



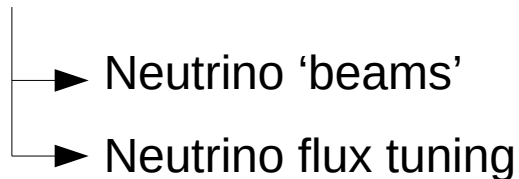
Neutrinos from accelerators:

- neutrino flux tuning with **hadro-production measurements**
- present status (**T2K, NOVA**), especially for CP-violation search
- **global analysis (3-flavours)**

Outline

□ Neutrino oscillations in long-baseline experiments:

- how do they happen?
- how do we measure them?



TODAY

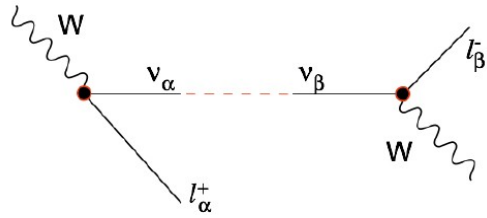
□ Neutrino oscillation at T2K and NOVA

- Context: brief history, latest results
 - global analysis by combining present experiments
- Details of T2K and NOVA analyses (selections, systematics, statistical treatment)

TOMORROW

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

Neutrino oscillations



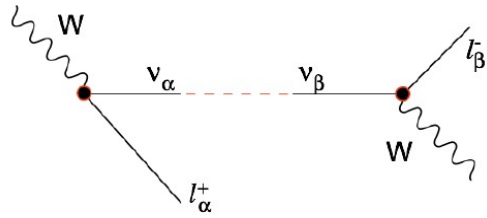
$$|\nu_\alpha\rangle = \sum_i U_{\alpha i}^* |\nu_i\rangle$$

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

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

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

Neutrino oscillations



$$|\nu_\alpha\rangle = \sum_i U_{\alpha i}^* |\nu_i\rangle$$

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

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

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

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

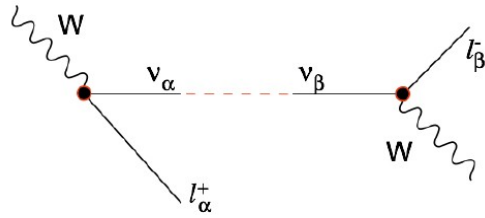
$$P_{\alpha \rightarrow \beta} = |\langle \nu_\beta(t) | \nu_\alpha \rangle|^2 = \left| \sum_i U_{\alpha i}^* U_{\beta i} e^{-im_i^2 L/2E} \right|^2 = \delta_{\alpha\beta} - 4 \sum_{i>j} \text{Re}(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*) \sin^2 \left(\frac{\Delta m_{ij}^2 L}{4E} \right)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

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

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

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

Neutrino oscillations



$$|\nu_\alpha\rangle = \sum_i U_{\alpha i}^* |\nu_i\rangle$$

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

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

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

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

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

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

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

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

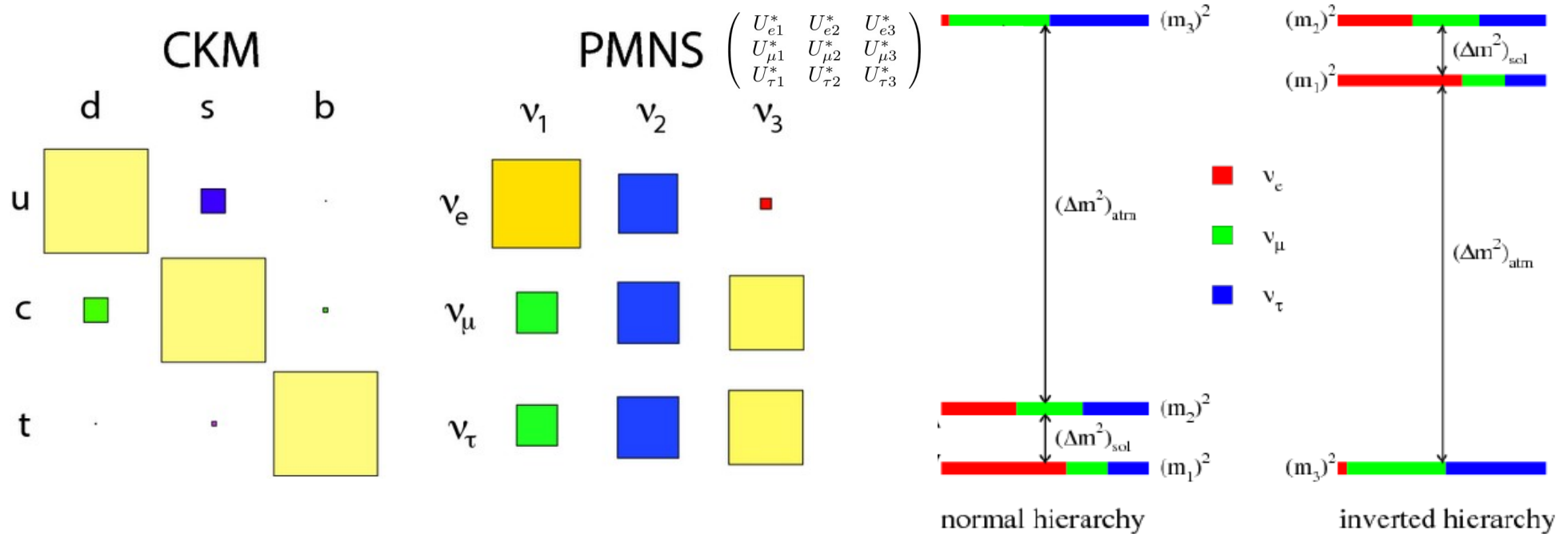
3 mass eigenstate \rightarrow two Δm^2

$|\Delta m_{32}^2| \sim 2.4 \times 10^{-3} \rightarrow$ Long baseline accelerator experiments ($\sim 300-1300$ km, $\sim 0.5-3$ GeV)
(atmospheric experiments integrate many oscillations)

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

$|\Delta m_{ee}^2| = |\Delta m_{32}^2| \pm \cos^2 \theta_{12} \Delta m_{21}^2 \sim 2.6 \times 10^{-3} \rightarrow$ Reactor experiments ($\sim 1-1.5$ km, ~ 3 MeV)

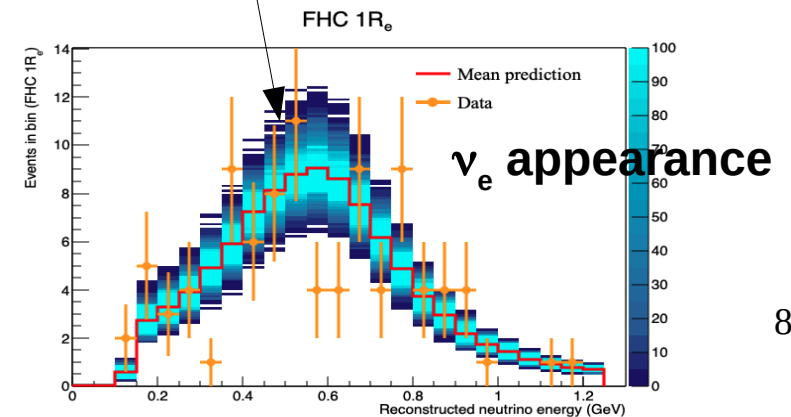
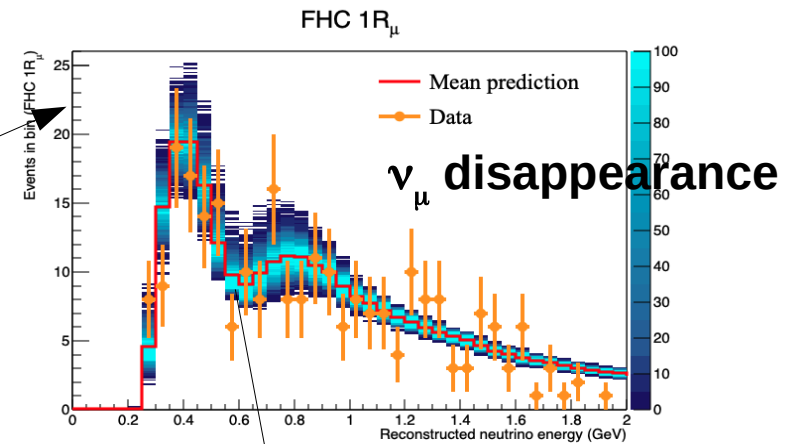
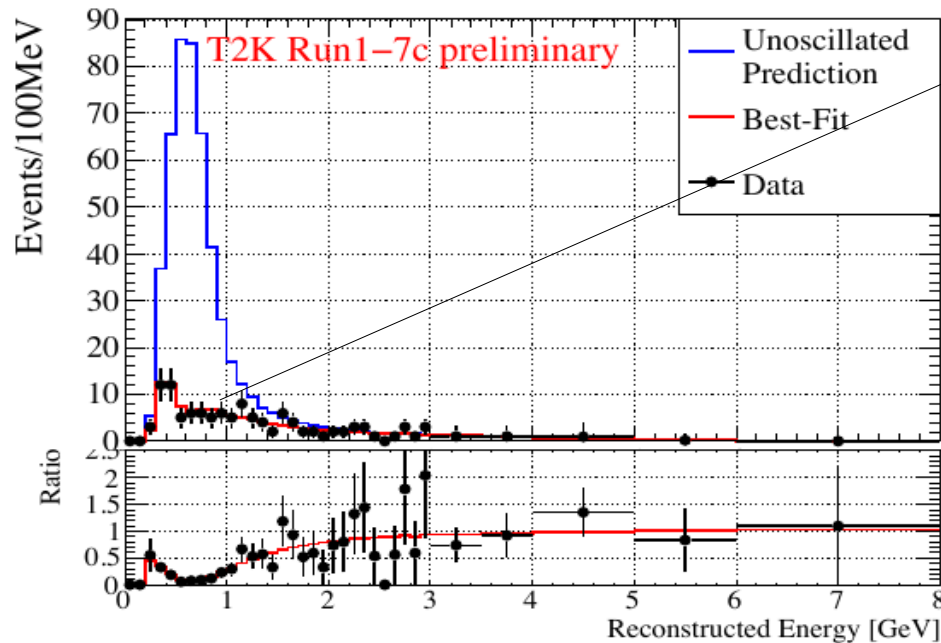
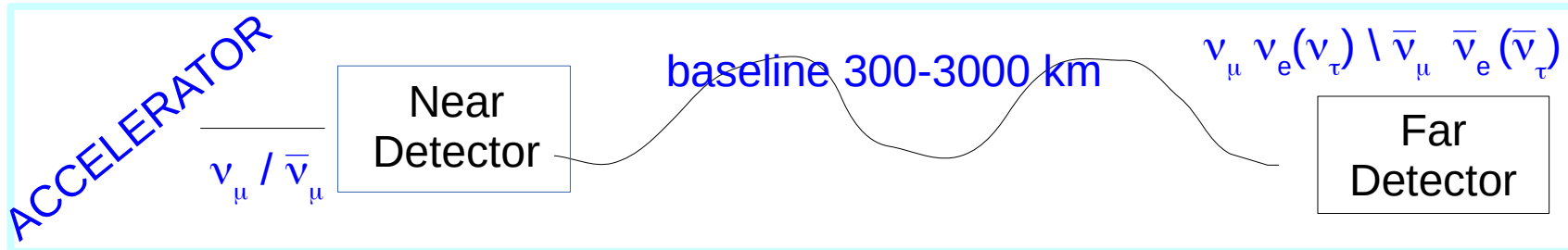
Status and open questions



- Precision measurements of flavour mixing pattern:**
 - very large mixing ($\theta_{23} \sim \pi/4$ would imply maximal mixing, ie $U_{\mu i} \sim U_{\tau i}$, if not which octant?)
 - θ_{13} smaller but not so small (U_{e1}) \rightarrow access to δ_{CP} phase
- δ_{CP} parametrizes **different oscillations for ν and $\bar{\nu}$** what is its value? If not $0, \pi$ **then new fundamental source of CP violation (and first in leptonic sector!)**
- 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:



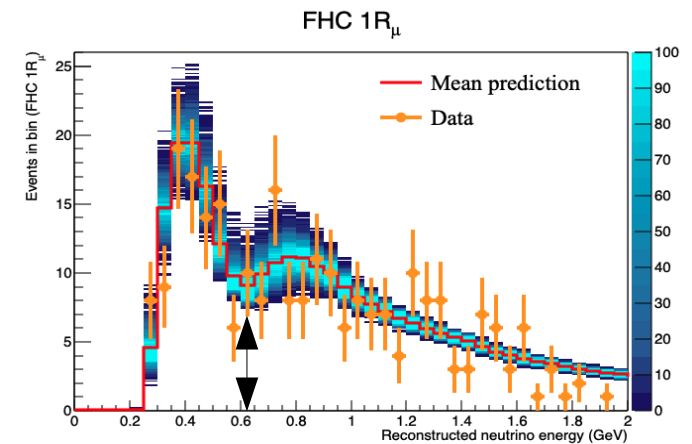
ν_μ disappearance: $\sin\theta_{23}$, $|\Delta m_{32}^2|$

$$P(\nu_\alpha \rightarrow \nu_\beta) = \underbrace{\sin^2(2\theta)}_{\text{amplitude}} \sin^2 \left(\underbrace{1.27 \frac{\Delta m_{ji}^2 [\text{eV}^2] L [\text{km}]}{E_\nu [\text{GeV}]} }_{\text{frequency}} \right) \quad (\text{simplified 2-flavors approximation})$$

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

$$P(\nu_\alpha \rightarrow \nu_\beta) = \underbrace{\sin^2(2\theta)}_{\text{amplitude}} \underbrace{\sin^2\left(1.27 \frac{\Delta m^2_{ji} [\text{eV}^2] L [\text{km}]}{E_\nu [\text{GeV}]}\right)}_{\text{frequency}} \quad (\text{simplified 2-flavors approximation})$$

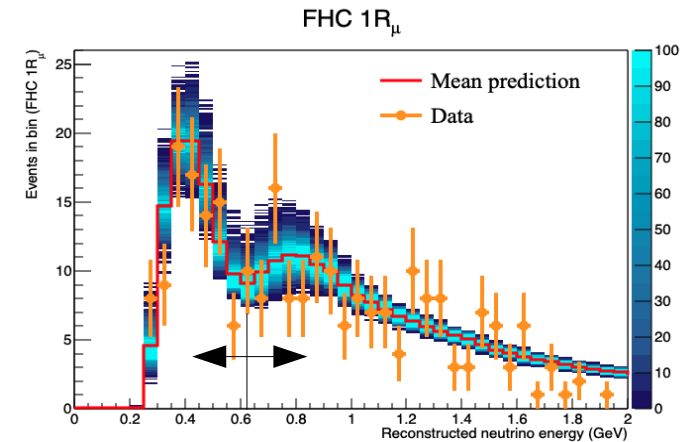
- $\sin\theta_{23} \sim$ amplitude of the ν_μ ($\bar{\nu}_\mu$) disappearance (height of spectrum minimum)



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

$$P(\nu_\alpha \rightarrow \nu_\beta) = \underbrace{\sin^2(2\theta)}_{\text{amplitude}} \underbrace{\sin^2\left(1.27 \frac{\Delta m^2_{ji} [\text{eV}^2] L [\text{km}]}{E_\nu [\text{GeV}]}\right)}_{\text{frequency}} \quad (\text{simplified 2-flavors approximation})$$

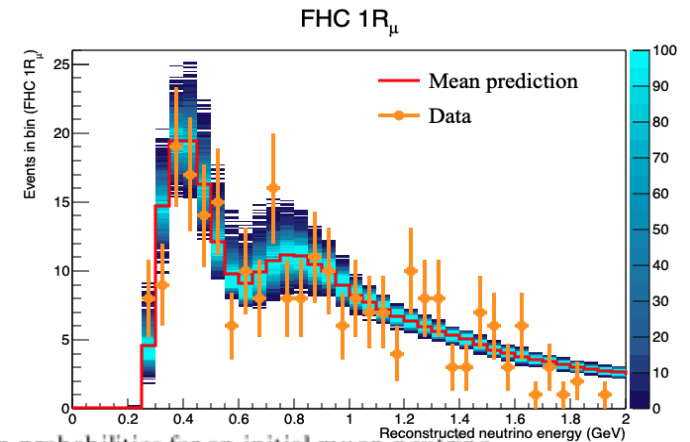
- $\sin\theta_{23} \sim$ amplitude of the ν_μ ($\bar{\nu}_\mu$) disappearance (height of spectrum minimum)
- $\Delta m^2_{31(32)} \sim$ frequency of the disappearance (position of spectrum minimum)



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

$$P(\nu_\alpha \rightarrow \nu_\beta) = \underbrace{\sin^2(2\theta)}_{\text{amplitude}} \underbrace{\sin^2\left(1.27 \frac{\Delta m^2_{ji} [\text{eV}^2] L [\text{km}]}{E_\nu [\text{GeV}]}\right)}_{\text{frequency}} \quad (\text{simplified 2-flavors approximation})$$

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

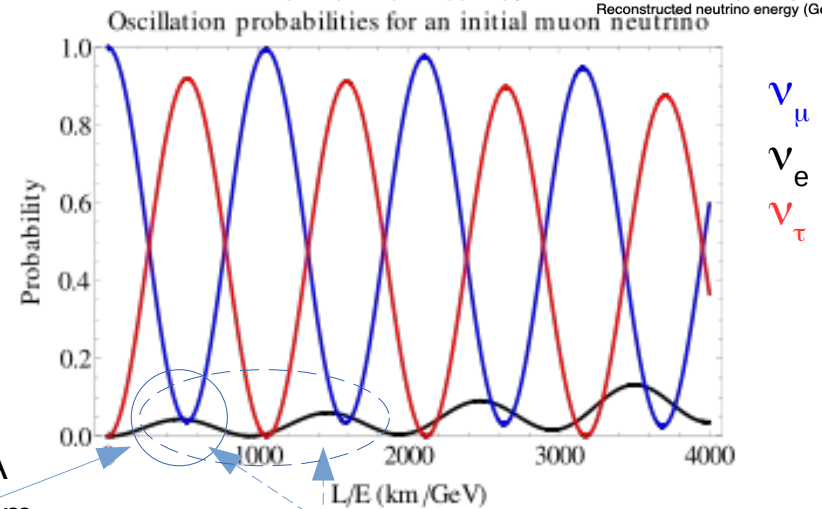


In the atmospheric sector $|\Delta m^2_{32}| \sim 2.4 \times 10^{-3} \text{ eV}^2$

Experiment	Energy	Baseline
T2K (T2HK)	0.6 GeV	295 km
Nova	2 GeV	810 km
DUNE	1-3 GeV	1300 km

(to exploit ν_τ need $E_\nu > m_\tau$ 1.78 GeV)

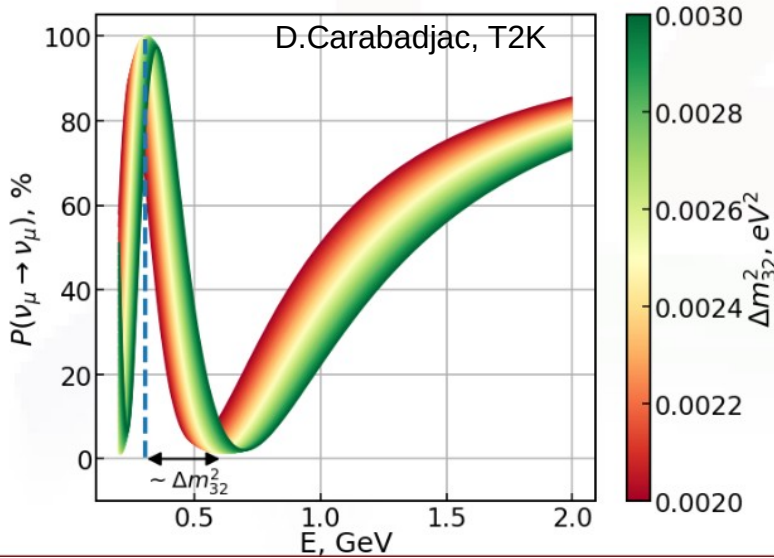
T2K (T2HK) and NOVA
same oscillation maximum
 $L/E \sim 0.5 \text{ km/GeV}$



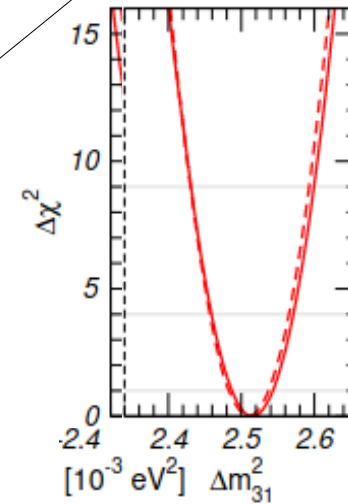
DUNE wideband beam covers (at low energy) also the second oscillation maximum

Atmospheric parameters: ν_μ disapp

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



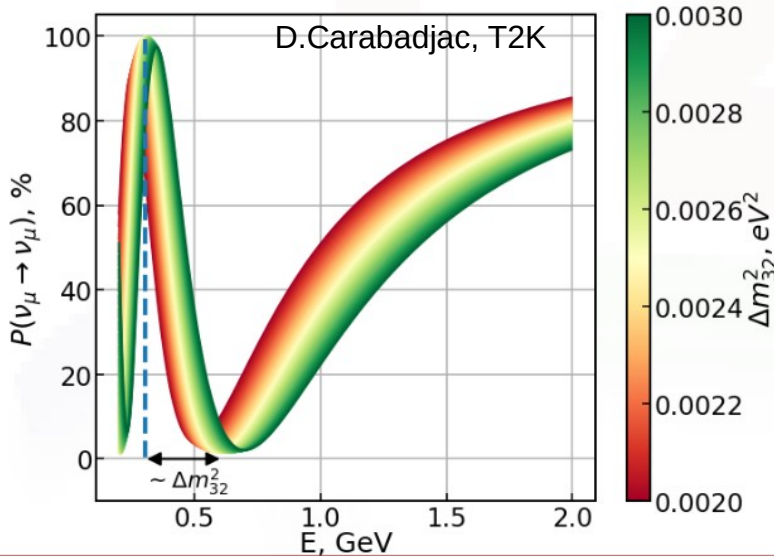
	Best fit (NH)	3σ range
$\frac{\Delta m_{3\ell}^2}{10^{-3} \text{ eV}^2}$	$+2.510^{+0.027}_{-0.027}$	$+2.430 \rightarrow +2.593$



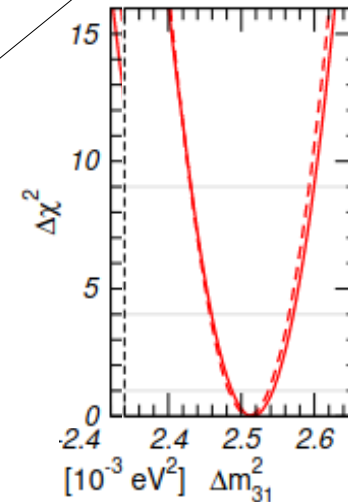
(joint fit results from
T. Schweitz talk
at Neutrino 2022,
NuFit 5.1)

Atmospheric parameters: ν_μ disapp

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



	Best fit (NH)	3σ range
$\frac{\Delta m_{3\ell}^2}{10^{-3} \text{ eV}^2}$	$+2.510^{+0.027}_{-0.027}$	$+2.430 \rightarrow +2.593$

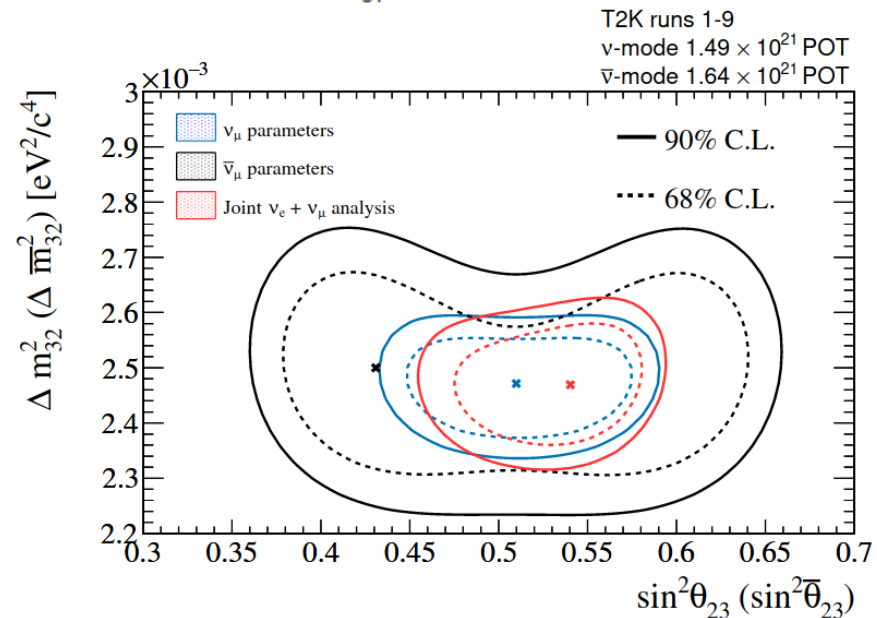


(joint fit results from T. Schweitz talk at Neutrino 2022, NuFit 5.1)

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

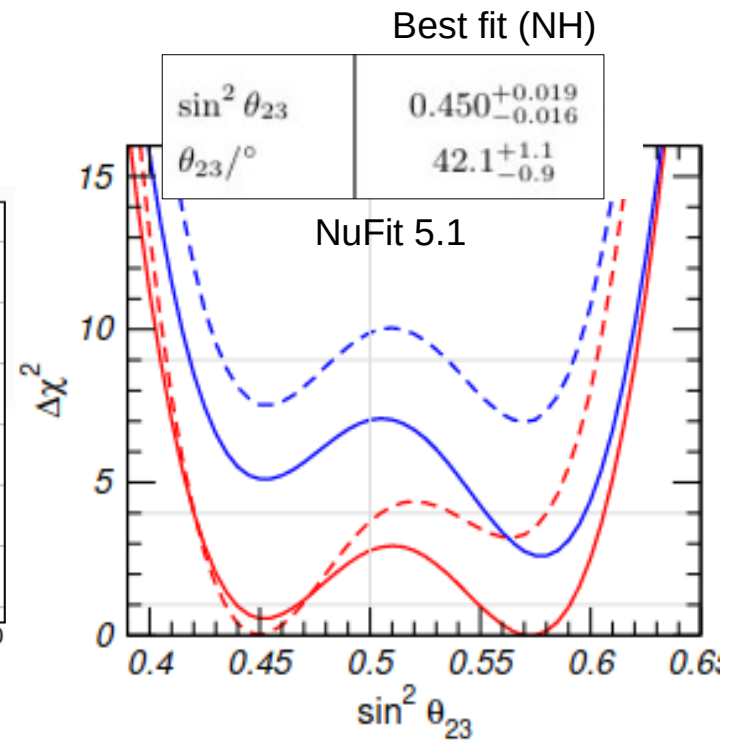
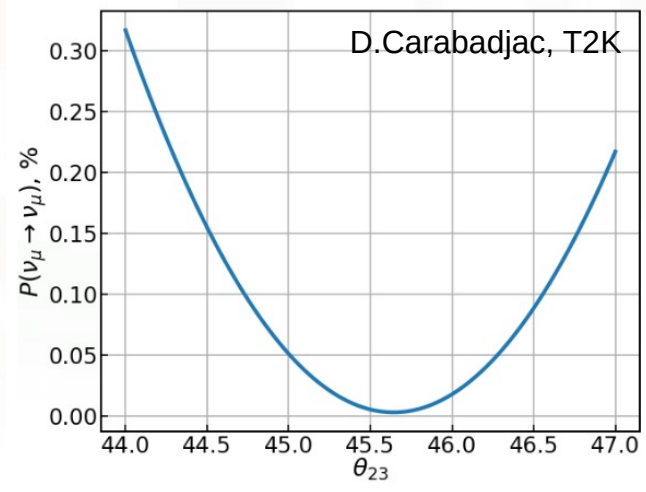
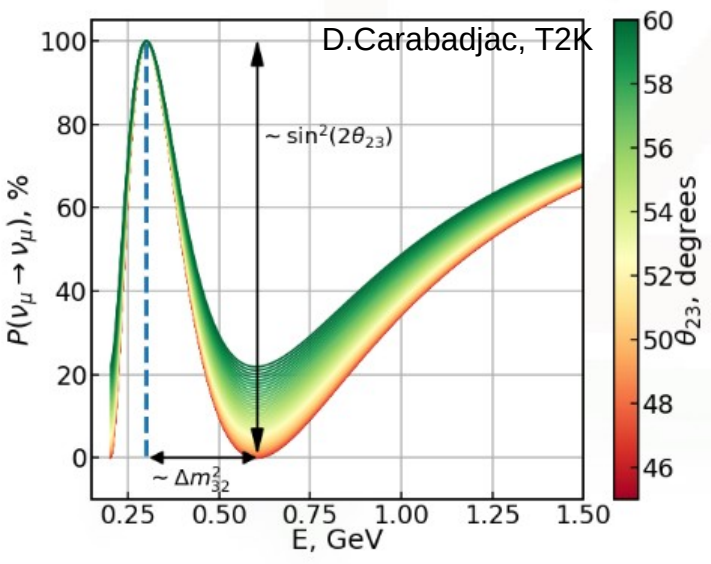
Precision at few % level (\rightarrow few MeV)

- Correlated effects in neutrino and antineutrino (assuming CPT invariance)



Atmospheric parameters: ν_μ disapp

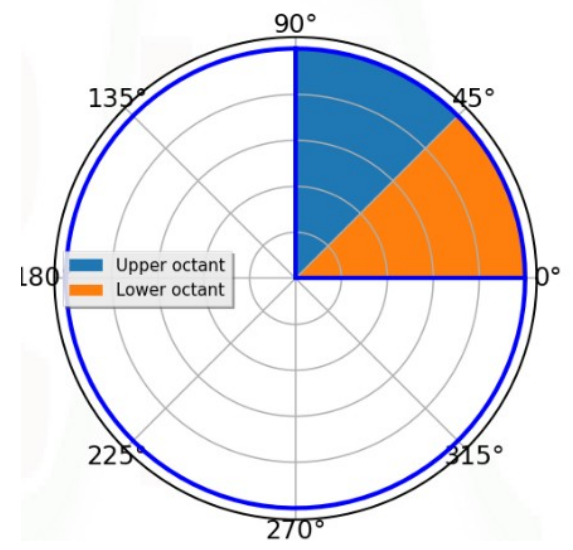
$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \cos^4 \theta_{13} \sin^2 \frac{\Delta m_{32}^2 L}{4E}$$



- Measurement **proportional to number of observed muon neutrino** at oscillation maximum
 → need control of ν_μ overall normalization at few %
 (again correlated between nu and nubar)

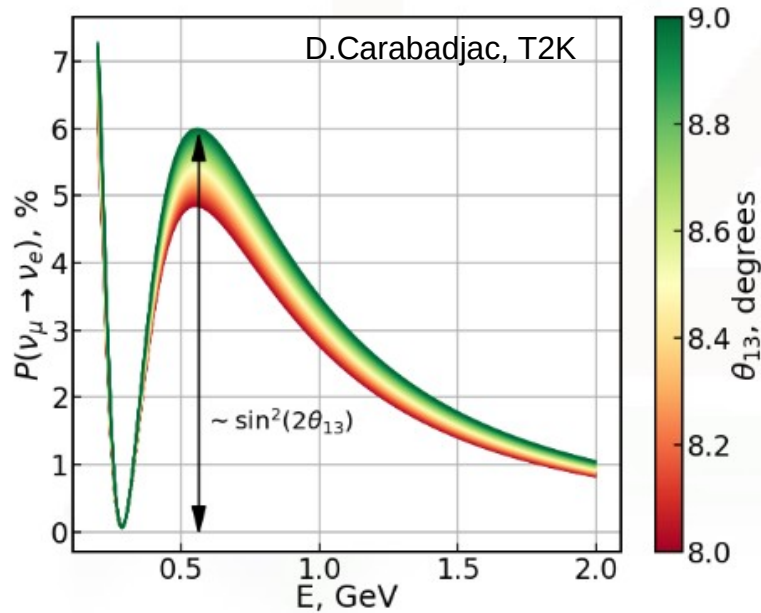
- Maximal mixing $\theta_{23} \sim \pi/4$ would be a very interesting symmetry.
 Away from that, **octant degeneracy due to quadratic dependence on $\sin^2 2\theta$**

- ① $\theta_{23} \in [0; \pi/4]$ - lower octant
- ② $\theta_{23} \in [\pi/4, \pi/2]$ - upper octant

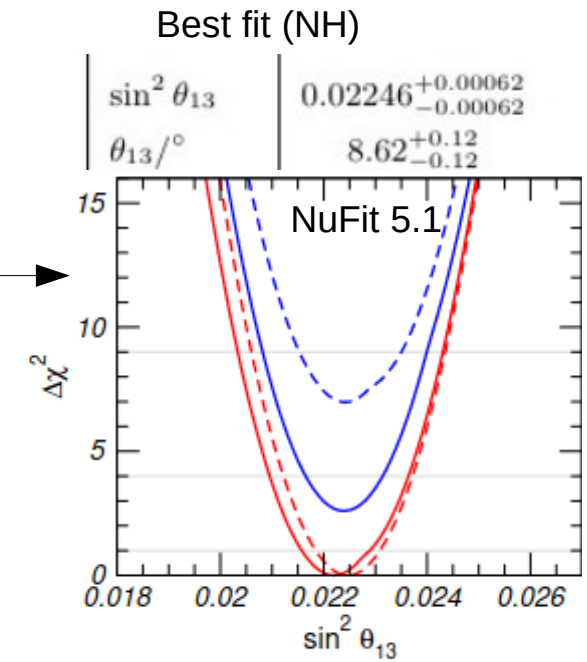


ν_e appearance

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

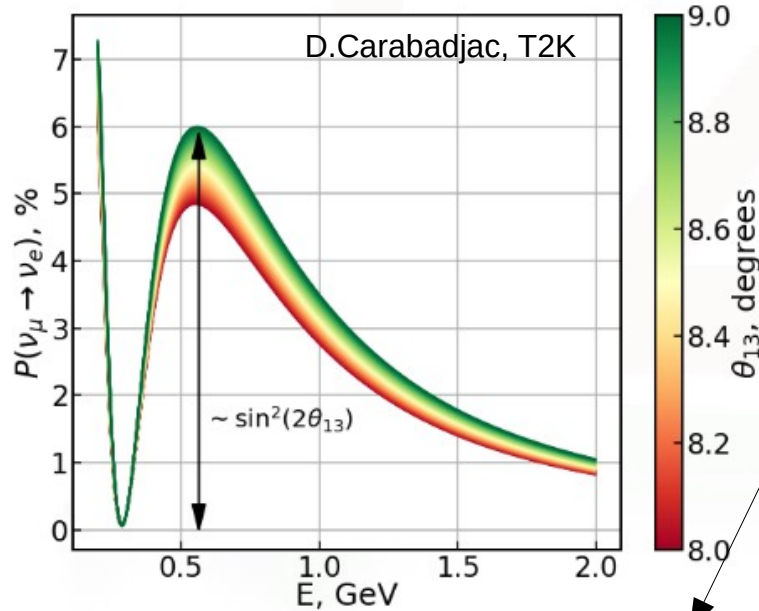


- Dominated by large uncertainty on θ_{23} , while θ_{13} well measured by reactor experiments.



ν_e appearance (at T2K)

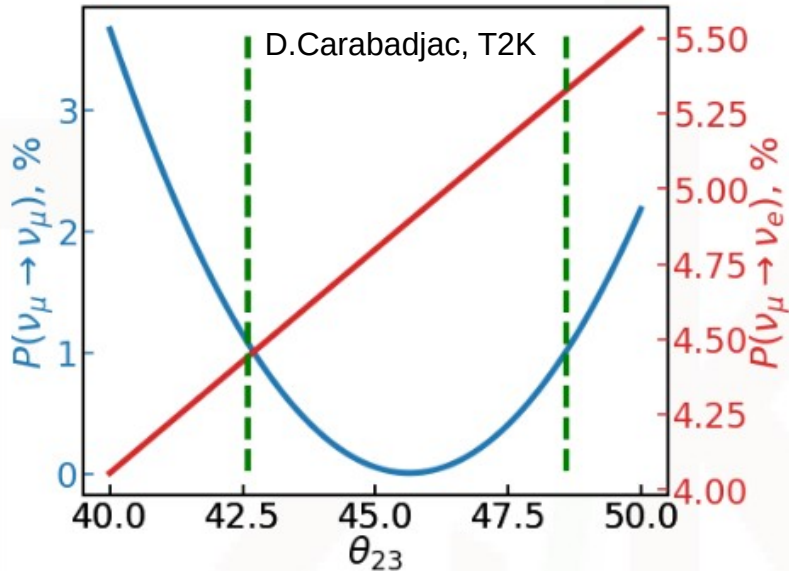
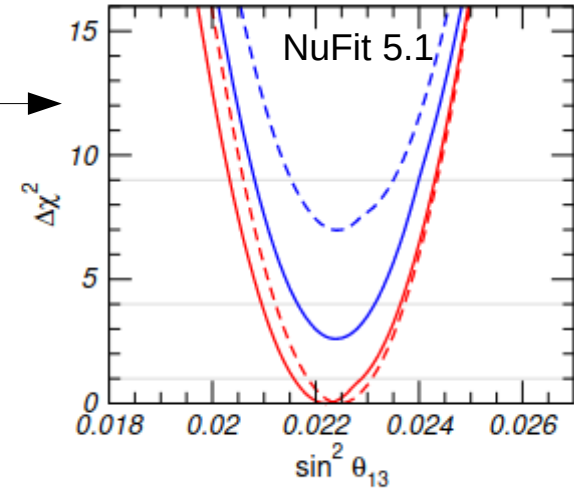
$$P(\nu_\mu \rightarrow \nu_e) \approx \boxed{\sin^2 2\theta_{13}} \sin^2 \theta_{23} \sin^2 \frac{\Delta m_{32}^2 L}{4E}$$



- Dominated by large uncertainty on θ_{23} , while θ_{13} well measured by reactor experiments.
 → **break degeneracy in θ_{23}** (~1% effect)

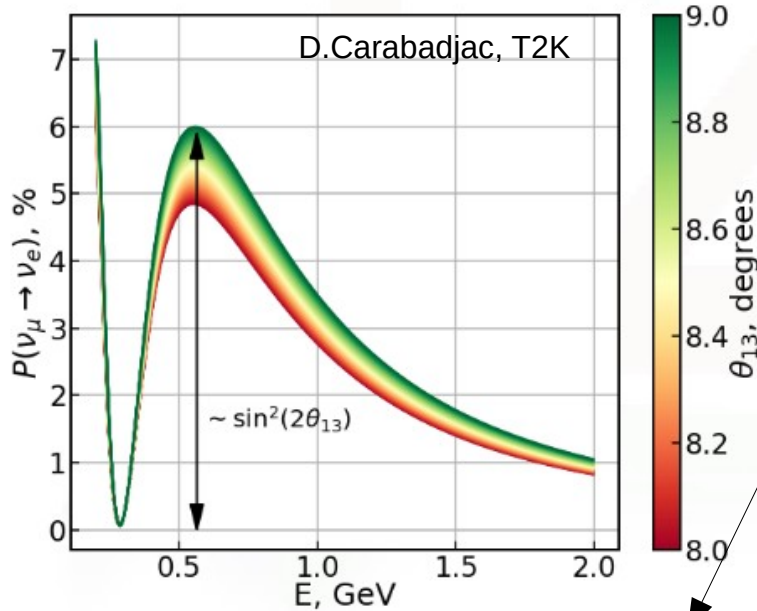
Best fit (NH)

$\sin^2 \theta_{13}$	$0.02246^{+0.00062}_{-0.00062}$
$\theta_{13}/^\circ$	$8.62^{+0.12}_{-0.12}$



ν_e appearance (at T2K)

$$P(\nu_\mu \rightarrow \nu_e) \approx \boxed{\sin^2 2\theta_{13}} \sin^2 \theta_{23} \sin^2 \frac{\Delta m_{32}^2 L}{4E} + \sim \sin \theta_{13} \times \sin \delta \sim$$



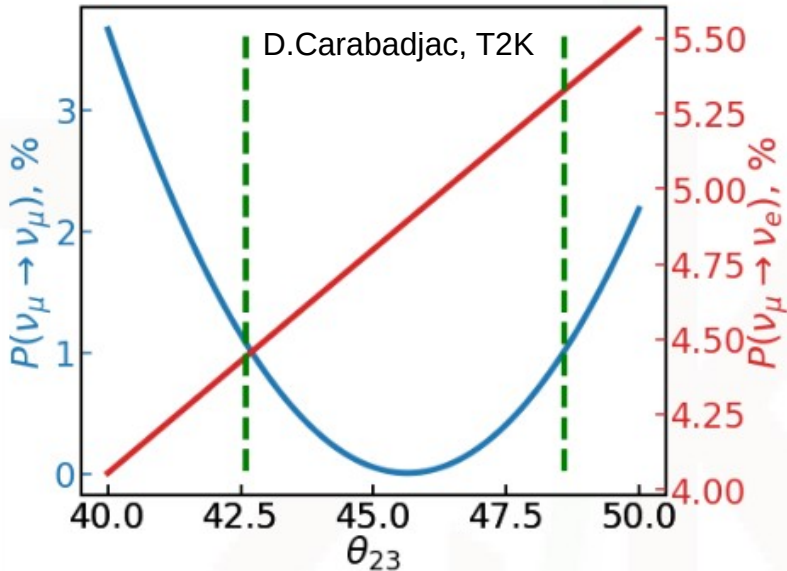
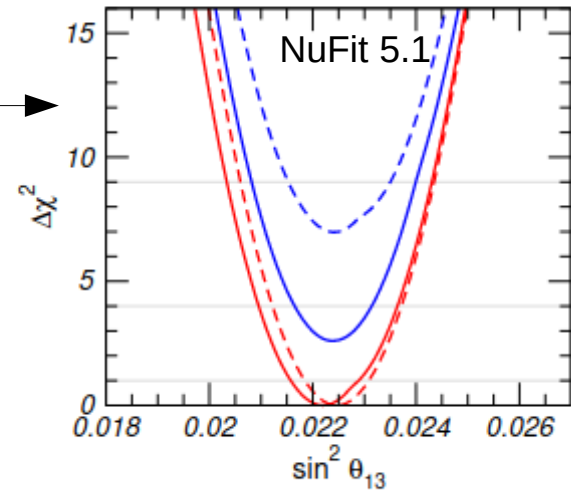
- Dominated by large uncertainty on θ_{23} , while θ_{13} well measured by reactor experiments.

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

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

Best fit (NH)

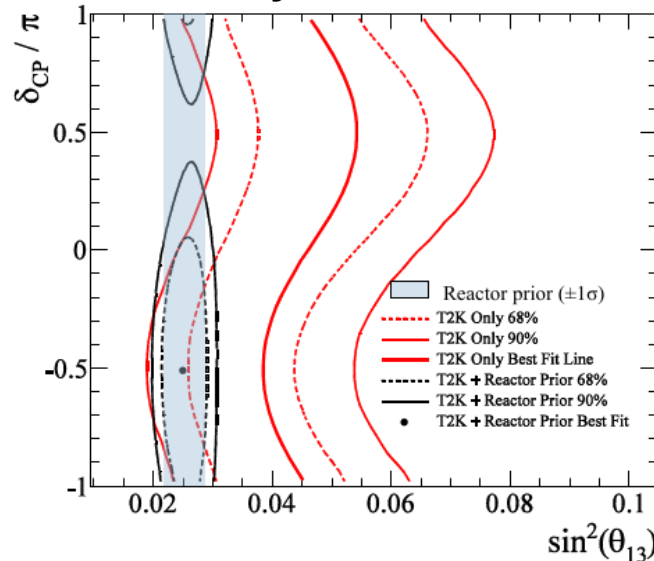
$\sin^2 \theta_{13}$	$0.02246^{+0.00062}_{-0.00062}$
$\theta_{13}/^\circ$	$8.62^{+0.12}_{-0.12}$



2015 ν only:

— T2K

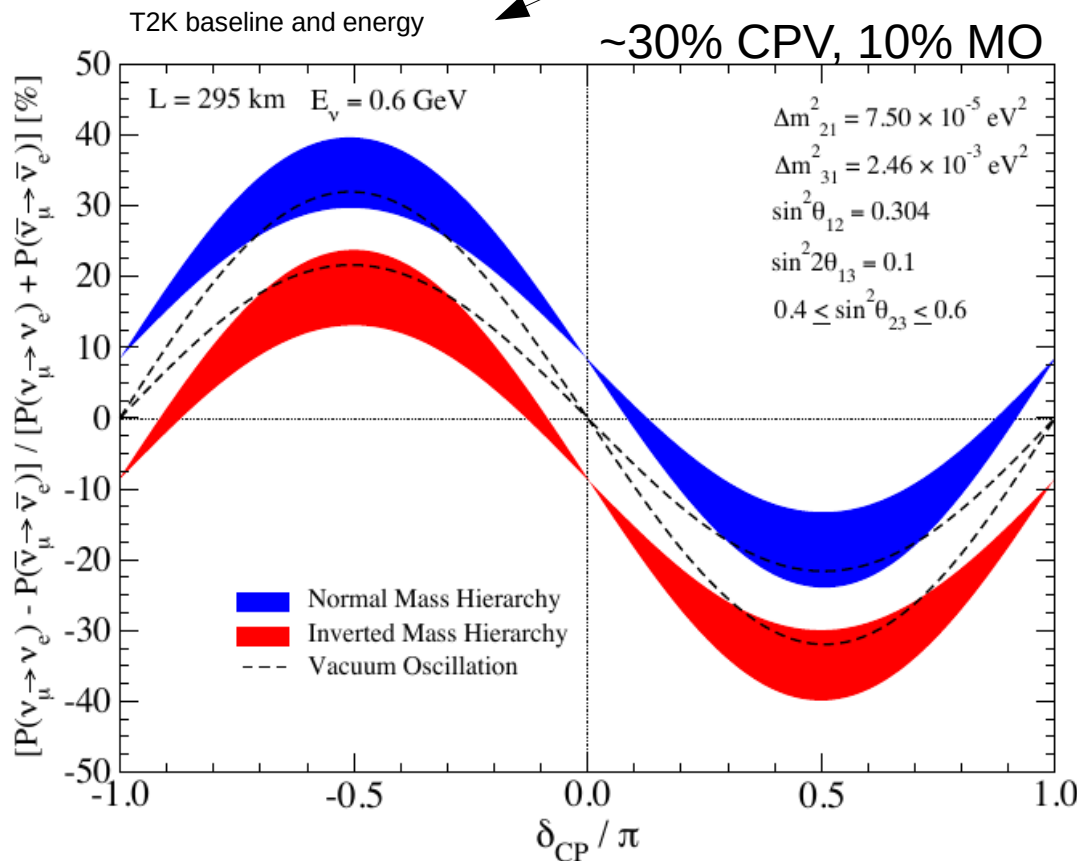
— T2K + θ_{13} from reactors



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

Both ν_μ and $\bar{\nu}_\mu$ enriched beam can be produced at long-baseline experiments

$$A_{CP} \equiv \frac{P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}{P(\nu_\mu \rightarrow \nu_e) + P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)} \simeq -\frac{\sin 2\theta_{12} \sin \delta}{\sin \theta_{13} \tan \theta_{23}} \Delta_{21} + \text{matter effects}$$



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) \rightarrow overall phase in mass eigenstate evolution which can be subtracted.
- ν_e also makes charged current interactions (W+-) with electrons in matter \rightarrow additional potential in matter of opposite sign for $\nu_e/\bar{\nu}_e$

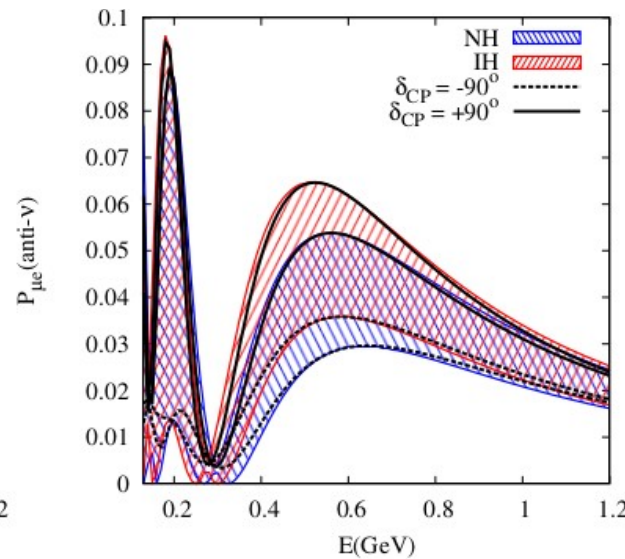
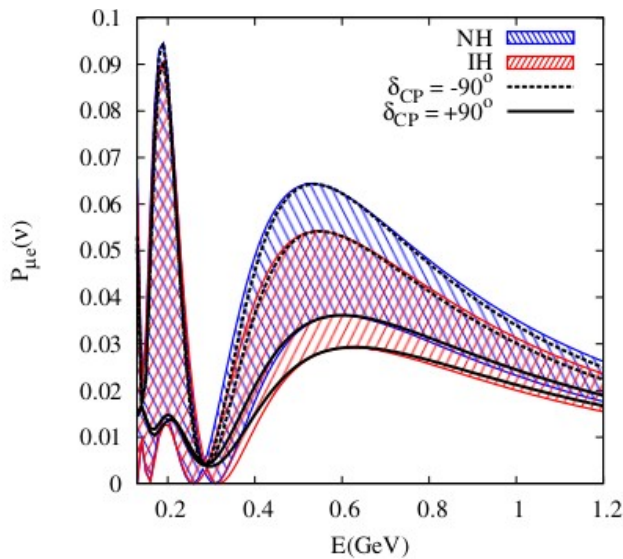
$$A = \pm 2\sqrt{2}G_F N_e E,$$
- larger neutrino energy and longer baseline \rightarrow larger the matter effect (Earth crust~constant density and at LBL below MSW effect)

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

Both ν_μ and $\bar{\nu}_\mu$ enriched beam can be produced at long-baseline experiments

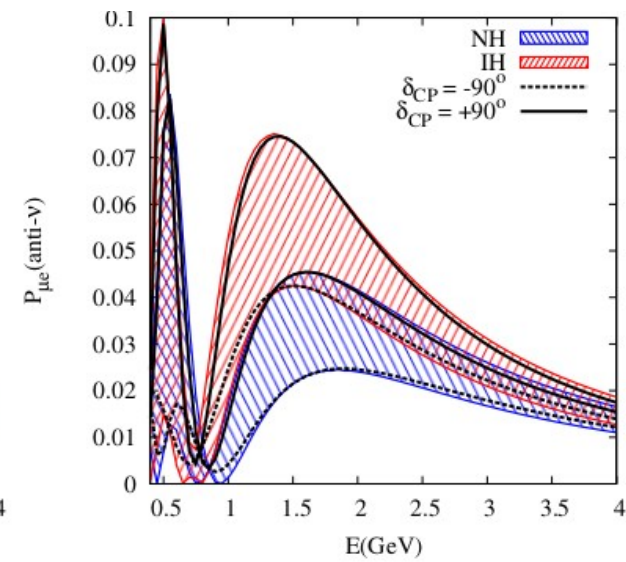
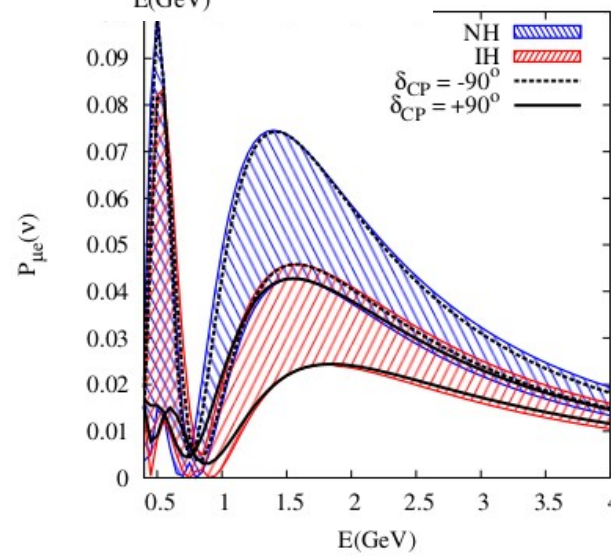
$$\mathcal{A}_{CP} \equiv \frac{P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}{P(\nu_\mu \rightarrow \nu_e) + P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)} \simeq -\frac{\sin 2\theta_{12} \sin \delta}{\sin \theta_{13} \tan \theta_{23}} \Delta_{21} + \text{matter effects}$$

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)



ν_e appearance full formula

L.Kormos NuFact 2022

Appearance

$$\begin{aligned}
 P(\nu_\mu \rightarrow \nu_e) = & 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2 \Delta_{31} \times \left(1 \pm \frac{2a}{\Delta m_{31}^2} (1 - s_{13}^2) \right) && \leftarrow \text{Leading term} \\
 & + 8c_{13}^2 s_{12} s_{13} s_{23} (c_{12} c_{23} \cos \delta - s_{12} s_{13} s_{23}) \cos \Delta_{32} \sin \Delta_{31} \sin \Delta_{21} && \leftarrow \text{CP Conserving} \\
 & \mp 8c_{13}^2 s_{13}^2 s_{23}^2 \cos \Delta_{32} \sin \Delta_{31} \frac{aL}{4E} (1 - 2s_{13}^2) && \leftarrow \text{Matter effect} \\
 & \mp 8c_{13}^2 c_{12} c_{23} s_{12} s_{13} s_{23} \sin \delta \sin \Delta_{32} \sin \Delta_{31} \sin \Delta_{21} && \leftarrow \text{CP Violating} \\
 & + 4s_{12}^2 c_{13}^2 (c_{12} c_{23} + s_{12}^2 s_{13}^2 s_{23}^2 - 2c_{12} c_{23} s_{12} s_{13} s_{23} \cos \delta) \sin^2 \Delta_{21} && \leftarrow \text{Solar term}
 \end{aligned}$$

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

ν vs. $\bar{\nu}$
sign
change

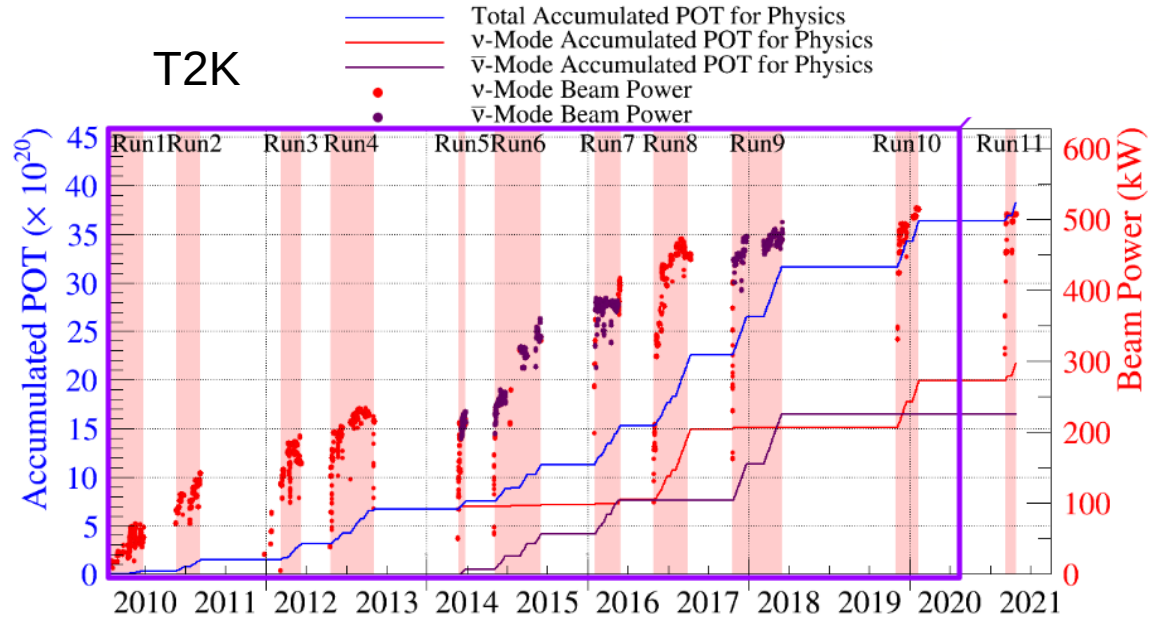
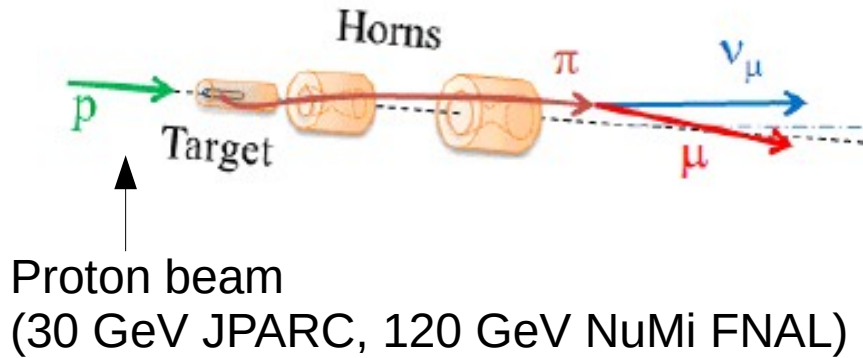
θ_{13} dependence Octant sensitivity CP-odd phase

- 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

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

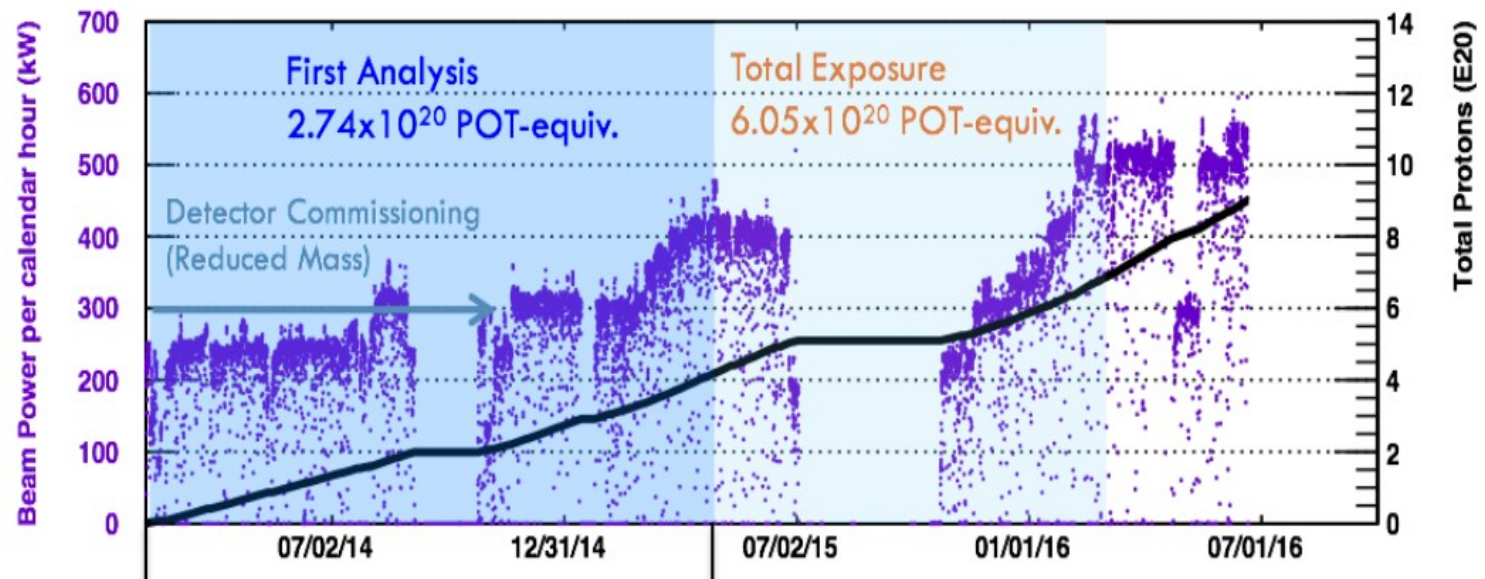
Neutrino 'beam'

Proton beam



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

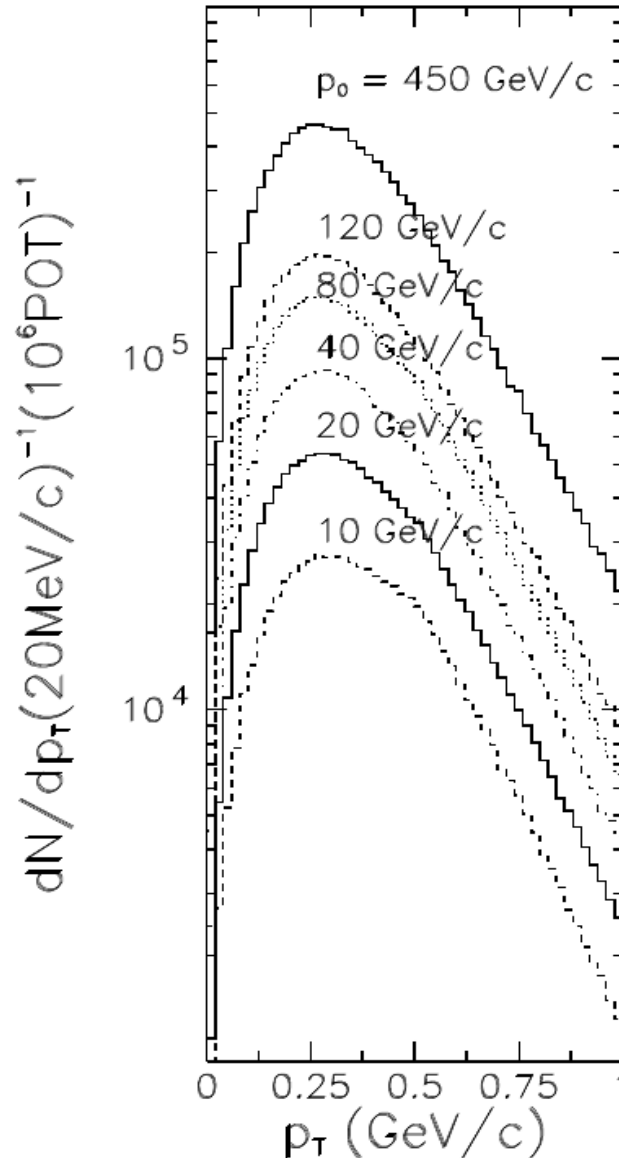
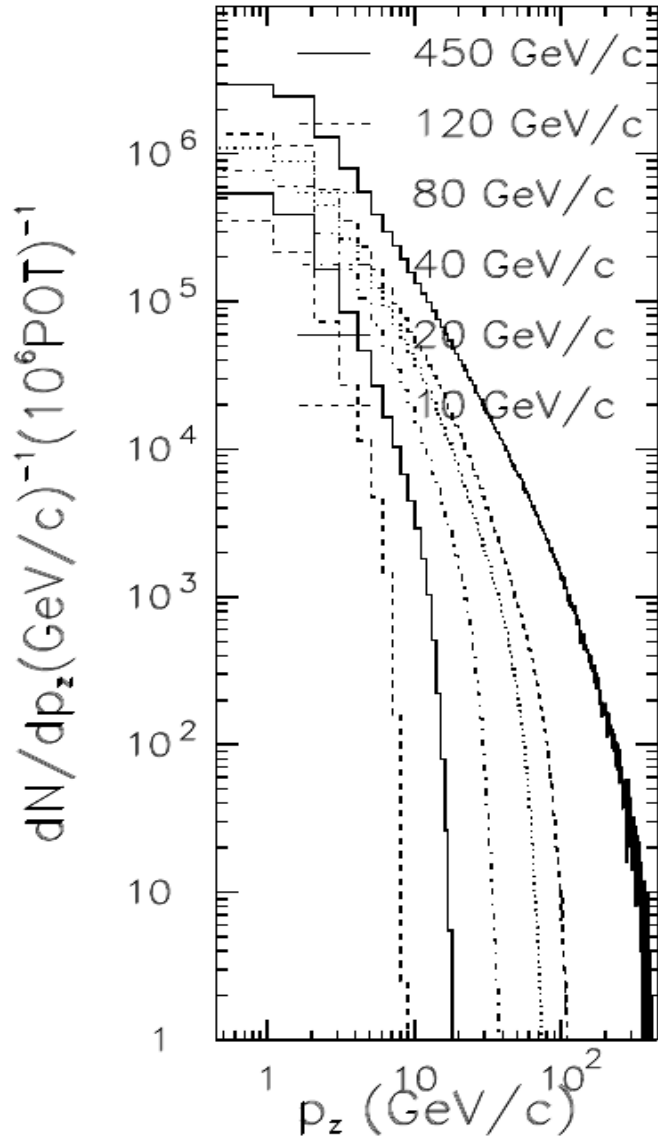
NOVA (old)



Next generation
of experiments:
1-2 MW (larger
POT and/or E)

Proton beam

Pion spectra for different proton momenta

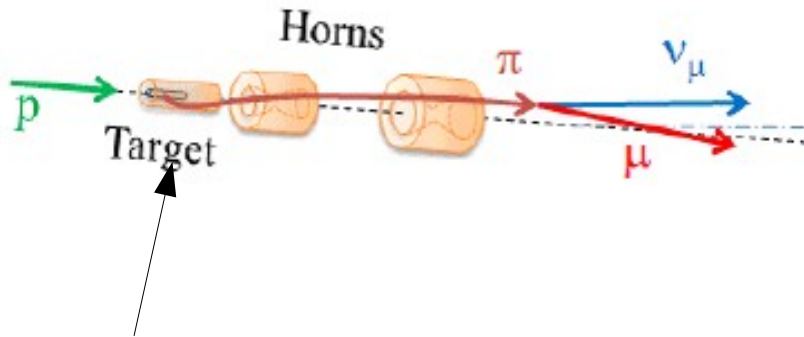


p_0 (GeV/c)	$\langle n_\pi \rangle$	$\langle p_T \rangle$ (MeV/c)	K/π
10	0.68	389	0.061
20	1.29	379	0.078
40	2.19	372	0.087
80	3.50	370	0.091
120	4.60	369	0.093
450	10.8	368	0.098

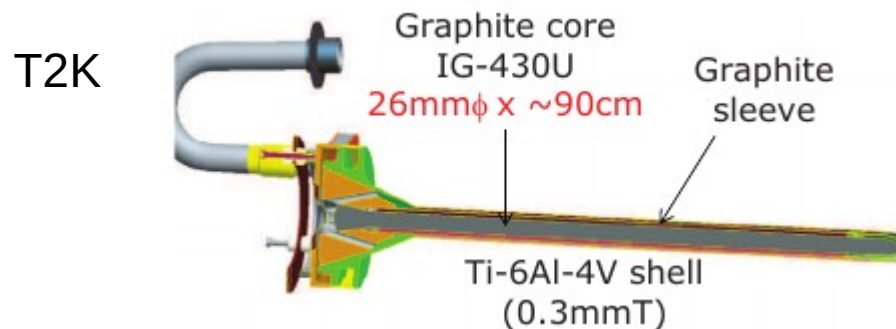
Roughly speaking: **higher proton energy produce more pions** without increasing much their transverse momentum

(but lower energy typically allows larger repetition rate)

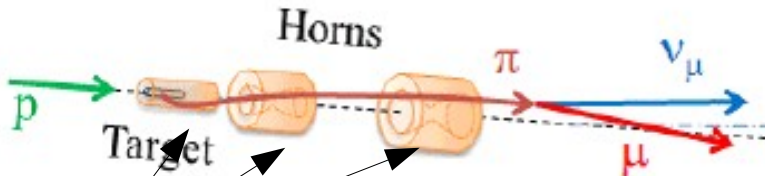
Target



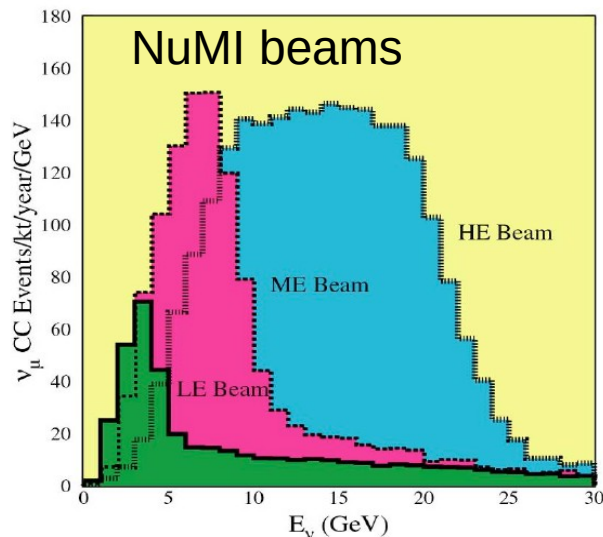
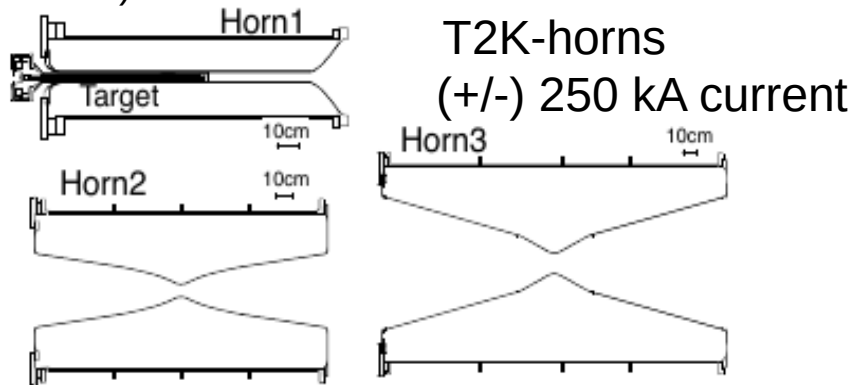
- **Shape:** cylindrical (or ruler) along proton beam direction to **maximize the probability of protons to interact** (~50-100cm)
(but re-interactions of hadrons inside the target are an additional complication)
Transversal section should be $\sim 3\sigma$ of proton beam width (~5-10mm)
- **Low Z** (Aluminium, Berillium, Carbon, ...) high probability of proton interacting and **low probability of radiating (losing energy in the target)**
- **Need cooling** (air or water): larger the beam intensity \rightarrow hotter the target



