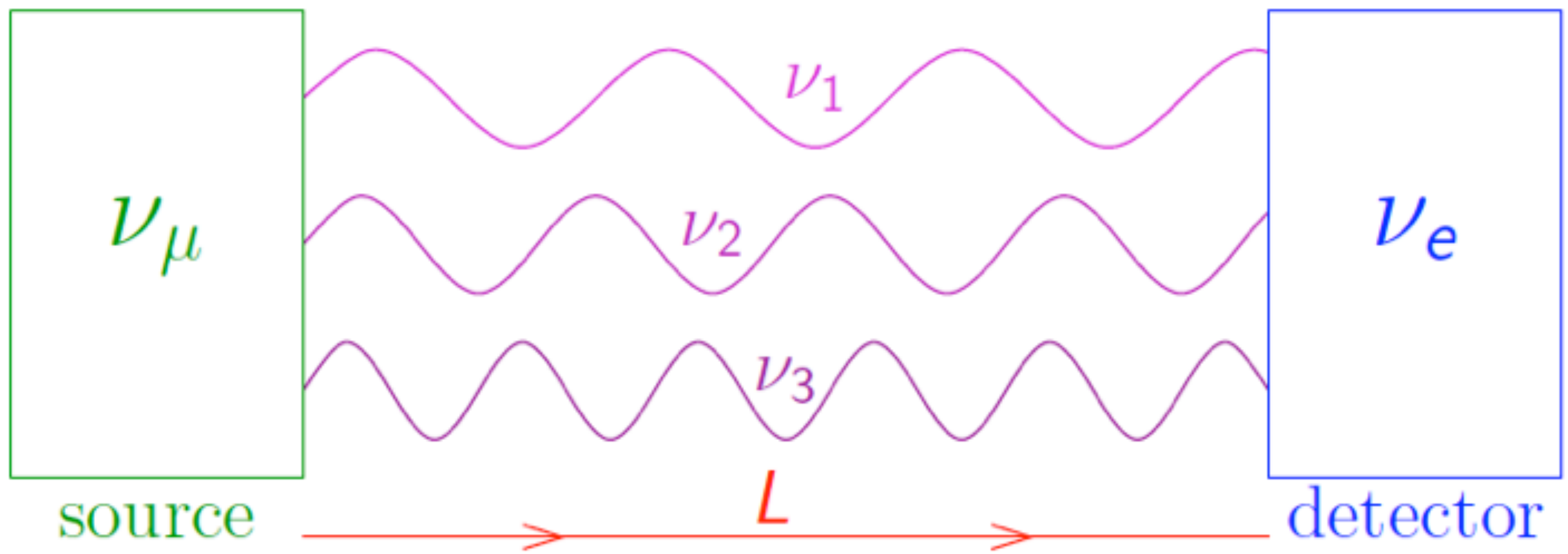
Lecture 4: LBL/accelerators

PhD Cycle XXXIV

Neutrino Oscillations

$$|\nu(t=0)\rangle = |\nu_\mu\rangle = U_{\mu 1}\,|\nu_1\rangle + U_{\mu 2}\,|\nu_2\rangle + U_{\mu 3}\,|\nu_3\rangle$$



$$|\nu(t>0)\rangle = U_{\mu 1}\,e^{-iE_1 t}\,|\nu_1\rangle + U_{\mu 2}\,e^{-iE_2 t}\,|\nu_2\rangle + U_{\mu 3}\,e^{-iE_3 t}\,|\nu_3\rangle \neq |\nu_\mu\rangle$$

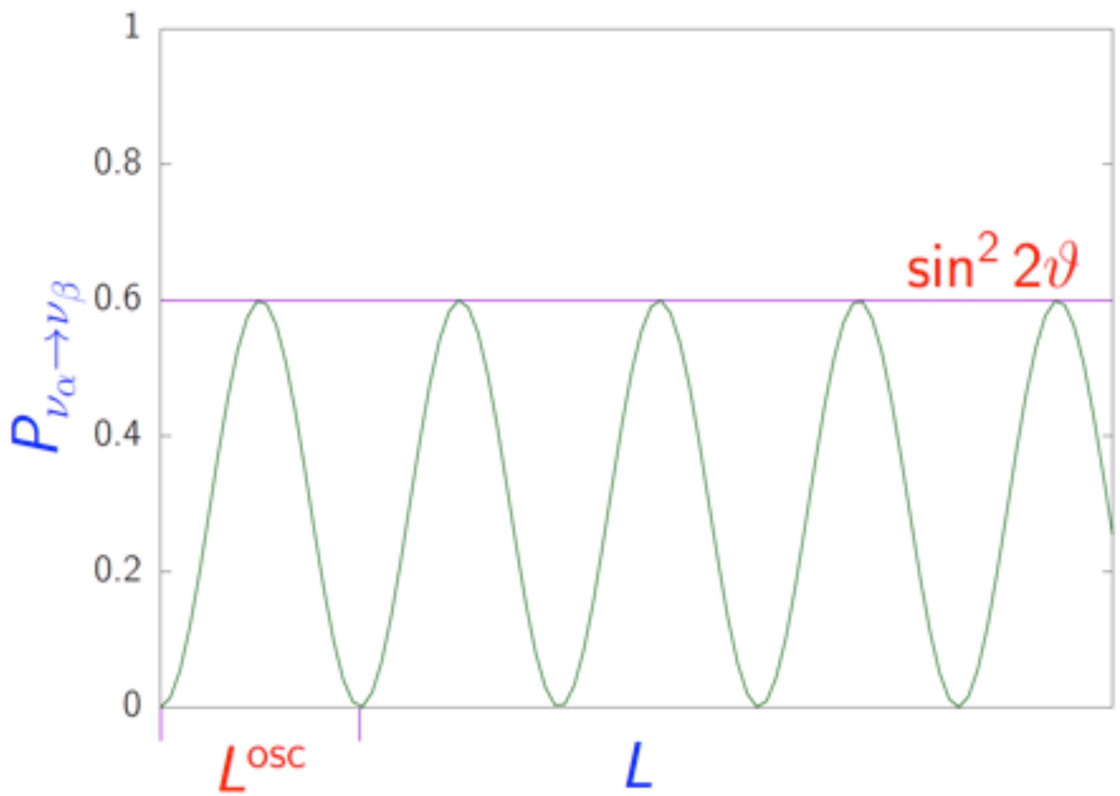
$$E_k^2 = p^2 + m_k^2$$

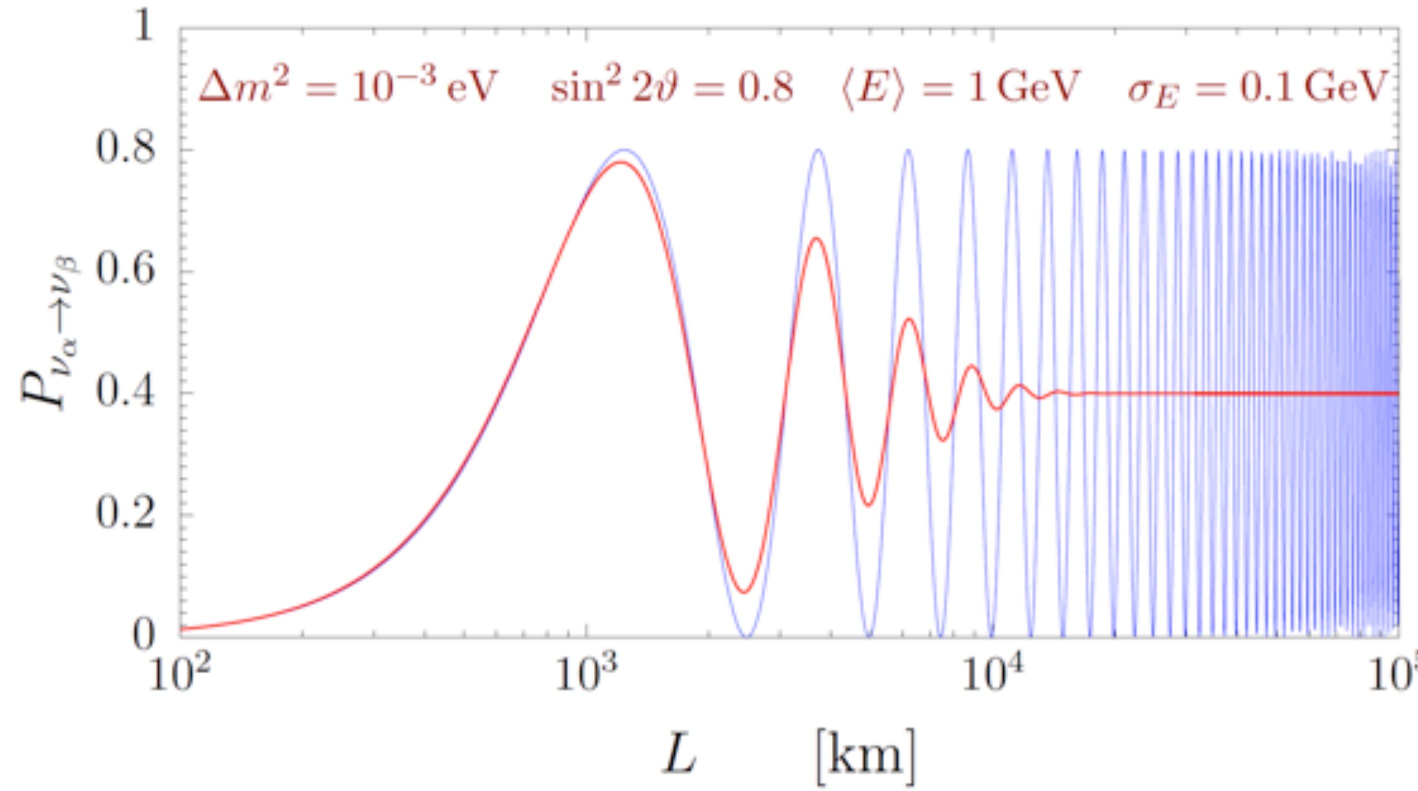
$$P_{\nu_\mu\to\nu_e}(t>0) = |\langle\nu_e|\nu(t>0)\rangle|^2 \sim \sum_{k>j} \mathrm{Re}\left[U_{ek}\,U_{\mu k}^*\,U_{ej}^*\,U_{\mu j}\right] \sin^2\left(\frac{\Delta m_{kj}^2 L}{4E}\right)$$

transition probabilities depend on U and $\Delta m_{kj}^2 \equiv m_k^2 - m_j^2$

$\nu_e \to \nu_\mu$	$\nu_e \to \nu_\tau$	$\nu_\mu \to \nu_e$	$\nu_\mu \to \nu_\tau$
$\bar\nu_e \to \bar\nu_\mu$	$\bar\nu_e \to \bar\nu_\tau$	$\bar\nu_\mu \to \bar\nu_e$	$\bar\nu_\mu \to \bar\nu_\tau$

2ν-mixing: $\quad P_{\nu_\alpha \to \nu_\beta} = \sin^2 2\vartheta \, \sin^2\left(\frac{\Delta m^2 L}{4E}\right) \quad \Longrightarrow \quad L^{\text{osc}} = \frac{4\pi E}{\Delta m^2}$





Tiny neutrino masses lead to observable macroscopic oscillation distances!

$\frac{L}{E} \lesssim$

$10 \, \frac{\text{m}}{\text{MeV}} \; \left(\frac{\text{km}}{\text{GeV}}\right)$	short-baseline experiments	$\Delta m^2 \gtrsim 10^{-1}\,\text{eV}^2$
$10^3 \, \frac{\text{m}}{\text{MeV}} \; \left(\frac{\text{km}}{\text{GeV}}\right)$	long-baseline experiments	$\Delta m^2 \gtrsim 10^{-3}\,\text{eV}^2$
$10^4 \, \frac{\text{km}}{\text{GeV}}$	atmospheric neutrino experiments	$\Delta m^2 \gtrsim 10^{-4}\,\text{eV}^2$
$10^{11} \, \frac{\text{m}}{\text{MeV}}$	solar neutrino experiments	$\Delta m^2 \gtrsim 10^{-11}\,\text{eV}^2$

Neutrino oscillations are the optimal tool to reveal tiny neutrino masses!

SOURCE	Flavour	Distance	Energy	Min Dm^2
Sun	ν_e	$\sim 1.5 \times 10^8$ km	0.2 –15 MeV	$\sim 10^{-11}$ eV^2
CR	ν_μ ν_e $\bar{\nu}_\mu$ $\bar{\nu}_e$	10 km – 13000 km	0. 2 GeV – 100 GeV	$\sim 10^{-4}$ eV^2
Reactors	$\bar{\nu}_e$	20 m – 250 km	<E> ≈ 3 MeV	$\sim 10^{-1} - 10^{-6}$ eV
Accelerators	ν_μ ν_e $\bar{\nu}_\mu$ $\bar{\nu}_e$	15 m – 730 km	20 MeV – 100 GeV	$\sim 10^{-3} - 10$ eV^2

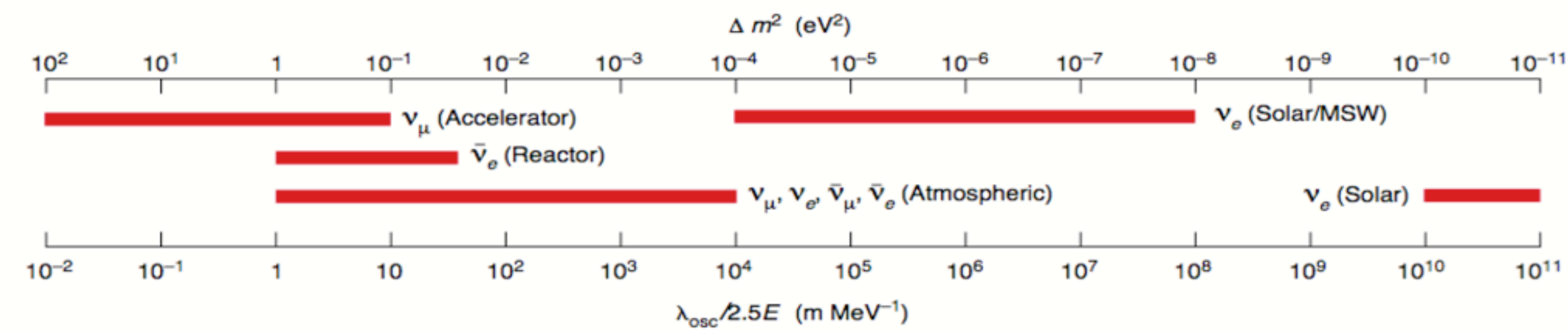


Figure 15. Accessible Ranges of Δm^2

Neutrino energies are specific to the source, and source-to-detector distances also vary with the source. The ratio of these two variables determines the range of values for Δm^2 that neutrino oscillation experiments can measure using each source. These ranges are labeled with the source and the neutrinos produced by that source. Two ranges are given for solar-neutrino experiments. One assumes that the MSW effect enhances oscillations, in which case, the range of Δm^2 is determined in part by the electron density of matter in the Sun. The other assumes no matter enhancement.

Three-Neutrino Mixing Paradigm

Standard Parameterization of Mixing Matrix

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{13}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{13}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\lambda_{21}} & 0 \\ 0 & 0 & e^{i\lambda_{31}} \end{pmatrix}$$

$$= \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23}-c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23}-s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}s_{23}-c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23}-s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\lambda_{21}} & 0 \\ 0 & 0 & e^{i\lambda_{31}} \end{pmatrix}$$

$c_{ab} \equiv \cos\vartheta_{ab}$ $\quad s_{ab} \equiv \sin\vartheta_{ab}$ $\quad 0 \leq \vartheta_{ab} \leq \frac{\pi}{2}$ $\quad 0 \leq \delta_{13}, \lambda_{21}, \lambda_{31} < 2\pi$

OSCILLATION PARAMETERS
- 3 Mixing Angles: ϑ_{12}, ϑ_{23}, ϑ_{13}
- 1 CPV Dirac Phase: δ_{13}
- 2 independent $\Delta m^2_{kj} \equiv m^2_k - m^2_j$: Δm^2_{21}, Δm^2_{31}

2 CPV Majorana Phases: λ_{21}, λ_{31} $\Longleftrightarrow$ $|\Delta L| = 2$ processes

Experimental Evidences of Neutrino Oscillations

Solar $\nu_e \to \nu_\mu, \nu_\tau$ — (SNO, BOREXino; Super-Kamiokande; GALLEX/GNO, SAGE; Homestake, Kamiokande)

VLBL Reactor $\bar{\nu}_e$ disappearance — (KamLAND)
L = 180 km
L/E ~ 6 10^4 m/MeV

$\to$

$$\Delta m^2_{\text{SOL}} = \Delta m^2_{21} \simeq 7.5 \times 10^{-5}\,\text{eV}^2$$
$$\sin^2\vartheta_{\text{SOL}} = \sin^2\vartheta_{12} \simeq 0.30$$

Atmospheric $\nu_\mu \to \nu_\tau$ — (Super-Kamiokande; Kamiokande, IMB; MACRO, Soudan-2)

LBL Accelerator ν_μ disappearance — (K2K, MINOS; T2K, NOνA)

LBL Accelerator $\nu_\mu \to \nu_\tau$ — (Opera)

$\to$

$$\Delta m^2_{\text{ATM}} = |\Delta m^2_{31}| \simeq 2.5 \times 10^{-3}\,\text{eV}^2$$
$$\sin^2\vartheta_{\text{ATM}} = \sin^2\vartheta_{23} \simeq 0.50$$

LBL Accelerator $\nu_\mu \to \nu_e$ — (T2K, MINOS, NOνA)

LBL Reactor $\bar{\nu}_e$ disappearance — (Daya Bay, RENO; Double Chooz)

$\to$

$$\Delta m^2_{\text{ATM}} = |\Delta m^2_{31}|$$
$$\sin^2\vartheta_{13} \simeq 0.023$$

Experimental knowledge (2018)

https://globalfit.astroparticles.es/

parameter	best fit $\pm$ 1σ	3σ range	relative 1σ uncertainty
Δm^2_{21} $[10^{-5}\mathrm{eV}^2]$	$7.55^{+0.20}_{-0.16}$	7.05–8.14	2.4%
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\mathrm{eV}^2]$ (NO)	2.50 ± 0.03	2.41–2.60	
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\mathrm{eV}^2]$ (IO)	$2.42^{+0.03}_{-0.04}$	2.31-2.51	1.3%
$\sin^2\theta_{12}/10^{-1}$	$3.20^{+0.20}_{-0.16}$	2.73–3.79	5.5%
$\sin^2\theta_{23}/10^{-1}$ (NO)	$5.47^{+0.20}_{-0.30}$	4.45–5.99	4.7%
$\sin^2\theta_{23}/10^{-1}$ (IO)	$5.51^{+0.18}_{-0.30}$	4.53–5.98	4.4%
$\sin^2\theta_{13}/10^{-2}$ (NO)	$2.160^{+0.083}_{-0.069}$	1.96–2.41	
$\sin^2\theta_{13}/10^{-2}$ (IO)	$2.220^{+0.074}_{-0.076}$	1.99–2.44	3.5%
δ/π (NO)	$1.32^{+0.21}_{-0.15}$	0.87–1.94	10%
δ/π (IO)	$1.56^{+0.13}_{-0.15}$	1.12–1.94	9%

de Salas et al, PLB782 (2018) 633

Open Problems

- $\vartheta_{23} \lesseqgtr 45^\circ$?
  - T2K (Japan), NOνA (USA), ...
- CP violation ? $\delta_{13} \approx 3\pi/2$?
  - T2K (Japan), NOνA (USA), DUNE (USA), HyperK (Japan), ...
- Mass Ordering ?
  - JUNO (China), RENO-50 (Korea), PINGU (Antarctica), ORCA (EU), INO (India), ...

- Let's devote a couple of our lectures to exploring the reach, strategy and issues of the current experiments at artificial sources

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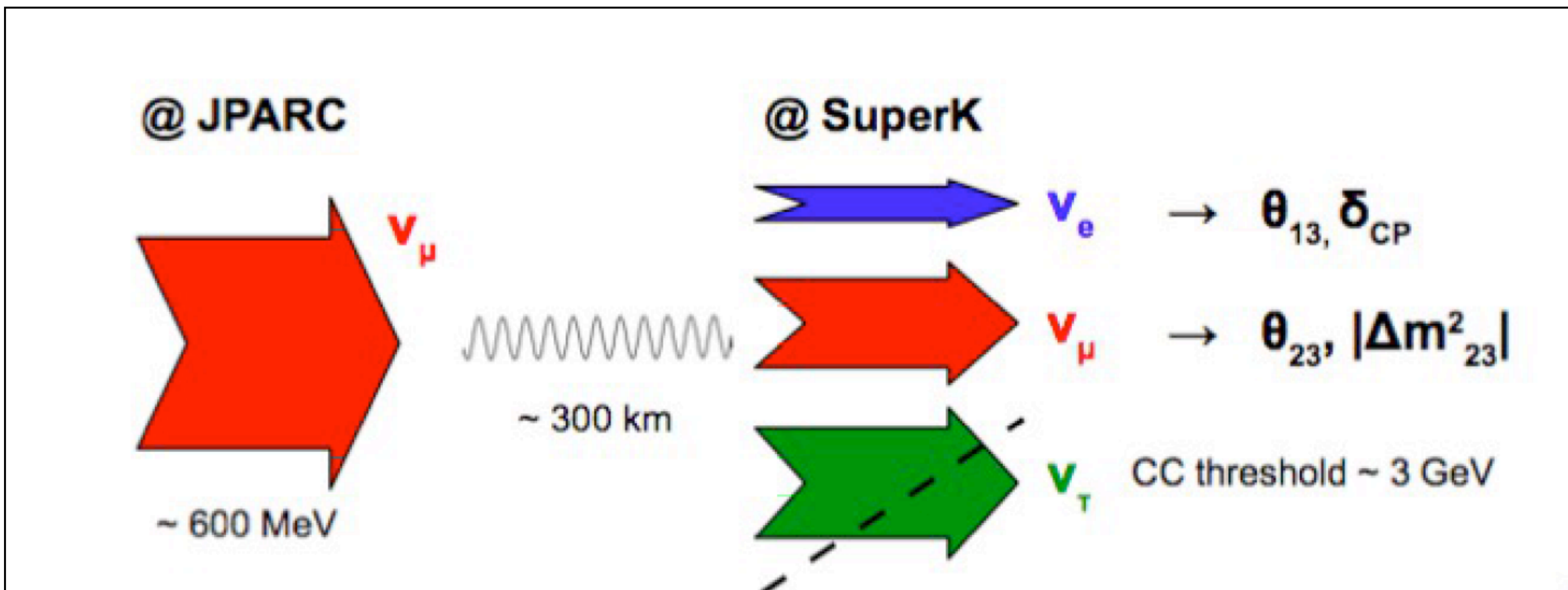
Current expts of ν_e appearance in ν_μ beam

- T2K (Tokai-To-Kamioka)
  - J-PARC: 50 GeV proton synchrotron @Tokai (JP)
  - High intensity
  - beam directed towards Super-Kamiokande
  - L=295 Km
- Nova: Fermilab neutrino beam (NuMI)
  - L=810 km
- Both experiments are at an angle with respect to the beam direction (off-axis experiments)

T2K



Neutrino oscillations at LBL

$$P(\nu_\mu \to \nu_\mu) \simeq 1 - (\cos^4\theta_{13}\sin^2 2\theta_{23})\sin^2\left(\Delta m^2_{31}\frac{L}{4E}\right)$$

E ~ 0.6 GeV
L ~ 295 km

- Precise measurement of $\sin^2 2\Theta_{23}$
- Test of CPT by comparing measured $\nu_\mu \to \nu_\mu$ with $\overline{\nu}_\mu \to \overline{\nu}_\mu$

$$P(\nu_\mu \to \nu_e) \simeq \sin^2 2\theta_{13} \times \sin^2\theta_{23} \times \frac{\sin^2[(1-x)\Delta]}{(1-x)^2}$$

Phys. Rev. D64 (2001) 053003

Leading term

CP violating $\quad -\alpha \sin\delta_{CP} \times \sin^2 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \times \sin\Delta \frac{\sin[x\Delta]}{x}\frac{\sin[(1-x)\Delta]}{(1-x)}$

"+" for antineutrino

CP conserving $\quad \alpha \cos\delta_{CP} \times \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \times \cos\Delta \frac{\sin[x\Delta]}{x}\frac{\sin[(1-x)\Delta]}{(1-x)}$

$+ O(\alpha^2)$

$$x = \frac{2\sqrt{(2)}G_F N_e E}{\Delta m^2_{31}} \quad \alpha = \left|\frac{\Delta m^2_{21}}{\Delta m^2_{31}}\right| \sim \frac{1}{30} \quad \Delta = \frac{\Delta m^2_{31} L}{4E}$$

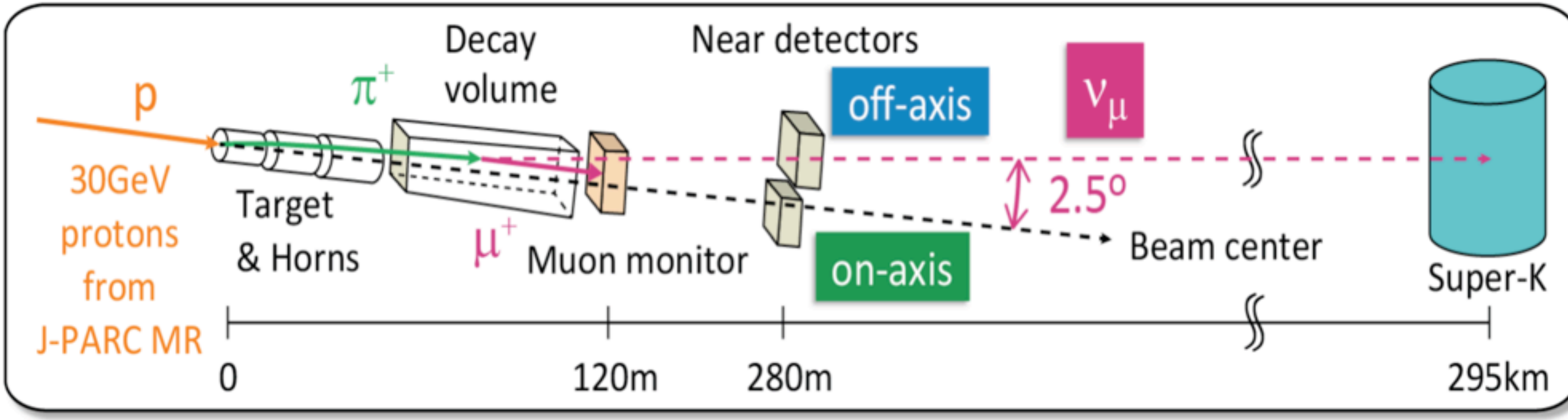
Matter effect

- The leading term defines the octant $\Theta_{23}>45°$ or $\Theta_{23}<45°$
- All mass splittings and mixing angles have been measured to be non-zero:

