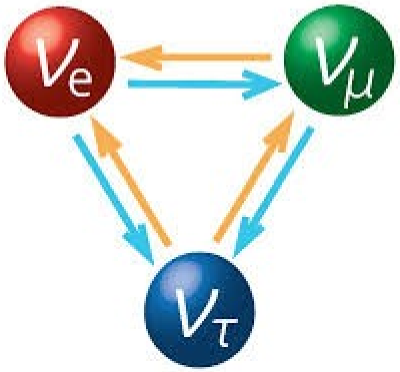
Neutrino oscillations:

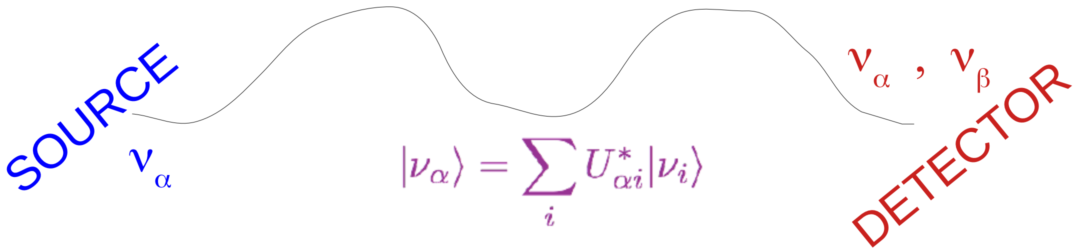
open questions



S.Bolognesi (CEA, IRFU)

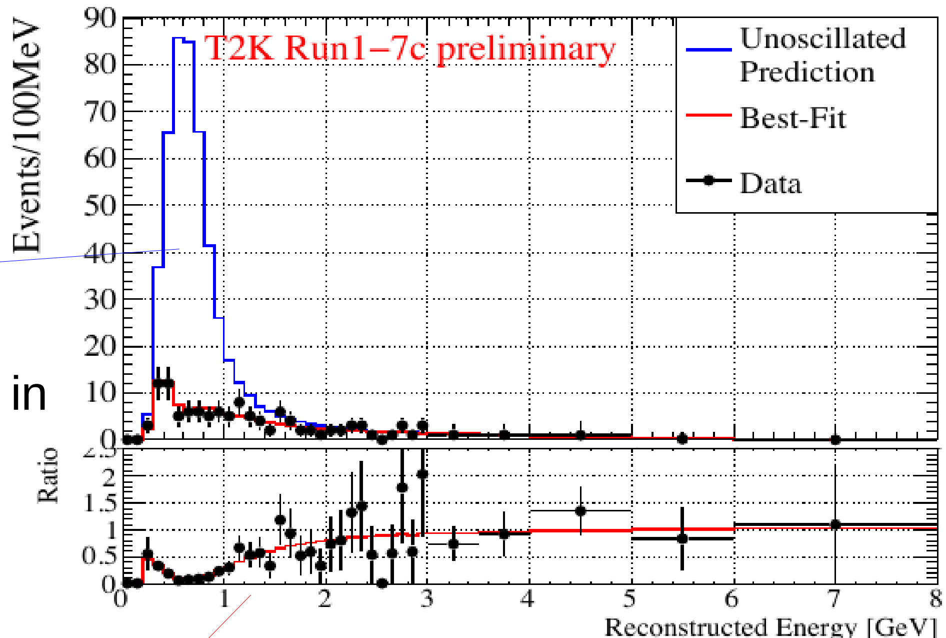
Neutrino oscillations

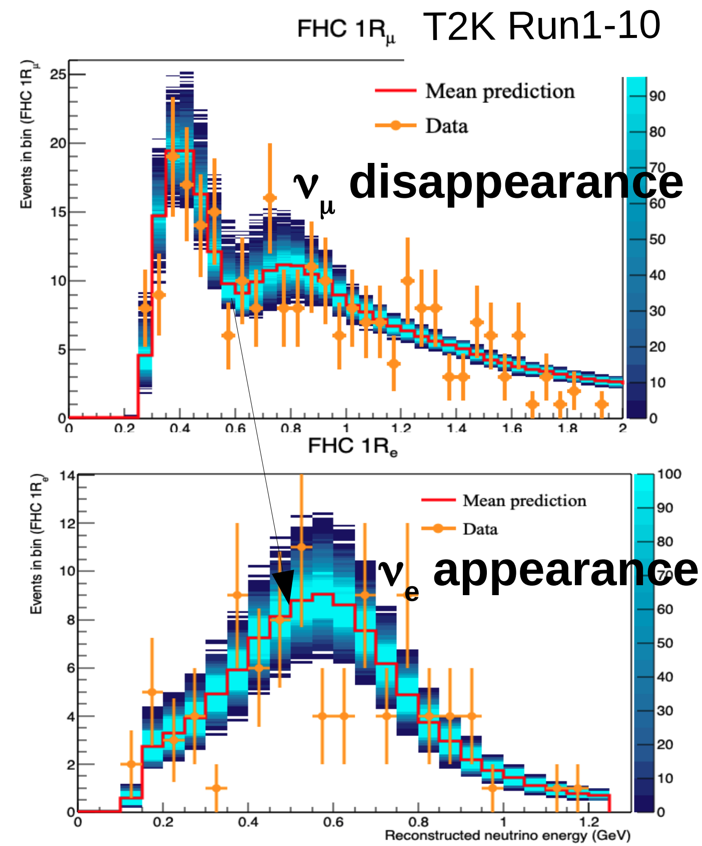
Produced/detected through EWK interactions (detection of flavour requires a charge current interactions), propagation as mass eigenstate



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

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





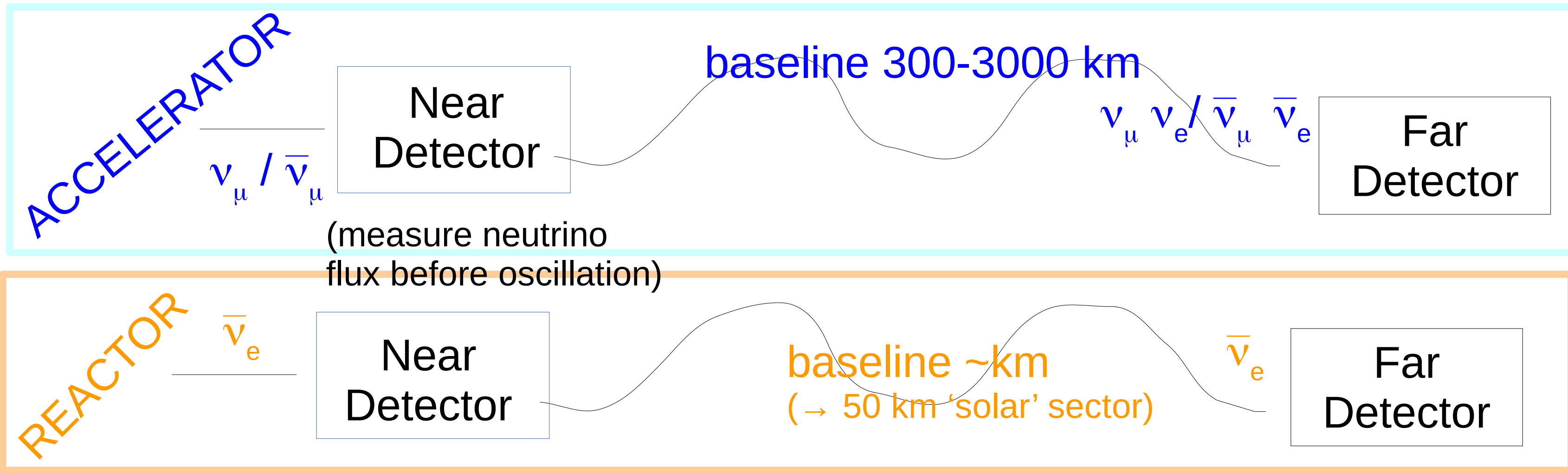
Oscillation in two flavour approximation

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

Neutrino oscillations

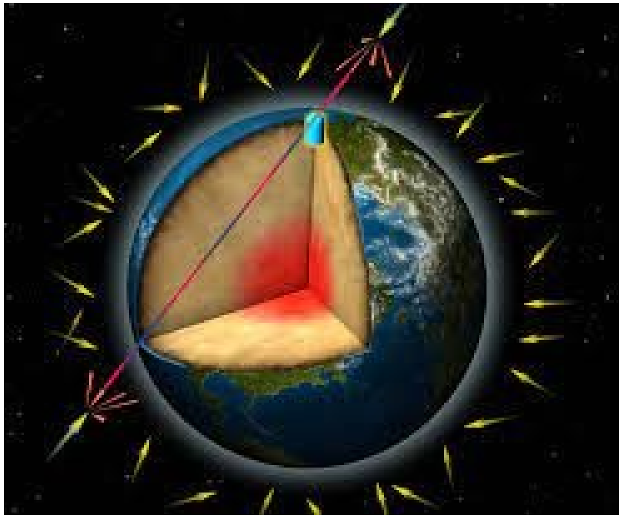
3 flavours (3 mixing angles, 2 mass difference) → different L/E experiments targeting different parameters

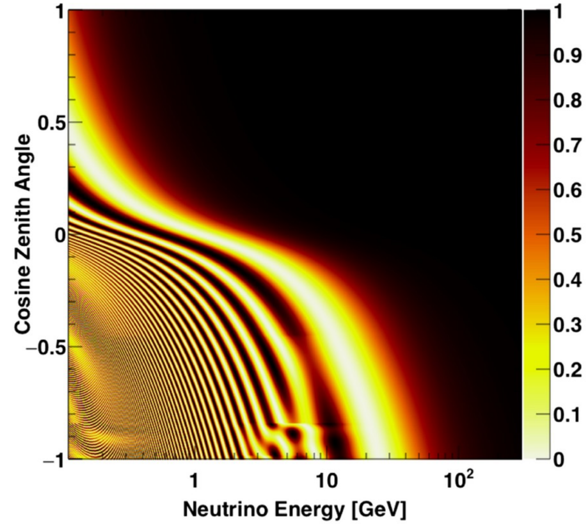
Controlled sources: energy and rate (flux) + fixed baseline



underground, very large mass

Also ν from "uncontrolled" sources: in **atmospherics** L correlated with azimuthal angle and very large energy spanning (solar, SuperNovae)





(a) $P(\nu_\mu \to \nu_\mu)$

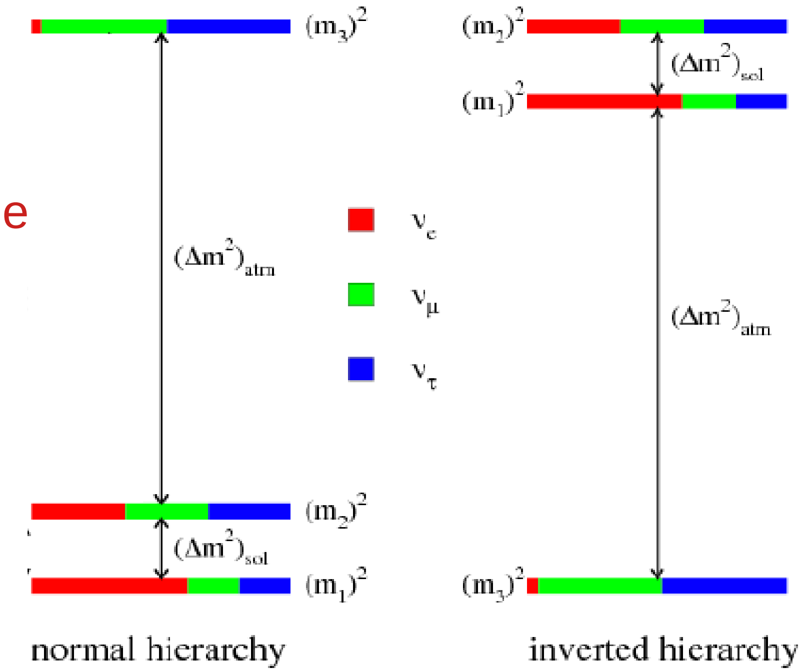
Open questions

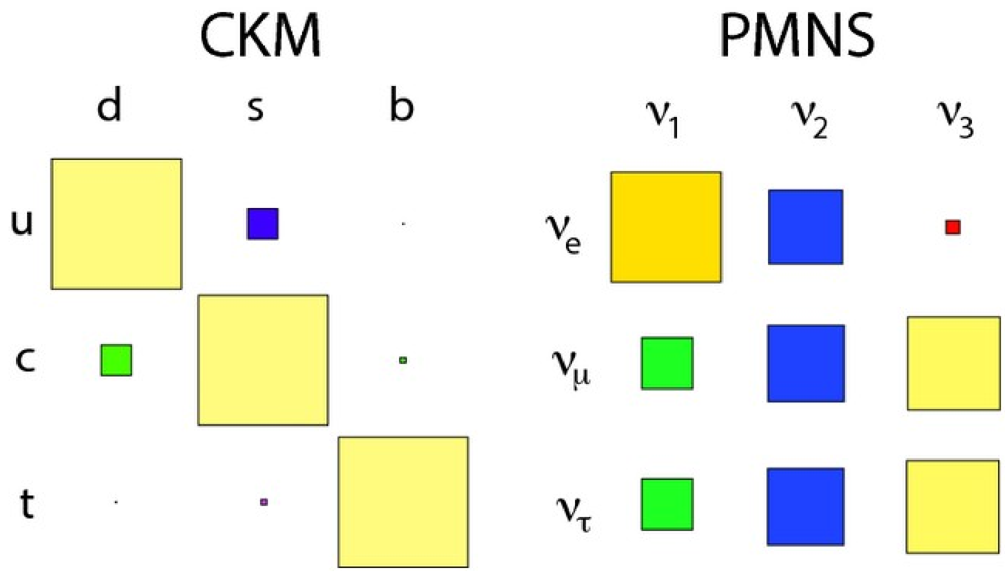
- The next step: high statistics in the PMNS framework

- establishing mass hierarchy → is the order in mass the same as charged leptons?

- possible discovery of CP violation if ν and $\bar{\nu}$ oscillation is different → first in lepton sector and a new fundamental source of CPV !

- PMNS precision physics: what is the simmetry hidden behind the flavour pattern?





Enabled by next generation of oscillation experiments with increased mass and increased accelerator power

→ **the challenge of precision:**
near and far detector performances and control of systematics

Open questions

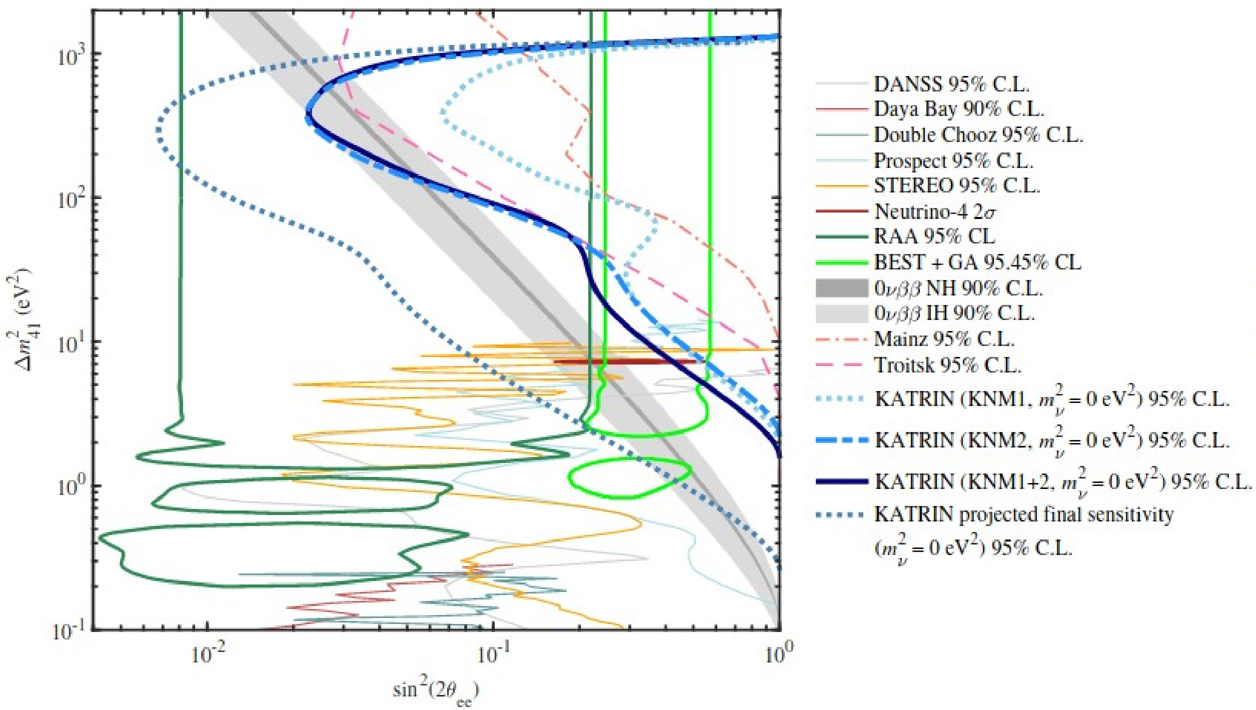
- **The next step: high statistics in the PMNS framework**

→ **the challenge of precision:** near and far detector performances and control of systematics

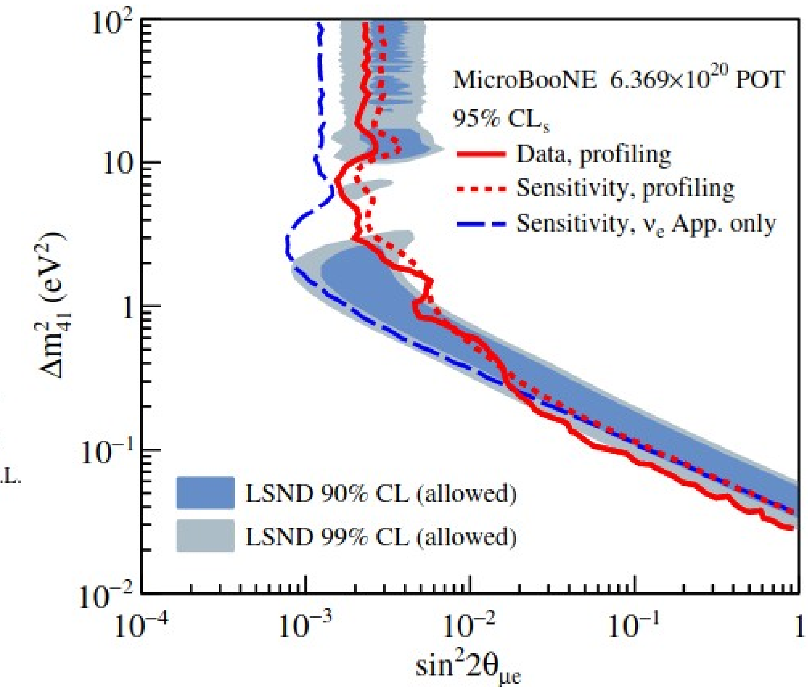
- **BSM searches: looking into 'standard' scenarios**

search for sterile neutrinos: many searches with different masses (unexpected oscillation shape at far and near detectors, dedicated experiments at accelerators"short baseline" and at reactors)

Phys. Rev. D 105, 072004



Phys. Rev. Lett. 130, 011801



Open questions

- The next step: high statistics in the PMNS framework

→ **the challenge of precision:** near and far detector performances and control of systematics

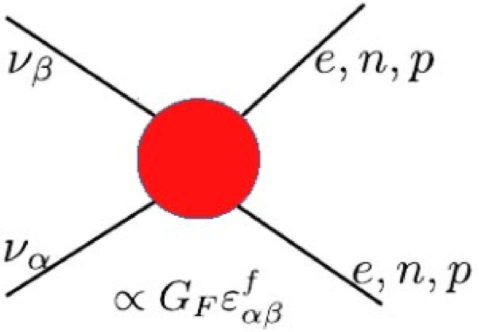
- BSM searches: looking into ‘standard’ scenarios

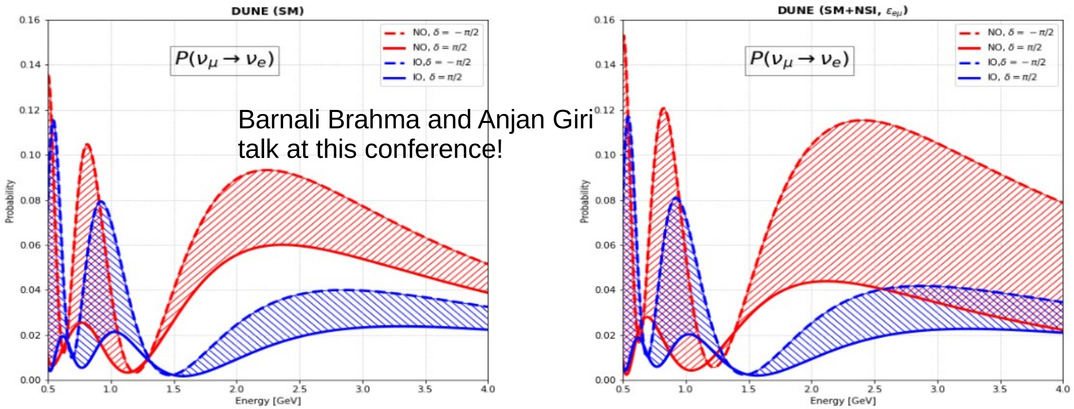
search for sterile neutrinos: many searches with different masses (unexpected oscillation shape at far and near detectors, dedicated experiments at accelerators”short baseline” and at reactors)

search for Non Standard Interactions: different oscillation results in the “standard” paradigm depending on the baseline of experiments

Dimension-six four-fermion operators

$$\mathcal{L}_{NSI} = -2\sqrt{2}G_F \sum_{\alpha,\beta,f,P} \epsilon_{\alpha\beta}^{f,P} [\overline{\nu_\alpha}\gamma^\mu \nu_\beta][\bar{f}\gamma_\mu f]$$





Barnali Brahma and Anjan Giri talk at this conference!

Also constraints from CEvNS measurements at reactors/accelerators + solar neutrinos (NSI in Sun core) + atmospheric neutrinos

B Brahma, A Giri EPJ C 82, 1145 (2022)

Open questions (and future questions!)

- **The next step: high statistics in the PMNS framework**

→ **the challenge of precision:** near and far detector performances and control of systematics

- **BSM searches: looking into ‘standard’ scenarios**

search for sterile neutrinos: many searches with different masses (unexpected oscillation shape at far and near detectors, dedicated experiments at accelerators”short baseline” and at reactors)

search for Non Standard Interactions: different oscillation results in the “standard” paradigm depending on the baseline of experiments

- The ultimate target: **open-mind/model-independent characterization of neutrino oscillation phenomena with L/E going beyond the strict present (B)SM paradigms**

→ **the challenge of versatility:** near and far detector design able to cover BSM signatures

→ **the power of combining multiple experiments:** solve degeneracies + ‘agnostic’ BSM test

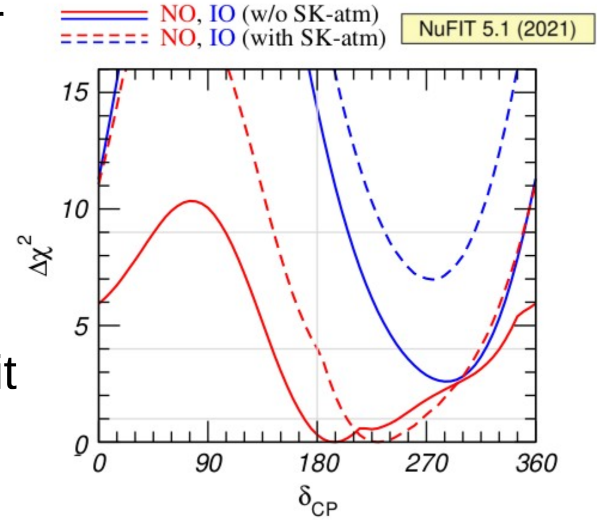
Difficulties to deal with:

- correlation of systematics
- publication of results in open way to make possible re-interpretation in different models (eg, dependence on priors?)

The road**s** to mass hierarchy

MH sensitivity from matter effects (CC interaction with e- in matter different for ν_e and $\bar{\nu}_e$) → longer baseline and larger energy for better sensitivity

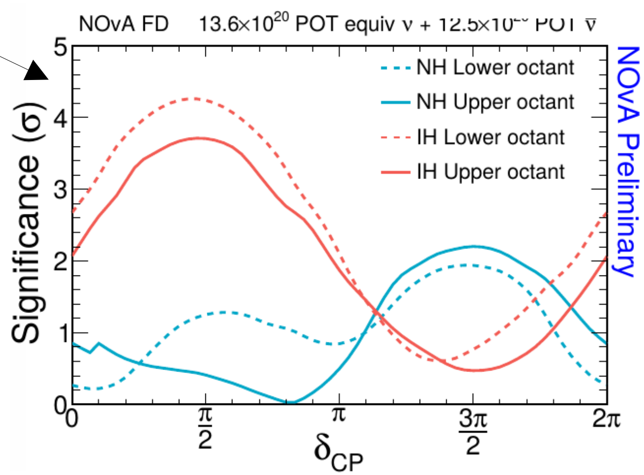
- Today sensitivity is dominated by SuperKamiokande atmospheric ν



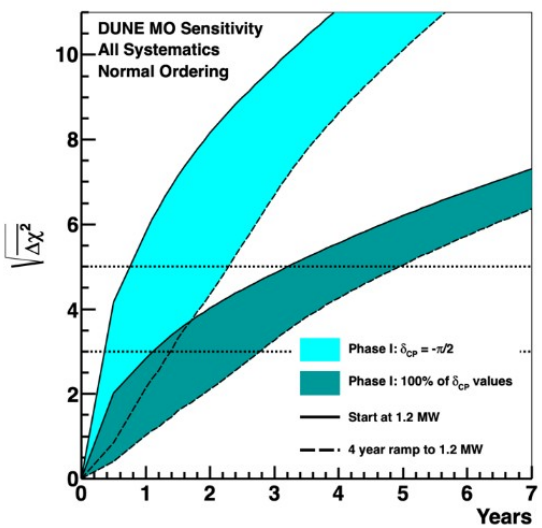
2.7σ in global fit

- Future similar experiments are HyperKamiokande (>8 times bigger detector) and ORCA (in the Mediterranean sea)

- With ν from accelerator NOVA has MH sensitivity (but degeneracy with CPV effects) → important to combine with T2K (clean CPV sensitivity ~w/o~ matter effects)



→ ultimate sensitivity with ν from accelerator in DUNE (much larger baseline)



- JUNO: sensitivity with oscillation in vacuum from reactor!

Also strong synergy with T2K, NOVA and ORCA (see previous talk)

The discovery of CPV

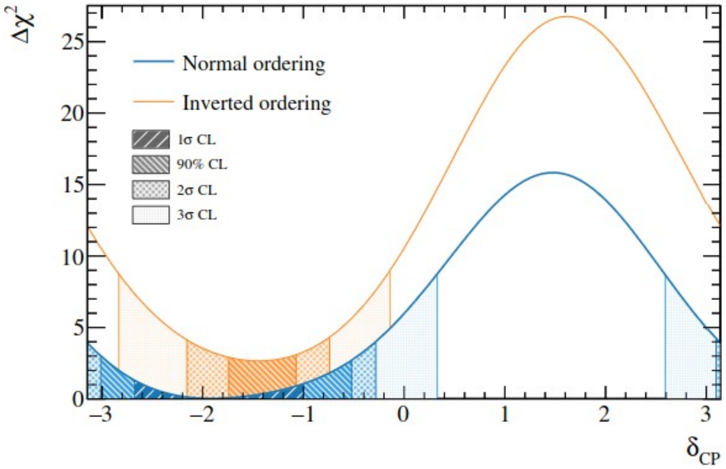
$$\mathcal{A}_{\rm CP} \equiv \frac{P(\nu_\mu \to \nu_e) - P(\overline{\nu}_\mu \to \overline{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\overline{\nu}_\mu \to \overline{\nu}_e)} \simeq -\frac{\sin 2\theta_{12} \sin\delta}{\sin\theta_{13}\tan\theta_{23}}\Delta_{21} + \text{matter effects}\,,$$

- T2K exclusion at 3σ of 50% of δ_{CP} values and ~2σ hints for CP violation: Nature 580 (2020) 7803, 339-344

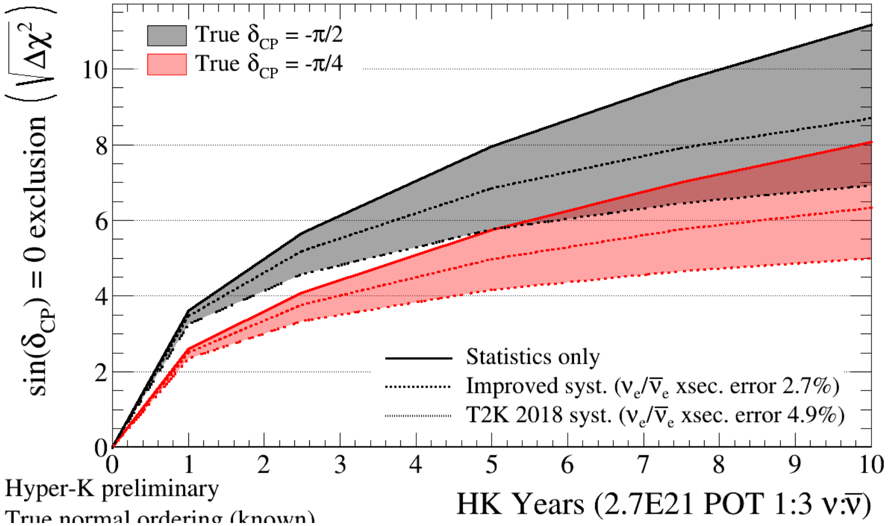
April 2020 Nature cover!

Statistically limited measurement!

Latest T2K results
https://arxiv.org/pdf/2303.03222.pdf



Upgrade of T2K beam up to 1.2MW into HK era with a seamless data taking program.
HK → x20 instantaneous stat of T2K: ultimate sensitivity

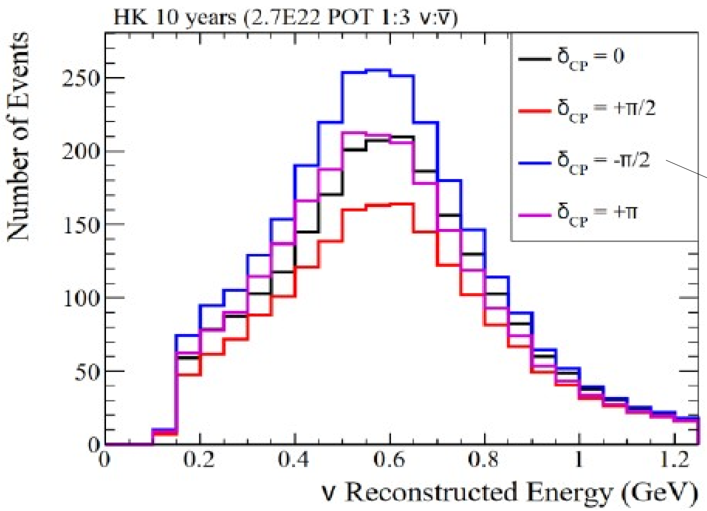


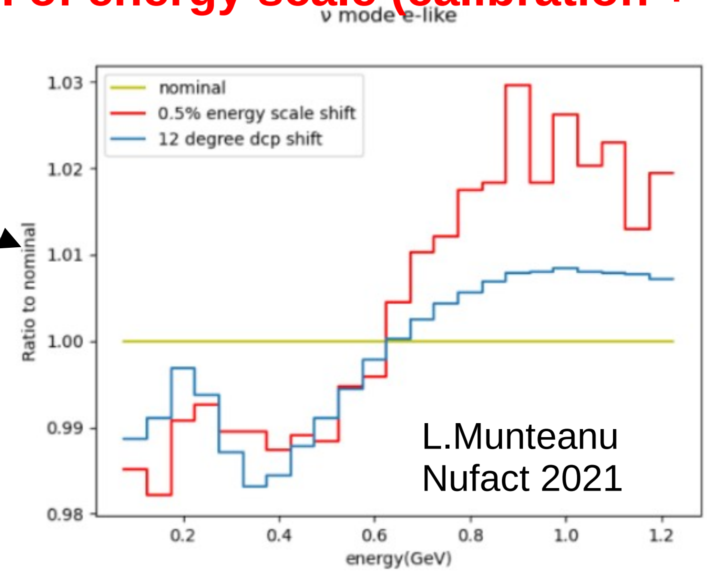
In case of very small CPV and (in any case) after the CPV discovery, **paradigm shift to precise measurement of δ_{CP}**

→In the precision era, **combination between experiments absolutely crucial to build confidence in the control of systematic uncertainties (complex ones, related with modeling of nuclear physics!)**

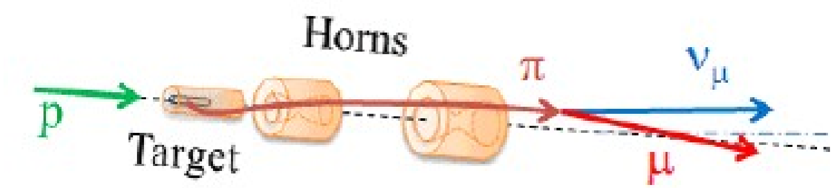
The challenge of precision

δ_{CP} <15deg precision requires **control of energy scale (calibration + nuclear effects) <1%**

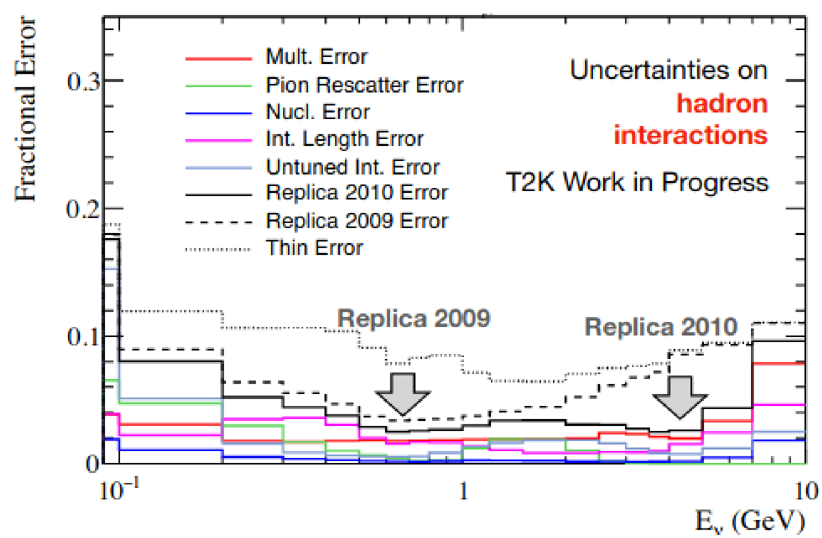




Control of produced flux of neutrinos:



hadro-production simulated with nuclear physics model and **tuned to external measurements: NA61 experiment at CERN + (MIPP) EMPHATIC**



NA61 will finish at the end of 2025: need to design new hadroproduction experiment to support (enable!) the precision physics fat future oscillation experiments

The challenge of precision: near detectors

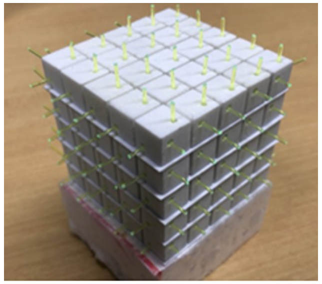
$$R_{FD}^{\nu'} = \int \Phi^{\nu}(E_\nu)\, P_{osc}^{\nu \to \nu'}(E_\nu) \frac{d\sigma^{\nu'}}{dE_\nu} dE_\nu$$

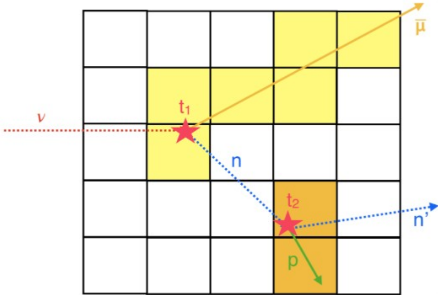
Need also to control **neutrino-nucleus cross-section** (→ detection probability).
New generation of near detectors:

- previous ones just measure leptons in limited acceptance (T2K ND280) or measure the inclusive deposited energy lepton+hadron (NOVA ND)

- NEW! Exclusive measurement of final state

ND280 upgrade (under installation): scintillator with 3D track reconstruction capabilities



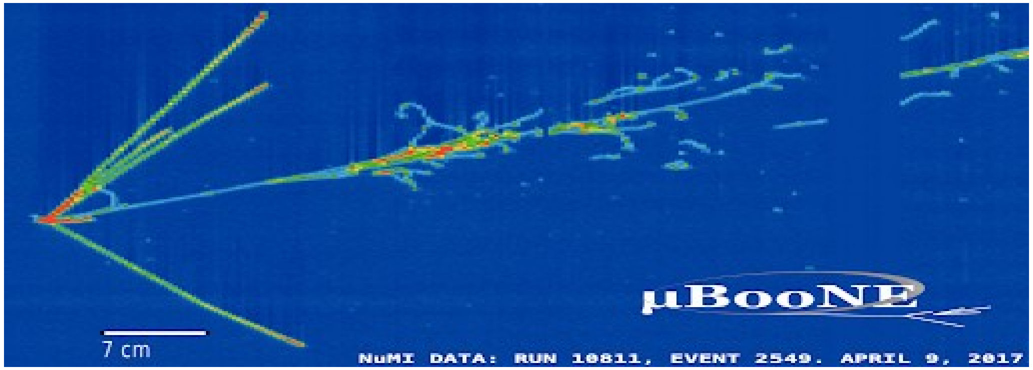


Liquid Argon capability: MicroBooNE running

- low threshold on proton, pion momentum

- for the first time neutron measurement event-by-event

→ unprecedents control on all final state particles (→ Eν precision)

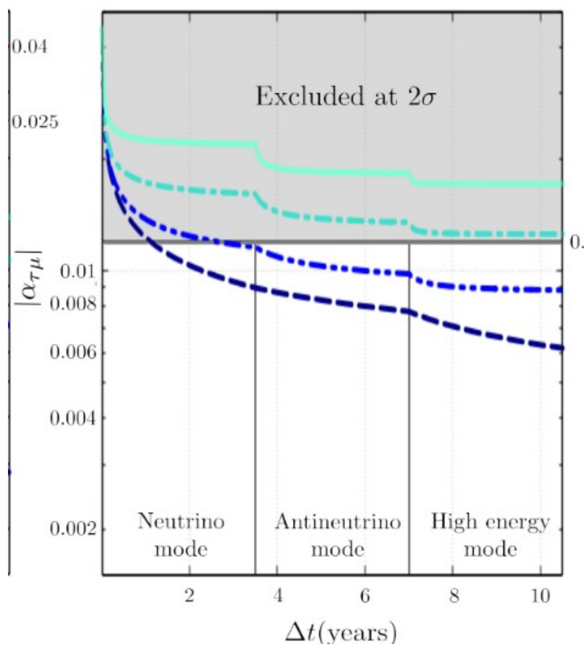


The road to future precision is being built NOW: new detectors, analysis techniques for near detectors measurements + collaboration with nuclear theory community for improved models

Versatility of near detectors for BSM

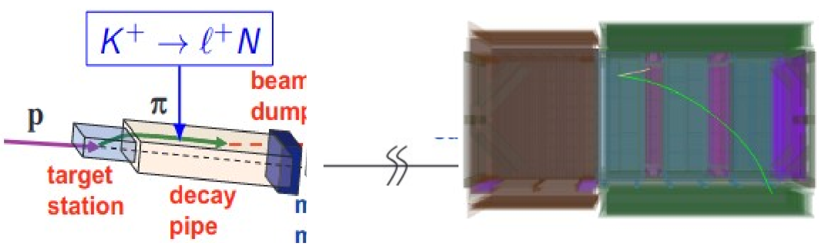
Steriles (of many different types) → inventive ways of use near detectors

- DUNE tau ν appearance at near detectors

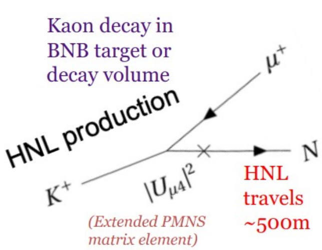


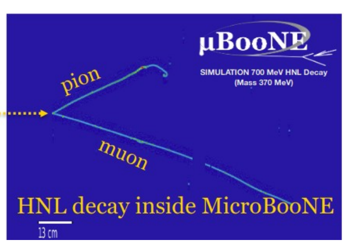
Sensitivity depending on energy shape uncertainty

- HNL from K decays in the beam



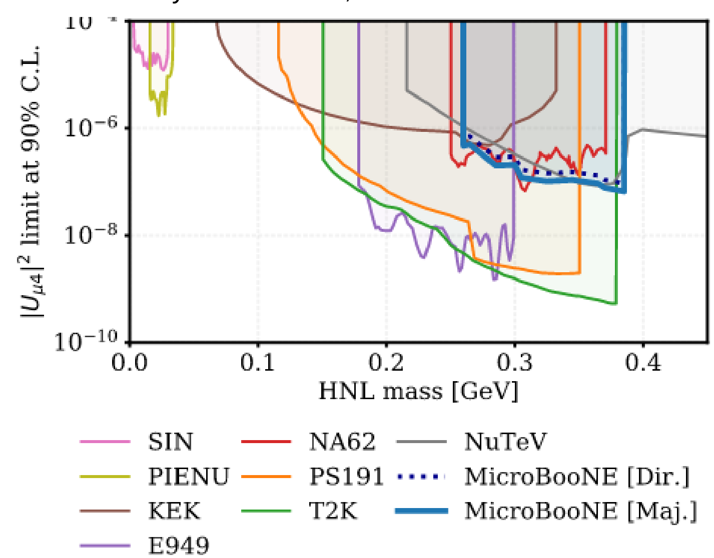
- ND280: decay of N in TPC gas volume (~no background)





- MicroBooNE: delayed N decays

Phys. Rev. D 100, 052006 (2019)
Phys. Rev. D 101, 052001



Beyond PMNS

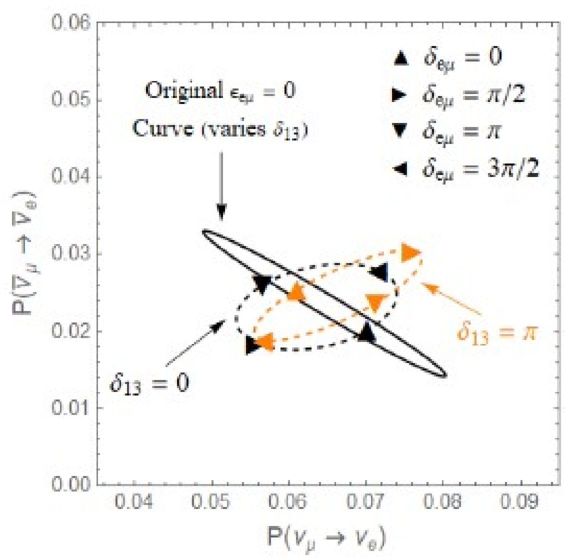
- **The 'standard' oscillation paradigm (PMNS-based) is very strict and not motivated by fundamental symmetries** (mixing angles and neutrino masses are 'accidental' numbers).

In particular it assumes
- minimal 3-flavour scenario
- standard neutrino interactions for production and detection
- standard matter effects along propagation

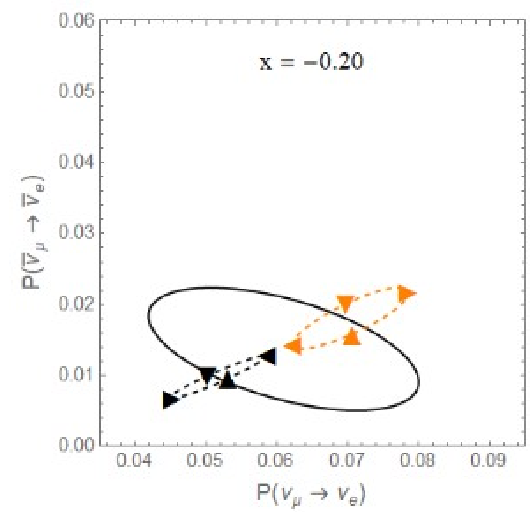
- When moving beyond the PMNS paradigm, combination of experiments is (again) crucial

- more than the sum of sensitivities: effects of New Physics can offuscate 'standard' PMNS interpretation and induce degeneracies: comparison between experiments at different L/E solve them

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



moving to different (L/)E



CIPANP 2018, Print:1809.11128 [hep-ph]

Beyond PMNS

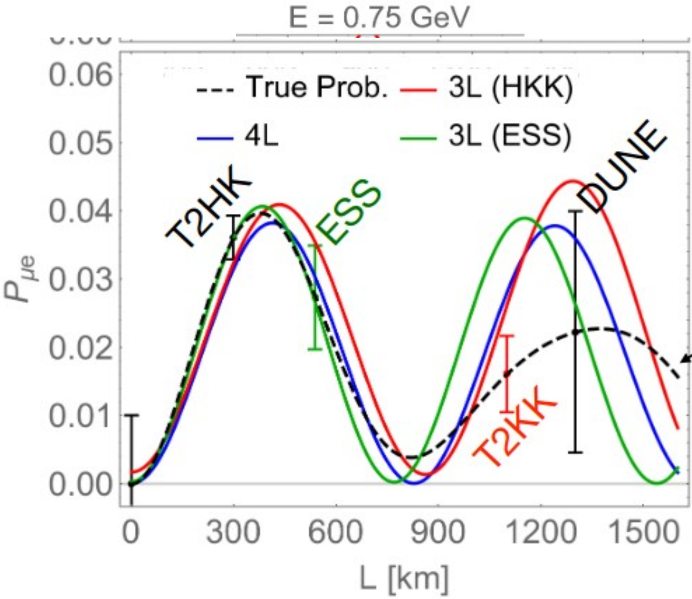
- Expand the oscillation study with a **more general paradigm: with next generation of experiments we will look at oscillations with a much more open-mind approach:** we want to characterize the L/E dependency of flavour mixing

arXiv:2106.16099 [hep-ph]

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

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

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



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

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

- Combination of experiments will be needed for a **comprehensive, precise and open-minded** characterization of ν oscillations

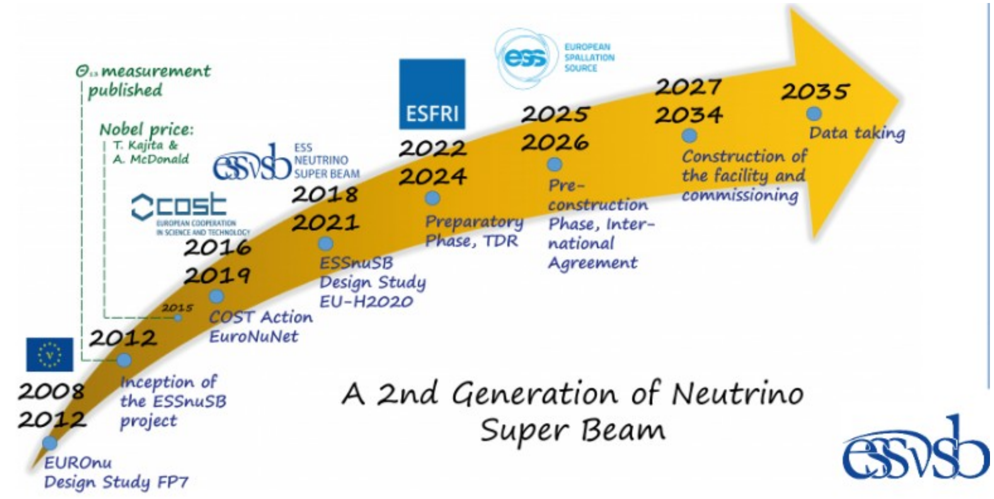
Crucial to have a coherent program of Near Detectors + establish a common language in terms of nuclear models, …

Reharsal: T2K+SK, T2K+NOVA combination → Start to plan for it well in advance!

Looking further into the future

- **T2KK:** second HK tank in Korea
- **ESSνSuperBeam:** covering 2nd oscillation peak + HIFI (demonstrator for low energy νSTORM)

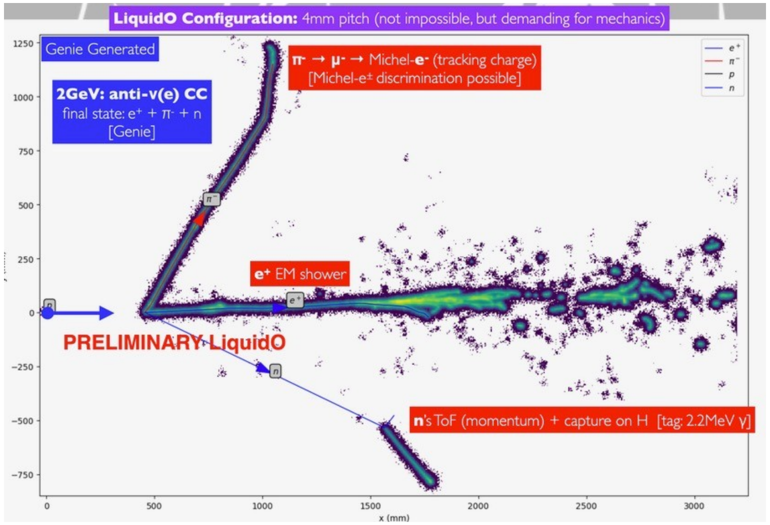
https://arxiv.org/abs/2107.07585



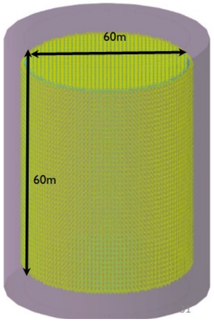
- **νSTORM:** muon storage ring giving very well known ν_e and ν_μ fluxes (R&D toward Neutrino Factories)

- **LiquidO:** studies for even improved S/B and resolution
→ θ_{13}, non-unitarity, solar neutrinos...

Opaque target readout by many fibers
→ SuperCHOOZ



- **THEIA:** water based (doped) optical detector for comprehensive neutrino program (scintillation + Cherenkov)



Last remarks

Change of gear: from statistically dominated domain to precision physics.

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

If we want to build a **safe path to 5σ / precision physics / unambigous results for next generation of experiments** (DUNE and HK), the work to do is still long:
- we need to validating our nuclear-physics model with better precisions with present near detectors (T2K, NOVA, MicroBooNE)
- we need a safe path to precise flux tuning (post-NA61 experiment[s]!)

The ultimate precision in PMNS and the open-minded BSM interpretation will rely on combination of experiments.
→ Long term effort of community building which need to start now!

Stay tuned!

A field of HEP in rapid development with new data coming and a lot of activity through new models, algorithms for recostruction and analyses…

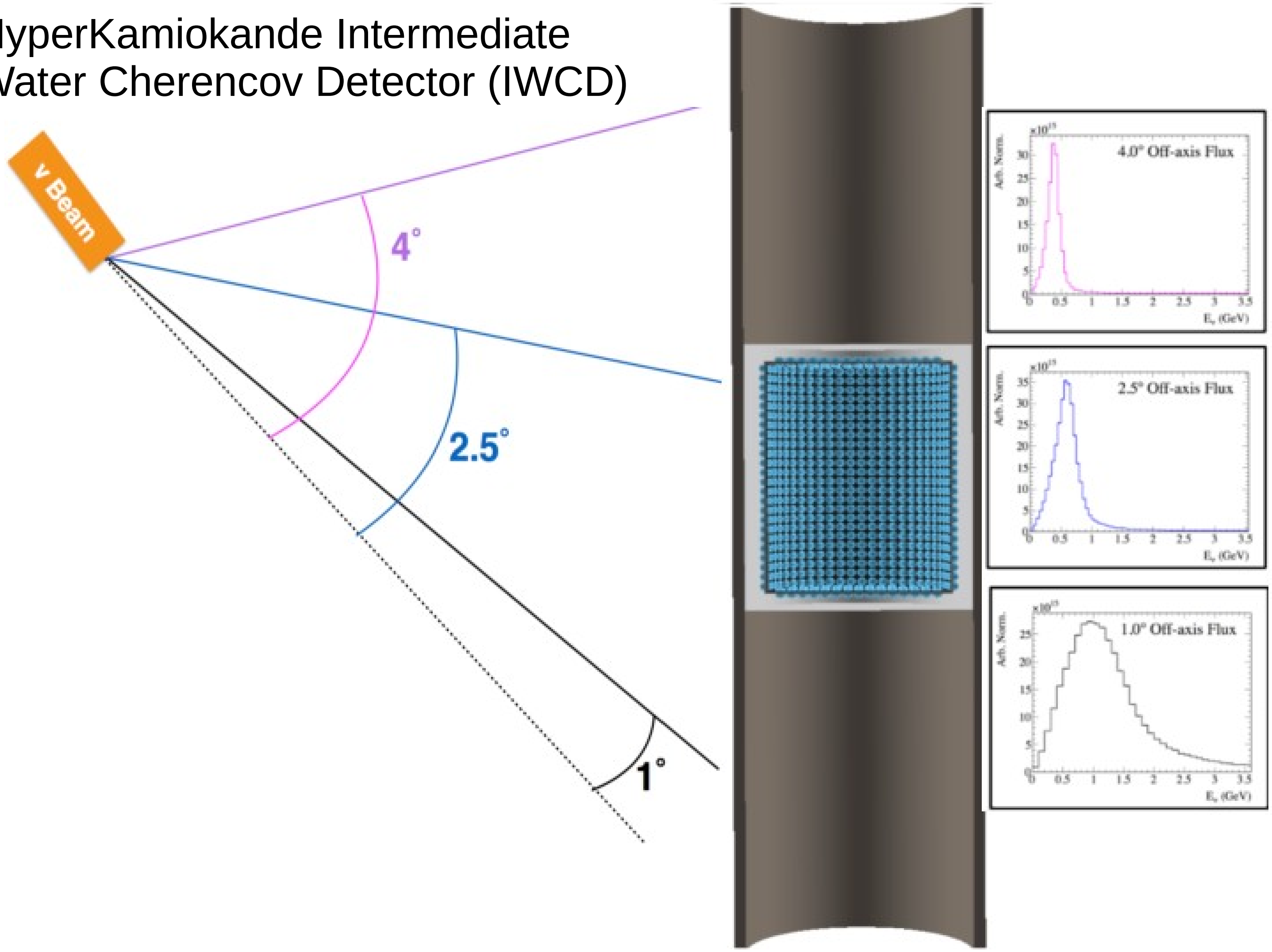
An exciting time to study neutrinos!!!

BACKUP

New approach to near to far extrapolation

Extract Eν dependence from off-axis angle

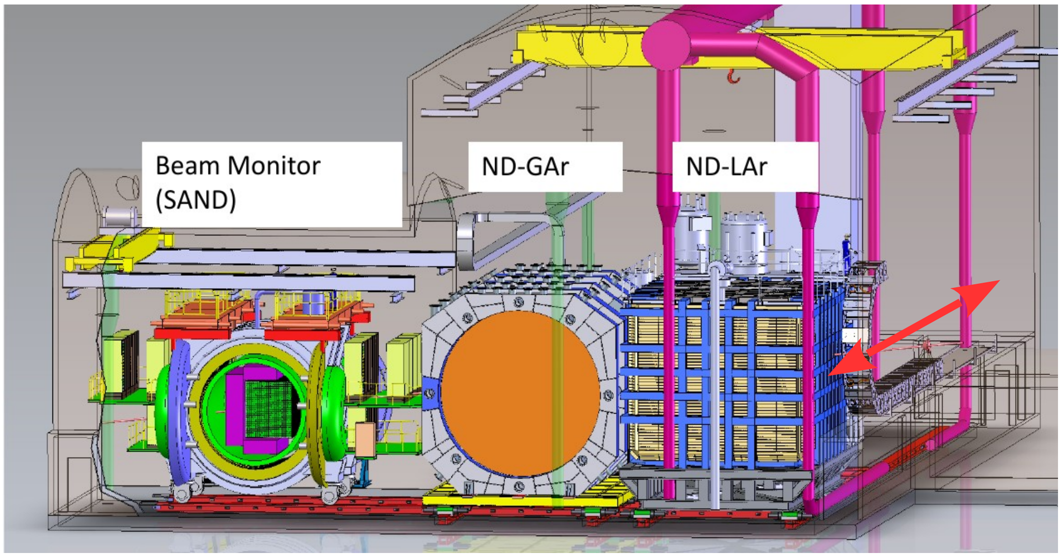
HyperKamiokande Intermediate
Water Cherencov Detector (IWCD)

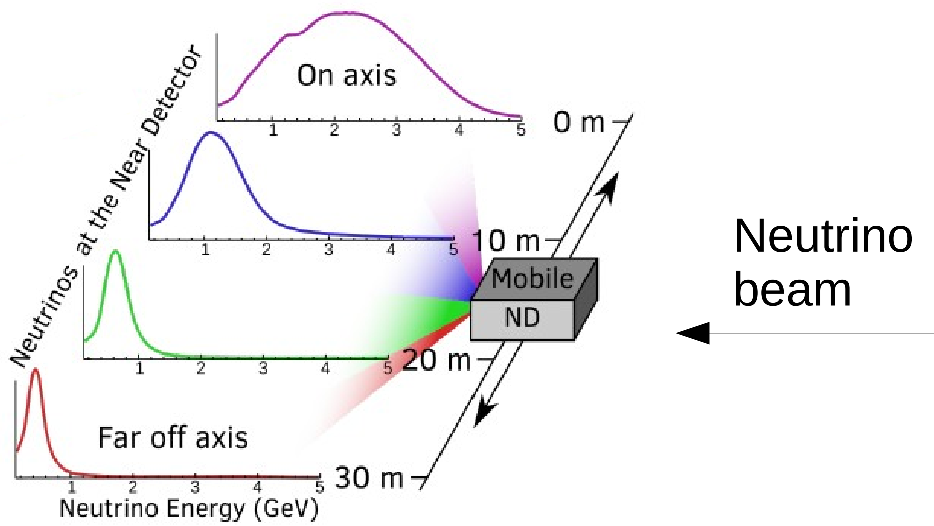


New approach
to near to far extrapolation

Extract Eν dependence from off-axis angle

DUNE LAr and GAr TPCs as movable near detectors: DUNE-Prism





New approach
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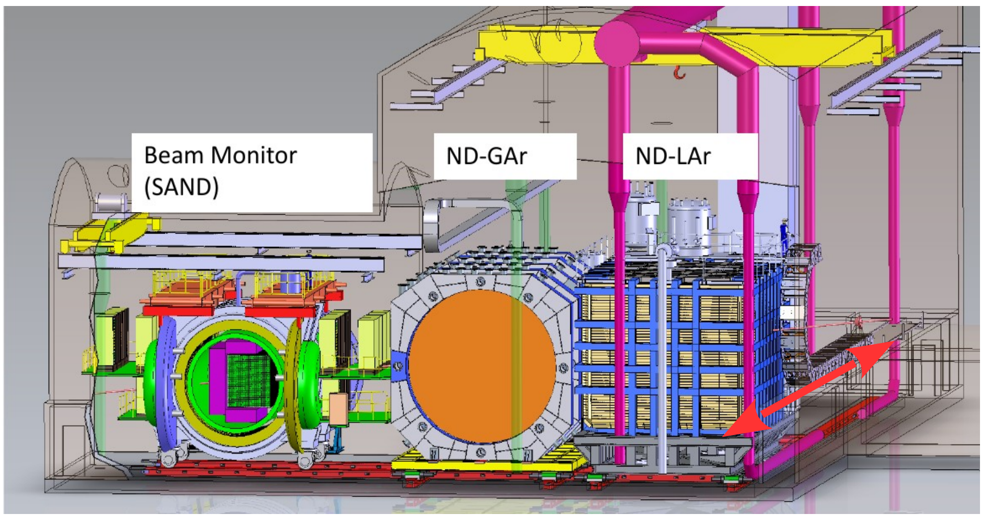
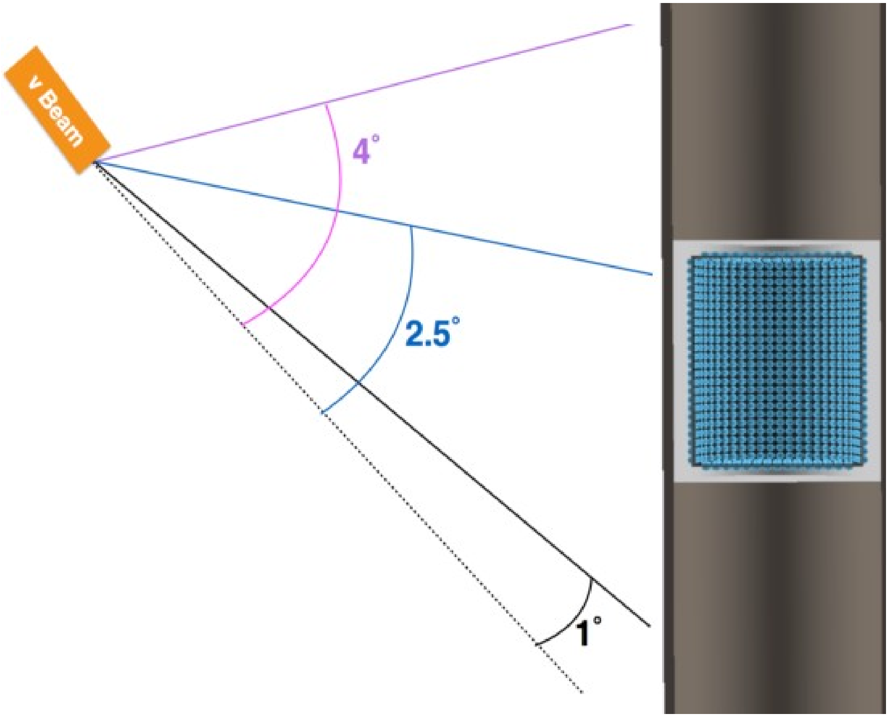
Extract Eν dependence from off-axis angle



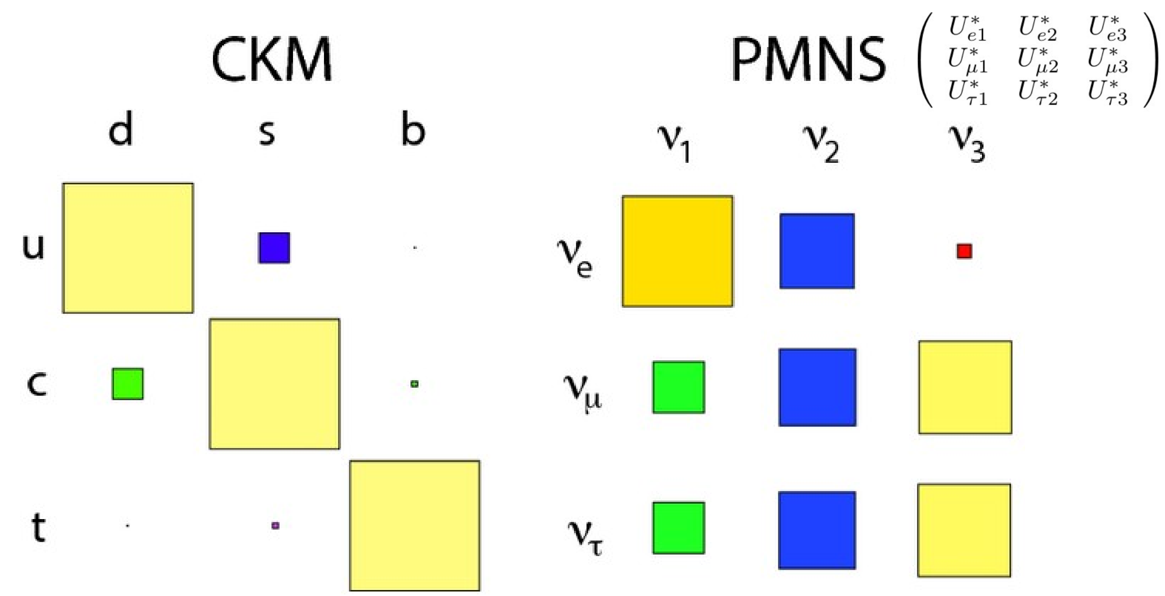


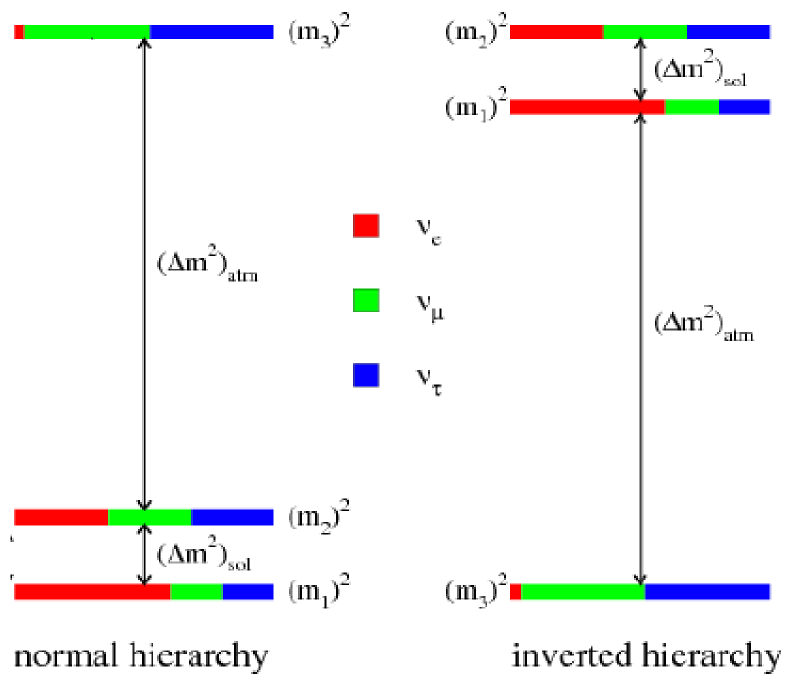
- Nuclear-level systematics becomes 'second order'
→ quantification on-going (acceptance, finite statistics, ...)

