Neutrino Oscillation Experiments and Recent Results from T2K

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Neutrino Oscillations

Theory of Neutrino Oscillations

- The 3 × 3 Pontecorvo-Maki-Nakagawa-Sakata (PMNS) unitary matrix governs neutrino oscillations

Flavor states **Mass states**

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

$c_{ij} = \cos\theta_{ij}\,,\ s_{ij} = \sin\theta_{ij}$

$$= \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{Atmospheric}} \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13} e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix}}_{\text{Reactor/Accelerator}} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{Solar}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

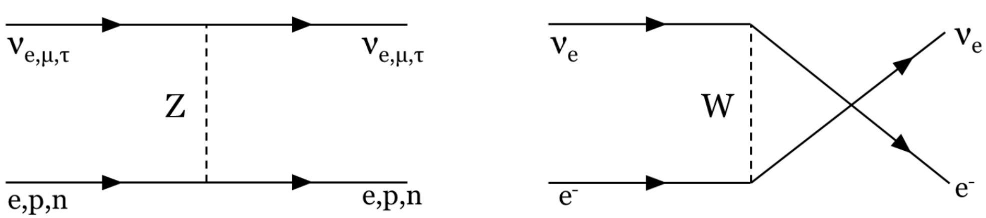
$$P(\nu_\alpha \to \nu_\beta / \bar{\nu}_\alpha \to \bar{\nu}_\beta) = \delta_{\alpha\beta} - 4 \sum_{i>j} Re\left(U_{\alpha i} U^*_{\beta i} U^*_{\alpha j} U_{\beta j}\right) sin^2 \left(\frac{\Delta m^2_{ji} L}{4E}\right)$$

$$\pm 2 \sum_{i>j} Im\left(U_{\alpha i} U^*_{\beta i} U^*_{\alpha j} U_{\beta j}\right) sin^2 \left(\frac{\Delta m^2_{ji} L}{2E}\right)$$

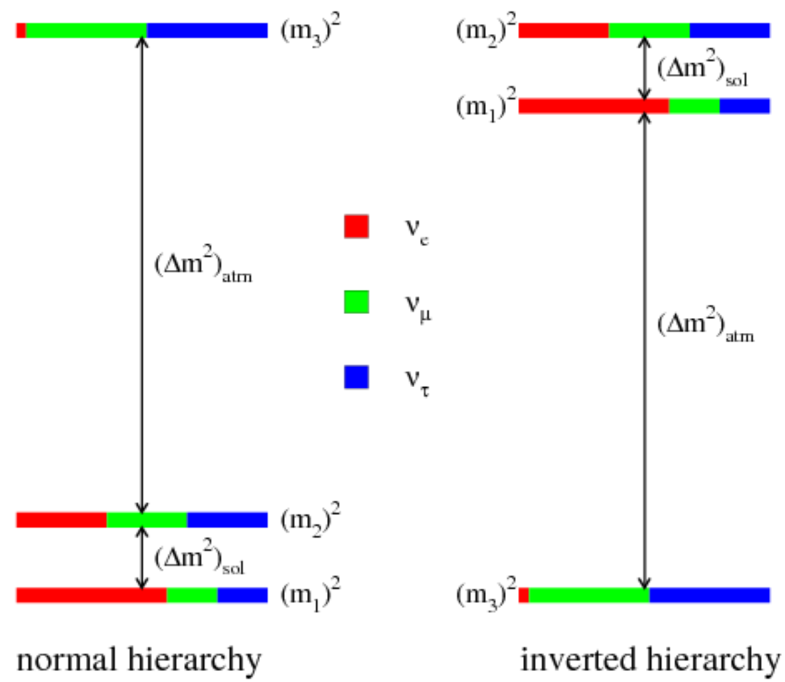
Measuring the Neutrino Oscillations

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \underbrace{\begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}}_{\text{Atmospheric}} \underbrace{\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta_{CP}}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13}\end{pmatrix}}_{\text{Reactor/Accelerator}} \underbrace{\begin{pmatrix}c_{12} & s_{12} & 0\\ s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}}_{\text{Solar}} \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

- Experimentally adjustable **L/E**
  - Oscillation parameters (Δm^2_{ij} , θ_{ij} , δ_{cp}) with dominant effects to different types of experiment
- **Mass hierarchy of Δm^2_{ji}**
  - Normal (NH) and inverted (IH)
  - **Matter effect** gives extra sensitivity to measure the hierarchy



(a) Neutral current (b) Charged current



Current State of Oscillation Parameters

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta_{CP}}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & 0\\ s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Atmospheric — **Reactor/Accelerator** — **Solar**

$\sin^2\theta_{23} = 0.51\ (0.50) \pm 0.04$

$\Delta m^2_{32} = 2.45\ (-2.52) \pm 0.05 \times 10^{-3}\ \mathrm{eV}^2$

for NH (IH)

$\sin^2\theta_{12} = 0.307^{+0.013}_{-0.012}$

$\Delta m^2_{21} = 7.53 \pm 0.18 \times 10^{-5}\ eV^2$

$\sin^2\theta_{13} = 0.021 \pm 0.0011$

$\delta_{CP} = ?$

More Questions to Answer

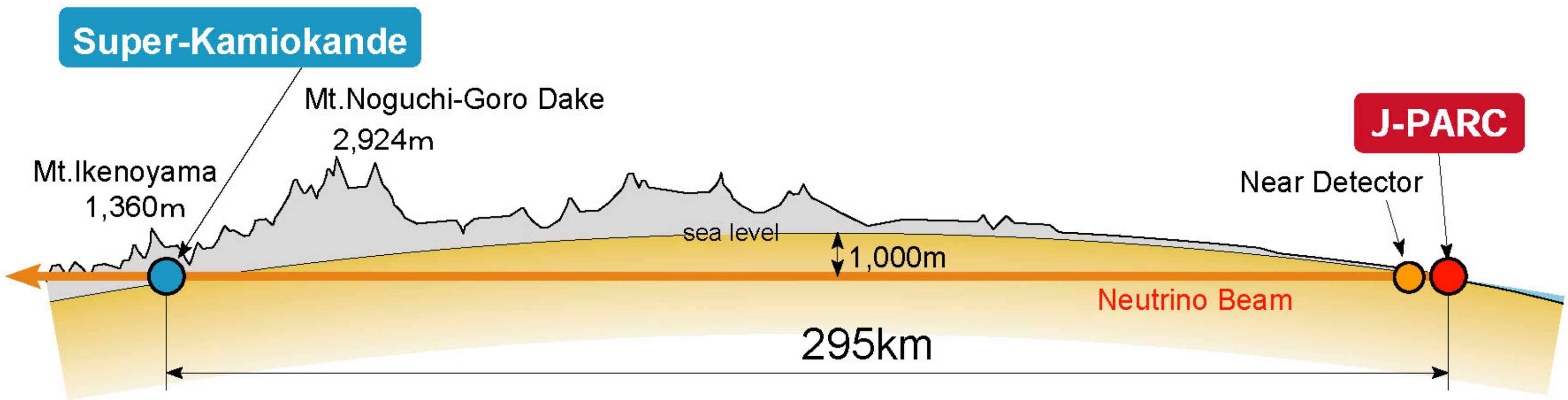
- CP violating phase (δ_{cp})
- Neutrino mass hierarchy (Δm^2)
- Oscillation parameter size (θ_{23})
  - $\theta_{23} > 45^o$, $\theta_{23} < 45^o$, or $\theta_{23} = 45^o$

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

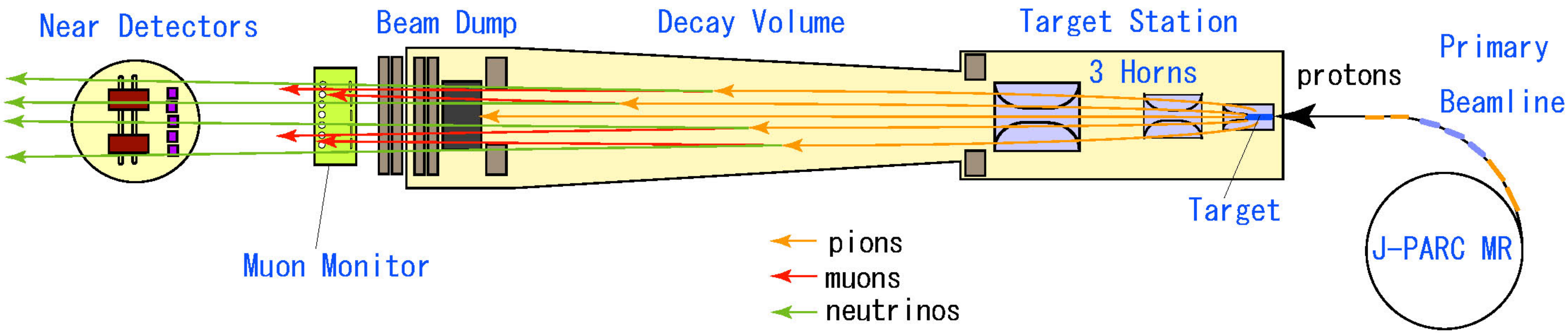
Neutrino Oscillation Experiments

T2K

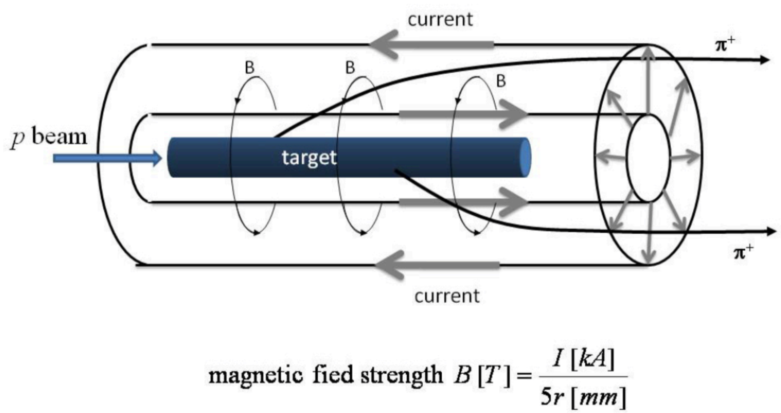
T2K Experiment

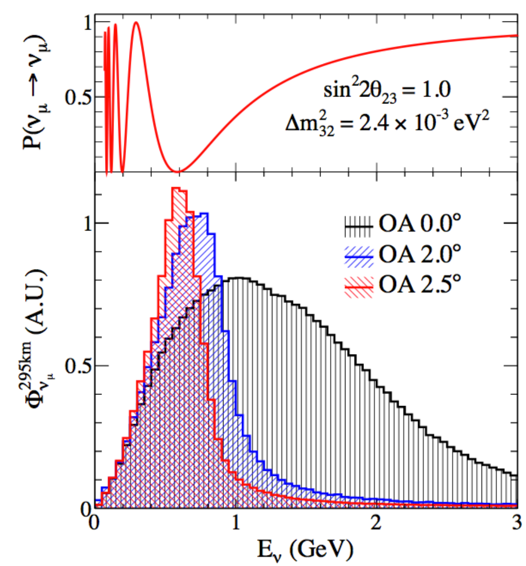


J-PARC and Neutrino Beamline



- 30 GeV proton beam generated by J-PARC Main Ring (MR) directed to the graphite target
- Secondary pions collected and focused by the toroidal magnetic field provided by horns
  - ν beam: $\pi^+ \rightarrow \mu^+ + \nu_\mu$ (Forward horn current (FHC))
  - $\overline{\nu}$ beam: $\pi^- \rightarrow \mu^- + \overline{\nu}_\mu$ (Reverse horn current (RHC))





- Uses off-axis method to make the spectrum peak at 600 MeV
  - Expected oscillation maximum at L = 295 km

Neutrino Oscillation Experiment

At designed energy spectrum peak (E=600 MeV) and L = 295 km…

$$P(\nu_\mu \to \nu_e) \approx 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2\Delta_{31}\left(1+\frac{2a}{\Delta m_{31}^2}\left(1-2s_{13}^2\right)\right)$$

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

$$-8c_{13}^2 c_{12}c_{23}s_{12}s_{13}s_{23}\sin\delta\sin\Delta_{32}\sin\Delta_{31}\sin\Delta_{21}$$