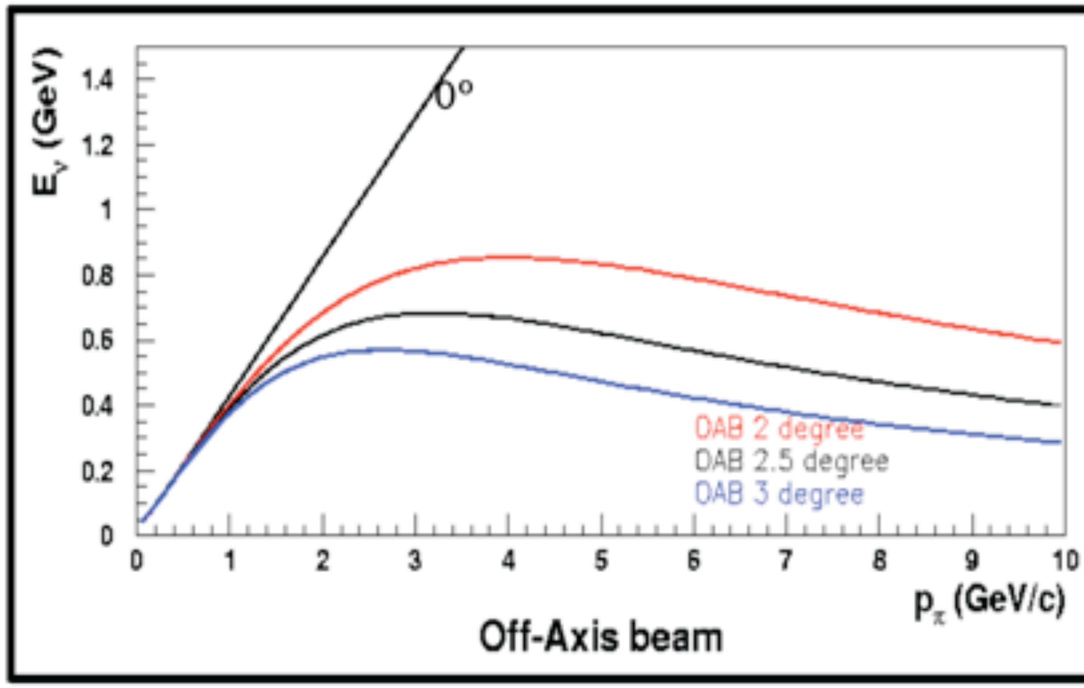
  second order term can violate the CP symmetry if $\sin\delta_{CP} \neq 0$

Design principle: the off-axis angle

T2K



- 30 GeV proton beam on 90 cm long graphite target
- ν_μ and $\overline{\nu}_\mu$ produced by pion and kaon decay:
  - $\pi^+ \rightarrow \mu^+ + \nu_\mu$
  - $\pi^- \rightarrow \mu^- + \overline{\nu}_\mu$
- Invert magnet polarity to produce a $\overline{\nu}_\mu$ beam
- First off-axis neutrino beam experiment (2.5°)
  - narrow spectrum peaked at 0.6 GeV, on the expected oscillation maximum



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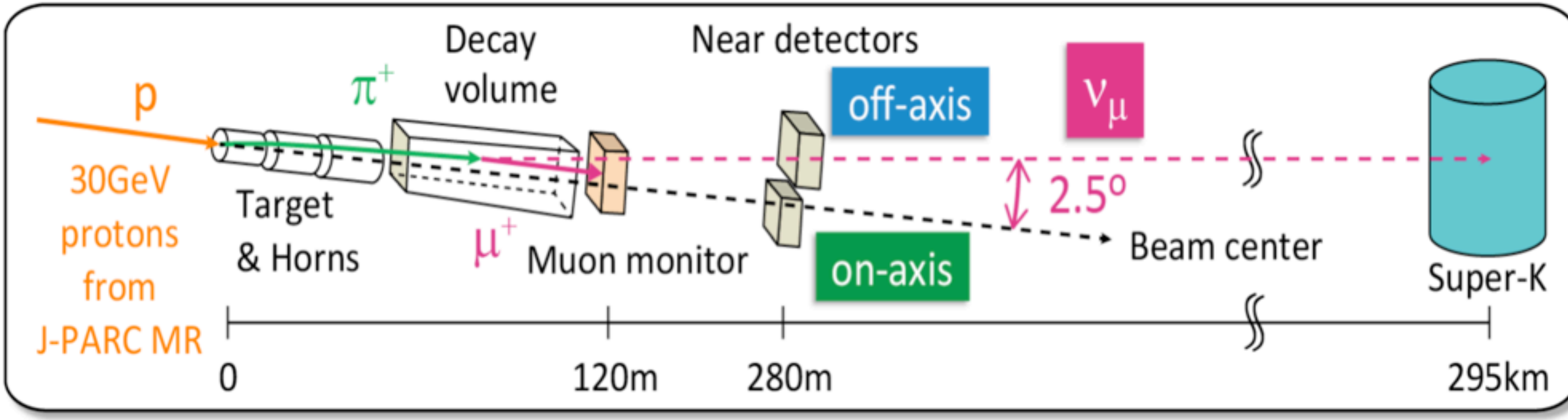

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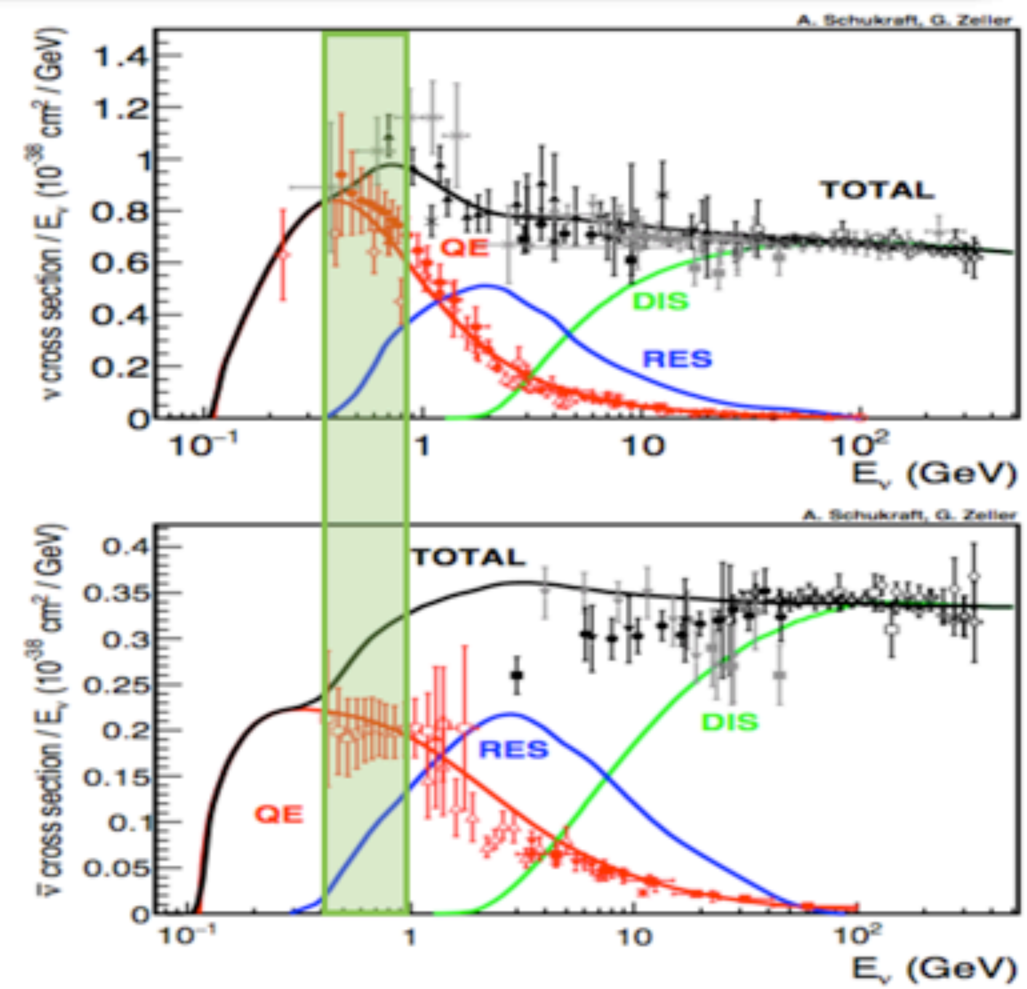

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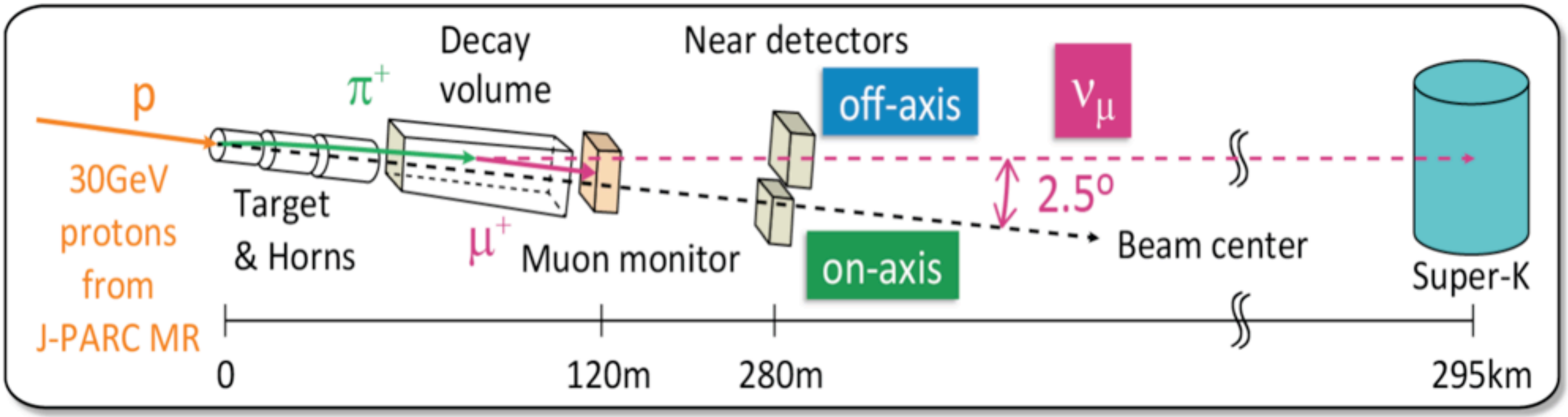

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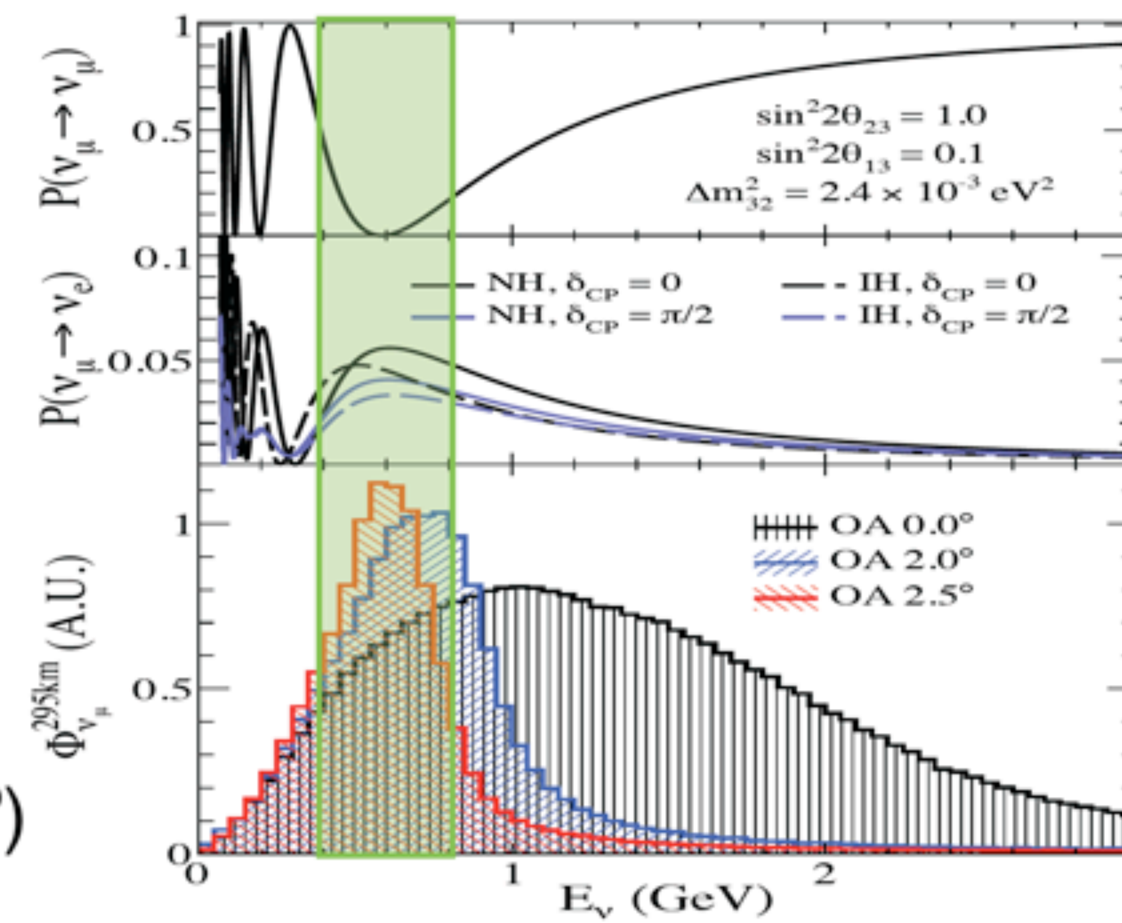

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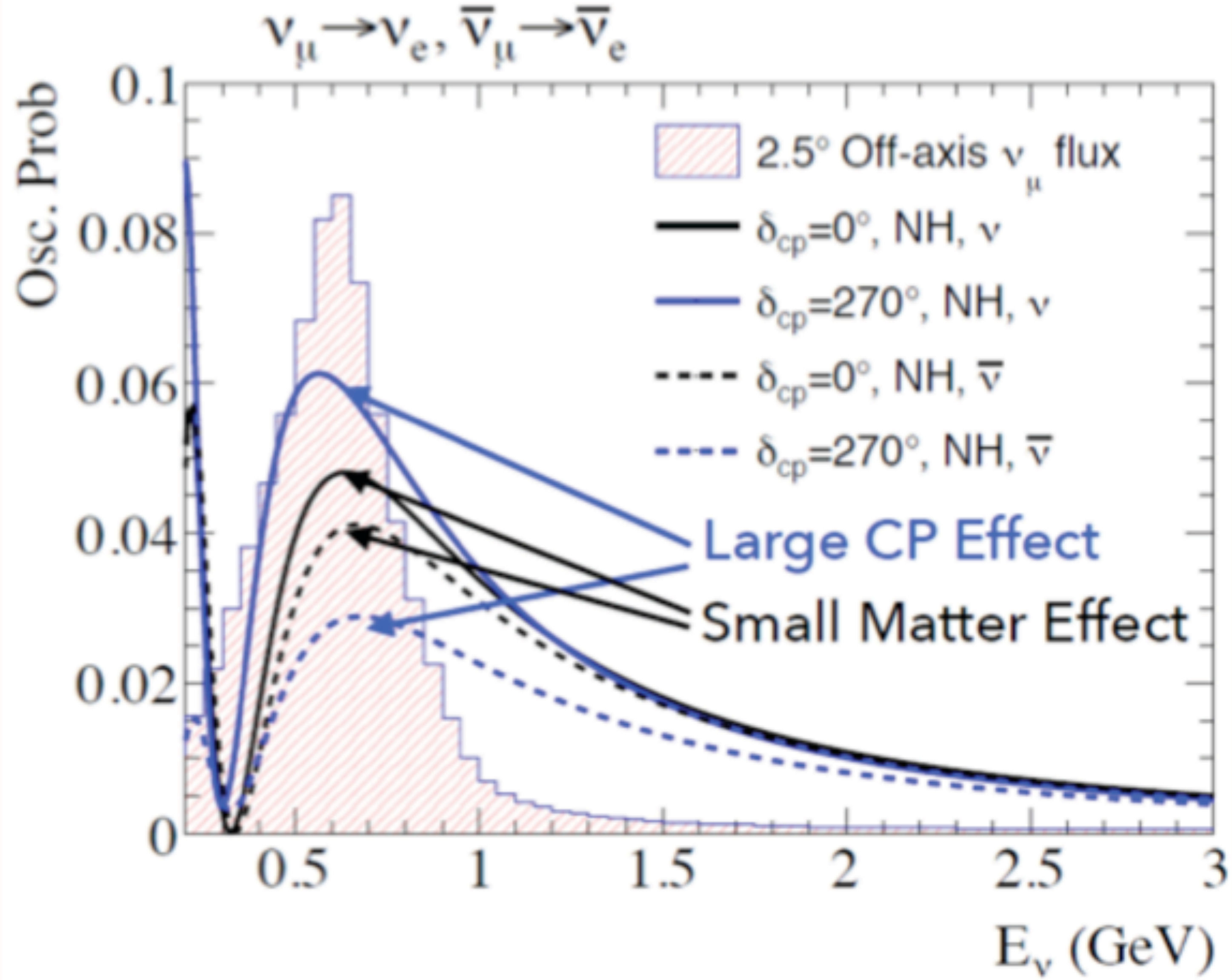
Effect of CP violation at T2K

T2K

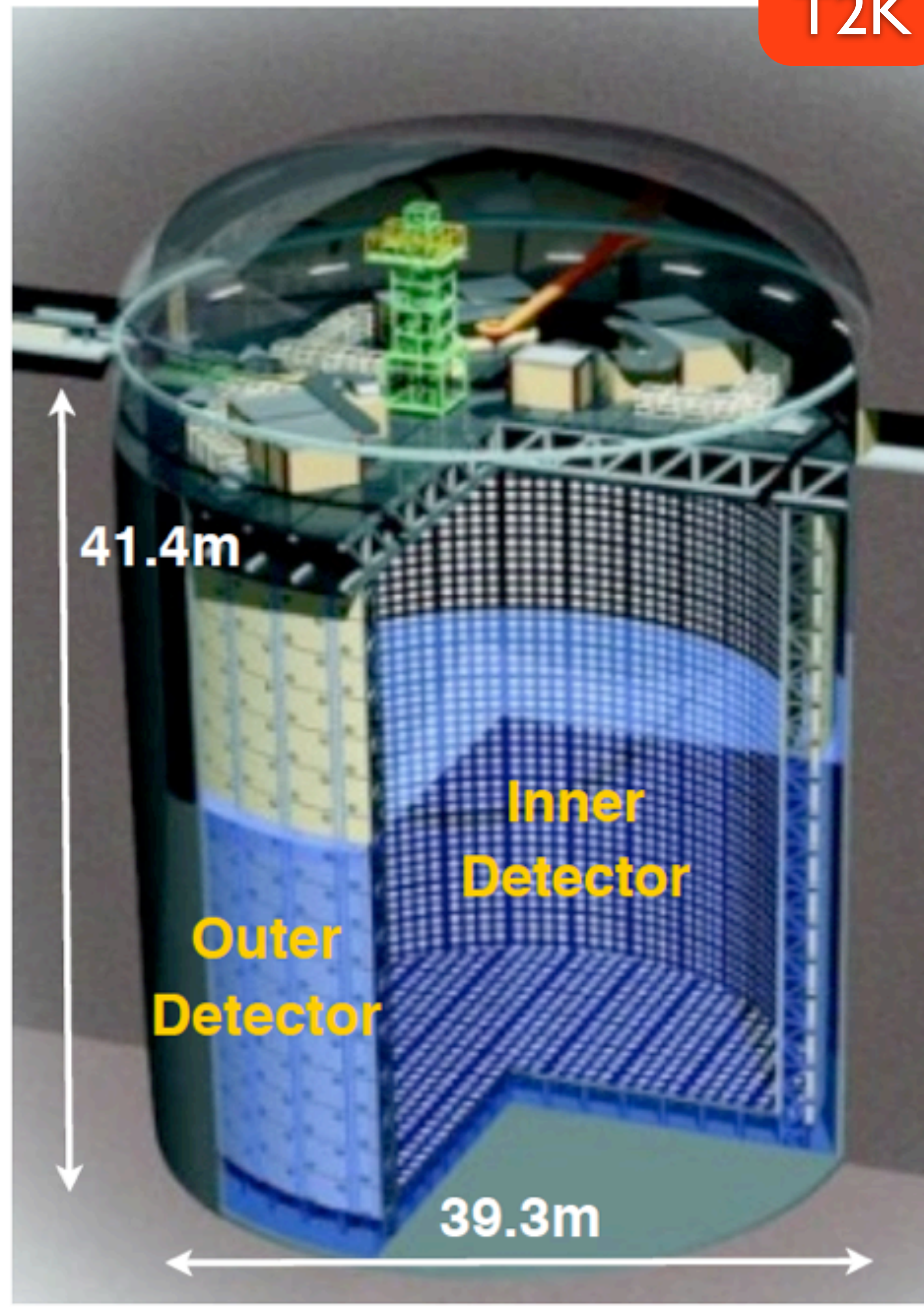
Correlation between CPV and matter effects present



- Asymmetric effect on $P(\nu_\mu \to \nu_e)$ and $P(\overline{\nu}_\mu \to \overline{\nu}_e)$:
  - δ_{CP} = $-\pi/2$ → maximizes $P(\nu_\mu \to \nu_e)$ and minimizes $P(\overline{\nu}_\mu \to \overline{\nu}_e)$
  - δ_{CP} = $+\pi/2$ → minimizes $P(\nu_\mu \to \nu_e)$ and maximizes $P(\overline{\nu}_\mu \to \overline{\nu}_e)$
- δ_{CP} and Mass Hierarchy have similar effects
- Effect of δ_{CP} on $\nu_\mu \to \nu_e$ and $\overline{\nu}_\mu \to \overline{\nu}_e$ is about ±20-30%
- Effect of Mass Hierarchy is about ±10%

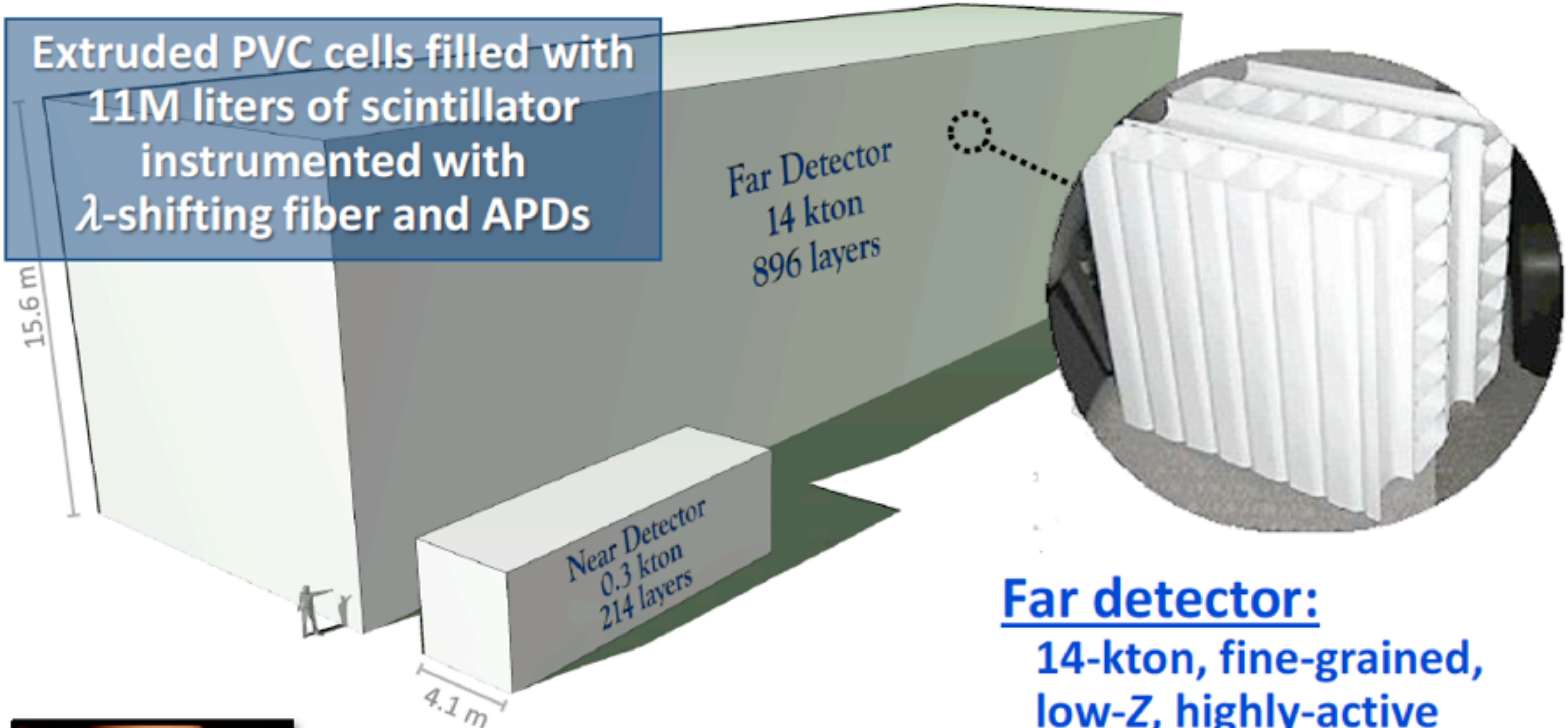
T2K far detector: Super-Kamiokande

- Located in Mozumi mine
  - 2700 m.w.e overburden
- Water Cherenkov detector (50 kton)
- Fiducial mass 22.5 kton
- Inner detector
  - 11129 20-inch PMTs
- Outer veto detector
  - 1885 8-inch PMTs
  - determine fully-contained events
- New DAQ system: no dead time
- T2K beam event: ±500 μs window