- Need to control well flux systematic uncertainties vs angle and flux stability vs time (DUNE SAND, T2(H)K INGRID)

- Movable ND are also **extremely useful measurement for ν_e cross-section** (first order systematics for CPV and MH) since ν_e / ν_μ change vs angle

Status and open questions

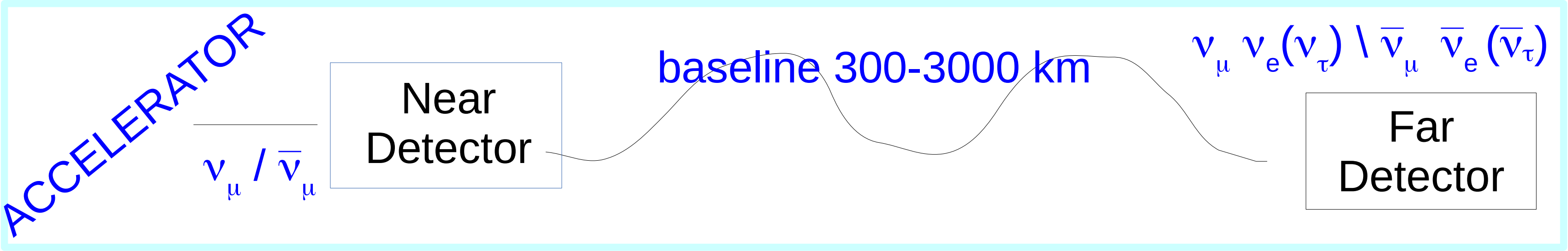


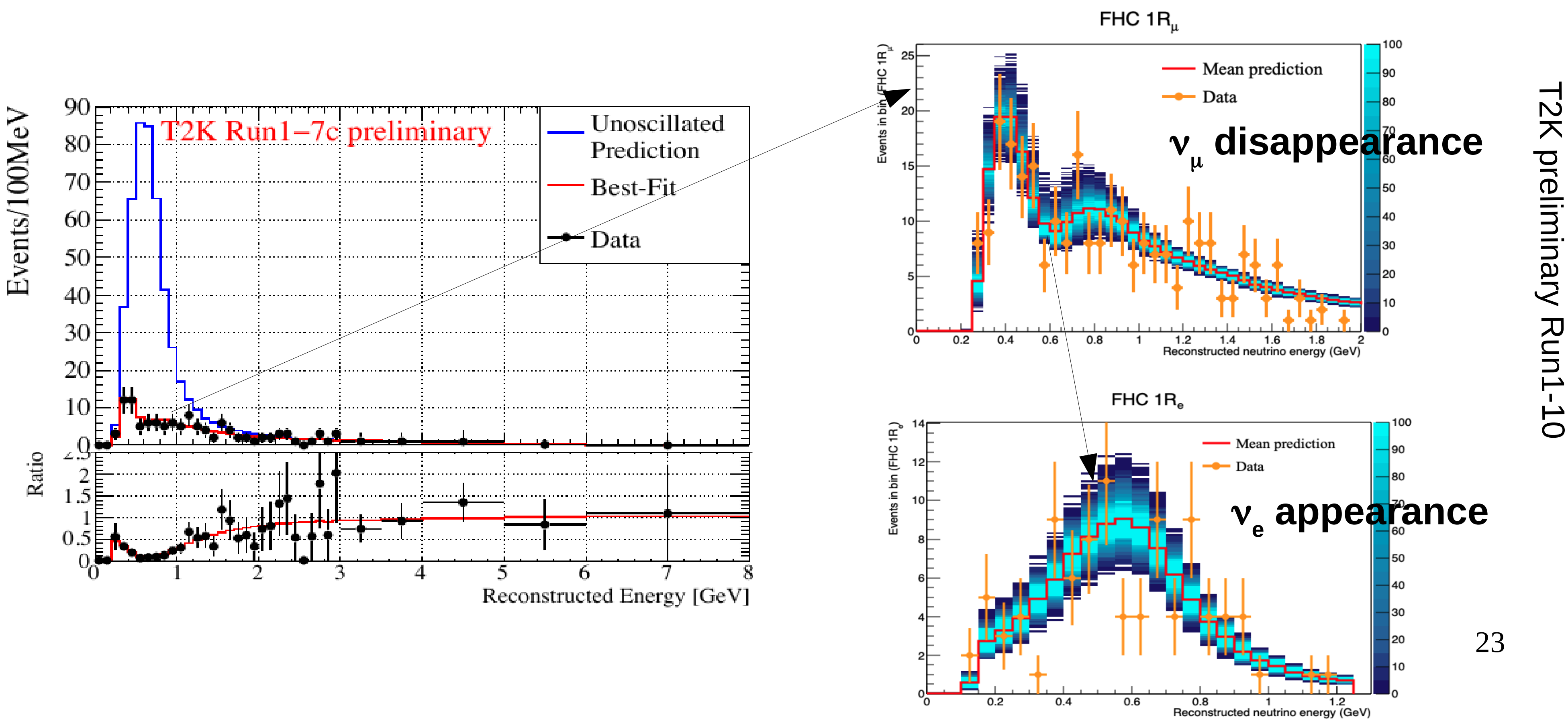


- **Precision measurements of flavour mixing pattern:**
  - very large mixing (θ_{23} ~π/4 would imply maximal mixing, ie $U_{\mu i}$~$U_{\tau i}$, if not which octant?)
  - θ_{13} smaller but not so small (U_{e1}) → access to δ_{CP} phase
- δ_{CP} parametrizes different oscillations for ν and $\bar{\nu}$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

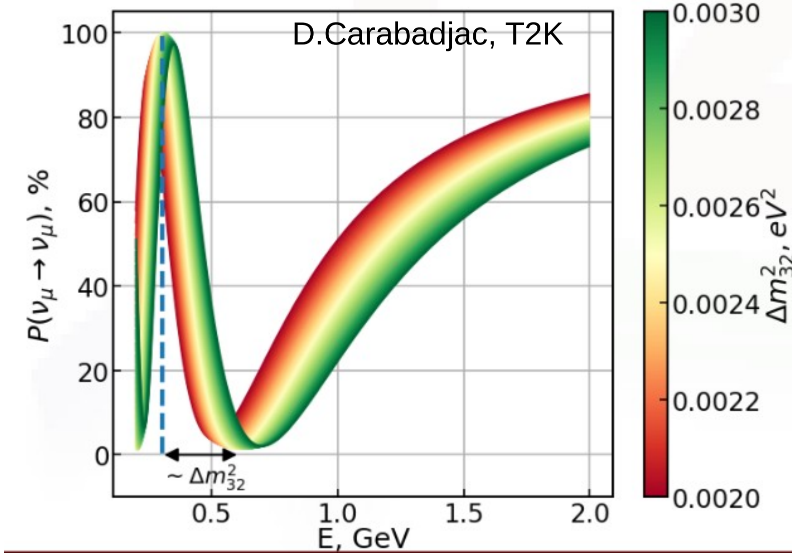
- **Oscillation probability estimated** by comparing ν (and $\bar{\nu}$) rate by flavor between source (near detectors) and far detectors:





Atmospheric parameters: ν_μ disapp

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



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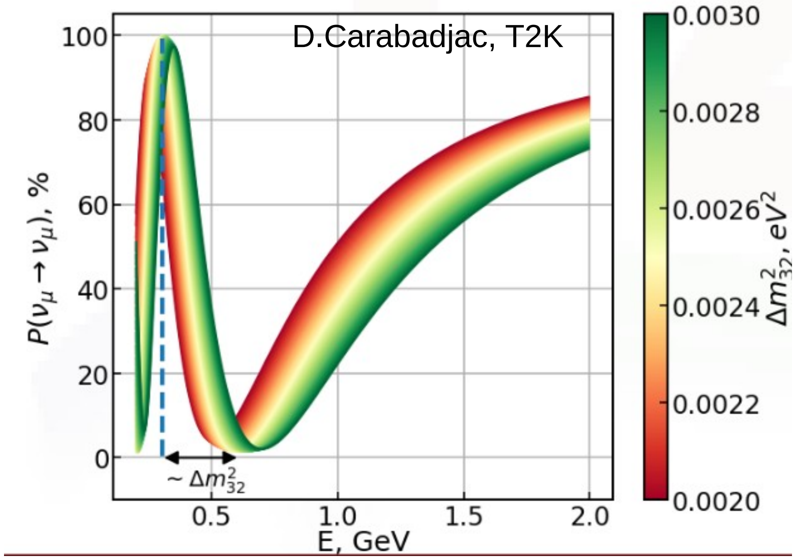

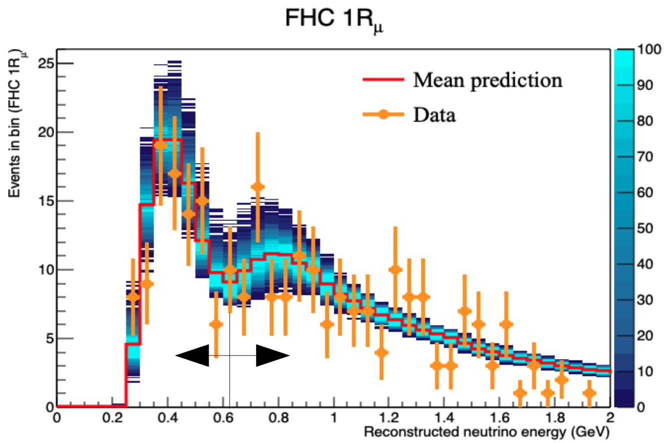

- Precise measurement of neutrino energy event by event is crucial: good resolution on neutrino energy reconstruction + avoid bias in energy scale

Precision at few % level (→ few MeV)

Atmospheric parameters: ν_μ disapp

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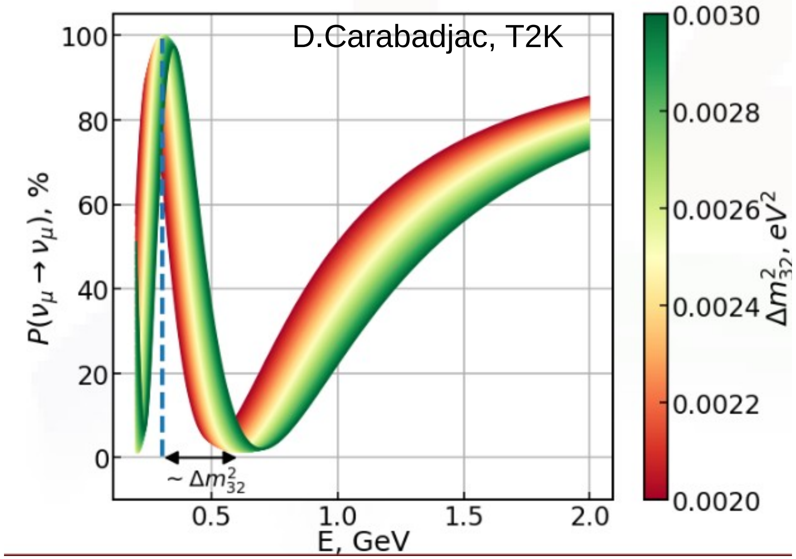
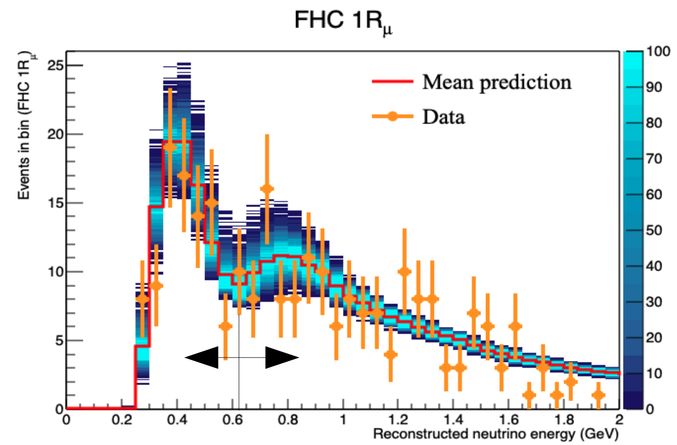
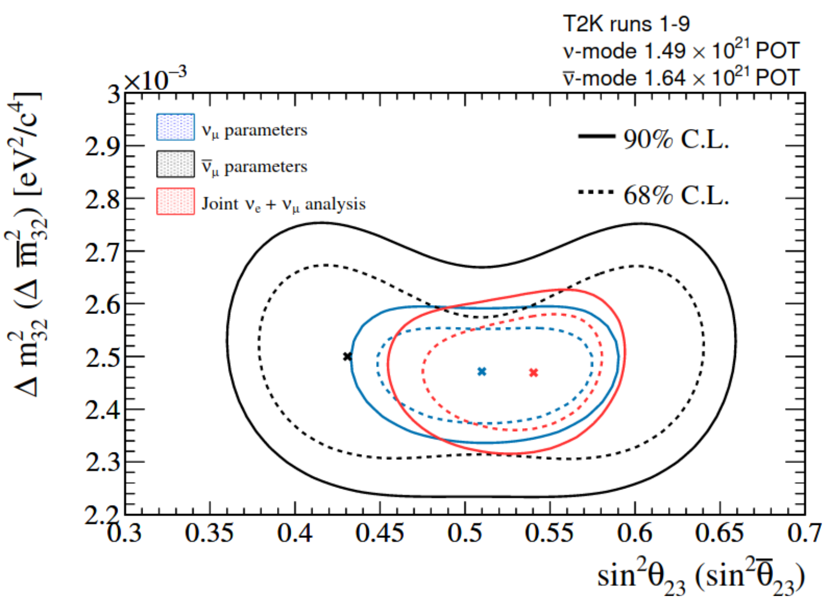




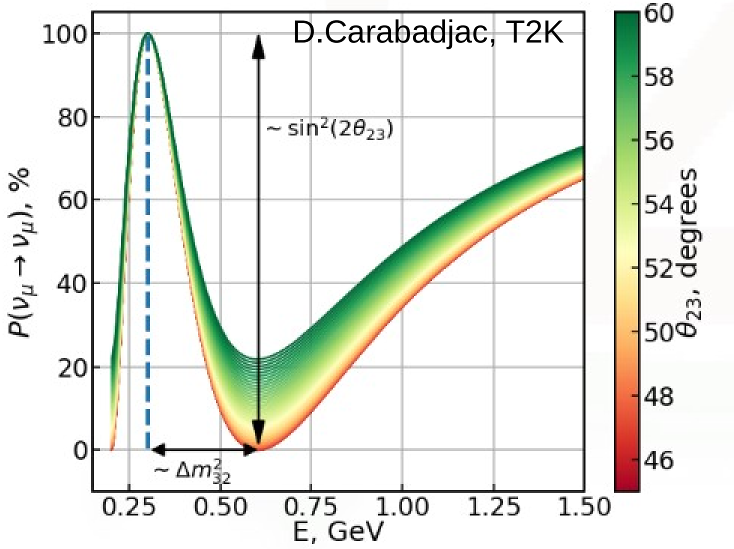
- Precise measurement of neutrino energy event by event is crucial: good resolution on neutrino energy reconstruction + avoid bias in energy scale
Precision at few % level (→ few MeV)

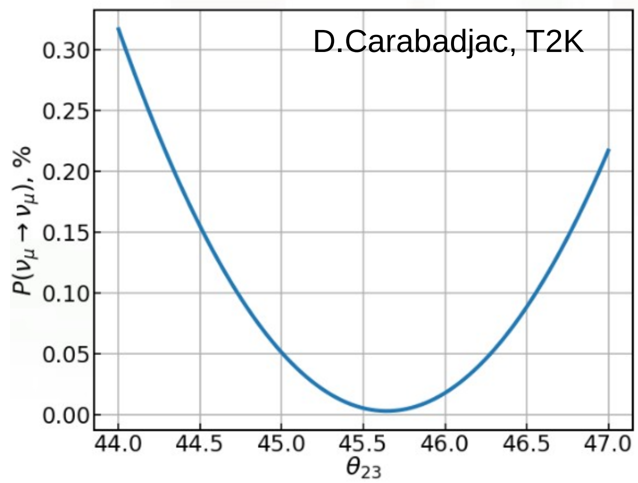
- Correlated effects in ν and $\bar{\nu}$
(assuming CPT invariance)

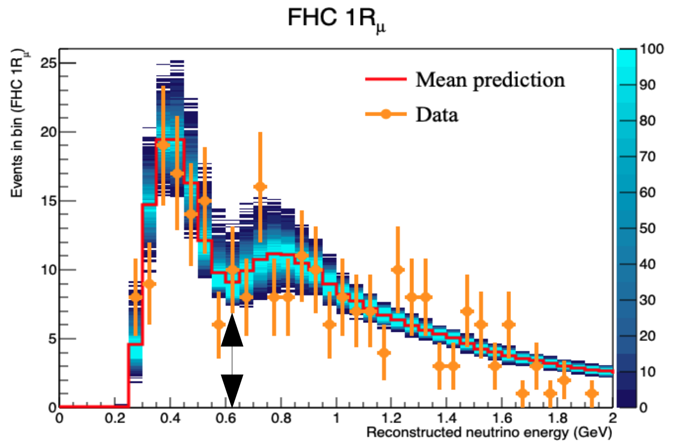


Atmospheric parameters: ν_μ disapp

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



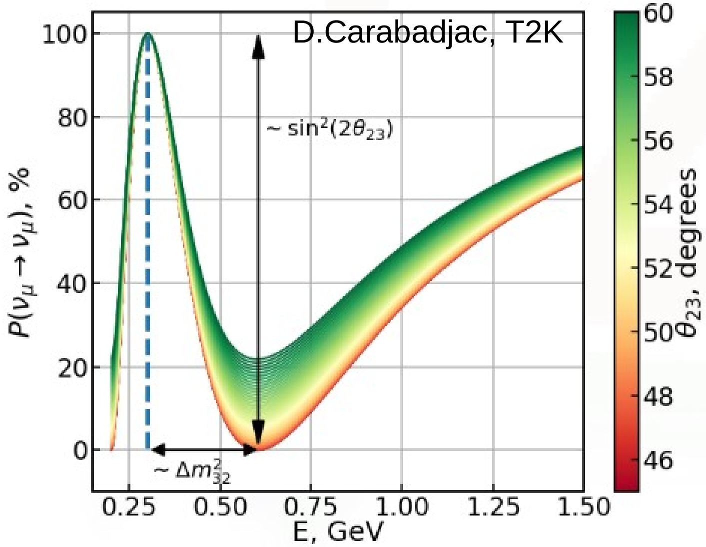


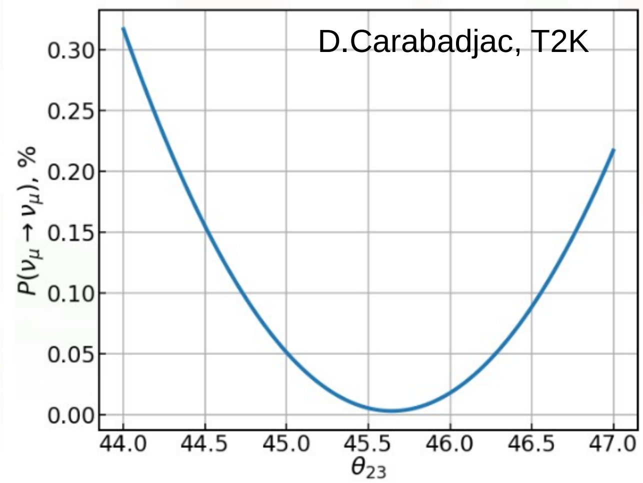


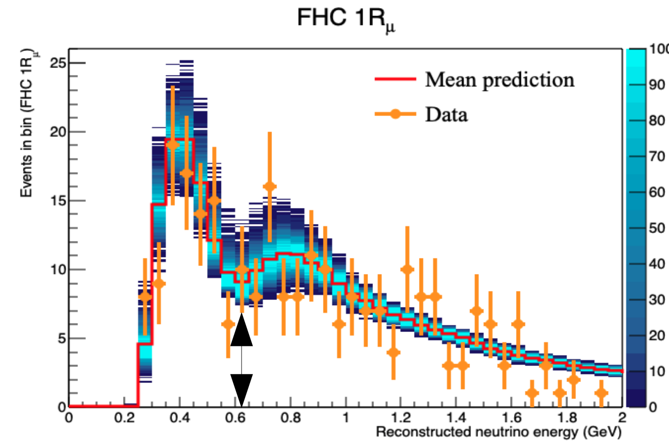
- Measurement proportional to number of observed muon neutrino at oscillation maximum
→ need control of ν_μ overall normalization at few %
(again correlated between ν and $\bar{\nu}$)

Atmospheric parameters: ν_μ disapp

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



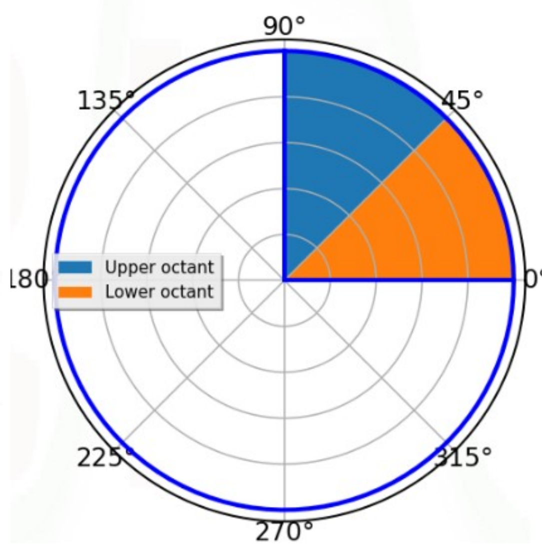




- Measurement proportional to number of observed muon neutrino at oscillation maximum
→ need control of ν_μ overall normalization at few %
(again correlated between ν and $\bar{\nu}$)

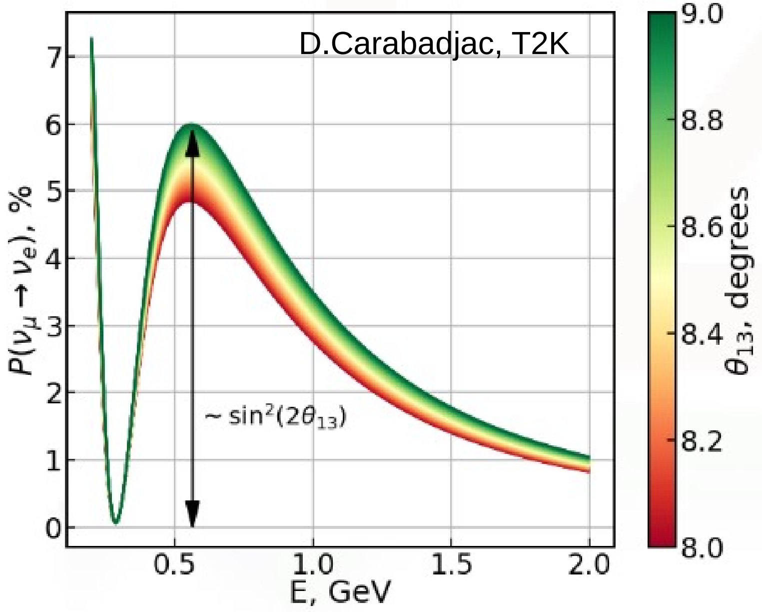
- Maximal mixing θ_{23}~π/4 would be a very interesting symmetry.
Away from that, octant degeneracy due to quadratic dependence on $\sin^2 2\theta$

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



ν_e appearance

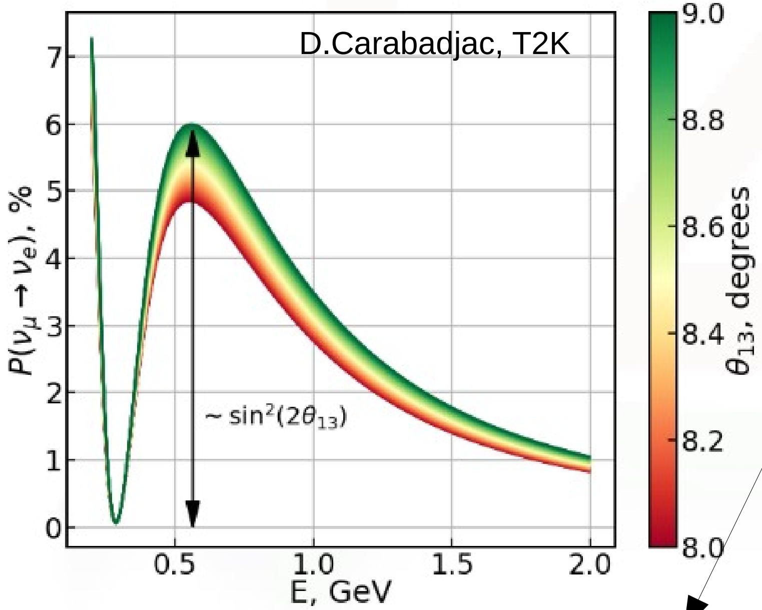
$$P(\nu_\mu \to \nu_e) \approx \boxed{\sin^2 2\theta_{13}} \sin^2\theta_{23} \sin^2 \frac{\Delta m^2_{32} L}{4E}$$



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

ν_e appearance

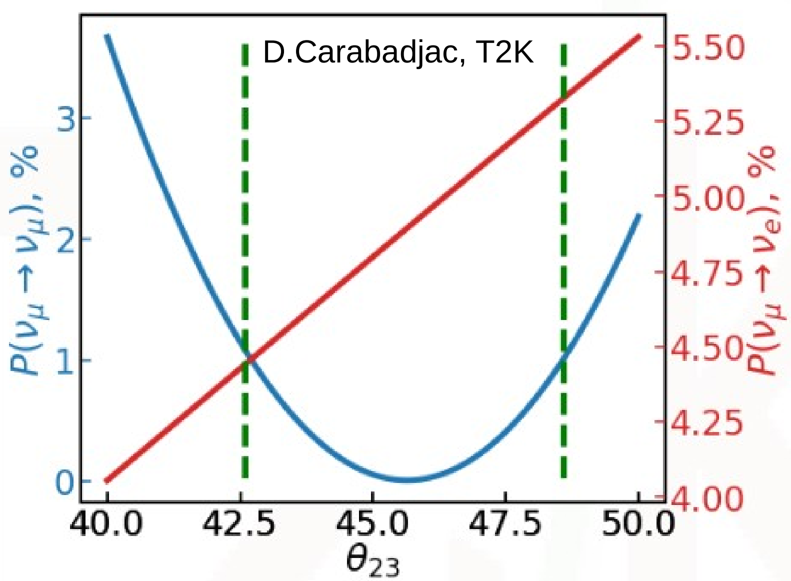
$$P(\nu_\mu \rightarrow \nu_e) \approx \boxed{\sin^2 2\theta_{13}} \boxed{\sin^2 \theta_{23}} \sin^2 \frac{\Delta m^2_{32} L}{4E}$$



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

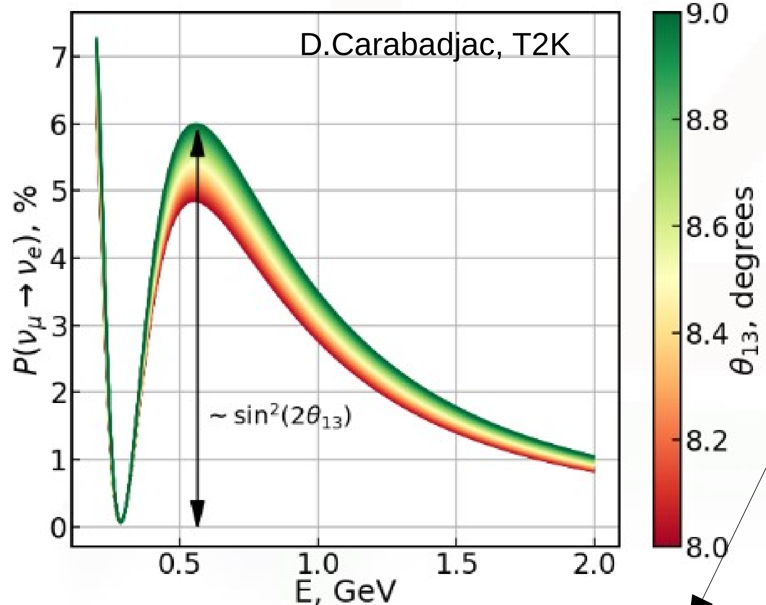
- sensitivity to θ_{23}

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



ν_e appearance

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

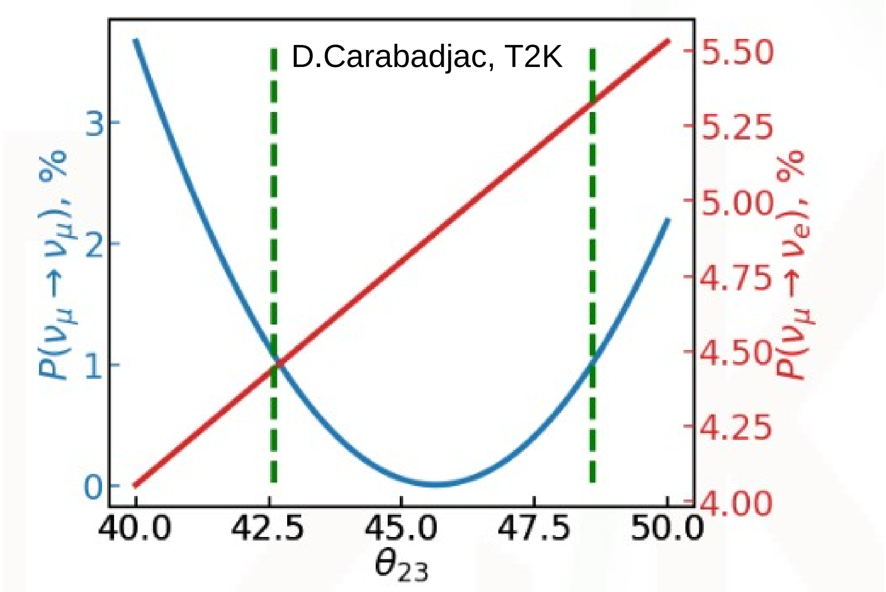


- **θ_{13}** well measured by reactor experiments (~1.5%)

- sensitivity to **θ_{23}**

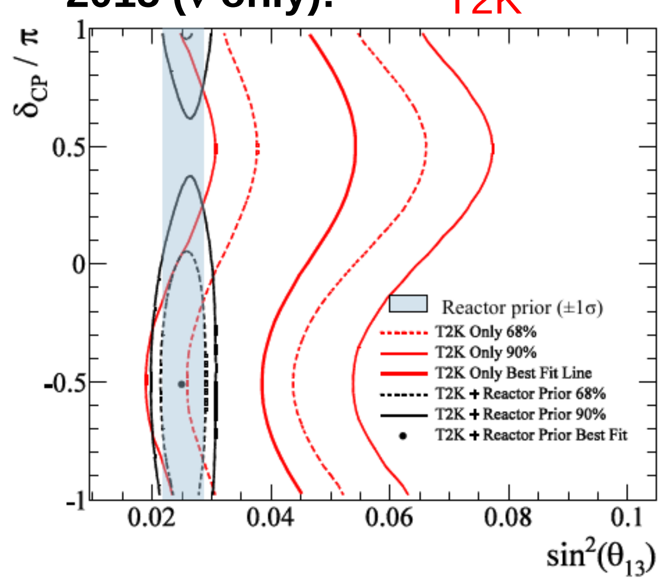
→ break degeneracy on θ_{23} octant (~1% effect)

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



2015 (ν only): T2K

T2K+ θ_{13} from reactors

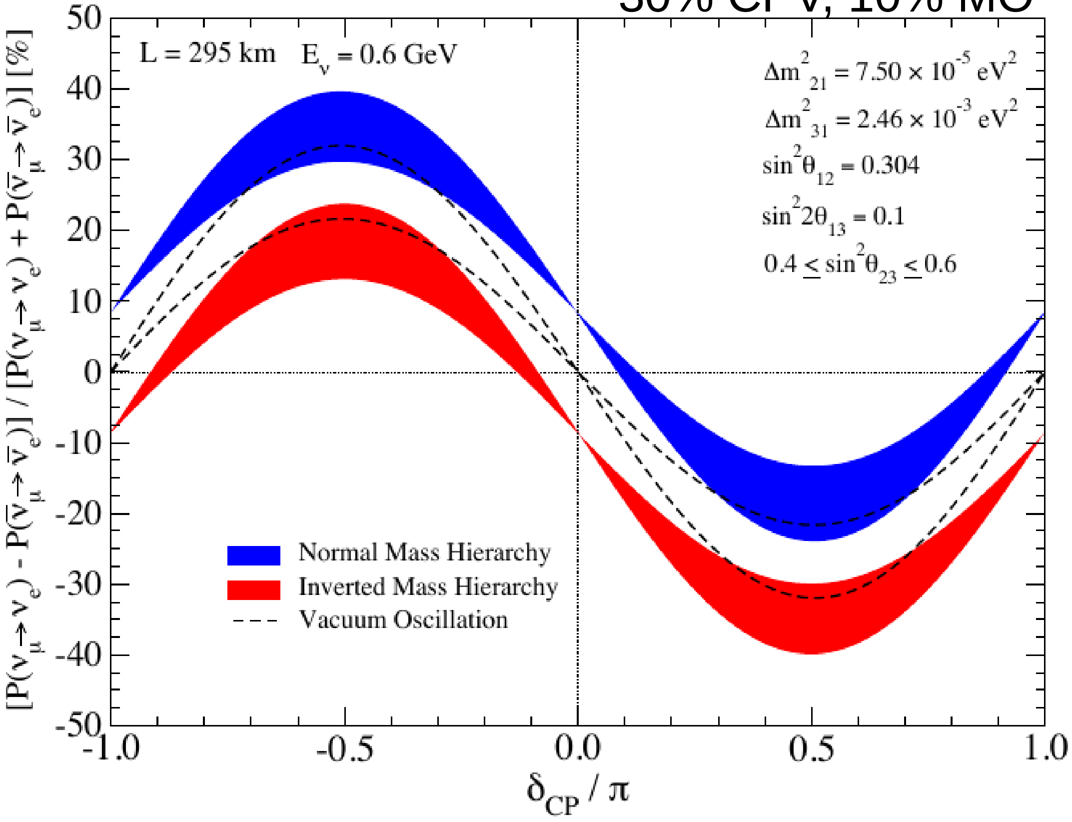


$\nu_e/\overline{\nu}_e$ appearance: δ_{CP} and MH

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

T2K baseline and energy

~30% CPV, 10% MO



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

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

- ν_e also makes charged current interactions (W+-) with electrons in matter
→ additional potential in matter of opposite sign for $\nu_e/\overline{\nu}_e$

$$A = \pm 2\sqrt{2} G_F N_e E\,,$$

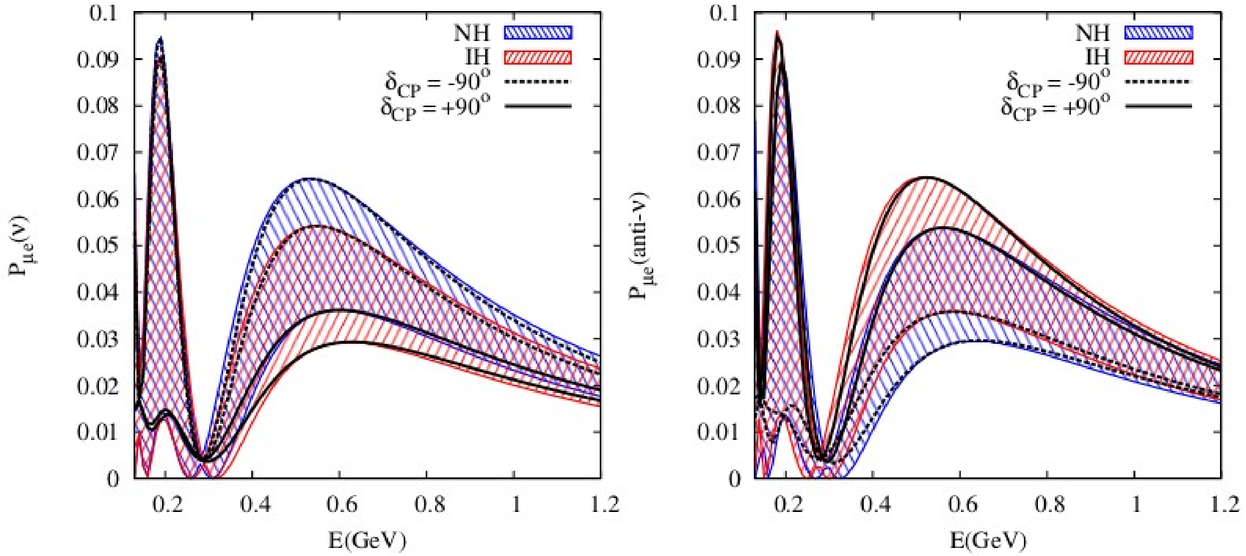
- larger neutrino energy and longer baseline → larger the matter effect
(Earth crust~constant density and at LBL below MSW effect)

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

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

Adv.High Energy Phys. 2014 (2014) 457803

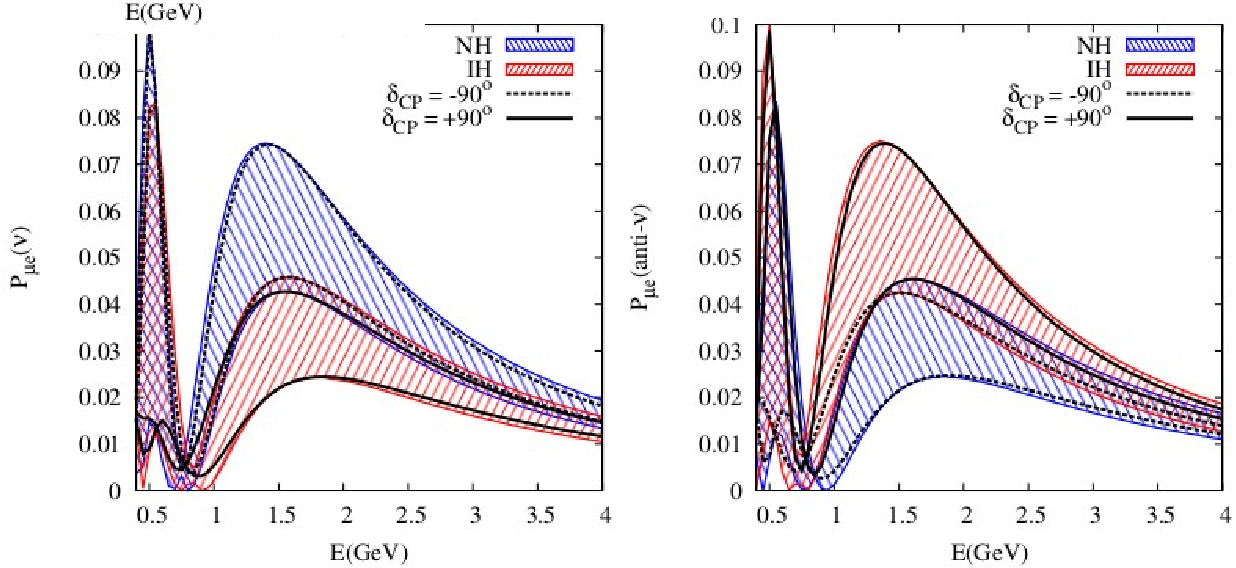
$\sin^2 2\theta_{13} = 0.089,\ \sin^2\theta_{23} = 0.5$



L=295km
(T2K)

L=810km
(NOVA)

30% CPV,
30% MH
(degeneracy)



From CPV discovery to δ_{CP} measurement

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

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

Actually at second order:

$P_{apperarance} \sim +/- A \sin\delta + B\cos\delta + ...$

detailed formula →

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

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

From CPV discovery to δ_{CP} measurement

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

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

Actually at second order:

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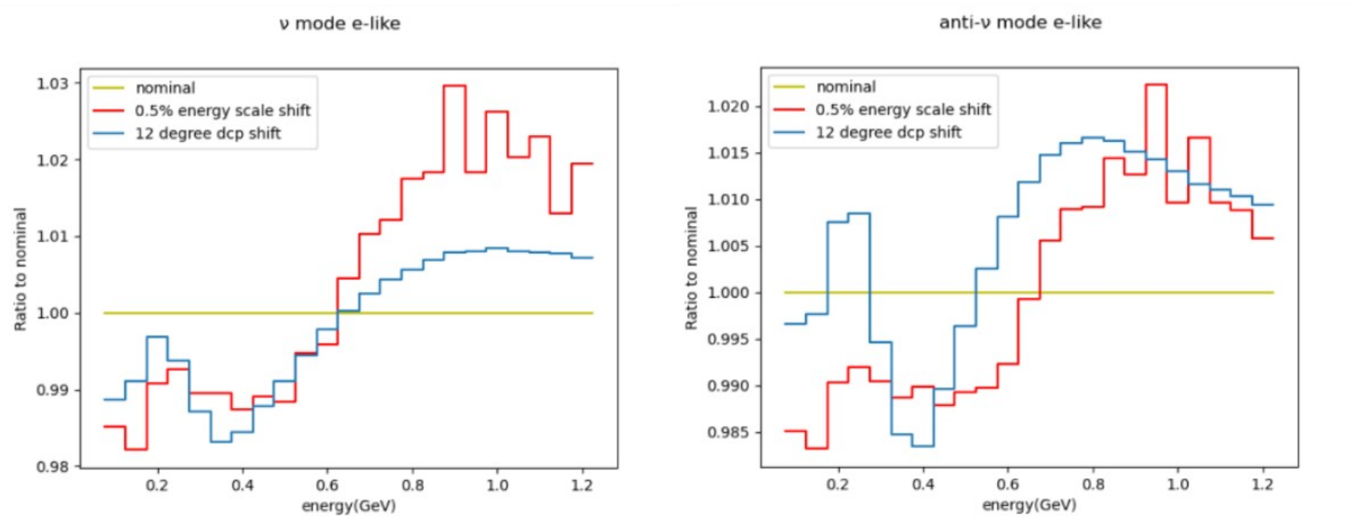
detailed formula →

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

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

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

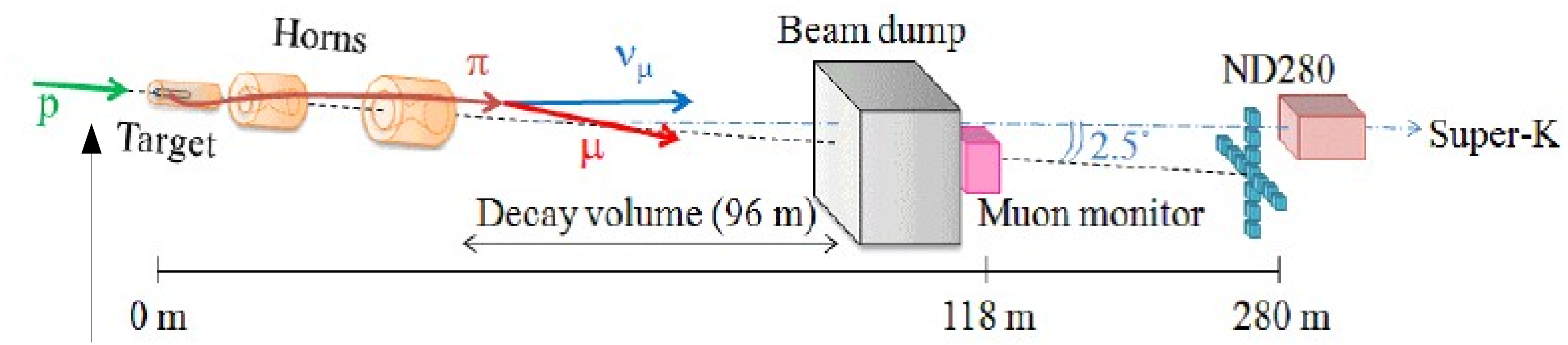


Neutrino oscillations in long-baseline experiments: how do we measure them?

Neutrino ‘beam’

Very complete reference (2006) arXiv:physics/0609129

Beam: protons → pions



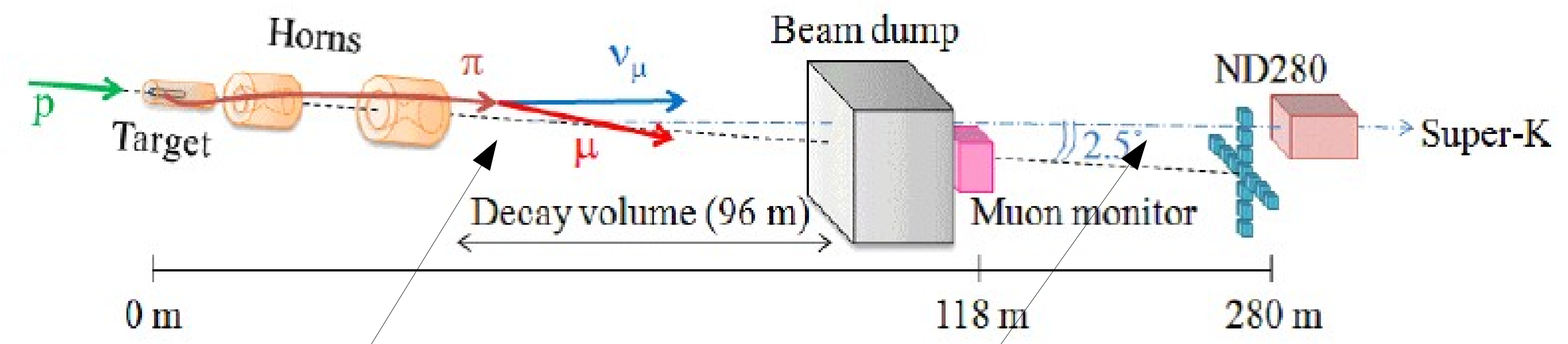
- Proton beam:
30 GeV JPARC, 120 GeV NuMi FNAL → 500 kW and above (next generation 1-2MW)

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

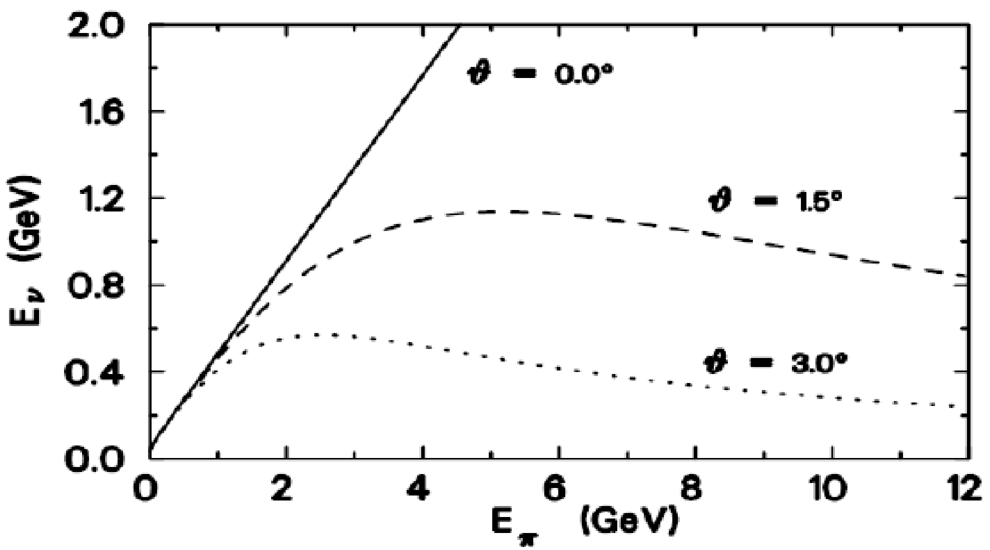
- Horns to focus all pions (kaons) of the right sign

  - $\pi^+ \to \mu^+ \nu_\mu$ Forward Horn Current (FHC) → ν_μ flux
  - $\pi^- \to \mu^- \bar{\nu}_\mu$ Reverse Horn Current (RHC) → $\bar{\nu}_\mu$ flux

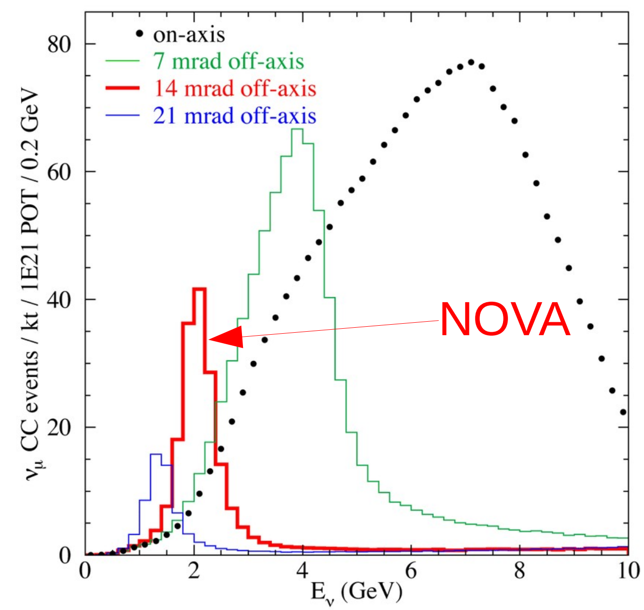
Beam: off-axis



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

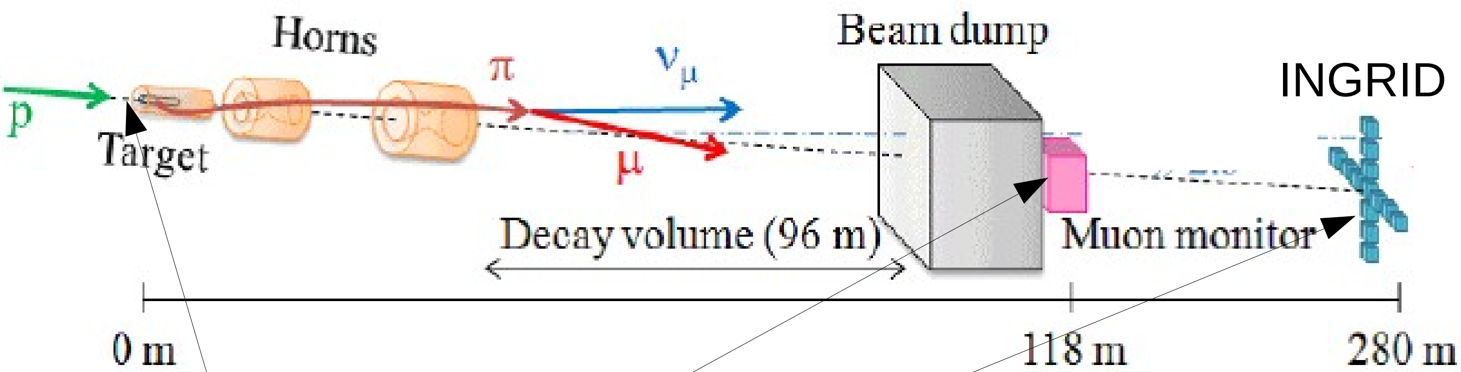


Tune the angle → tune the energy to be at the peak of ν_μ disappearance (~E/L)

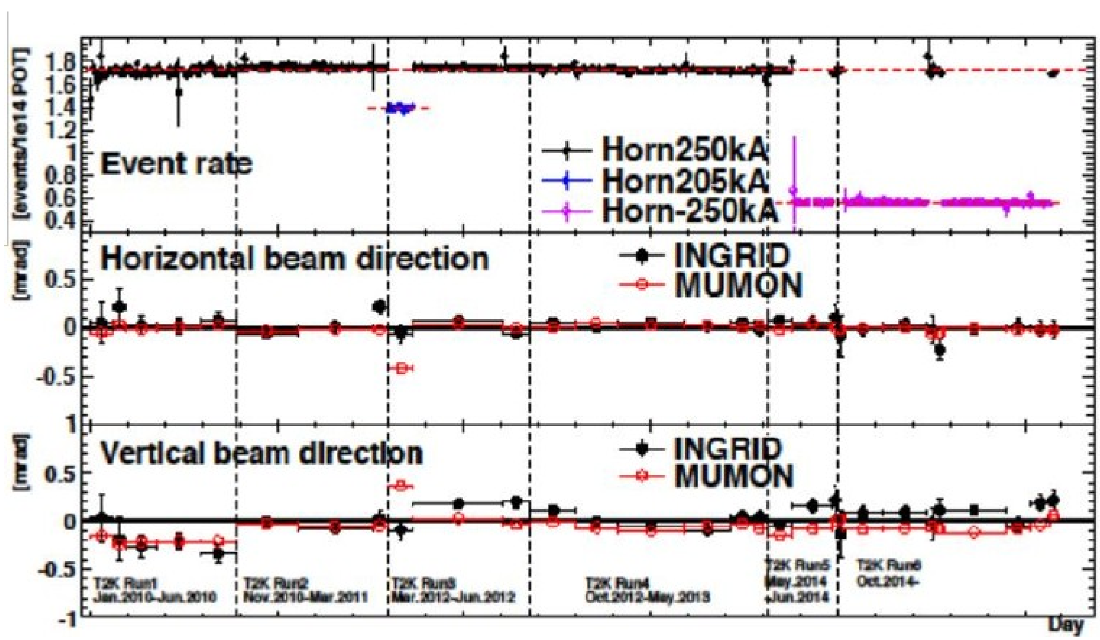


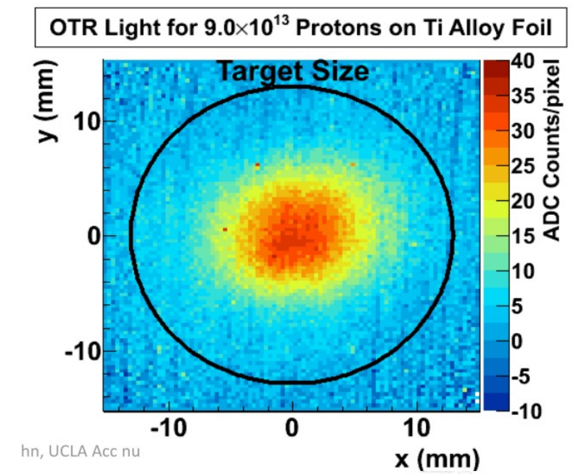
Beam: monitoring

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



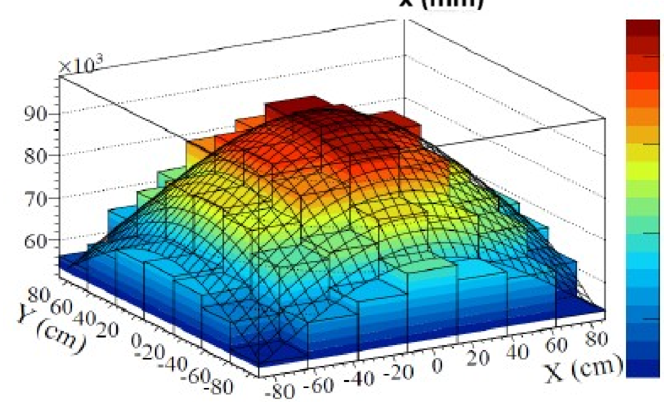
- looking at **protons**
- looking at **muons**
- looking at **neutrinos**



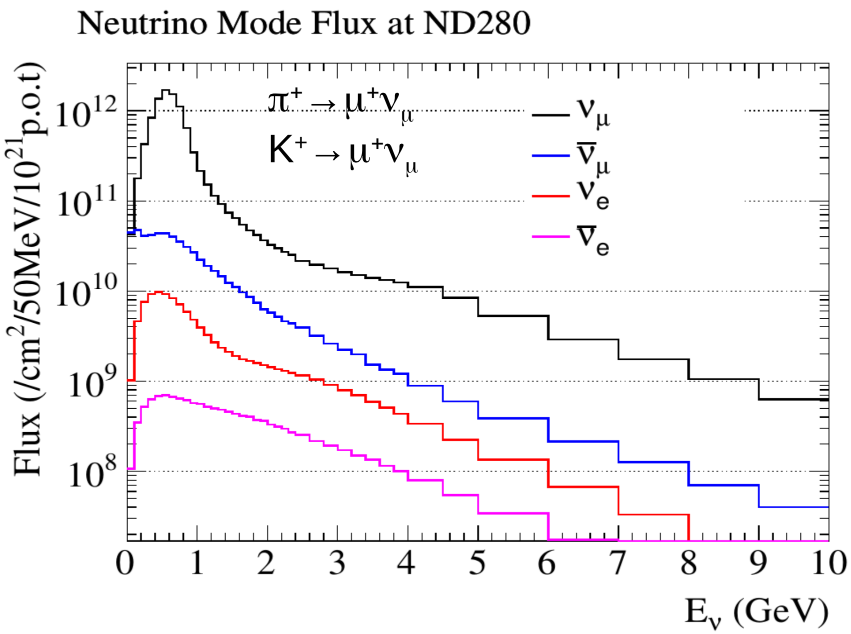


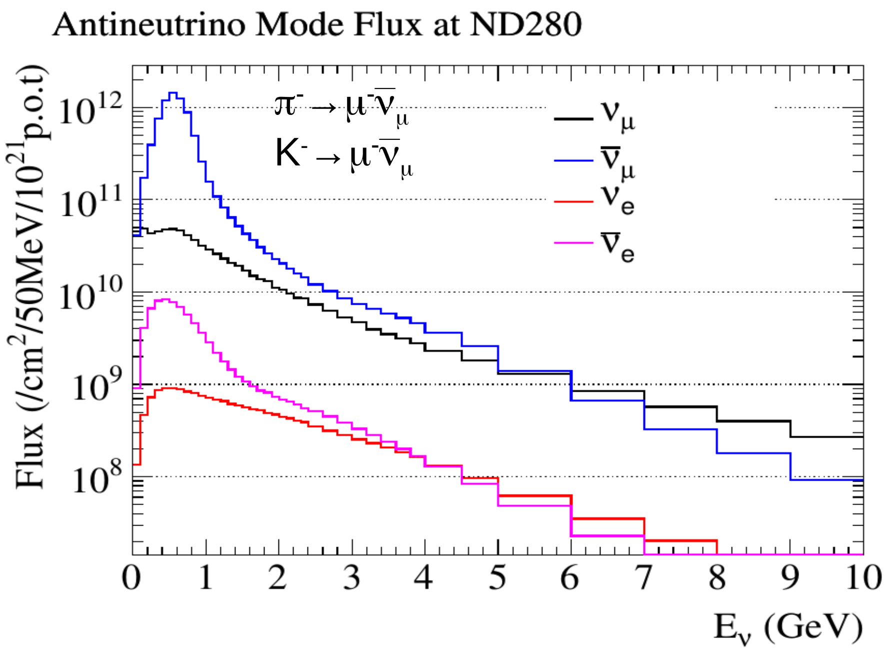
Protons

Muons



Flux

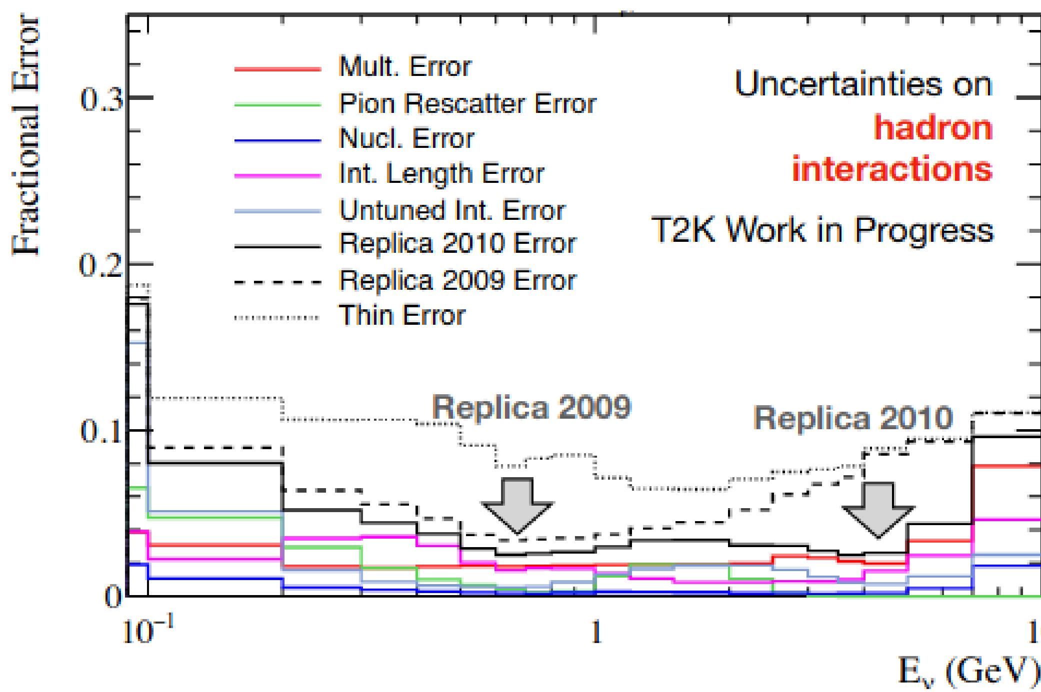




- ν_e intrinsic background
- Wrong sign background (ν in $\bar{\nu}$ beam)

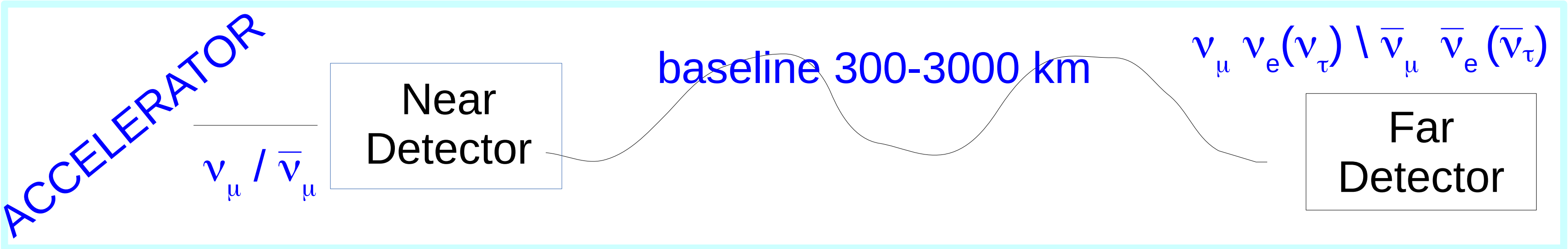
- Flux tuning with hadroproduction measurements at dedicated experiments.

Example from NA61 with replica-target of T2K



From near to far detector

Oscillation analysis: the basics



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

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

Number of neutrinos at the Near detector (ND)

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

Dependence on neutrino energy

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

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

→ 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

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

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

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

Flux and cross-section

- So the oscillation probability becomes:

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

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

measured number of neutrino interactions at the ND

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

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

- But the most complicated part is :

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

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

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

The difficult part ...

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

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

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

Present status of oscillation parameters

Status of PMNS measurements: joint fits

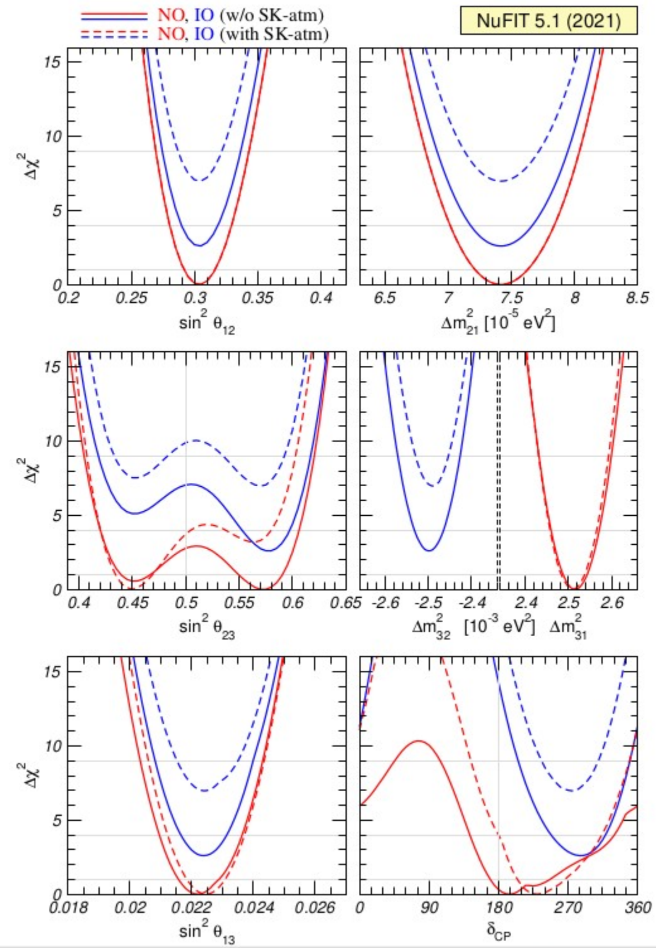
Recent reference with full details:

Three flavour oscillation parameters

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

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

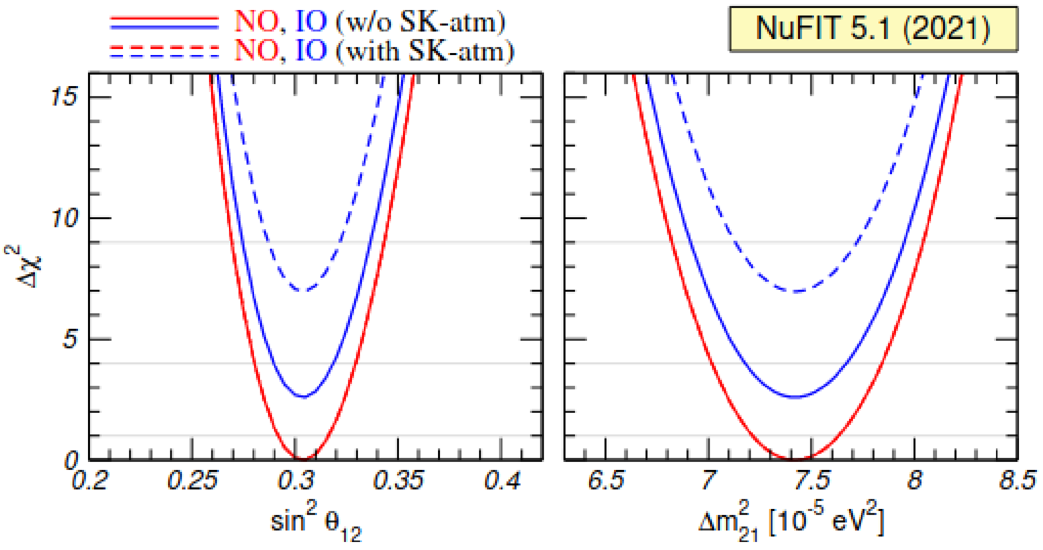
		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 7.0$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
with SK atmospheric data	$\sin^2\theta_{12}$	$0.304^{+0.012}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$
	$\theta_{12}/^\circ$	$33.45^{+0.77}_{-0.75}$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



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

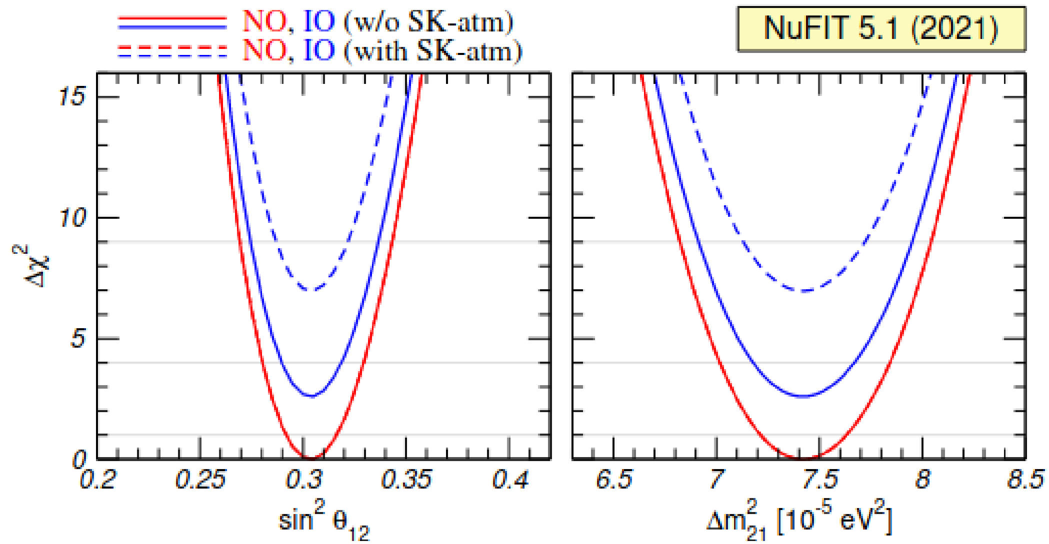
4 Th. Schwetz - Neutrino 2022 — 1. 6. 2022

Status of PMNS measurements: joint fits



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

Status of PMNS measurements: joint fits



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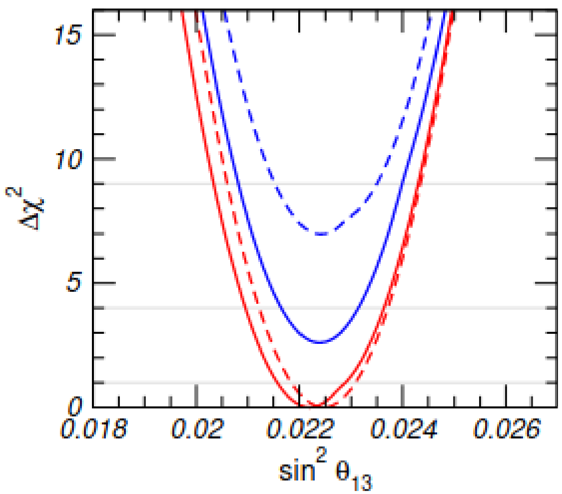
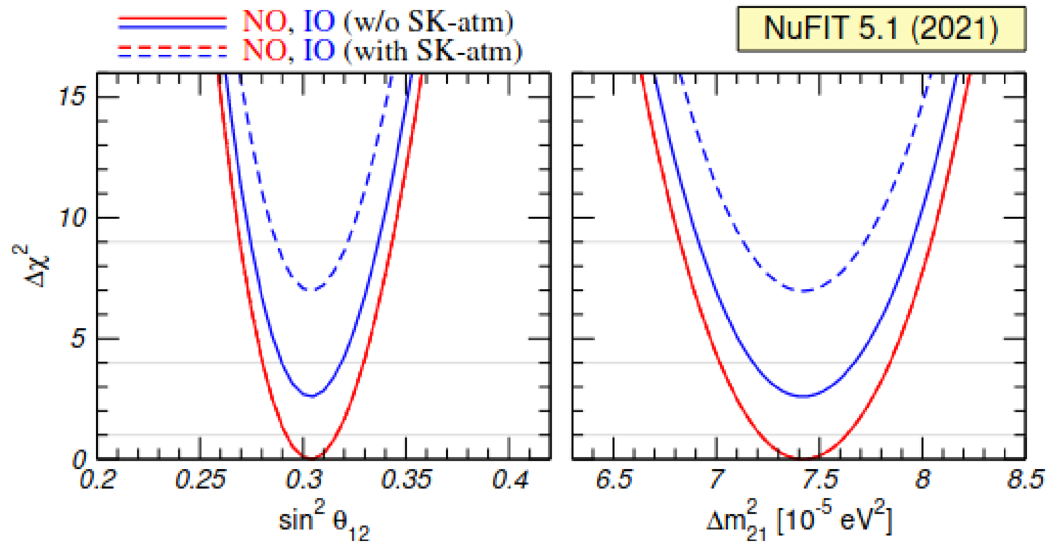


θ_{13} measured with reactor experiments at ~1% precision

Status of PMNS measurements: joint fits



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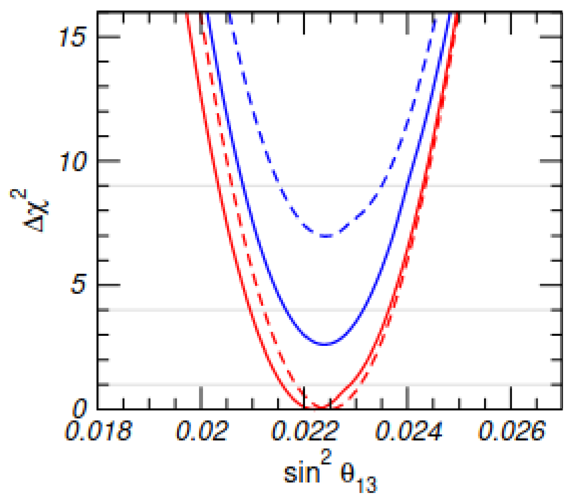
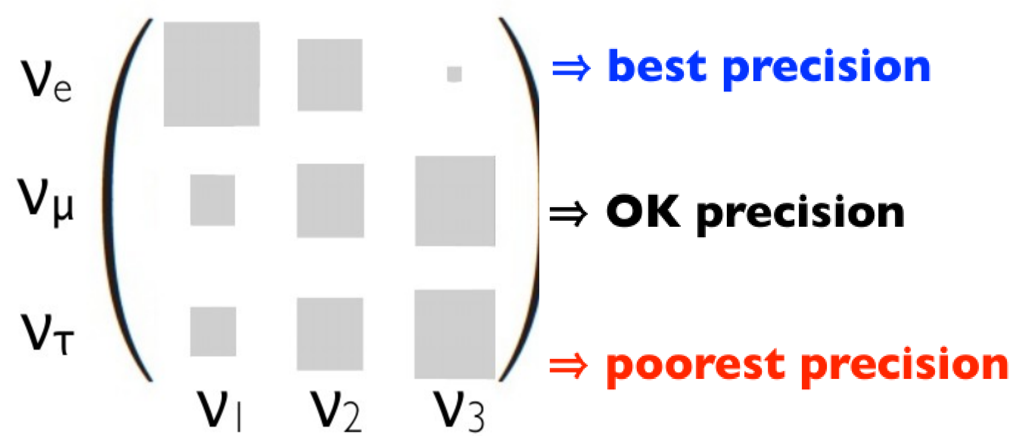


θ_{13} measured with reactor experiments at ~1% precision

Best avenue for PMNS unitarity test:

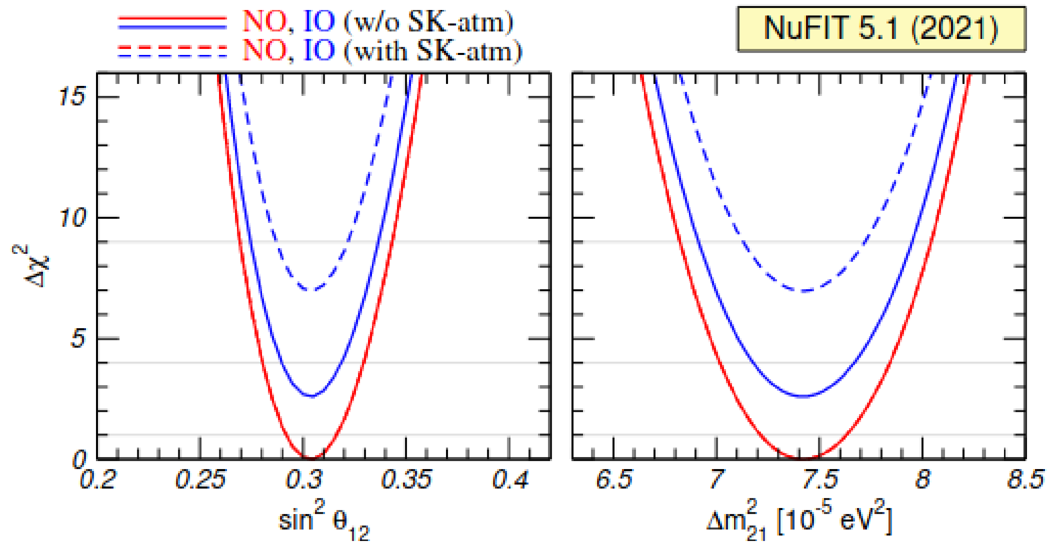


Exploring unitarity from different rows

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

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

Status of PMNS measurements: joint fits



Solar parameters: θ_{12}, Δm^2_{21} known with **~few% precision** since KamLAND (no recent updates)
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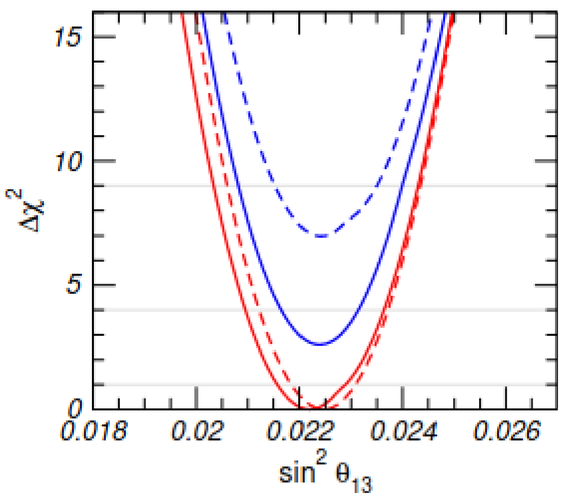
Atmospheric parameters:
- **θ_{23} ~few%** precision @1σ (improved by a factor of 2 in the last 10 years) but **~25%** precision @3σ: octant degeneracy, need high stat ν_e appearance



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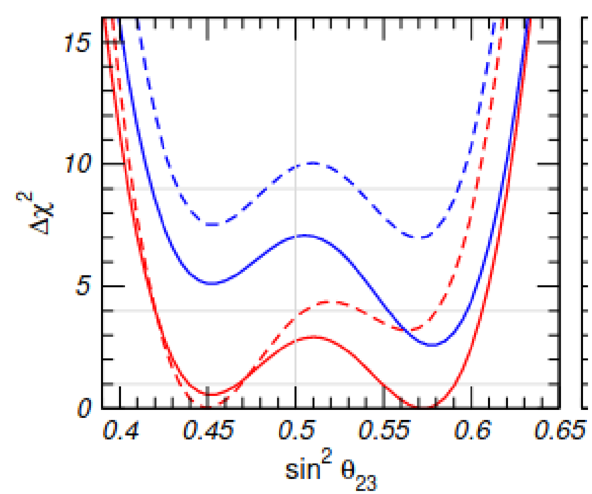

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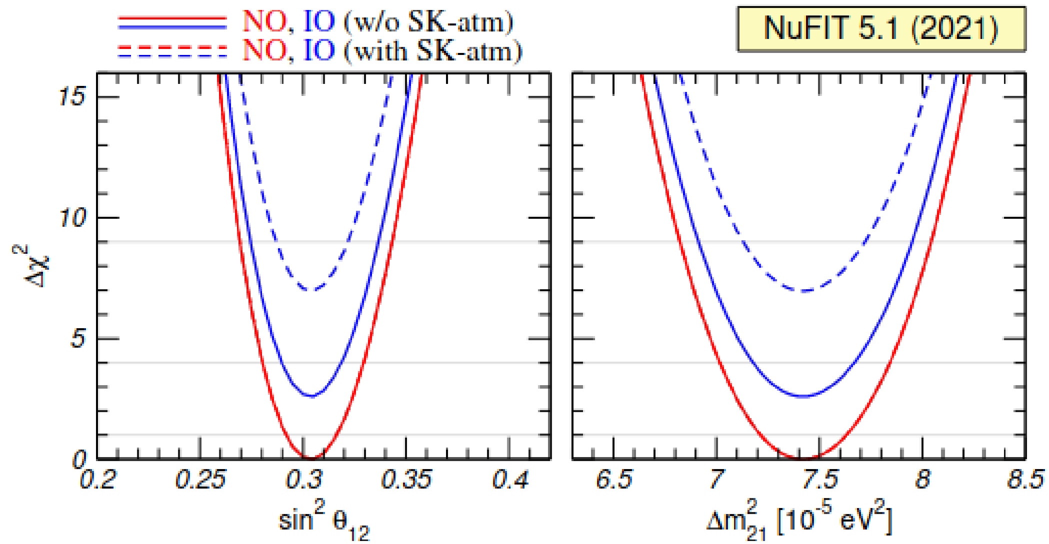

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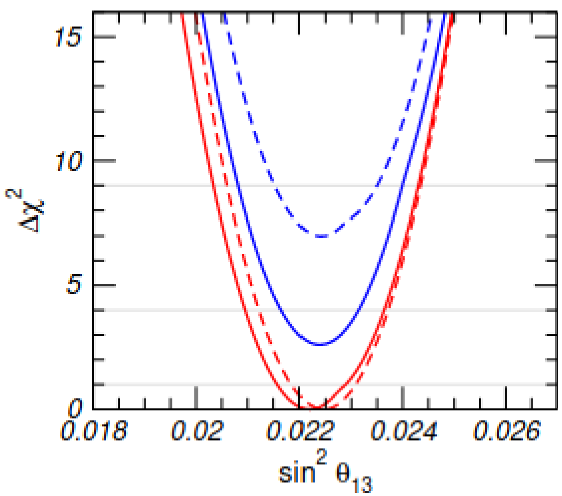
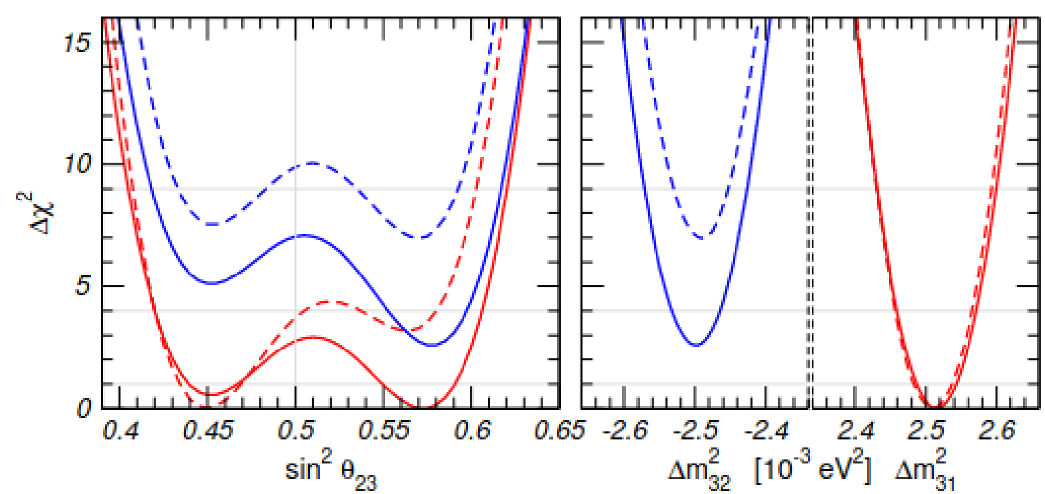


θ_{13} measured with reactor experiments at ~1% precision

Atmospheric parameters:

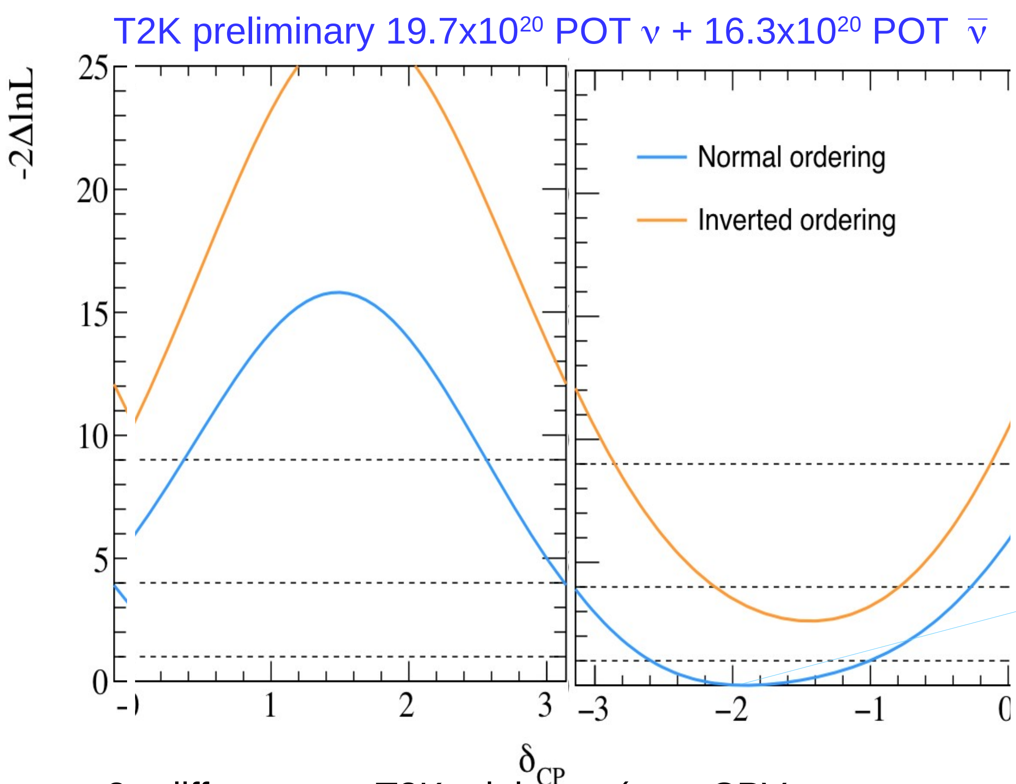
- **θ_{23} ~few%** precision @1σ (improved by a factor of 2 in the last 10 years) but **~25%** precision @3σ: octant degeneracy, need high stat ν_e appearance

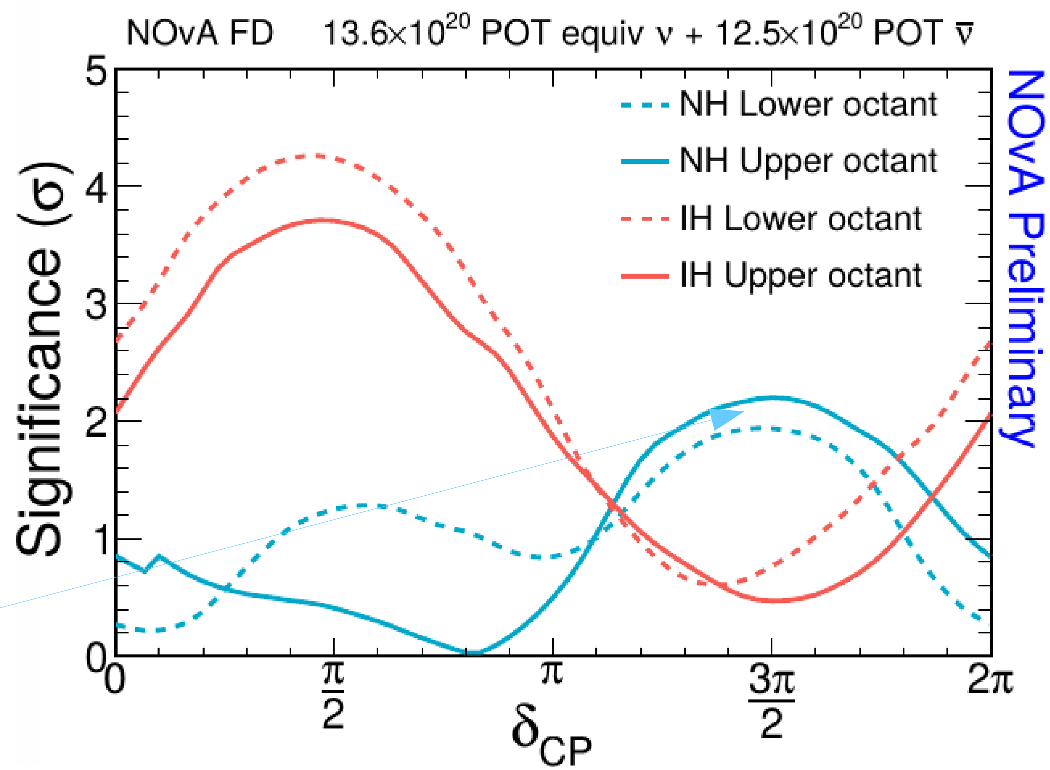
- **$|\Delta m^2_{31(32)}|$ ~1%** (not so robust...) → important to get <1% (see later) challenging to control systematics uncertainties



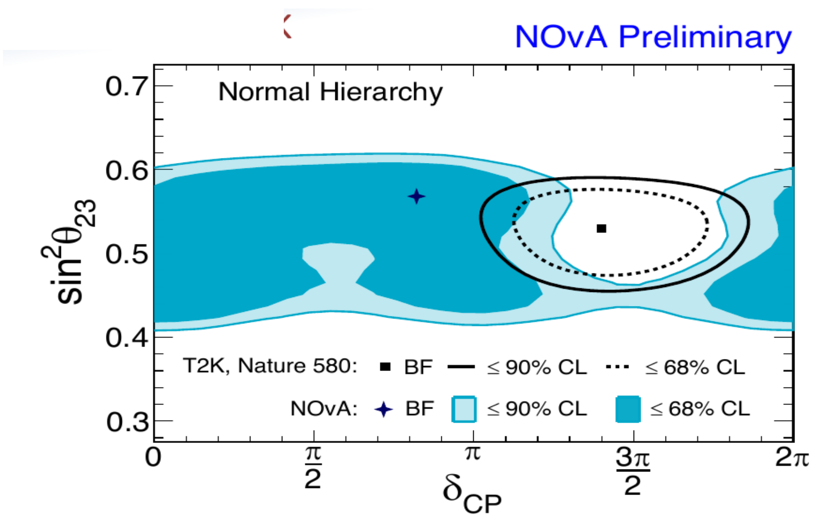
δ_{CP}

Using 2020 results (2022 results in next talks!)



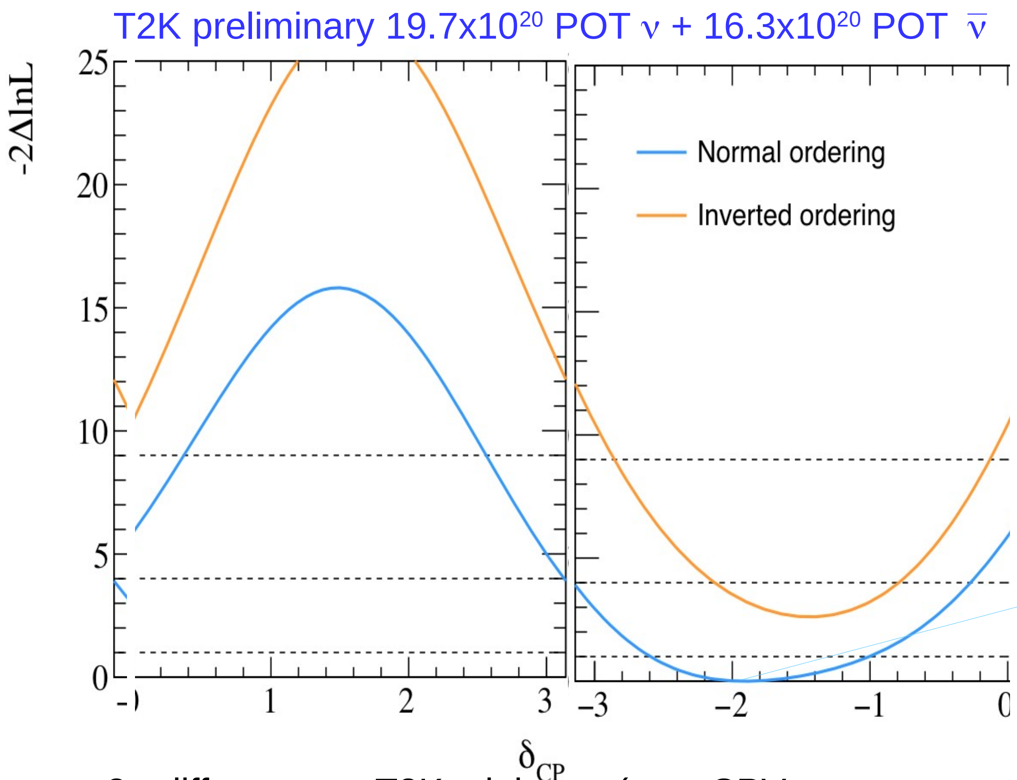


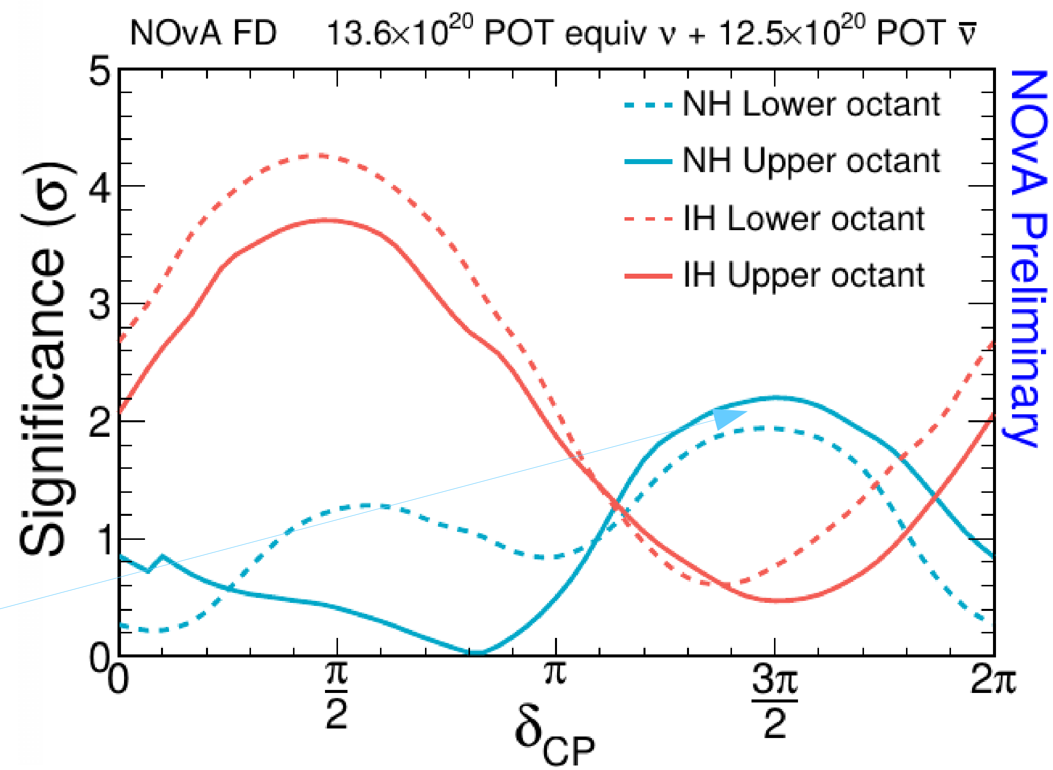
2σ difference at T2K minimum (max CPV, NH) but still common regions at 1σ



δ_{CP}

Using 2020 results
(2022 results in next talks!)





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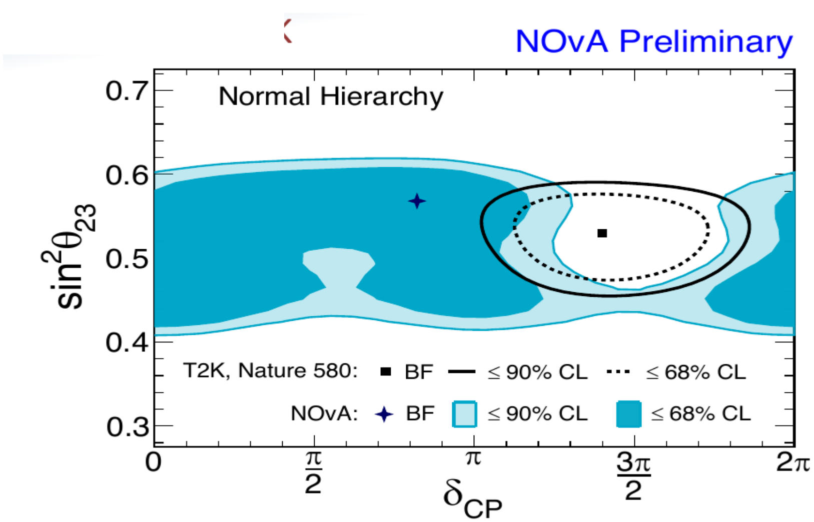
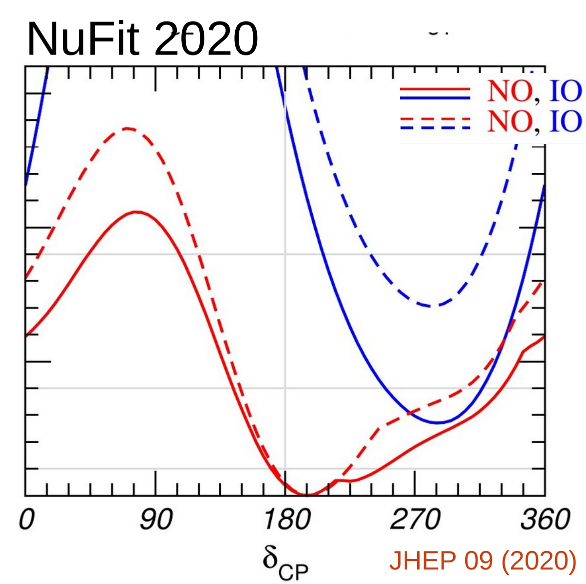


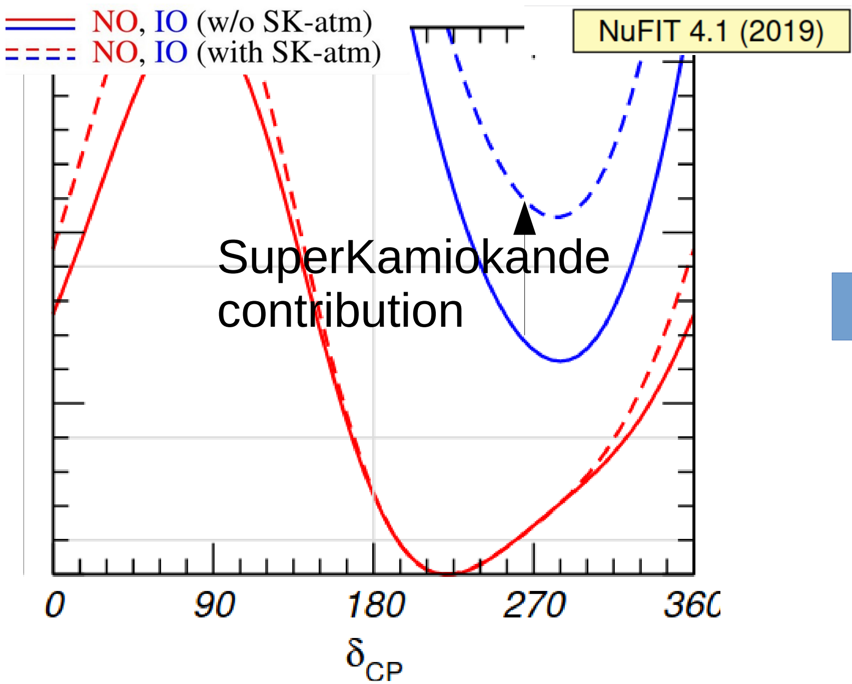


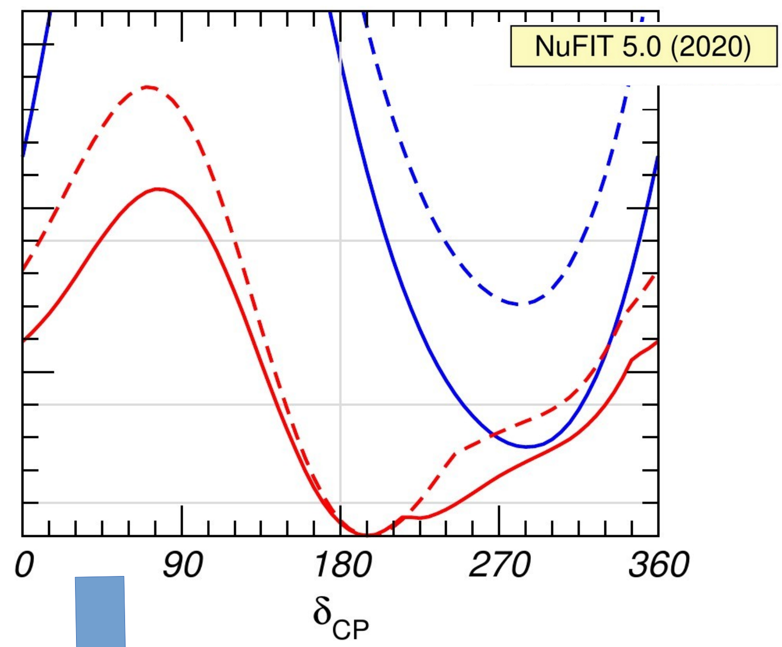
JHEP 09 (2020) 178 [arXiv:2007.14792]

Agreement in IO gives a penalty to NO

In NO shift on δ_{CP} favoured value

Mass Hierarchy: 2019 → 2022



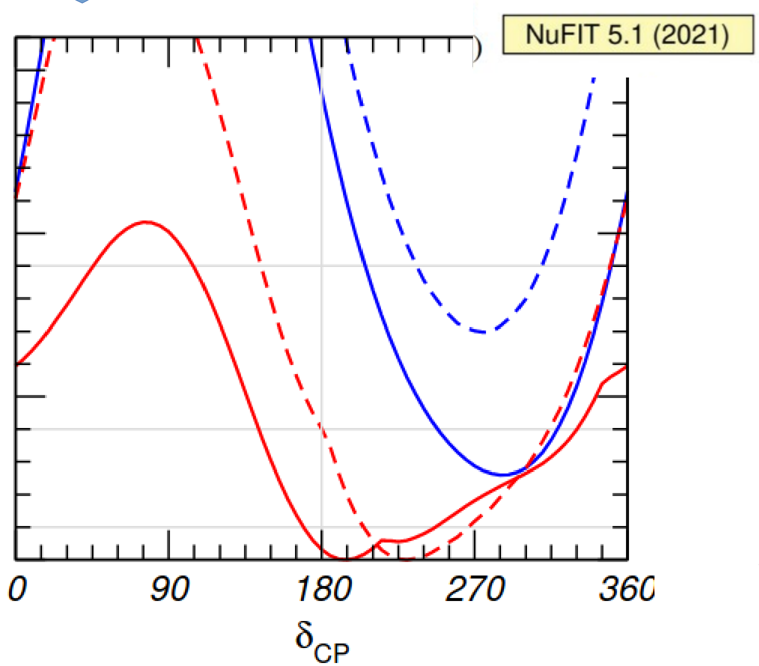


- **MO sensitivity dominated by SuperKamioande**

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

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

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



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

→ CP conservation disfavoured at ~2σ

Summary

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

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

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

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

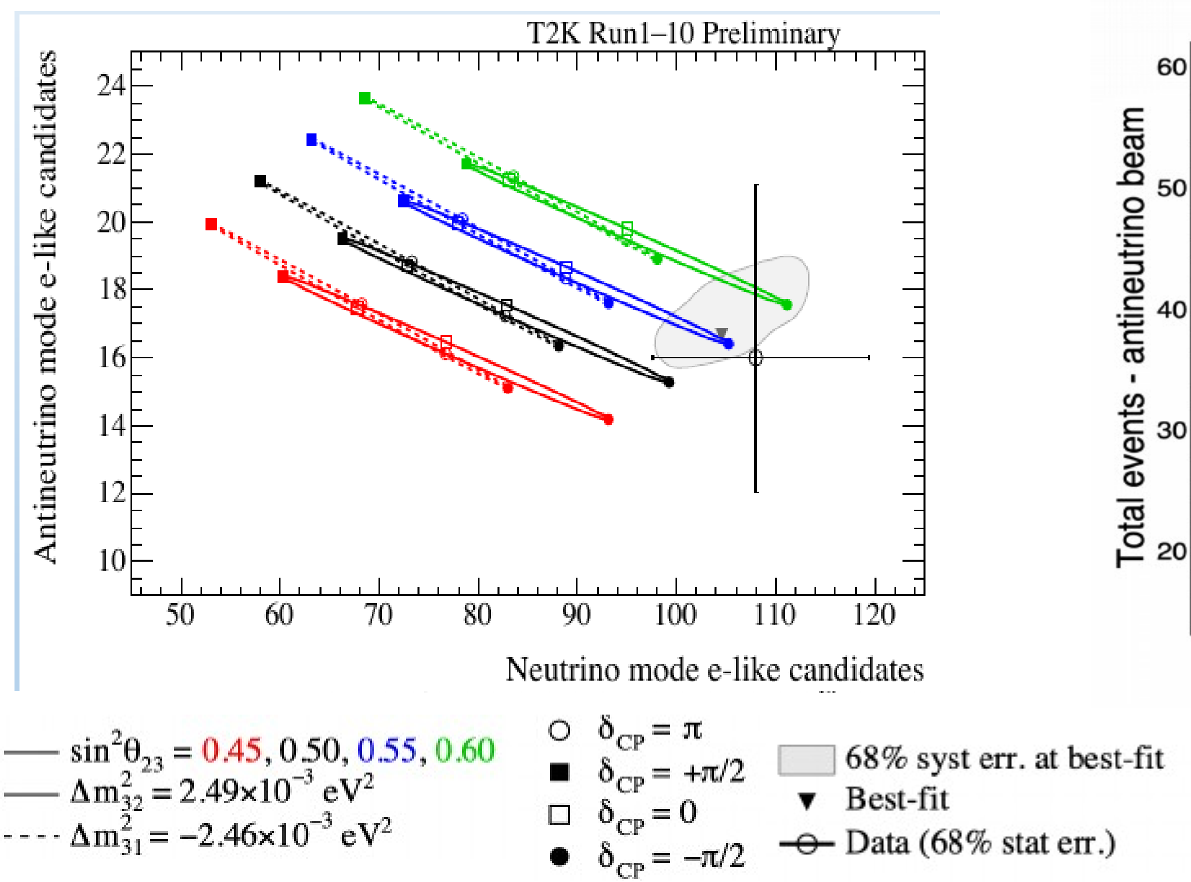
$\nu_e/\bar{\nu}_e$ apperance: MH, δ_{CP}

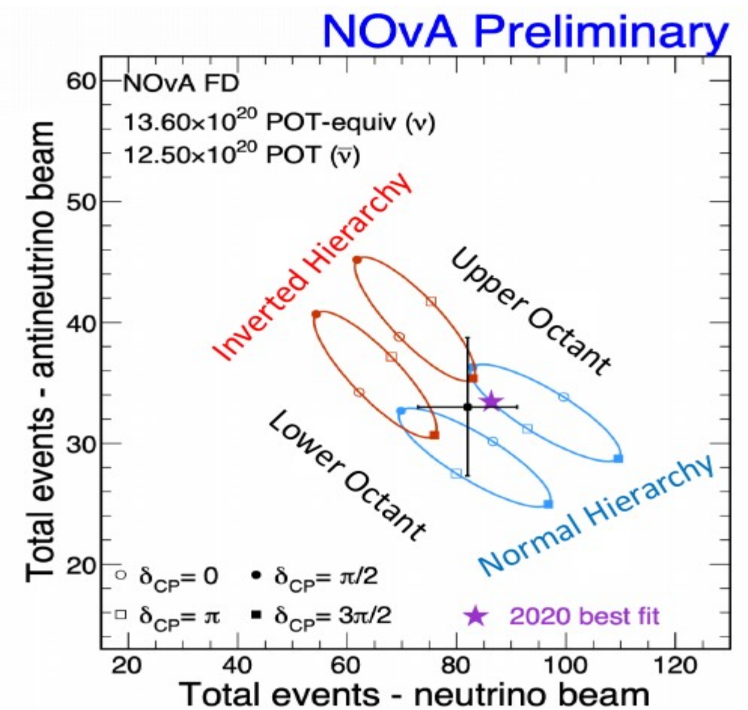
Experiment	CP asymmetry	Mass Hierarchy
T2K (T2HK)	~30%	~10%
Nova	~30%	~30%

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

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

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





A bit of (recent) history...

SuperKamiokande
1996 – today!

1998 Discovery of ν oscillation

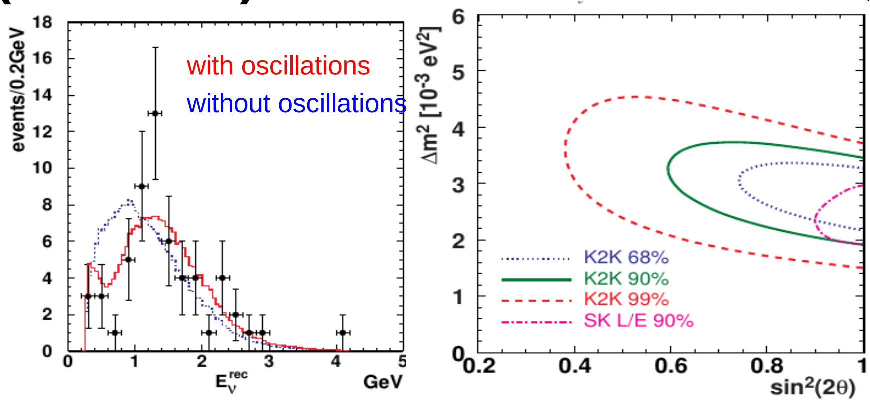
from zenith angle dependence of atmospheric ν_μ rate

Sudbury Neutrino Observatory (SNO)
1999 – 2006

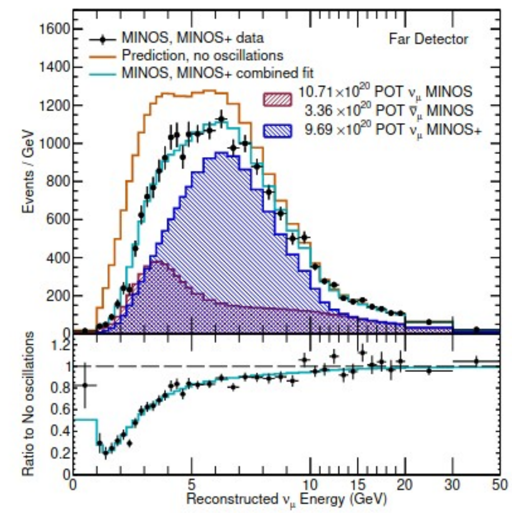
2001 Solution of solar puzzle: $\nu_e / \Sigma\nu_\alpha \sim 1/3$

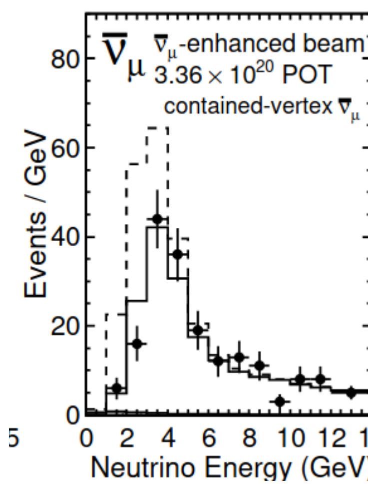
Precision from accelerator experiment: high purity and tunable neutrino flux

(1999-2006) K2K



2003 – 2015 MINOS (→ - 2016 MINOS+)





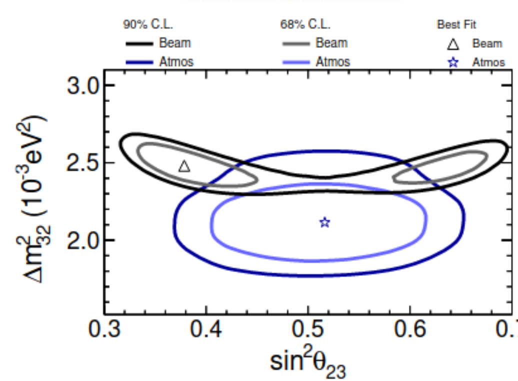
(2008-2012) OPERA : 5 $\nu_\mu \rightarrow \nu_\tau$ events obs.

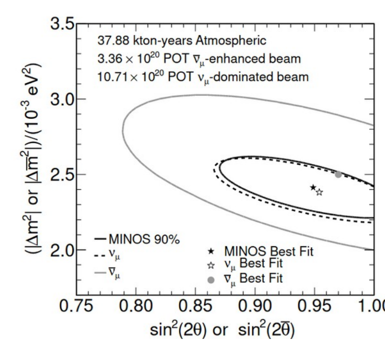
Beyond ν_μ disappearance (θ_{23} and Δm_{32}): large statistics experiments looking for ν_e appearance

→ observation of ν_e apperance
T2K (2010 - today)

→ to measure MH, longer baseline:
NOVA started 2014

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





ν_e appearance full formula

L.Kormos NuFact 2022

Appearance

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

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

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

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

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

ν vs. $\bar{\nu}$ sign change

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

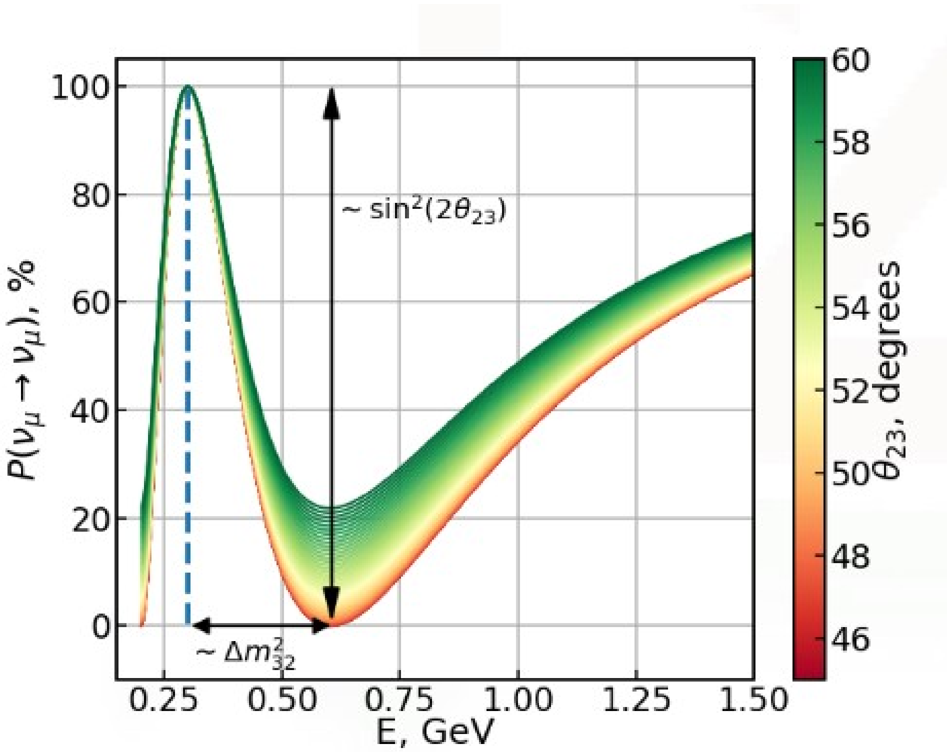
θ_{13} dependence — Octant sensitivity — CP-odd phase

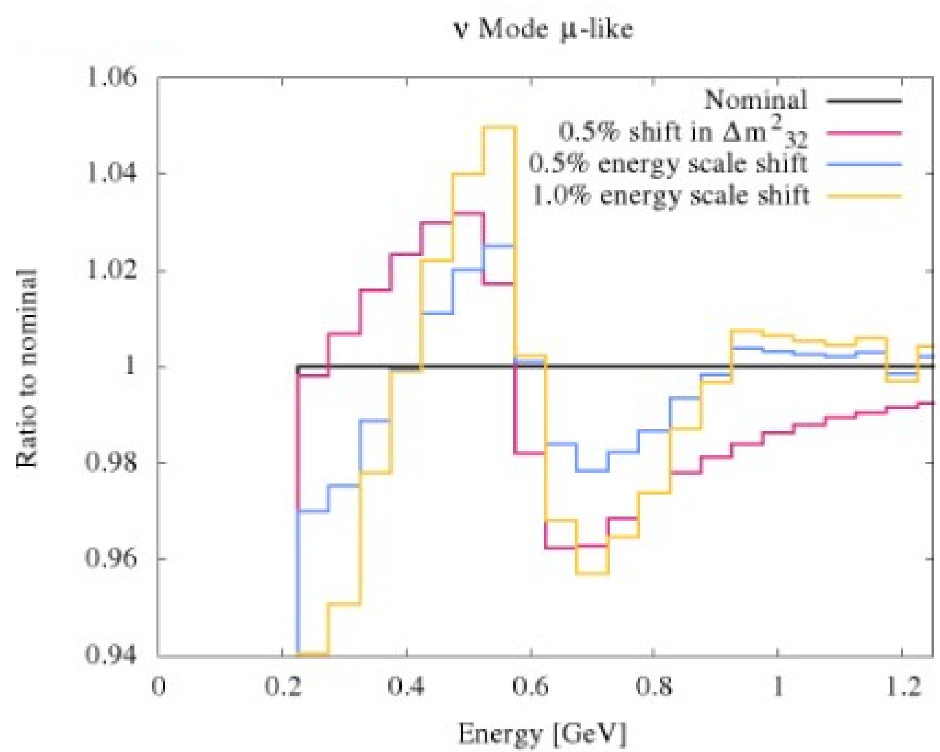
- leading dependence on δ_{CP} and MO (prop. to L), changing sign for ν and $\bar{\nu}$
- need large θ_{13} to access $\sin\delta_{CP}$ (sensitivity to δ_{CP} from ν only if θ_{13} well known)
- subleading dependence on $\cos\delta_{CP}$ → important for δ_{CP} precision measurement

Impact of systematics will hit first in ν_μ disappearance

As already discussed yesterday:

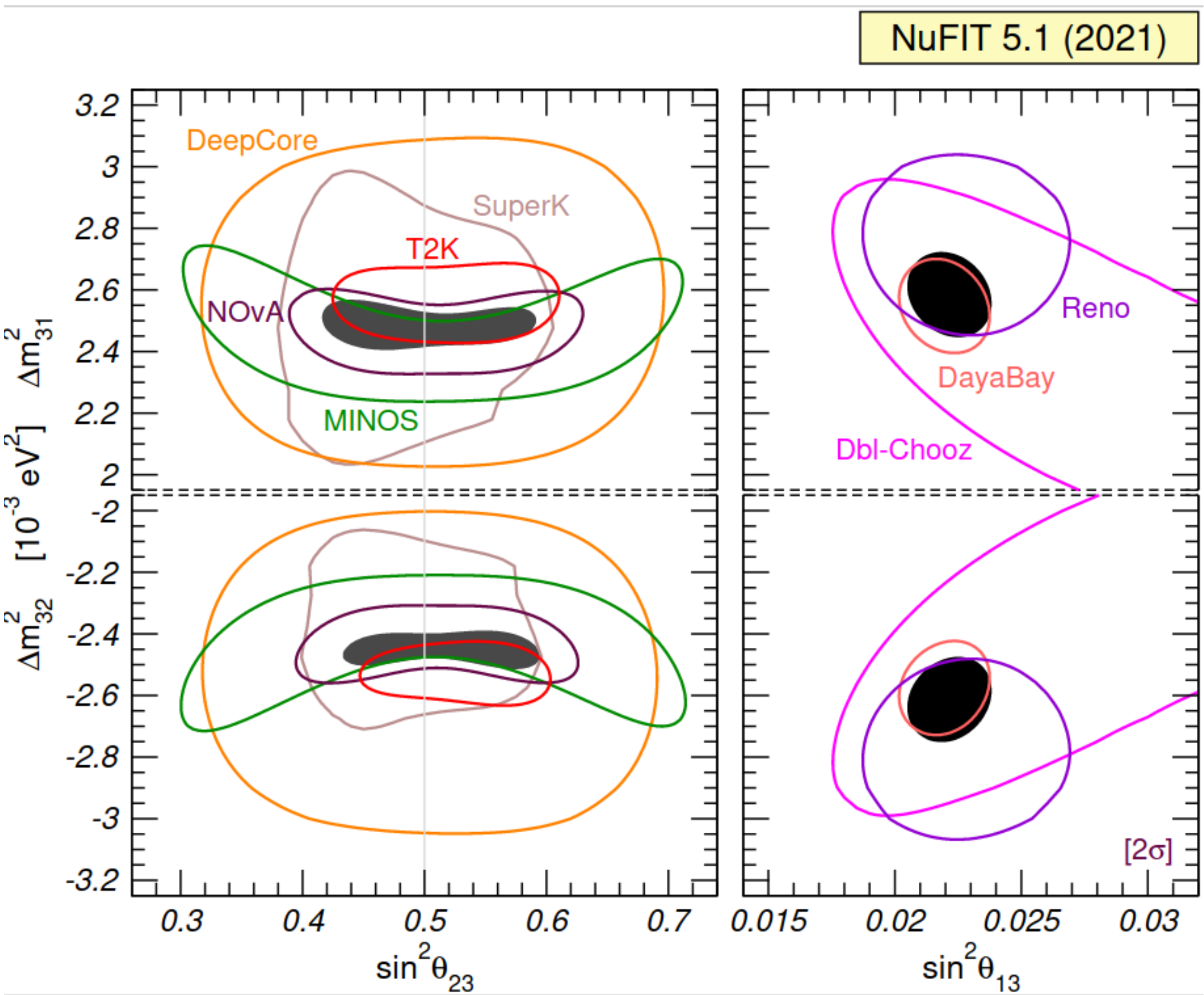
- precision $\sin\theta_{23}$ requires precision on neutrino rate at oscillation maximum
- precision on $|\Delta m^2_{31(32)}|$ requires precise neutrino energy reconstruction

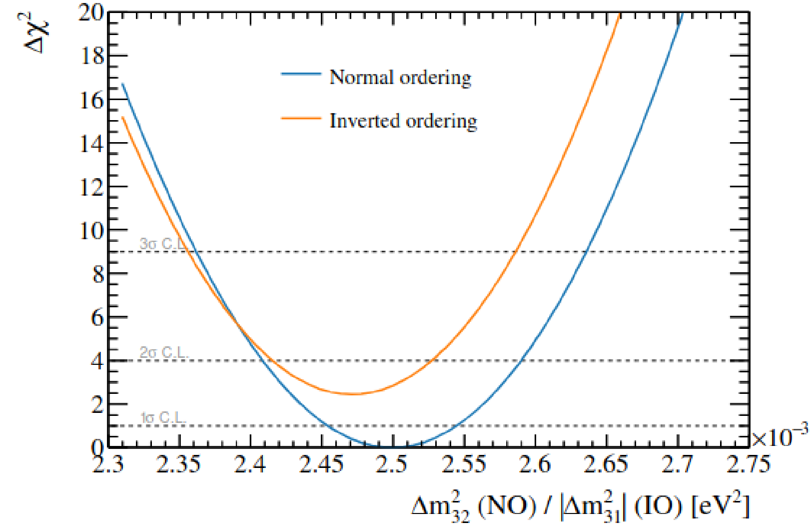




Need improved flux and xsec models (and tuning: NA61, Minerva, ...) and improved near detectors to better constrain model, notably for precise reconstruction of full final state
→ improved neutrino energy reconstruction

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





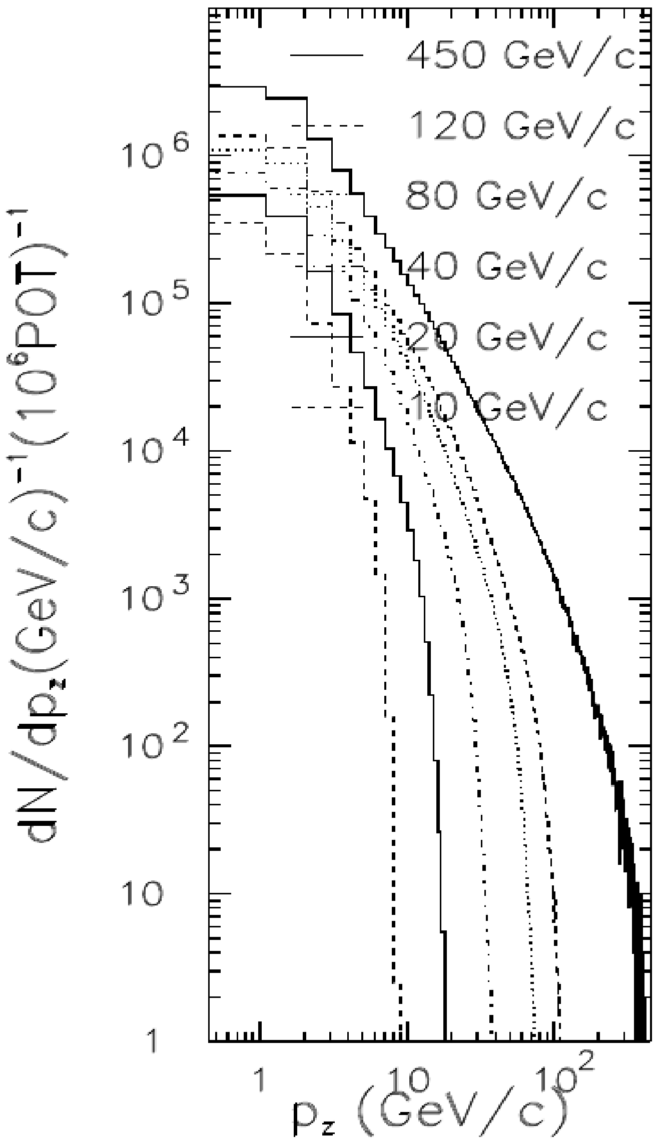
(b) T2K + reactor

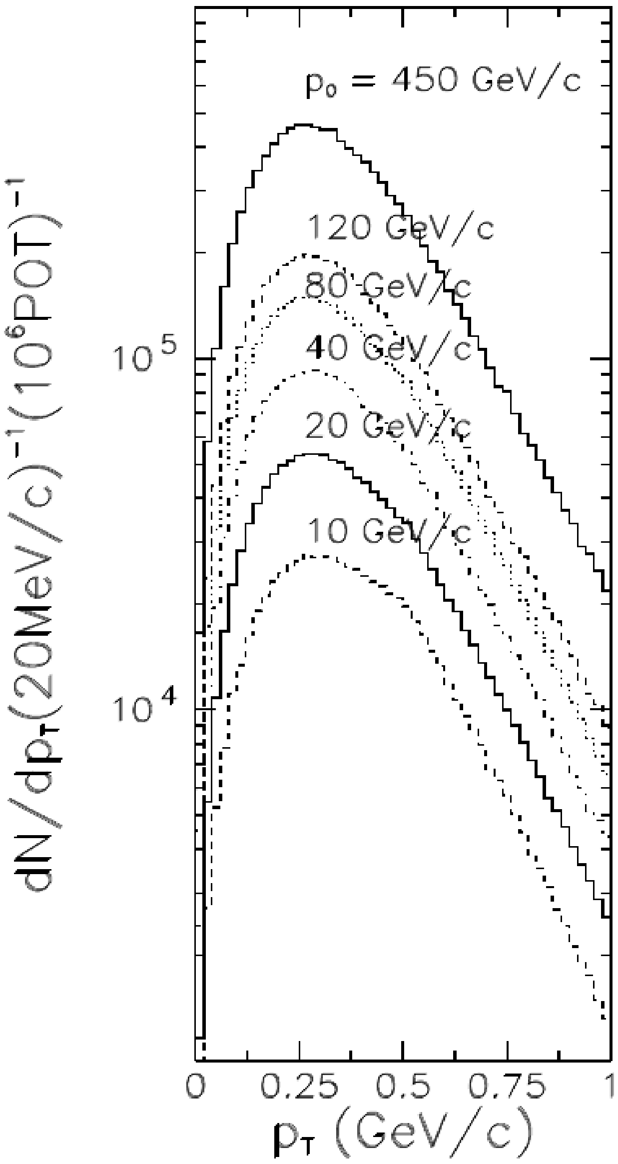
T2K: 2% precision with 1% shift between NO and IO

Similar resolution and shift in NOVA

Proton beam

Pion spectra for different proton momenta



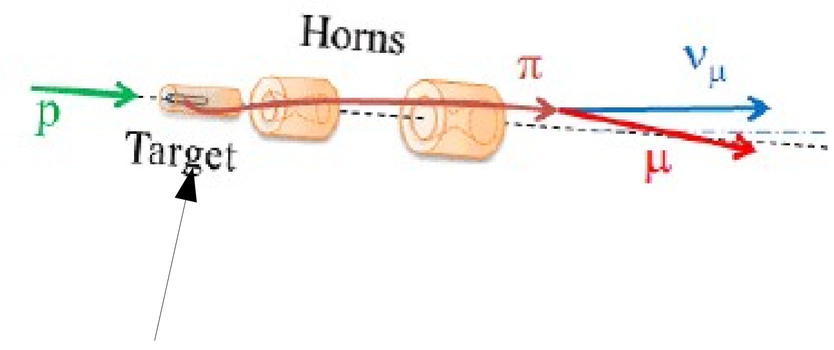


p_0 (GeV/c)	$\langle n_\pi \rangle$	$\langle p_T \rangle$ (MeV/c)	K/π
10	0.68	389	0.061
20	1.29	379	0.078
40	2.19	372	0.087
80	3.50	370	0.091
120	4.60	369	0.093
450	10.8	368	0.098

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

(but lower energy typically allows larger repetition rate)

Target



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

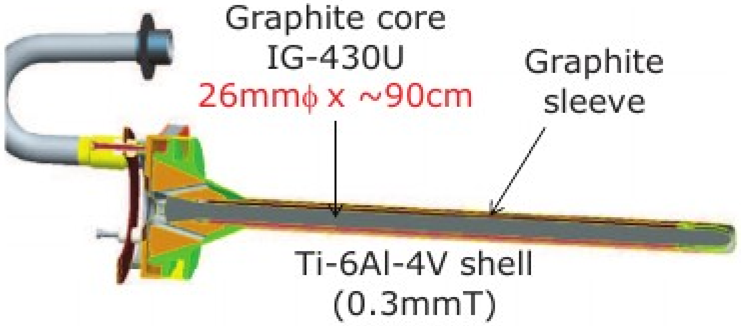
  (but re-interactions of hadrons inside the target are an additional complication)

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

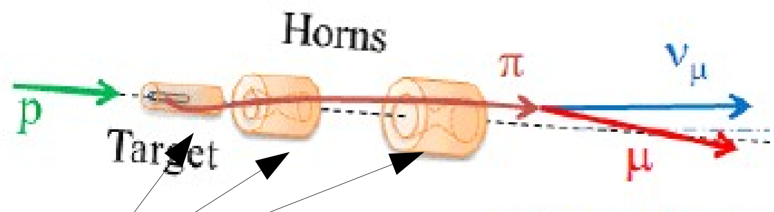
- **Low Z** (Aluminium, Berillium, Carbon, …) high probability of proton interacting and low probability of radiating (loosing energy in the target)

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

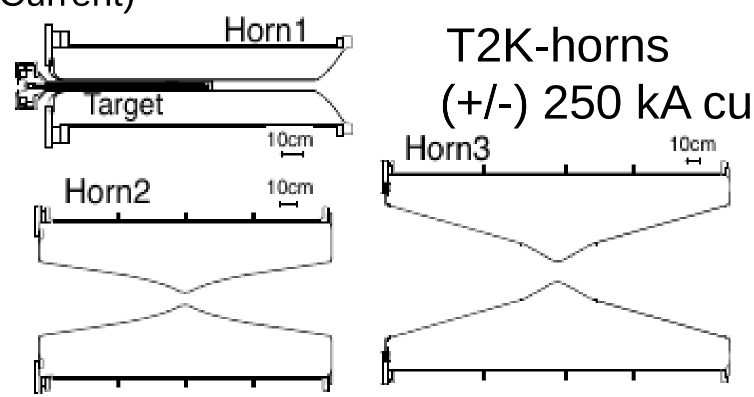
T2K



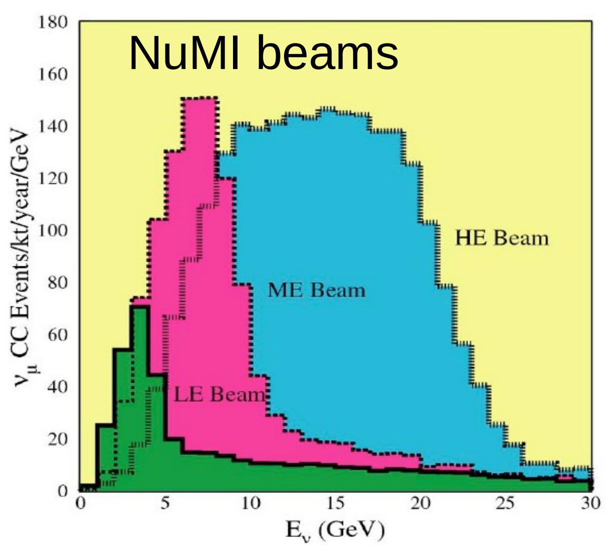
Horns



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

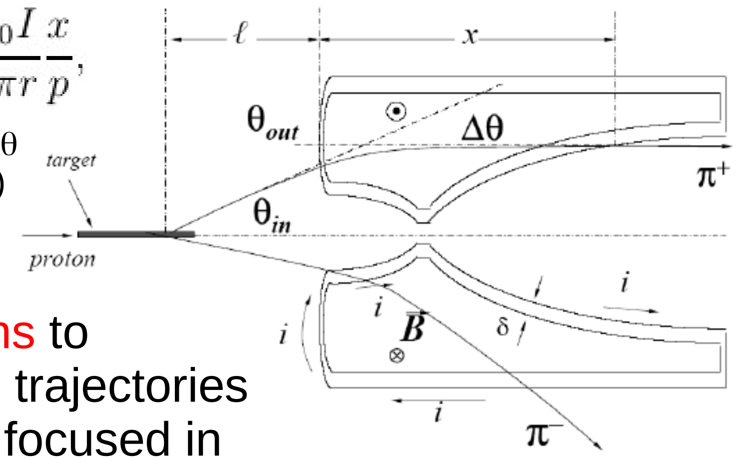


T2K-horns
(+/-) 250 kA current

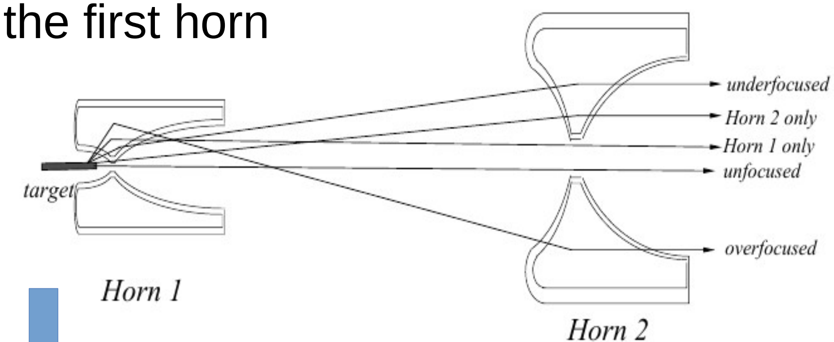


- $$\Delta\theta = \frac{Bx}{p} = \frac{\mu_0 I}{2\pi r}\frac{x}{p},$$

  (parabolic: same θ kink for all angles)

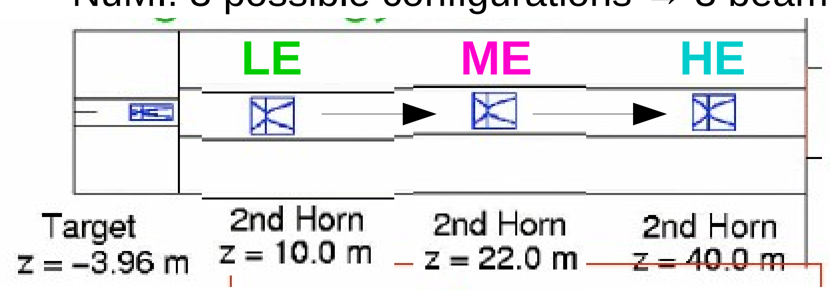


- multiple horns to recover pion trajectories not properly focused in the first horn



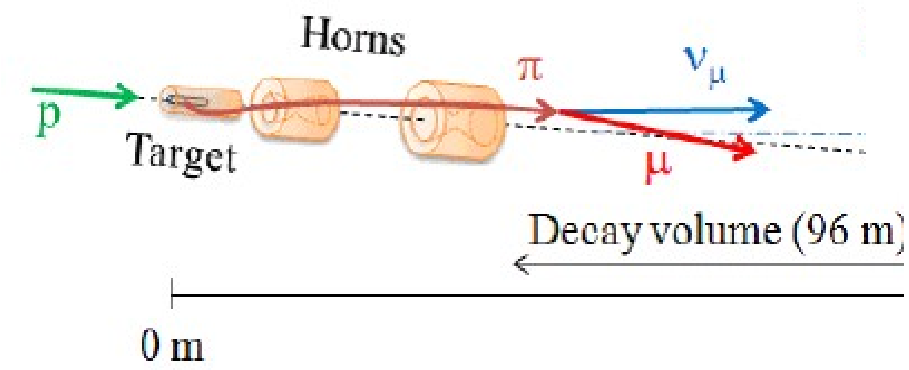
- the pions with smallest angle are the most energetic → to focus them need to move the horns

NuMI: 3 possible configurations → 3 beam energies



Decay volume

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



- most ν_μ's from 2-body decays:

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

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

- most ν_e's from 3-body decays:

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

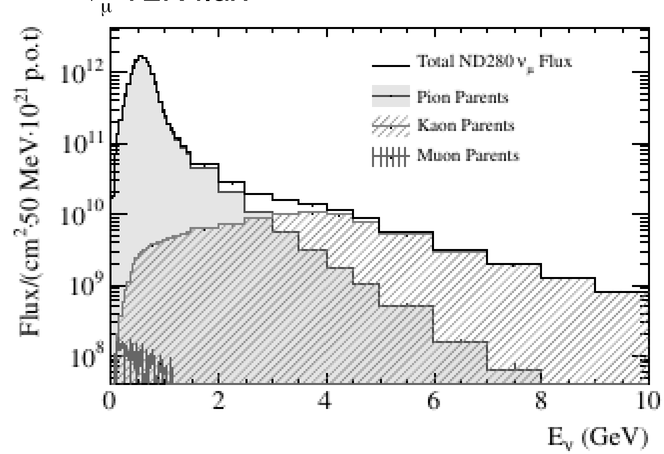
$K^+ \rightarrow \pi^0 e^+\nu_e$

Decay volume (T2K: He filled):

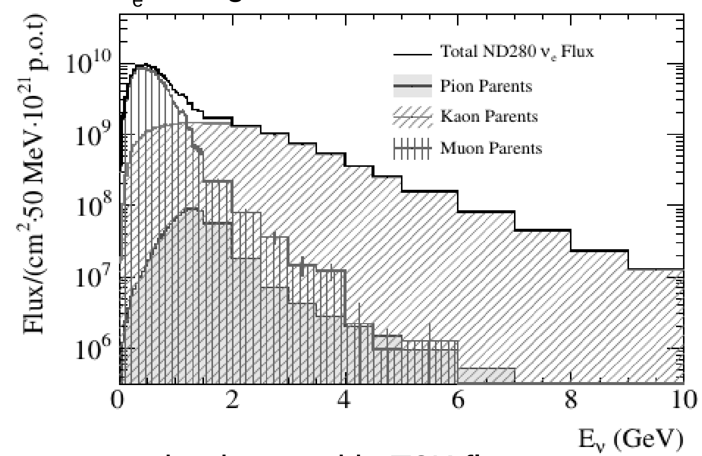
- Long to let most of the pion decaying
- not too long to avoid muon decay (ν_e pollution)

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

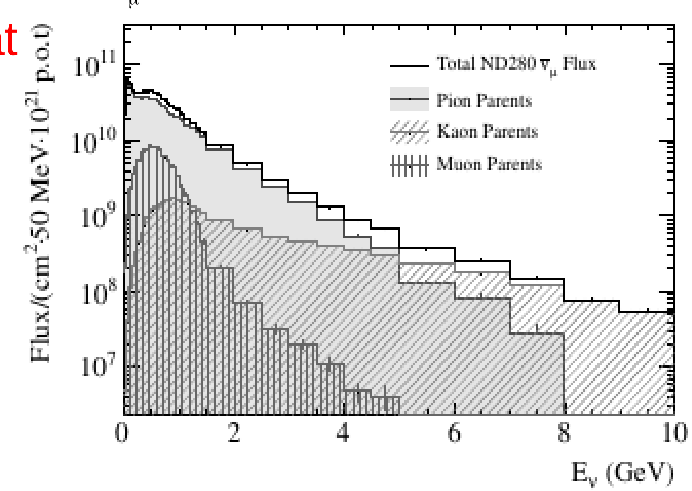
ν_μ T2K flux



ν_e background in T2K flux

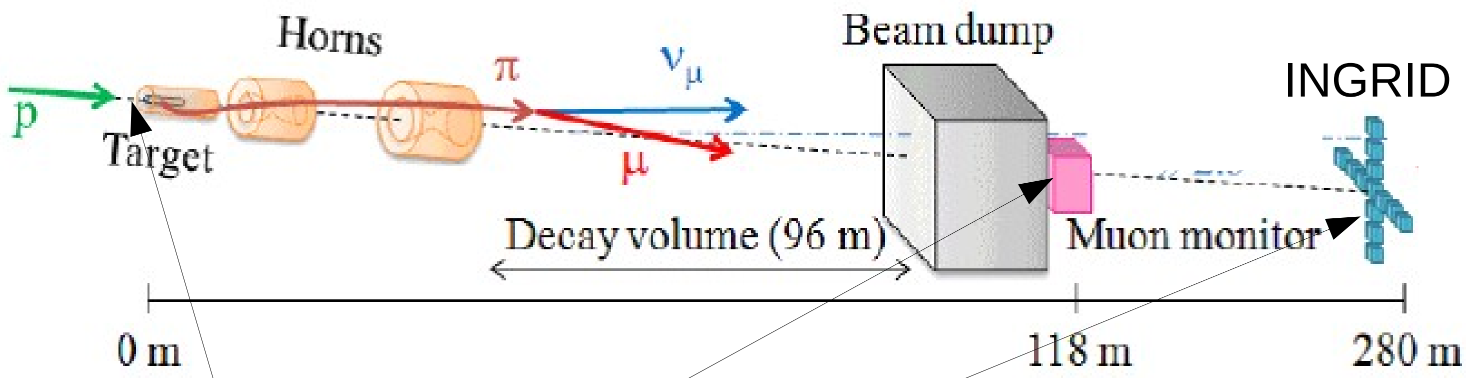


$\bar{\nu}_\mu$ background in T2K flux

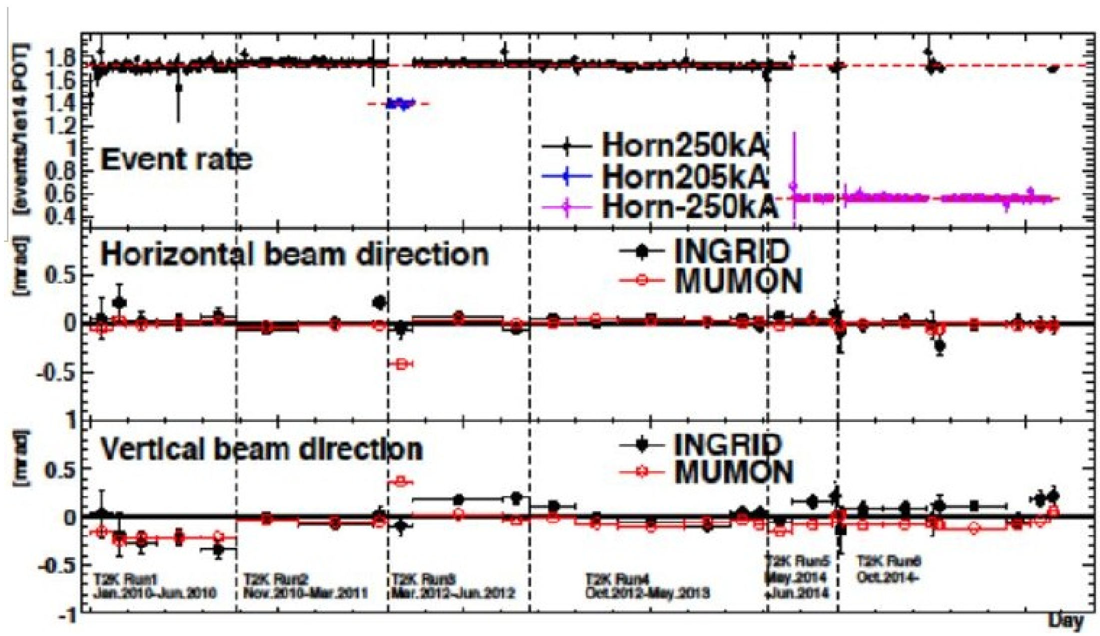


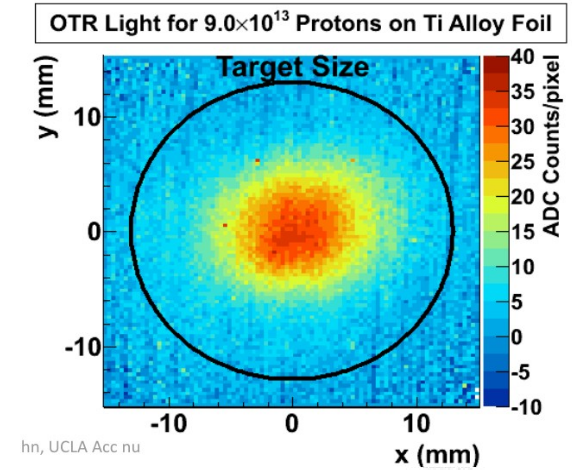
Beam monitoring

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



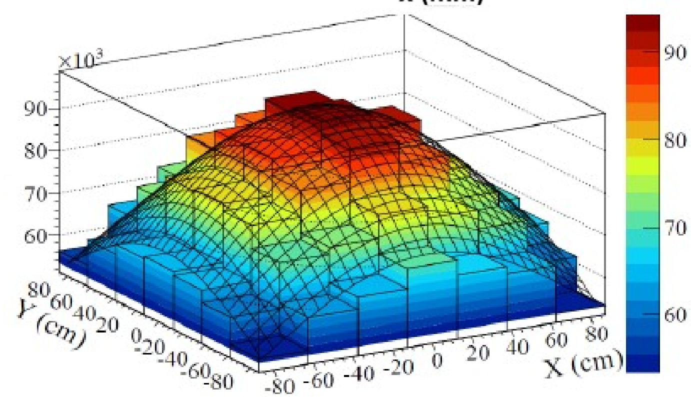
- looking at **protons**
- looking at **muons**
- looking at **neutrinos**