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

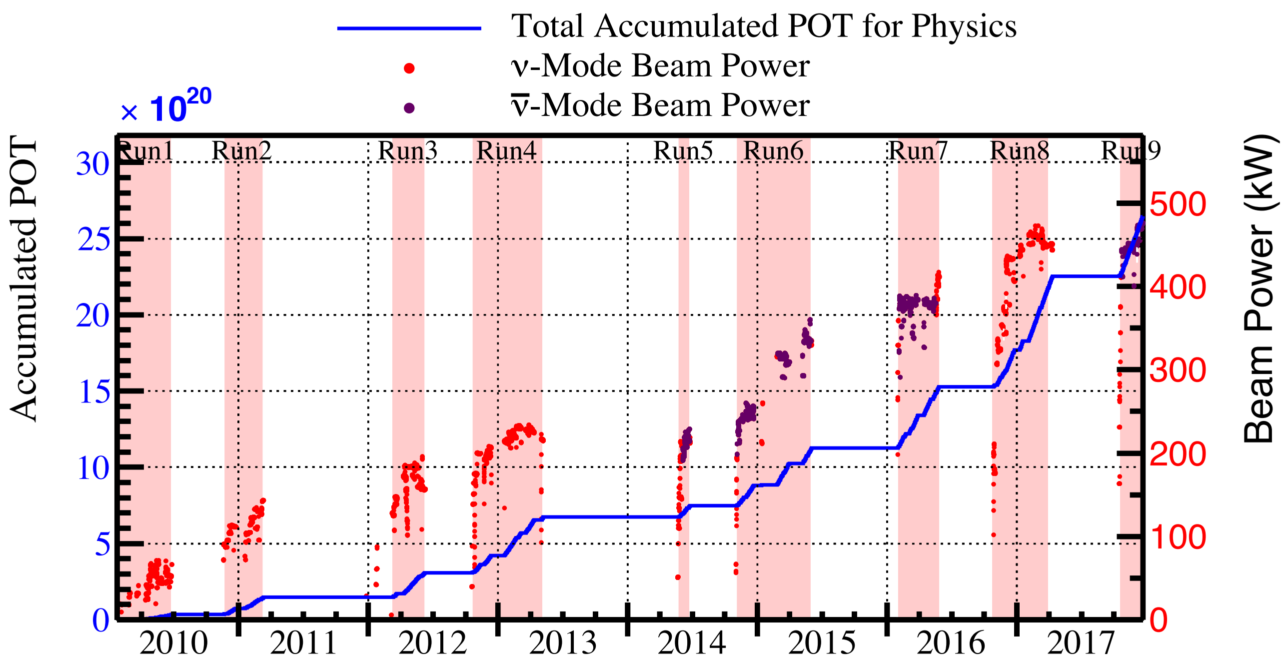
$$-8c_{13}^2 s_{13}^2 s_{23}^2(1-2s_{13}^2)\frac{aL}{4E}\cos\Delta_{32}\sin\Delta_{31}$$

$\Delta_{ji} = \Delta m_{ji}^2 \frac{L}{4E}$, $a = 2\sqrt{2}\mathrm{G_F n_e E}$ (Matter effect)

δ and a change signs for $\bar{\nu}$-mode $P(\bar{\nu}_\mu \to \bar{\nu}_e)$

δ_{CP}: $\pm$27% effect in the appearance probability at T2K
Matter effect: < $\pm$10% effect

Beam Power and Data Accumulation



23 Jan. 2010 - 22 Dec. 2017

POT total: 2.65×10^{21}

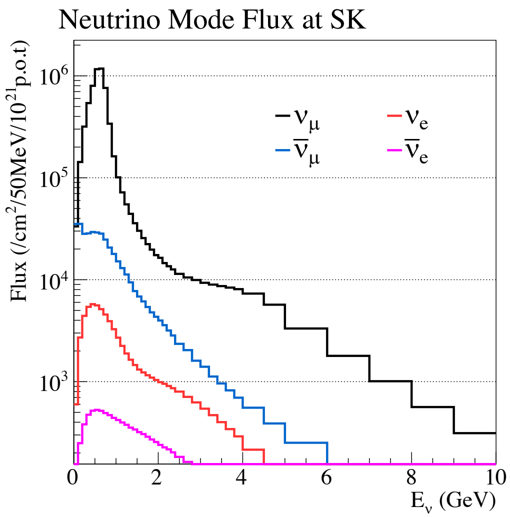
ν-mode 1.51×10^{21} (57.14%)

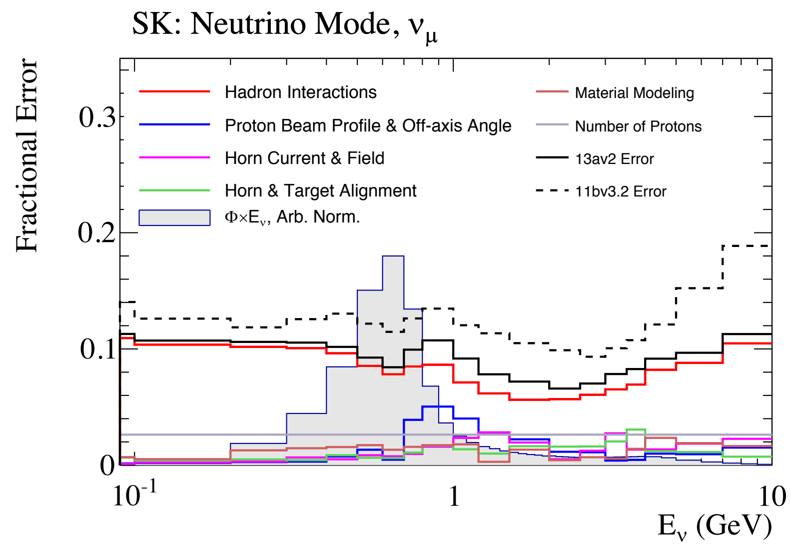
$\bar{\nu}$-mode 1.14×10^{21} (42.86%)

- **ν-mode data doubled during 2016-2017 run**
- **$\bar{\nu}$-mode data expected to be doubled during 2017-2018 summer run**
  - Approximately half already achieved by the latest run
- Today's results obtained by statistics up to April 2017 (22.54×10^{20} POT)

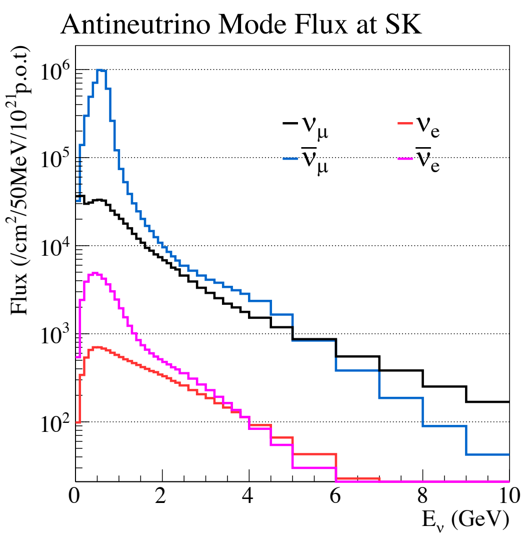
Flux Predictions

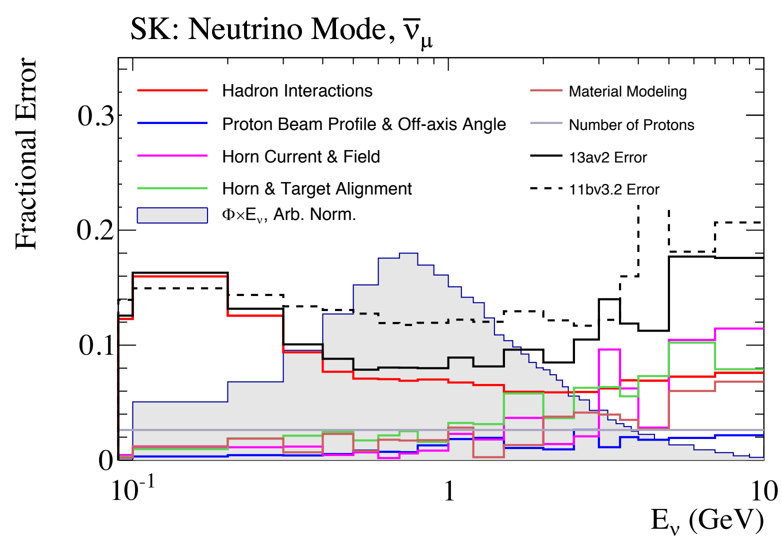
ν





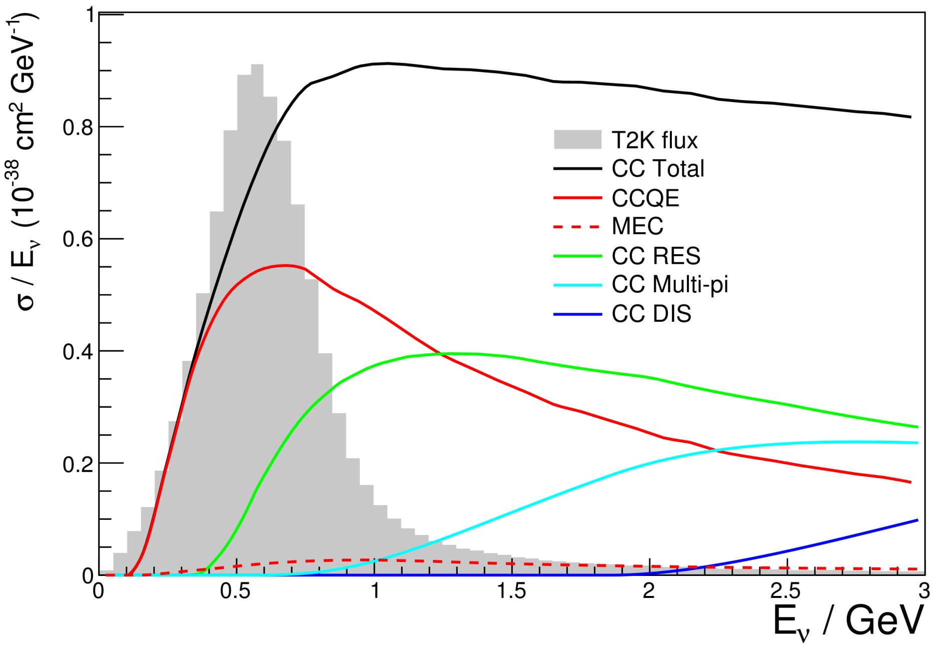
$\bar{\nu}$

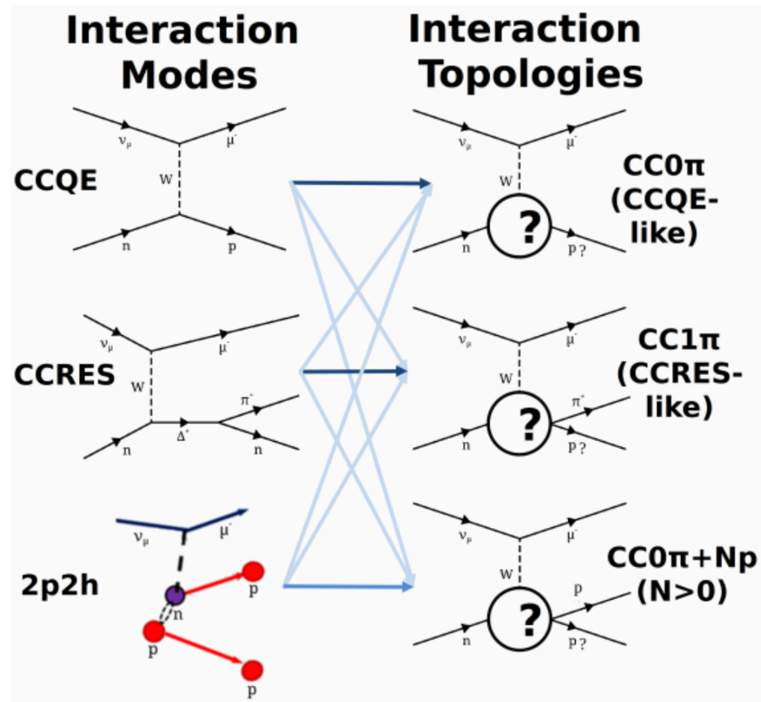




Flux simulation tuned with external data and the measurement at the beamline

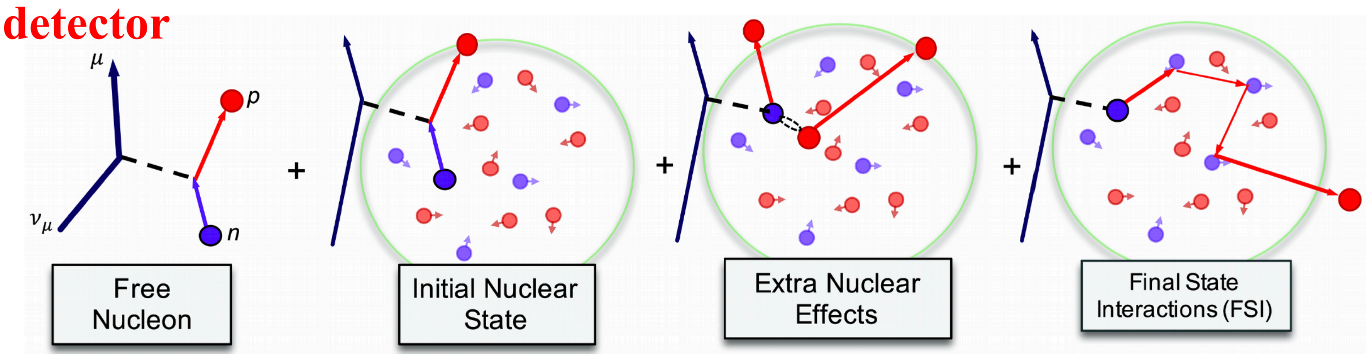
Neutrino Interaction Measurement





Theoretical models to simulate how neutrinos interact and leptons in phase space are detected inside the detector