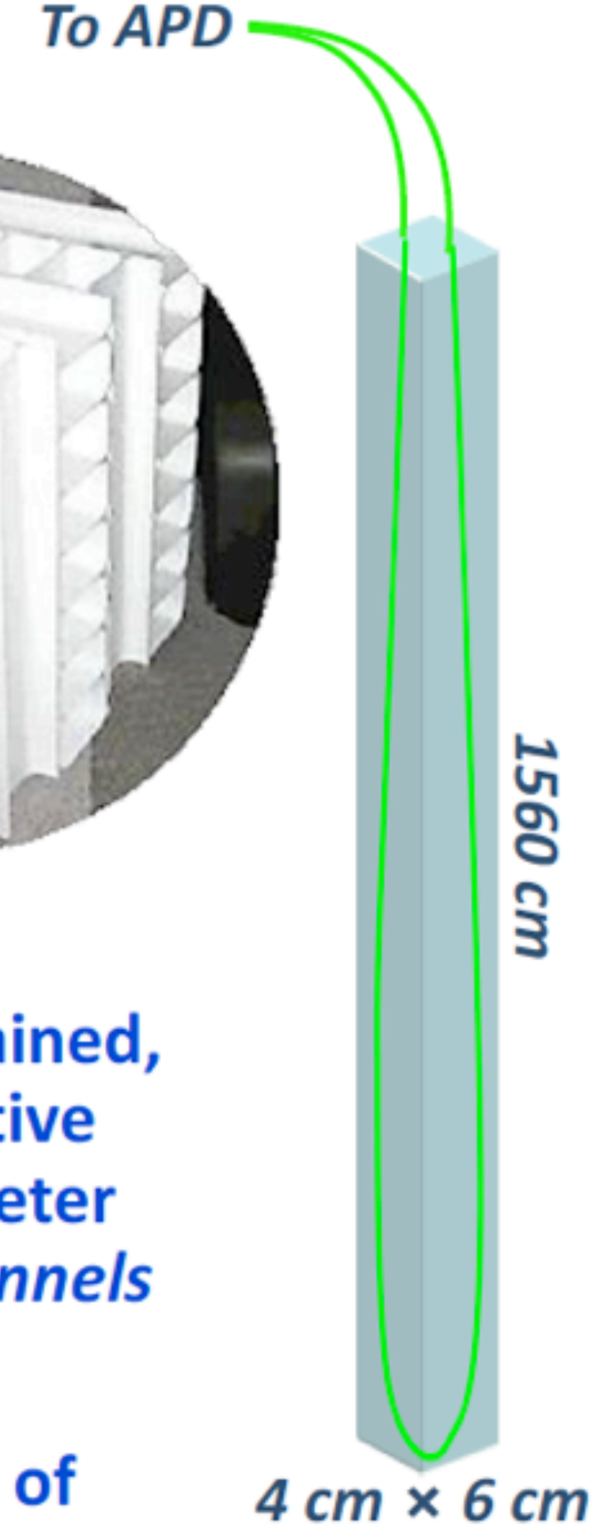


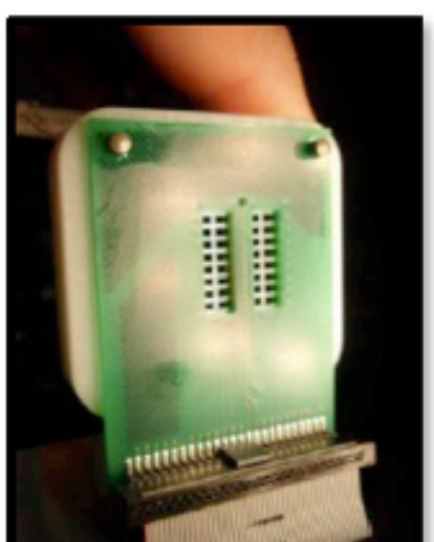
NOνA detectors

Extruded PVC cells filled with 11M liters of scintillator instrumented with λ-shifting fiber and APDs



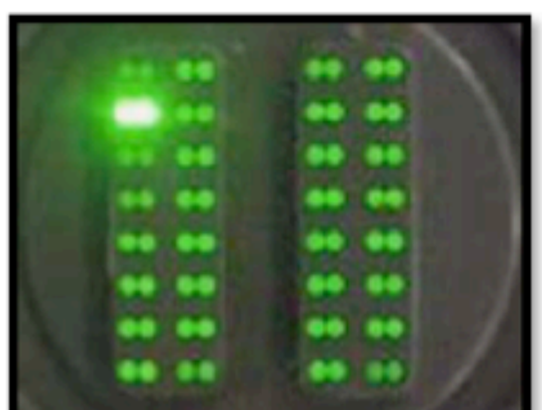
A NOνA cell





32-pixel APD ←

Fiber pairs from 32 cells →



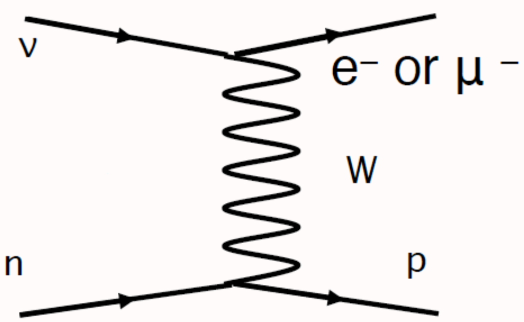
Far detector:

14-kton, fine-grained, low-*Z*, highly-active tracking calorimeter
→ *344,000 channels*

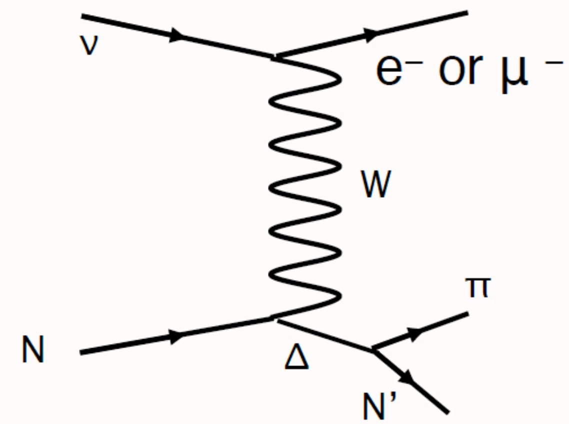
Near detector:

0.3-kton version of the same
→ *20,000 channels*

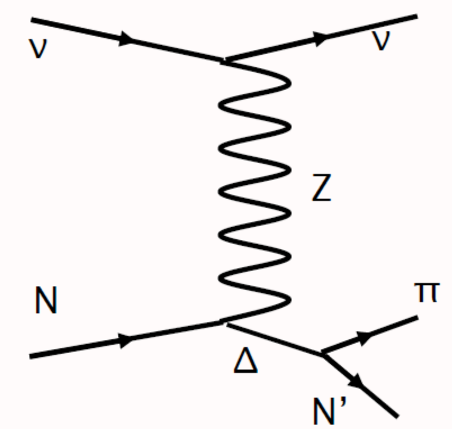
Charged-Current Quasi-Elastic (CCQE)



Charged-Current π



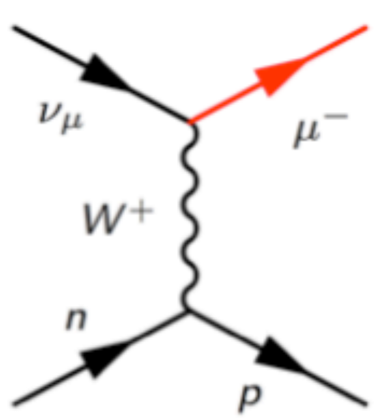
Neutral-Current π



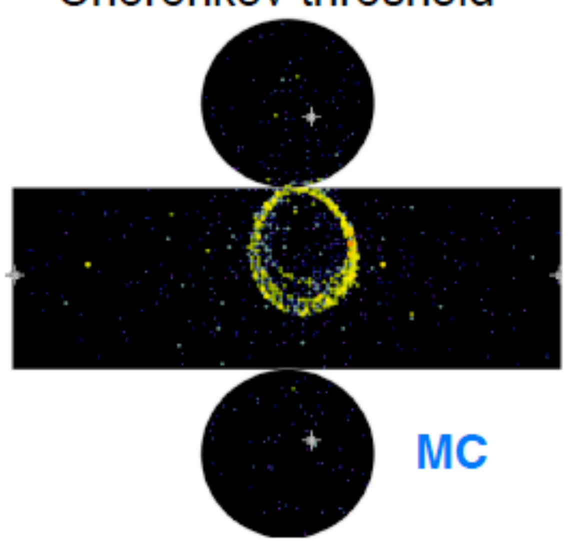
Super-Kamiokande events

T2K

ν_μ CCQE

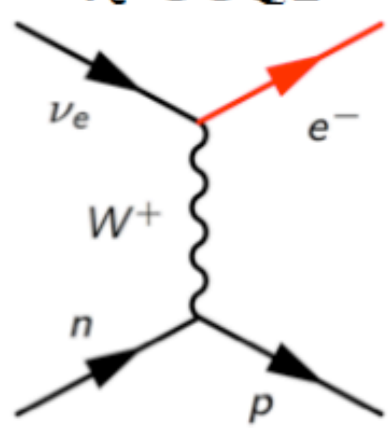


- Low scattering
- Ring with sharp edge
- Protons below Cherenkov threshold

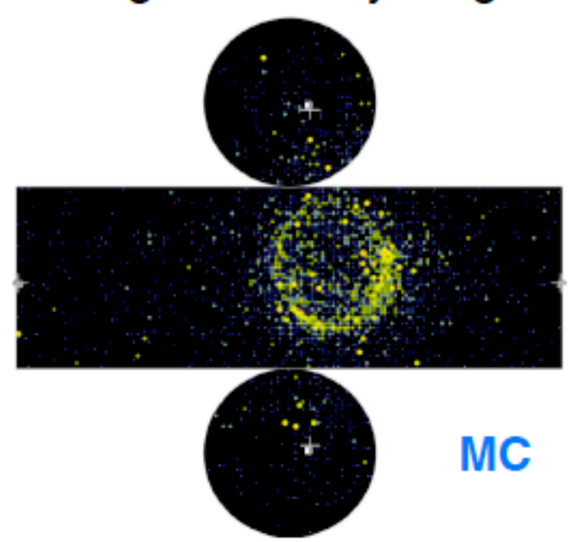


MC

ν_e CCQE

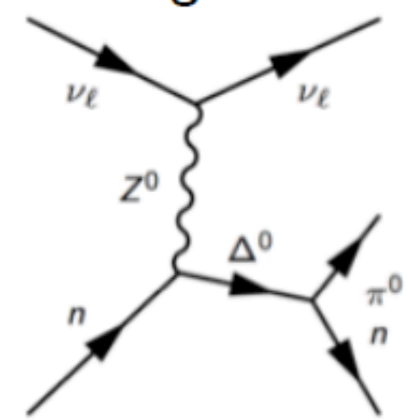


- Multiple scattering
- EM shower
- Ring with "fuzzy" edge

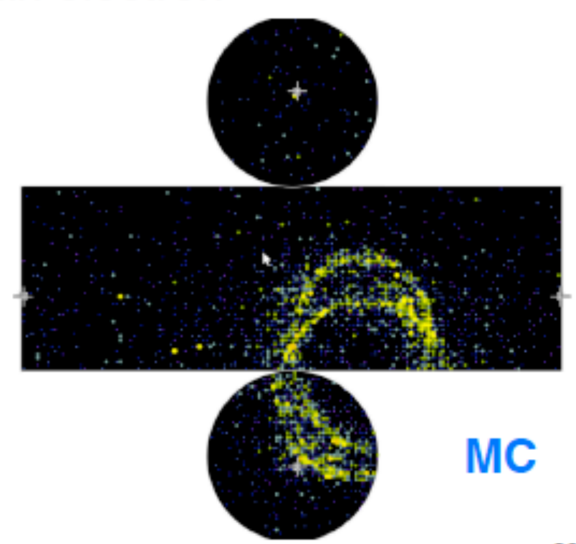


MC

Background



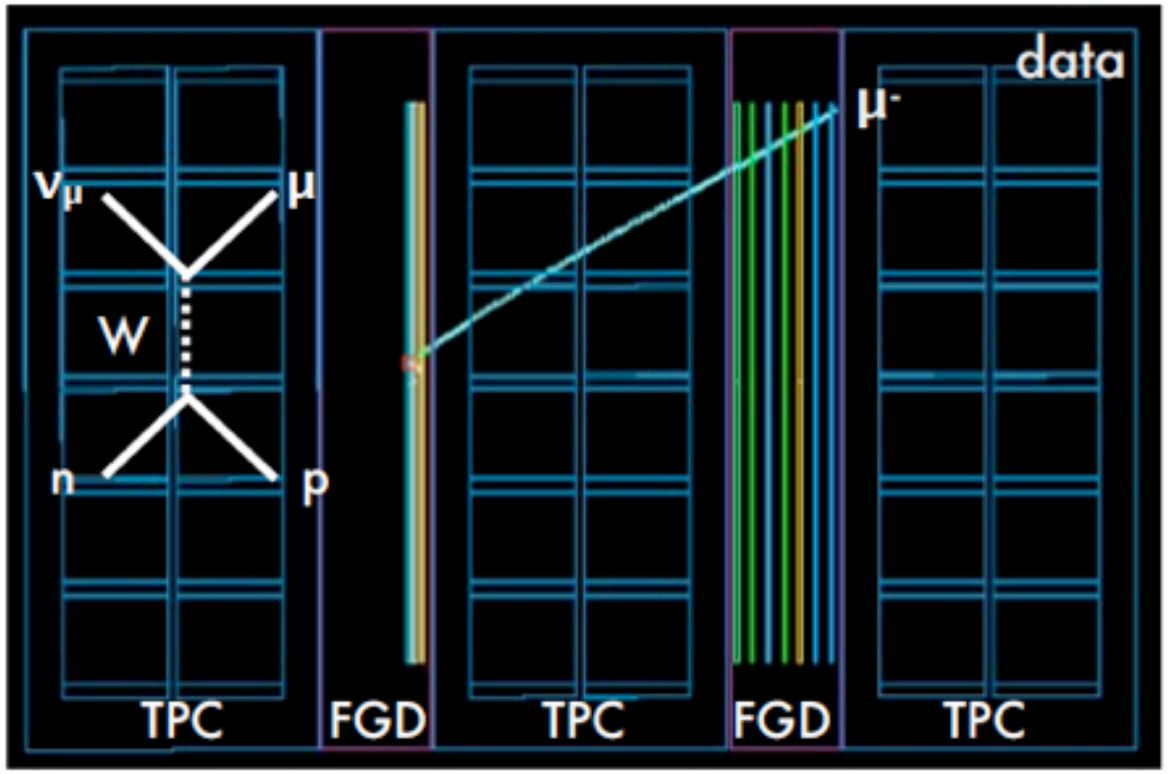
- EM shower from $\pi^0 \rightarrow \gamma\gamma$
- Can be misidentified as an electron