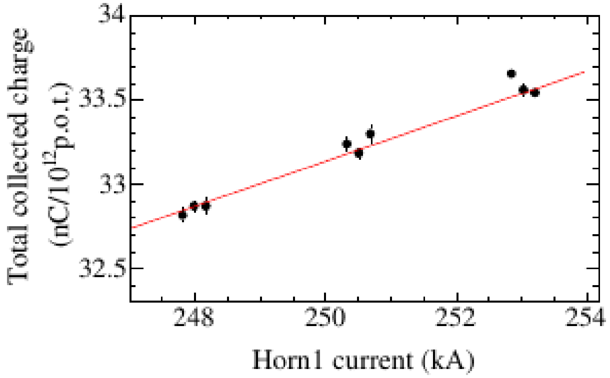
Protons

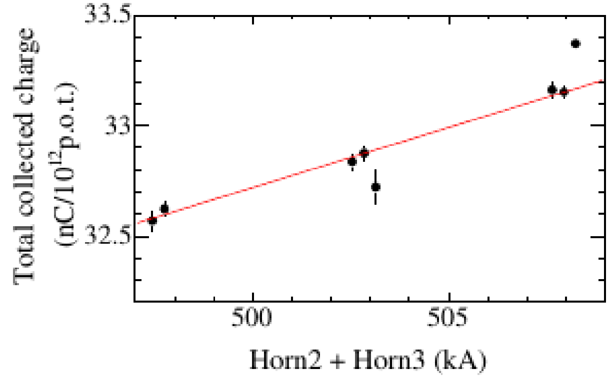
Muons

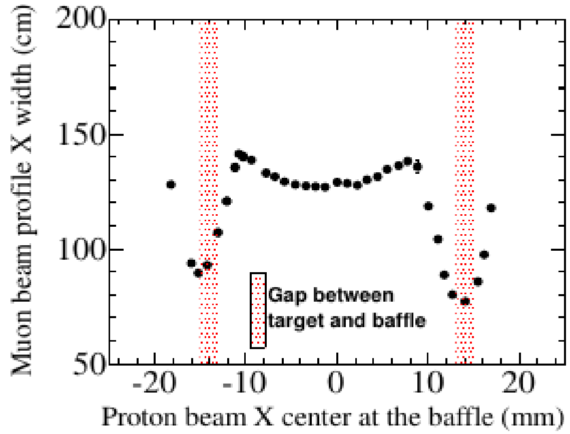


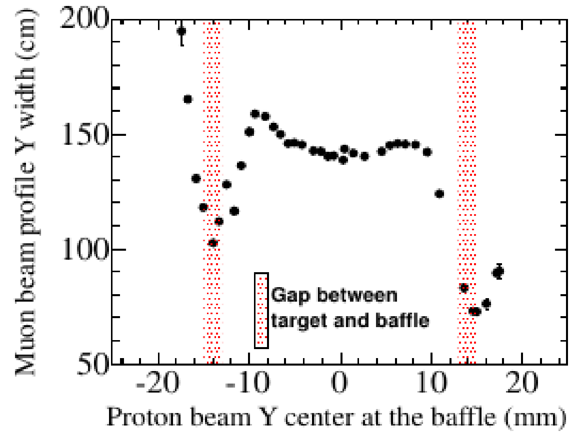
Playing around with the muon monitor

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

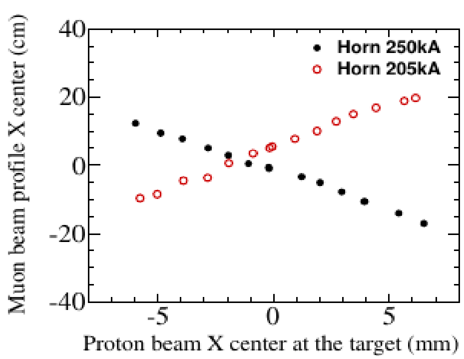


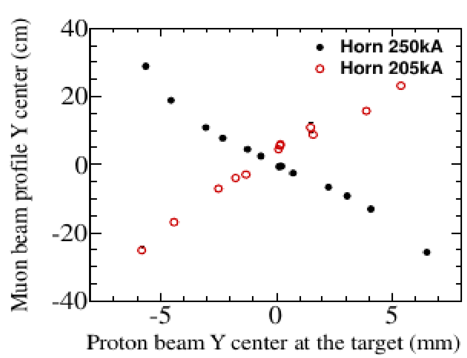


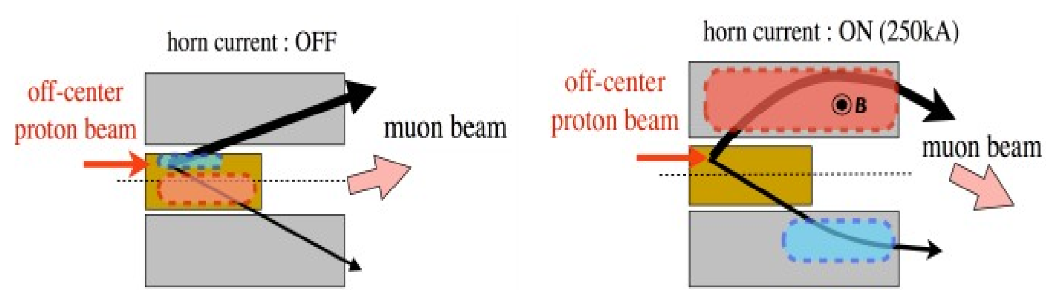




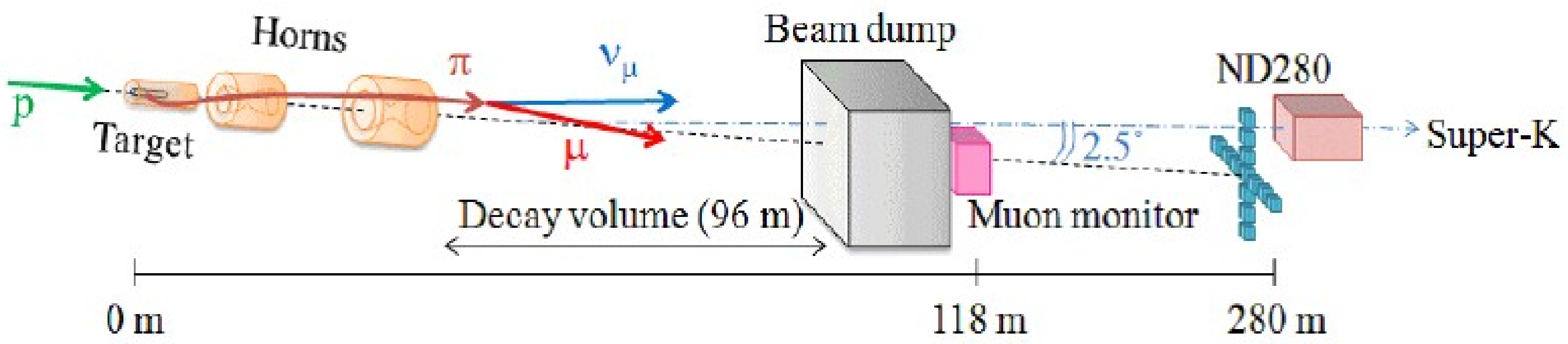
- Correlation between muon profile and proton beam position depends on the current





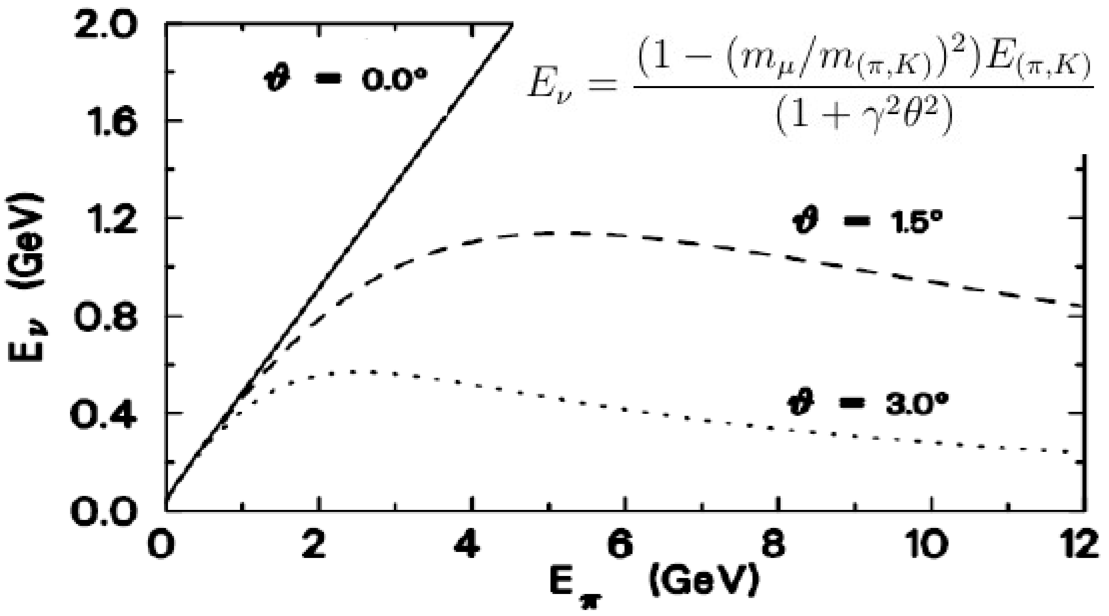


Tuning the neutrino energy

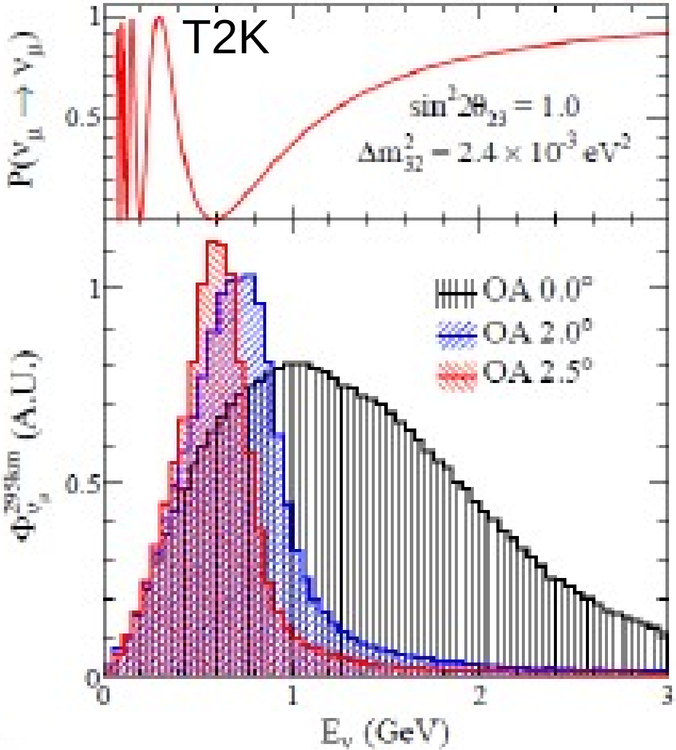


Energy of ν emitted in 2-body decay at an angle relative to π (K) direction is only weakly dependent on parent's momentum

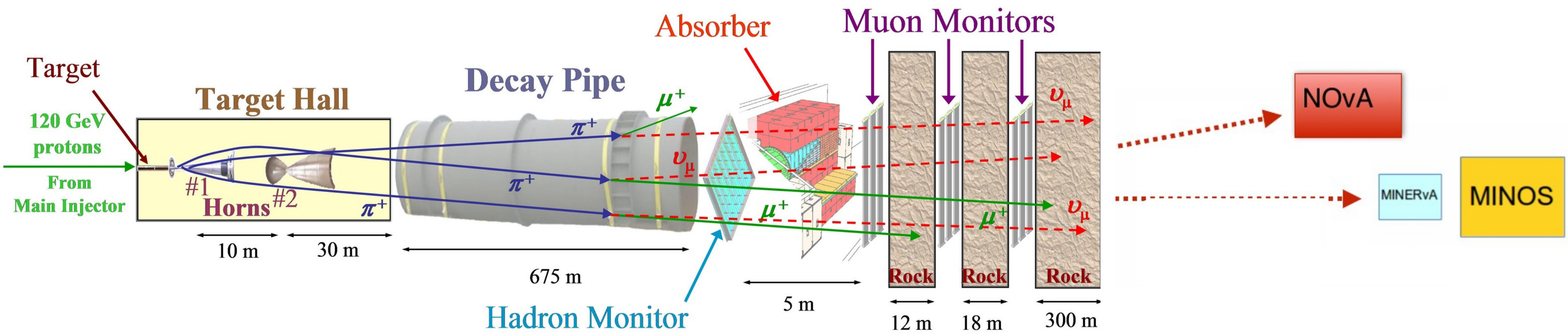
$$E_\nu = \frac{(1-(m_\mu/m_{(\pi,K)})^2)E_{(\pi,K)}}{(1+\gamma^2\theta^2)}$$

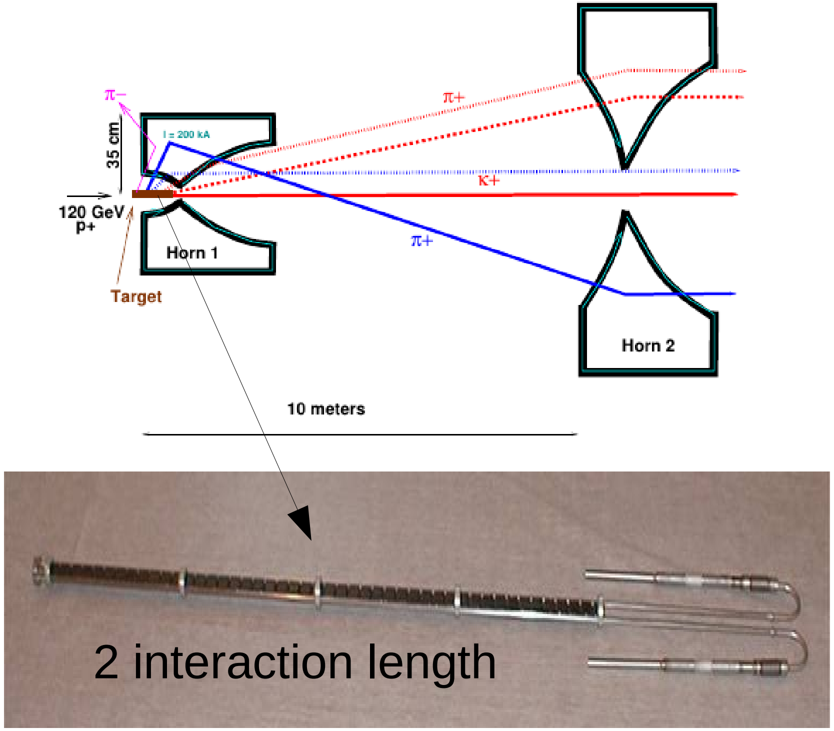


Off-axis → narrow flux at the maximum of the neutrino oscillation

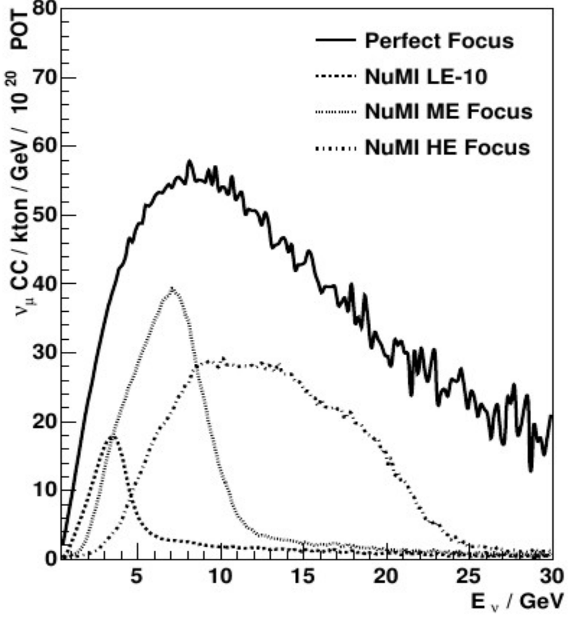


NuMI beam

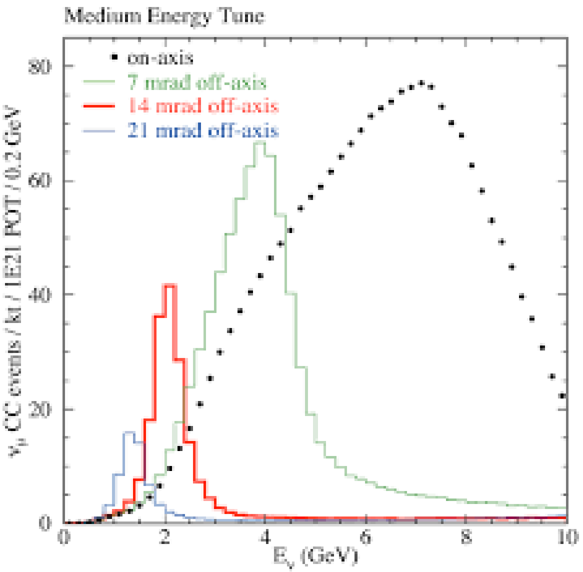




Change energy by moving target and horns



Off-axis technique



Flux tuning

Flux simulation

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

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

T2K

Parent	Flux percentage of each(all) flavor(s) ν_μ	$\bar{\nu}_\mu$	ν_e	$\bar{\nu}_e$
Secondary				
$\pi^\pm$	60.0(55.6)%	41.8(2.5)%	31.9(0.4)%	2.8(0.0)%
$K^\pm$	4.0(3.7)%	4.3(0.3)%	26.9(0.3)%	11.3(0.0)%
K_L^0	0.1(0.1)%	0.9(0.1)%	7.6(0.1)%	49.0(0.1)%
Tertiary				
$\pi^\pm$	34.4(31.9)%	50.0(3.0)%	20.4(0.2)%	6.6(0.0)%
$K^\pm$	1.4(1.3)%	2.6(0.2)%	10.0(0.1)%	8.8(0.0)%
K_L^0	0.0(0.0)%	0.4(0.1)%	3.2(0.0)%	21.3(0.0)%

NuMI low energy

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

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

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

Flux tuning

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

T2K

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

NuMI

NA49 pC @ 158 GeV (+HARP)

MIPP pC @ 120 GeV

Barton et Al [Phys. Rev. D 27, 2580 (1983)]

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

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

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

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

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

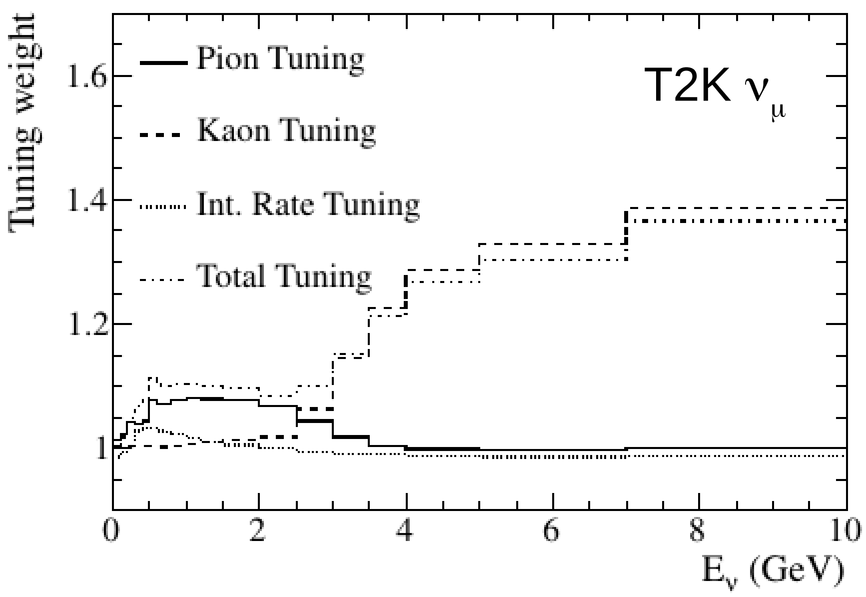
$$\frac{dn}{dp}(\theta, p_{in}, A) = \frac{1}{\sigma_{prod}(p_{in}, A)} \frac{d\sigma}{dp}(\theta, p_{in}, A).$$

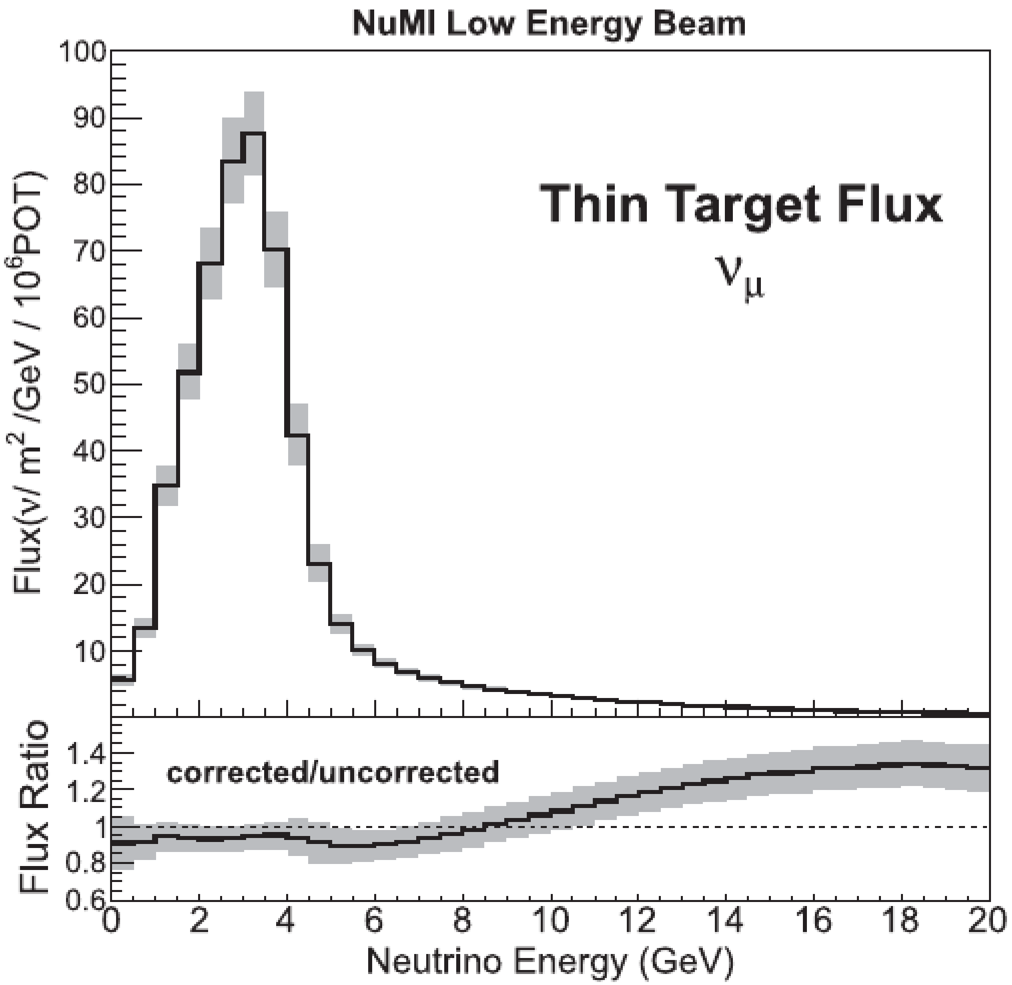
$$W(p_{in}, A) = \frac{[\frac{dn}{dp}(\theta, p_{in}, A)]_{data}}{[\frac{dn}{dp}(\theta, p_{in}, A)]_{MC}}$$

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

Tuning factors

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



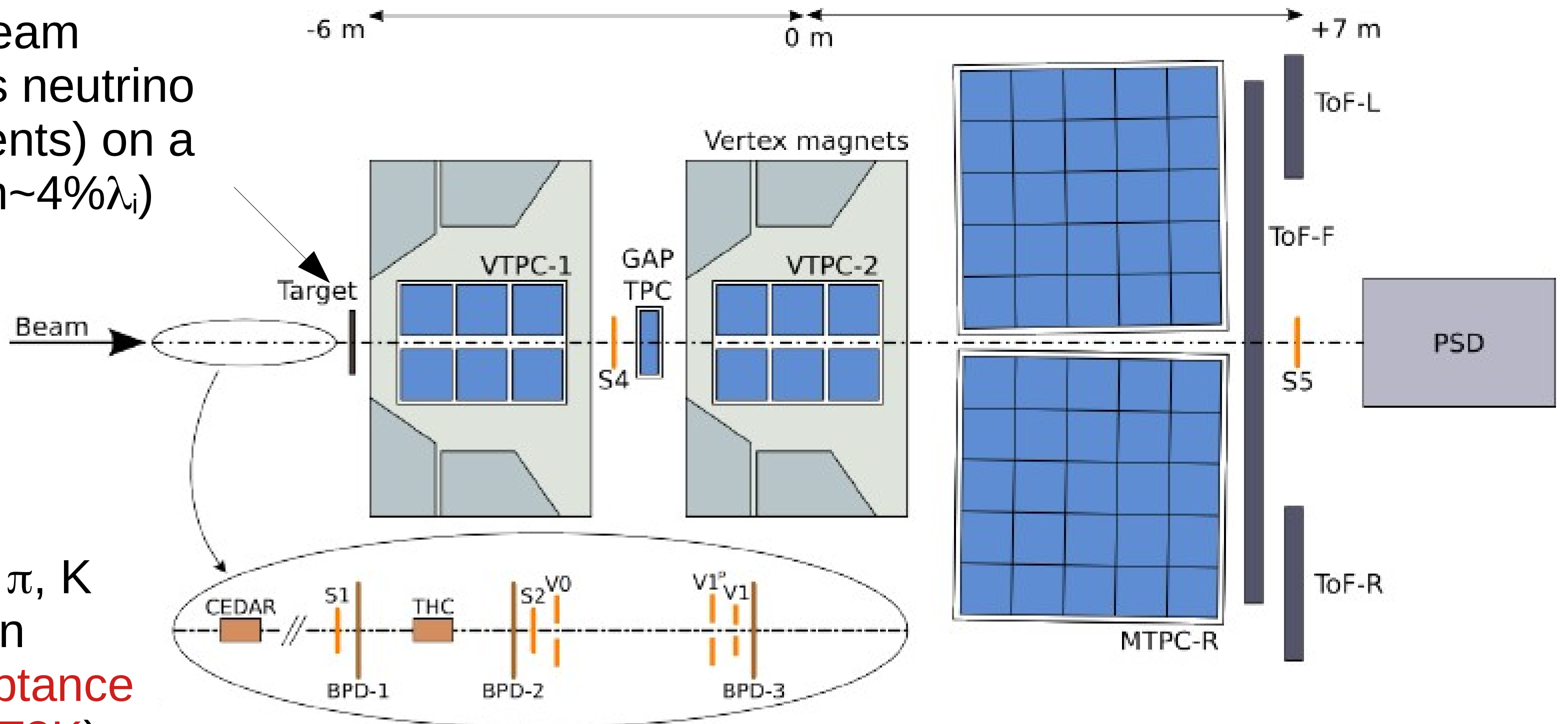


Uncertainties from theory corrections (scaling to different proton energies, targets, not covered phase space…) and from hadro-production data (statistics and systematics uncertainty)

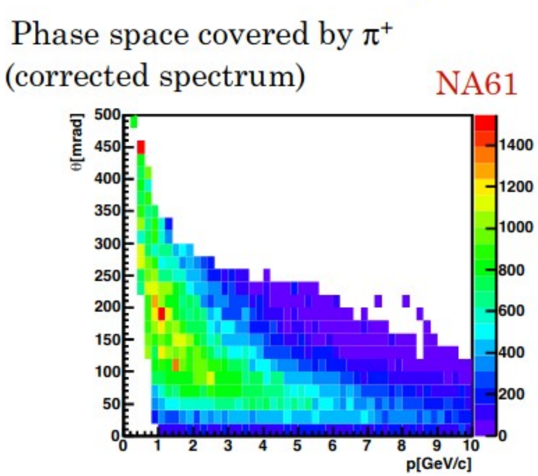
NA61/SHINE

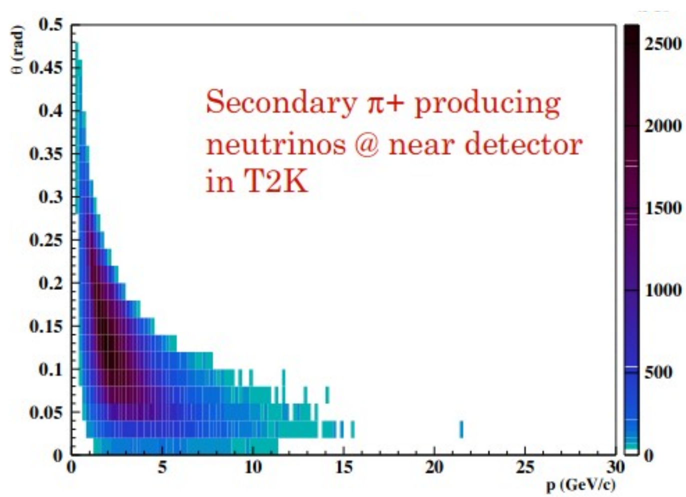
SPS Heavy Ion and Neutrino Experiment: Fixed target experiment using CERN SPS

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



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



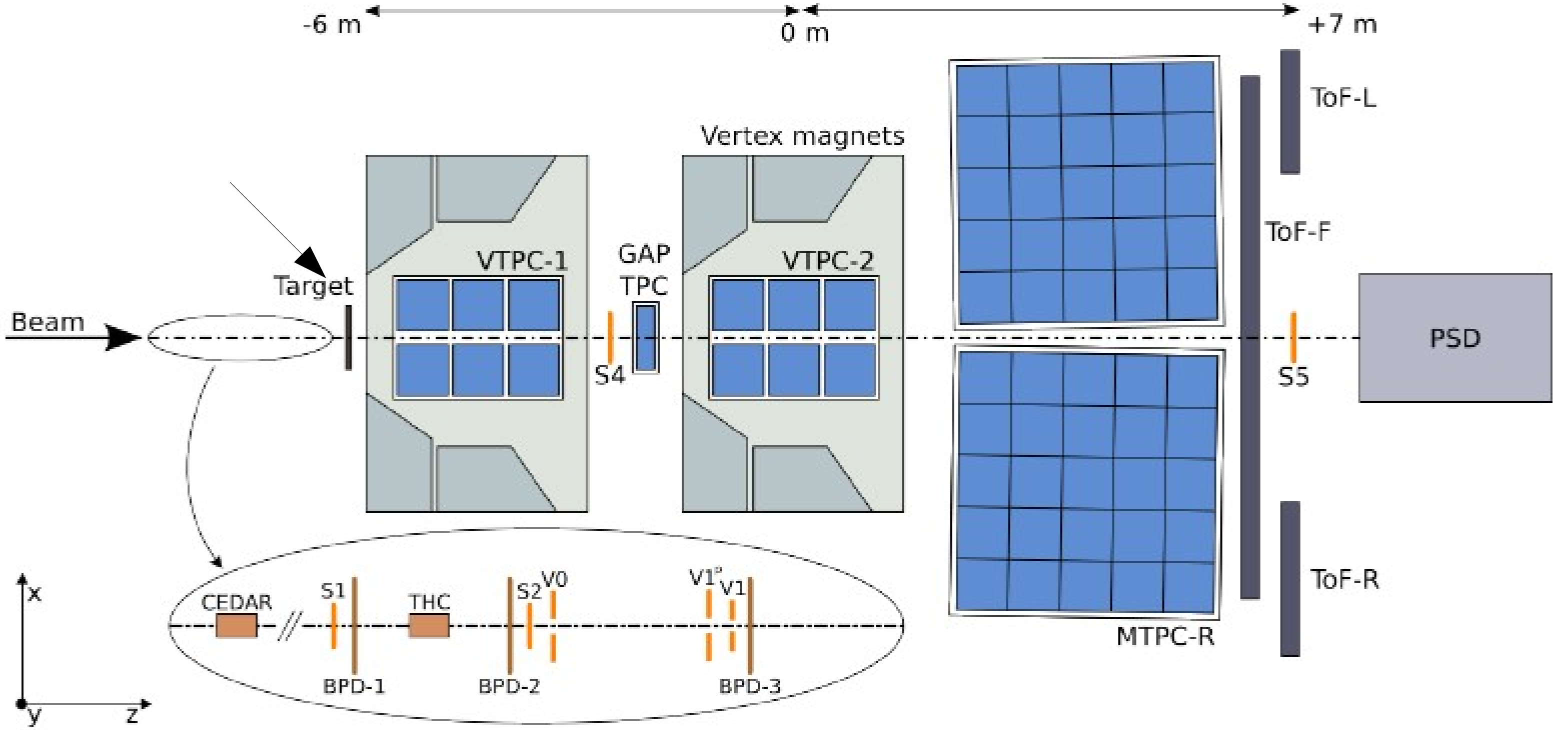


Momentum measurement with TPC in magnetic field (σ_p/p^2~0.005 GeV^{-1})

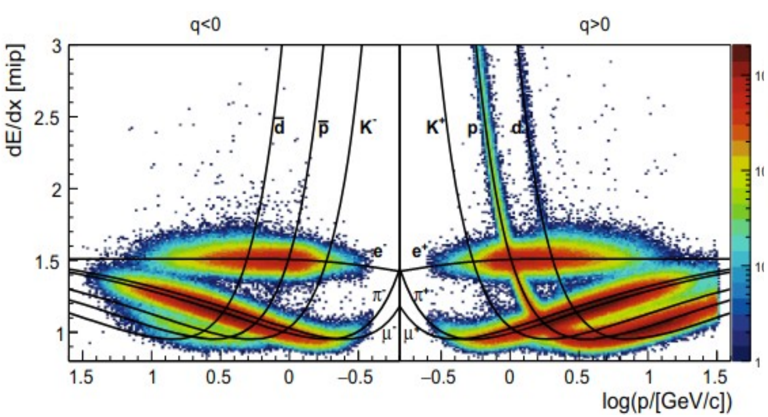
Angular measurement with 3-4 mrad resolution

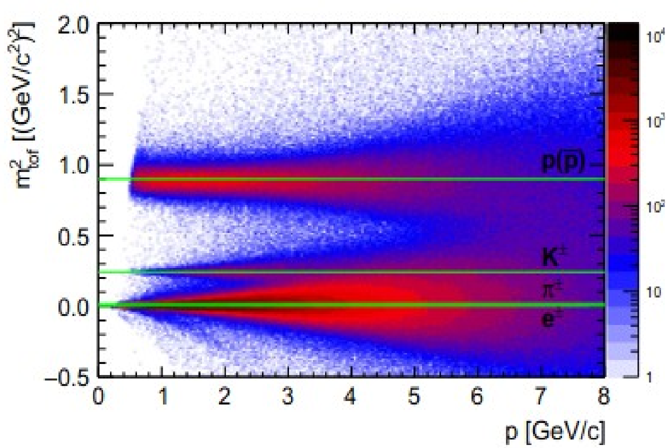
NA61/SHINE

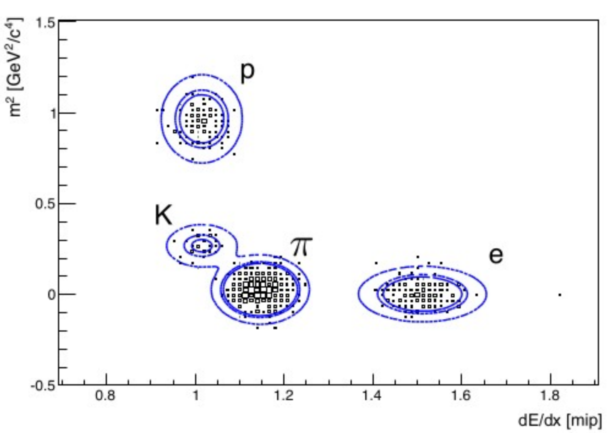
SPS Heavy Ion and Neutrino Experiment: Fixed target experiment using CERN SPS



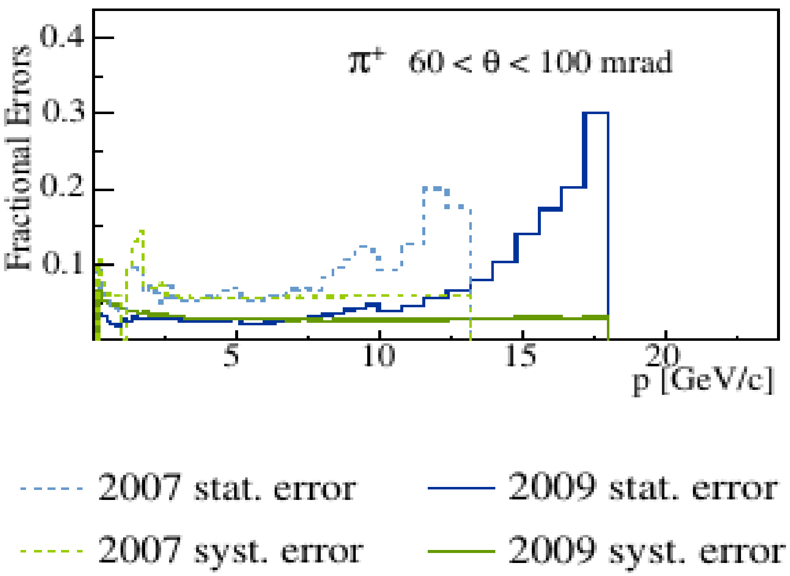
dE/dx + ToF measurement for clean PID



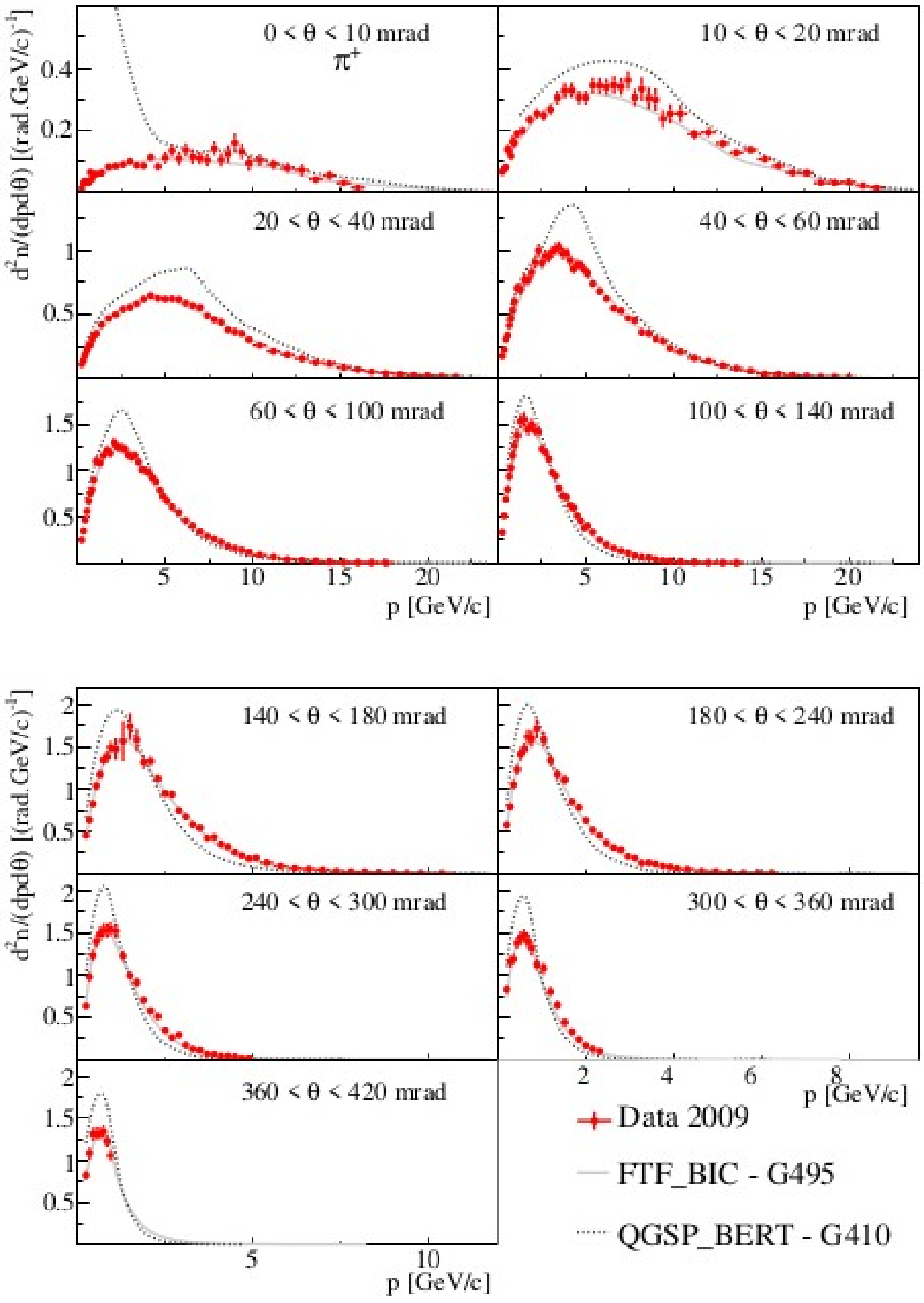




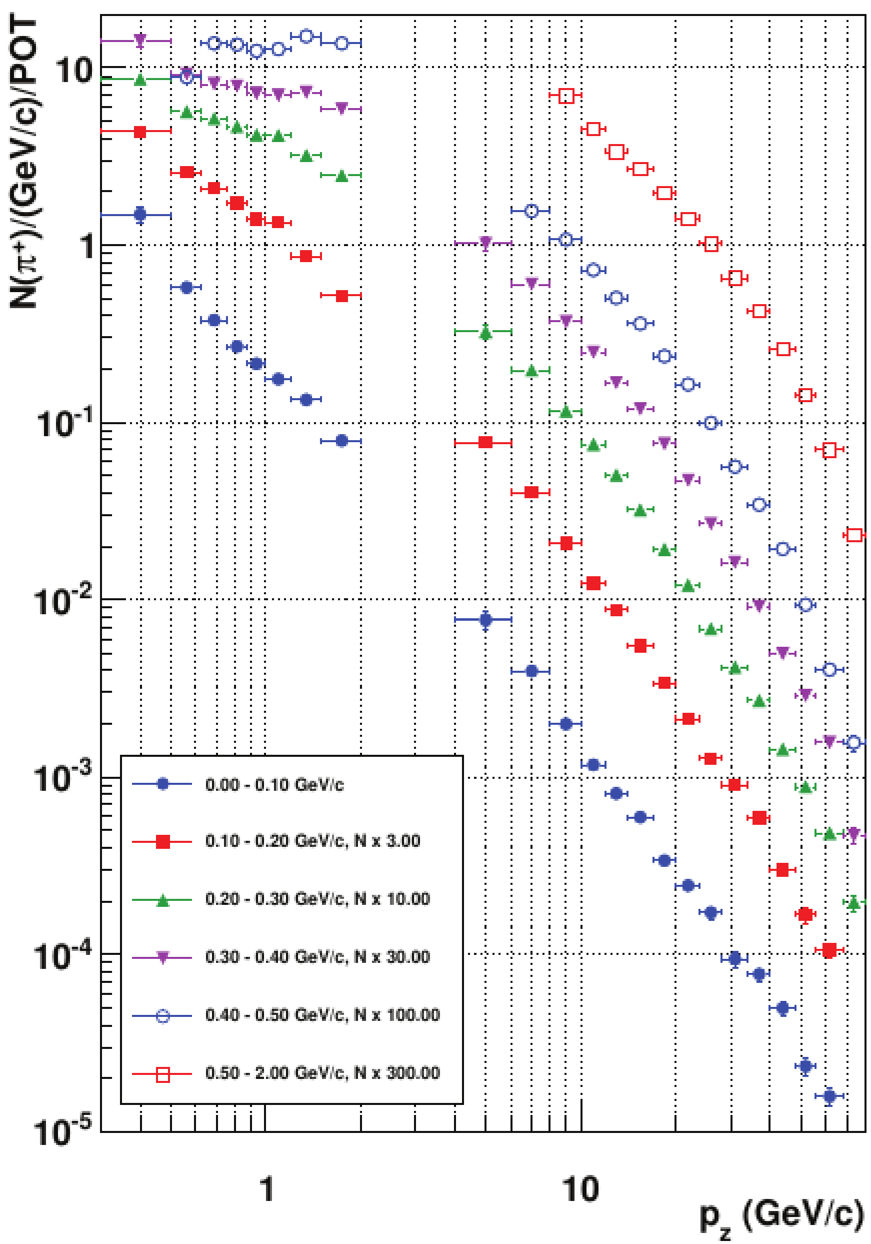
(Old) results

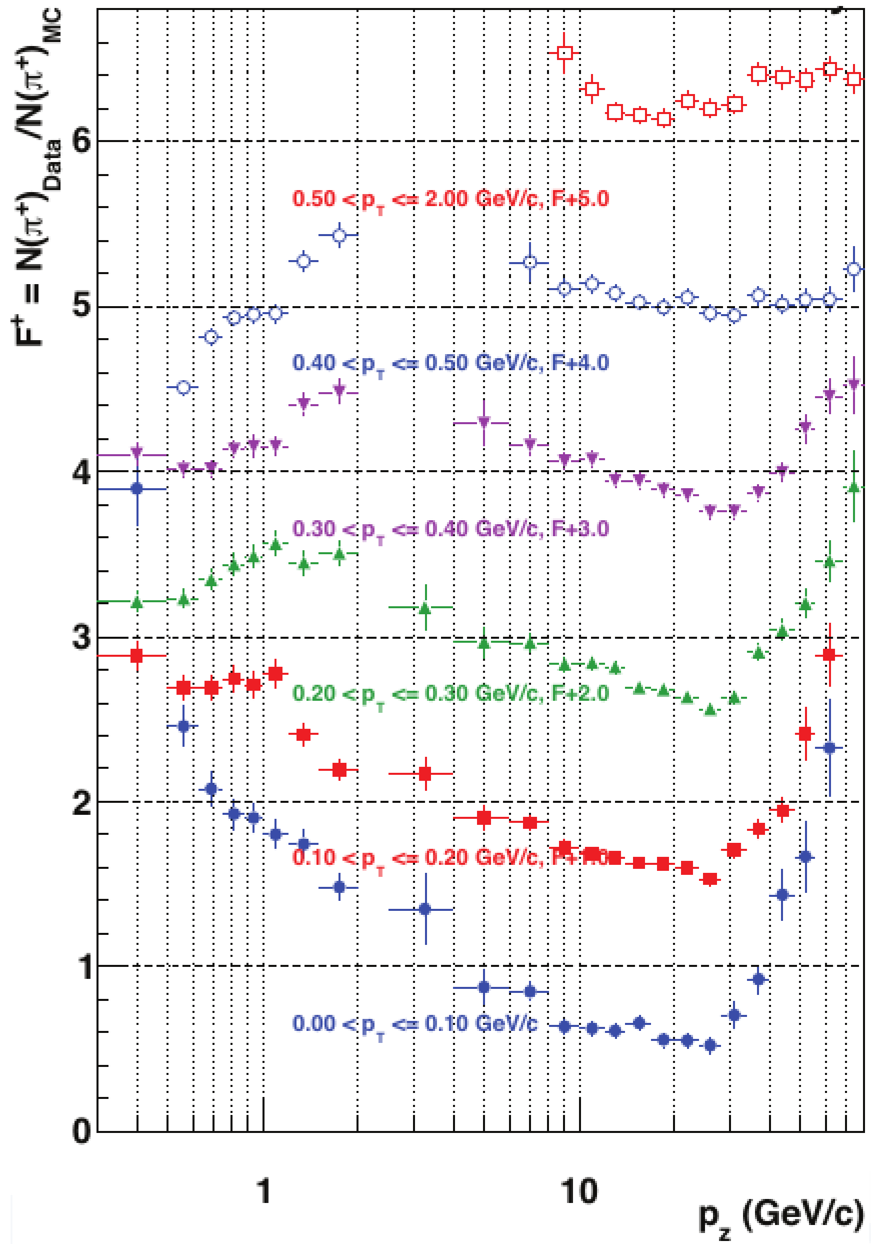


Full measurement of π+, π-, K+,K-



MIPP results for NuMI





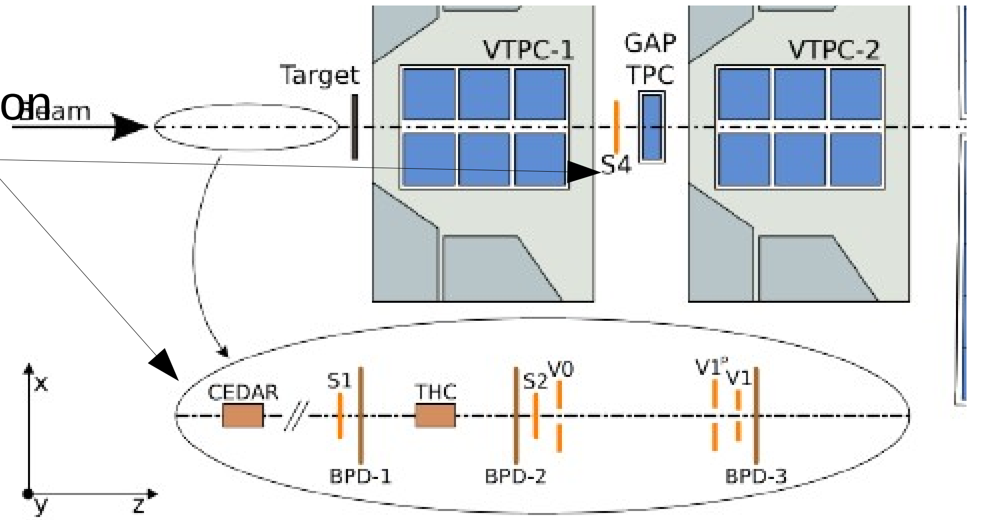
Cross-section normalization

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

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

(normalized to number of carbon nuclei in the target)

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



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

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

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

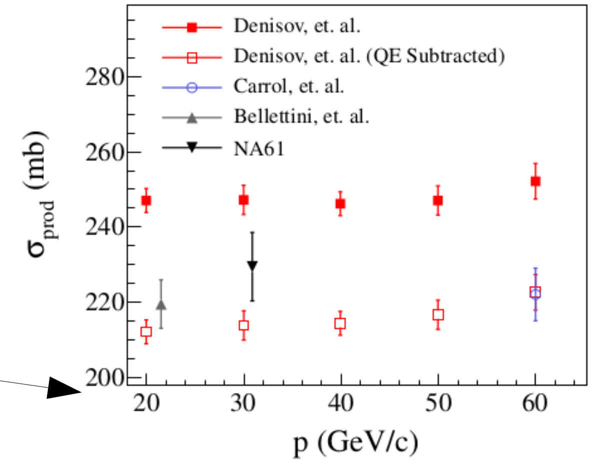
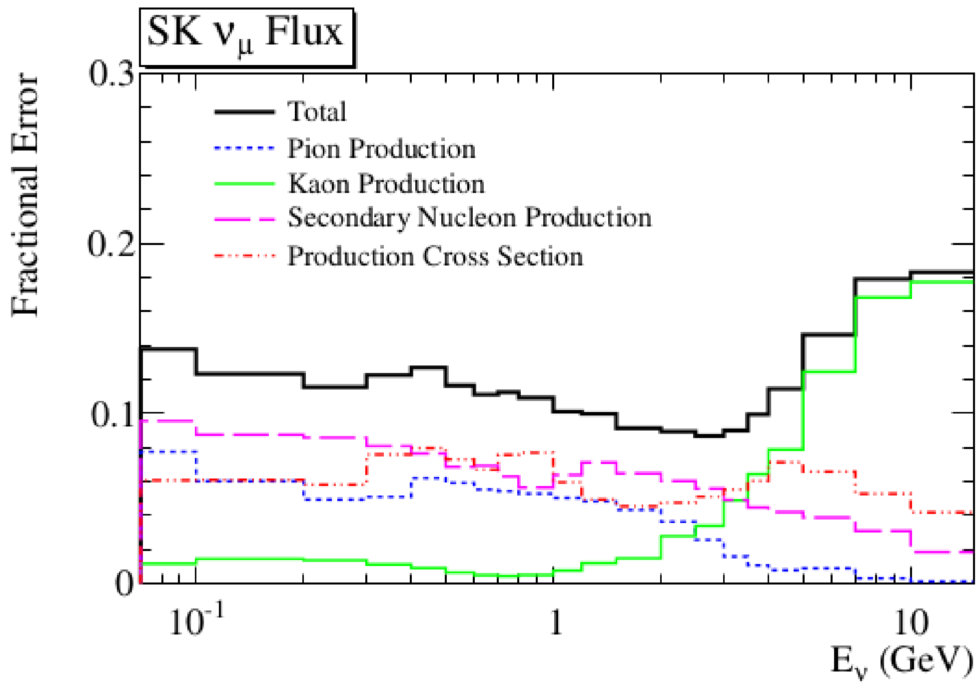


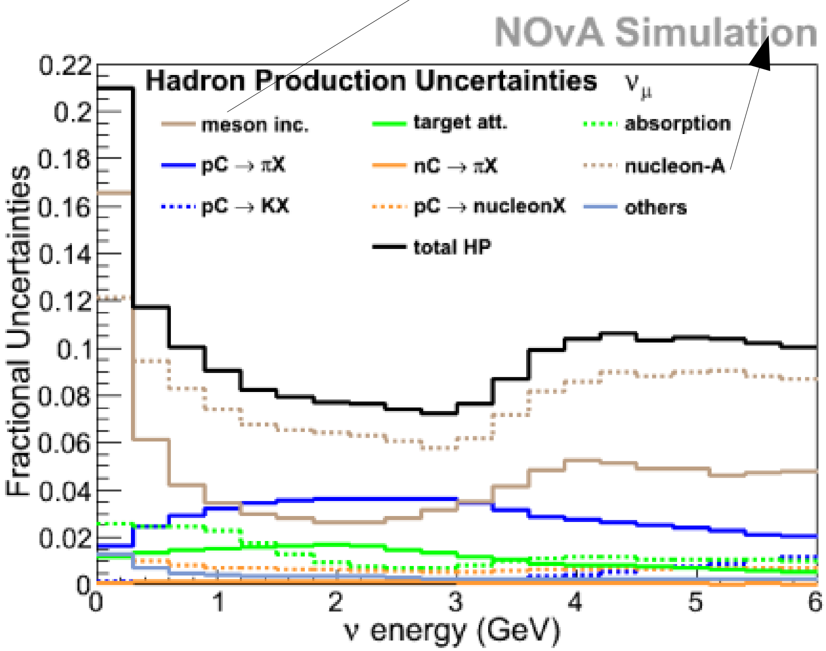
FIG. 37: Production cross-section measurements for protons on graphite targets for momenta 20–60 GeV/c. The data from Denisov *et al.* are shown with and without the quasi-elastic estimate subtracted since the quantity that is measured is ambiguous.

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

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



not C/target interactions

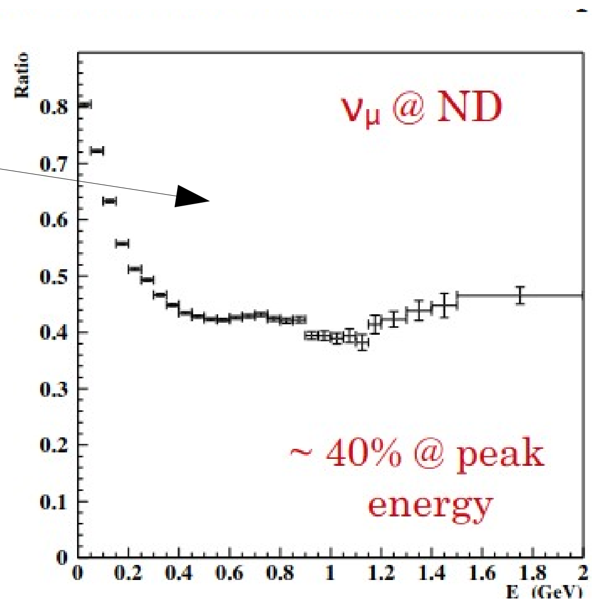


The remaining uncertainties were dominated by the total production cross-section and re-interactions in the horns

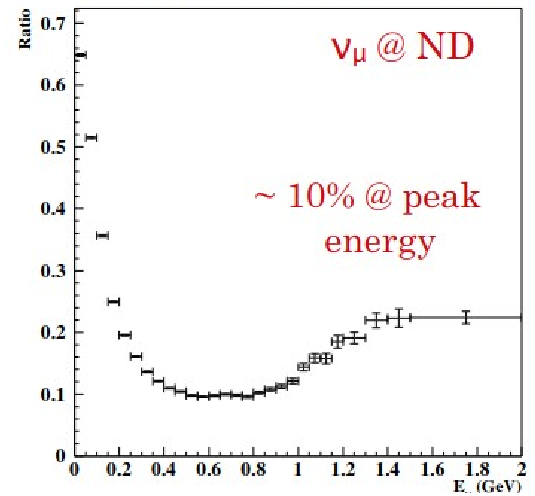
→ new NA61 measurement ‘more directly portable’ to T2K

Need for replica target: T2K example

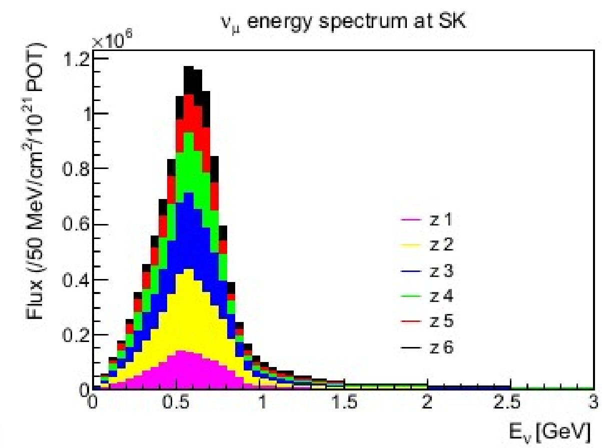
Fraction of neutrinos from re-interactions in the target and in the beam line (~40%)



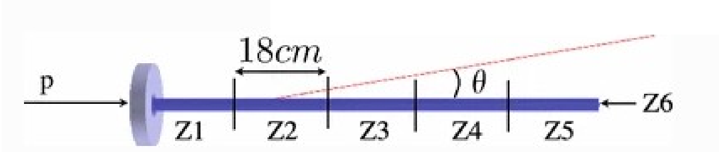
re-interactions in the beamline



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

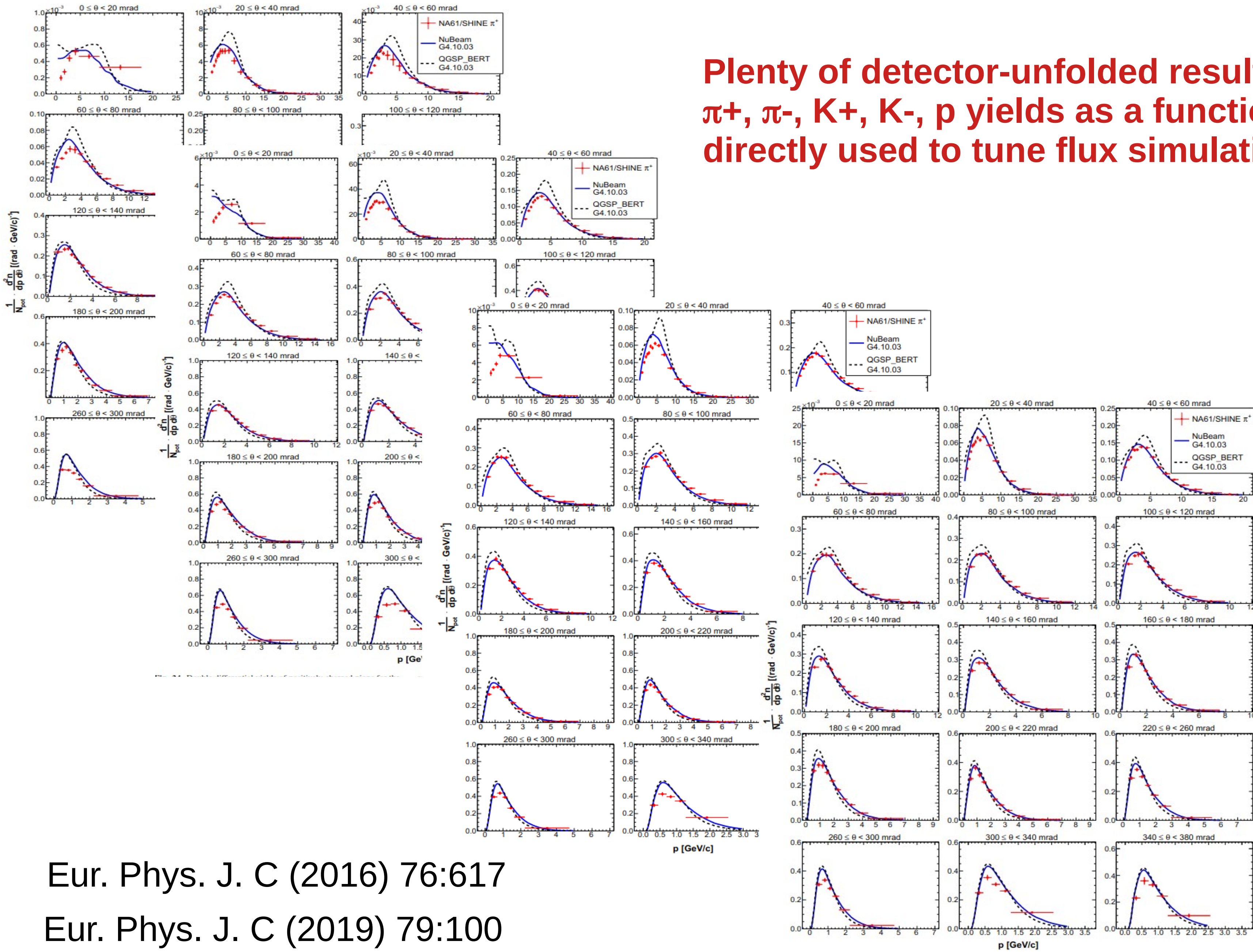


Measurements of **hadron multiplicity vs angle and momentum (dn/dpdθ) in longitudinal bins of the target** (particles in different longitudinal bins follow a different path inside the horns and are focused differently)



NA61 results with replica target

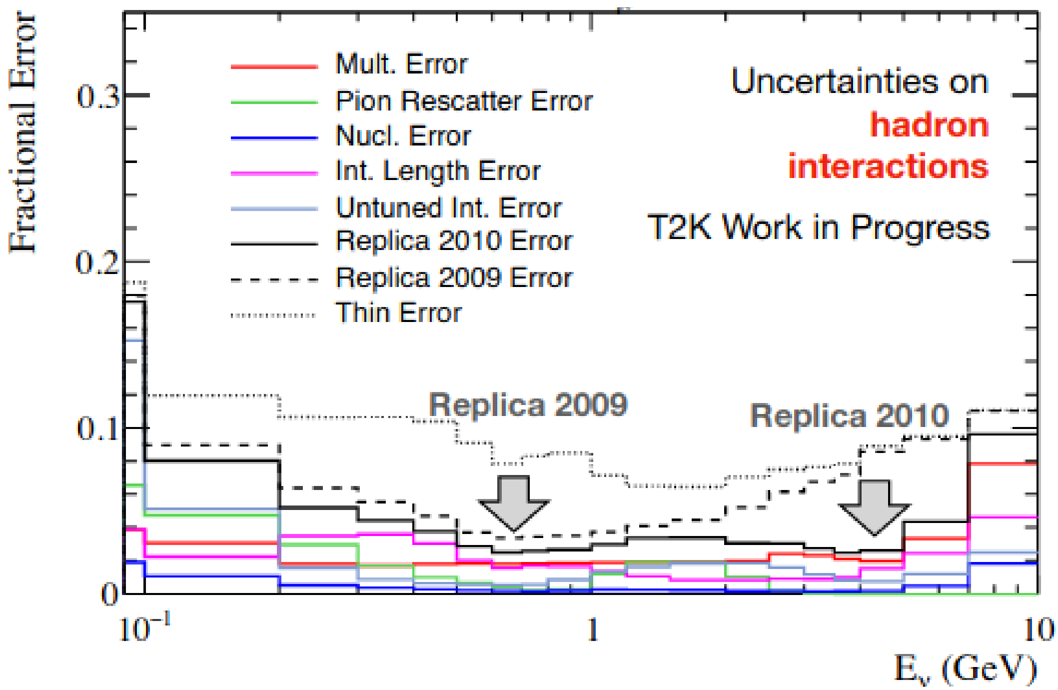
Plenty of detector-unfolded results:
π+, π-, K+, K-, p yields as a function of p, θ, z_{target}
directly used to tune flux simulation



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

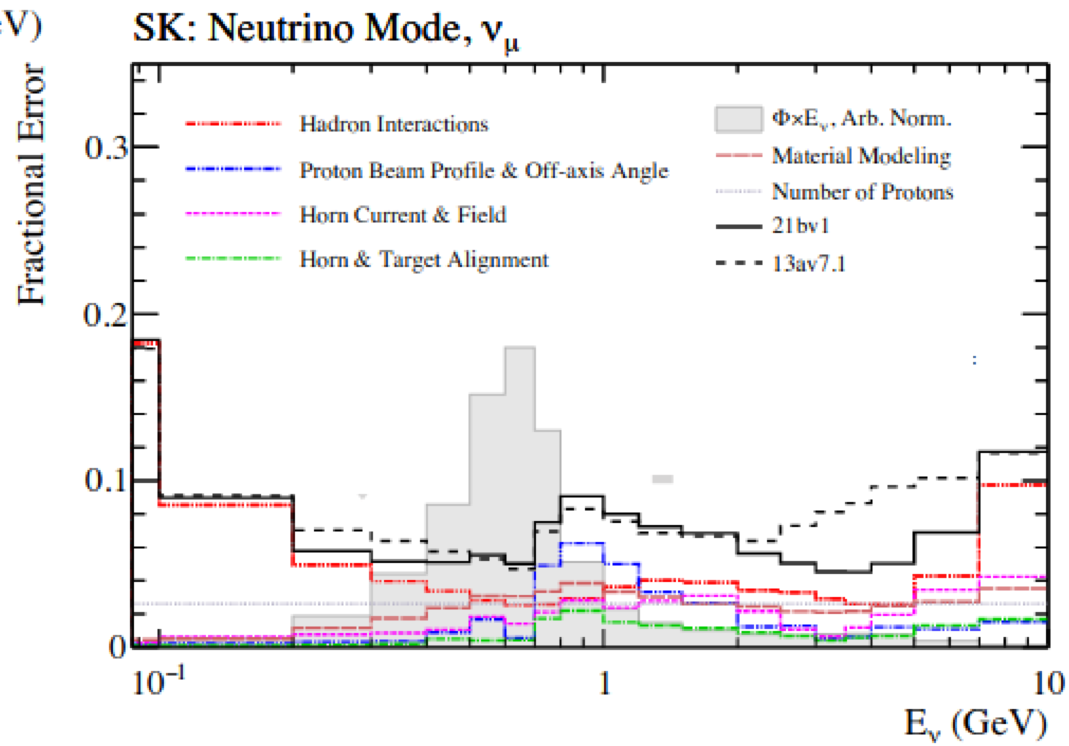
Eur. Phys. J. C (2019) 79:100

Flux uncertainties



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

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



Future prospects

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

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

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

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

→ new small TPC downstream the target)

Future prospects

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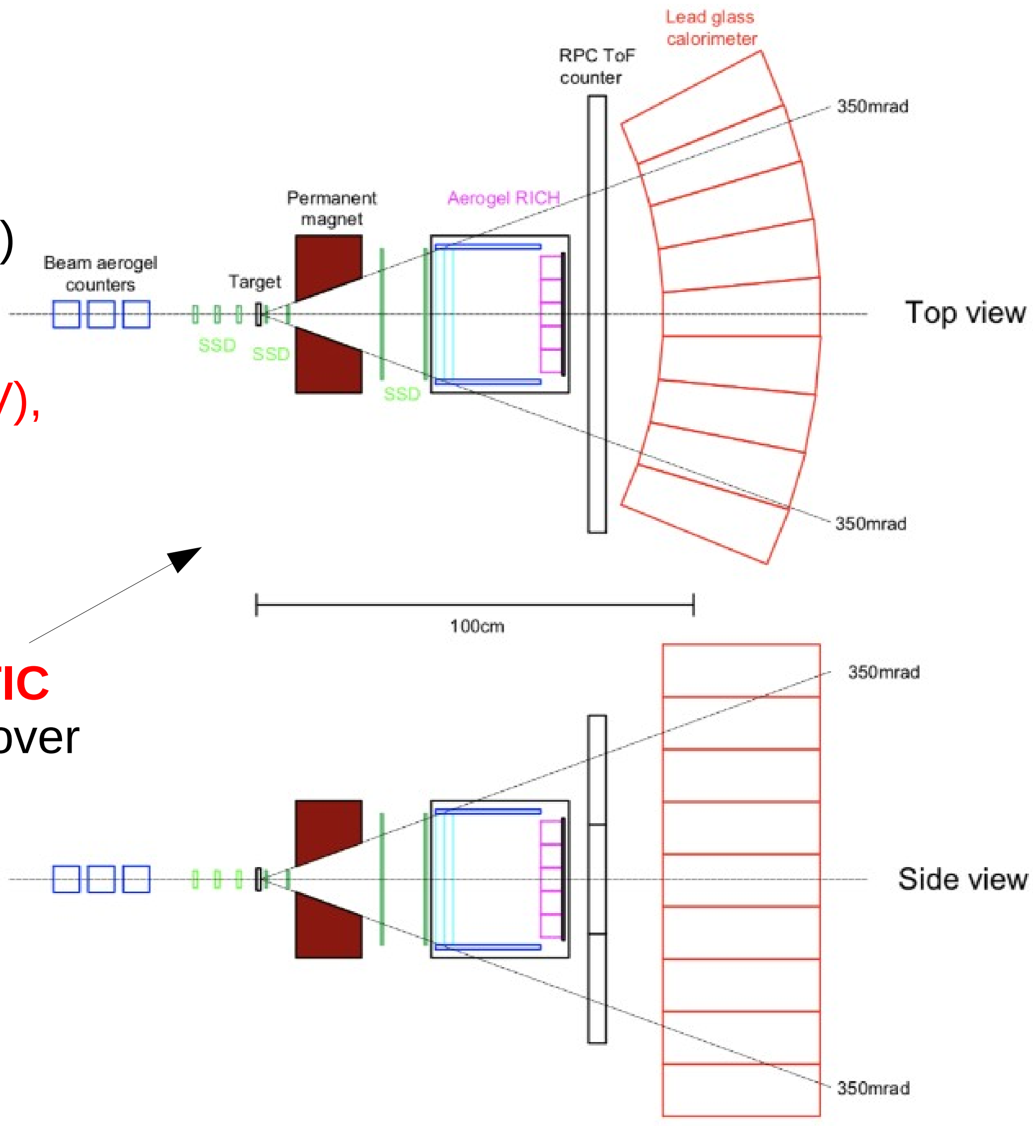
- Interactions not tuned are due to Kaons (for ν_e) and to low energy interactions in beamline materials
→ **NA61 future:** low energy beamline (<15 GeV),
(also improvements to present results: major systematics is due to bwd extrapolation
→ new small TPC downstream the target)