Horns

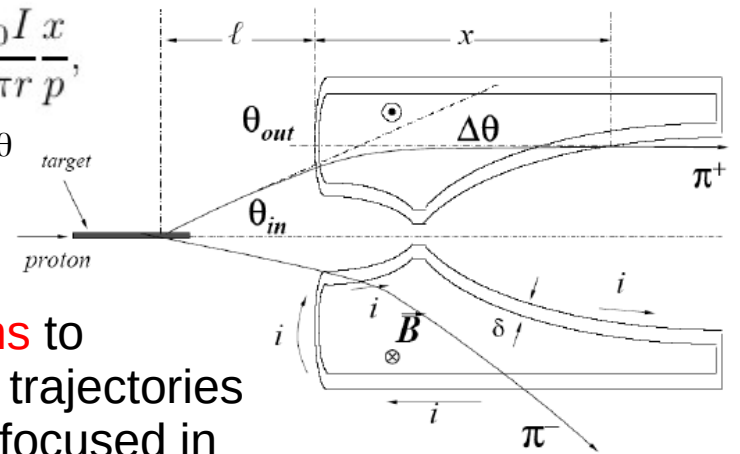


Horns to focus π^{\pm} parallel to beam axis
 → ν_{μ} or $\bar{\nu}_{\mu}$ beam (aka Forward/Reverse Horn Current)

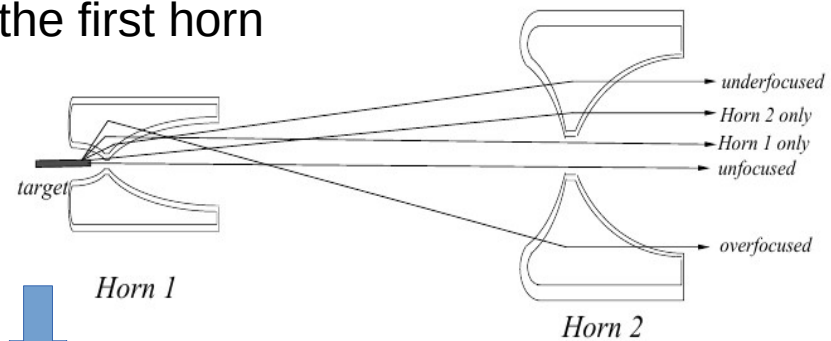


$$\Delta\theta = \frac{Bx}{p} = \frac{\mu_0 I x}{2\pi r p}$$

(parabolic: same θ kink for all angles)

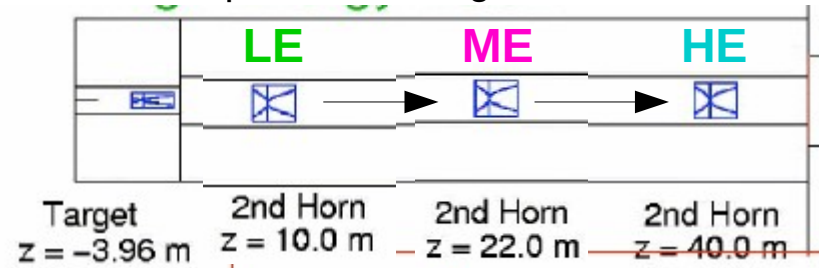


- multiple horns to recover pion trajectories not properly focused in the first horn



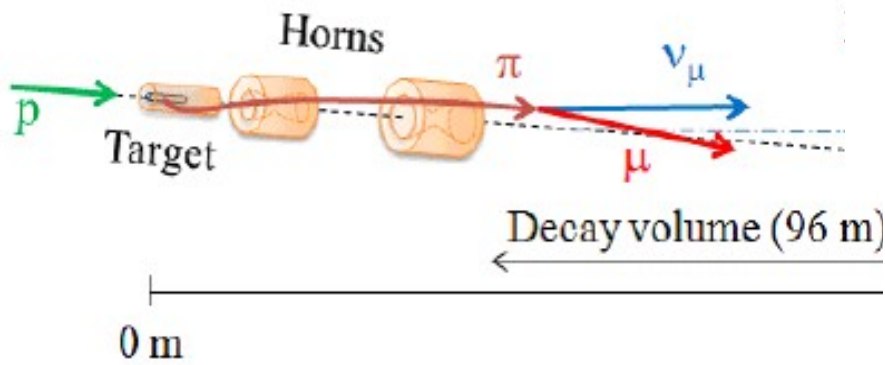
- the pions with smallest angle are the most energetic → to focus them need to **move the horns**

NuMI: 3 possible configurations → 3 beam energies



Decay volume

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

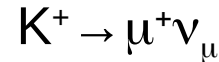
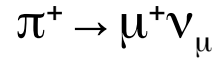


Decay volume (T2K: He filled):

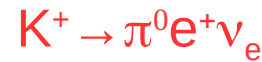
- Long to let most of the pion decaying
- not too long to avoid muon decay (ν_e pollution)



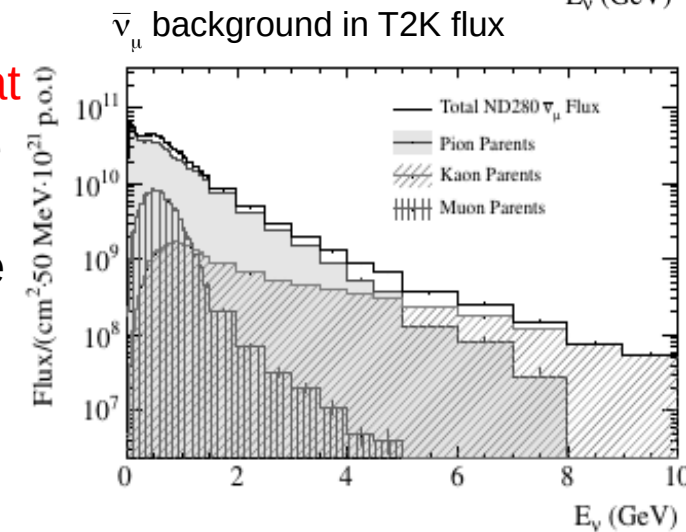
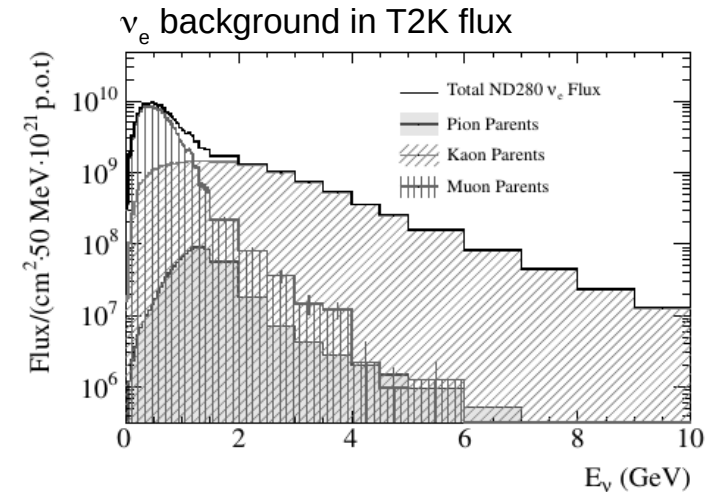
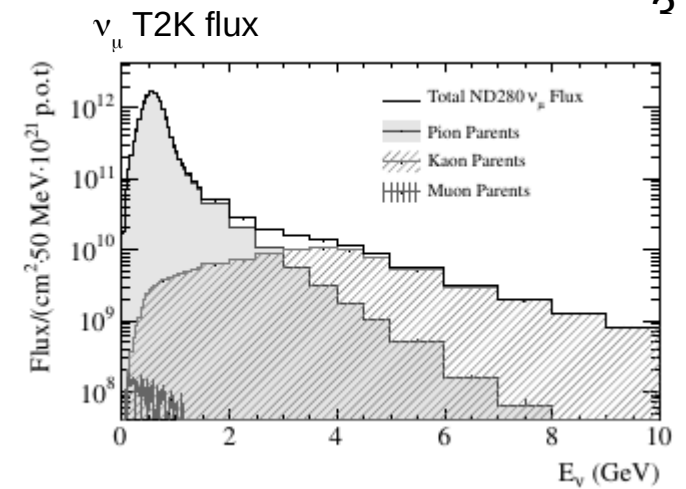
- most ν_μ 's from 2-body decays:



- most ν_e 's from 3-body decays:

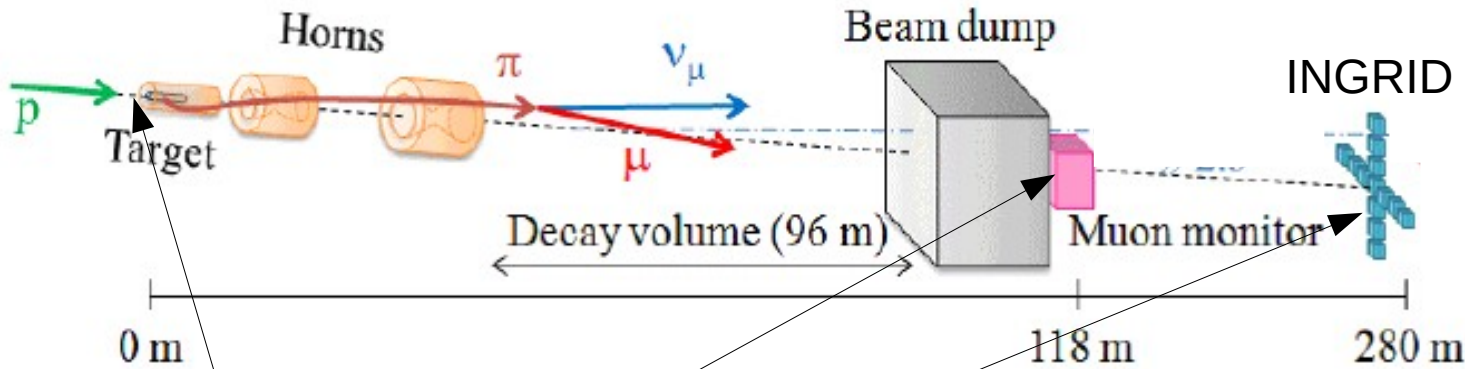


- $\bar{\nu}_\mu / \nu_\mu$ larger at high energy due to high $p_\perp \pi^-$ which cannot be (de-) focused

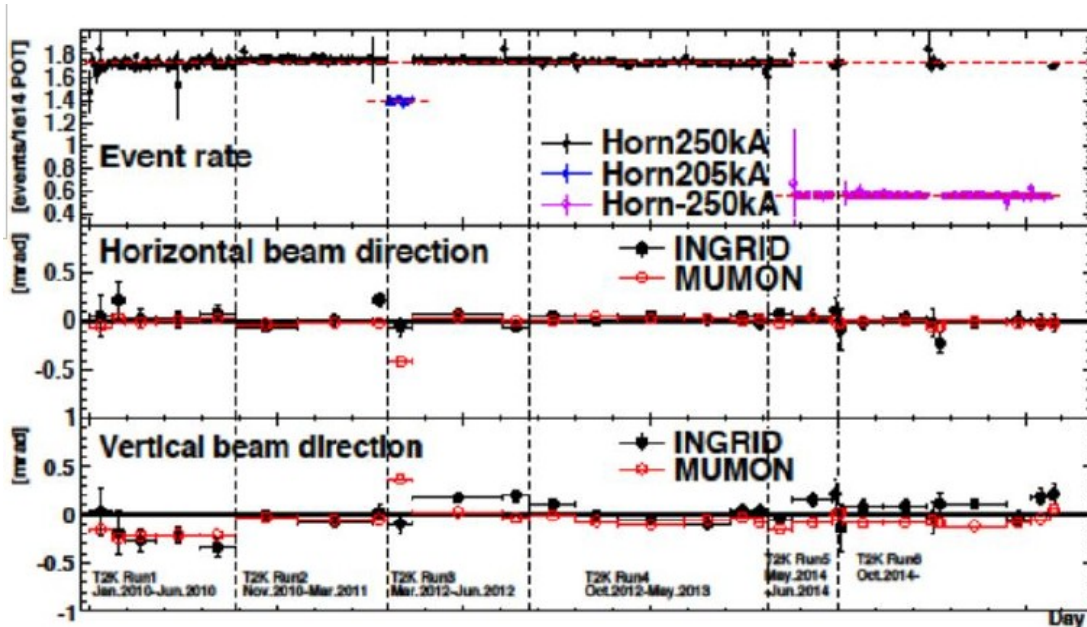


Beam monitoring

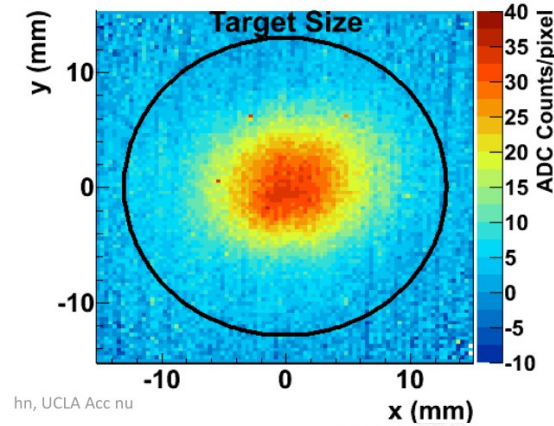
- **Monitoring of the beam:** intensity, position, direction



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

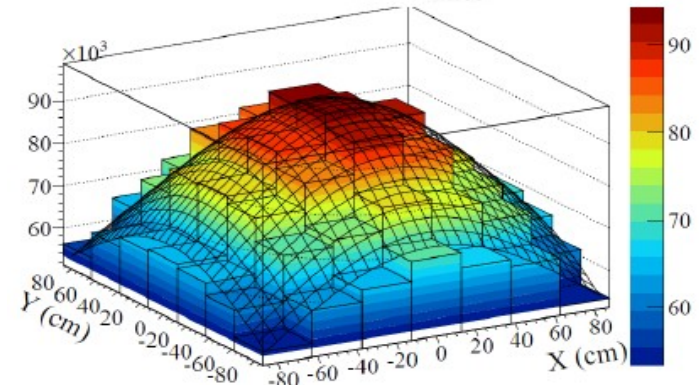


OTR Light for 9.0×10^{13} Protons on Ti Alloy Foil



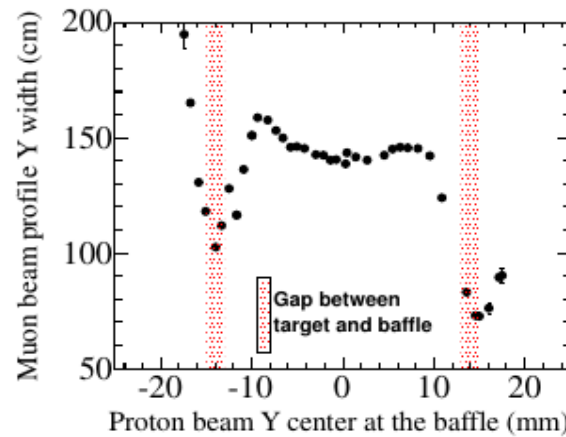
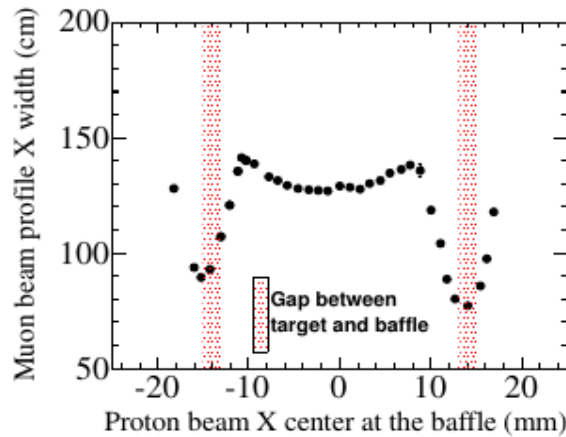
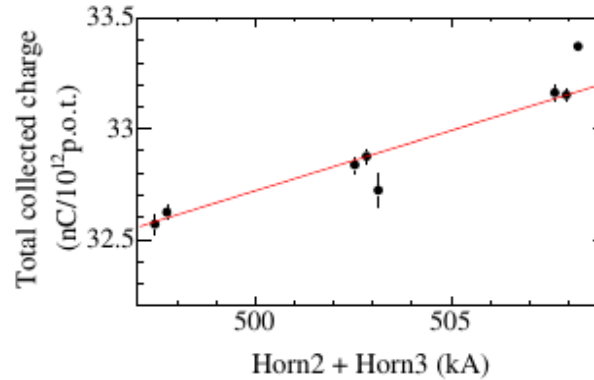
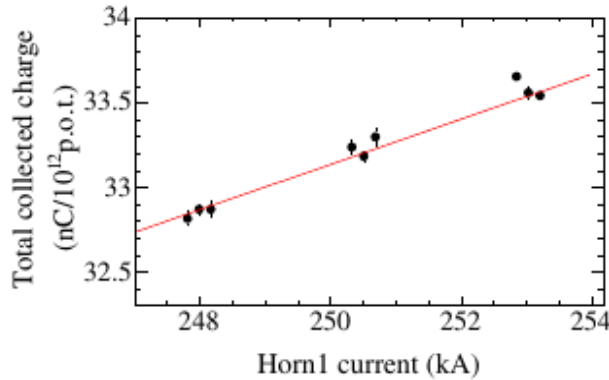
Protons

Muons

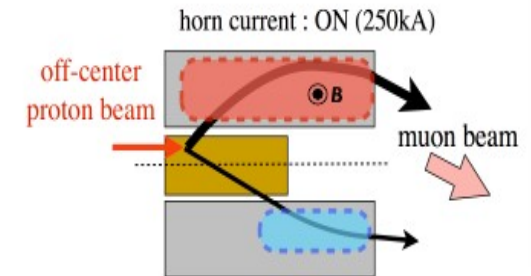
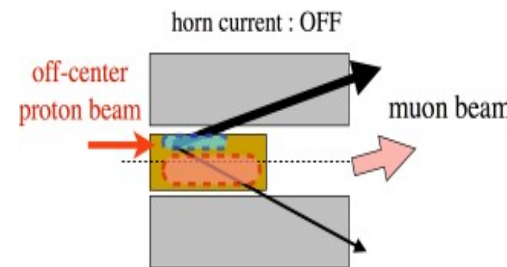
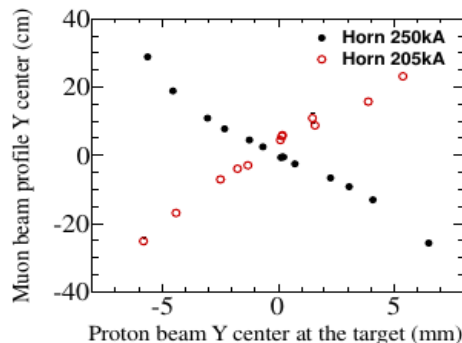
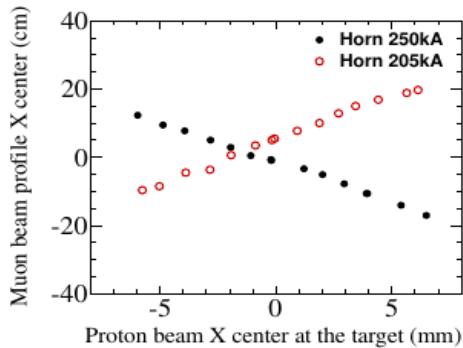


Playing around with the muon monitor

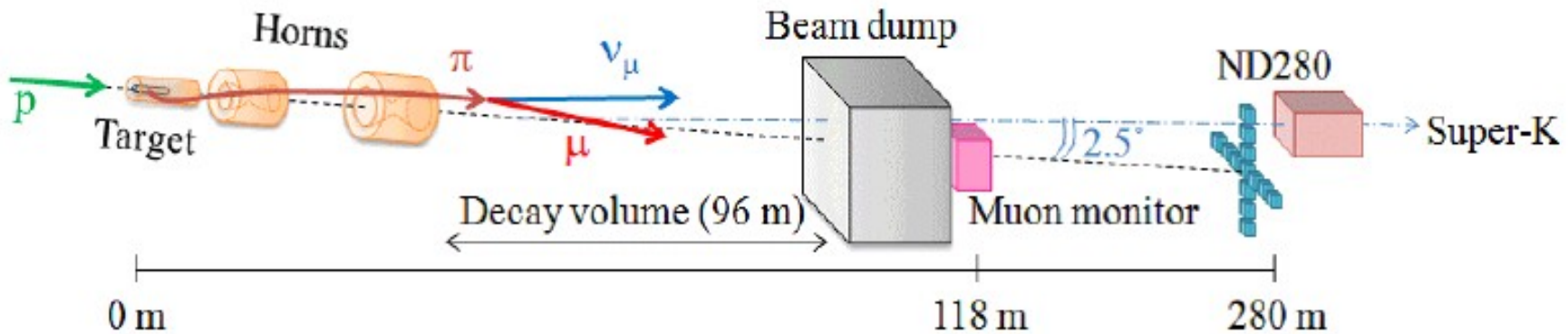
- Example from T2K: **sensitivity to horn current and proton beam position**



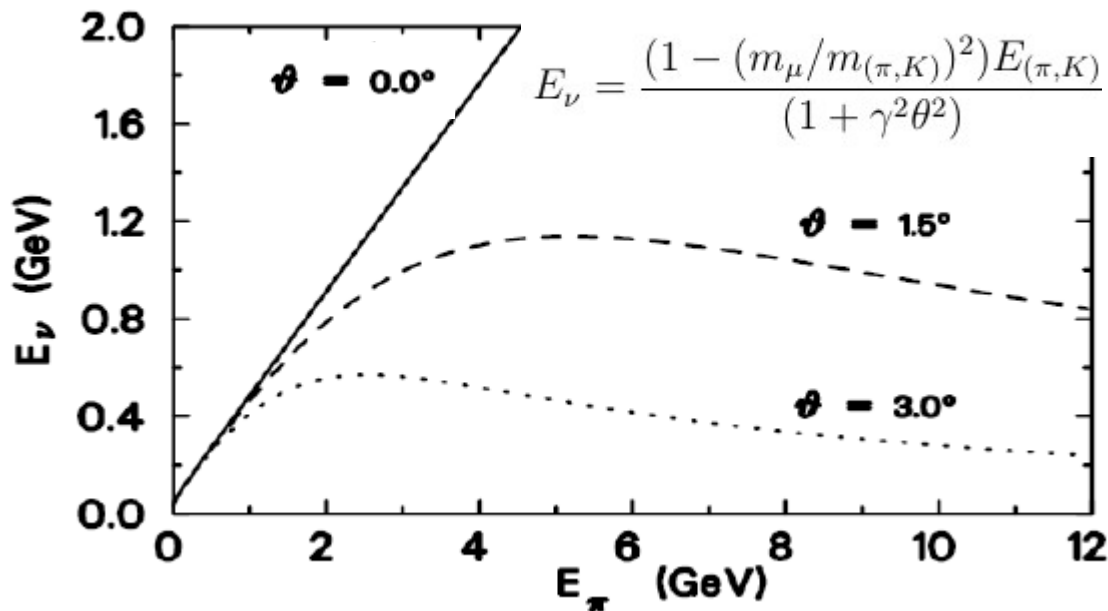
- **Correlation** between muon profile and proton beam position depends on the current



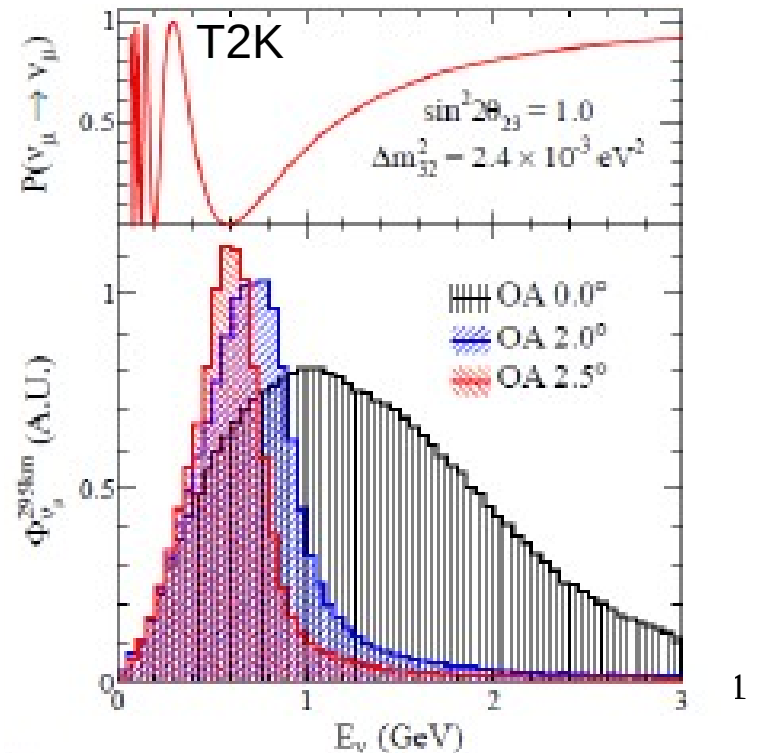
Tuning the neutrino energy



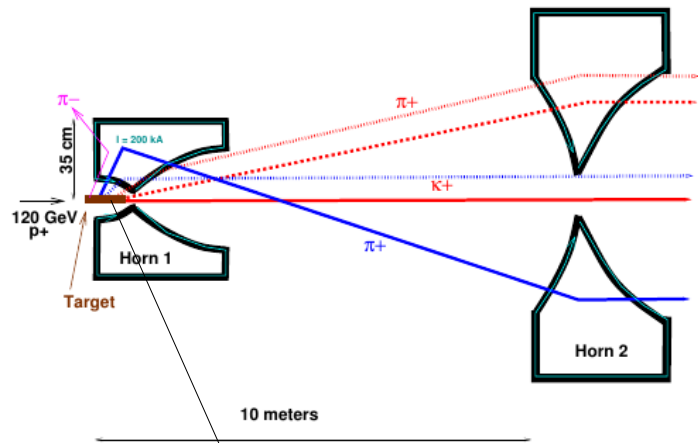
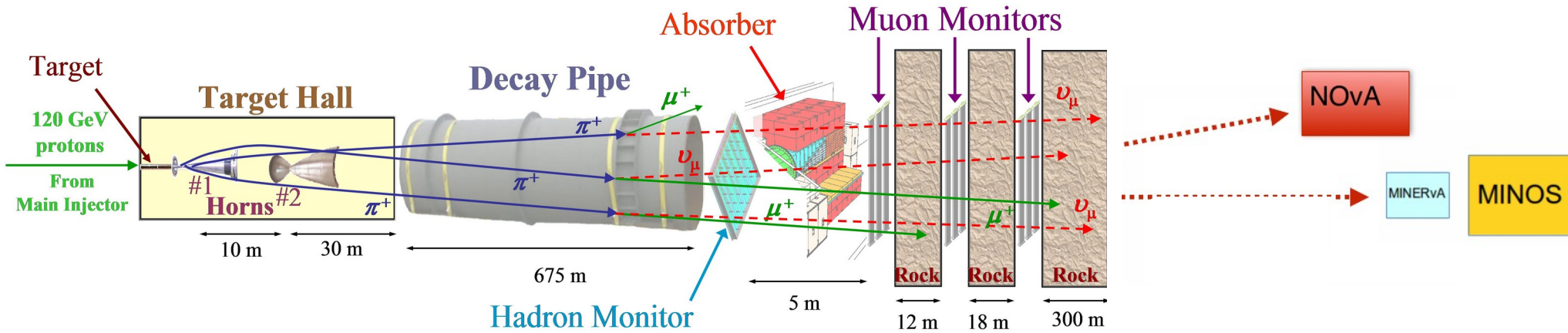
Energy of ν emitted in 2-body decay at an angle relative to π (K) direction is only weakly dependent on parent's momentum



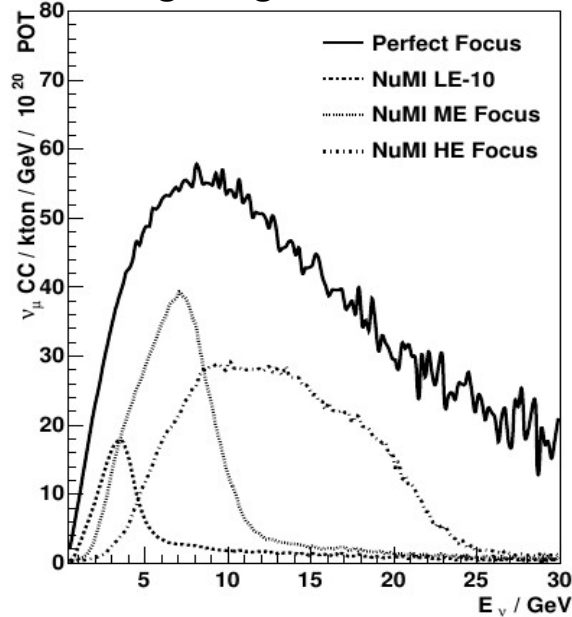
Off-axis → narrow flux at the maximum of the neutrino oscillation



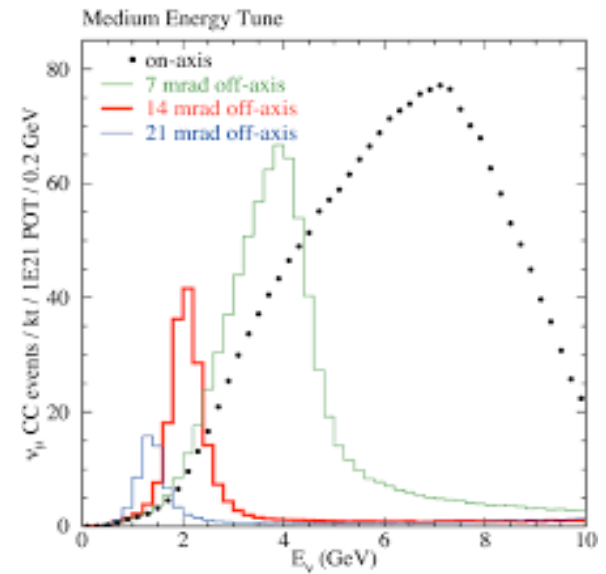
NuMI beam



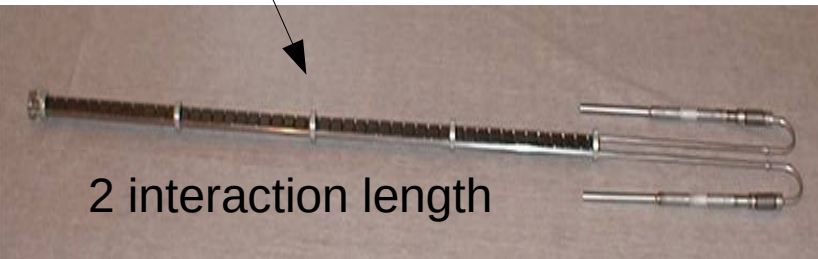
Change energy by moving target and horns



Off-axis technique

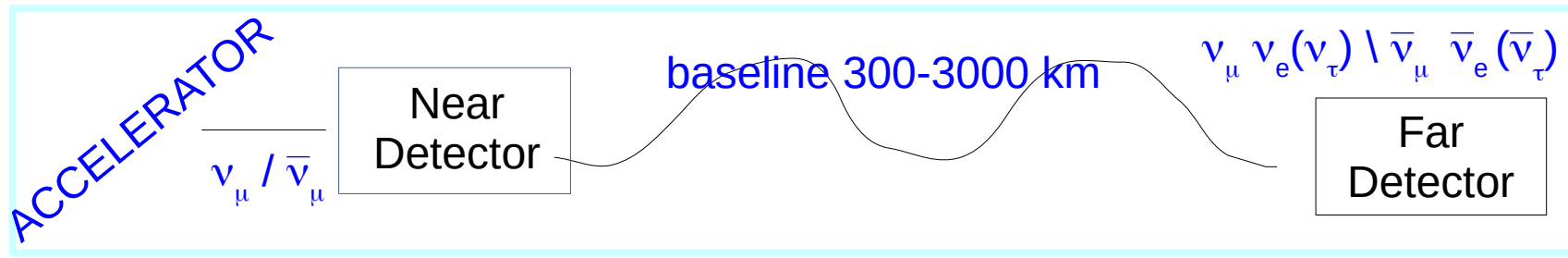


2 interaction length



From near to far detector

Oscillation analysis: the basics



$$N_{\nu_{\alpha'}}^{FD} \approx P_{\nu_\alpha \rightarrow \nu_{\alpha'}} \times N_{\nu_\alpha}^{ND}$$

Number of **neutrinos at the Far Detector (FD)** of a given flavour α' ($\alpha=e,\mu,\tau$)

Number of **neutrinos at the Near detector (ND)**

The **oscillation probability** $\nu_\alpha \rightarrow \nu_{\alpha'}$ which you want to estimate: it depends on the parameters you want to measure (long baseline experiments: $\theta_{13}, \theta_{23}, \Delta m_{32}^2, \delta_{CP}$)

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:

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

→ we need to know the **number of neutrinos as a function of E_ν** at near and far detectors

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

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

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

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

$$[\sigma] = [\text{cm}^2]$$

Flux and cross-section

- So the oscillation probability becomes:

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

$$\frac{N_{\nu_{\alpha'}}^{FD}(E_{\nu})}{N_{\nu_{\alpha}}^{ND}(E_{\nu})} \approx P_{\nu_{\alpha} \rightarrow \nu_{\alpha'}}(E_{\nu}) \times \frac{\phi_{\nu_{\alpha'}}^{FD}(E_{\nu})}{\phi_{\nu_{\alpha}}^{ND}(E_{\nu})} \times \frac{\sigma_{\nu_{\alpha'}}^{FD}(E_{\nu})}{\sigma_{\nu_{\alpha}}^{ND}(E_{\nu})}$$

measured number of neutrino interactions at the ND

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

→ systematic minimized if same flux (eg, same off-axis angle) and same target material (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 hard stuff...

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
- separate flux and xsec evaluation from ND data
- extrapolation of xsec and flux to different energy spectrum

Need reliable models of flux (this lecture) and neutrino-nucleus cross-section models (lecture from Martini)

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				
π^\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				
π^\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

Projectile	Material						
	C	Fe	Al	Air	He	H ₂ O	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	π^\pm, K^+
Eichten <i>et al.</i> [27]	24	Be, Al, ...	p, π^\pm, K^\pm
Allaby <i>et al.</i> [28]	19.2	Be, Al, ...	p, π^\pm, K^\pm
BNL-E910 [29]	6.4 – 17.5	Be	π^\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:

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

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

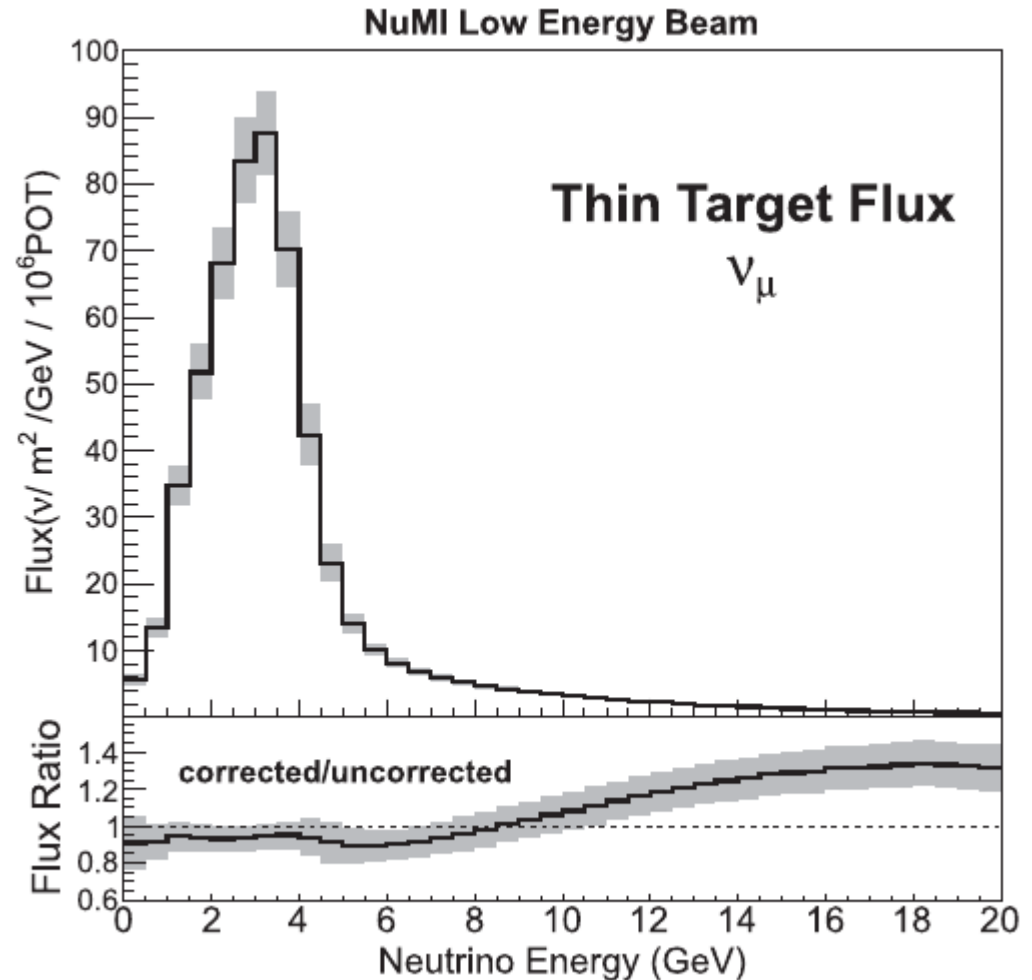
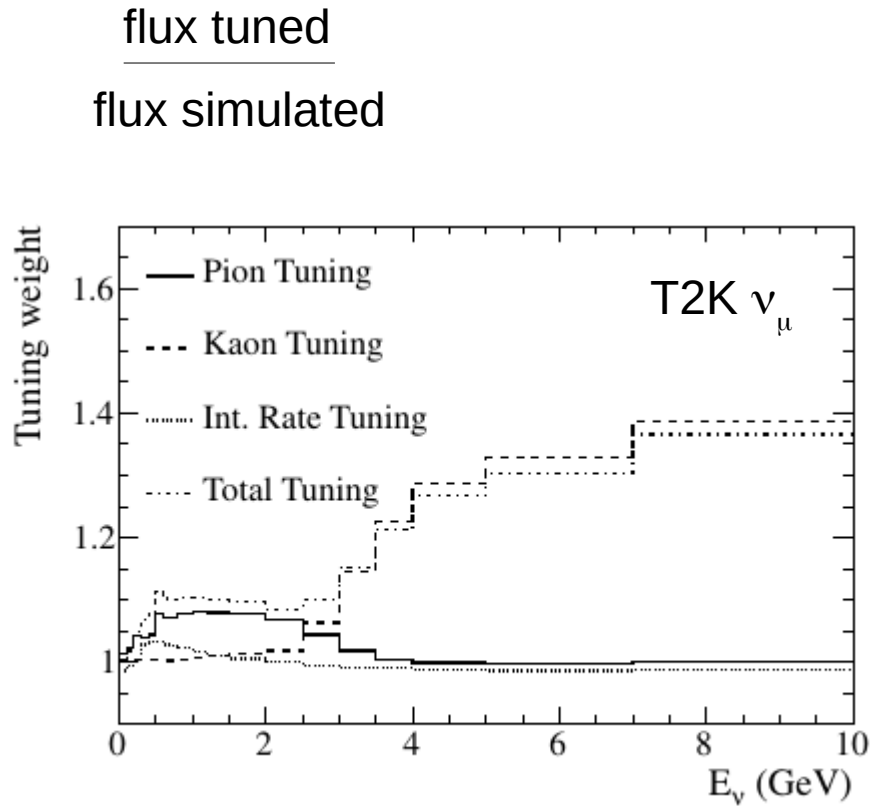
$$W = \frac{P(x; \sigma'_{prod})}{P(x; \sigma_{prod})}$$

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

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

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

Tuning factors

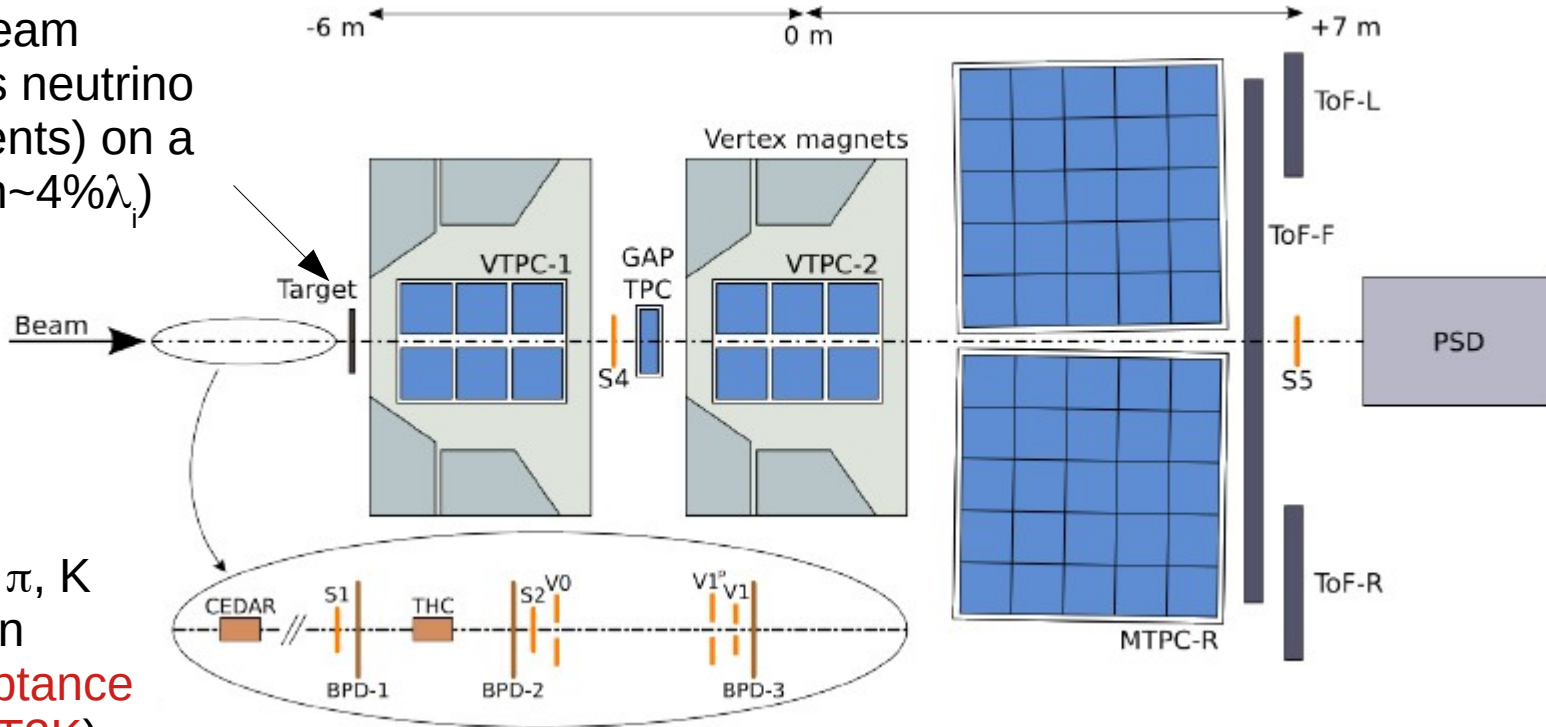


Uncertainties from theory corrections (scaling to different proton energies, targets, not covered phase space...) and from hadro-production data (statistics and systematics uncertainty)

NA61/SHINE

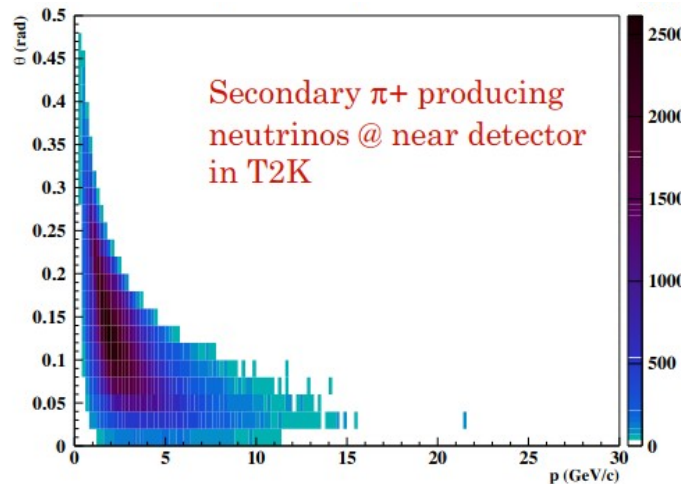
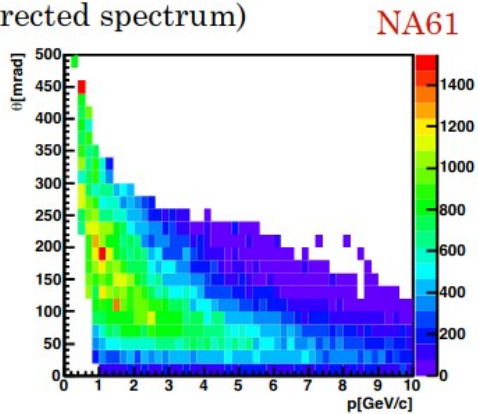
SPS Heavy Ion and Neutrino Experiment: Fixed target experiment using CERN SPS

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



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

Phase space covered by π^+
(corrected spectrum)

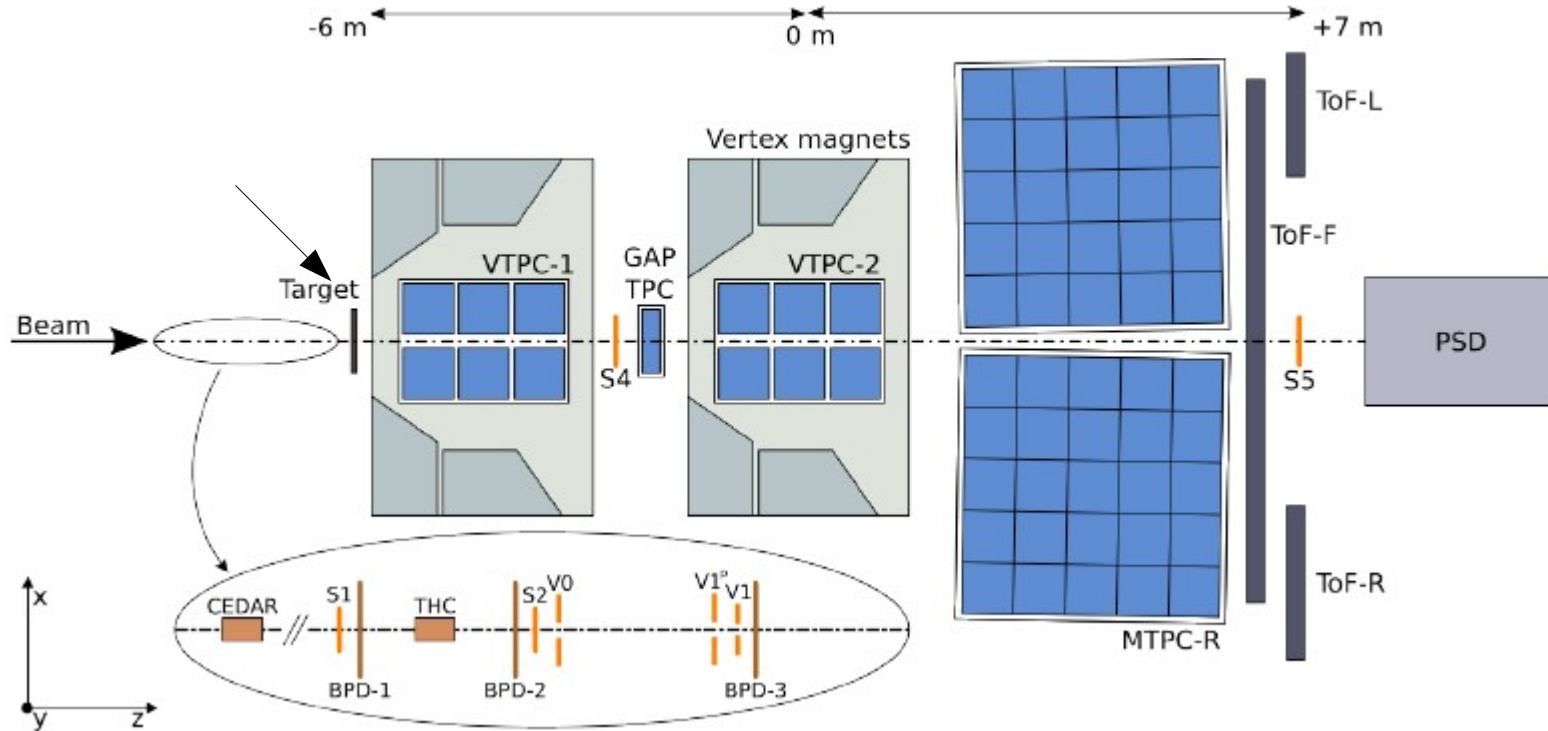


Momentum measurement with
TPC in magnetic field
($\sigma_p/p^2 \sim 0.005 \text{ GeV}^{-1}$)

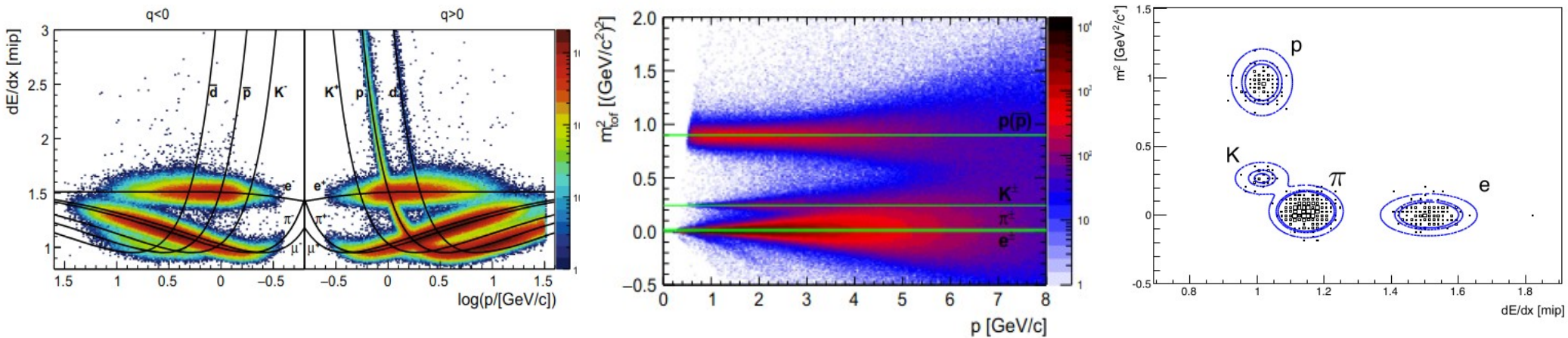
Angular measurement
with 3-4 mrad resolution

NA61/SHINE

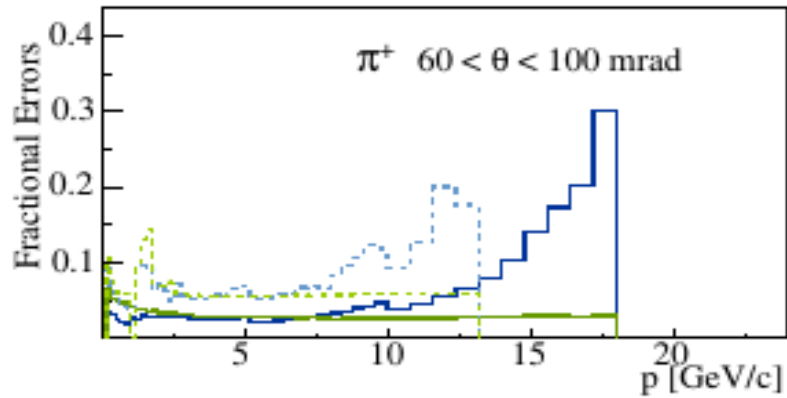
SPS Heavy Ion and Neutrino Experiment: Fixed target experiment using CERN SPS



dE/dx + ToF measurement for clean PID

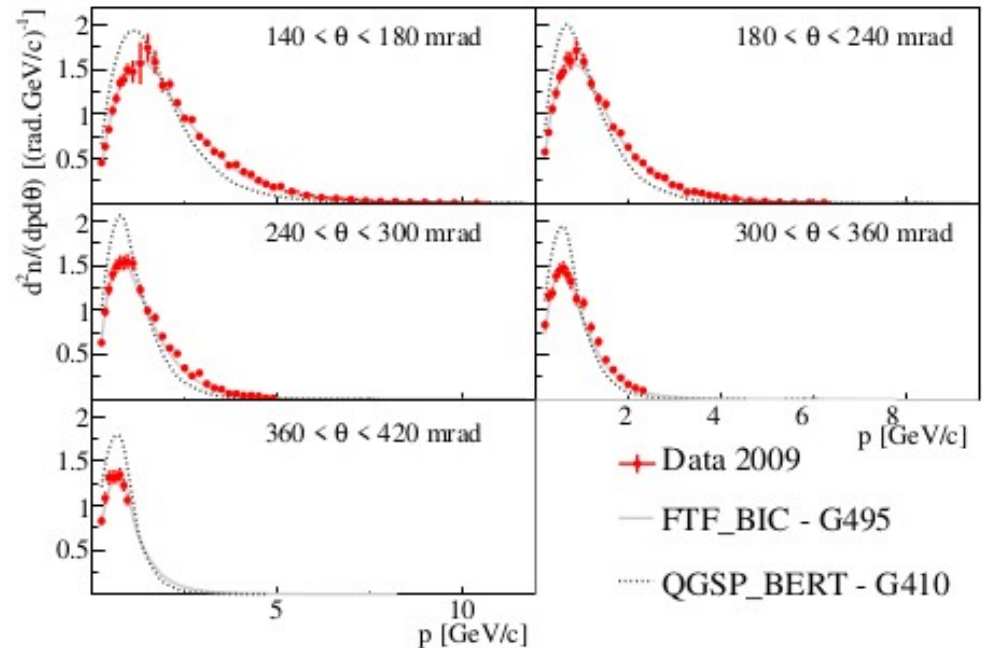
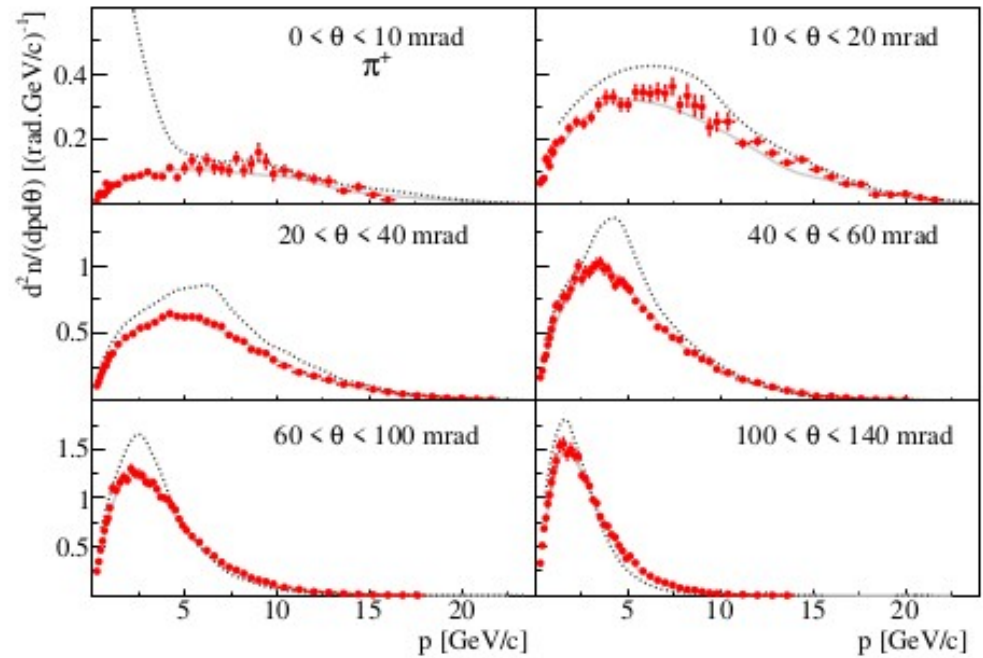


(Old) results

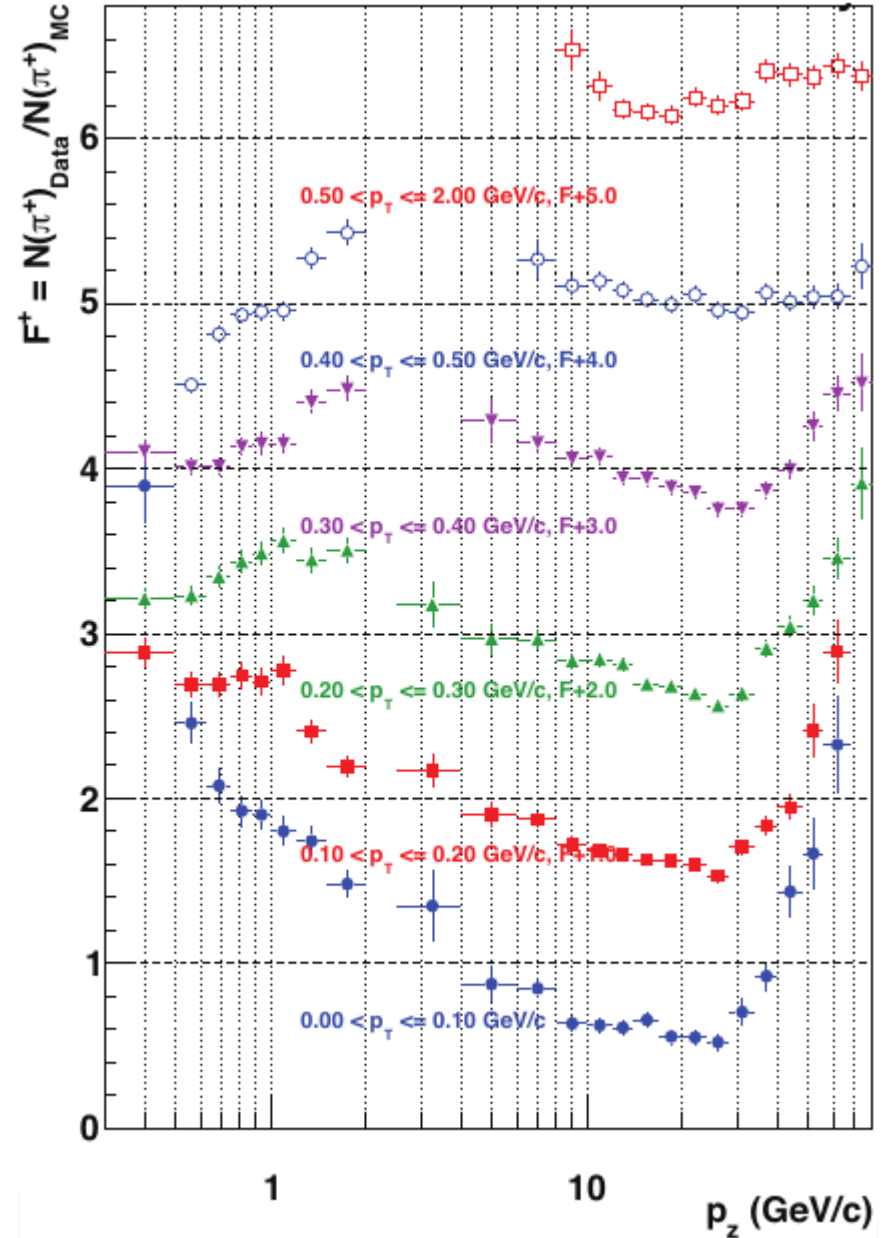
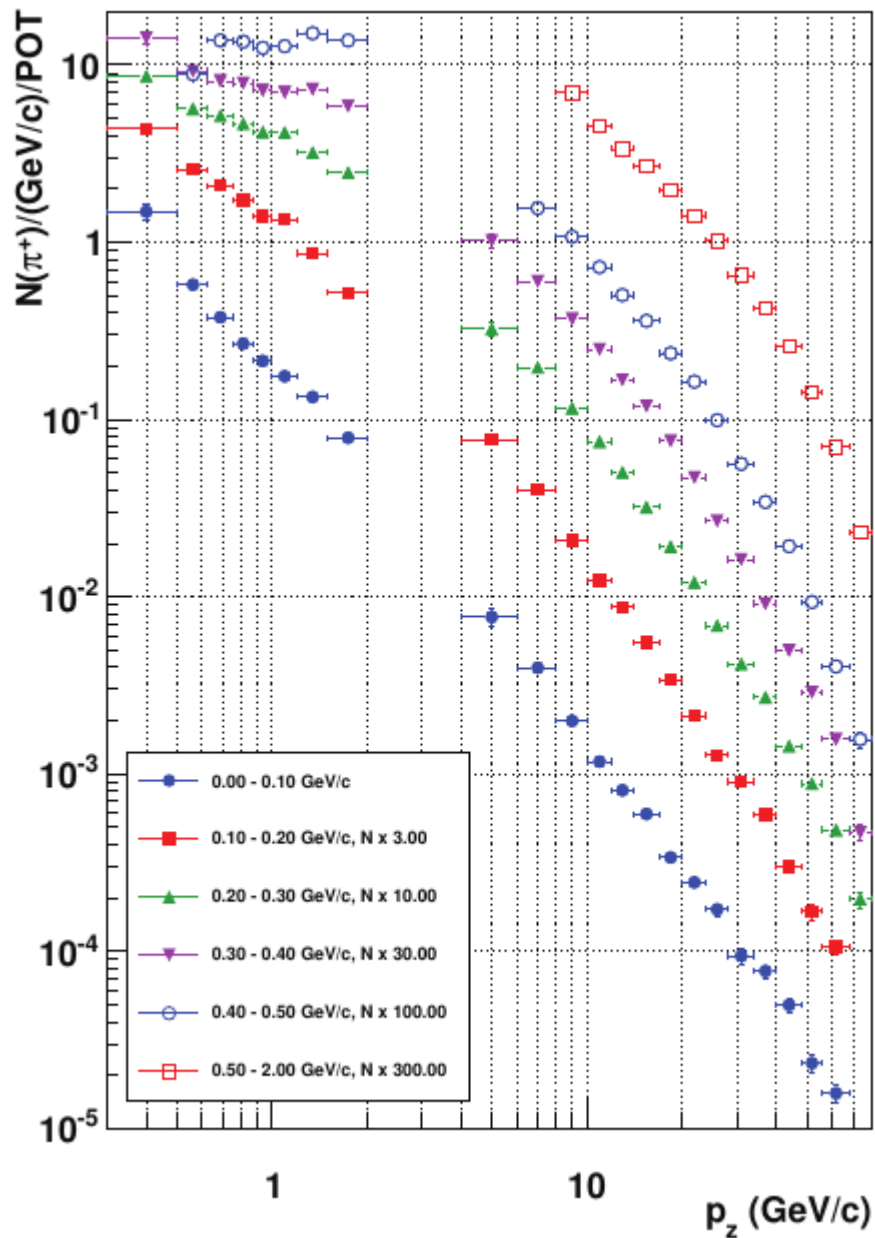


- - - 2007 stat. error — 2009 stat. error
 - - - 2007 syst. error — 2009 syst. error

Full measurement of π^+ , π^- , K^+ , K^-



MIPP results for NuMI



Cross-section normalization

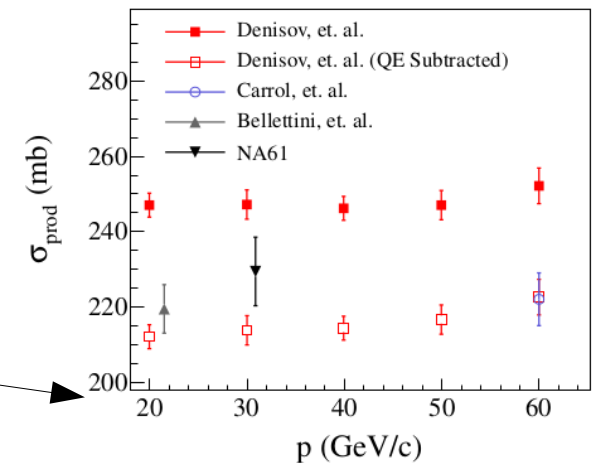
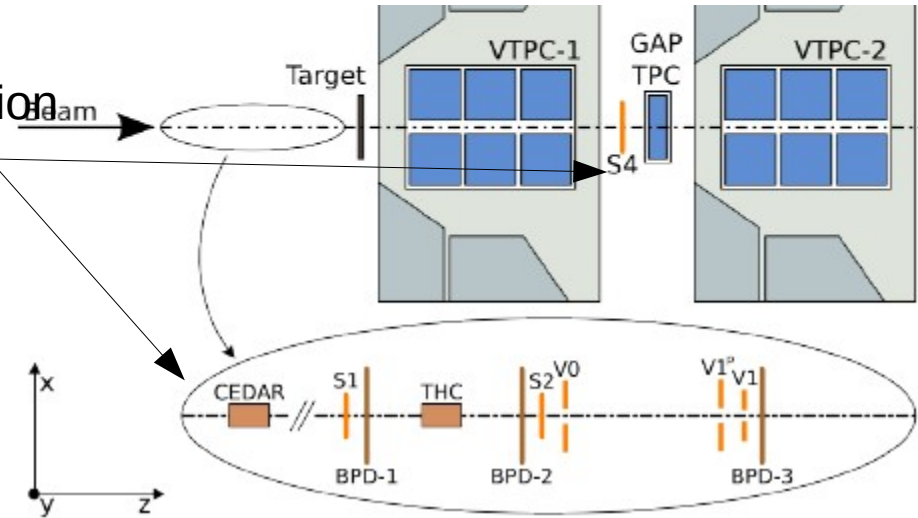
$$\sigma_{hadroprod} = \sigma_{tot} - \sigma_{el} - \sigma_{qe}$$

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)

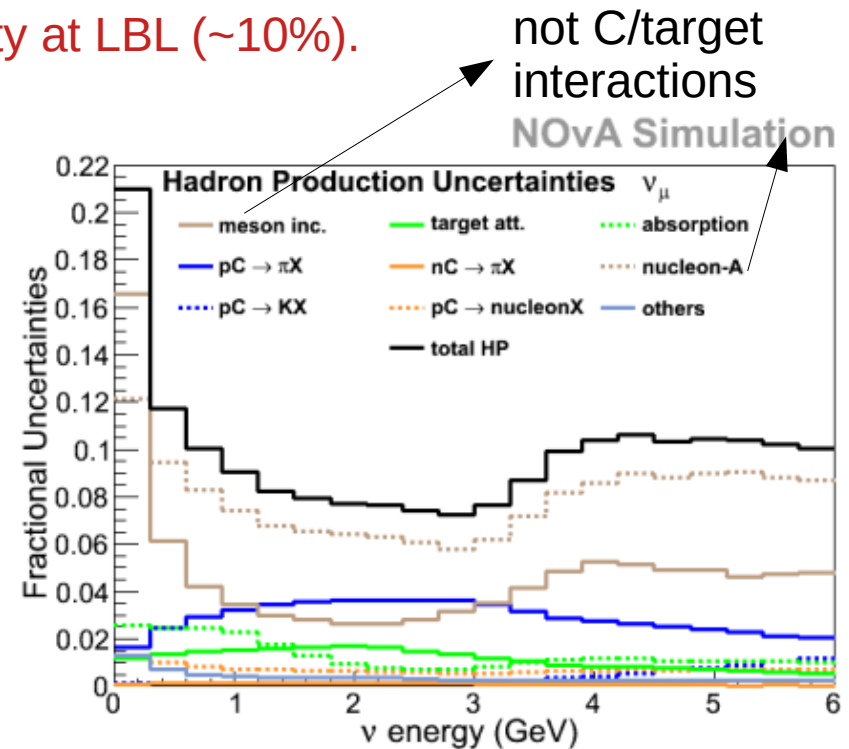
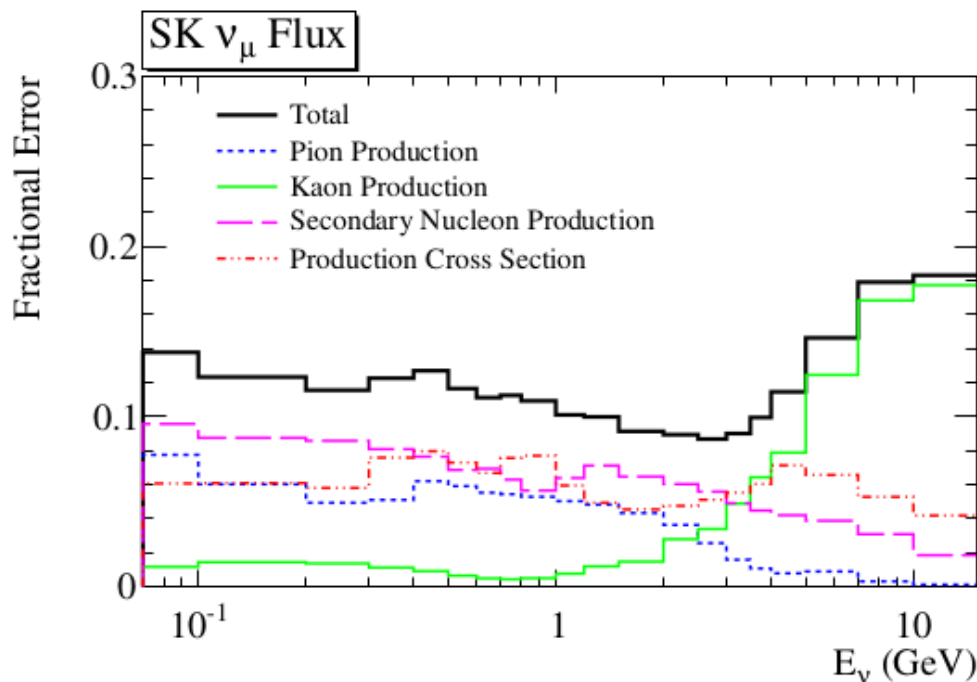


$$\sigma_{prod} = 230.7 \pm 2.8(\text{stat}) \pm 1.2(\text{det}) \begin{matrix} +6.3 \\ -3.5 \end{matrix}(\text{mod}) \text{ mb}$$

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%).