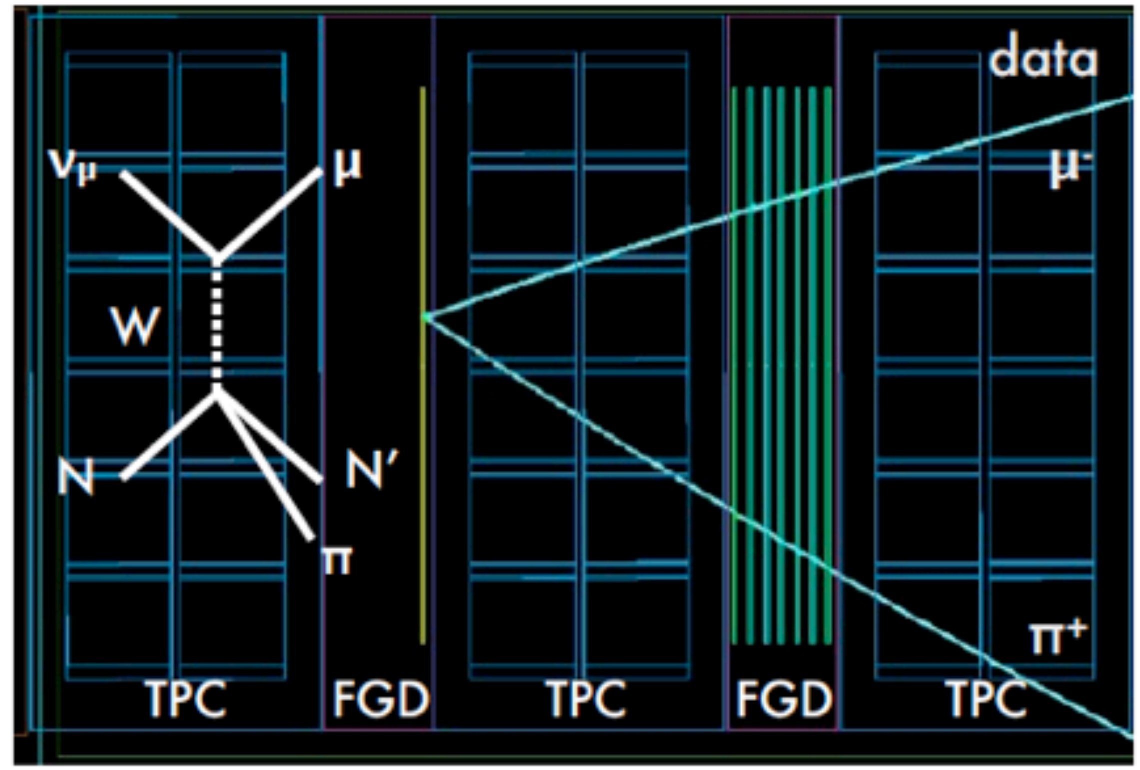
MC

26

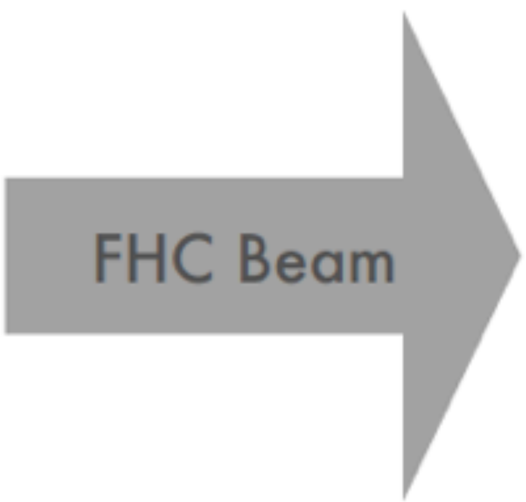
CC0π

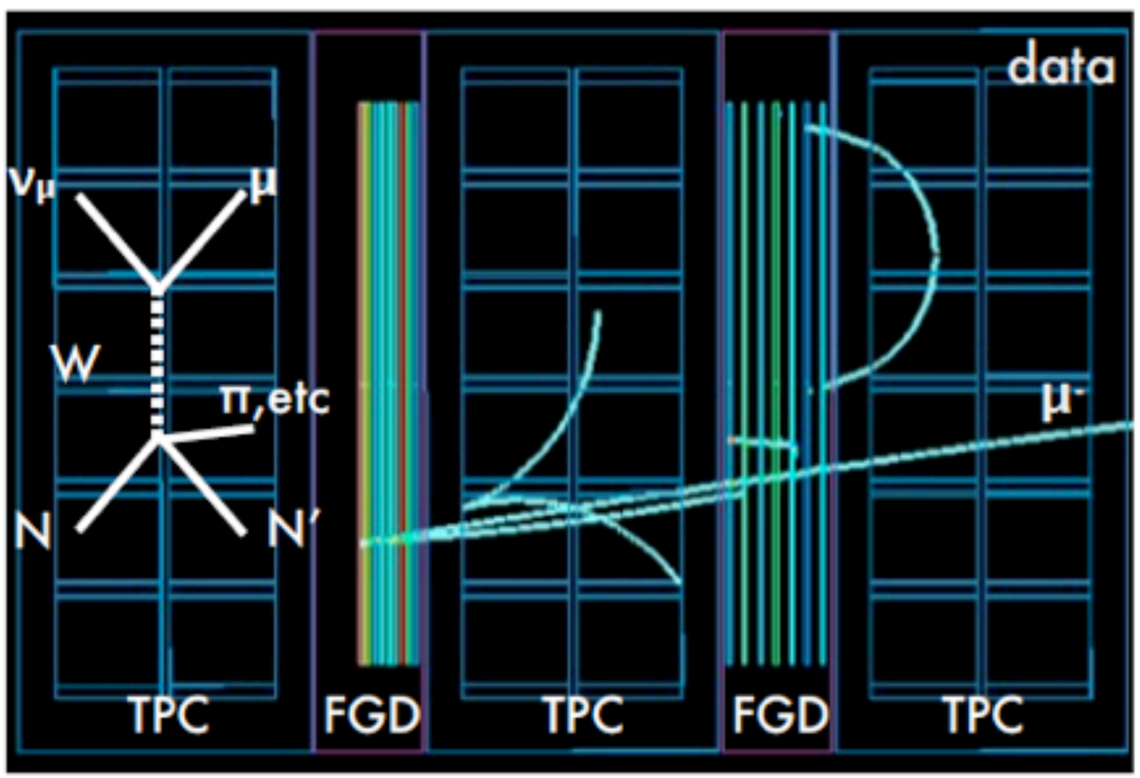


CC1π+



CC other



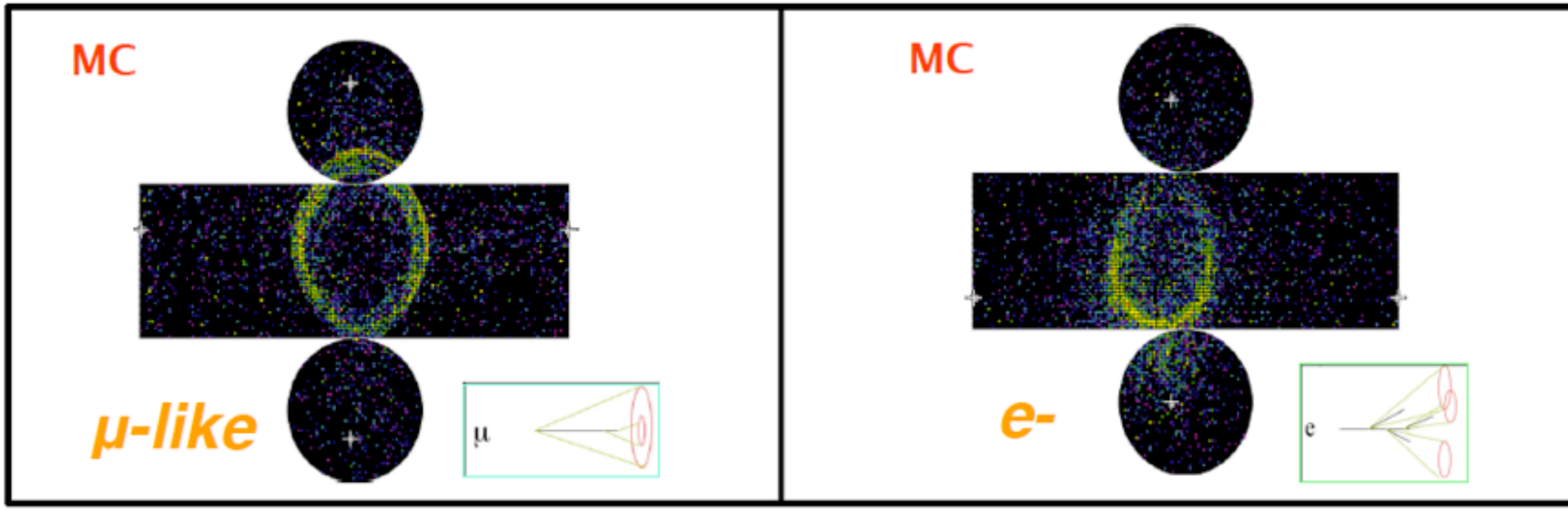


17

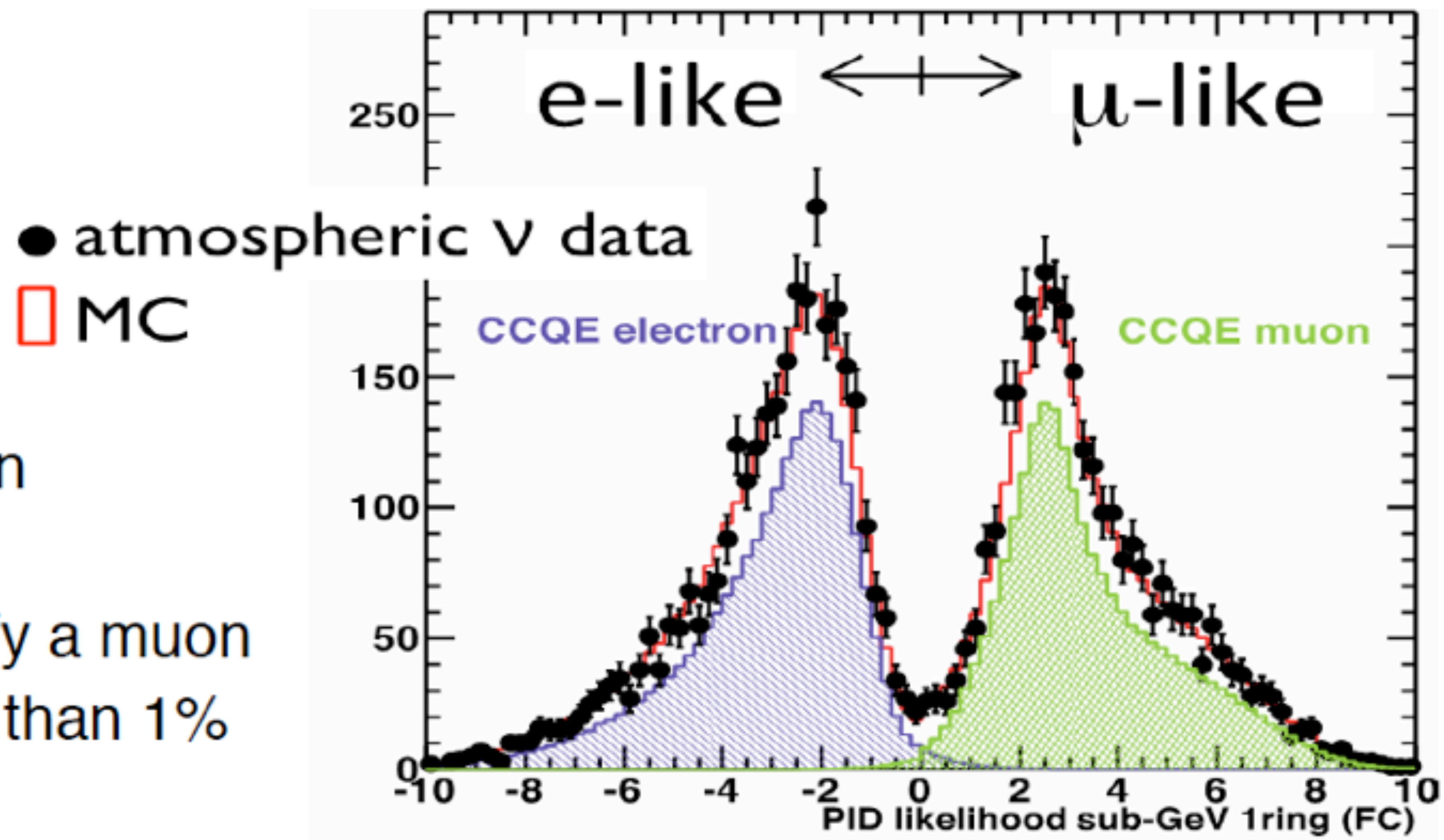
ROYAL HOLLOWAY UNIVERSITY OF LONDON

T2K

Particle Identification at the far detector



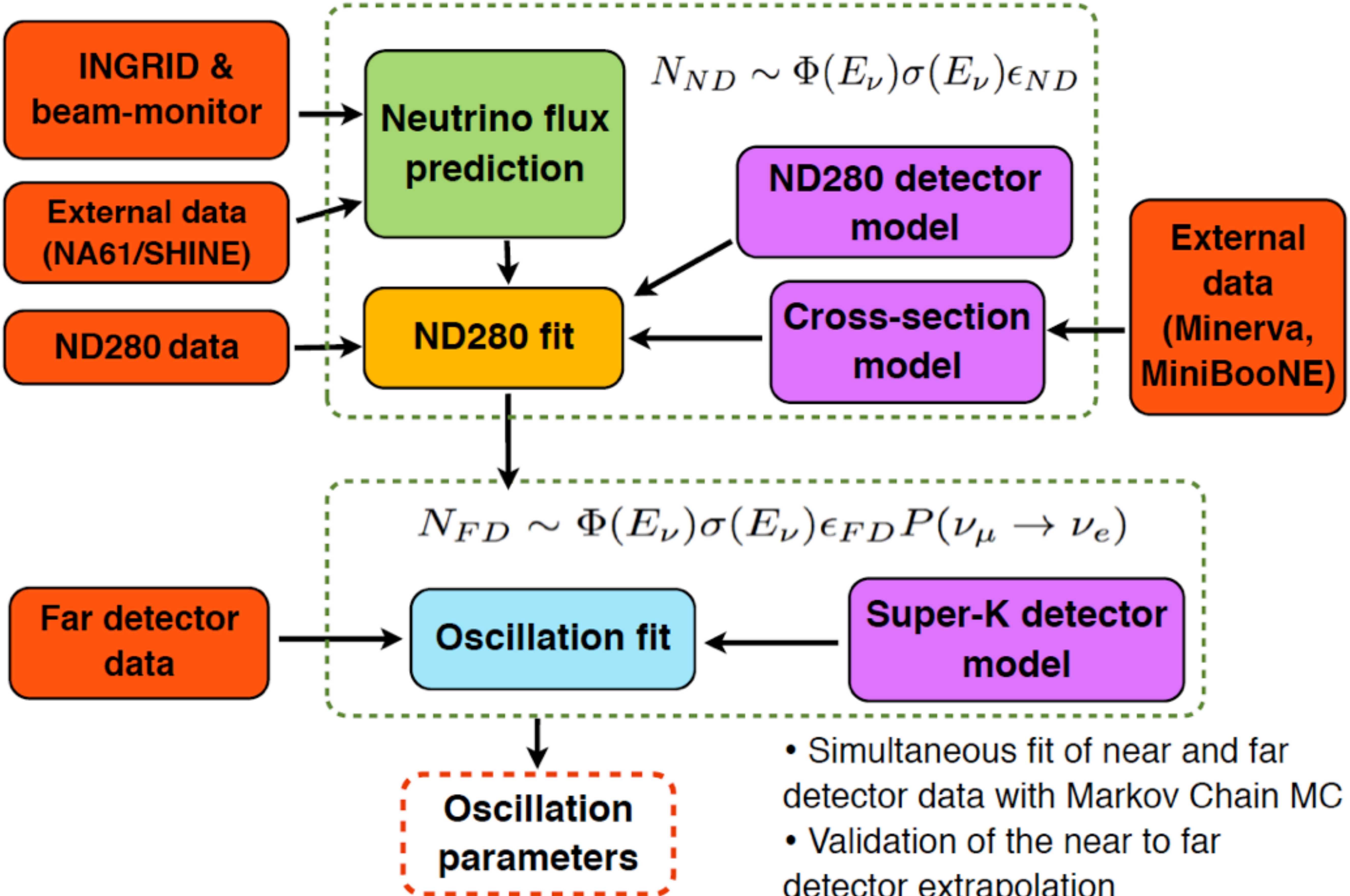
T2K



- Excellent e/μ separation
- Probability to misidentify a muon as an electron is smaller than 1%

Strategy for oscillation analyses

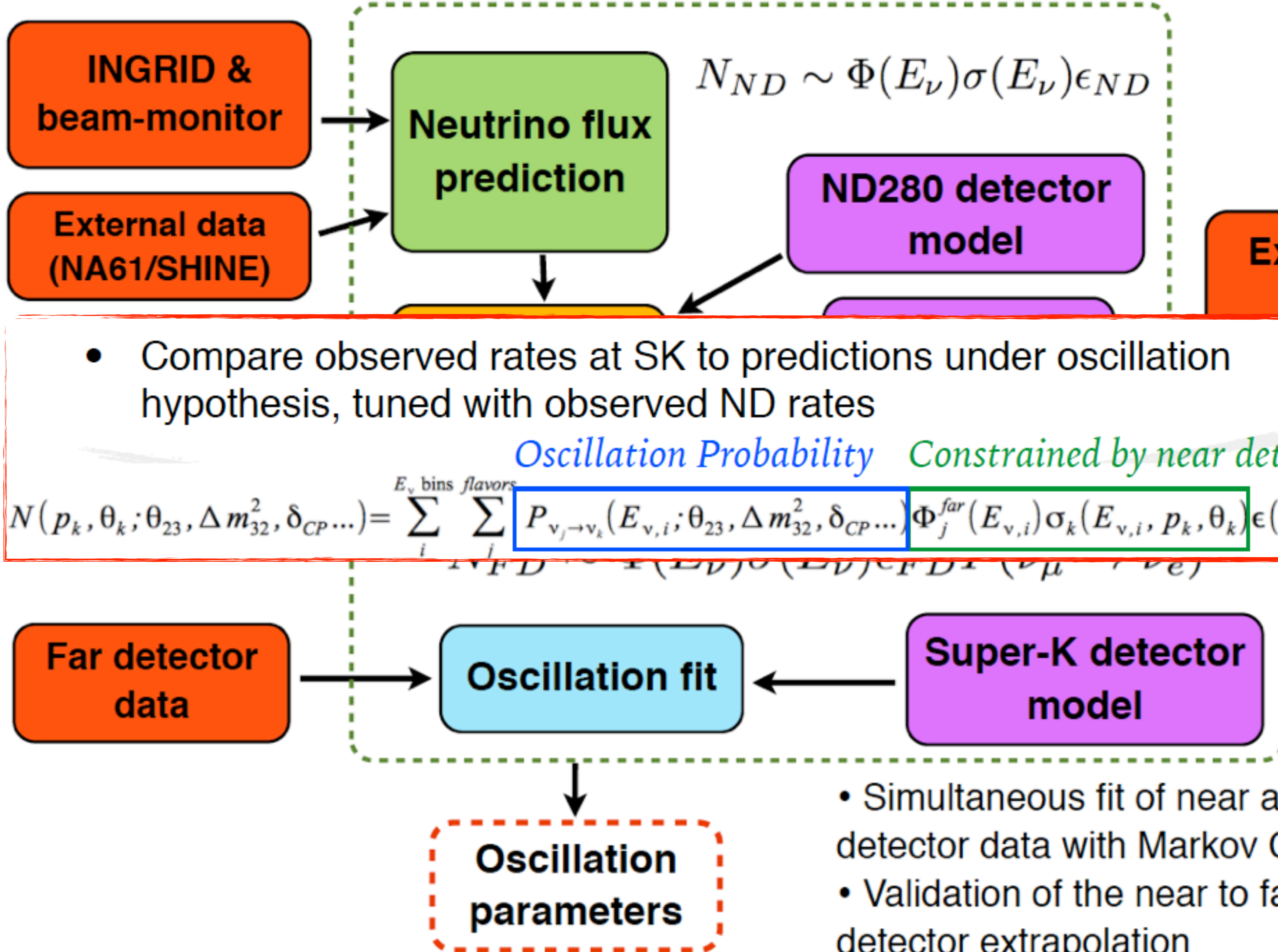
T2K



- Simultaneous fit of near and far detector data with Markov Chain MC
- Validation of the near to far detector extrapolation

Strategy for oscillation analyses

T2K



- Compare observed rates at SK to predictions under oscillation hypothesis, tuned with observed ND rates

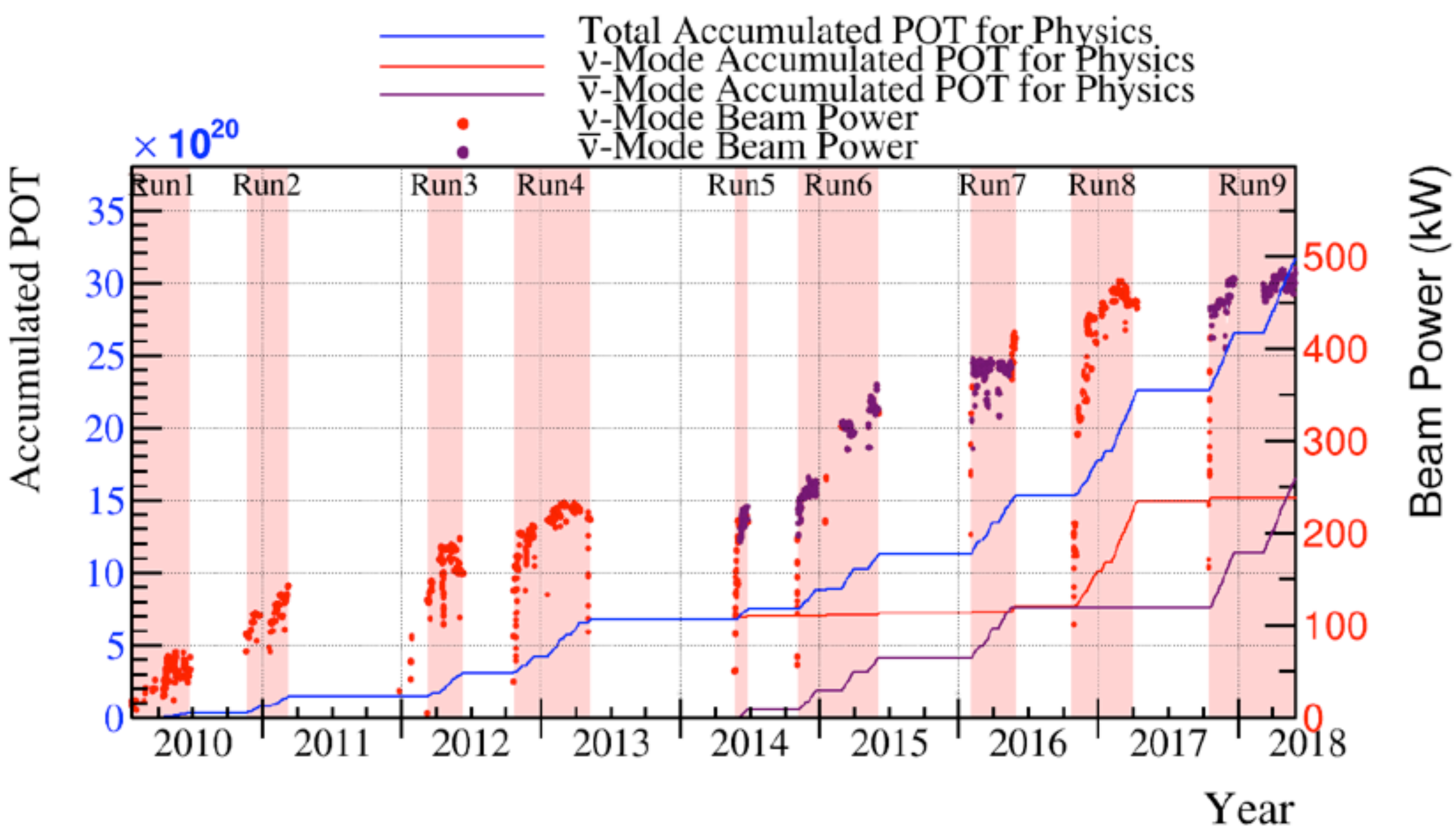
Oscillation Probability — *Constrained by near detector fit*

$$N(p_k,\theta_k;\theta_{23},\Delta m^2_{32},\delta_{CP}...)=\sum_i^{E_\nu\ \text{bins}}\sum_j^{flavors}\underbrace{P_{\nu_j\to\nu_k}(E_{\nu,i};\theta_{23},\Delta m^2_{32},\delta_{CP}...)}_{\text{Oscillation Probability}}\underbrace{\Phi_j^{far}(E_{\nu,i})\sigma_k(E_{\nu,i},p_k,\theta_k)}_{\text{Constrained by near detector fit}}\epsilon(p_k,\theta_k)M_{det}$$

- Simultaneous fit of near and far detector data with Markov Chain MC
- Validation of the near to far detector extrapolation

T2K

Beam Operations



Used for this ND analysis: ν mode, Runs 2–4; ν̄ mode, Run 5–6

Used for this SK analysis: ν mode, Runs 1–8; ν̄ mode, Run 5–9

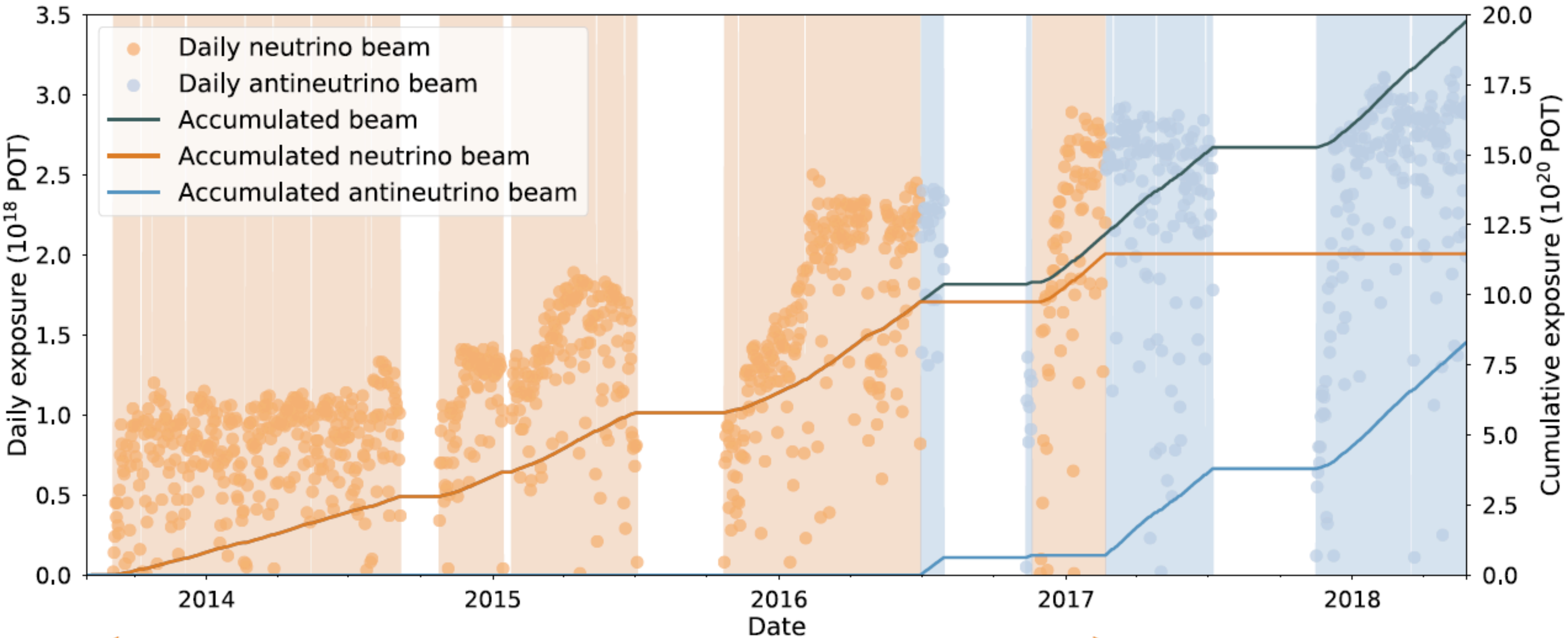
ν-mode is also known as "forward horn current" (FHC) or "positive focusing" (PF)

ν̄-mode is also known as "reverse horn current" (RHC) or "negative focusing" (NF)

NB same accumulated statistics for nu and nu-bar

Karl Warburton, for the NOvA Collaboration
Iowa State University

NOvA



8.85×10^{20} POT Neutrino Beam

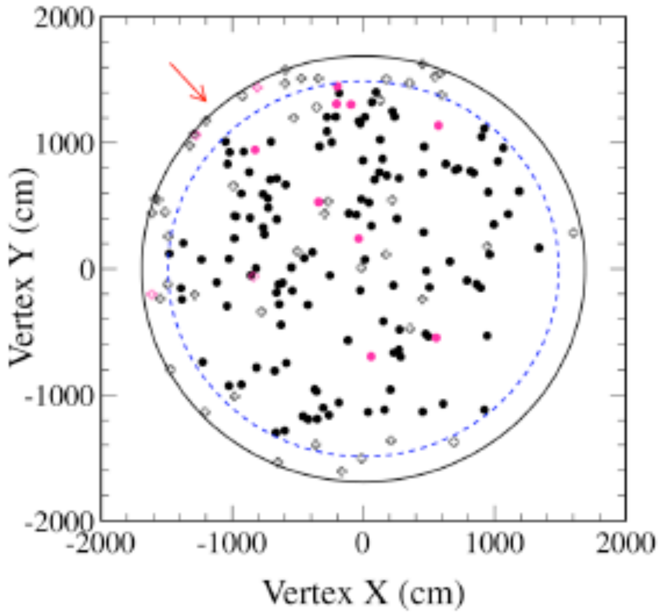
~2/3 of statistics of T2K overall

nu-bar to nu ~70%

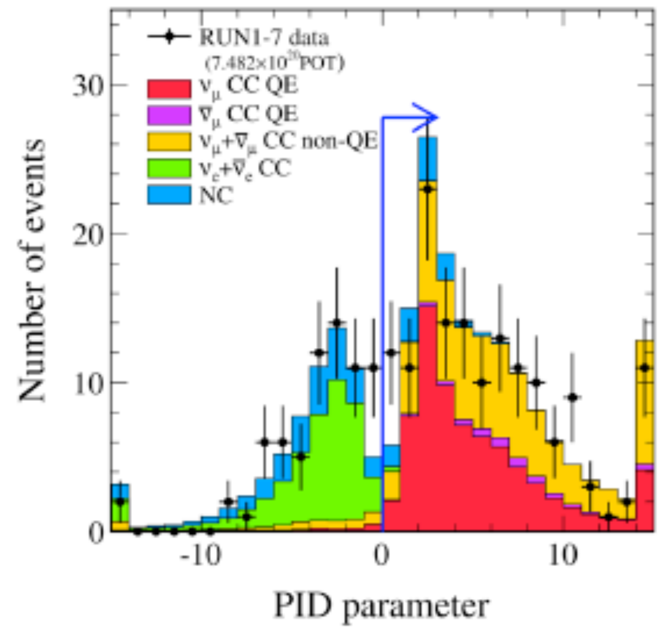
ν_μ / $\bar{\nu}_\mu$ selection at Far Detector

T2K

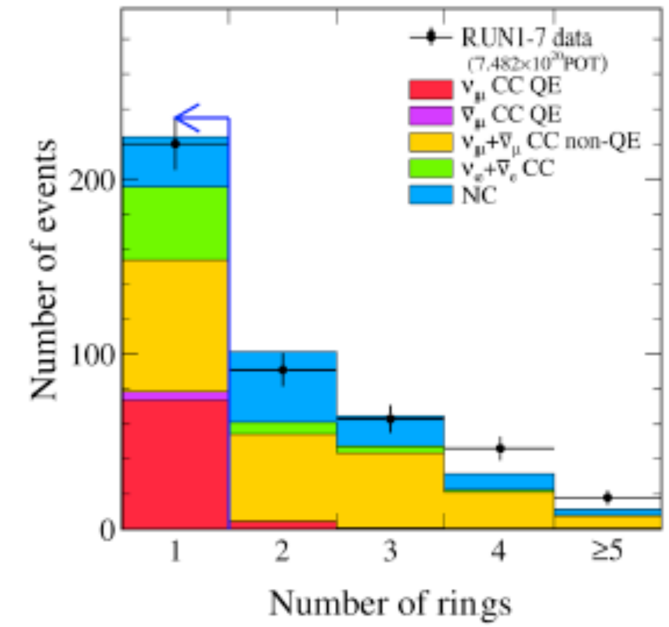
1) Fully contained in fiducial volume rings



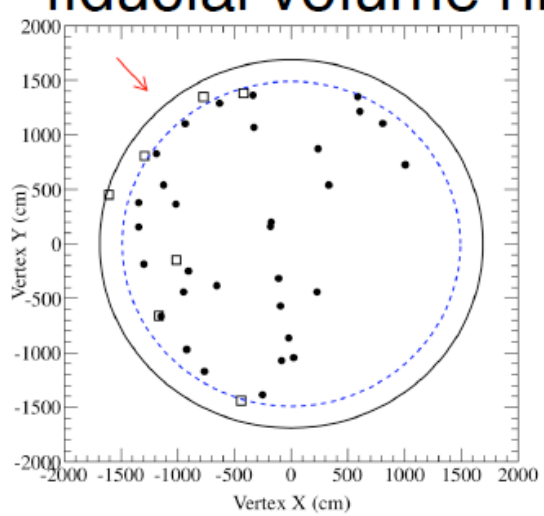
2) μ-like PID



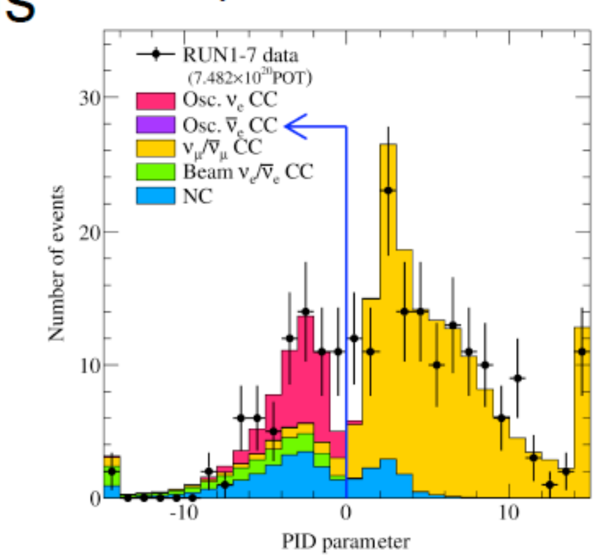
3) Single ring event



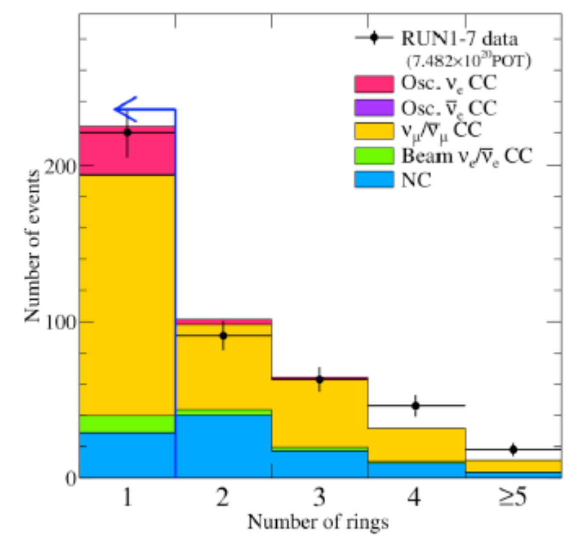
1) Fully contained in fiducial volume rings