- 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

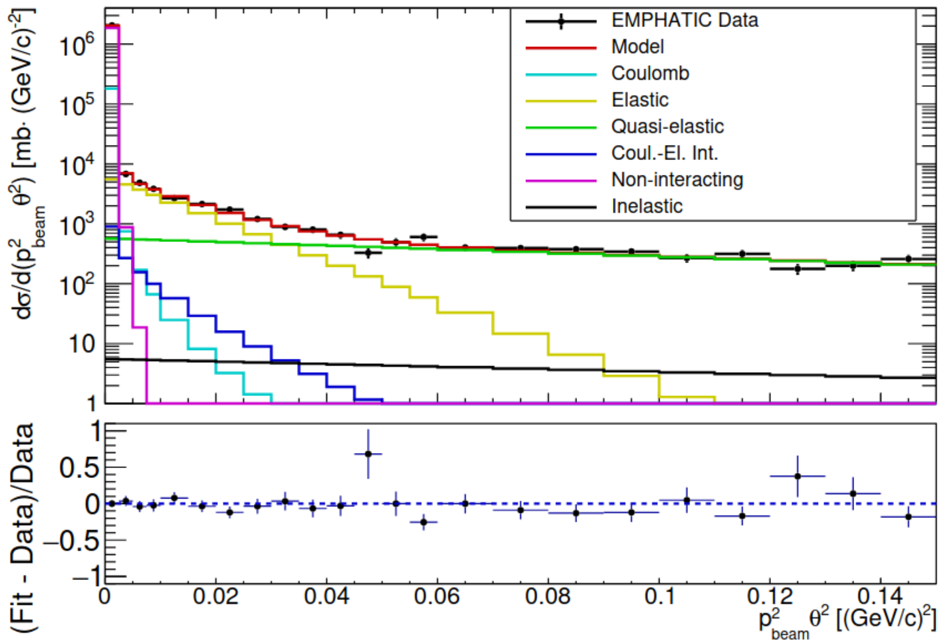
Total xsec can be measured by combination of

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

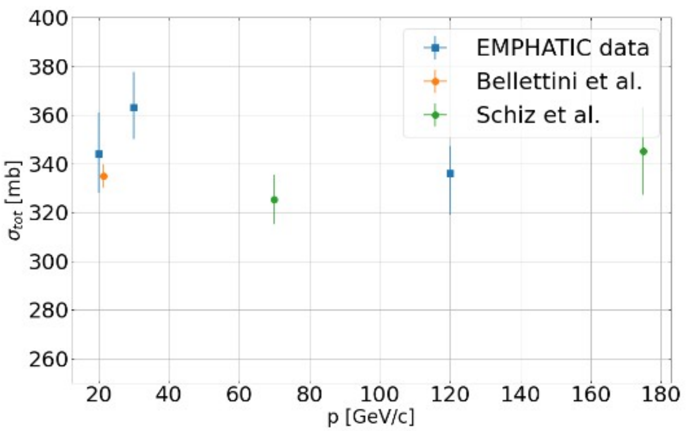
- optical theorem: Im part of limit at t^2=0 GeV^2 of scattering amplitude

First pilot run for proof of principle

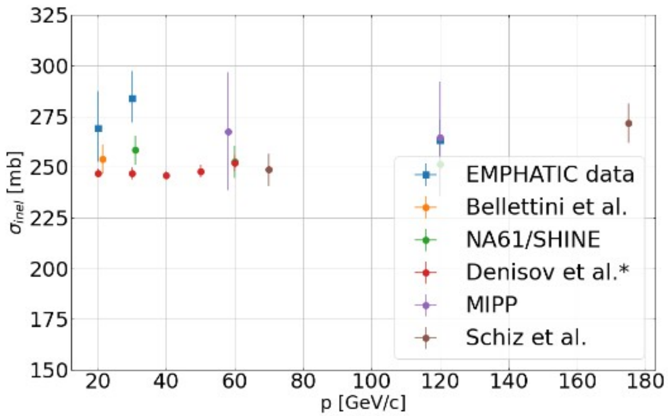
e-Print:2106.15723 [physics.ins-det]



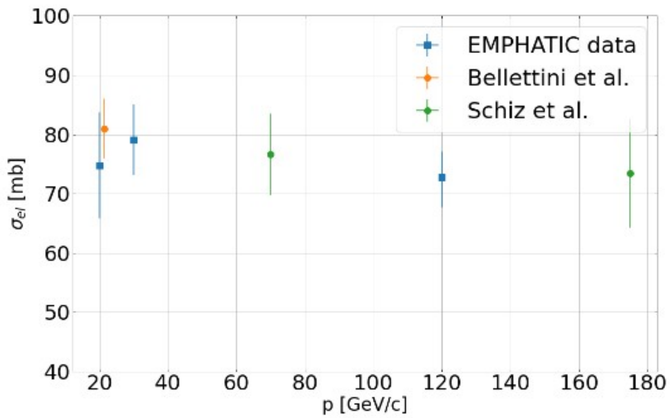
σ_{tot}



$\sigma_{inelastic}$

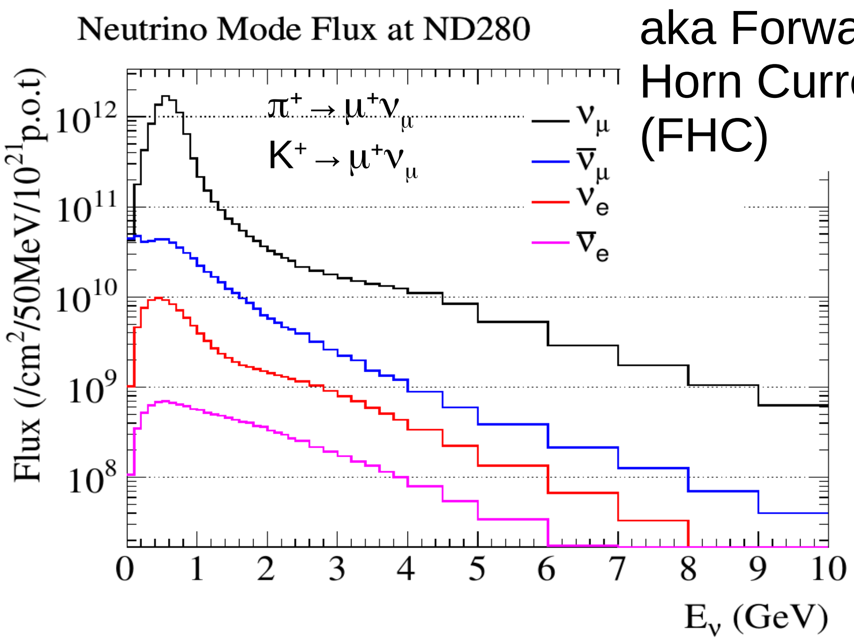


$\sigma_{elastic}$

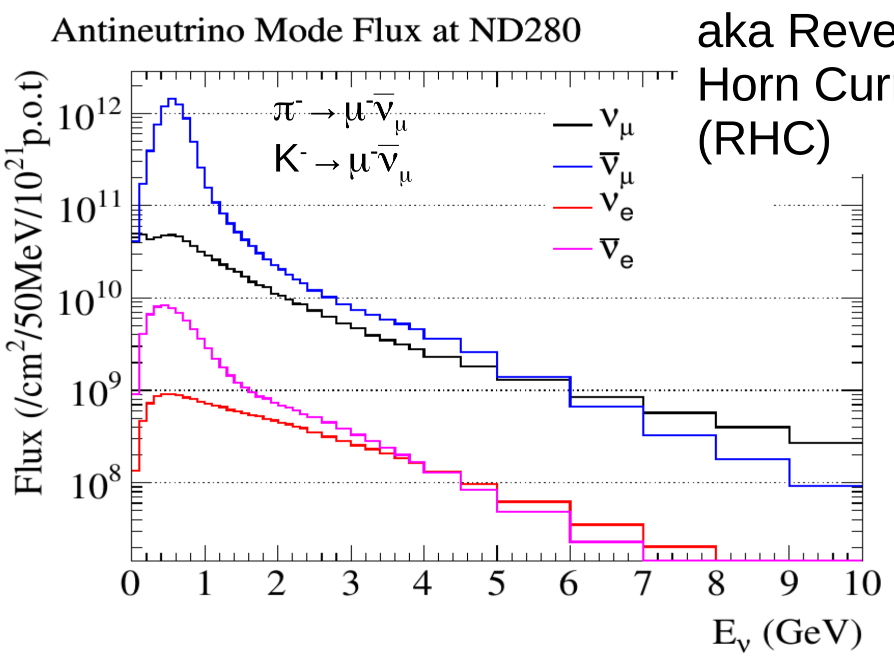


Flux in accelerator experiments

Flux in T2K: wrong sign

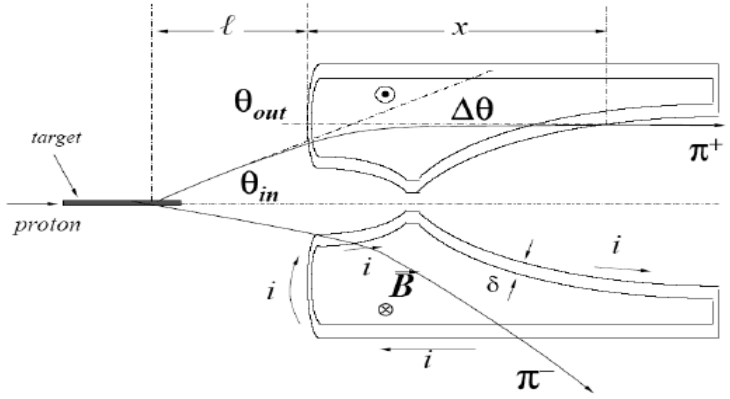


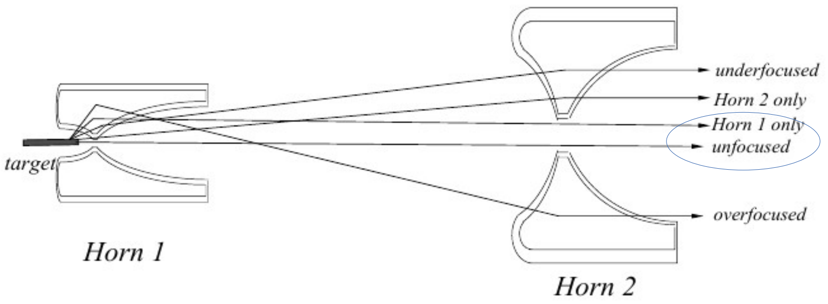
aka Forward Horn Current (FHC)



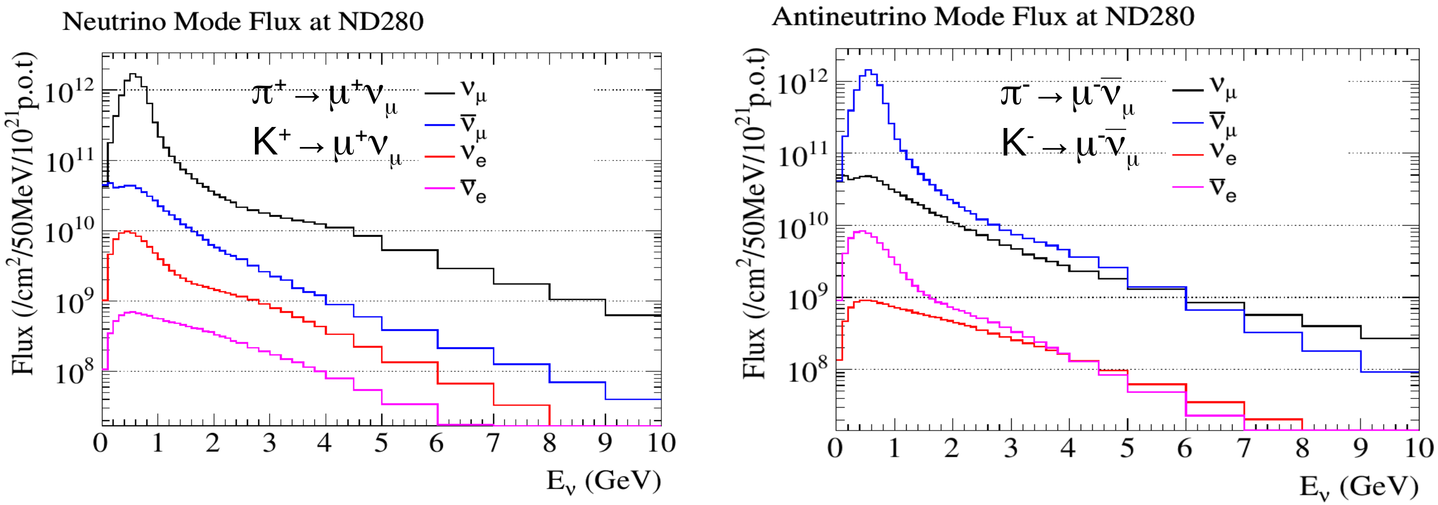
aka Reverse Horn Current (RHC)

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

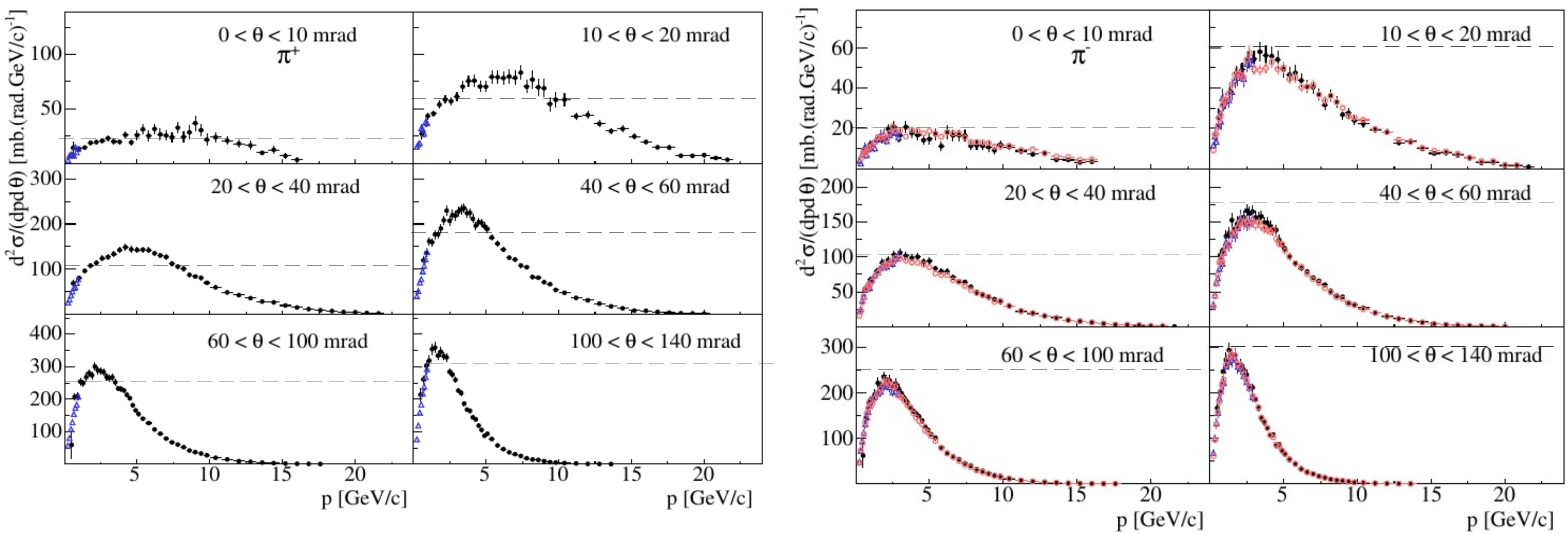




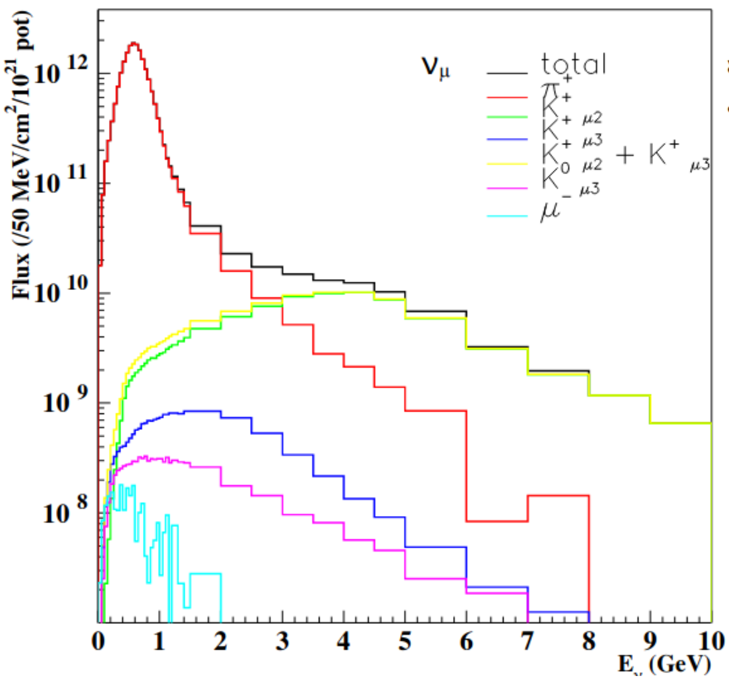
Flux in T2K: wrong sign

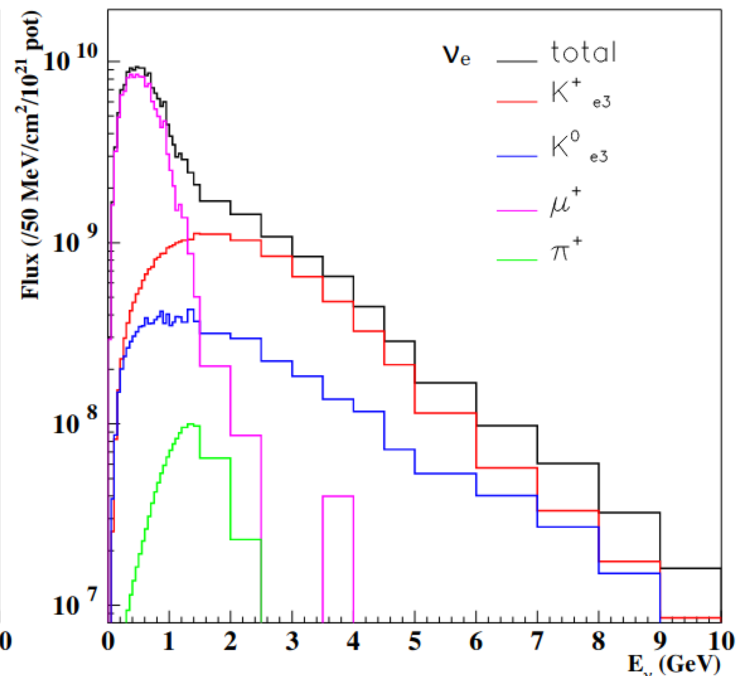


The 'wrong sign' background is larger in antineutrino mode since when proton hits the target it is more probable to create positive charged hadrons than negative ones



Flux in T2K: intrinsic ν_e





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

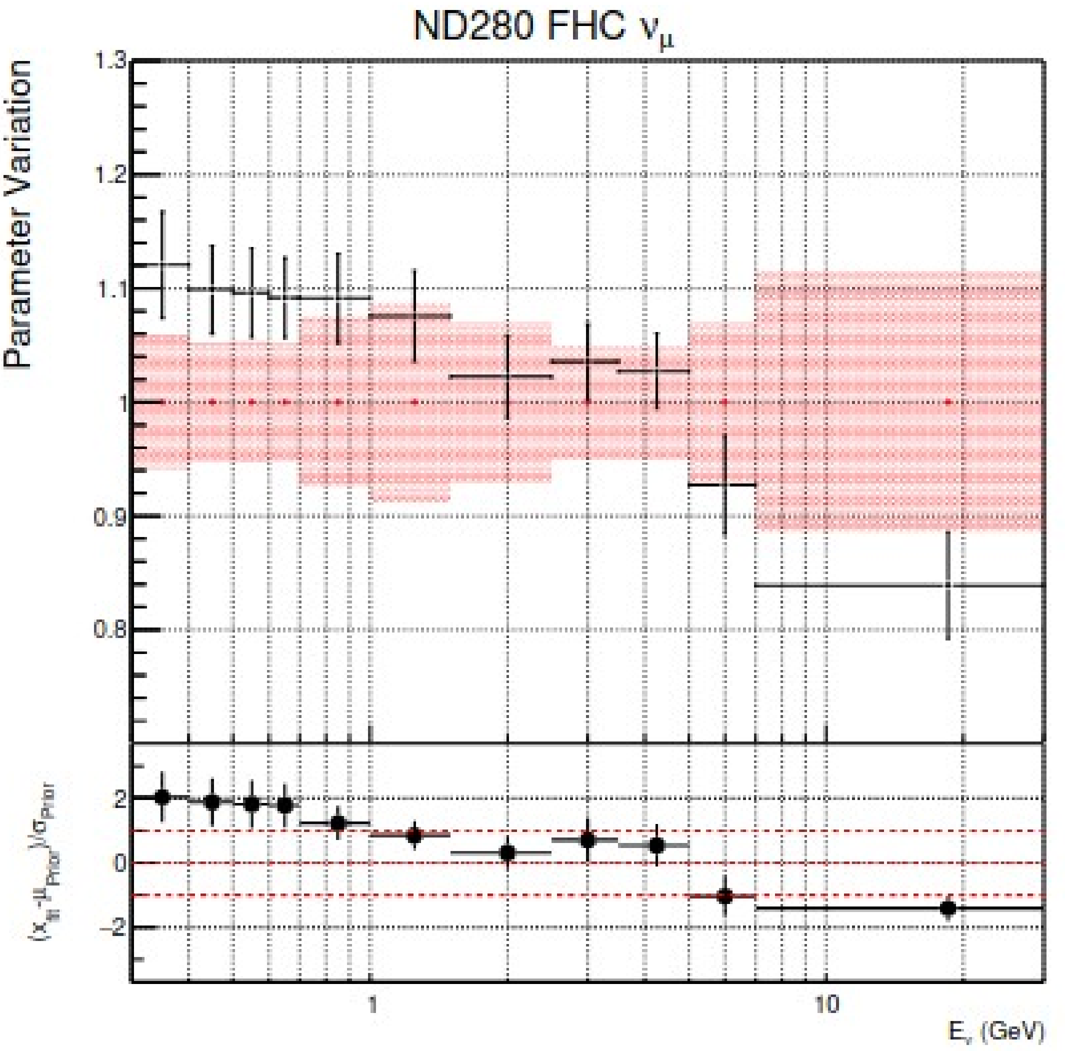
- Small intrinsic background to ν_e appearance measurements (important for δ_{CP} and MO).
- It can also be used to measure ν_e xsec at the near detector (with limited statistics)

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

Flux constraint from the ND

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

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



Flux constraint from the ND

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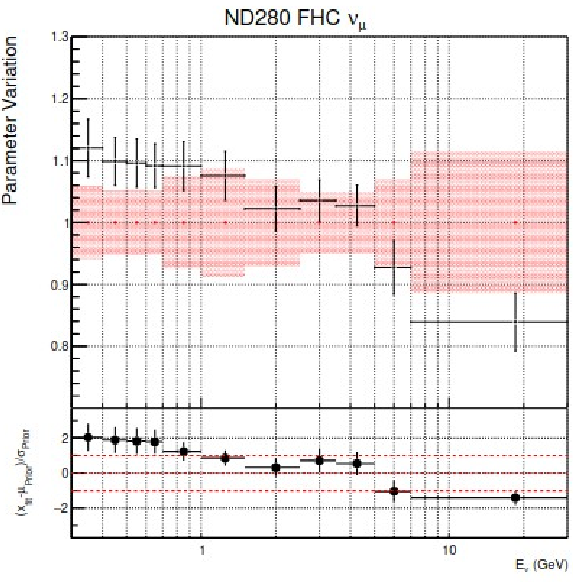

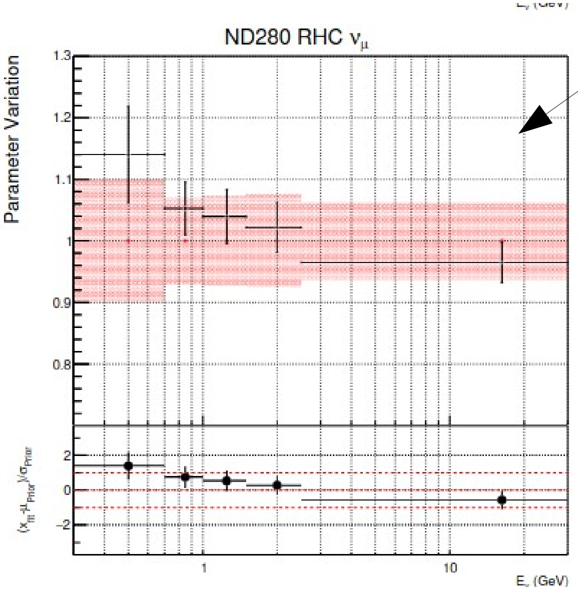

ND280 magnetized → measurement of wrong sign background

Flux constraint from the ND

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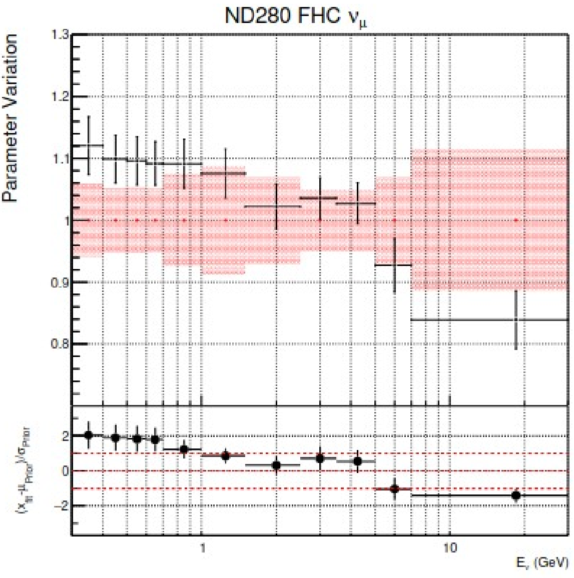
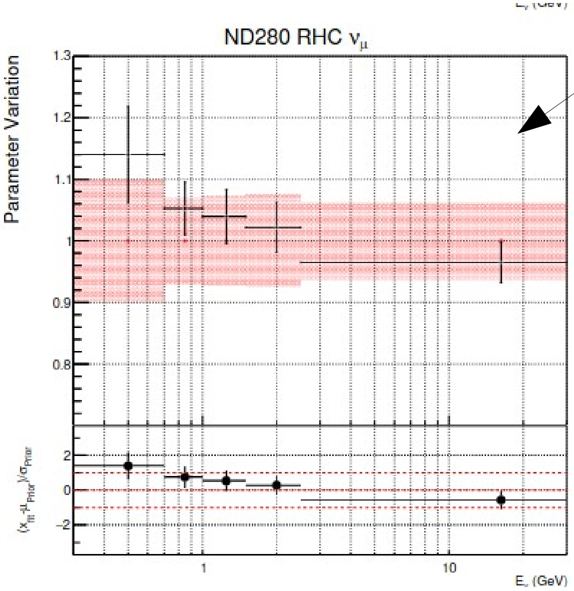
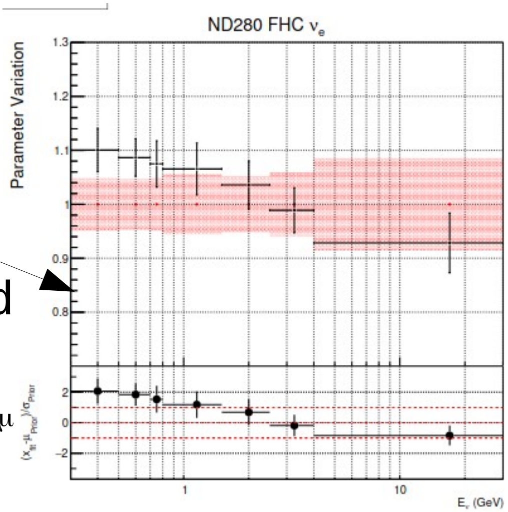
$$N_{\nu_\alpha}^{ND}(E_\nu) = \phi(E_\nu) \times \sigma(E_\nu)\, dE_\nu$$





ND280 magnetized → measurement of wrong sign background

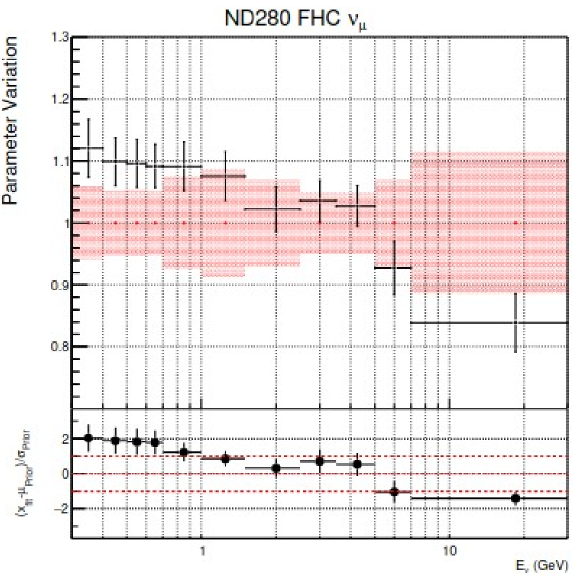
Low intrinsic ν_e stat → constrained only through correlations with ν_μ

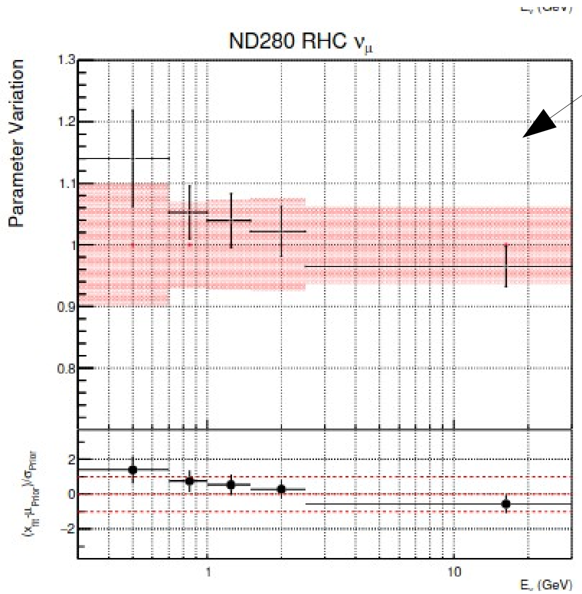


Flux constraint from the ND

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

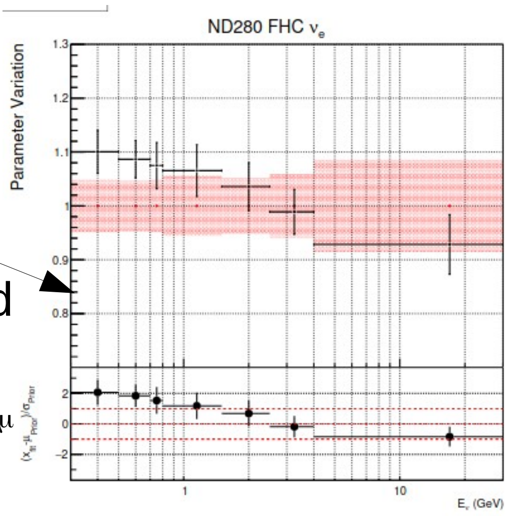
$$N_{\nu_\alpha}^{ND}(E_\nu)=\phi(E_\nu)\times\sigma(E_\nu)\,dE_\nu$$





ND280 magnetized → measurement of wrong sign background

Low intrinsic ν_e stat → constrained only through correlations with ν_μ



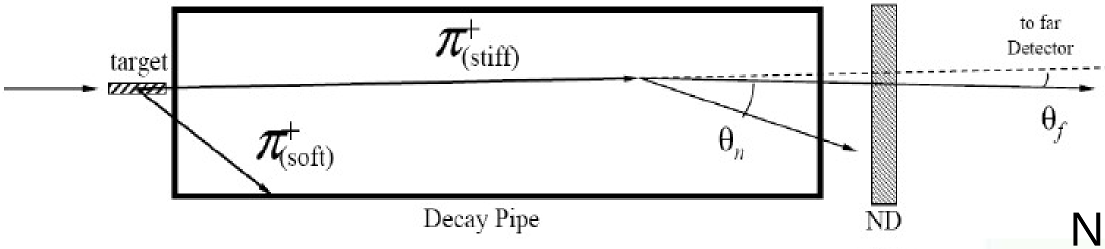
	Pre- ND fit	Post- ND fit
flux	~5%	~2.8-3.0%
cross-section	~10-15%	~3.5-3.8%
flux+xsec		~2.6-2.8%
Total (+ xsec not accessible at ND, SK detector)	~17%	~3.5-5%

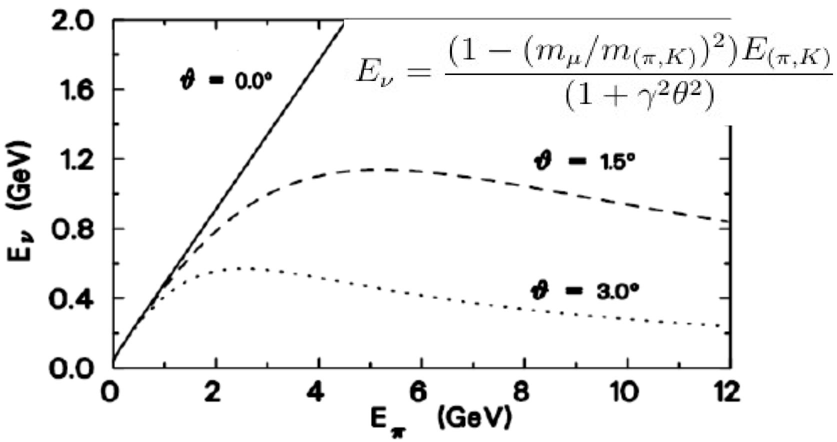
- Today xsec uncertainties dominate before the fit
- strong anticorrelation between flux and xsec (would be 5-10% if uncorrelated)
- flux*xsec constitutes ~50% of the final systematic error budget

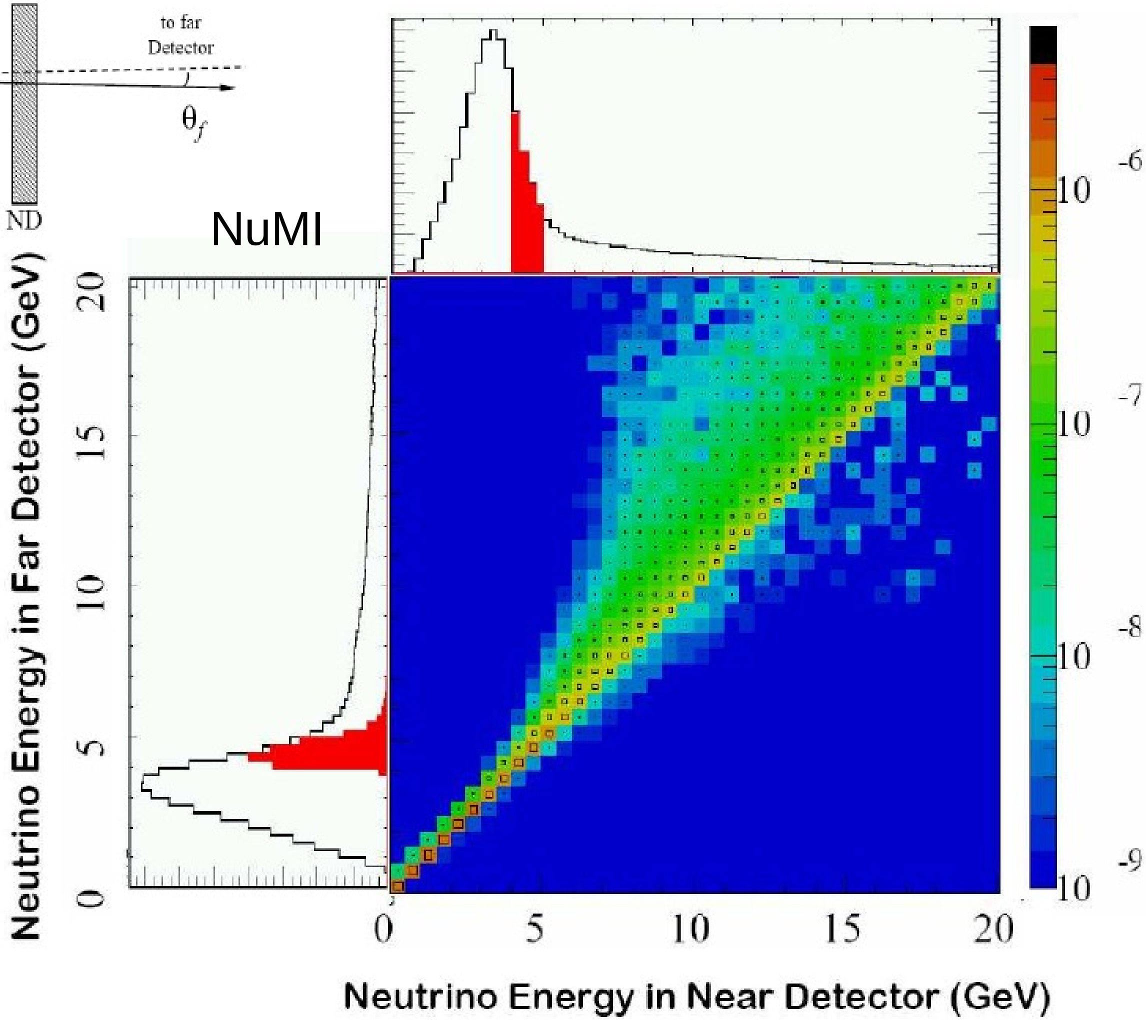
From ND to FD flux extrapolation

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

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





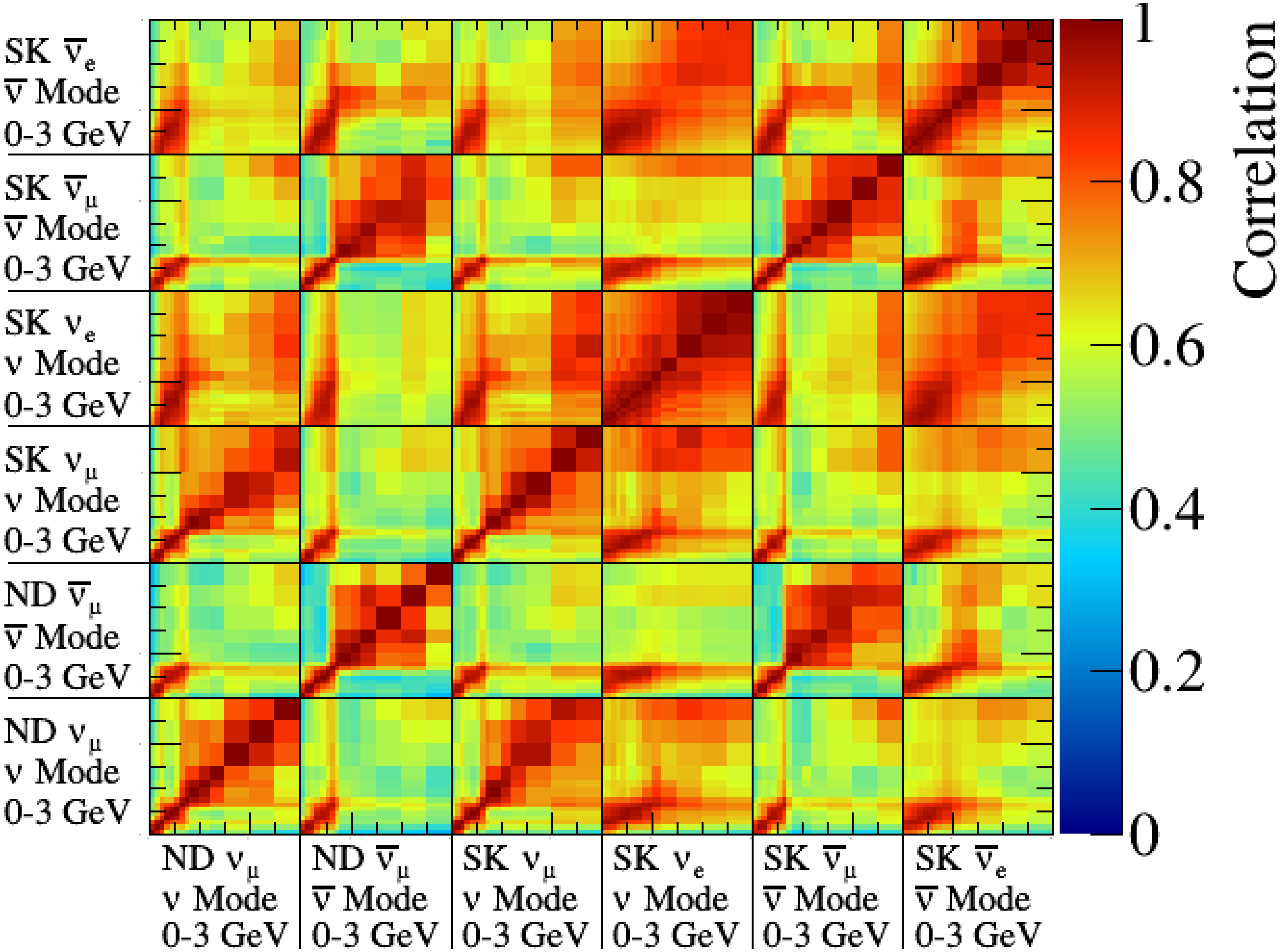


Extrapolation ND->FD uncertainties smaller (~1%) than overall flux uncertainties (10% → 5%)

Flux correlations

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

T2K



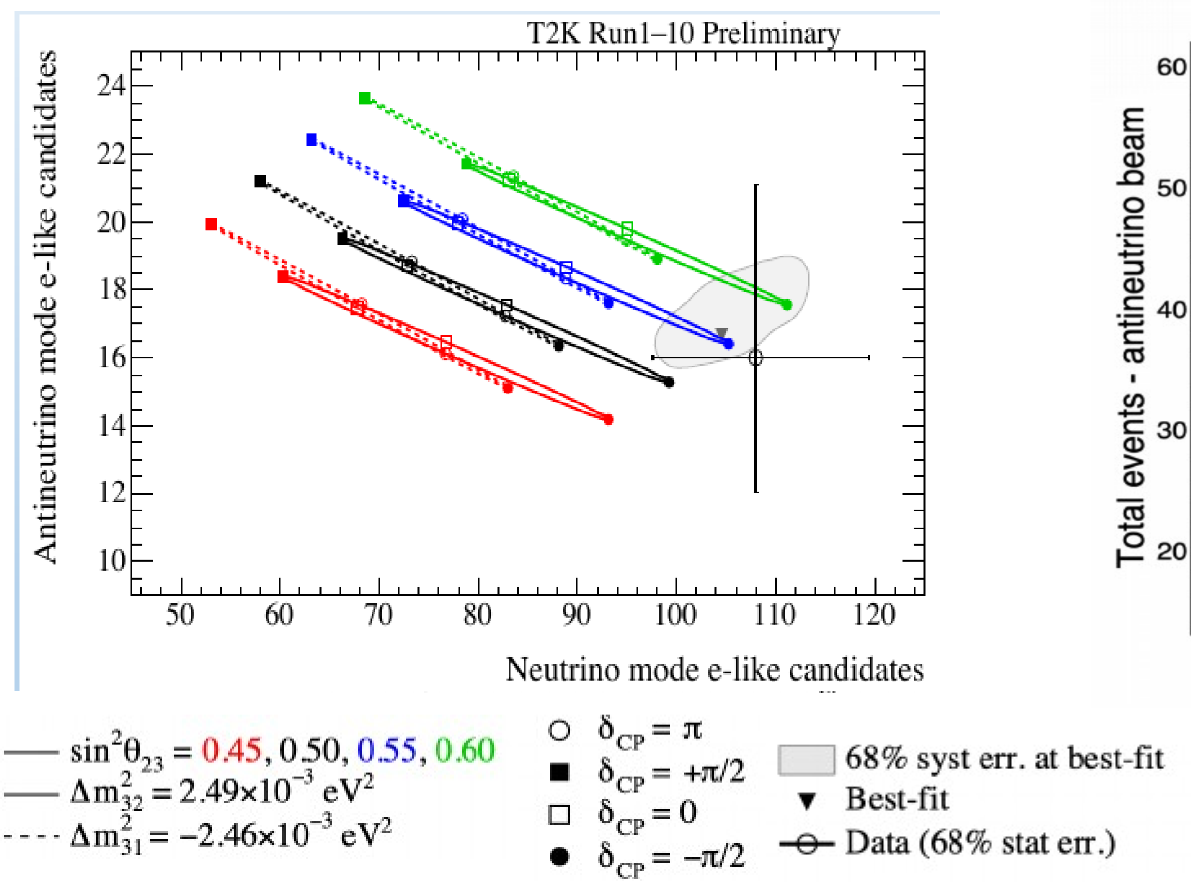
- **large correlation between ND and SK fluxes**
- Large correlations between different bins in the same 'mode' → **flux uncertainty is to large extent an overall normalization** (shape uncertainties are smaller)
- **Correlations between different modes and neutrino flavors:** (to a certain extent) we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

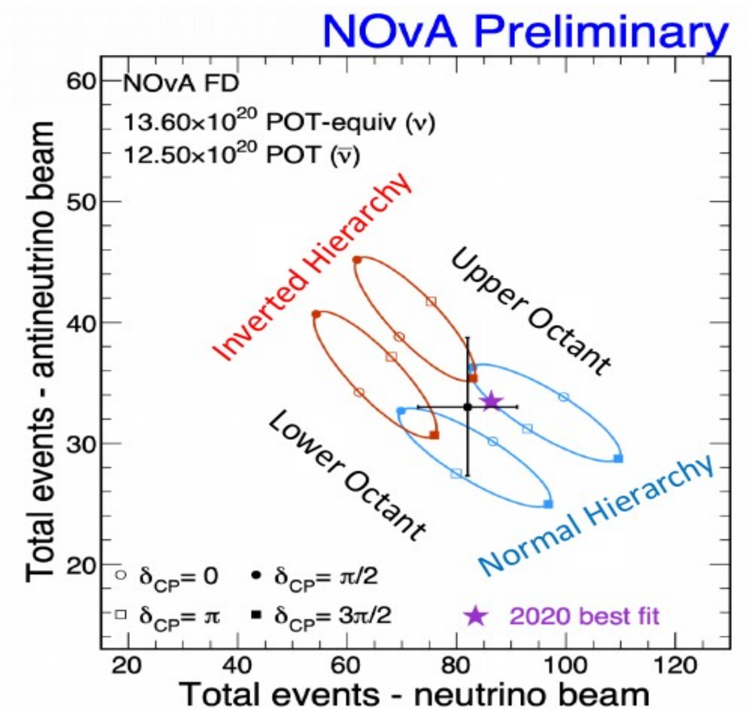
$\nu_e/\bar{\nu}_e$ apperance: MH, δ_{CP}

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

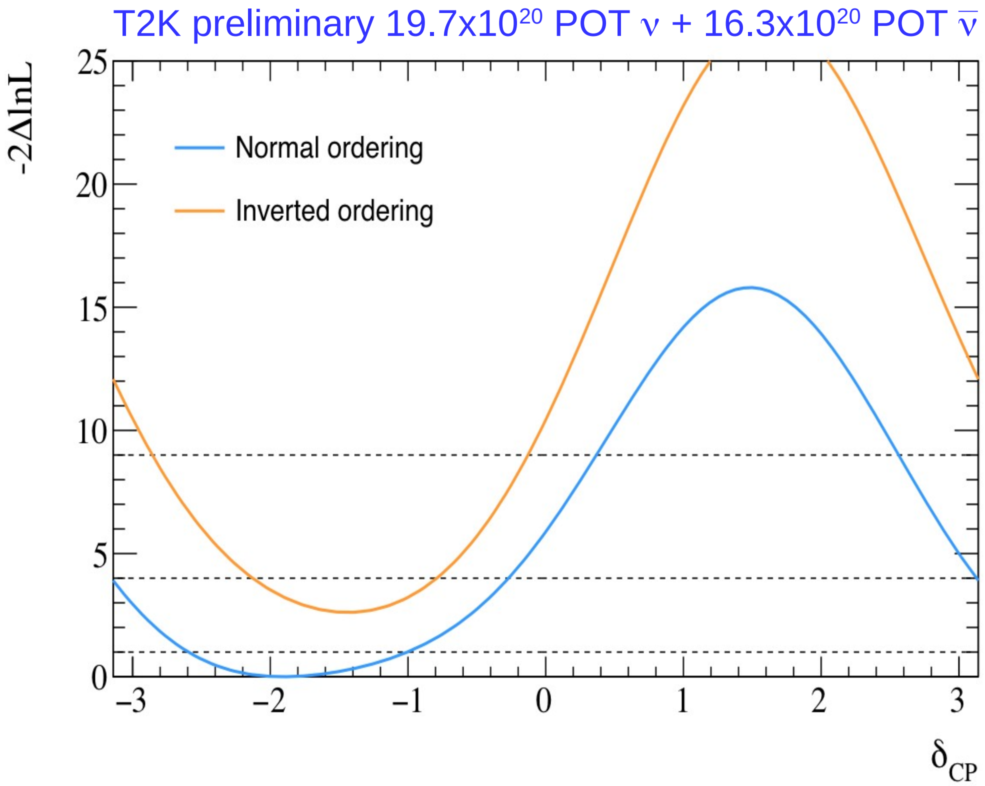
- **T2K: clean δ_{cp} measurement with small MH sensitivity**
- **NOVA: degenerate δ_{cp} and MH:** (δ_{CP} $3\pi/2$ and IH = δ_{CP} $\pi/2$ and NH)

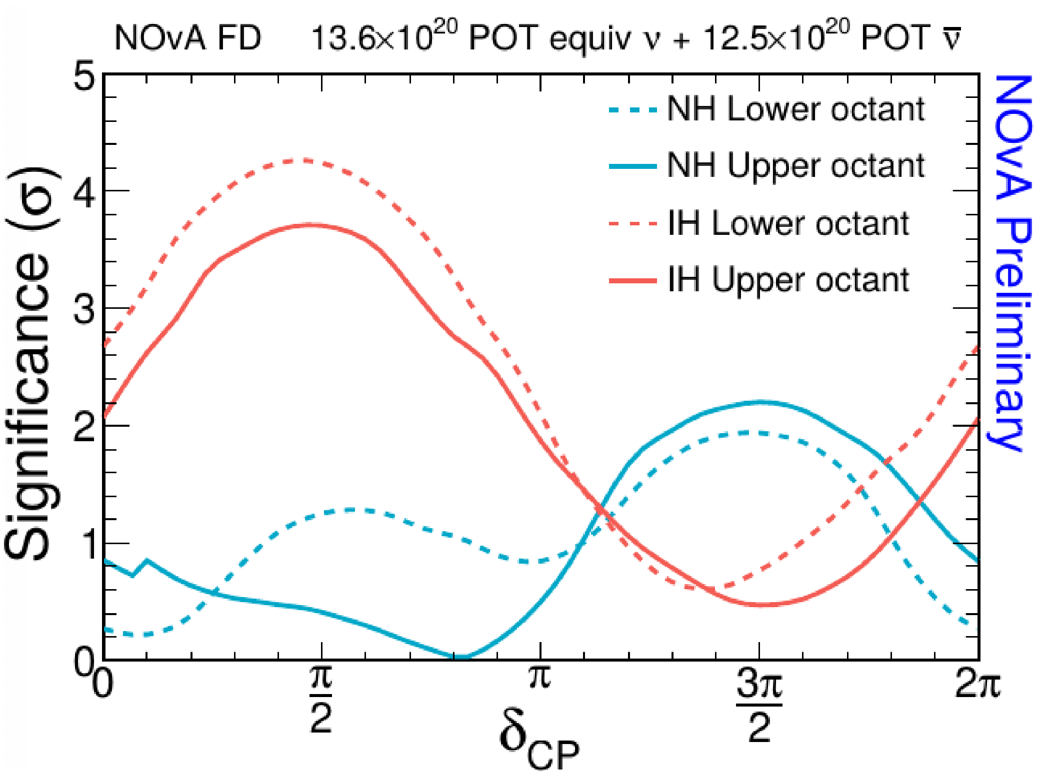
Using 2020 results in the following (2022 improved analyses confirmed the situation)





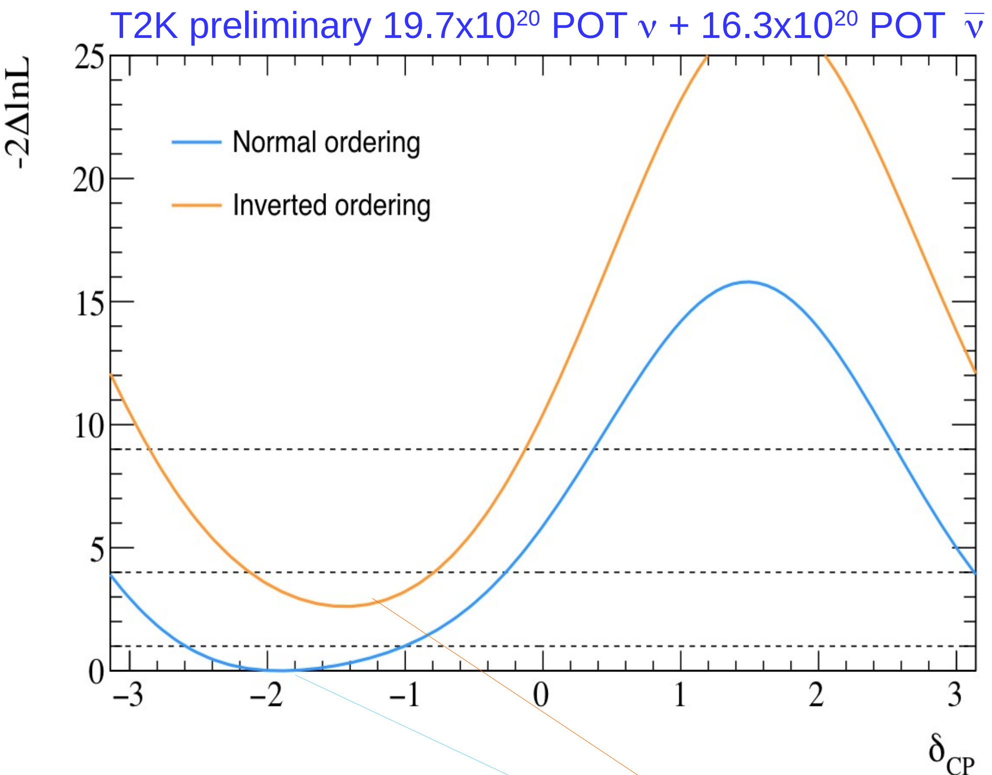
Results



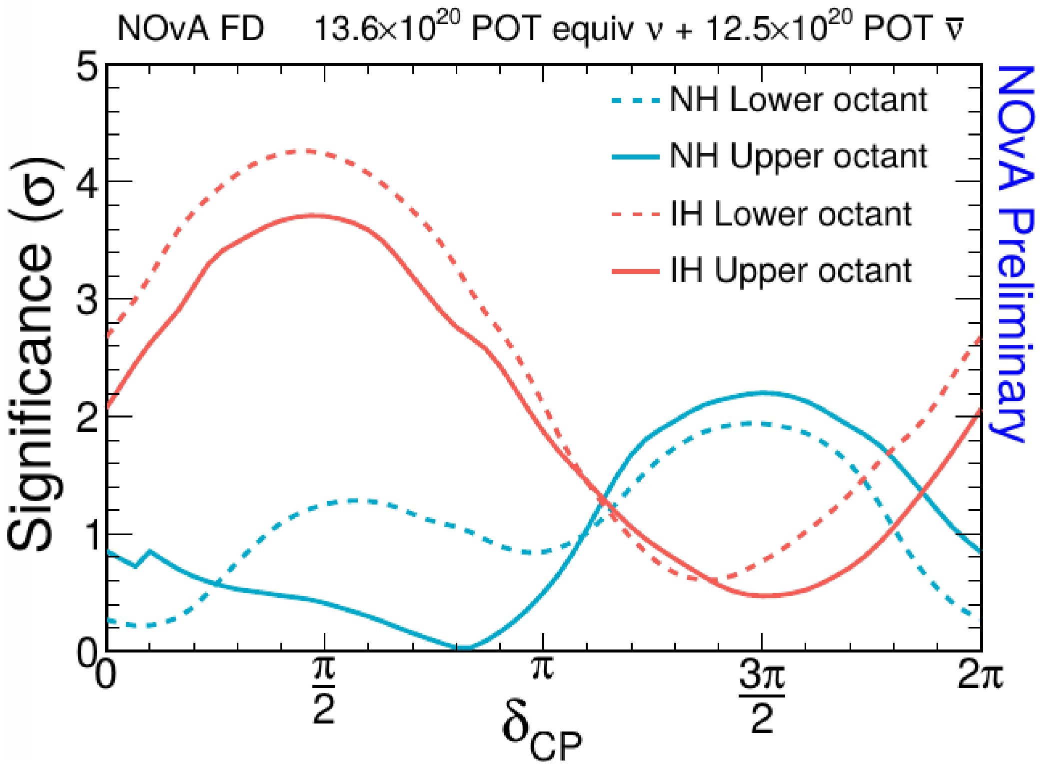


- Large **region disfavoured at 3σ** (T2K Nature cover in 2020). And for T2K even some region at 5σ but precision of statistical treatment will be discussed later.
Similar region disfavoured at T2K for NH and IH, while 3σ exclusion in NOVA only for IO

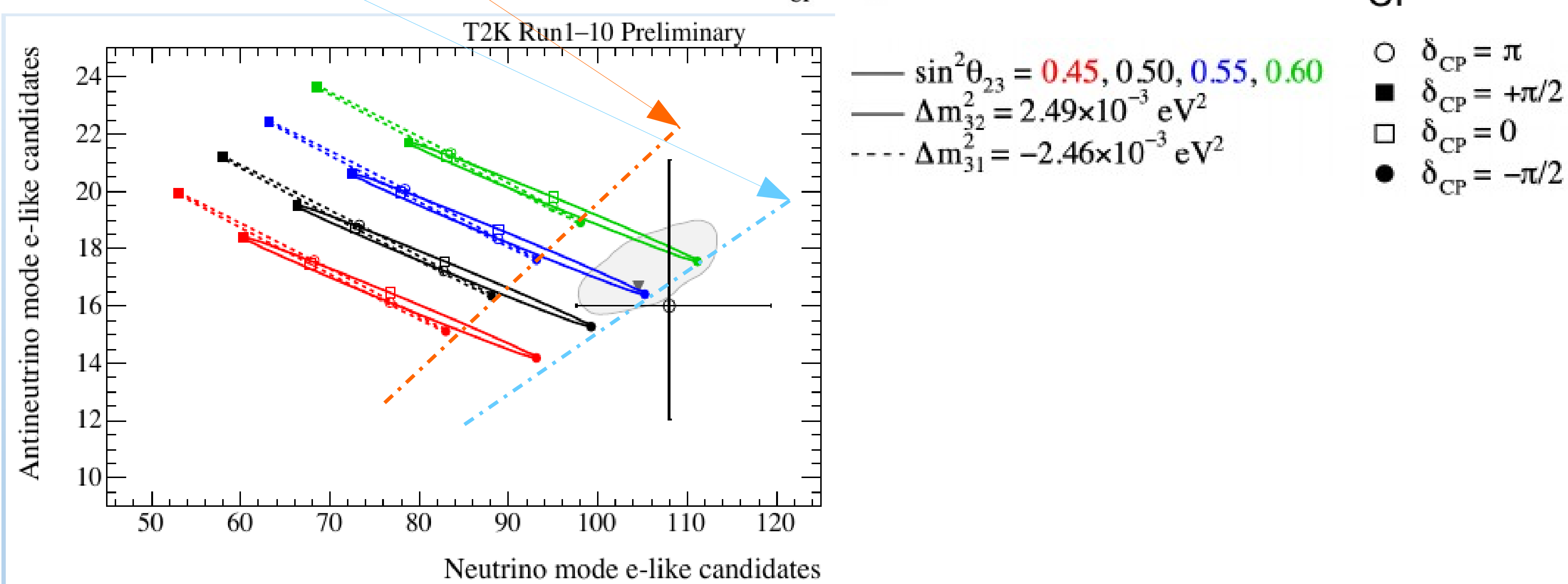
Results



T2K preliminary 19.7x10^20 POT ν + 16.3x10^20 POT ν̄
-2ΔlnL
Normal ordering
Inverted ordering
δ_CP

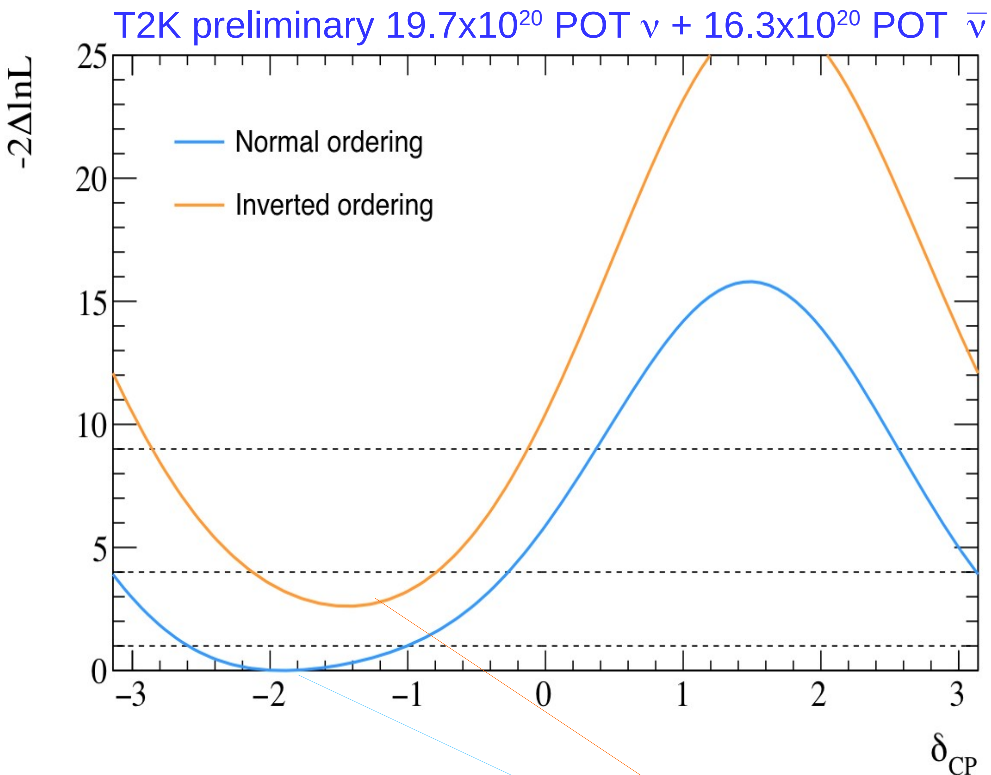


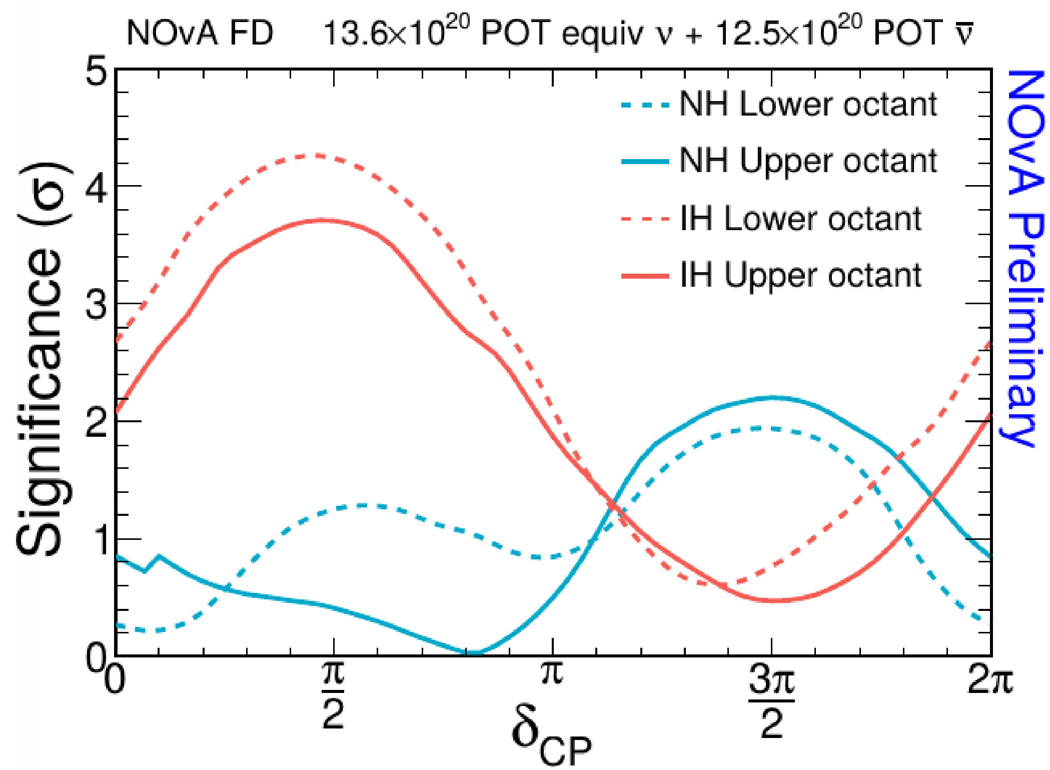
NOvA FD 13.6×10^20 POT equiv ν + 12.5×10^20 POT ν̄
Significance (σ)
NH Lower octant
NH Upper octant
IH Lower octant
IH Upper octant
NOvA Preliminary
δ_CP

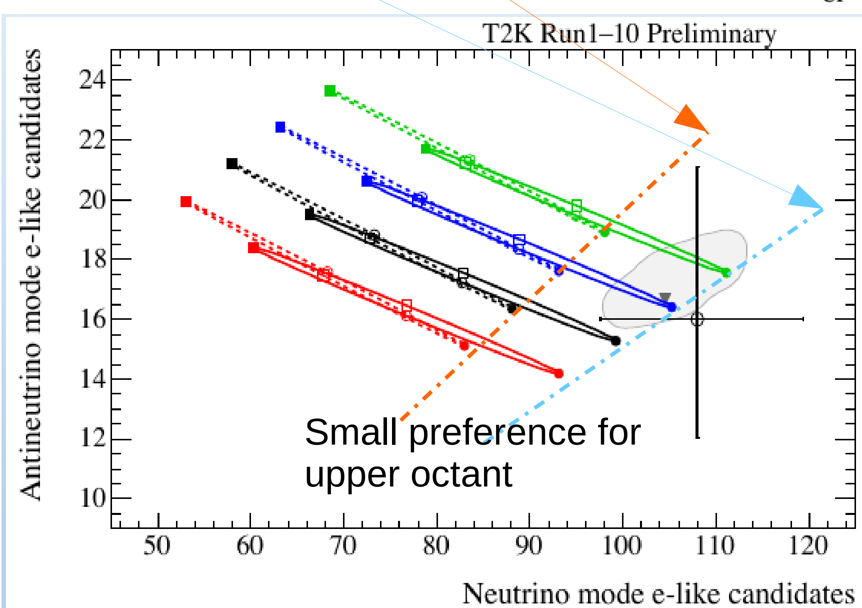


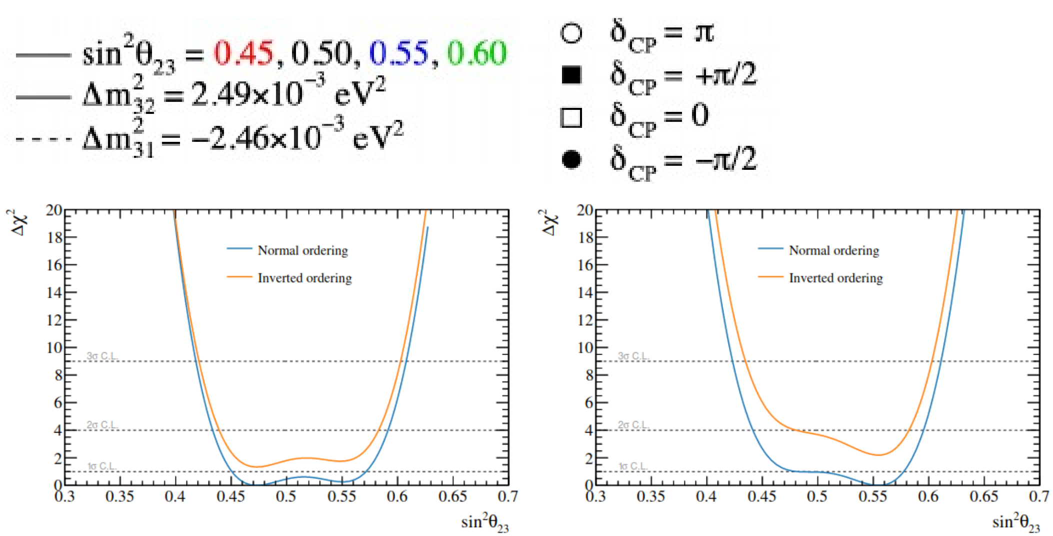
T2K Run1–10 Preliminary
Antineutrino mode e-like candidates
Neutrino mode e-like candidates
sin²θ23 = 0.45, 0.50, 0.55, 0.60
Δm²32 = 2.49×10⁻³ eV²
Δm²31 = −2.46×10⁻³ eV²
δCP = π
δCP = +π/2
δCP = 0
δCP = −π/2