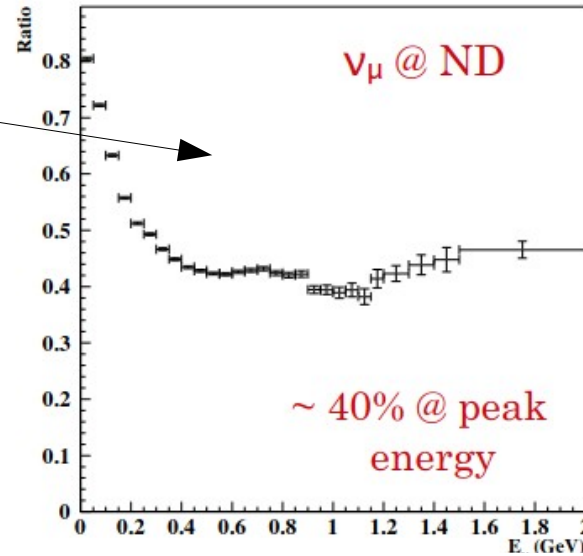
The remaining uncertainties were dominated by the total production cross-section and re-interactions in the horns

→ new NA61 measurement ‘more directly portable’ to T2K

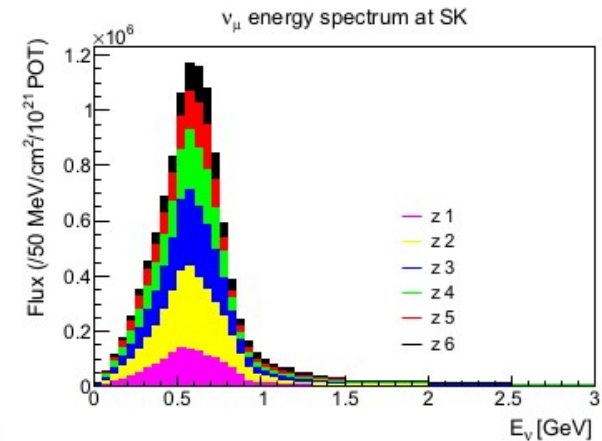
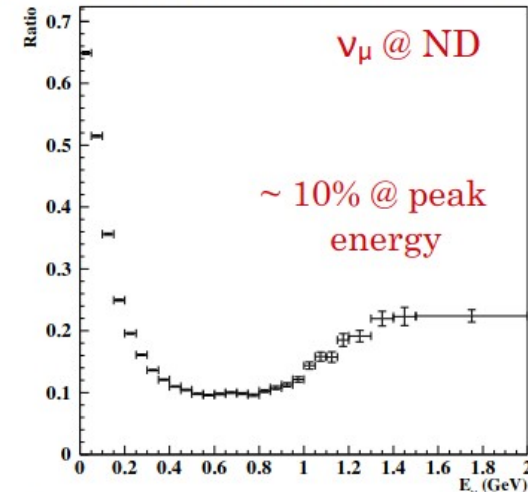
Need for replica target: T2K example

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

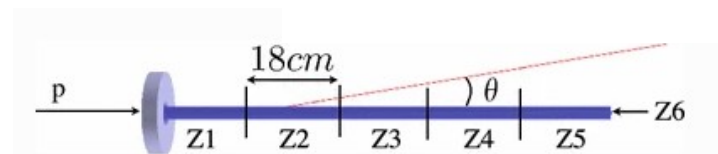
→ **measurement of hadro-production with 'replica target'** (= same target geometry as the neutrino experiment) allows to tune 90% of the flux (60% with thin target)



re-interactions in the beamline

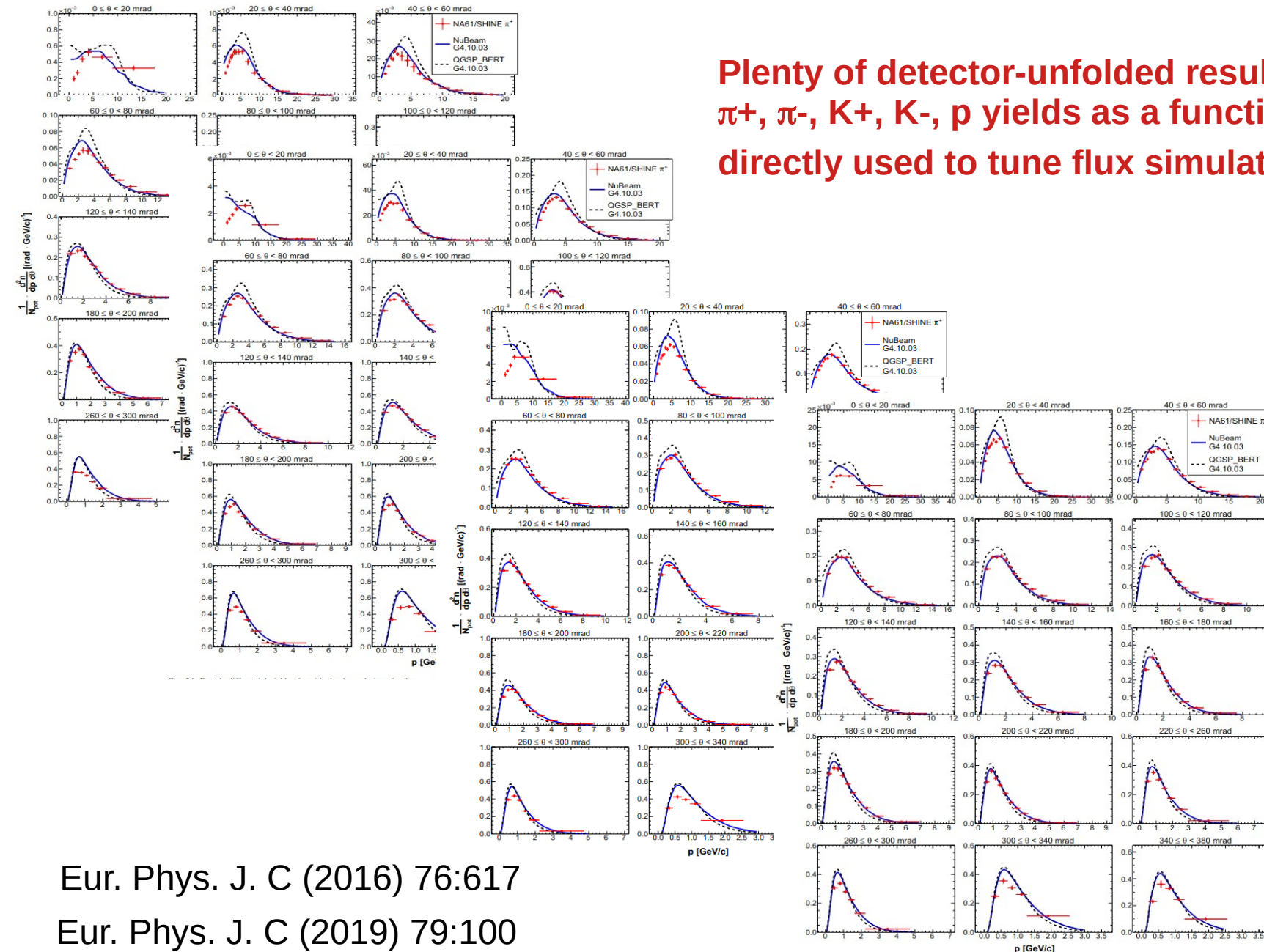


Measurements of **hadron multiplicity vs angle and momentum ($dn/dpd\theta$) in longitudinal bins of the target** (particles in different longitudinal bins follow a different path inside the horns and are focused differently)



NA61 results with replica target

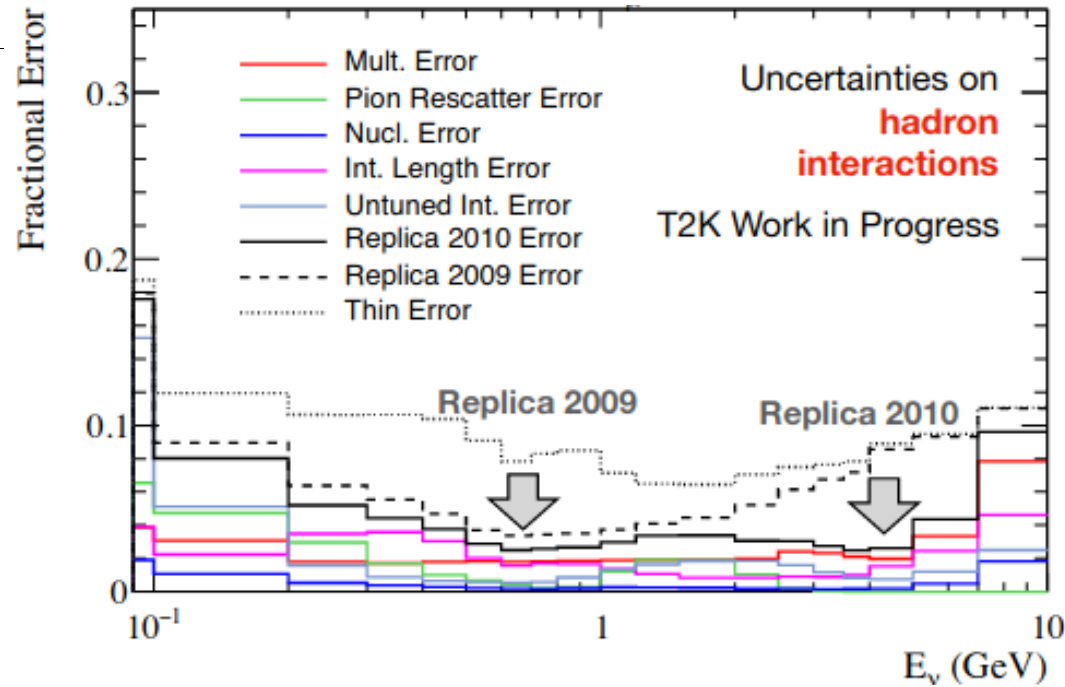
Plenty of detector-unfolded results:
 π^+ , π^- , K^+ , K^- , p yields as a function of p , θ , z_{target}
 directly used to tune flux simulation



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

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

Flux uncertainties

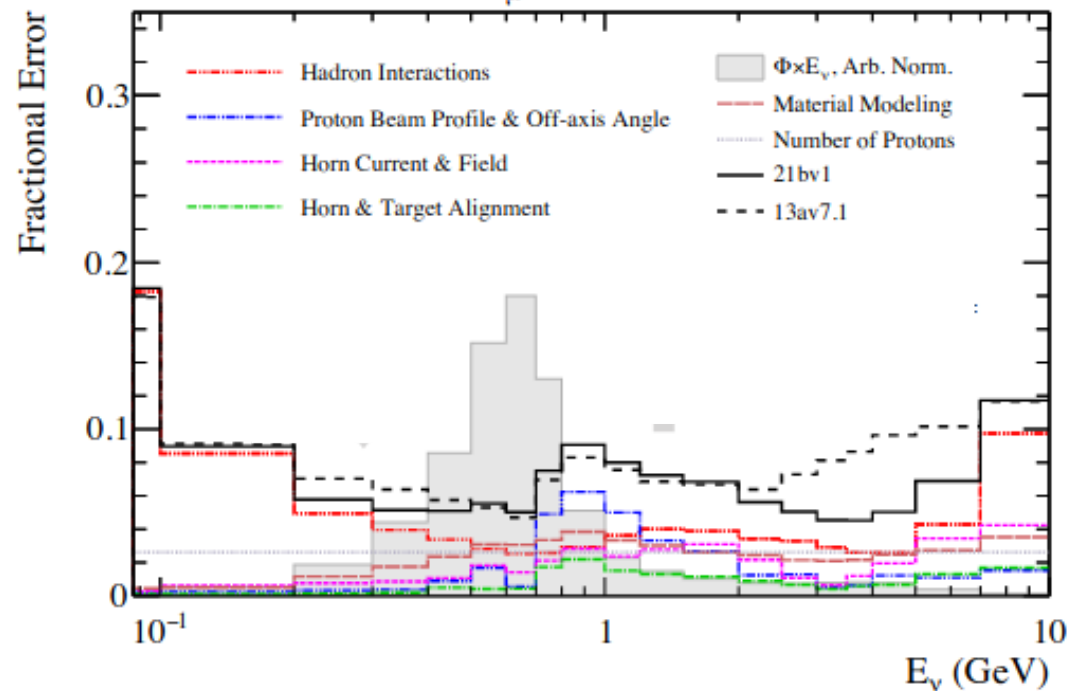


Huge improvement (~factor 2) of hadron-interaction uncertainties using NA61/SHINE replica target data (<5% in the flux peak)

Total flux uncertainties today:

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

SK: Neutrino Mode, ν_μ



Future prospects

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

Horn Mode	Fraction of Hadronic Interactions			
	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

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

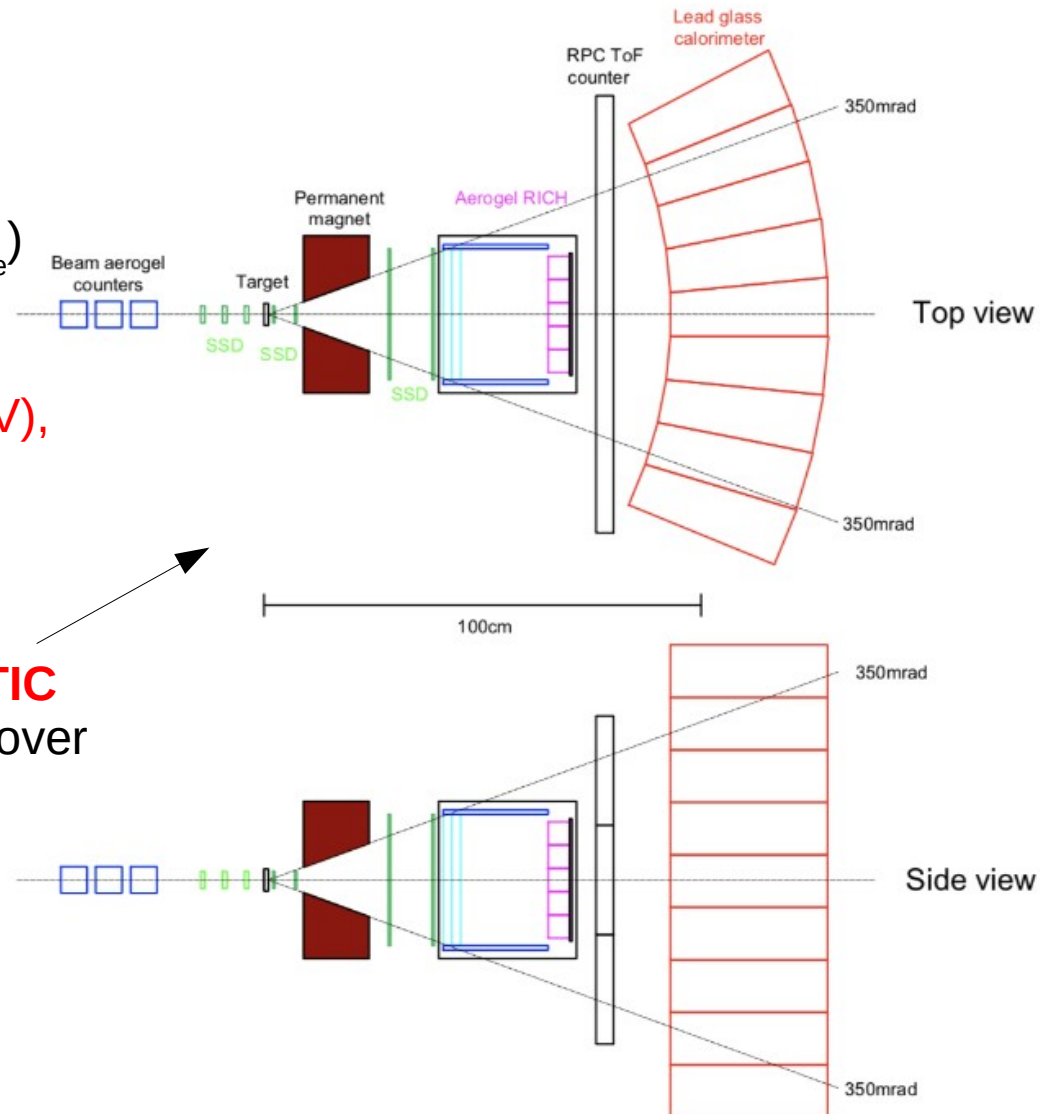
Horn Mode	Fraction of Hadronic Interactions			
	ν_μ	$\bar{\nu}_\mu$	ν_e	$\bar{\nu}_e$
Neutrino Mode	0.97	0.87	0.91	0.77
Antineutrino Mode	0.87	0.96	0.77	0.92

- 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)**

- **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!)



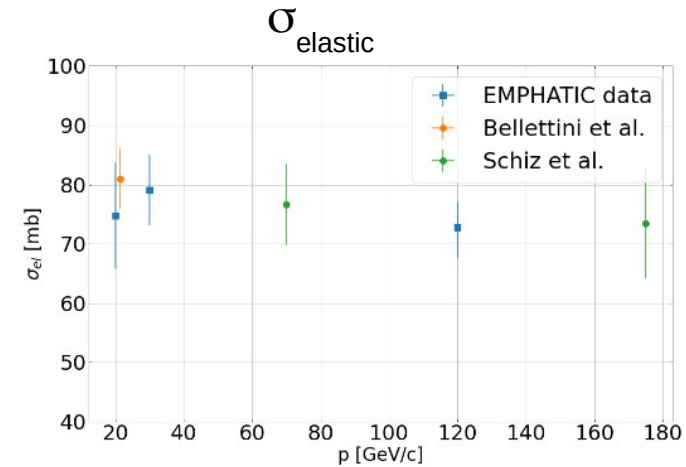
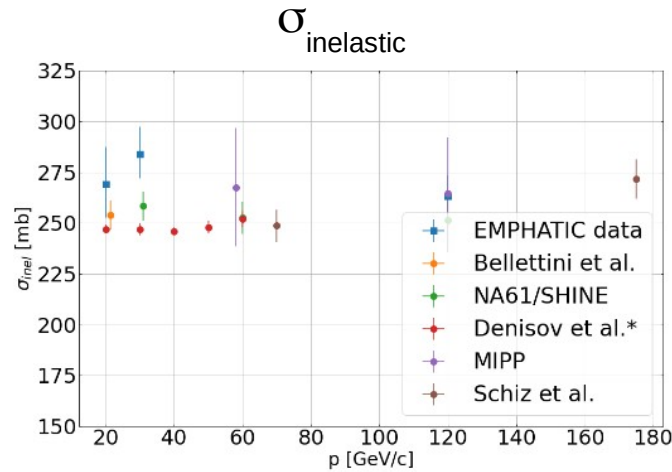
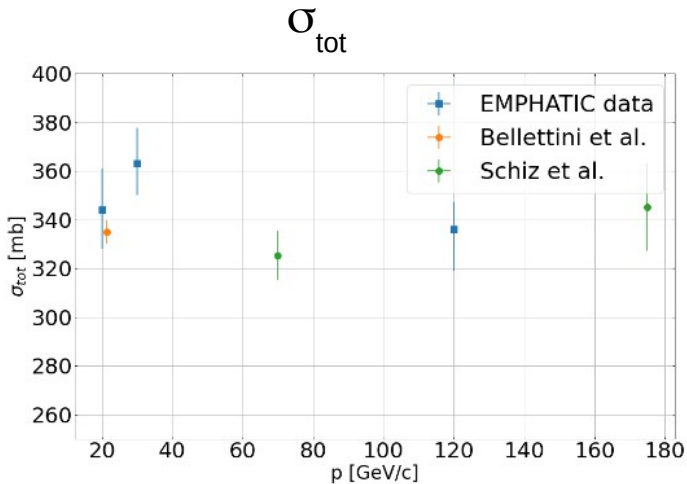
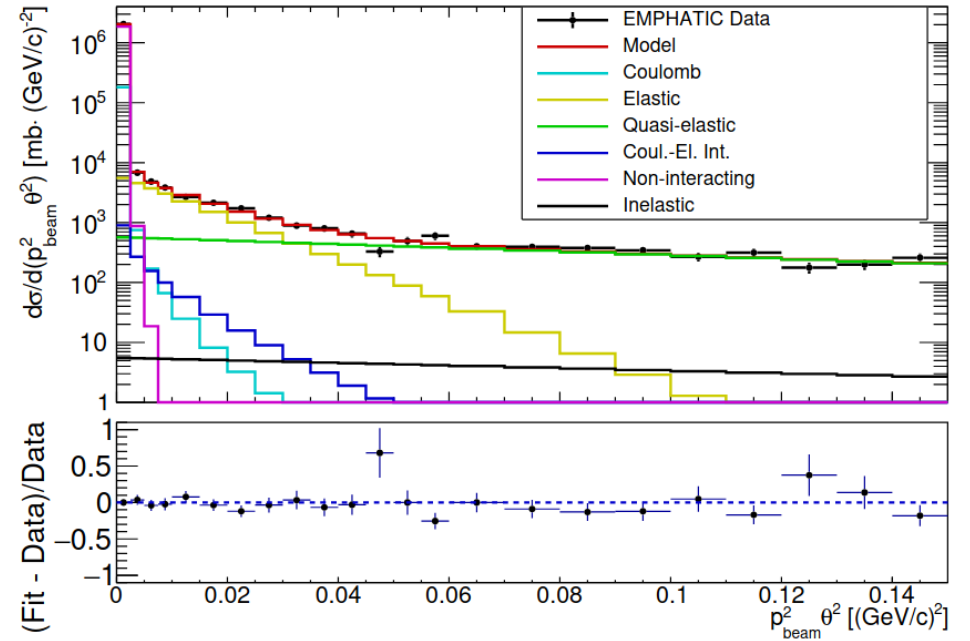
EMPHATIC first results

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

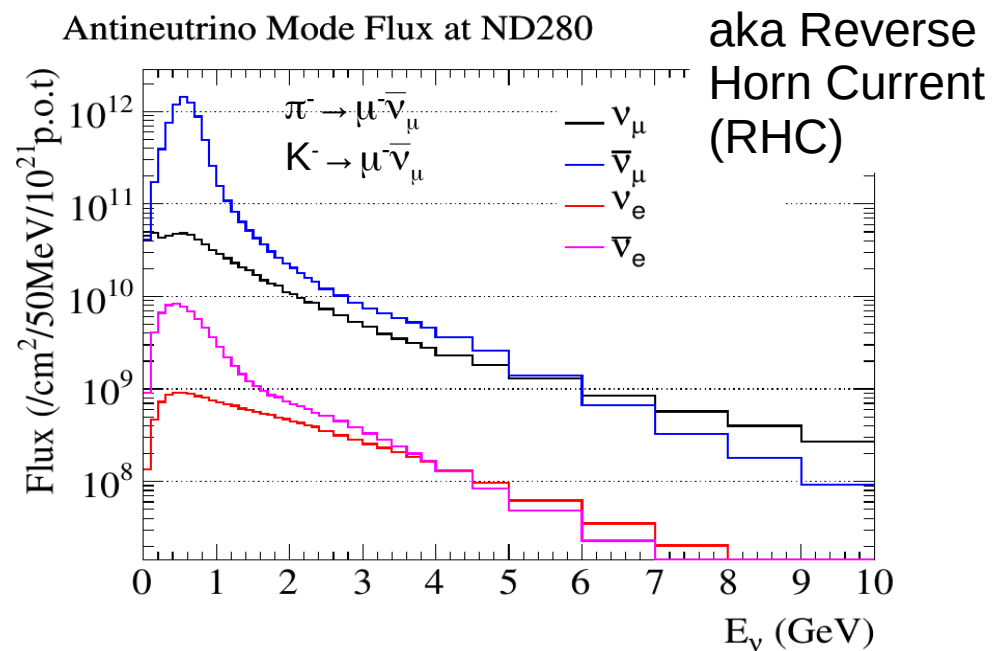
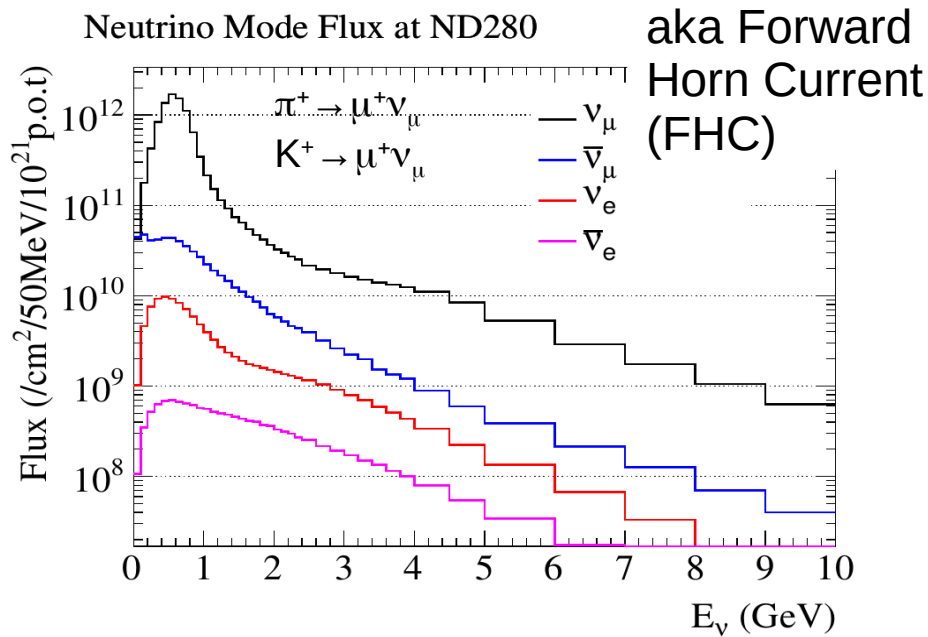
First pilot run for proof of principle

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

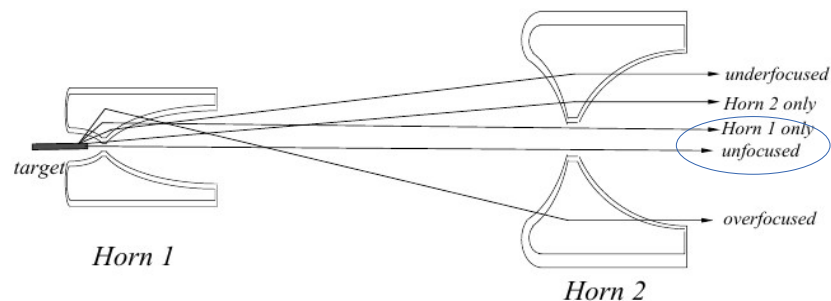
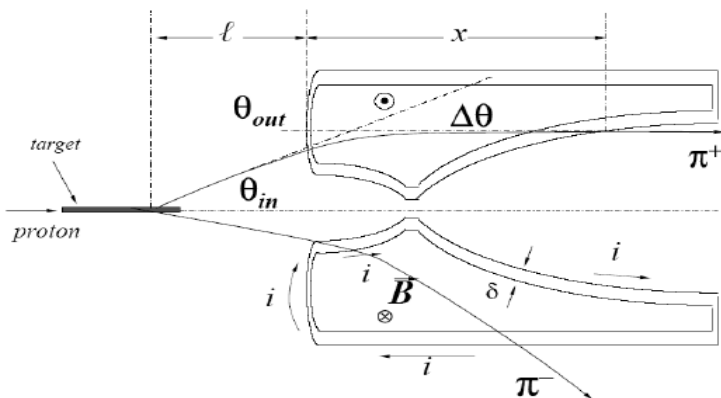


Flux in accelerator experiments

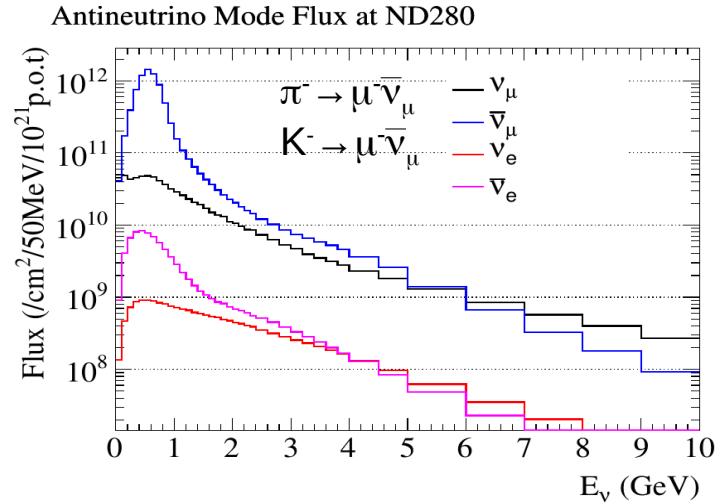
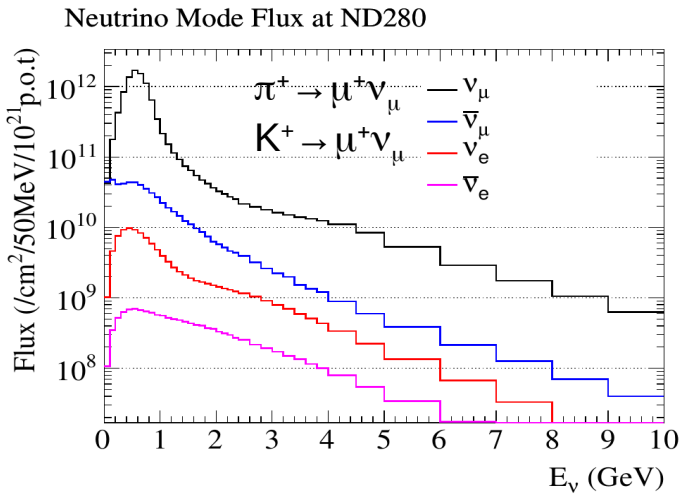
Flux in T2K: wrong sign



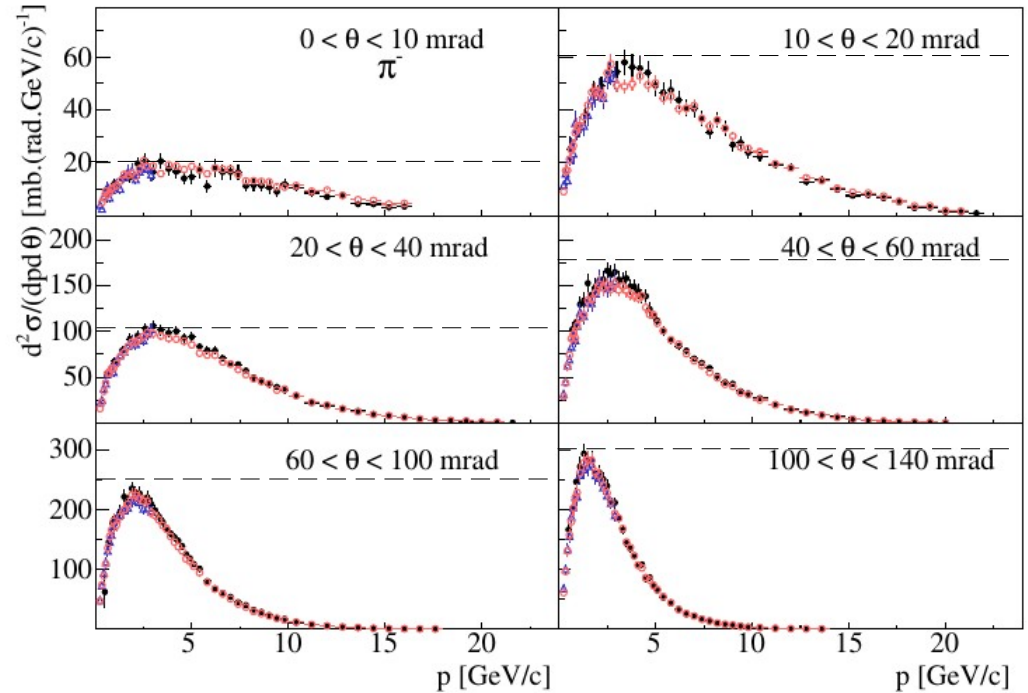
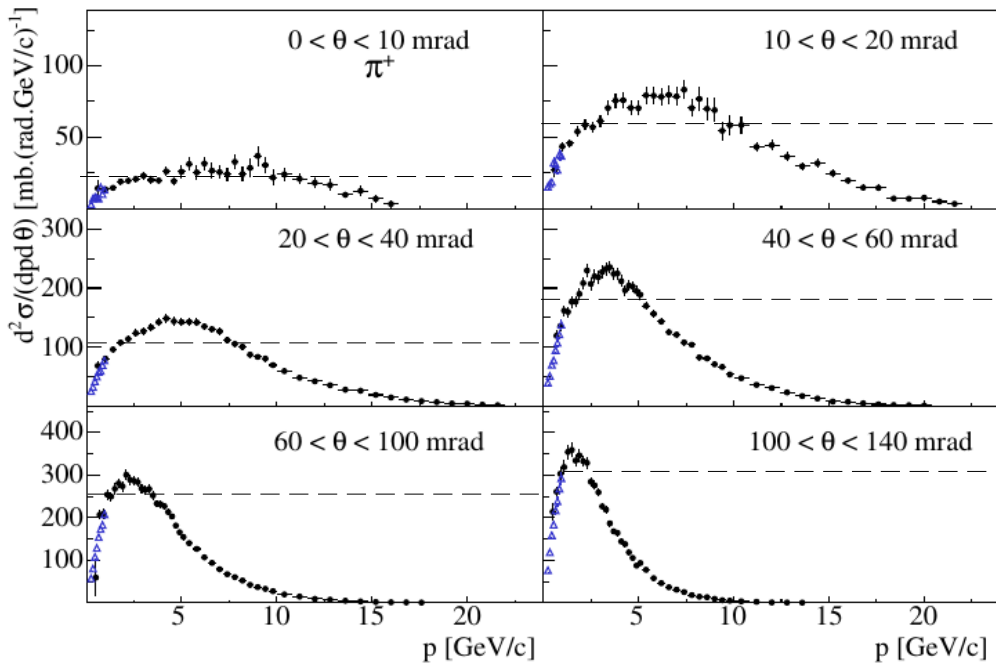
The 'wrong sign' background (important for δ_{CP} and MO) comes from high p_L pions (kaons) which cannot be defocused properly because they miss the horns
 → fractional contribution larger at high neutrino energies



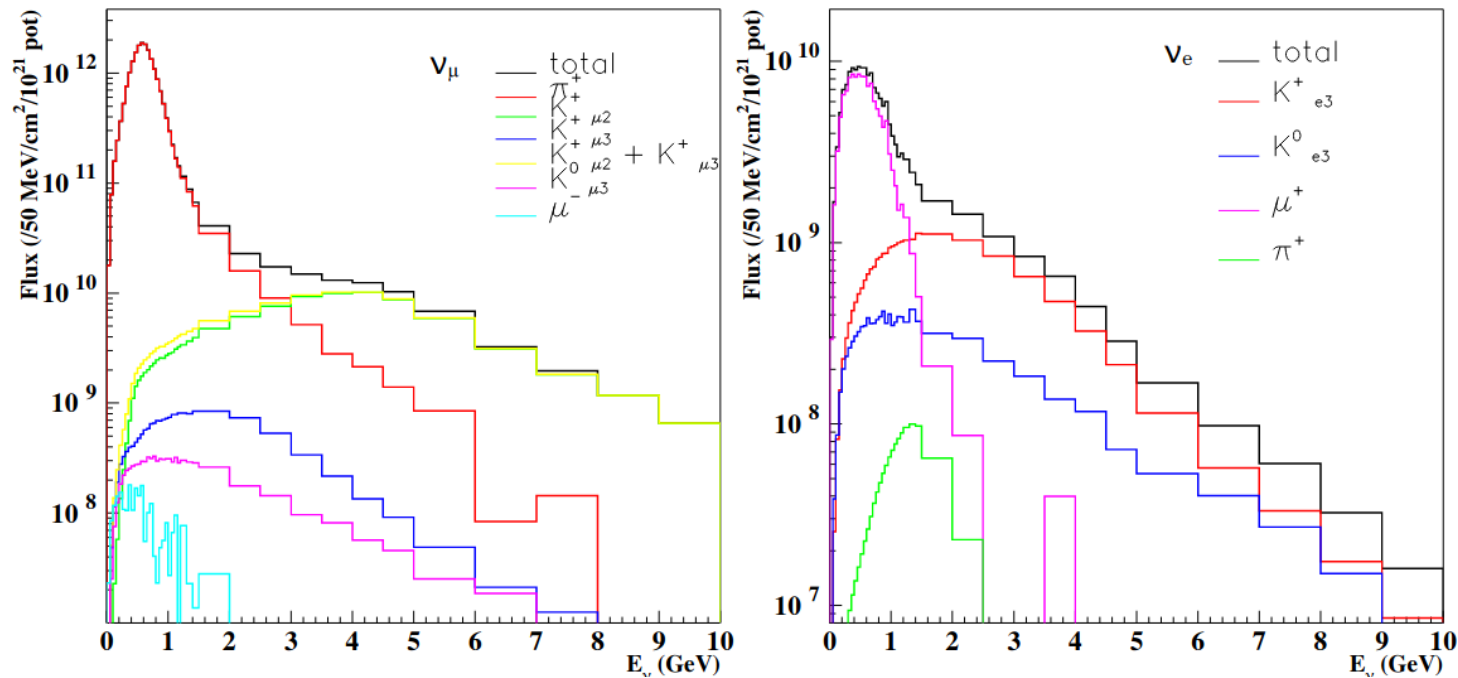
Flux in T2K: wrong sign



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



ν species	Source											
	Flux		π^+ or π^-		K^+ or K^- (K2)		K^+ or K^- (K3)		K_L^0		μ^+ or μ^-	
	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

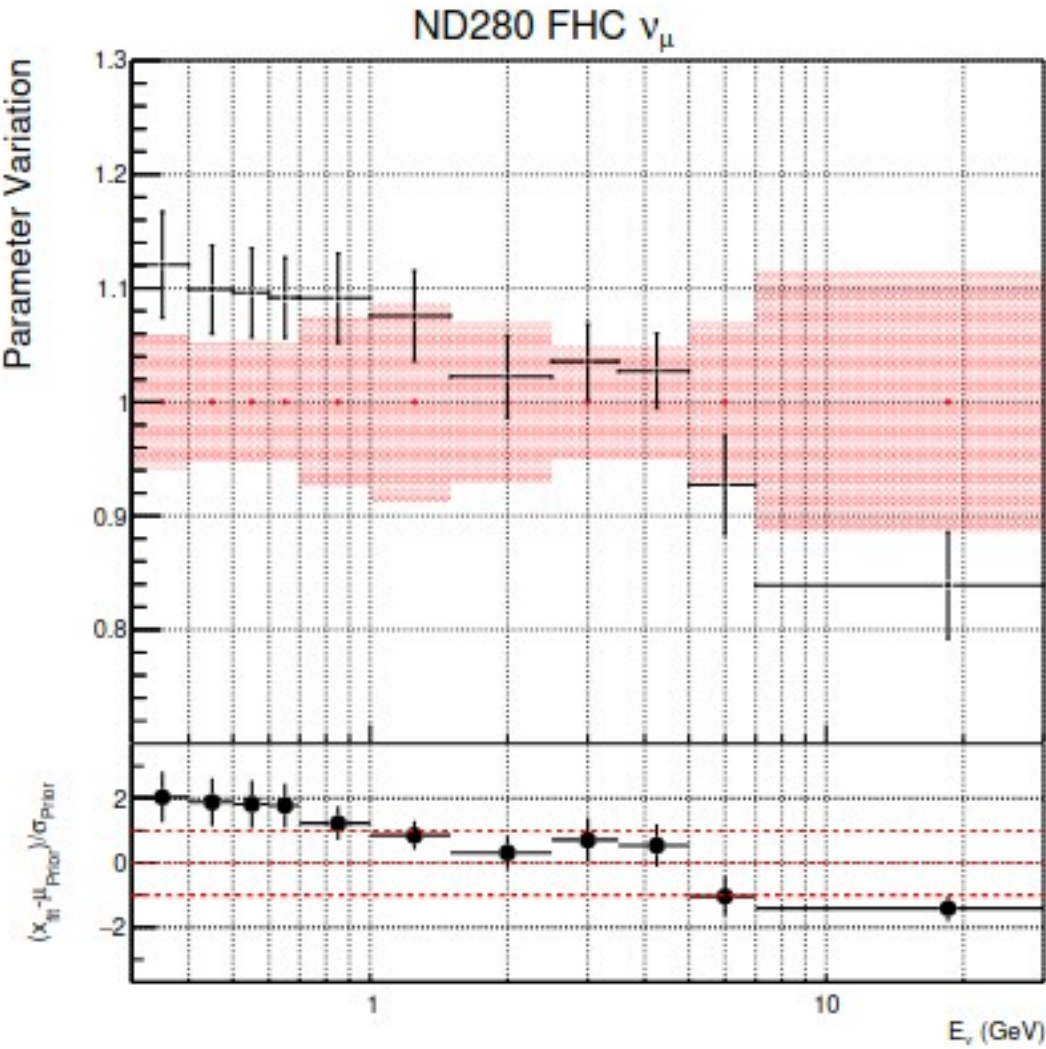
- Small intrinsic background to ν_e appearance measurements (important for δ_{CP} and MO).
- It can also be used to measure ν_e xsec at the near detector (with limited statistics)

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

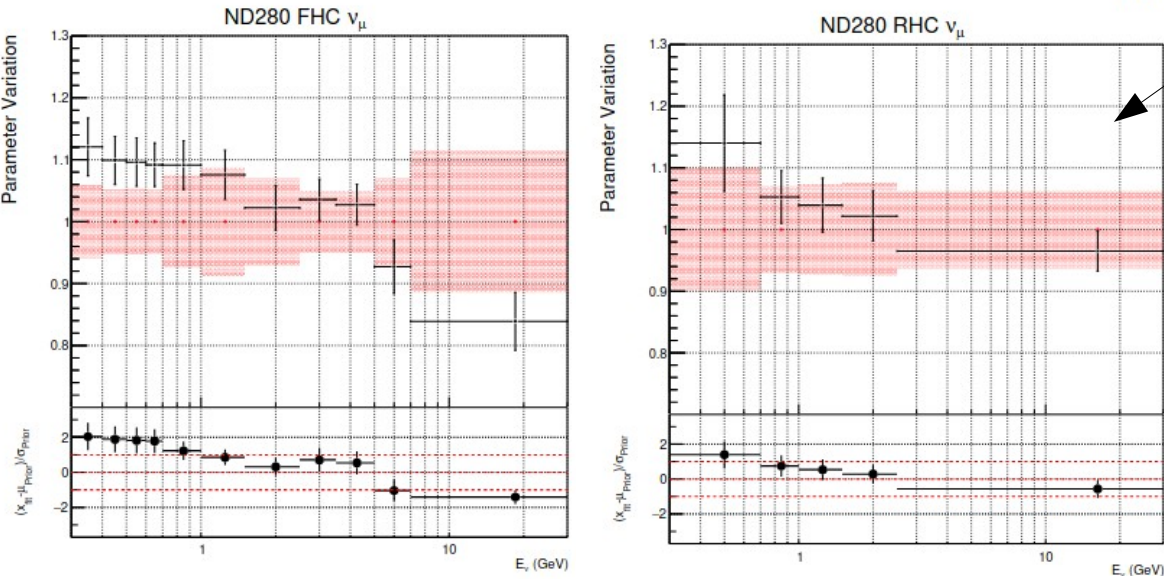
$$N_{\nu_\alpha}^{ND}(E_\nu) = \phi(E_\nu) \times \sigma(E_\nu) dE_\nu$$



Flux constraint from the ND

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

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

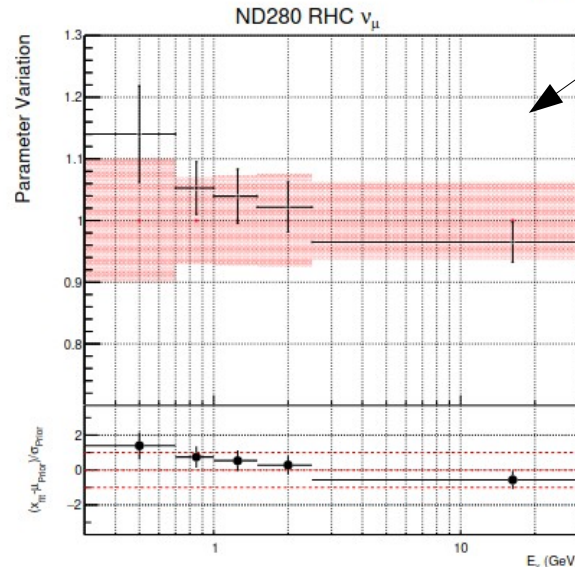
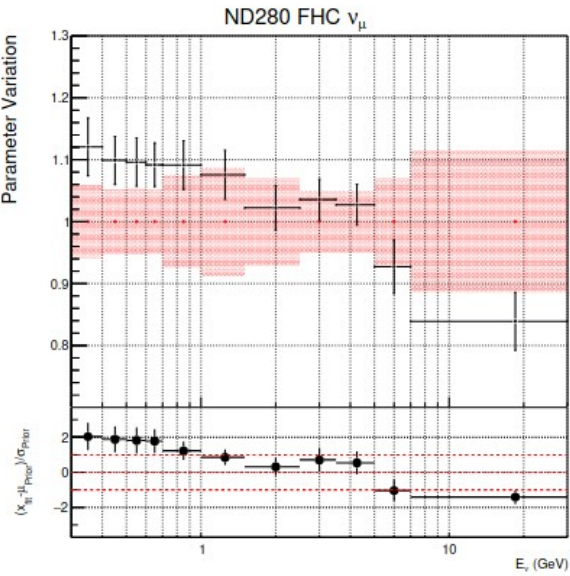


ND280
magnetized
→ measurement
of wrong sign
background

Flux constraint from the ND

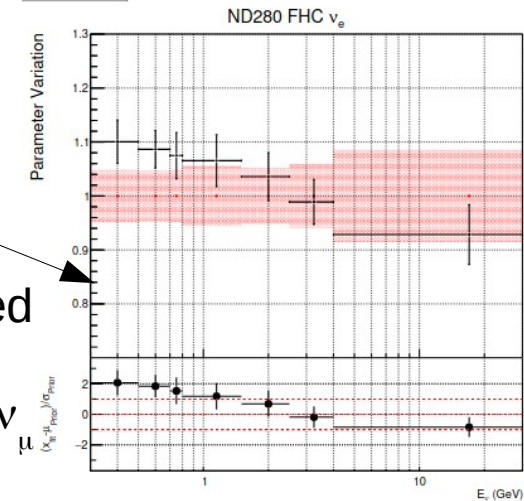
The ND measures the rate of neutrinos therefore it further constrain the flux

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



ND280 magnetized
→ measurement of wrong sign background

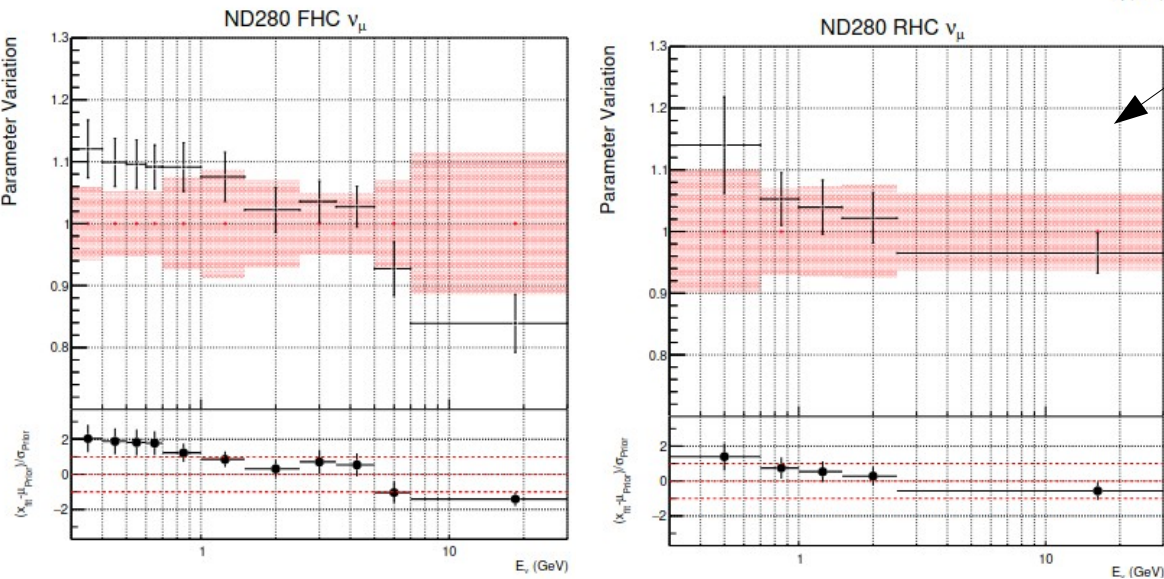
Low intrinsic ν_e stat → constrained only through correlations with ν_μ



Flux constraint from the ND

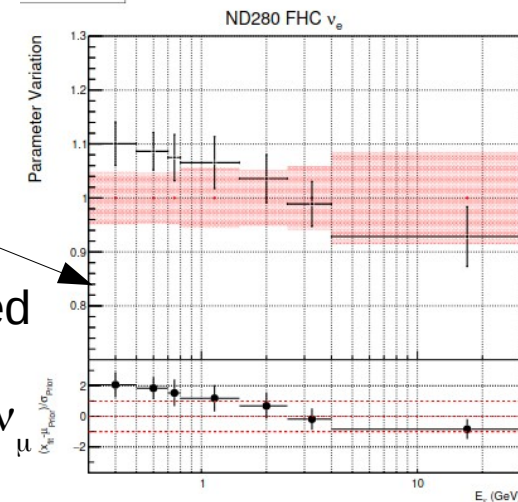
The ND measures the rate of neutrinos therefore it further constrain the flux

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



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

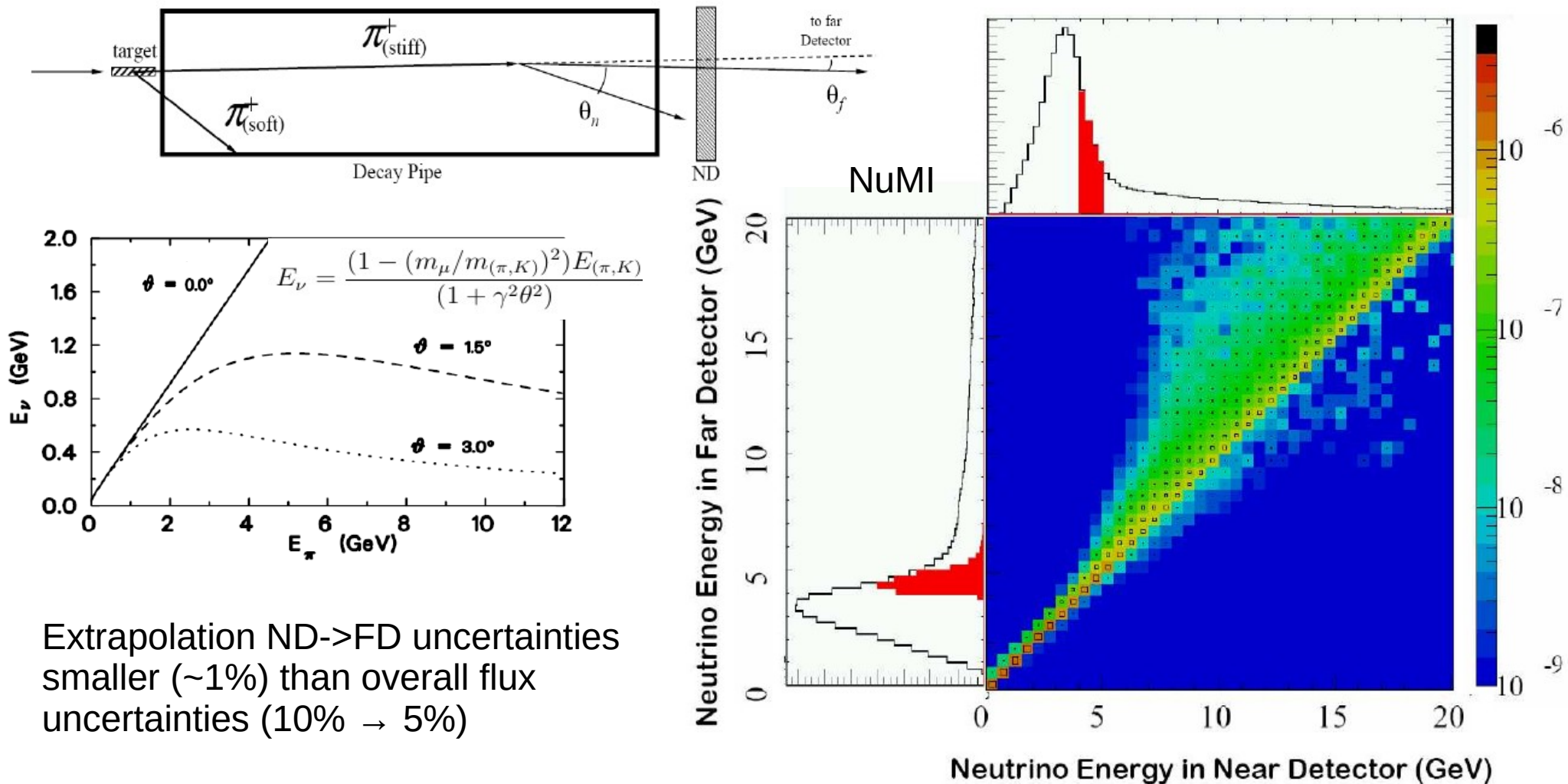
(would be 5-10% if uncorrelated)

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

From ND to FD flux extrapolation

$$\frac{N_{\nu_{\alpha'}}^{FD}(E_{\nu})}{N_{\nu_{\alpha}}^{ND}(E_{\nu})} \approx P_{\nu_{\alpha} \rightarrow \nu_{\alpha'}}(E_{\nu}) \times \frac{\phi_{\nu_{\alpha'}}^{FD}(E_{\nu})}{\phi_{\nu_{\alpha}}^{ND}(E_{\nu})} \times \frac{\sigma_{\nu_{\alpha'}}^{FD}(E_{\nu})}{\sigma_{\nu_{\alpha}}^{ND}(E_{\nu})}$$

Different acceptance of pion angles \rightarrow different neutrino energies for same pion kinematics



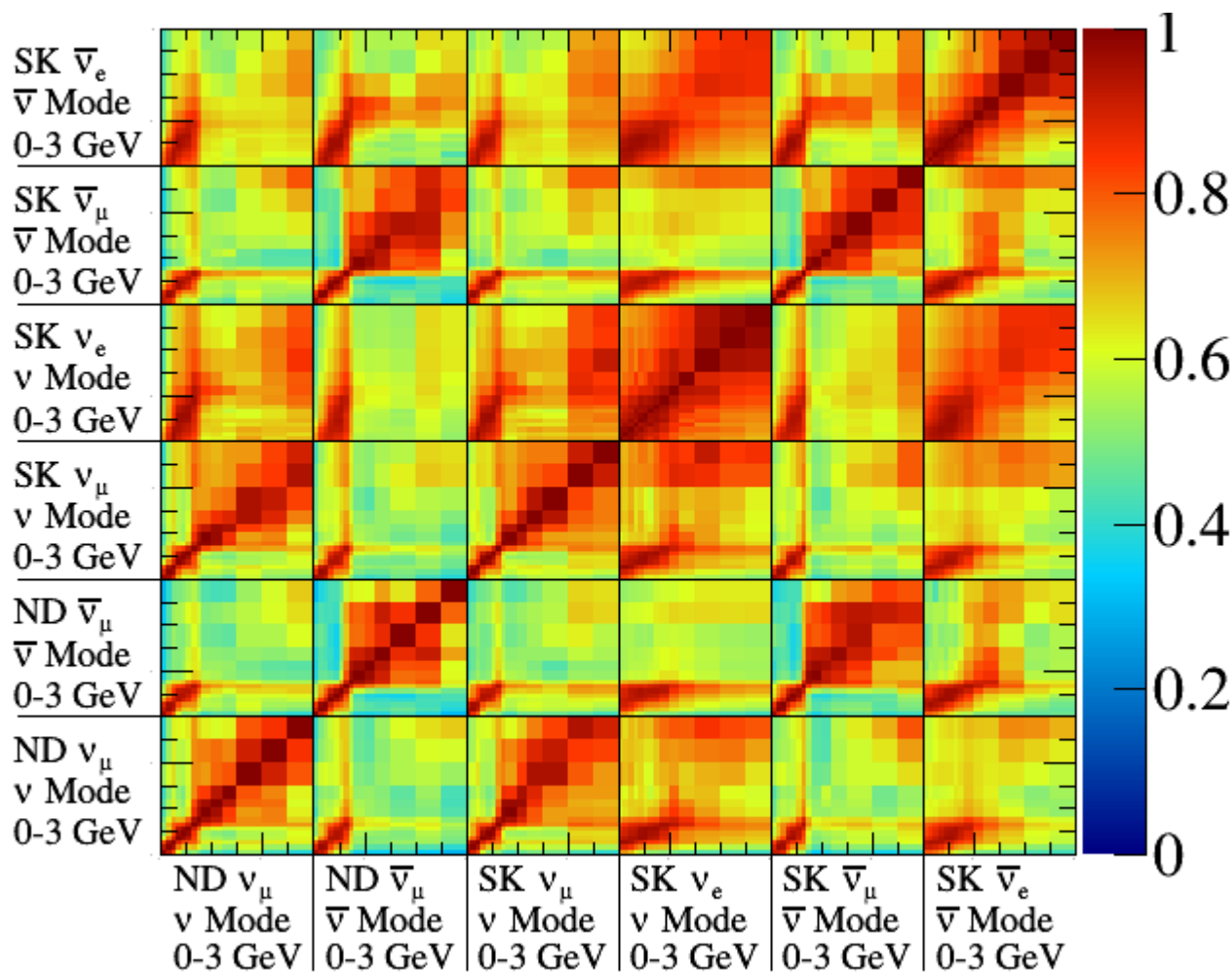
Extrapolation ND \rightarrow FD uncertainties smaller ($\sim 1\%$) than overall flux uncertainties (10% \rightarrow 5%)

Flux correlations

Flux Correlations

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

T2K

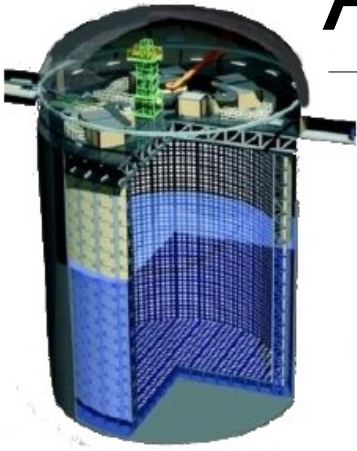


- **large correlation between ND and SK fluxes**
- Large correlations between different bins in the same 'mode' → **flux uncertainty is to large extent an overall normalization** (shape uncertainties are smaller)
- **Correlations between different modes and neutrino flavors:** (to a certain extent) we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

End of first lecture

Neutrino oscillation measurements (mostly) in T2K and NOVA

A bit of (recent) history...

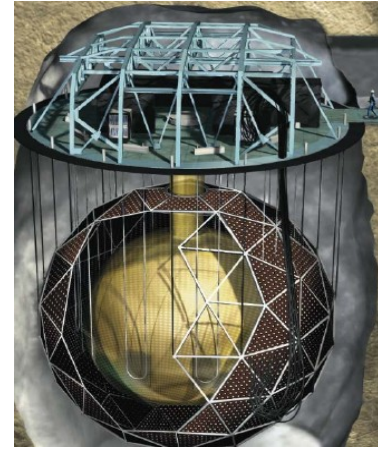


SuperKamiokande
1996 – today!

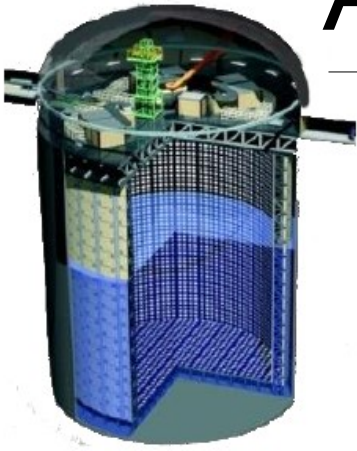
1998 Discovery of ν oscillation
from zenith angle dependence
of atmospheric ν_μ rate

**Sudbury Neutrino
Observatory (SNO)**
1999 – 2006

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



A bit of (recent) history...



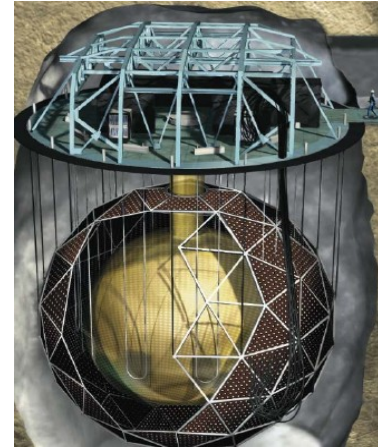
SuperKamiokande
1996 – today!

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



A bit of (recent) history...

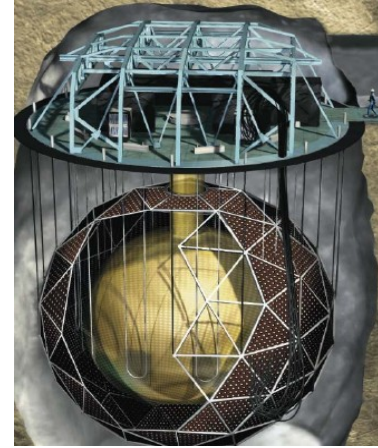


SuperKamiokande
1996 – today!

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

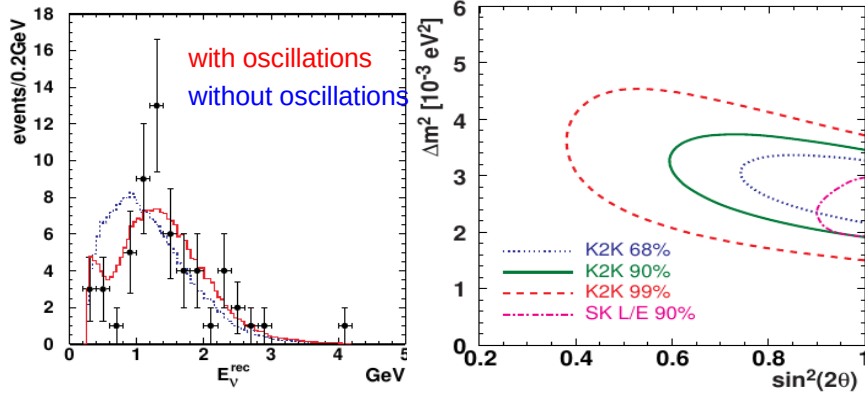
Sudbury Neutrino Observatory (SNO)
1999 – 2006

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



A bit of (recent) history...

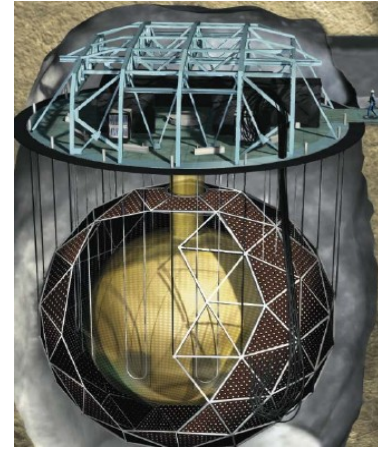


SuperKamiokande
1996 – today!

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

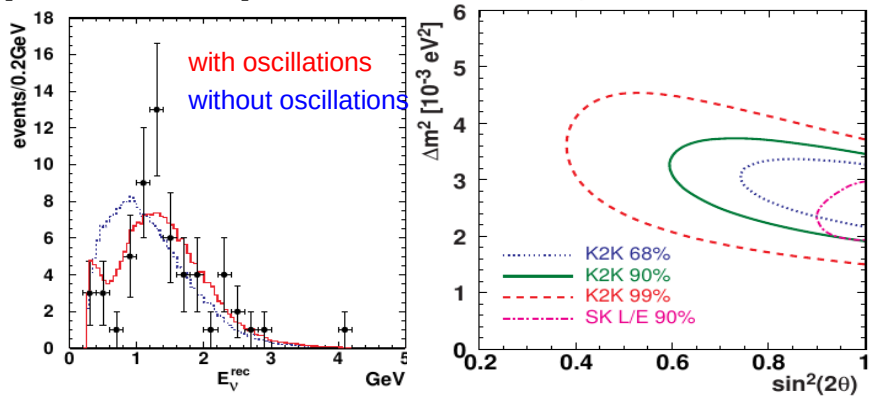
Sudbury Neutrino Observatory (SNO)
1999 – 2006

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



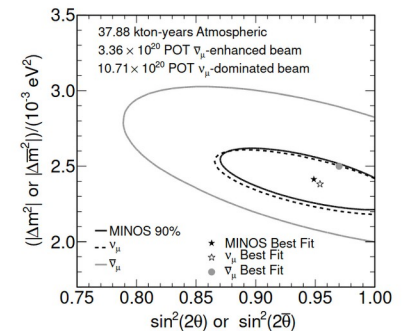
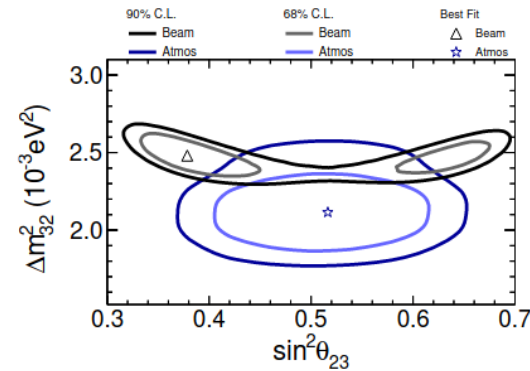
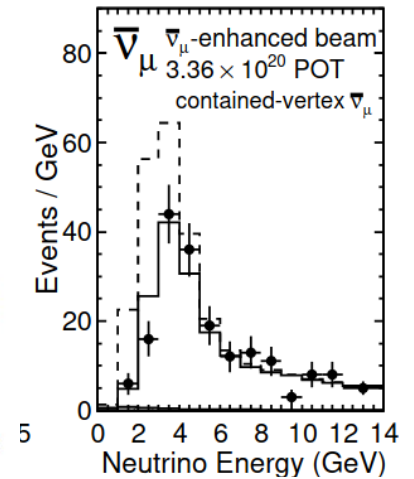
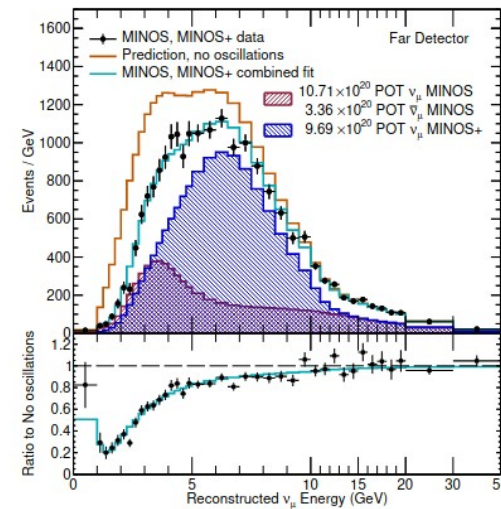
Precision from accelerator experiment:
high purity and tunable neutrino flux

(1999-2006) K2K



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

2003 – 2015 MINOS (→ - 2016 MINOS+)



A bit of (recent) history...

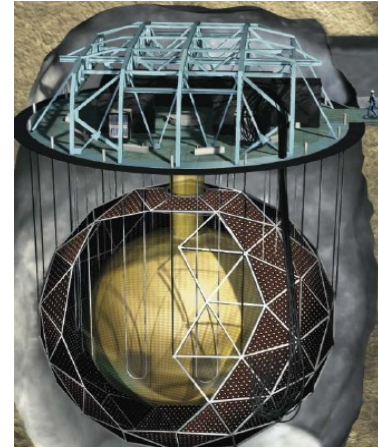


SuperKamiokande
1996 – today!