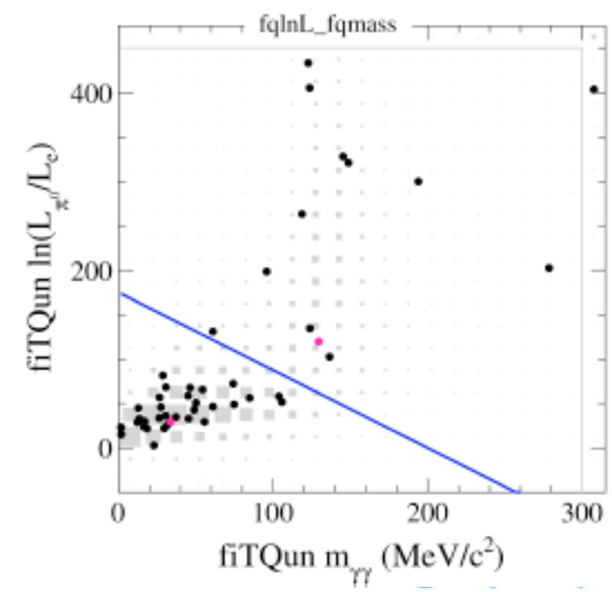
2) e-like PID



3) Single ring event



7) π^0 rejection cut



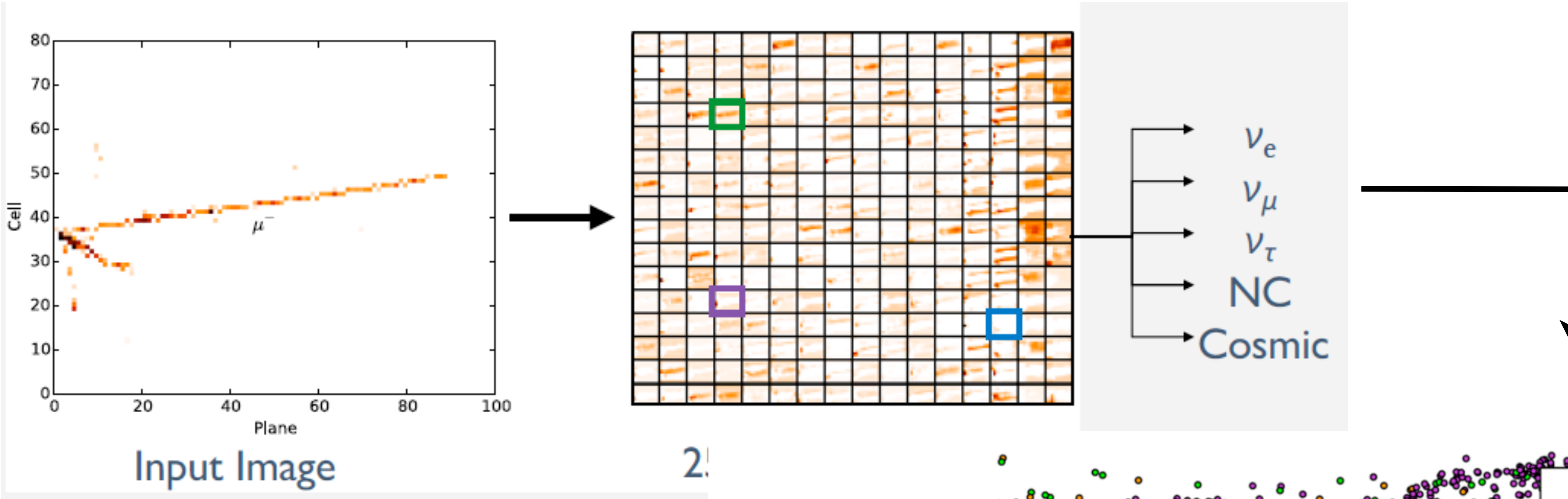
Validated using cosmic rays

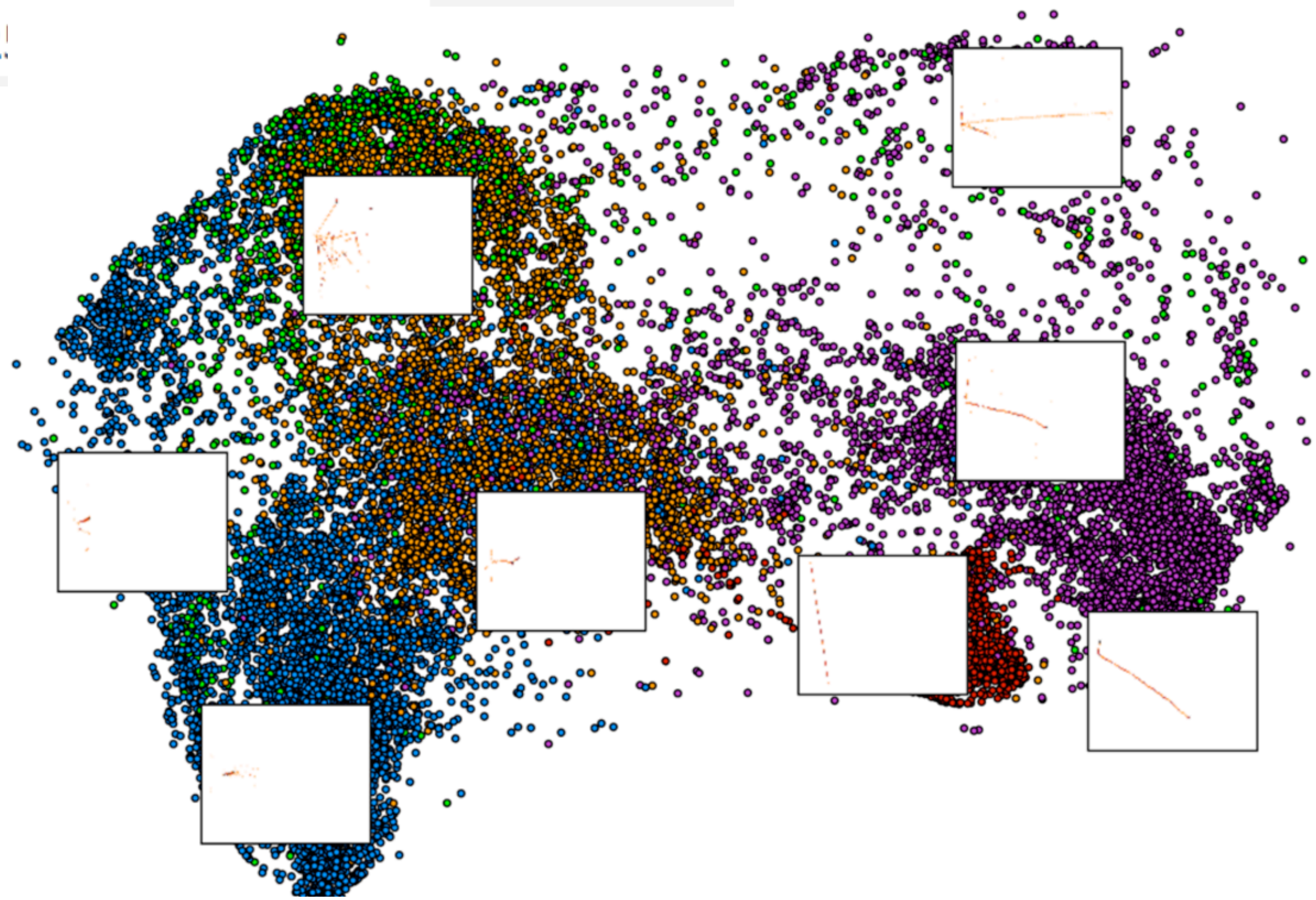
ν_e / $\bar{\nu}_e$ selection at Far Detector

NOvA

Signal identification is done by CVN (Convolutional Visual Network).

- event classifier in the "image recognition" style.
- The network is trained on two dimensional views of the event's calibrated hits.
- trained separately on neutrinos and anti-neutrinos.





Updated $\overline{\nu}_\mu$ disappearance results

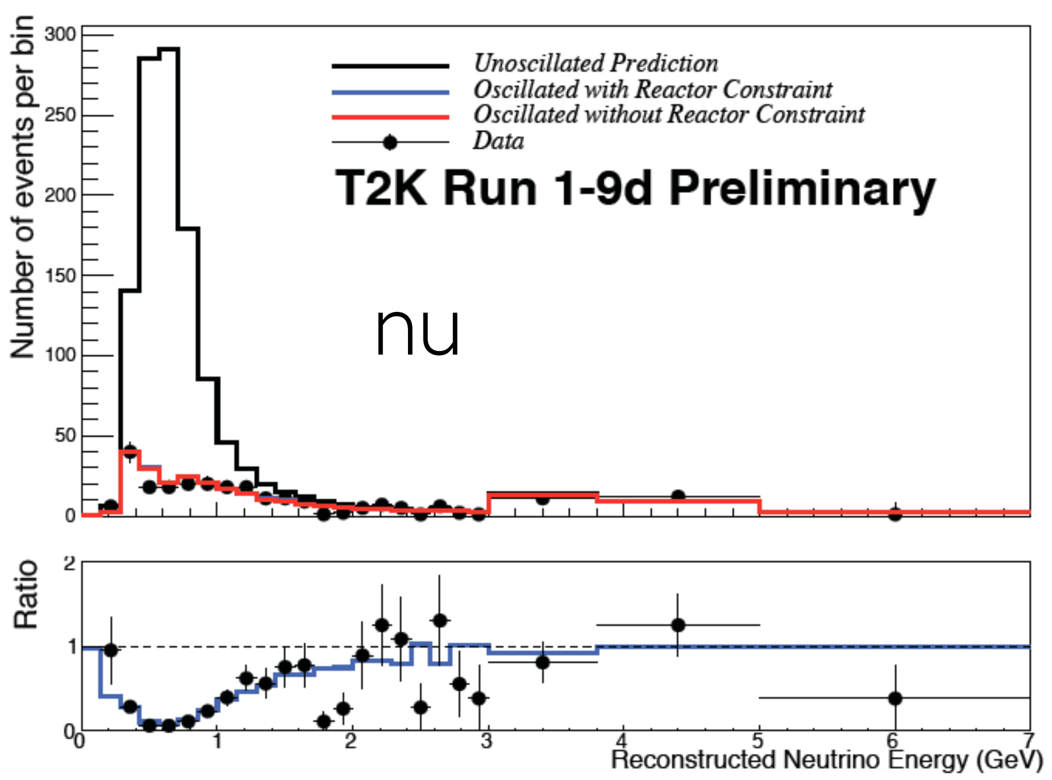
- In PMNS framework $P(\nu_\mu \to \nu_x) = P(\overline{\nu}_\mu \to \overline{\nu}_x)$ for any value of δ_{CP}
- No "± terms" for neutrino / antineutrino

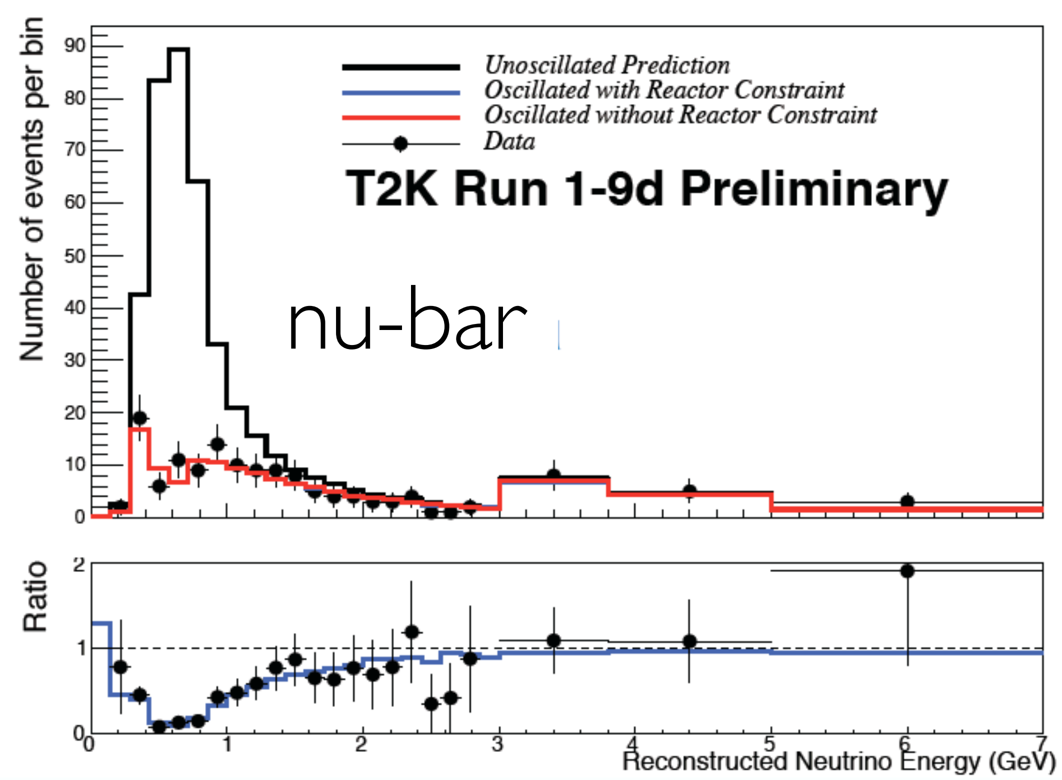
$$P(\nu_\mu \to \nu_\mu) \simeq 1 - (\cos^4\theta_{13}\sin^2 2\theta_{23})\sin^2\left(\Delta m^2_{31}\frac{L}{4E}\right)$$

T2K

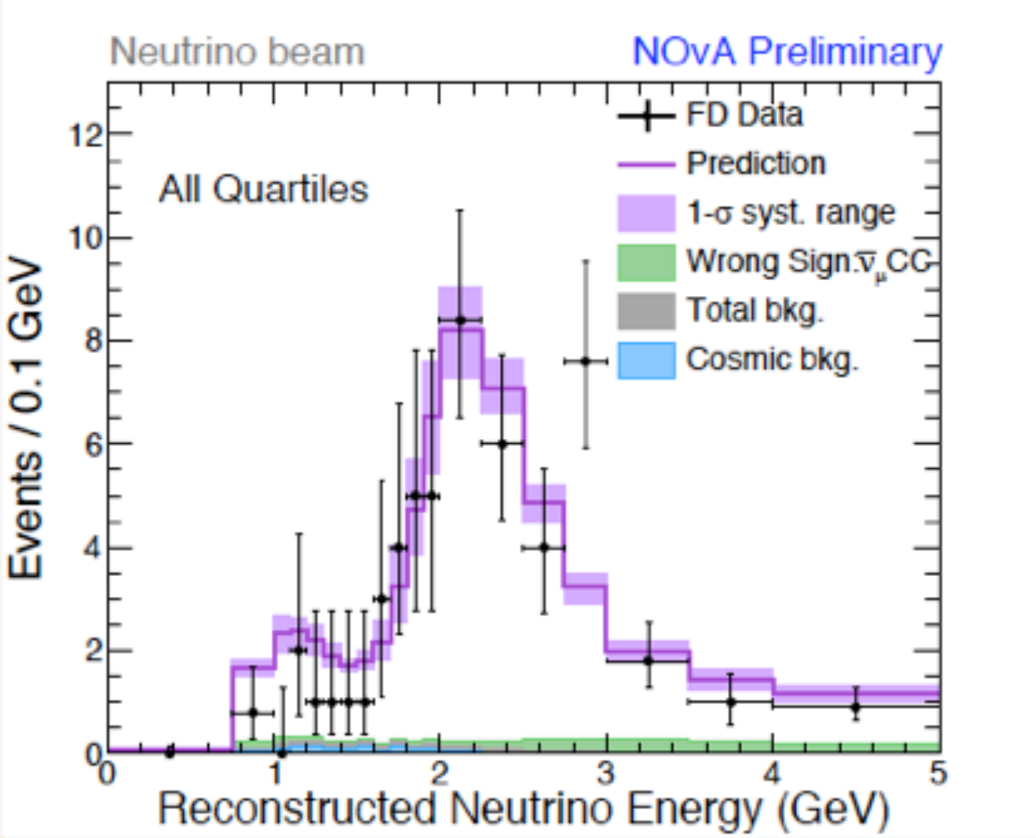
Predictions with: $\sin^2\theta_{13}=0.0212$, $\sin^2\theta_{23}=0.528$, $\Delta m^2_{32}=2.51\times10^{-3}$, NH

Sample	$\delta_{CP}=-\pi/2$	$\delta_{CP}=0$	$\delta_{CP}=\pi/2$	$\delta_{CP}=\pi$	Observed
nu	272.4	272.0	272.4	272.8	243
nu-bar	139.5	139.2	139.5	139.9	140

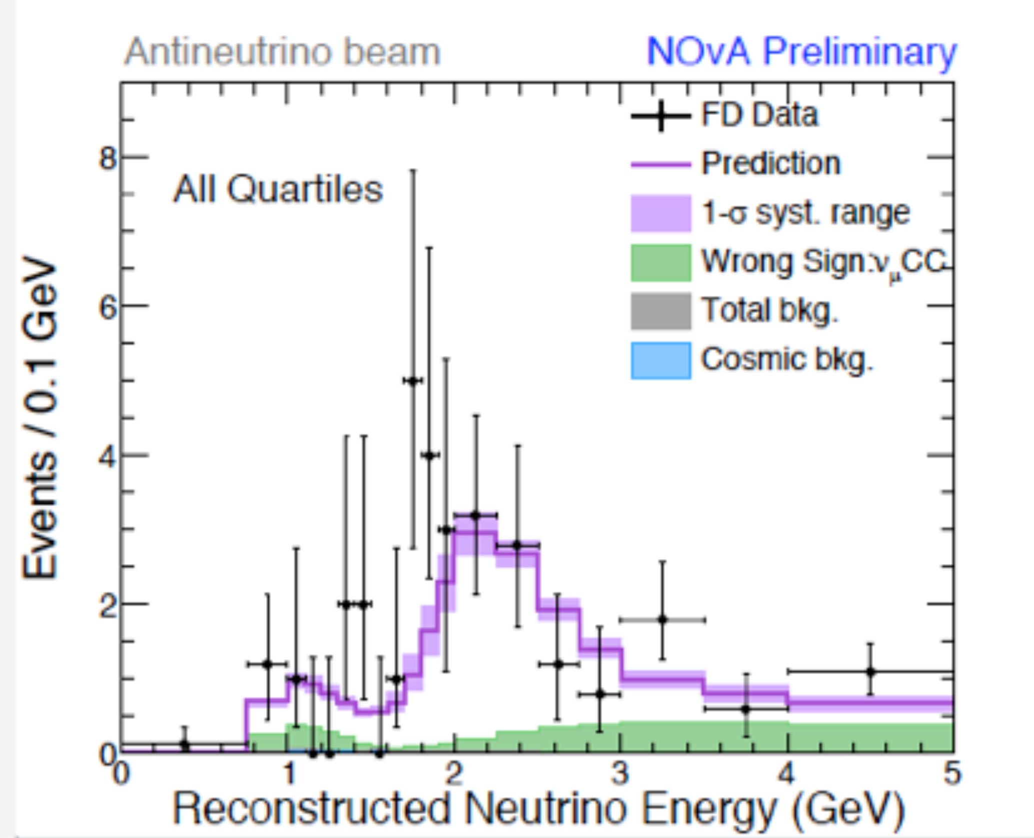




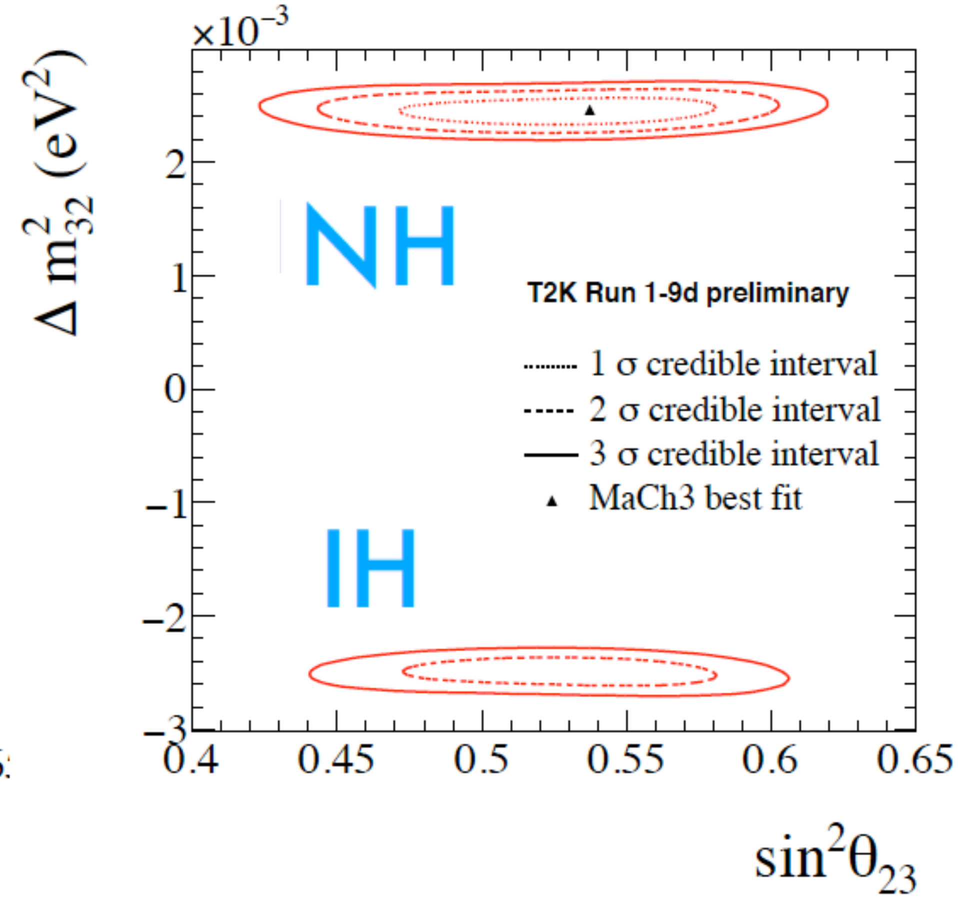
MUON (ANTI)NEUTRINO DISAPPEARANCE RESULTS



Observed	113
Best Fit Integral	121
Cosmic Background	2.1
Beam Background	1.2
Un-oscillated Prediction	730

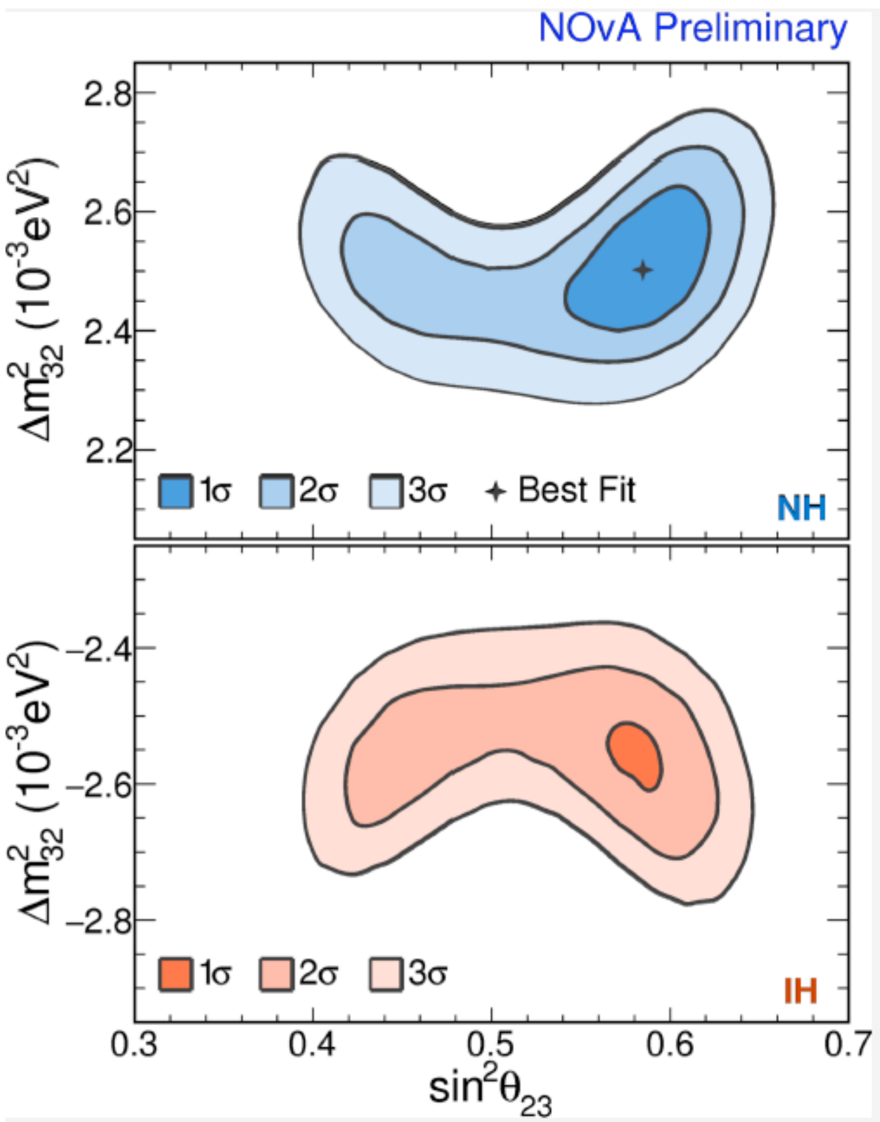


Observed	65
Best Fit Integral	50
Cosmic Background	0.5
Beam Background	0.6
Un-oscillated Prediction	266



T2K

- T2K prefers NH with a Bayes factor of 8.0, assuming an equal prior between NH and IH
- T2K is consistent with $\sin^2\theta_{23}$=0.5
- Best fit value of $\sin^2\theta_{23}$=0.537 (NH)
- Best fit value of Δm^2_{32}=2.46x10^{-3} eV^2 (NH)



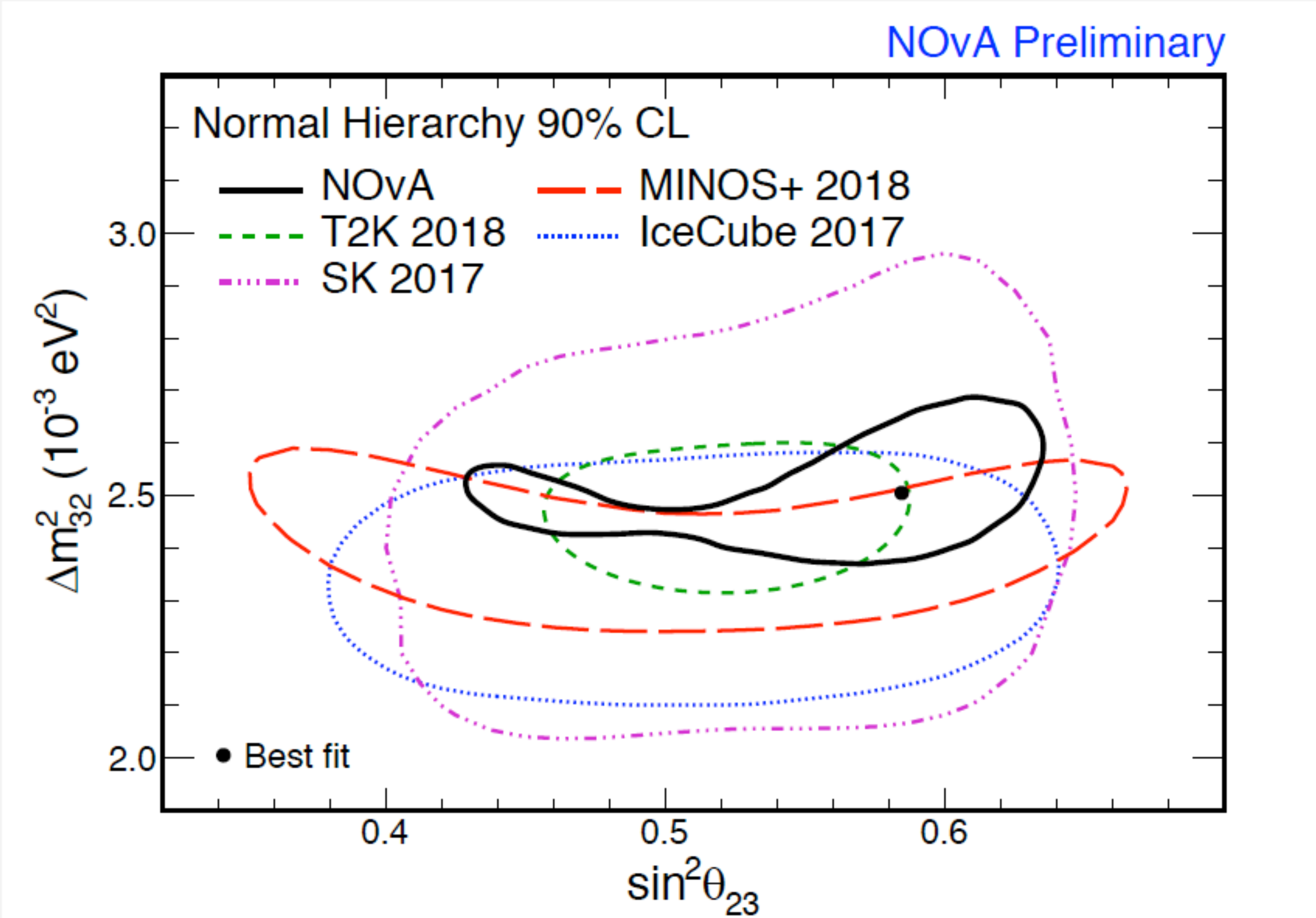
NOvA

- Prefer non-maximal mixing at 1.8 σ.
- Favour upper octant at a similar level.