Nuclear Model

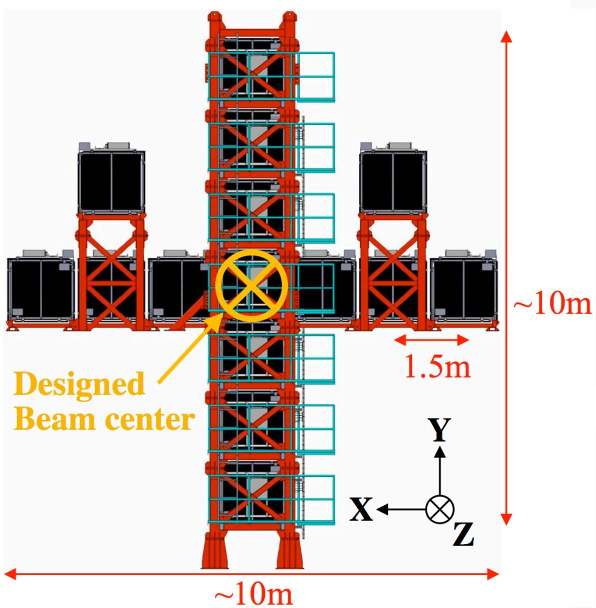


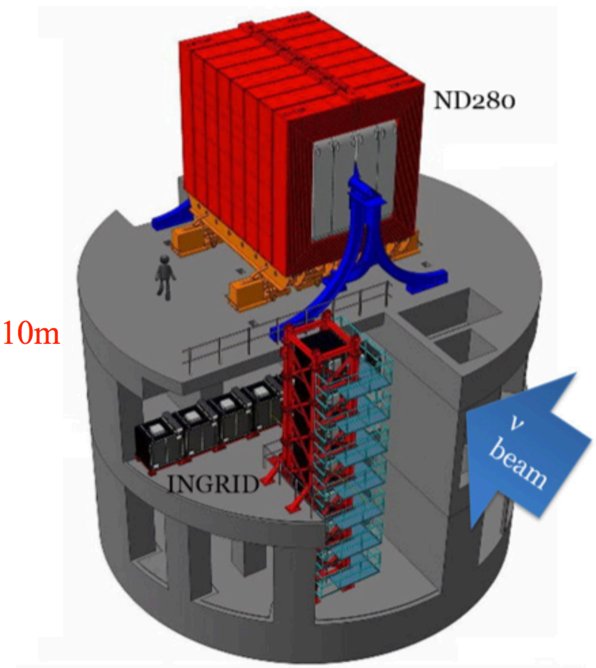
Diagrams by L. Maret and P. Stowell

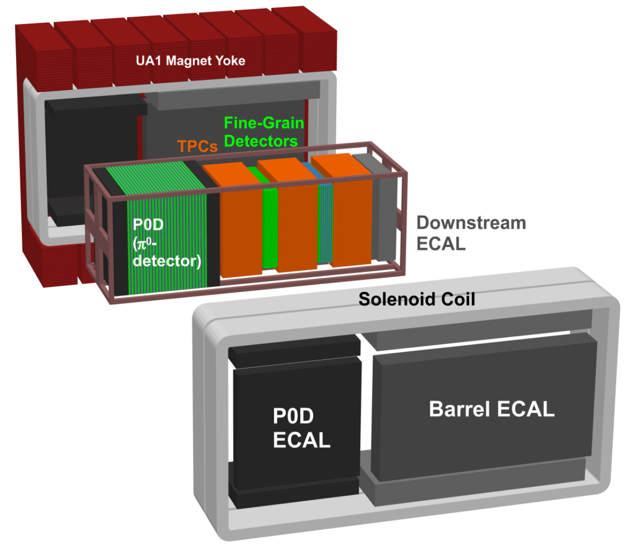
T2K Near Detectors

On-axis **INGRID** and off-axis **ND280:**

ν beam







INGRID

- Scintillators and iron targets
- measure neutrino beam direction and stability

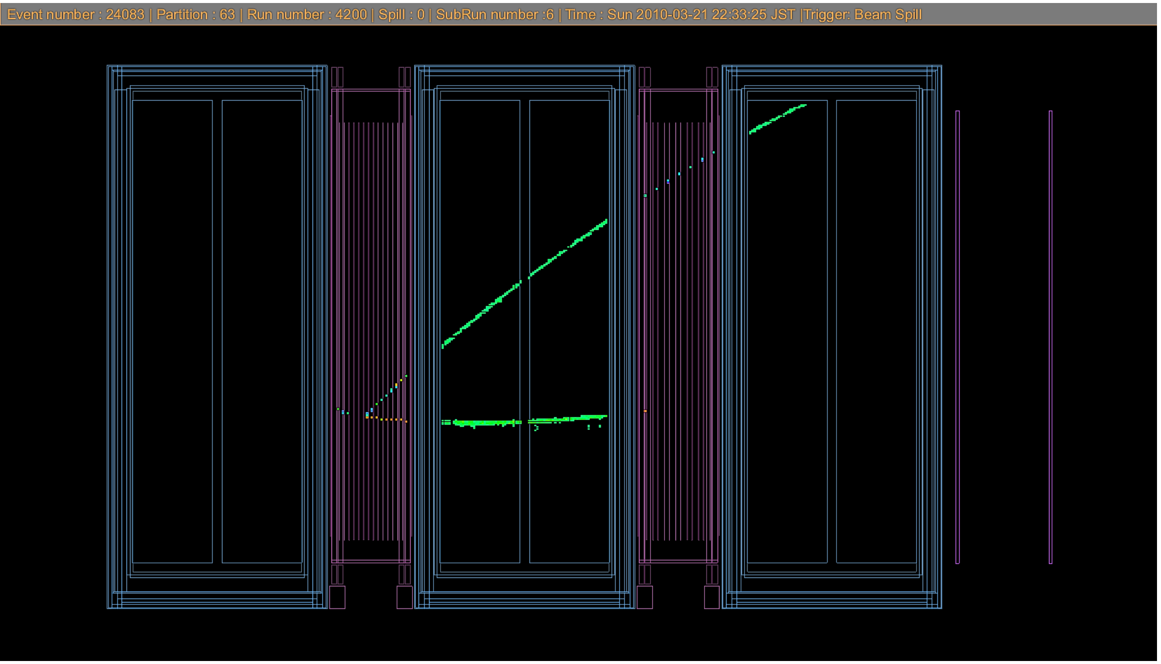
ND280

- Scintillators and water targets
- Consists of gas trackers, calorimeters, and muon detectors
- UA1 magnet (0.2T)
- Measures neutrino flux and interactions

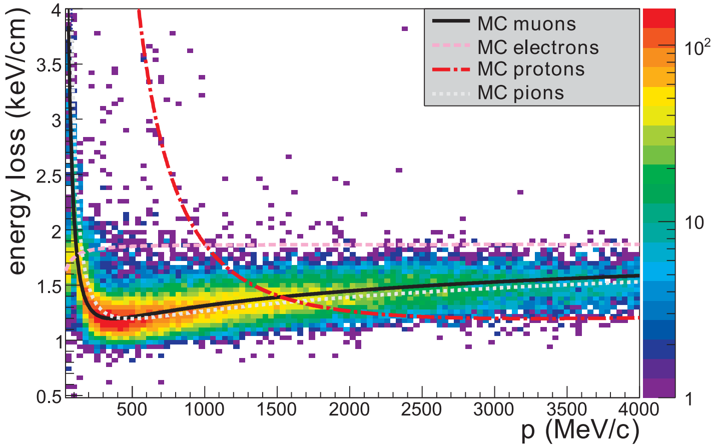
ND280 Measurements

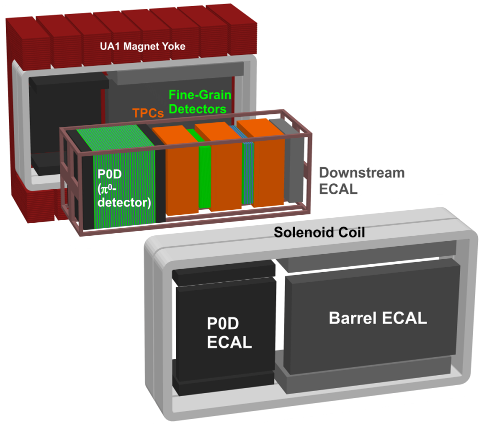
- Layers of scintillators and gas trackers allow to measure the charged particles produced by neutrino interactions with various targets
- Curvature of the trajectory caused by the magnetic field provides momentum information

TPC1 TPC2 TPC3



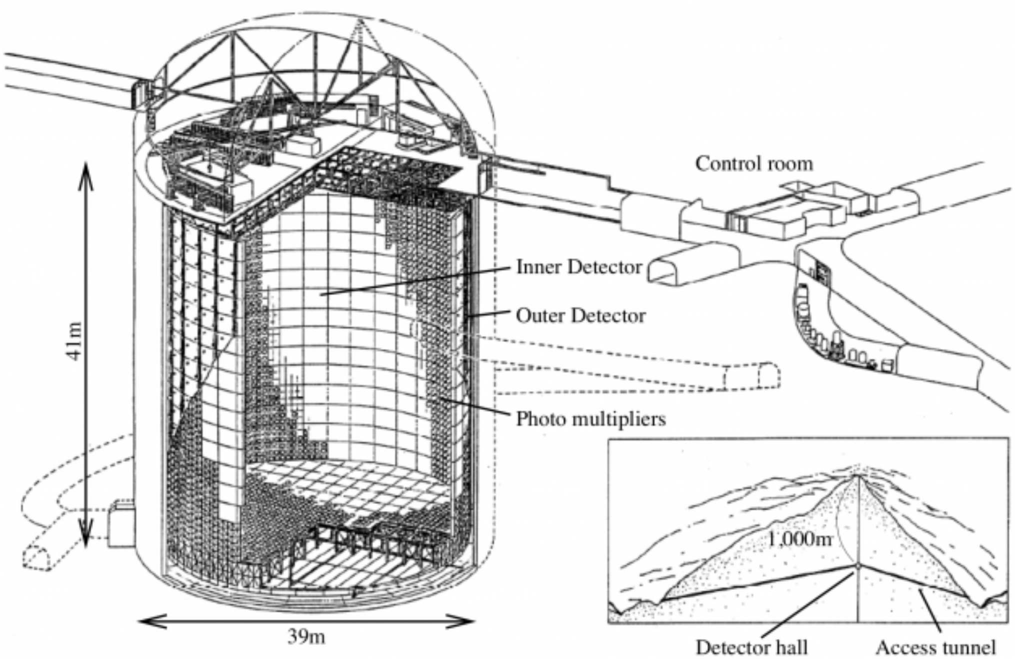
FGD1 FGD2

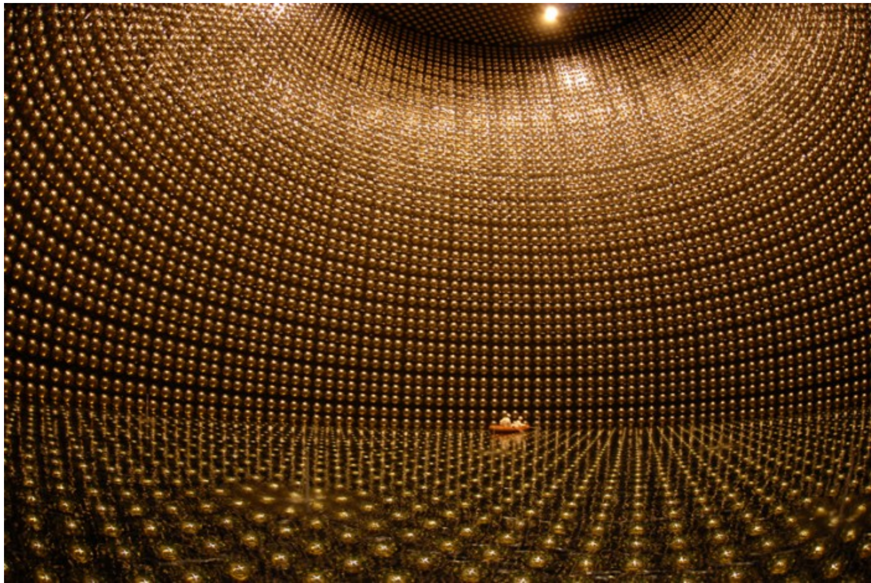




T2K Far Detector (Super-Kamiokande)