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

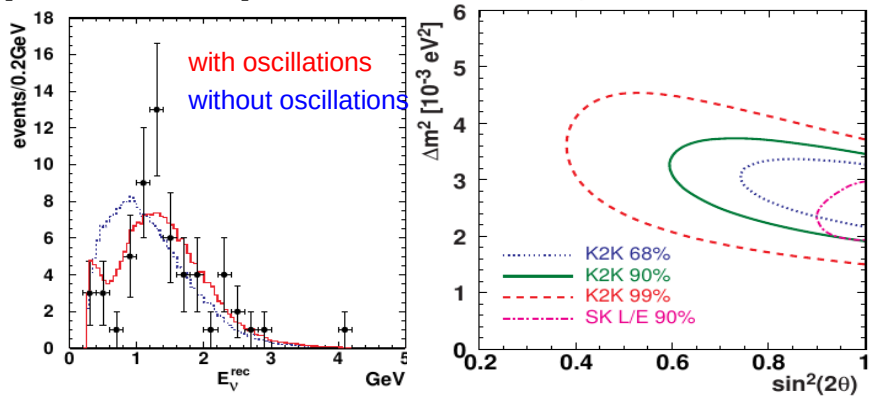
Sudbury Neutrino Observatory (SNO)
1999 – 2006

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

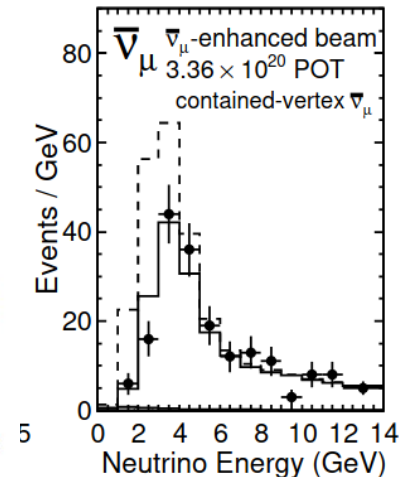
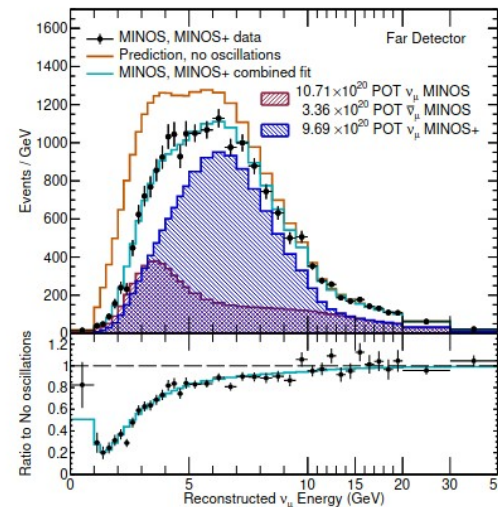


Precision from accelerator experiment:
high purity and tunable neutrino flux

(1999-2006) K2K



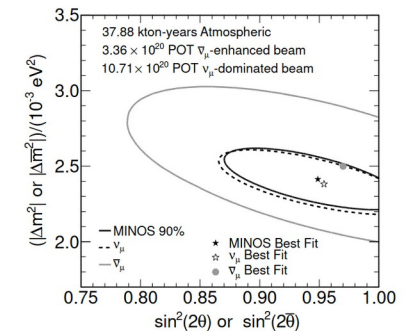
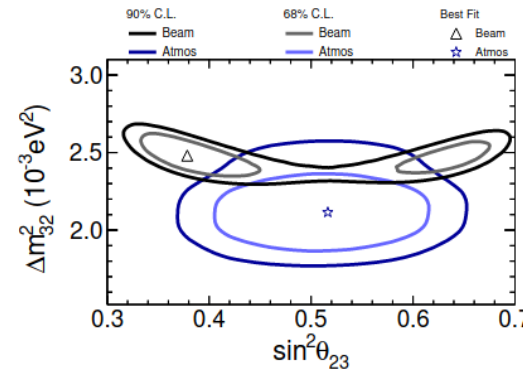
2003 – 2015 MINOS (→ - 2016 MINOS+)



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

Beyond ν_μ disappearance (θ_{23} and Δm_{32}^2): large statistics experiments looking for ν_e appearance

- observation of ν_e appearance
- T2K (2010 - today)**
- to measure θ_{13} , longer baseline:
- NOVA started 2014**
- **T2K Nature 2020 first results on δ_{CP} !**



Status of PMNS measurements: joint fits

Recent reference with full details:

Three flavour oscillation parameters

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

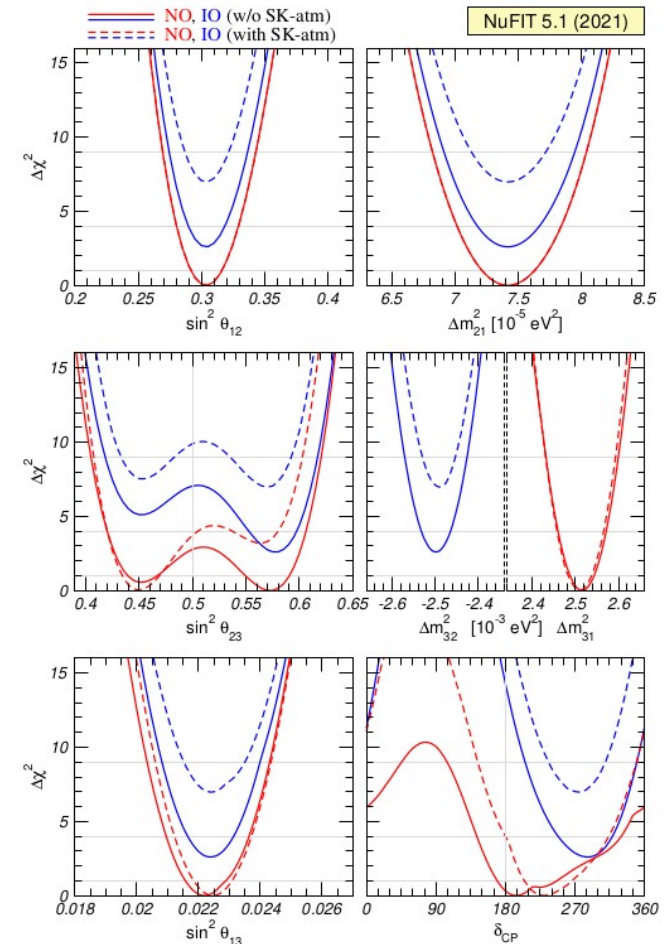
Esteban, Gonzalez-Garcia, Maltoni, Schwetz, Zhou, JHEP'20 [2007.14792]

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

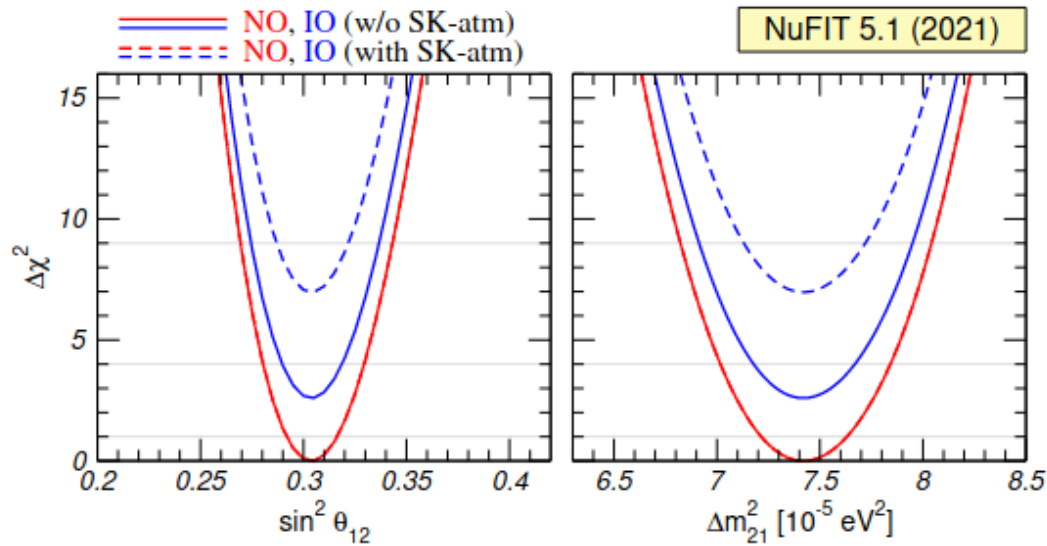
comparable results:

Bari: e.g. Capozzi et al., 2107.00532

Valencia: e.g. deSalas et al., 2006.11237



Status of PMNS measurements:

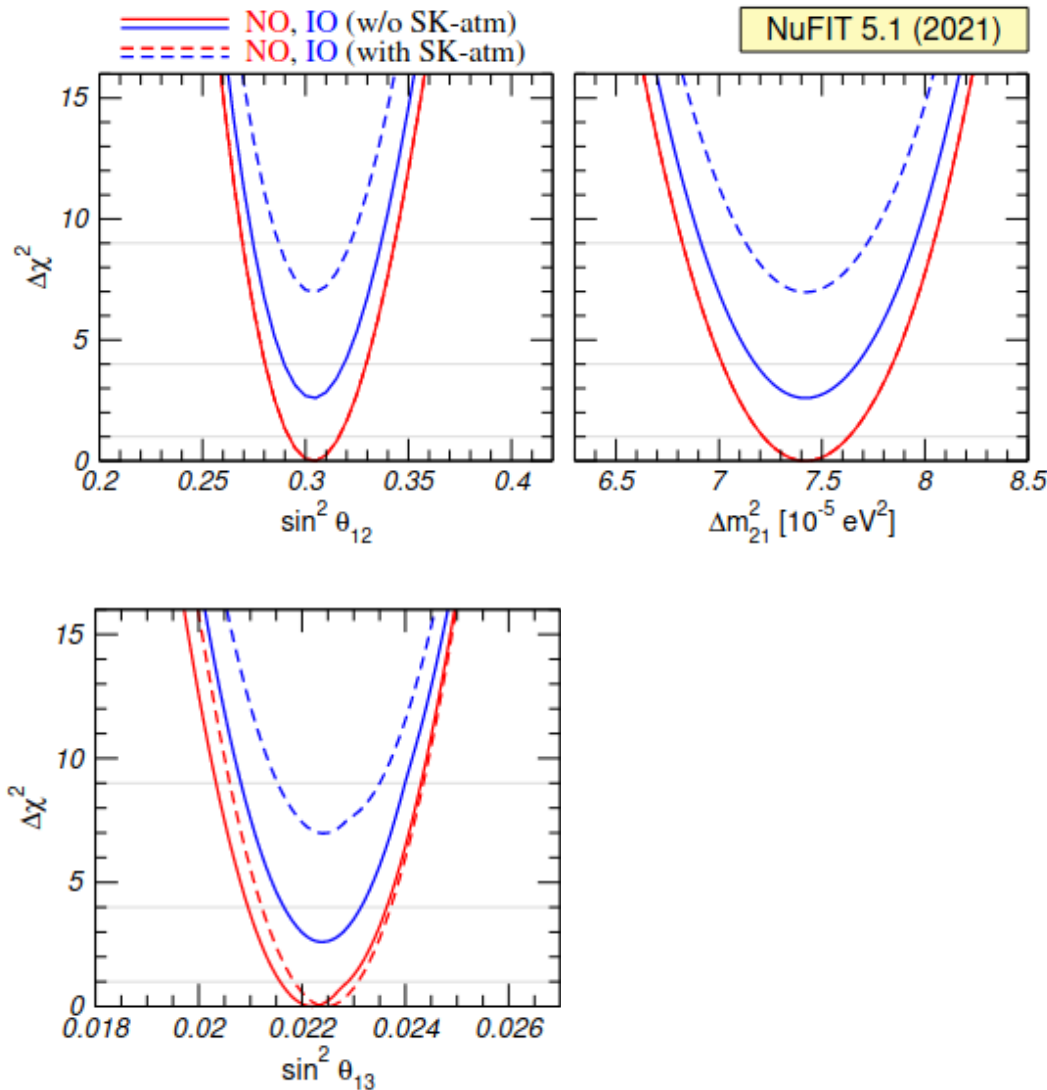


joint fits

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

Status of PMNS measurements:

joint fits

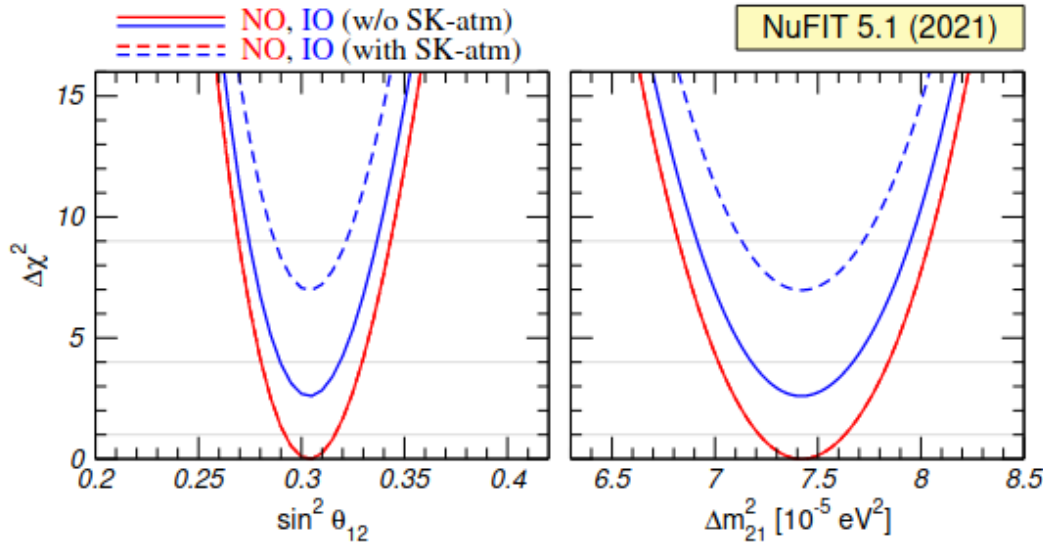


Solar parameters: θ_{12} , Δm_{21}^2
known with **~few% precision** since
KamLAND (no recent updates)
→ future prospects: JUNO <1%

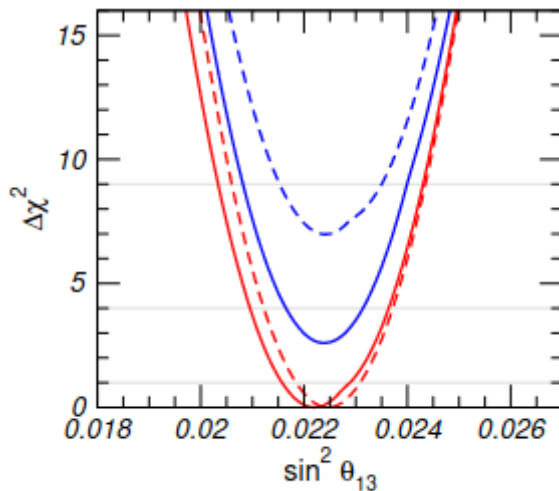
θ_{13} measured with
reactor experiments
at **~1% precision**

Status of PMNS measurements:

joint fits

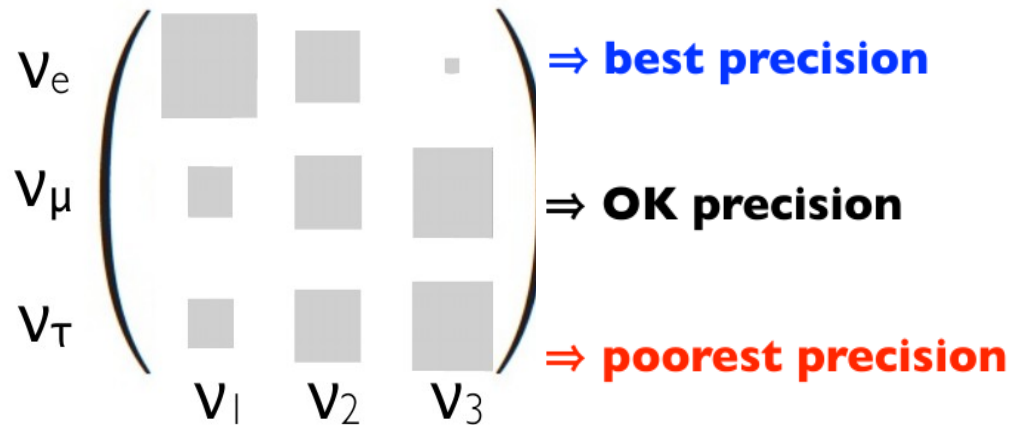


Solar parameters: θ_{12} , Δm_{21}^2
 known with **~few% precision** since KamLAND (no recent updates)
 → future prospects: JUNO <1%



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

Best avenue for PMNS unitarity test:



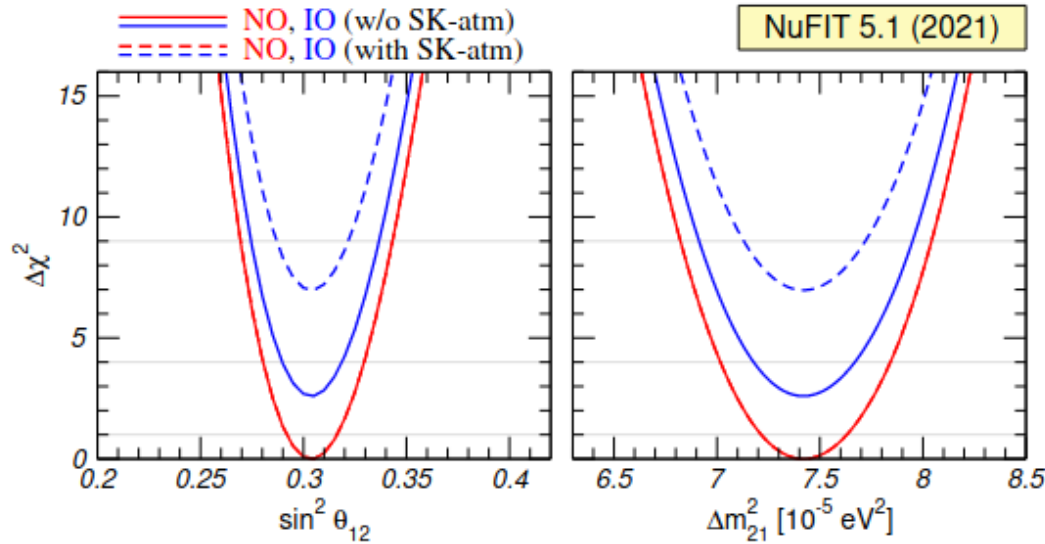
Exploring unitarity from different rows

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

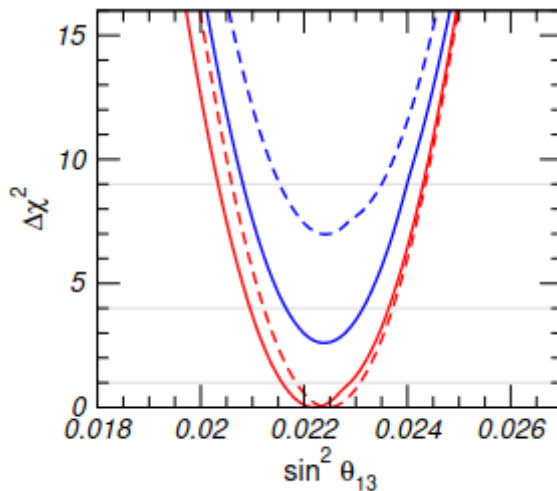
→ best limit expected from **electron top row**: θ_{13}
 from reactors and θ_{12} from JUNO

Status of PMNS measurements:

joint fits

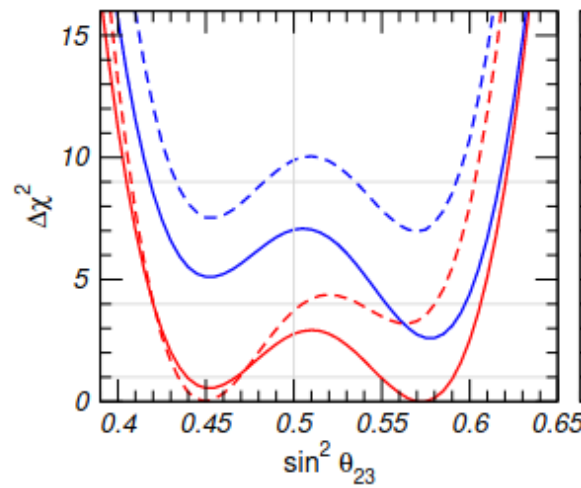


Solar parameters: θ_{12} , Δm_{21}^2
 known with **~few%** precision since KamLAND (no recent updates)
 → future prospects: JUNO <1%



Atmospheric parameters:

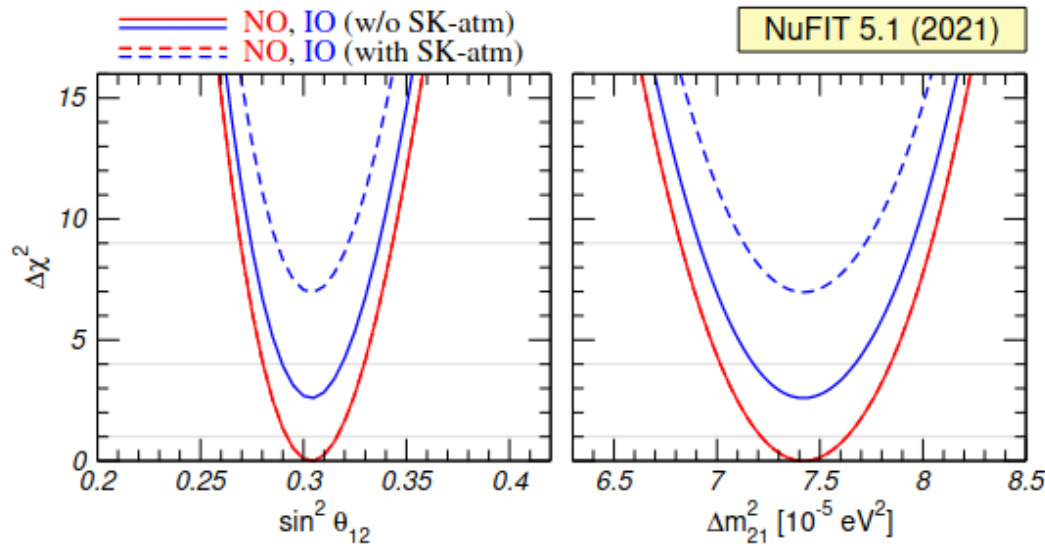
- θ_{23} **~few%** precision @1 σ (improved by a factor of 2 in the last 10 years) but **~25%** precision @3 σ : **octant degeneracy, need high stat ν_e appearance**



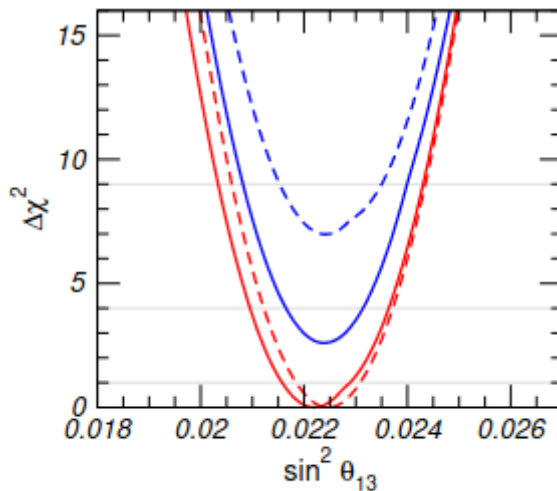
θ_{13} measured with reactor experiments at **~1%** precision

Status of PMNS measurements:

joint fits

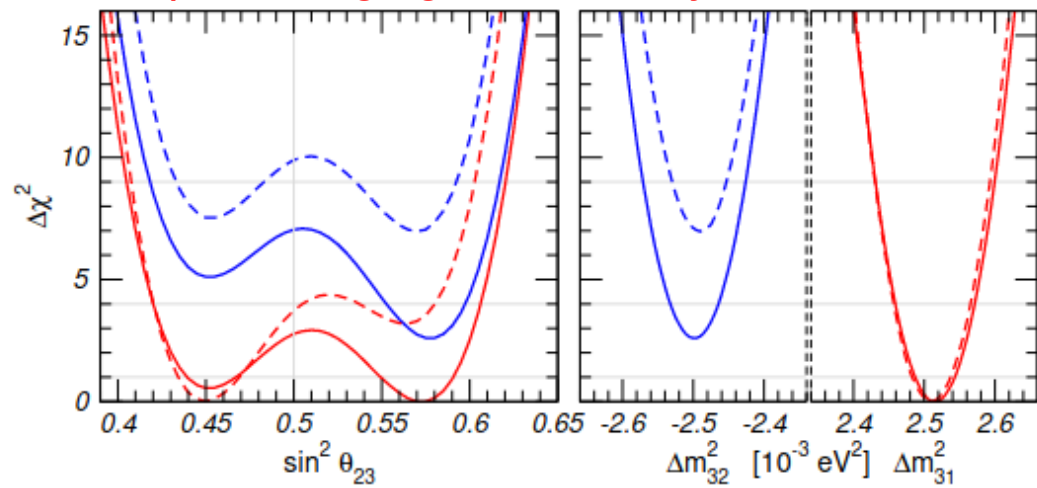


Solar parameters: θ_{12} , Δm^2_{21}
 known with **~few%** precision since KamLAND (no recent updates)
 → future prospects: JUNO <1%



Atmospheric parameters:

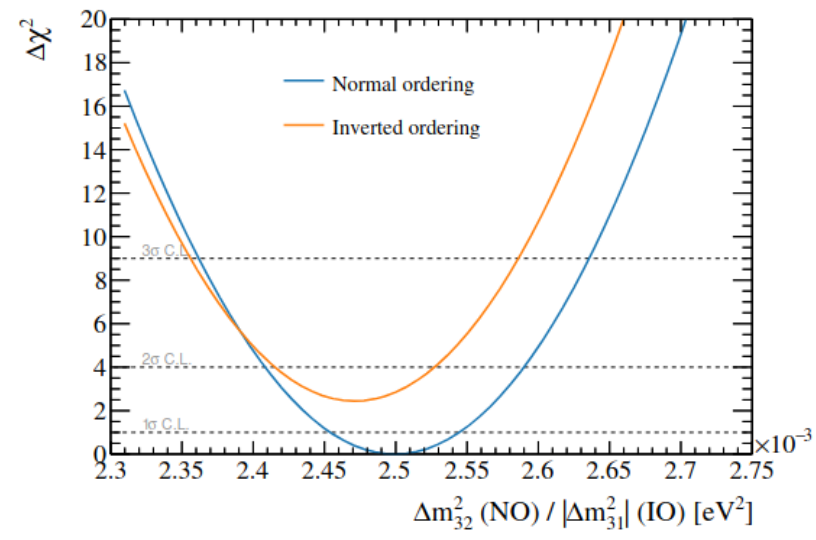
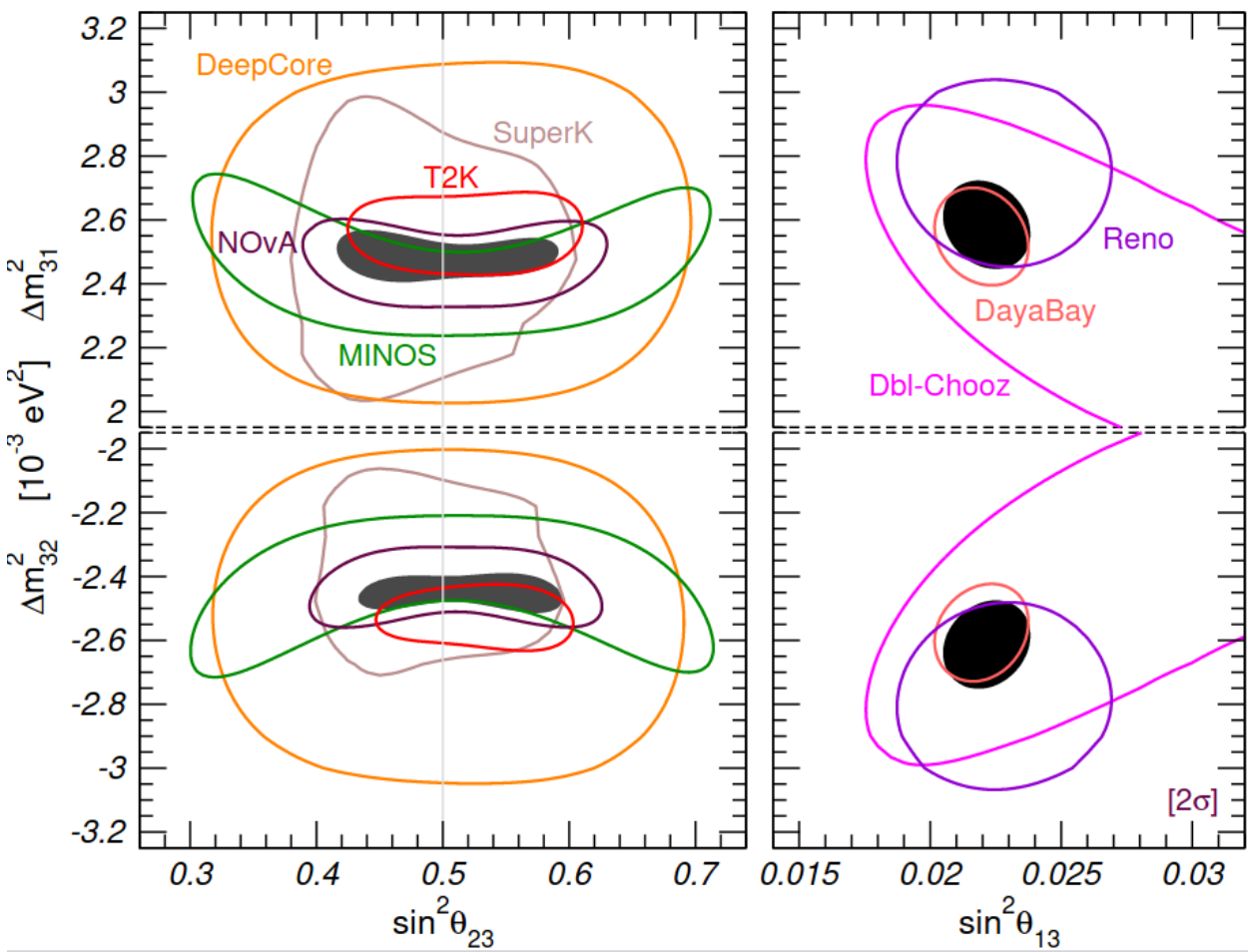
- θ_{23} **~few%** precision @1 σ (improved by a factor of 2 in the last 10 years) but **~25%** precision @3 σ : **octant degeneracy, need high stat ν_e appearance**
- $|\Delta m^2_{31(32)}|$ **~1%** (not so robust...) → **important to get <1%** (see later) **challenging to control systematics uncertainties**



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

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

NuFIT 5.1 (2021)



(b) T2K + reactor

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

Similar resolution and shift in NOVA

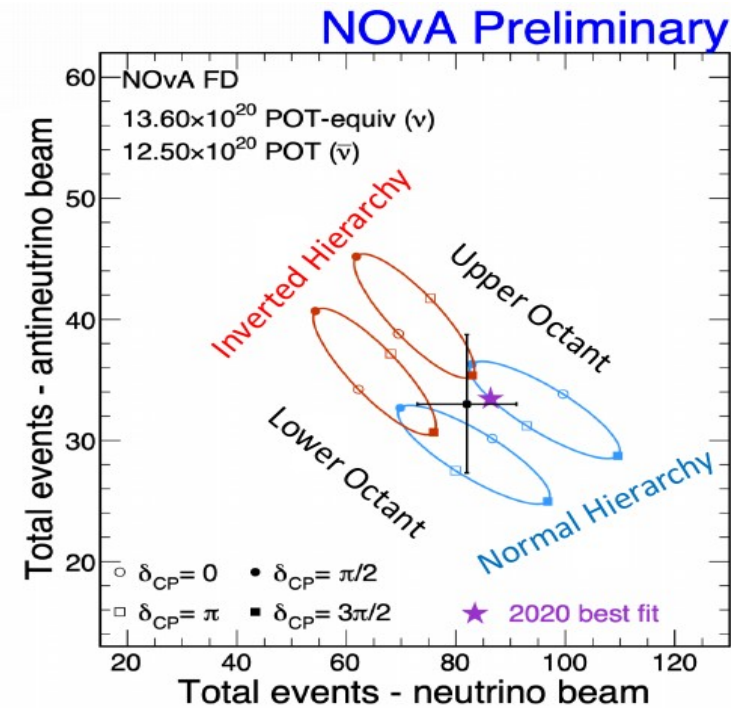
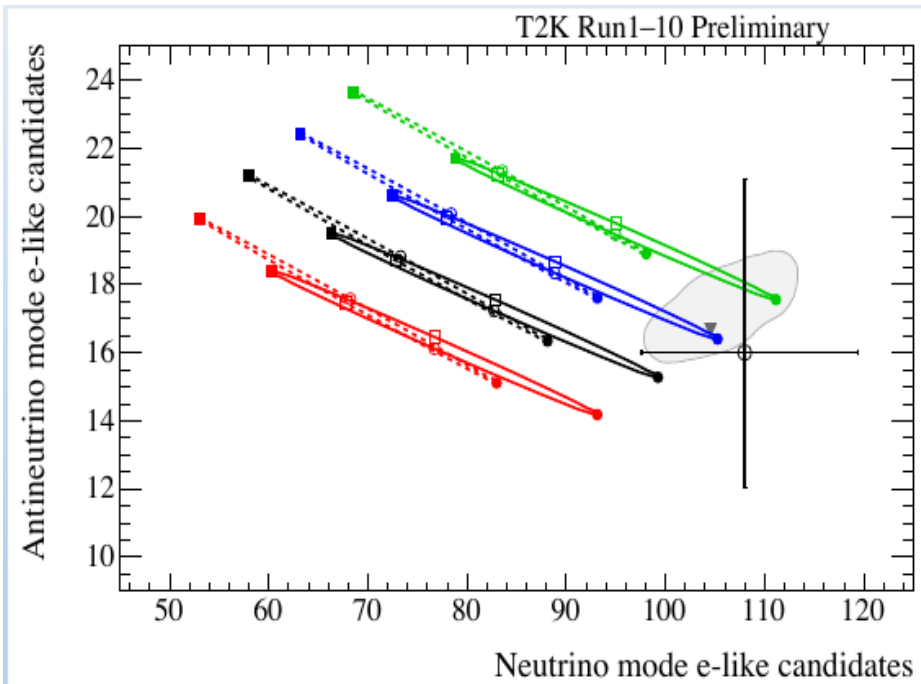
$\nu_e/\bar{\nu}_e$ appearance: MH, δ_{CP}

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

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

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

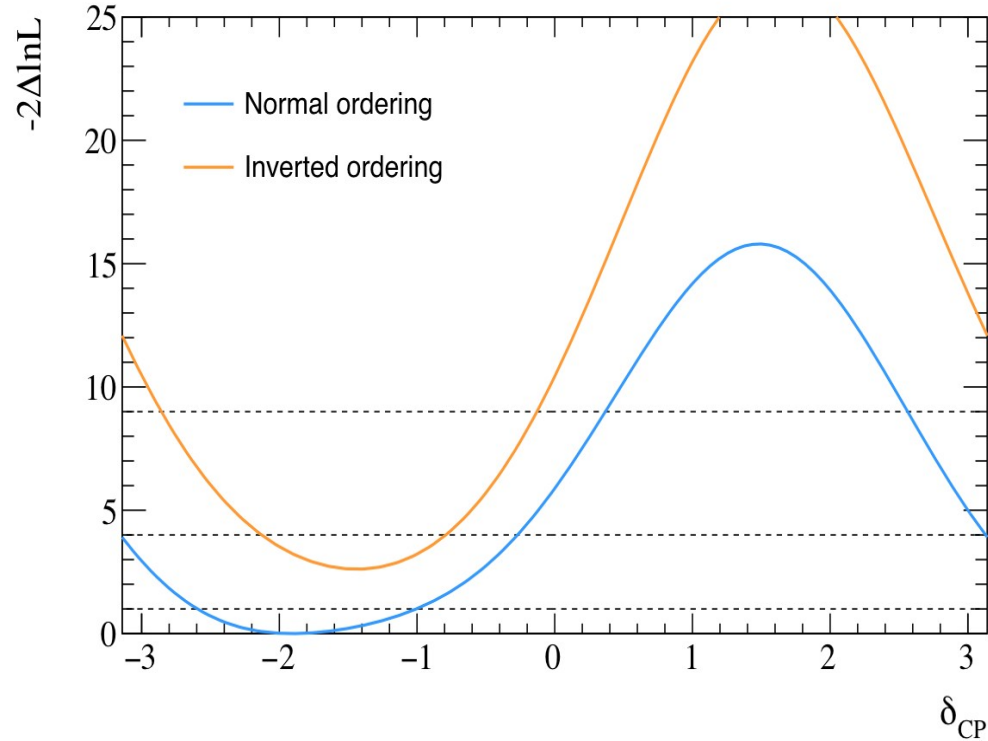
Using 2020 results in the following (2022 improved analyses confirmed the situation)



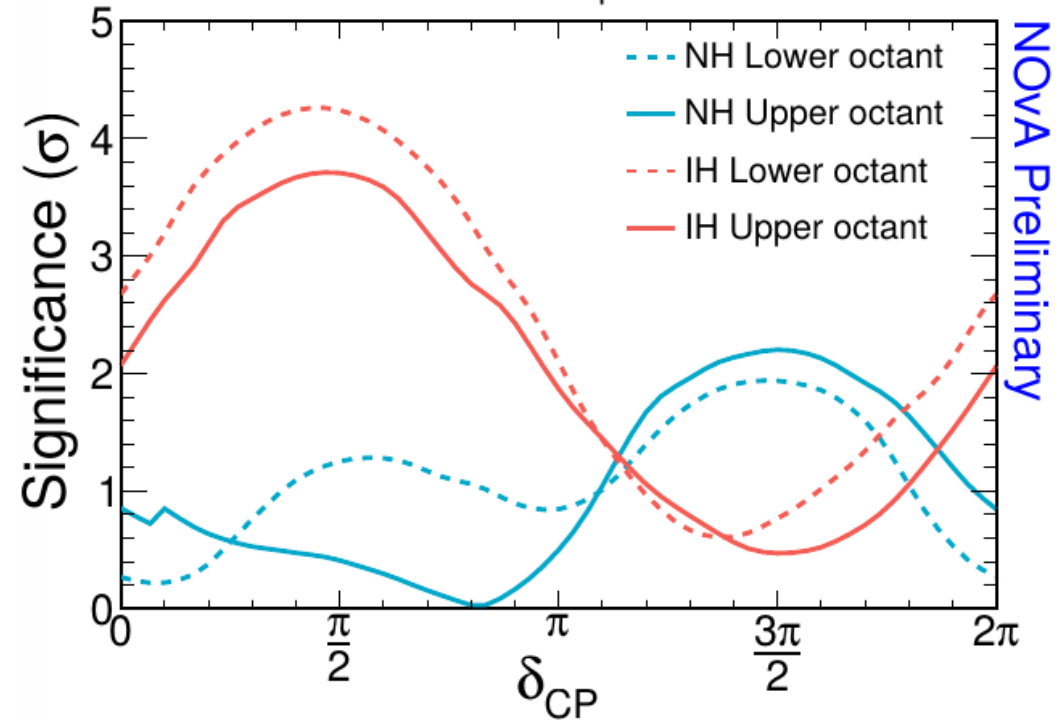
- $\sin^2 \theta_{23} = 0.45, 0.50, 0.55, 0.60$
- $\Delta m_{32}^2 = 2.49 \times 10^{-3} \text{ eV}^2$
- - - $\Delta m_{31}^2 = -2.46 \times 10^{-3} \text{ eV}^2$
- $\delta_{CP} = \pi$
- $\delta_{CP} = +\pi/2$
- $\delta_{CP} = 0$
- $\delta_{CP} = -\pi/2$
- ⊠ 68% syst err. at best-fit
- ▼ Best-fit
- ⊙ Data (68% stat err.)

Results

T2K preliminary 19.7×10^{20} POT ν + 16.3×10^{20} POT $\bar{\nu}$

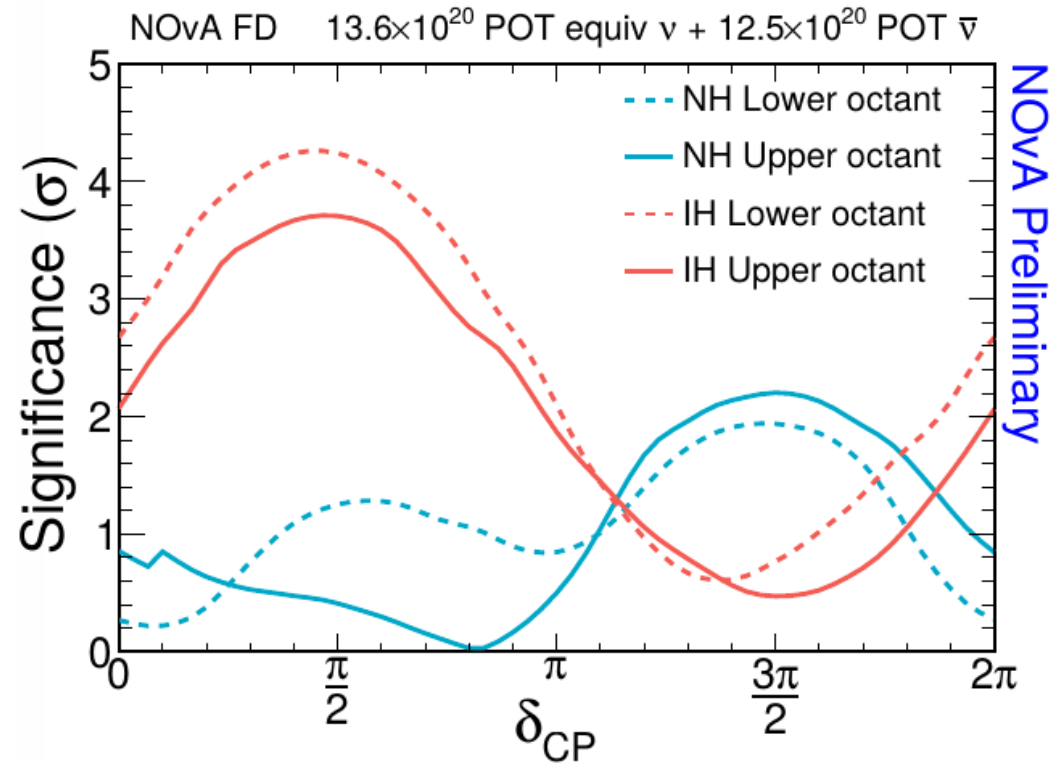
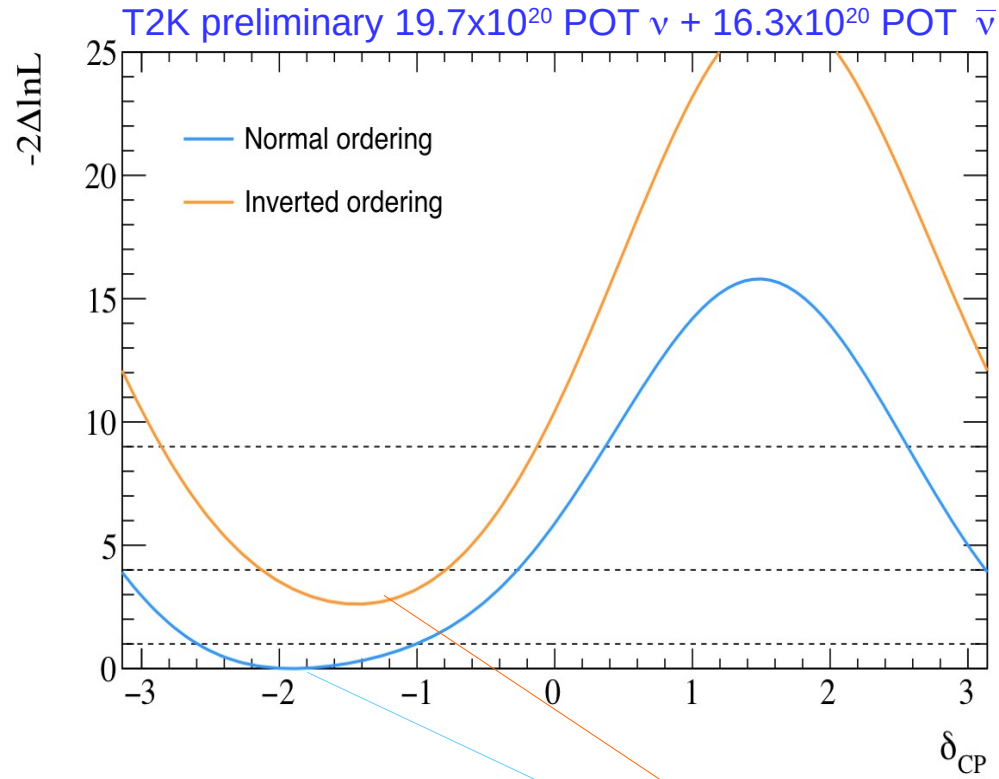


NOvA FD 13.6×10^{20} POT equiv ν + 12.5×10^{20} POT $\bar{\nu}$

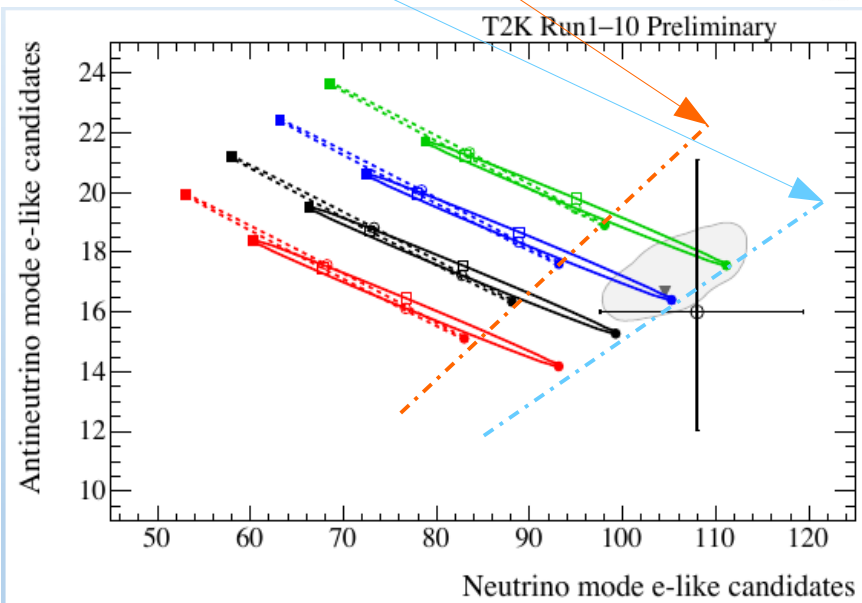


- Large **region disfavoured at 3σ** (T2K Nature cover in 2020). And for T2K even some region at 5σ but precision of statistical treatment will be discussed later.
- Similar region disfavoured at T2K for NH and IH, while 3σ exclusion in NOvA only for IO

Results

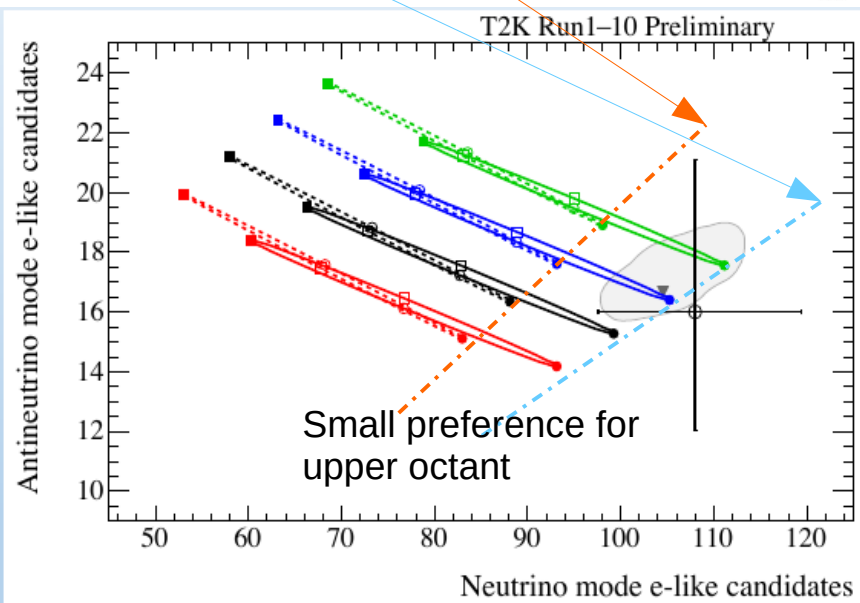
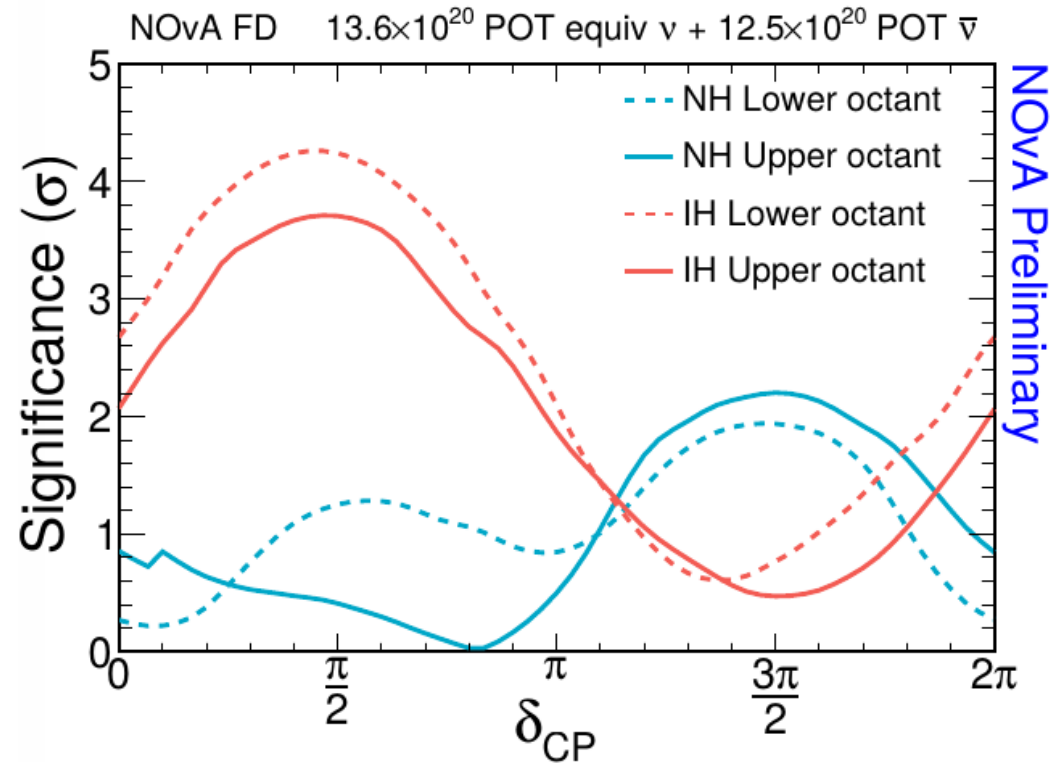
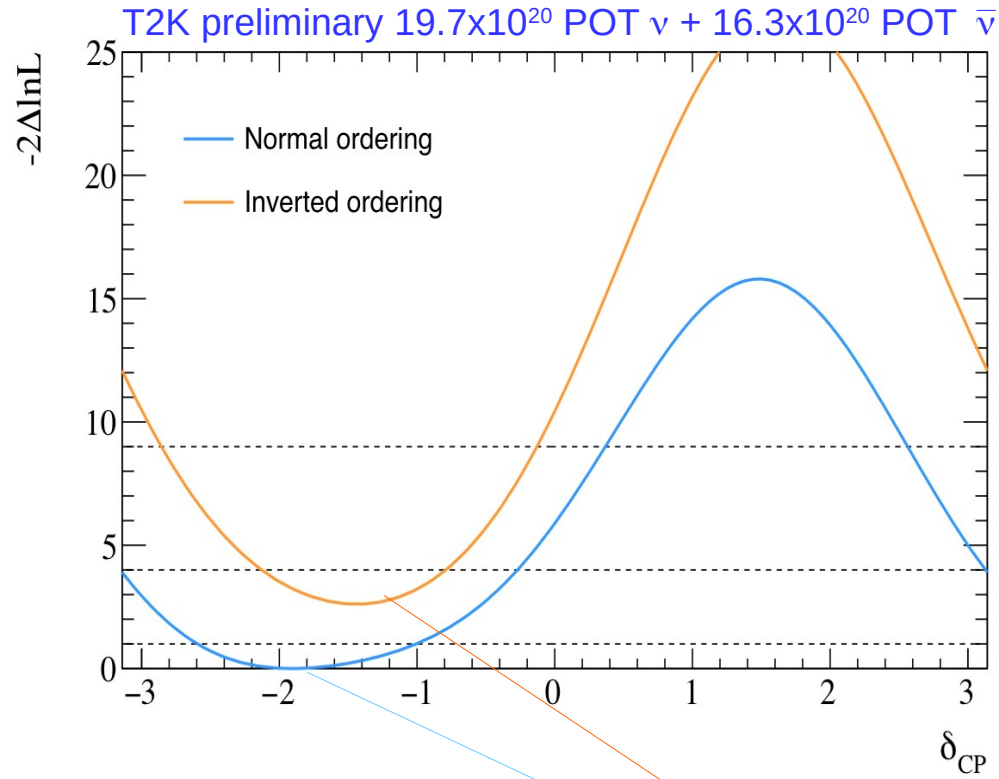


NOvA Preliminary

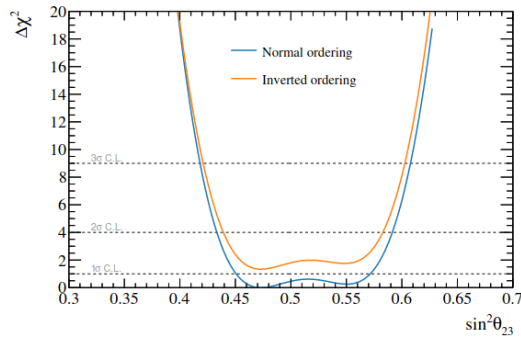


- $\sin^2 \theta_{23} = 0.45, 0.50, 0.55, 0.60$
- $\Delta m_{32}^2 = 2.49 \times 10^{-3} \text{ eV}^2$
- $\Delta m_{31}^2 = -2.46 \times 10^{-3} \text{ eV}^2$
- $\delta_{CP} = \pi$
- $\delta_{CP} = +\pi/2$
- $\delta_{CP} = 0$
- $\delta_{CP} = -\pi/2$

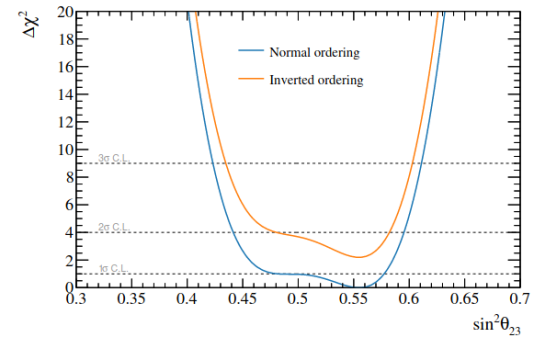
Results



- $\sin^2 \theta_{23} = 0.45, 0.50, 0.55, 0.60$
- $\Delta m_{32}^2 = 2.49 \times 10^{-3} \text{ eV}^2$
- - $\Delta m_{31}^2 = -2.46 \times 10^{-3} \text{ eV}^2$
- $\delta_{CP} = \pi$
- $\delta_{CP} = +\pi/2$
- $\delta_{CP} = 0$
- $\delta_{CP} = -\pi/2$



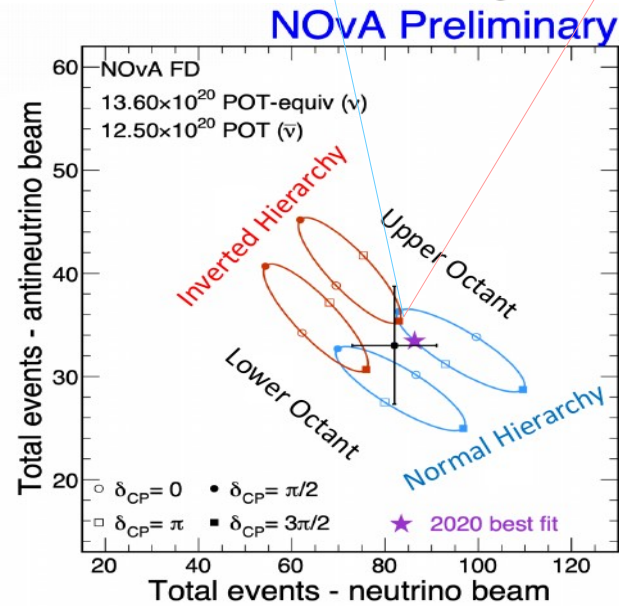
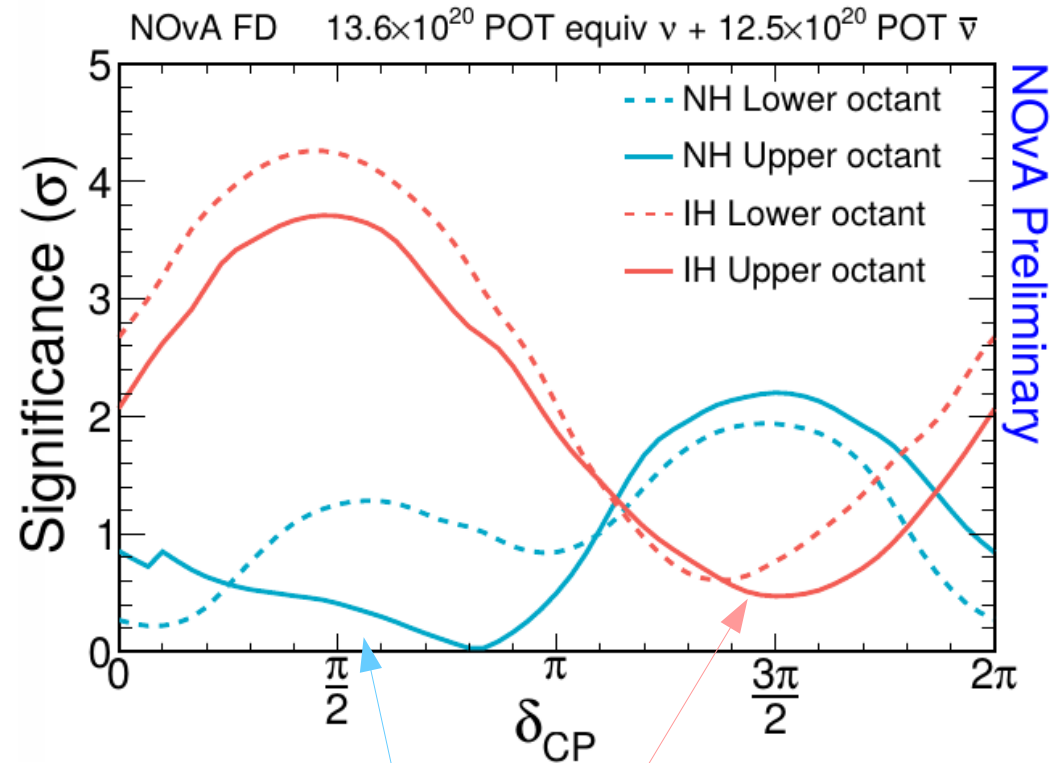
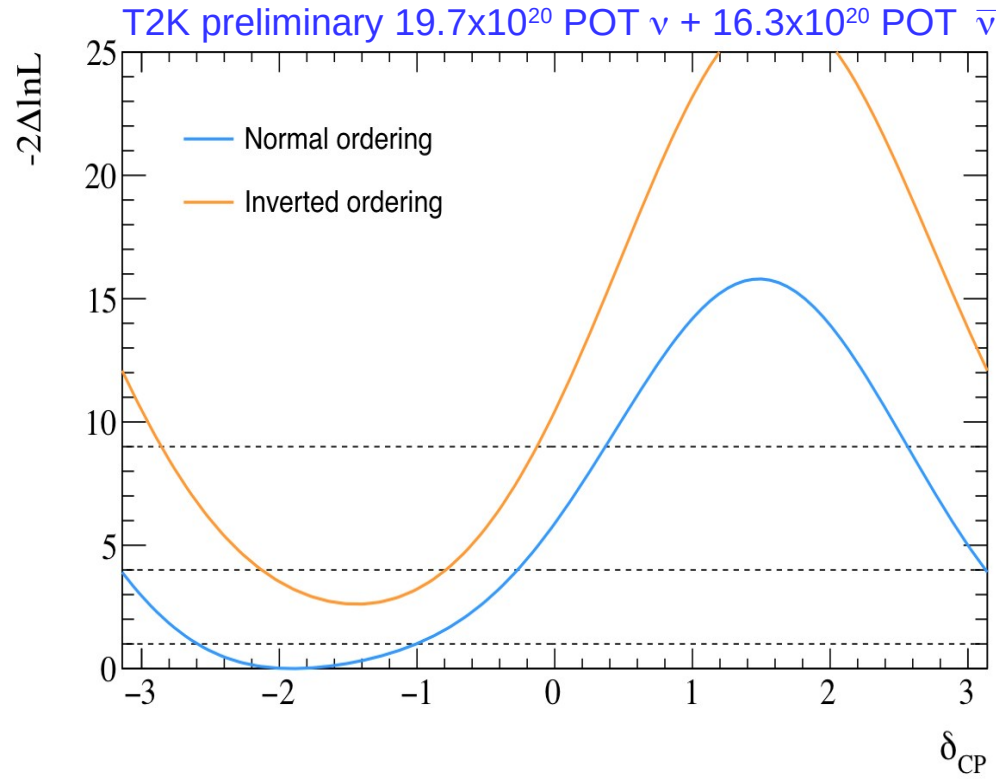
(a) T2K only



(b) T2K + reactor

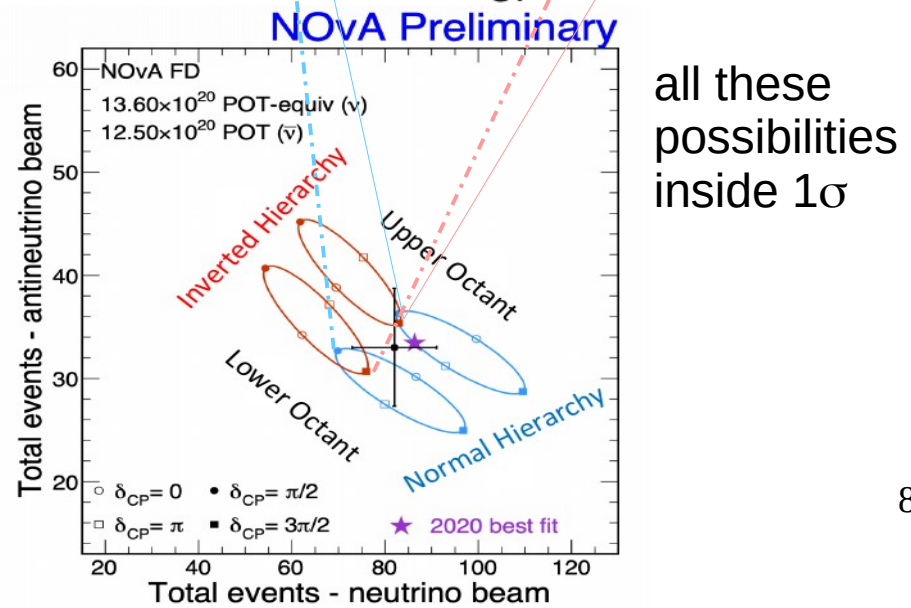
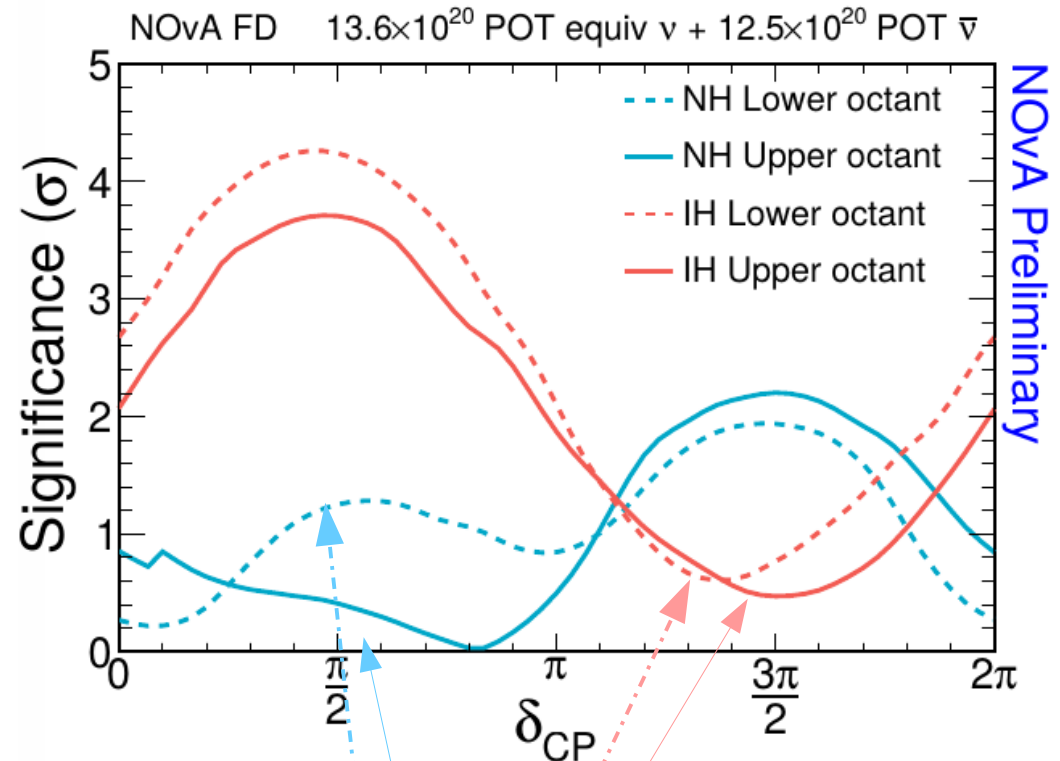
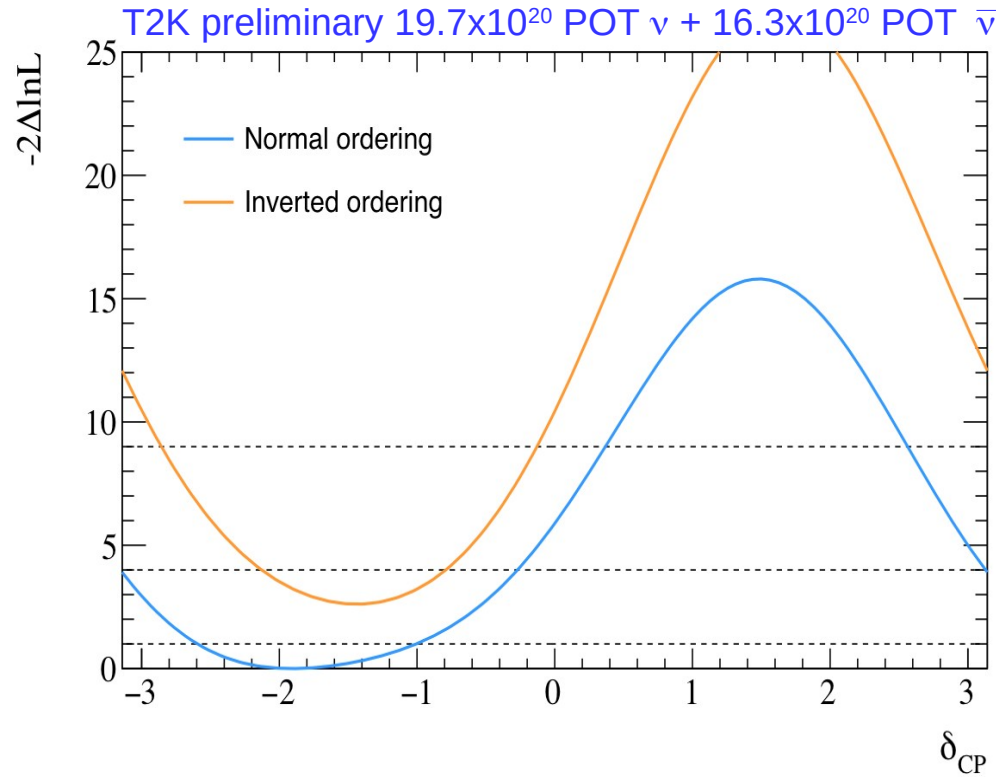
NOvA Preliminary

Results



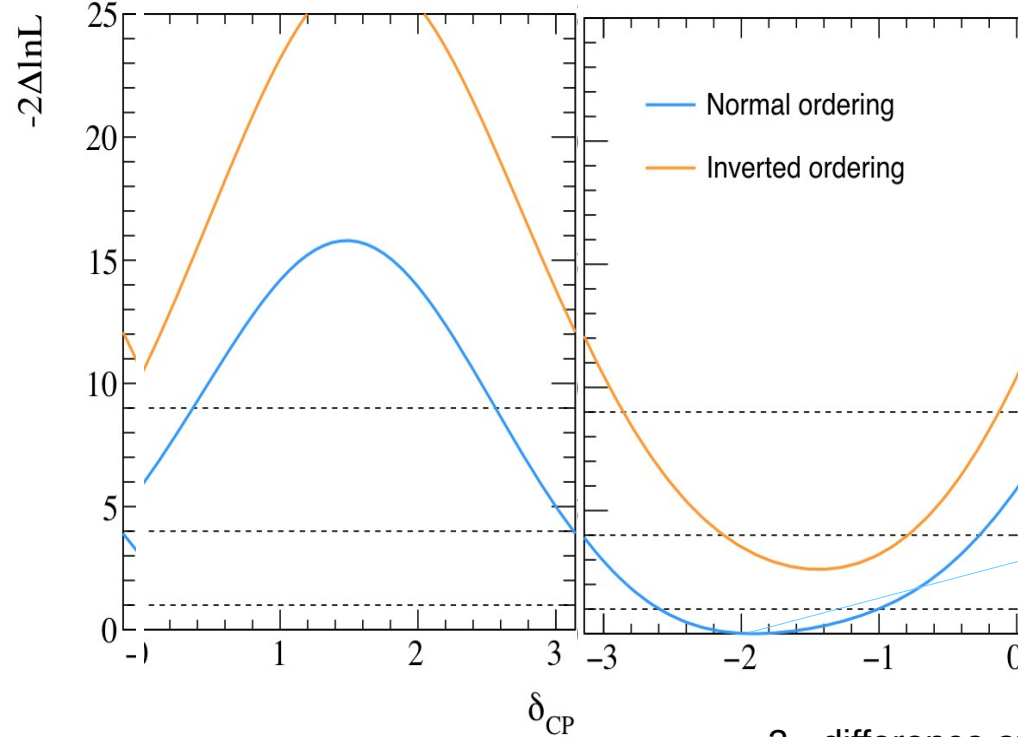
NOvA Preliminary

Results

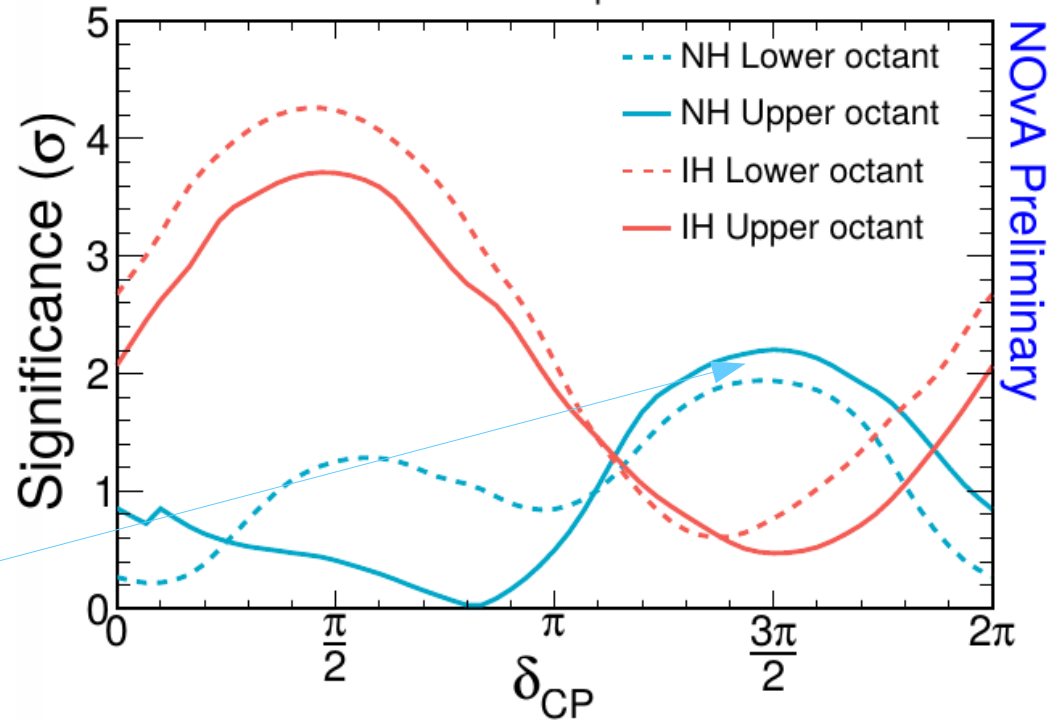


Results

T2K preliminary 19.7×10^{20} POT ν + 16.3×10^{20} POT $\bar{\nu}$



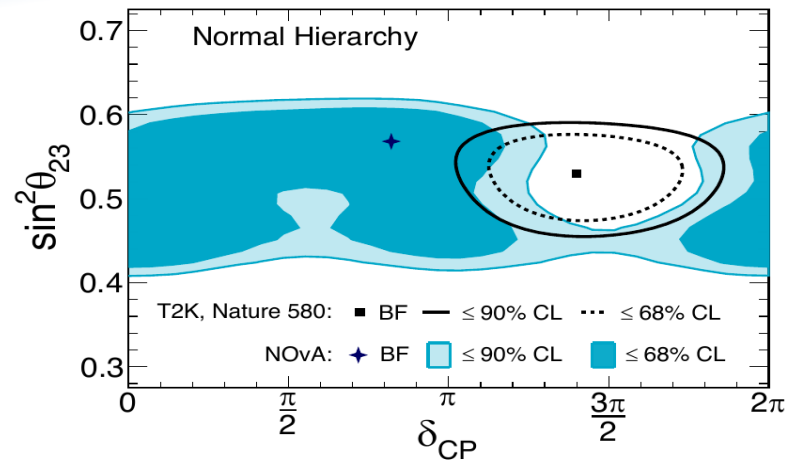
NOvA FD 13.6×10^{20} POT equiv ν + 12.5×10^{20} POT $\bar{\nu}$