Best Fit

$$\Delta m^2_{32} = 2.52^{+0.13}_{-0.18} \times 10^{-3}\ eV^2 \quad \text{(NH)}$$
$$\sin^2\theta_{23} = 0.58 \pm 0.03 \quad \text{(UO)}$$

- NOvA is consistent with other long baseline and atmospheric neutrino experiments.



Accelerator appearance experiment

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) = \; & 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2\Delta_{31} \\
& + 8c_{13}^2 s_{12} s_{13} s_{23} (c_{12} c_{23} \boxed{\cos\delta} - s_{12} s_{13} s_{23}) \cos\Delta_{32} \sin\Delta_{31} \sin\Delta_{21} \quad \text{CP non-violating} \\
& - 8c_{13}^2 c_{12} c_{23} s_{12} s_{13} s_{23} \boxed{\sin\delta} \sin\Delta_{32} \boxed{\sin\Delta_{31}} \sin\Delta_{21} \quad \text{CP violating} \\
& + 4s_{12}^2 c_{13}^2 (c_{12}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12} c_{23} s_{12} s_{23} s_{13} \boxed{\cos\delta}) \sin^2\Delta_{21} \quad \text{CP non-violating} \\
& - 8c_{13}^2 s_{13}^2 s_{23}^2 (1 - 2s_{13}^2) \frac{\boxed{a}L}{4E} \cos\Delta_{32} \boxed{\sin\Delta_{31}} \quad \text{matter effect}
\end{aligned}
$$

MH

$a = 2\sqrt{2} G_F N_e E$ $\qquad P(\bar{\nu}_\mu \to \bar{\nu}_e)$ $\qquad a \to -a, \delta \to -\delta$

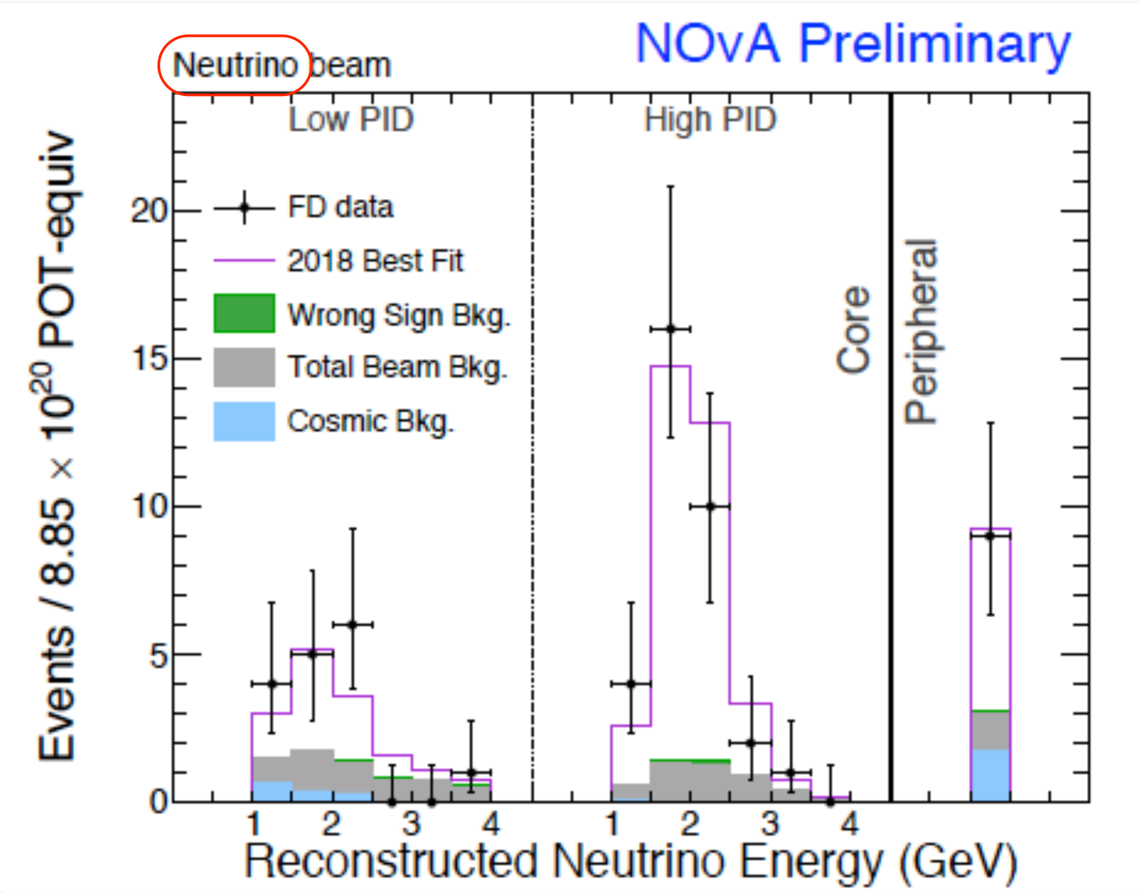
potential to measure:

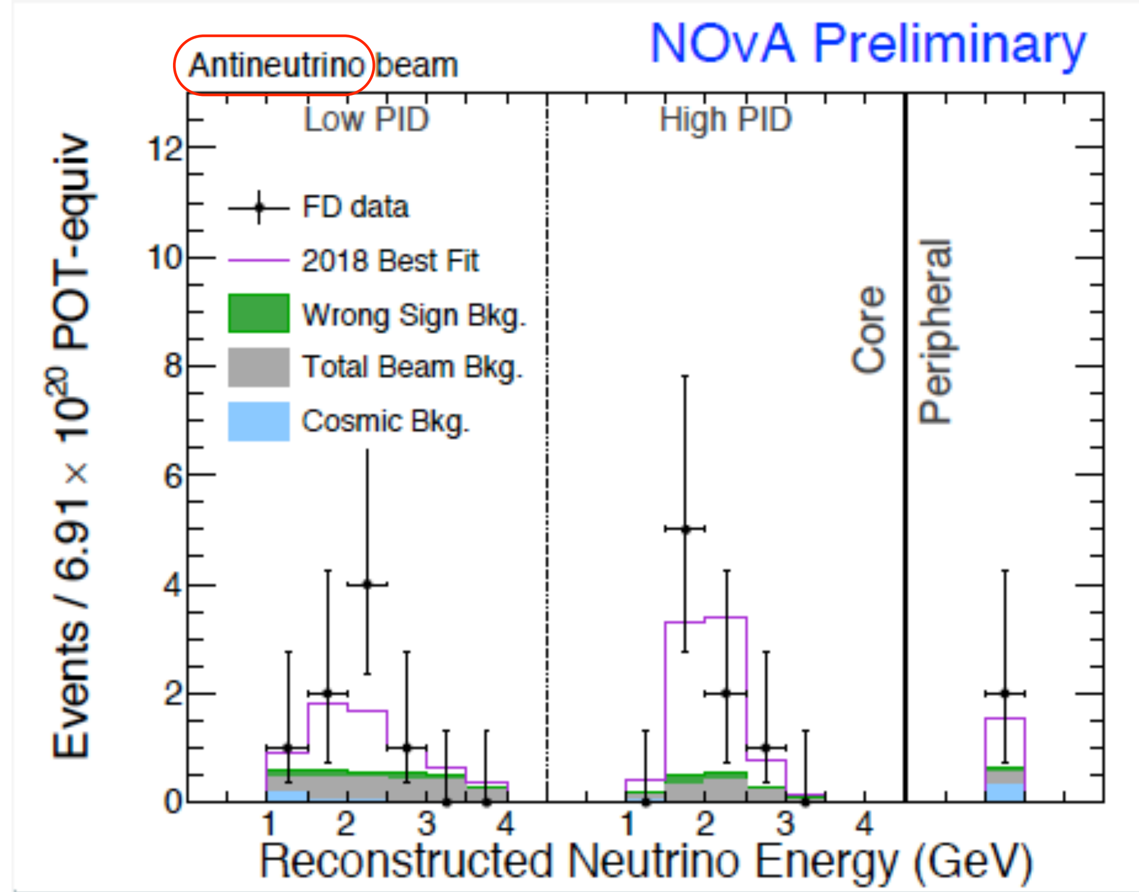
- CP phase, δ
- $\text{sign}(\theta_{23} - 45^\circ)$ $\qquad s_{23}^2 = \frac{1 \pm \sqrt{1 - \sin^2 2\theta_{23}}}{2}$
- $\text{sign}(\Delta m_{31}^2)$ $\qquad$ mass hierarchy

- *No chance to test CPV if it was $\theta_{13} = 0$ (it's small but not 0)*
- δ_{CP} <u>never</u> singled out, ambiguities remain and need to be solved with external inputs (e.g. reactor)
- Possible to test also w/o anti-ν, by fitting all parameters together instead of only δ_{CP} and a or a Δij, but obviously less sensitive

Strong (> 4σ) evidence of electron antineutrino appearance

NOvA



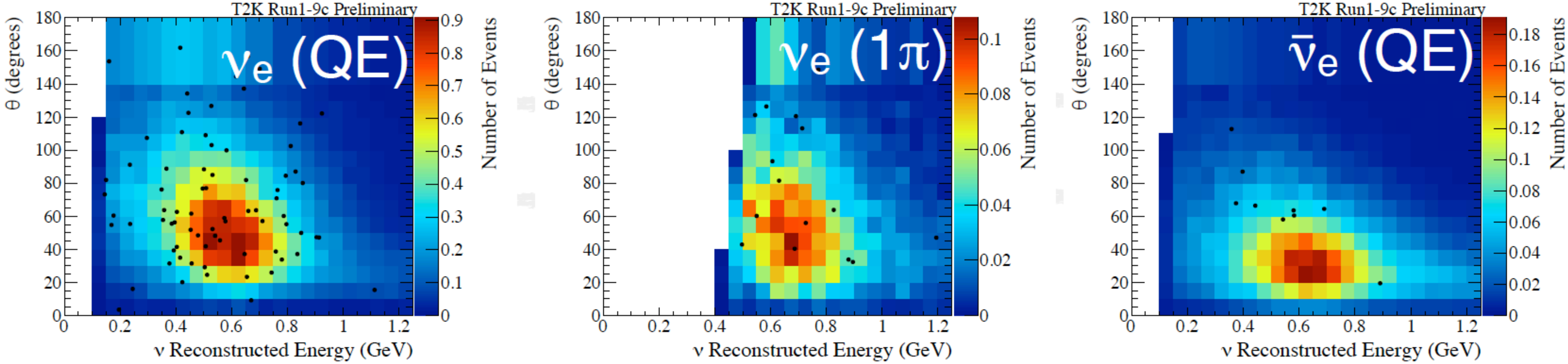


Observed	58
Best Fit Prediction	59
Cosmic Background	3.3
Beam Background	11.1
Wrong Sign Background	0.7

Observed	18
Best Fit Prediction	15.9
Cosmic Background	0.7
Beam Background	3.5
Wrong Sign Background	1.1

- Events are separated into two samples, based on imaging techniques
- Otherwise good events that pass either containment/cosmic rej are called "peripheral"

$\nu_e/\bar{\nu}_e$ appearance



Predictions with: $\sin^2\theta_{13}=0.0212$, $\sin^2\theta_{23}=0.528$, $\Delta m^2_{32}=2.51\times10^{-3}$, NH

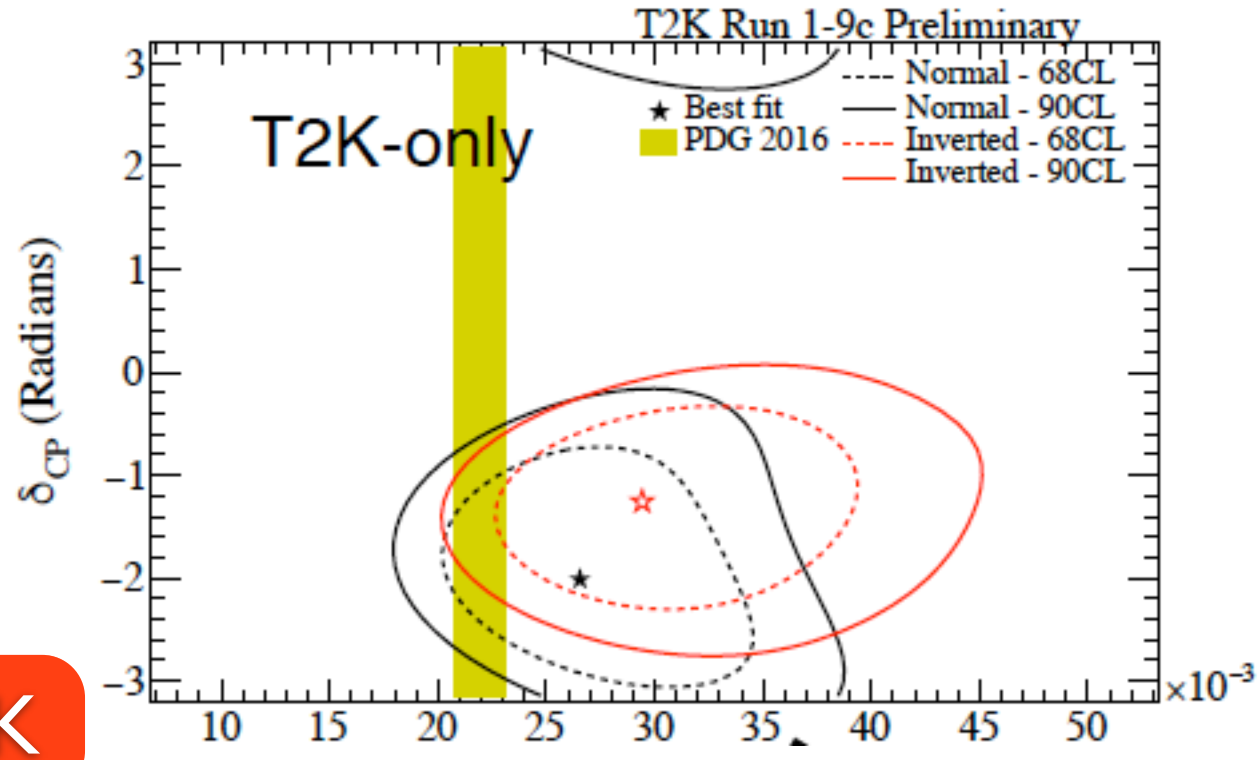
Sample	$\delta_{CP}=-\pi/2$	$\delta_{CP}=0$	$\delta_{CP}=\pi/2$	$\delta_{CP}=\pi$	Observed
nu	74.4	62.2	50.6	62.7	75
nu-bar	17.1	19.4	21.7	19.3	15
nu+1π	7.0	6.1	4.9	5.9	15

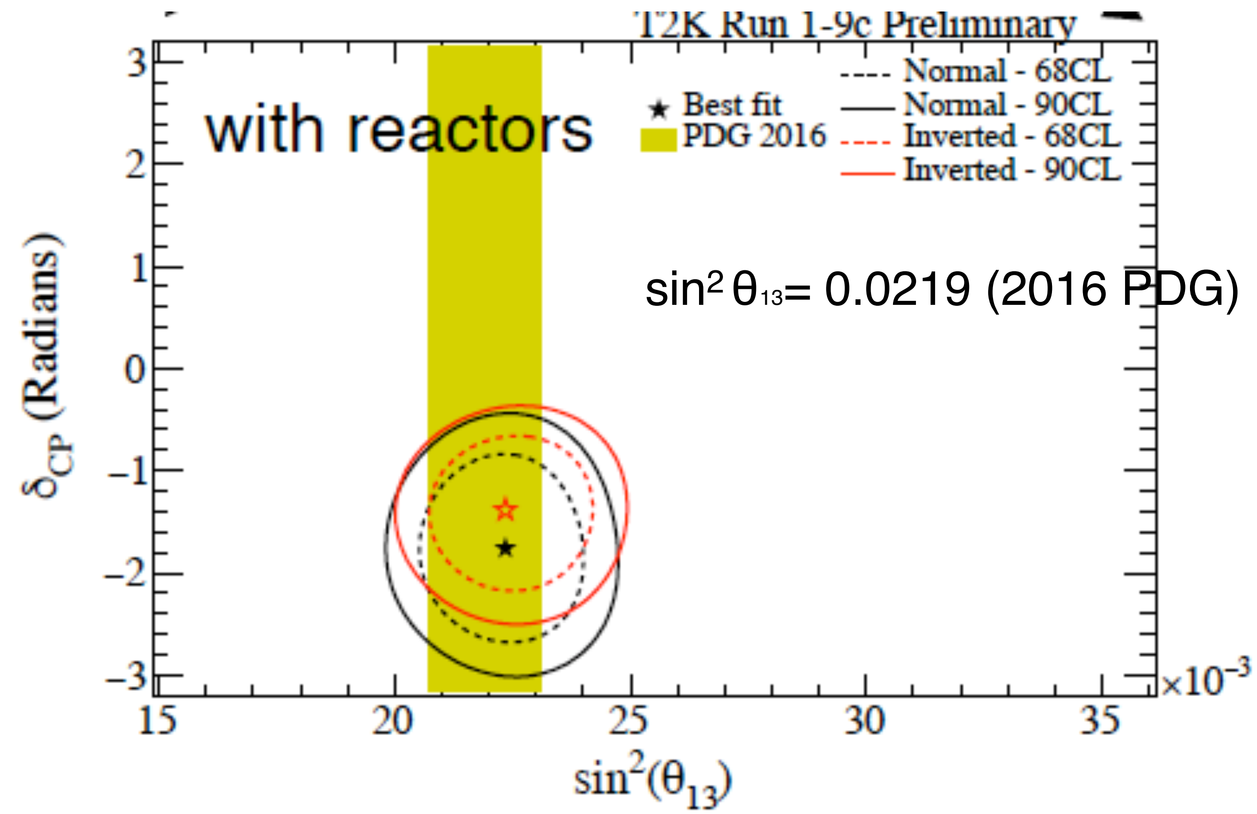
β	HYPOTHESIS	P-VALUE
β=0	NO appearance	p=0.233
β=1	PMNS appearance	p=0.0867

No sound statistical conclusions on nu_e-bar appearance yet

- SK event rates are in line with expectations based on oscillation model
  - Of note: 15 events observed in CC1π ν_e sample, with prediction of 6.9 maximum
    - p-value for up/down fluctuation in 1 of 5 samples is: ~5% (1% with single sample).

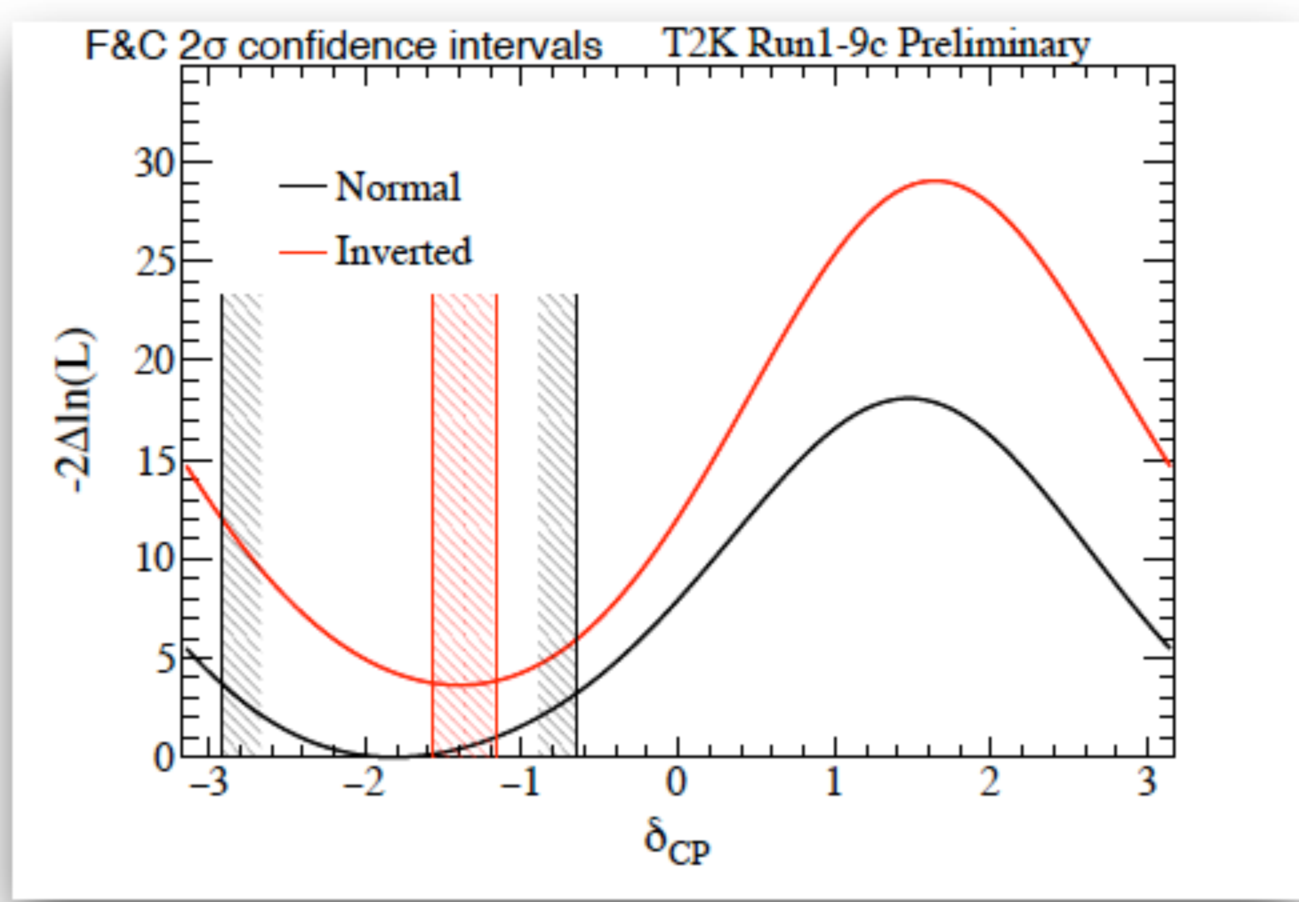
DATA FIT





T2K

DATA FIT with reactor constraint



δ_{CP}	Hierarchy	90%	2σ
0	NH	0.421	0.288
π	NH	0.388	0.248
0	IH	0.768	0.660
π	IH	0.783	0.685

NOvA

JOINT FIT RESULTS

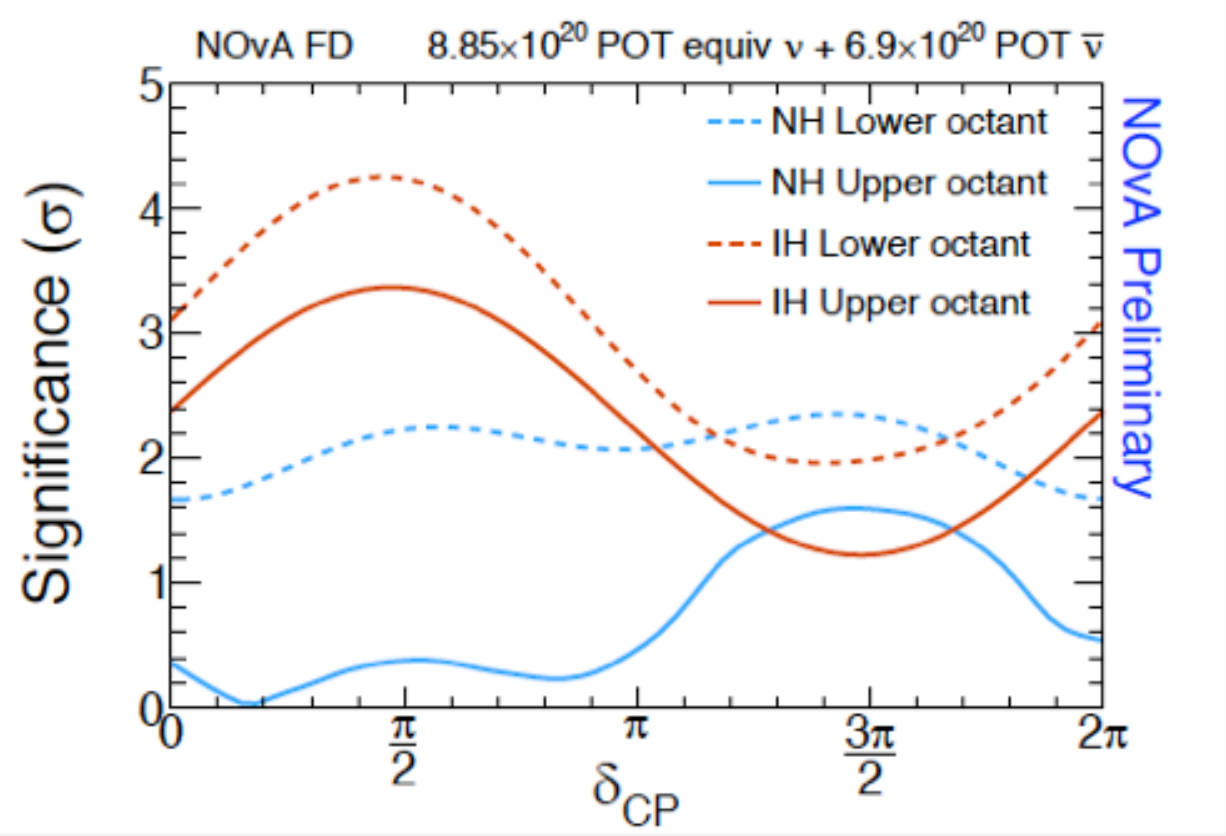
- Prefer NH by 1.8 σ.
- Exclude $\delta_{CP} = \pi/2$ for IH at >3 σ.