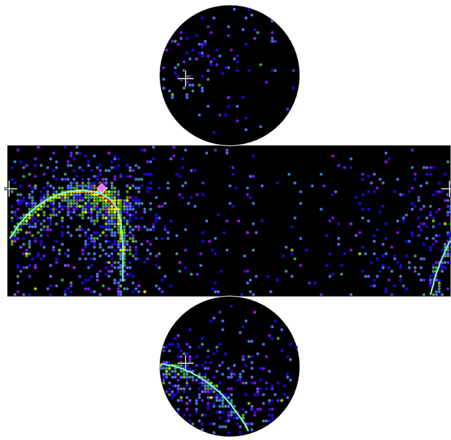
- Located 1,000m underground in Kamioka, Japan, 295km away from J-PARC
- 41.4 m tall, 39.3 m in diameter, filled with 50 k-ton purified water
- Consists of inner and outer detectors (ID and OD):
  - ID: 11,129 50-cm diameter photo-multiplier tubes (PMTs)
  - OD: 1,885 20-cm diameter PMTs facing outwards

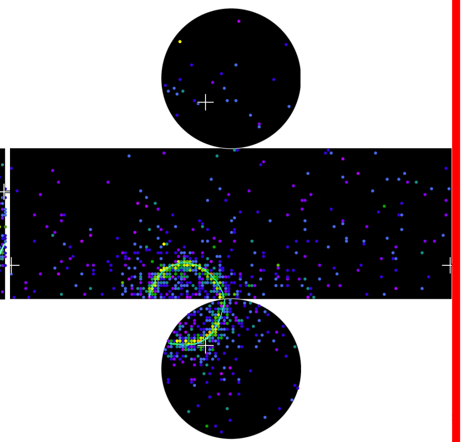




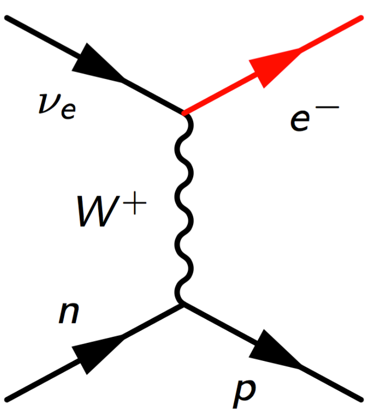
Neutrino Detection at SK Far Detector

Signal (ν_e)

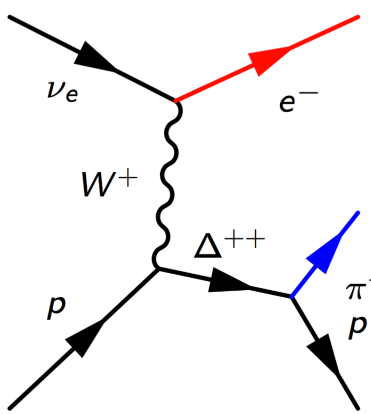




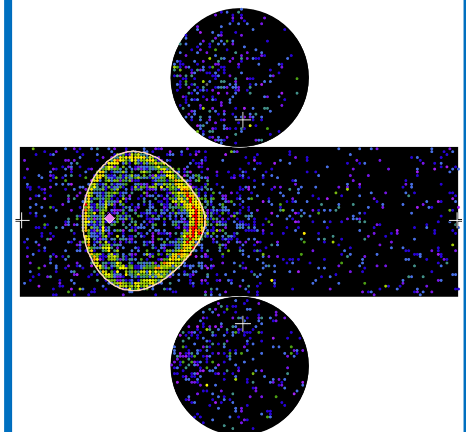
ν_e CCQE



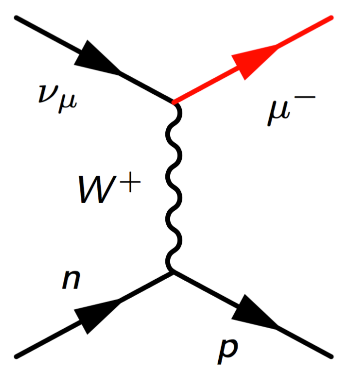
ν_e CC1π^+



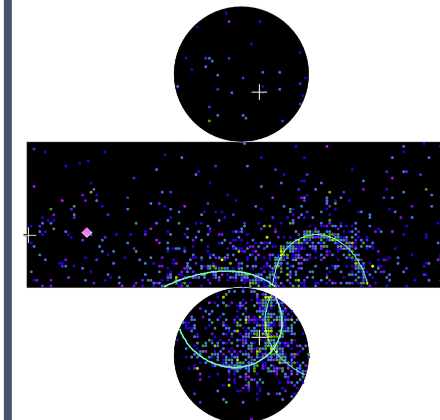
Signal (ν_μ)



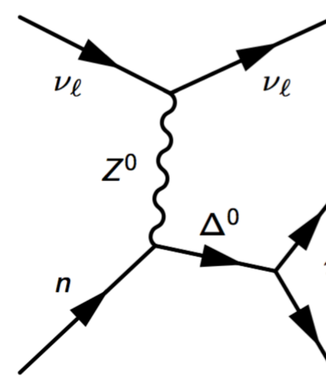
ν_μ CCQE



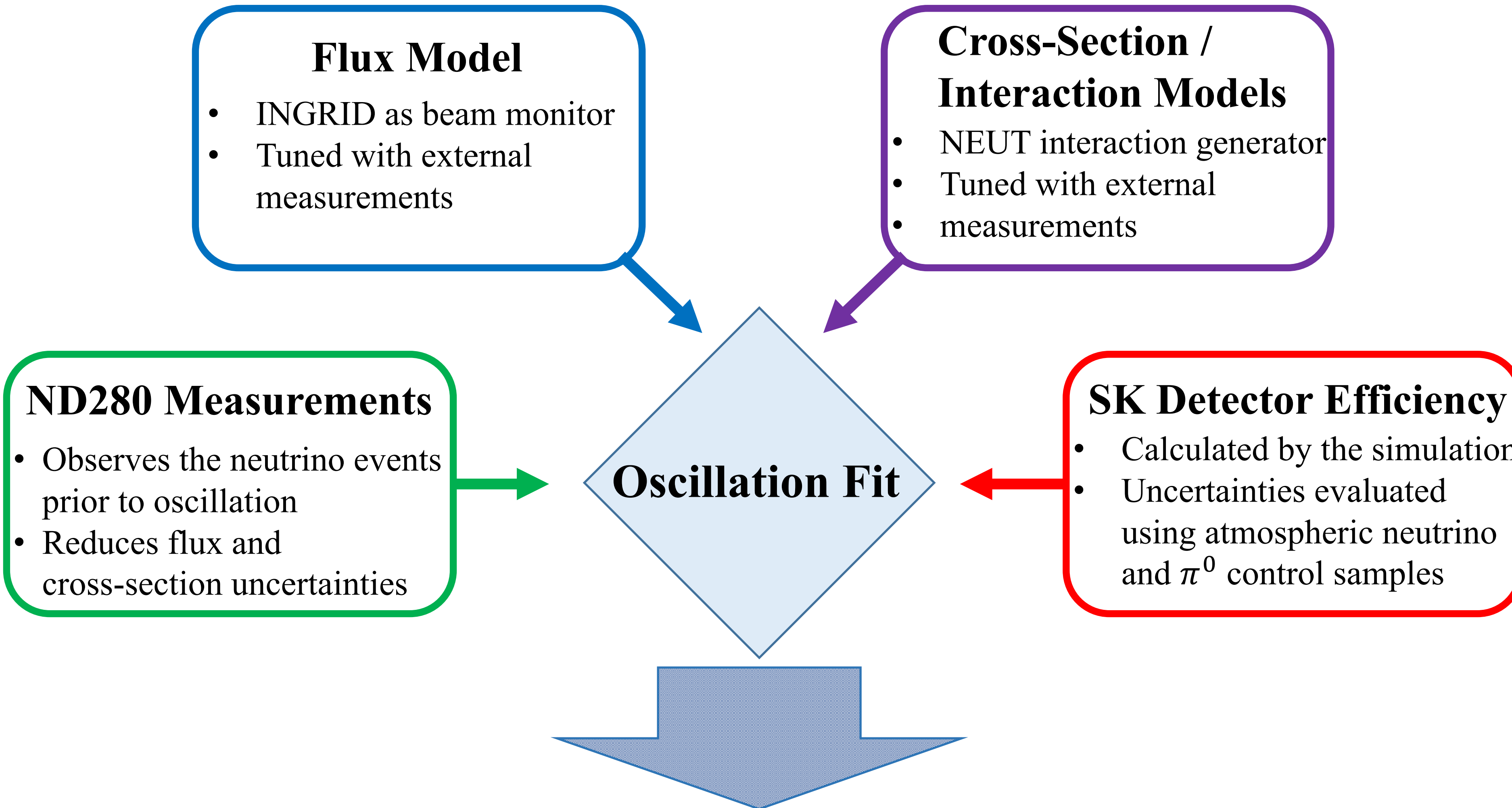
Background



ν_ℓ NC1π^0



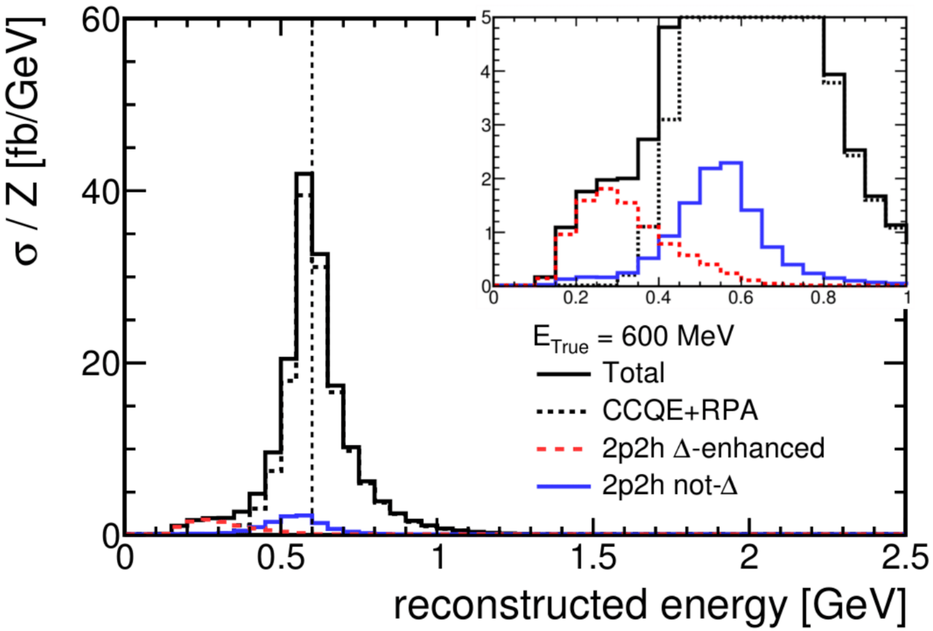
T2K Analysis Method

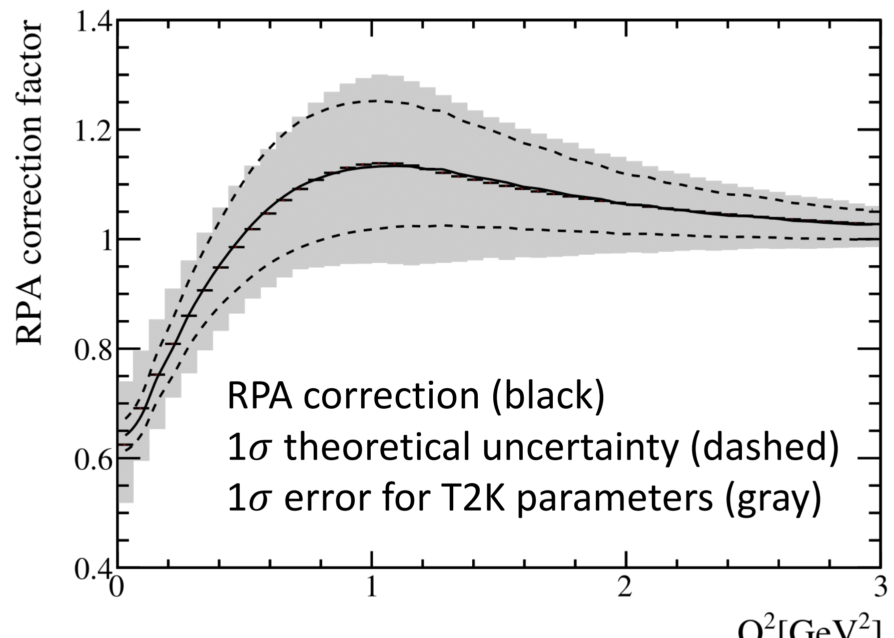


Oscillation Parameters ($\theta_{13}, \delta_{cp}, \Delta m^2_{32}, \theta_{23}$)
for Normal and Inverted Hierarchies (NH and IH)