NOvA Preliminary

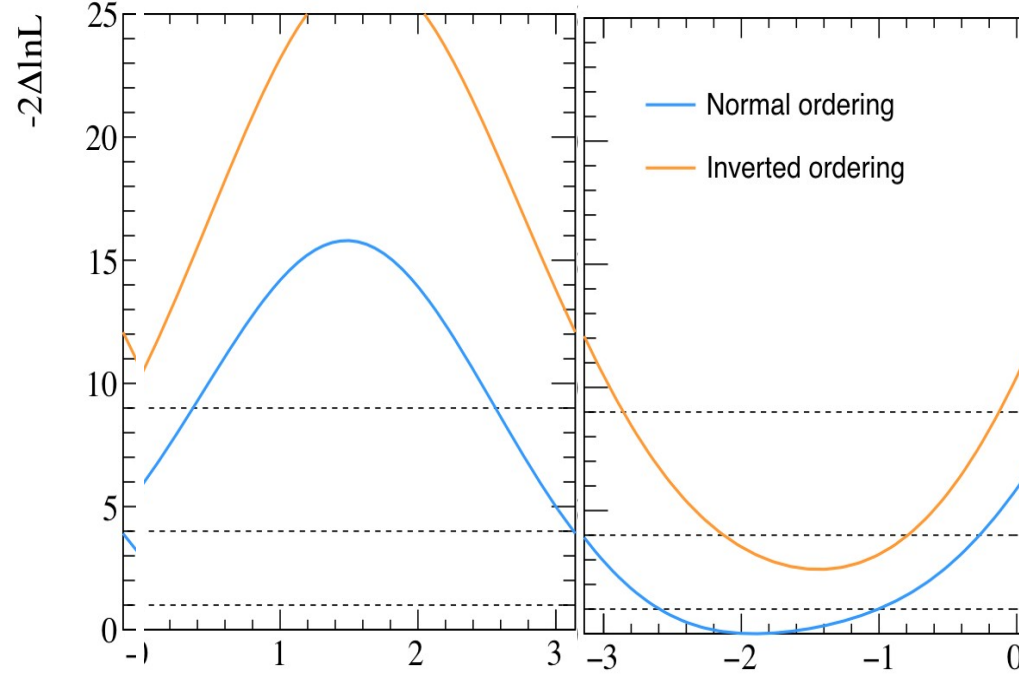
2σ difference at T2K minimum (max CPV, NH) but still common regions at 1σ

NOvA Preliminary

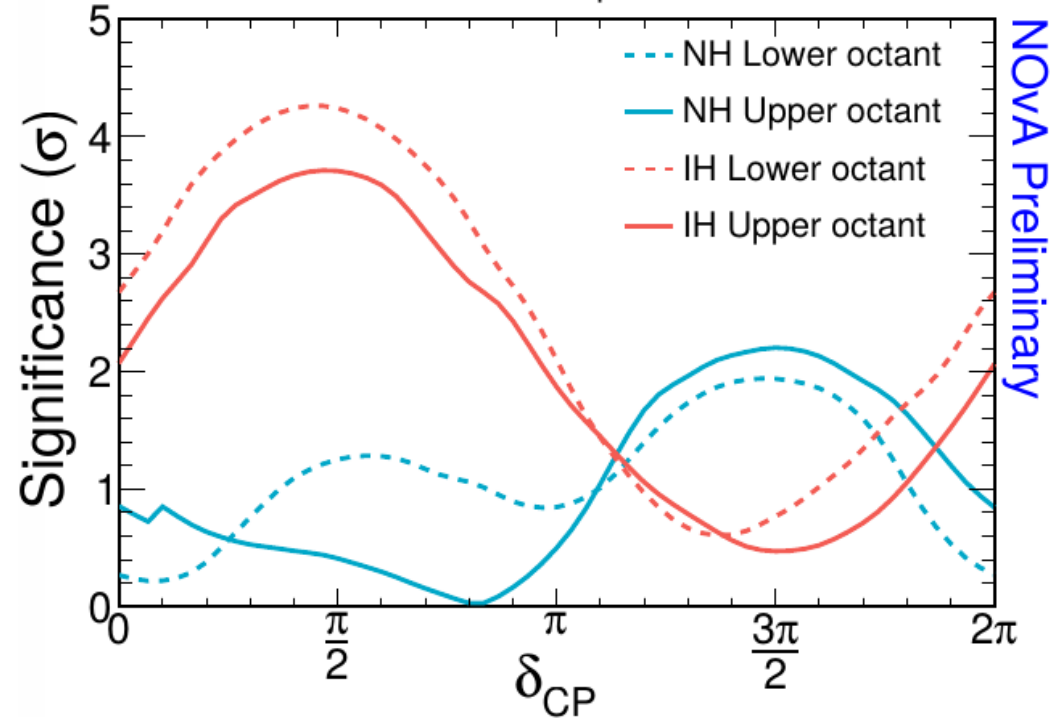


Results

T2K preliminary 19.7×10^{20} POT ν + 16.3×10^{20} POT $\bar{\nu}$

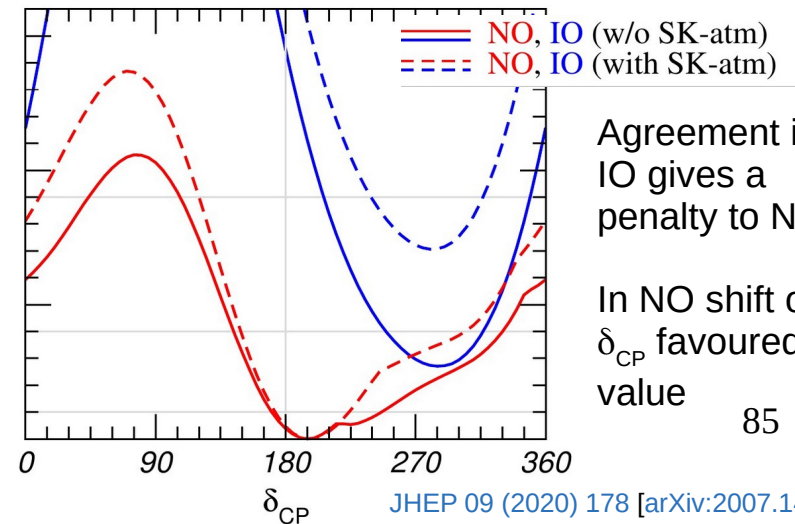
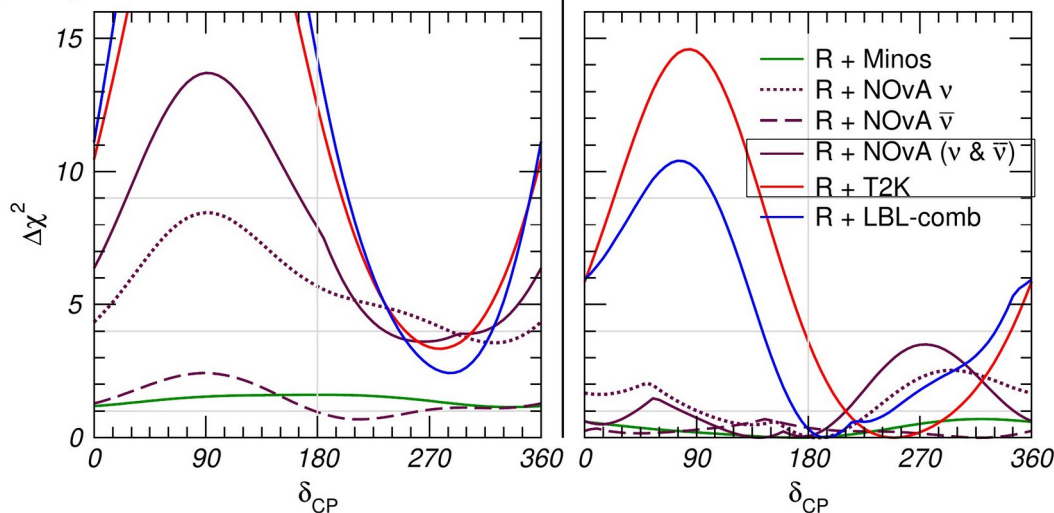


NOvA FD 13.6×10^{20} POT equiv ν + 12.5×10^{20} POT $\bar{\nu}$



NuFIT 5.0 (2020)

IO | NO

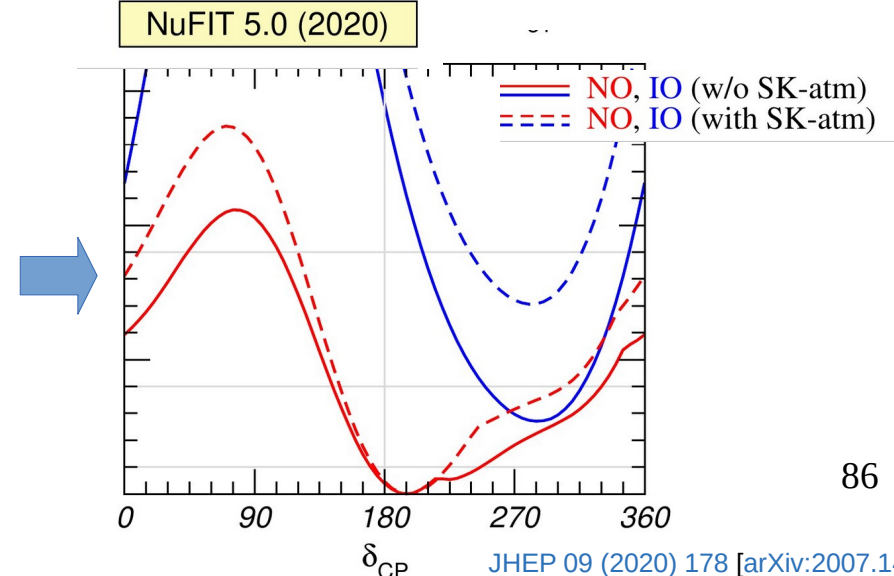
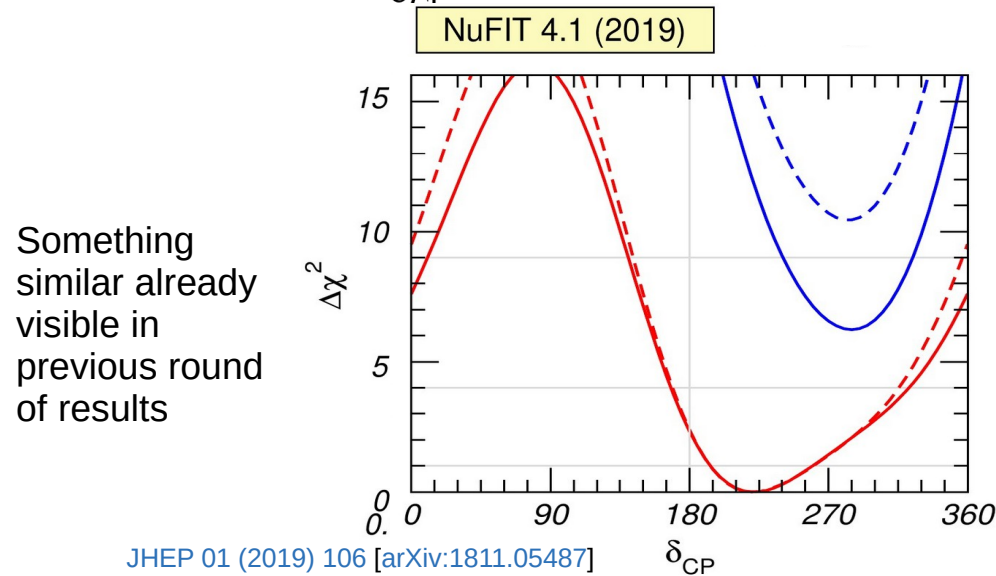
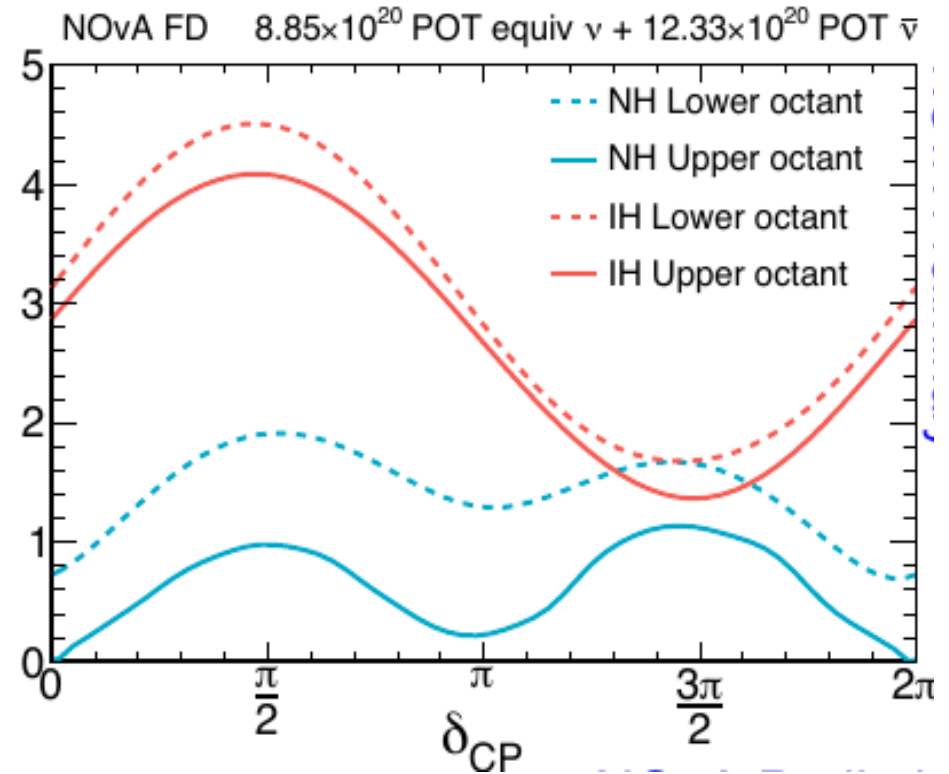
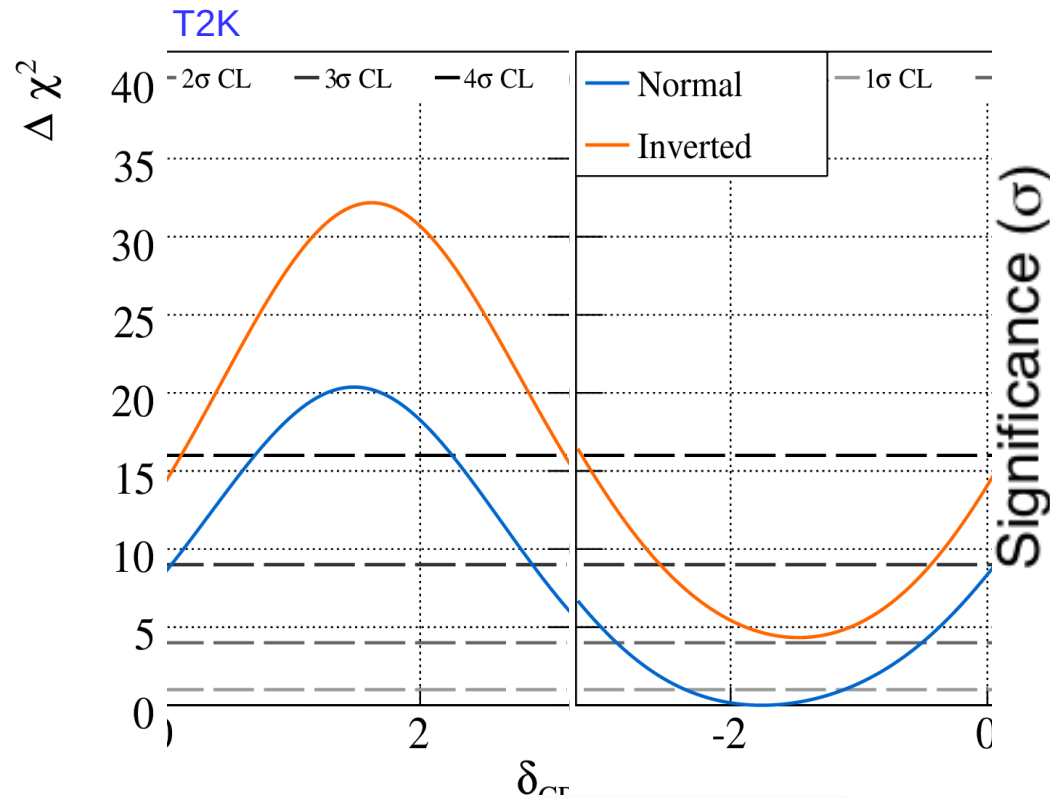


Agreement in IO gives a penalty to NO

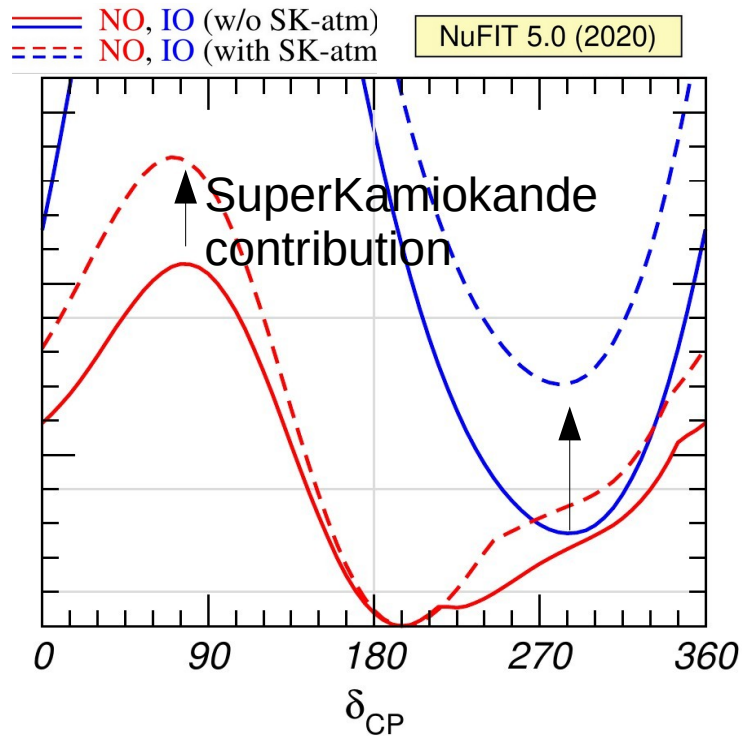
In NO shift on δ_{CP} favoured value

85

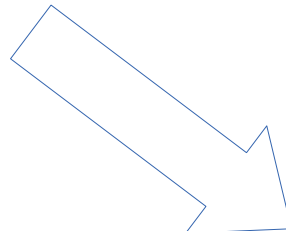
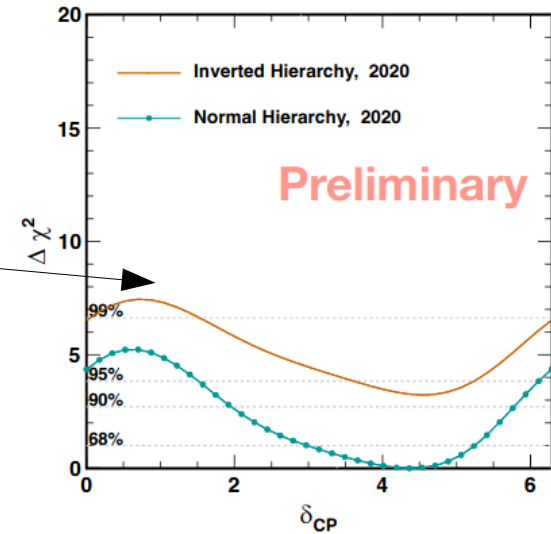
Results 2019 → 2020



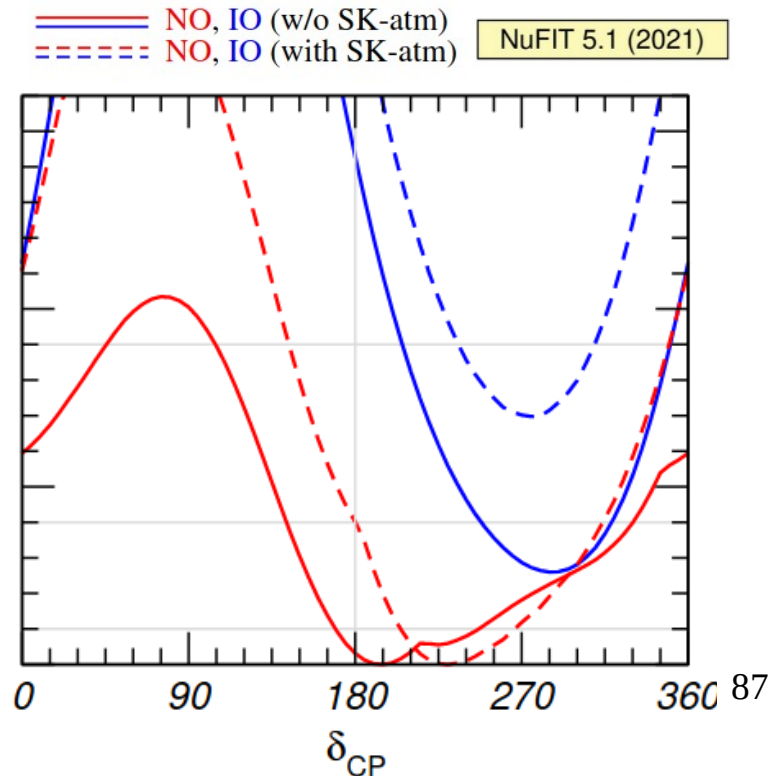
Mass Hierarchy



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

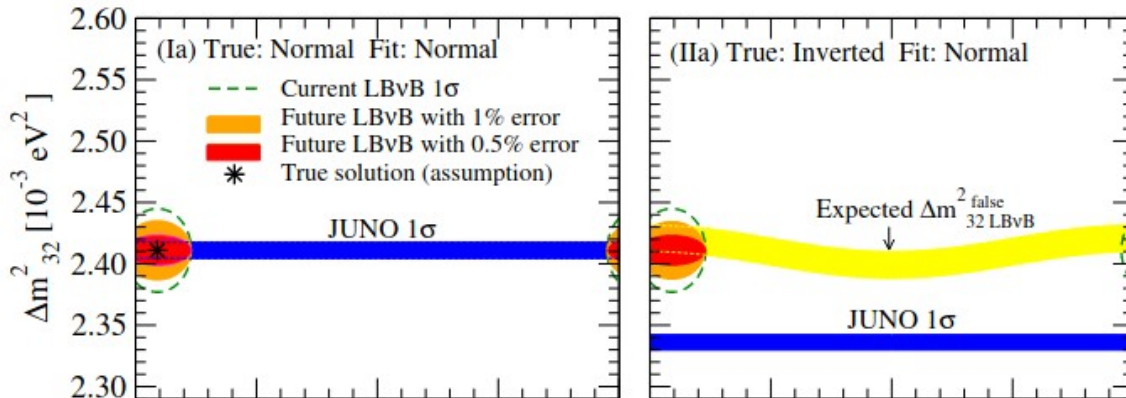
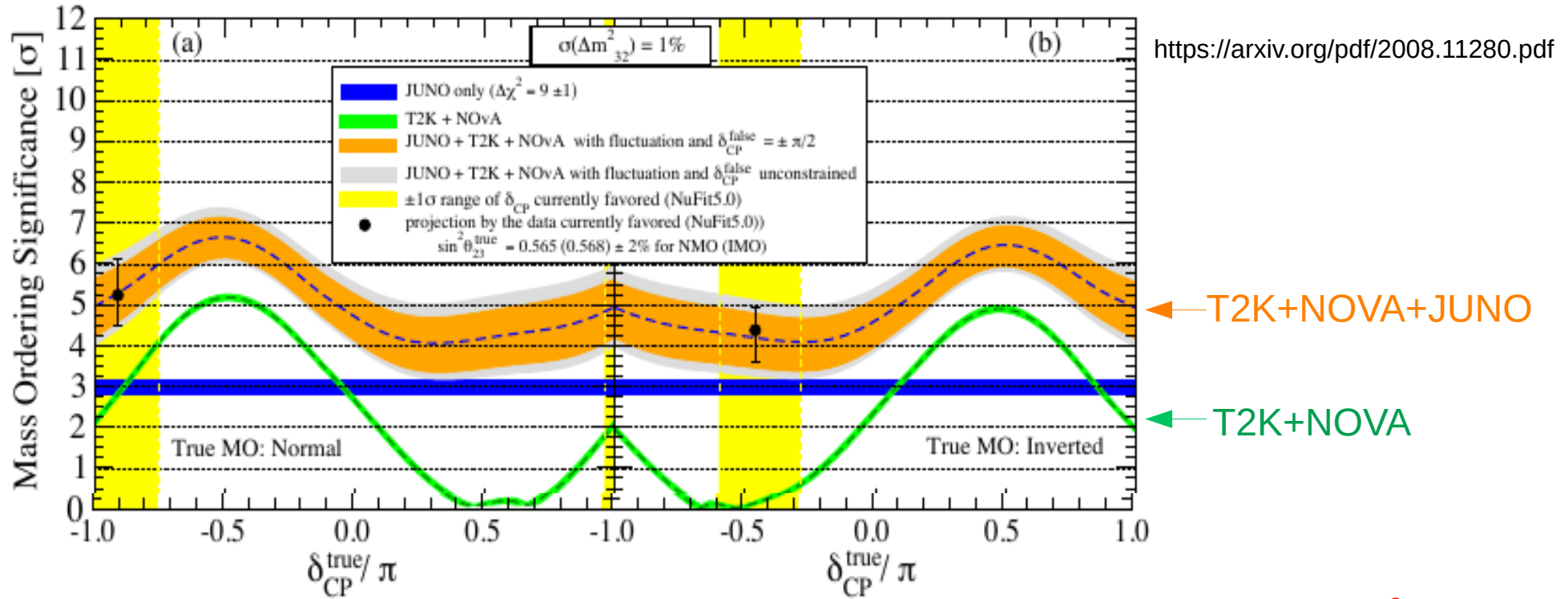


- Before 2020 NO favoured ($\Delta\chi^2=10.4 >3\sigma$)
- Lost some NO significance due to T2K-NOVA mild tension in 2020 ($\Delta\chi^2=7.1$)
- **MO sensitivity dominated by SK**
 - shift best δ_{CP} in combination with T2K+NOVA
 - CP conservation disfavoured at $\sim 2\sigma$



Combinations for MH: prospects

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

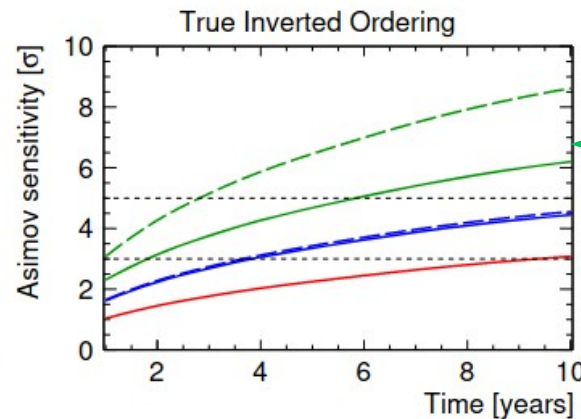
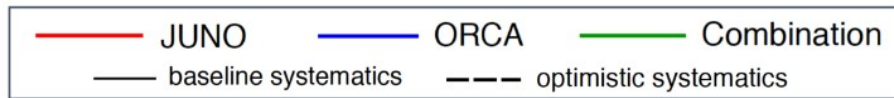


Boost of sensitivity from $|\Delta m_{31(32)}^2|$ discrepancy (for wrong mass hierarchy) between ν_e (JUNO) and ν_μ (LBL) disappearance $\rightarrow \sim 2\%$

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

Combinations for MH: prospects

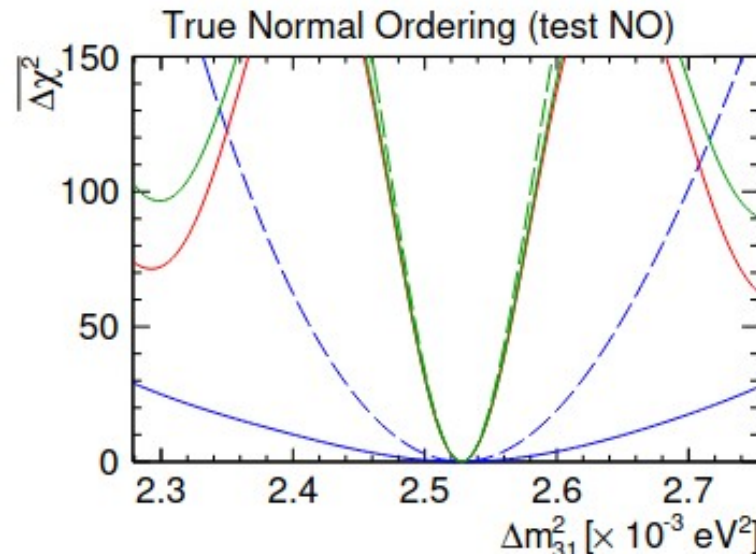
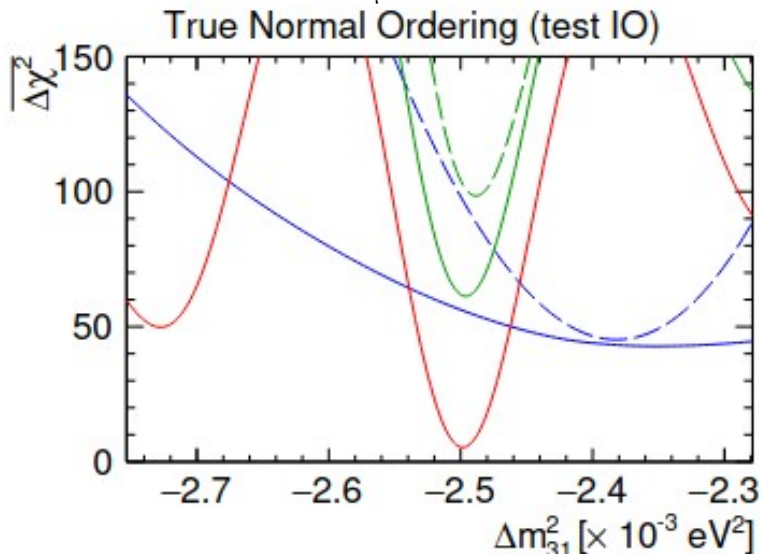
Further combination including ORCA (missing NOVA, T2K and SuperKamiokande):



← JUNO+ORCA

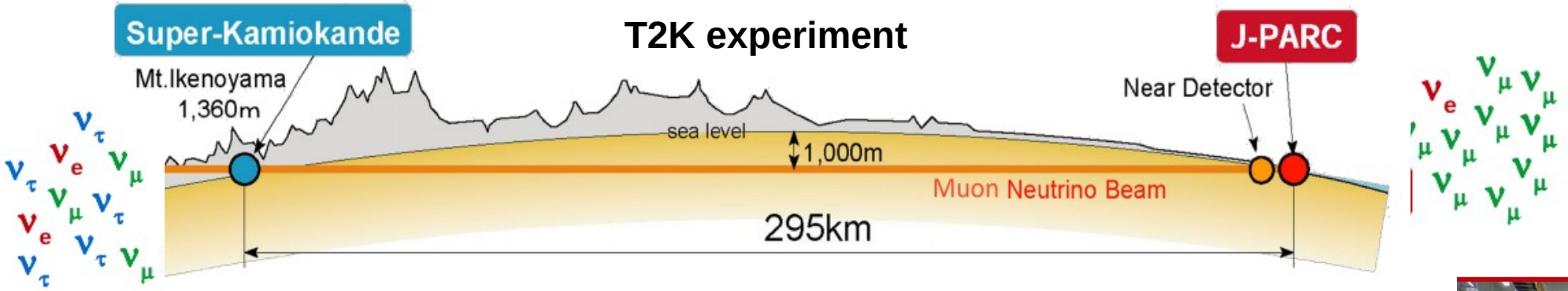
<https://arxiv.org/pdf/2107.00344.pdf>

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

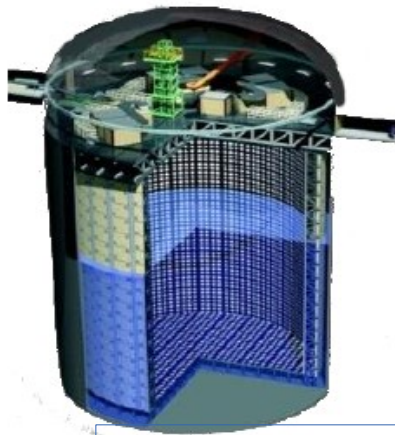


Anatomy of T2K and NOVA oscillation analysis

T2K

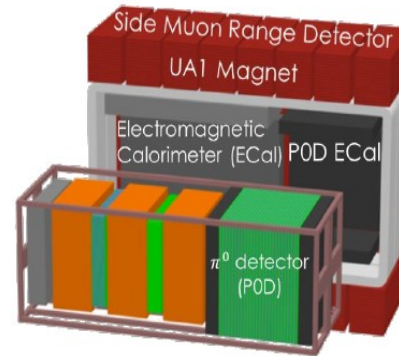


Super-Kamiokande

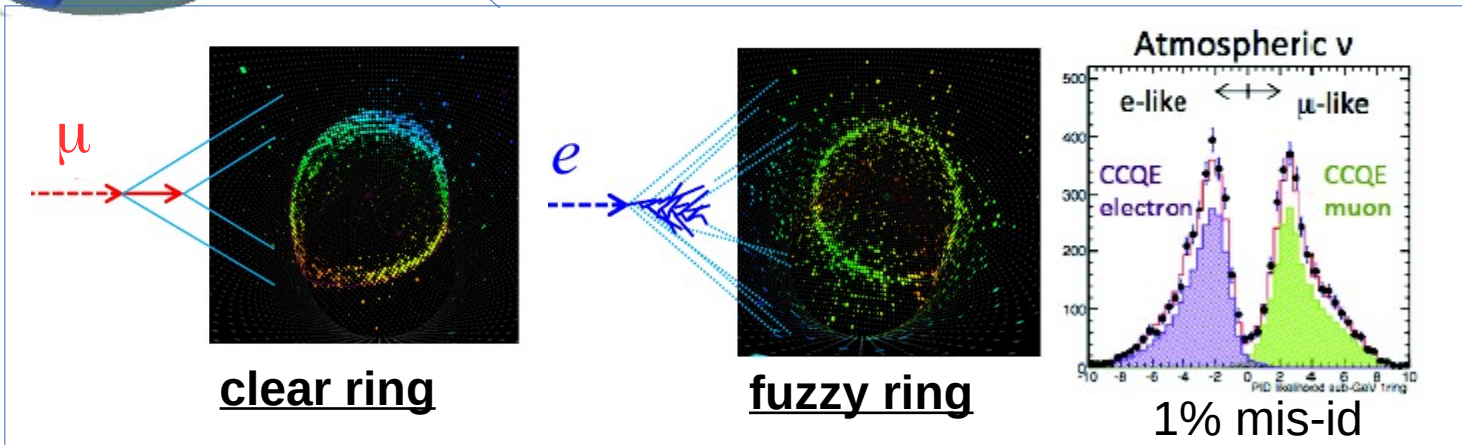


huge **water cherenkov** detector (50 kTon) with optimal μ/e identification to distinguish ν_e, ν_μ

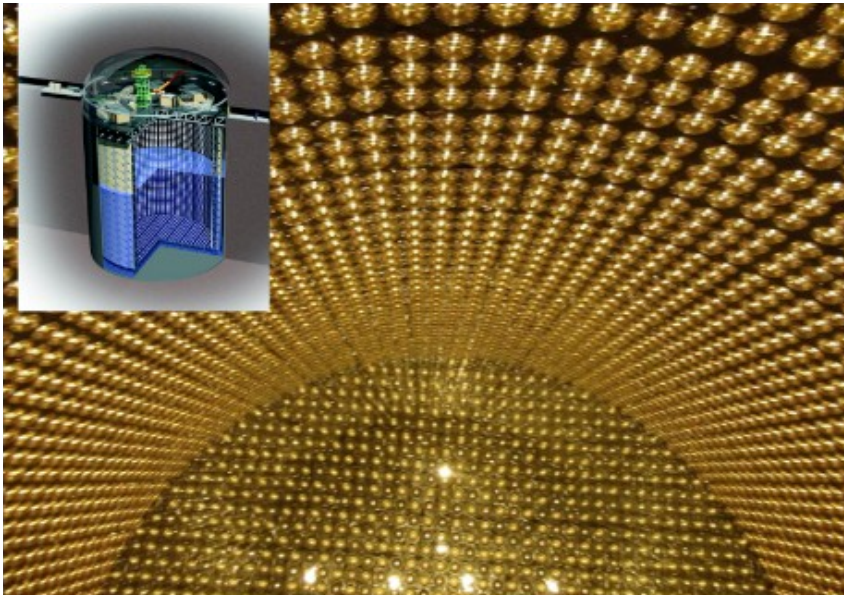
ND280 near detector



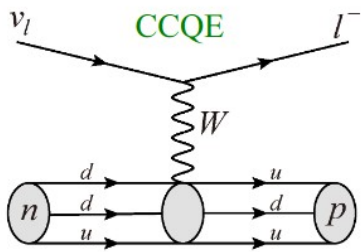
J-PARC facility: neutrino beam



SuperKamiokande samples



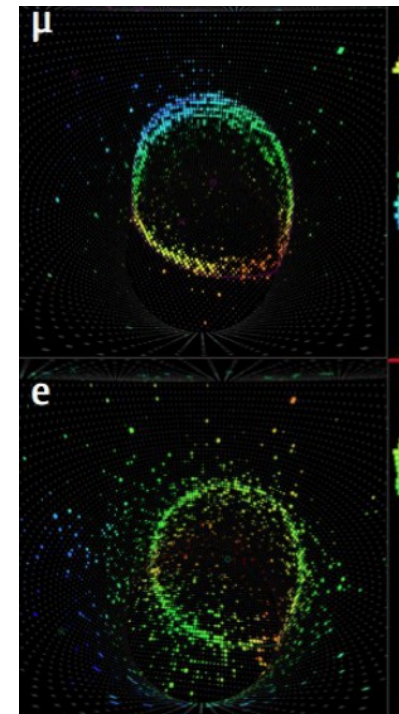
- Reconstruct **Cherenkov ring** from charged particles (above Cherenkov threshold)
- Use information of **time, position and amount of light** in the ring to estimate momentum and direction of particle (likelihood algo 'fitqun')
- '**ring fuzzyness**' to distinguish e/μ (note: $\pi \sim \mu$)
- **Michel e-** from muon (or $\pi \rightarrow \mu$) decay: e- ring delayed in time



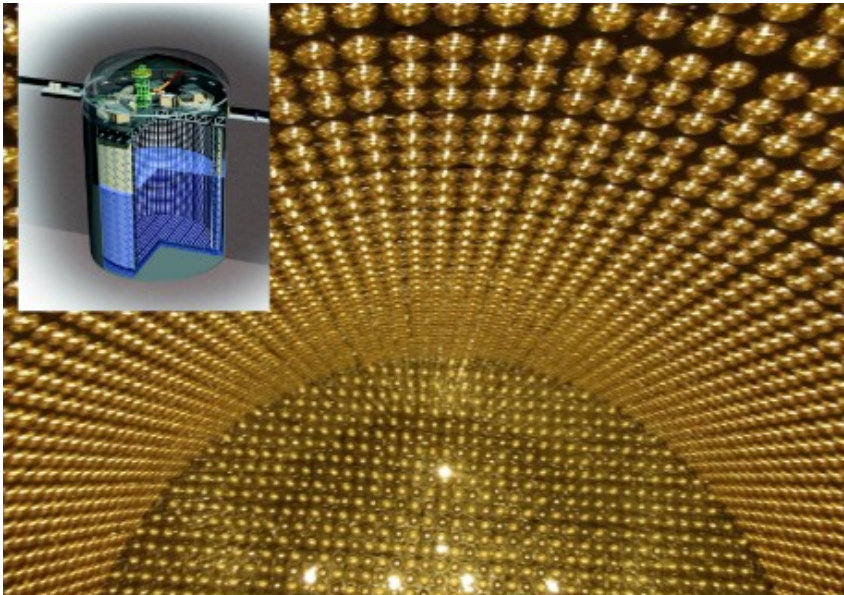
- Main channel at T2K energy:
single ring events (e or μ)
= Quasi-Elastic channel: can reconstruct neutrino energy from lepton kinematics only
 [with nuclear physics uncertainty: see Martini lecture]

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

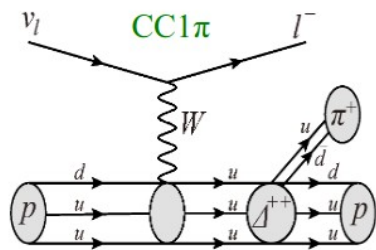
where m_n, m_p and m_μ are the masses of neutron, proton, and the charged lepton, $E_b = 27$ MeV is the nominal nucleon binding energy of oxygen, E_l and \mathbf{p}_l are the reconstructed energy and three-momentum of the lepton, and θ_l is the reconstructed angle of the lepton with respect to the neutrino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



SuperKamiokande samples

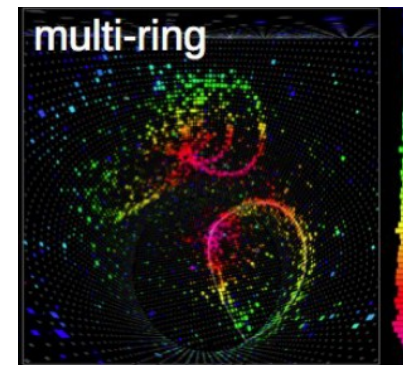


- Reconstruct **Cherenkov ring** from charged particles (above Cherenkov threshold)
- Use information of **time, position and amount of light** in the ring to estimate momentum and direction of particle (likelihood algo 'fitqun')
- '**ring fuzzyness**' to distinguish e/μ (note: $\pi \sim \mu$)
- **Michel 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:**

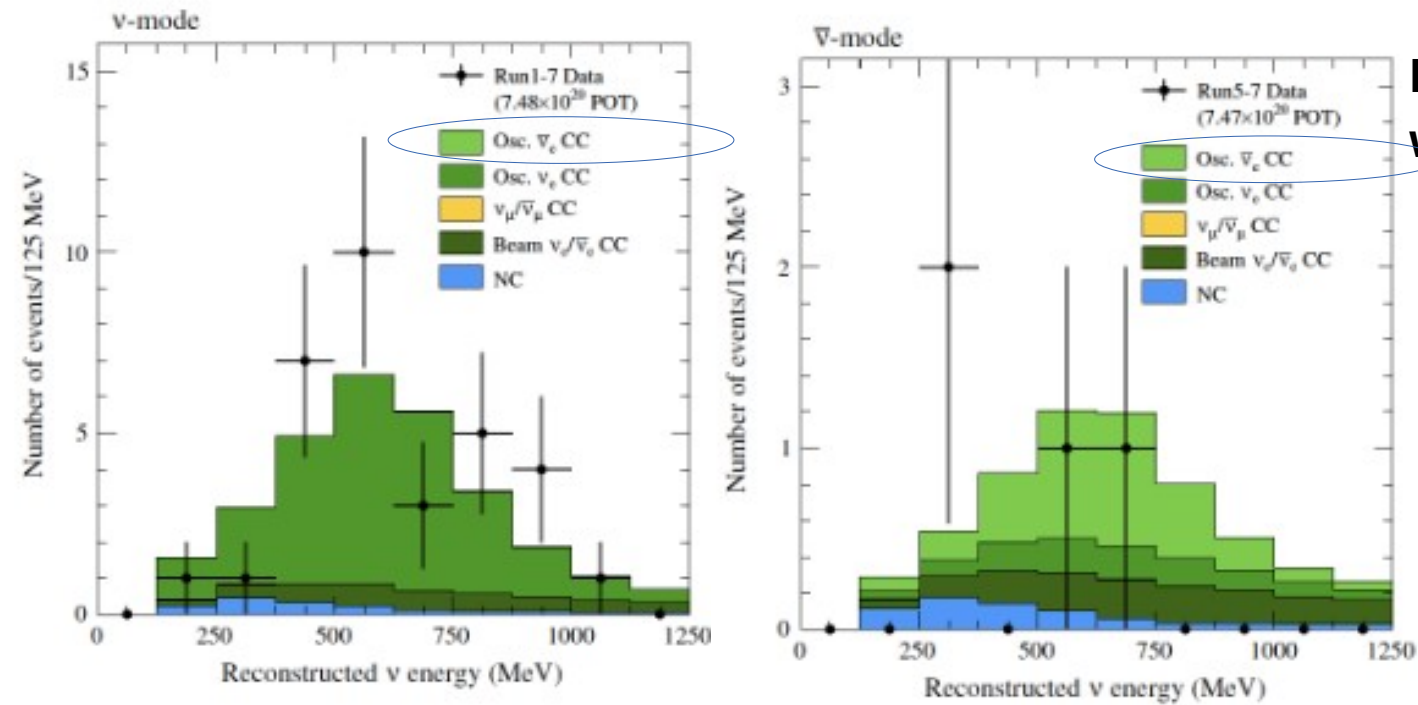
- 1 ring electron (from ν_e) with 1 Michel electron
→ add statistics for ν_e sample
- 1 ring muon (from ν_μ) + 1,2 Michel electron(s) and/or other ring from π
→ add high-energy 'control sample' for ν_μ



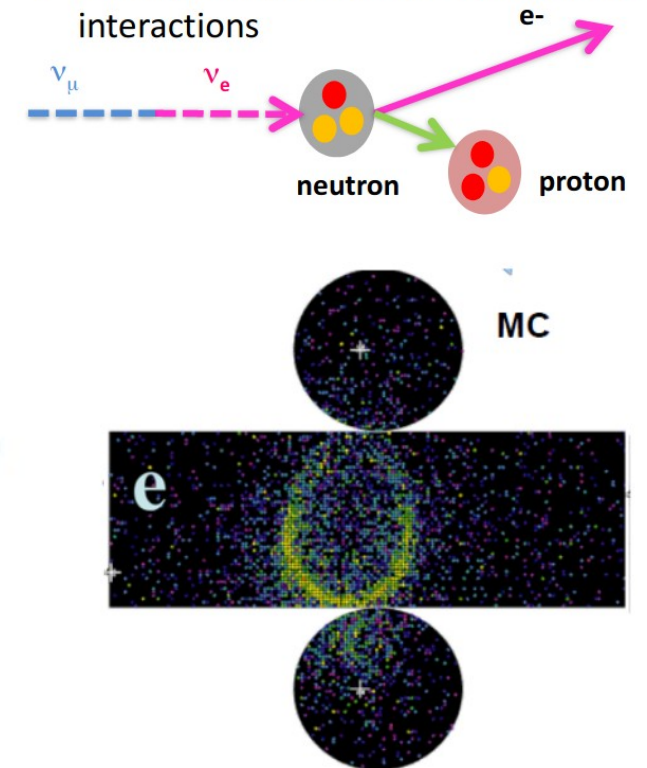
$$E_\nu^{\text{rec}} = \frac{m_{\Delta^{++}}^2 - m_p^2 - m_l^2 + 2m_p E_l}{2(m_p - E_l + p_l \cos \theta_l)}$$

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

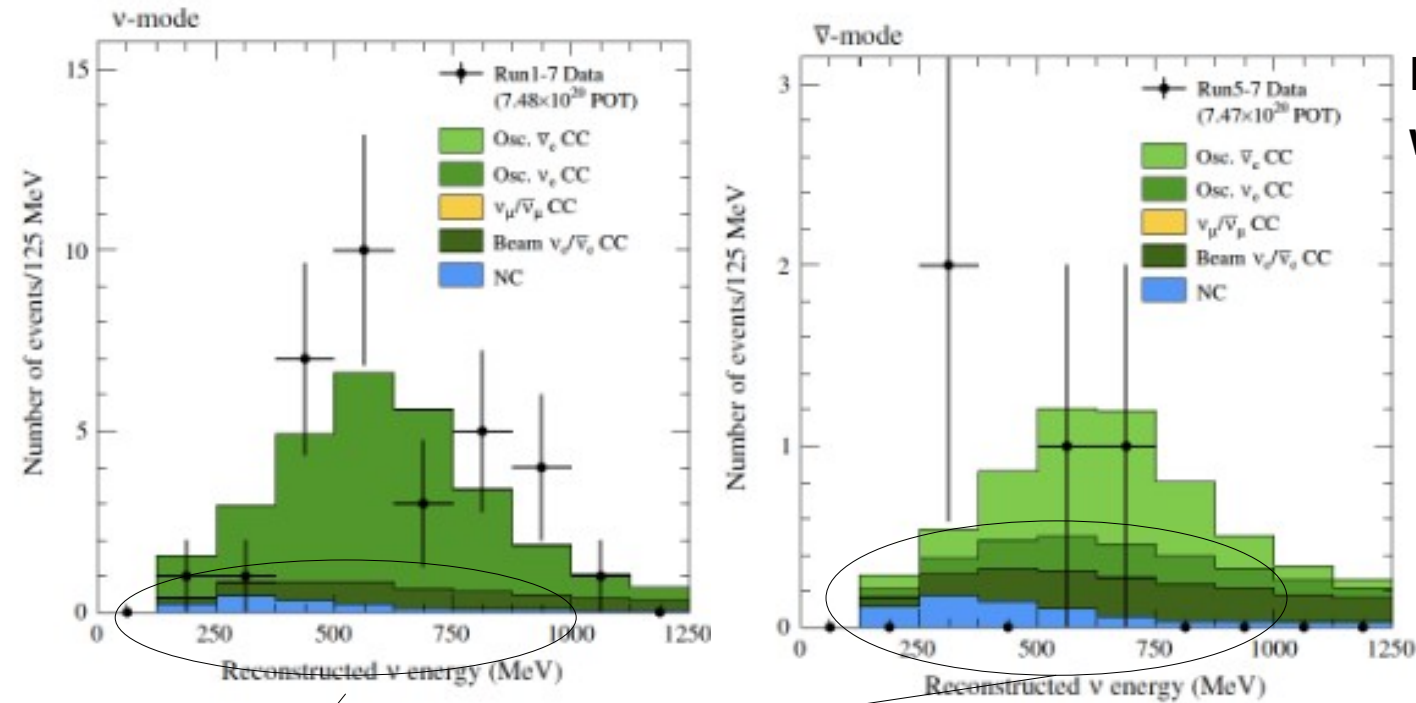
SuperKamiokande samples



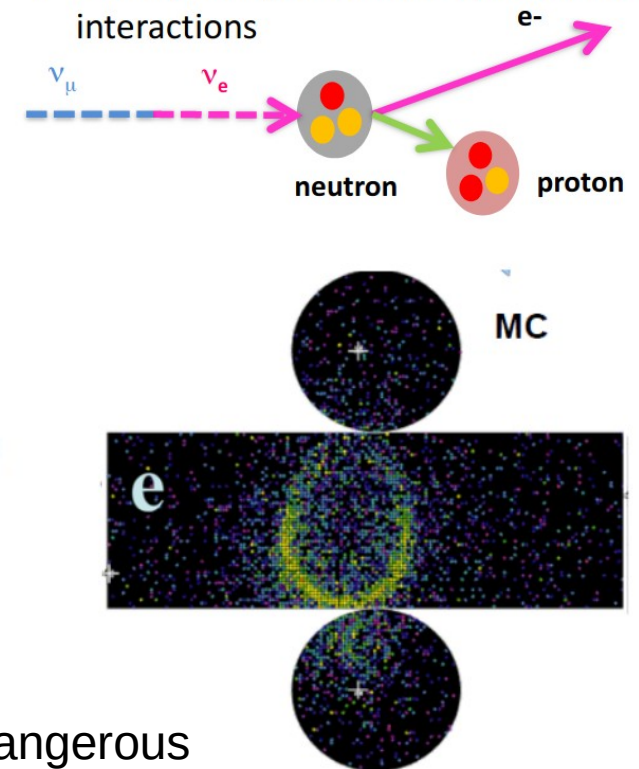
Main signal: ν_e ($\bar{\nu}_e$) appearance with single e-like ring



SuperKamiokande samples



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



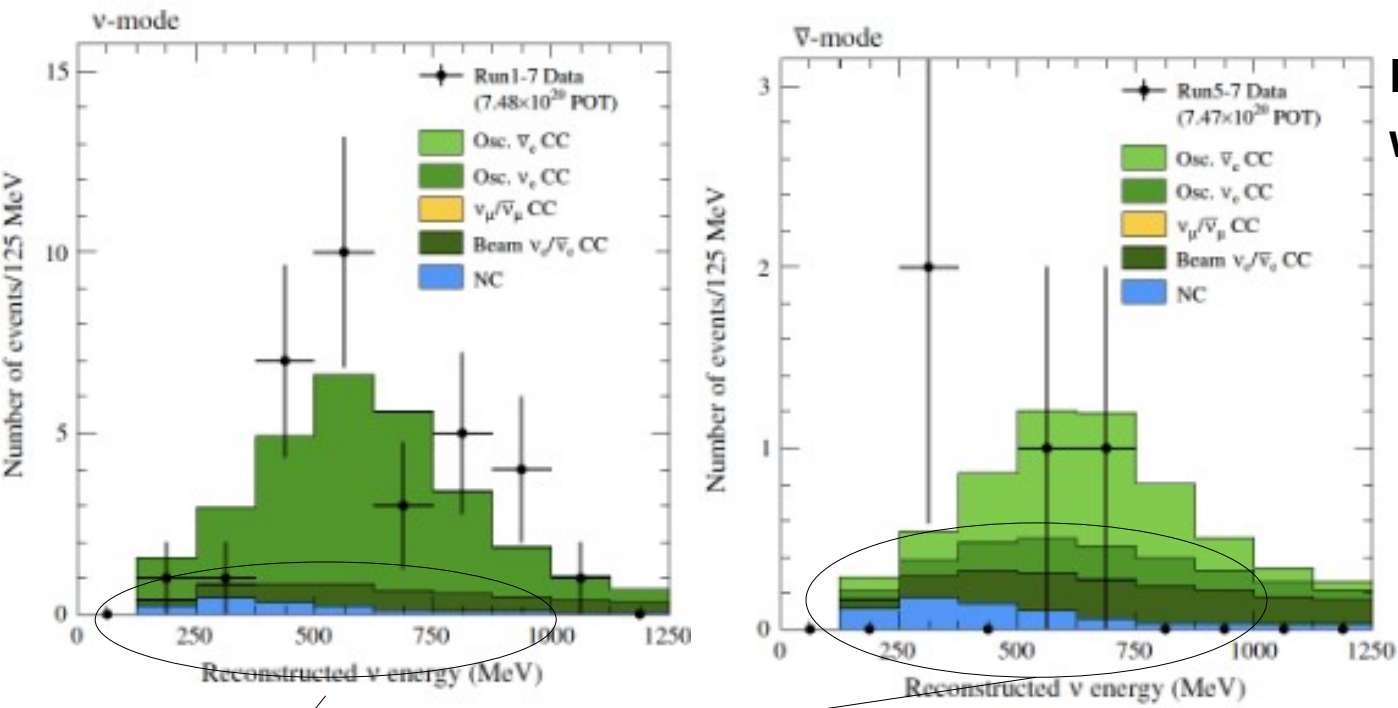
Backgrounds

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

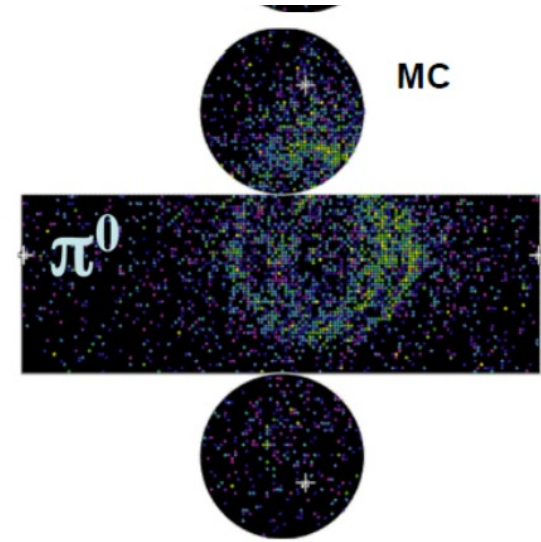
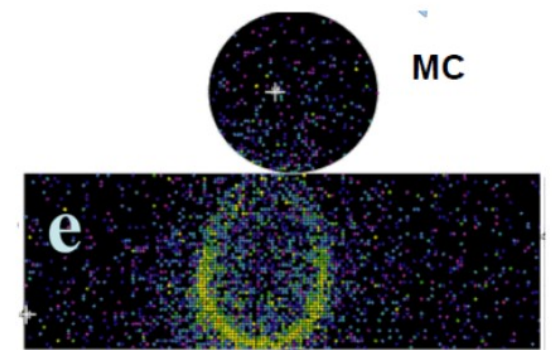
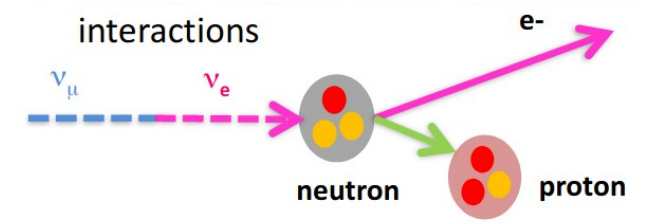
Especially ν_e **wrong sign background** in $\bar{\nu}_e$ RHC sample dangerous for δ_{CP} : need to control $\nu_e/\bar{\nu}_e$ flux and xsec with near detector

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

SuperKamiokande samples

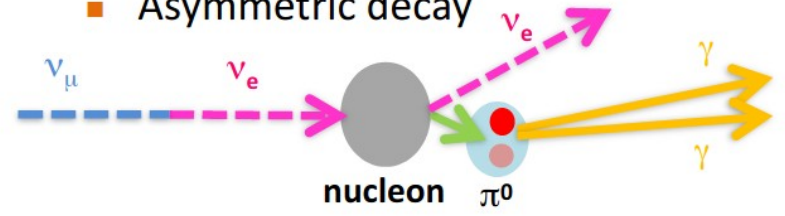


Main signal: ν_e ($\bar{\nu}_e$) appearance with single e-like ring

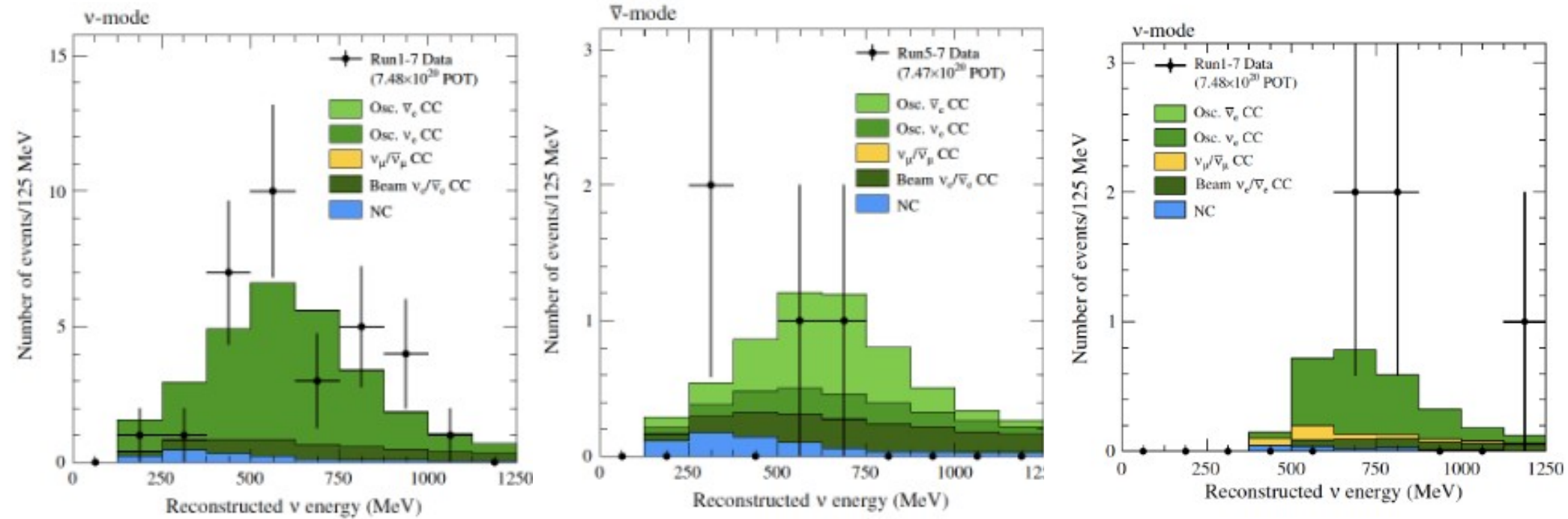


Backgrounds

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

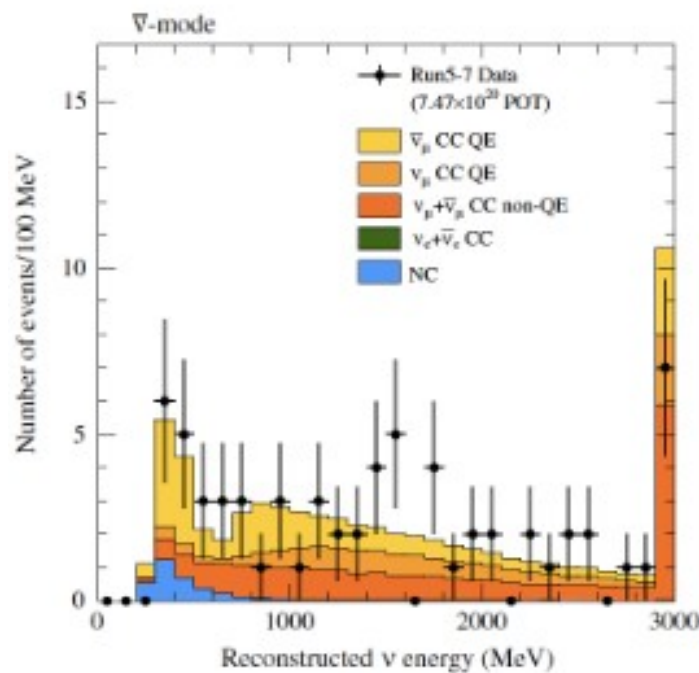
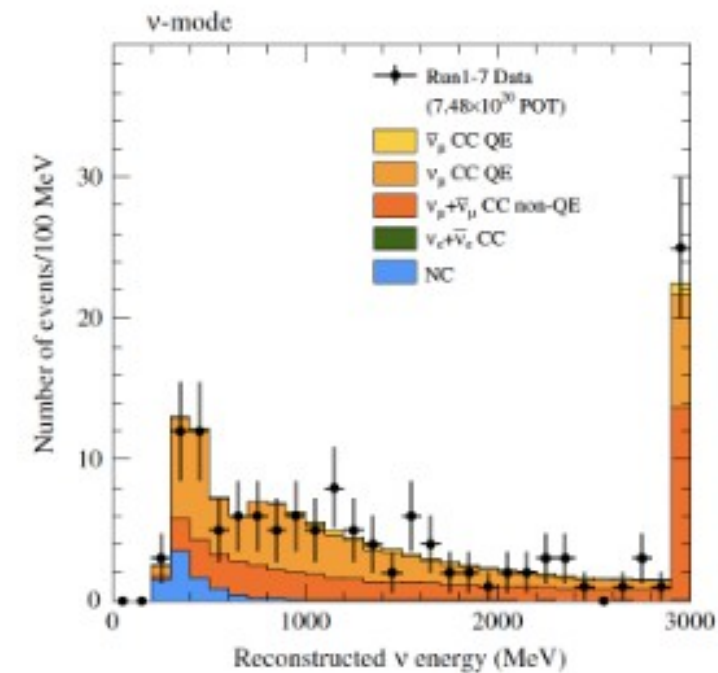
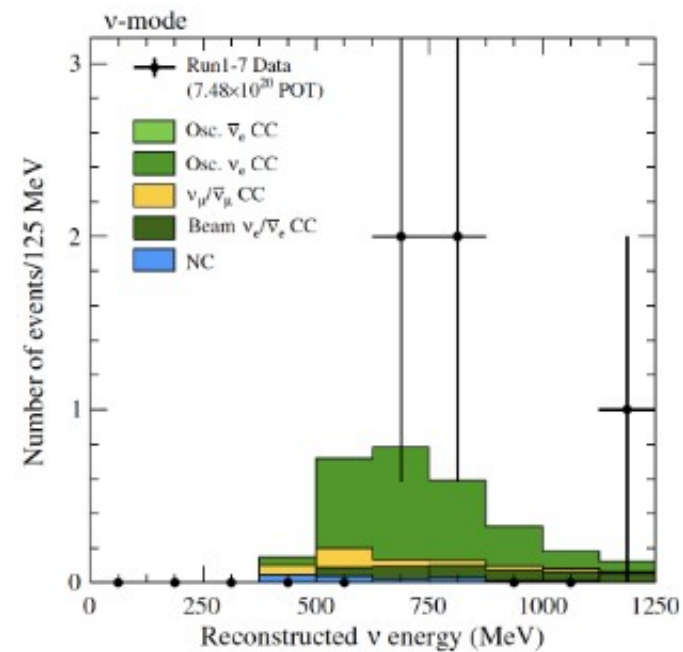
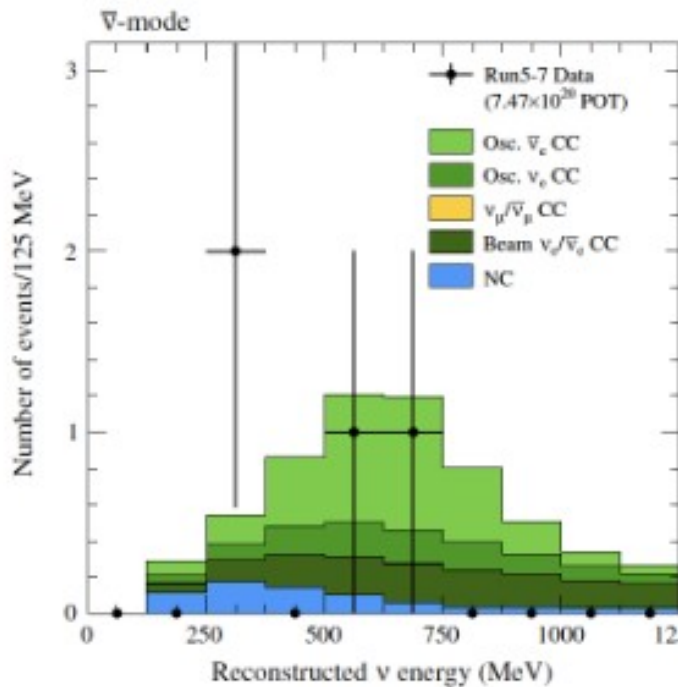
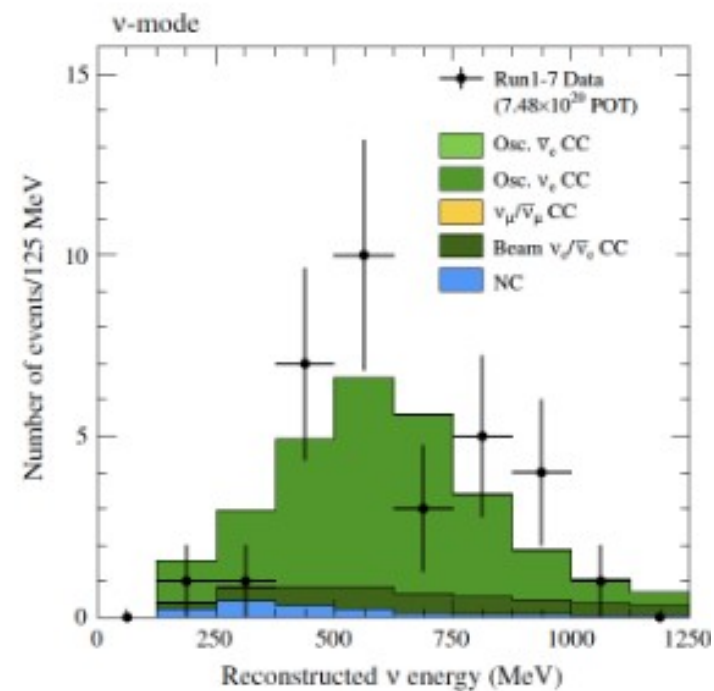


