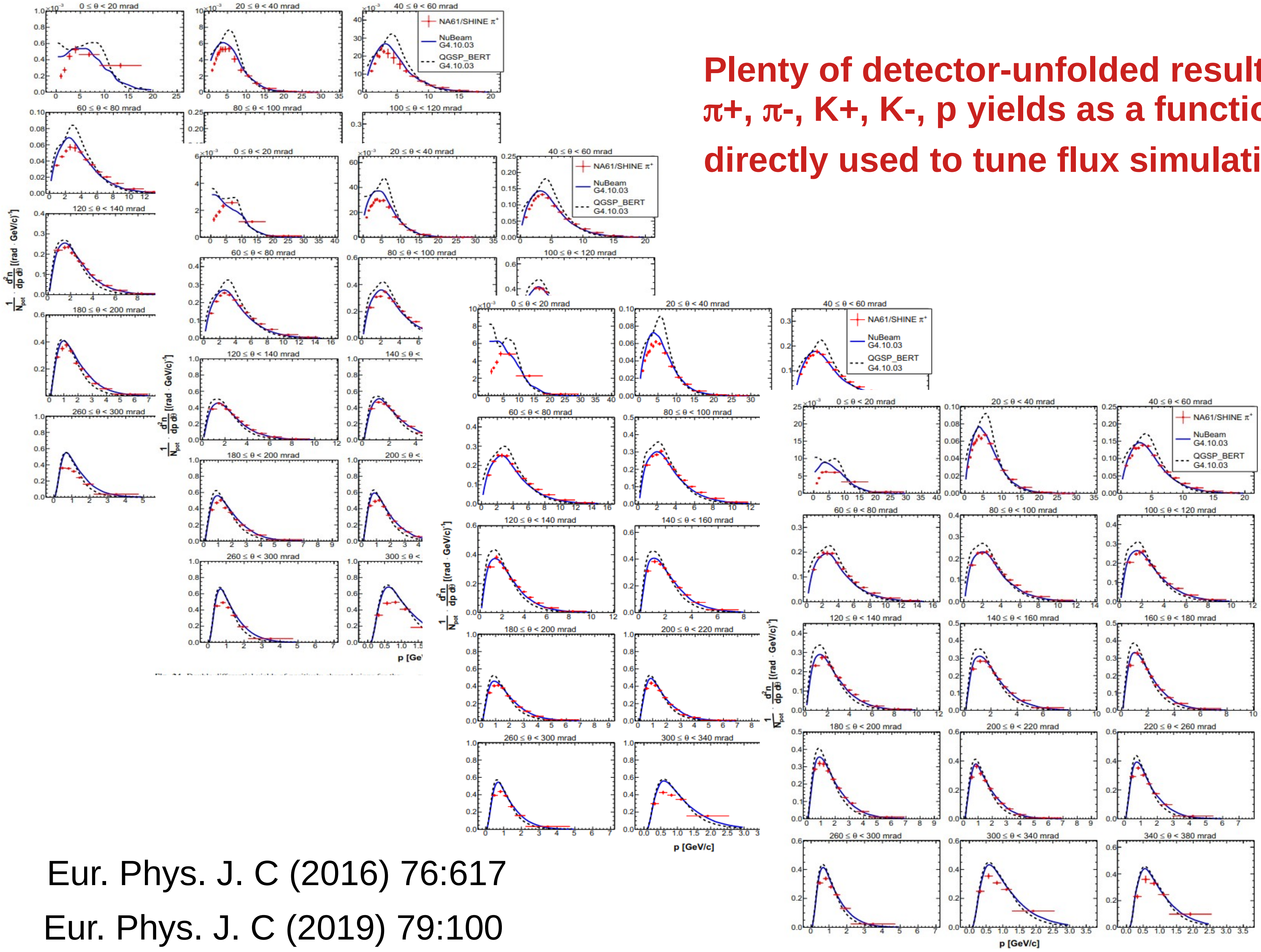
→ **measurement of hadro-production with 'replica target'** (= same target geometry as the neutrino experiment) allows to tune 90% of the flux (60% with thin target)



Measurements of **hadron multiplicity vs angle and momentum (dn/dpdθ) in longitudinal bins of the target** (particles in different longitudinal bins follow a different path inside the horns and are focused differently)



NA61 results with replica target



Plenty of detector-unfolded results:

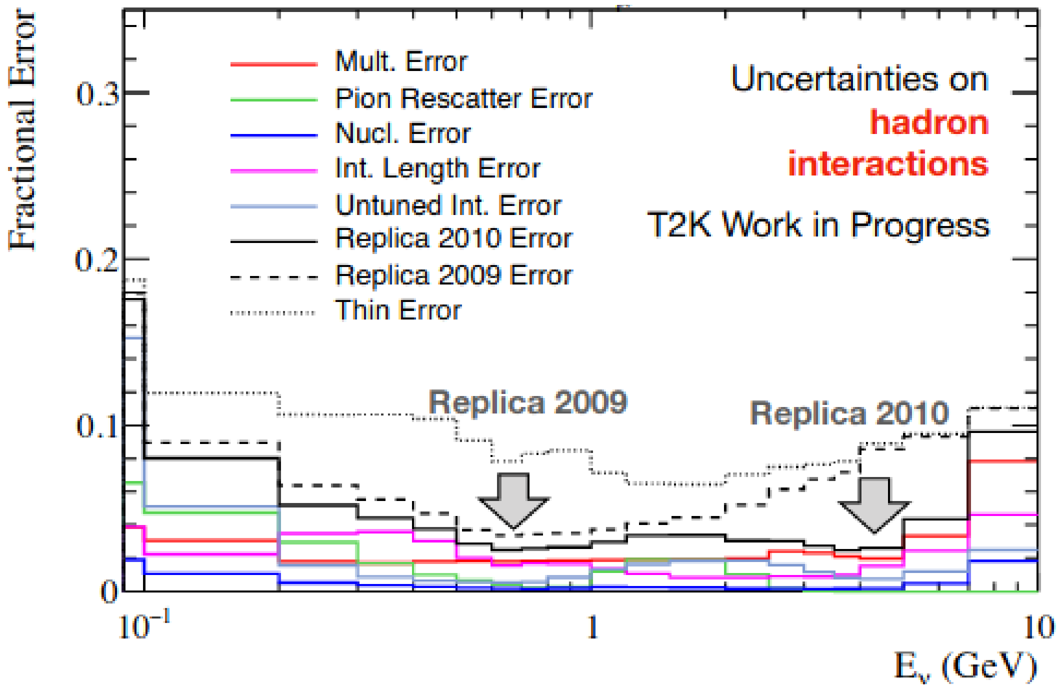
π+, π-, K+, K-, p yields as a function of p, θ, z_{target}

directly used to tune flux simulation

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

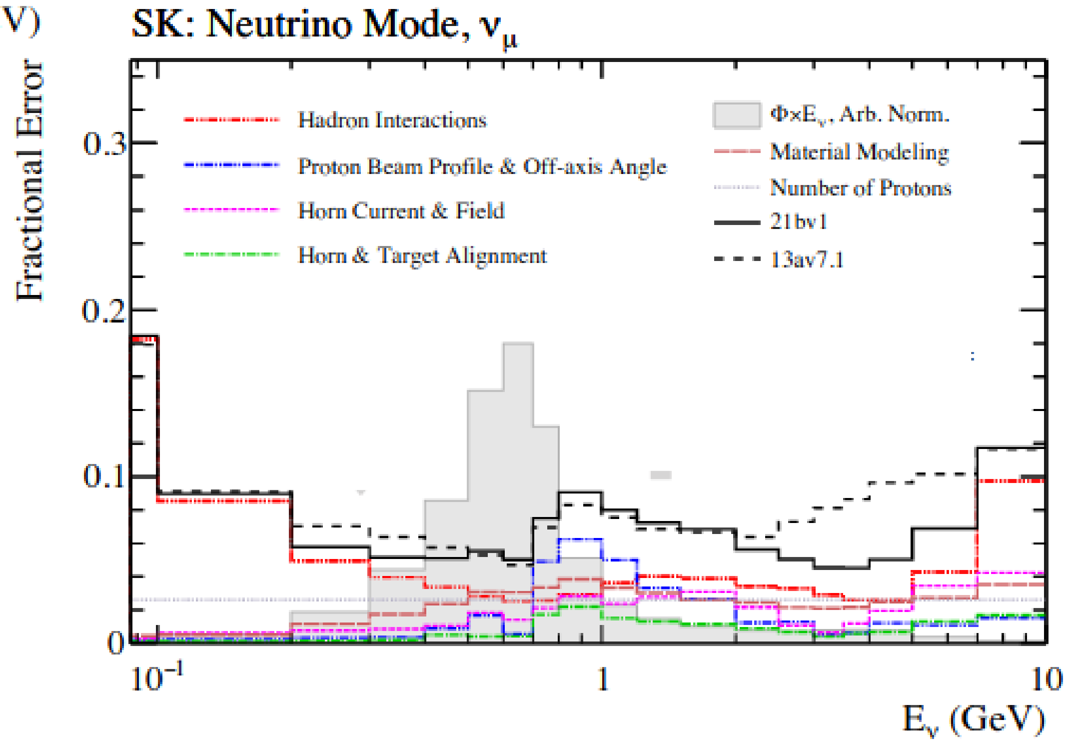
Eur. Phys. J. C (2019) 79:100

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

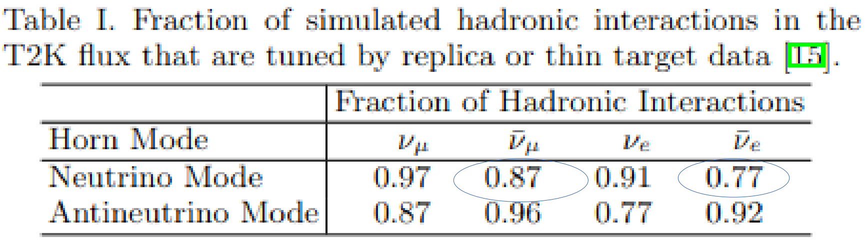


Table I. Fraction of simulated hadronic interactions in the T2K flux that are tuned by replica or thin target data [15].

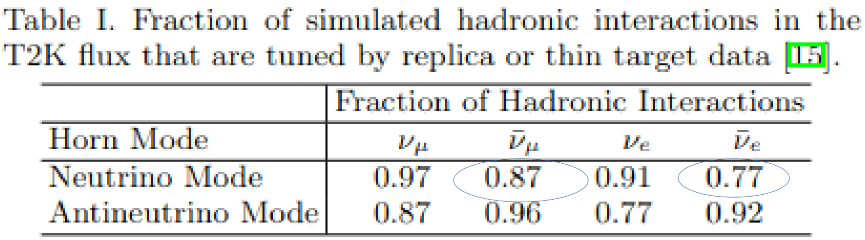
	Fraction of Hadronic Interactions			
Horn Mode	ν_μ	$\bar{\nu}_\mu$	ν_e	$\bar{\nu}_e$
Neutrino Mode	0.97	0.87	0.91	0.77
Antineutrino Mode	0.87	0.96	0.77	0.92

- Interactions not tuned are due to Kaons (for ν_e) and to low energy interactions in beamline materials

→ **NA61 future:** low energy beamline (<15 GeV), (also improvements to present results: major systematics is due to bwd extrapolation

→ new small TPC downstream the target)

Future prospects



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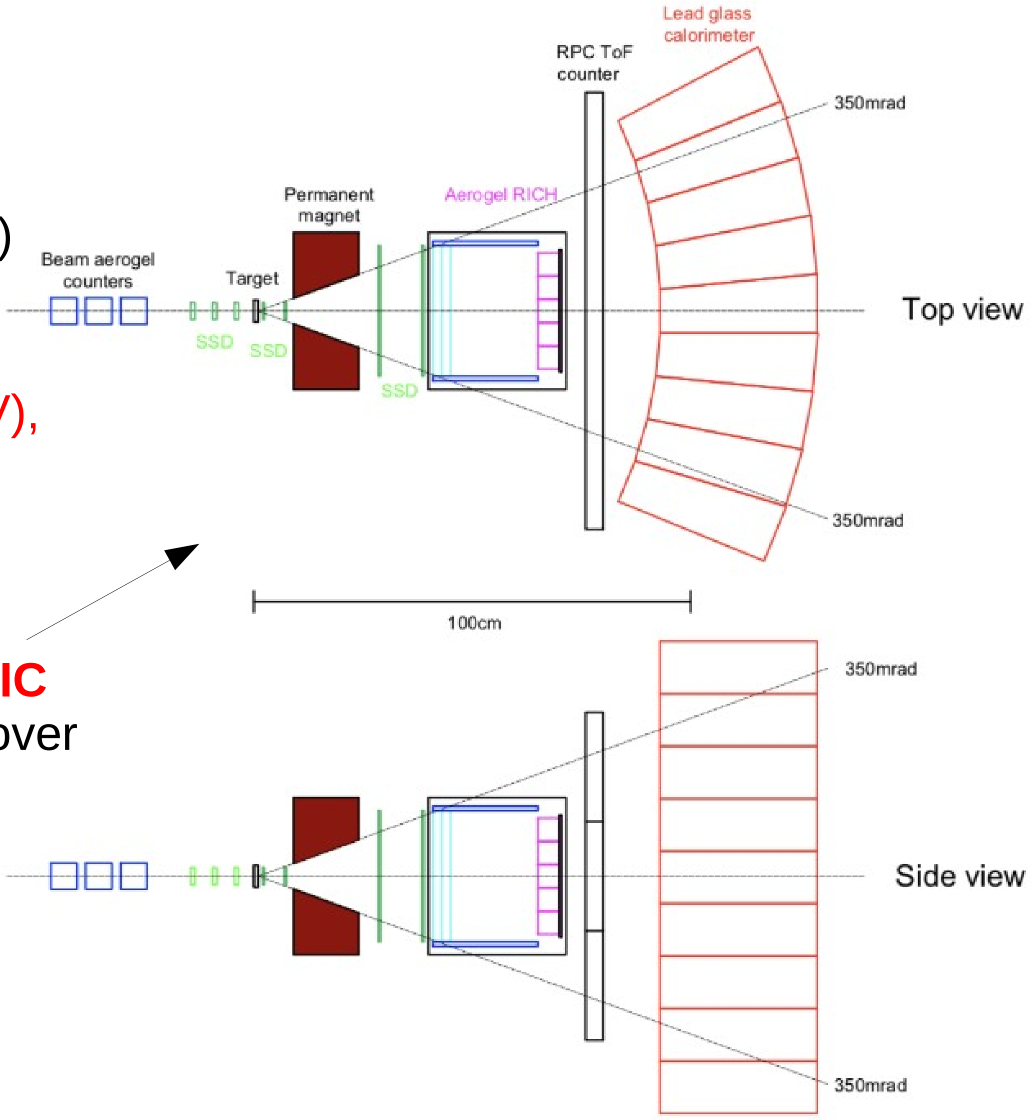
→ **NA61 future:** low energy beamline (<15 GeV),
(also improvements to present results: major systematics is due to bwd extrapolation
→ new small TPC downstream the target)

- 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!)

EMPHATIC first results

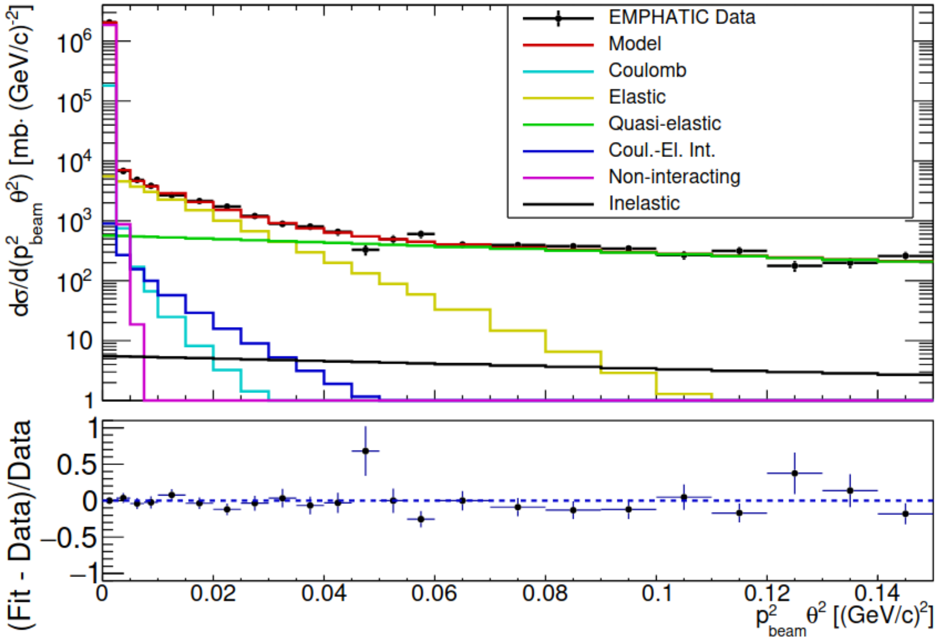
Total xsec can be measured by combination of

- transmission method $N_S = N_0 e^{-nd\sigma_{tot}}$

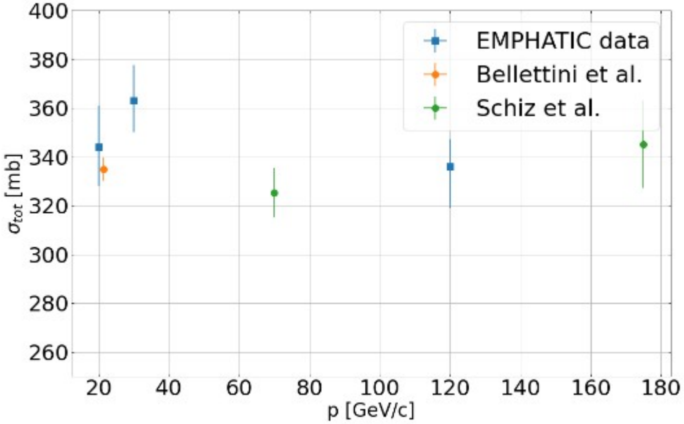
- optical theorem: Im part of limit at t^2=0 GeV^2 of scattering amplitude

First pilot run for proof of principle

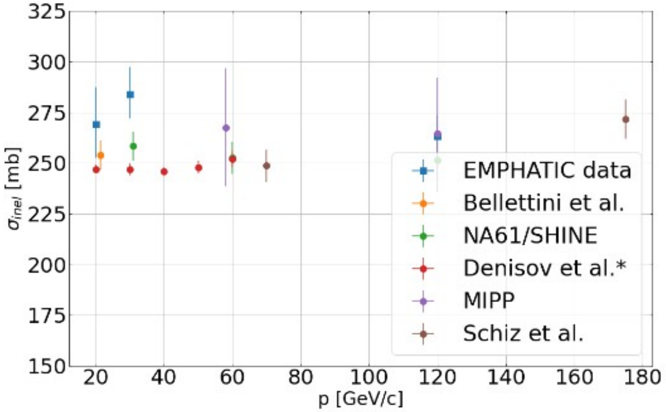
e-Print:2106.15723 [physics.ins-det]



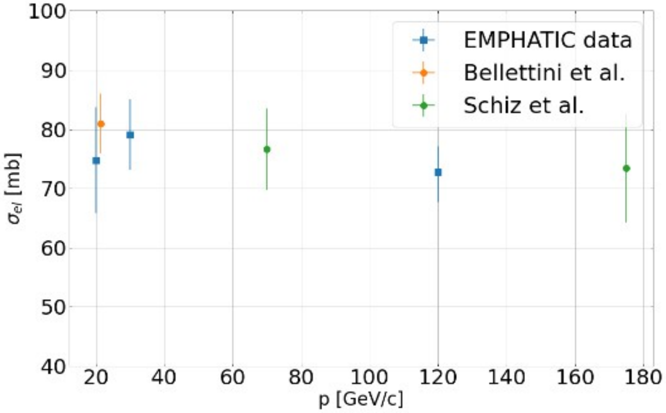
σ_{tot}



$\sigma_{inelastic}$

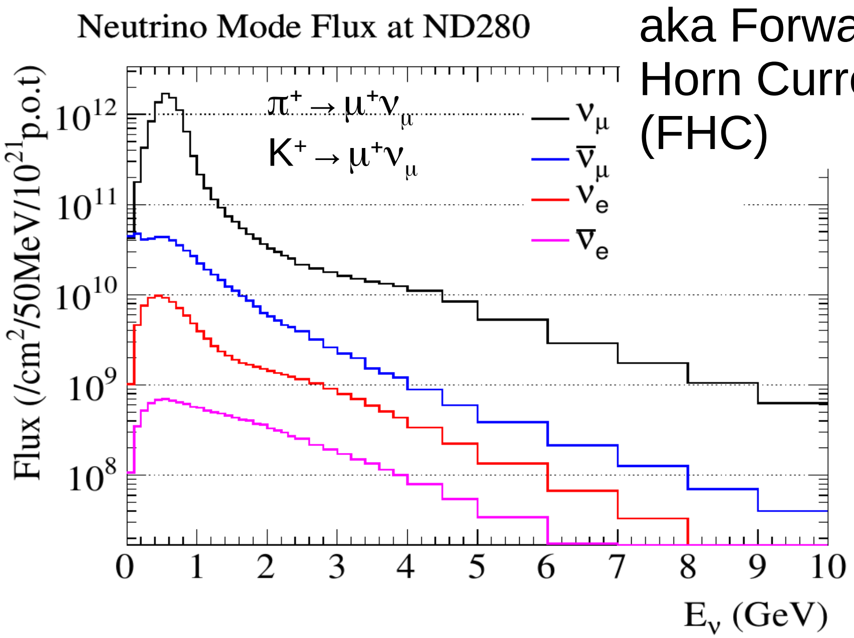


$\sigma_{elastic}$

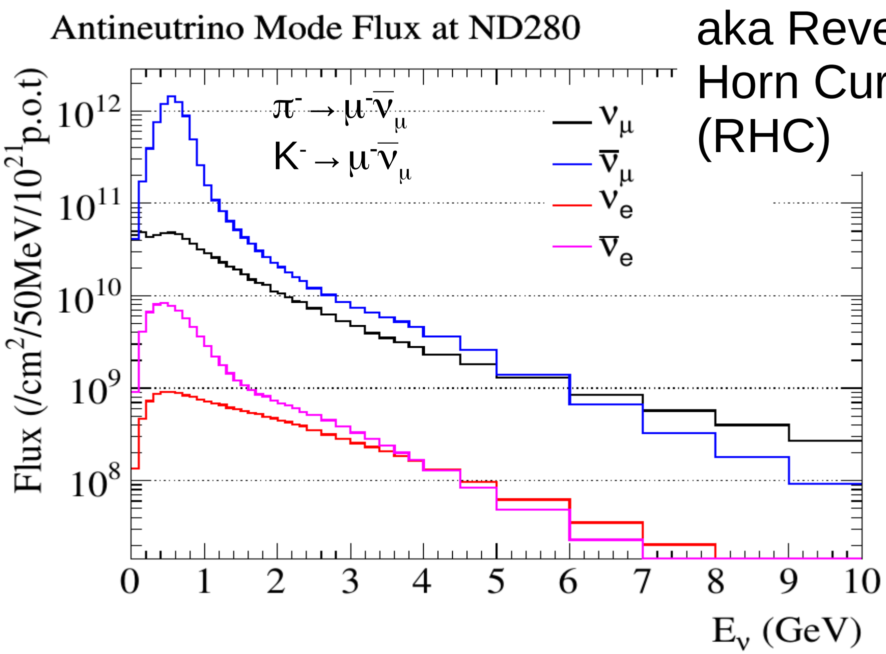


Flux in accelerator experiments

Flux in T2K: wrong sign



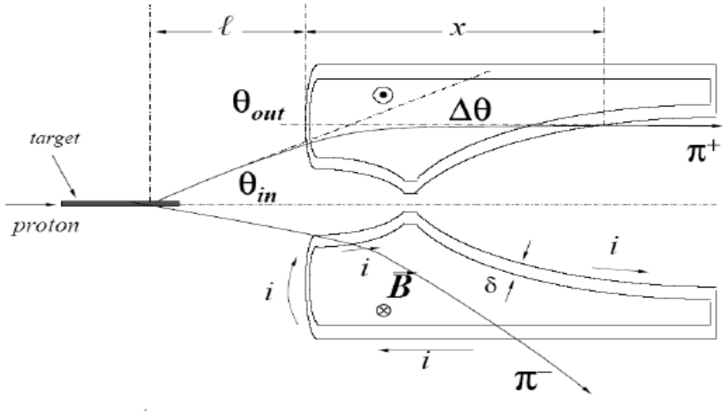
aka Forward Horn Current (FHC)

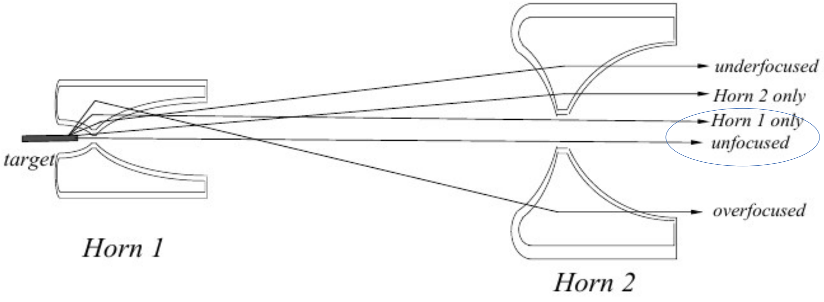


aka Reverse Horn Current (RHC)

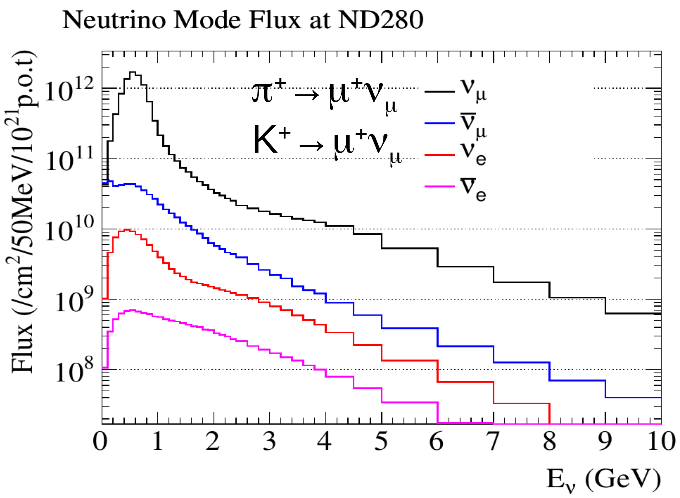
The 'wrong sign' background (important for δ_{CP} and MO) comes from high p_L pions (kaons) which cannot be defocused properly because they miss the horns

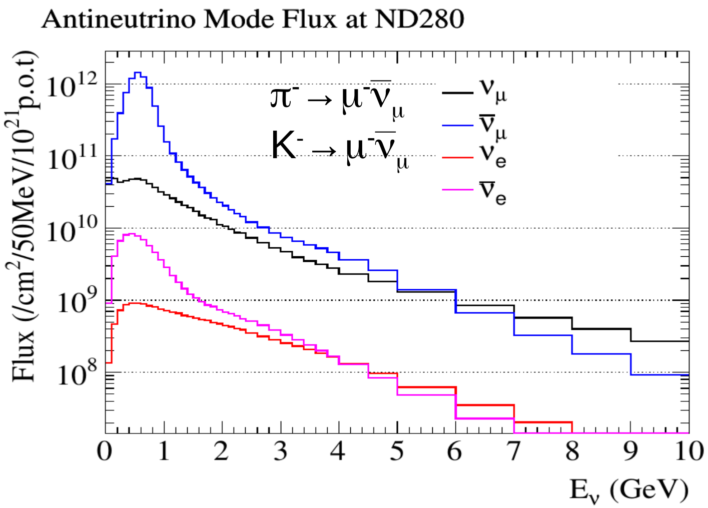
→ fractional contribution larger at high neutrino energies





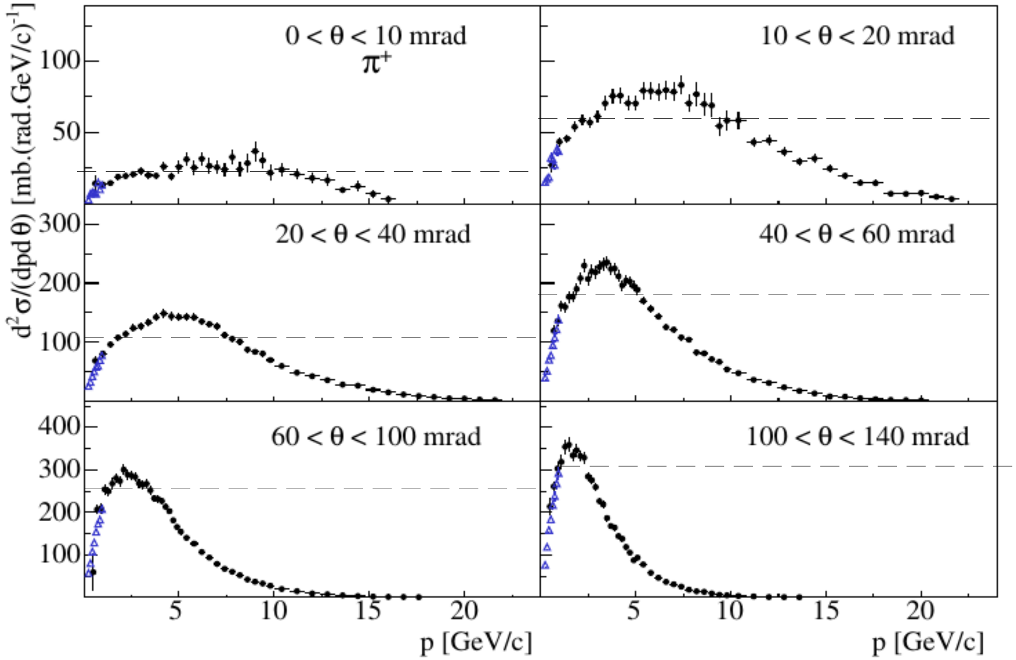
Flux in T2K: wrong sign

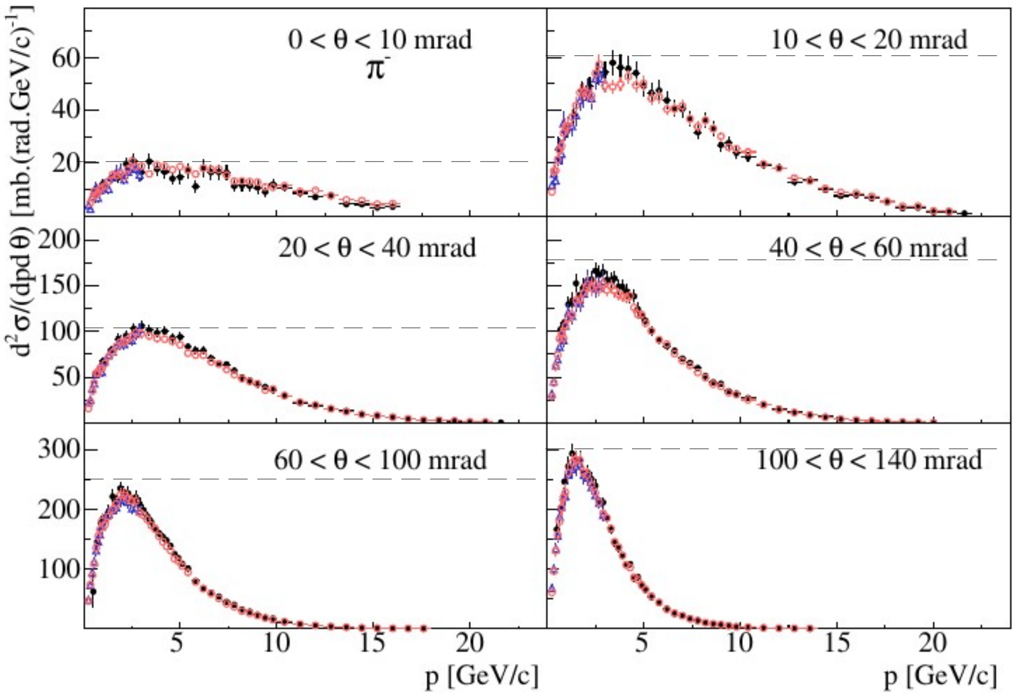




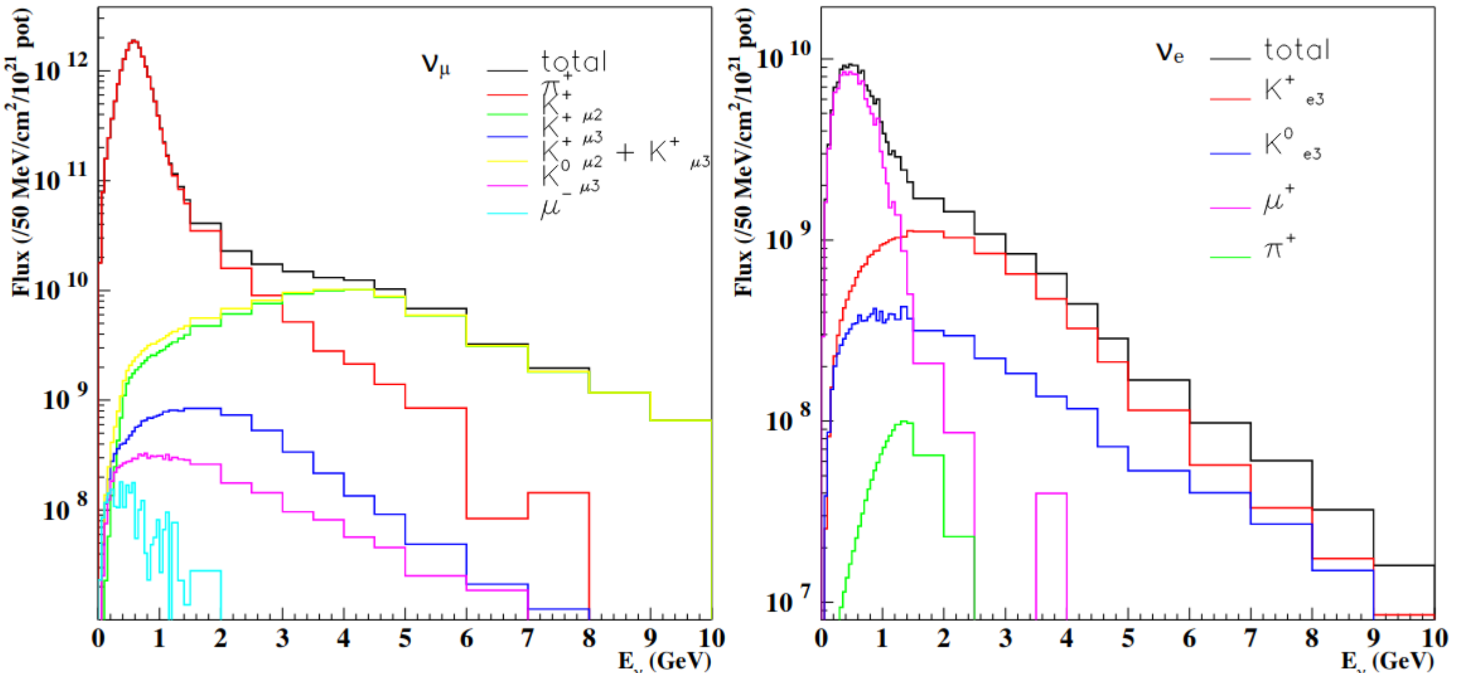
The 'wrong sign' background is larger in antineutrino mode since

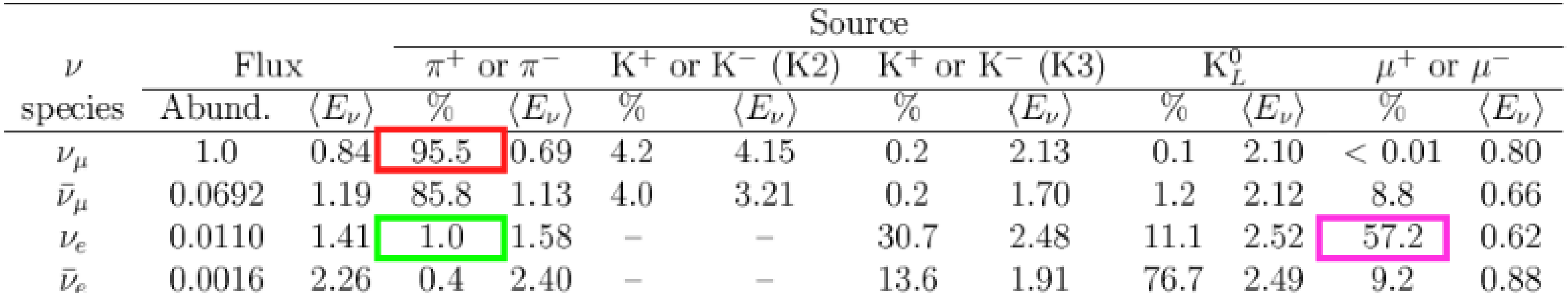
when proton hits the target it is more probable to create positive charged hadrons than negative ones





Flux in T2K: intrinsic ν_e





			Source									
ν	Flux		π^+ or π^-		K^+ or K^- (K2)		K^+ or K^- (K3)		K_L^0		μ^+ or μ^-	
species	Abund.	$\langle E_\nu \rangle$	%	$\langle E_\nu \rangle$	%	$\langle E_\nu \rangle$	%	$\langle E_\nu \rangle$	%	$\langle E_\nu \rangle$	%	$\langle E_\nu \rangle$
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

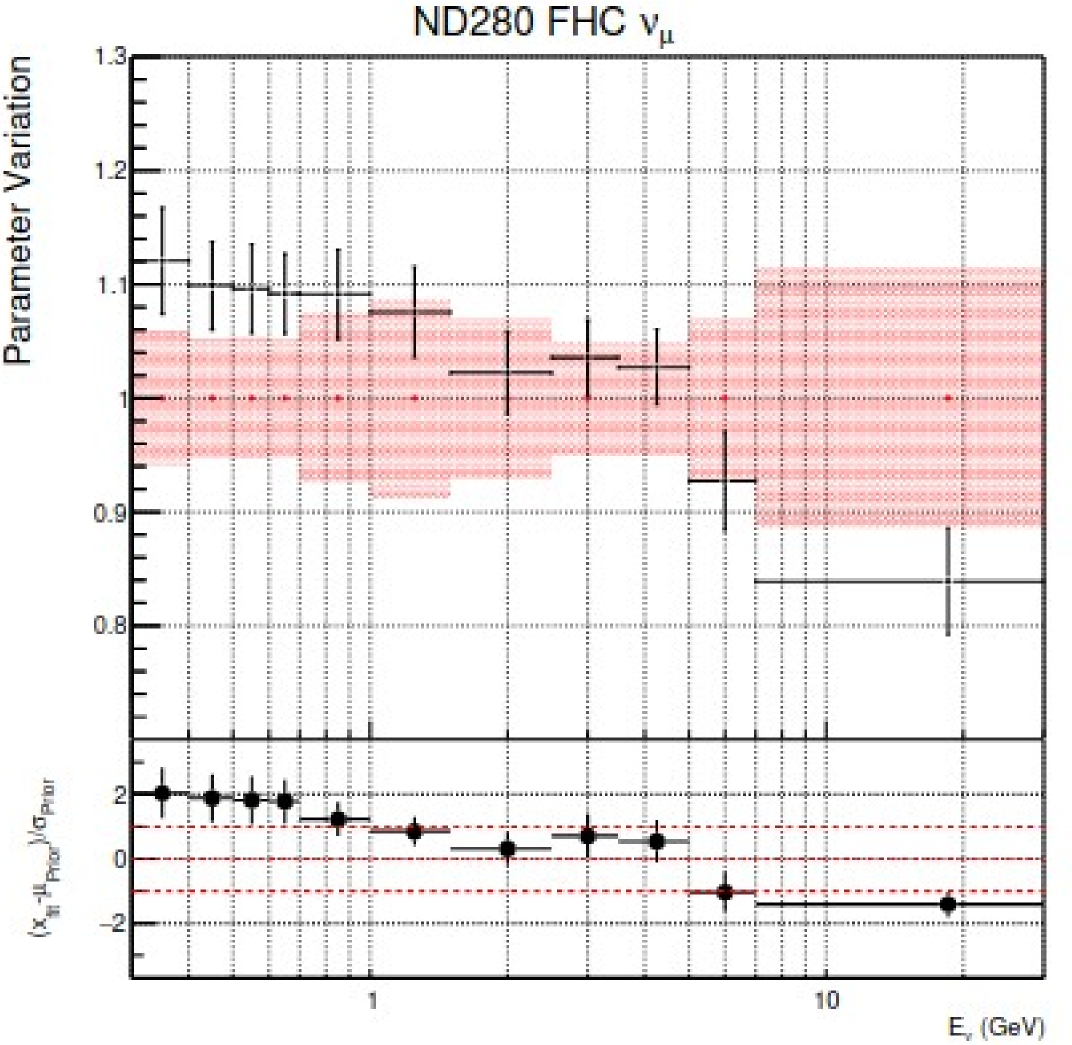
- Small intrinsic background to ν_e appearance measurements (important for δ_{CP} and MO).
- It can also be used to measure ν_e xsec at the near detector (with limited statistics)

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

Flux constraint from the ND

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

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



Flux constraint from the ND

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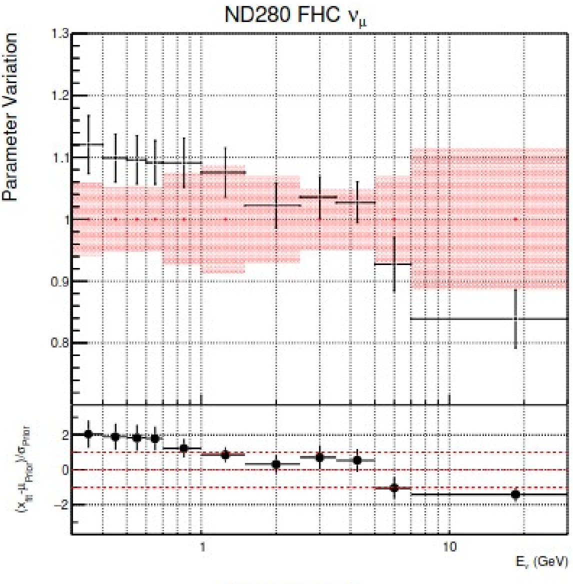