Updates in T2K Neutrino Interaction Models

- Improvement in the quasi-elastic interaction prediction:
  - Long range correlations in nucleus corrected by random phase approximation (**RPA**)
  - Inclusion of the multi-nucleon (**2p2h**) model which can produce biased neutrino energy measurement



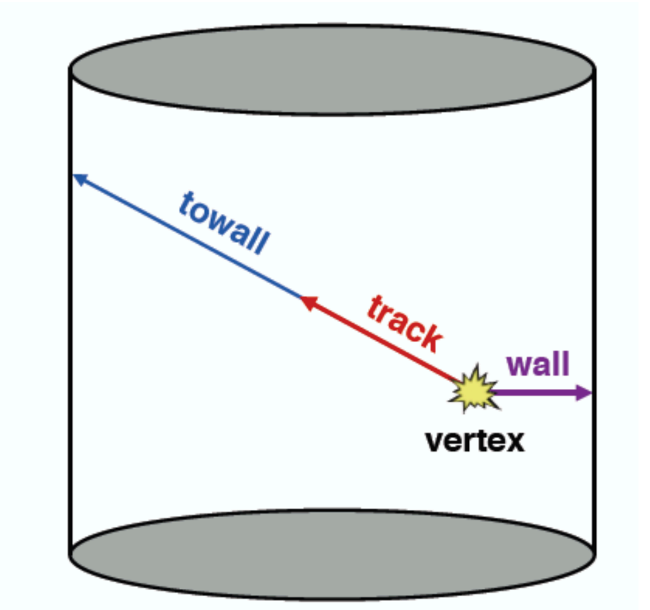


Updates in T2K SK Event Reconstruction

- SK event reconstruction changed from **APFit** to **fiTQun**, previously used only for π^0 rejection
- Combines timing and charge information of the ID PMTs with/without hit to calculate likelihood for different ring hypotheses
- **Re-optimizes fiducial volume cuts for different samples**

	fiTQun		**APFit**	
Sample	**Candidates**	**Purity**	**Candidates**	**Purity**
ν_μ CC0π	261.6	**80 %**	268.7	**68 %**
$\bar{\nu}_\mu$ CC0π	62.0	**80 %**	65.4	**71 %**
ν_e CC0π	**69.5**	81 %	**56.5**	81 %
ν_e CC1π^+	**6.9**	79 %	**5.6**	72 %
$\bar{\nu}_e$ CC0π	**7.6**	62 %	**6.1**	64 %

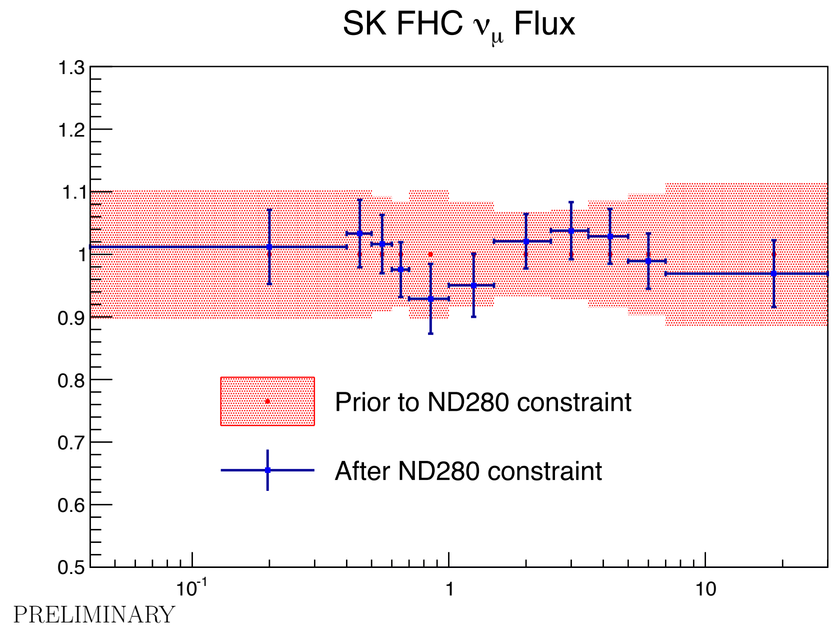
- **20/30 % more statistics for $\nu_e/\bar{\nu}_e$ sample**
- **Better purity for $\nu_\mu/\bar{\nu}_\mu$ sample**

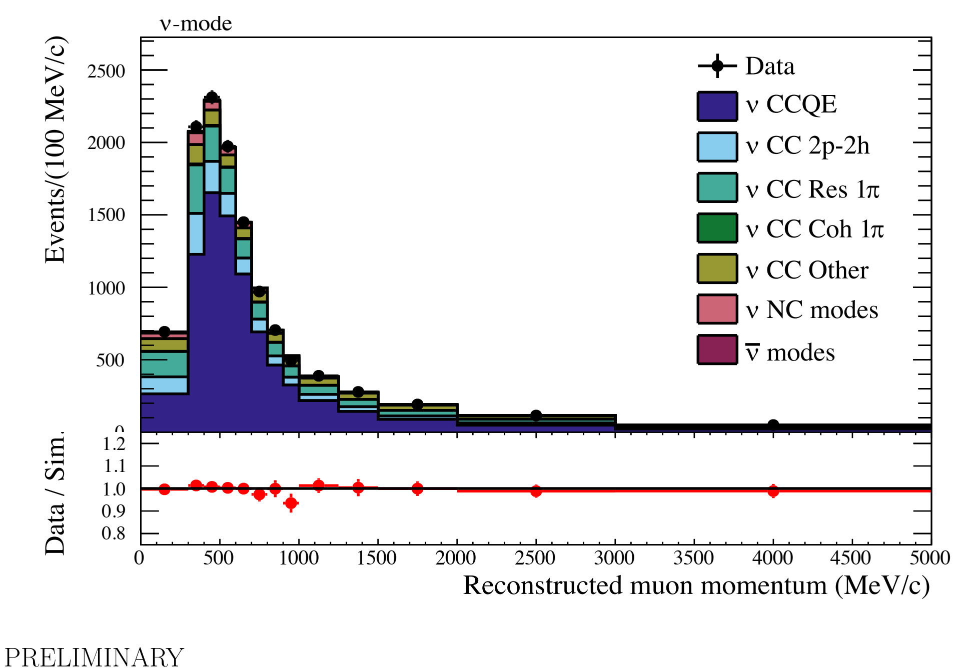


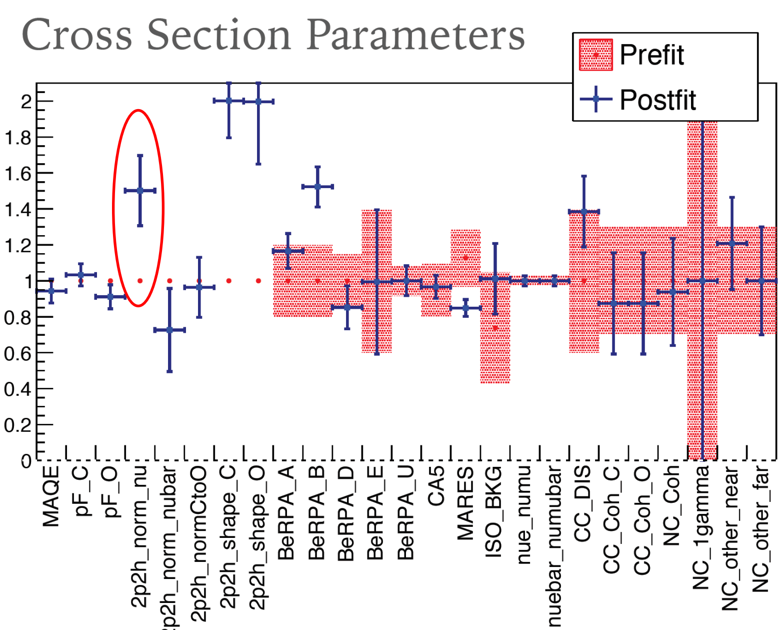
towall = distance to the wall along the trajectory

Near Detector Fit

- ND data fit to constrain flux and cross section models
  - Can also compensate the deficit of one model to another
    - eg.) 2p2h enhancement
- Post fit parameters used in the oscillation fit with SK data





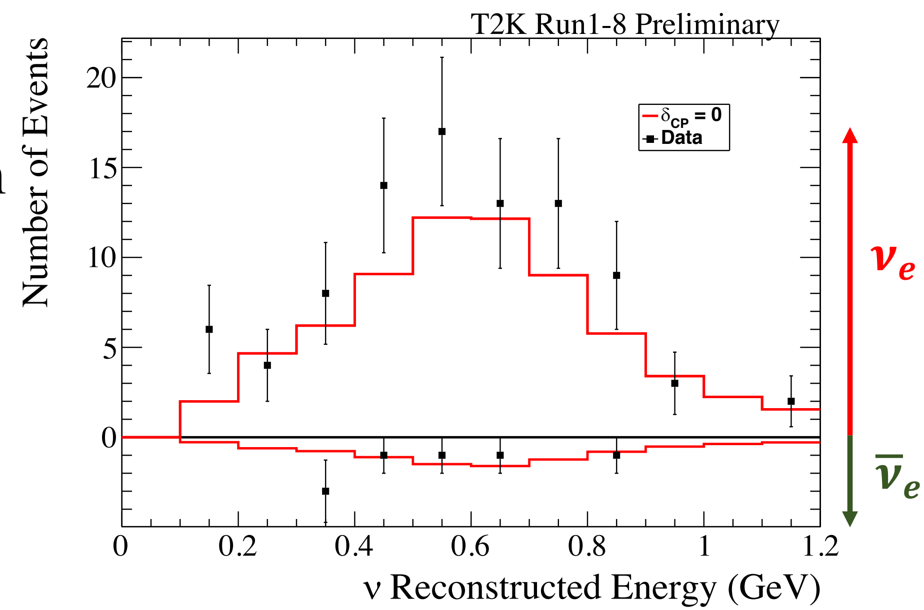


T2K Observed Events

	Predicted				Data
Sample	$\delta_{CP} = -\pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = +\pi/2$	$\delta_{CP} = +\pi$	
ν_μ CC0π	267.8	267.4	267.7	268.2	240
$\bar{\nu}_\mu$ CC0π	63.1	62.9	63.1	63.1	68
ν_e CC0π	73.5	61.5	49.9	62.0	74
ν_e CC1π^+	6.9	6.0	4.9	5.8	15
$\bar{\nu}_e$ CC0π	7.9	9.0	10.0	8.9	7

$\nu_e/\bar{\nu}_e$ appearance data comparison with $\delta_{CP} = 0$ predicted event rate:

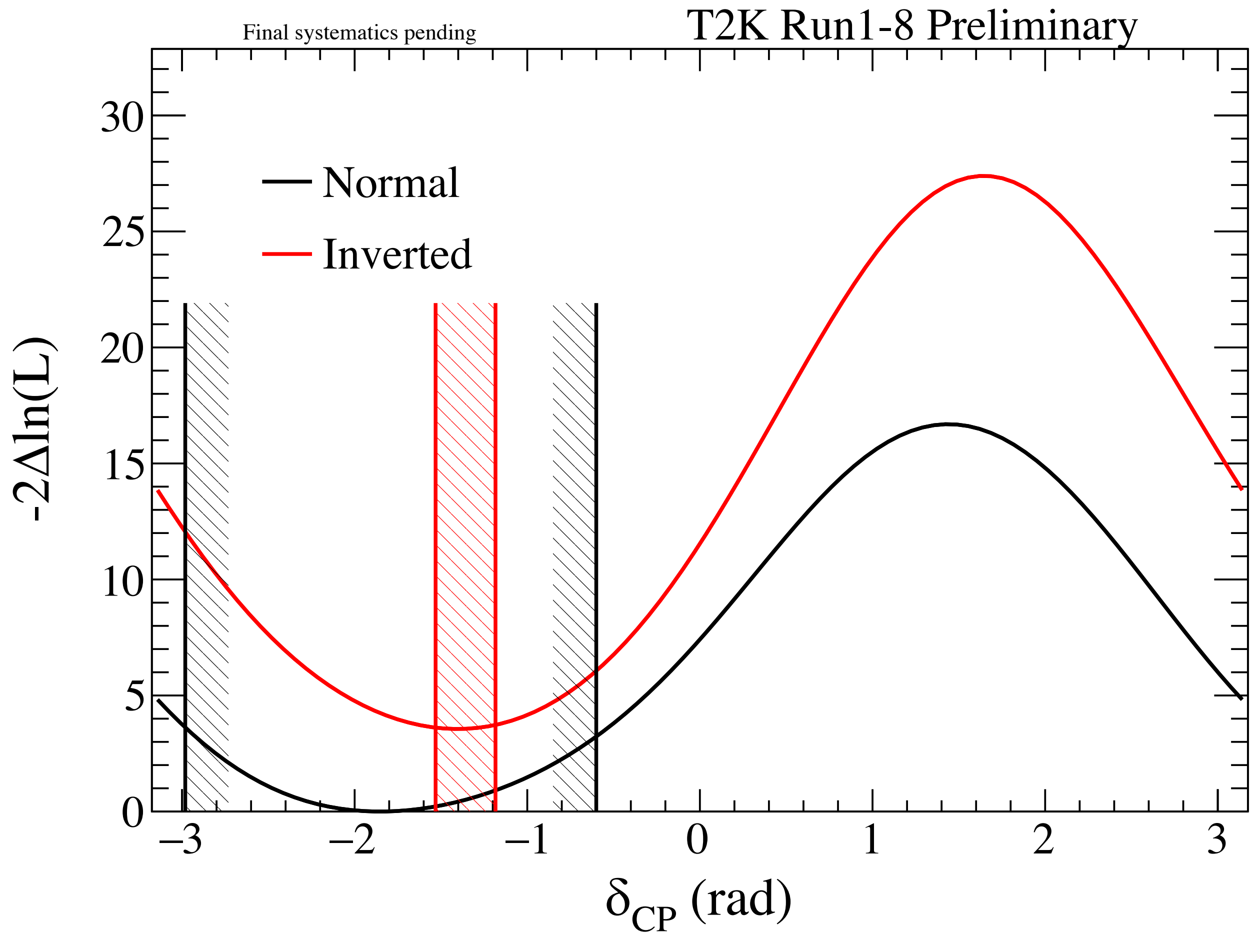
- **Enhanced ν_e appearance**
- **Suppressed $\bar{\nu}_e$ appearance**



Preference for maximal δ_{CP} mixing

δ_{cp}

T2K result with reactor constraint (2σ confidence interval (CL)):

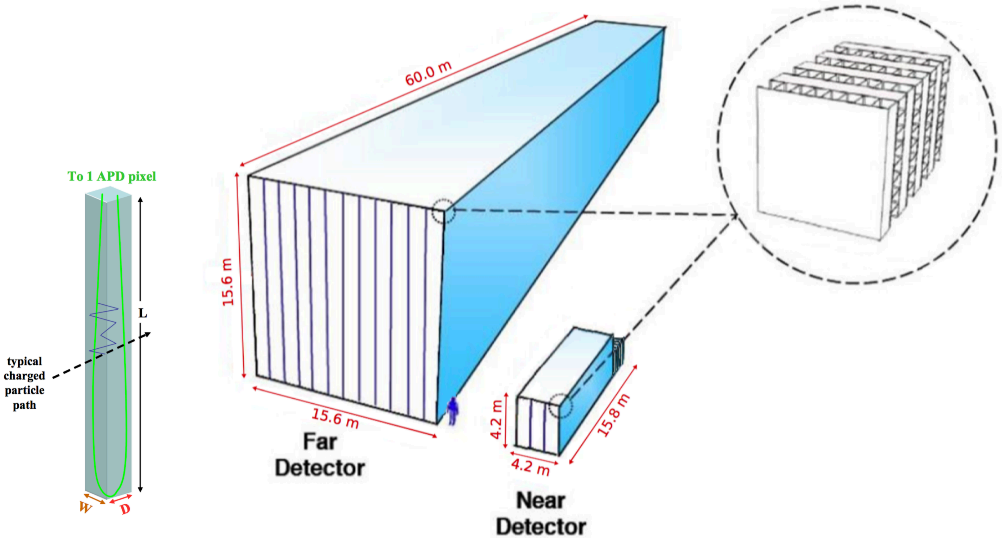


$\boldsymbol{\delta_{cp} = [-2.981, -0.600](NH), [-1.531, -1.184]\ (IH)}$ **at 2σ CL**

Current T2K measurement yields 2σ CL to reject the CP conservation

NOνA

NOνA Experiment



1560 cm x 4 cm x 6 cm

Liu, Ji FERMILAB-THESIS-2017-01

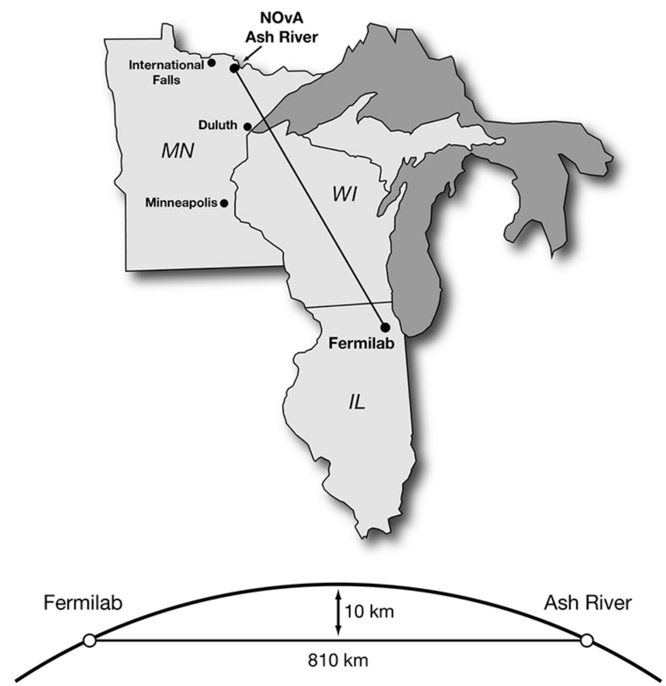
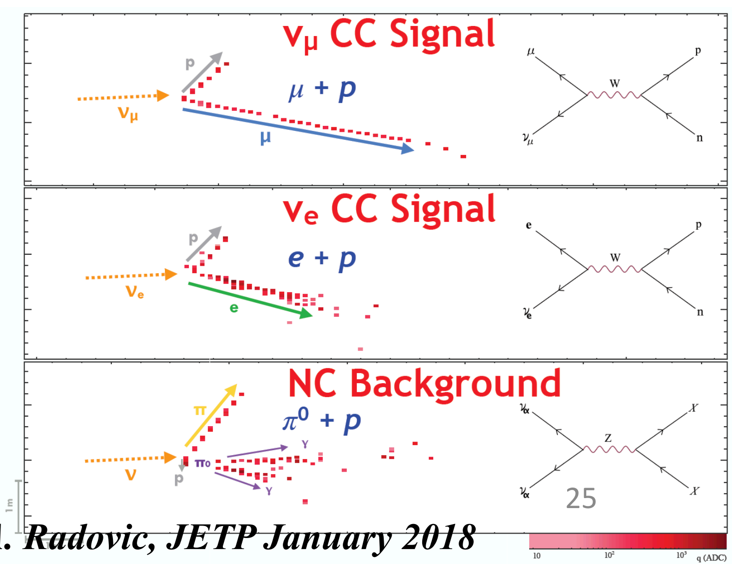


Diagram from Technology.org

- 810 km long baseline neutrino oscillation experiment at Fermilab
  - **More sensitive to mass hierarchy via the matter effect**
- ND and FD functionally identical liquid scintillator
  - ND: 330 ton (~20,000 channels)
    - 1 km away from the NuMI ν_μ beamline
  - FD: 14 kton (~344,000 channels)

1 radiation length = 38cm (6 cell depths, 10 cell widths)



A. Radovic, JETP January 2018

NOνA Recent Results

- Presented the latest result with 8.85×10^{20} POT-equivalent neutrino sample in January 2018 Wine & Cheese Seminar at Fermilab
- **Antineutrino data fit expected this summer**

Atmospheric Mixing and World Constraints

54 A. Radovic, JETP January 2018

- Consistent with world expectation.
- Competitive measurement of Δm^2_{32}.

Best fit:

$\Delta m^2_{32} = 2.444^{+0.079}_{-0.077} \times 10^{-3}\ \mathrm{eV}^2$

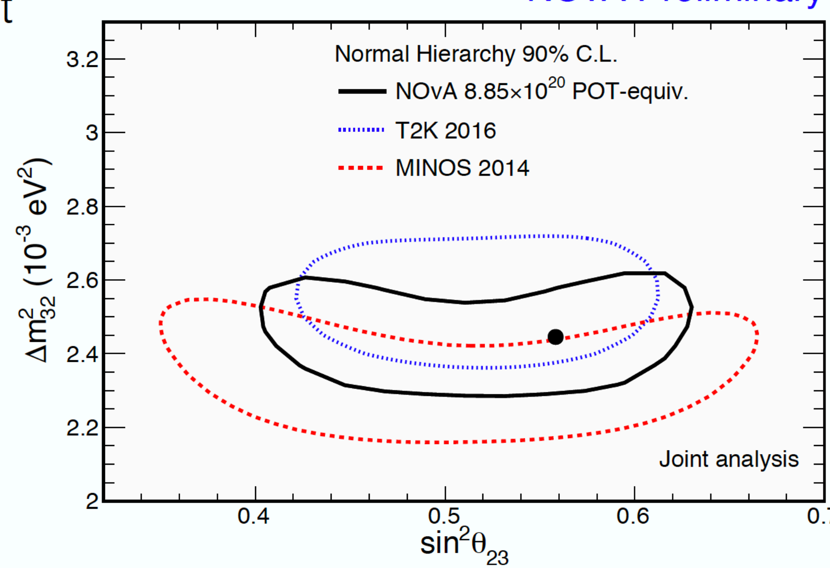
UO preferred at 0.2σ

$\sin^2\theta_{23} =$

UO: $0.558^{+0.041}_{-0.033}$

LO: $0.475^{+0.036}_{-0.044}$

NOvA Preliminary

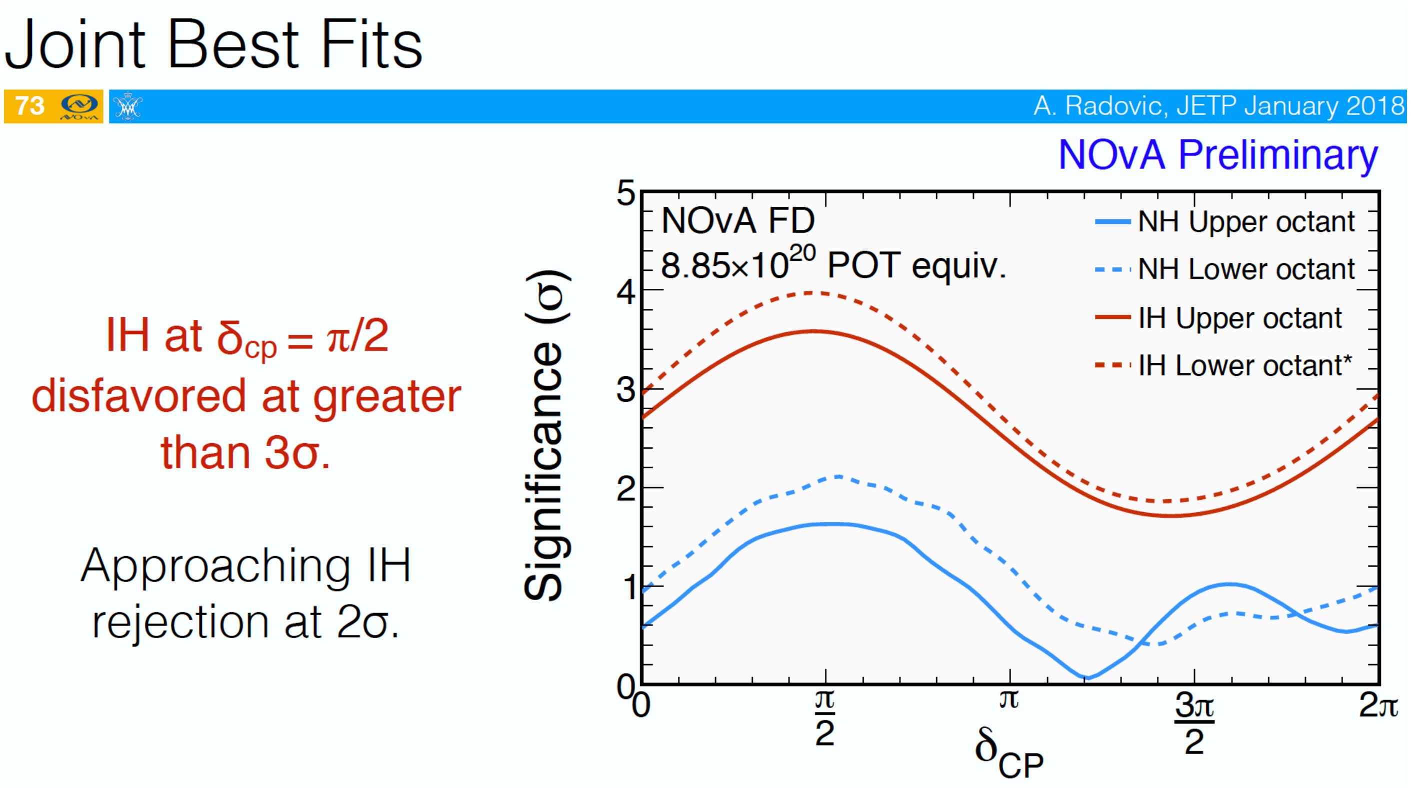


A. Radovic, JETP January 2018

- **$\nu_e + \nu_\mu$ joint fit results in atmospheric parameters consistent with T2K**