SuperKamiokande samples



ν_e single ring + 1 Michel
electron delayed

SuperKamiokande samples

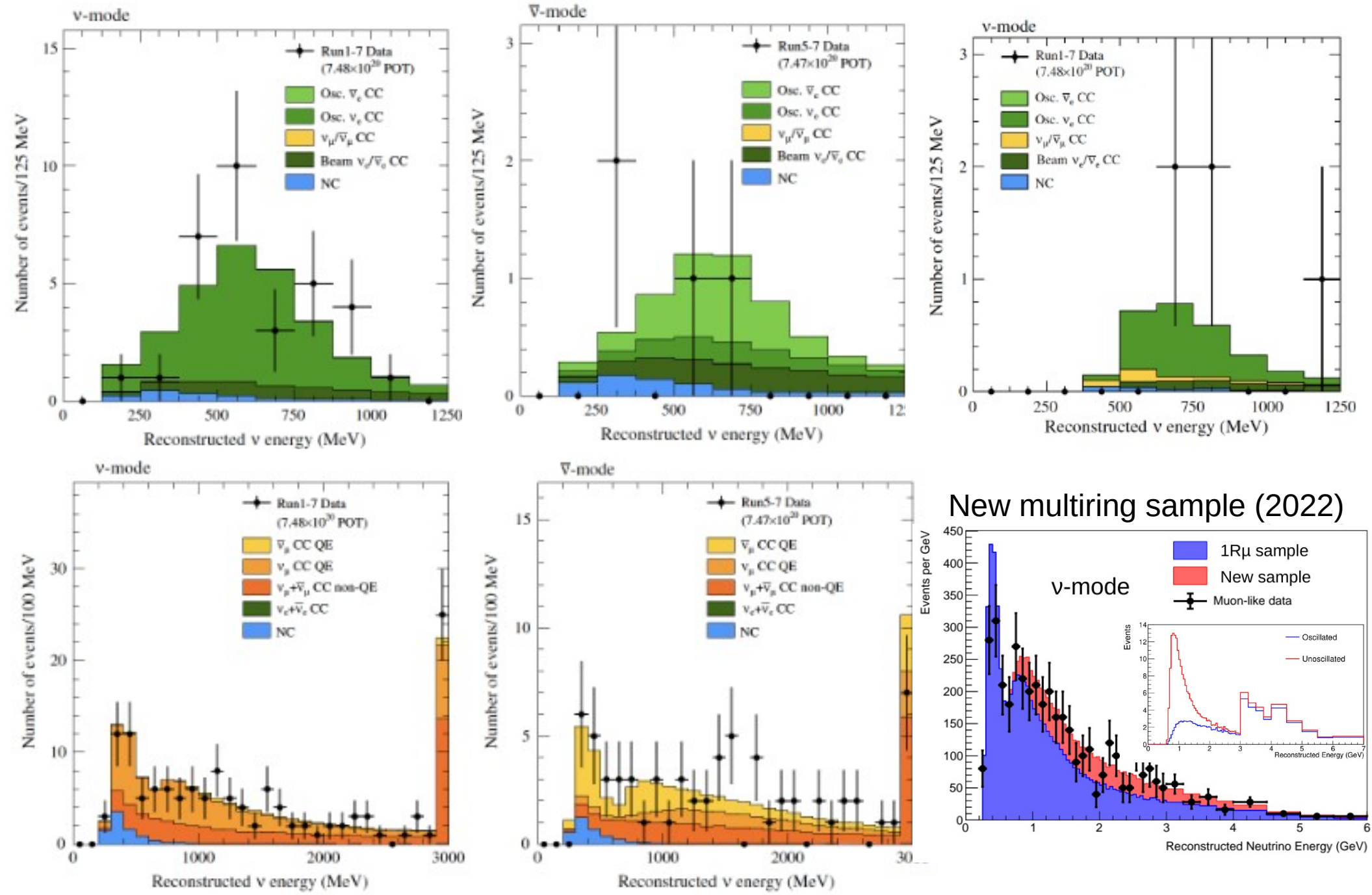


**Main disappearance channel:
 ν_μ with 1 mu-like ring**

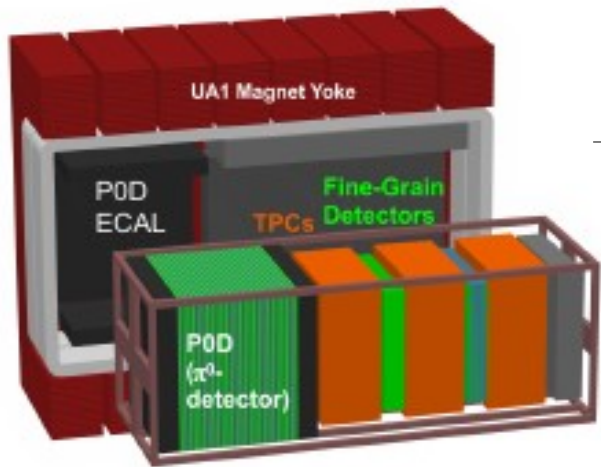
CC-nonQE does disappear but
- higher energy
→ not at oscillation maximum
- but much less precise E_ν^{rec}

Important to have a dedicated
CC- 1π sample at far detector
for x-check 'feed-down' 98

SuperKamiokande samples



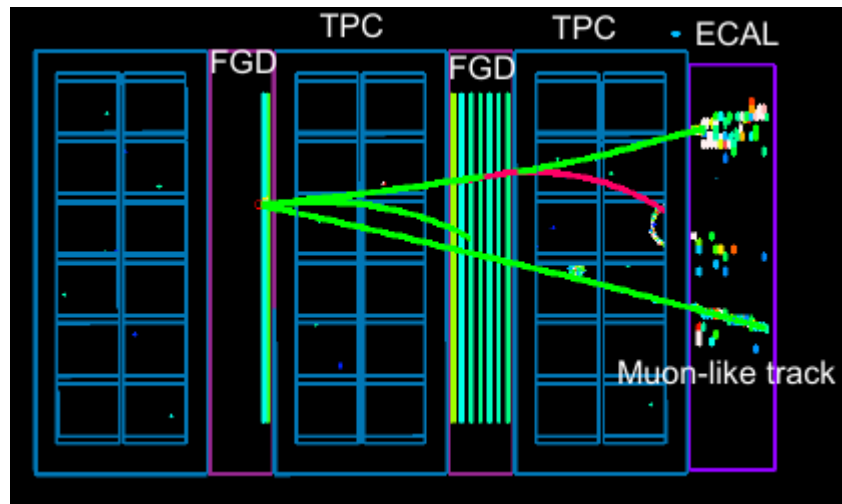
T2K near detectors



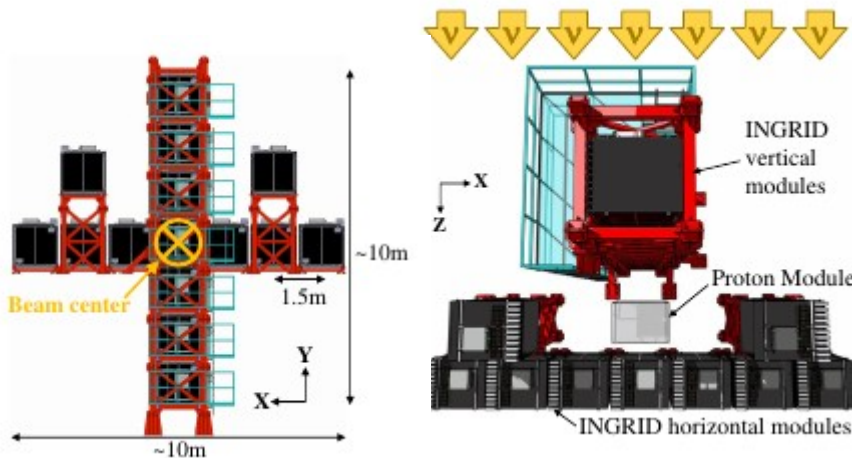
ND280 : off-axis (2.5°)

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 $p_T \sim 1\text{GeV}$) **and particle identification**
- P0D sampling scintillator for pi0 detection (water in/out)



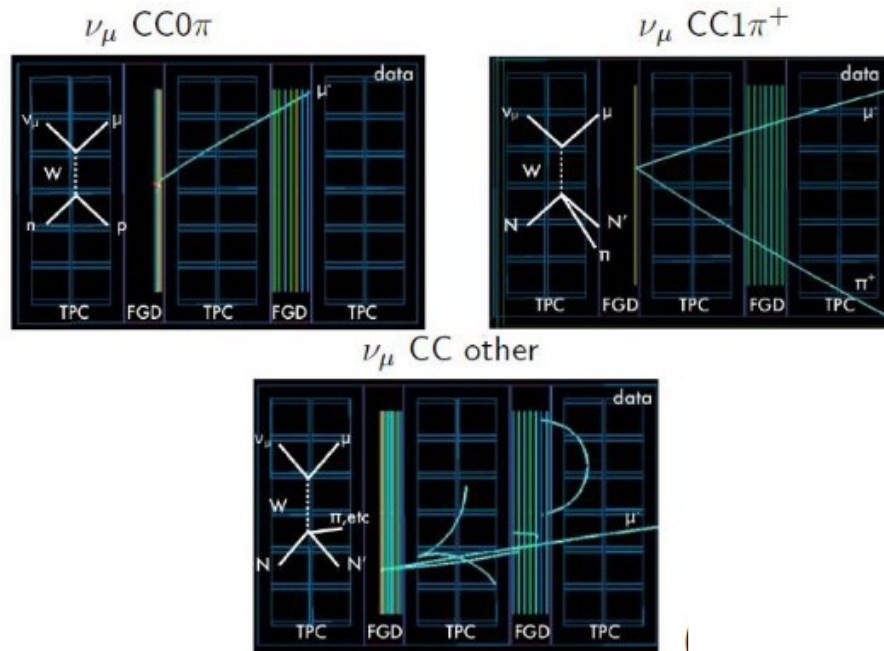
INGRID : on-axis

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

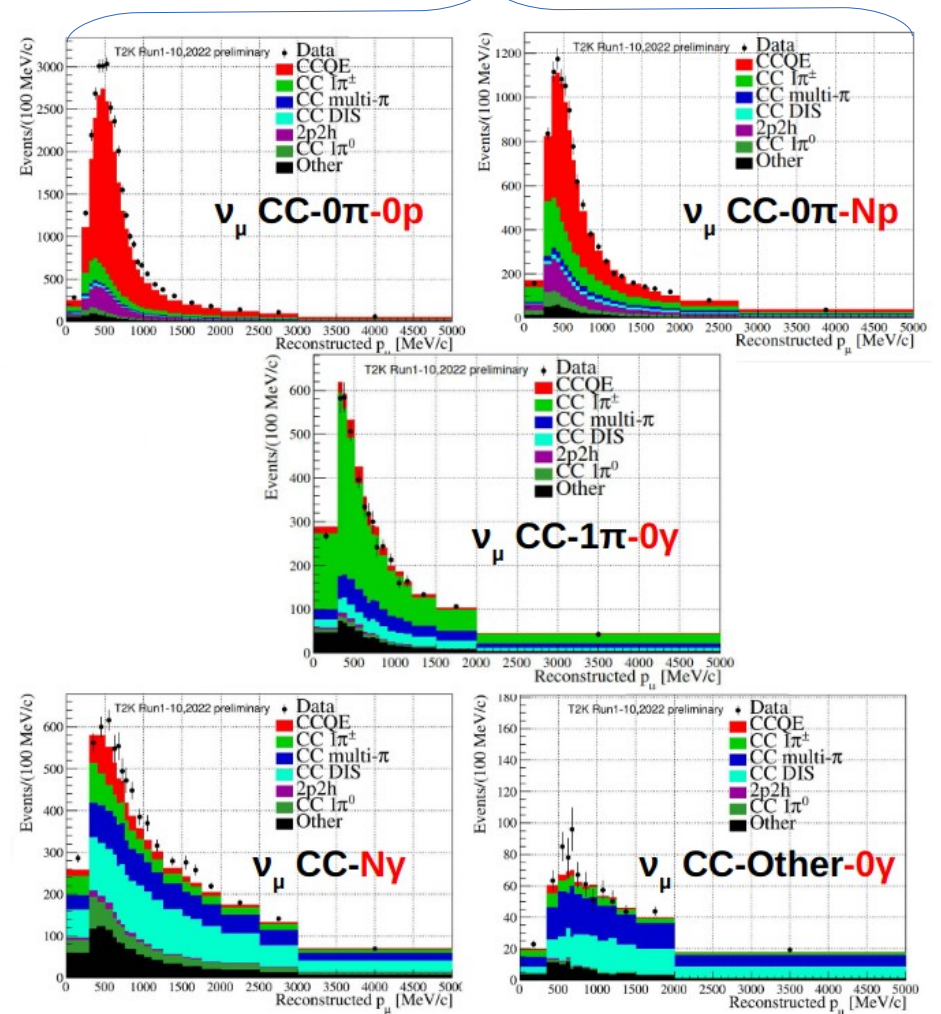
- iron plates alternated with CH scintillator (+ proton module : fully active scintillator)
- **coarser granularity, not magnetized but larger mass** : 2.5×10^{30} nucleons (Fe) + 1.8×10^{29} nucleons (CH)

T2K ND selection

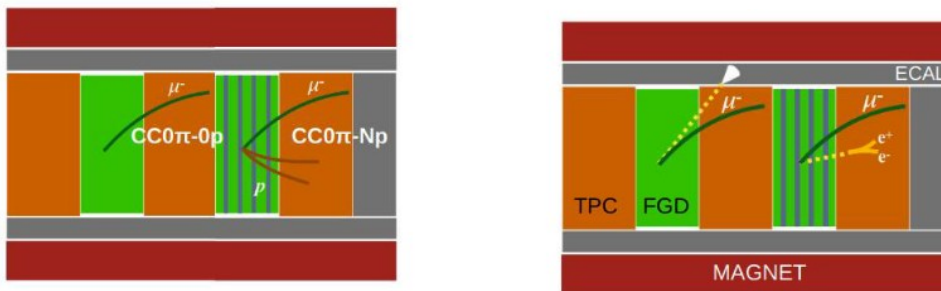
- Require **one muon + separate sample based on proton, pion and g multiplicity (full exclusive final state reconstruction)**
- Until now, similar to SK: **lepton kinematics only used for neutrino energy assessment**



Main QE channel

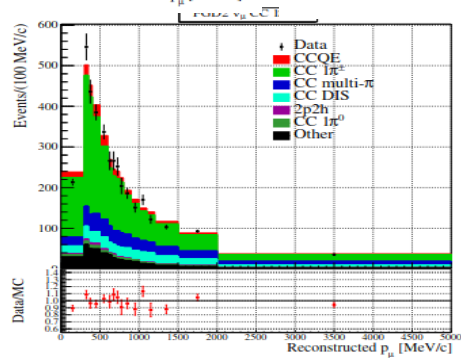
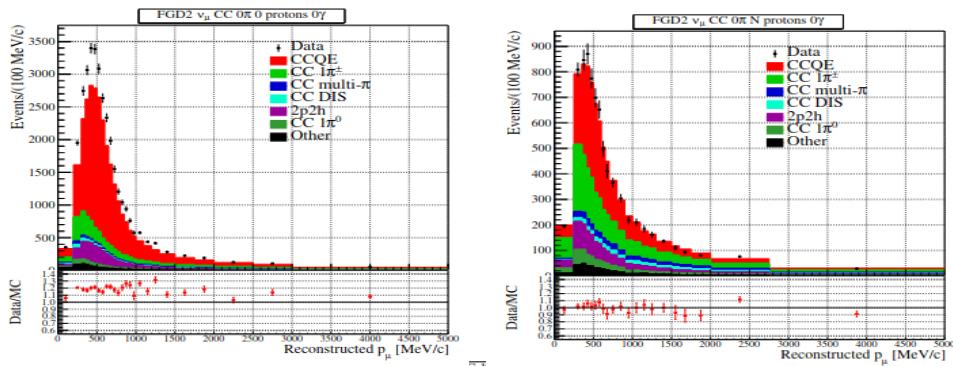


Proton and γ tagging: new in 2022

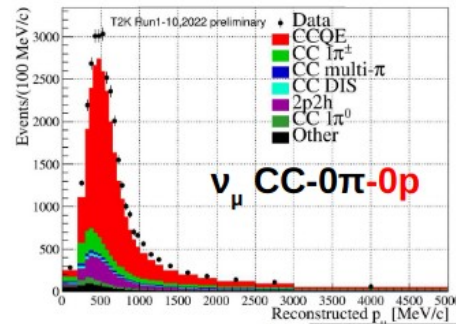
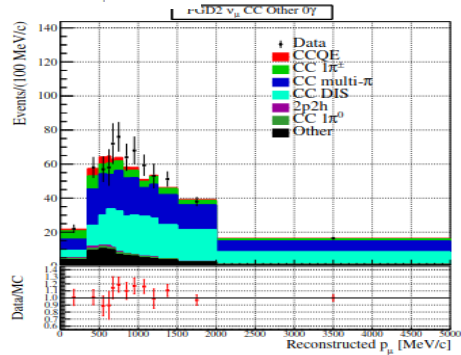
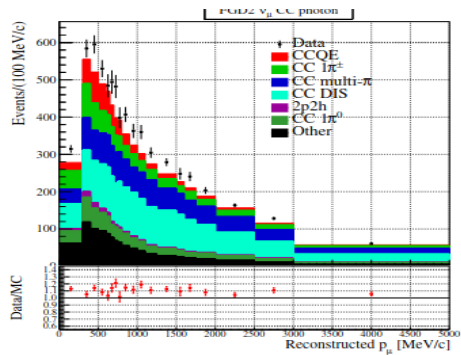


T2K ND selection

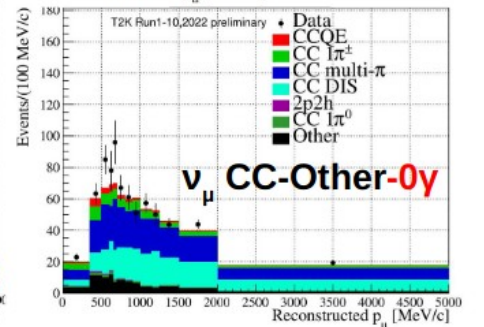
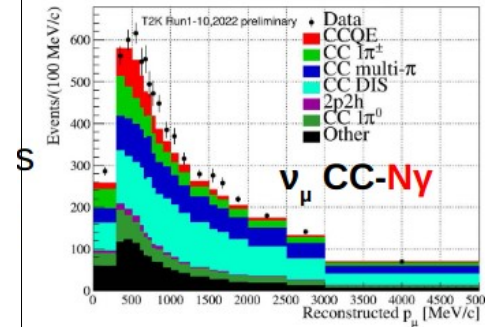
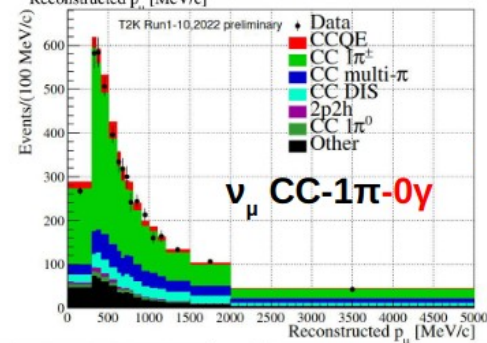
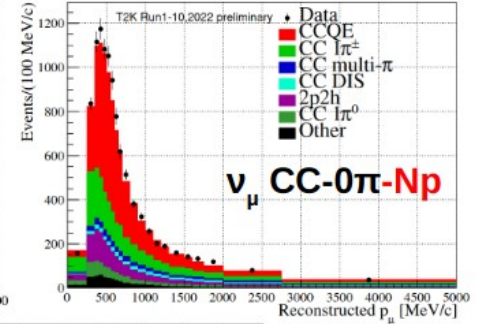
- Require one muon + separate sample based on proton, pion and g multiplicity (**full exclusive final state reconstruction**)
- Until now, similar to SK: lepton kinematics only used for neutrino energy assessment
- Two sets of samples for **FGD1 (CH only)** and **FGD2 (CH+water)**



FGD2



FGD1

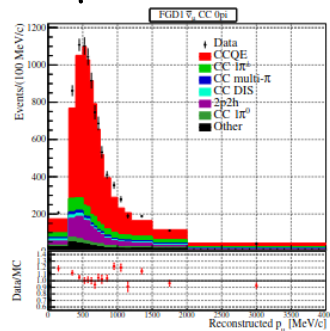


T2K ND selection

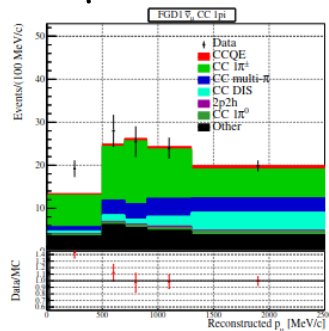
- Require one muon + separate sample based on proton, pion and g multiplicity (**full exclusive final state reconstruction**)
- Until now, similar to SK: lepton kinematics only used for neutrino energy assessment
- Two sets of samples for **FGD1 (CH only)** and **FGD2 (CH+water)**
- RHC mode: μ^+ ($\bar{\nu}_\mu$) and μ^- (ν_μ) **separate samples**

FGD1 RHC

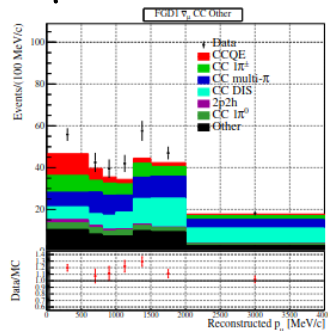
μ^+ CC0 π



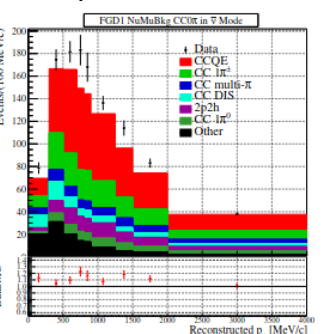
μ^+ CC1 π



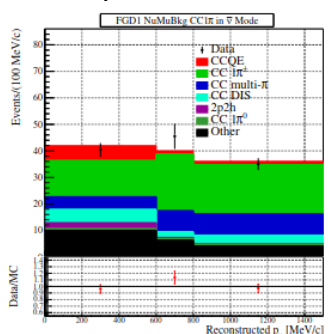
μ^+ CC-Other



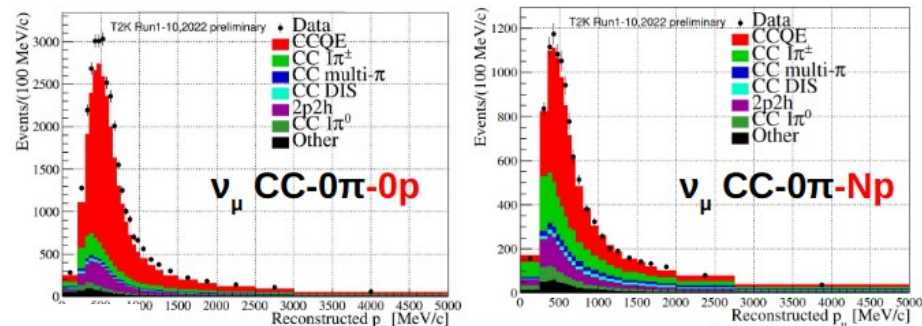
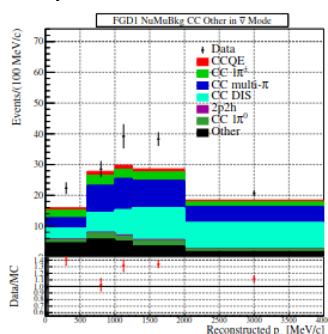
μ^- CC0 π



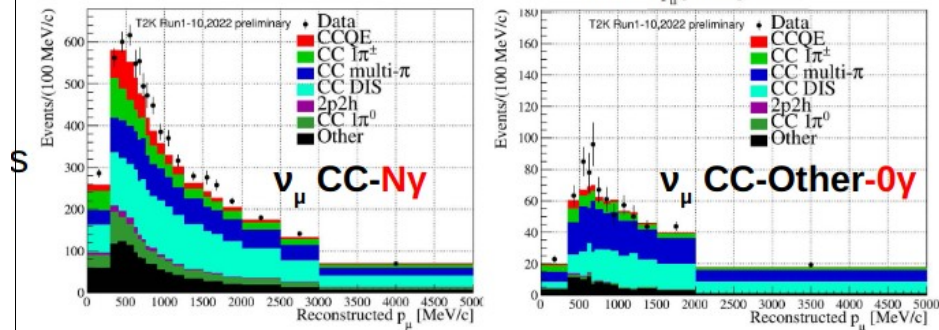
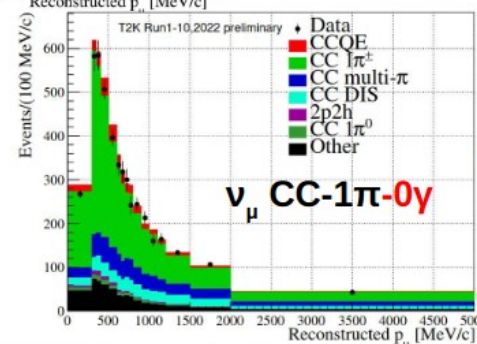
μ^- CC1 π



μ^- CC-Other

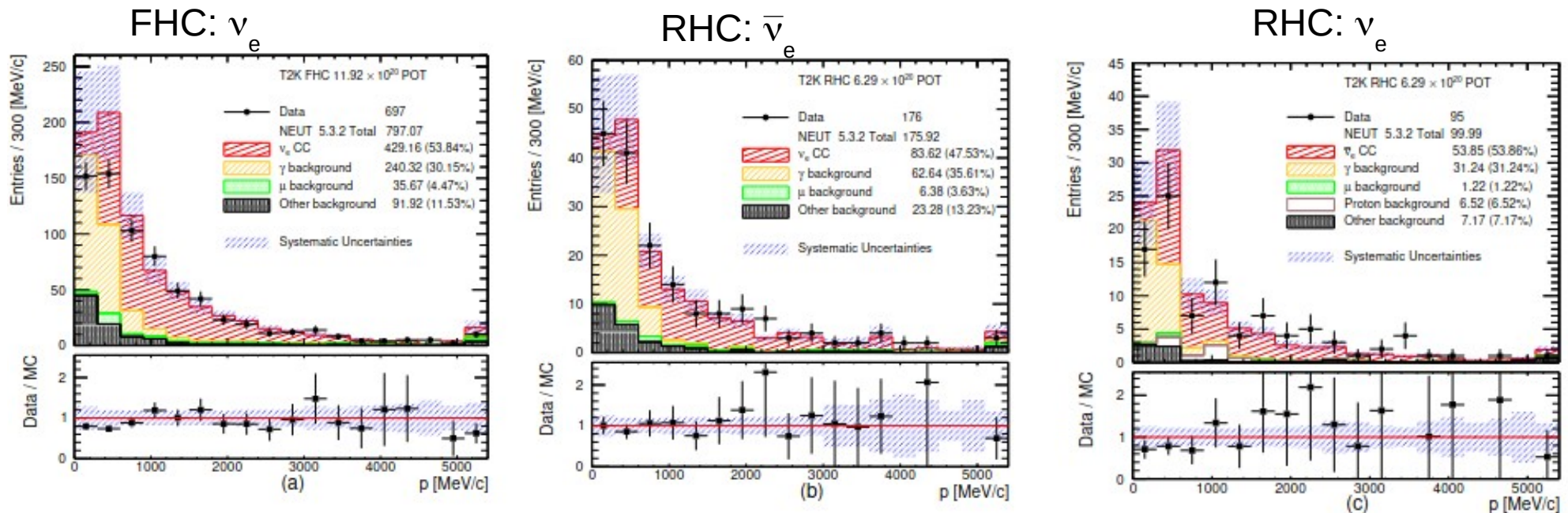


FGD1 FHC



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 $\nu_\mu/\bar{\nu}_\mu$ purity of the beam. What really matters for δ_{CP} in $\nu_e/\bar{\nu}_e$ flux and xsec (from nuclear theory $\sim <2\%$)
- Dedicated ν_e cross-section measurement shows agreement with model but with large stat and systematics uncertainties.



T2K ND fit

- ND measurement

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

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

~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

- ND measurement

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

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

~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
 - measurement as a function of energy
 - needs to rely on models (tuned to ND data)

T2K ND fit

- ND measurement

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

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

~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
 - measurement as a function of energy
 - needs to rely on models (tuned to ND data)

- Fit to ND observed distributions:

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

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

T2K ND fit

- ND measurement

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

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

~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
 - measurement as a function of energy
 - needs to rely on models (tuned to ND data)

- Fit to ND observed distributions:

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

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

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

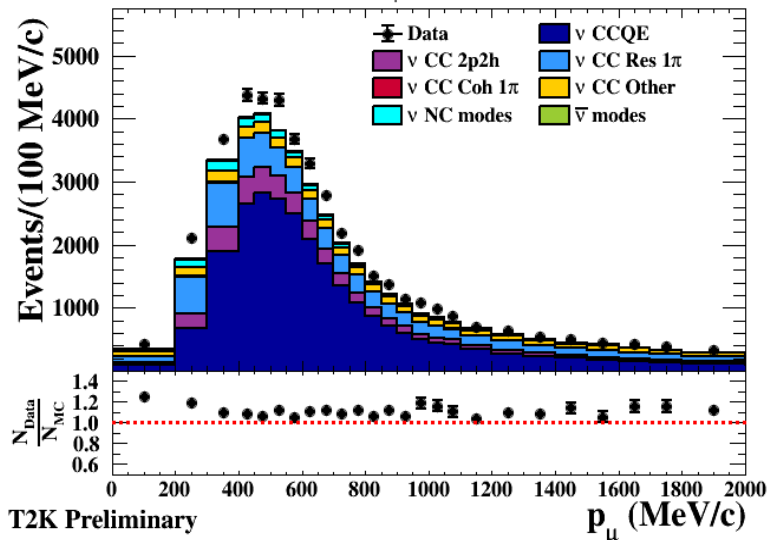
$$E_{\nu} = R(p_{\mu}, \cos \theta_{\mu}; \alpha_{FD}, \alpha_{model})$$

T2K ND: data fit

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

PREFIT

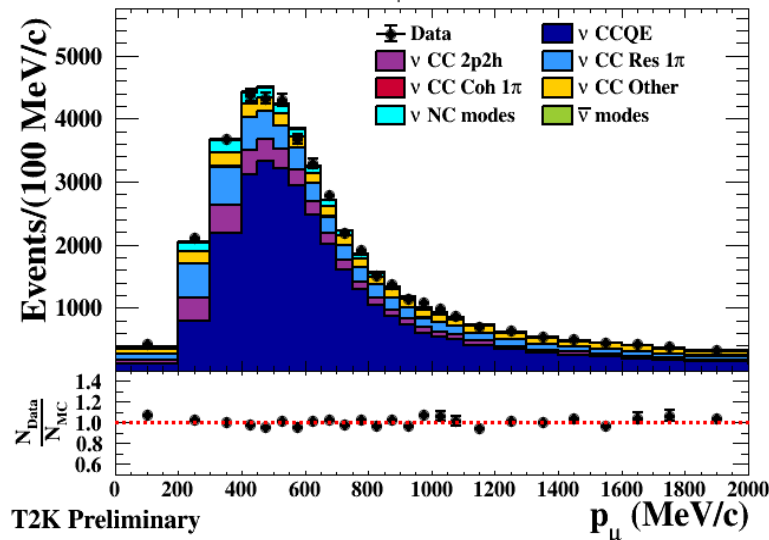
FGD1 ν_μ CC0 π



T2K Preliminary

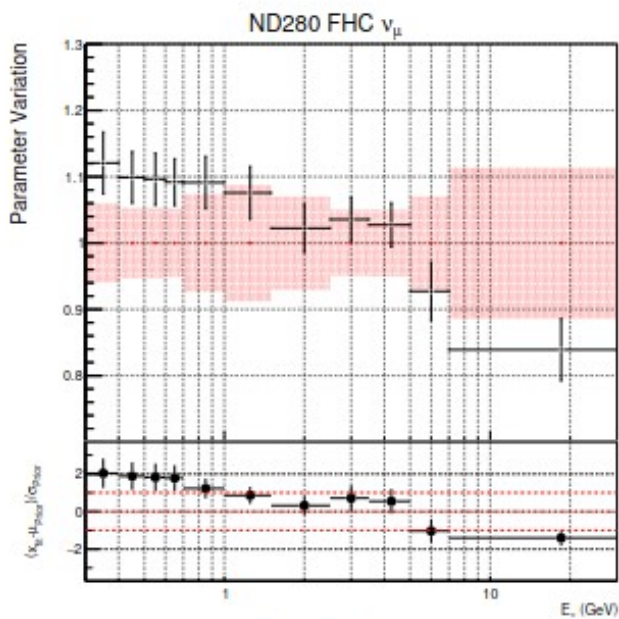
POSTFIT

FGD1 ν_μ CC0 π

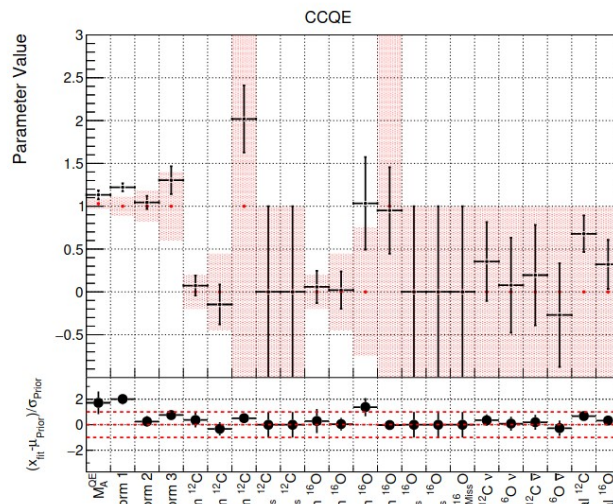


T2K Preliminary

Tuning of flux and xsec model



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

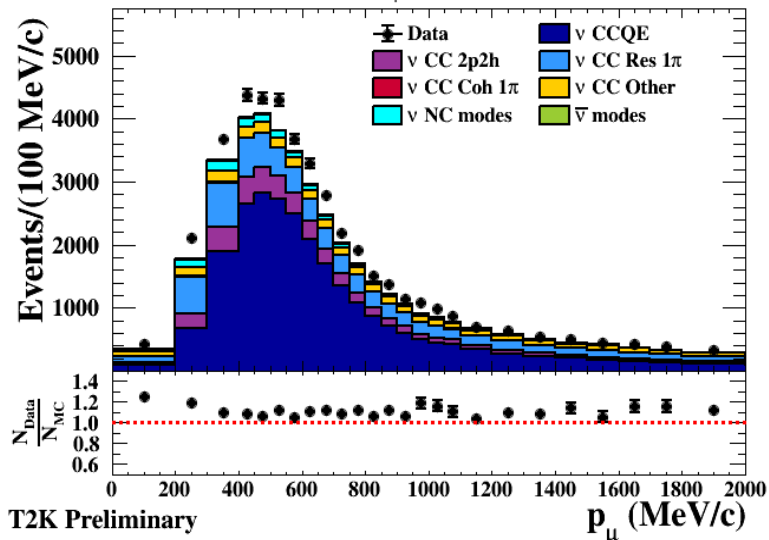


T2K ND: data fit

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

PREFIT

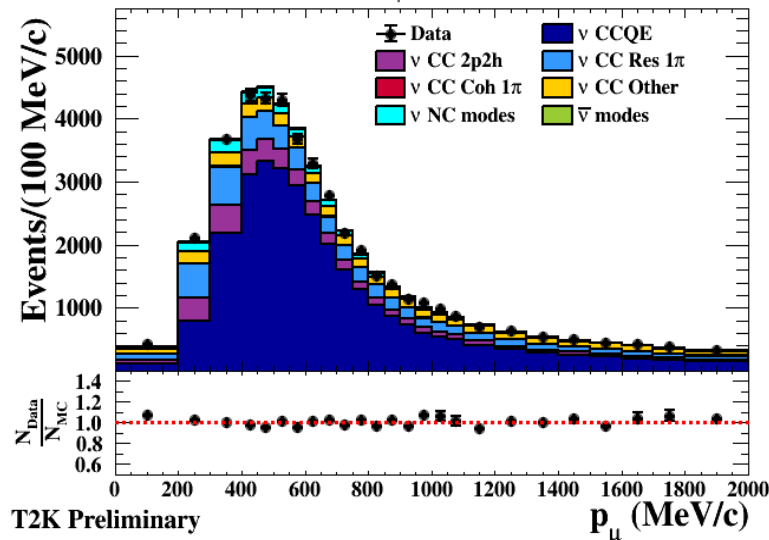
FGD1 ν_μ CC0 π



T2K Preliminary

POSTFIT

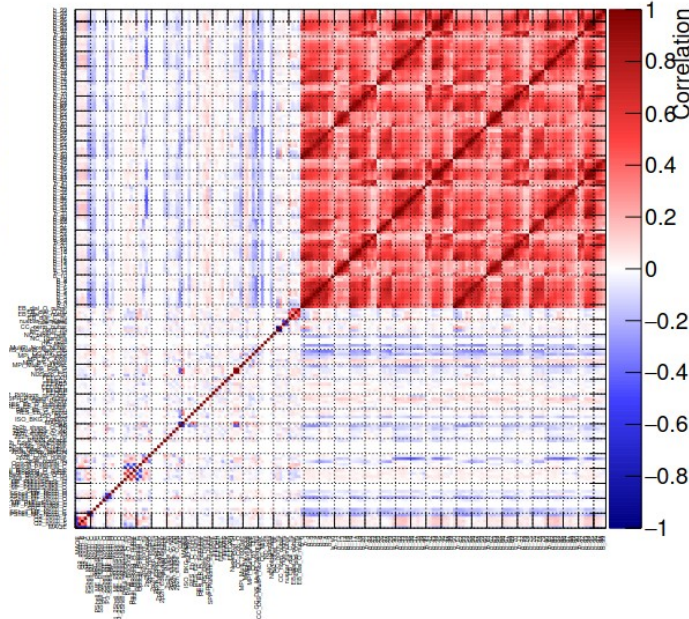
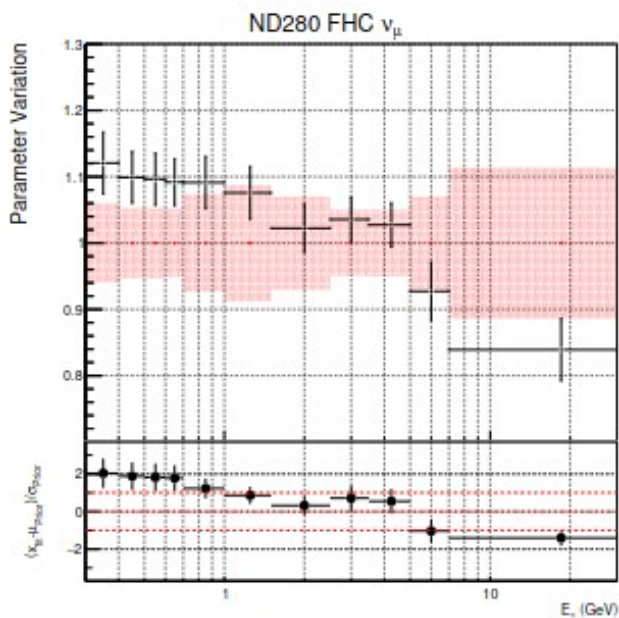
FGD1 ν_μ CC0 π



T2K Preliminary



Tuning of flux and xsec model



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

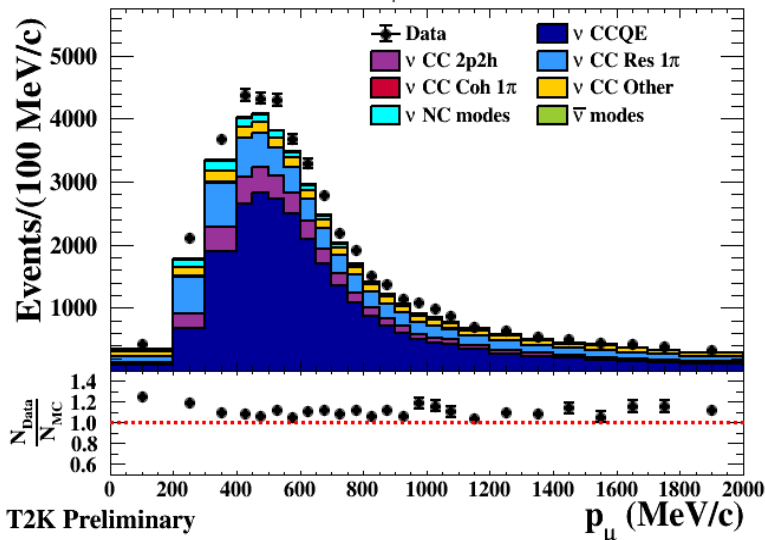
All parameters got correlated from the fit

T2K ND: data fit

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

PREFIT

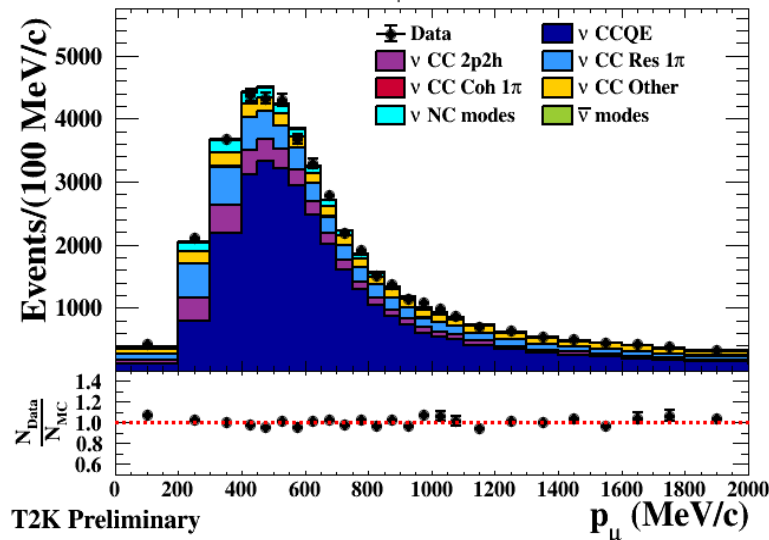
FGD1 ν_μ CC0 π



T2K Preliminary

POSTFIT

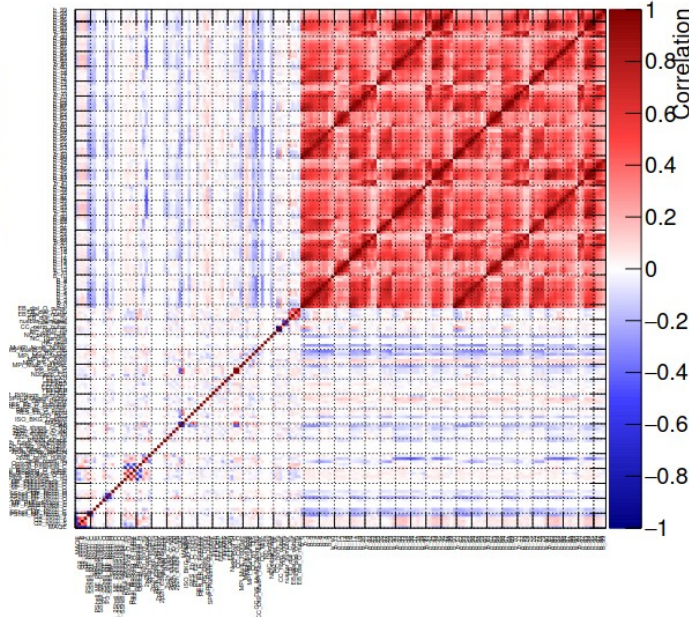
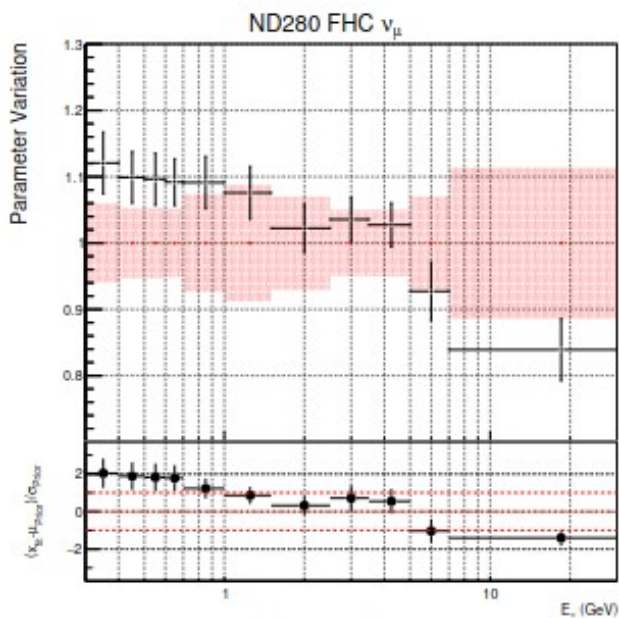
FGD1 ν_μ CC0 π



T2K Preliminary



Tuning of flux and xsec model



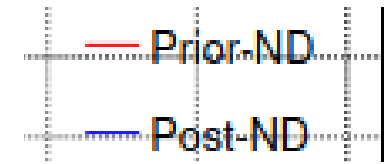
Actually hundreds of parameters (only main flux and xsec channel shown)

All parameters got correlated from the fit

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

SuperKamiokande tuned distribution

(Only main samples shown)

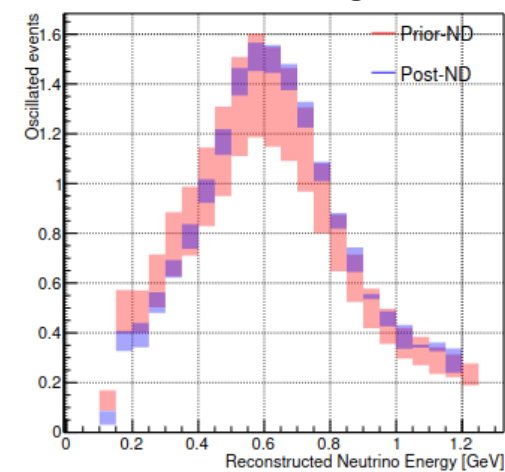
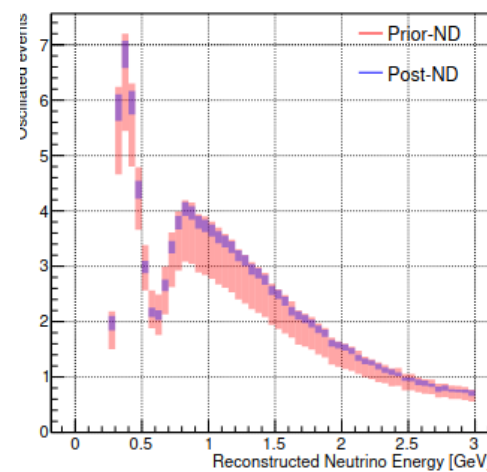
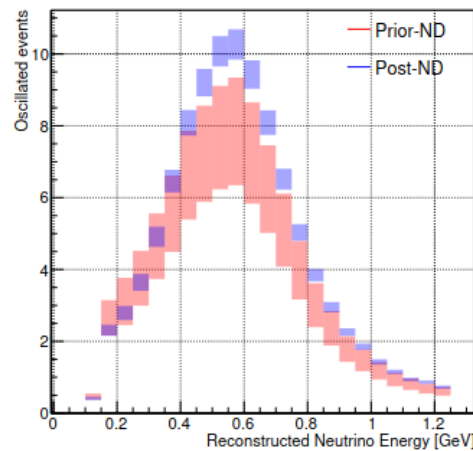
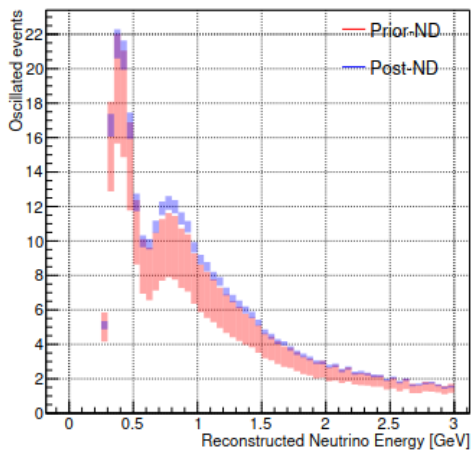


FHC 1ring μ

FHC 1ring e

RHC 1ring μ

RHC 1ring e



Before the ND fit

After the ND fit

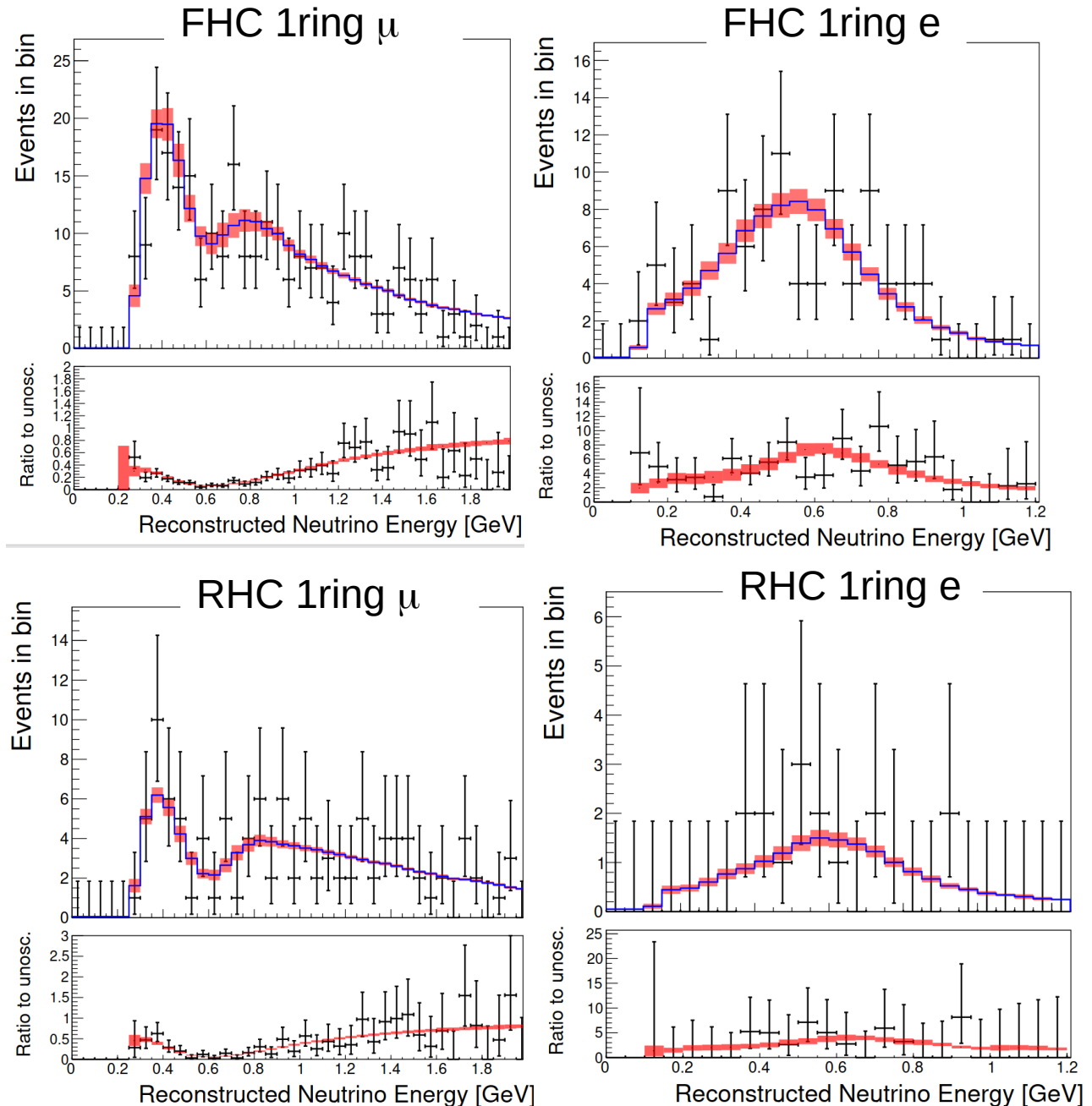
Error source (units: %)	1ring μ		1ring e		
	FHC	RHC	FHC	RHC	FHC/RHC
Flux	5.0	4.6	4.9	4.6	4.5
Cross-section (all)	15.8	13.6	16.3	13.1	10.5
SK+SI+PN	2.6	2.2	3.1	3.9	1.3
Total All	16.7	14.6	17.3	14.4	11.6

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

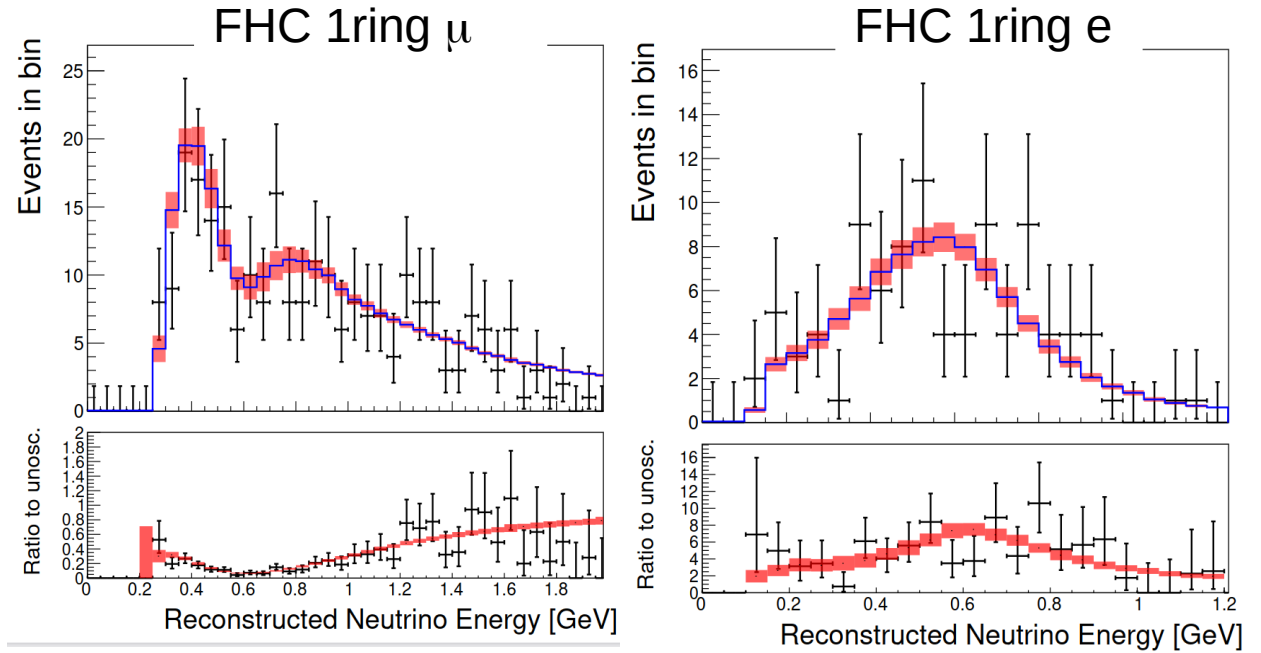


(Only main samples shown)

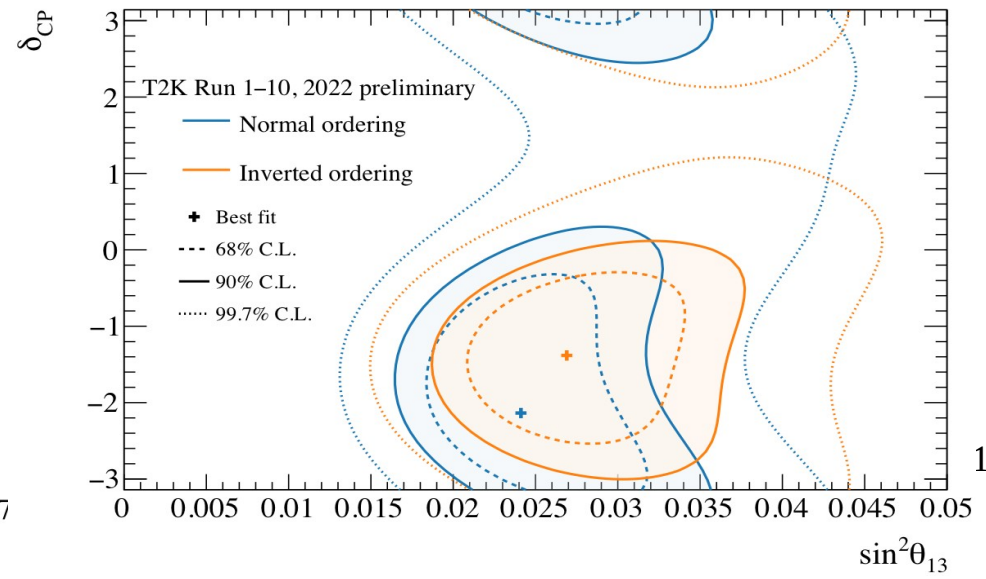
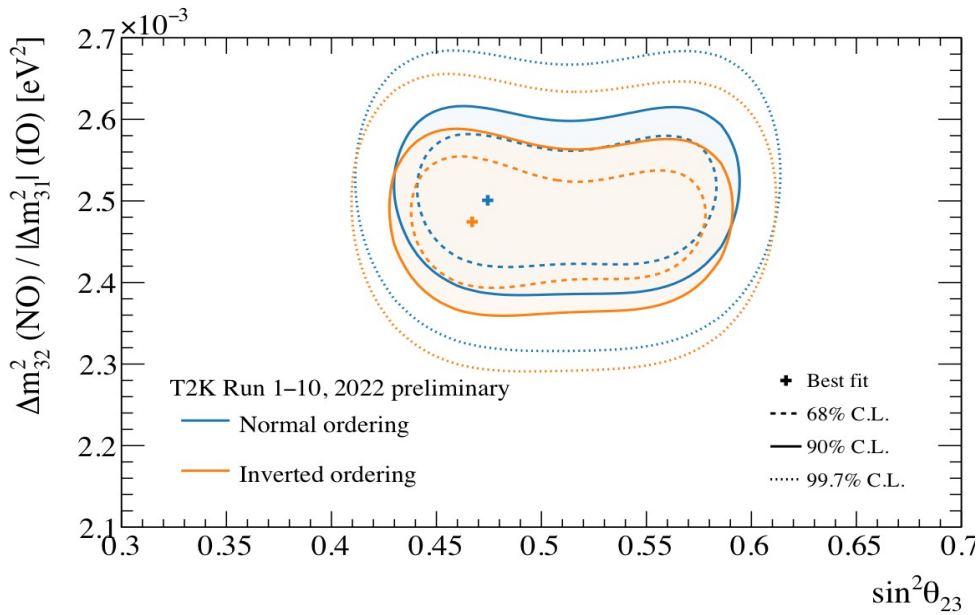
SuperKamiokande fit

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

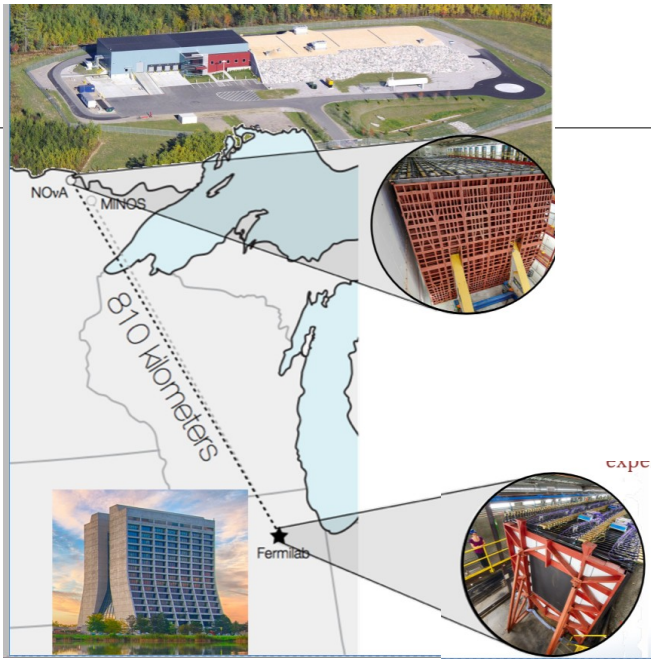
(SuperKamiokande detector systematics are evaluated from atmospheric neutrinos and from dedicated control samples)



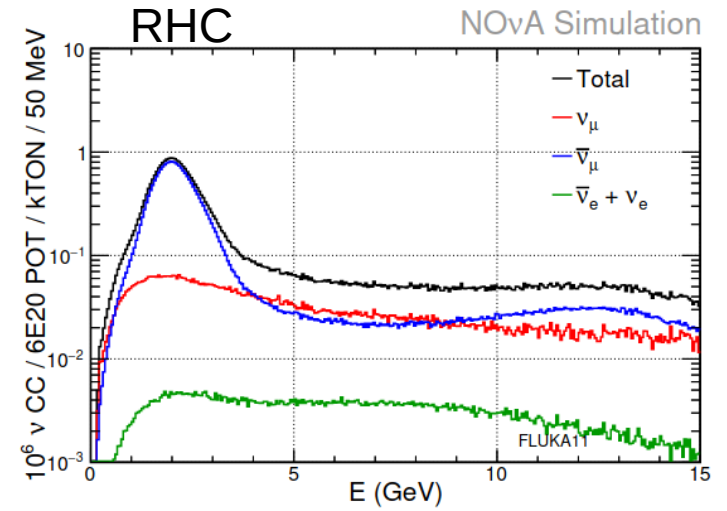
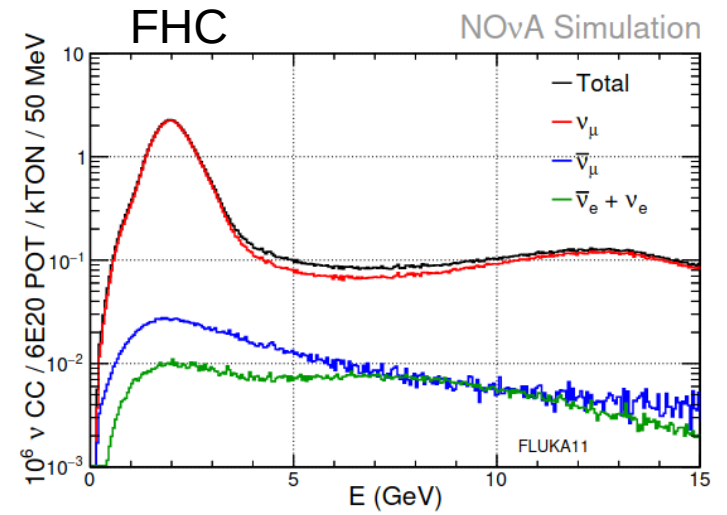
- Both a joint ND+FD fit and sequential ND \rightarrow FD fit are done and compared. Both frequentist and bayesian analysis are performed and compared



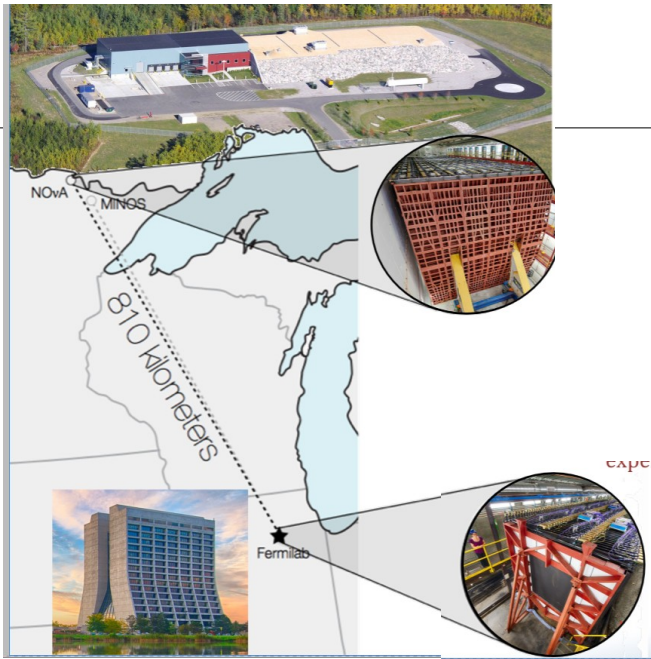
NOVA



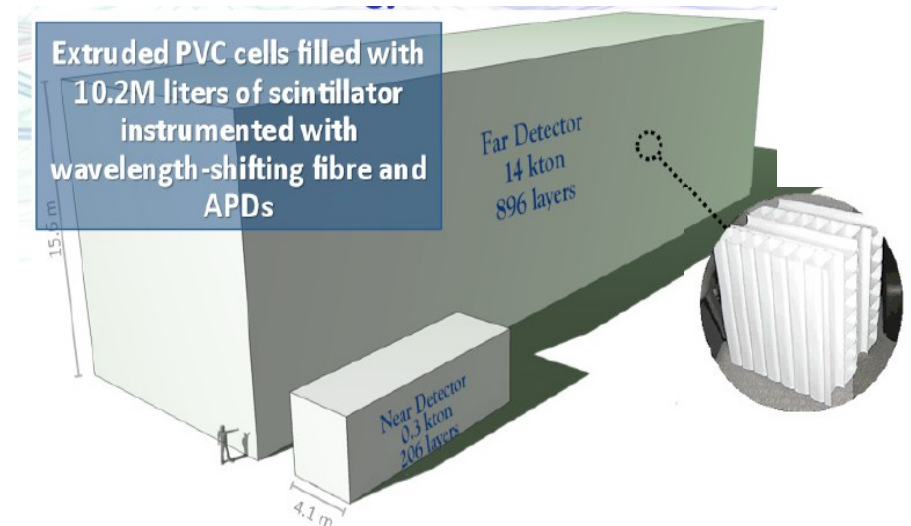
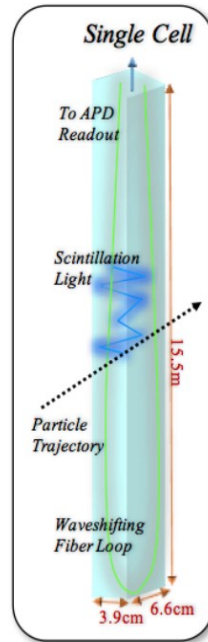
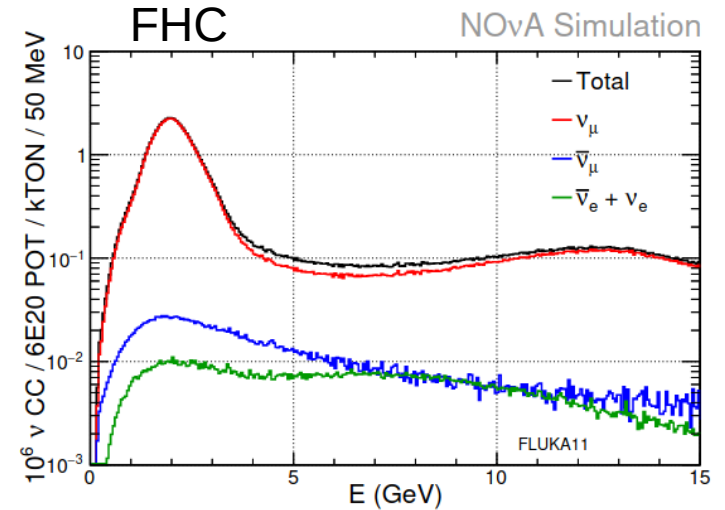
NUMI beam at FNAL
14mrad off-axis
(narrow-band spectrum)
Baseline: 810km



NOVA



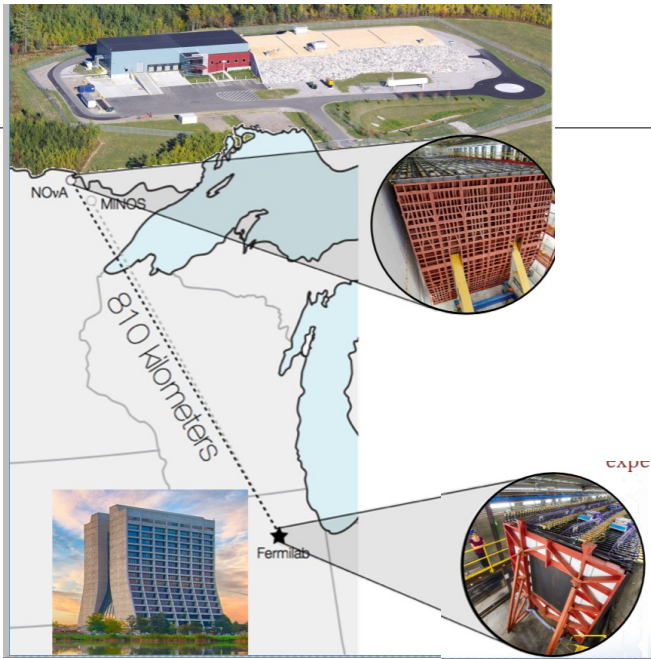
NUMI beam at FNAL
 14mrad off-axis
 (narrow-band spectrum)
Baseline: 810km



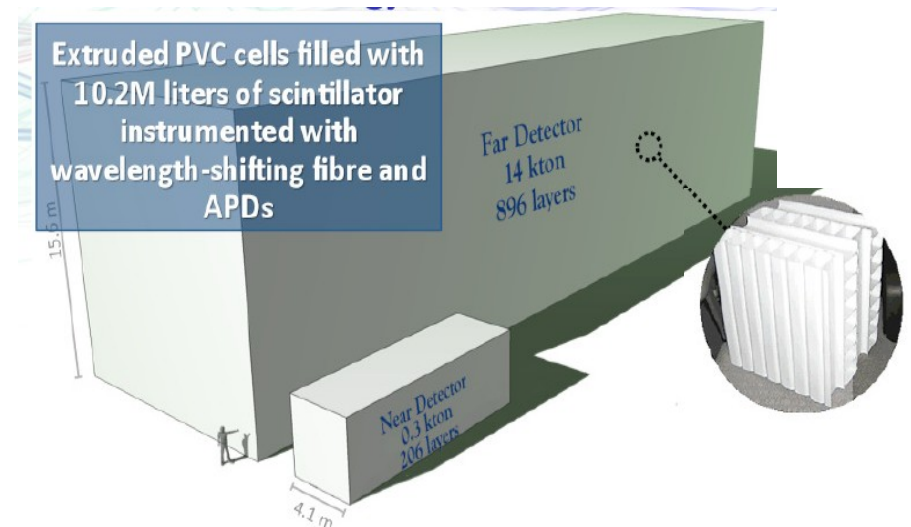
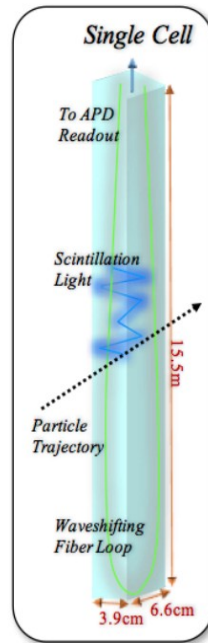
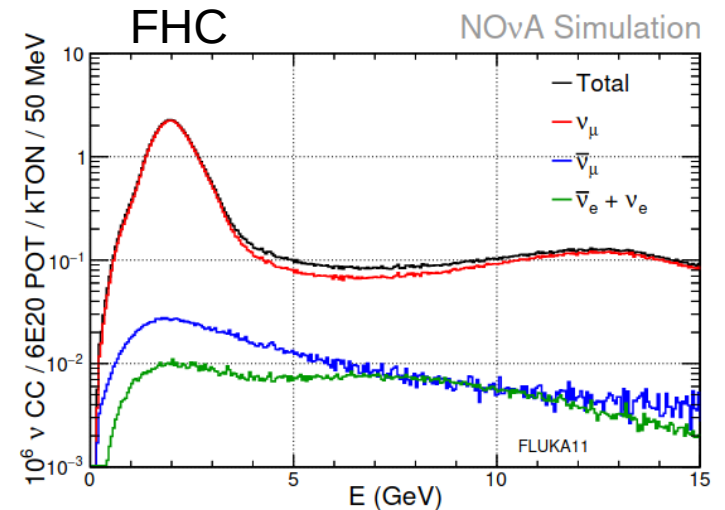
- Same technology (liquid scintillator) for near and far detector

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

NOVA



NUMI beam at FNAL
14mrad off-axis
(narrow-band spectrum)
Baseline: 810km

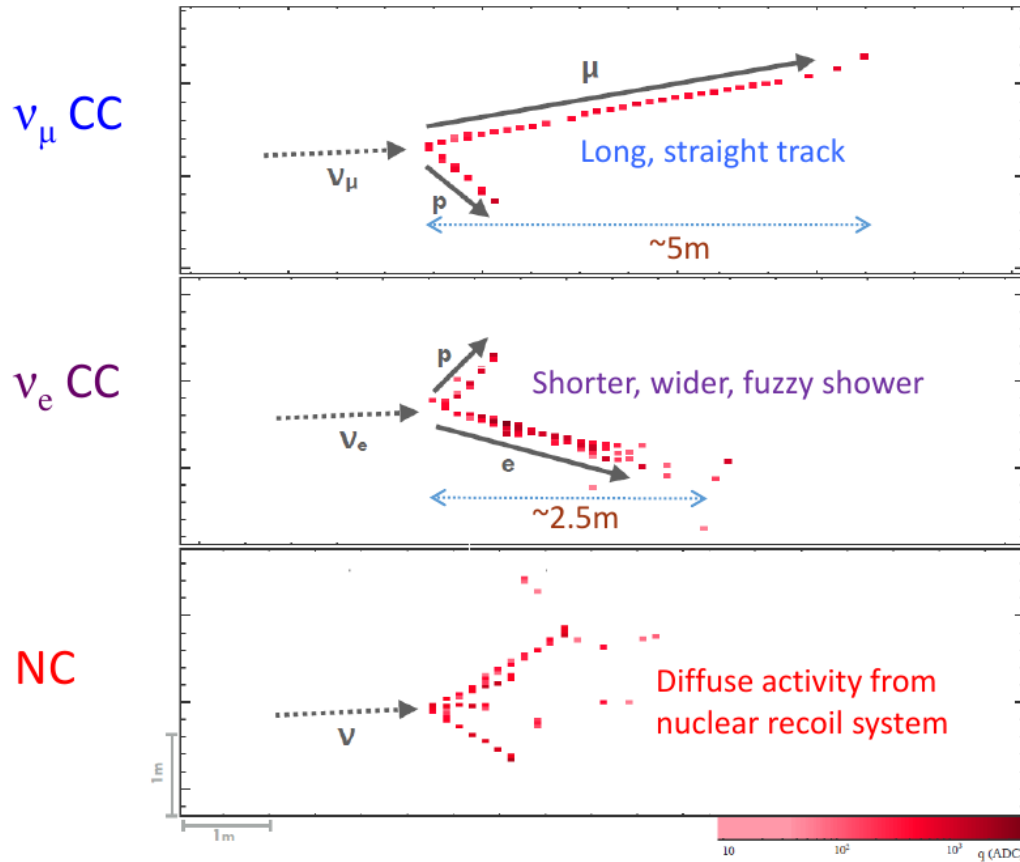


- Same technology (liquid scintillator) for near and far detector

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

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

What do we measure?