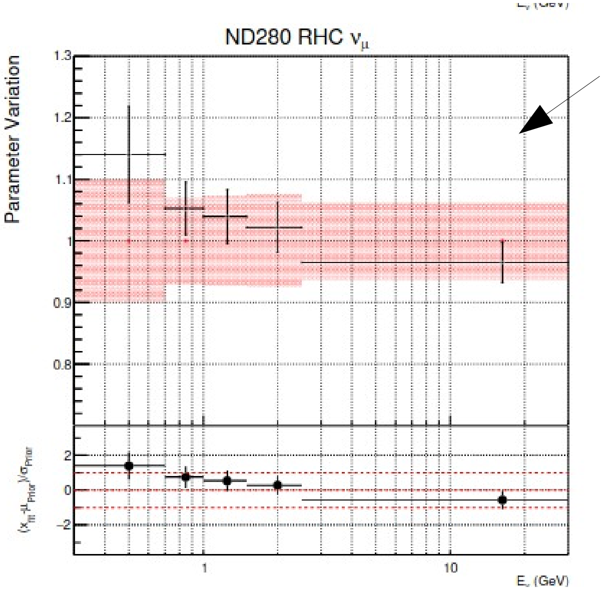

ND280 magnetized → measurement of wrong sign background

Flux constraint from the ND

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

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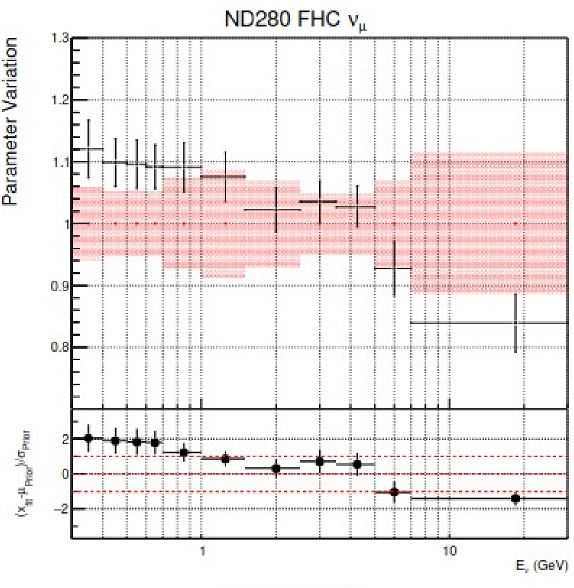
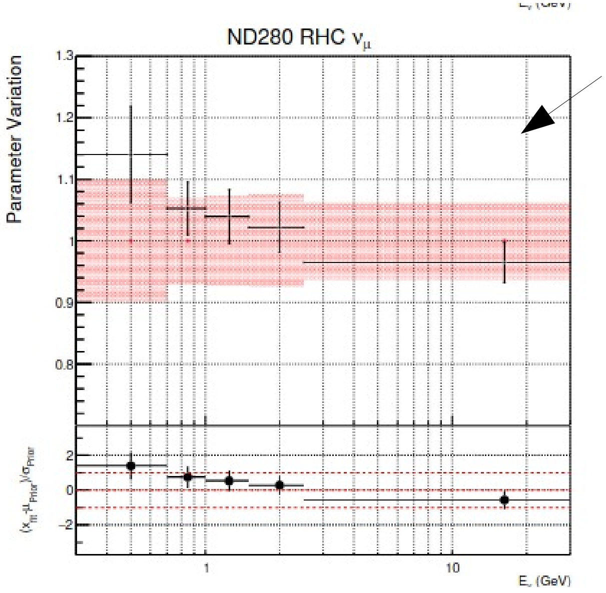
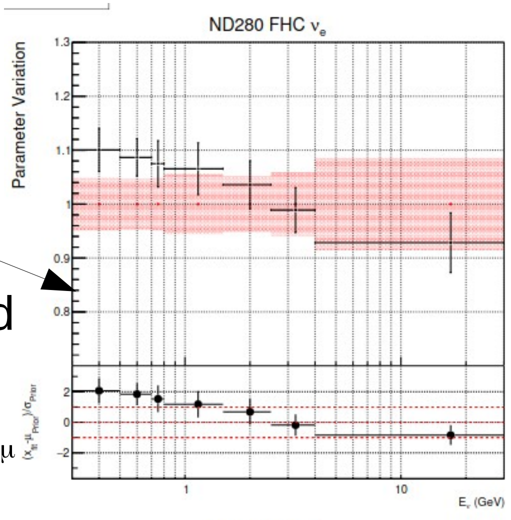




ND280 magnetized → measurement of wrong sign background

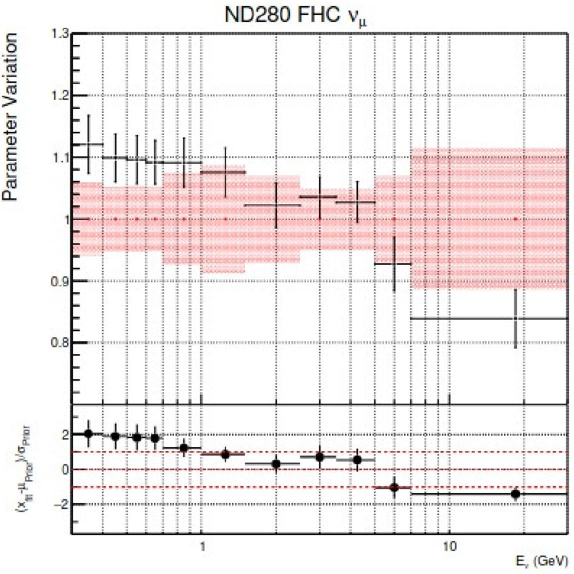


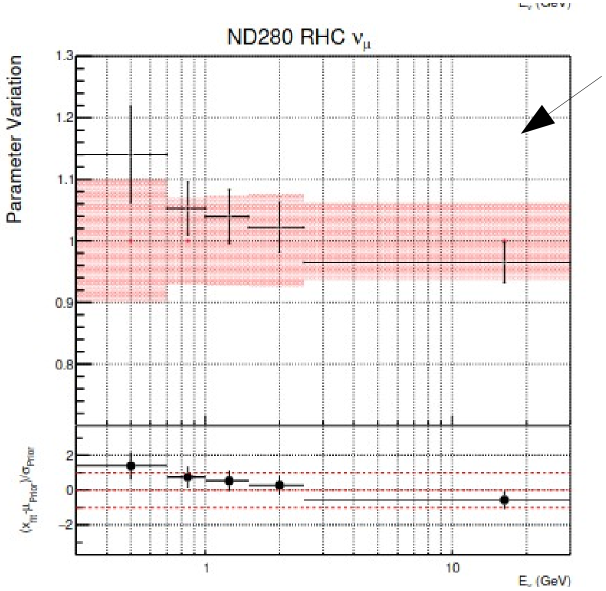
Low intrinsic ν_e stat → constrained only through correlations with ν_μ

Flux constraint from the ND

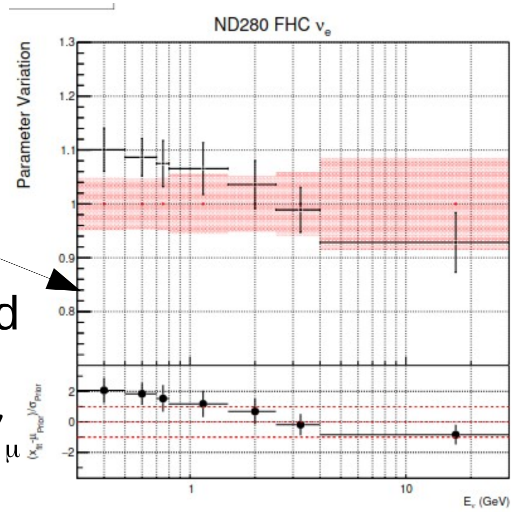
The ND measures the rate of neutrinos therefore it further constrain the flux

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





ND280 magnetized → measurement of wrong sign background



Low intrinsic ν_e stat → constrained only through correlations with ν_μ

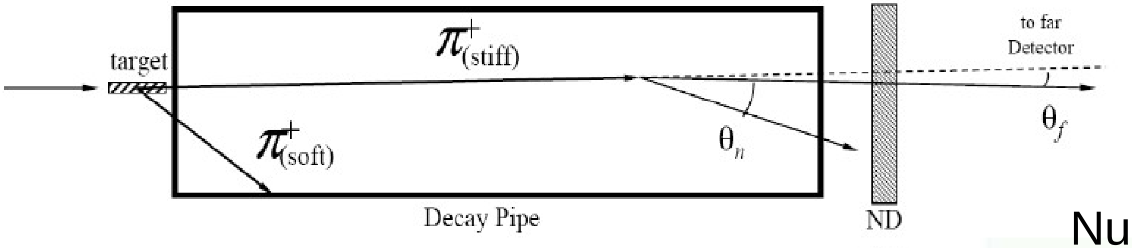
	Pre- ND fit	Post- ND fit
flux	~5%	~2.8-3.0%
cross-section	~10-15%	~3.5-3.8%
flux+xsec		~2.6-2.8%
Total (+ xsec not accessible at ND, SK detector)	~17%	~3.5-5%

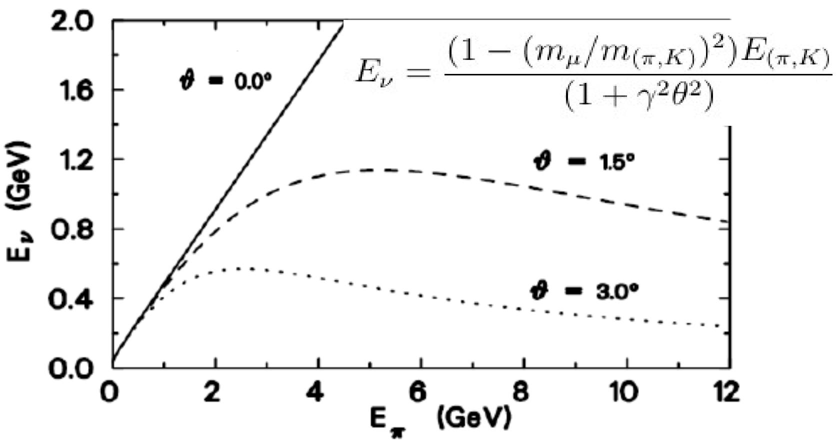
- Today xsec uncertainties dominate before the fit
- strong anticorrelation between flux and xsec (would be 5-10% if uncorrelated)
- flux*xsec constitutes ~50% of the final systematic error budget

From ND to FD flux extrapolation

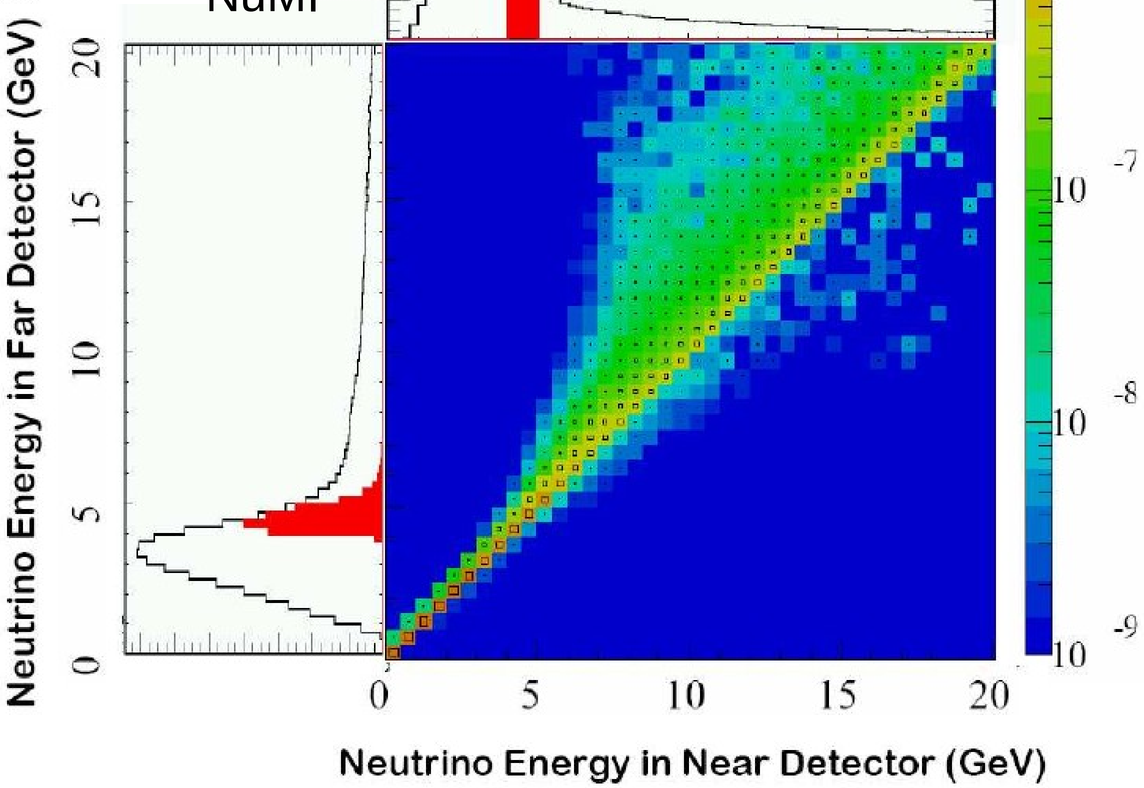
$$\frac{N^{FD}_{\nu_{\alpha'}}(E_\nu)}{N^{ND}_{\nu_\alpha}(E_\nu)} \approx P_{\nu_\alpha\to\nu_{\alpha'}}(E_\nu)\times\boxed{\frac{\phi^{FD}_{\nu_{\alpha'}}(E_\nu)}{\phi^{ND}_{\nu_\alpha}(E_\nu)}}\times\frac{\sigma^{FD}_{\nu_{\alpha'}}(E_\nu)}{\sigma^{ND}_{\nu_\alpha}(E_\nu)}$$

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





NuMI

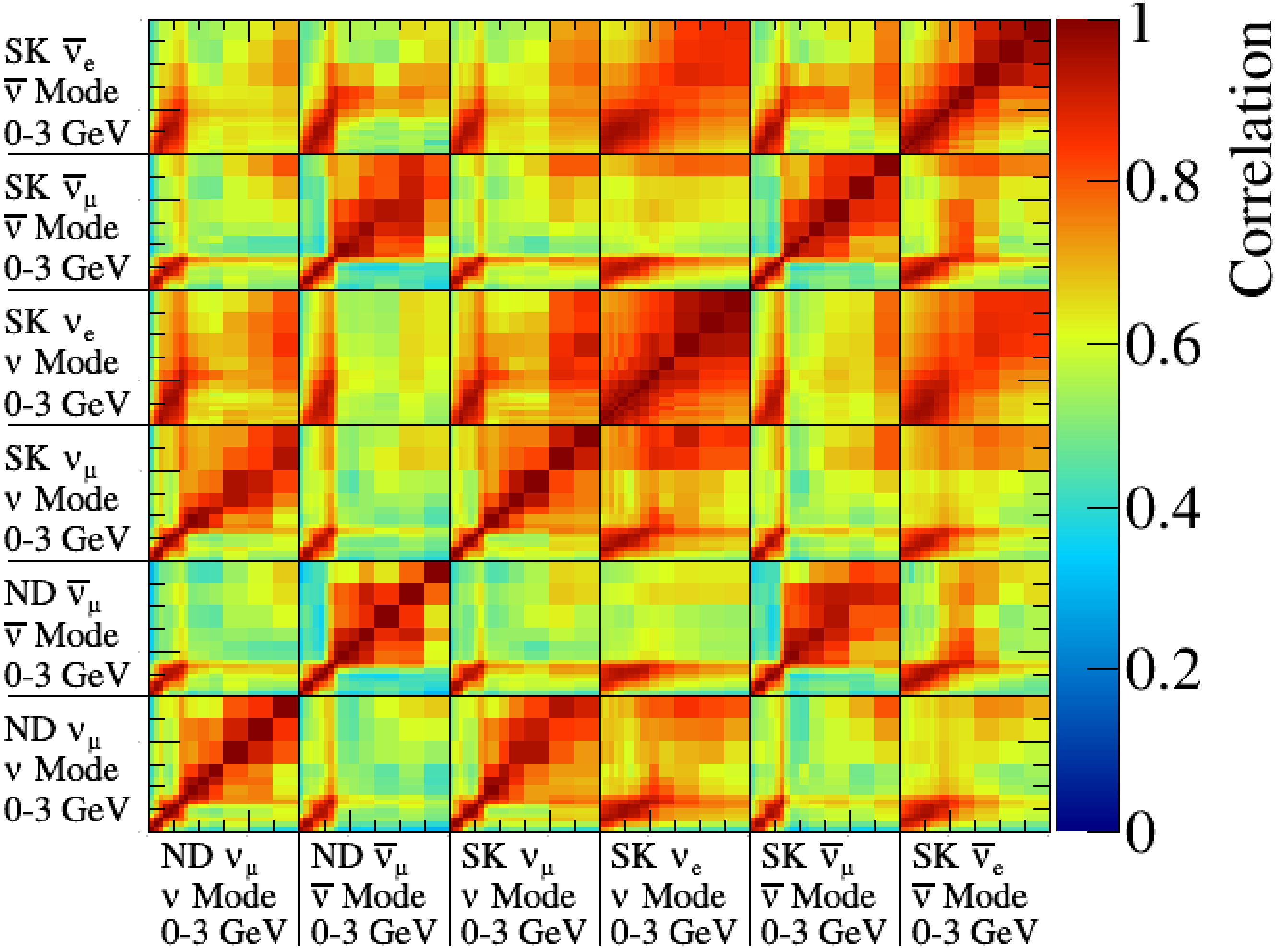


Extrapolation ND->FD uncertainties smaller (~1%) than overall flux uncertainties (10% → 5%)

Flux correlations

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

T2K



- **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

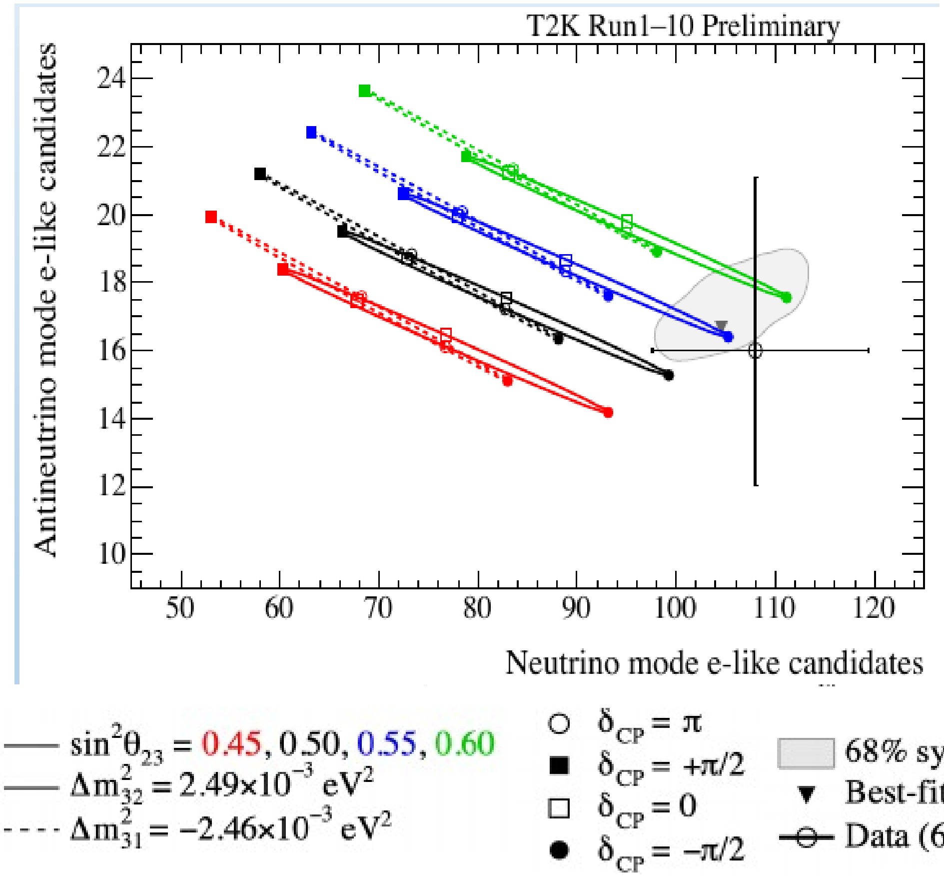
$\nu_e/\bar{\nu}_e$ apperance: MH, δ_{CP}

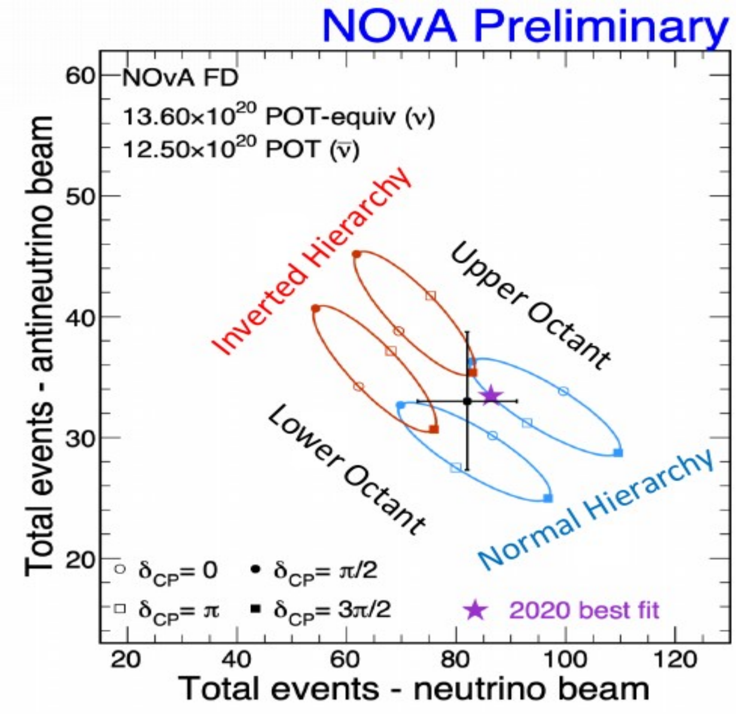
Experiment	**CP asymmetry**	**Mass Hierarchy**
T2K (T2HK)	~30%	~10%
Nova	~30%	~30%

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

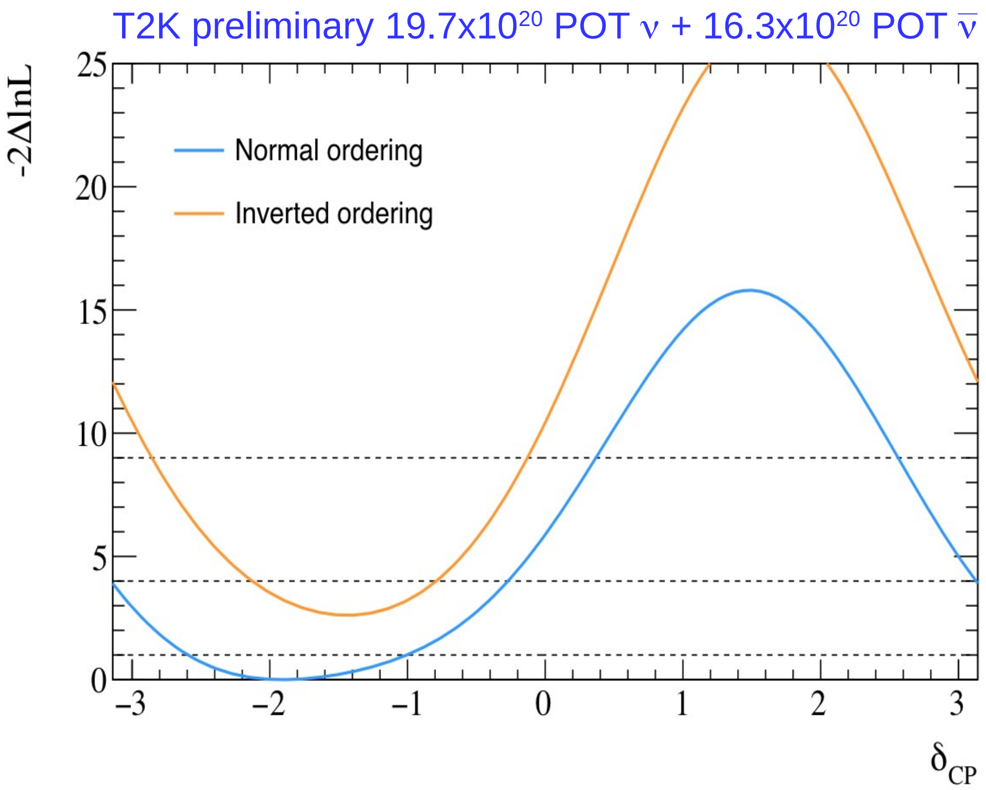
- **NOVA: degenerate δ_{CP} and MH:** (δ_{CP} $3\pi/2$ and IH = δ_{CP} $\pi/2$ and NH)

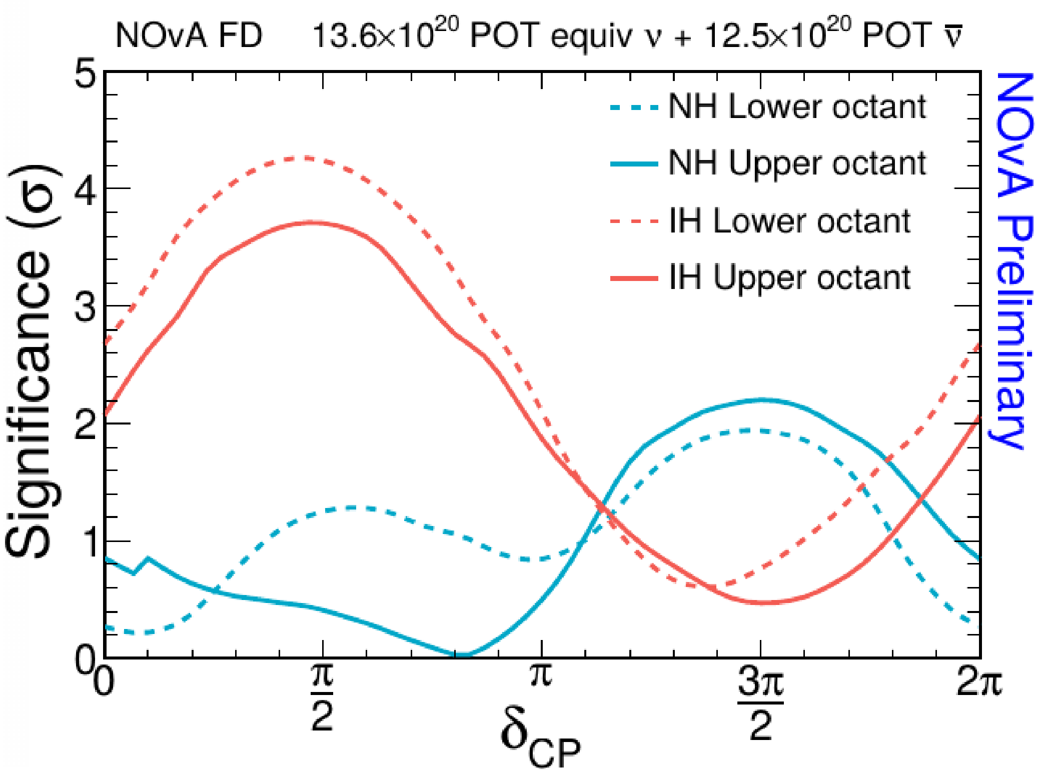
Using 2020 results in the following (2022 improved analyses confirmed the situation)





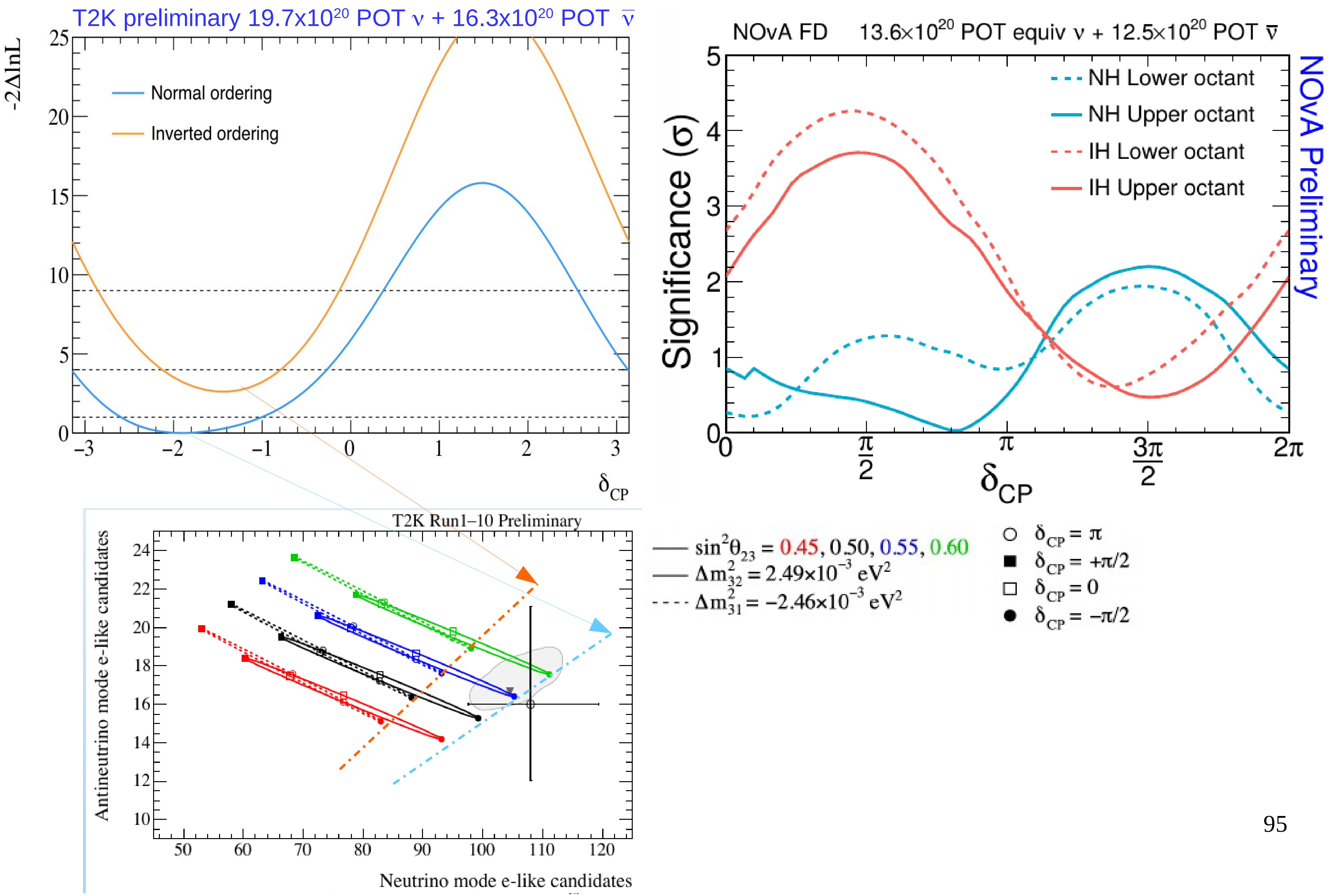
Results



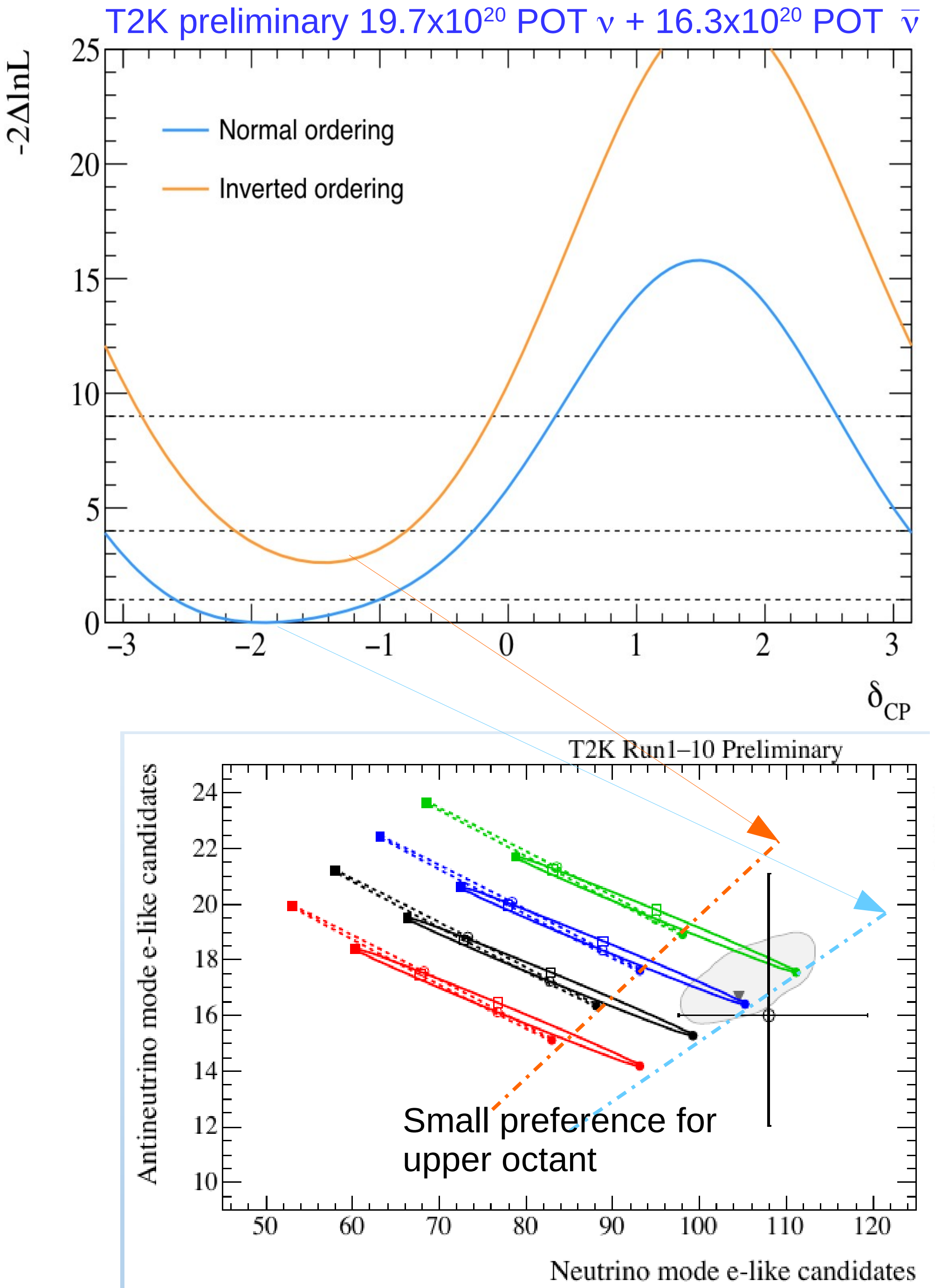


- Large **region disfavoured at 3σ** (T2K Nature cover in 2020). And for T2K even some region at 5σ but precision of statistical treatment will be discussed later.
Similar region disfavoured at T2K for NH and IH, while 3σ exclusion in NOVA only for IO

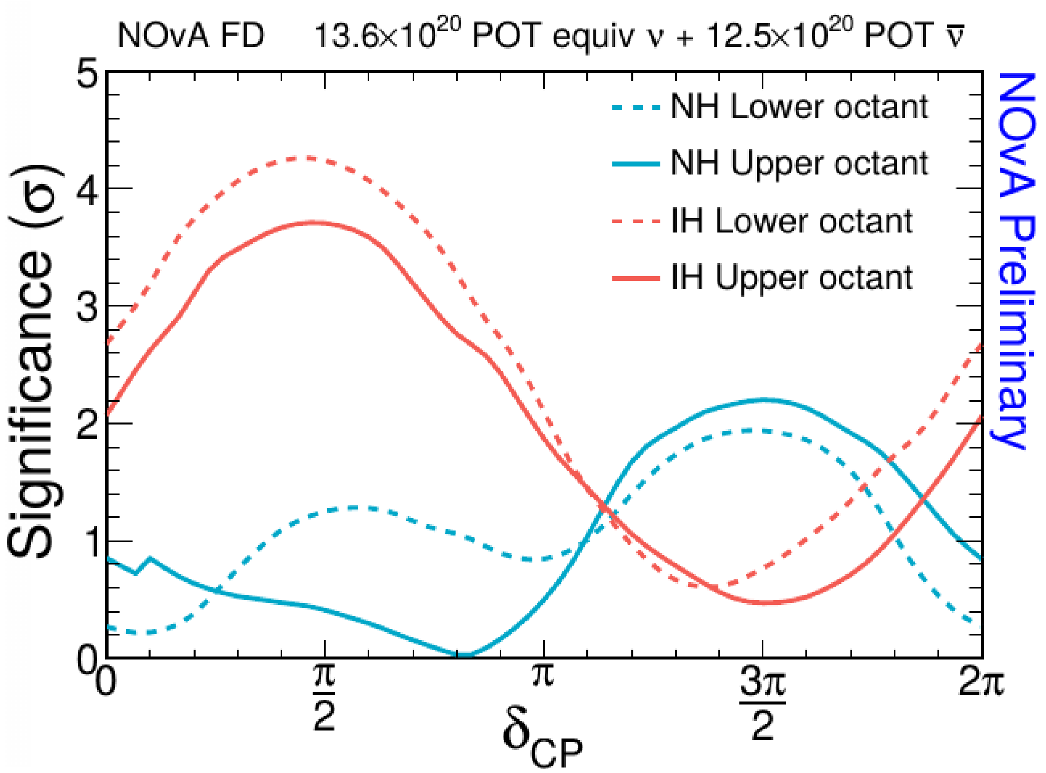
Results

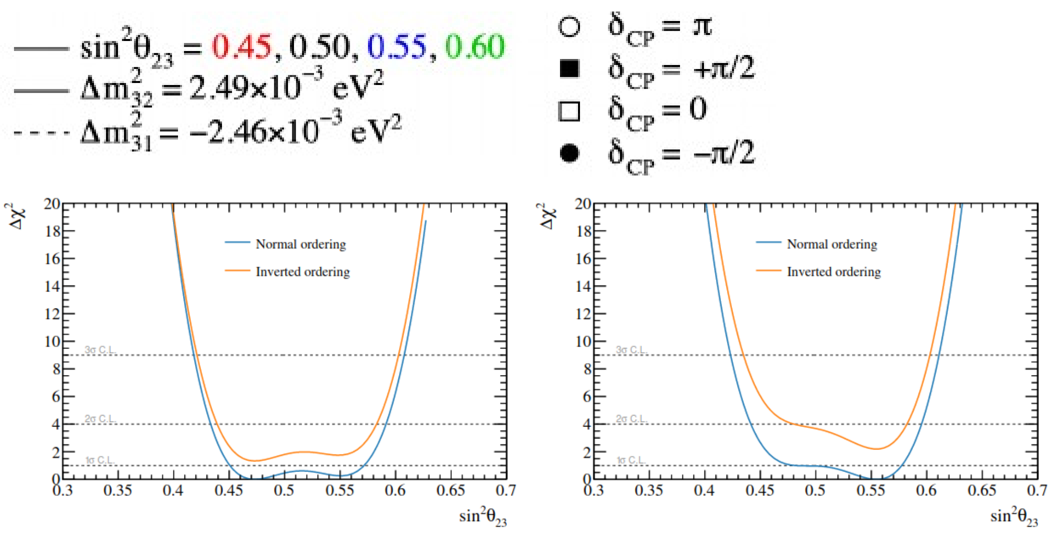

T2K preliminary 19.7x10^20 POT ν + 16.3x10^20 POT ν̄
-2ΔlnL
25
20
15
10
5
0
−3
−2
−1
0
1
2
3
δCP
Normal ordering
Inverted ordering
NOvA FD 13.6×10^20 POT equiv ν + 12.5×10^20 POT ν̄
NOvA Preliminary
Significance (σ)
5
4
3
2
1
0
0
π/2
π
3π/2
2π
δCP
NH Lower octant
NH Upper octant
IH Lower octant
IH Upper octant
T2K Run1–10 Preliminary
Antineutrino mode e-like candidates
24
22
20
18
16
14
12
10
50
60
70
80
90
100
110
120
Neutrino mode e-like candidates
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