NOνA Recent Results

- Presented the latest result with 8.85×10^{20} POT-equivalent neutrino sample in January 2018 Wine & Cheese Seminar at Fermilab
- **Antineutrino data fit expected this summer**



A. Radovic, JETP January 2018

Future Prospects

~2021: T2K-NOνA Joint Analysis

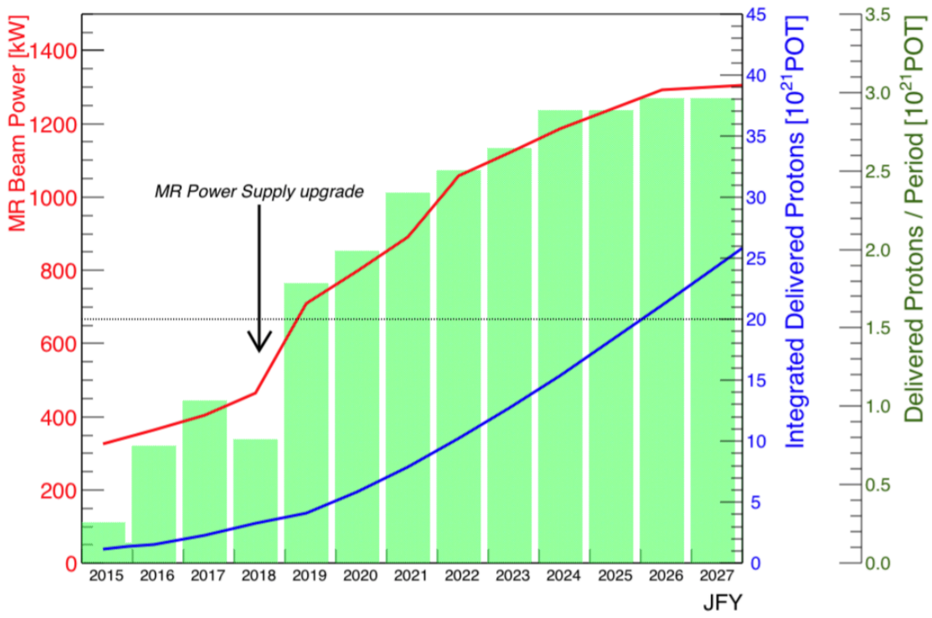
T2K and NOνA making an announcement to work towards the joint working group:

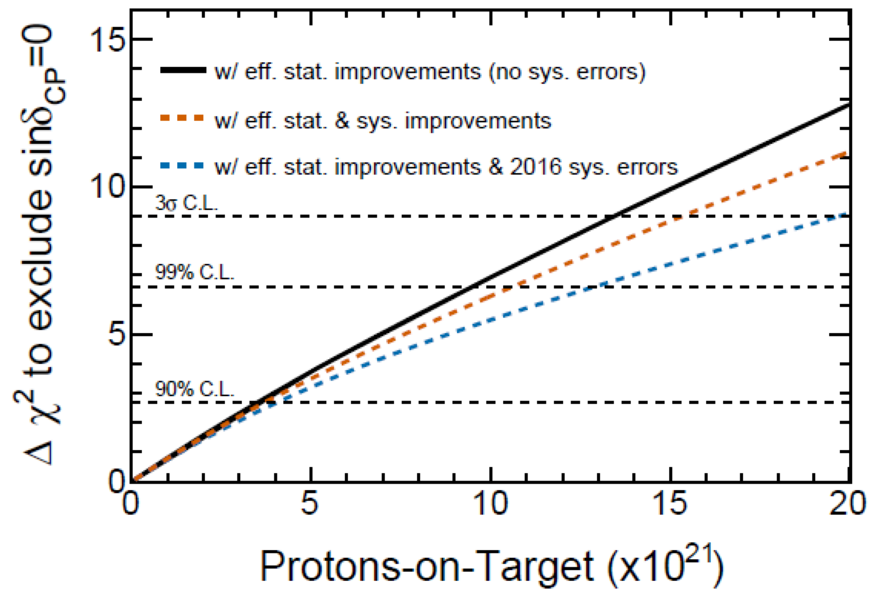
"The NOvA and T2K Collaborations are working towards the formation of a joint working group to enhance the measurements of neutrino oscillation parameters made by each Collaboration individually.
The projected timescale of the NOvA-T2K working group is for production of a full joint neutrino oscillation analysis by 2021."

-T2K Public Website (Jan. 30, 2018)

Photo from NOvA-T2K Workshop at Tokai (Oct 15, 2017)

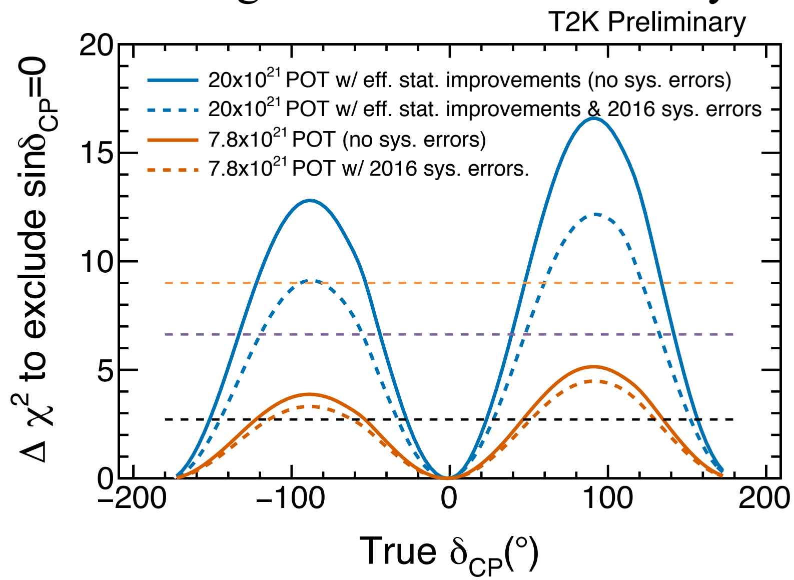
2021~2026: T2K to T2K-II





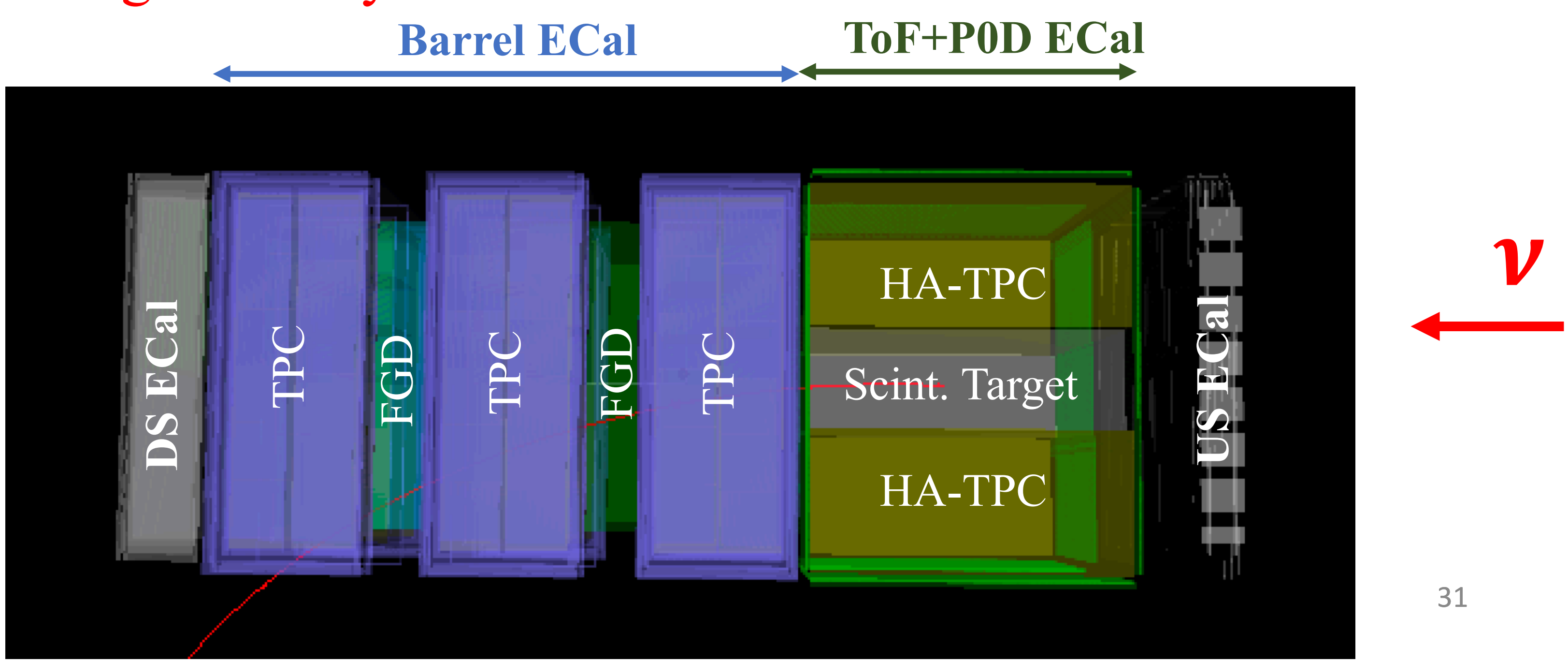
- Approved T2K statistics 7.8×10^{21} POT, expected to achieve ~2020
- **T2K-II extends T2K run to 20×10^{21} POT on the time scale of 2026**
- **$> 3\sigma$ sensitivity to reject CP conservation with improved systematic error evaluation**

Assuming Known Mass Hierarchy



ND280 Upgrade

- Cross section uncertainty becomes increasingly important as more POT is accumulated with T2K-II
  - **Goal to reduce from ~6% to ~4%**
- **ND280 Upgrade** rearranges the current configuration to include two high-angle TPCs and fine-grained scintillator target in the upstream
  - Wide angle acceptance
  - Finer granularity

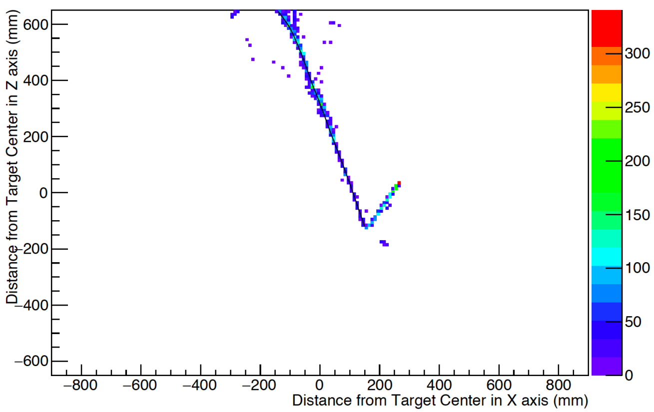


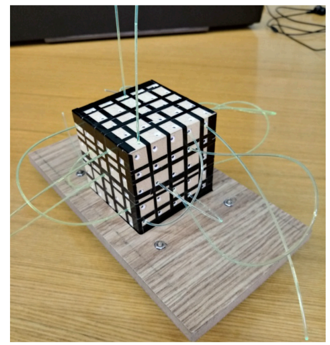
CERN-SPSC-2018-001 ; SPSC-P-357

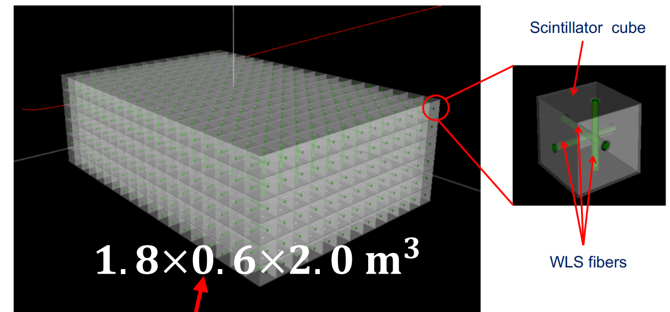
ND280 Upgrade

In progress!!