Results



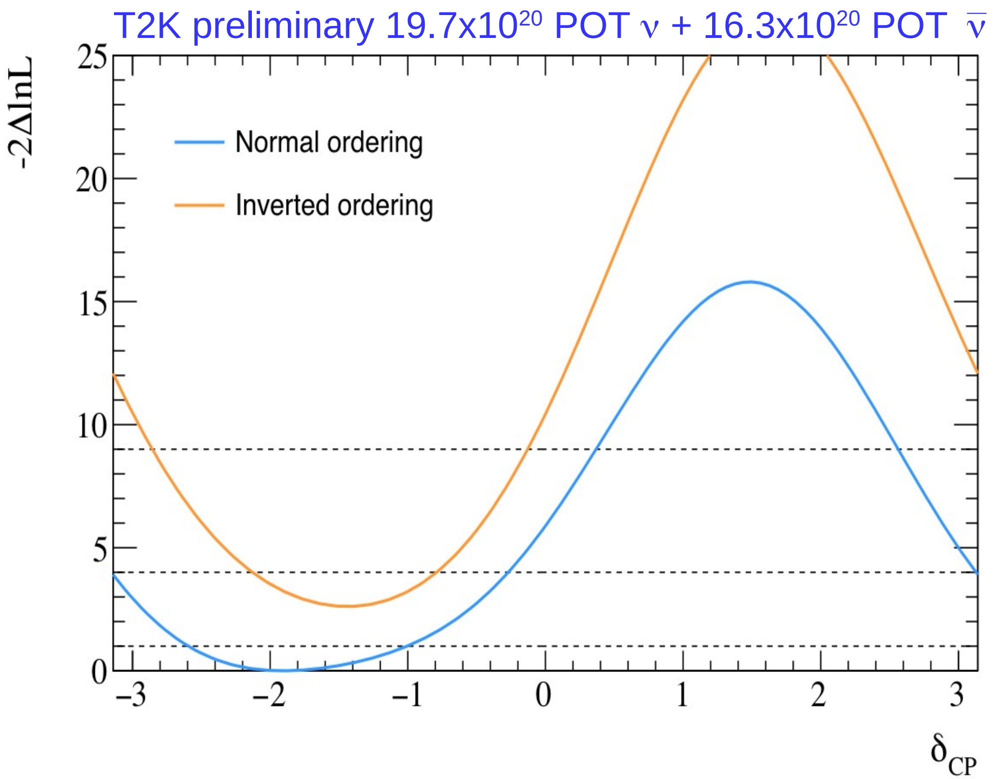


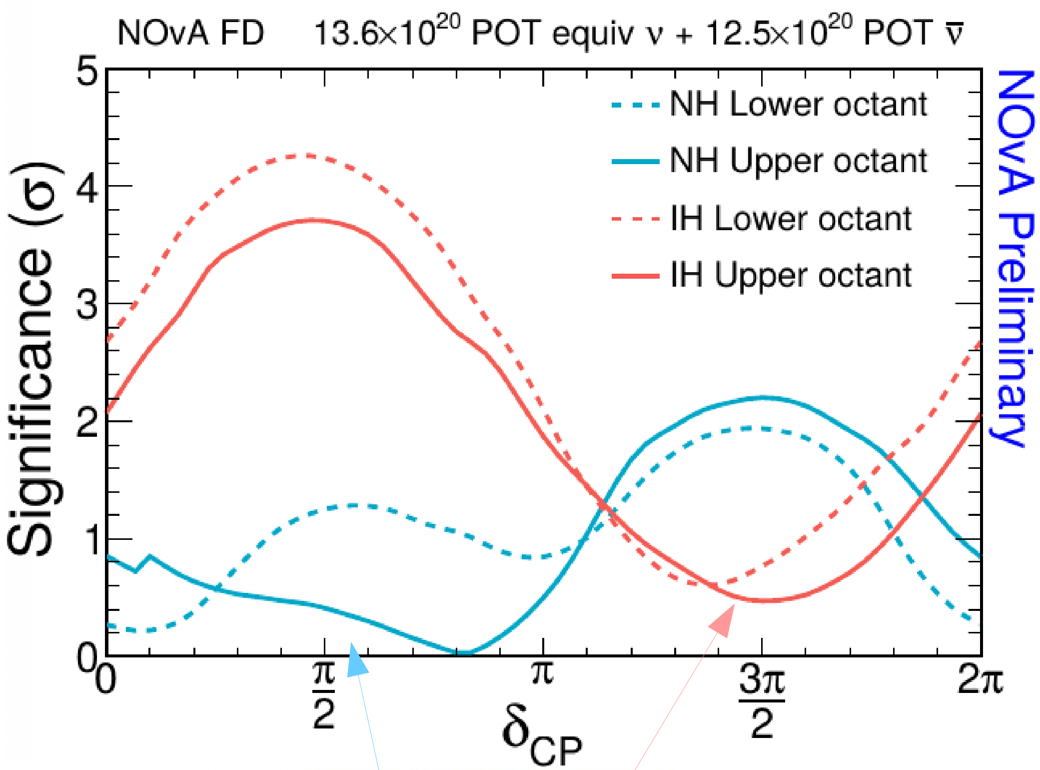




(a) T2K only (b) T2K + reactor

Results


T2K preliminary 19.7x10^20 POT ν + 16.3x10^20 POT ν̄
-2ΔlnL
Normal ordering
Inverted ordering
δCP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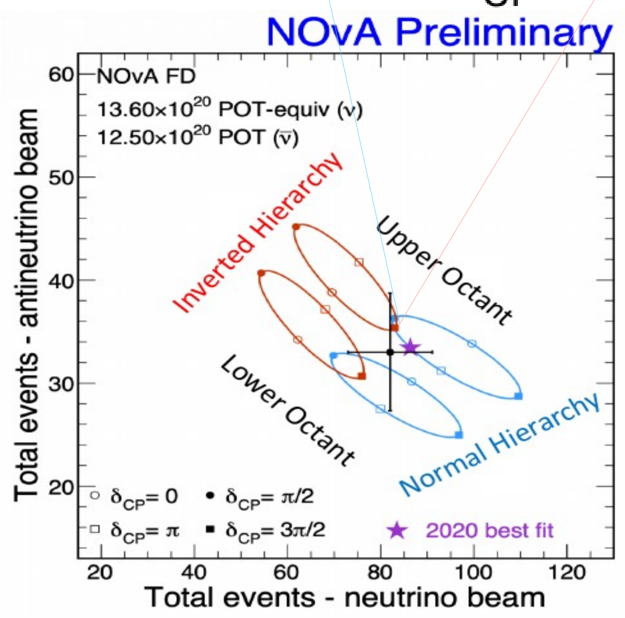
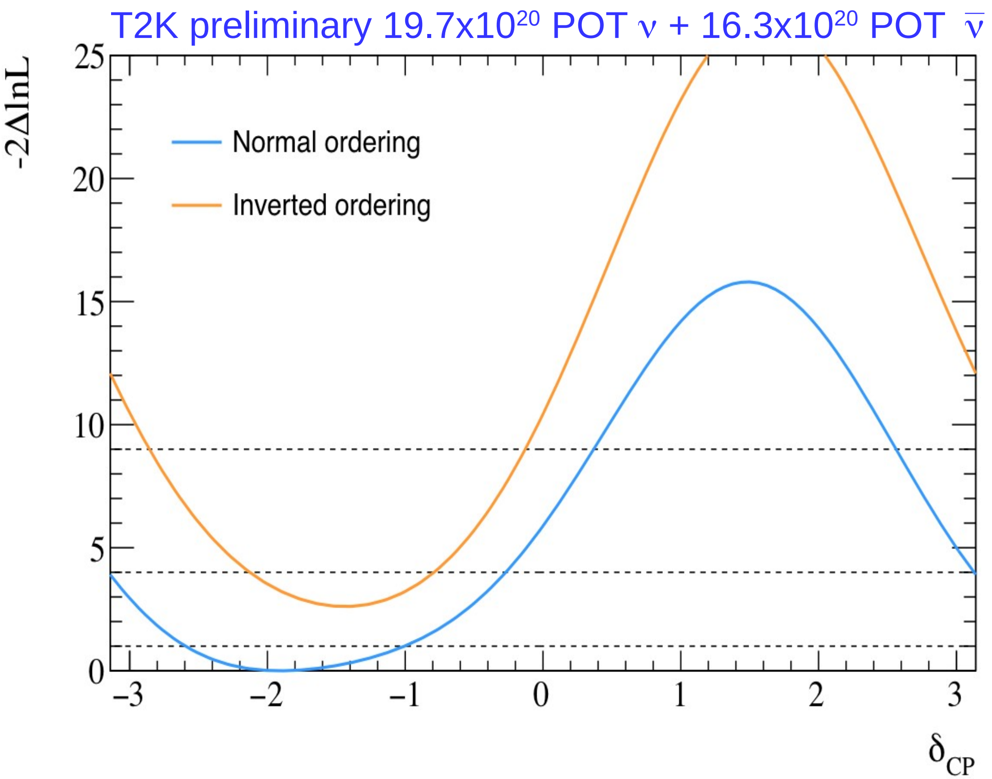
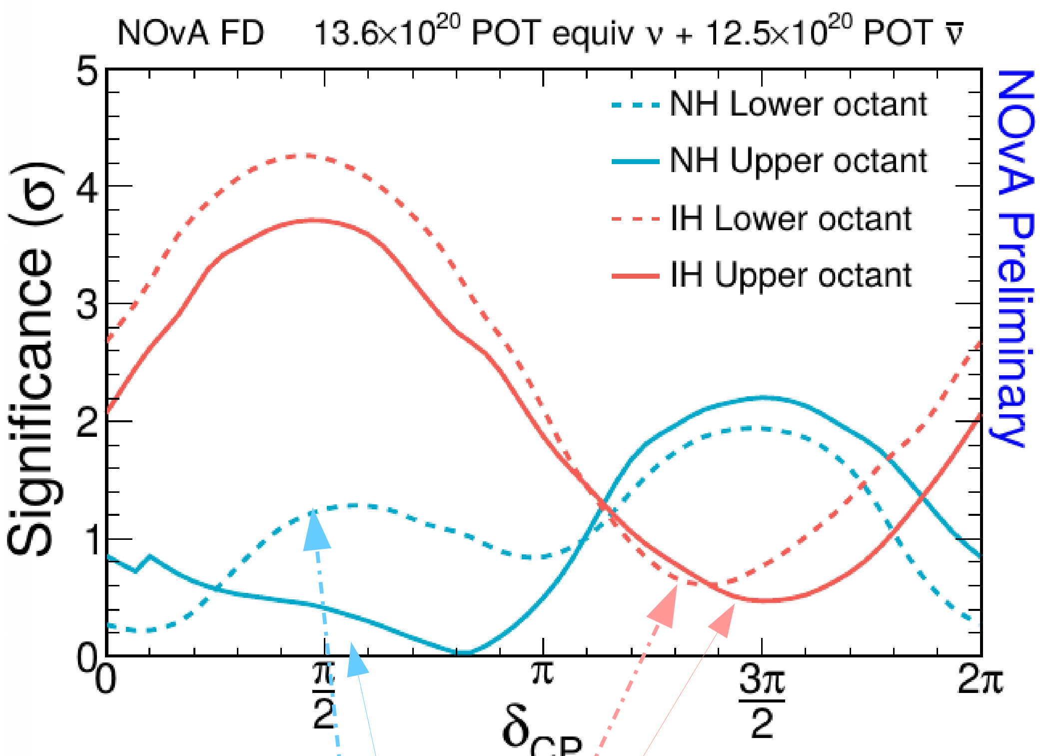
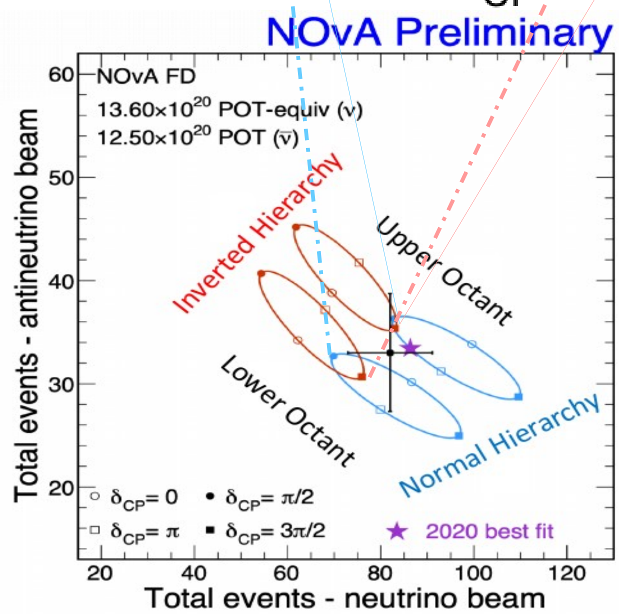
NH Lower octant
NH Upper octant
IH Lower octant
IH Upper octant
NOvA Preliminary
δCP


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

Results

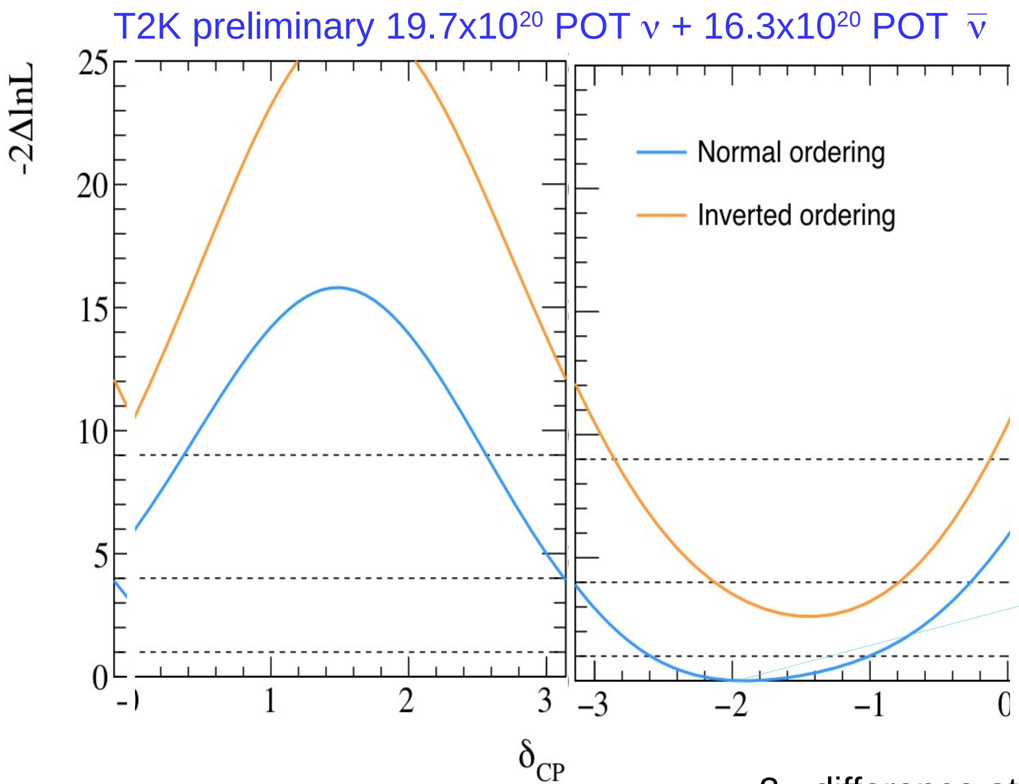


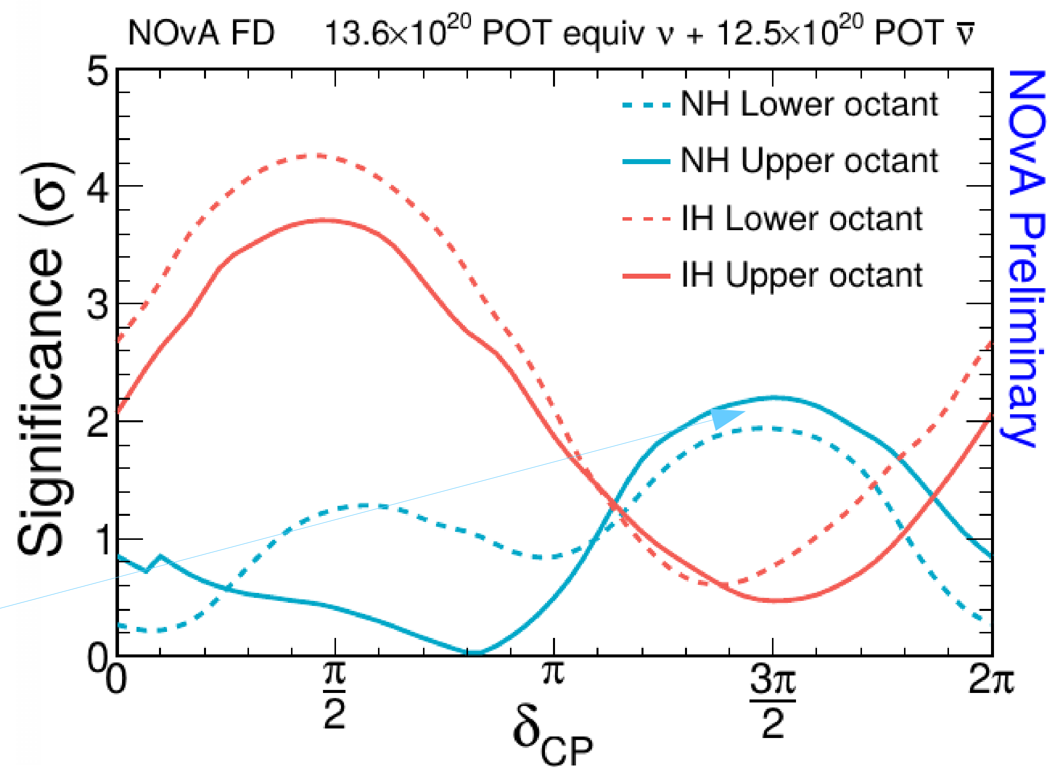




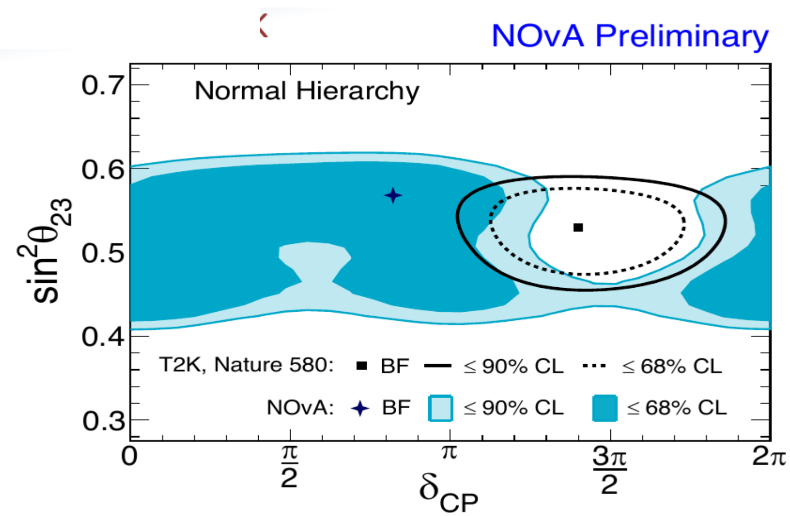
all these possibilities inside 1σ

Results

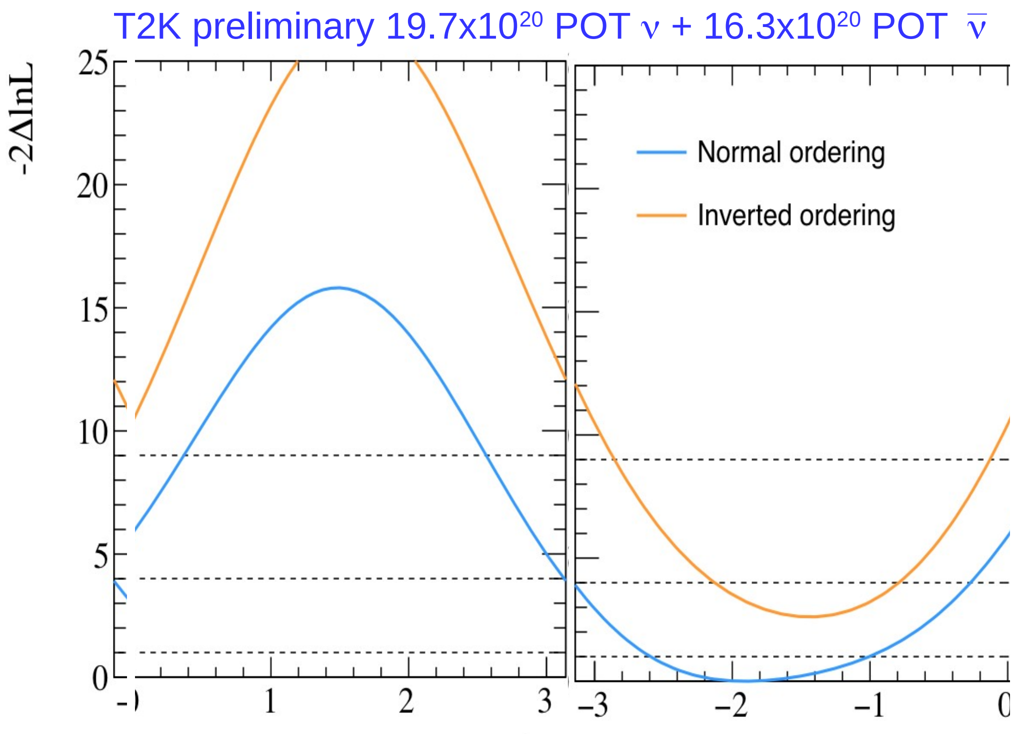


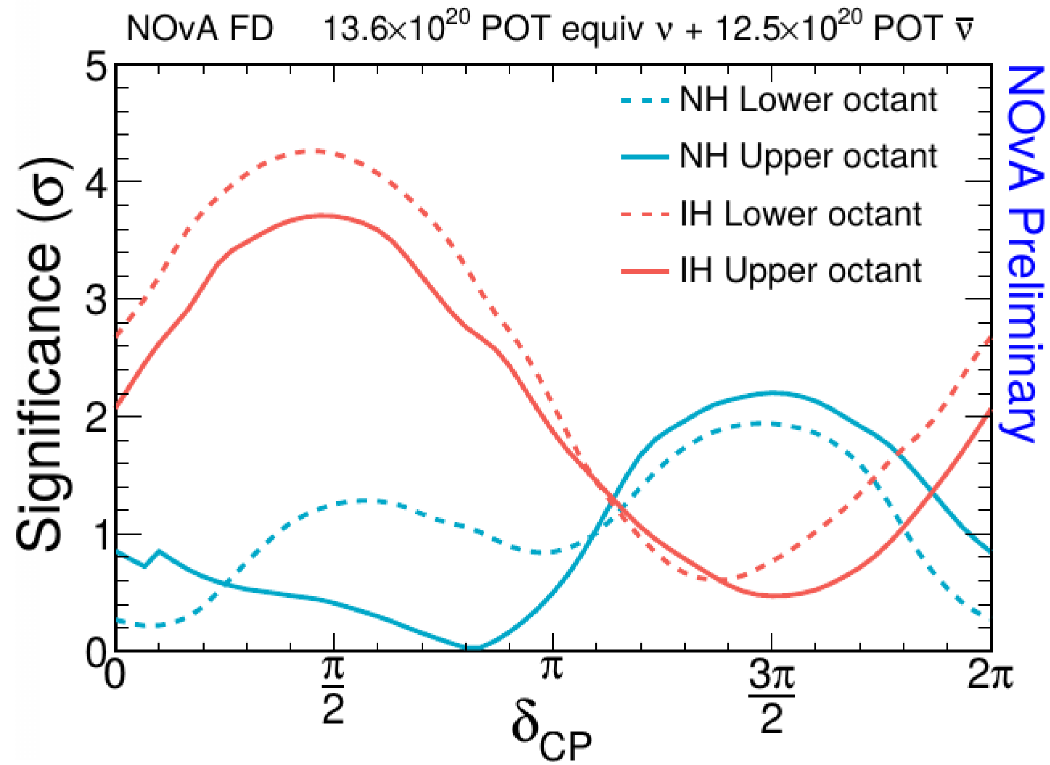


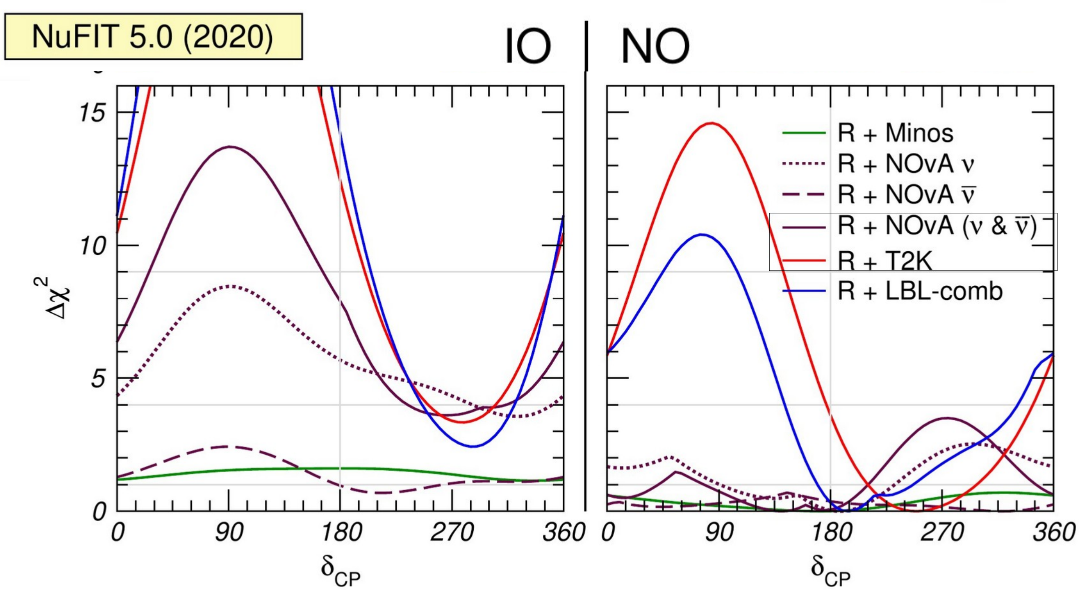
2σ difference at T2K minimum (max CPV, NH) but still common regions at 1σ

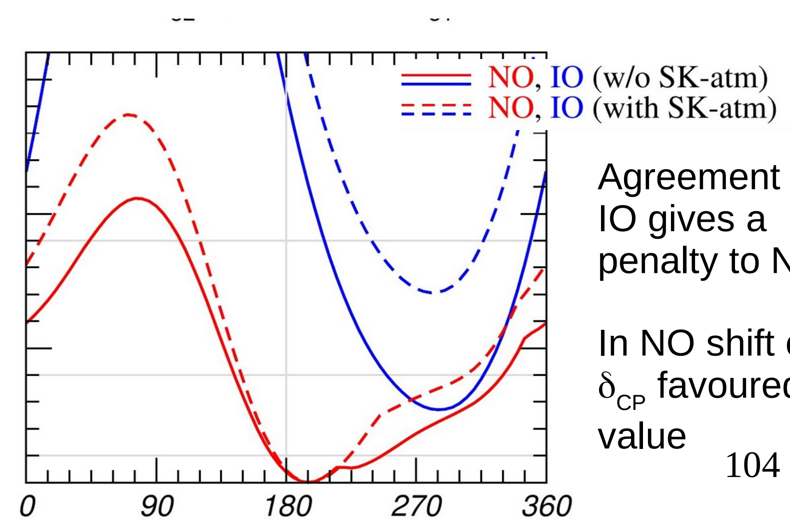


Results







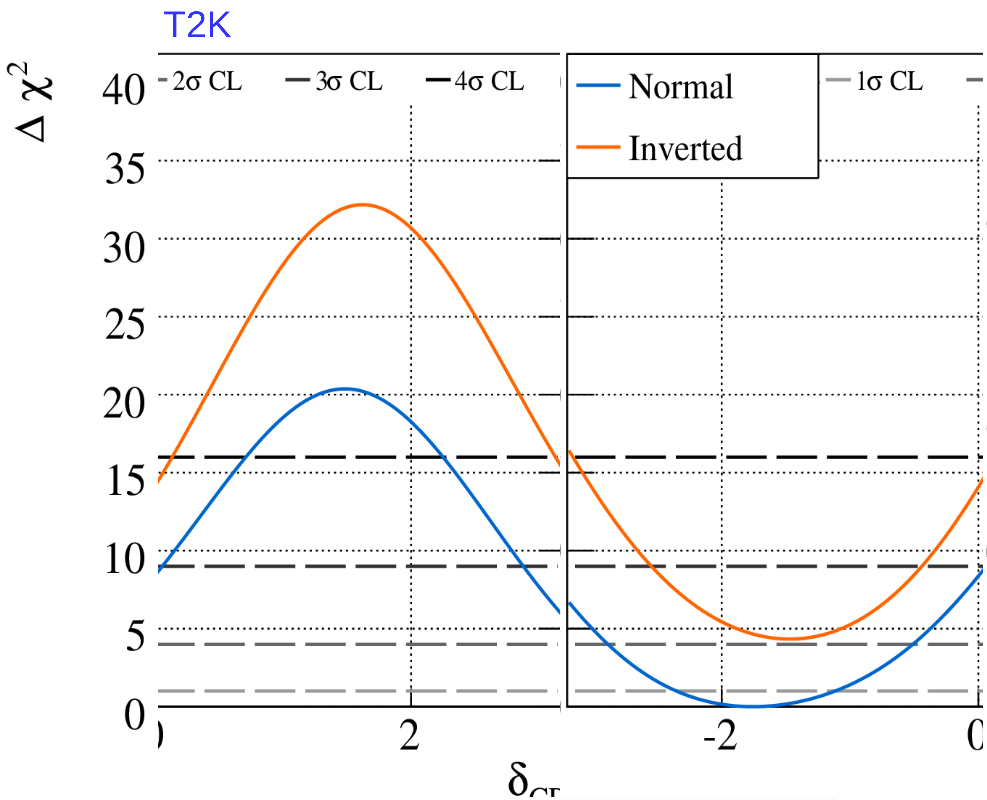


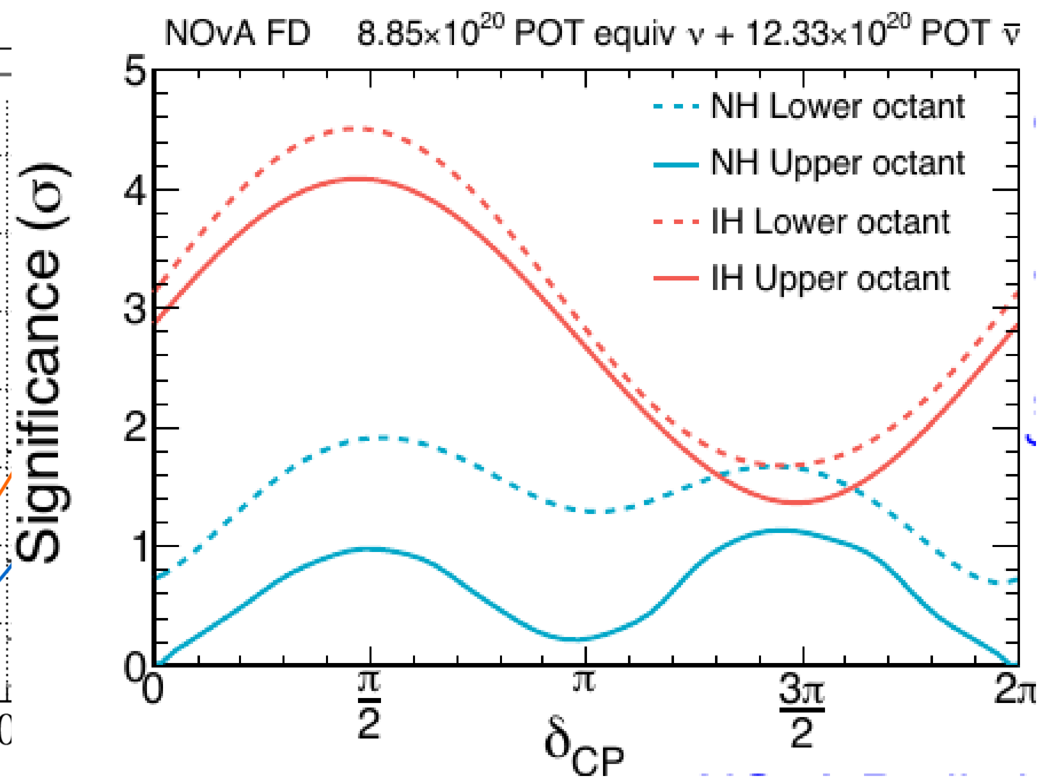
Agreement in IO gives a penalty to NO

In NO shift on δ_{CP} favoured value

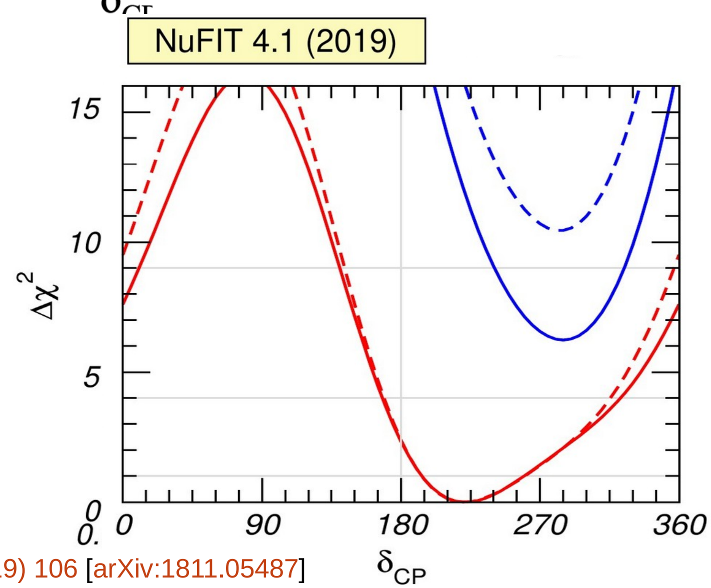
JHEP 09 (2020) 178 [arXiv:2007.14792]

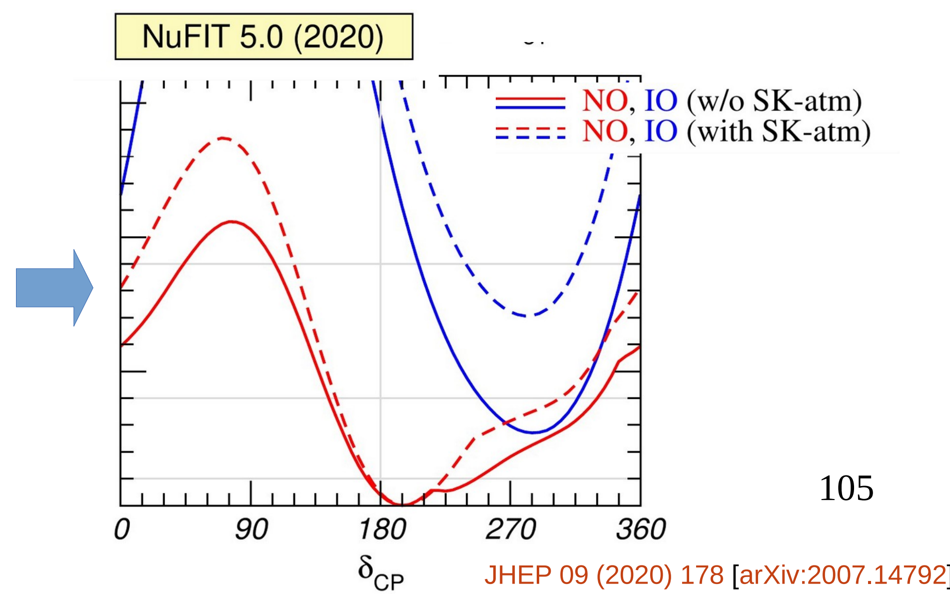
Results *2019 → 2020*



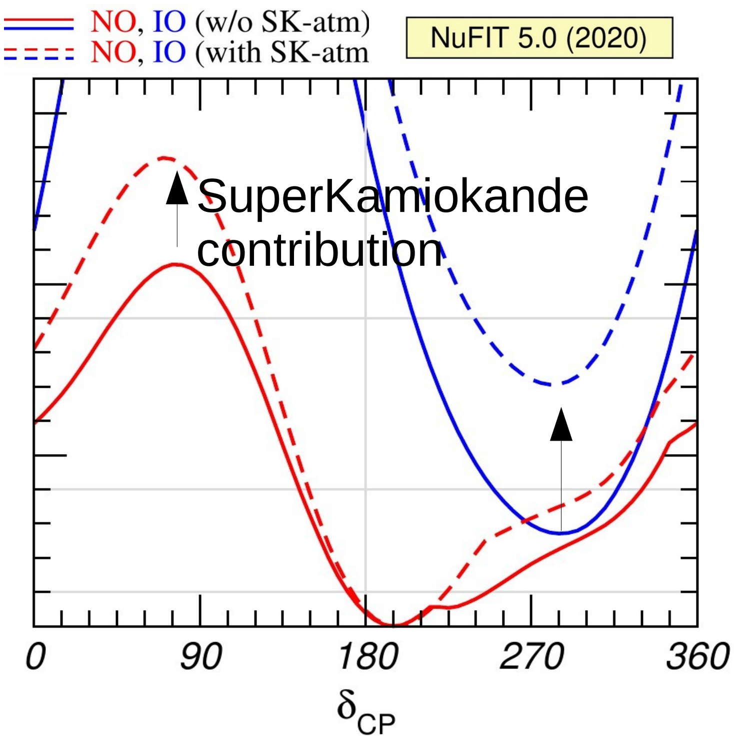


Something similar already visible in previous round of results

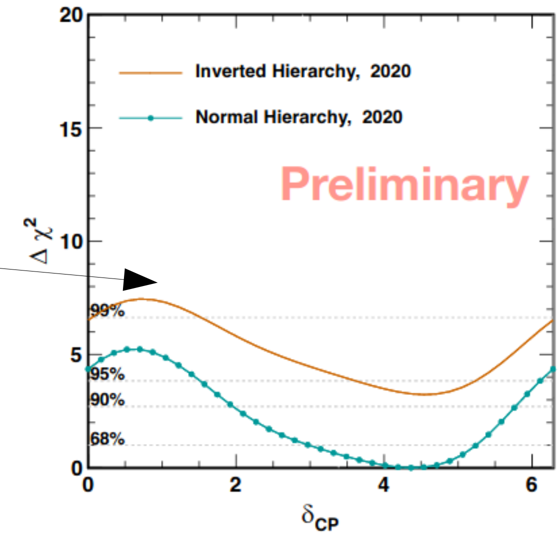


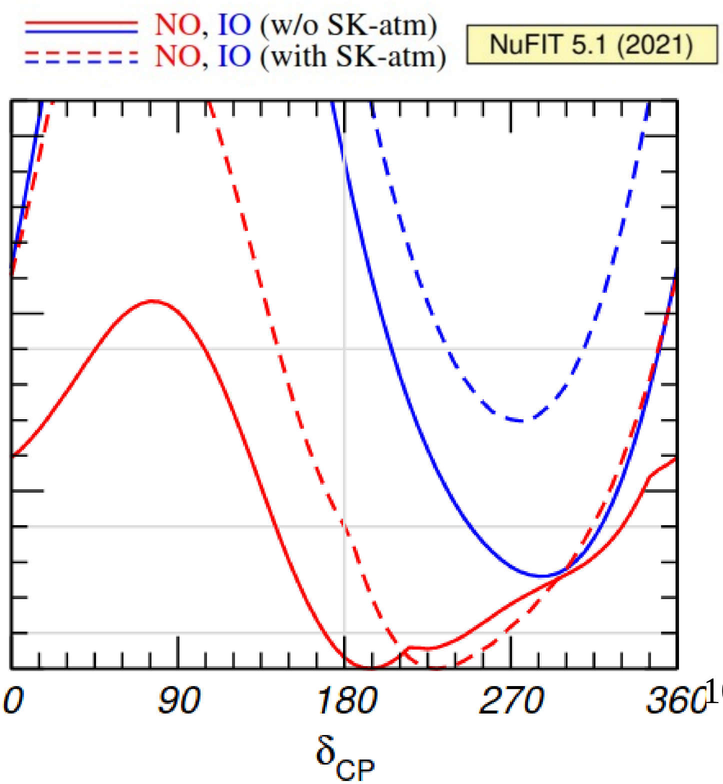


Mass Hierarchy



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





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

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

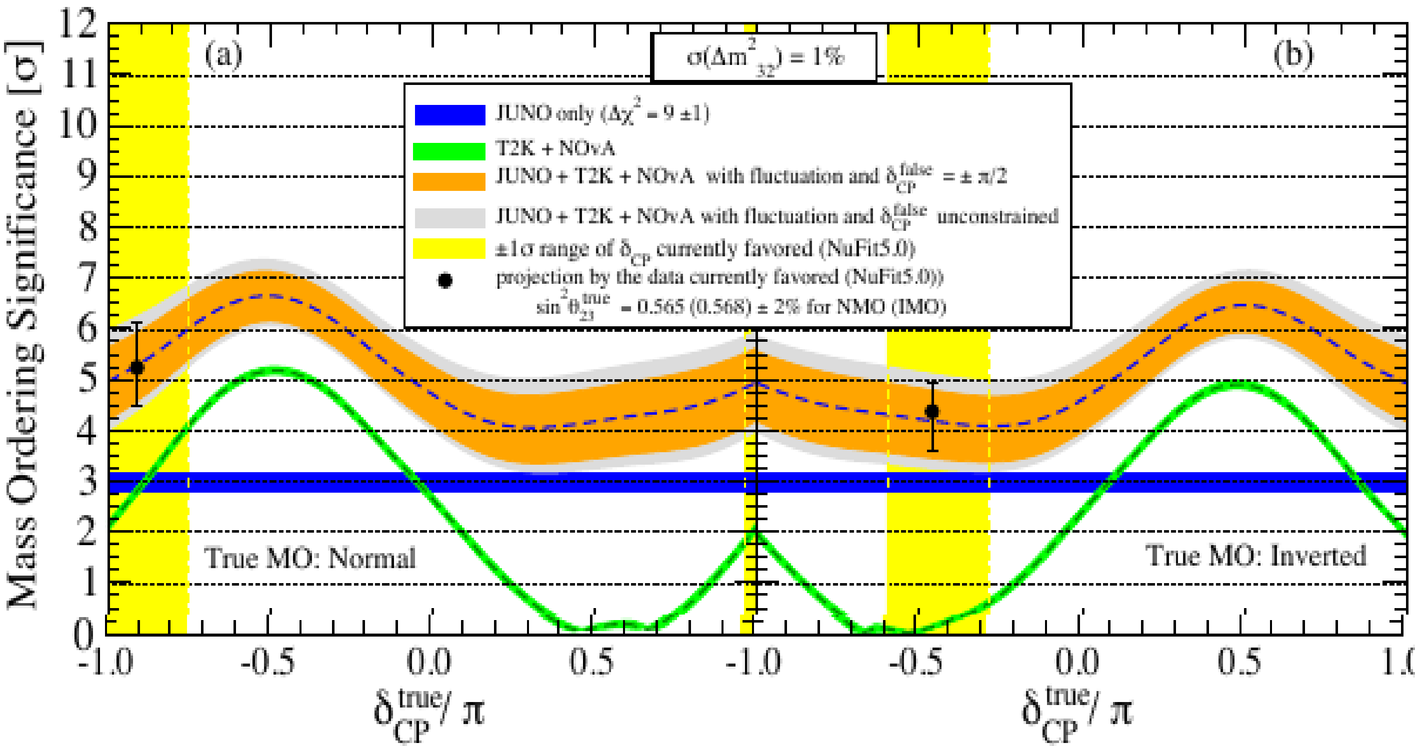
- **MO sensitivity dominated by SK**

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

→ CP conservation disfavoured at ~2σ

Combinations for MH: prospects

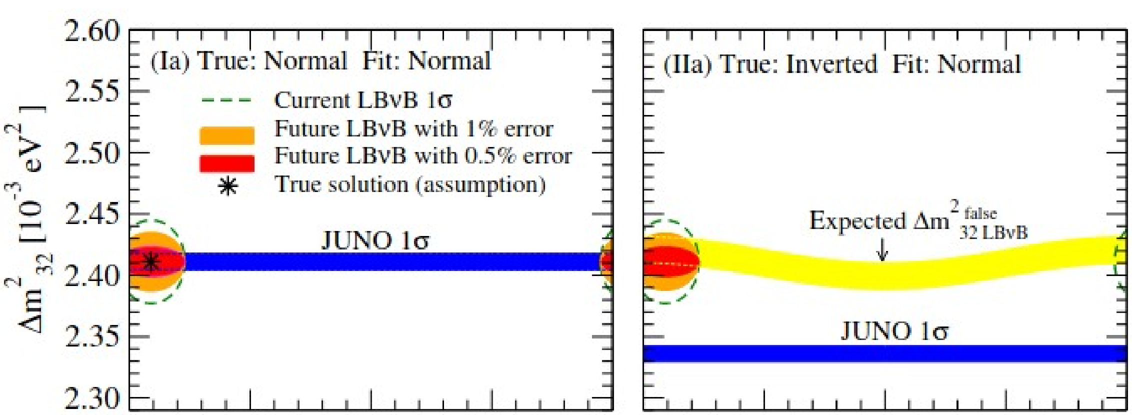
Very bright prospects for the future (and still not including SuperKamiokande!):



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

T2K+NOVA+JUNO

T2K+NOVA

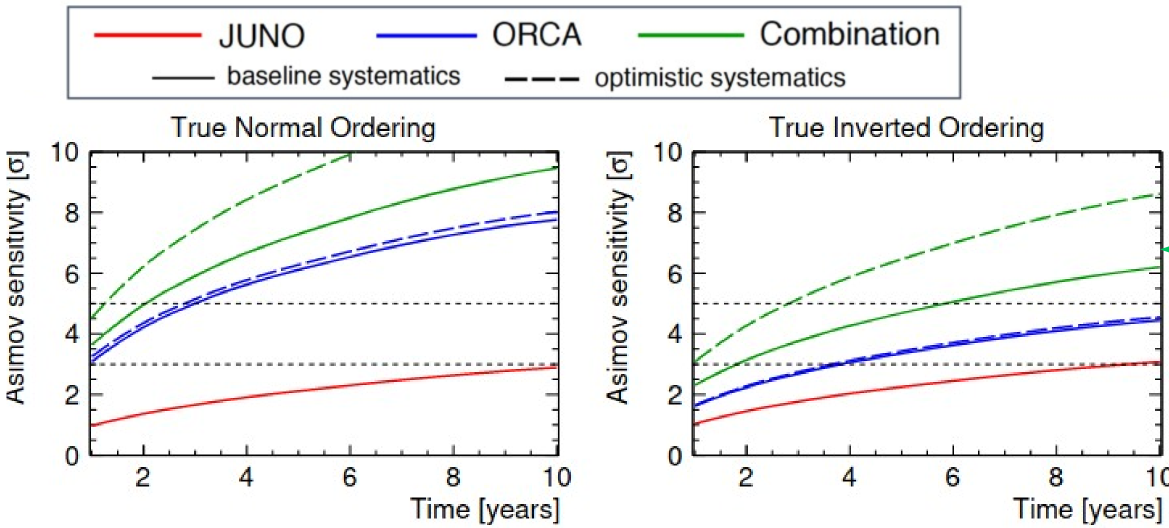


Boost of sensitivity from **|Δm$^2_{31(32)}$|** discrepancy (for wrong mass hierarchy) between ν_e (JUNO) and ν_μ (LBL) disappearance → ~2%

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

Combinations for MH: prospects

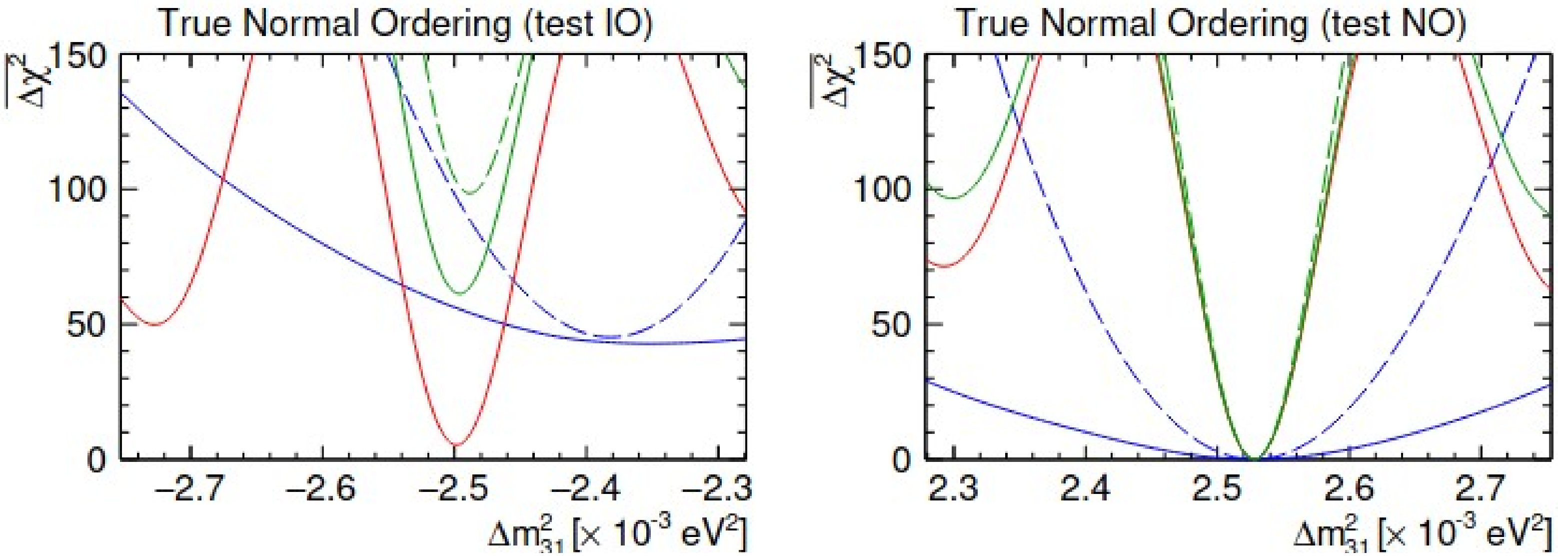
Further combination including ORCA (missing NOVA, T2K and SuperKamiokande):



JUNO+ORCA

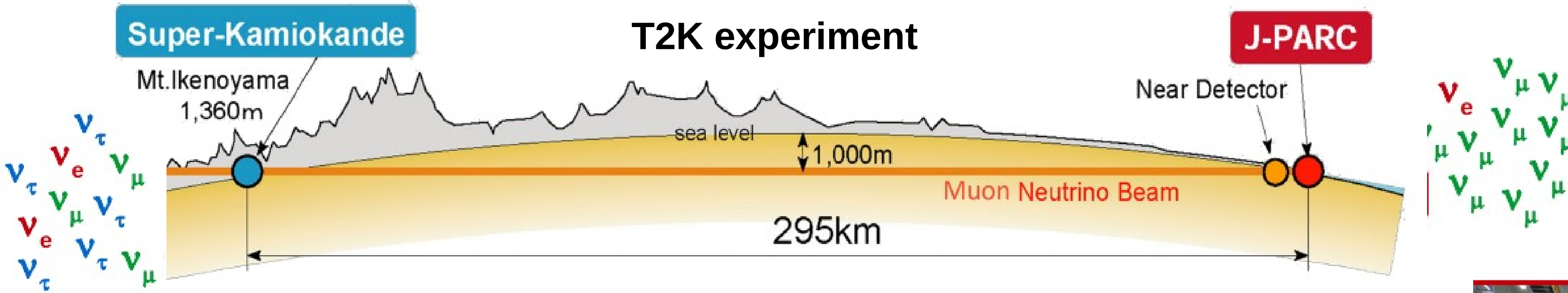
https://arxiv.org/pdf/2107.00344.pdf

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

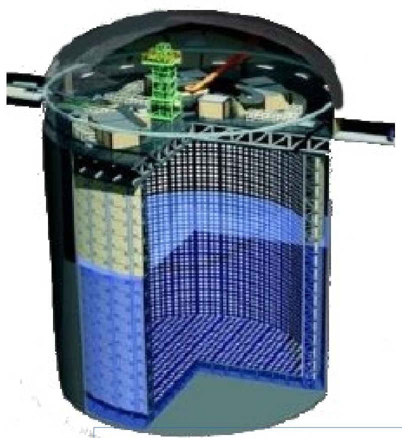


Anatomy of T2K and NOVA oscillation analysis

T2K

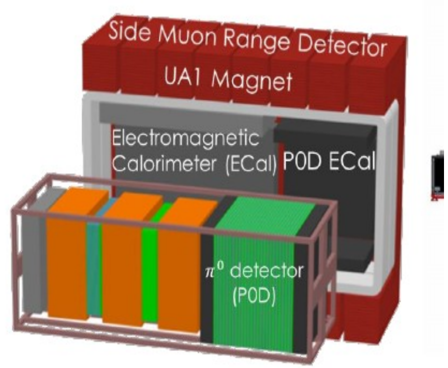


Super-Kamiokande

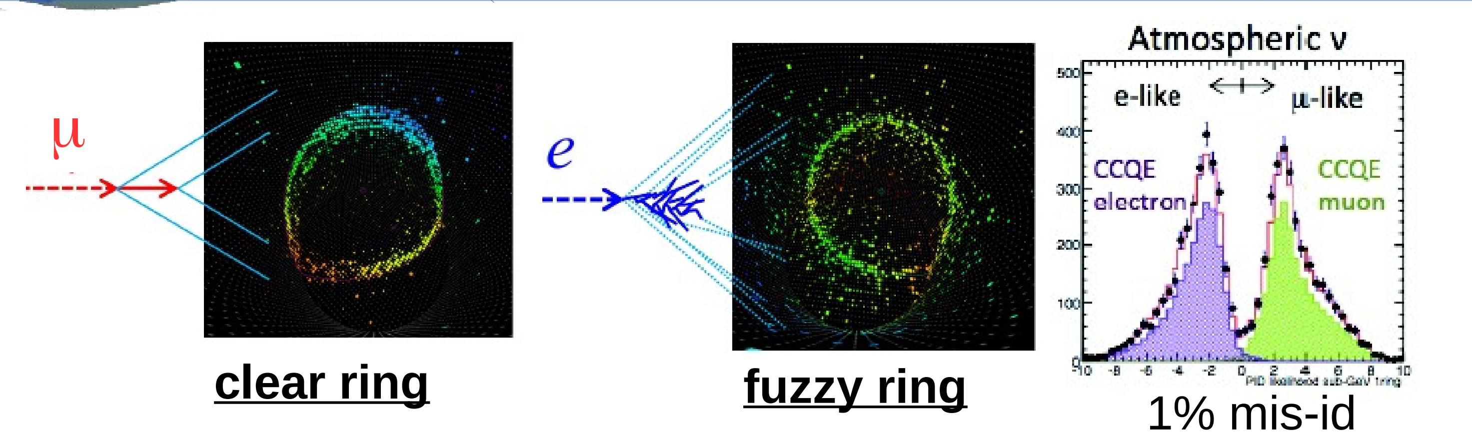


huge water cherenkov detector (50 kTon) with optimal μ/e identification to distinguish ν_e, ν_μ

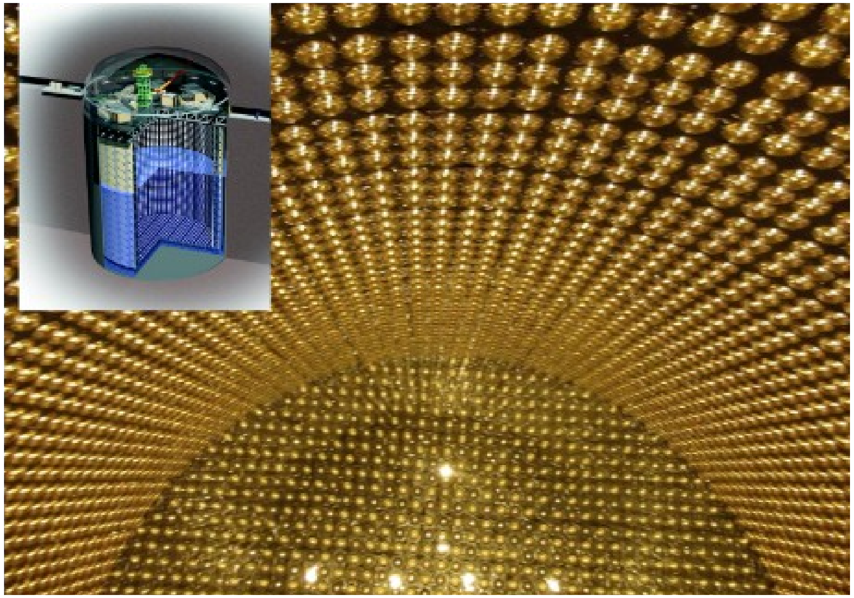
ND280 near detector



J-PARC facility: neutrino beam



SuperKamiokande samples

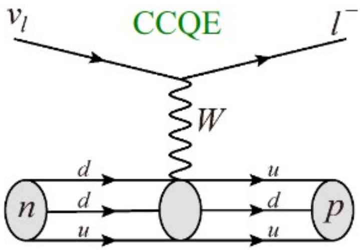


- Reconstruct Cherenkov ring from charged particles (above Cherenkov threshold)

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

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

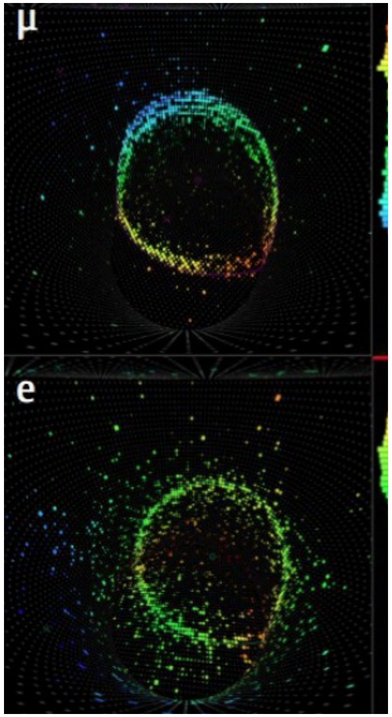
- Michel e- from muon (or π→μ) decay: e- ring delayed in time



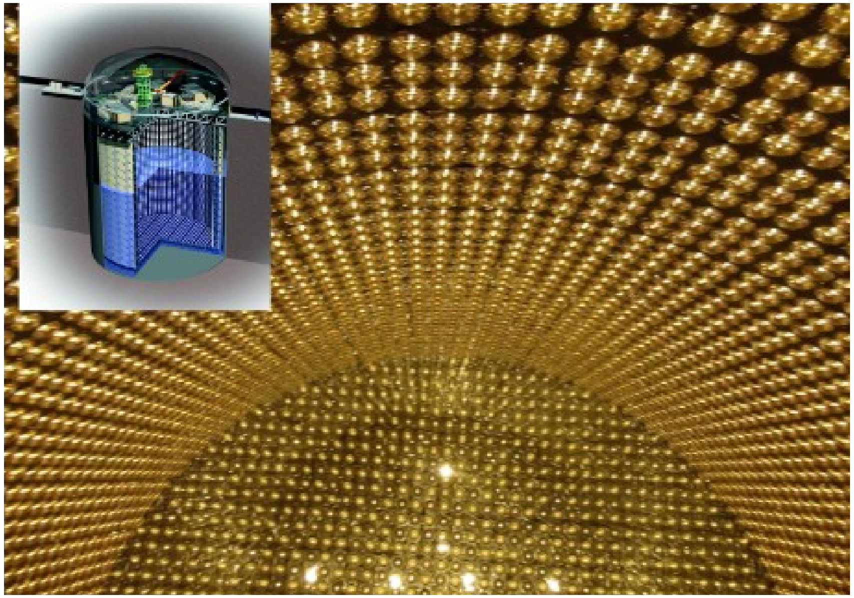
- Main channel at T2K energy:
single ring events (e or μ)
= Quasi-Elastic channel: can reconstruct neutrino energy from lepton kinematics only
[with nuclear physics uncertainty: see Martini lecture]

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

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



SuperKamiokande samples



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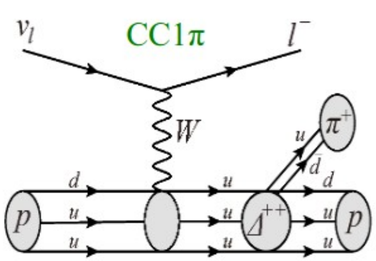
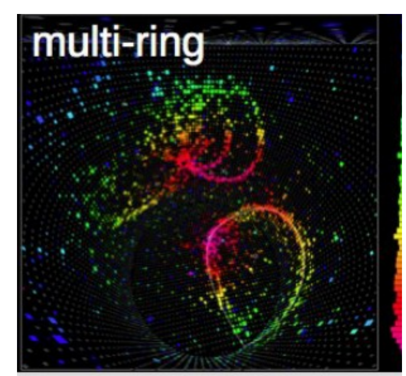


- Additional channels with pion production (FHC), subleading and mostly at higher energy:

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

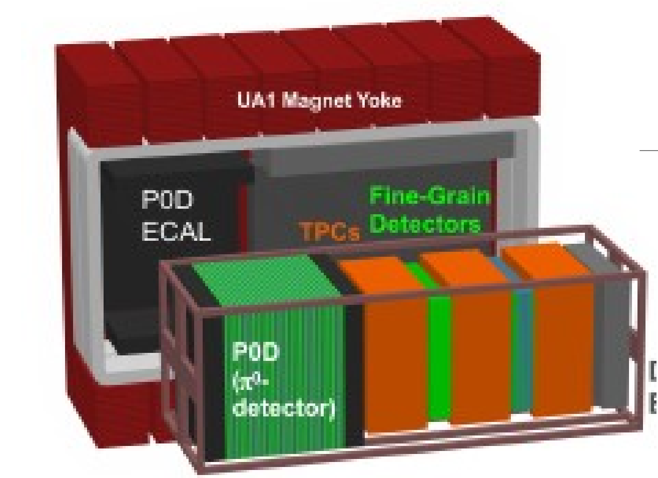
  - 1 ring muon (from ν_μ) + 1,2 Michel electron(s) and/or other ring from π
  → add high-energy 'control sample' for ν_μ

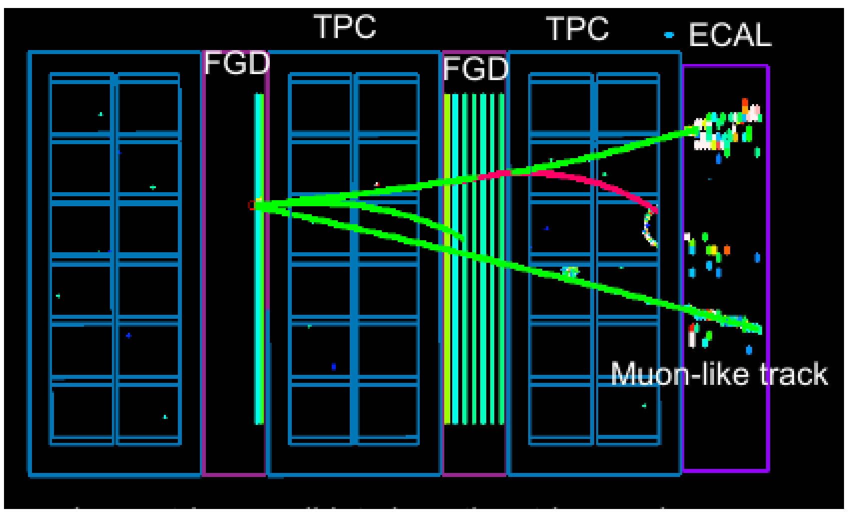


$$E_\nu^{\text{rec}} = \frac{m_{\Delta^{++}}^2 - m_p^2 - m_l^2 + 2m_p E_l}{2(m_p - E_l + p_l \cos\theta_l)}$$

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

T2K near detectors



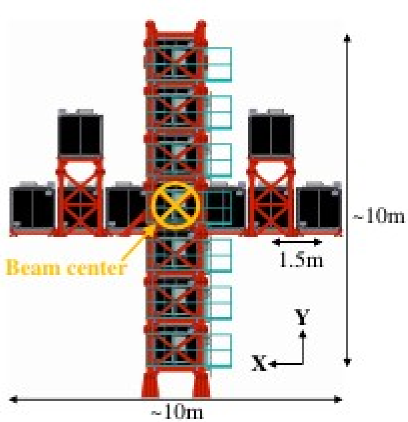


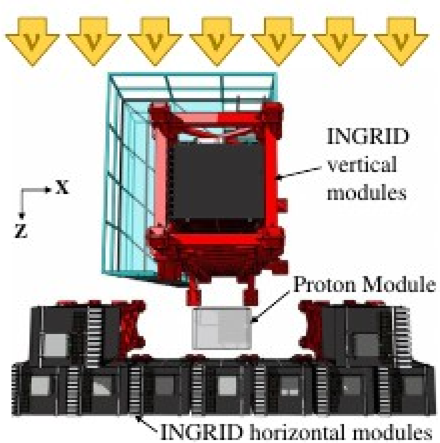
ND280 : off-axis (2.5º)

Measure flux and xsec for oscillation analysis

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

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





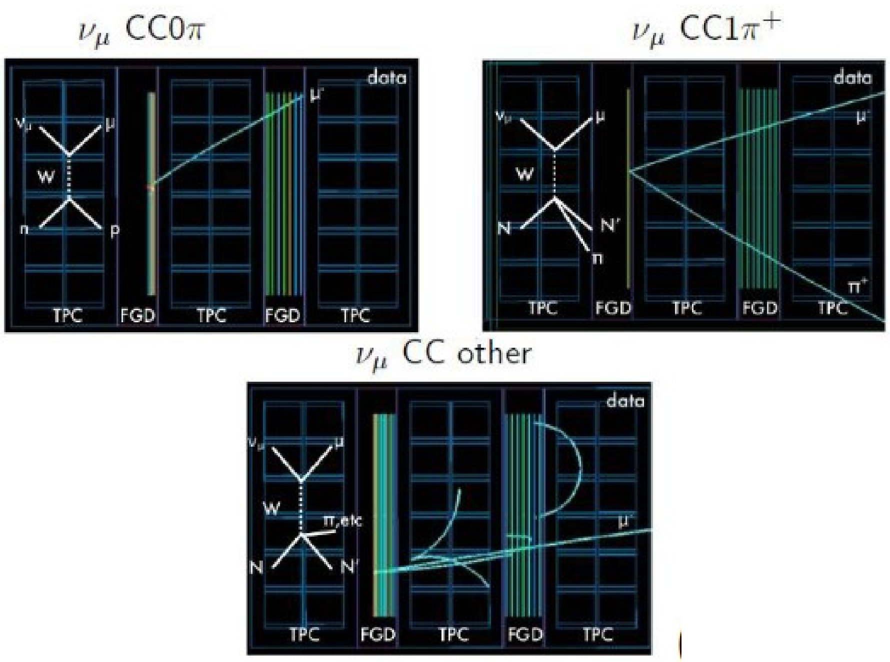
INGRID : on-axis

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

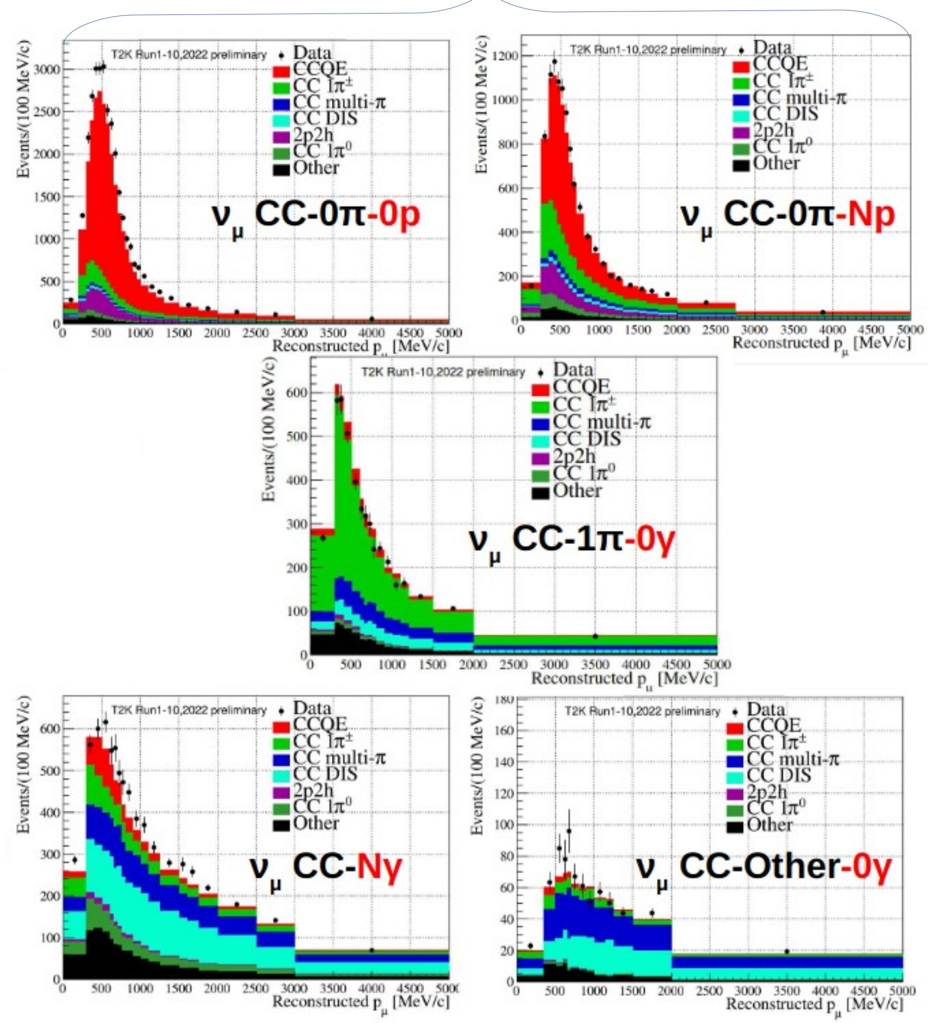
- iron plates alternated with CH scintillator (+ proton module : fully active scintillator)
- **coarser granularity, not magnetized but larger mass :** 2.5×10^{30} nucleons (Fe) + 1.8×10^{29} nucleons (CH)