Small preference for upper octant

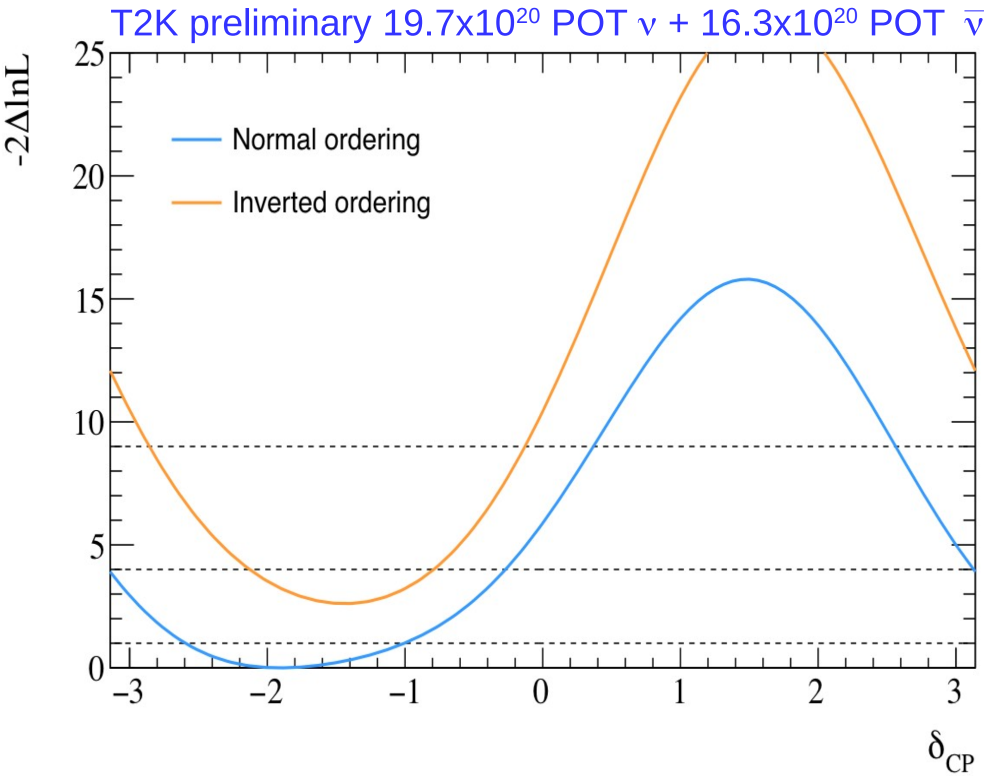


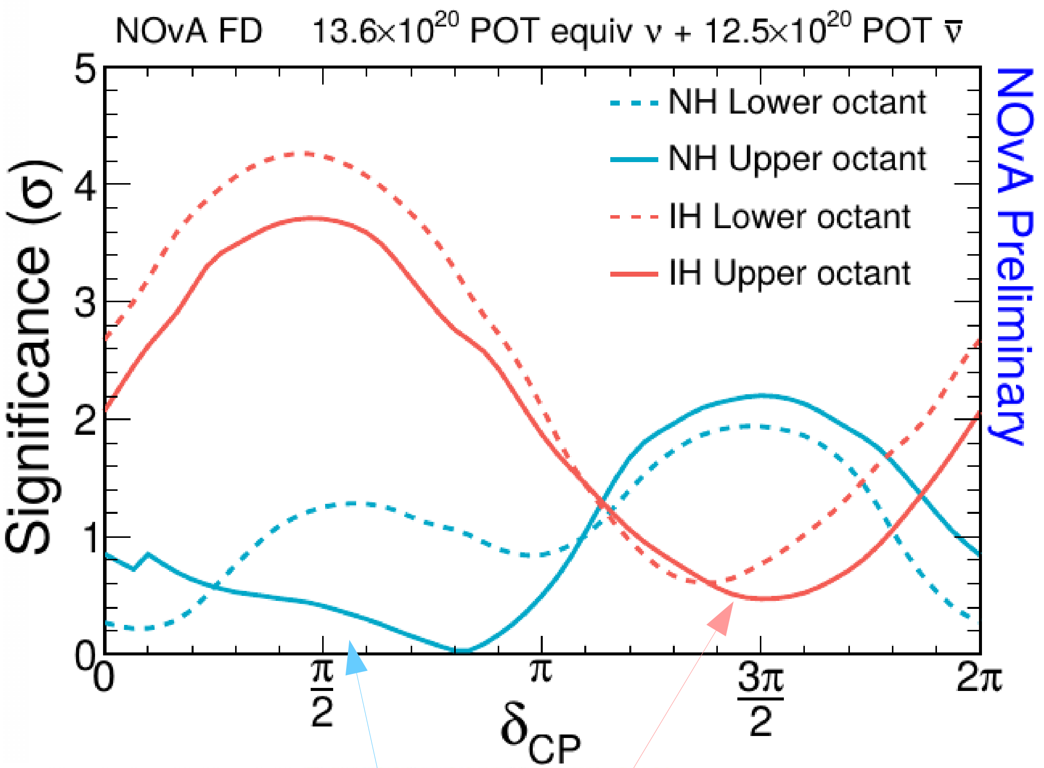


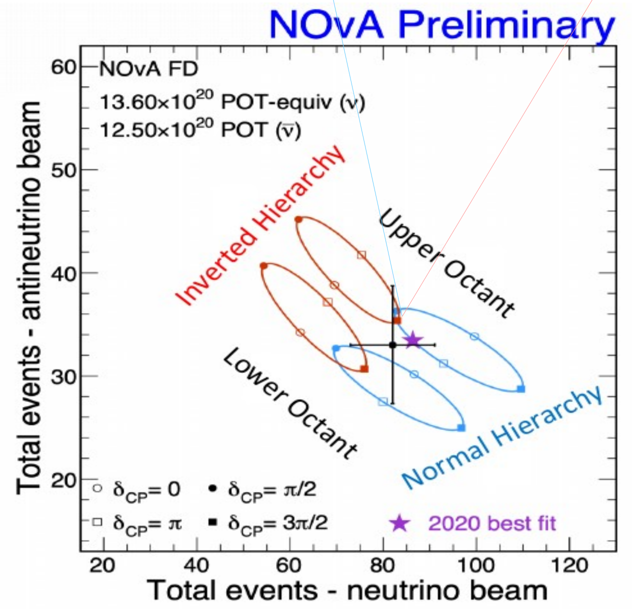
(a) T2K only

(b) T2K + reactor

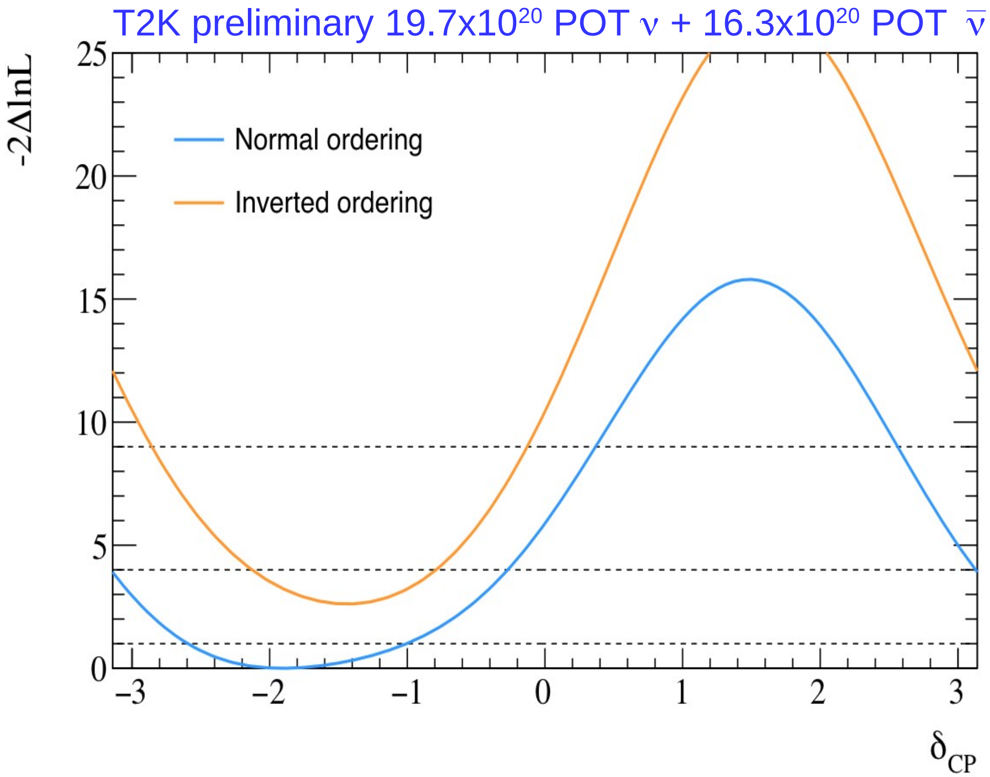
Results

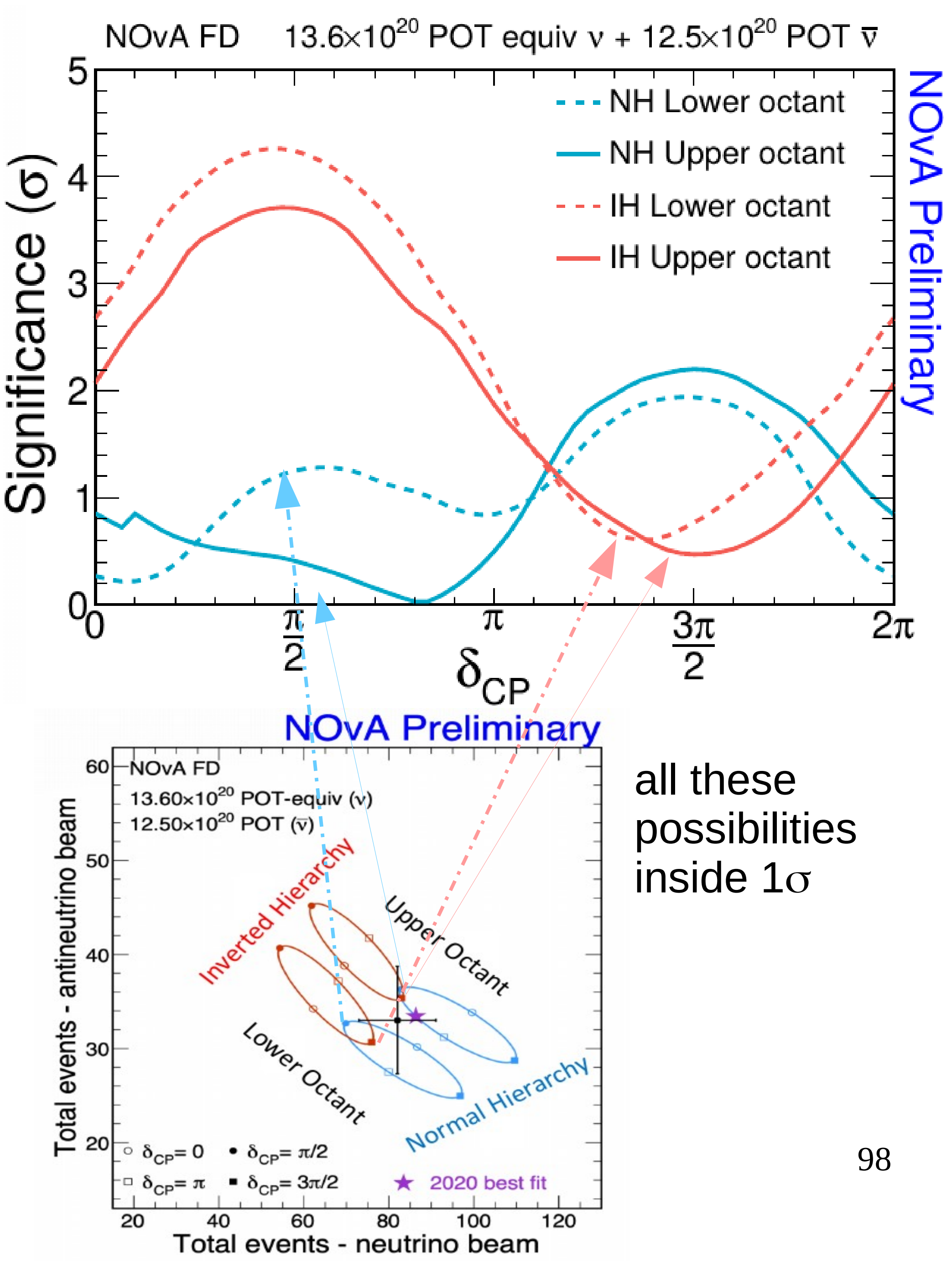

T2K preliminary 19.7x10^20 POT ν + 16.3x10^20 POT ν̄
-2ΔlnL
Normal ordering
Inverted ordering
0
5
10
15
20
25
–3
–2
–1
0
1
2
3
δ_CP


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
0
1
2
3
4
5
0
π/2
π
3π/2
2π
δ_CP


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
Total events - antineutrino beam
Total events - neutrino beam
20
30
40
50
60
20
40
60
80
100
120
δ_CP= 0
δ_CP= π/2
δ_CP= π
δ_CP= 3π/2
2020 best fit

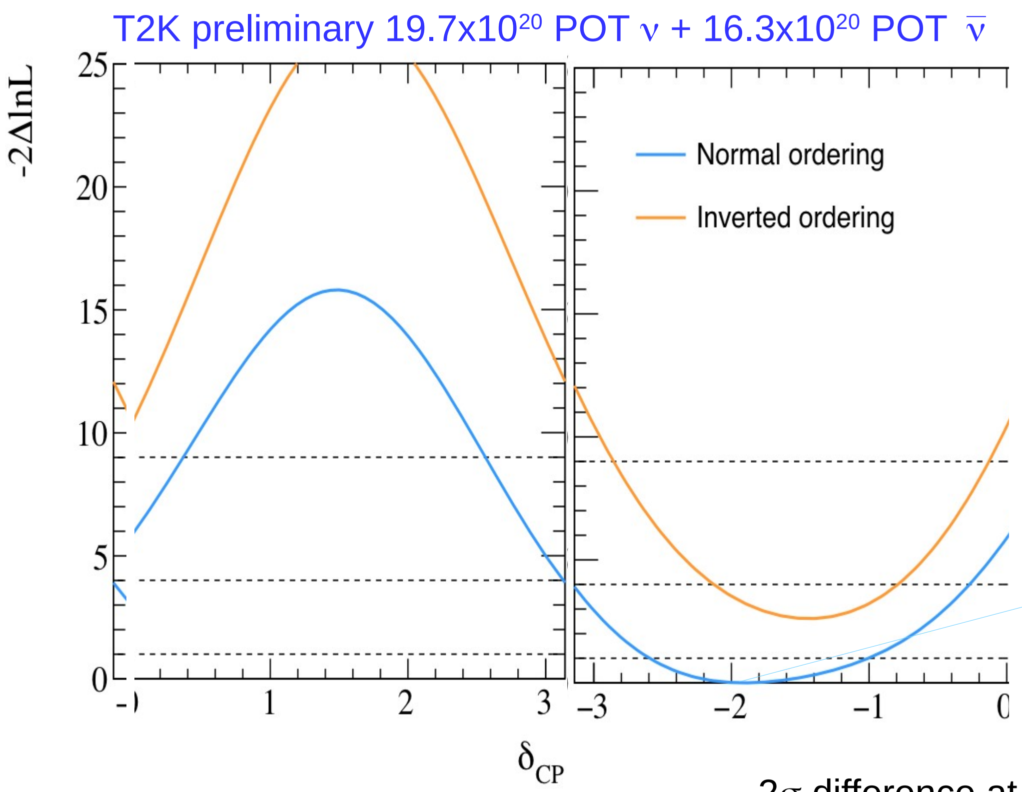
Results

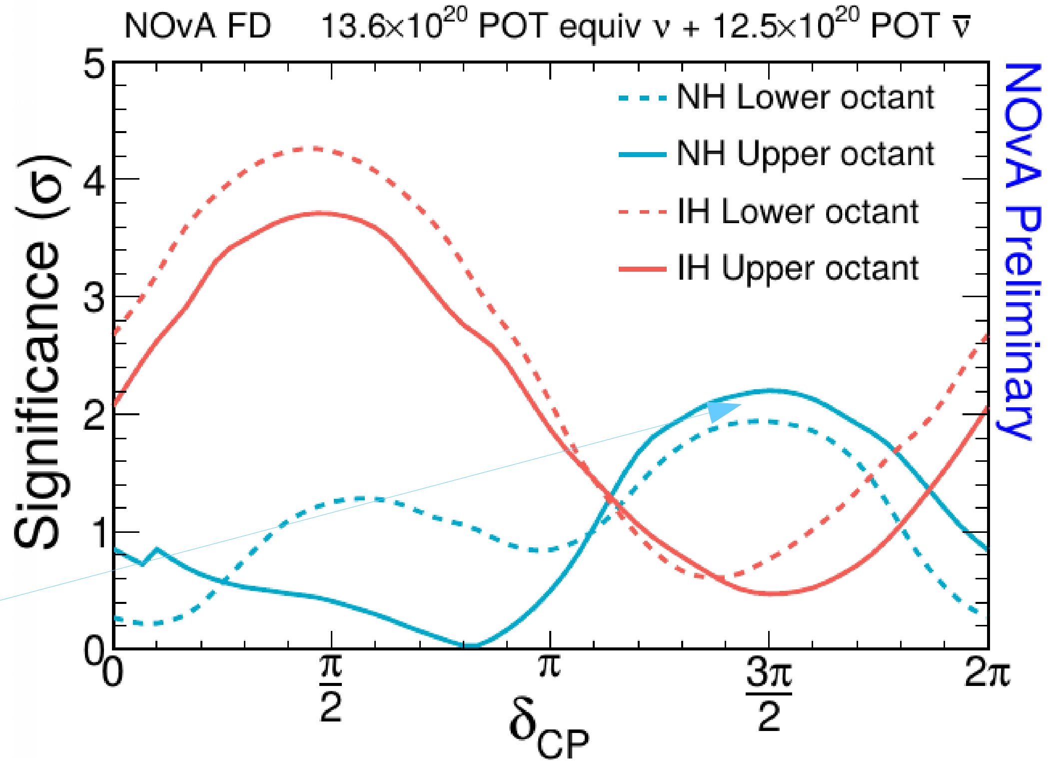




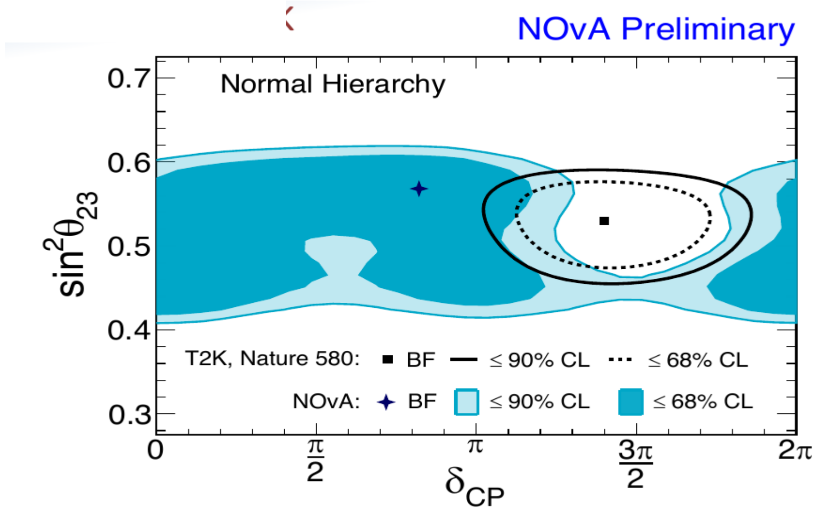
all these possibilities inside 1σ

Results

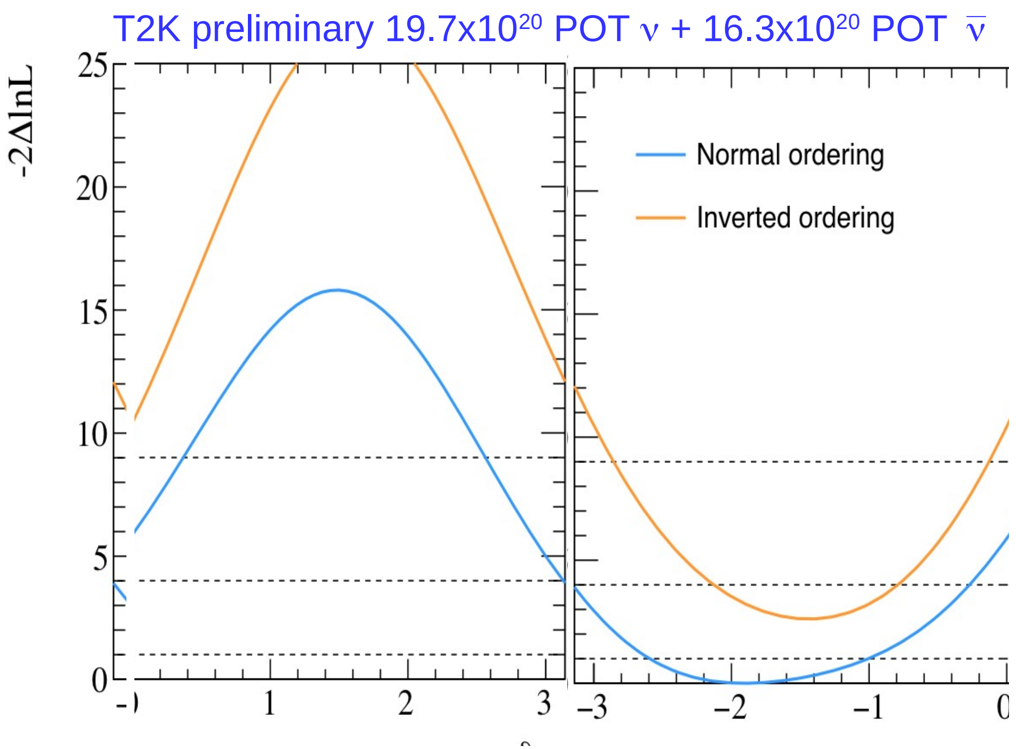


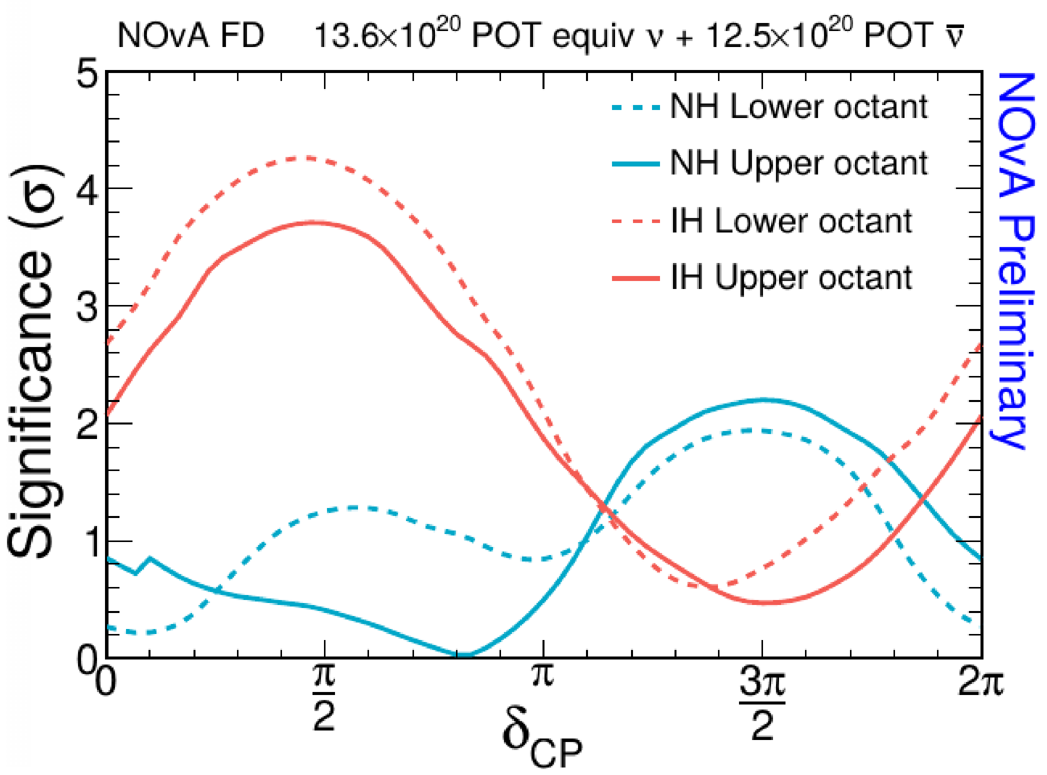


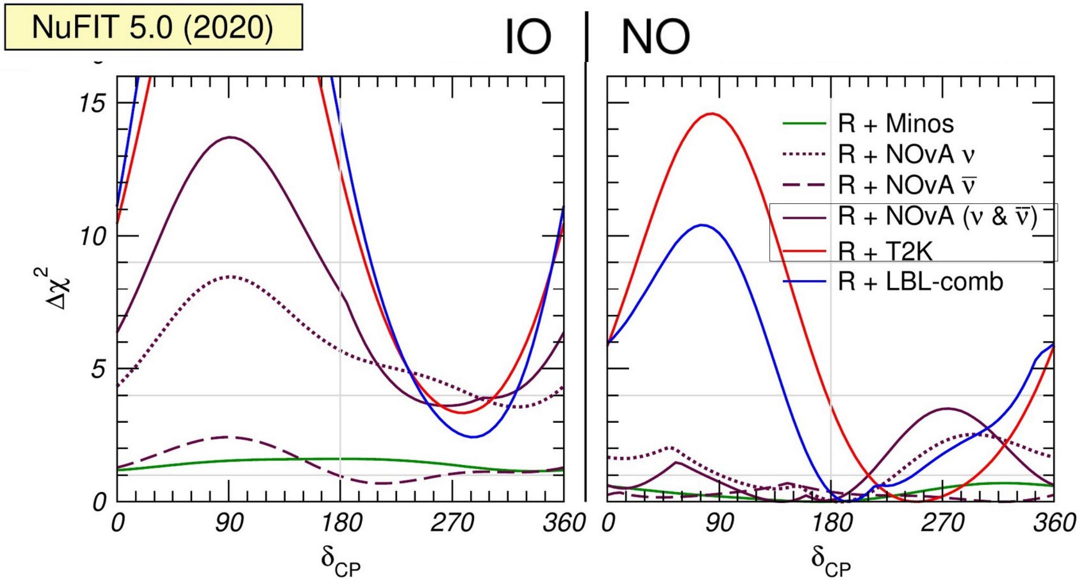
2σ difference at T2K minimum (max CPV, NH) but still common regions at 1σ

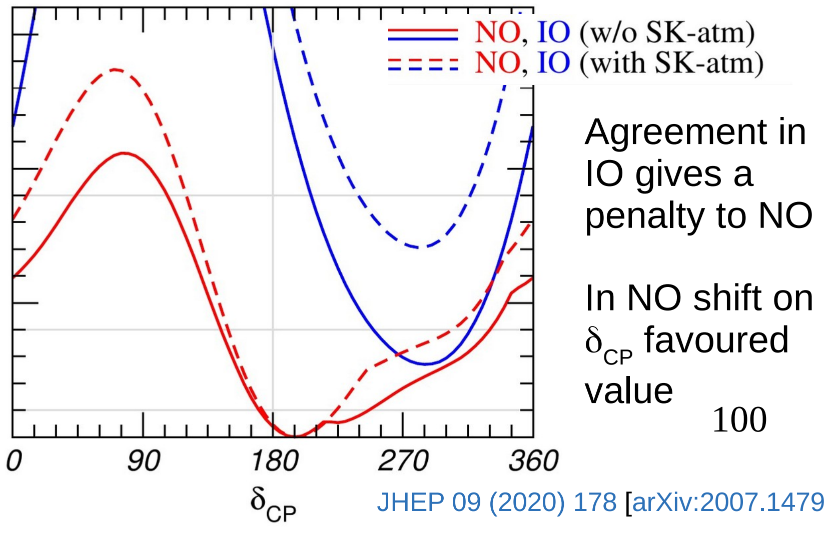


Results







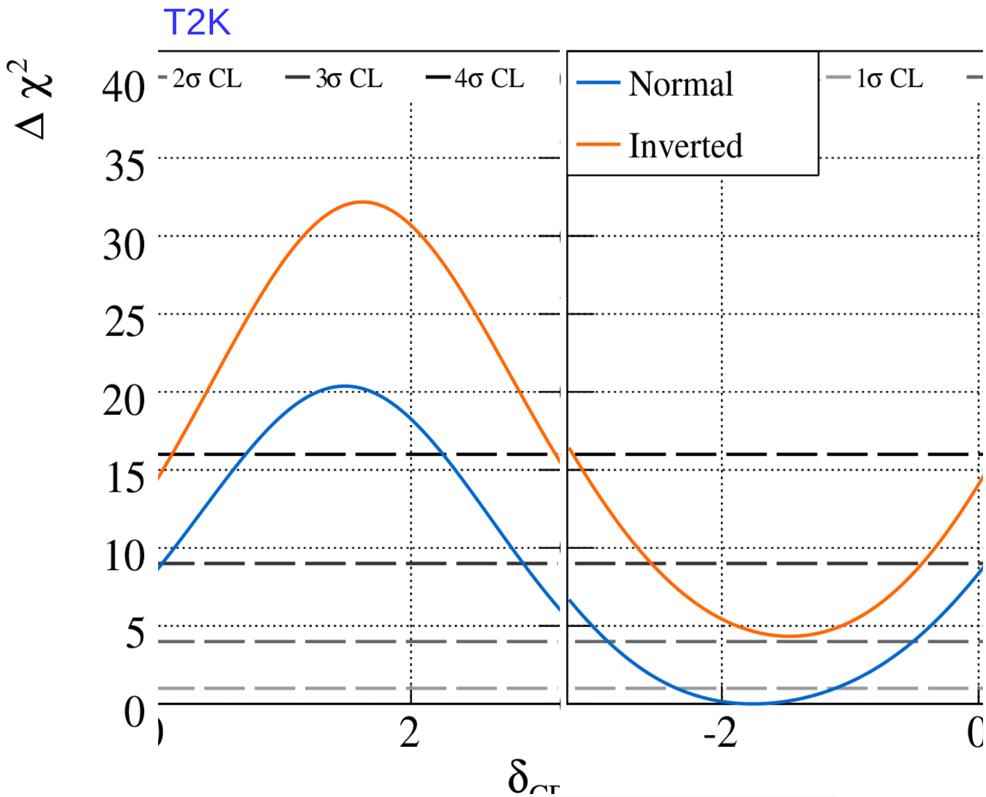


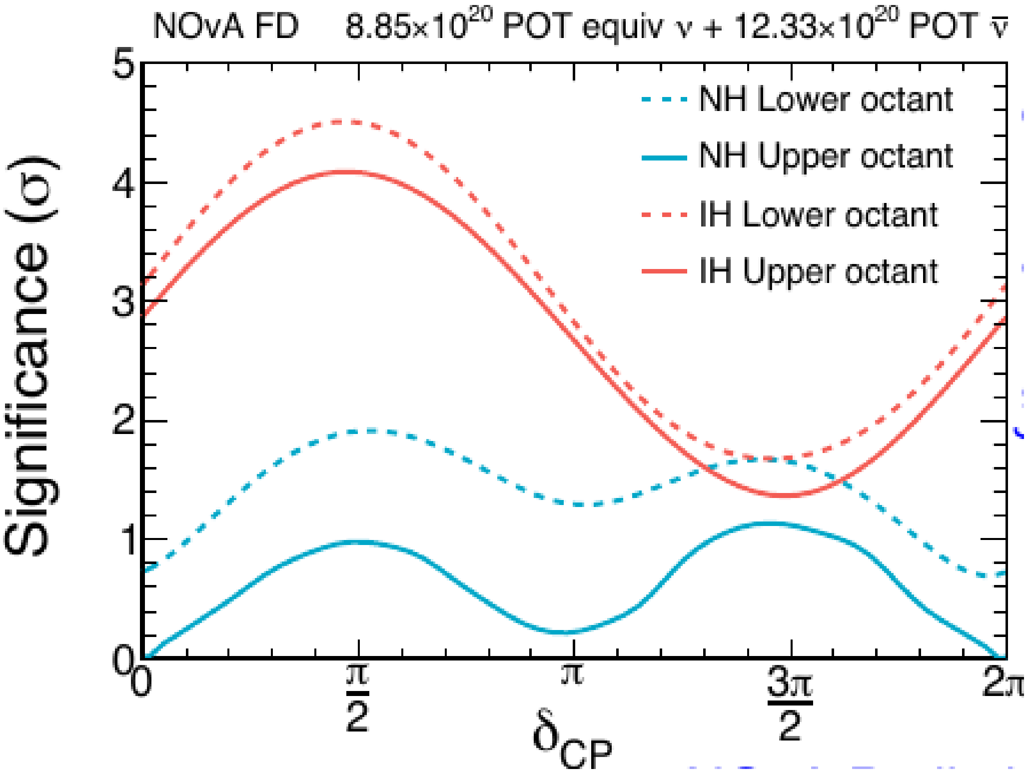
Agreement in IO gives a penalty to NO

In NO shift on δ_{CP} favoured value

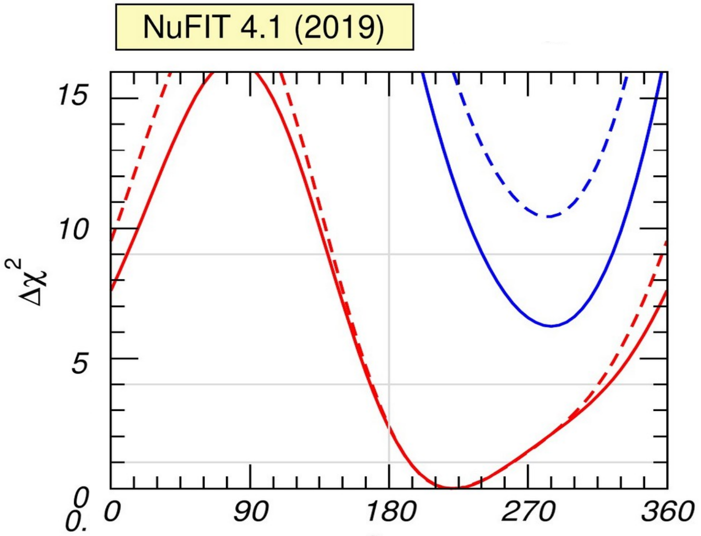
JHEP 09 (2020) 178 [arXiv:2007.14792]

Results ***2019 → 2020***

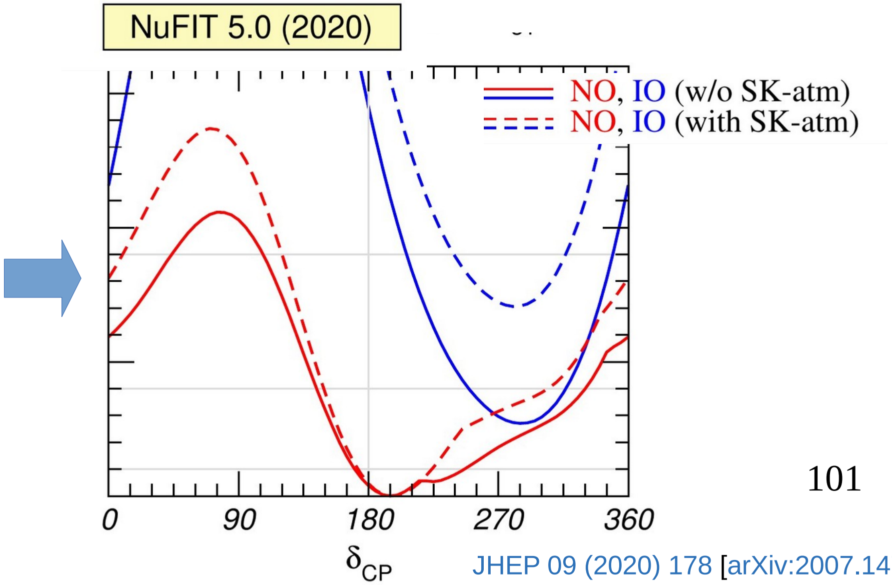




Something similar already visible in previous round of results

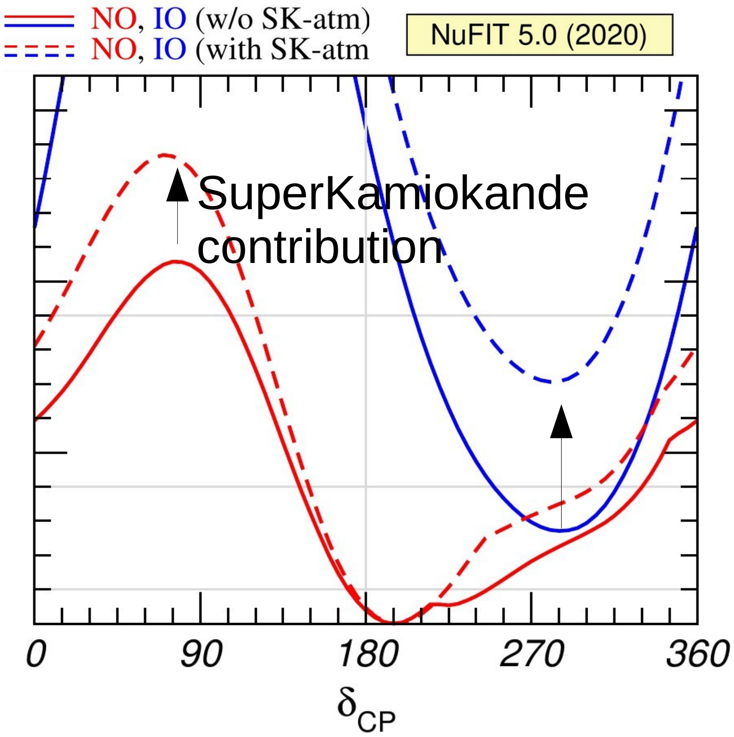


JHEP 01 (2019) 106 [arXiv:1811.05487]



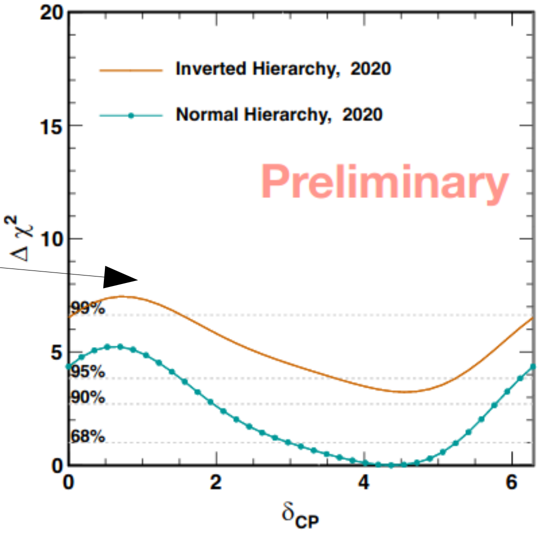
JHEP 09 (2020) 178 [arXiv:2007.14792]

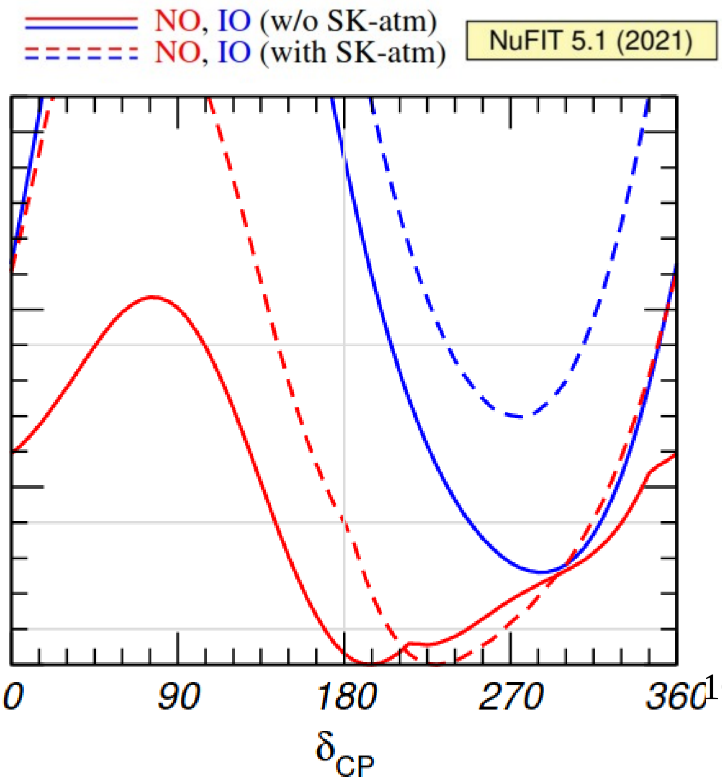
Mass Hierarchy



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)

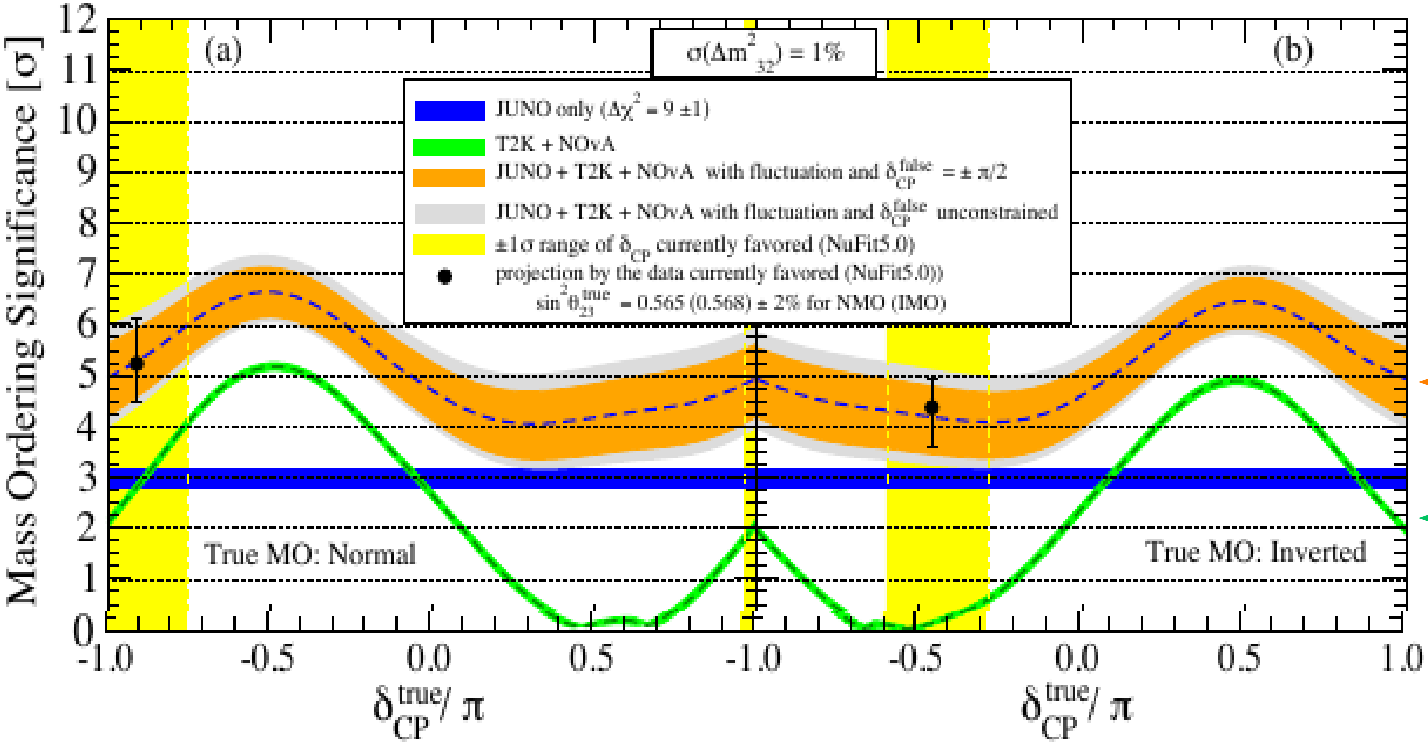
- **MO sensitivity dominated by SK**

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

→ CP conservation disfavoured at ~2σ

Combinations for MH: prospects

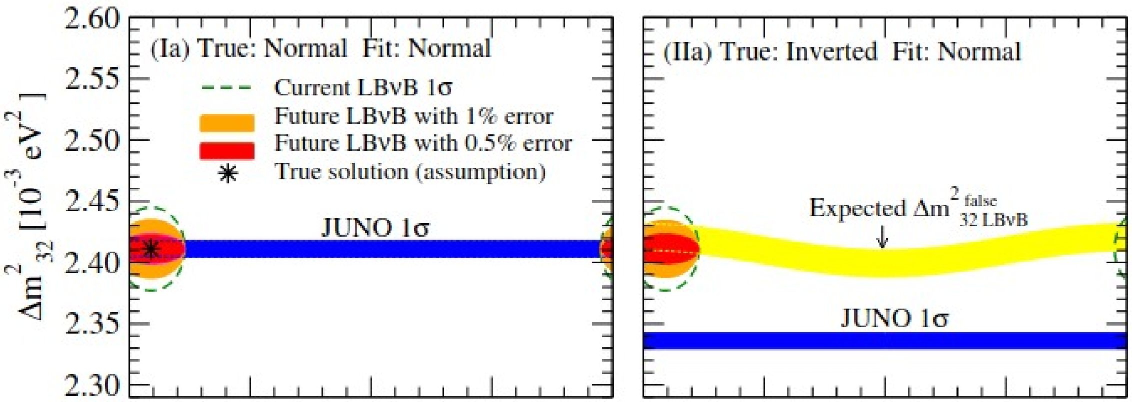
Very bright prospects for the future (and still not including SuperKamiokande!):



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

T2K+NOVA+JUNO

T2K+NOVA

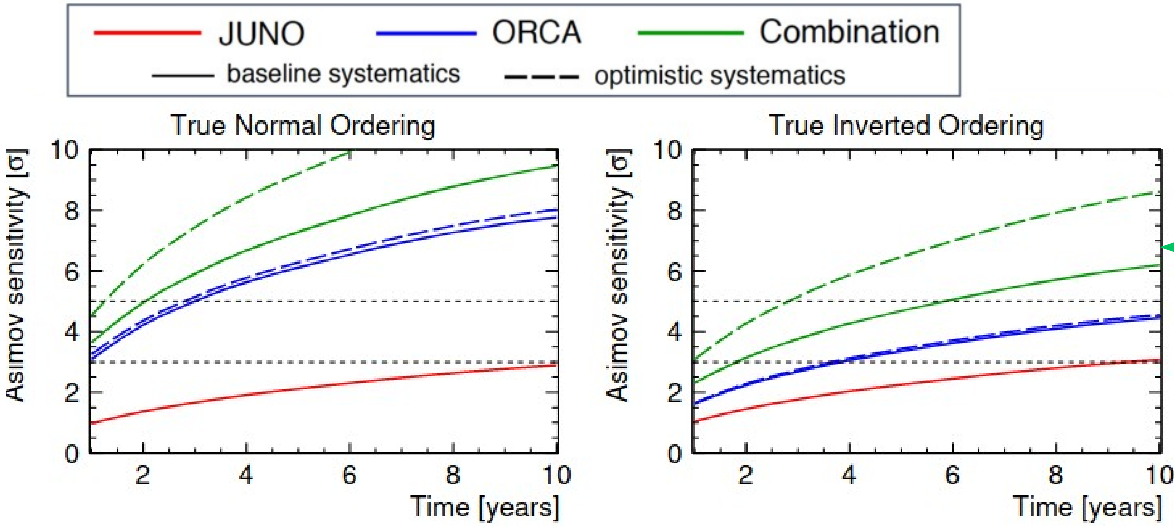


Boost of sensitivity from **$|\Delta m^2_{31(32)}|$** discrepancy (for wrong mass hierarchy) between ν_e (JUNO) and ν_μ (LBL) disappearance → ~2%

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

Combinations for MH: prospects

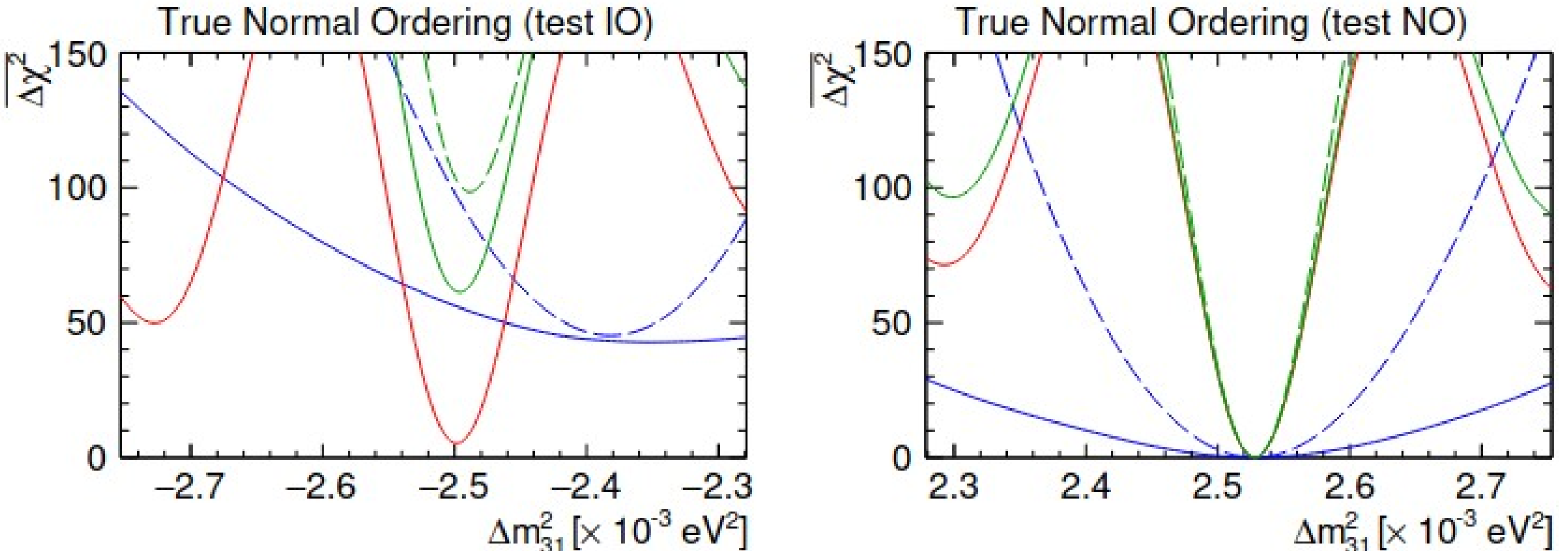
Further combination including ORCA (missing NOVA, T2K and SuperKamiokande):