Muons (if contained)

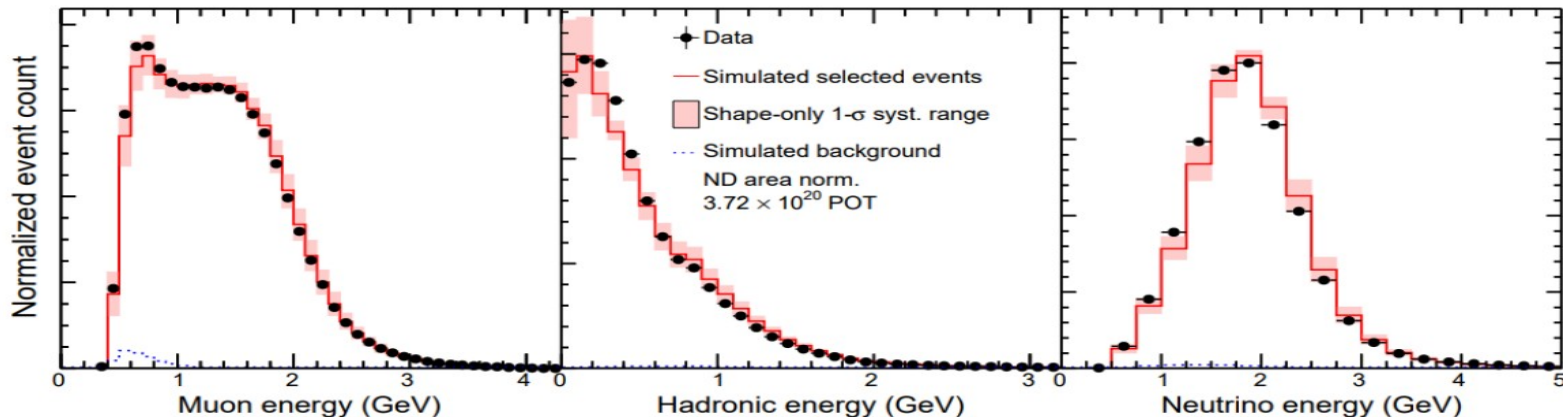
Electrons as shower



Hadrons (mostly as diffuse activity + tracks)

High energy flux: pion production and DIS \rightarrow large fraction of E_ν goes into hadrons

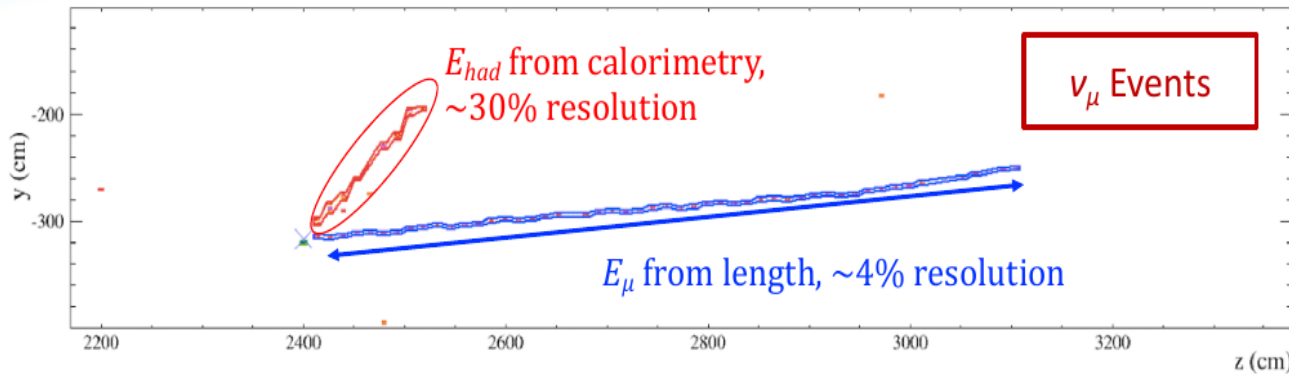
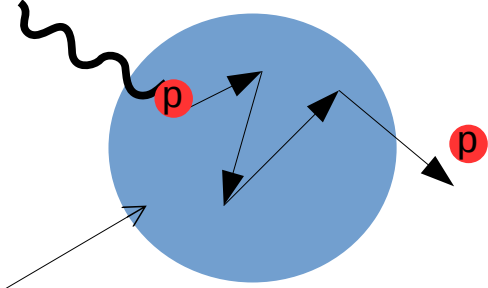
$$E_\nu = E_\mu + E_{had}$$



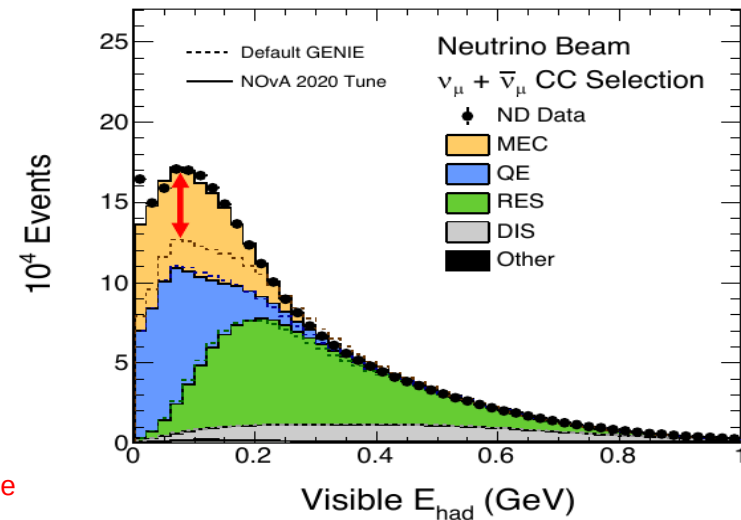
E_ν reconstruction

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

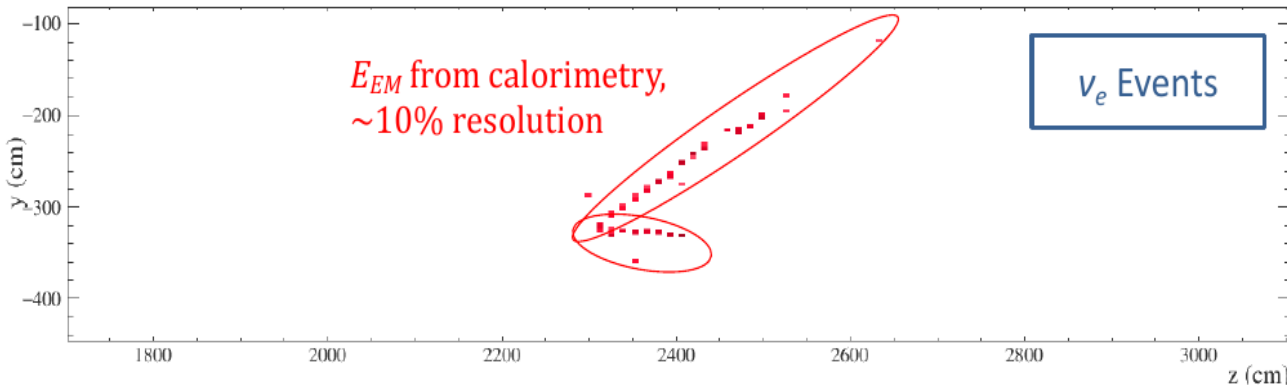
Final State Interactions



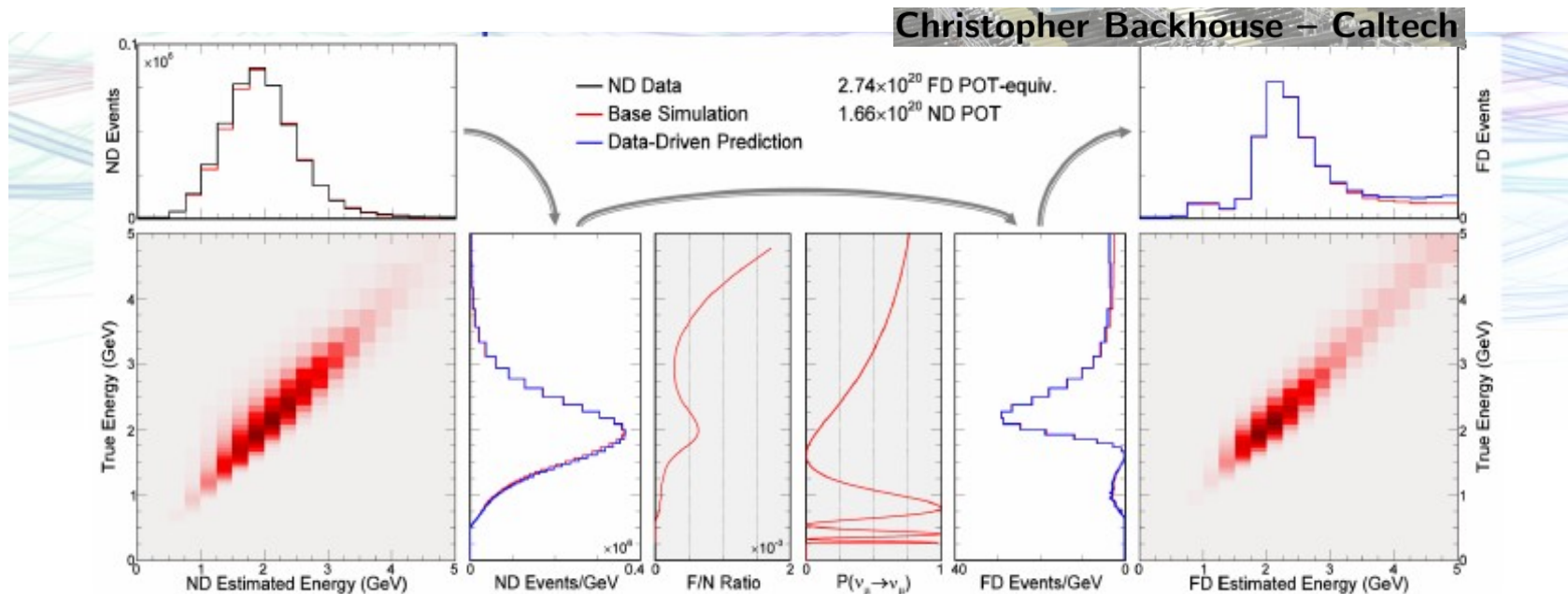
Important to tune model predictions for E_{had} NOvA Preliminary



- Different reconstruction and energy resolution for ν_μ and ν_e



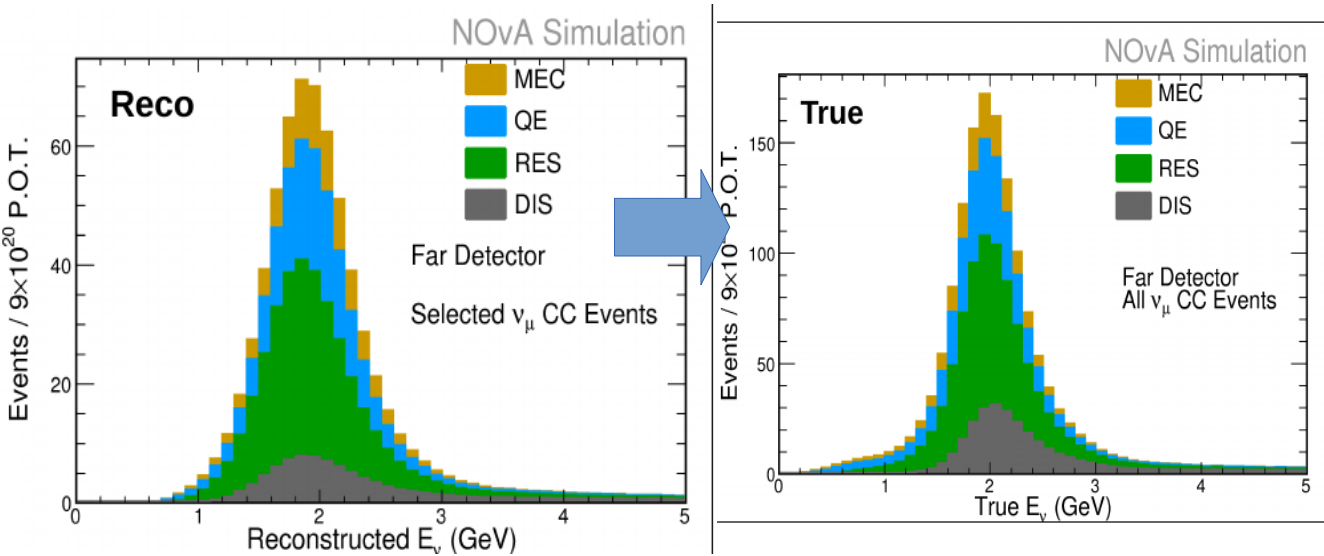
ND to FD extrapolation



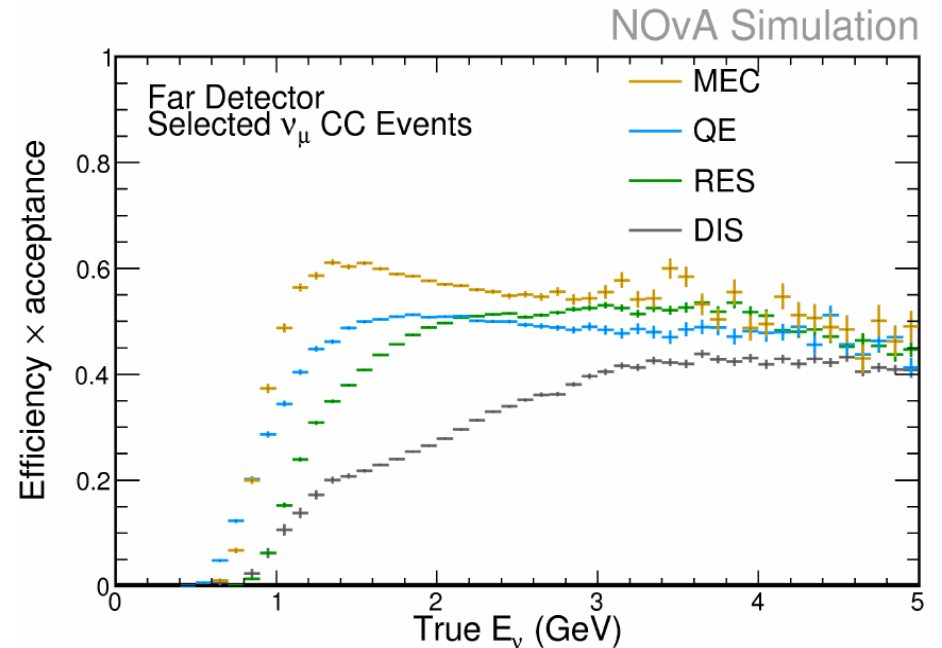
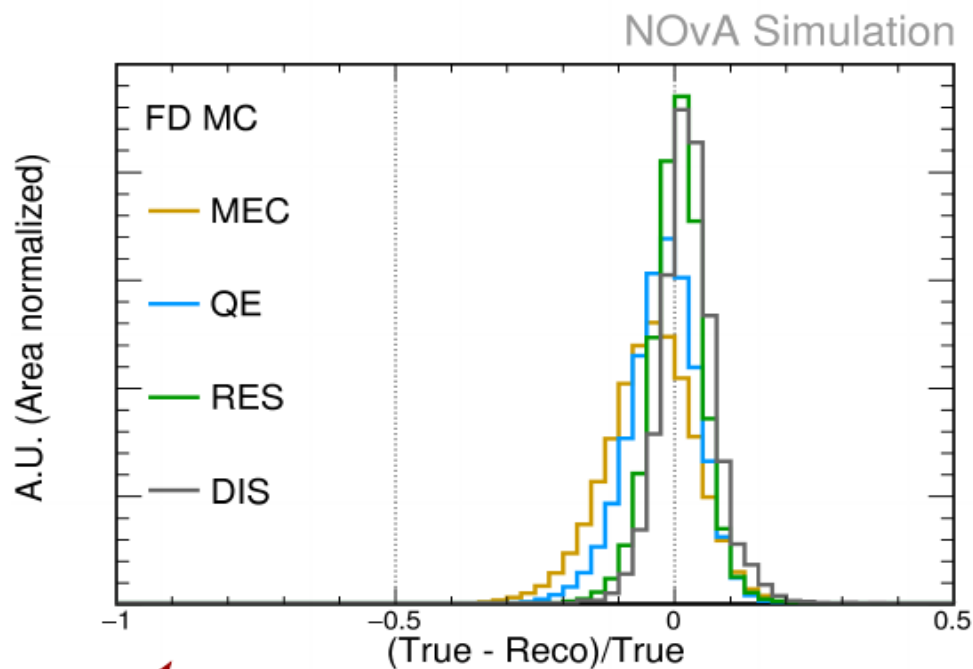
- ▶ Subtract NC expectation in ND, reweight MC in reco energy to match
- ▶ Transform to true energy, transport to FD with oscillations
- ▶ Transform to reco energy, add FD NC expectation back in
- ▶ Dependence on MC for **background subtraction and true/reco matrix**

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

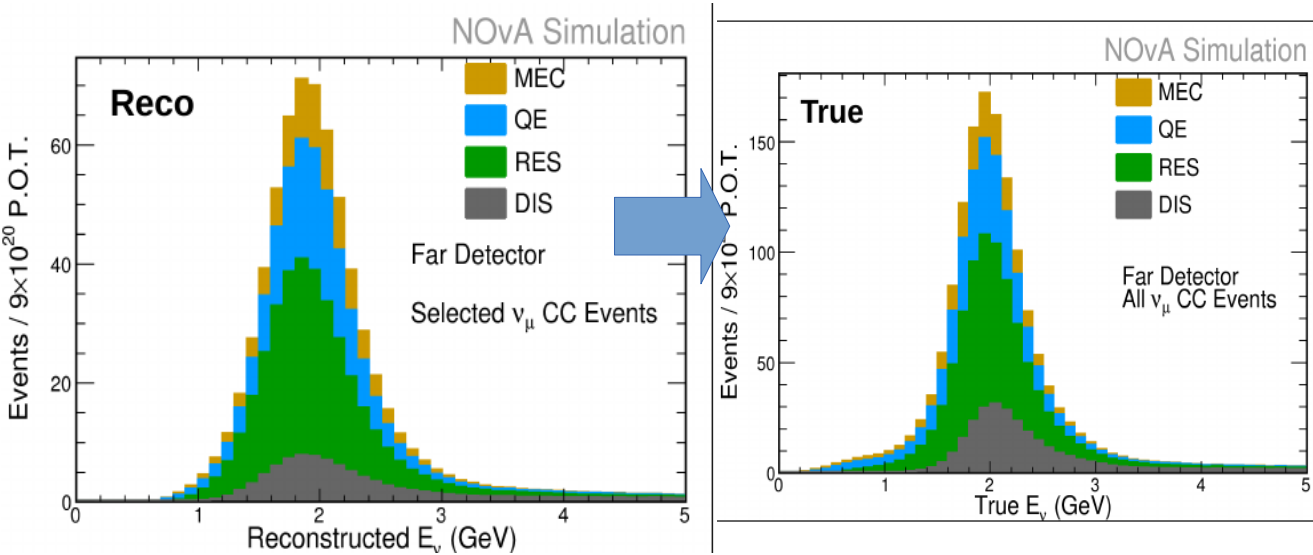
Resolution, efficiency, acceptance



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

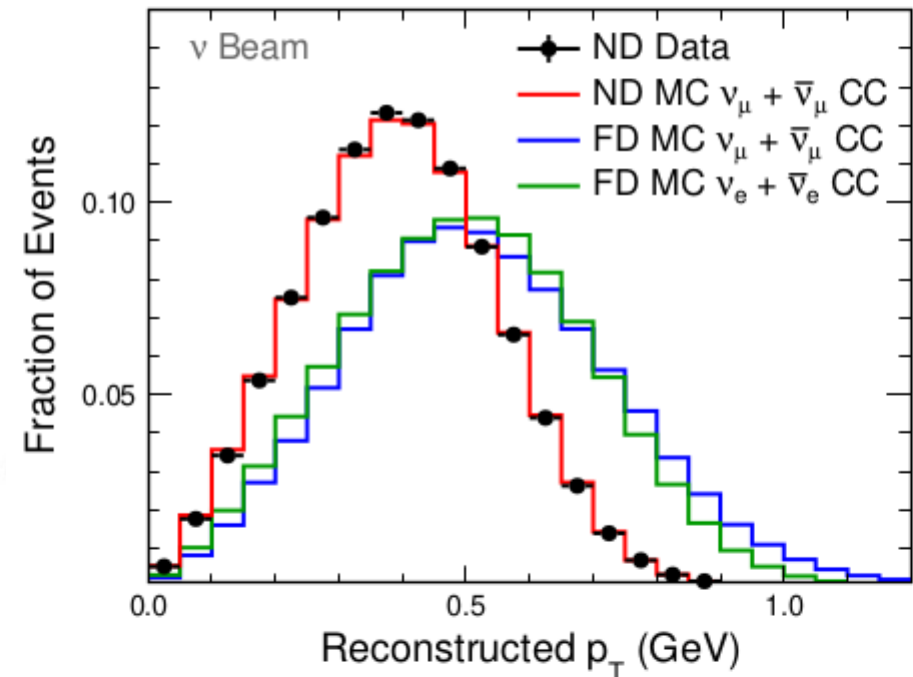
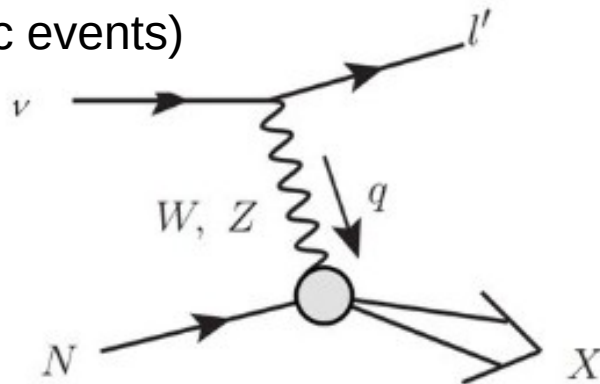


Resolution, efficiency, acceptance



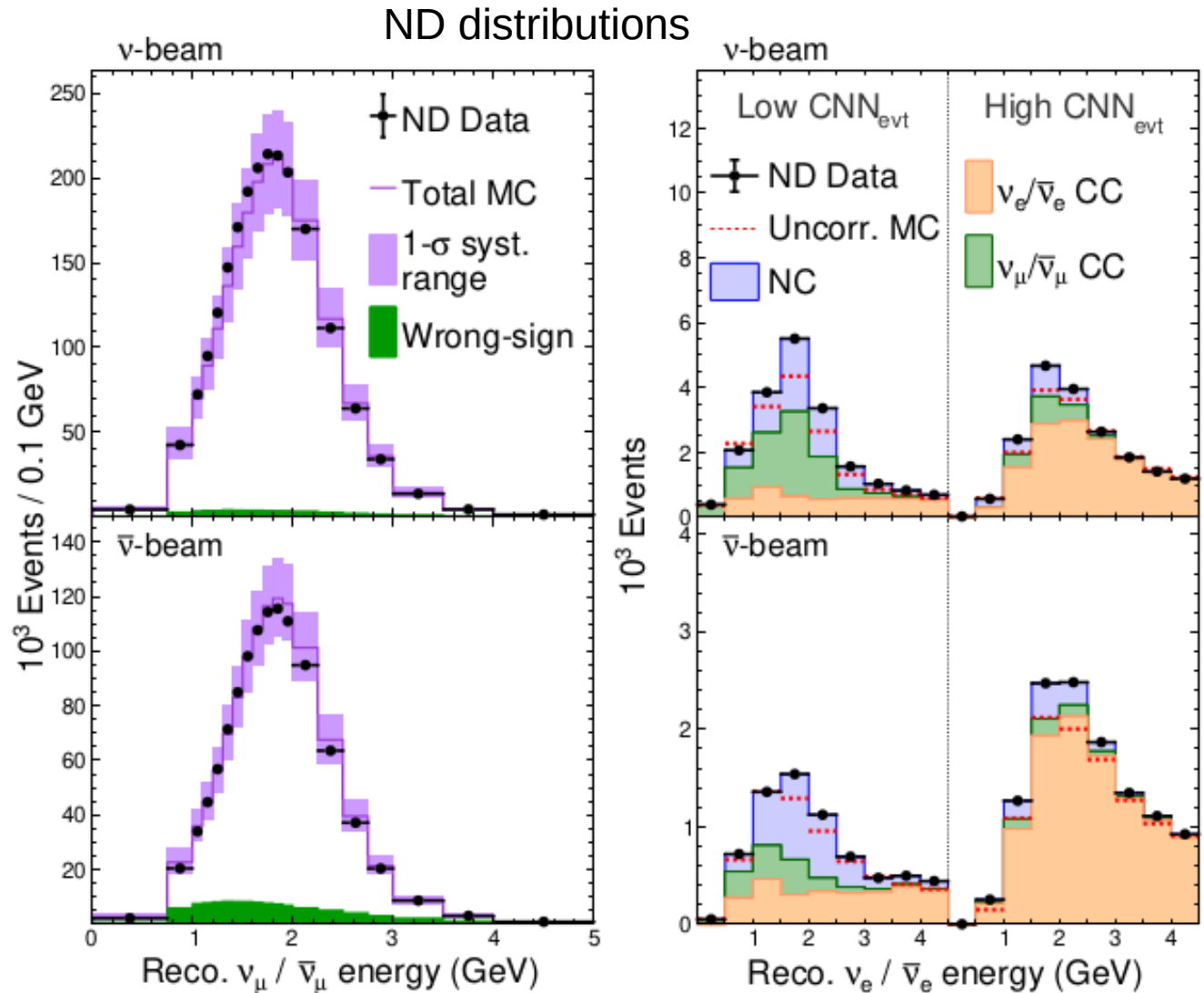
Each process has different neutrino energy resolution and efficiency: dependence on hadron multiplicity, π^0 fraction, kinematics of leptons ...

- 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)



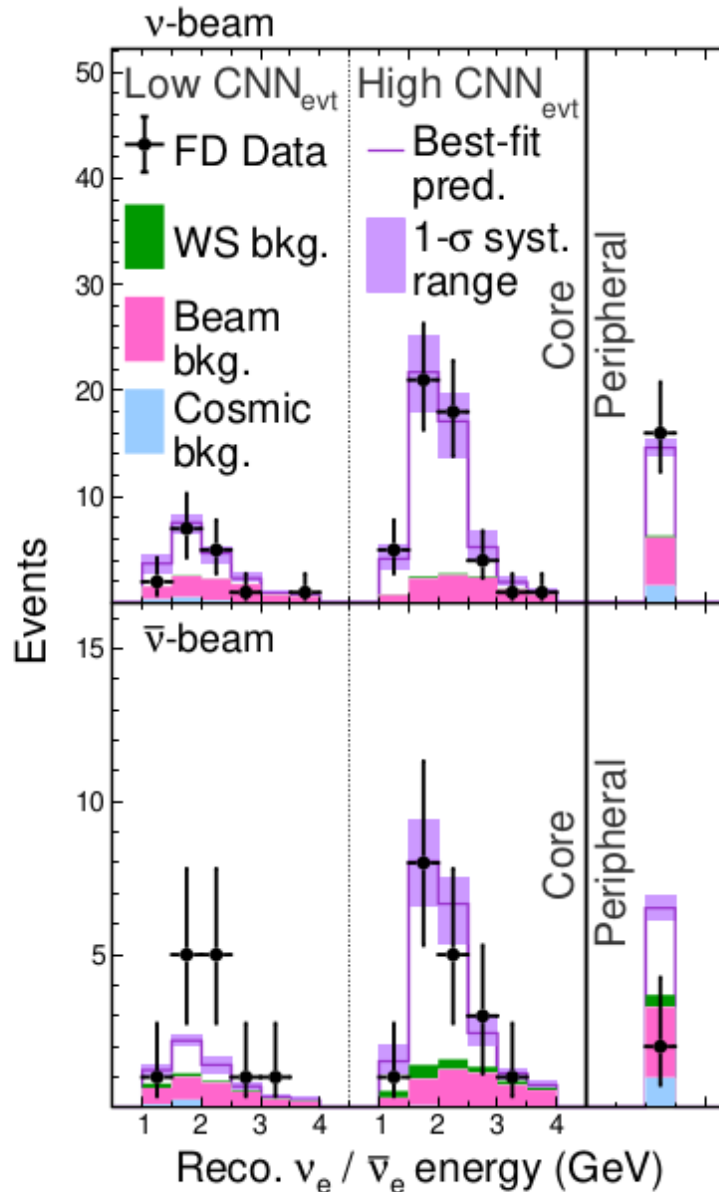
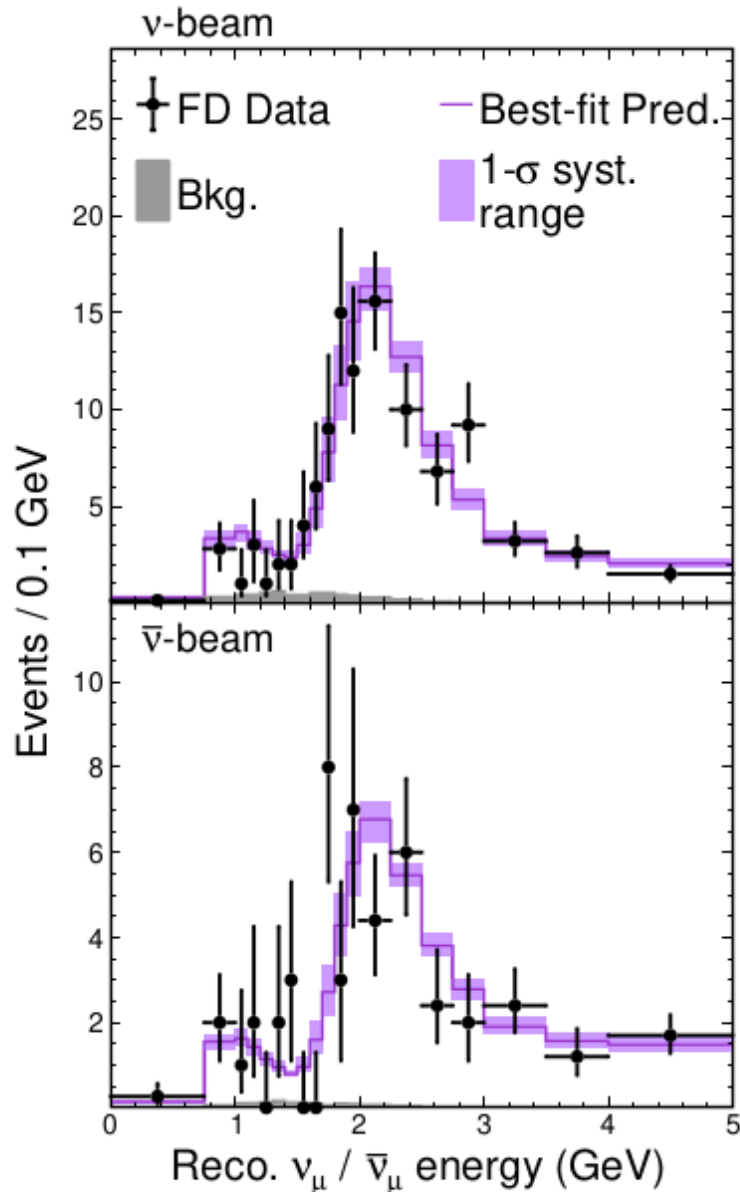
Selection

- 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



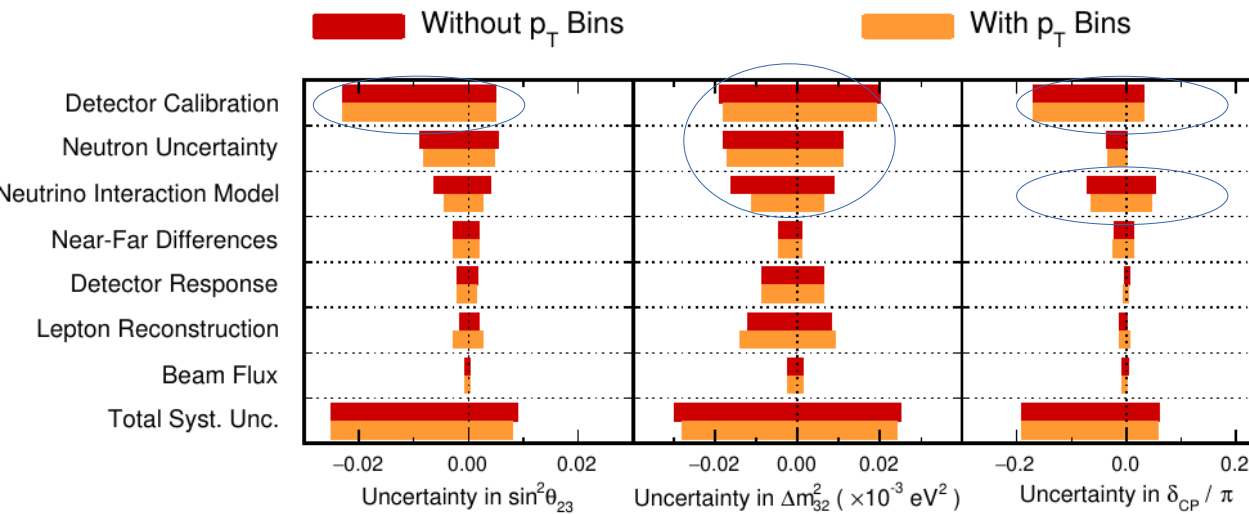
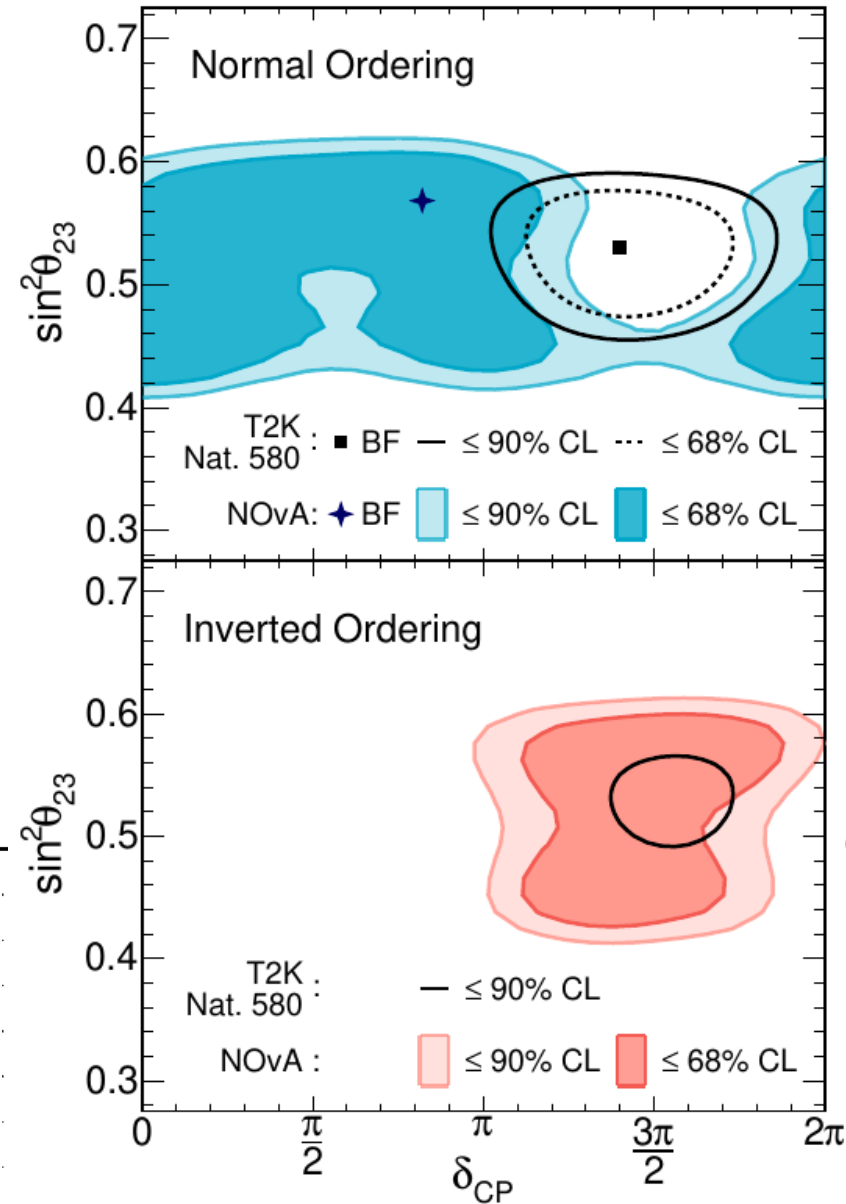
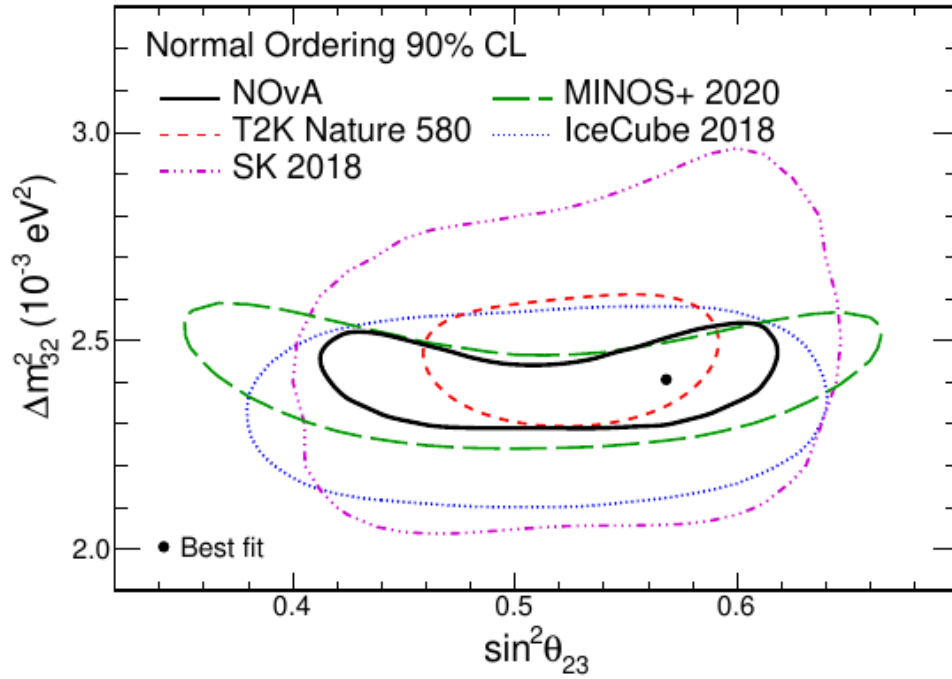
- Measurement of all the visible energy in the event to estimate the neutrino energy

Far detector results



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

Far detector results

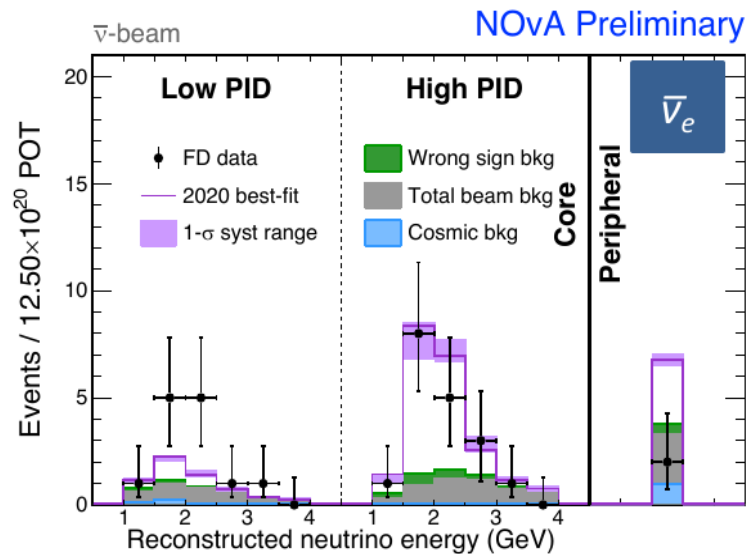
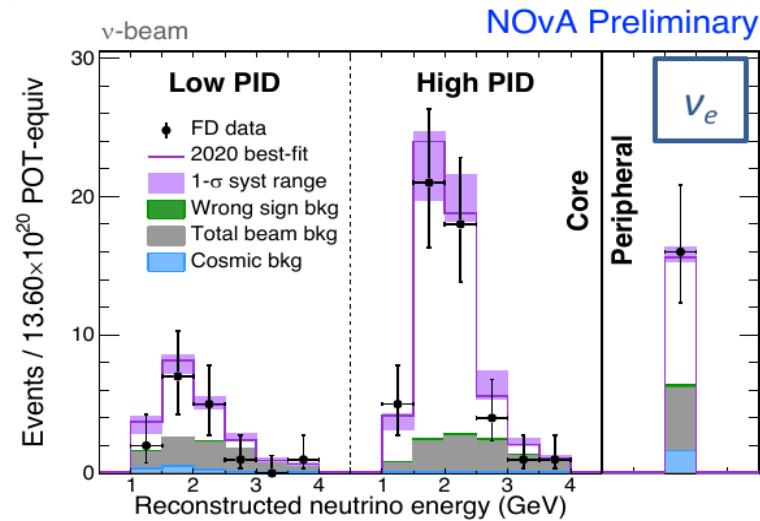
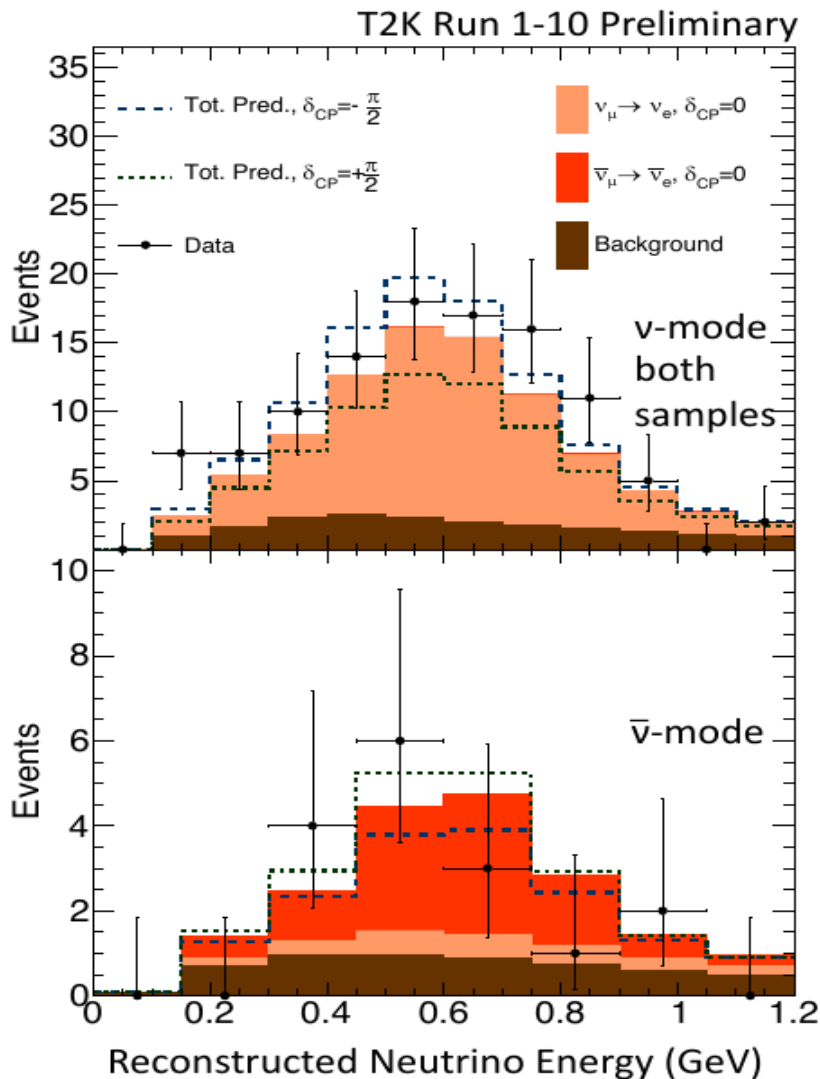


Limitations and future challenges

δ_{CP} : statistically limited

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

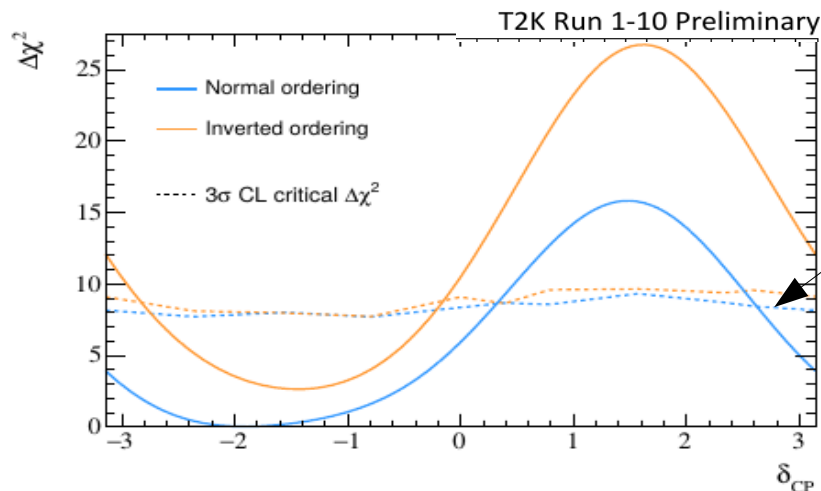
→ further data at T2K and NOVA (and next generation of experiments with more powerful beams and enlarged far detector mass)



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 \rightarrow need to run toys over all the parameters)



For each values of true δ_{CP} \rightarrow 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 sensitivity from data) is less obvious: eg, sample over nuisances distribution for Asimov at that true δ_{CP} value?

Safe at 3σ but what about $>3\sigma$? 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

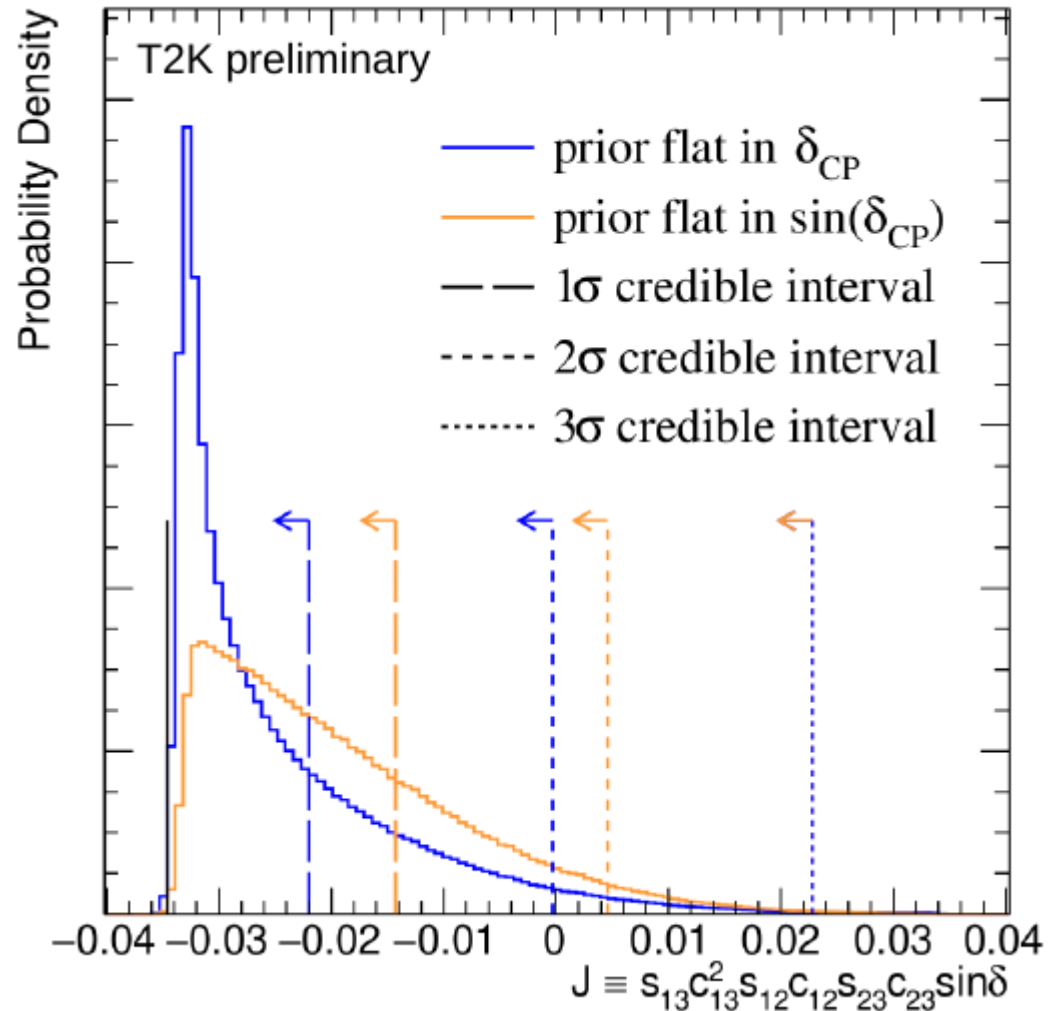
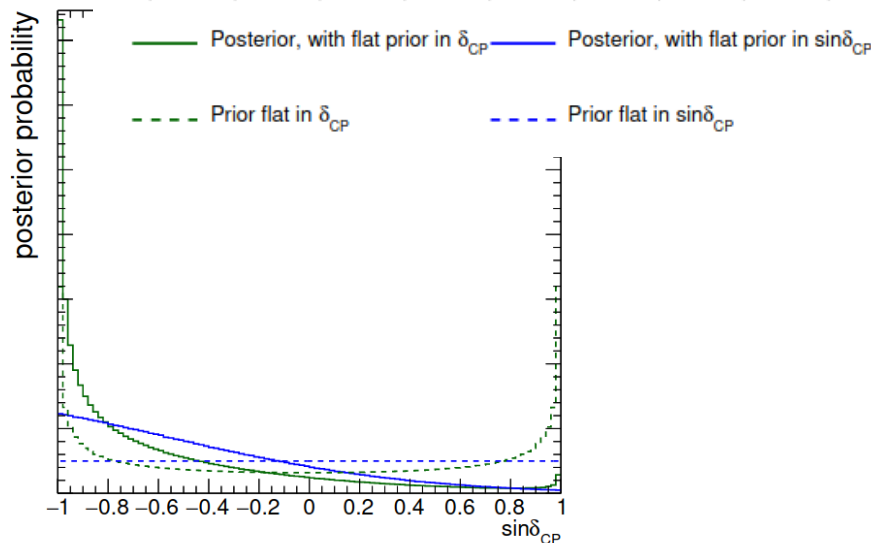
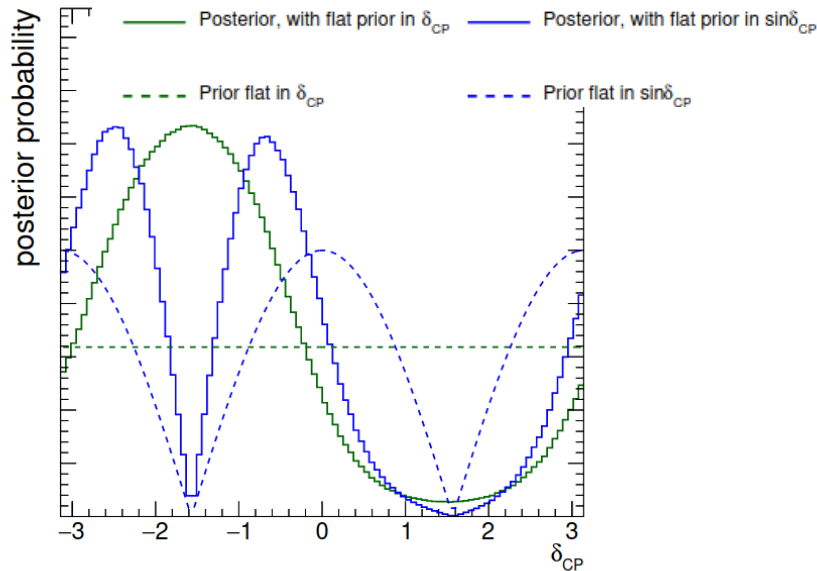
What is the 'physical parameter':

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 $\sin\delta_{CP}$?)



From CPV discovery to δ_{CP} measurement

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

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

Actually at second order:

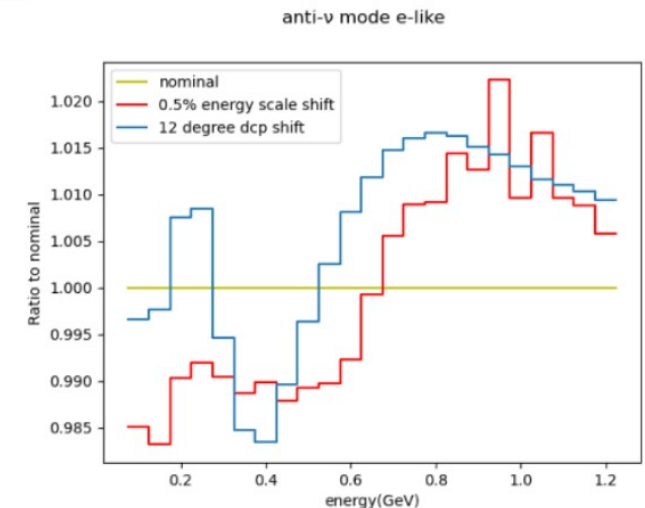
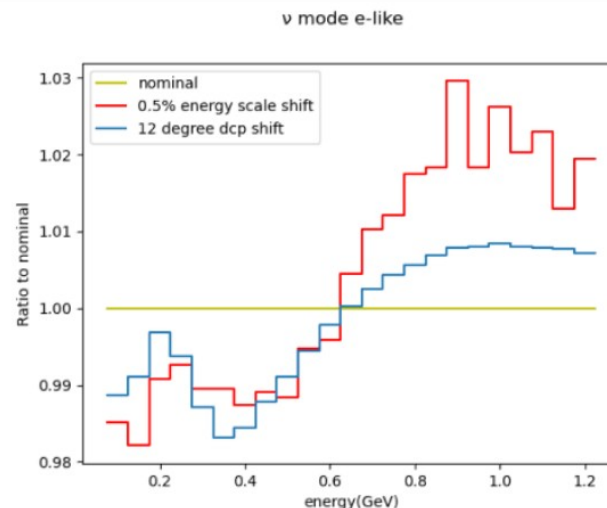
$$P_{\text{appearance}} \sim \pm A \sin \delta + B \cos \delta + \dots \quad \xrightarrow{\text{detailed formula}} \quad \bullet$$

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

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

- At $\delta_{CP} \sim 0, \pi$ the derivative of the second term goes to 0 and the precision is **fully dominated** by the measurement of the $\sin \delta$ so **by the asymmetry between ν_e and $\bar{\nu}_e$ samples** (as it is the case for CPV sensitivity itself)

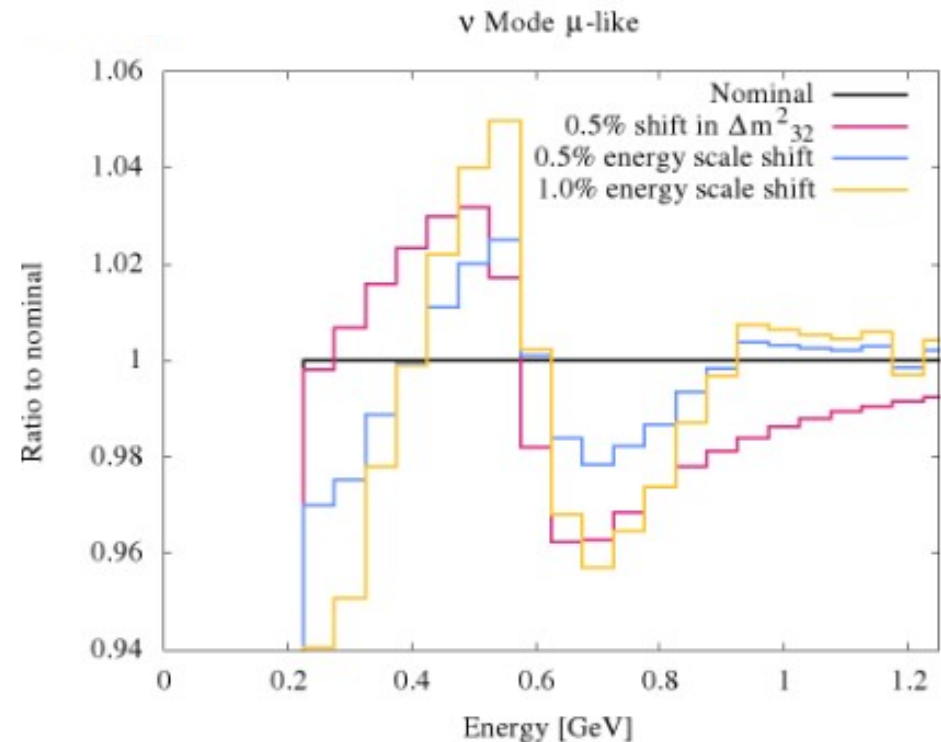
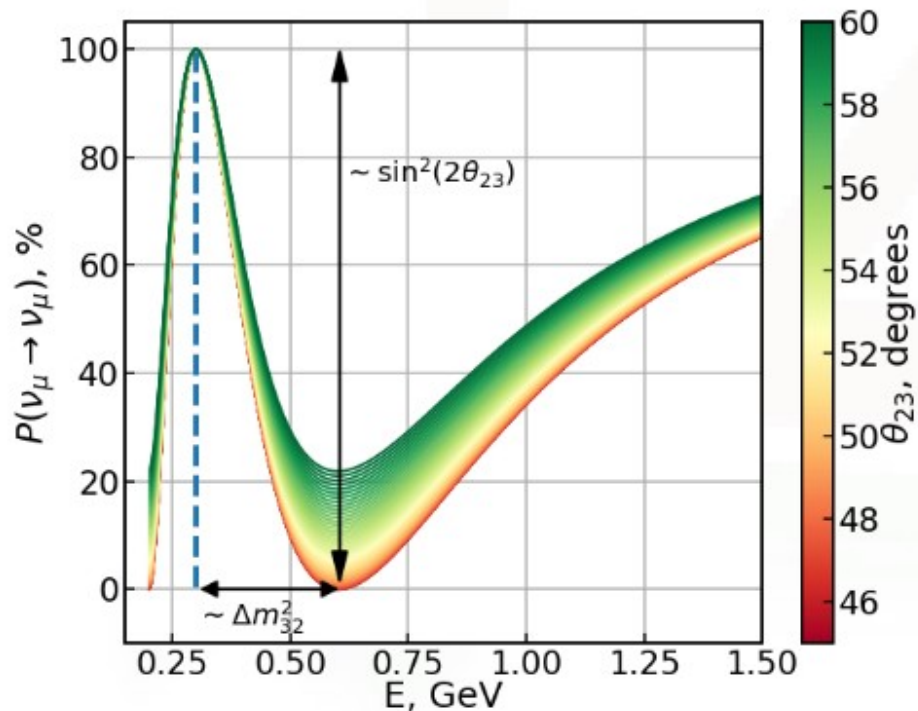
- At $\delta_{CP} \sim \pm \pi/2$ the precision on δ_{CP} ($\sim P_{\text{app}}$ derivative vs δ_{CP}) is dominated by the second term: **precise energy spectrum measurement ($\cos \delta_{CP}$ dependance) dominate the resolution**



Impact of systematics will hit first in ν_μ disappearance

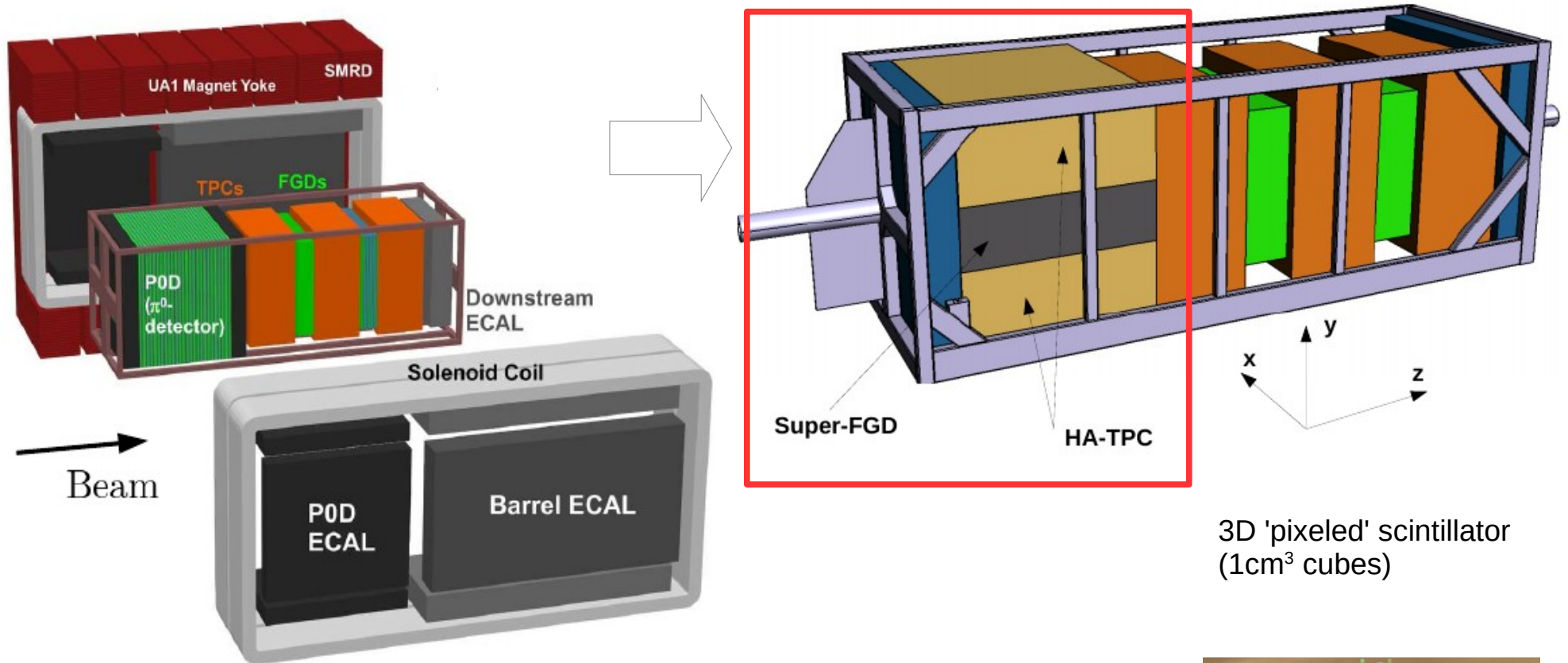
As already discussed yesterday:

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

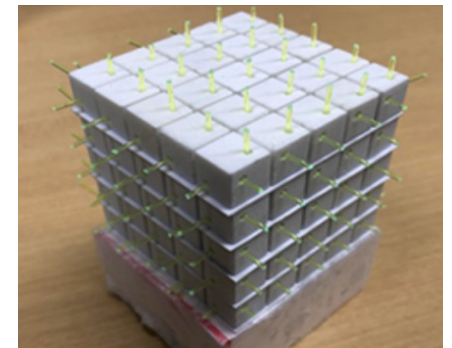


Need **improved flux and xsec models (and tuning: NA61, Minerva, ...)** and **improved near detectors** to better constrain model, notably for precise reconstruction of full final state
 → improved neutrino energy reconstruction

ND280 → ND280 upgrade

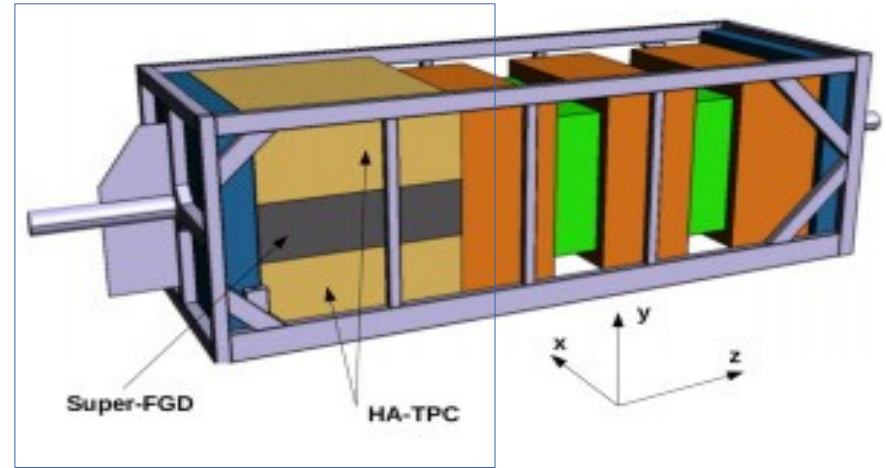
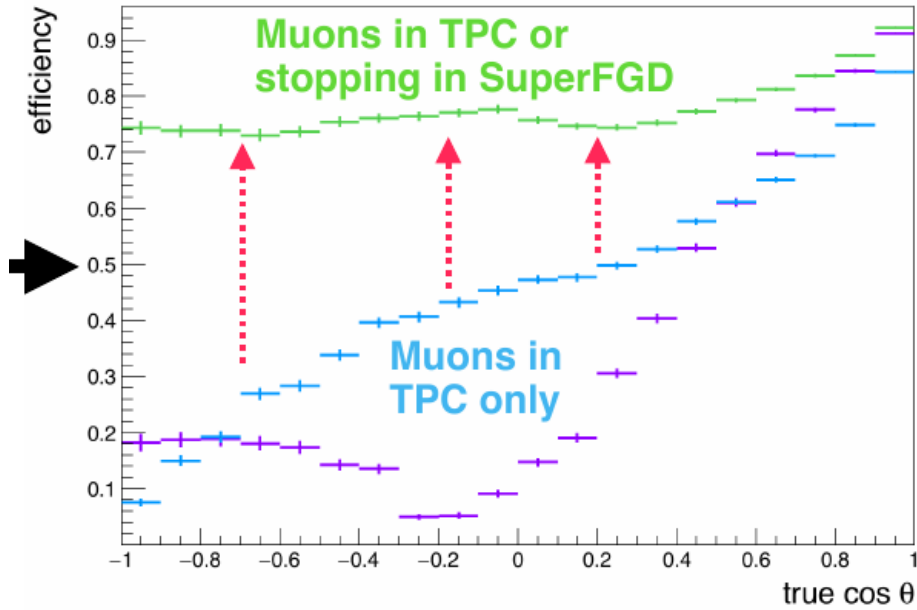


- **New target** with much lower threshold for track reconstruction (p,p)
- **High angle TPCs with resistive Micromegas:** coverage at high angle and improved momentum resolution
- Scintillator planes all around the **new detectors** for **Time of Flight measurement of charged particles**