T2K ND selection

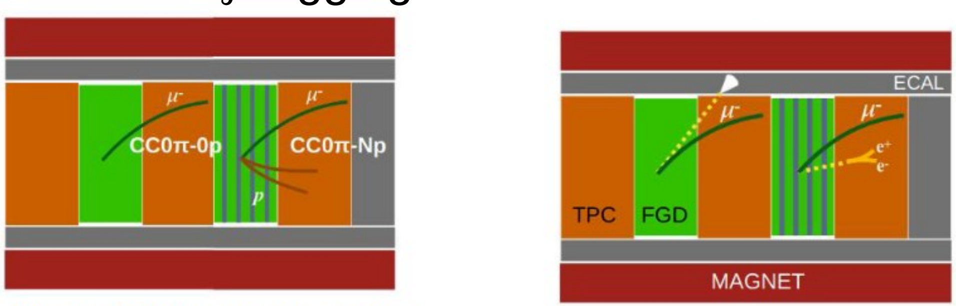
- Require one muon + separate sample based on proton, pion and g multiplicity **(full exclusive final state reconstruction)**
- Until now, similar to SK: lepton kinematics only used for neutrino energy assessment



Main QE channel



Proton and γ tagging: new in 2022



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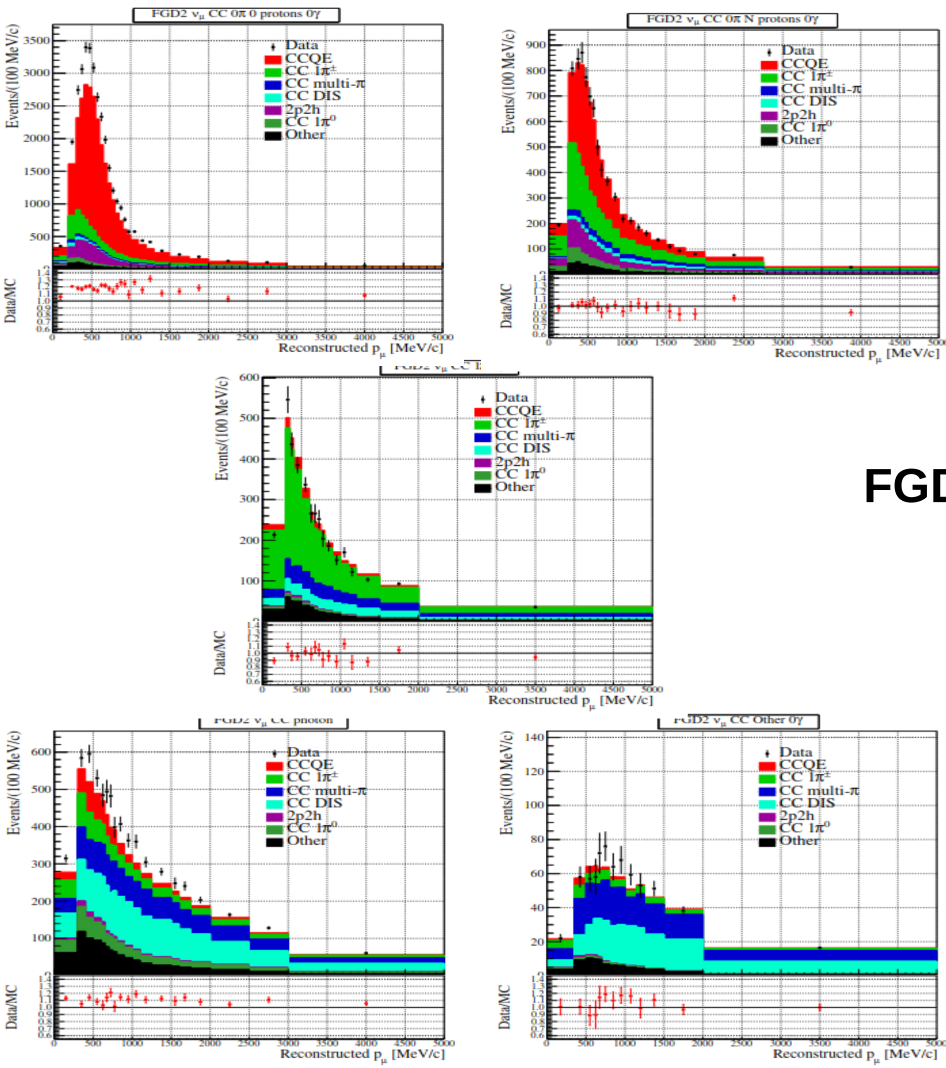
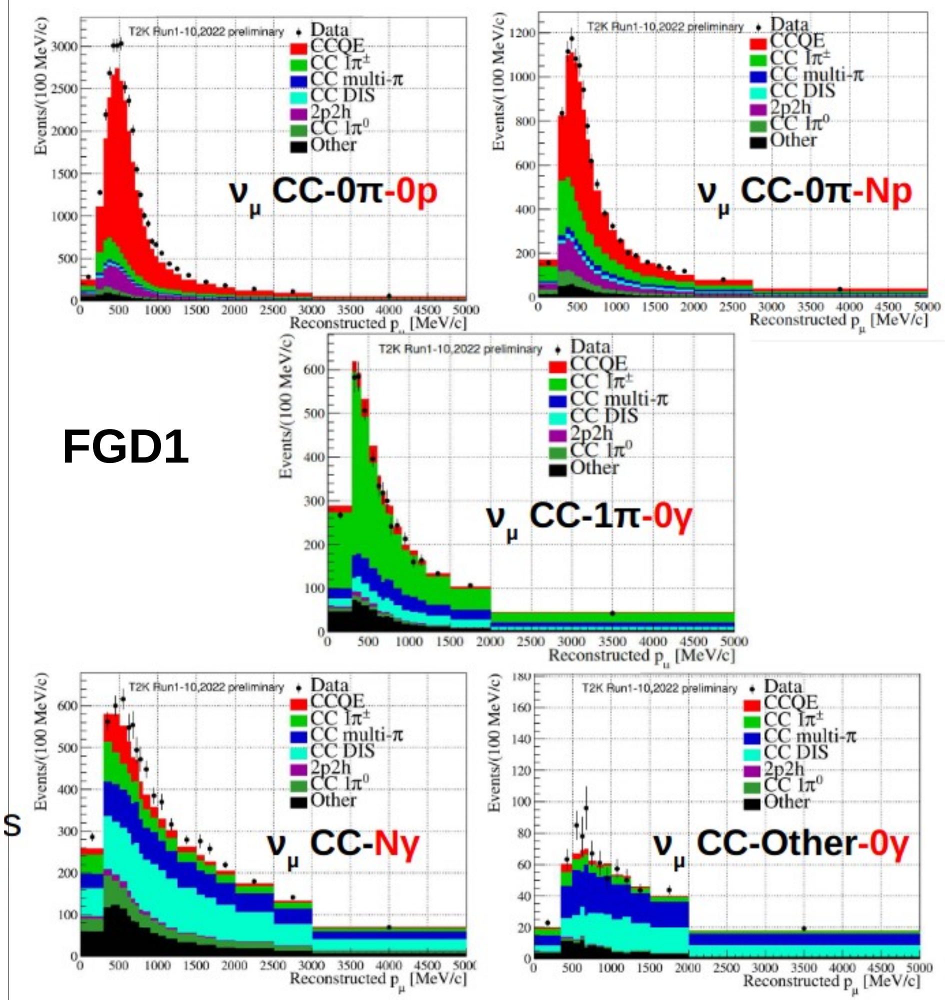
- Two sets of samples for **FGD1 (CH only) and FGD2 (CH+water)**



FGD2

FGD1



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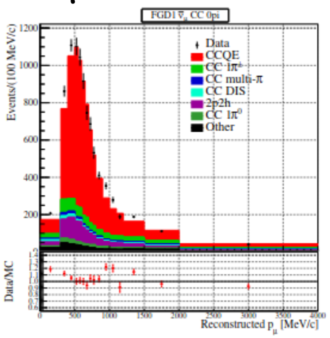
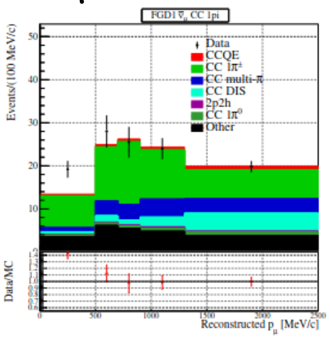
FGD1 RHC

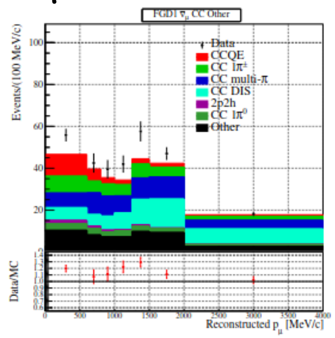
μ+ CC0π



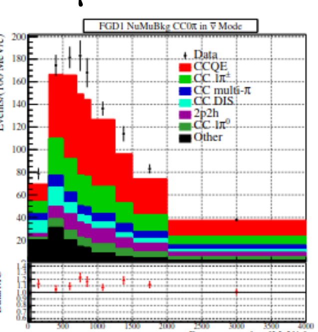
μ+ CC1π



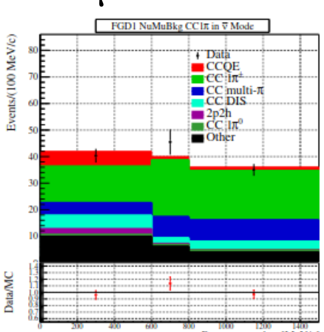
μ+ CC-Other



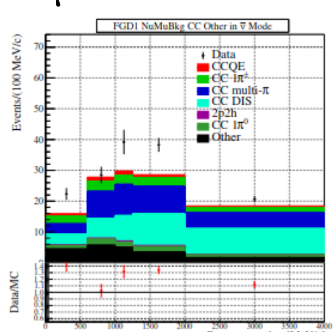
μ- CC0π



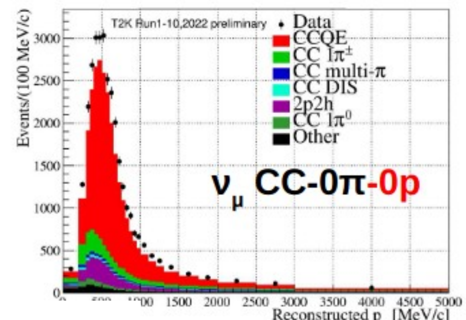
μ- CC1π

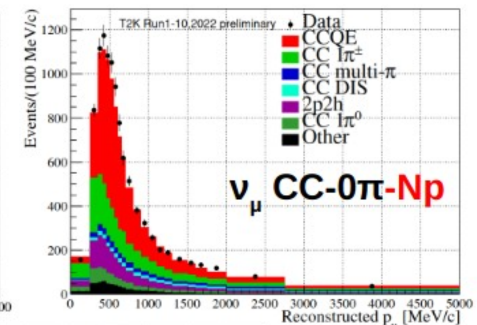


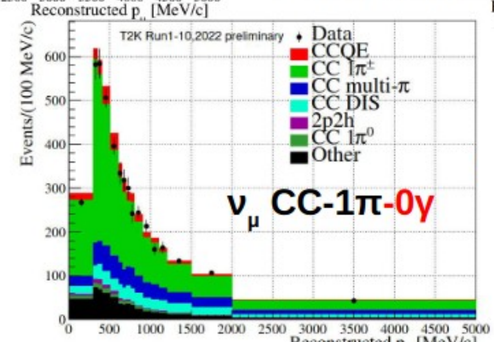
μ- CC-Other

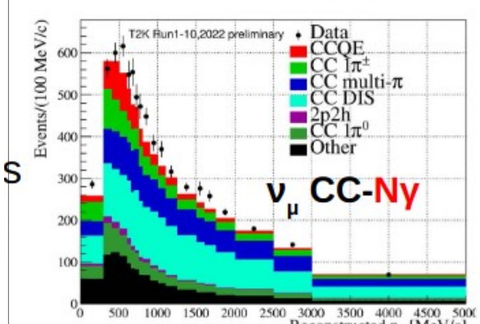


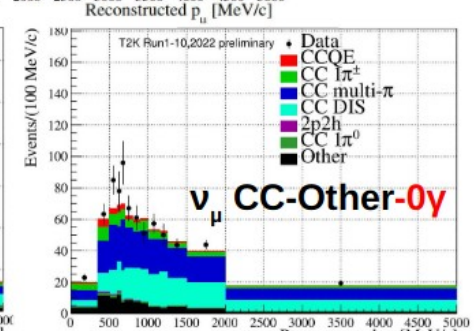
FGD1 FHC











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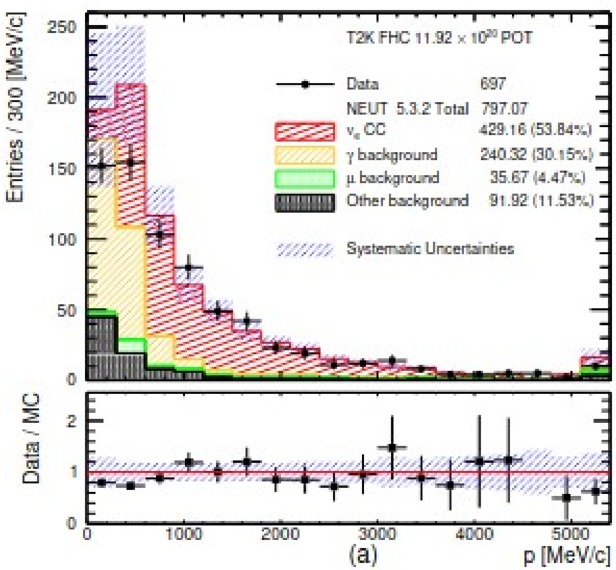
- RHC mode: **μ+ ($\bar{\nu}_\mu$) and μ- (ν_μ) separate samples**

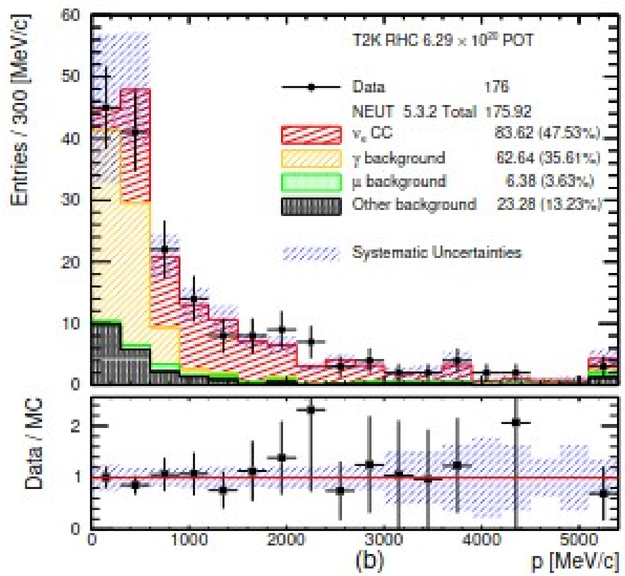
- **ν_e at ND: too low statistics (~8% precision)** due to the very good ν_μ/ν_e purity of the beam. What really matters for δ_{CP} in $\nu_e/\bar{\nu}_e$ flux and xsec (from nuclear theory ~<2%)

Dedicated ν_e cross-section measurement shows agreement with model but with large stat and systematics uncertainties.

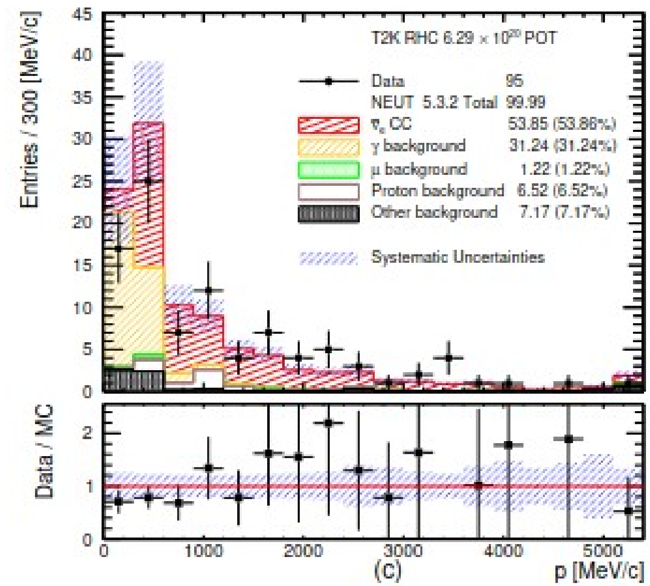
FHC: ν_e



RHC: $\bar{\nu}_e$



RHC: ν_e



T2K ND fit

- **ND measurement**

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

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

~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

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

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- **Fit to ND observed distributions:**

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

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

T2K ND fit

- **ND measurement**

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

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

~same flux at ND and FD

what we want to measure: oscillation probability

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

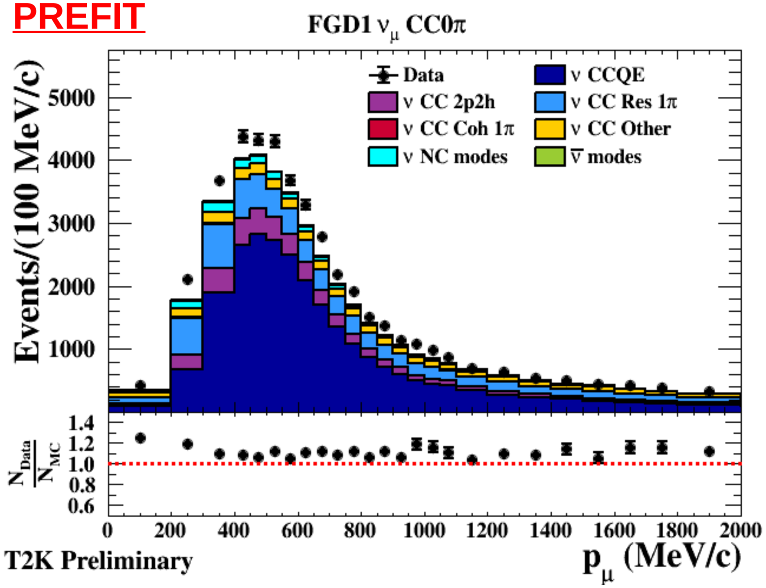
- **Tuned model** used for flux and cross-section disentagling and their extrapolation to FD +correct reconstruction of energy at the far detector

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

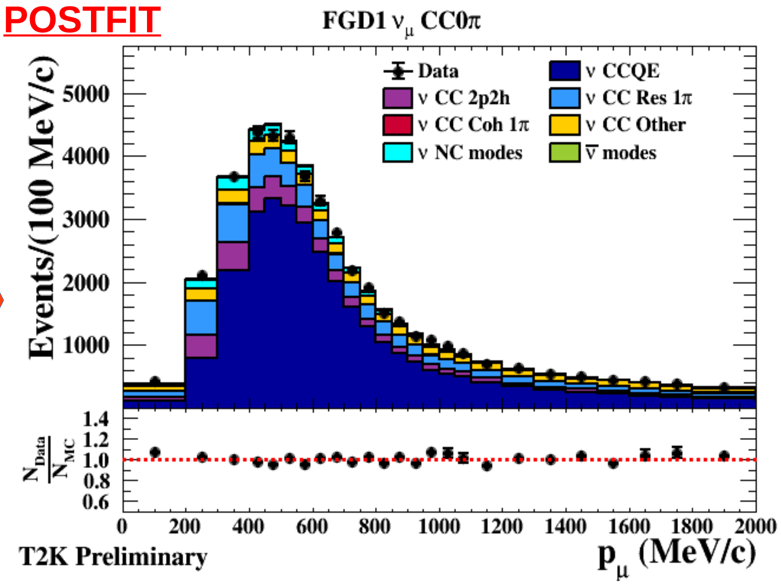
T2K ND: data fit

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

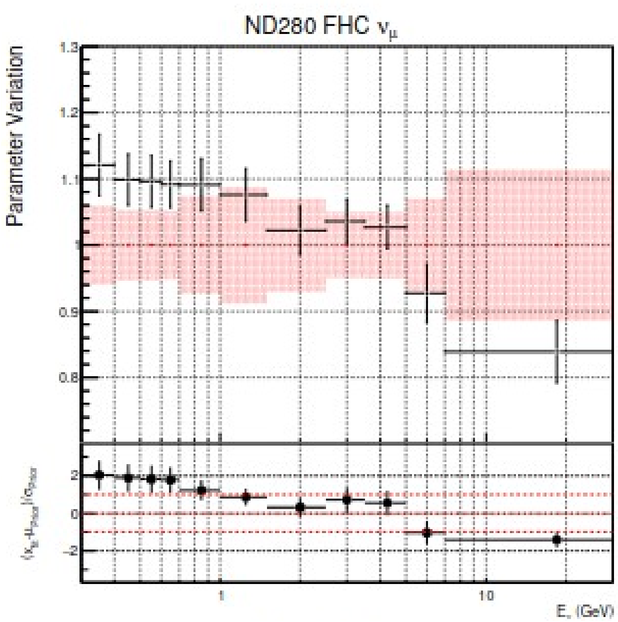
PREFIT

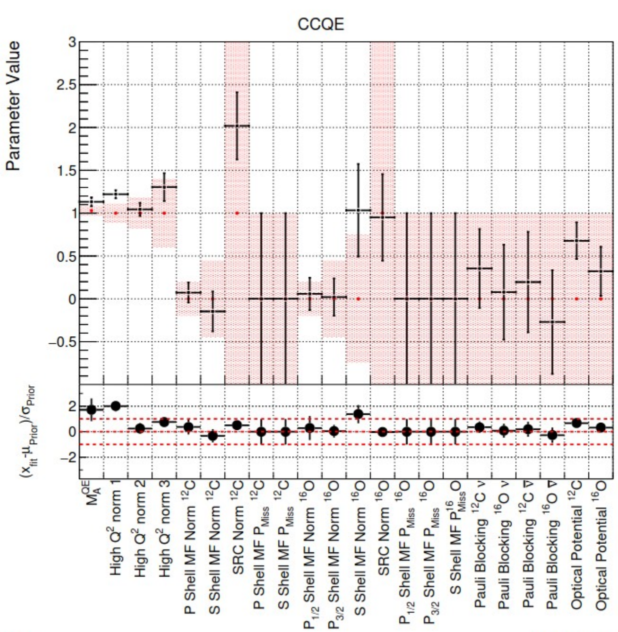


POSTFIT



Tuning of flux and xsec model





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

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

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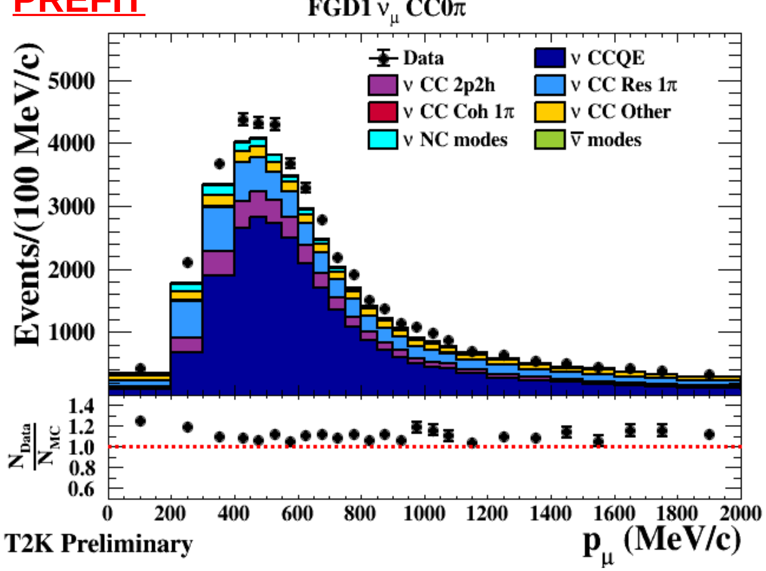

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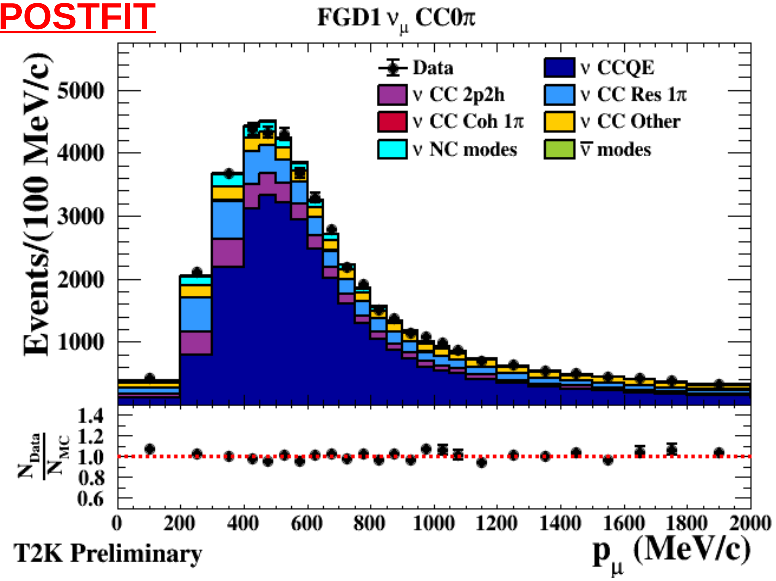

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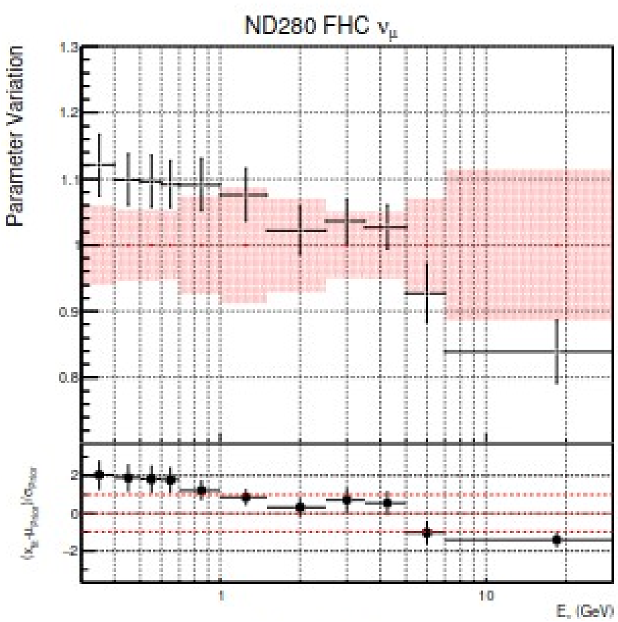
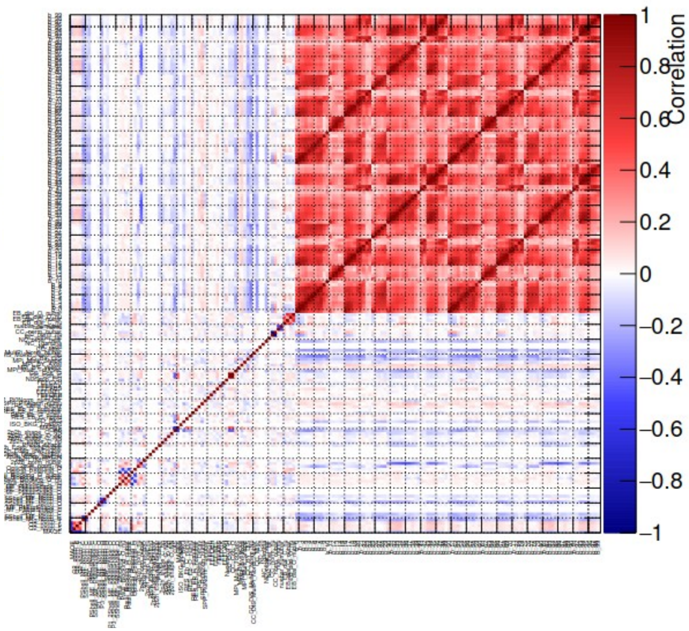




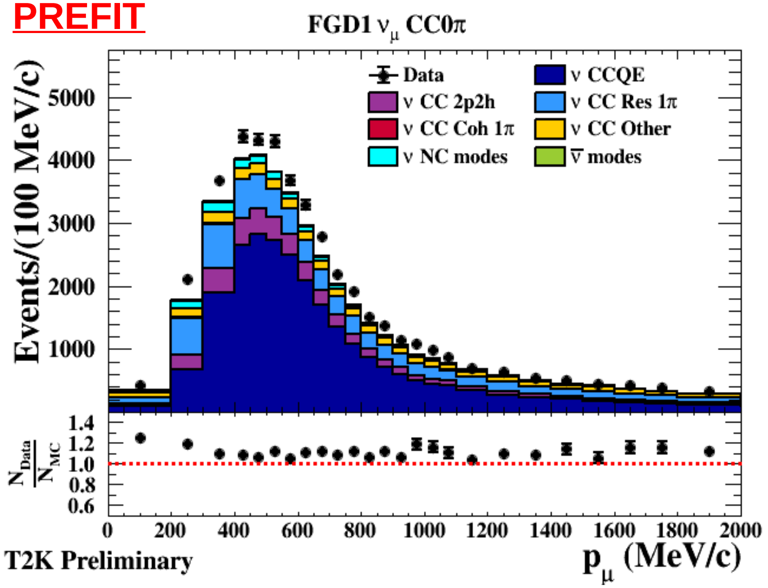
Actually hundreds of parameters (only main flux and xsec channel shown)

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



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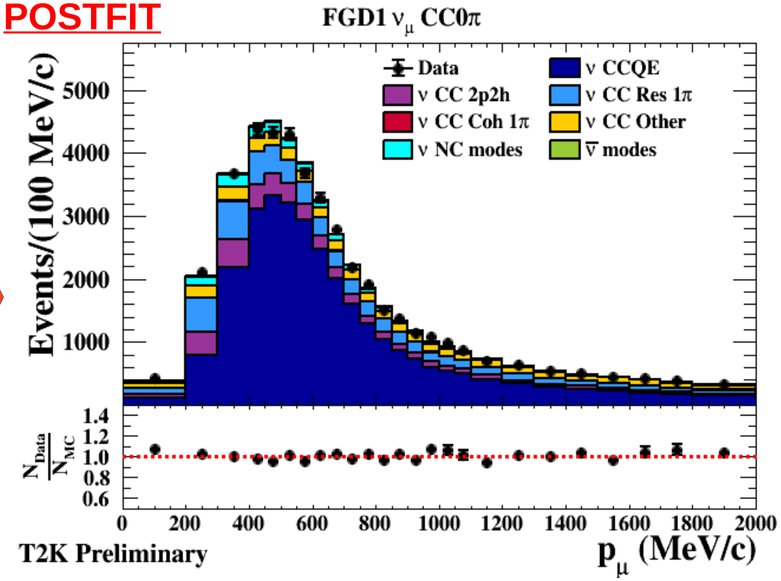
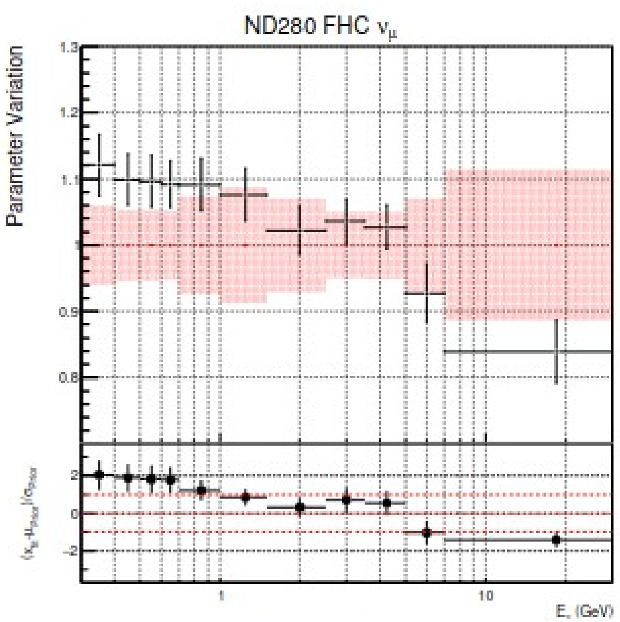
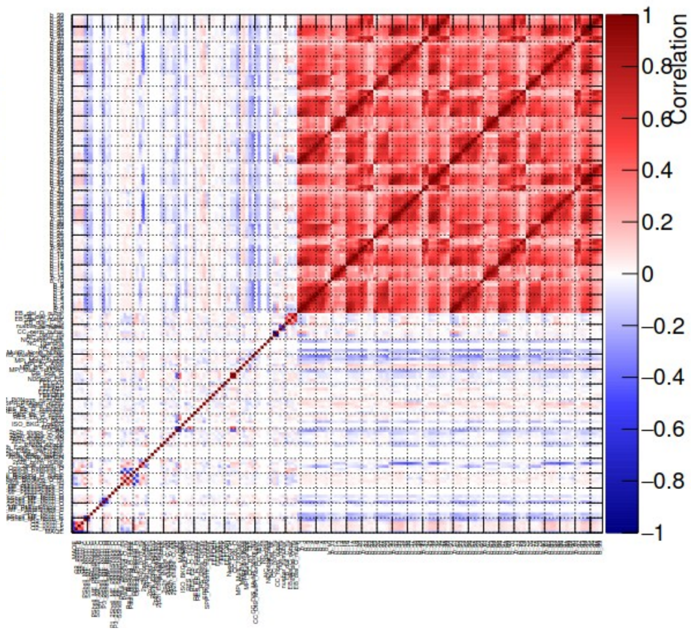


Tuning of flux and xsec model





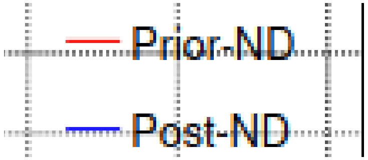
Actually hundreds of parameters (only main flux and xsec channel shown)

All parameters got correlated from the fit

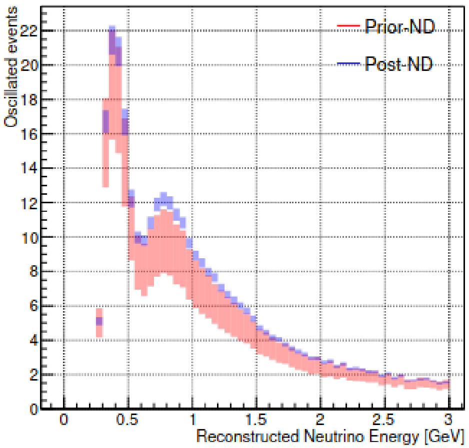
Tuned model used to estimate flux and xsec at far detector and tune Eν reconstruction at far detector

SuperKamiokande tuned distribution

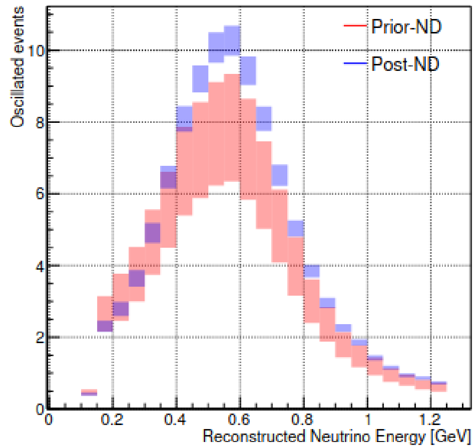
(Only main samples shown)



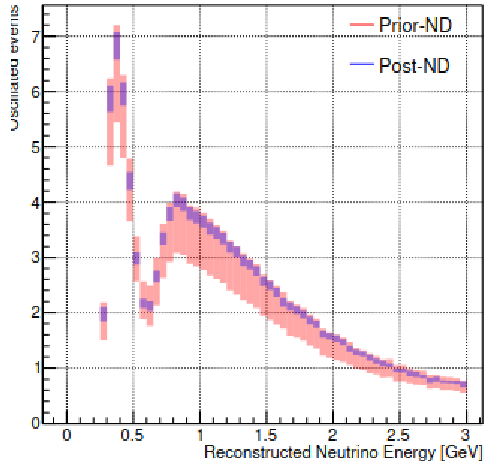
FHC 1ring μ



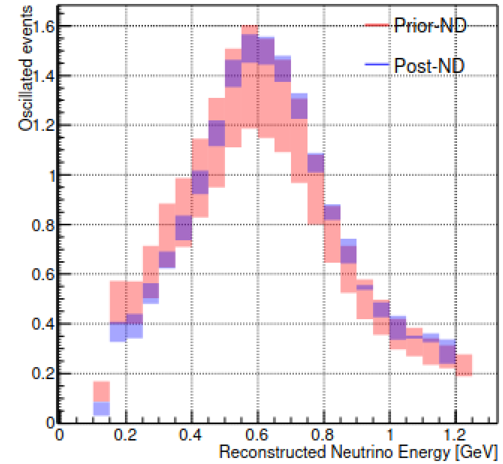
FHC 1ring e



RHC 1ring μ



RHC 1ring e



Before the ND fit

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

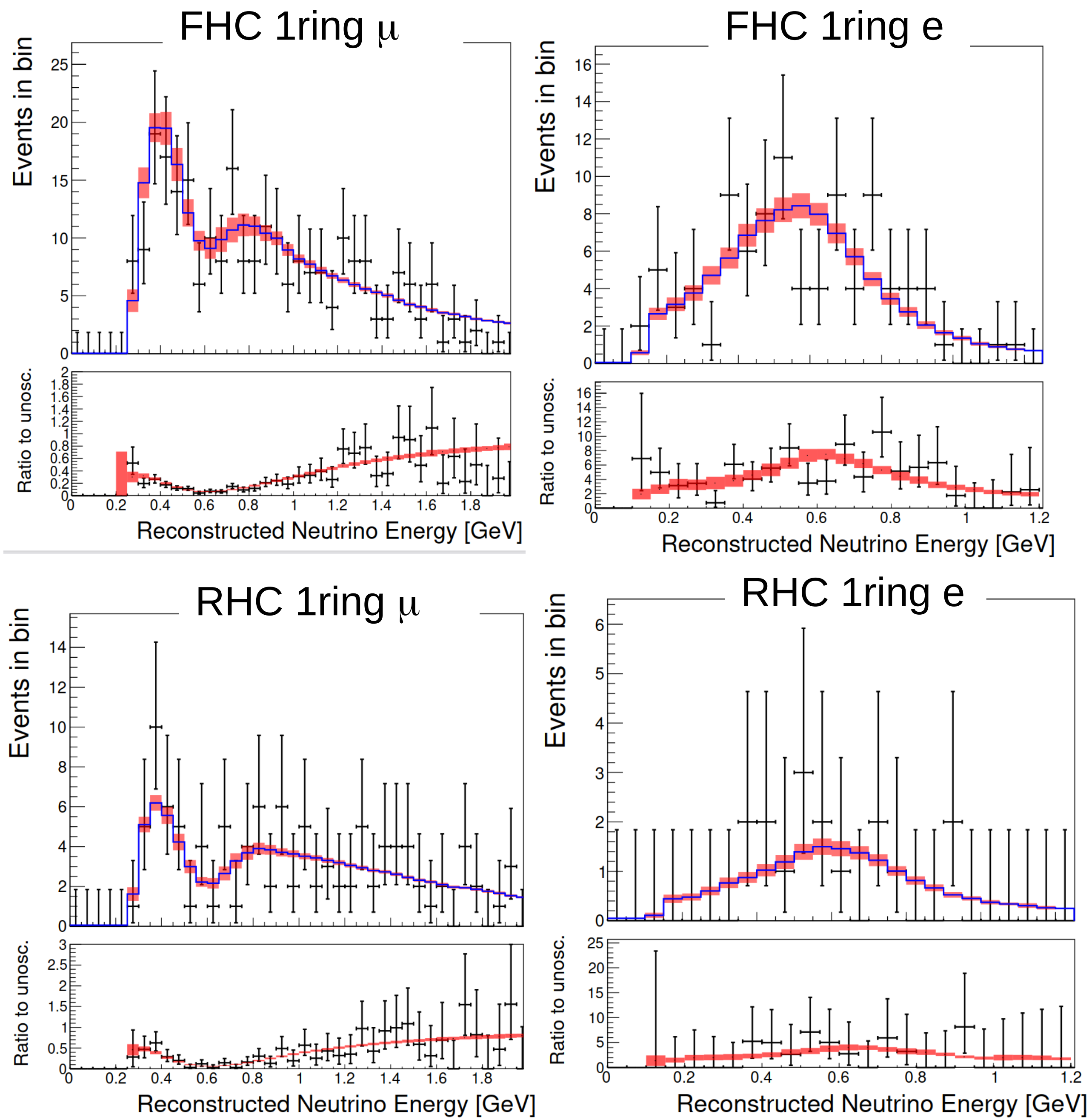
After the ND fit

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

SuperKamiokande fit

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

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



(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

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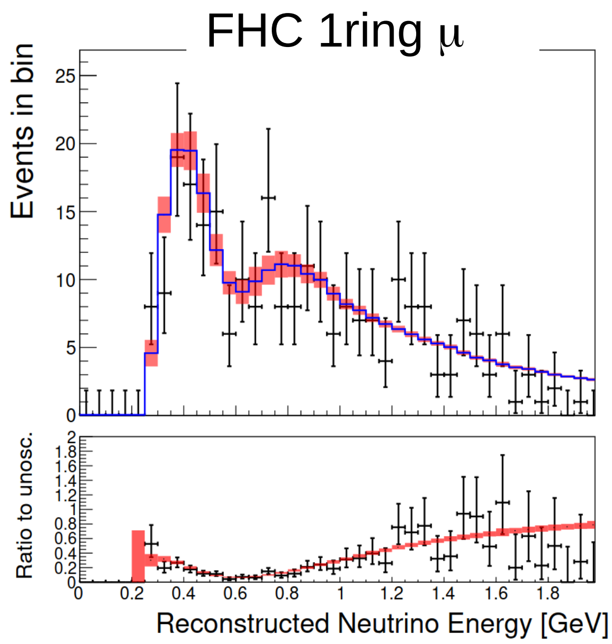
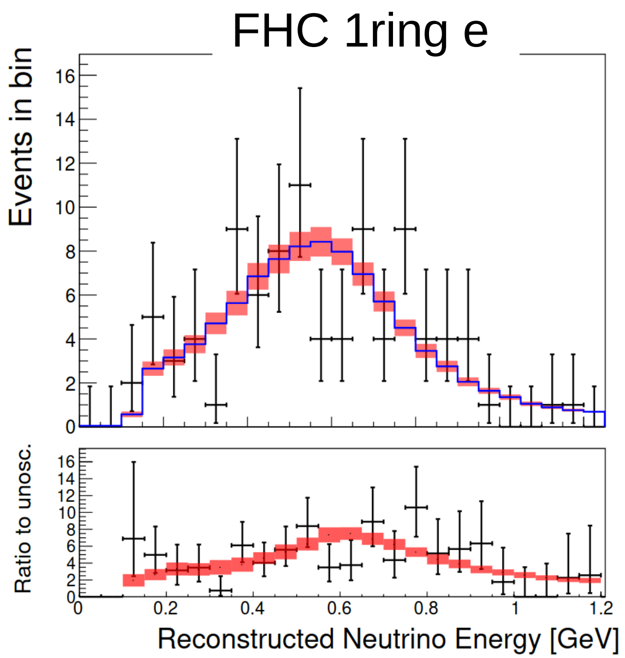
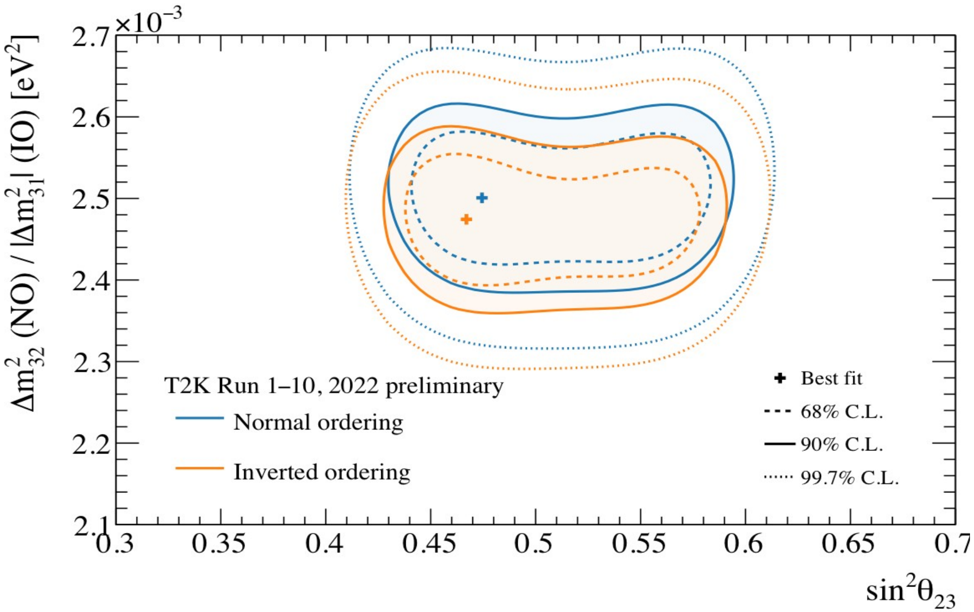
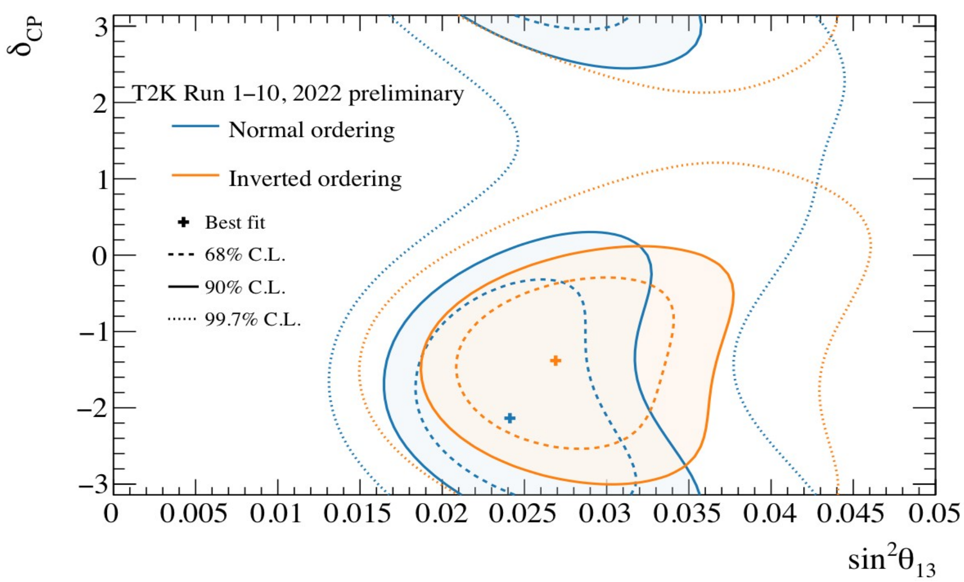


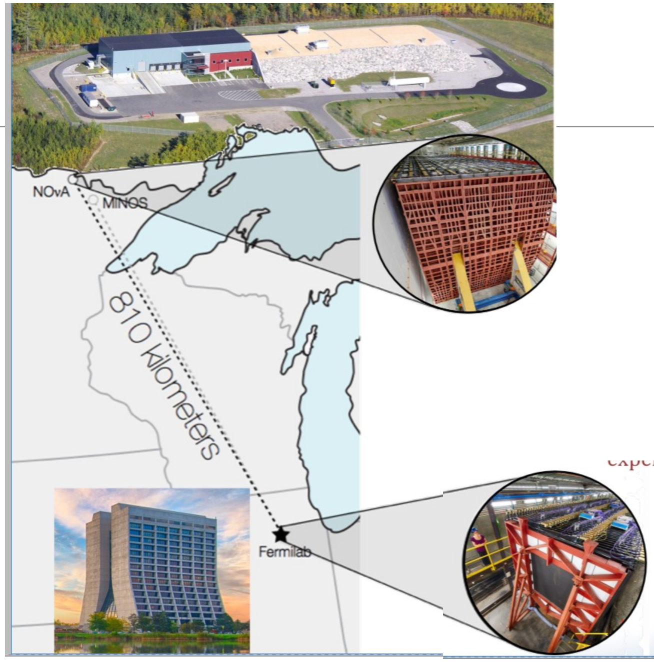


- Both a joint ND+FD fit and sequential ND → FD fit are done and compared.
Both frequentist and bayesian analysis are performed and compared





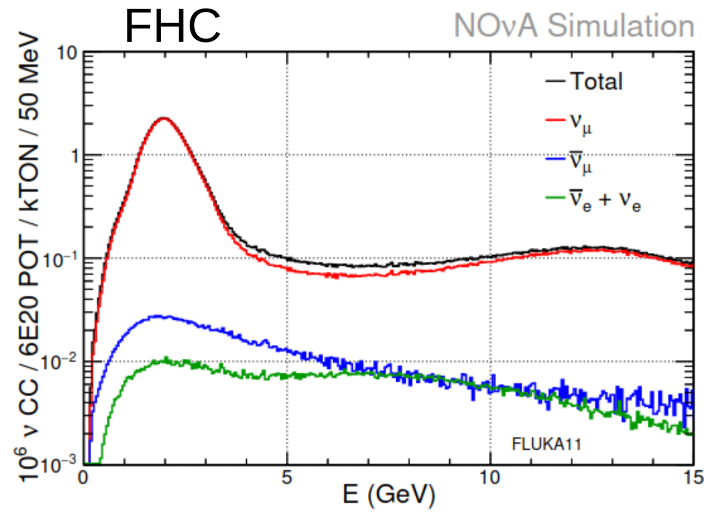
NOVA

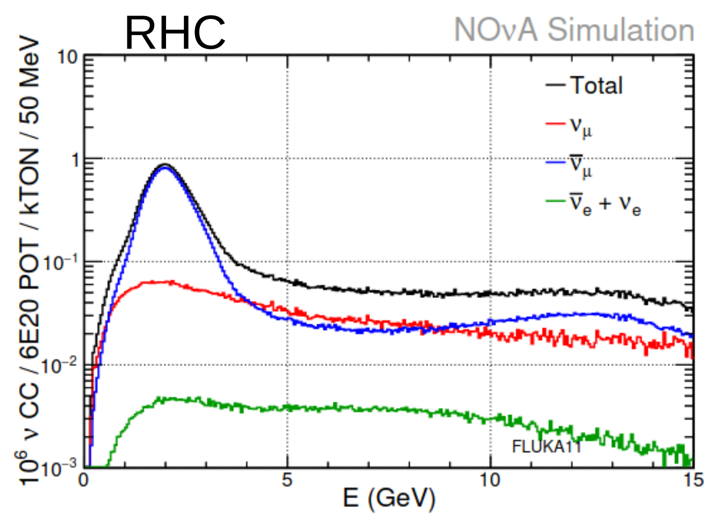


NUMI beam at FNAL

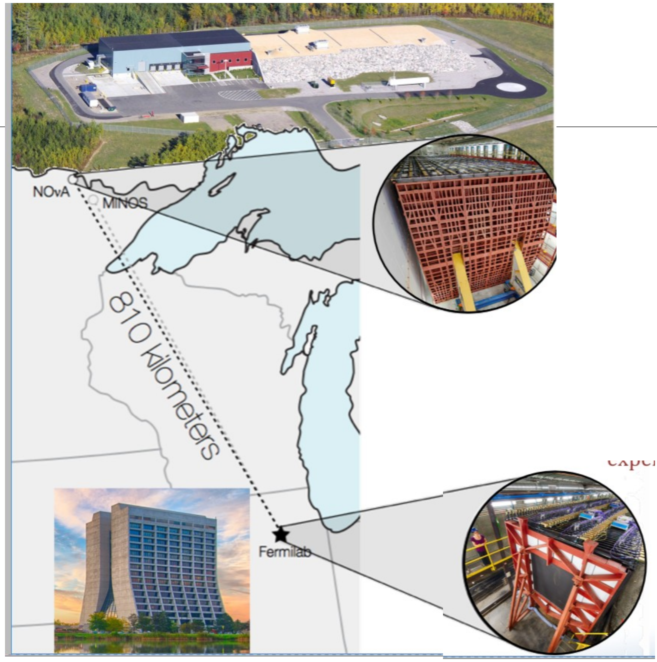
14mrad off-axis
(narrow-band spectrum)

Baseline: 810km





NOVA



NUMI beam at FNAL

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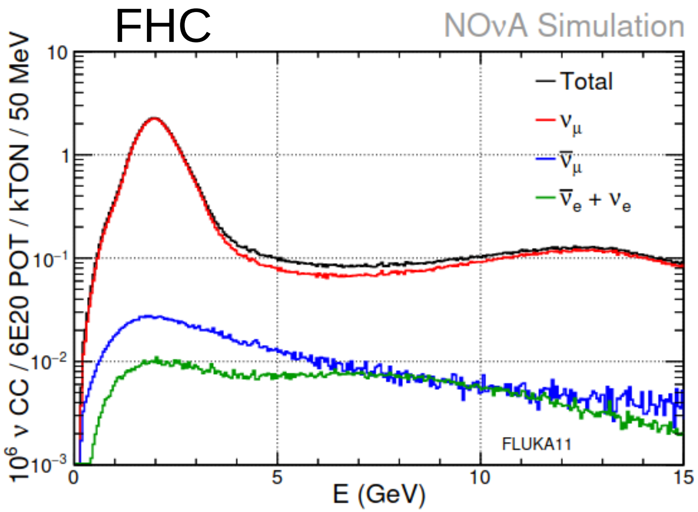
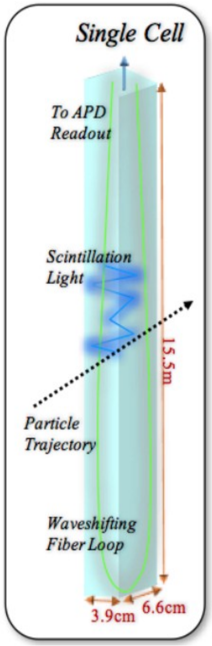
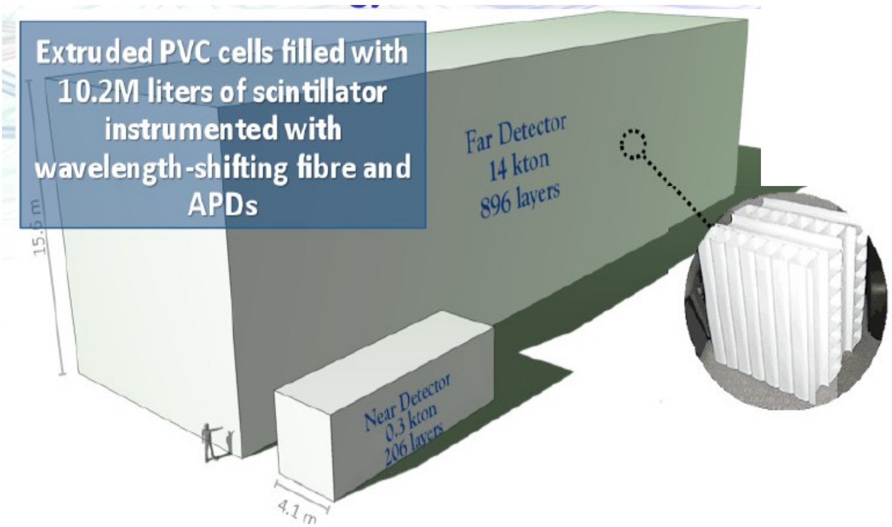


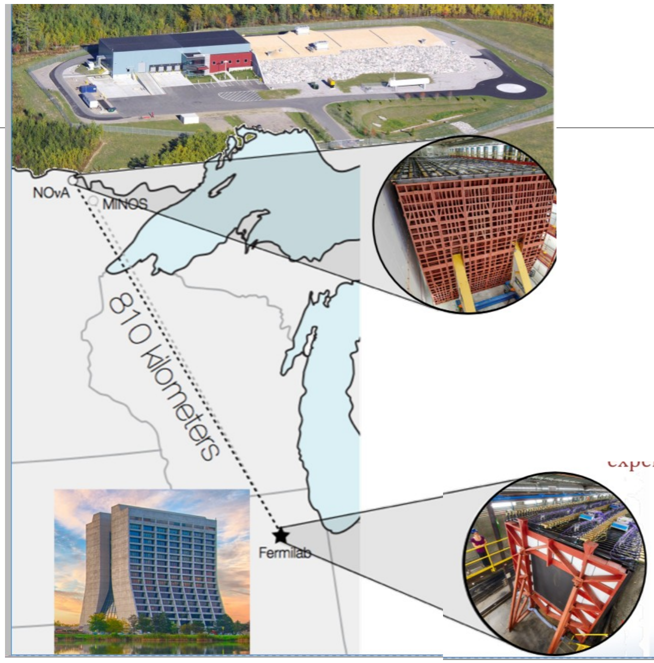
- **Same technology (liquid scintillator) for near and far detector**

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





NOVA



NUMI beam at FNAL

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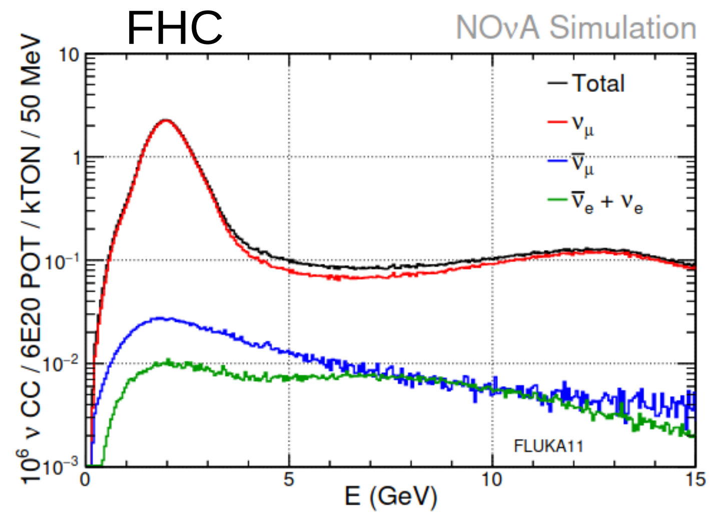
Baseline: 810km



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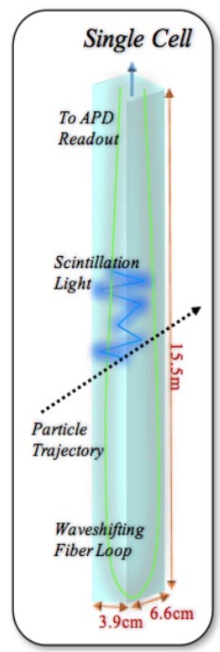
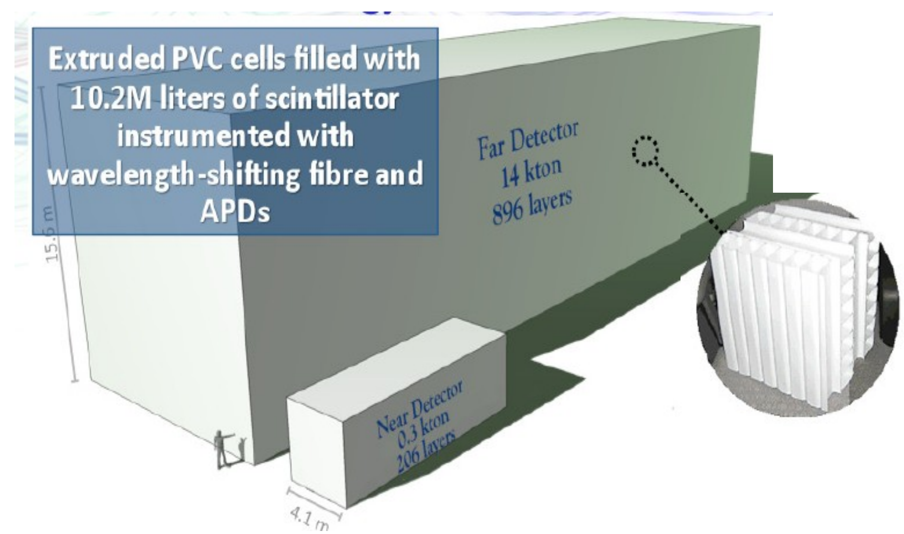




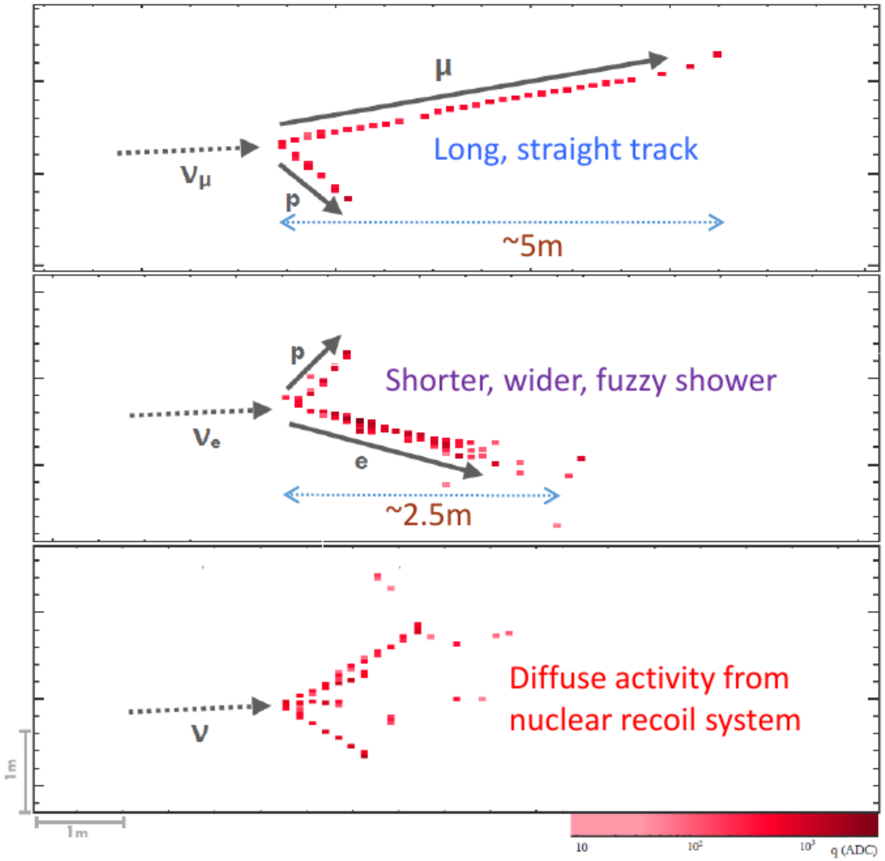
- **How systematics on nuclear effects still affect ND to FD extrapolation:**
  - different Eν at ND and FD (before and after oscillation) → different $E_{had}/E\nu$, different resolution..
  - still need to disentangle flux and xsec since they depends on Eν differently
  - different acceptance (in p_T)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

What do we measure?