JUNO+ORCA

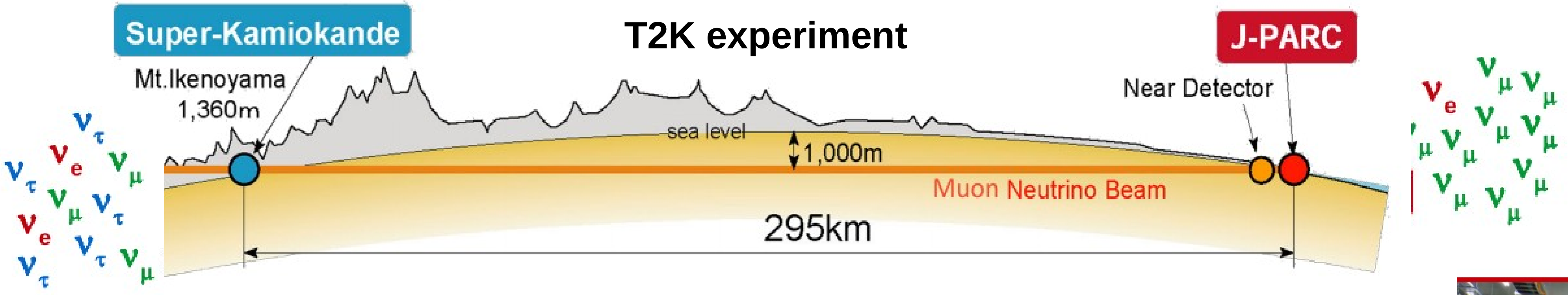
https://arxiv.org/pdf/2107.00344.pdf

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



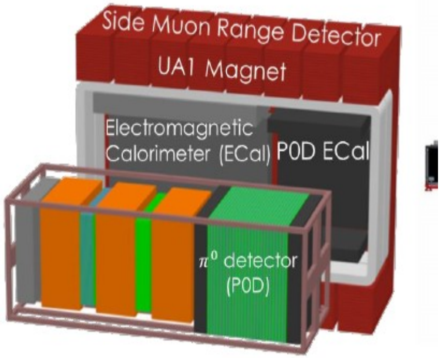
Anatomy of T2K and NOVA oscillation analysis

T2K

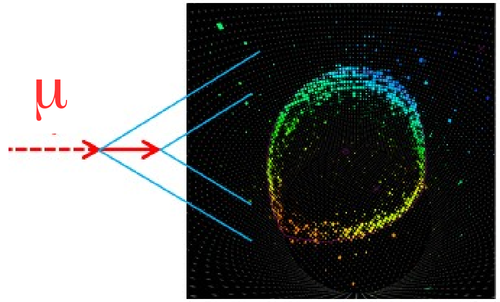


huge water cherenkov detector (50 kTon) with optimal μ/e identification to distinguish ν_e, ν_μ

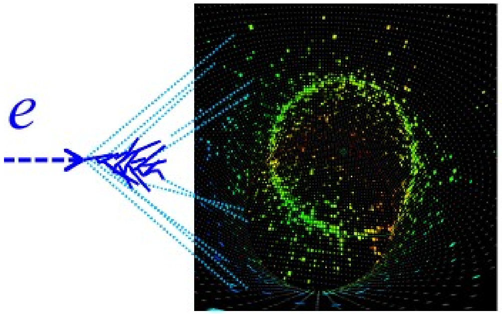
ND280 near detector



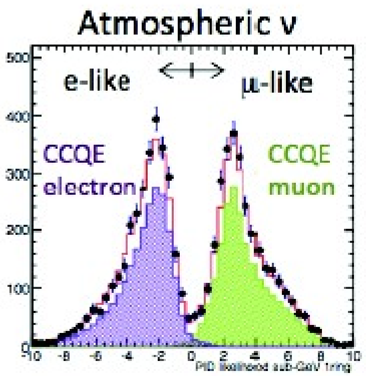
J-PARC facility: neutrino beam



clear ring

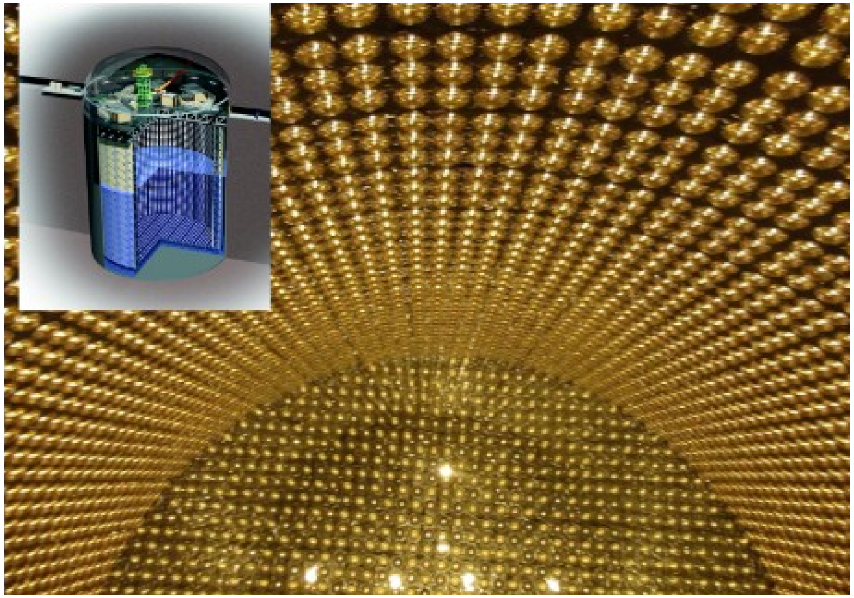


fuzzy ring



1% mis-id

SuperKamiokande samples

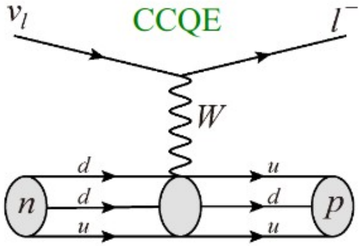


- Reconstruct Cherenkov ring from charged particles (above Cherenkov threshold)

- 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)

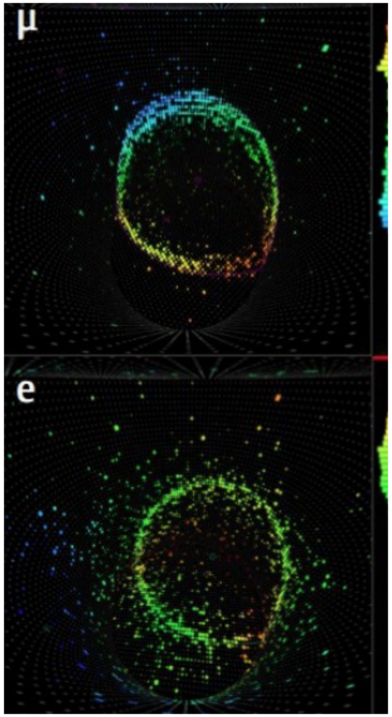
- Michel e- from muon (or π→μ) decay: e- ring delayed in time



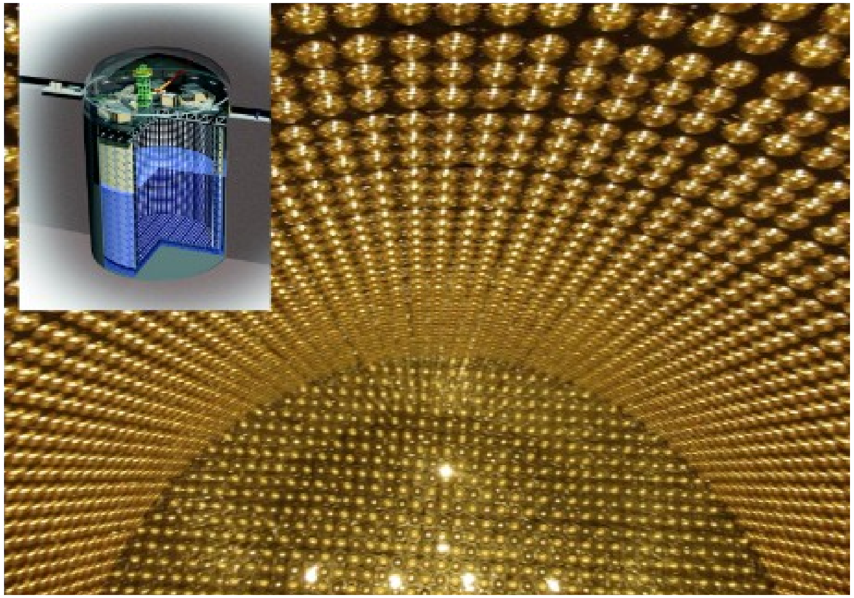
- Main channel at T2K energy:
single ring events (e or μ)
= Quasi-Elastic channel: can reconstruct neutrino energy from lepton kinematics only
[with nuclear physics uncertainty: see Martini lecture]

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

where m_n, m_p and m_μ are the masses of neutron, proton, and the charged lepton, $E_b = 27\,\mathrm{MeV}$ 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

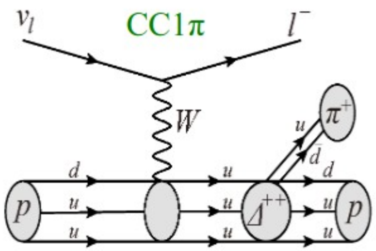


- Reconstruct Cherenkov ring from charged particles (above Cherenkov threshold)

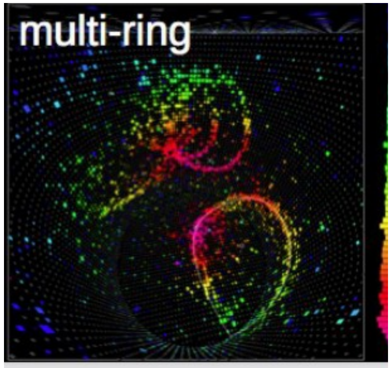
- Use information of time, position and amount of light in the ring to estimate momentum and direction of particle (likelihood algo ‘fitqun’)

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

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



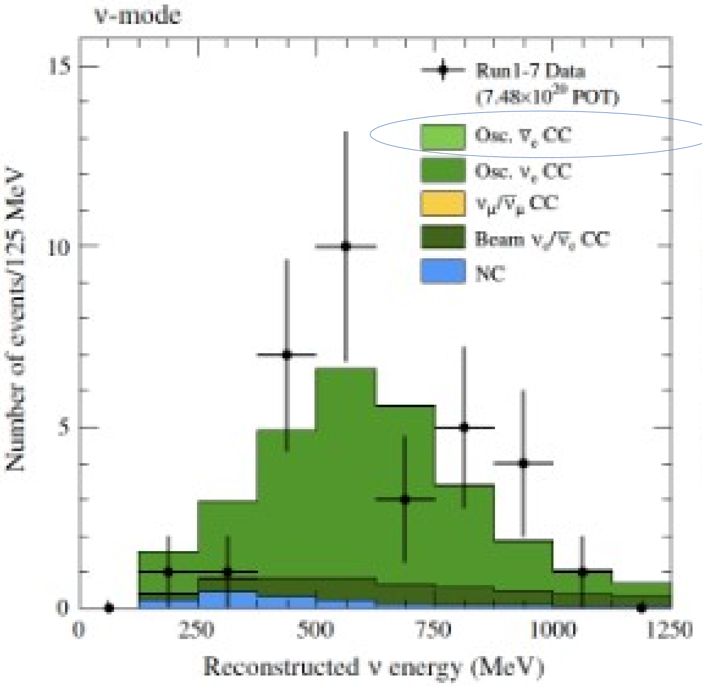
- Additional channels with pion production (FHC), subleading and mostly at higher energy:
  - 1 ring electron (from ν_e) with 1 Michel electron
    → add statistics for ν_e sample
  - 1 ring muon (from ν_μ) + 1,2 Michel electron(s) and/or other ring from π
    → add high-energy ‘control sample’ for ν_μ

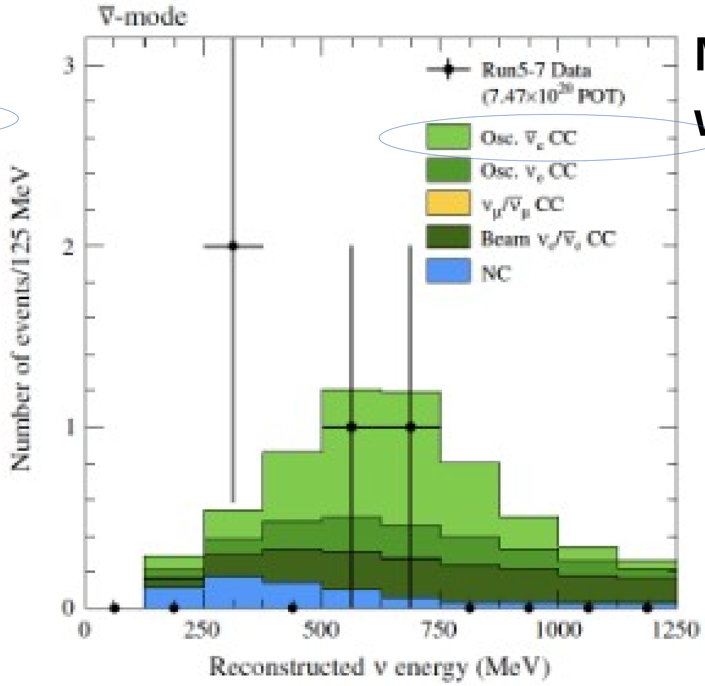


$$E_\nu^{\mathrm{rec}} = \frac{m_{\Delta^{++}}^2 - m_p^2 - m_l^2 + 2m_p E_l}{2(m_p - E_l + p_l \cos\theta_l)}$$

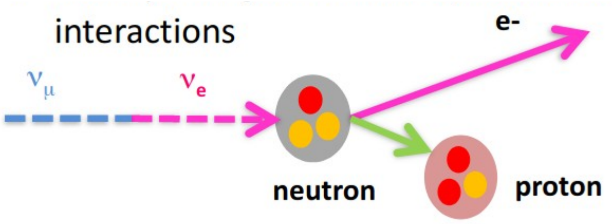
Reconstruct neutrino energy from lepton kinematics only, assuming Δ++ resonance (mostly true in FHC at T2K energy)

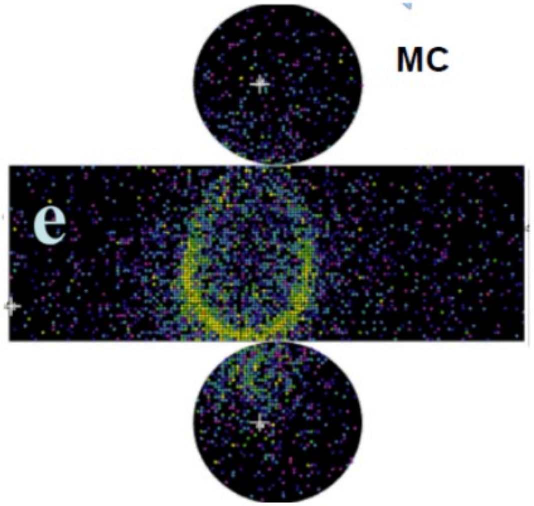
SuperKamiokande samples



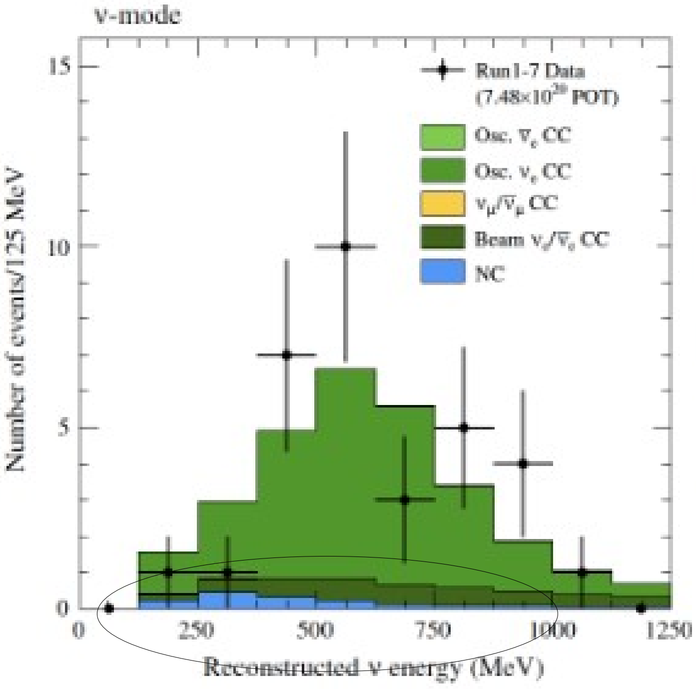


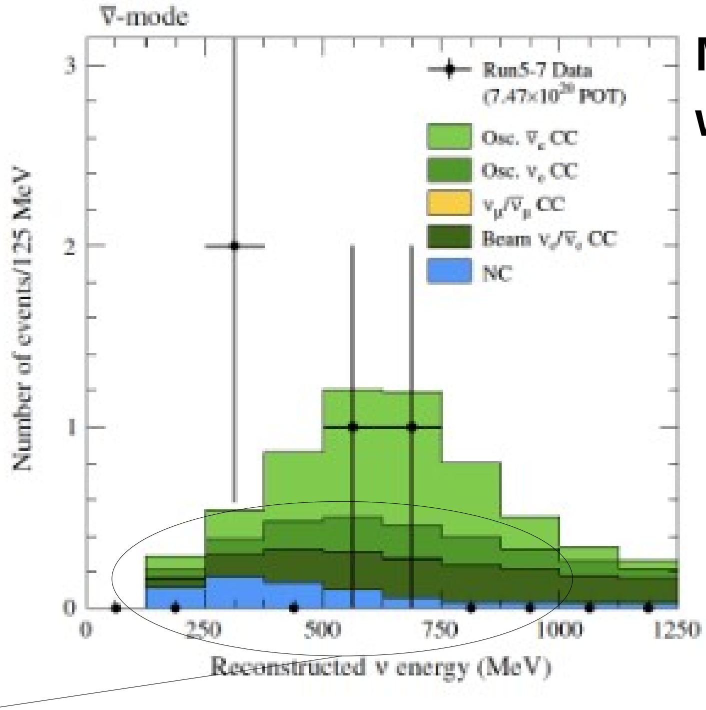
Main signal: ν_e ($\bar{\nu}_e$) appearance with single e-like ring



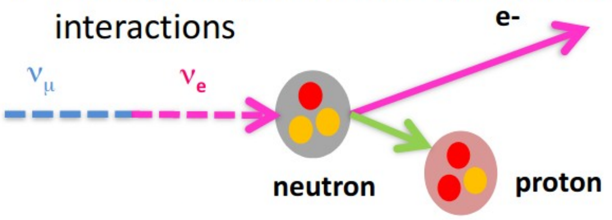


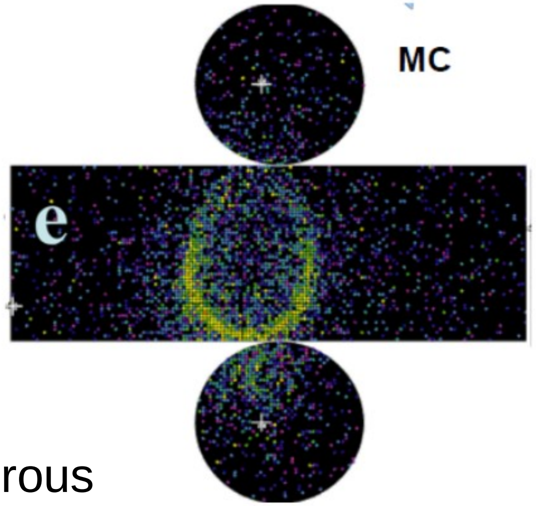
SuperKamiokande samples





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





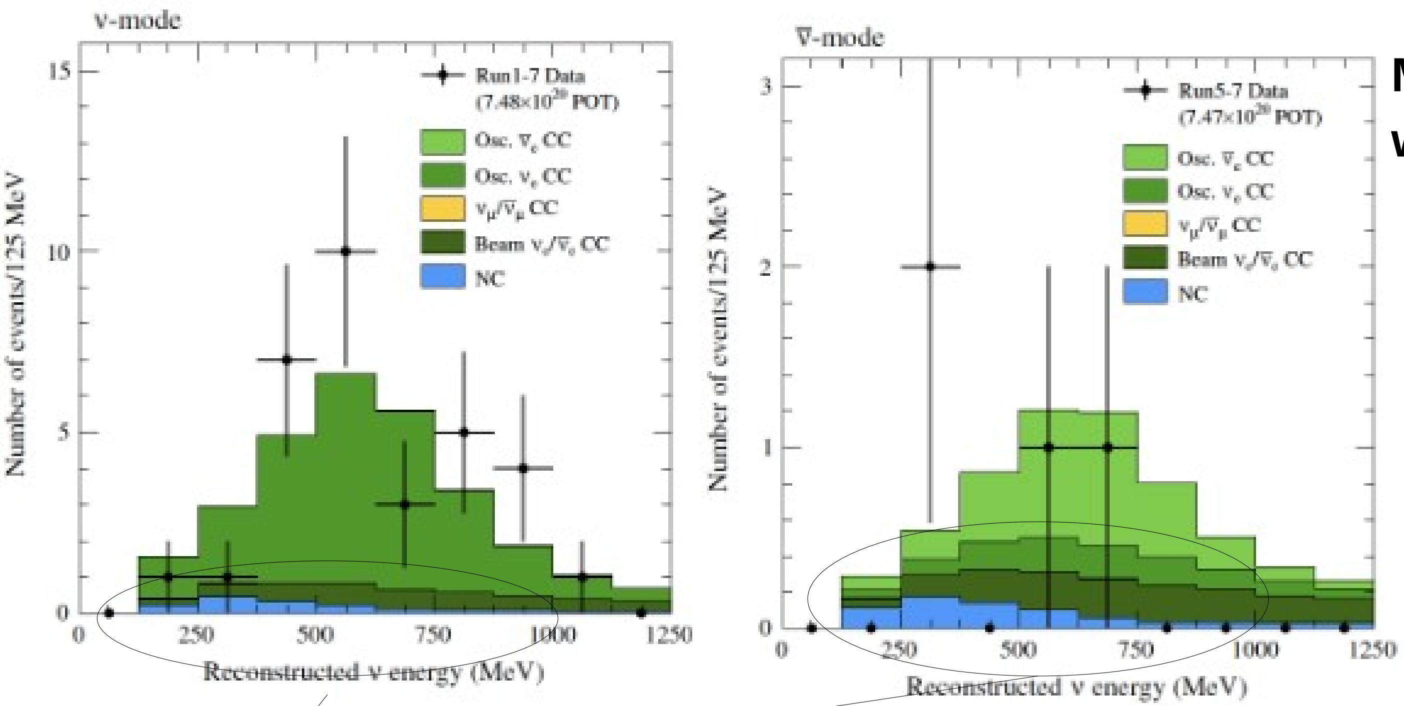
Backgrounds

- 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

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

SuperKamiokande samples



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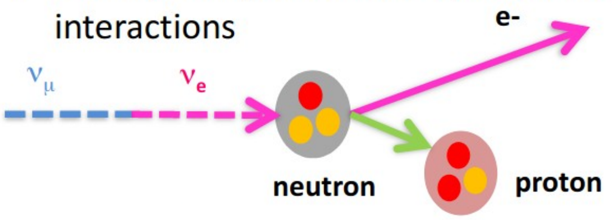
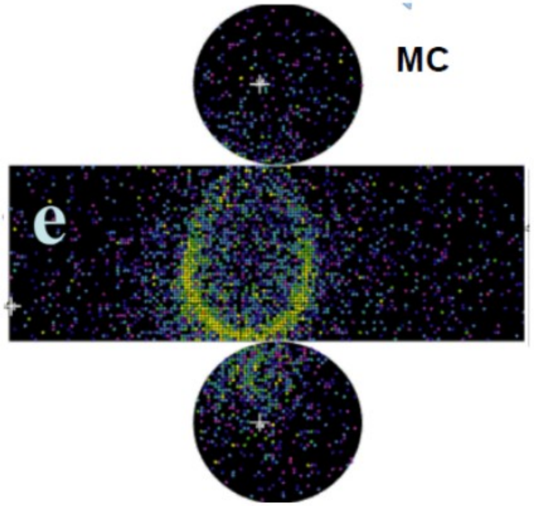
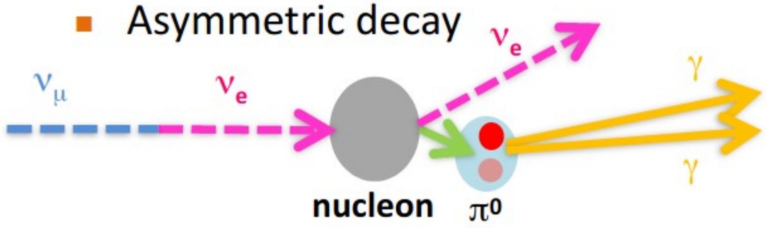
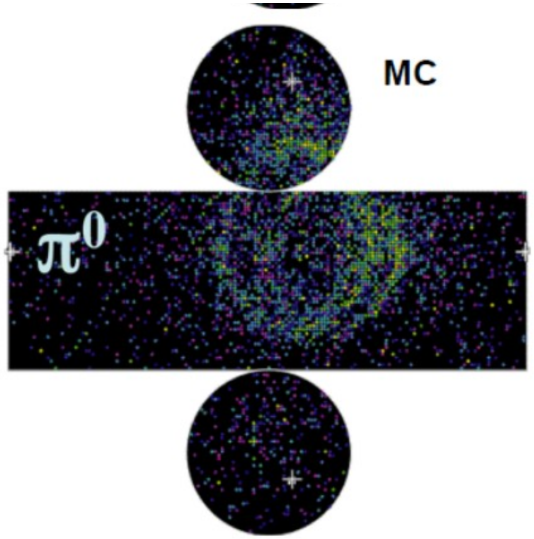




Backgrounds

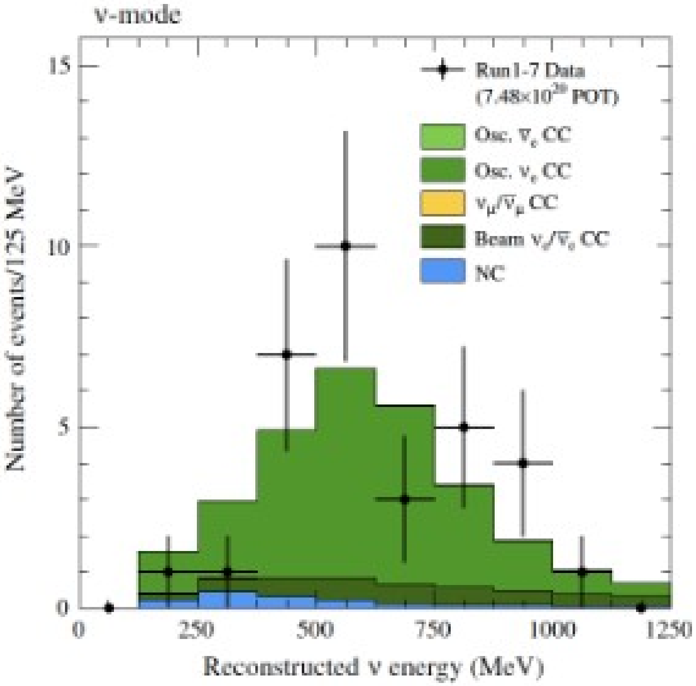
- Intrinsic ν_e from m,K decays $(\nu_e \rightarrow \nu_e)$
- NC single π^0 production
  - Overlap of gammas
  - Asymmetric decay

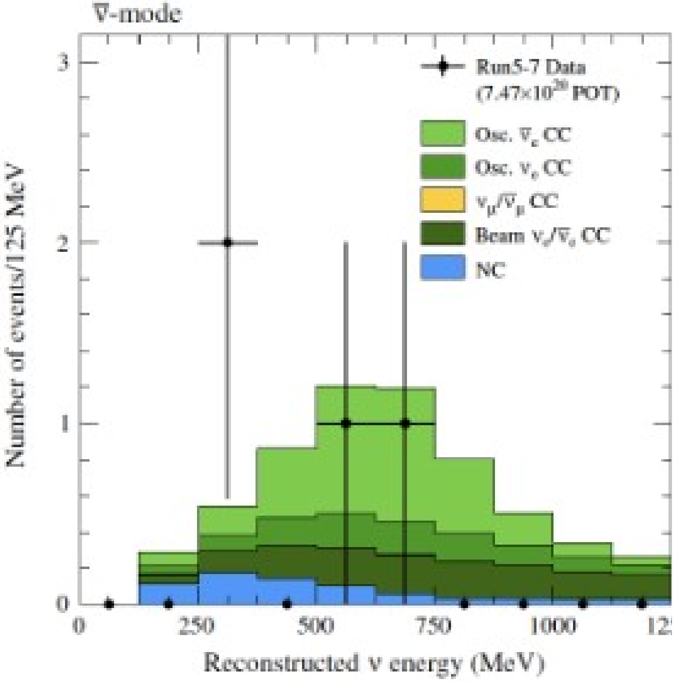


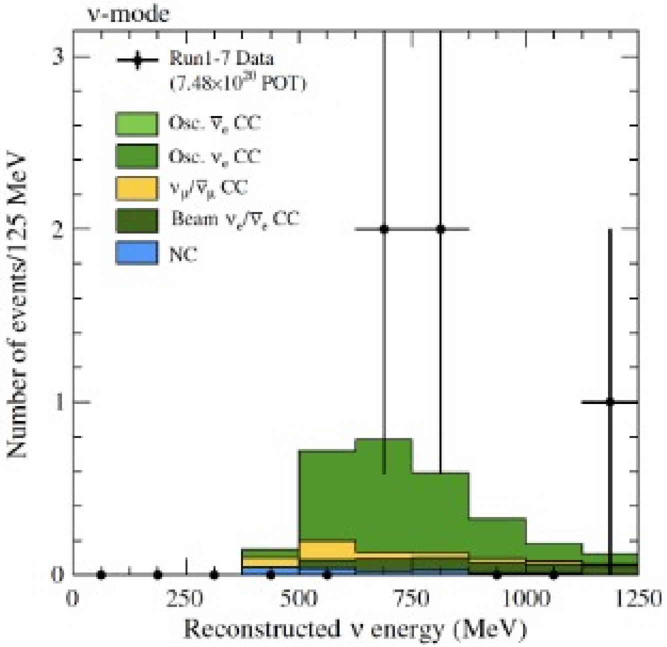


Roger Wendell

SuperKamiokande samples

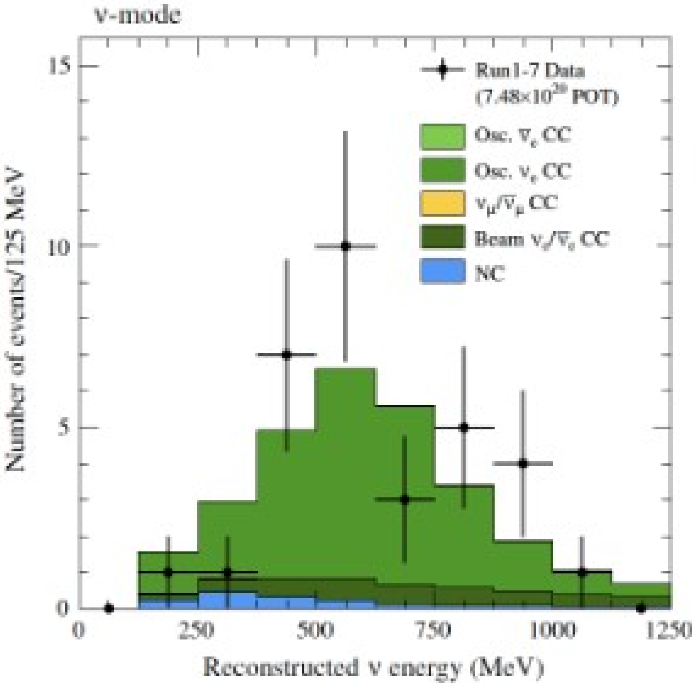


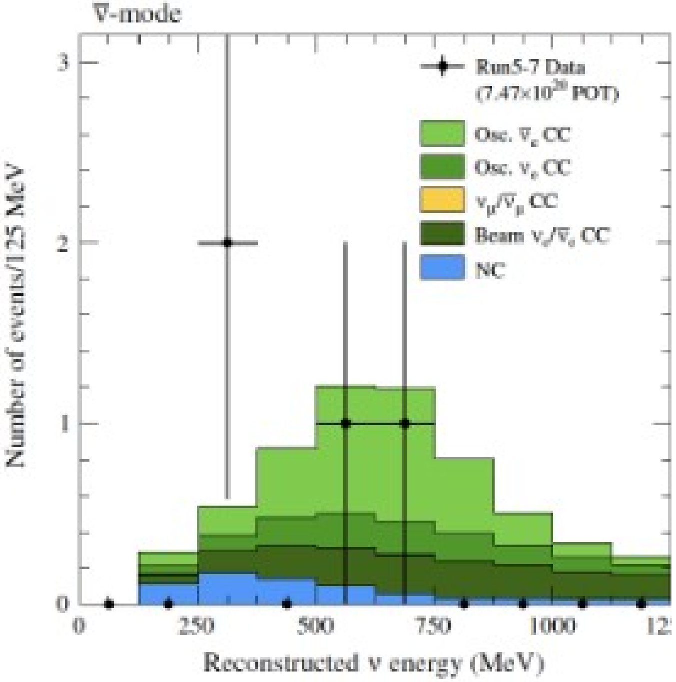


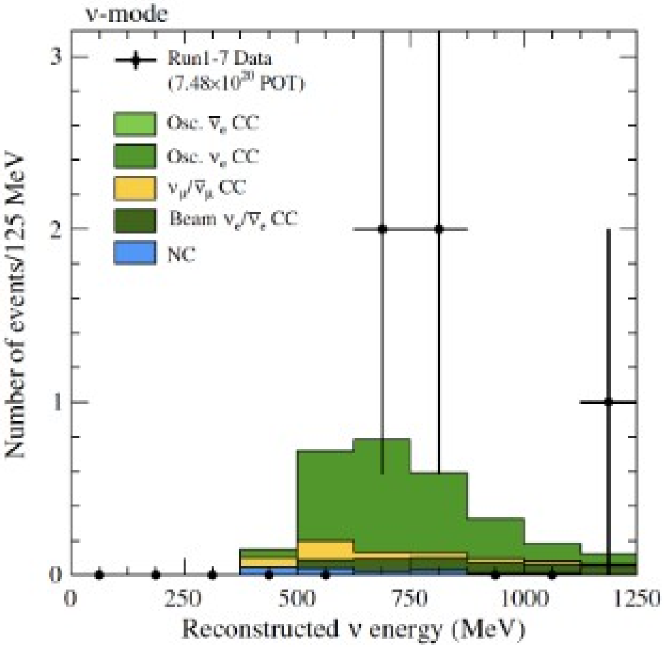


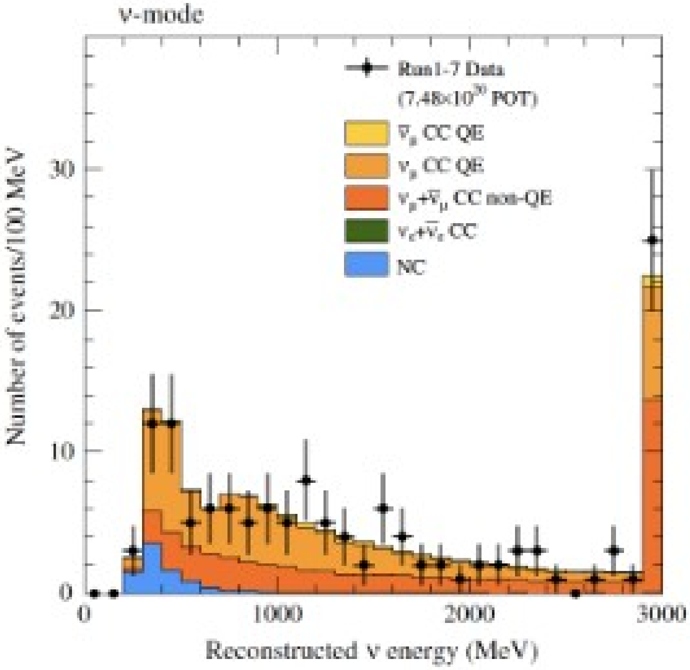
ν_e single ring + 1 Michel electron delayed

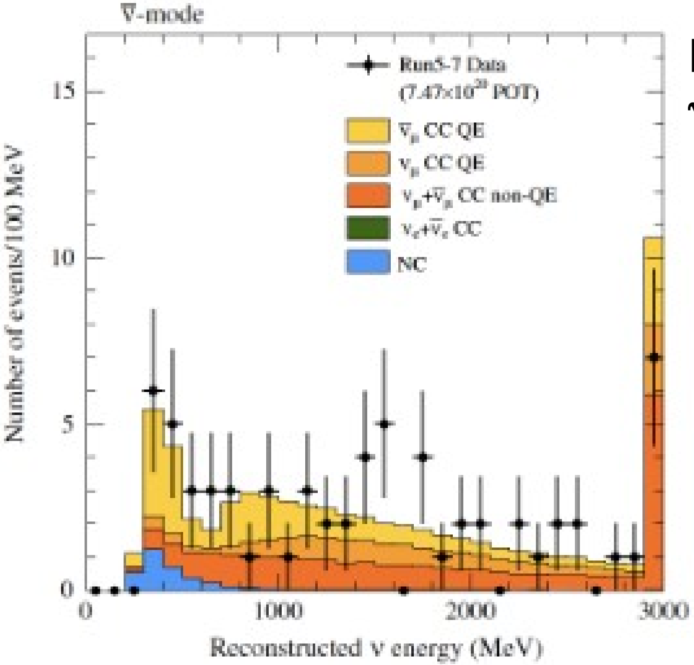
SuperKamiokande samples









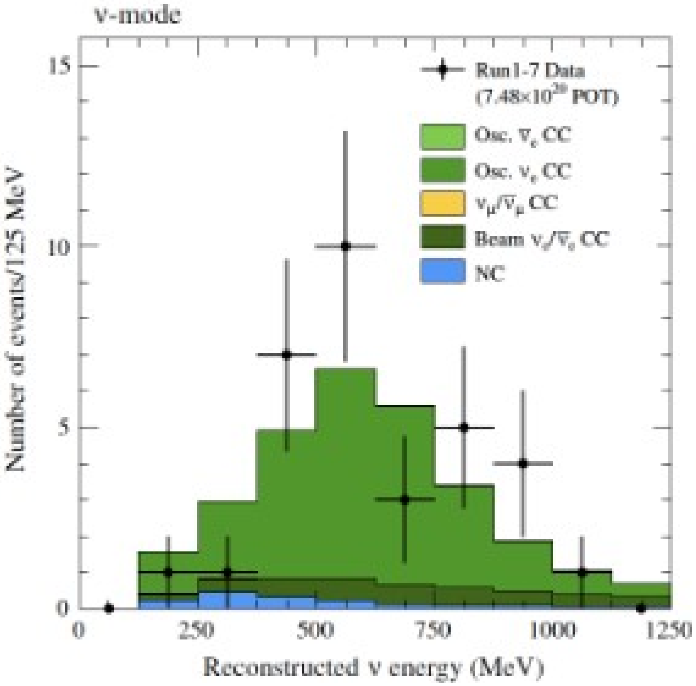


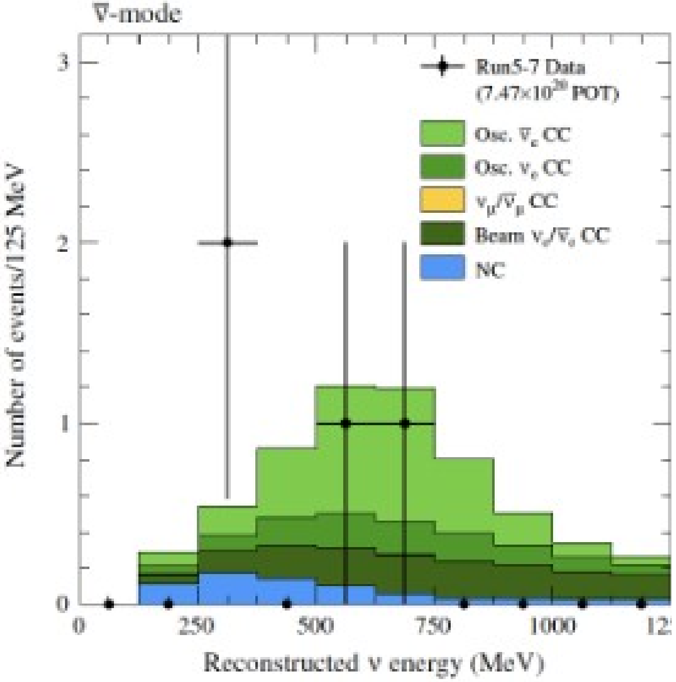
Main disappearance channel:
ν_μ with 1 mu-like ring

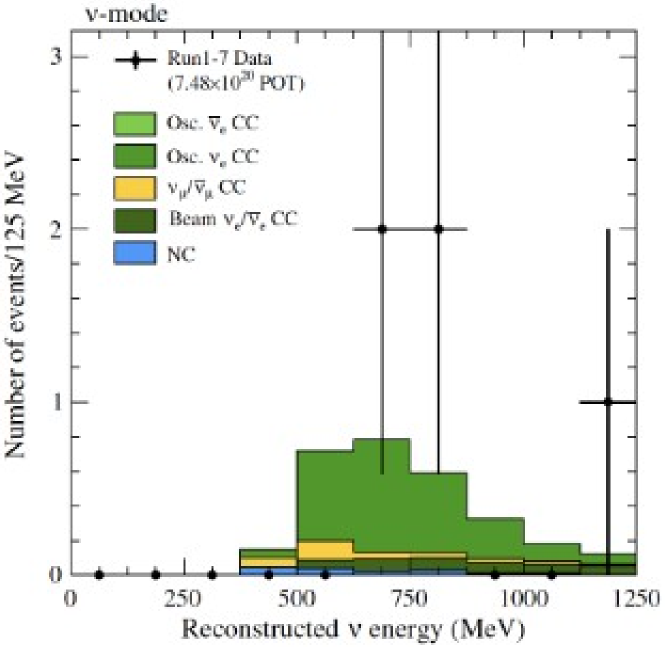
CC-nonQE does disappear but
- higher energy
→ not at oscillation maximum
- but much less precise E_ν^{rec}

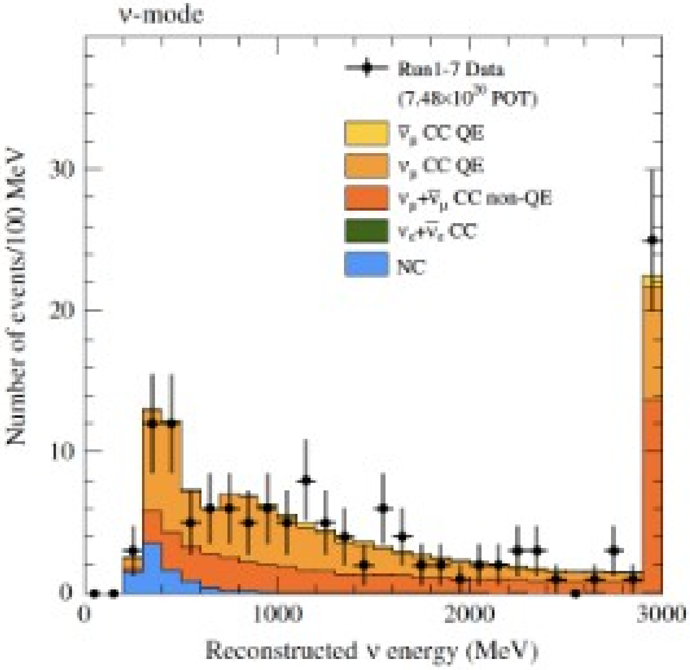
Important to have a dedicated CC-1π sample at far detector for x-check ‘feed-down’