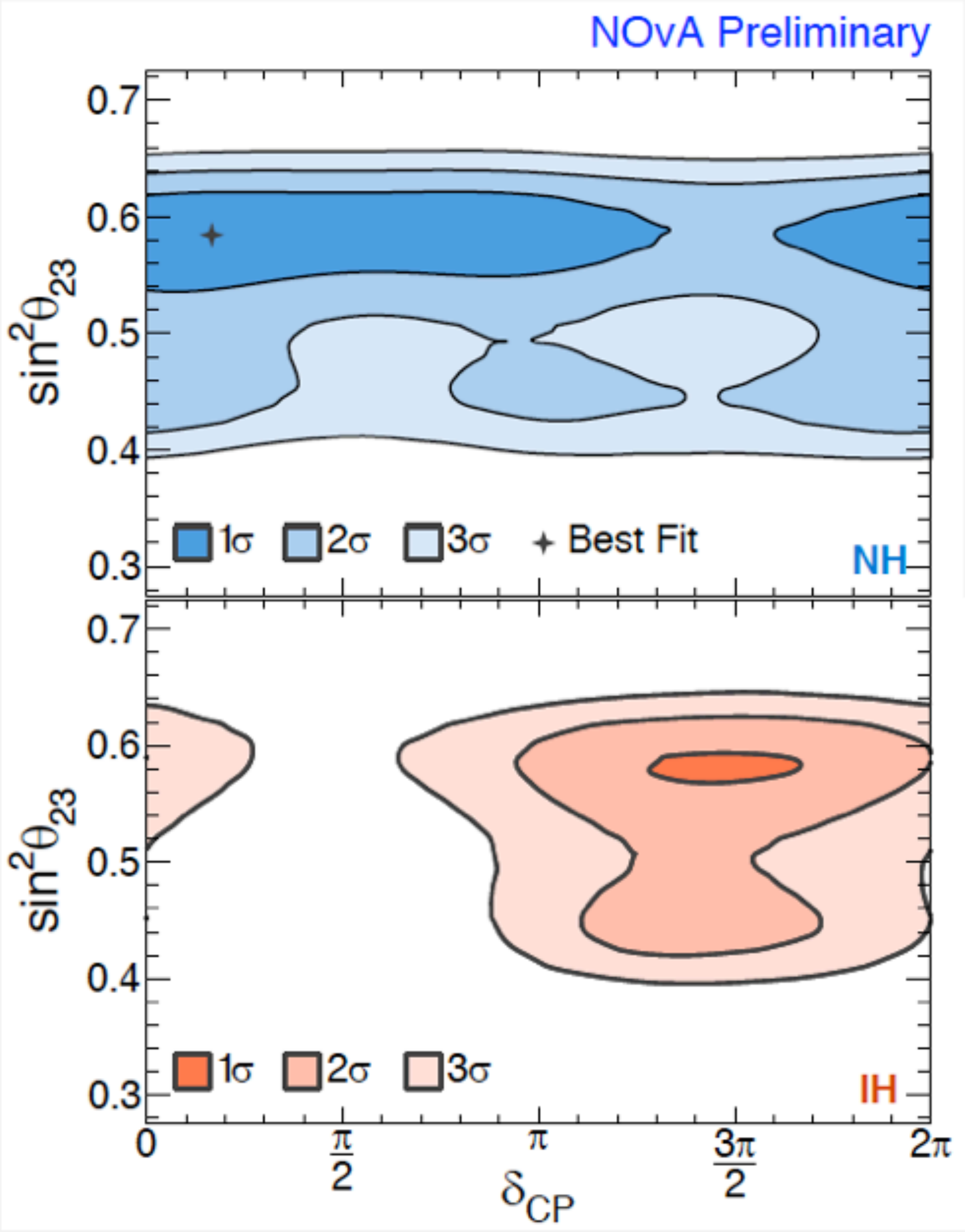
Best Fit

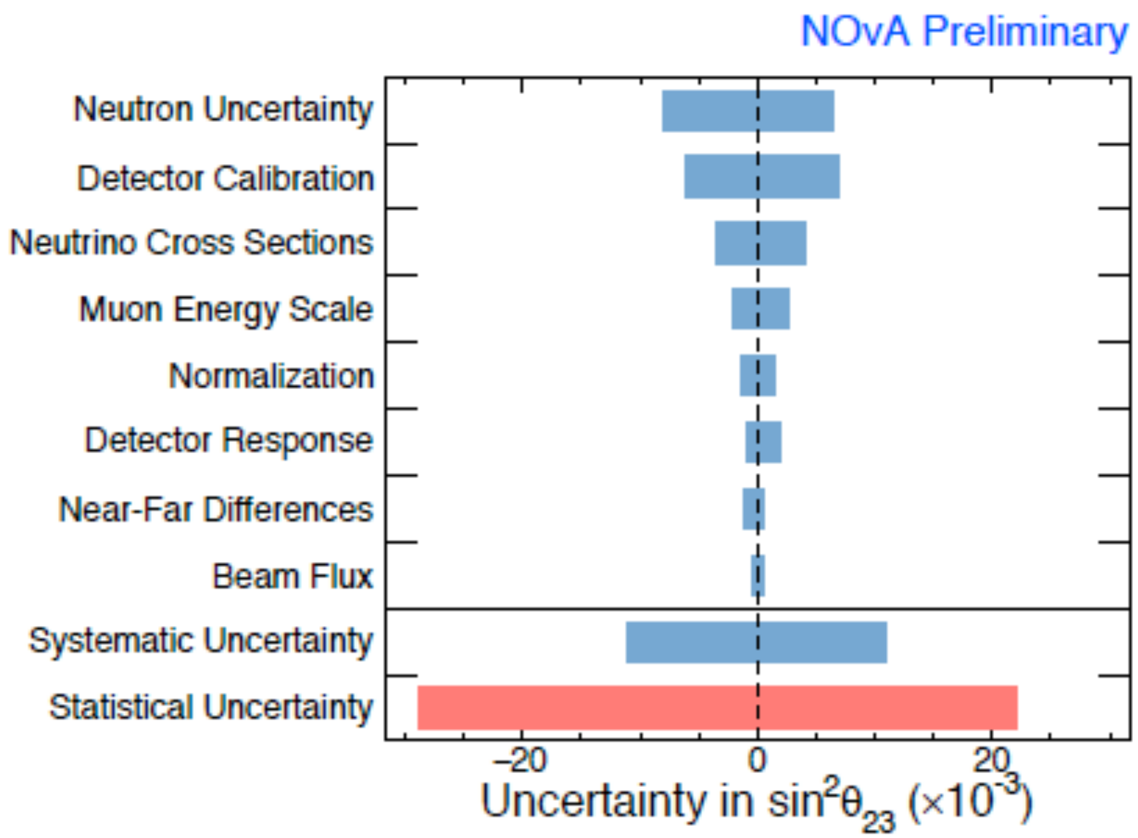
$\delta_{CP} = 0.17\pi$

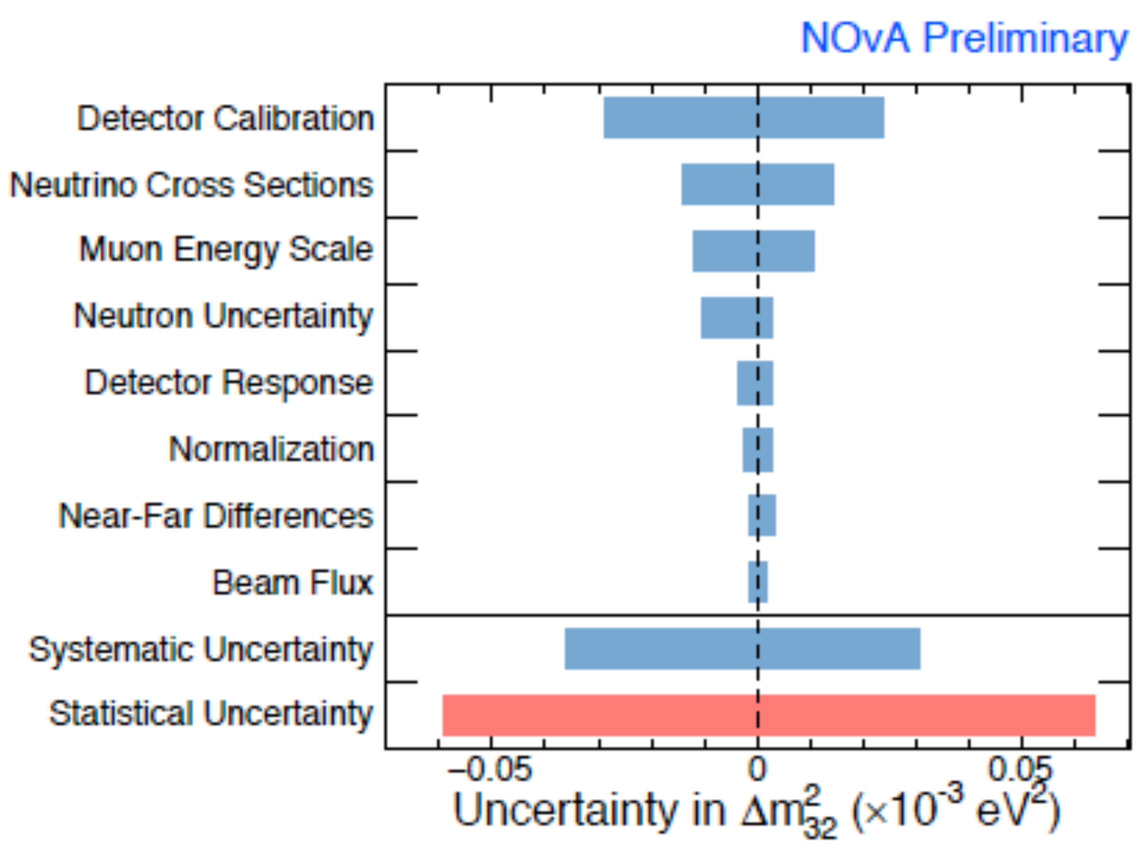
$\Delta m^2_{32} = 2.52^{+0.13}_{-0.18} \times 10^{-3}\ eV^2$ (NH)

$\sin^2\theta_{23} = 0.58 \pm 0.03$ (UO)









NOvA

Systematic uncertainties have been reduced in this analysis, however analyses are still statistics limited.

- The upcoming test beam program will improve the calibration and detector response systematics.
- Neutron uncertainty important (and new) for $\bar{\nu}$.
- Neutrino cross-sections (MEC,RPA) also important.

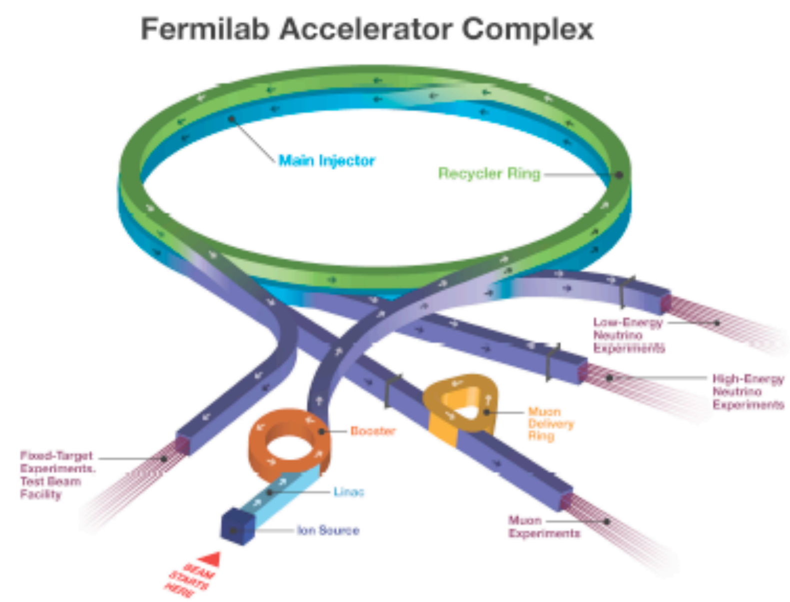
Both NOvA and T2K have extensive upgrade ahead for both ND and FD

T2K: https://zenodo.org/record/1286758#.XFwZyNF7mi4

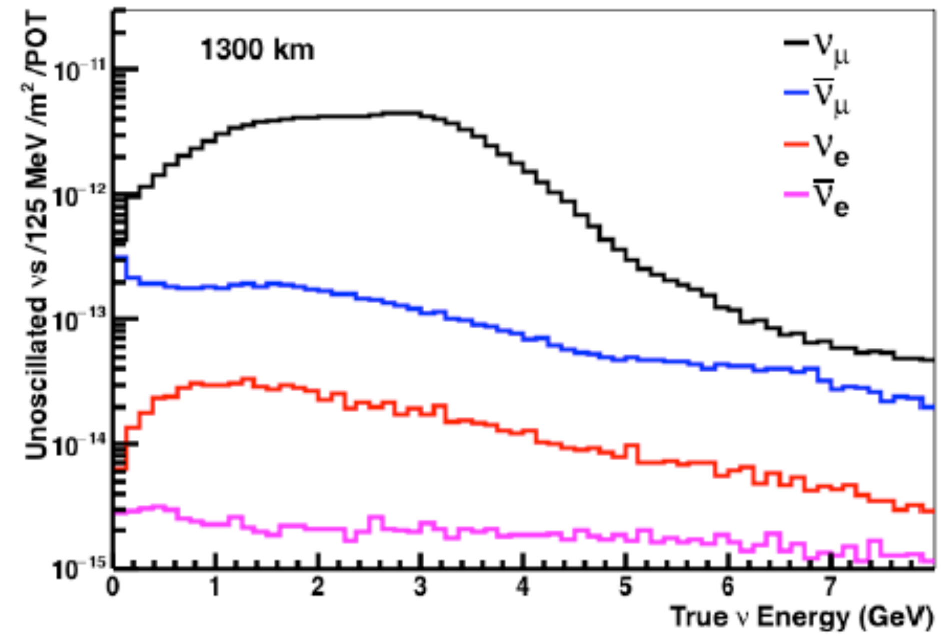
Future LBL experiments

DUNE

LBNF Beam



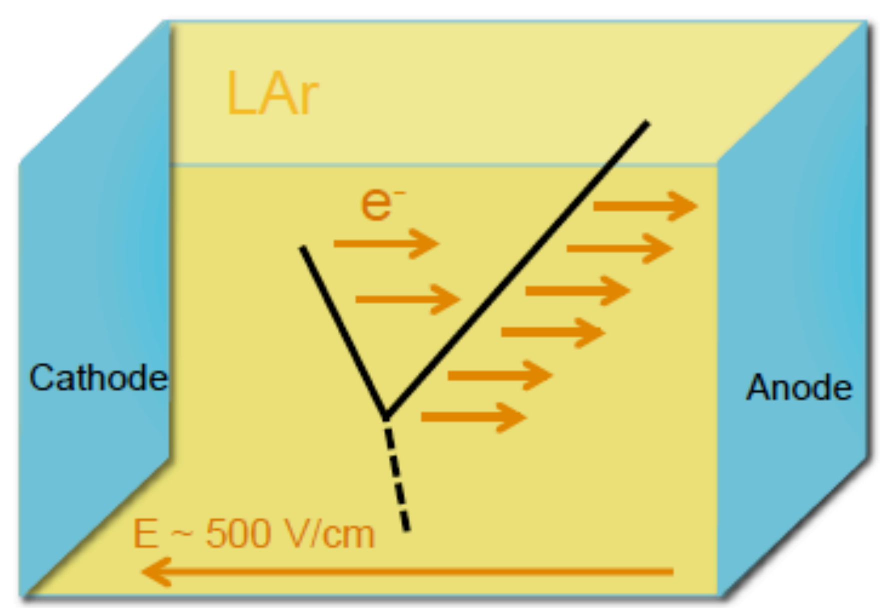
Neutrino Flux at 1300 km
(CDR Optimized Beam)



- 60-120 GeV proton beam

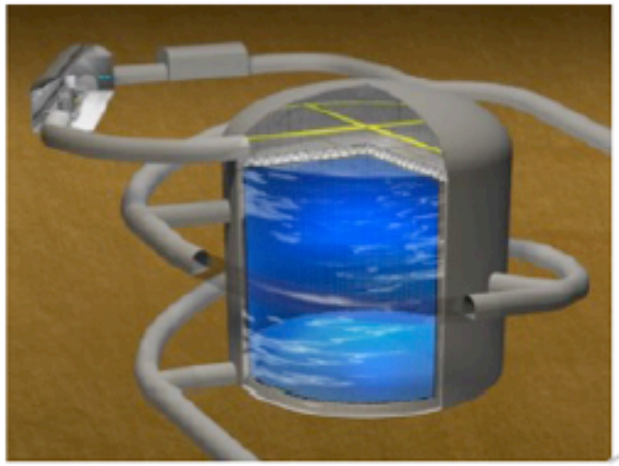
DUNE Far Detector

- 4 10-kt (fiducial) liquid argon TPC modules
- **Single-** and dual-phase detector designs (1st module will be single phase)
- Integrated photon detection
- Modules will not be identical



https://zenodo.org/record/1286764#.XFw4L9F7mi4

Hyper-Kamiokande



Hyper-K

J-PARC
Accelerator Complex

- ✓Gigantic neutrino and nucleon decay detector
  - ✓186 kton fiducial mass : ~10 × Super-K
  - ✓× 2 higher photon sensitivity than Super-K
  - ✓Superb detector capability, technology still evolving
  - ✓2nd oscillation maximum by 2nd tank in Korea under study
- ✓MW-class world-leading ν-beam by upgraded J-PARC
- ✓Project now is a priority project by MEXT's Roadmap
  - ✓Aiming to start construction in FY2019, operation in FY2026

5

https://zenodo.org/record/1286768#.XFwb49F7mi4

Future experiments/DUNE

DEEP UNDERGROUND **NEUTRINO** EXPERIMENT

Timeline

2018: protoDUNEs at CERN

↓

2019: Technical Design Report

↓

2019: Far Site Primary Excavation Begins

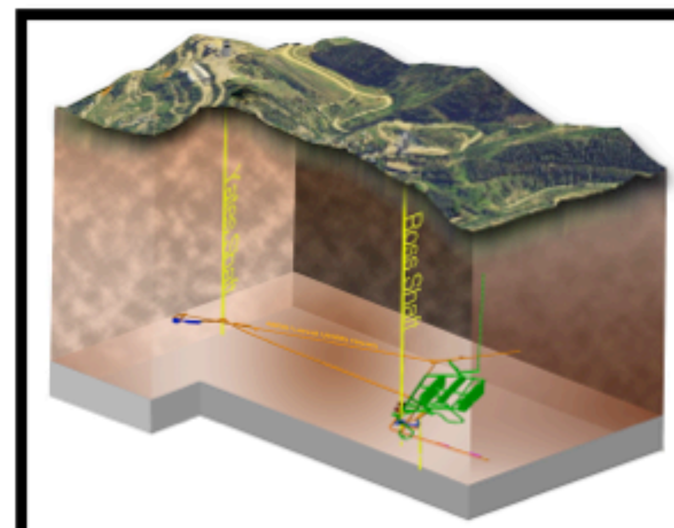
↓

2022: First Module Installation Begins

↓

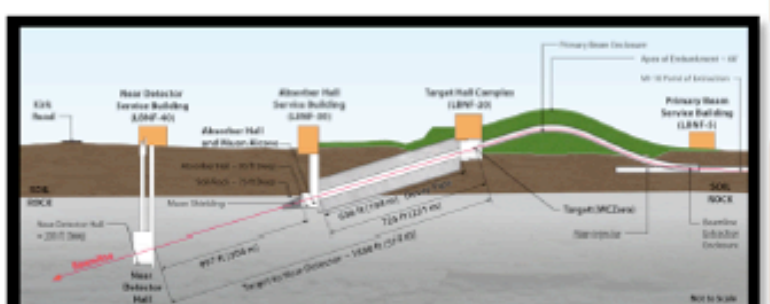
2026: Neutrino Beam Available

DUNE Far Detector Interim Design Report (2018)
Will be made public soon…



Physics data as soon as 1st module complete

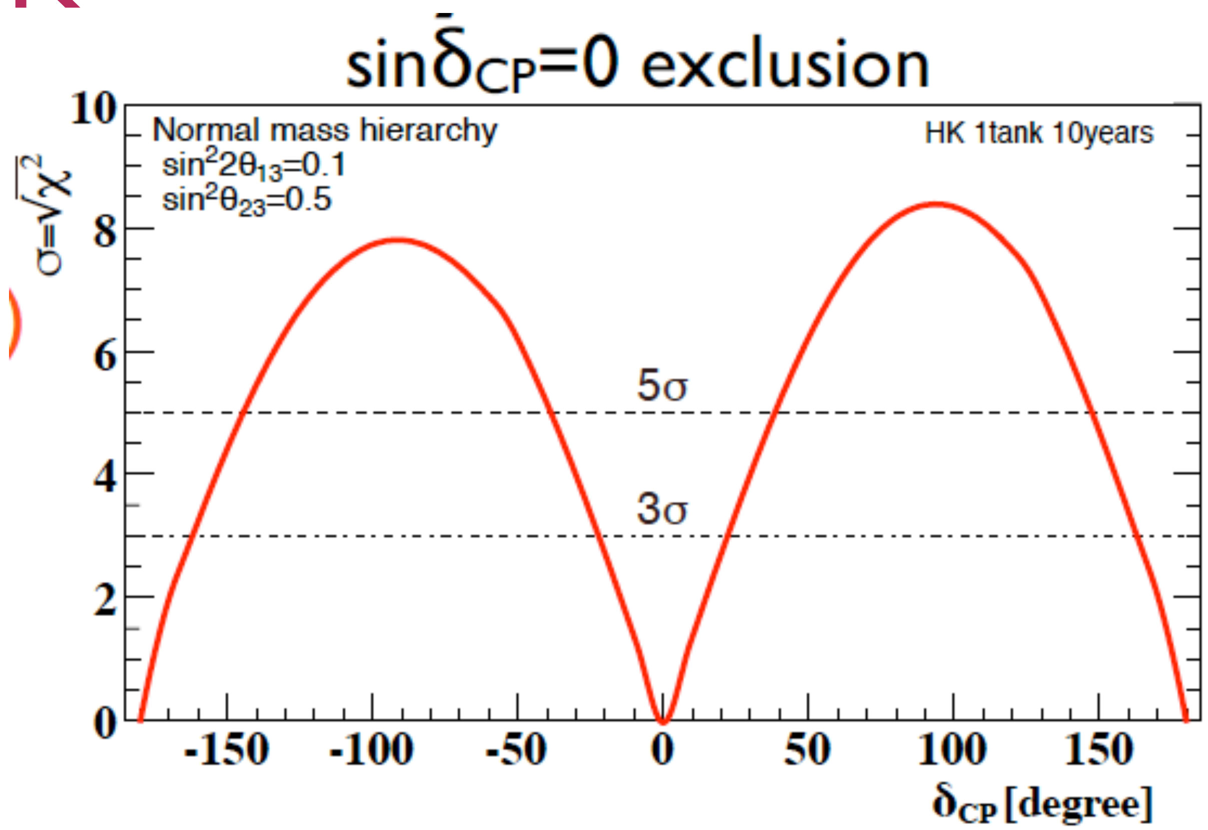
- Atmospheric νs
- SNB and solar νs
- Baryon number violation
- Detector calibration