ν_μ CC

ν_e CC

NC



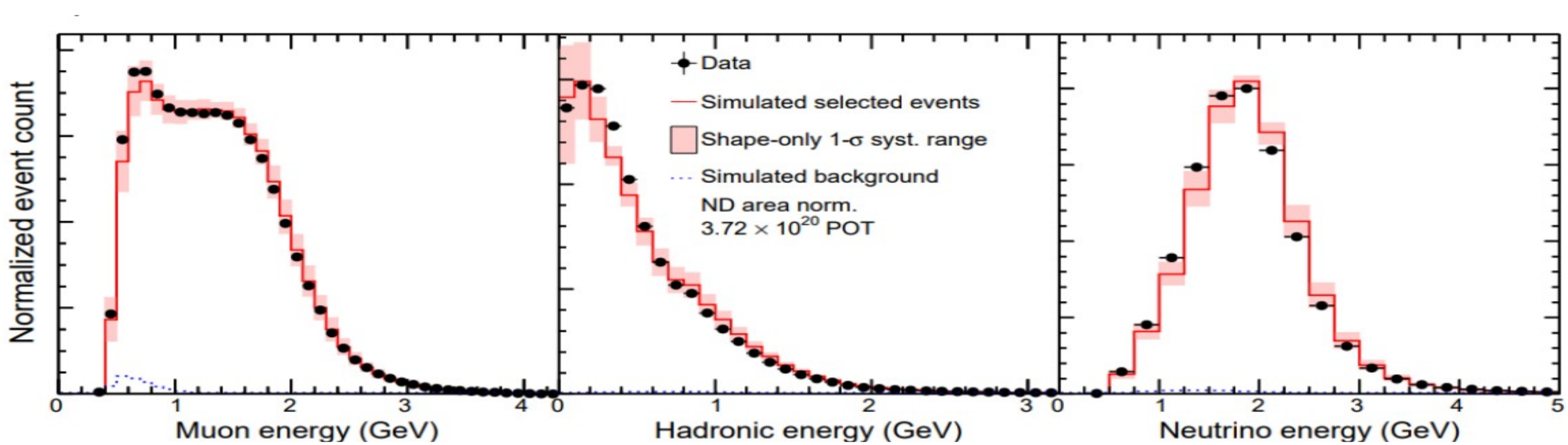
Muons (if contained)

Electrons as **shower**

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

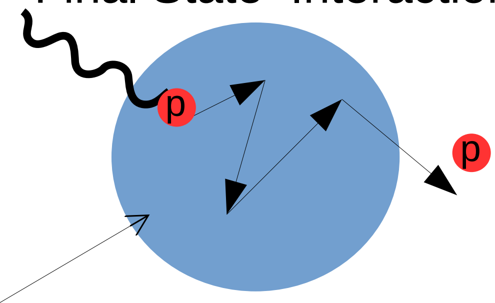
High energy flux: pion production and DIS → large fraction of Eν goes into hadrons

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

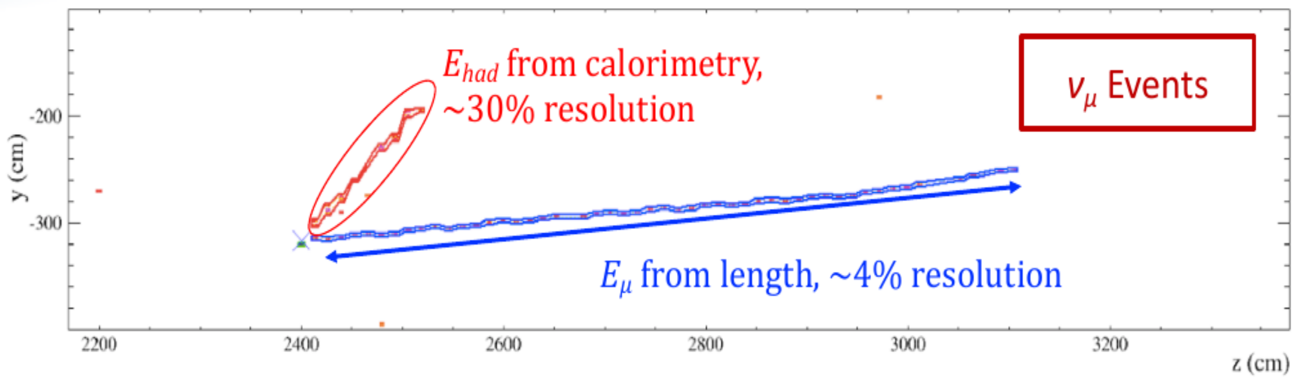


Eν reconstruction

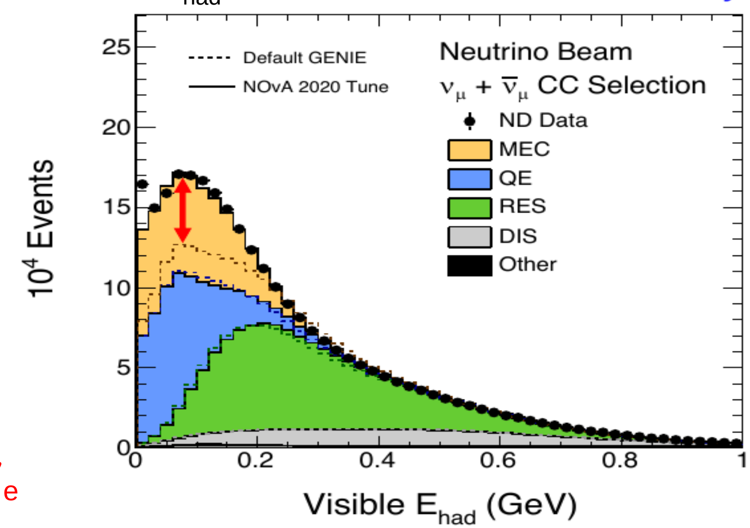
Final State Interactions



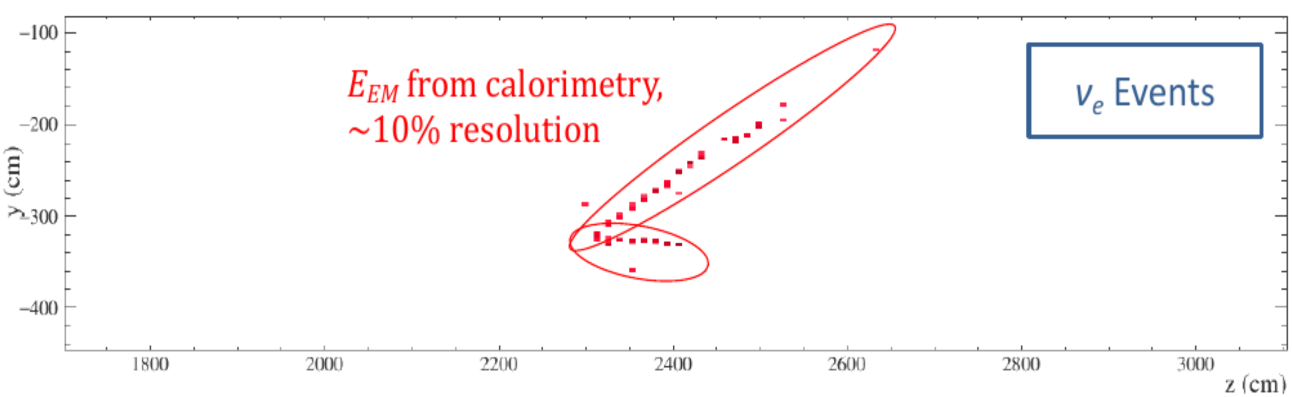
- **Eν reconstructed with hadronic deposits:**
  - important difference $\nu - \bar{\nu}$: proton vs neutron (~undetected)
  - proton/pion energy smeared by Final State Interactions



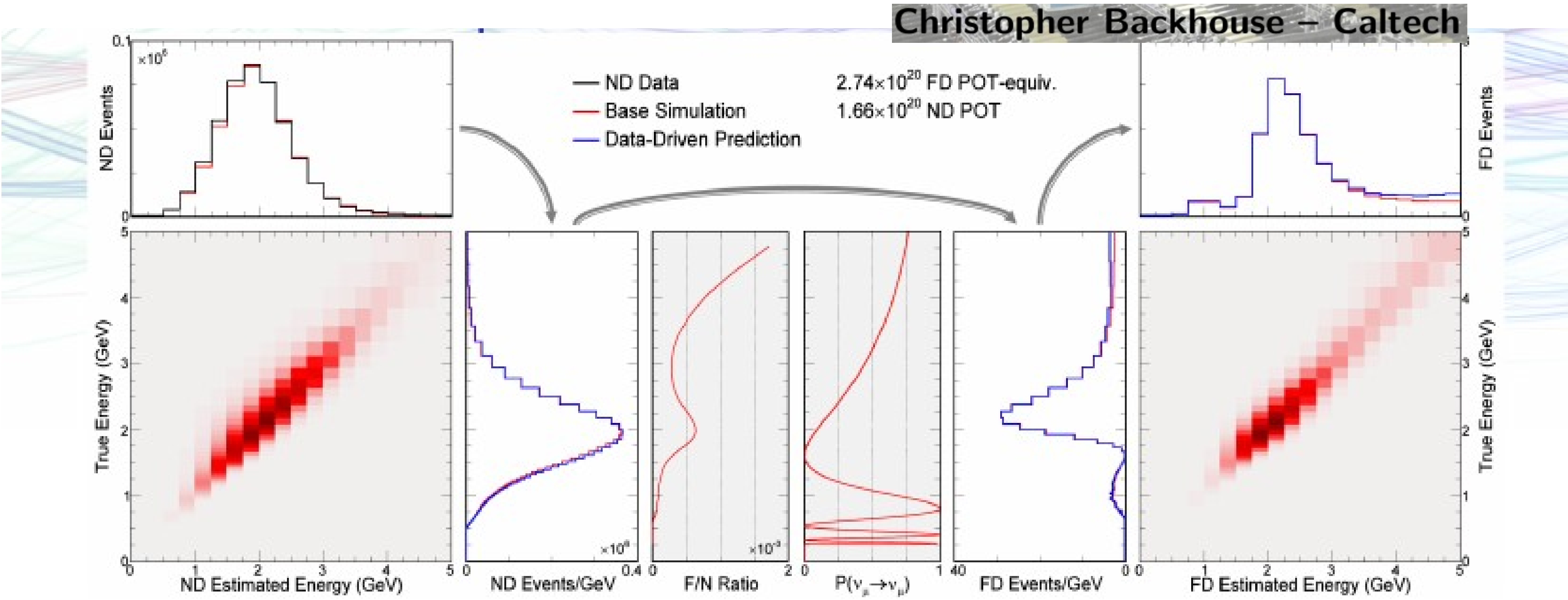
Important to tune model predictions for E_{had} NOvA Preliminary



- Different reconstruction and energy resolution for ν_μ and ν_e



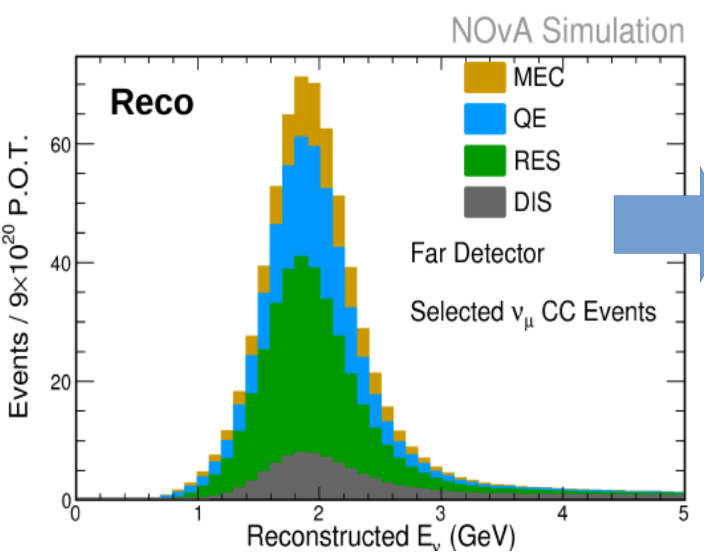
ND to FD extrapolation

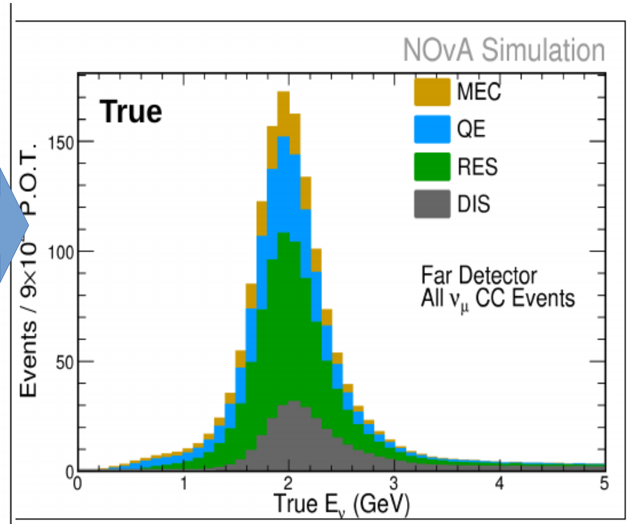


- Subtract NC expectation in ND, reweight MC in reco energy to match
- Transform to true energy, transport to FD with oscillations
- Transform to reco energy, add FD NC expectation back in
- Dependence on MC for background subtraction and true/reco matrix

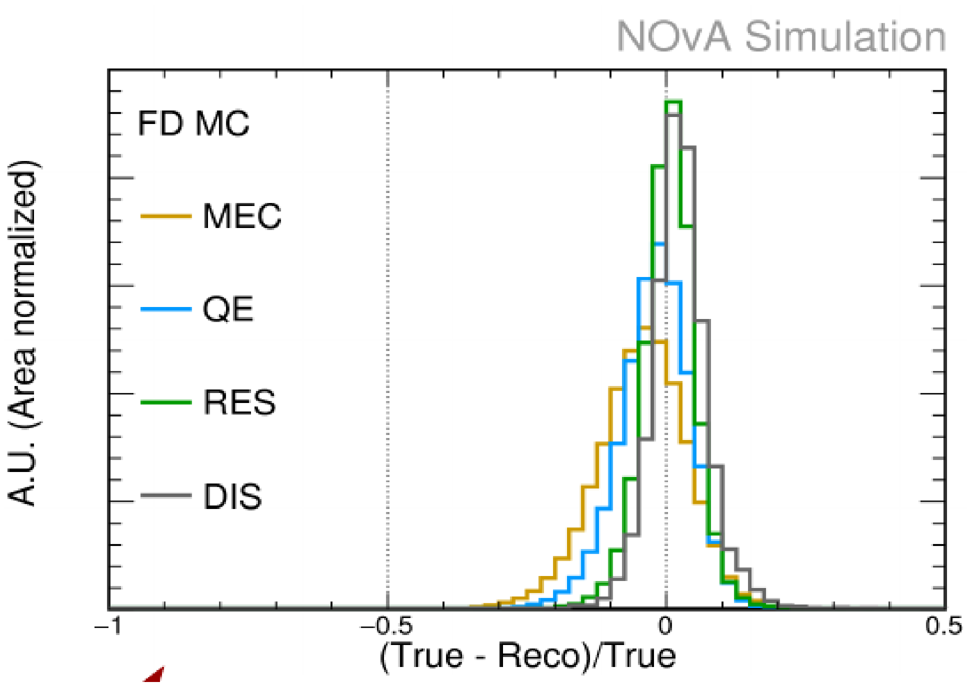
Not only detector systematics but also theoretical uncertainties (FSI, multiplicity in the final state, fraction of neutrons...) do affect the true ↔ reco correspondance

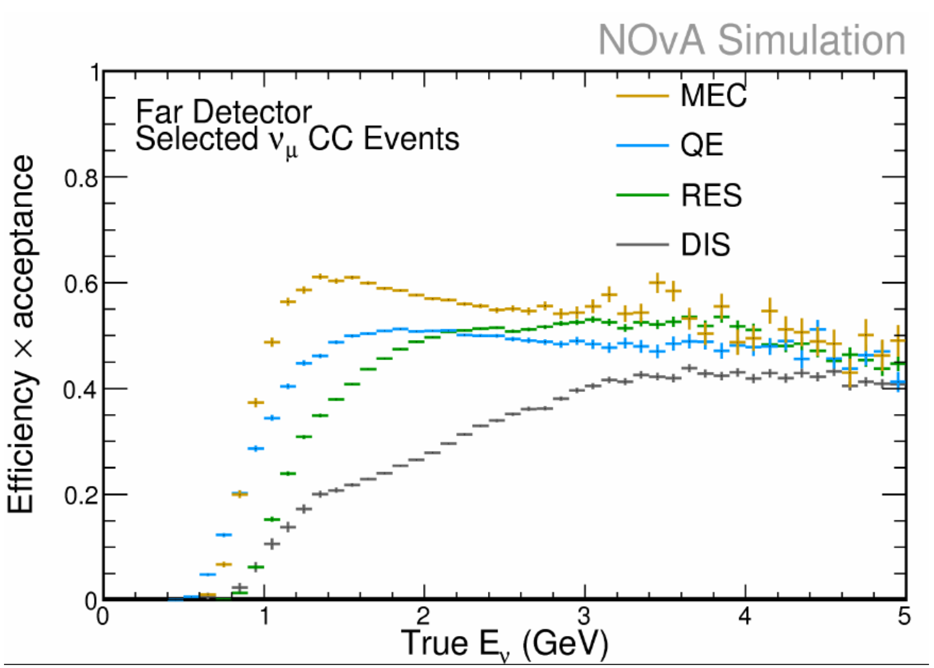
Resolution, efficiency, acceptance



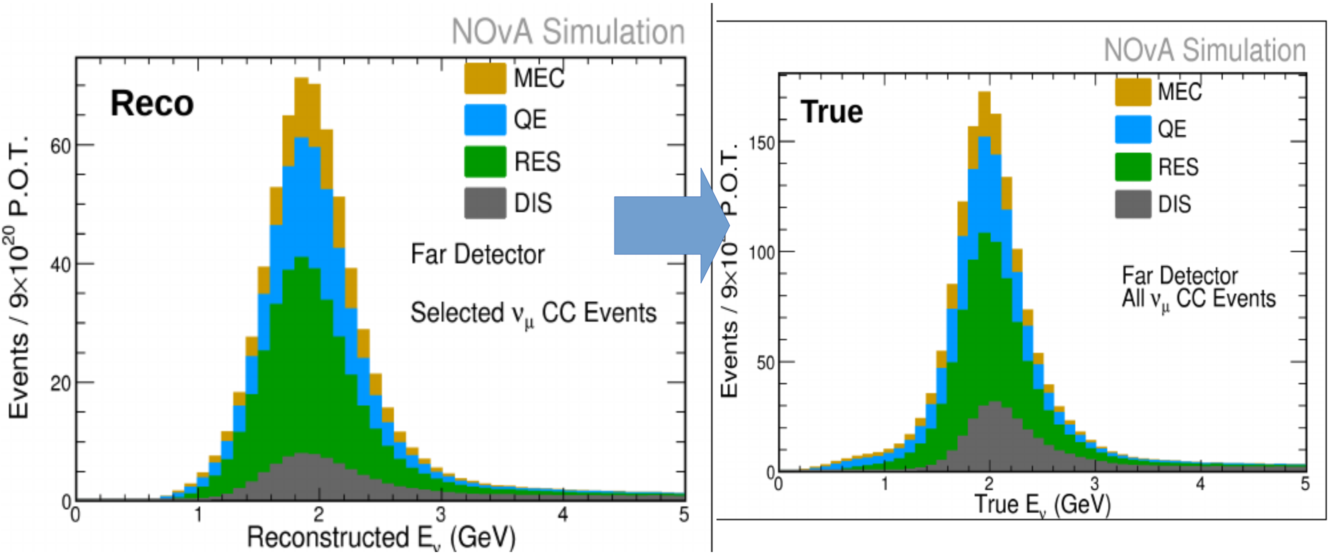


Each process has different neutrino energy resolution and efficiency: dependence on hadron multiplicity, π^0 fraction, kinematics of leptons ...



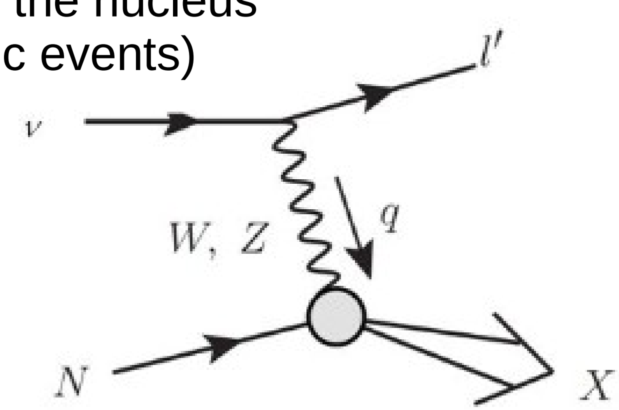


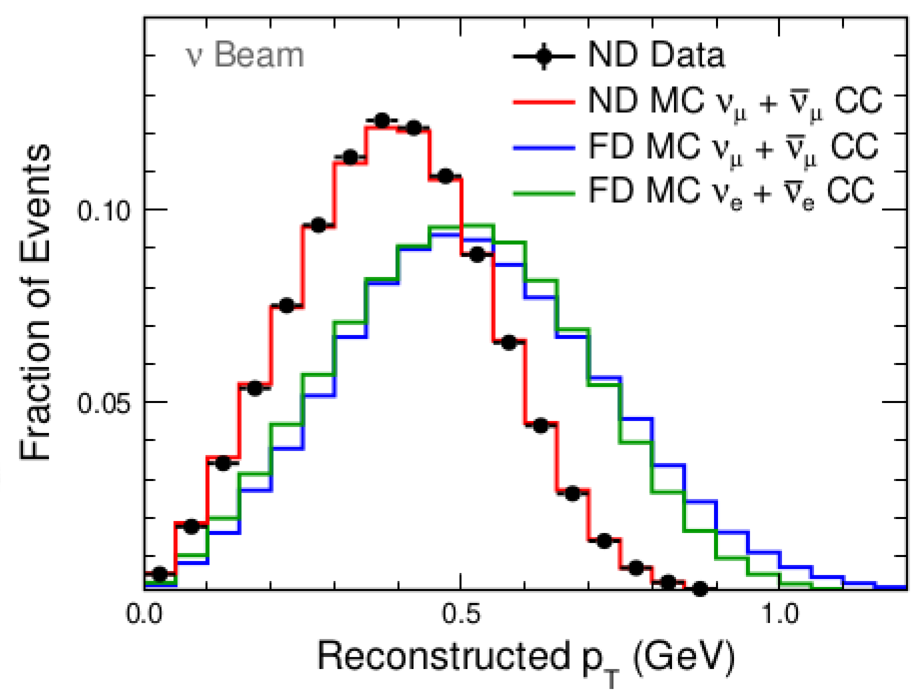
Resolution, efficiency, acceptance



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

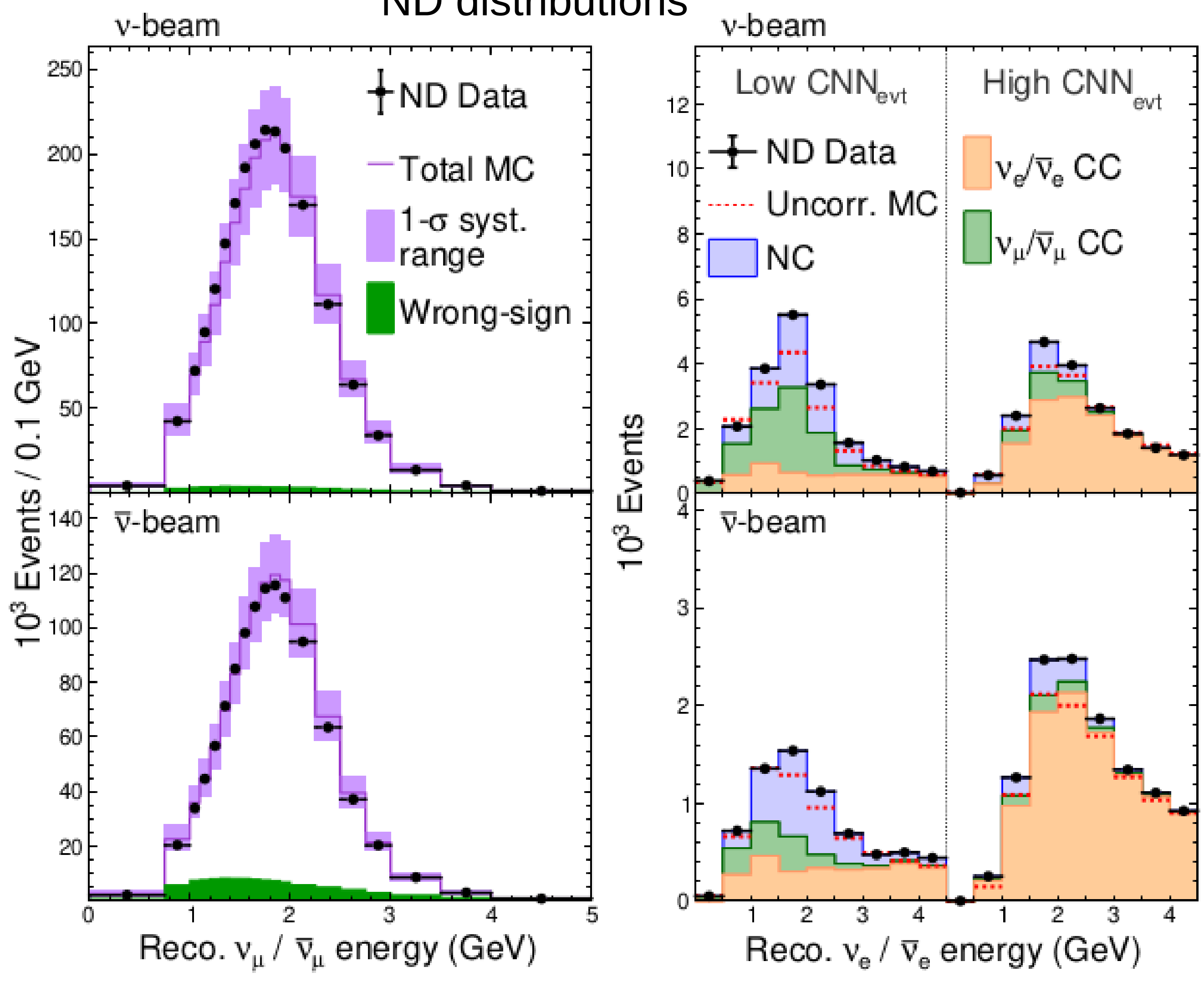
- Inclusive selection: require one muon/electron. Convolutional Neural Network (CNN to separate nm, ne, NC, cosmogenic background)

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

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

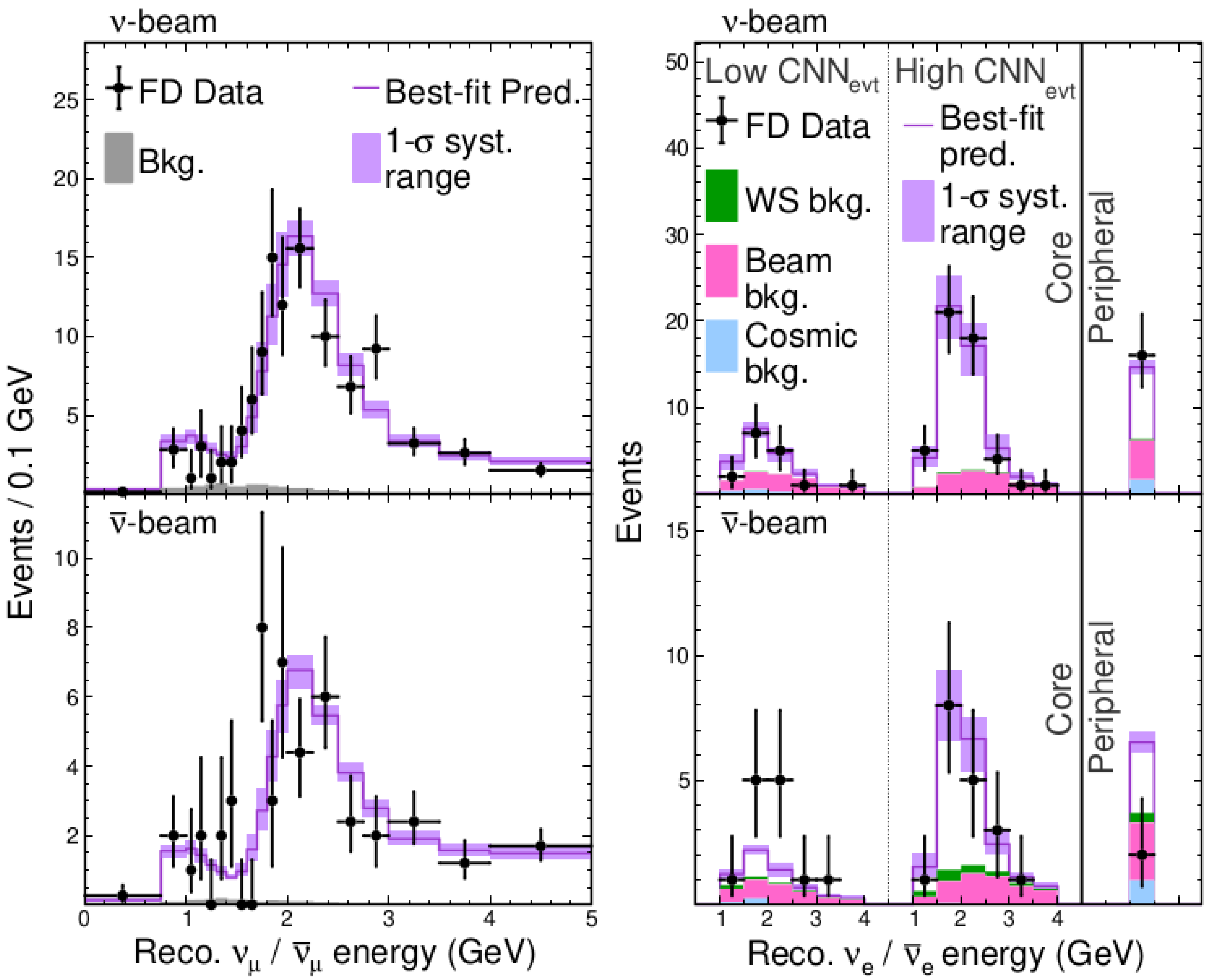
  - All samples subdivided in lepton transverse momentum to minimize impact of different acceptance at ND and FD

ND distributions



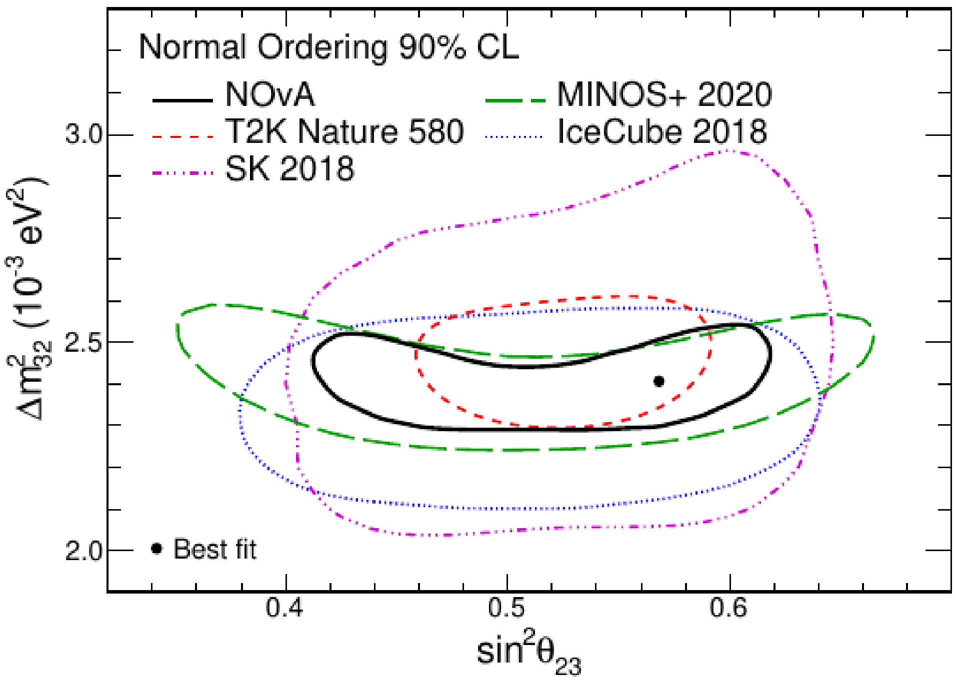
- Measurement of all the visible energy in the event to estimate the neutrino energy

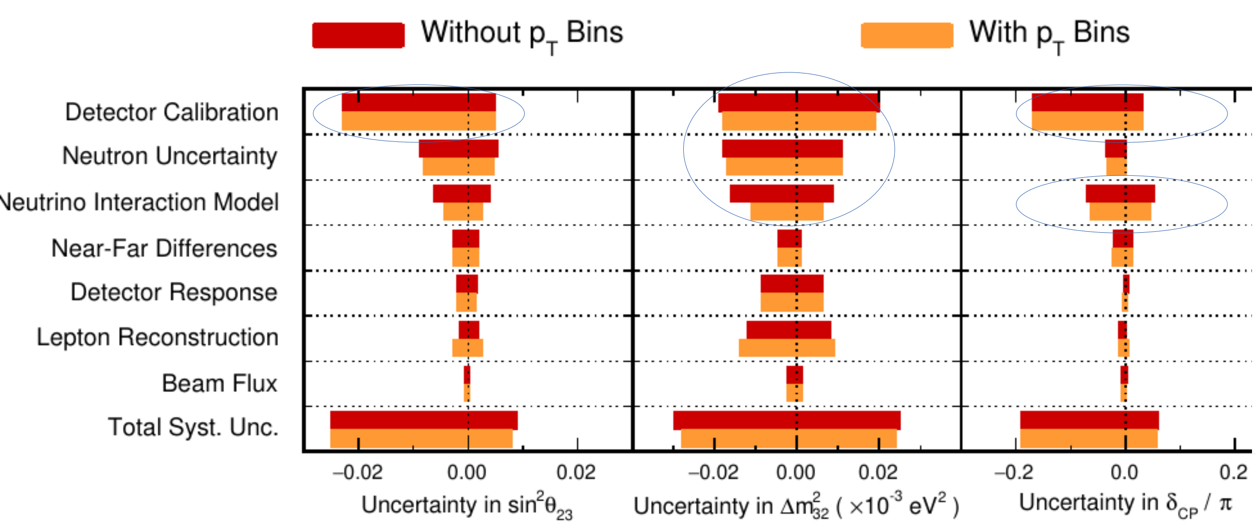
Far detector results

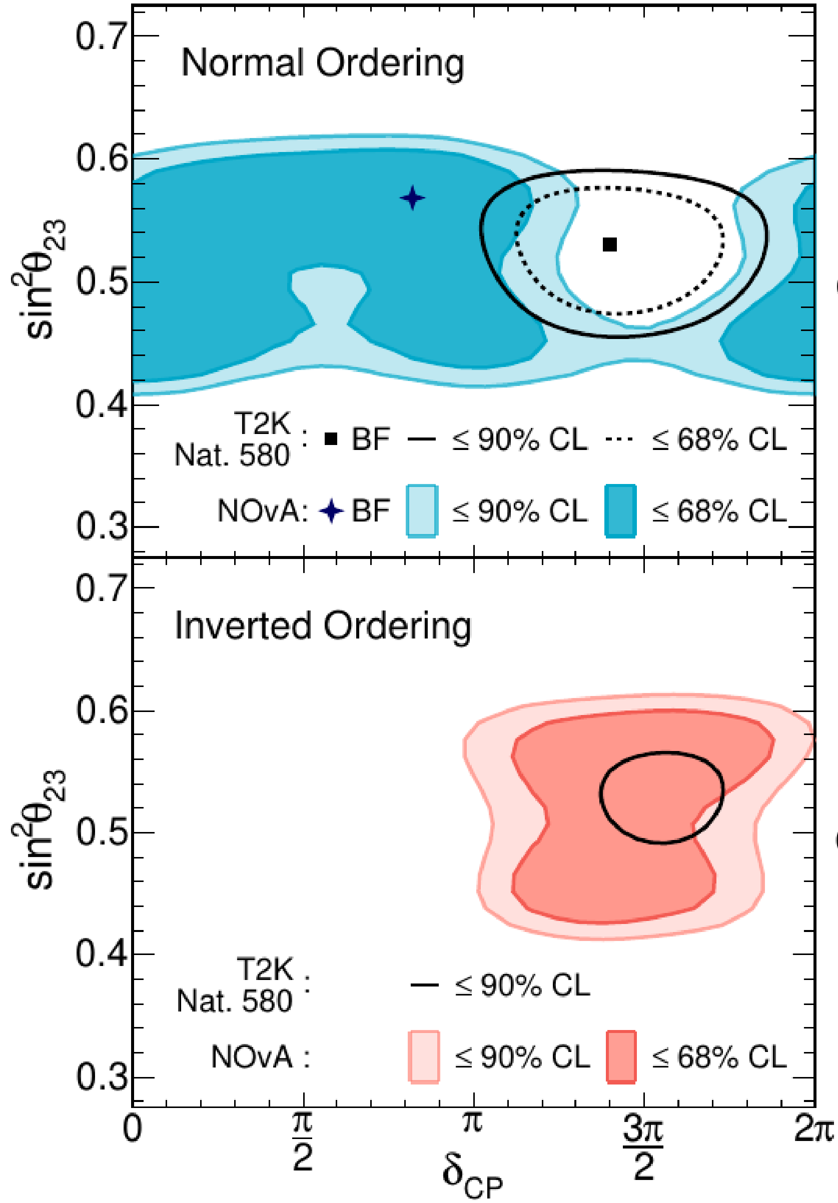


Fit to FD data with “ND-tuned” distribution
→ extract measurement of oscillation parameters

Far detector results





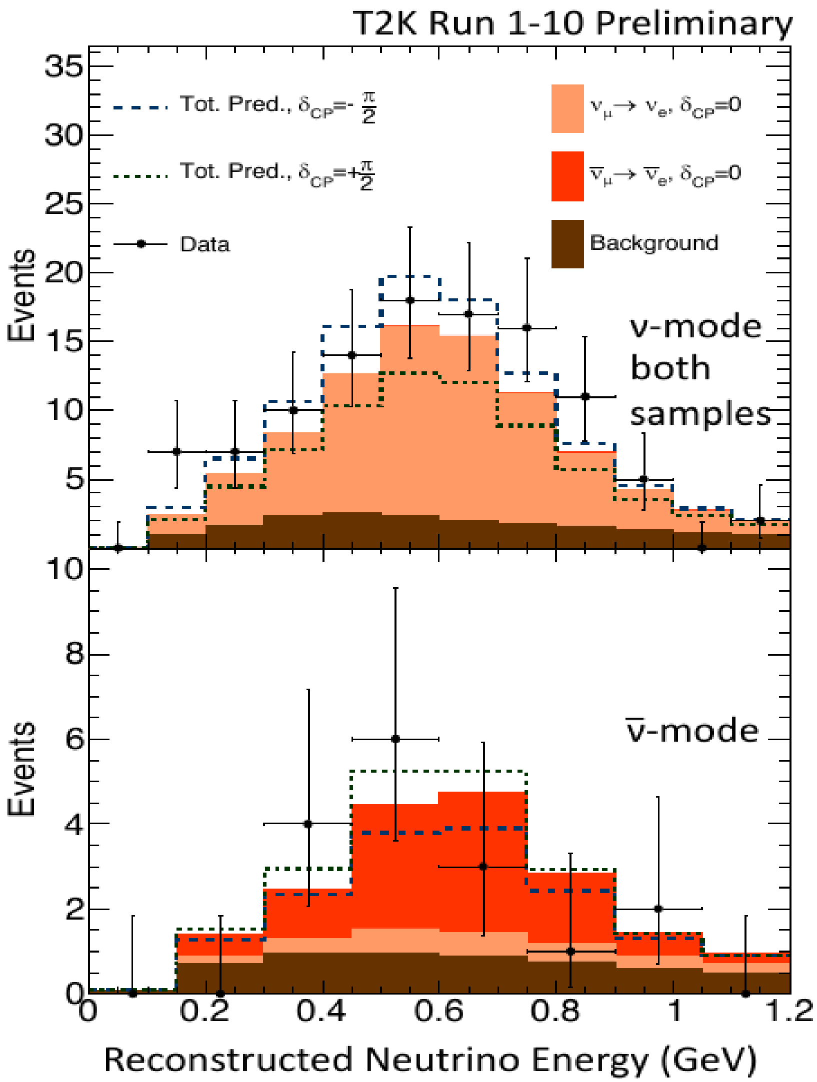


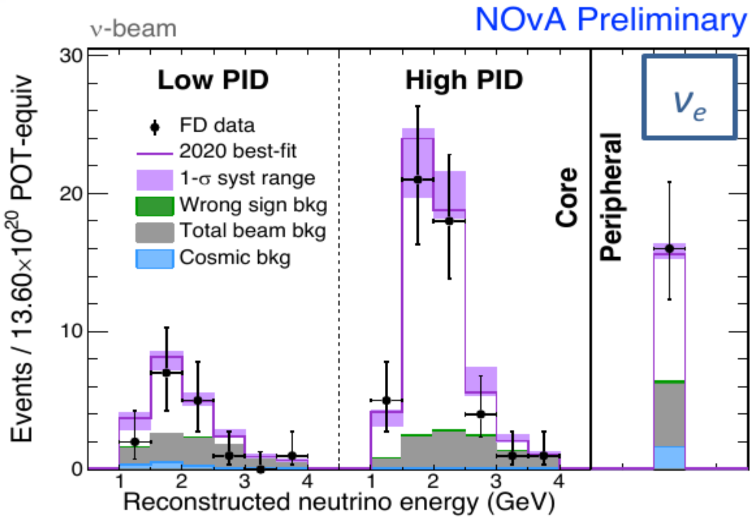
Limitations and future challenges

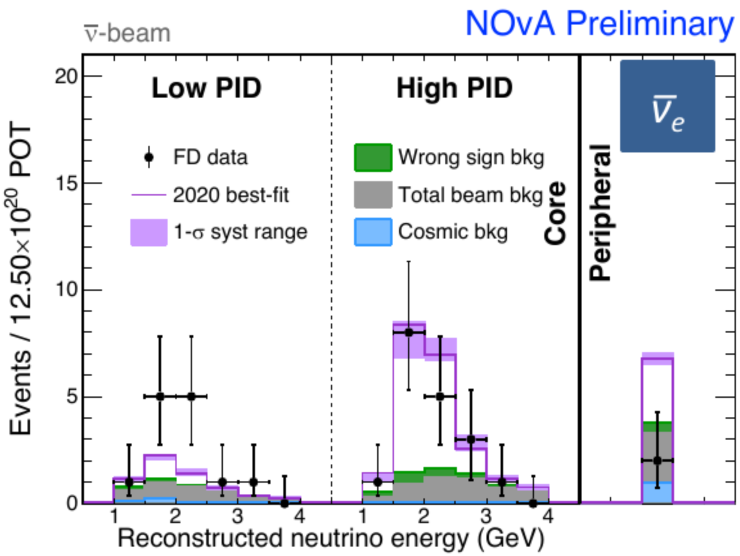
δ_{CP}: statistically limited

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

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



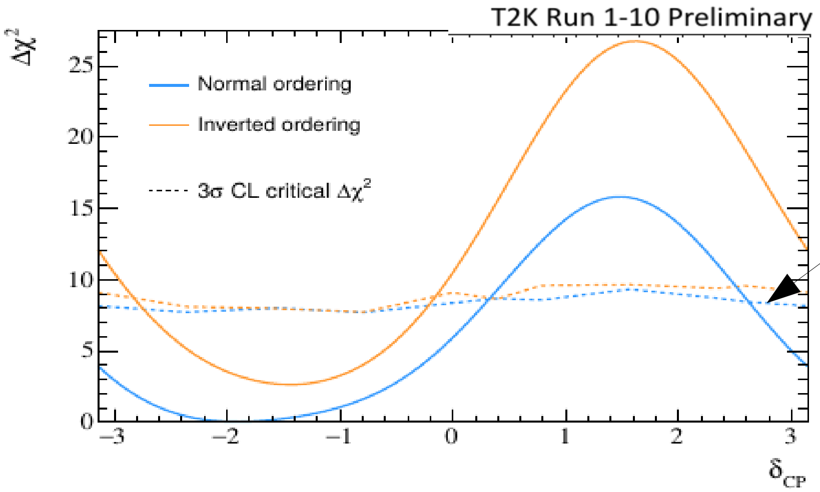




Statistical treatment: Fieldman Cousin

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

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



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

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

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

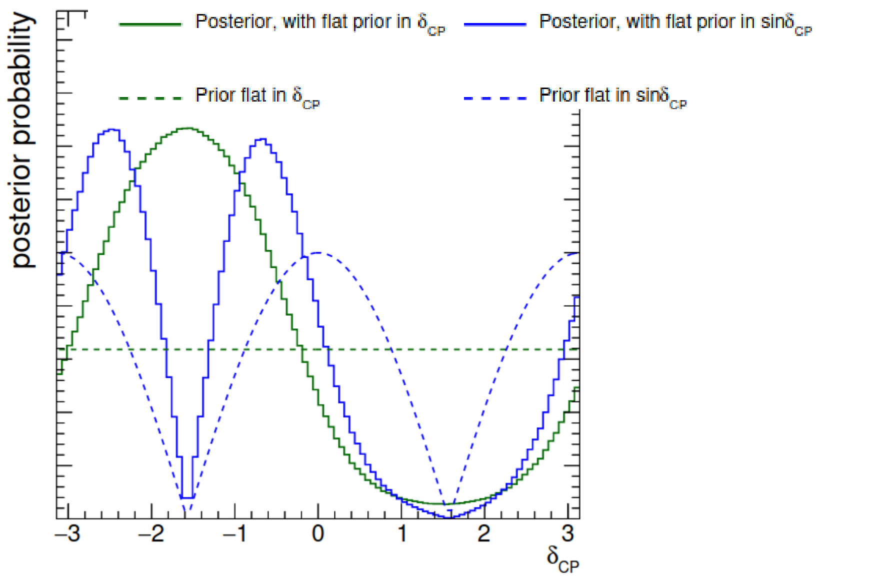
  Safe at 3σ but what about >3σ? Studies on-going

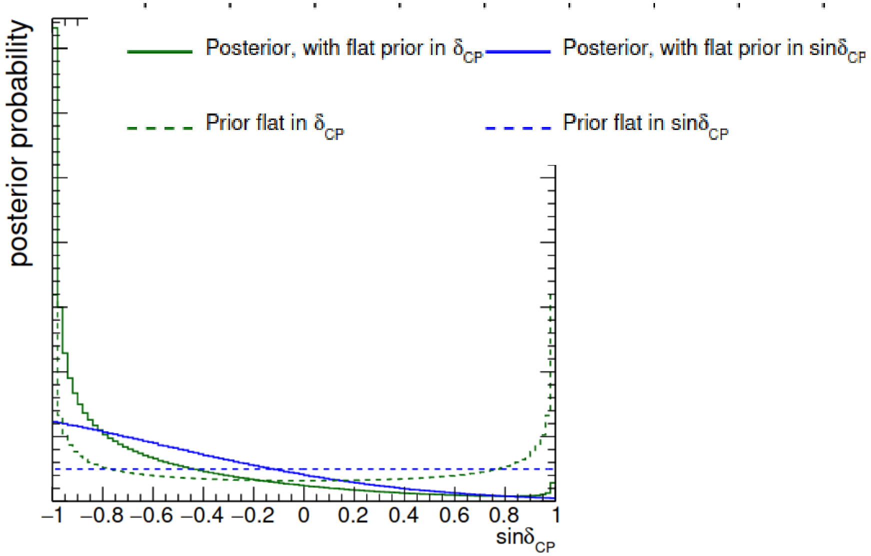
- Effect become important because of degeneracies and boundary effects

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

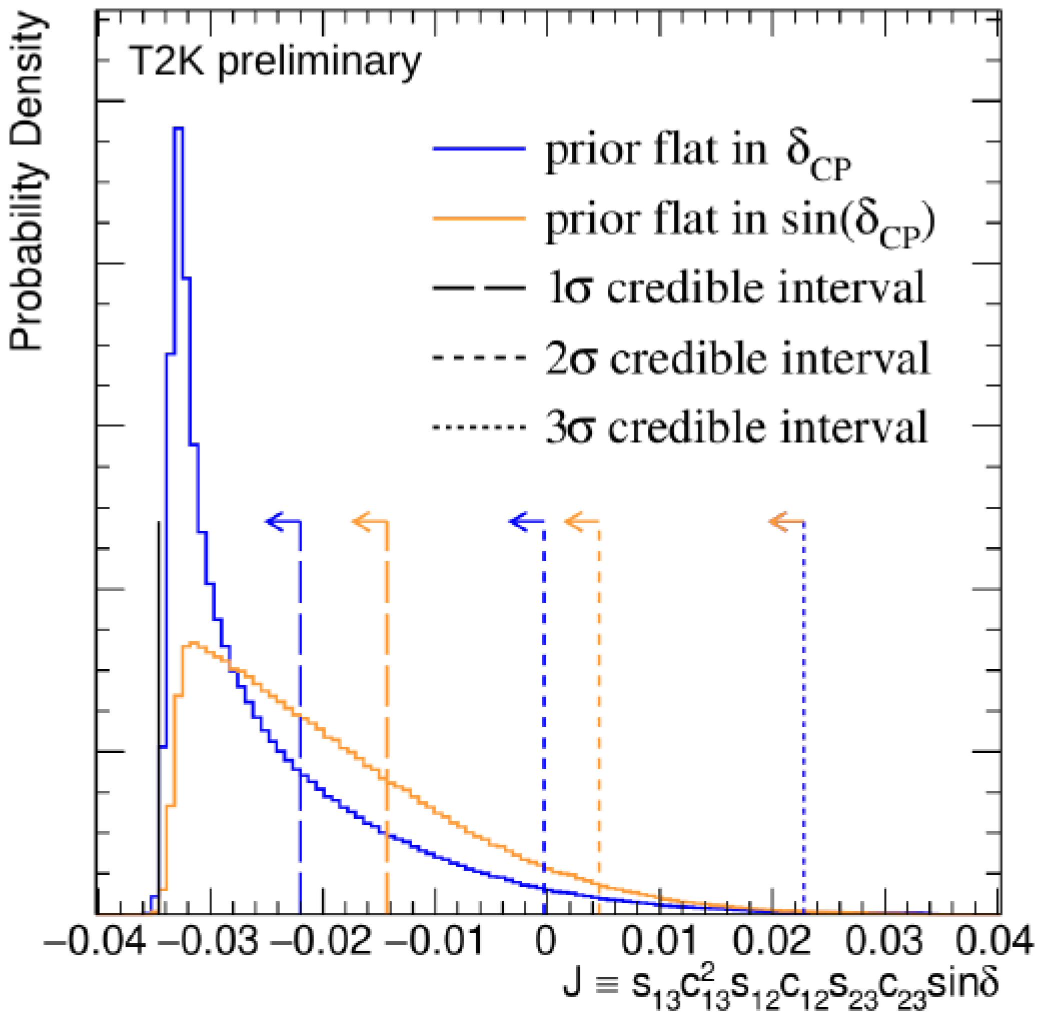
Statistical treatment: prior

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

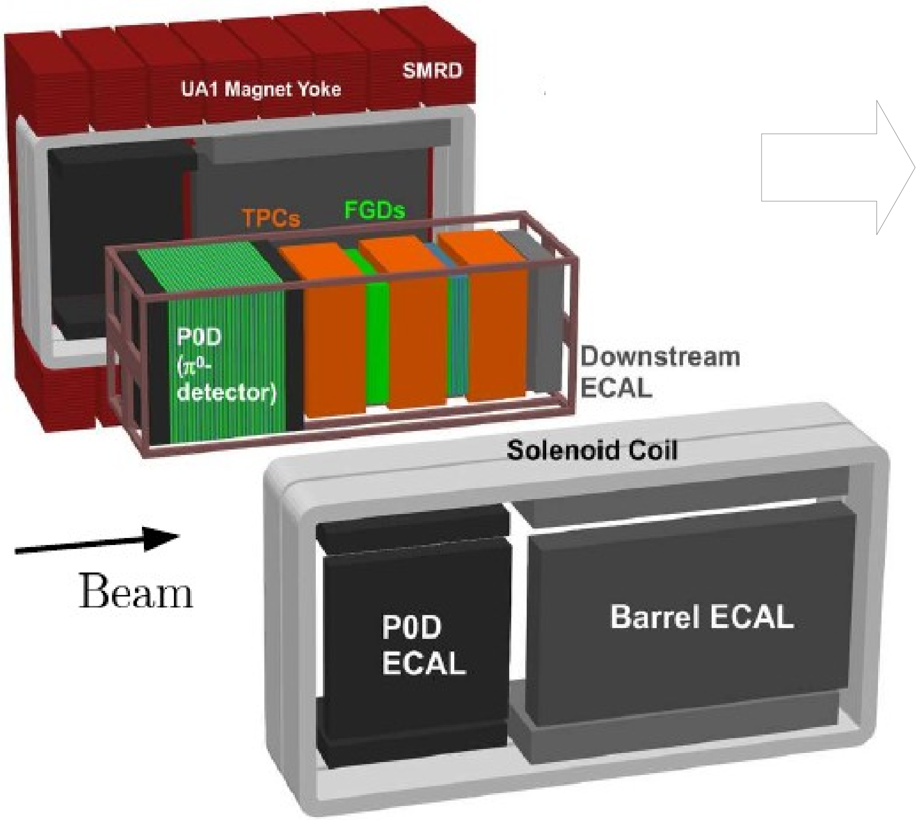


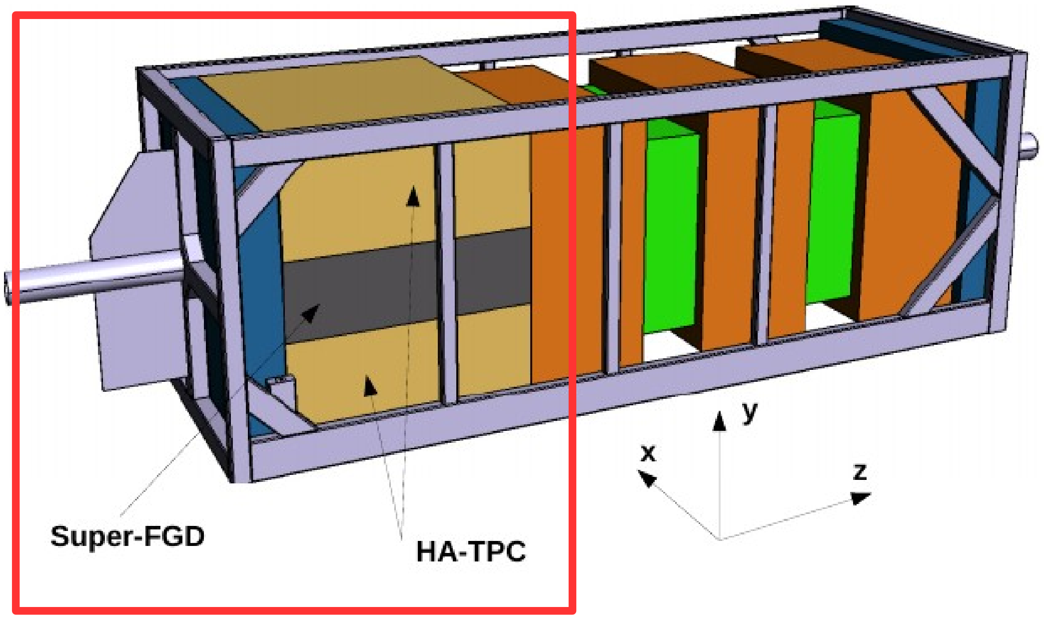


CPV = Jarlskog invariant sign
(still impact from prior assumption:
flat on δ_{CP} or $\sin\delta_{CP}$?)

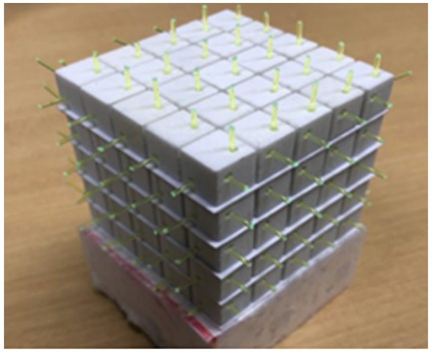


ND280 → ND280 upgrade





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



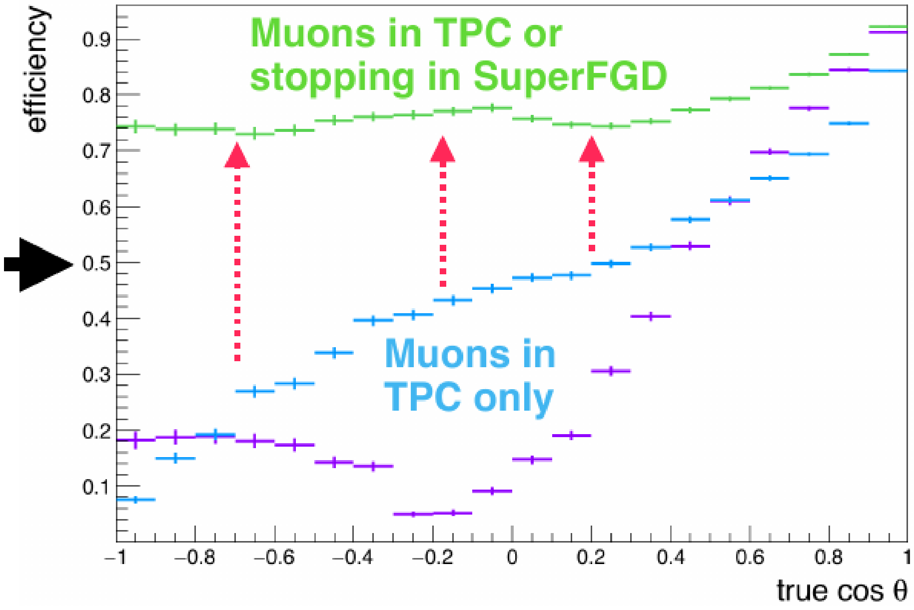
- **New target** with much lower threshold for track reconstruction (p,p)

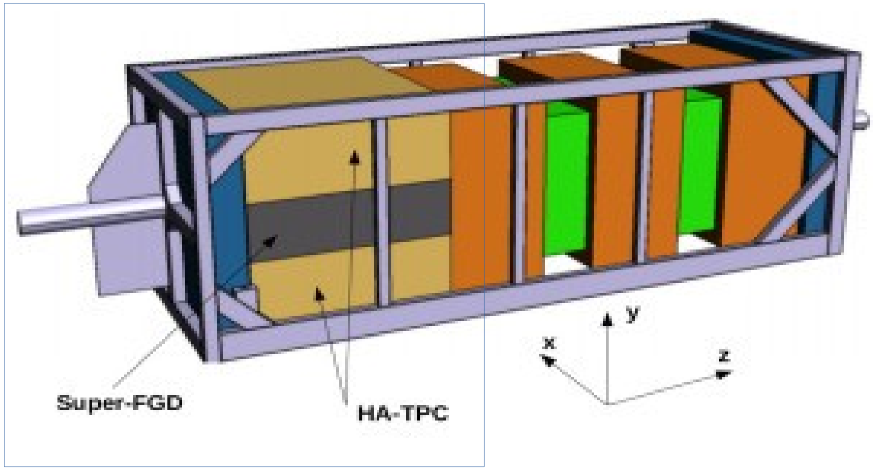
- **High angle TPCs with resistive Micromegas:** coverage at high angle and improved momentum resolution

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

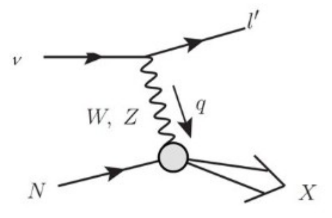
ND280 upgrade

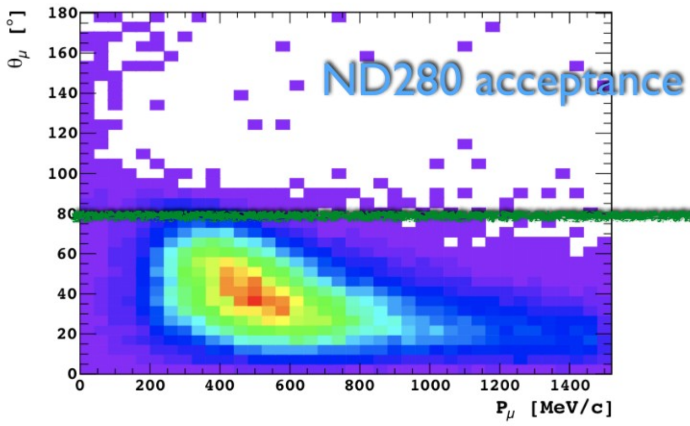
- larger statistics from new target + improved angular acceptance

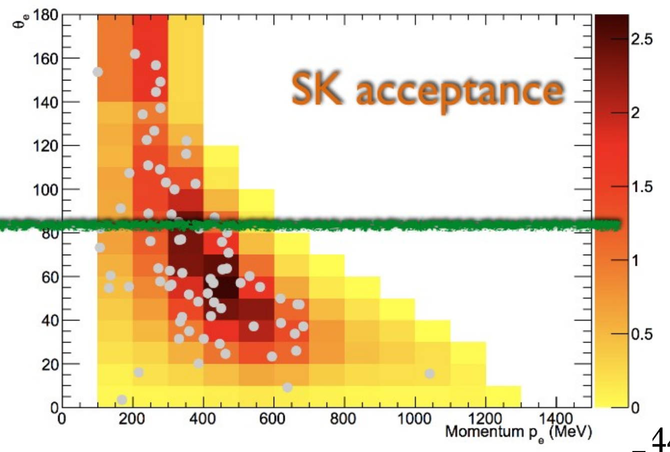




Leptons at larger angle correspond to more inelastic events







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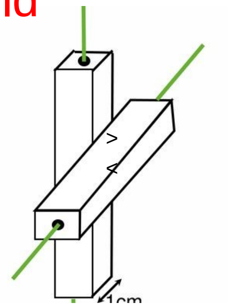
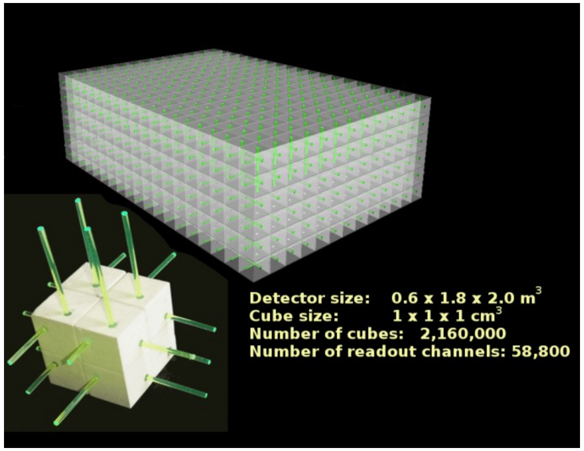
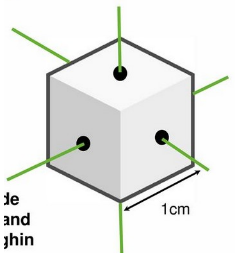
ND280 upgrade

- larger statistics from new target + improved angulaire acceptance

- proton kinematics measurement down to low momentum threshold



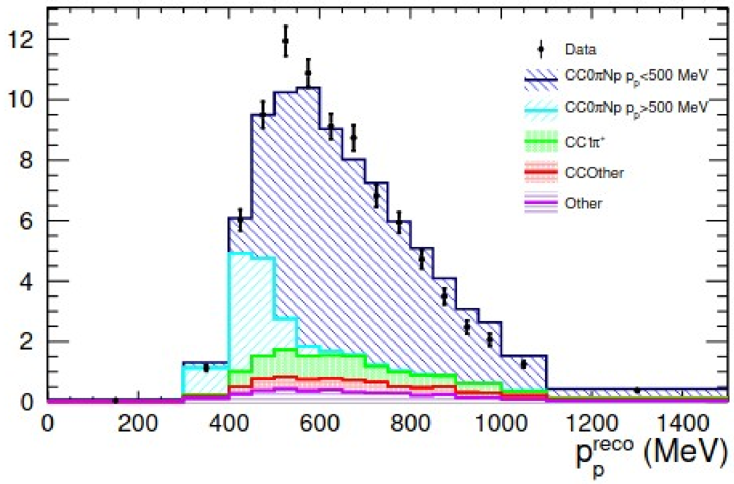




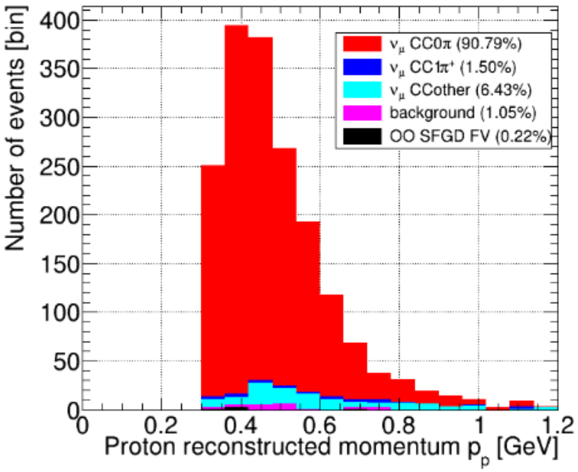
New '3D' scintillating detector

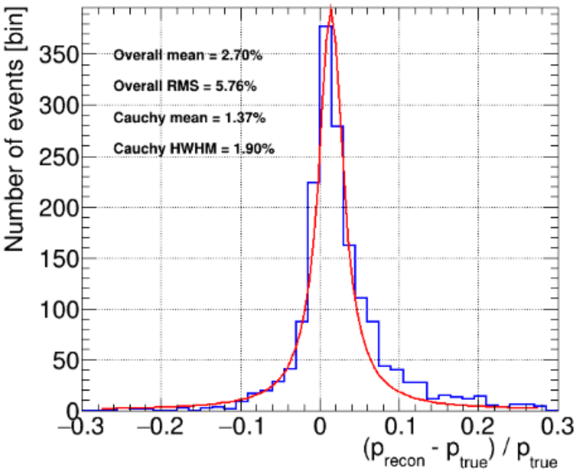
ND280 FGDs are '2D' scintillating detectors

ND280 measurement



ND280 upgrade (ν MC):





ND280 upgrade

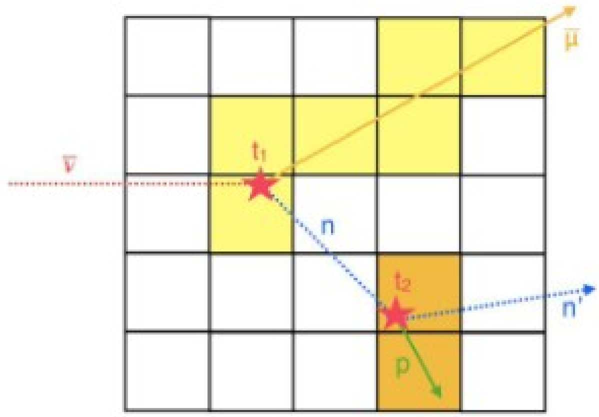
New analysis features are also preparing the road to the analysis of ND280 upgrade data:

- larger statistics from new target + improved angulaire acceptance

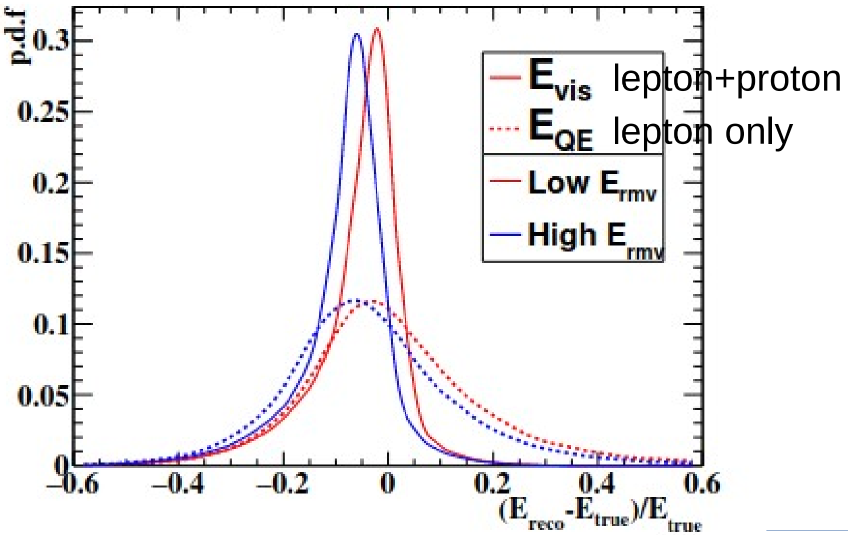
- proton kinematics measurement down to low momentum threshold

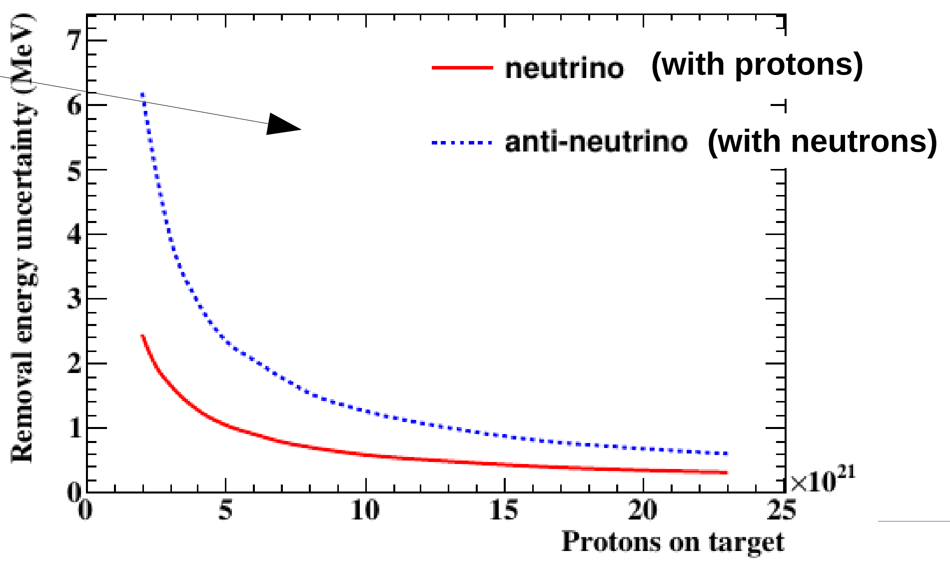
- neutron measurement event-by-event: NEW!!!

Time-of-flight technique



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





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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

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

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

Near detectors and nuclear theory

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

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

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

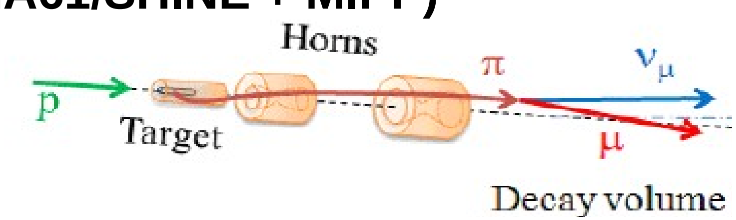
~same flux at ND and FD

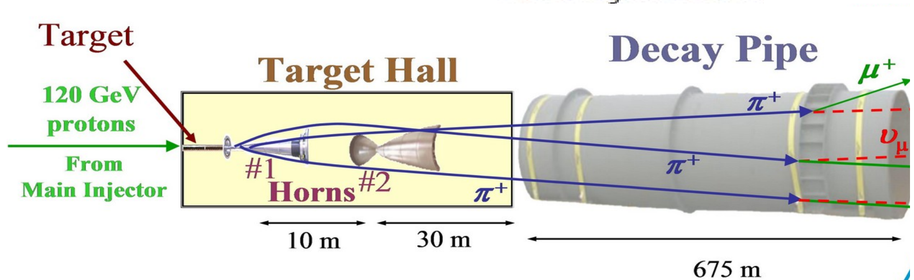
what we want to measure: oscillation probability

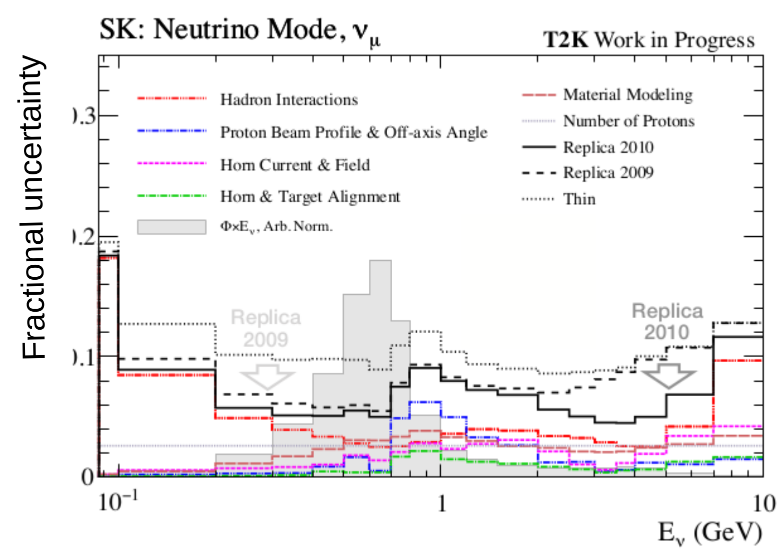
cross-section must be extrapolated from ND to FD:
- different neutrino energy distribution
- ND measure flux times xsec

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 xsce

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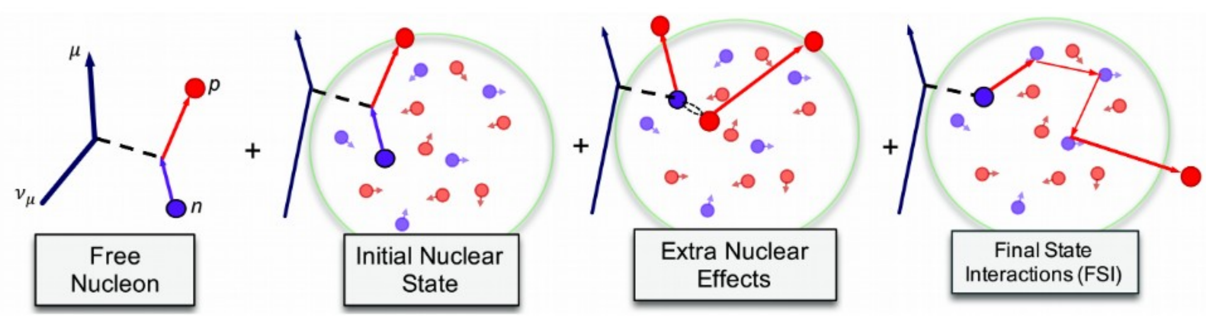
~same flux at ND and FD

what we want to measure: oscillation probability

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

Need nuclear theory models!

ν-nucleus interaction modeling and tuning



(and similarly for pion(s) production)

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

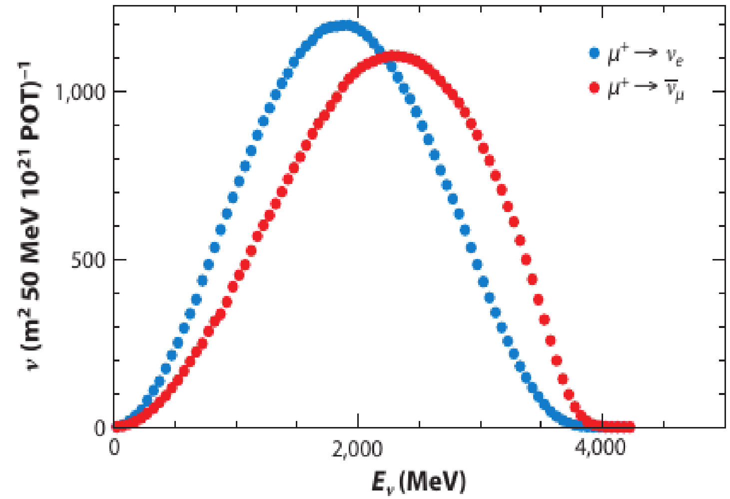
→ fundamentally the name of the game: precise Eν reconstruction

Non standard beams and fluxes

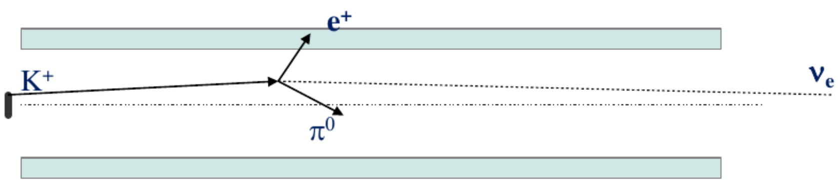
- Neutrinos from Stored Muons (**nuSTORM**): beams from the decay of 3.8 GeV muons confined within a storage ring


well known energy of neutrinos


large ν_e statistics



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



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

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