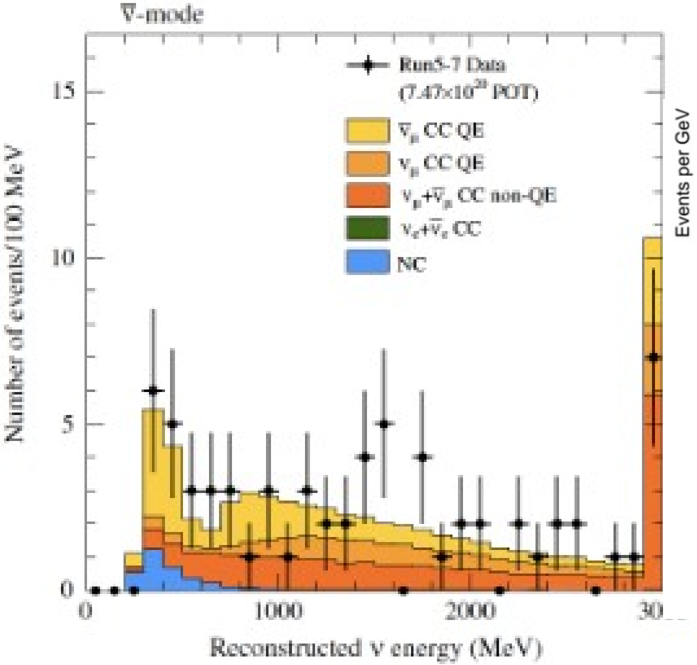
SuperKamiokande samples



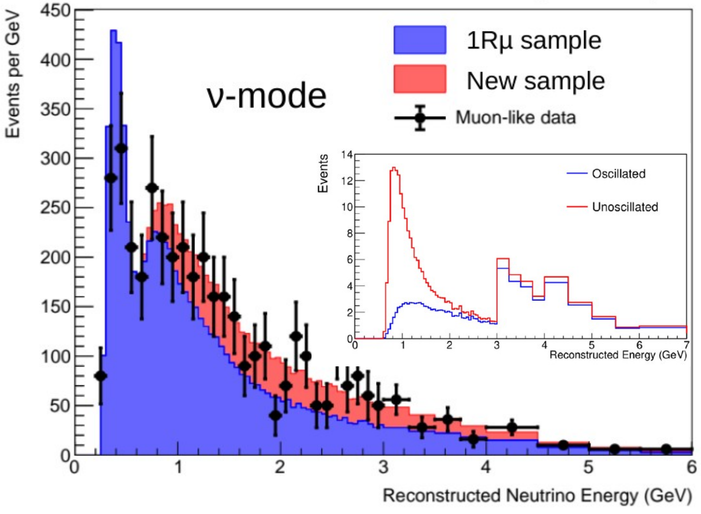




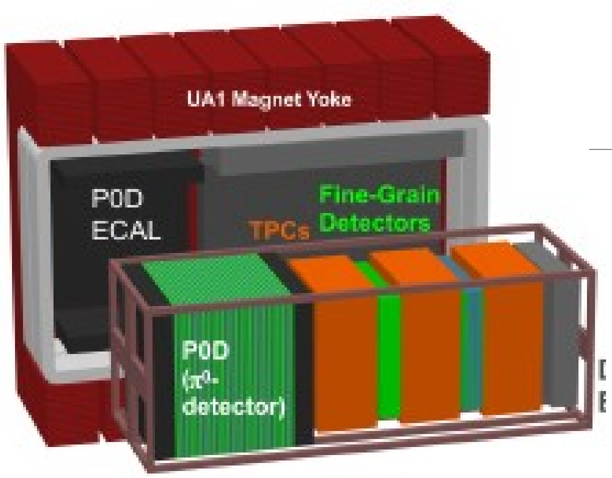


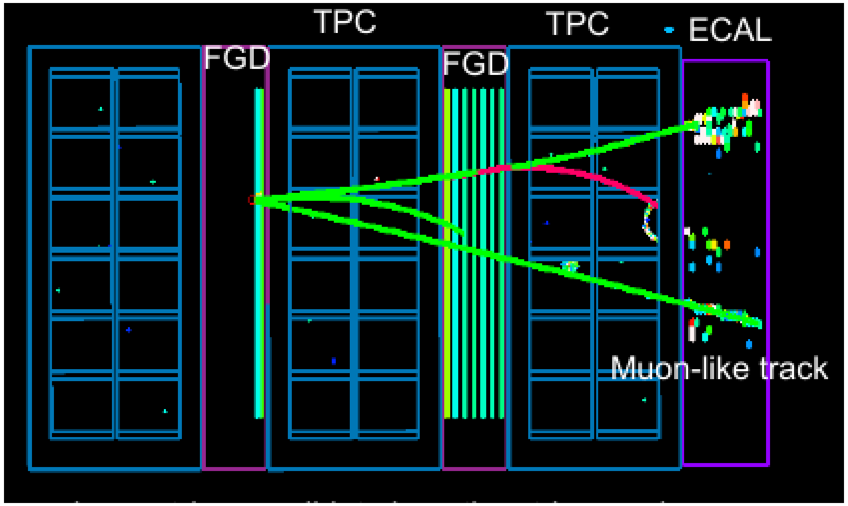


New multiring sample (2022)



T2K near detectors



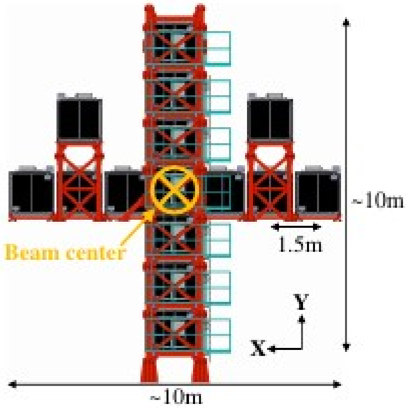


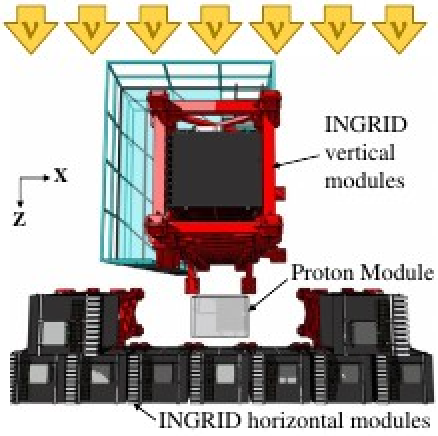
ND280 : off-axis (2.5º)

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

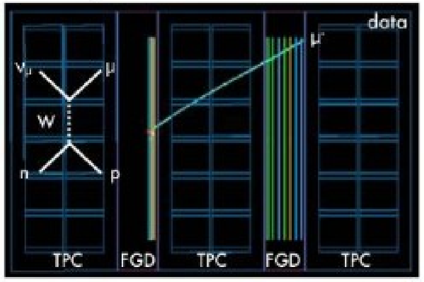
Beam stability monitoring: position and direction (off-axis: Eν depends on angle)

- iron plates alternated with CH scintillator (+ proton module : fully active scintillator)
- **coarser granularity, not magnetized but larger mass :** 2.5x10^{30} nucleons (Fe) + 1.8x10^{29} nucleons (CH)

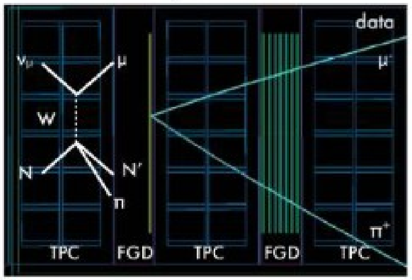
T2K ND selection

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

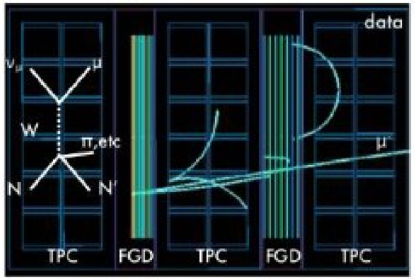
ν_μ CC0π



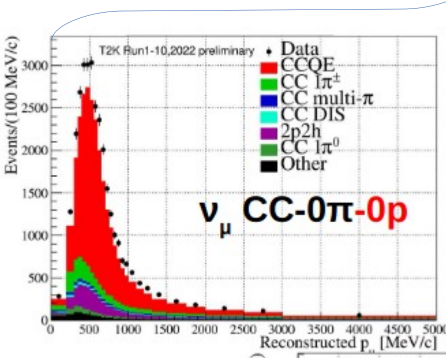
ν_μ CC1π^+

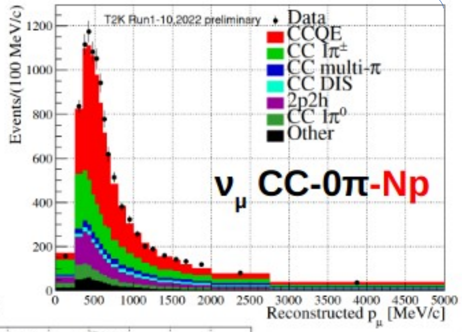


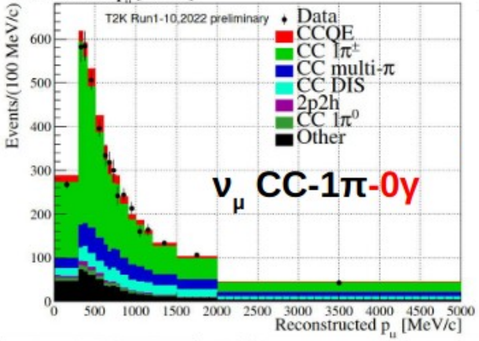
ν_μ CC other



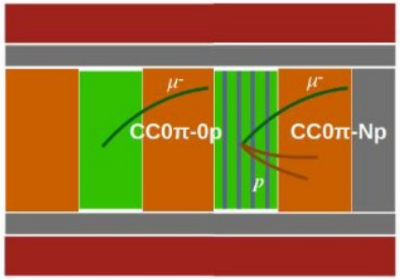
Main QE channel

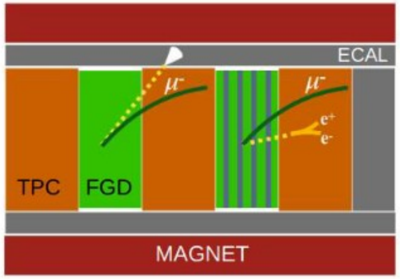


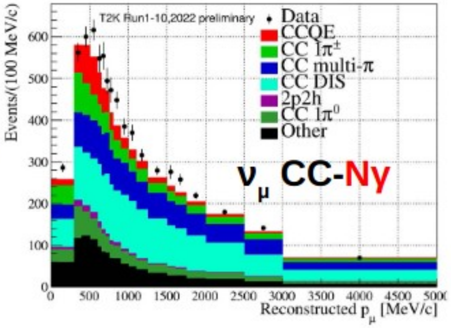


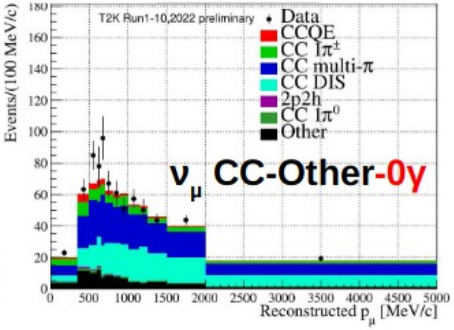


Proton and γ tagging: new in 2022





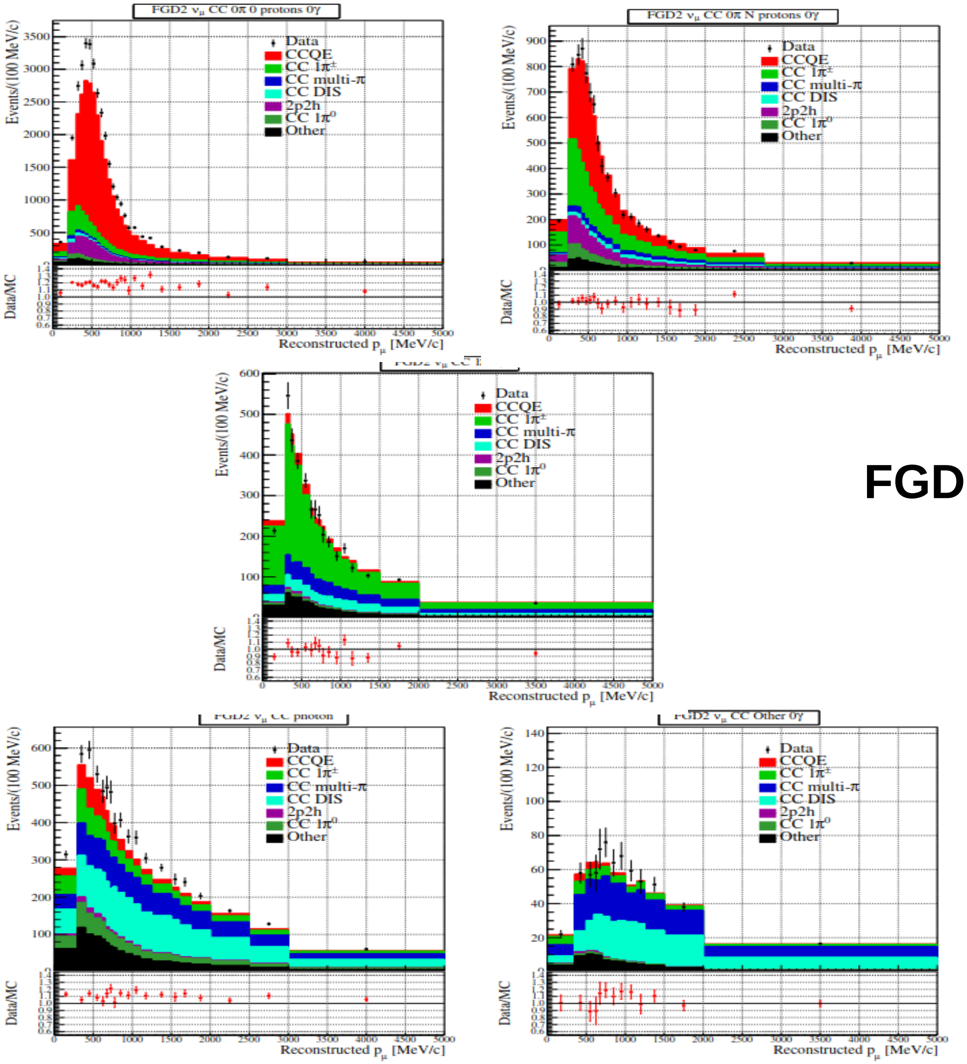




T2K ND selection

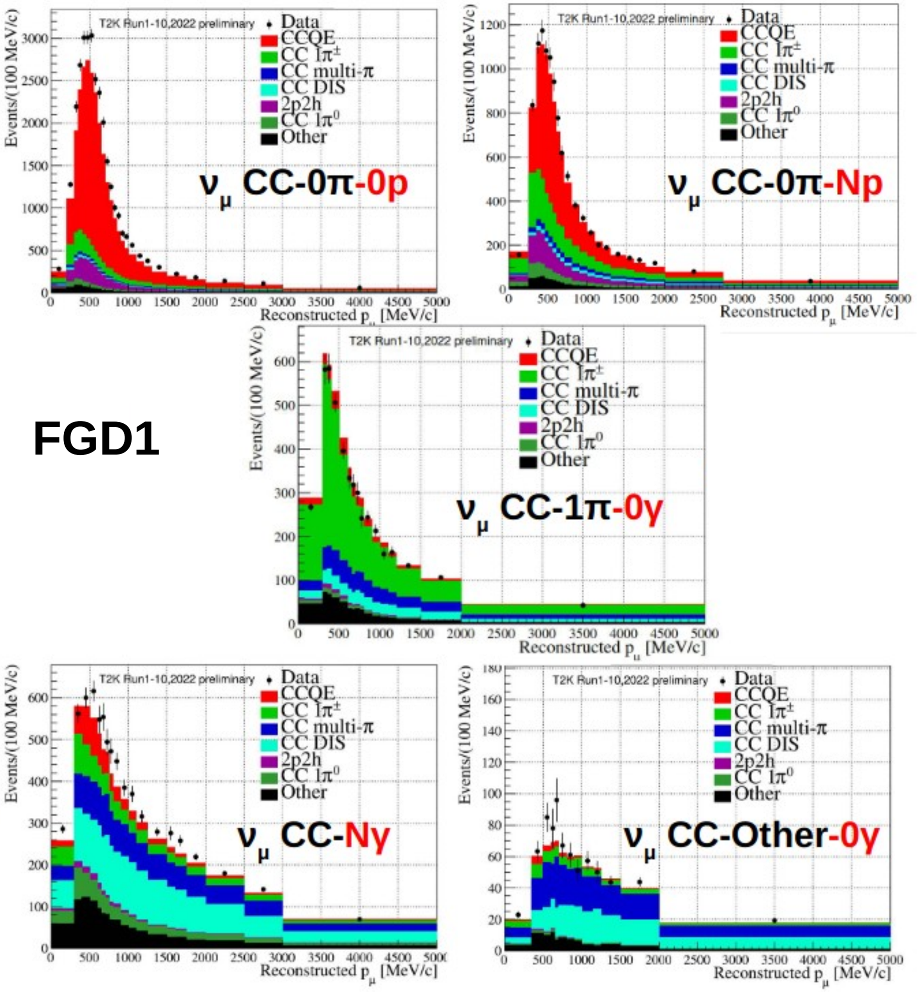
- Require one muon + separate sample based on proton, pion and g multiplicity **(full exclusive final state reconstruction)**
- Until now, similar to SK: lepton kinematics only used for neutrino energy assessment

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



FGD2

FGD1



T2K ND selection

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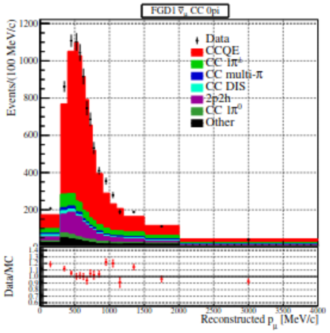
- Until now, similar to SK: lepton kinematics only used for neutrino energy assessment

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

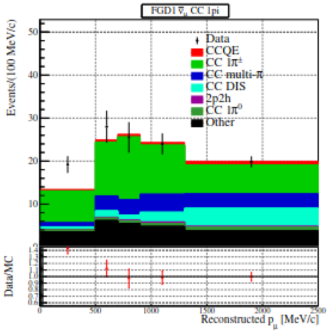
- RHC mode: **μ+ ($\bar{\nu}_\mu$) and μ- (ν_μ) separate samples**

FGD1 RHC

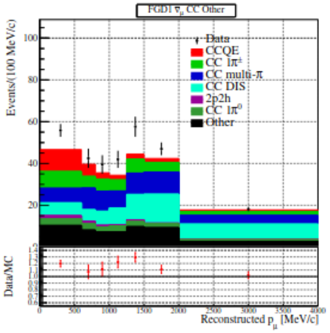
μ+ CC0π



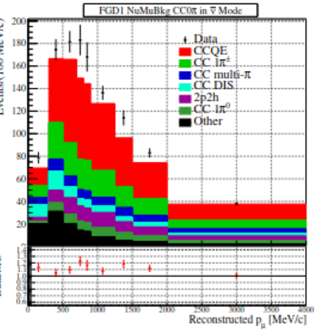
μ+ CC1π



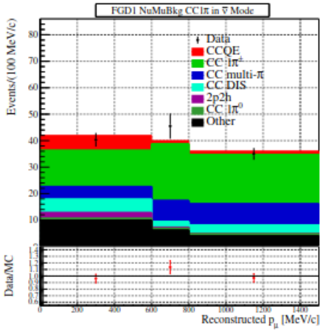
μ+ CC-Other



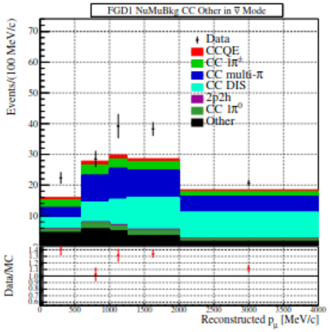
μ- CC0π



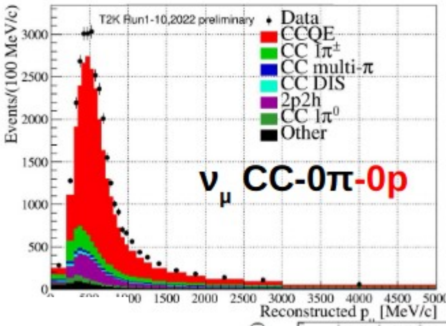
μ- CC1π

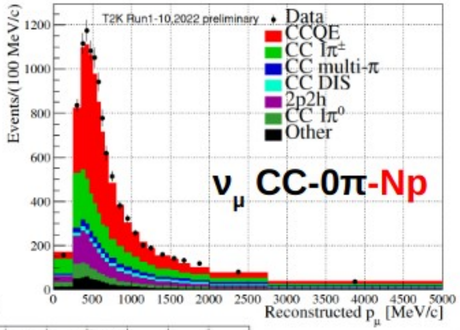


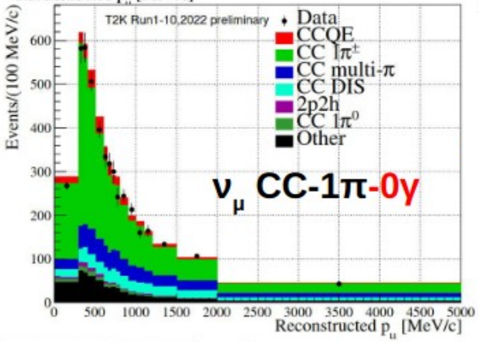
μ- CC-Other



FGD1 FHC







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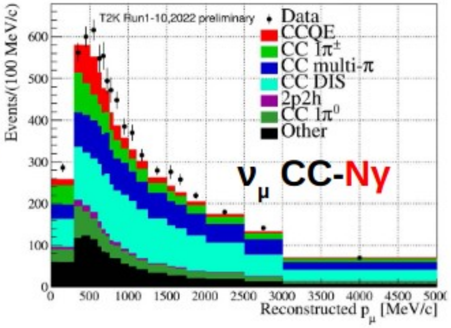
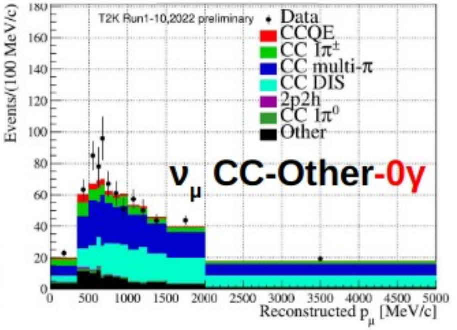




T2K ND selection

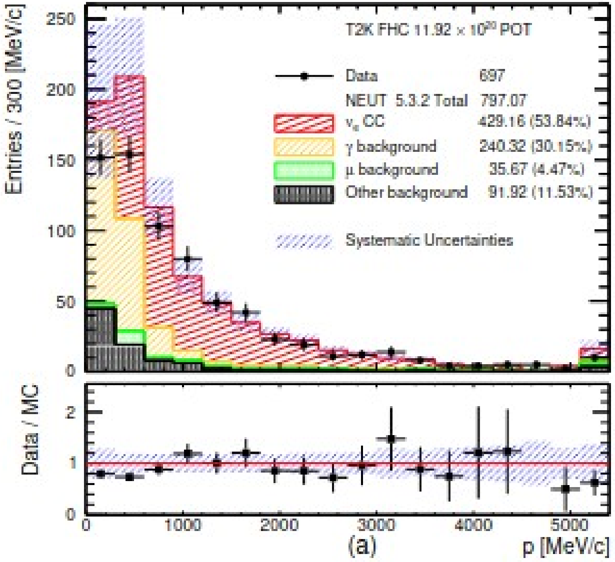
- Require one muon + separate sample based on proton, pion and g multiplicity **(full exclusive final state reconstruction)**
- Until now, similar to SK: lepton kinematics only used for neutrino energy assessment

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

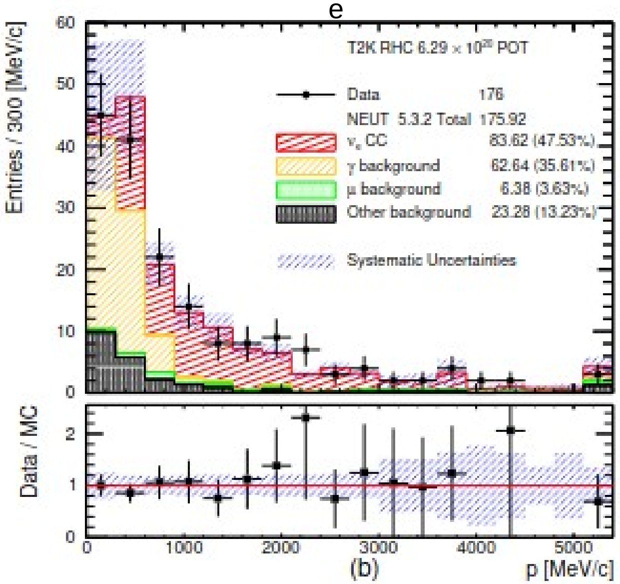
- RHC mode: **μ+ ($\bar{\nu}_\mu$) and μ- (ν_μ) separate samples**

- **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.

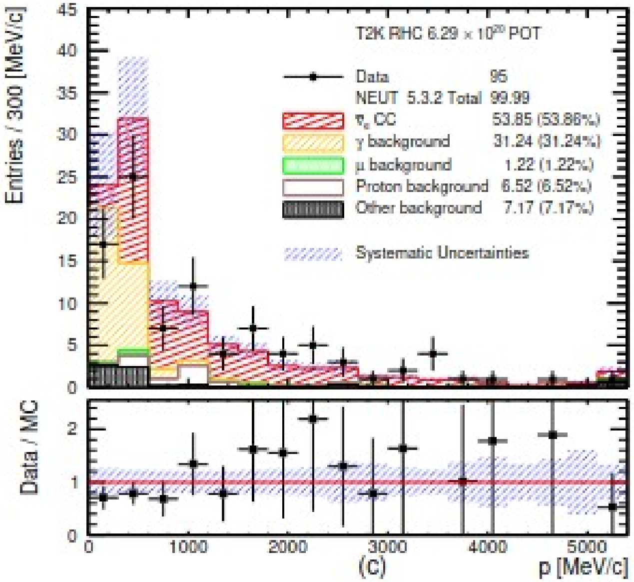
FHC: ν_e



RHC: $\bar{\nu}_e$



RHC: ν_e



T2K ND fit

- **ND measurement**

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

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

~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)
- flux and xsec must be disentangled

T2K ND fit

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→ needs to rely on models (tuned to ND data)

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

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

T2K ND fit

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

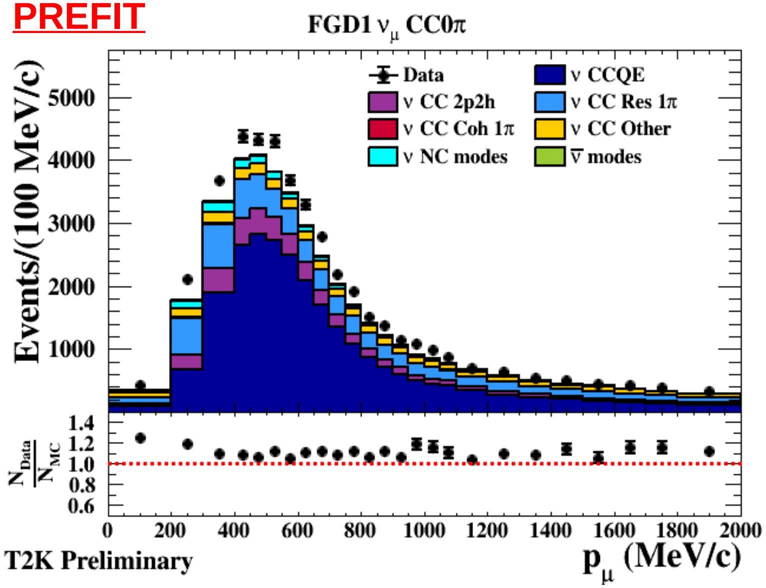
- **Tuned model** used for flux and cross-section disentagling and their extrapolation to FD
+correct reconstruction of energy at the far detector

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

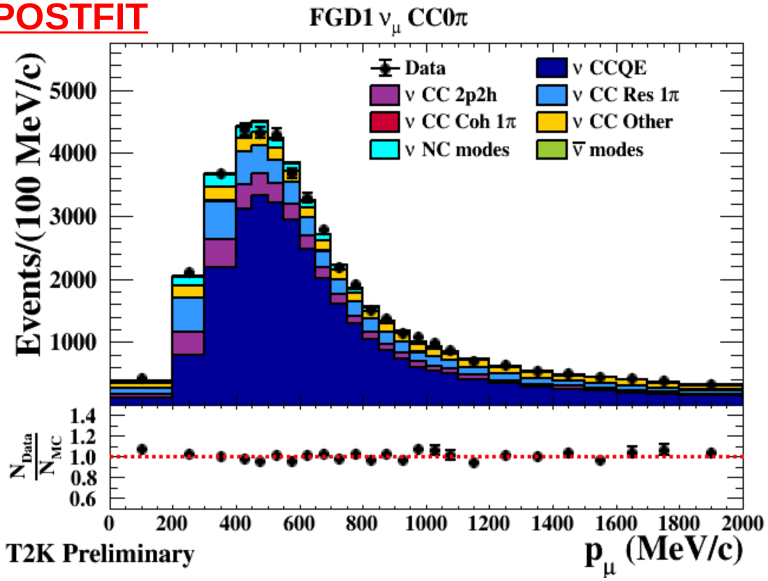
T2K ND: data fit

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

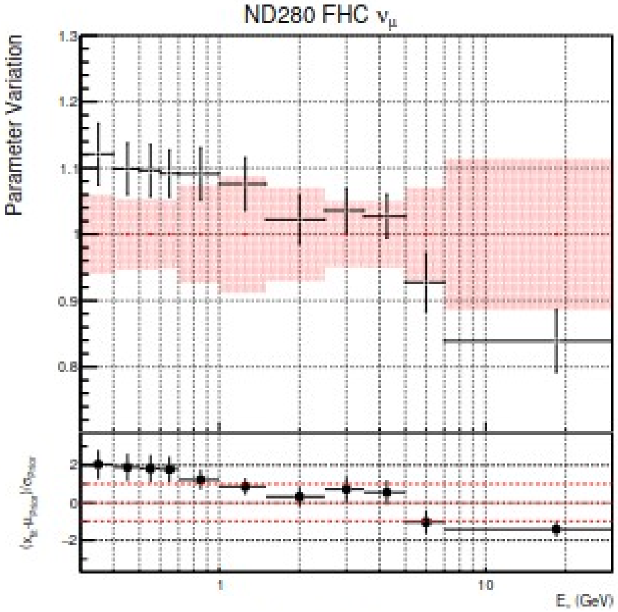
PREFIT

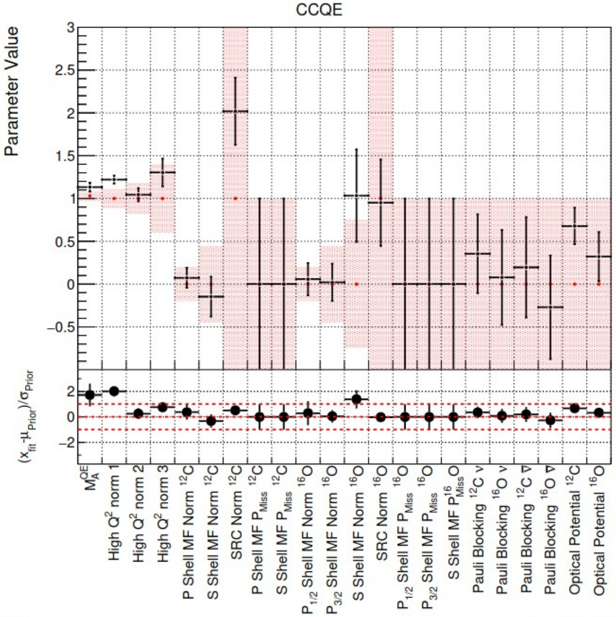


POSTFIT



Tuning of flux and xsec model





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

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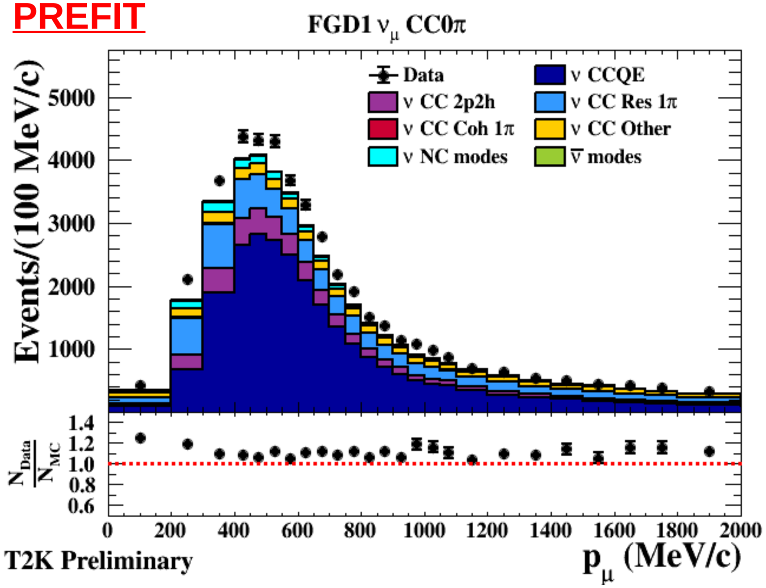
Simultaneous fit to all ND separate samples (only example of main channel shown)

PREFIT



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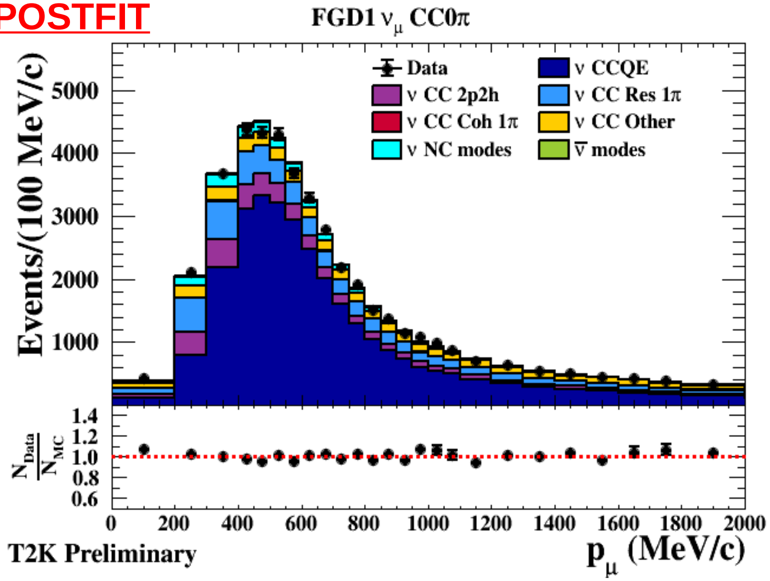

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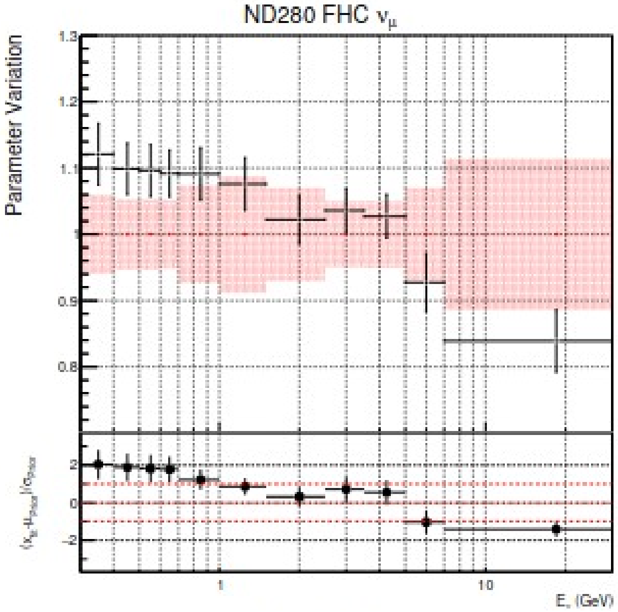

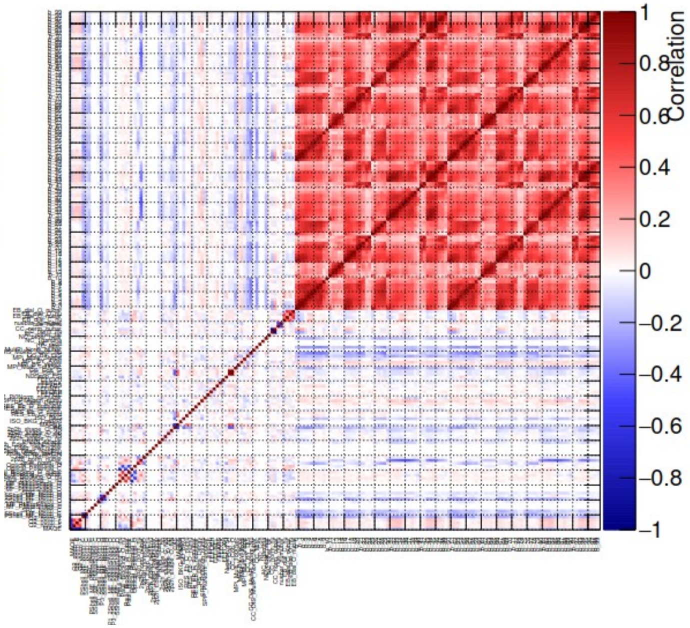

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All parameters got correlated from the fit

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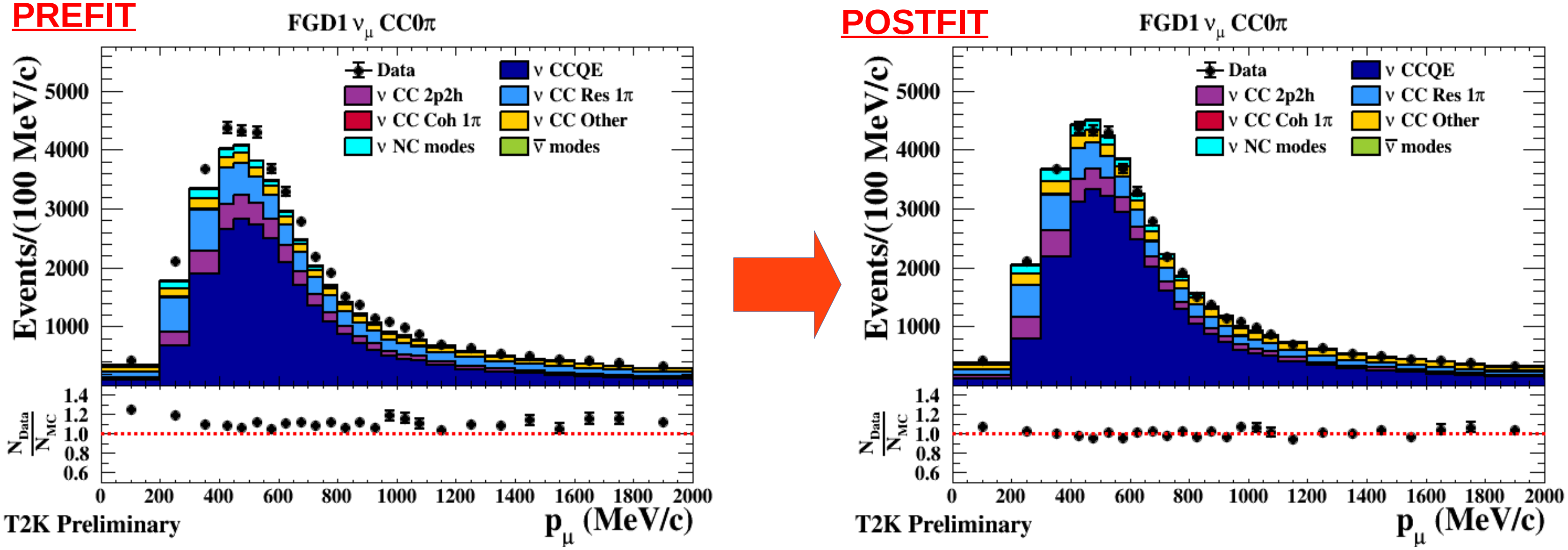
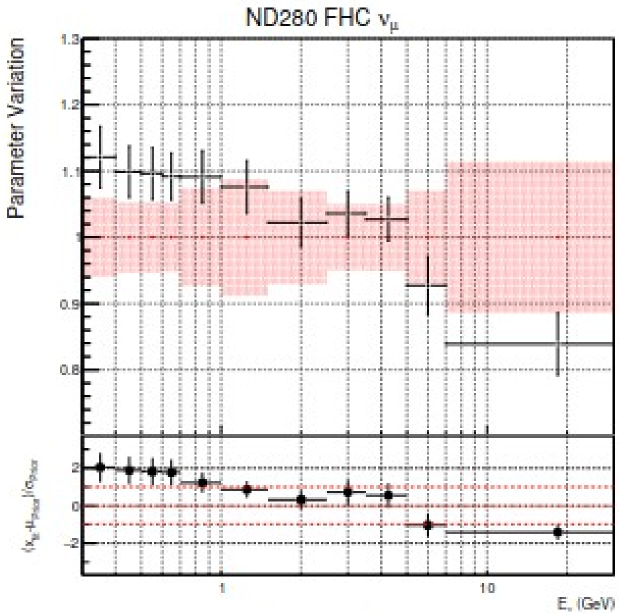
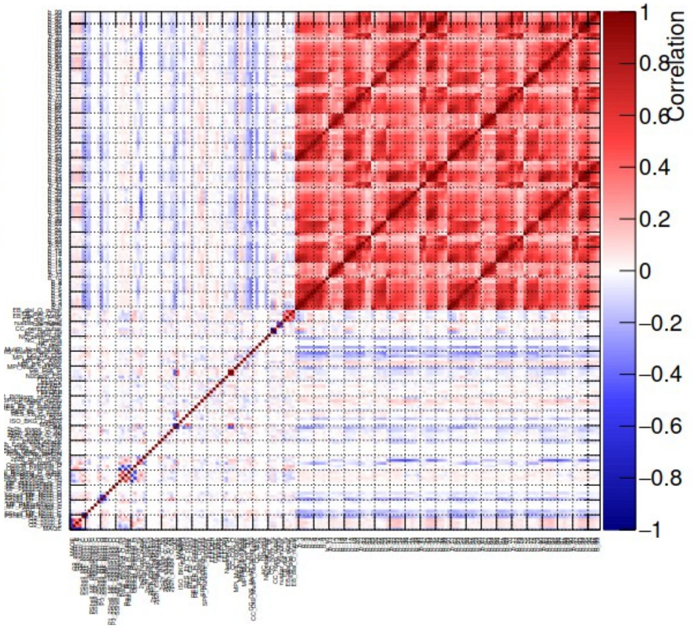
POSTFIT



Tuning of flux and xsec model





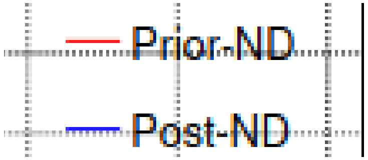
Actually hundreds of parameters (only main flux and xsec channel shown)

All parameters got correlated from the fit

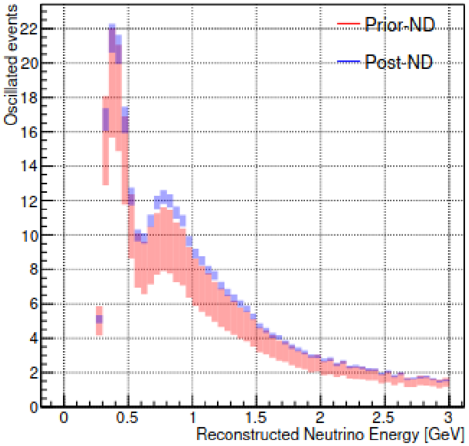
Tuned model used to estimate flux and xsec at far detector and tune Eν reconstruction at far detector