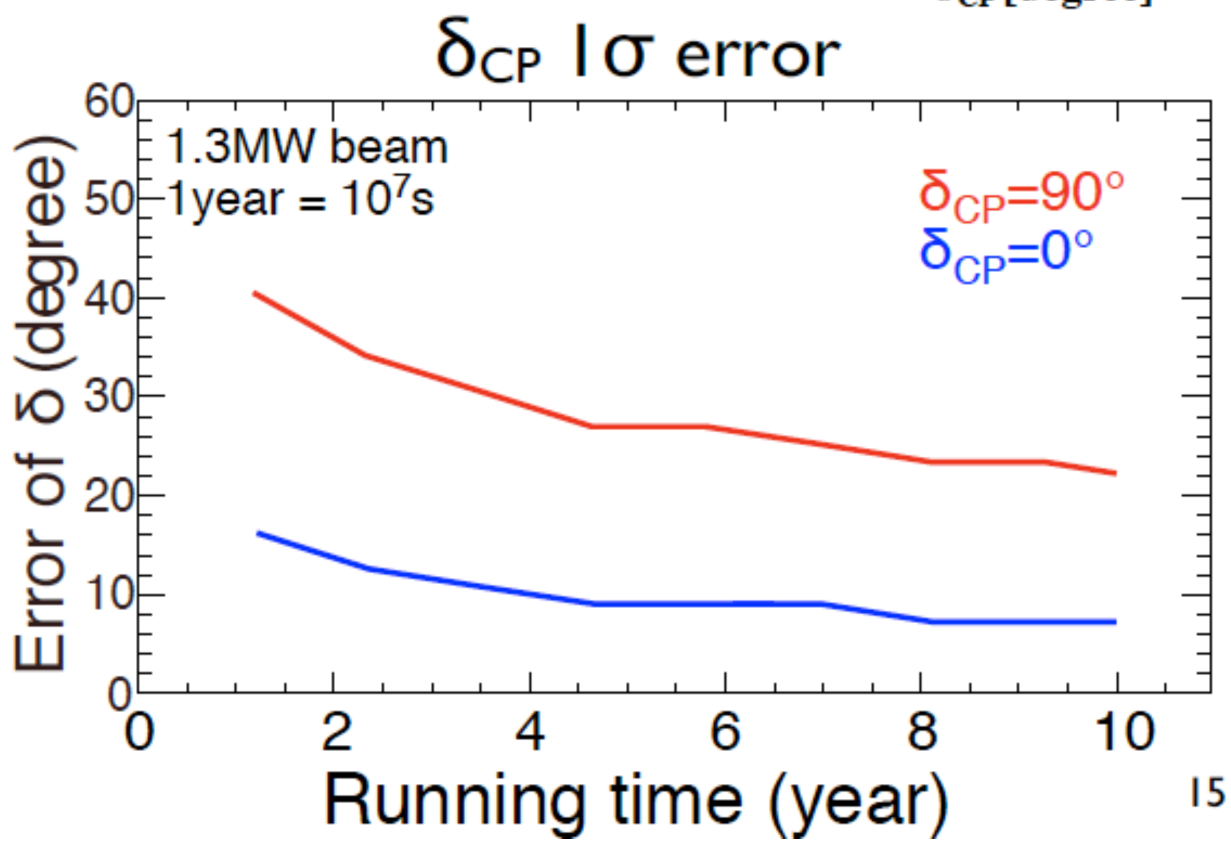
E. Worcester: Neutrino 2018 **13**

HK

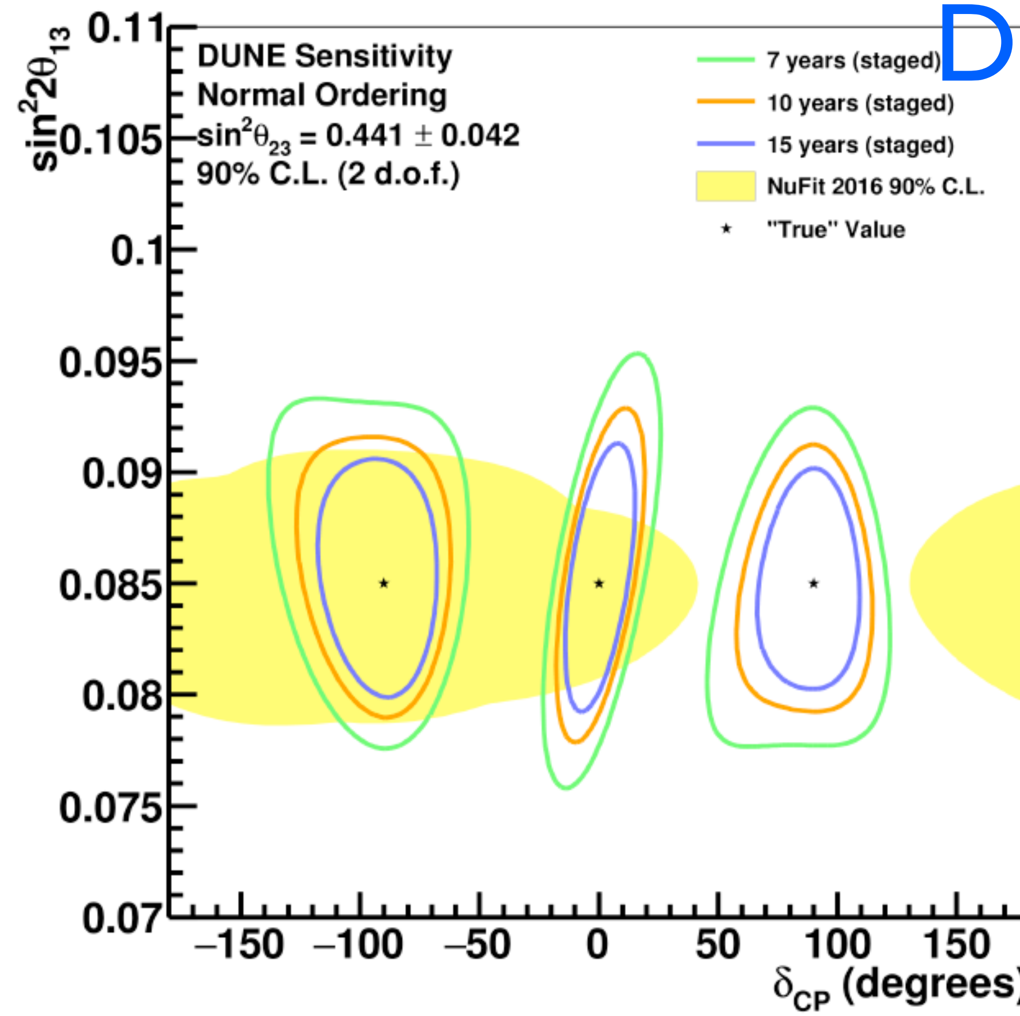
DUNE



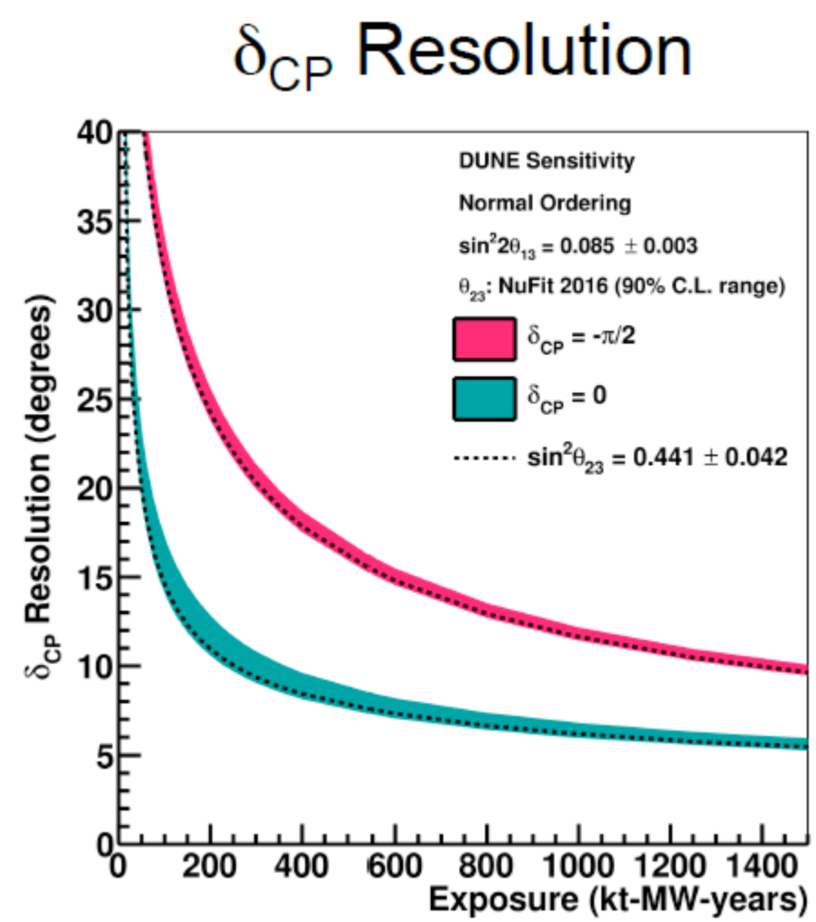
sinδCP=0 exclusion
Normal mass hierarchy
sin²2θ13=0.1
sin²θ23=0.5
HK 1tank 10years
5σ
3σ
σ=√χ²
δCP [degree]



δCP 1σ error
1.3MW beam
1year = 10⁷s
δCP=90°
δCP=0°
Error of δ (degree)
Running time (year)
15



DUNE Sensitivity
Normal Ordering
sin²θ23 = 0.441 ± 0.042
90% C.L. (2 d.o.f.)
7 years (staged)
10 years (staged)
15 years (staged)
NuFit 2016 90% C.L.
"True" Value
sin²2θ13
δCP (degrees)



δCP Resolution
DUNE Sensitivity
Normal Ordering
sin²2θ13 = 0.085 ± 0.003
θ23: NuFit 2016 (90% C.L. range)
δCP = -π/2
δCP = 0
sin²θ23 = 0.441 ± 0.042
δCP Resolution (degrees)
Exposure (kt-MW-years)

Additional material

Matter effect, MSW

2-flavour, vacuum:

$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = M_V\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = \left[\frac{m_1^2+m_2^2}{4p}\right]\begin{pmatrix}1 & 0\\ 0 & 1\end{pmatrix}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} + \left(\frac{\Delta m^2}{4p}\right)\begin{pmatrix}-\cos 2\theta & \sin 2\theta\\ \sin 2\theta & \cos 2\theta\end{pmatrix}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}$$

In ordinary matter (e.g. sun or earth) an additional interaction of ν_e with **e** occurs, with potential:

$$V_e = G_F\sqrt{2}N_e \qquad m^2 = E^2 - p^2 \rightarrow (E+V_e)^2 - p^2 = m^2 + 2EV_e$$

N_e = electron density

$$\Delta m_{(e)}{}^2 = 2\sqrt{2}G_F N_e E$$

$$\frac{1}{2}\left(m_1^2+m_2^2\right)\begin{pmatrix}1 & 0\\ 0 & 1\end{pmatrix} + 2\sqrt{2}G_F N_e p\begin{pmatrix}1 & 0\\ 0 & 0\end{pmatrix} = \left[\frac{1}{2}\left(m_1^2+m_2^2\right)+\sqrt{2}G_F N_e p\right]\begin{pmatrix}1 & 0\\ 0 & 1\end{pmatrix} + \sqrt{2}G_F N_e p\begin{pmatrix}1 & 0\\ 0 & -1\end{pmatrix}$$

Therefore, time evolution of 2-flavour, in matter:

$A' = 2\sqrt{2}G_F N_e p/\Delta m^2$

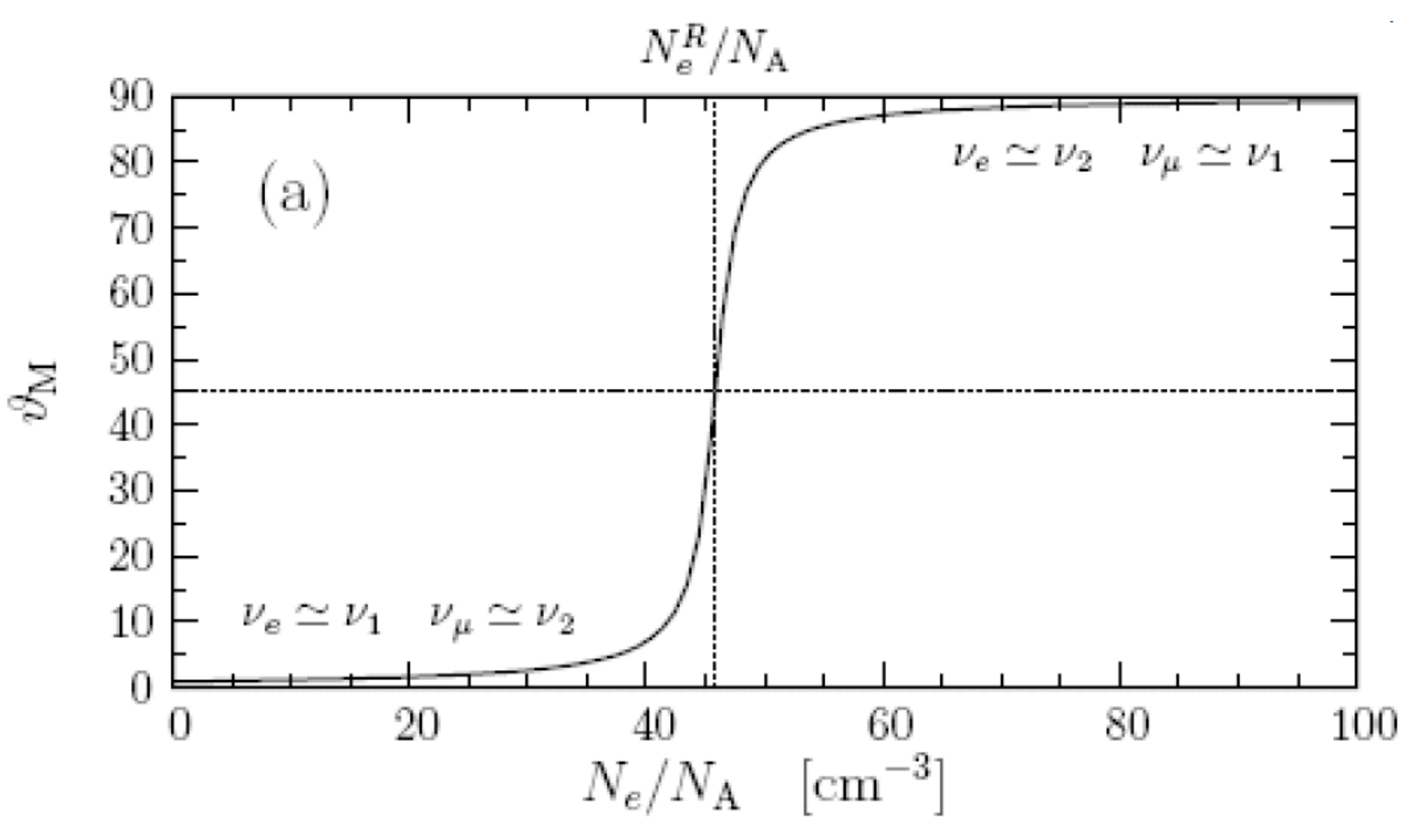
$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = M_m\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = \left[\frac{\left(m_1^2+m_2^2\right)}{4p} + \frac{\sqrt{2}G_F N_e p}{2}\right]\begin{pmatrix}1 & 0\\ 0 & 1\end{pmatrix}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} + \left[\frac{\Delta m^2}{4p}\begin{pmatrix}-\cos 2\theta + A' & \sin 2\theta\\ \sin 2\theta & \cos 2\theta - A'\end{pmatrix}\right]\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}$$

$$M_m \quad \left[\frac{\Delta m_m^2}{4p}\begin{pmatrix} -\cos 2\theta_m & \sin 2\theta_m \\ \sin 2\theta_m & \cos 2\theta_m \end{pmatrix}\right]\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} \longrightarrow \tan 2\theta_m = \frac{\sin 2\theta}{\cos 2\theta - A'} = \frac{\tan 2\theta}{1 - \frac{A'}{\cos 2\theta}}$$

- Effectively this translates into a "revised" mixing angle
- But with a resonance effect, when A' = cos 2ϑ (ϑ=mixing angle in vacuum)
- i.e. an electron density

$$N_e(ris) = \Delta m^2 \frac{\cos 2\theta}{2\sqrt{2} G_F p}$$

- Correspondingly, new mass difference: $\Delta m_m^2 = \Delta m^2 \sqrt{\left[(\cos 2\theta - A')^2 + \sin^2 2\theta\right]}$



Evolution in the case of slow change of matter density along the neutrino path

Systematics

	% errors on predicted event rates				
	1R μ-like		1R e-like		
	ν-mode	$\bar{\nu}$-mode	ν-mode	ν-mode (+1π)	$\bar{\nu}$-mode
SK detector	1.9 %	1.5%	3.0%	16.7%	4.2%
SK FSI+SI+PN	2.2%	2.0%	3.0%	11.4%	2.3%
ND constraint (flux & cross-section)	3.2%	2.7%	3.2%	4.1%	2.9%
$\sigma(\nu_e)/\sigma(\nu_\mu)$	<0.05 %	<0.05 %	2.6%	2.6%	1.5%
Neutral currents	0.3%	0.3%	1.1%	1.0%	2.6%
Total	4.4%	3.8%	6.1%	20.9%	6.5%

- Uncertainties between 4% and 7% (except e-like+1π → small stat.)
- Contributions from flux and cross-section constrained by ND280
- SK detector and FSI+SI uncertainties (not constrained by ND280)
- Only use ν_μ selection at ND280 → uncertainties due to possible ν_e/ν_μ cross-section (theoretical uncertainties)

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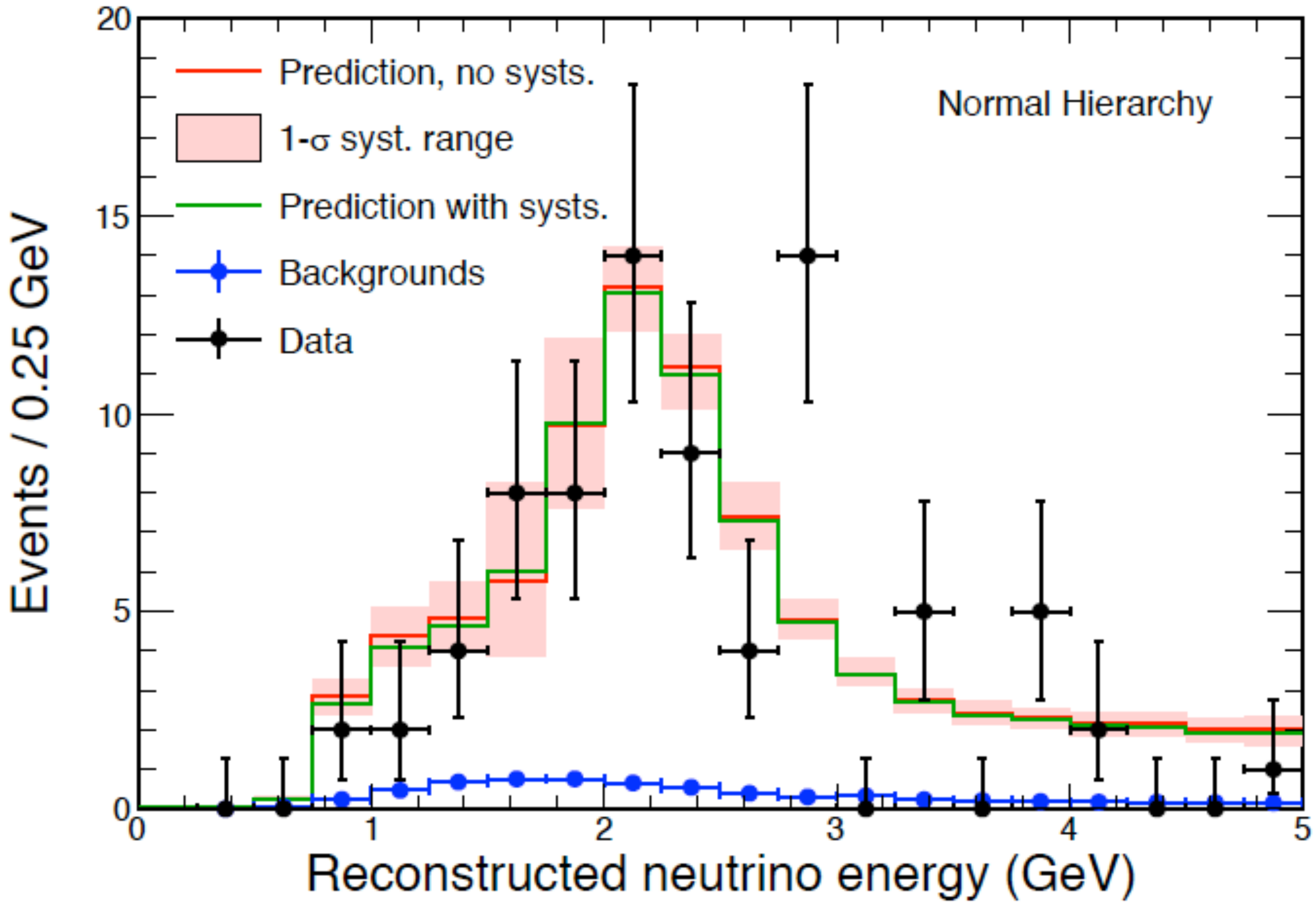
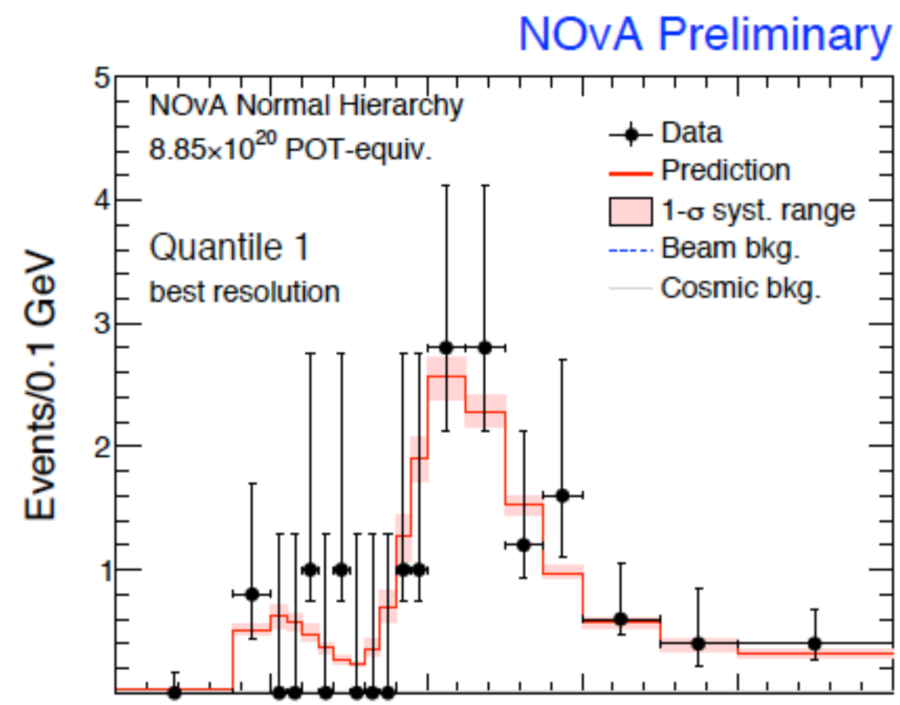
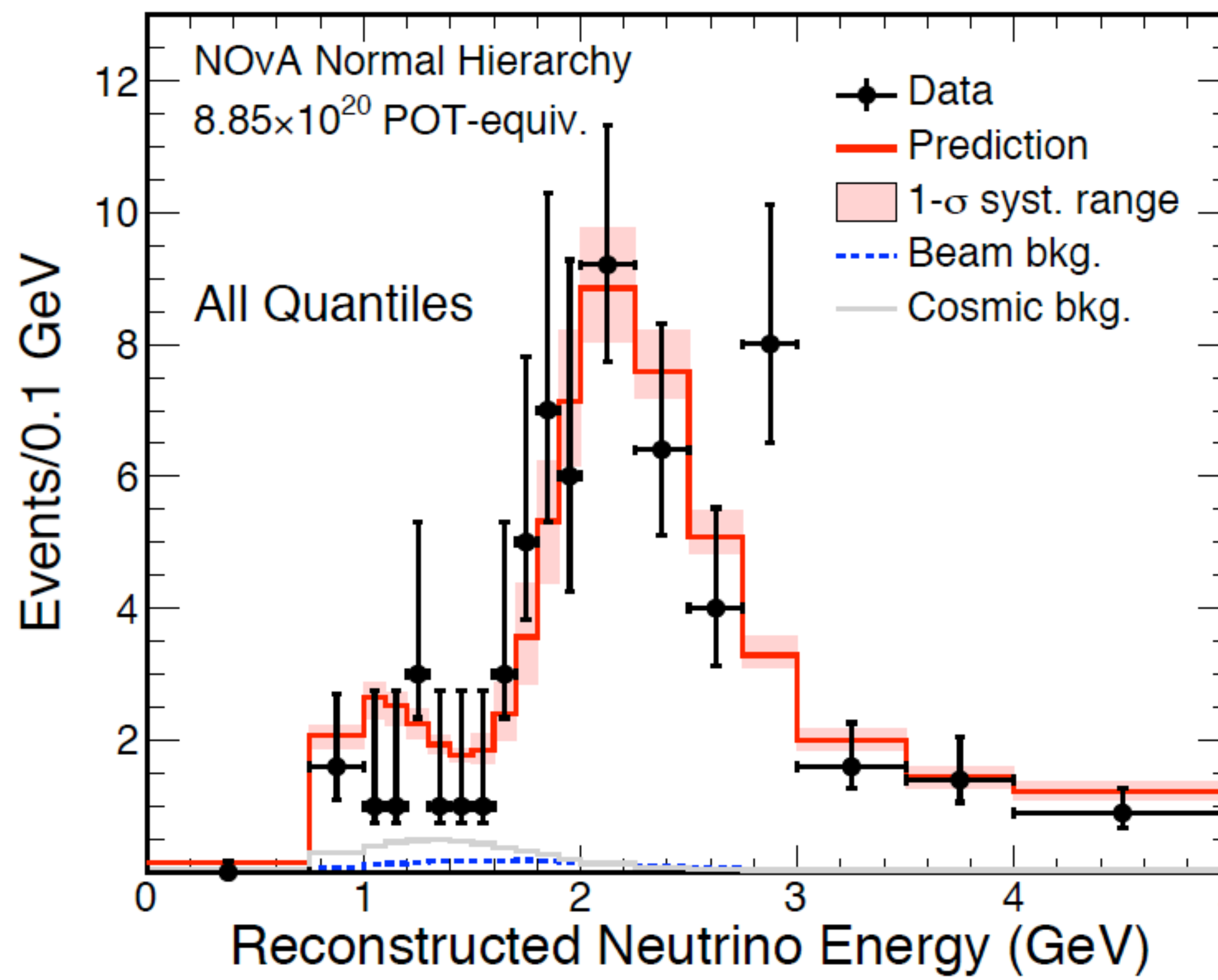


Quantile with best resolution





Off-axis neutrino beam

arXiv:1005.0574v2 [hep-ex]

- In the charged pion decay the neutrino in the CM frame has E*=29.8MeV
- In the LAB frame:

$$\begin{aligned} E &= \gamma E^*(1+\beta\cos\theta^*) \\ E\ \cos\theta &= \gamma E^*(\cos\theta^*+\beta) \\ E\ \sin\theta &= E^*\sin\theta^* \end{aligned}$$

$$\begin{aligned} \cos\theta &= \frac{\cos\theta^*+\beta}{1+\beta\cos\theta^*} \\ \sin\theta &= \frac{\sin\theta^*}{\gamma(1+\beta\cos\theta^*)} \end{aligned}$$

$$\sin\theta \leq \frac{E^*}{E}$$

$$\theta_{\max}(E) = \arcsin\frac{E^*}{E} \simeq \frac{30\ \mathrm{MeV}}{E}$$

$$E_{\max}(\theta) = \frac{E^*}{\sin\theta}$$

For each given angle in the LAB there is a maximum neutrino energy

ν_e Near Detector Data

NOvA

- Select ν_e CC interactions with 73% efficiency and 76% purity
- Use ND data to predict background in FD
  - NC, CC, beam ν_e each propagate differently
  - constrain beam ν_e using selected ν_μ CC spectrum
  - constrain ν_μ CC using Michel Electron distribution

beam ν_e up by 4%
NC up by 17%
ν_μ CC up by 10%