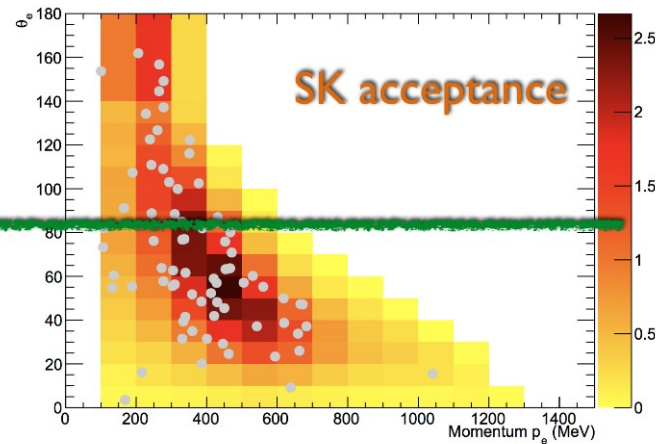
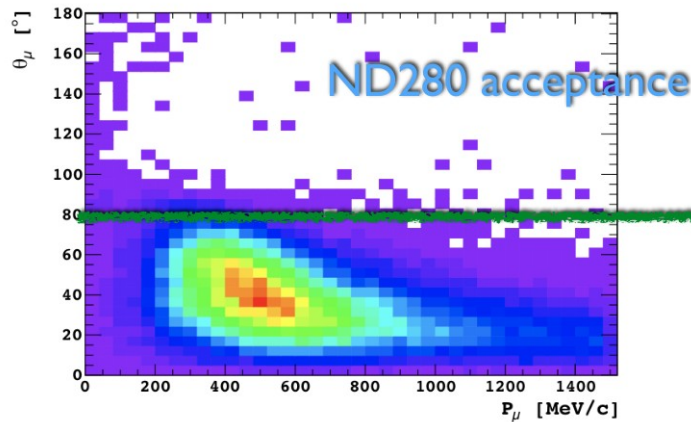
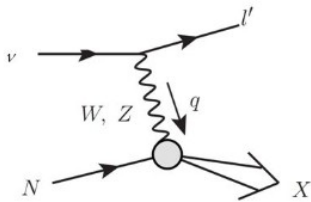


ND280 upgrade

- larger statistics from new target + improved angular acceptance



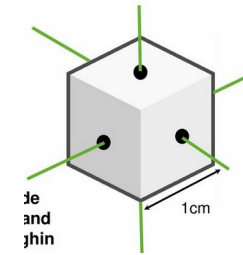
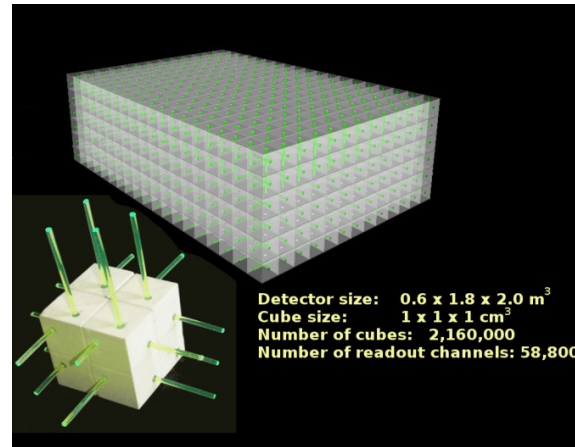
Leptons at larger angle correspond to more inelastic events



ND280 upgrade

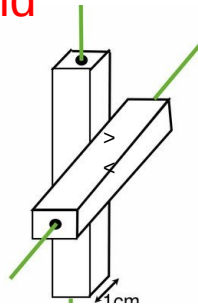
- larger statistics from new target + improved angular acceptance

- proton kinematics measurement down to low momentum threshold

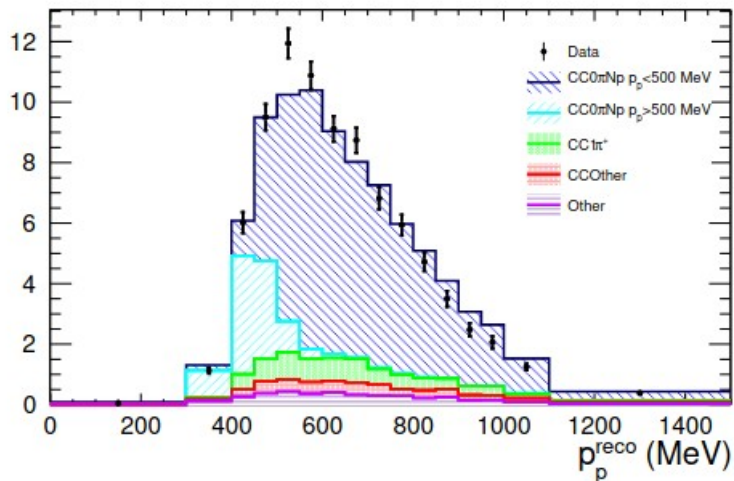


New '3D' scintillating detector

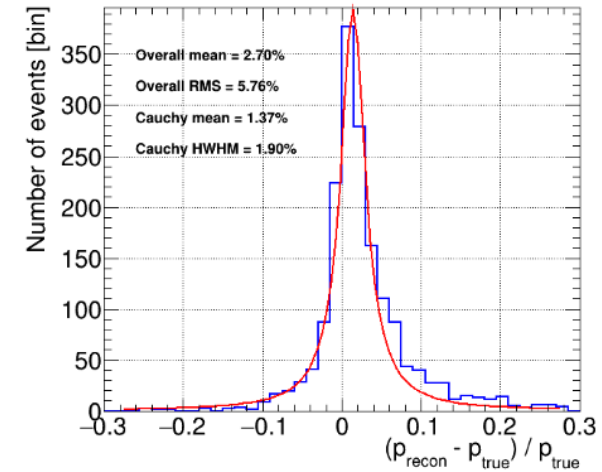
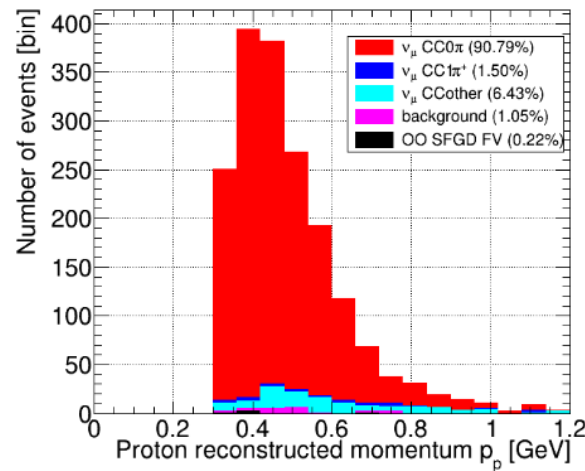
ND280 FGDs are '2D' scintillating detectors



ND280 measurement



ND280 upgrade (ν MC):

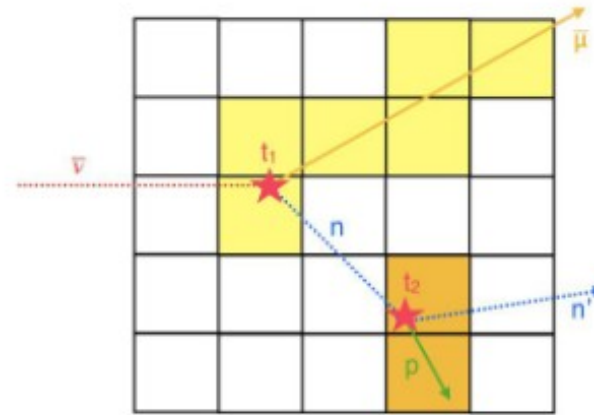


ND280 upgrade

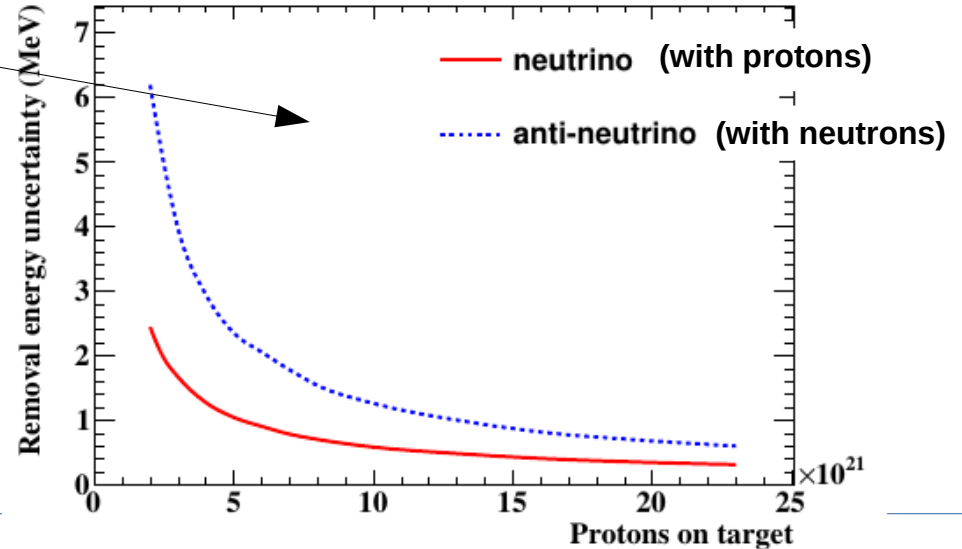
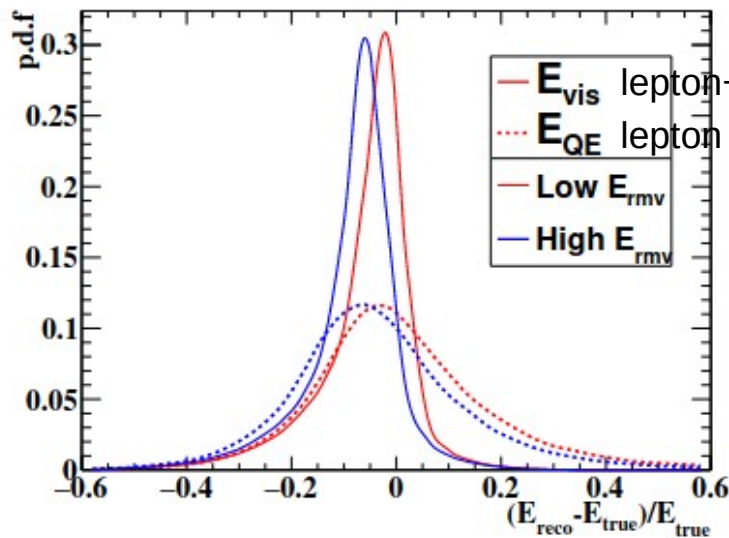
New analysis features are also preparing the road to the analysis of ND280 upgrade data:

- larger statistics from new target + improved angular acceptance
- proton kinematics measurement down to low momentum threshold
- neutron measurement event-by-event: NEW!!!

Time-of-flight technique



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



Last remarks

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

The **role of T2K and NOVA** is similar to LEP to open the road to LHC:

- establish analysis strategies and best detector design (notably in terms of ND)
- some $\sim 3\sigma$ (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:

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

ND measures rate vs neutrino energy

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

~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 \bar{n} (xsec and flux)**

Notably, “wrong sign” background: n in \bar{n} mode (p^+ focused beam)

- **n_e intrinsic background:** n_e produced in the beam by $K / p \rightarrow m$ decays

Near detectors and nuclear theory

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

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

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

~same flux at ND and FD

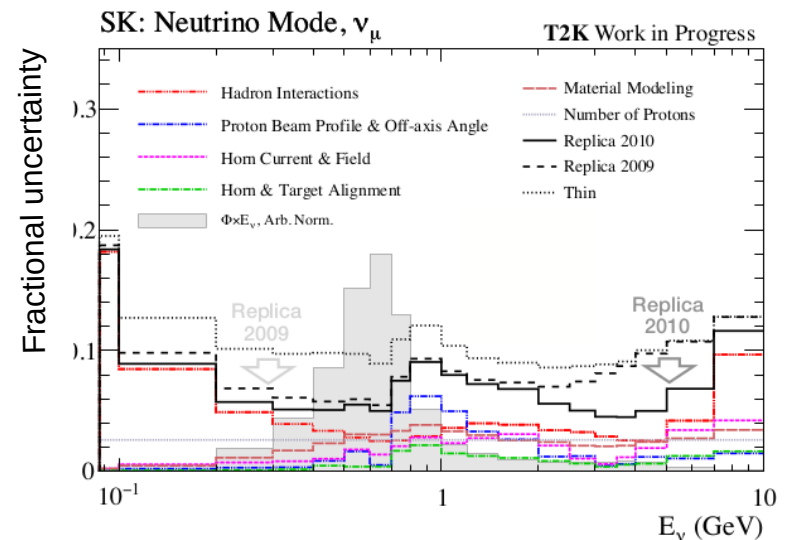
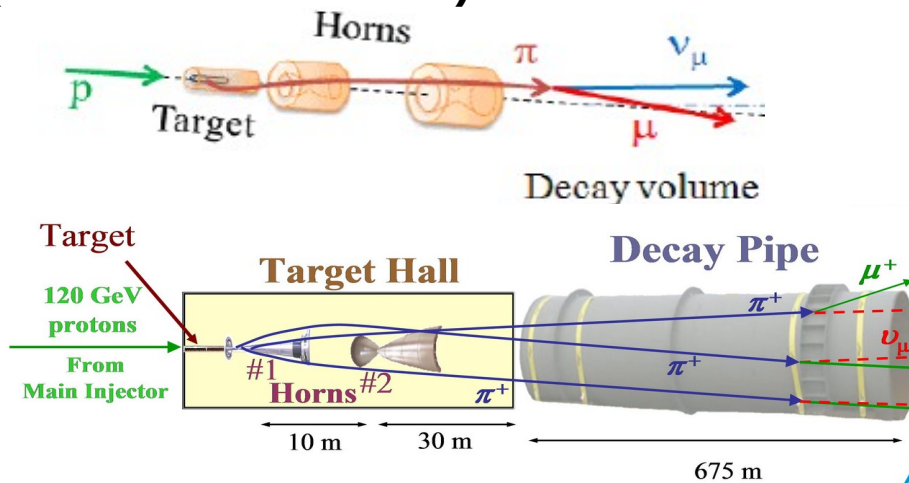
what we want to measure:
 oscillation probability

cross-section must be extrapolated from ND to FD:

- different neutrino energy distribution
- ND measure flux times xsec

Need nuclear theory models!

Flux simulation and tuning (NA61/SHINE + MIPP)



Near detectors and nuclear theory

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

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

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

~same flux at ND and FD

what we want to measure:
 oscillation probability

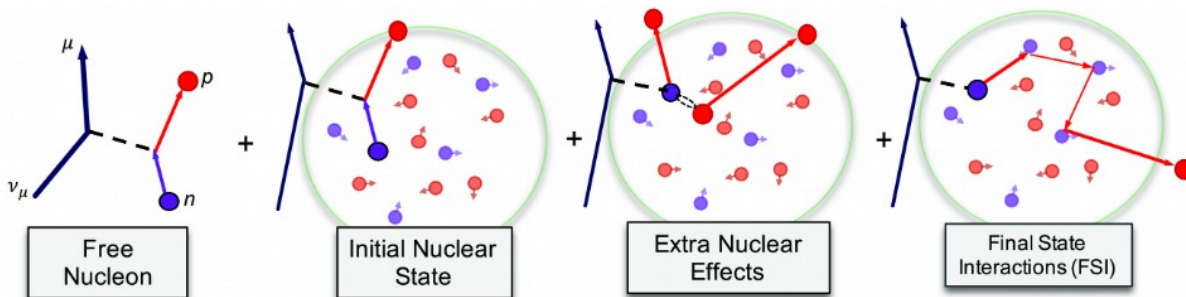
cross-section must be extrapolated from

ND to FD:

- different neutrino energy distribution
- ND measure flux times xsec

Need nuclear theory models!

ν -nucleus interaction modeling and tuning

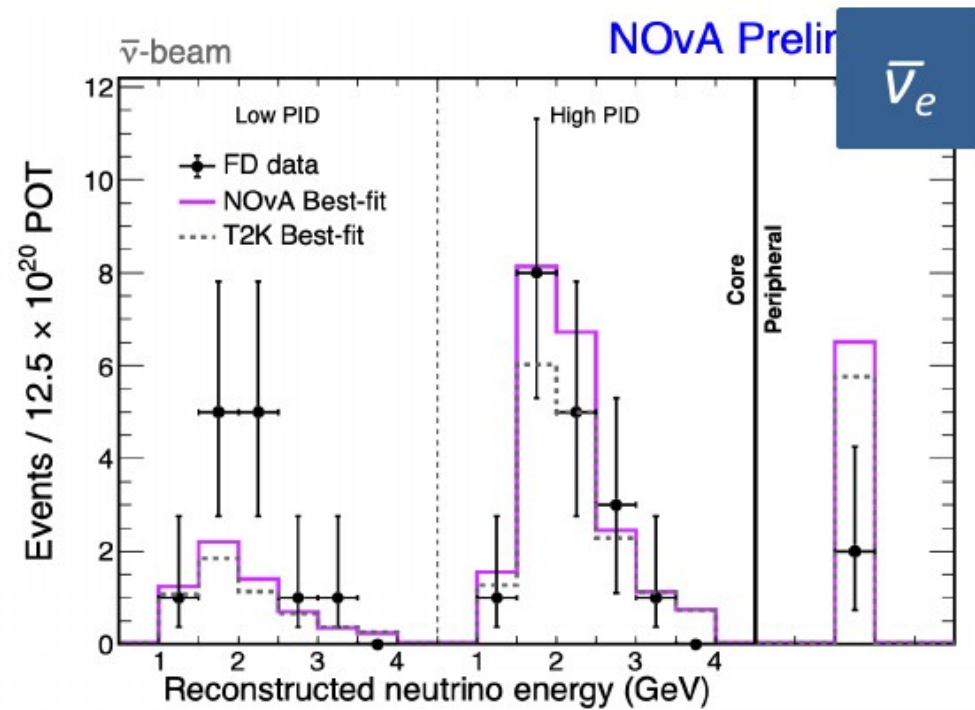
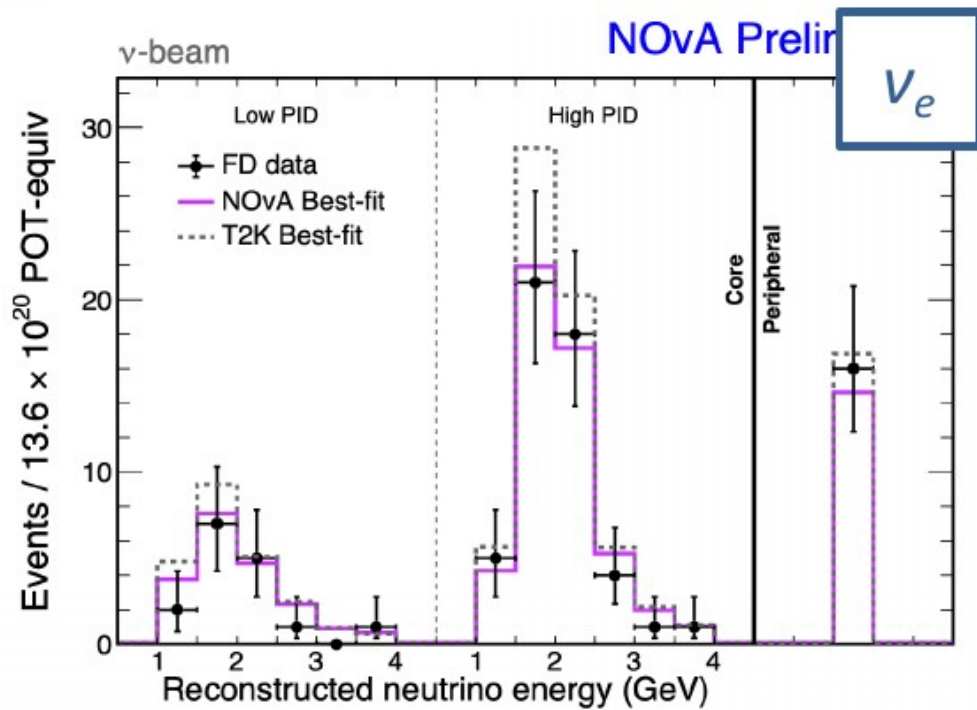


- Nuclear theory
- External data (eg e-scattering)
- ν -nucleus xsec measurements at near detectors and dedicated experiments (Minerva, ArgoNeuT, ..)

(and similarly for pion(s) production)

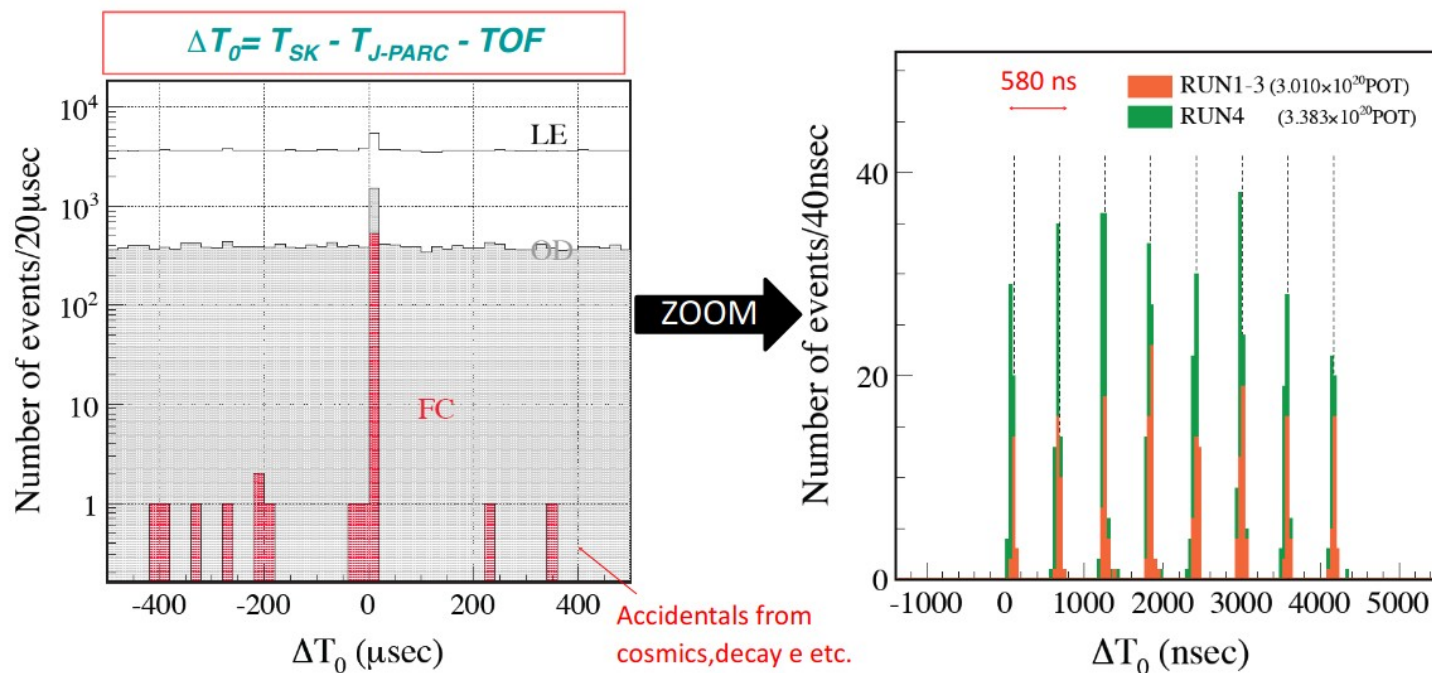
→ **fundamentally the name of the game: precise E_{ν} reconstruction**¹⁴⁰

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



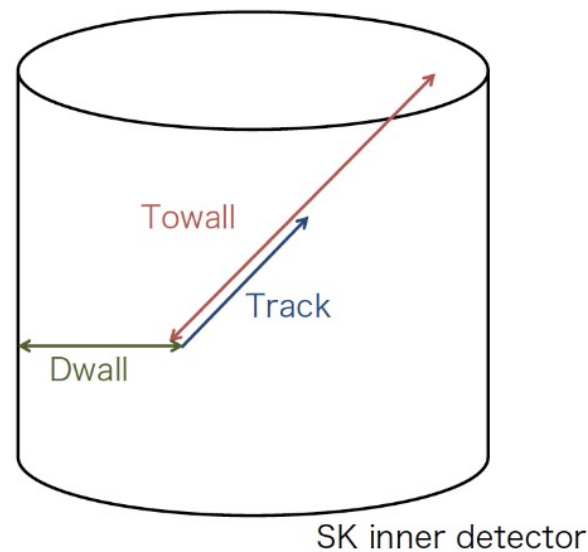
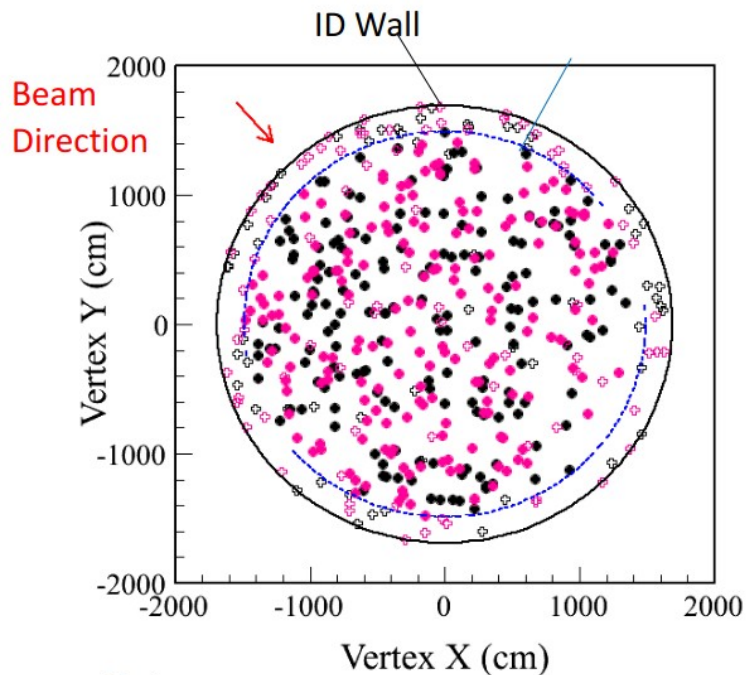
- Still in $\mathbf{n}_e / \bar{\nu}_e$ (so d_{CP} measurements) **the statistic uncertainties at the far detector is dominant over the systematics**
- The **model of systematics is extremely different in T2K and NOVA and their impact and treatment is extremely different**
- The evaluation of systematics is the big challenge for the next years: **T2K and NOVA are crucial to open the road to higher-statistics future LBL**

Event Selection (Timing)



- Tokai and Kamioka sites equipped with GPS information
 - Coordinated via the commonview method
- At SK all PMT information in a 1 ms of the beam timing is recorded
- 8 bunch structure of the primary proton beam is clearly visible within 6 μ s of the beam

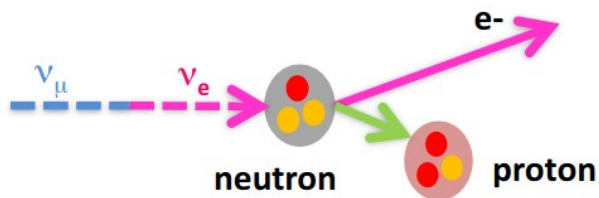
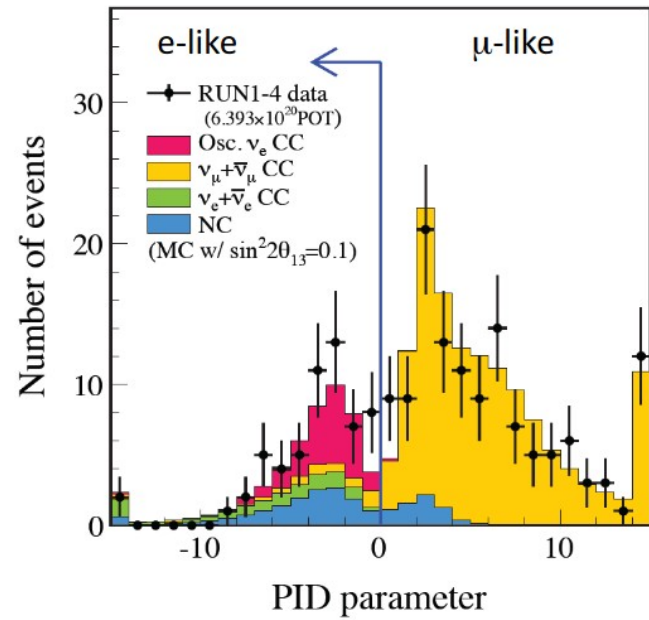
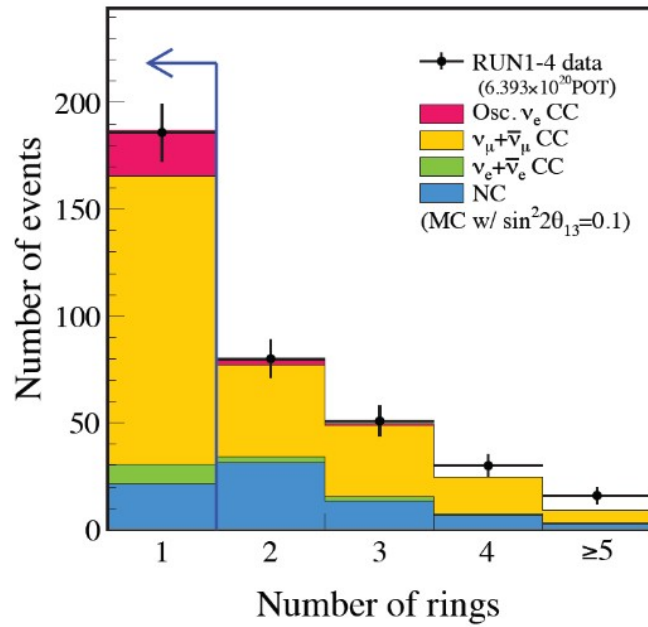
Event Selection (Fully Fiducial Volume Cut)



- Cuts on
 - vertex D_{wall} and T_{owall} → Select events with reliable reconstruction
 - No OD Activity → Select events isolated to the inner detector

I Ring E-like

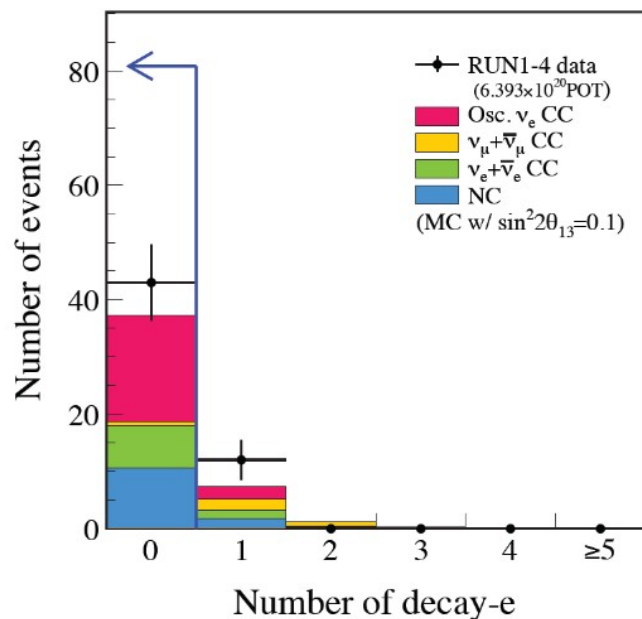
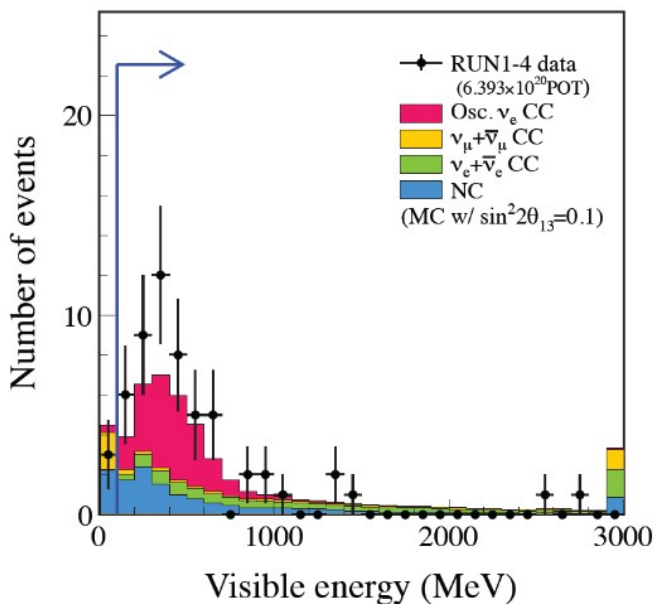
Oscillation Fit



- $N_{ring} == 1$
→ Enrich sample with CCQE
- Electron like PID
→ Enrich sample in ν_e interactions (N.B. protons are below cherenkov threshold)

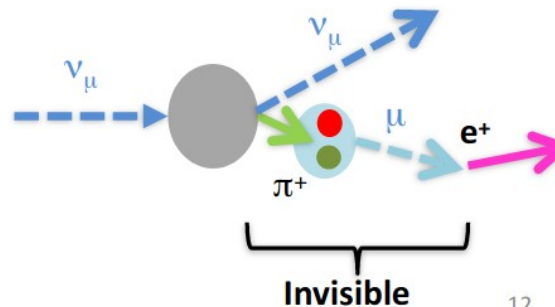
Visible Energy and Decay Electron Cuts

Oscillation Fit



- Visible Energy $E_{vis} > 100$ MeV
- No Decay Electrons

Reduce backgrounds coming from low energy NC interactions, or electrons from the decay of unseen muons and pions

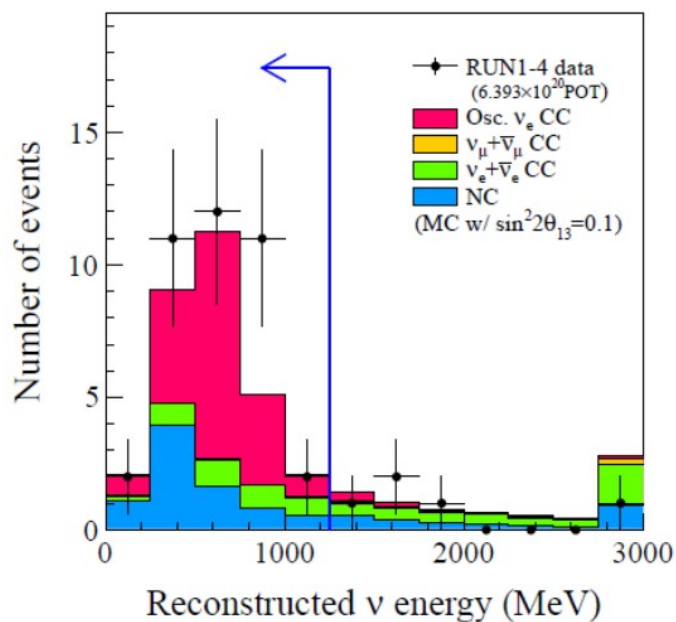


Roger Wendell

12

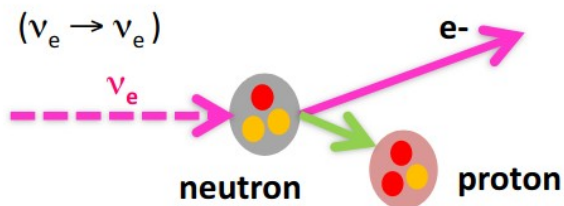
Reconstructed Energy < 1250 MeV

Oscillation Fit

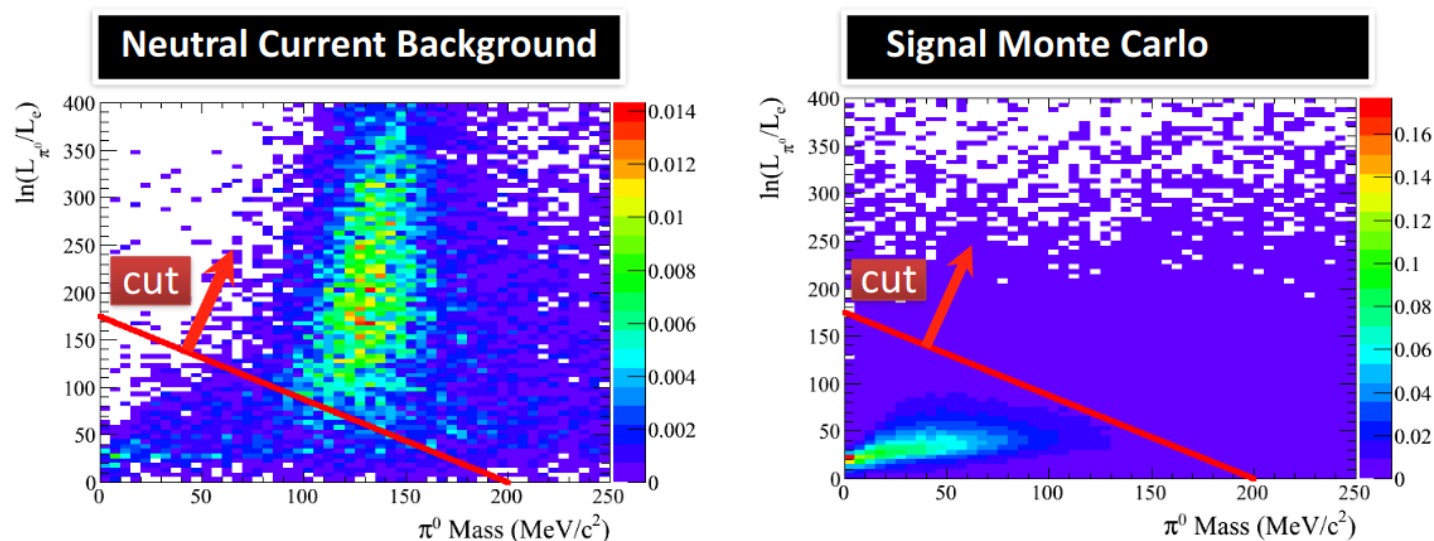


$$E_\nu^{\text{rec}} = \frac{(M_n - V_{nuc}) \cdot E_e - m_e^2/2 + M_n \cdot V_{nuc} - V_{nuc}^2/2 + (M_p^2 - M_n^2)/2}{M_n - V_{nuc} - E_e + P_e \cos \theta_{\text{beam}}}$$

- Assuming a CCQE interaction the original neutrino energy can be calculated based on
 - Out-going electron **momentum**
 - Angle** of electron momentum relative to the neutrino (ie, the beam)
- Cut at $E_{\text{rec}} < 1250$ MeV
 - Removes higher energy intrinsic ν_e events



The Final Cut : π^0 Rejection



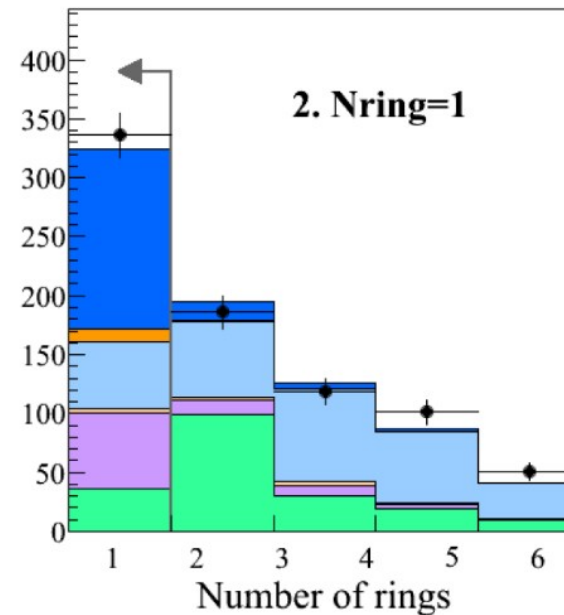
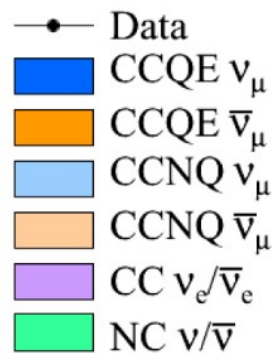
- fitQun uses both the **likelihood ratio** of the π^0 and e^- hypothesis fits to reject π^0 events
- Combined with the reconstructed π^0 mass (2D cut) the fitQun selection **removes 70% more background** for the same signal efficiency
 - Beam ν_e background does not change

Event Selection Single-Ring μ -like sample

R. Akutsu thesis

Run 1-9 FHC $1R\nu_\mu$ sample

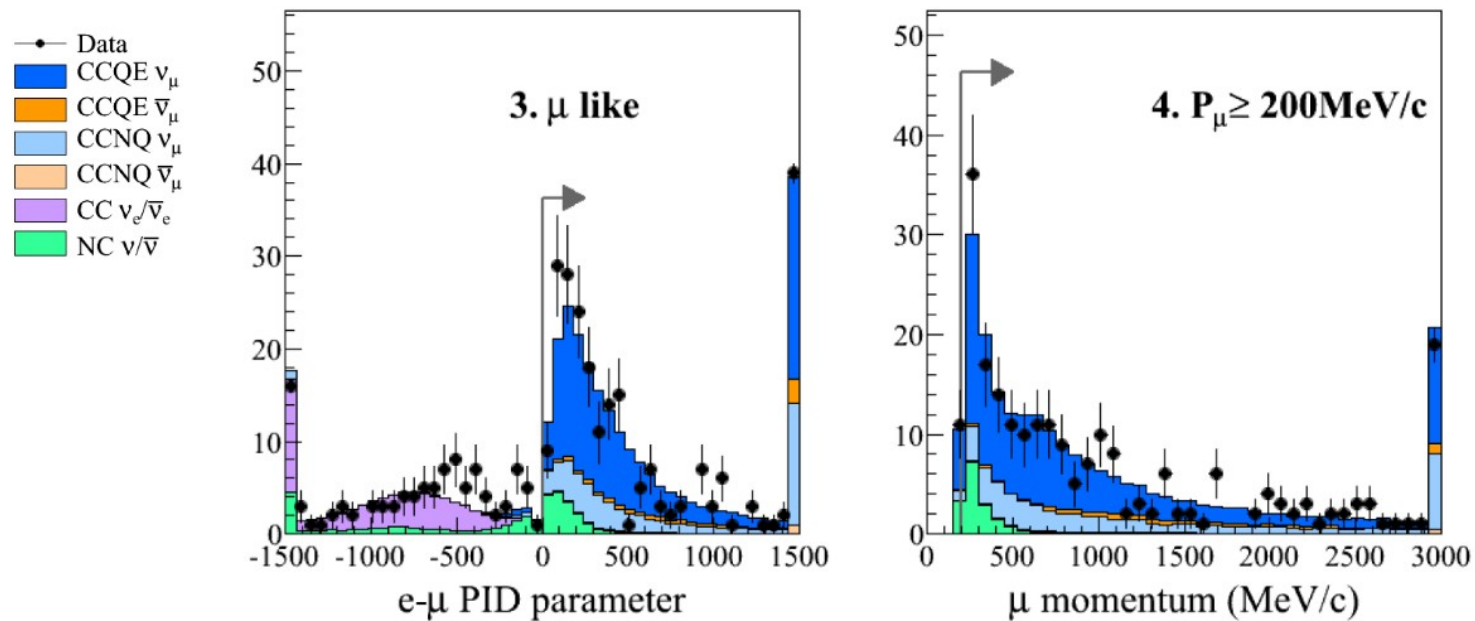
- Norm. by Run 1-9 POT
- $D_{wall} > 2m$



- Again, try to enhance CCQE component

Event Selection Single-Ring μ -like sample

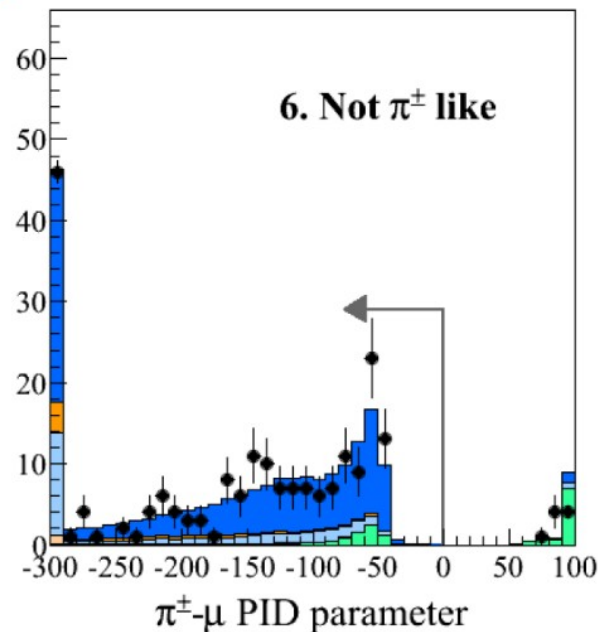
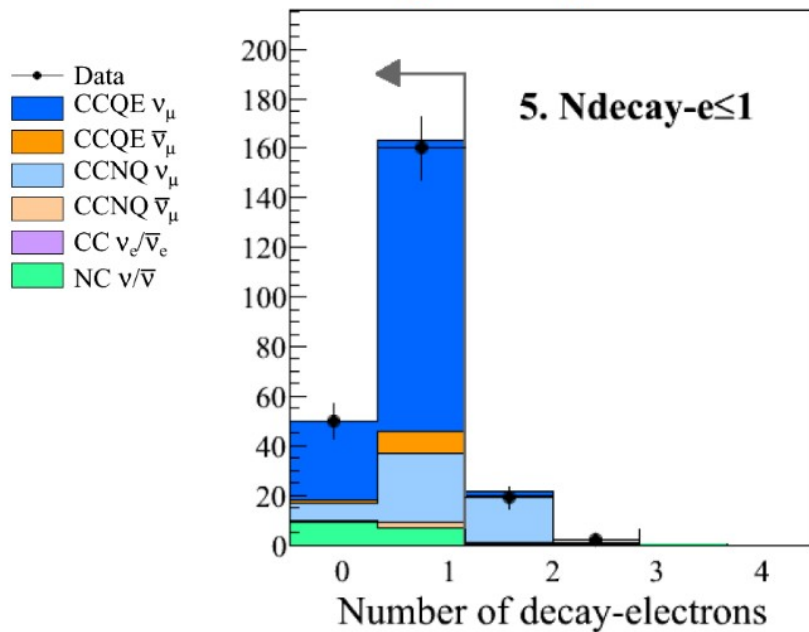
R. Akutsu thesis



- Leading lepton is mu-like
- Remove some low momentum NC events

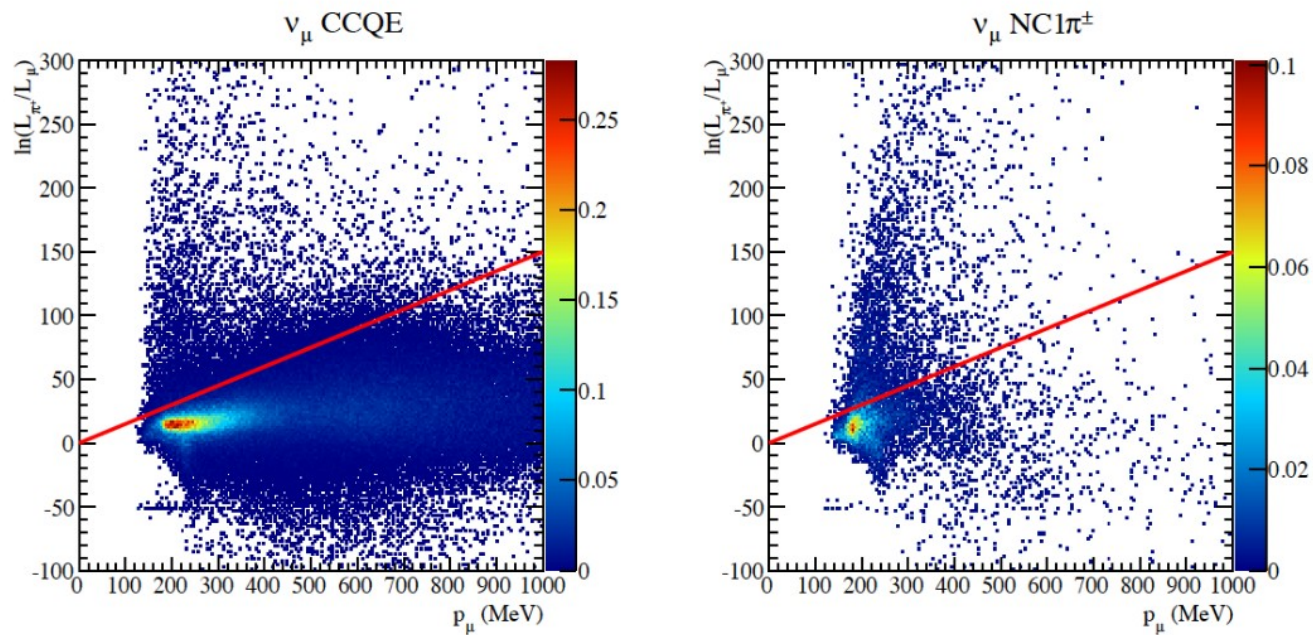
Event Selection Single-Ring μ -like sample

R. Akutsu thesis



- Reject CCNQ (non-quasielastic, ie multi-pion events)
- Reject NC single-pion events

π^+/μ Discrimination



- Cut on the previous page is the distance to the red line in these plots

Selection Summary

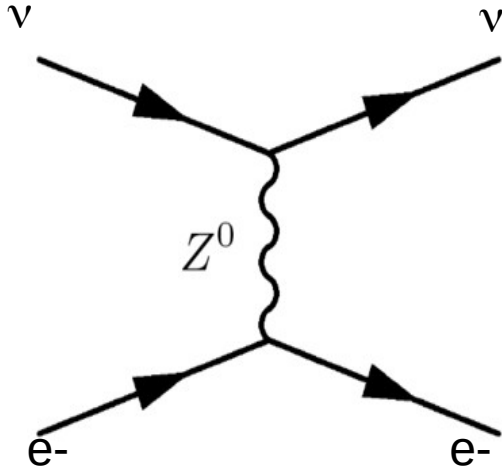
Table 4.4: Summary of conventional single-ring selections.

	$\nu_\mu/\bar{\nu}_\mu$ CCQE-like	$\nu_e/\bar{\nu}_e$ CCQE-like	ν_e CC1 π^+ -like
Dwall	> 50 cm	> 80 cm	> 50 cm
Towall	> 250 cm	> 170 cm	> 270 cm
Number of rings	1	1	1
e/μ identification	μ -like	e -like	e -like
Momentum	$p_\mu > 200 \text{ MeV}/c$	$p_e > 100 \text{ MeV}/c$	$p_e > 100 \text{ MeV}/c$
Number of decay electrons	0 or 1	0	1
Reconstructed neutrino energy	-	< 1250 MeV	< 1250 MeV
Pion rejection	π^+ rejection	π^0 rejection	π^0 rejection

- T. Yoshida T2K Thesis
- Event selection is (for the most part) done using the result of various fitQun 1-ring fits
-

Further constraint from the ND (2)

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

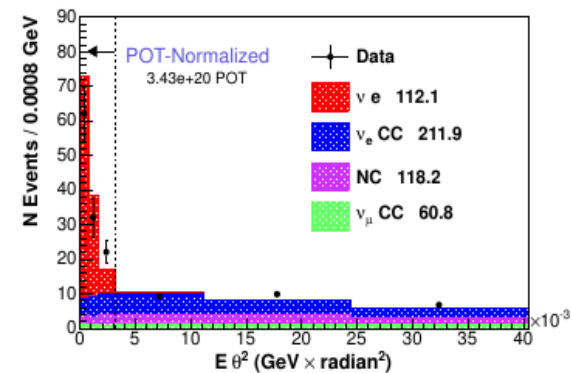
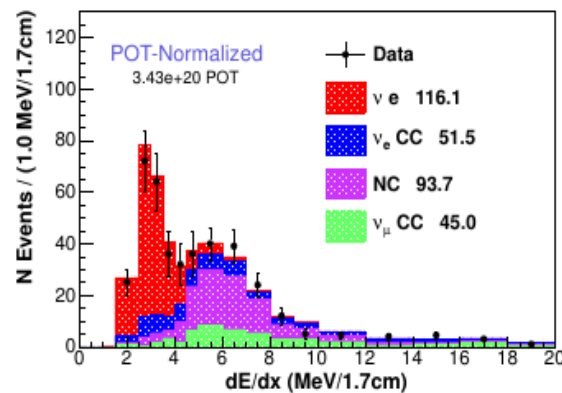
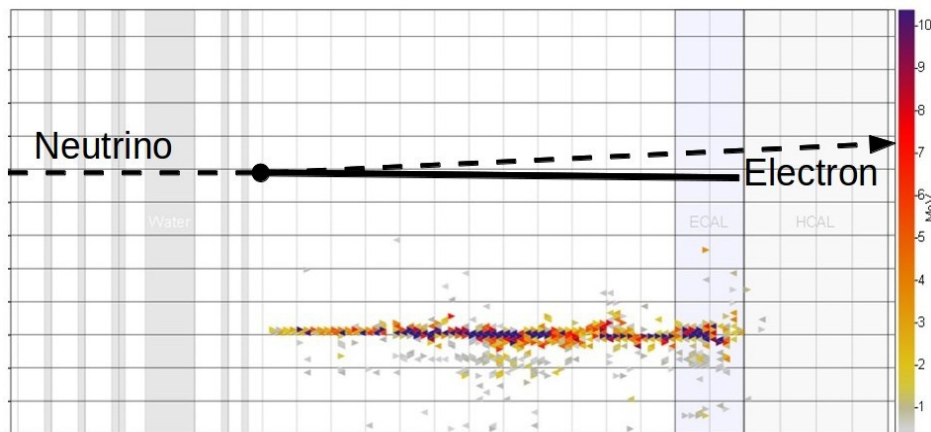


Neutrino scattering on electrons:

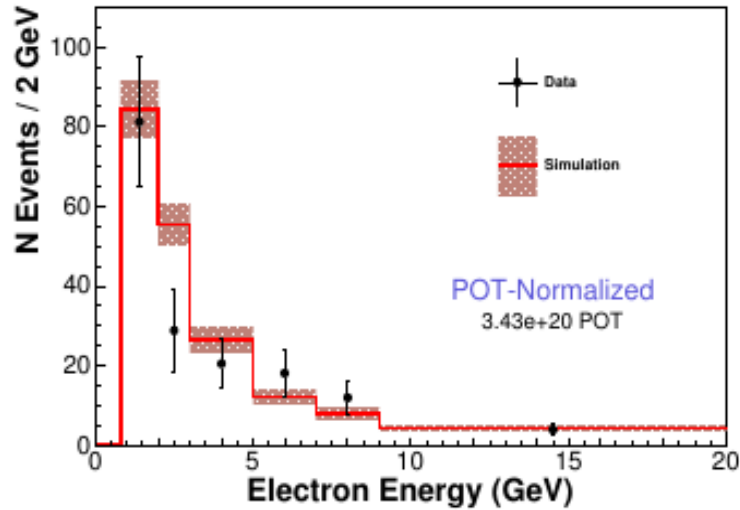
simple electroweak Neutral Current process for ν_μ and ν_τ ,
(some Neutral Current – Charged Current interference for ν_e)

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

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

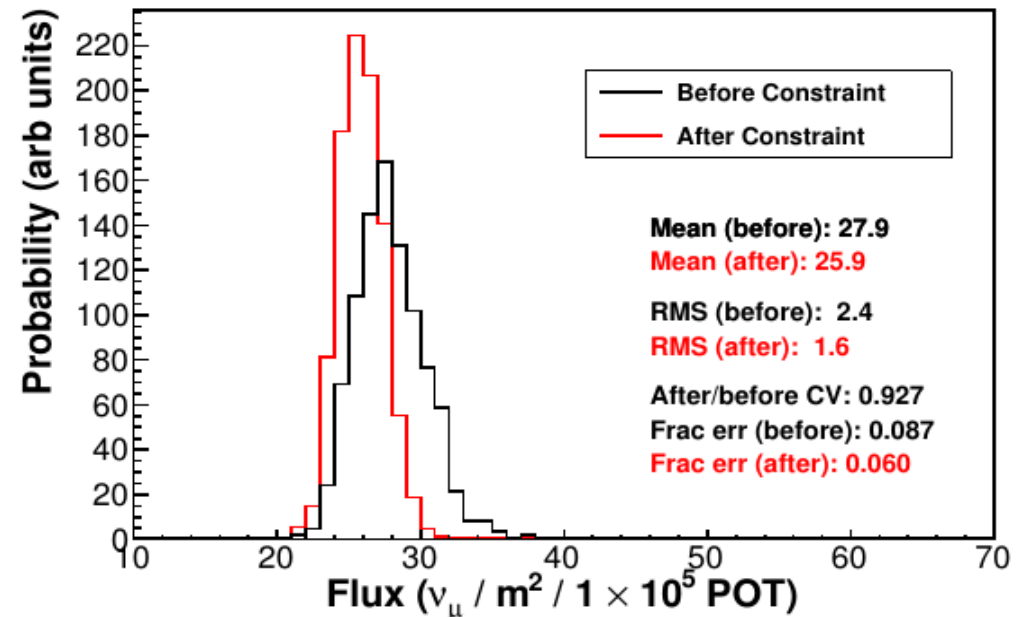
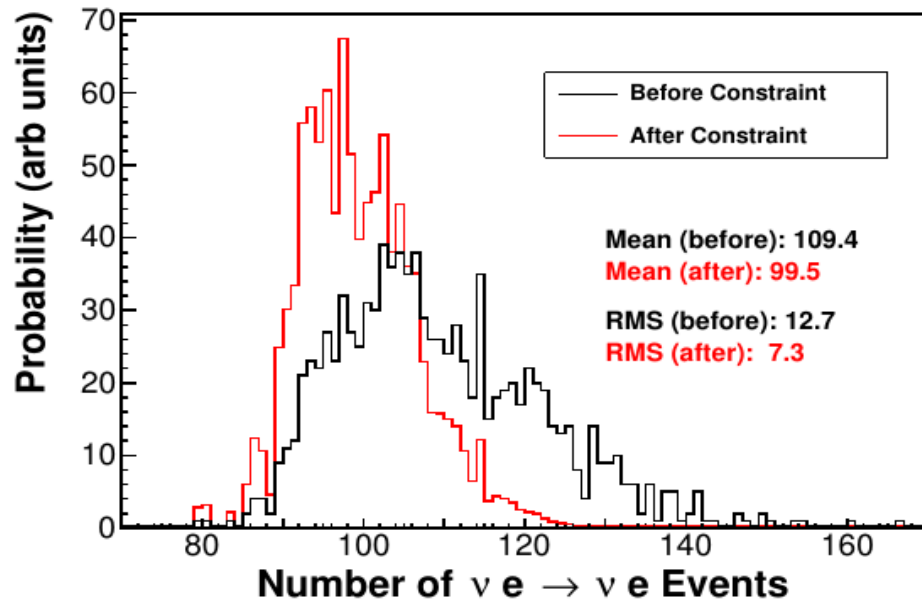


Constraints from ν -e scattering



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

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



Constraints from low- ν method

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

ν = energy transferred to the nucleus

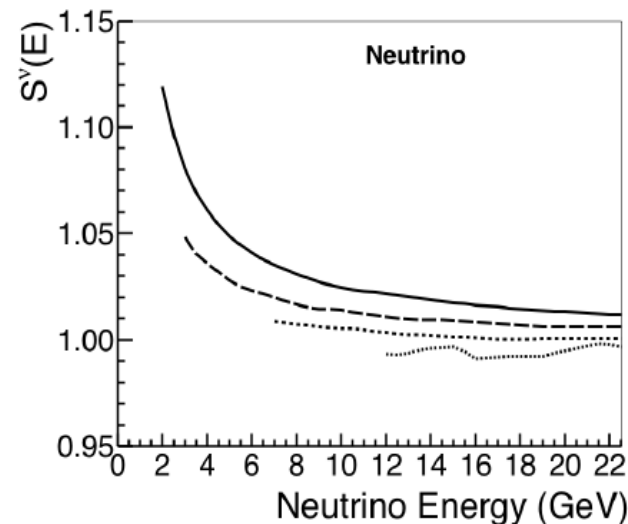
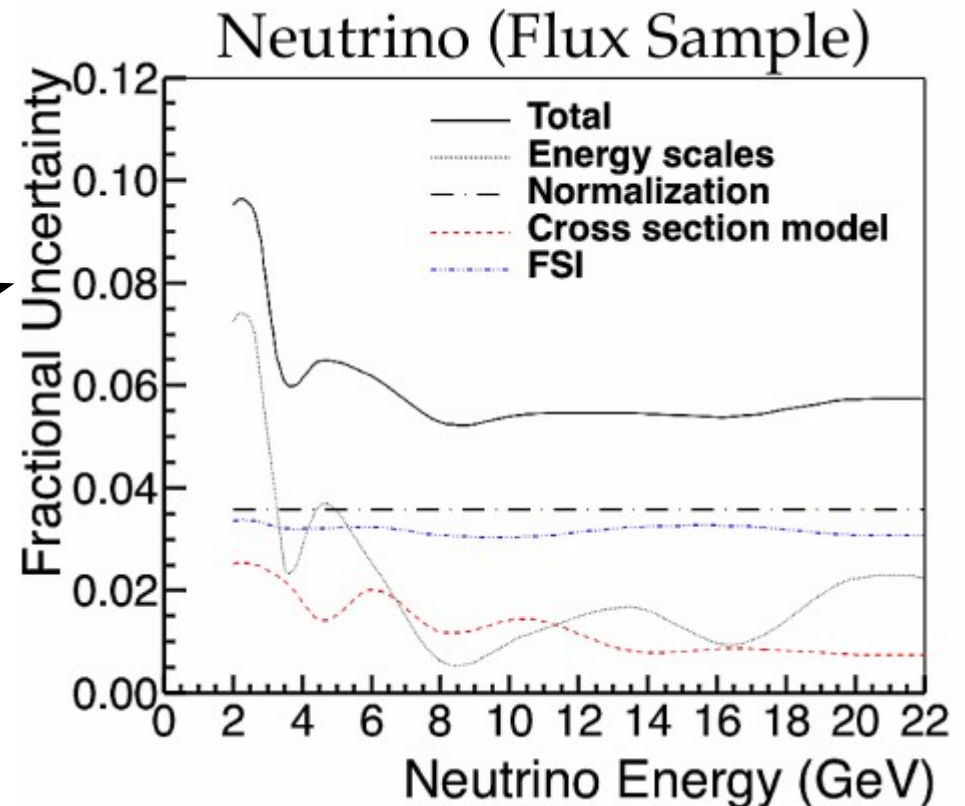
In the limit of $\nu \rightarrow 0$ the xsec does not depend on $E\nu$

→ event rate at low ν can be used to constraint the flux shape as a function of $E\nu$

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 $E\nu$ is an approximation → need to correct with xsec models:

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



Non standard beams and fluxes

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



well known energy of neutrinos

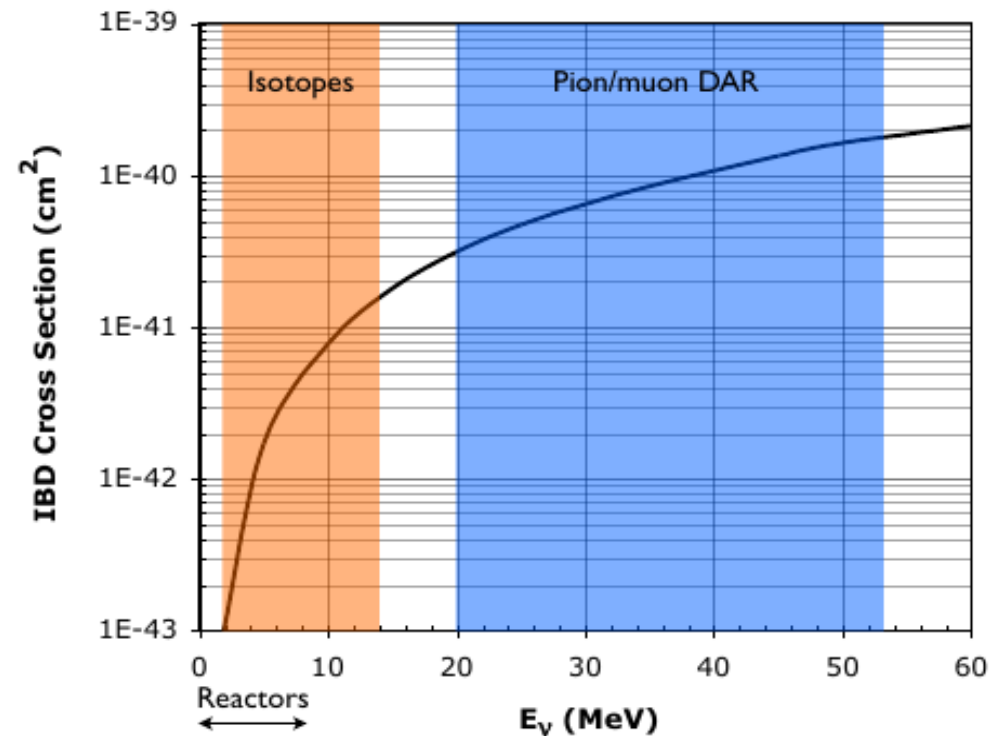
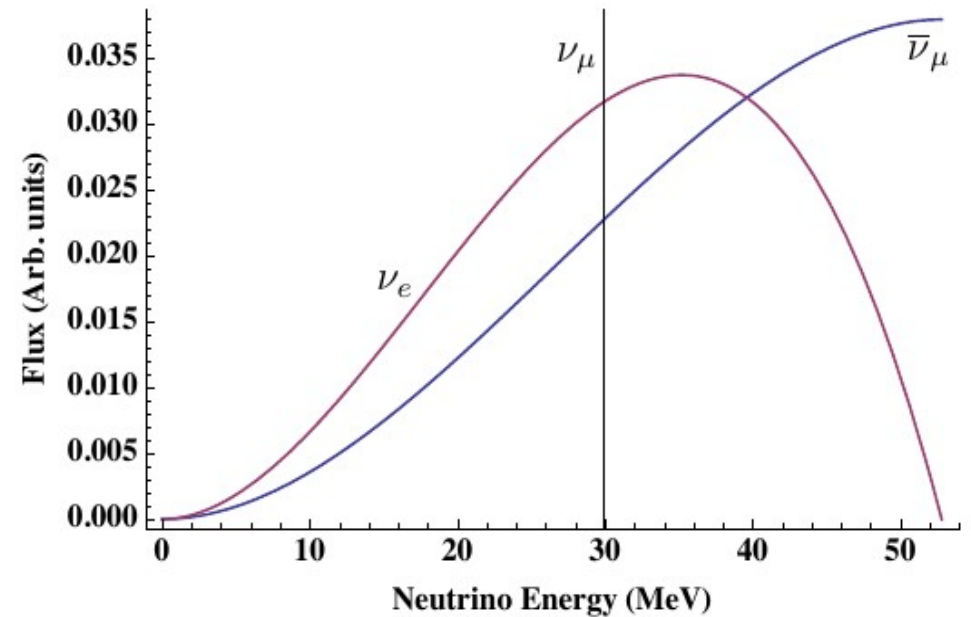


low energy \rightarrow well known cross-section: IBD ($\bar{\nu}_e + p \rightarrow e^+ n$) and ν -e elastic scattering



low energy \rightarrow very low xsec need VERY intense sources

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

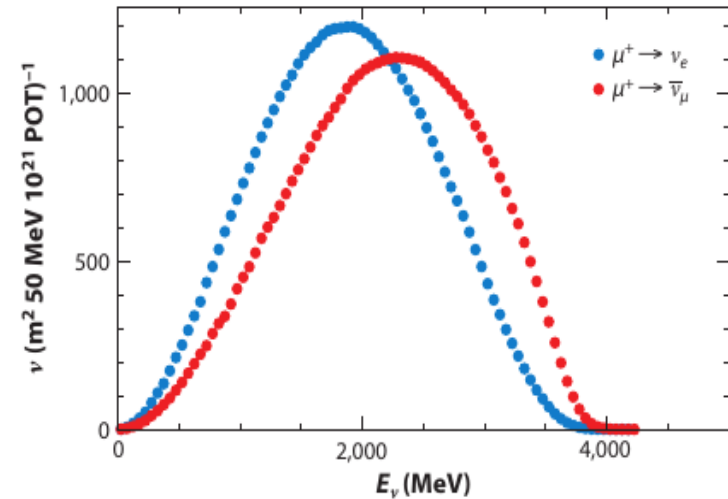


Non standard beams and fluxes

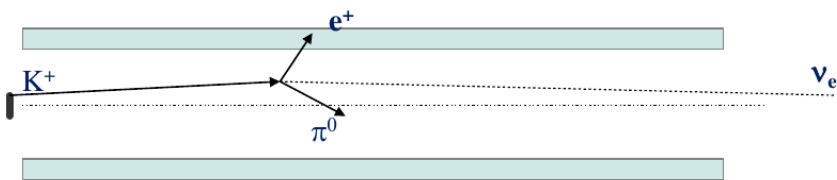
- **Neutrinos from Stored Muons (nuSTORM):** beams from the decay of 3.8 GeV muons confined within a storage ring

😊 well known energy of neutrinos

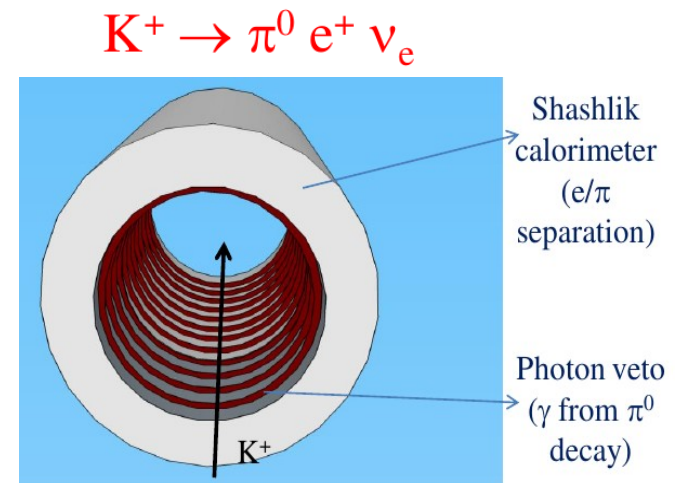
😊 large ν_e statistics



- **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



Alternative concept: NuPRISM

Flux at different off-axis angle = different E_ν spectra

Combine measurements at different angles to

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