SuperKamiokande tuned distribution

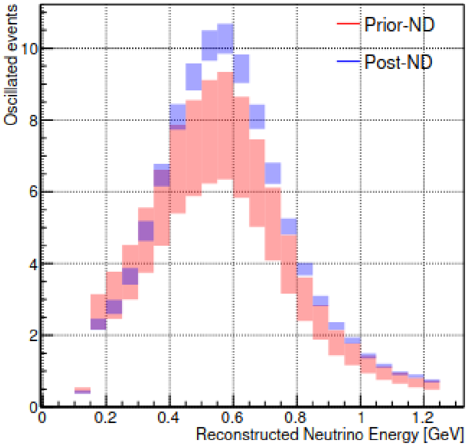
(Only main samples shown)



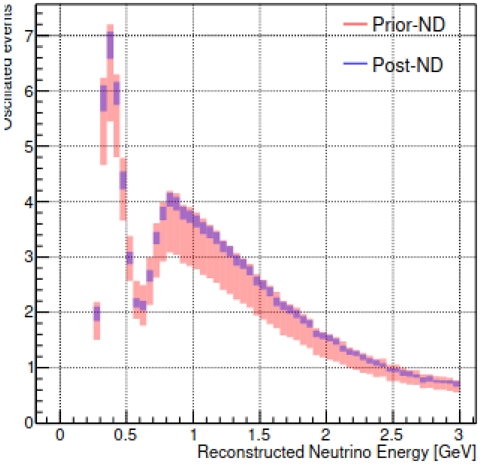
FHC 1ring μ



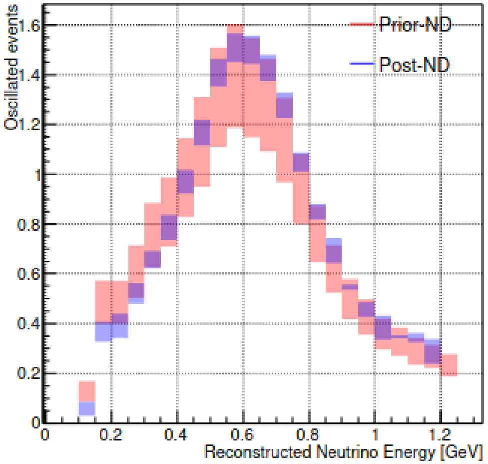
FHC 1ring e



RHC 1ring μ



RHC 1ring e



Before the ND fit

	1ring μ		1ring e		
Error source (units: %)	FHC	RHC	FHC	RHC	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

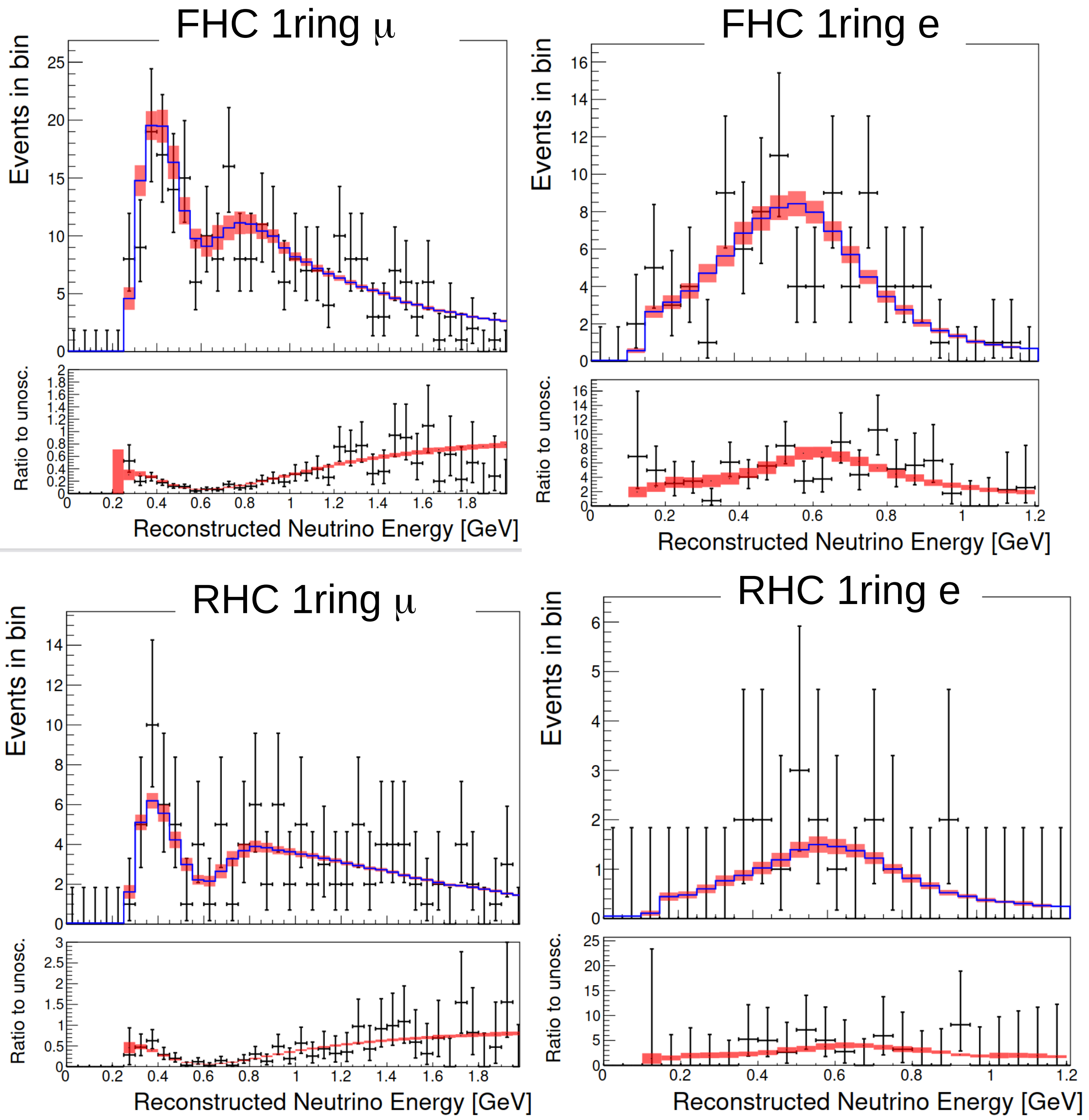
After the ND fit

	1ring μ		1ring e		
Error source (units: %)	FHC	RHC	FHC	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 atmospehric neutrinos and from dedicated control samples)



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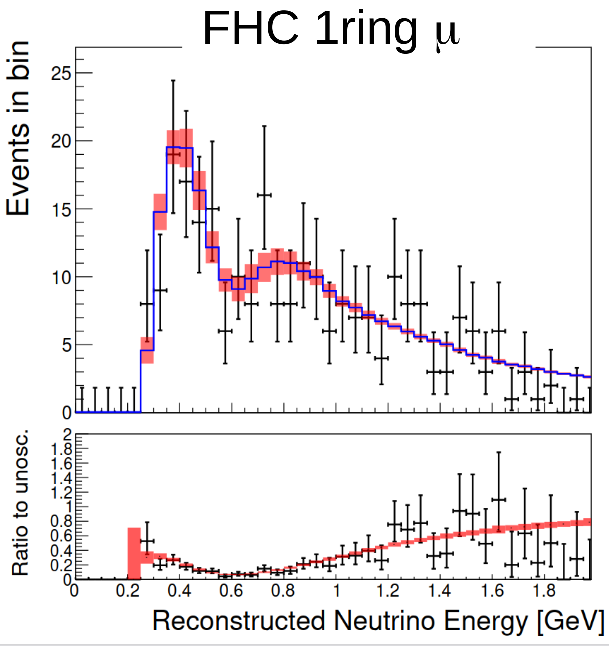
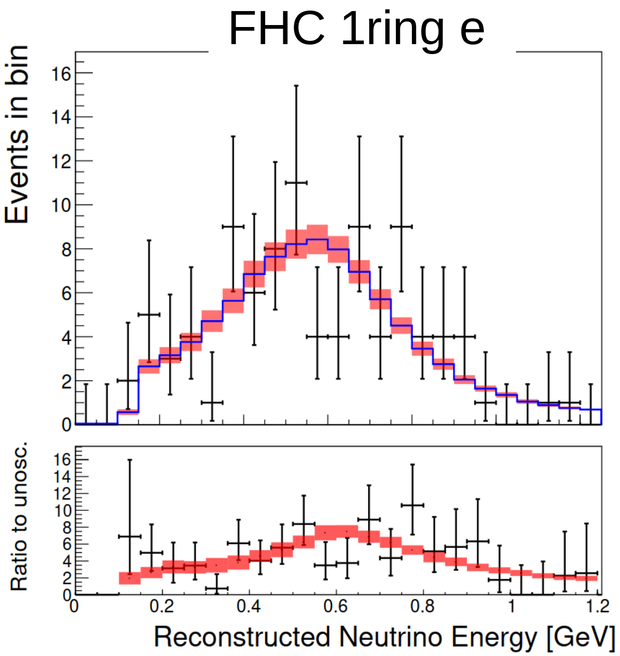
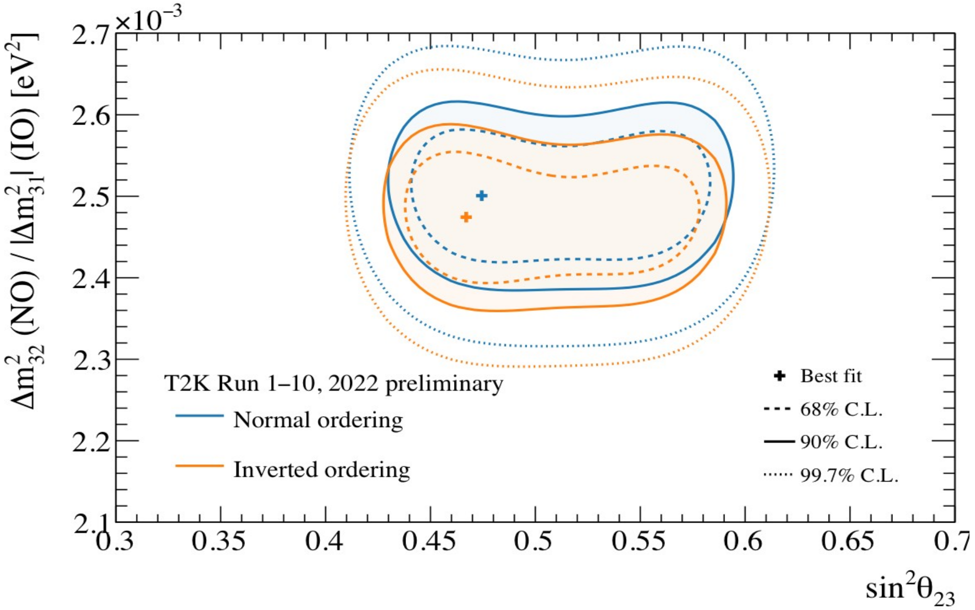
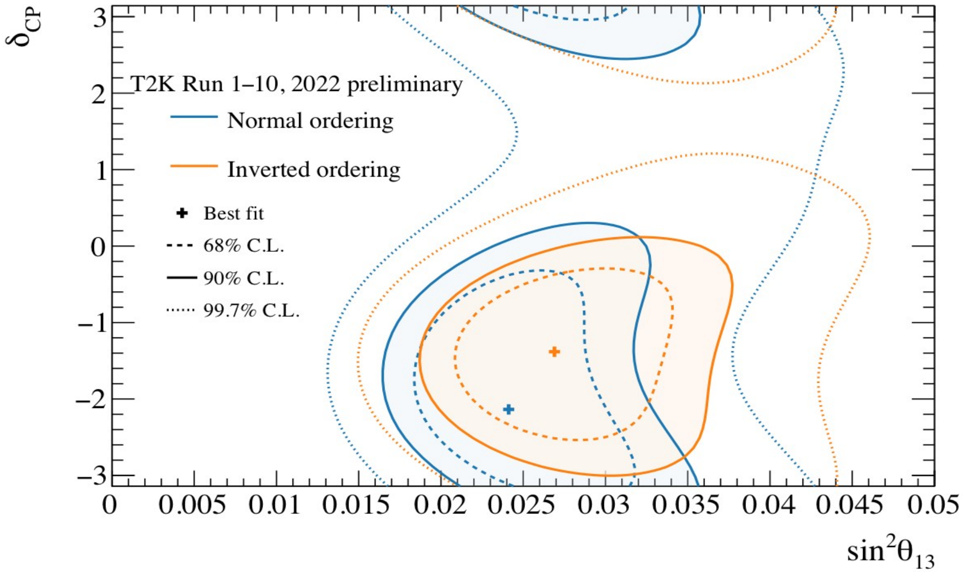


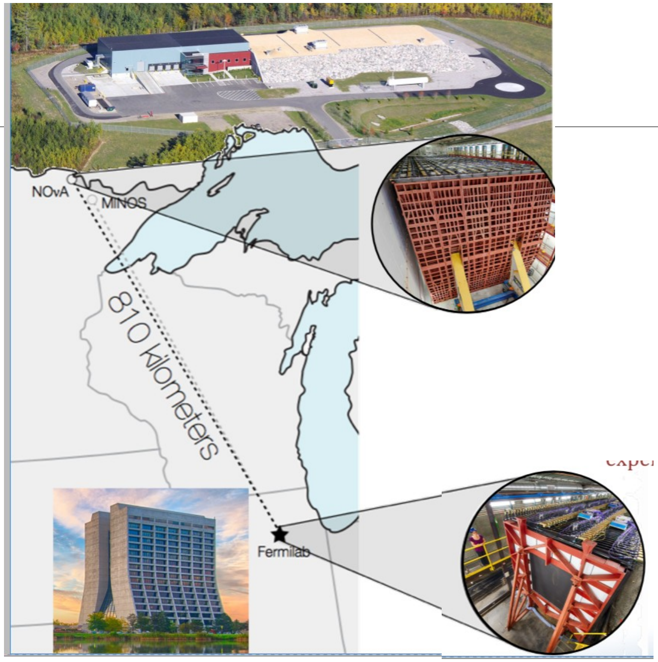


- Both a joint ND+FD fit and sequential ND → FD fit are done and compared. Both frequentist and bayesian analysis are performed and compared





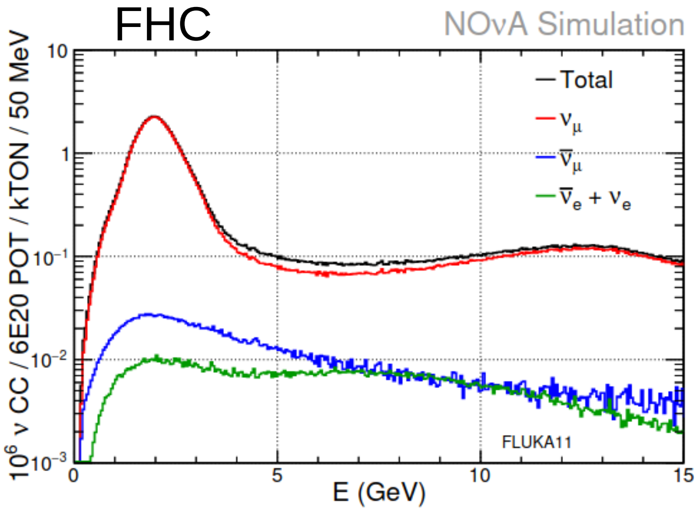
NOVA

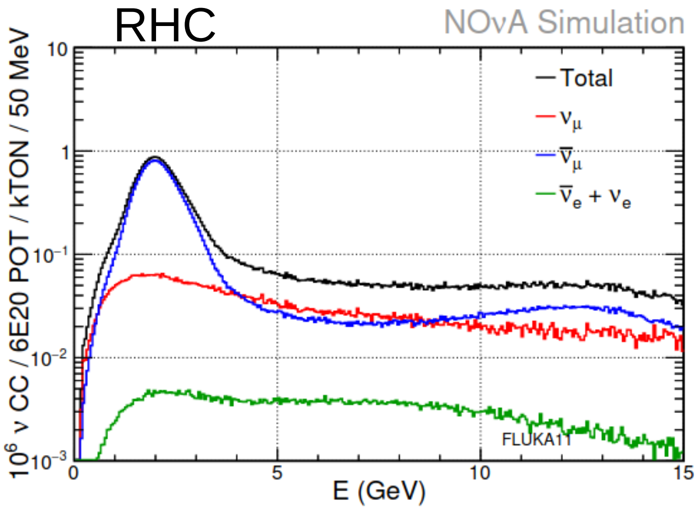


NUMI beam at FNAL

14mrad off-axis
(narrow-band spectrum)

Baseline: 810km





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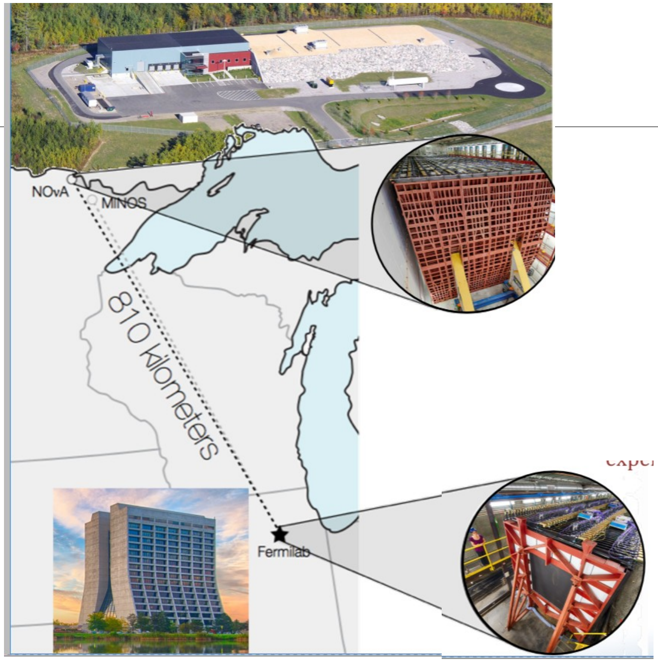

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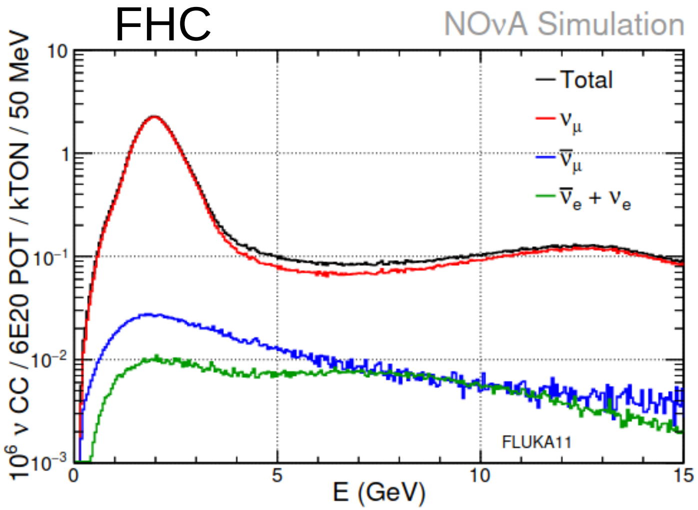
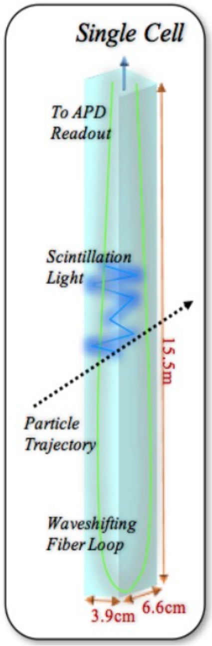
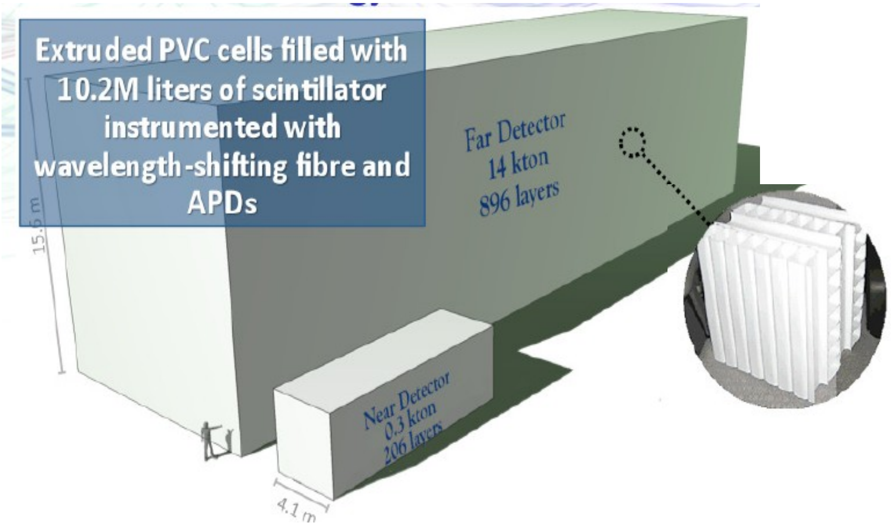


- **Same technology (liquid scintillator) for near and far detector**

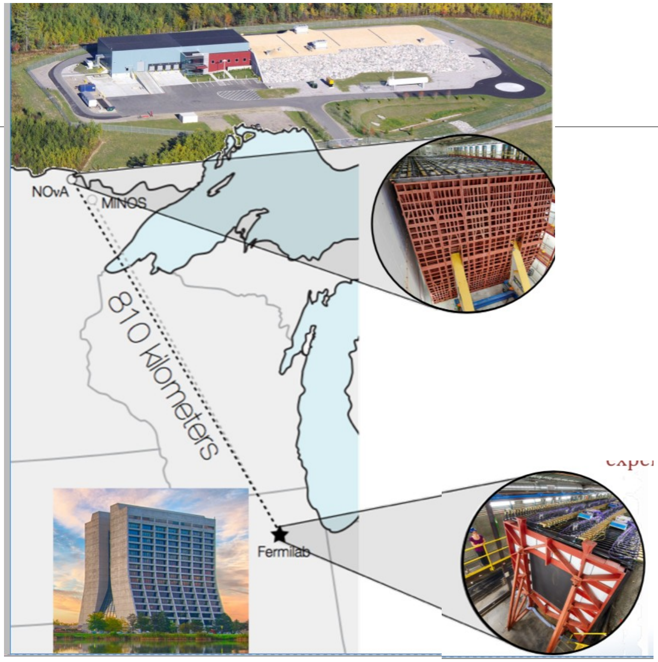
Near Detector: 300T underground
Far detector: 14 kT on the surface





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

NOVA



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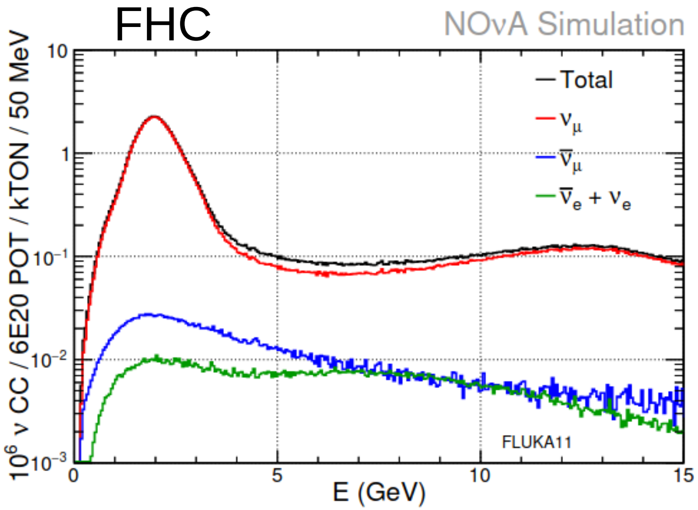

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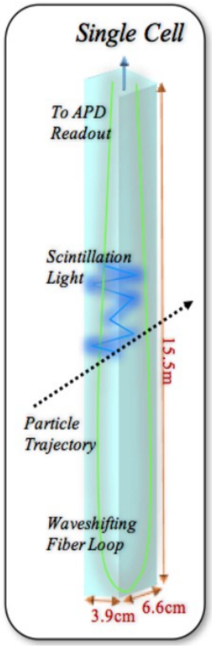
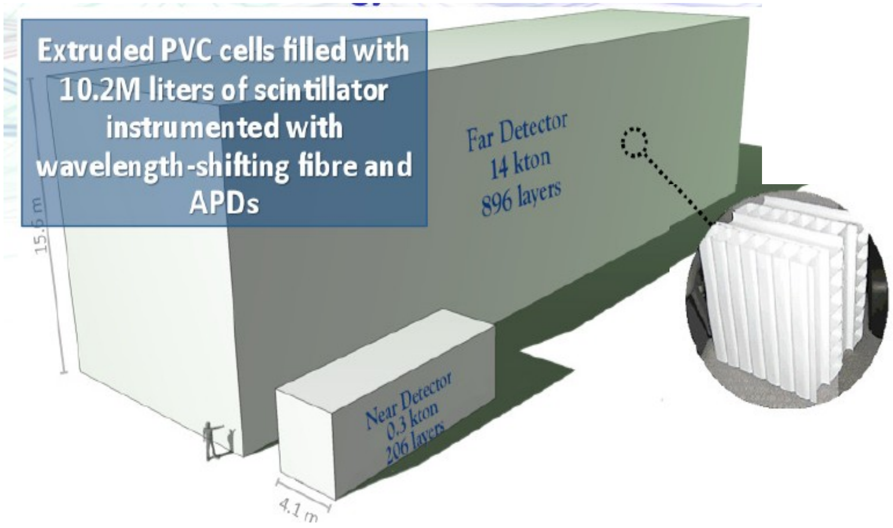




Extruded PVC cells filled with 10.2M liters of scintillator instrumented with wavelength-shifting fibre and APDs

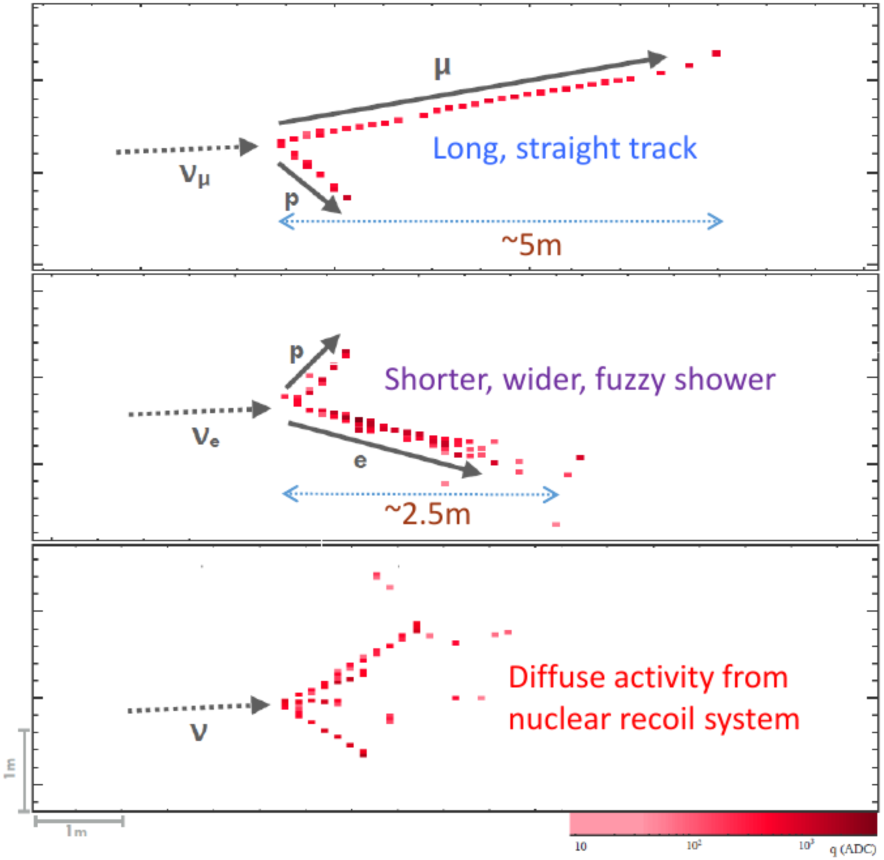
- **How systematics on nuclear effects still affect ND to FD extrapolation:**
  - different Eν at ND and FD (before and after oscillation) → different E_{had}/Eν, different resolution..
  - still need to disentangle flux and xsec since they depends on Eν differently
  - different acceptance (in p_T)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

What do we measure?

ν_μ CC

ν_e CC

NC



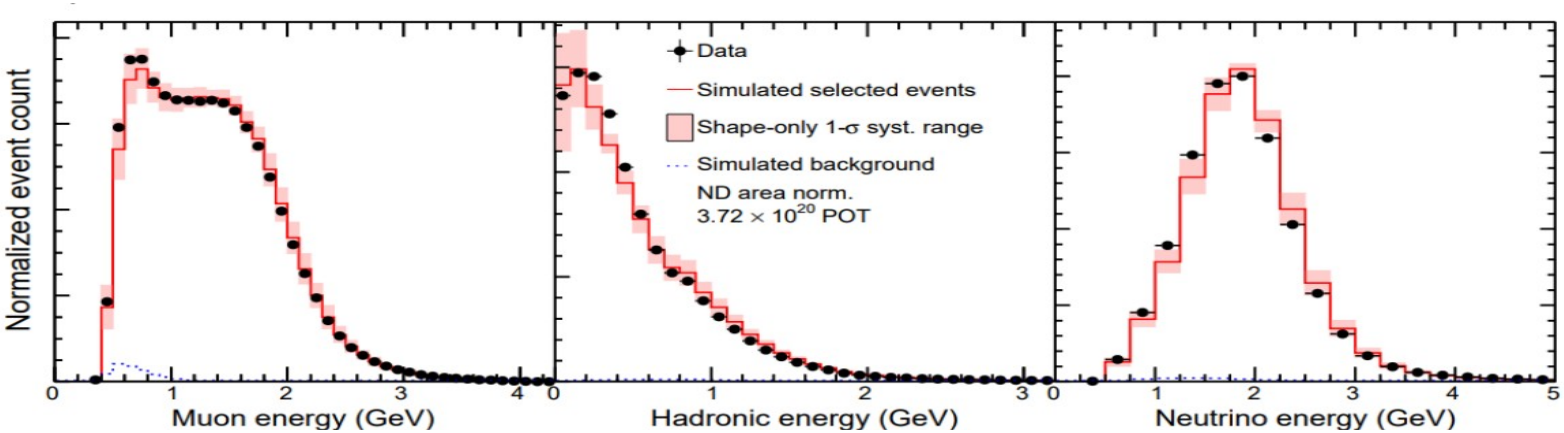
Muons (if contained)

Electrons as **shower**

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

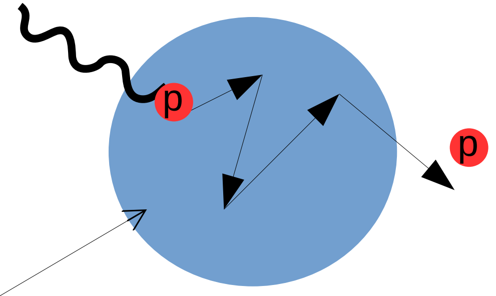
High energy flux: pion production and DIS → large fraction of Eν goes into hadrons

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

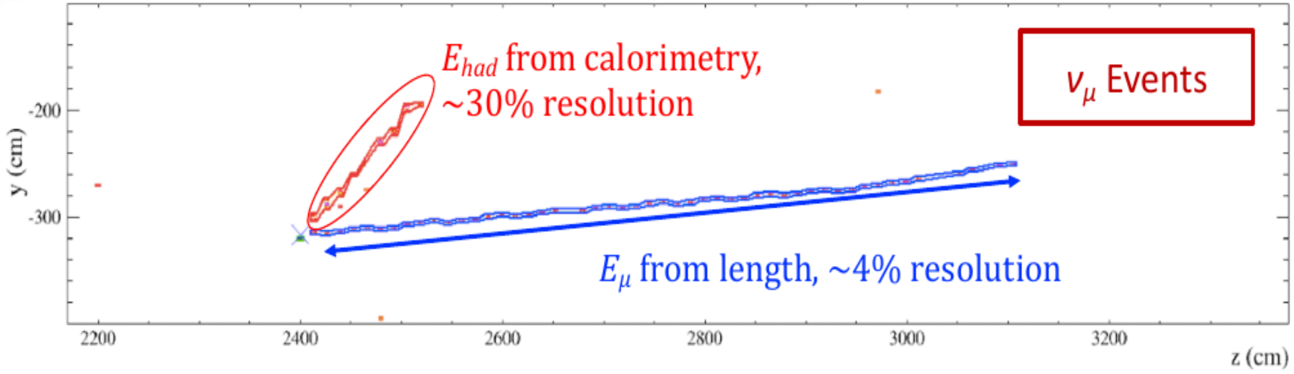


Eν reconstruction

Final State Interactions



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



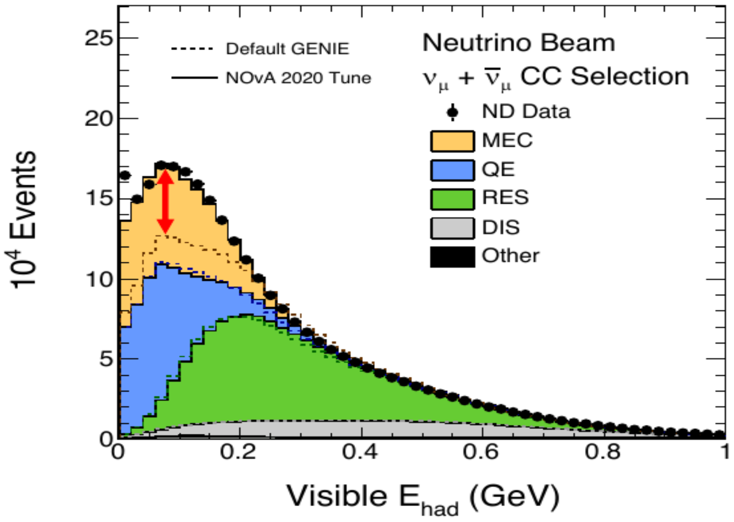
E_{had} from calorimetry, ~30% resolution

ν_μ Events

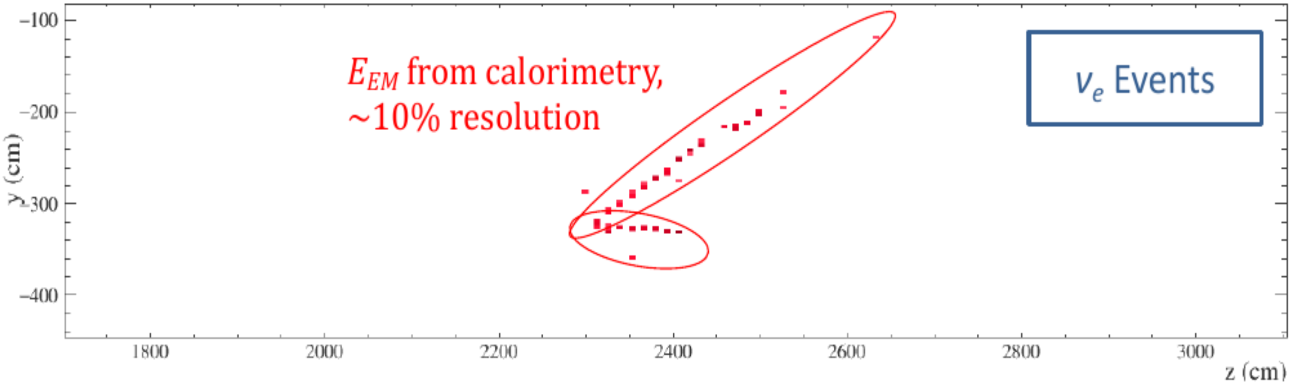
E_μ from length, ~4% resolution

Important to tune model predictions for E_{had}

NOvA Preliminary



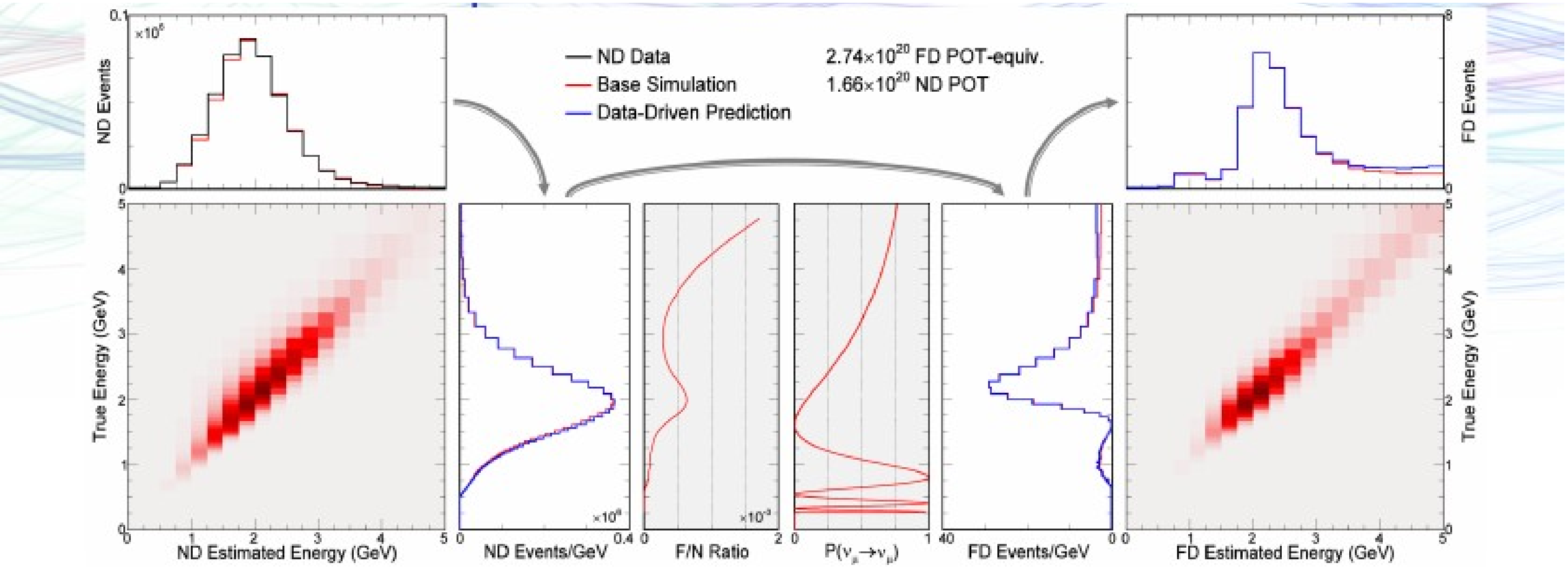
- Different reconstruction and energy resolution for ν_μ and ν_e



E_{EM} from calorimetry, ~10% resolution

ν_e Events

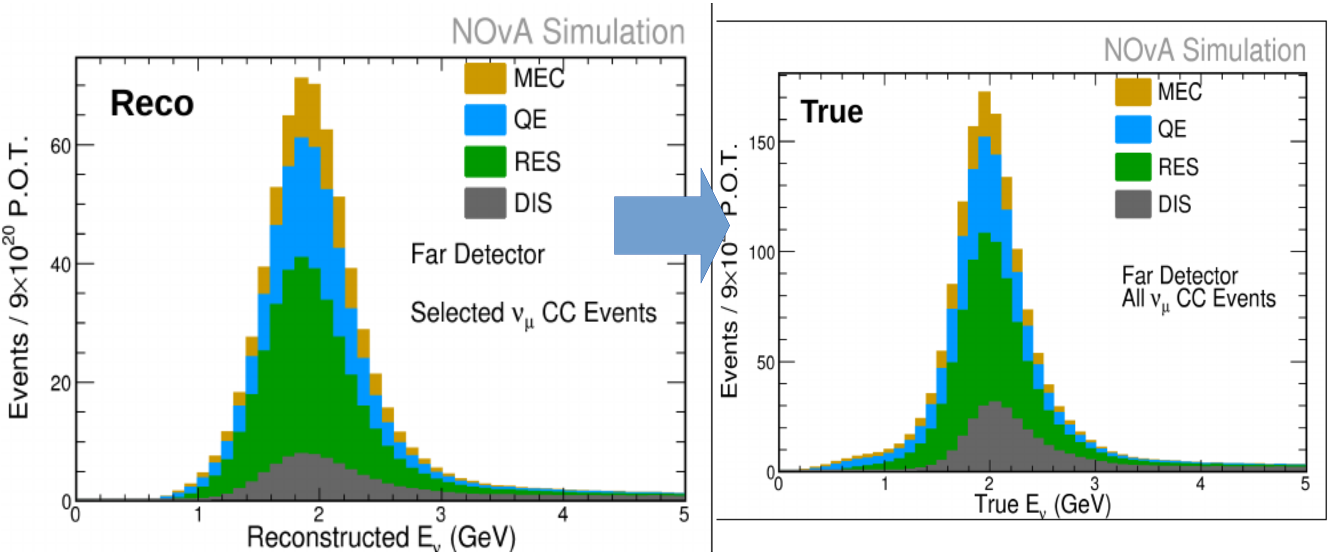
ND to FD extrapolation



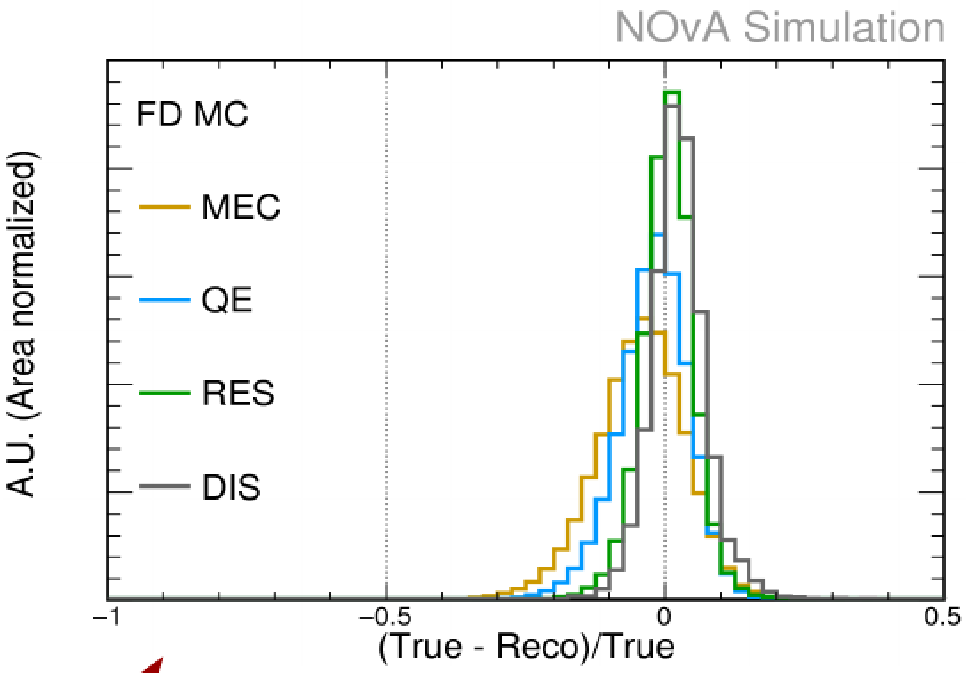
- Subtract NC expectation in ND, reweight MC in reco energy to match
- Transform to true energy, transport to FD with oscillations
- Transform to reco energy, add FD NC expectation back in
- Dependence on MC for background subtraction and true/reco matrix

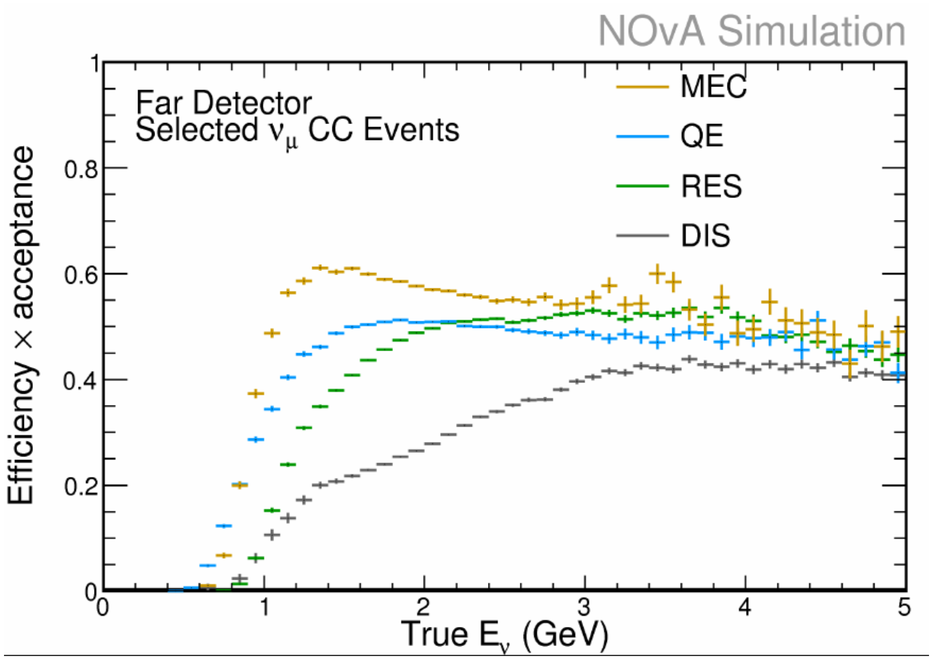
Not only detector systematics but also theoretical uncertainties (FSI, multiplicity in the final state, fraction of neutrons...) do affect the true ↔ reco correspondance

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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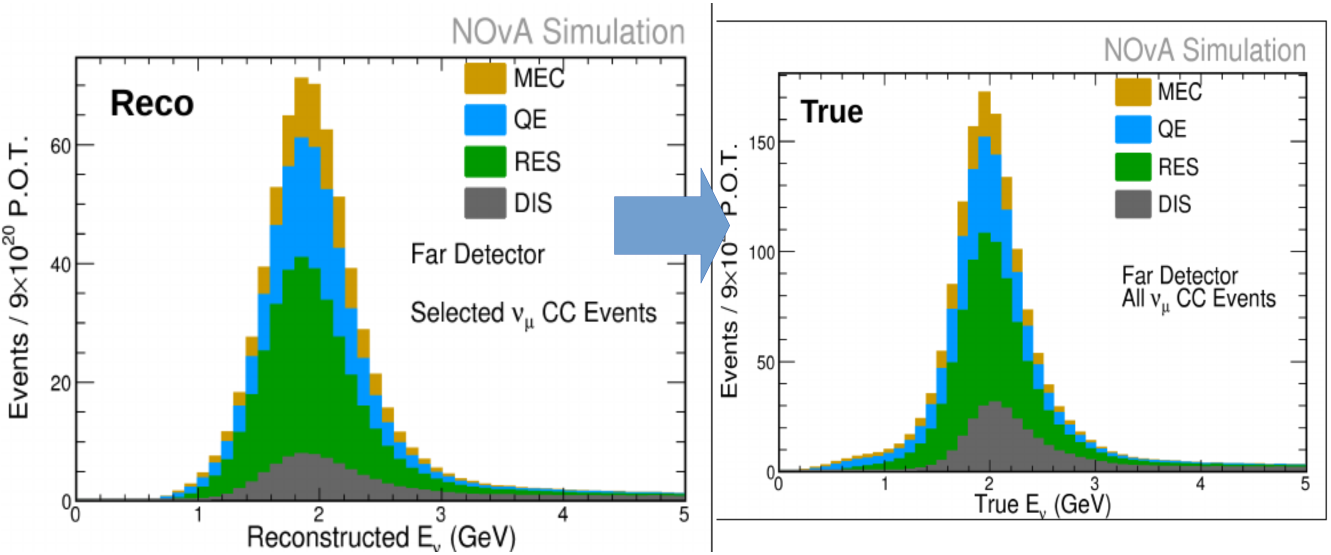
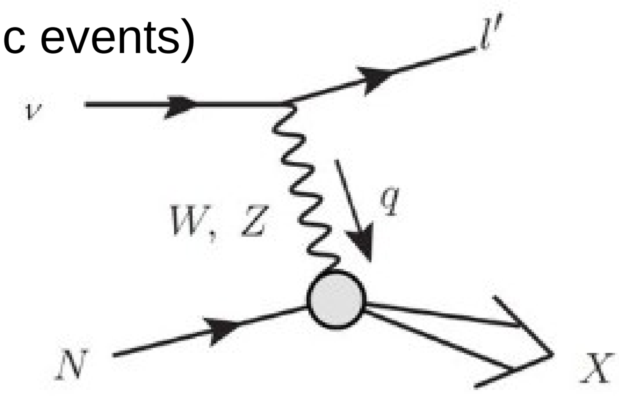
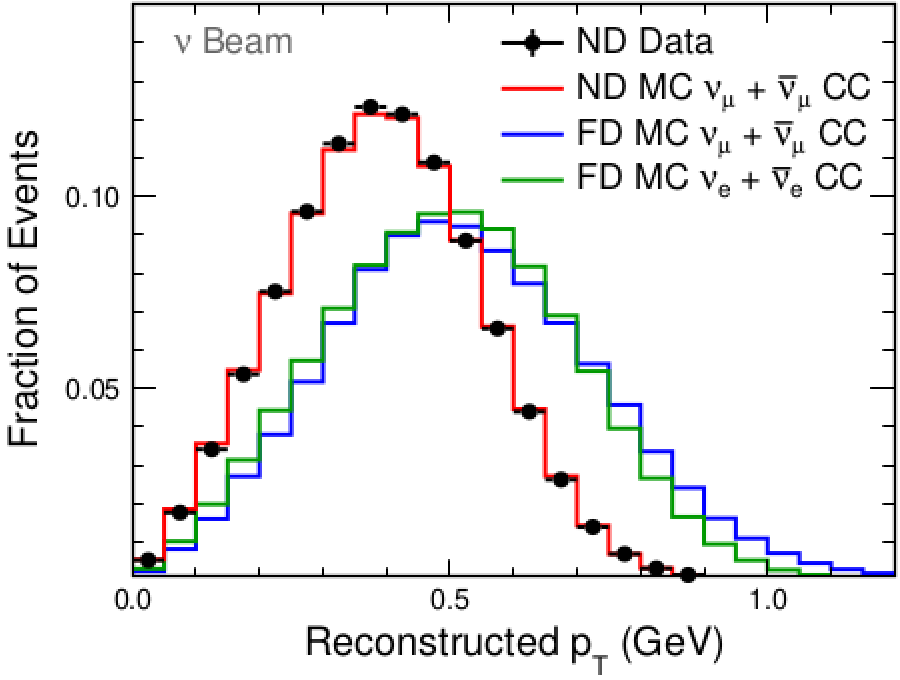


Each process has different neutrino energy resolution and efficiency: dependence on hadron multiplicity, π^0 fraction, kinematics of leptons ...

- 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

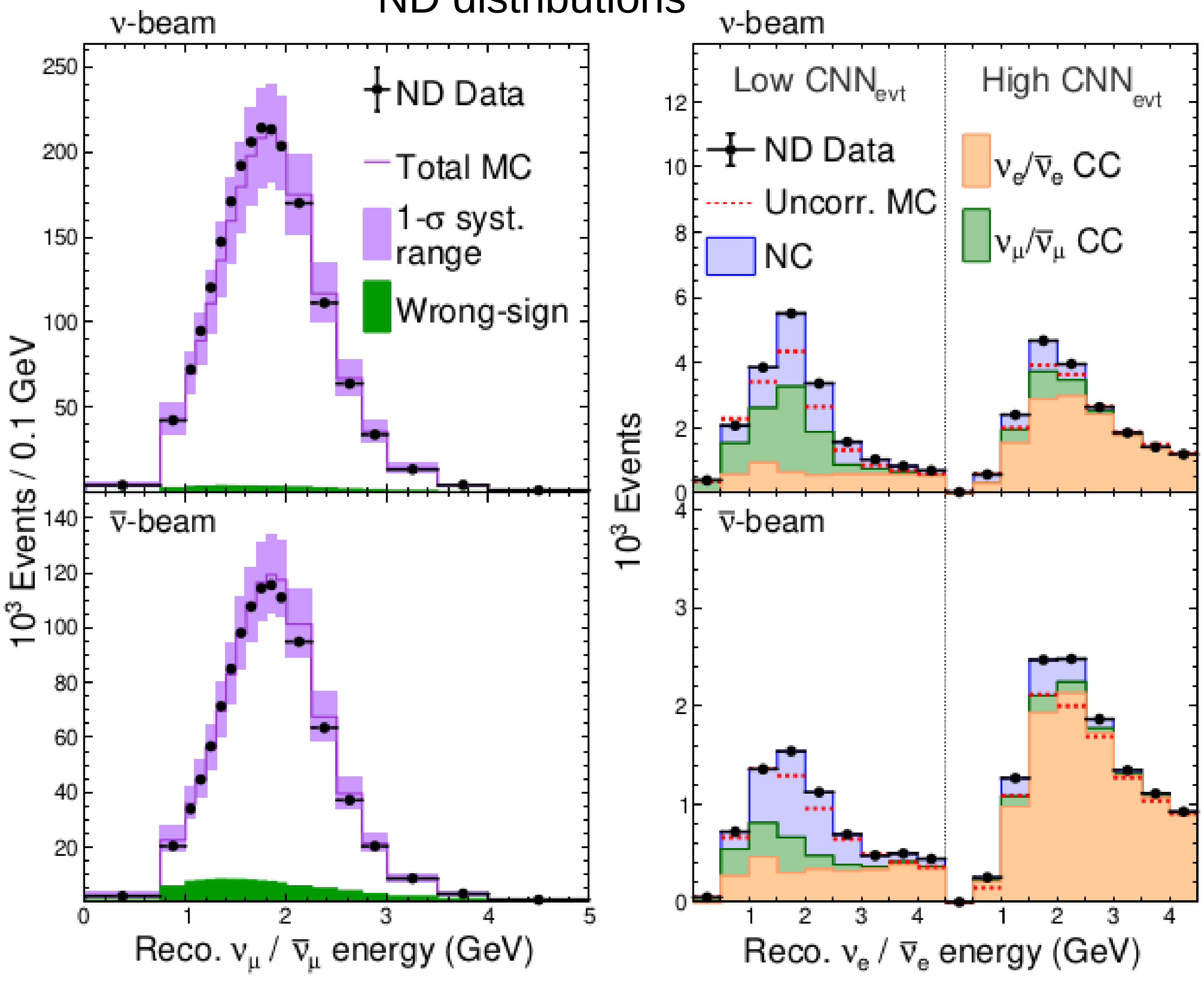
- Inclusive selection: require one muon/electron. Convolutional Neural Network (CNN to separate nm, ne, NC, cosmogenic background)

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

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

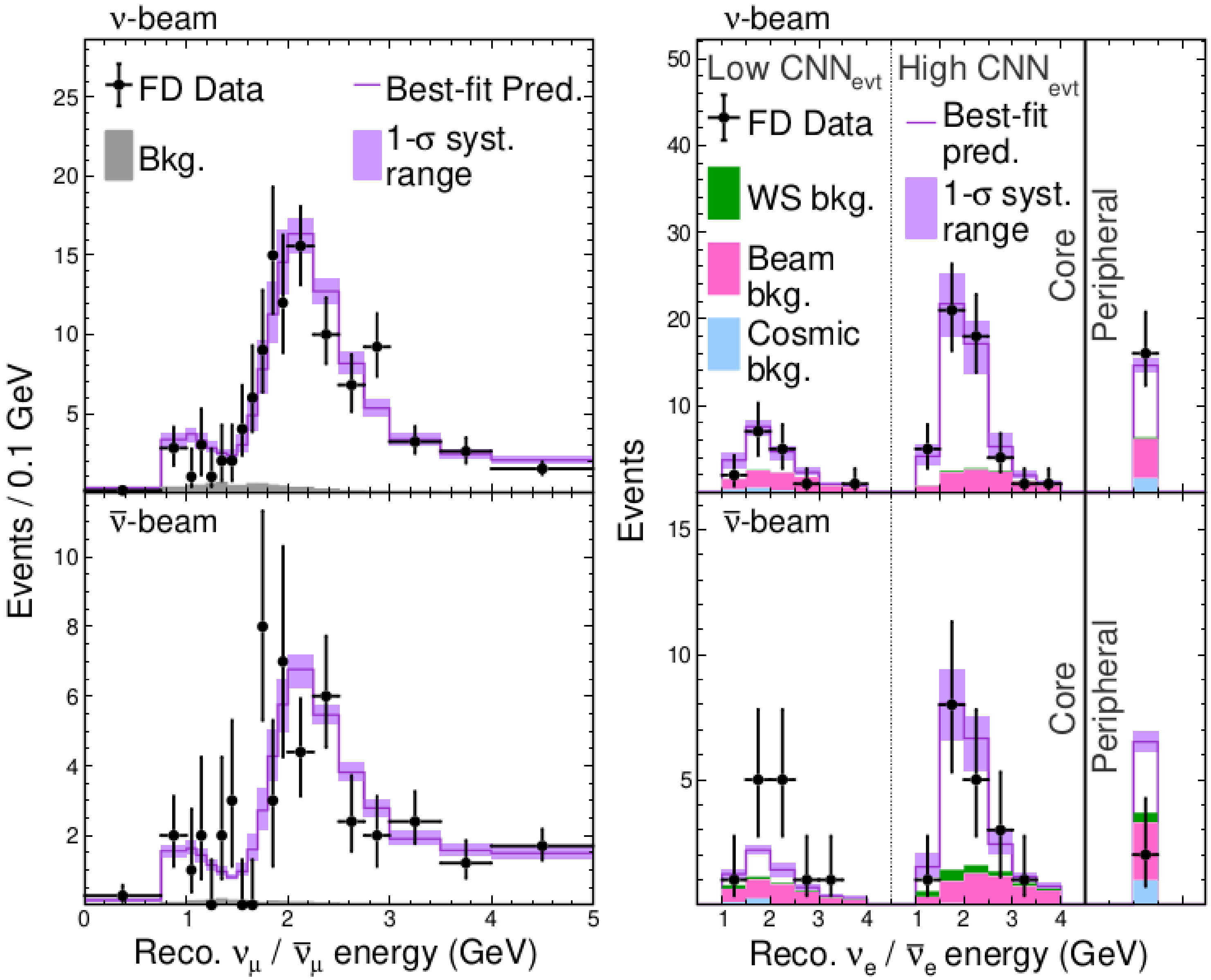
  - All samples subdivided in lepton transverse momentum to minimize impact of different acceptance at ND and FD

ND distributions



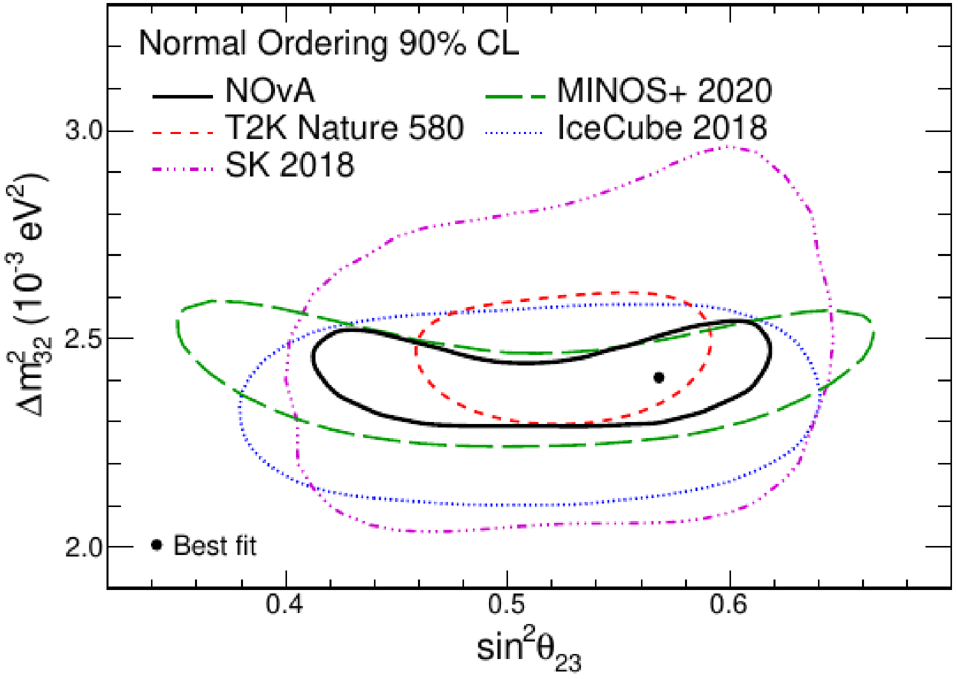
- Measurement of all the visible energy in the event to estimate the neutrino energy

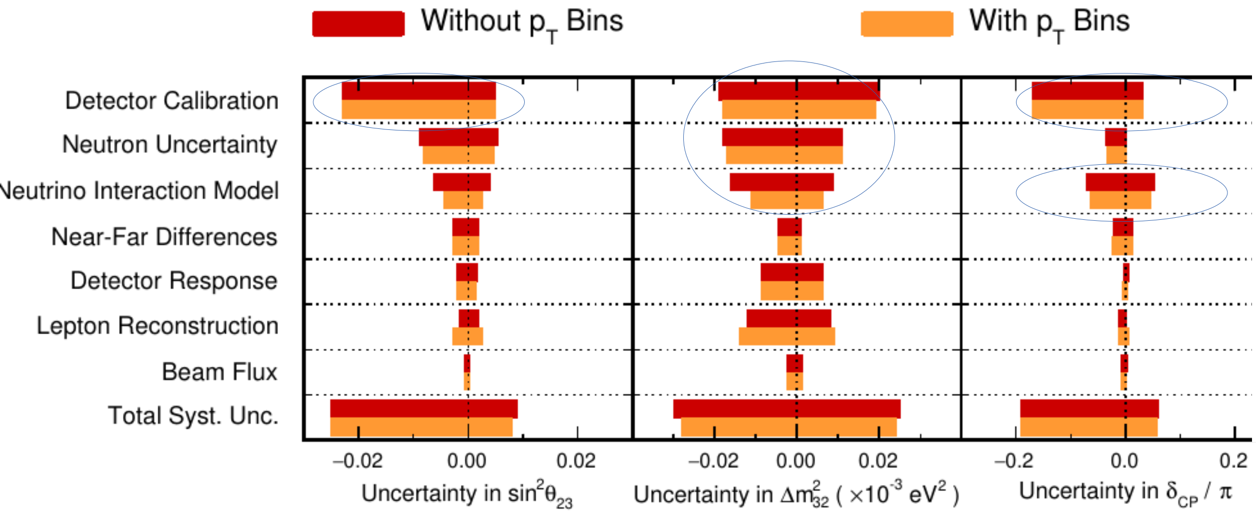
Far detector results

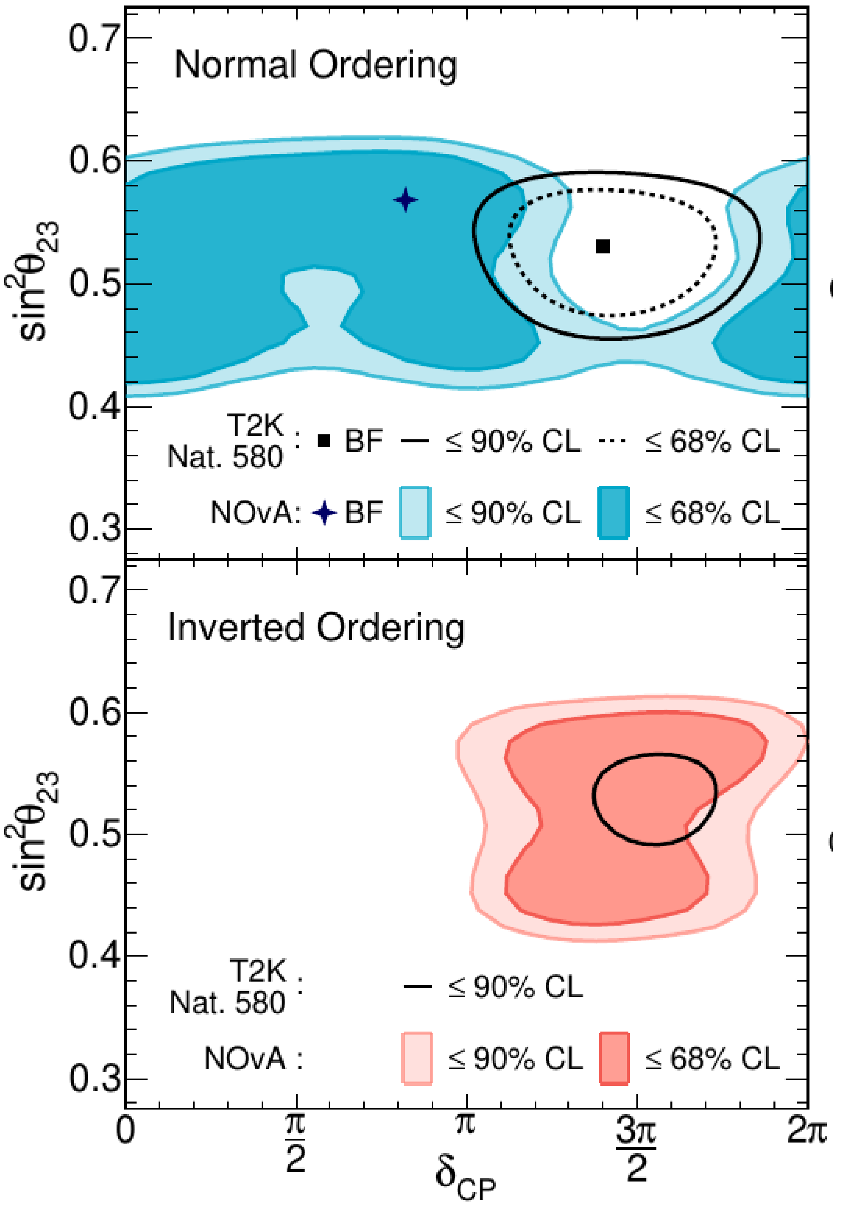


Fit to FD data with “ND-tuned” distribution → extract measurement of oscillation parameters

Far detector results





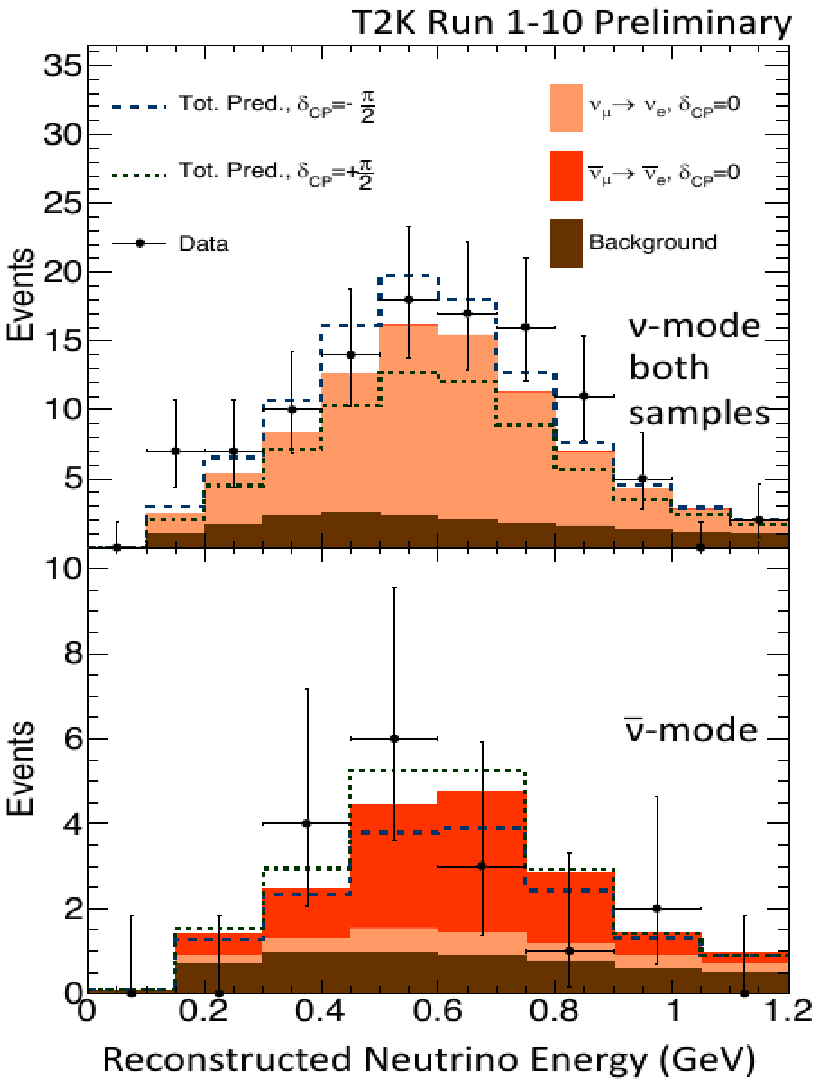


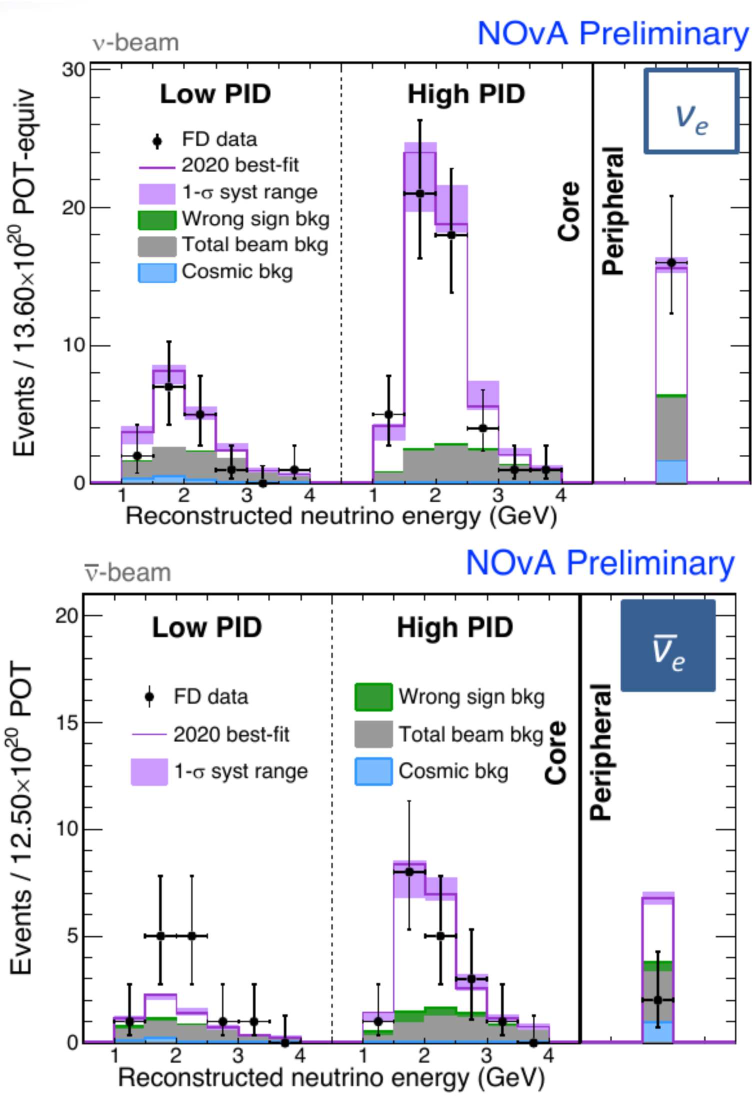
Limitations and future challenges

δ_{CP}: statistically limited

The δ_{CP} results 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)

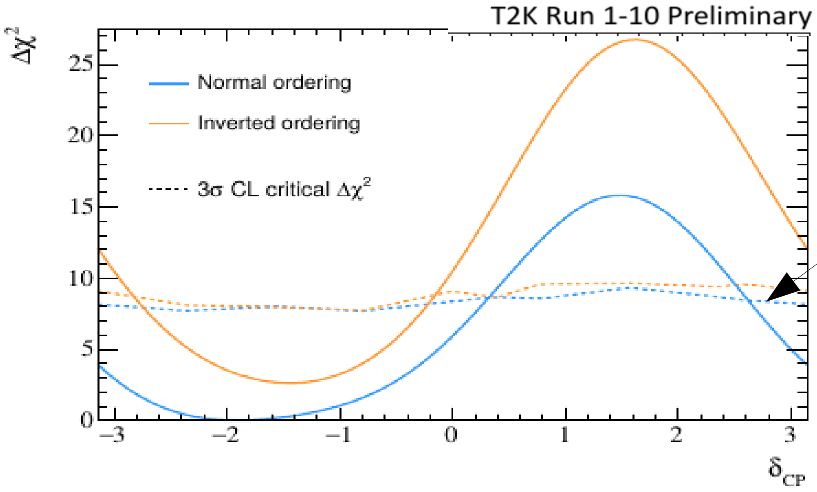




Statistical treatment: Fieldman Cousin

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)

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?]

- 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 sensitvity 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

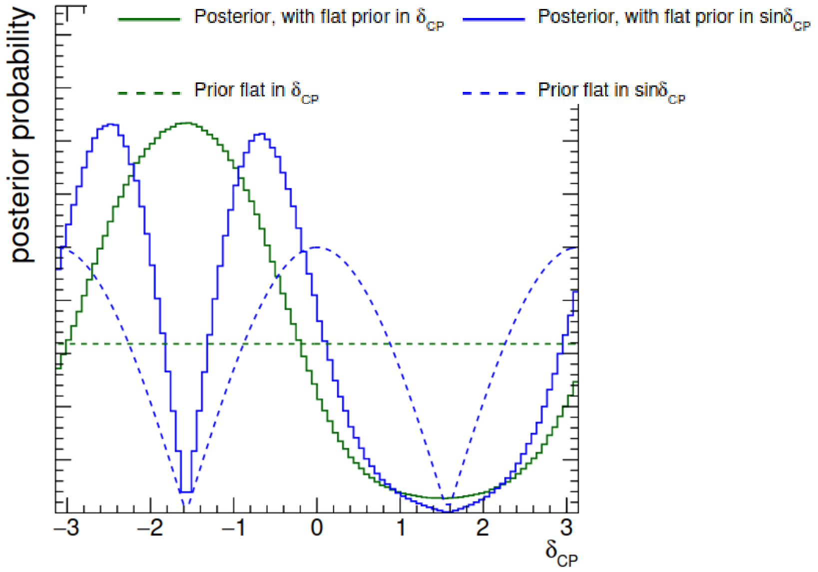
- Effect become important because of degeneracies and boundary effects

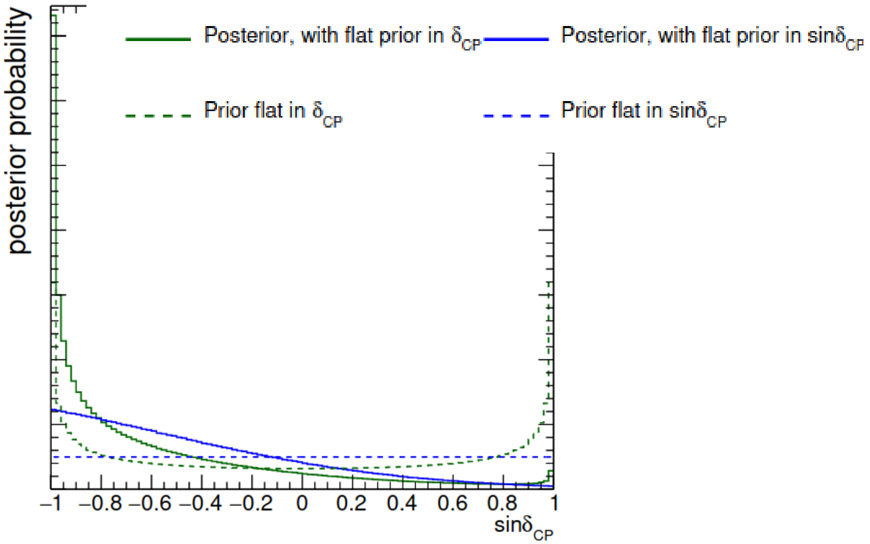
- Important effect for (future?) high stat results: in practice the region of 5σ exclusion may change and does not scale like 1/sqrt(N)!

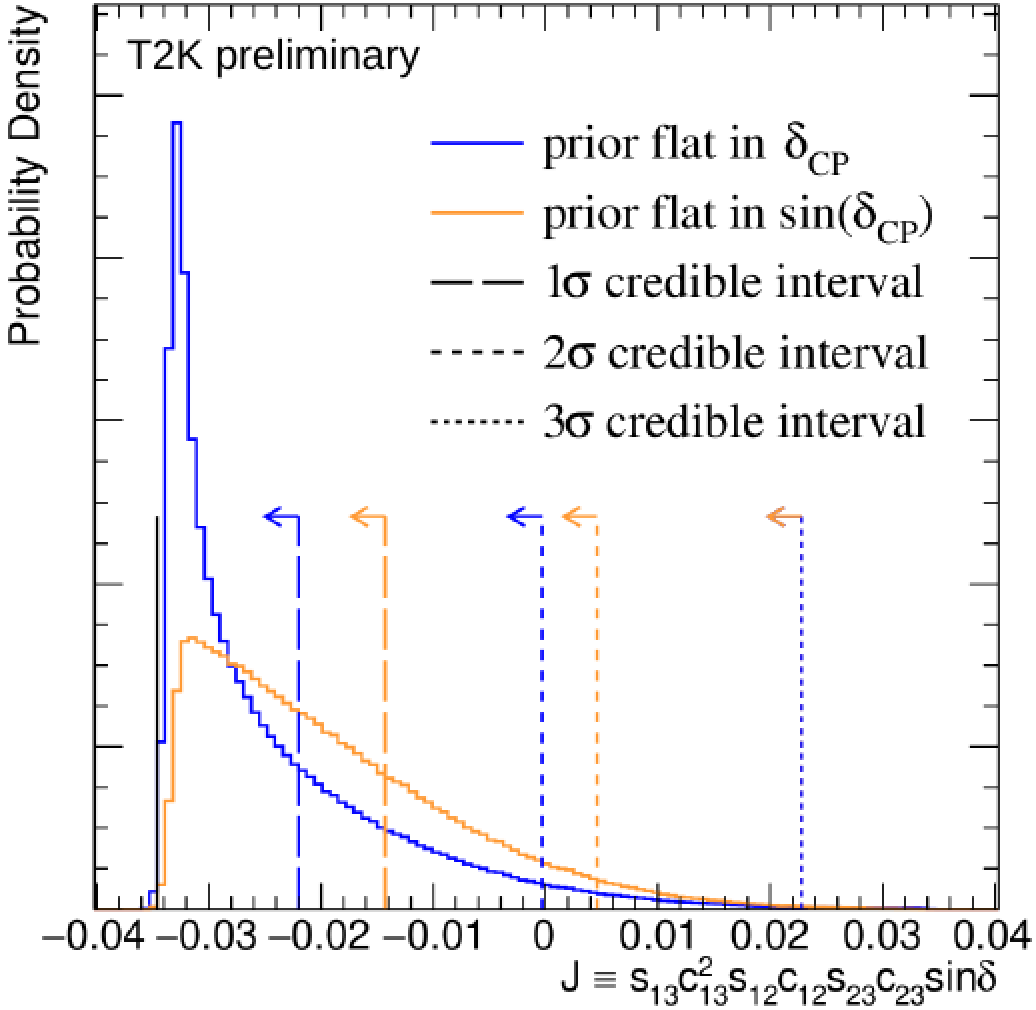
Statistical treatment: prior

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...

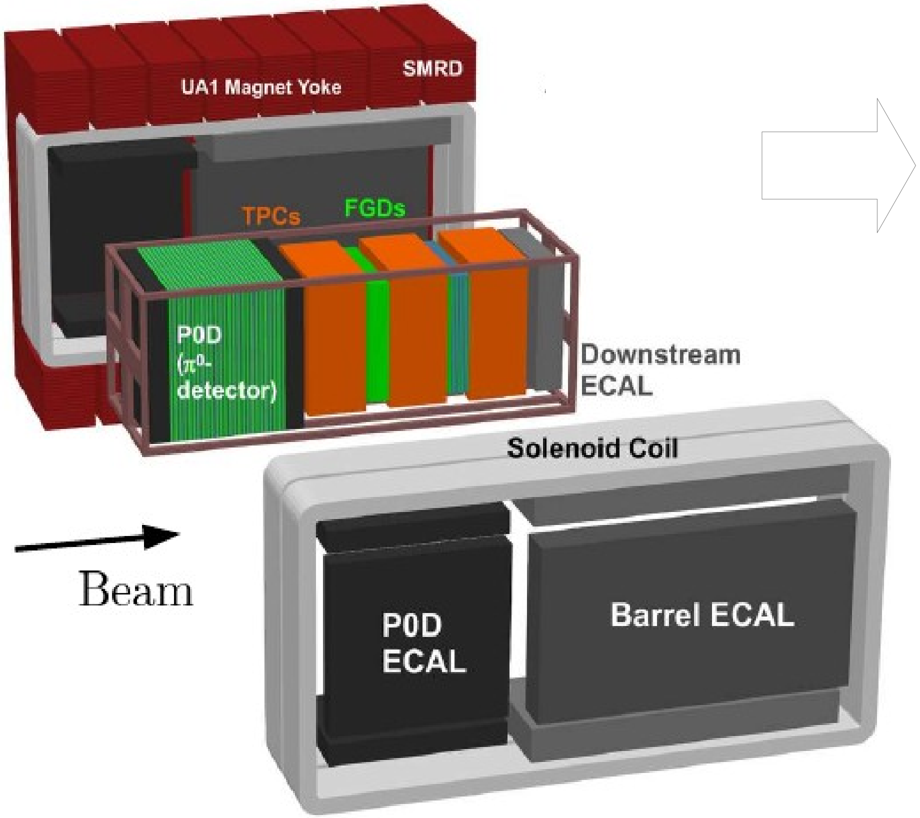
CPV = Jarlskog invariant sign
(still impact from prior assumption:
flat on δ_{CP} or $\sin\delta_{CP}$?)

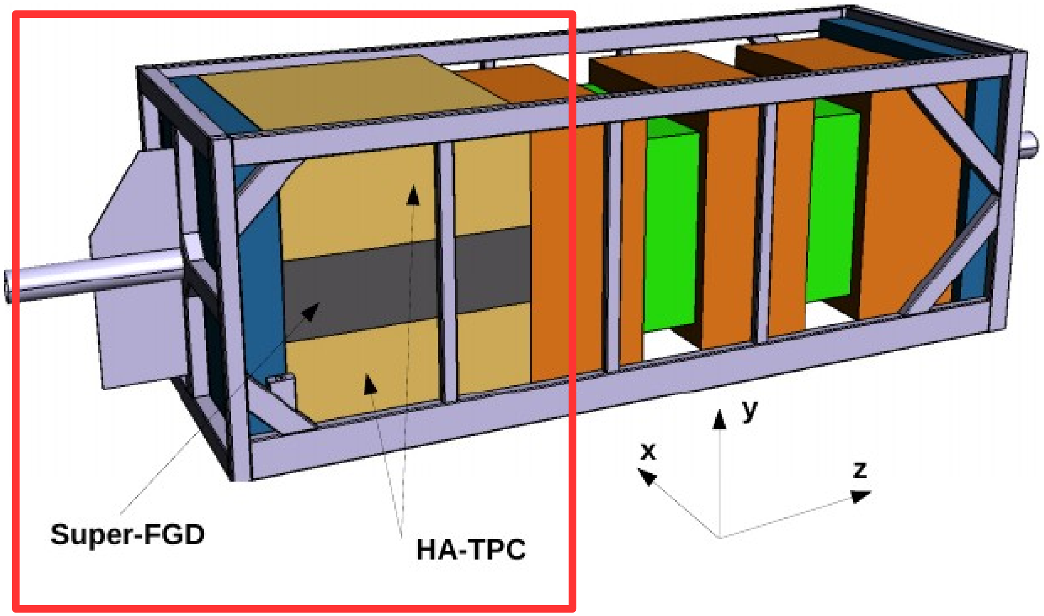




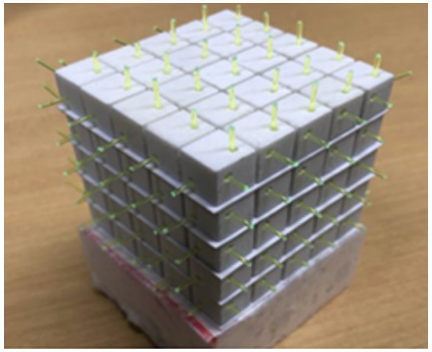


ND280 → ND280 upgrade





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



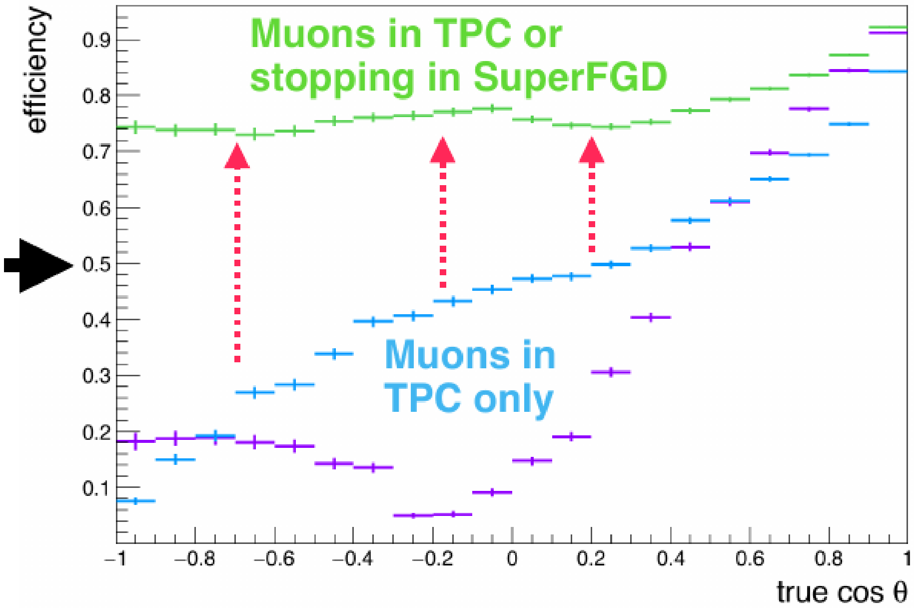
- **New target** with much lower threshold for track reconstruction (p,p)

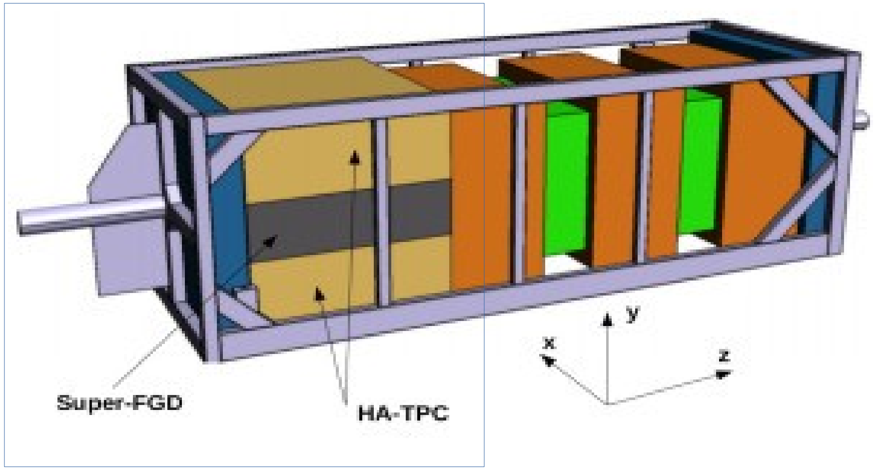
- **High angle TPCs with resistive Micromegas:** coverage at high angle and improved momentum resolution

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

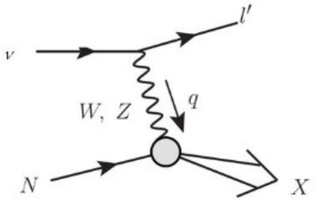
ND280 upgrade

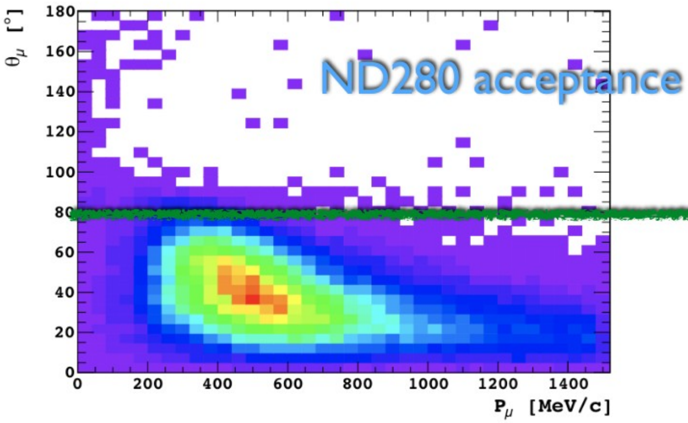
- larger statistics from new target + improved angular acceptance

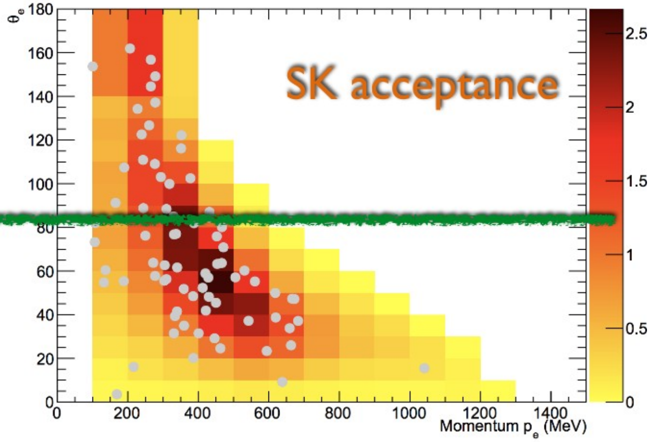




Leptons at larger angle correspond to more inelastic events





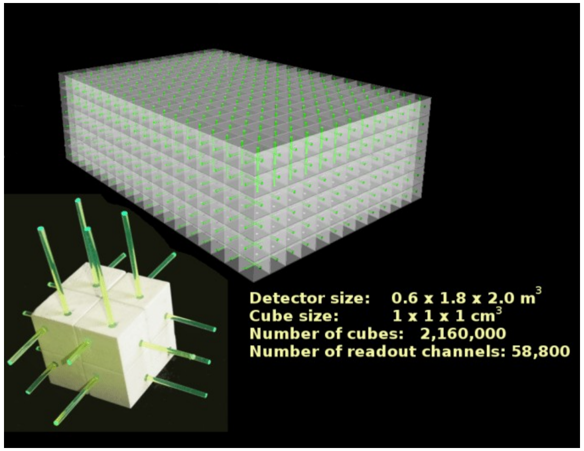


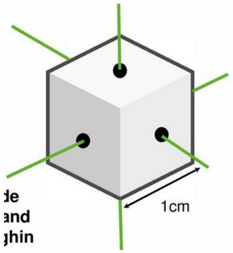
ND280 upgrade

T2K Work in Progress

- larger statistics from new target + improved angulaire acceptance

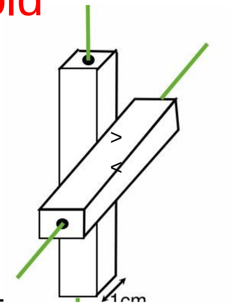
- proton kinematics measurement down to low momentum threshold



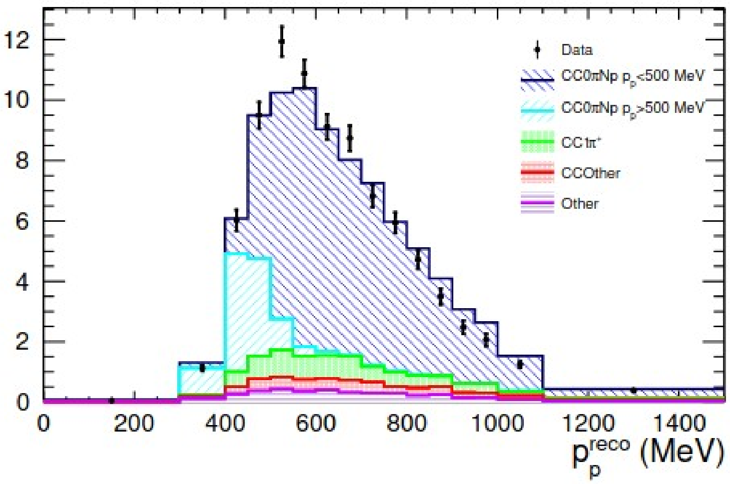


New ‘3D’ scintillating detector

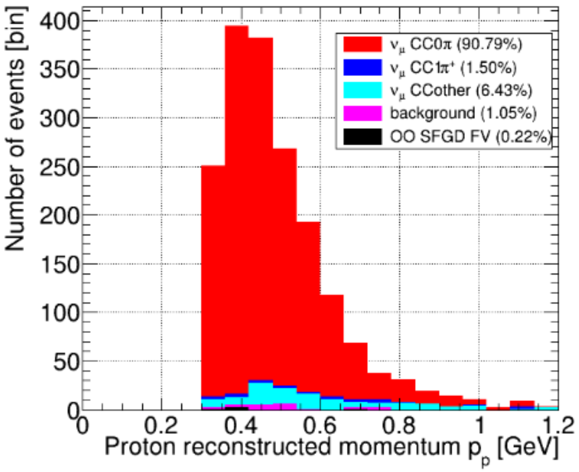
ND280 FGDs are ‘2D’ scintillating detectors

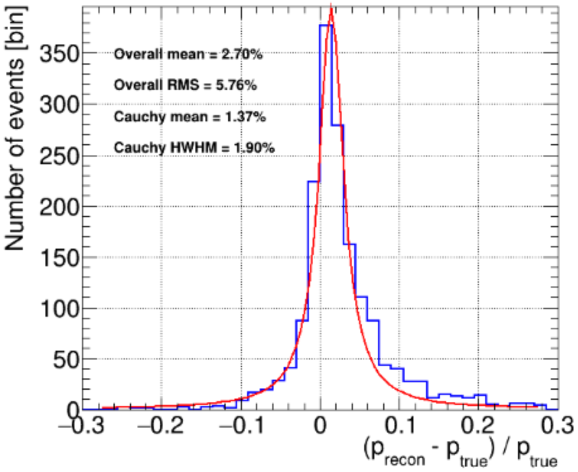


ND280 measurement



ND280 upgrade (ν MC):





ND280 upgrade

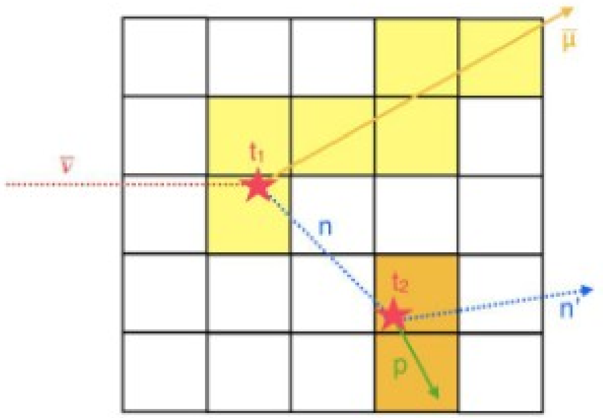
New analysis features are also preparing the road to the analysis of ND280 upgrade data:

- larger statistics from new target + improved angulaire acceptance

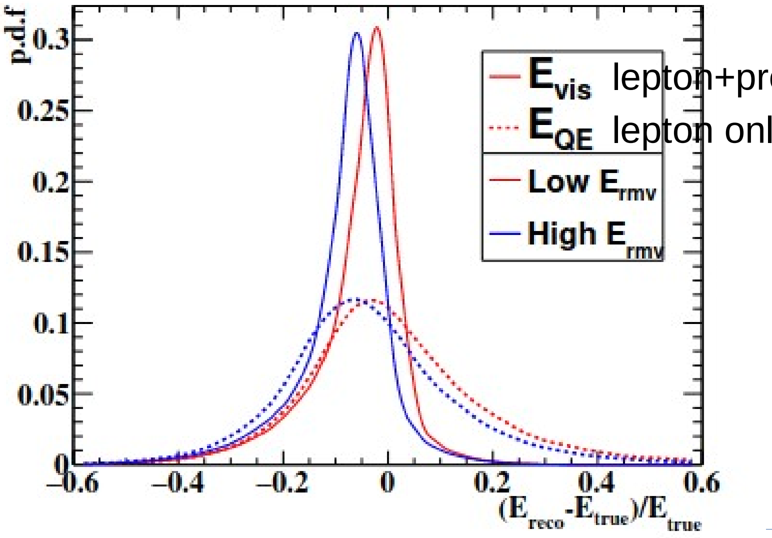
- proton kinematics measurement down to low momentum threshold

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

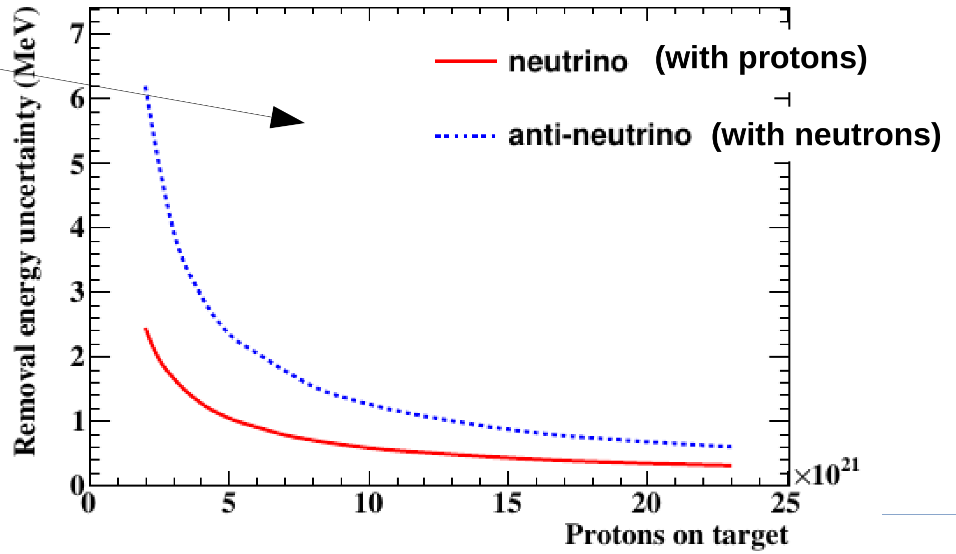
Time-of-flight technique



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



lepton+proton
lepton only



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...

BACKUP

Systematics

- Crucial **role of Near Detectors:**

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

ND measures rate vs neutrino energy

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

~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) → 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)
  - **n_e intrinsic background:** n_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

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

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

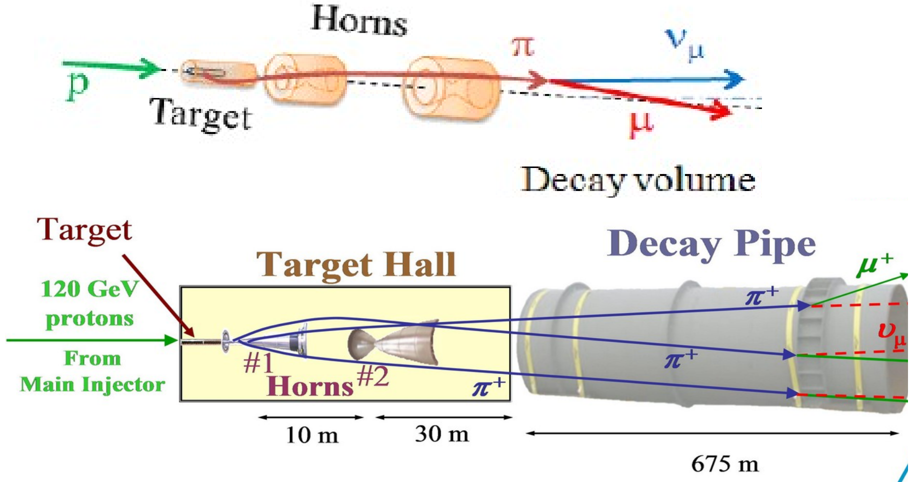
~same flux at ND and FD

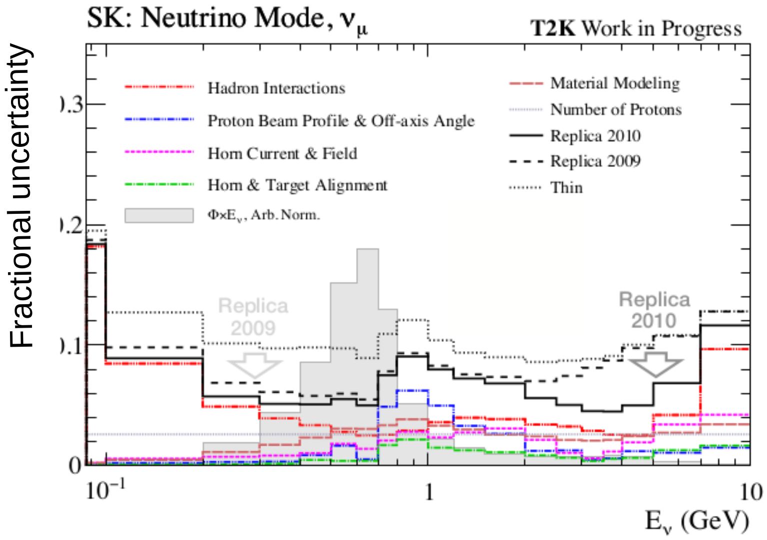
what we want to measure:
oscillation probability

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

Need nuclear theory models!

Flux simulation and tuning (NA61/SHINE + MIPP)





Near detectors and nuclear theory

ND measures rate vs neutrino energy before oscillation
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$$R_{ND}^{\nu'} = \int \boxed{\Phi^{\nu}(E_\nu)\frac{d\sigma^{\nu'}}{dE_\nu}} dE_\nu$$

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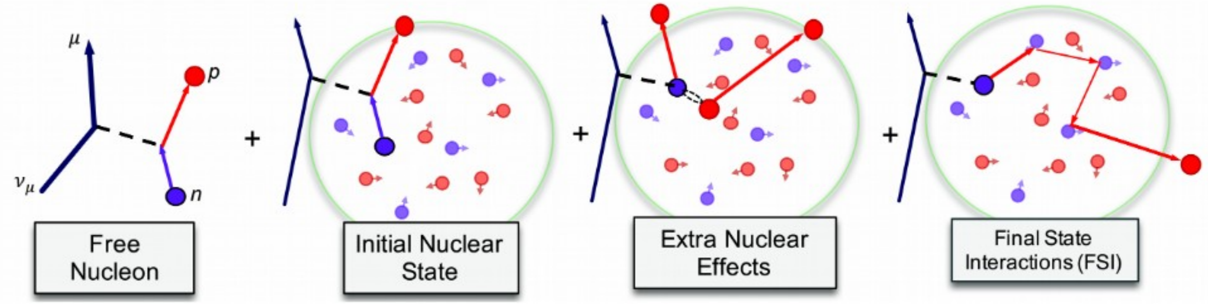
~same flux at ND and FD

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

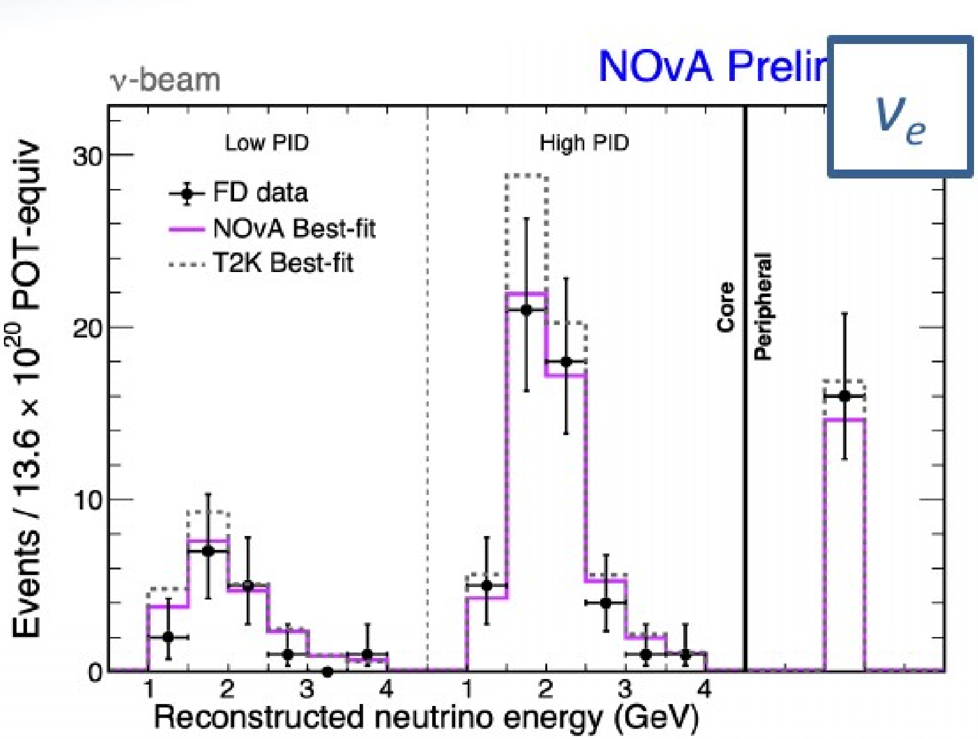


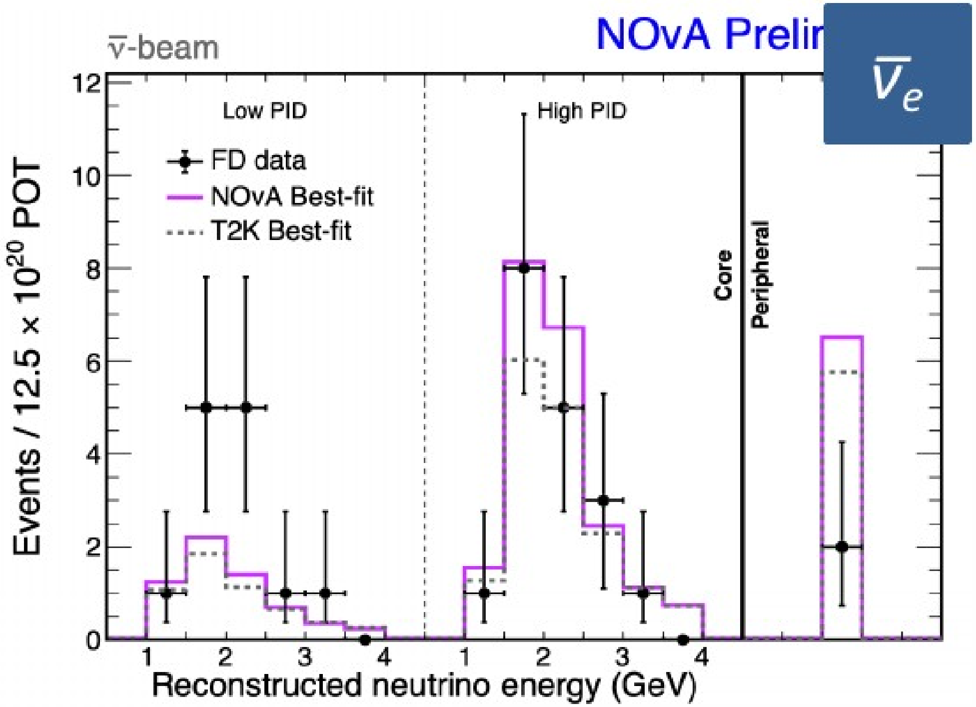
(and similarly for pion(s) production)

- 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!





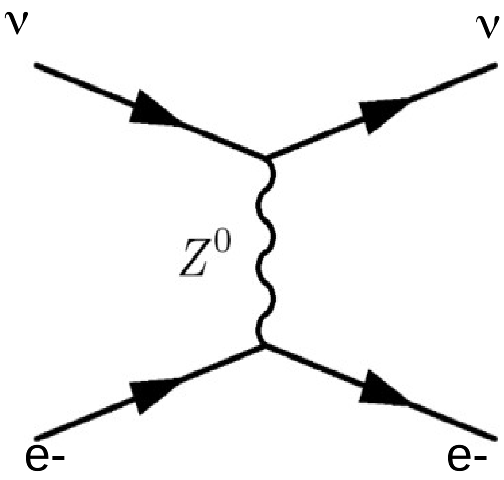
- Still in **n**$_{\mathbf{e}}$ **/ ▯**$_{\mathbf{e}}$ (so d$_{CP}$ measurements) **the statistic uncertainties at the far detector is dominant over the systematics**

- 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)

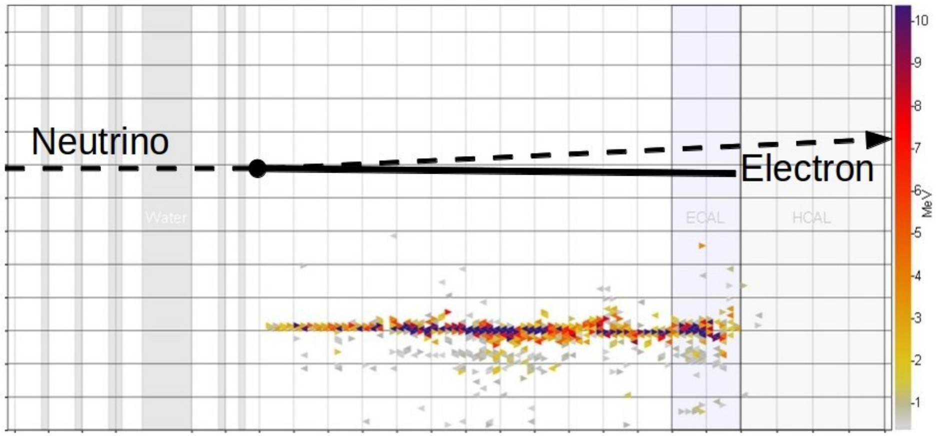
One nice exception: a cross-section which we know very well (no nuclear effects!)

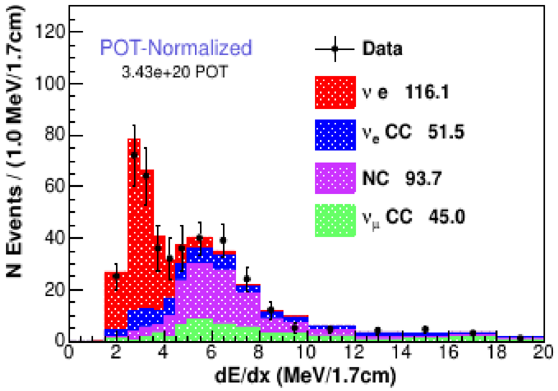


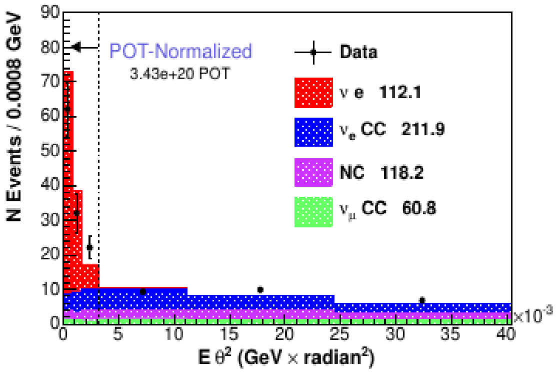
Neutrino scattering on electrons:
simple electroweak Neutral Current process for ν_μ and ν_τ,
(some Neutral Current – Charged Current interference for ν_e)

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

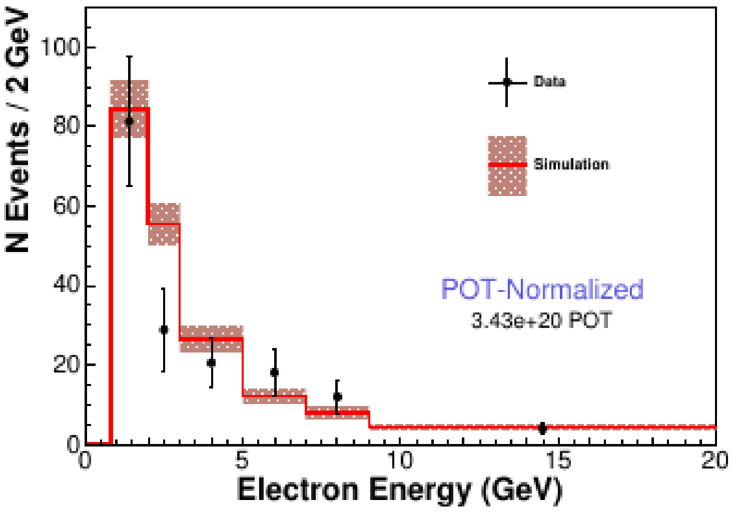
Minerva: clever cuts on electron ID and kinematics (forward electrons)





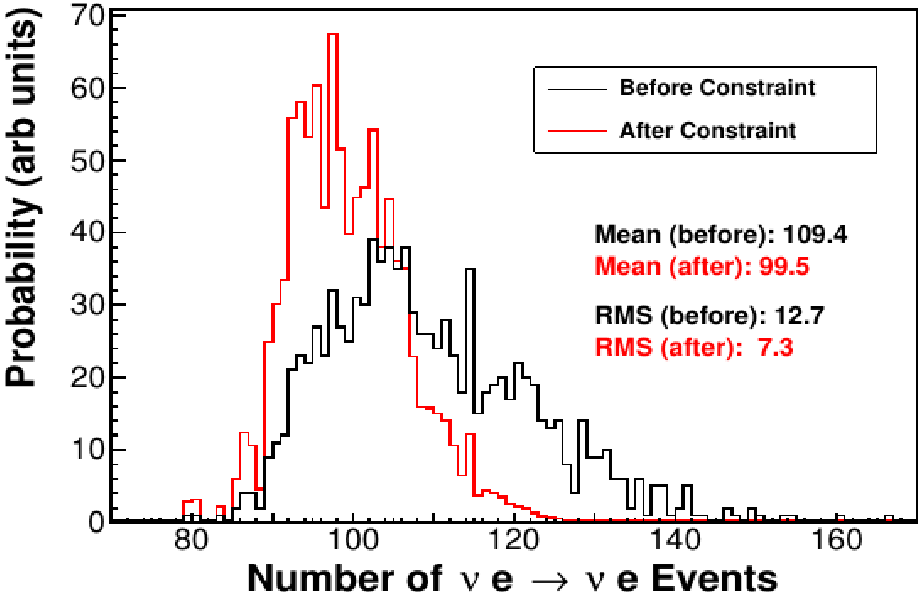


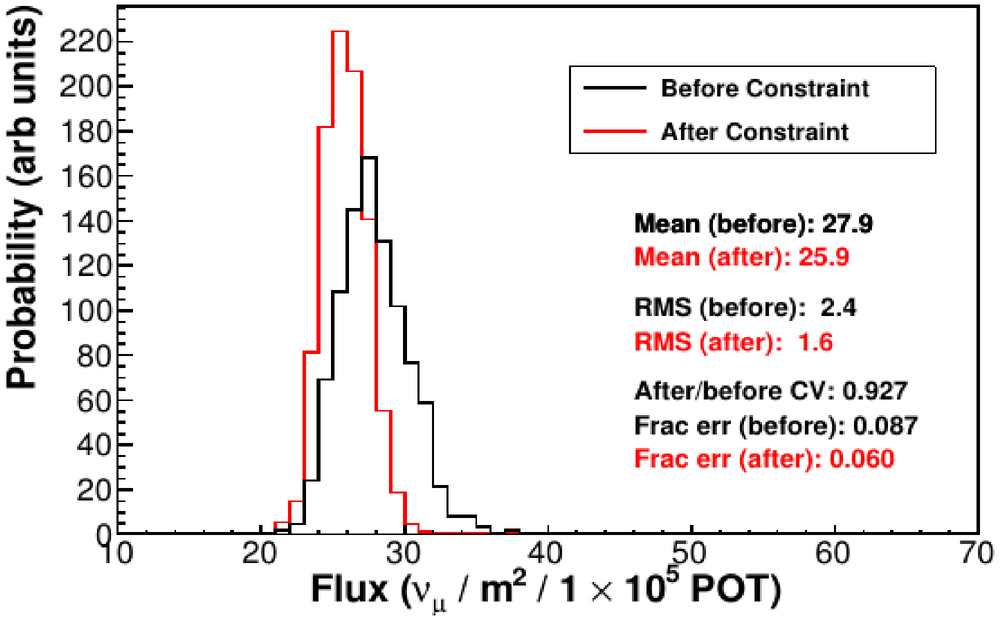
Constraints from ν-e scattering



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





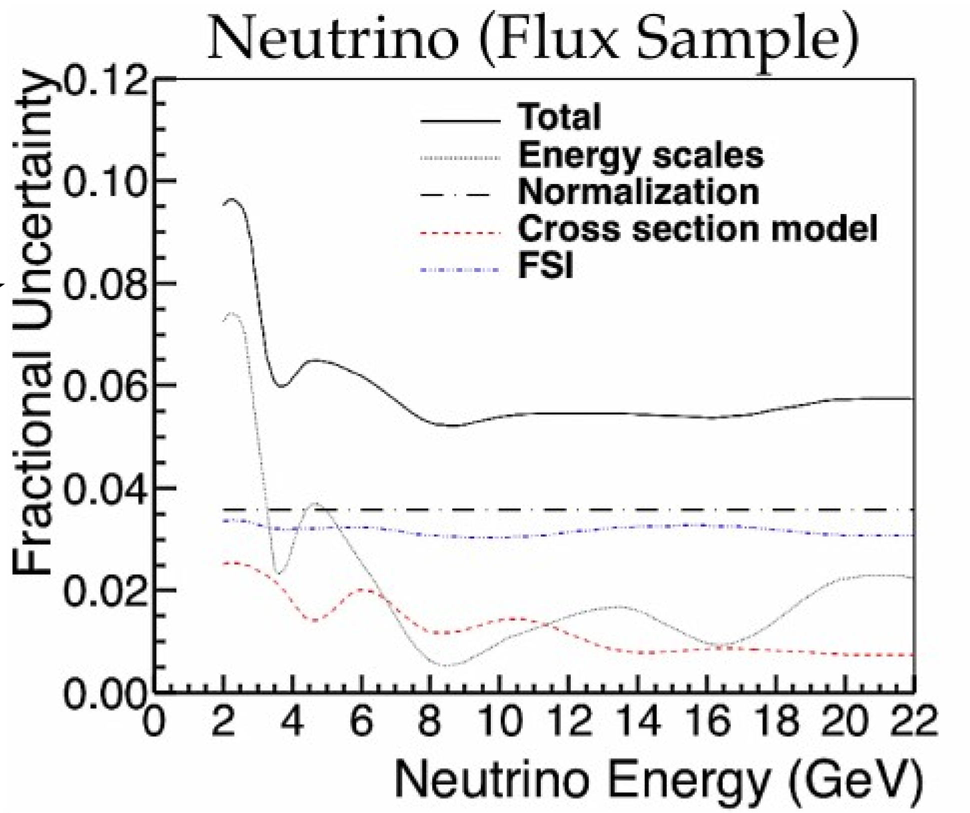
Constraints from low-ν method

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

ν= energy transferred to the nucleus

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

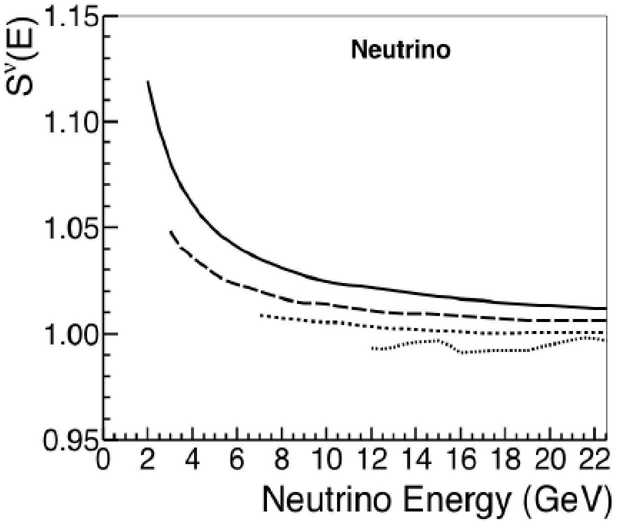
→ **event rate at low ν can be used to constraint the flux shape as a function of Eν**



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

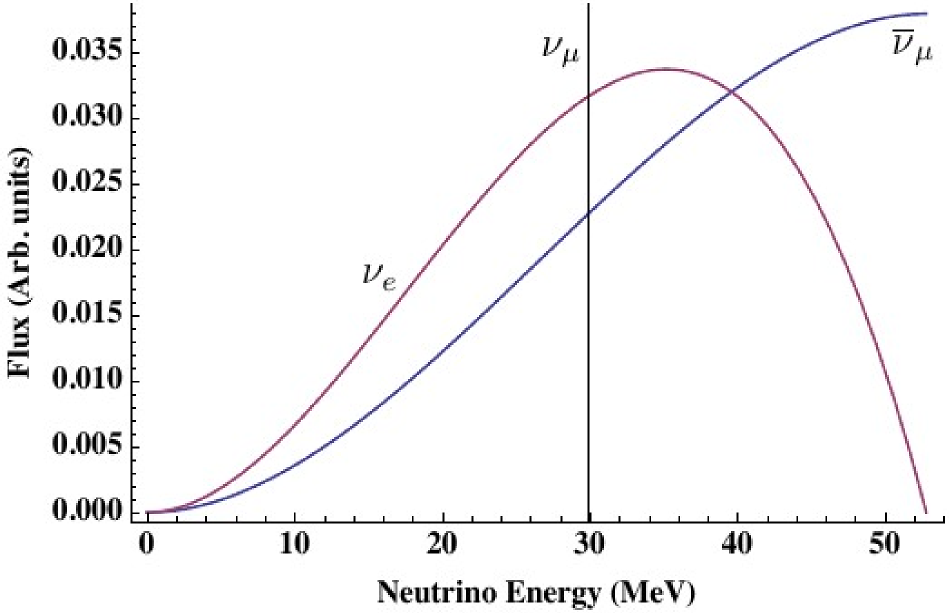
Pion decay at rest (DAR) in contrast to standard pion decay in flight (DIF)

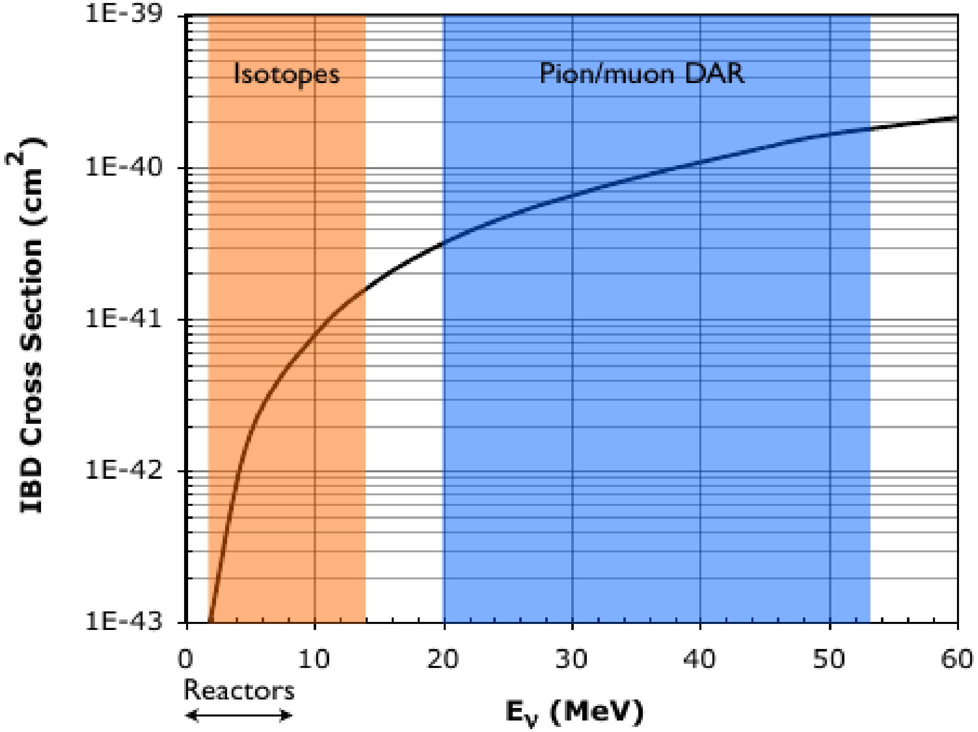
😄 well known energy of neutrinos

😄 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



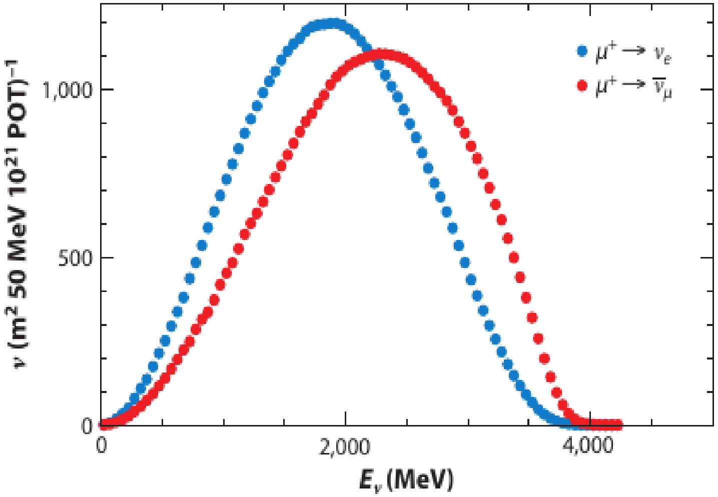


Non standard beams and fluxes

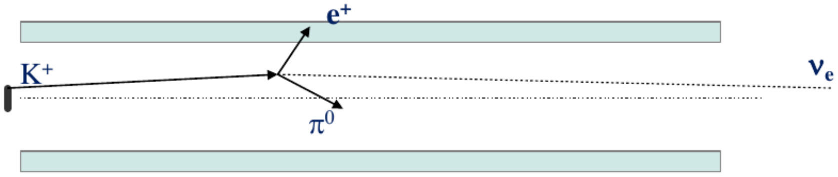
- Neutrinos from Stored Muons (**nuSTORM**): beams from the decay of 3.8 GeV muons confined within a storage ring

😄 well known energy of neutrinos

😄 large ν_e statistics

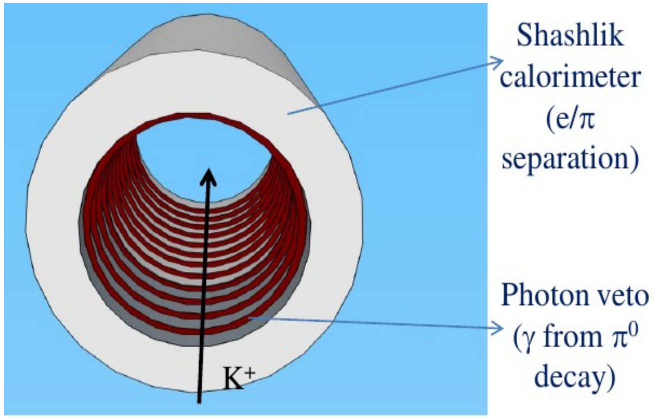


- Monitor the production of electrons in standard ν beam: uncertainty on ν_e flux improved by one order of magnitude



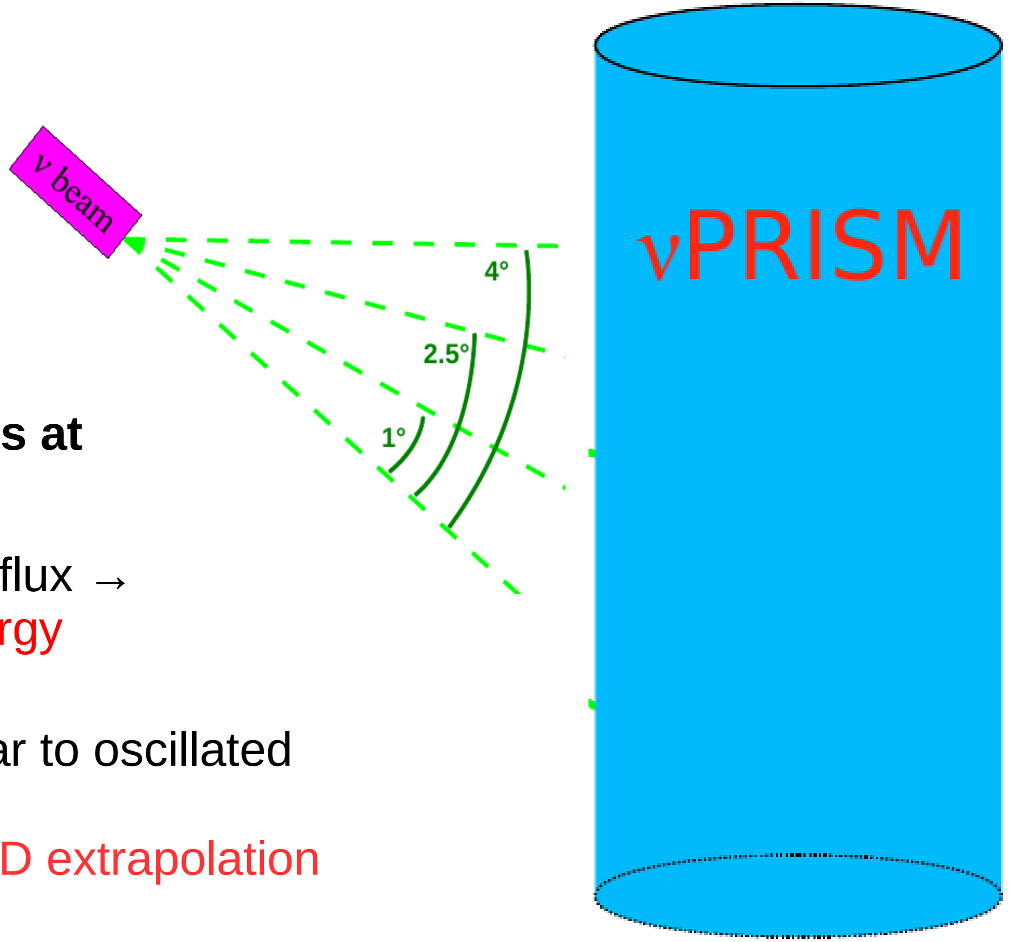
A. Longhin, L. Ludovici, F. Terranova EPJC 75 (2015) 155

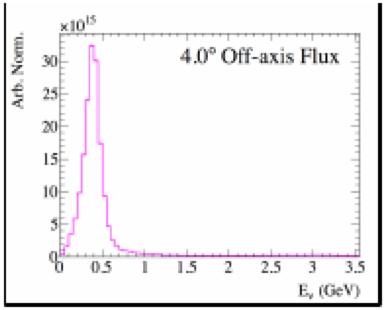
$K^+ \to \pi^0 e^+ \nu_e$

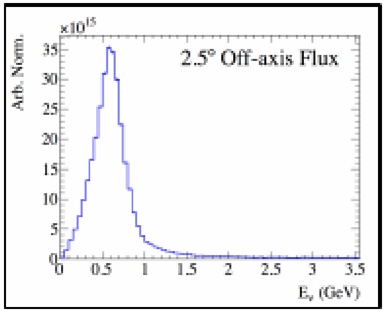


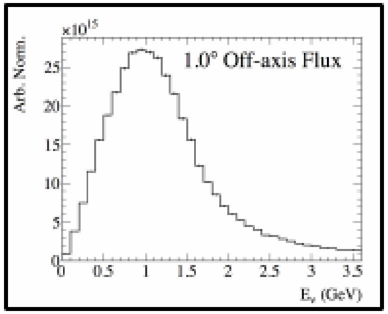
Alternative concept: NuPRISM

Flux at different off-axis angle = different E_ν spectra









Combine measurements at different angles to

- build monochromatic flux → measure xsec vs energy
- build flux shape similar to oscillated flux at far detector → decrease the ND → FD extrapolation uncertainty