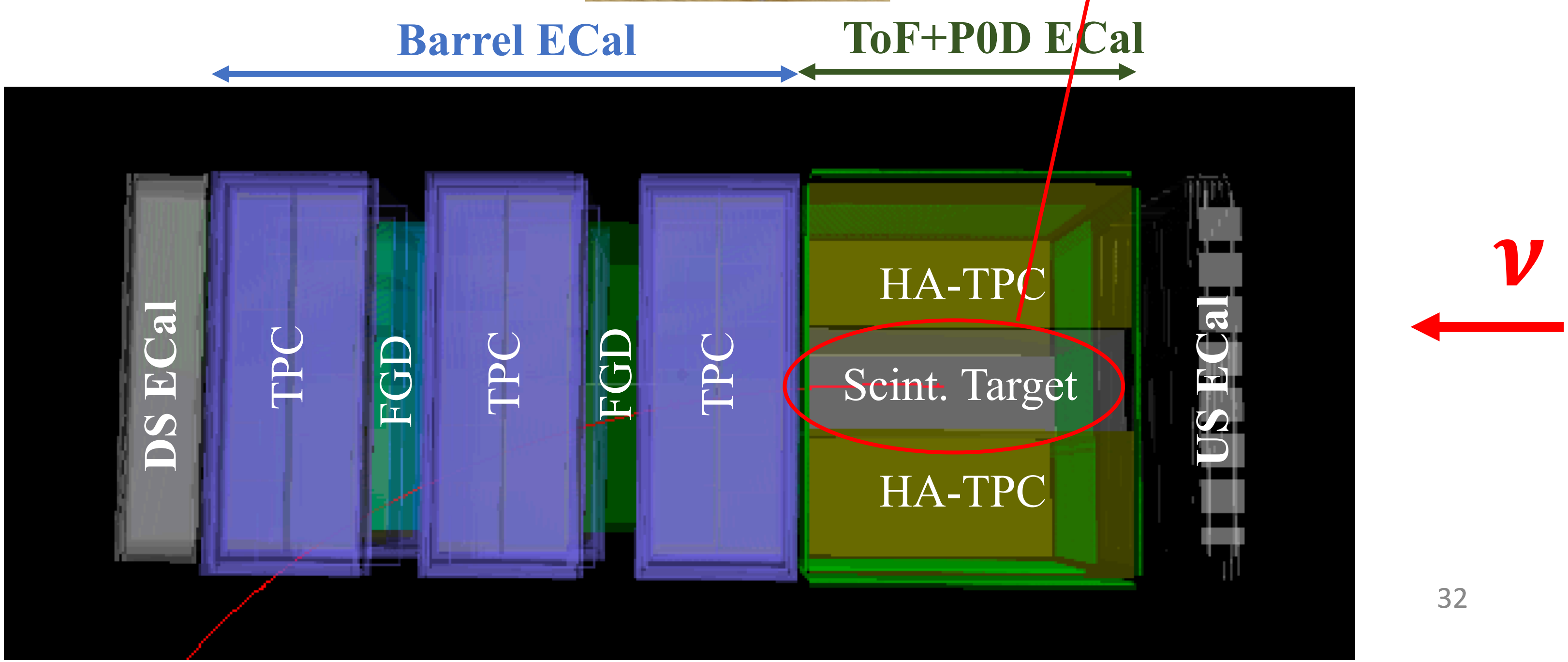
SuperFGD







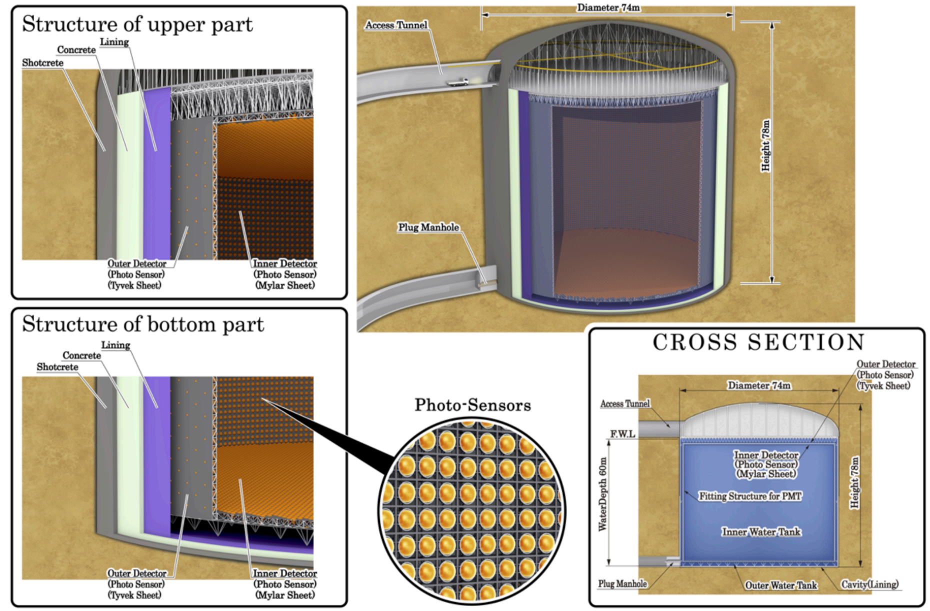
$10 \times 10 \times 10$ mm^3 scint. cube



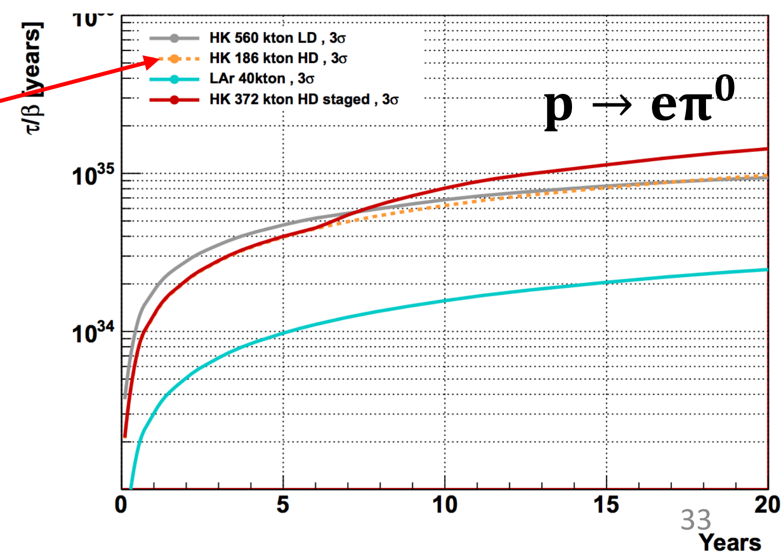
KEK-PREPRINT-2016-21, ICRR-REPORT-701-2016-1

2026~: Hyper Kamiokande

- **10 times larger FV than SK; will be world largest underground water tank**
  - 186 kton fiducial mass
  - 60 m tall, 74 m diameter
  - 40,000 50 cm ID PMTs
    - **Twice better photon detection efficiency (40%) than the SK PMTs**
  - 6,700 20 cm OD PMTs



- **The world largest precision measuring instrument for:**
  - **Neutrino oscillations**
  - **Nucleon decays**
    - **3σ discovery potential**
  - **Supernova burst, relic neutrinos**



Summary

Summary

- **Recent Results from T2K**
  - 26.50×10^{20} POT delivered as of December 22, 2017
  - Doubled ν-mode data in one year
    - Currently half way there to double $\overline{\nu}$-mode data as well
  - Updated SK reconstruction and cross section models
  - Data continue to prefer $\delta_{cp} \sim -\frac{\pi}{2}$:
    - $\boldsymbol{\delta_{cp} = [-2.981, -0.600](NH),}$
      $\boldsymbol{[-1.531, -1.184]\ (IH)}$ **at 2σ CL**

- **Future Prospects**
  - NOνA-T2K joint analysis (~2021)
  - T2K-II (2021~2026)
  - Hyper Kamiokande (2026~)

Neutrino oscillation physics continues to be exciting!!

Thank you very much!!!

Back-Up

Neutrino Oscillation Probability

- In the ultra-relativistic limit, t ≈ L
- Time evolution of the neutrino flavor state expressed in terms of neutrino energy E and travel distance L:

$$|\nu_\alpha(t)\rangle = \sum_i U_{\alpha i}\, e^{-\frac{i m_i^2 L}{2E}} |\nu_i\rangle$$

$$= \sum_{i,\beta} U_{\alpha i}\, e^{-\frac{i m_i^2 L}{2E}}\, U_{\beta i}^{*} |\nu_\beta\rangle$$

- Oscillation probability of the neutrino in vacuum expressed in terms of the measurable parameters (Δm_{ji}^2 , θ_{ij} , δ_{cp}):

$$P\left(\nu_\alpha \to \nu_\beta / \bar{\nu}_\alpha \to \bar{\nu}_\beta\right) = \left|\langle \nu_\beta | \nu_\alpha(t)\rangle\right|^2$$

$$= \sum_{i,j} U_{\alpha i}^{*} U_{\beta i} U_{\alpha j} U_{\beta j}^{*} e^{-i\,\frac{\Delta m_{ji}^2 L}{2E}};$$

$$\Delta m_{ji}^2 = m_j^2 - m_i^2$$

Neutrino Oscillations and CP Violation

The oscillation probabilities in vacuum for ν and $\overline{\nu}$:

$$P(\nu_\alpha \to \nu_\beta / \overline{\nu}_\alpha \to \overline{\nu}_\beta) = \sum_{i,j} U_{\alpha i} U^*_{\beta i} U^*_{\alpha j} U_{\beta j} e^{-i \frac{\Delta m^2_{ji} L}{2E}}$$

$$= \delta_{\alpha\beta} - 4 \sum_{i>j} Re\left(U_{\alpha i} U^*_{\beta i} U^*_{\alpha j} U_{\beta j}\right) \sin^2\left(\frac{\Delta m^2_{ji} L}{4E}\right)$$

$$\pm 2 \sum_{i>j} Im\left(U_{\alpha i} U^*_{\beta i} U^*_{\alpha j} U_{\beta j}\right) \sin^2\left(\frac{\Delta m^2_{ji} L}{2E}\right)$$

- CP phase δ_{CP} changes sign for $\overline{\nu}$-mode $P(\overline{\nu}_\alpha \to \overline{\nu}_\beta)$
- **Non-zero $\boldsymbol{\delta_{CP}}$ allows different oscillation probability for neutrino and anti-neutrino**
- **Neutrino oscillation occurs only if the neutrinos have non-zero and different masses**

Neutrino Oscillations at T2K

Considering only the leading term (and $\sin\delta_{CP}$ term) and with the approximation $|\Delta m^2_{32}| \approx |\Delta m^2_{31}| \gg |\Delta m^2_{21}|$…

ν_e Appearance

$$P(\nu_\mu \to \nu_e) \approx \sin^2 2\theta_{13} \sin^2\theta_{23} \sin^2\Delta_{31}\left(1 + \frac{2a}{\Delta m^2_{31}}(1 - 2\sin^2\theta_{13})\right)$$
$$- \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \cos\theta_{13} \boxed{\sin\delta_{CP}} \sin^2\Delta_{32} \sin^2\Delta_{21}$$

ν_μ Disappearance

$$P(\nu_\mu \to \nu_\mu) \approx 1 - (\cos^4\theta_{13} \sin^2 2\theta_{23} + \sin^2 2\theta_{13} \sin^2\theta_{23}) \sin^2\Delta_{32}$$

$\boldsymbol{\delta_{cp}}$: $\pm$27% effect in the appearance probability at T2K

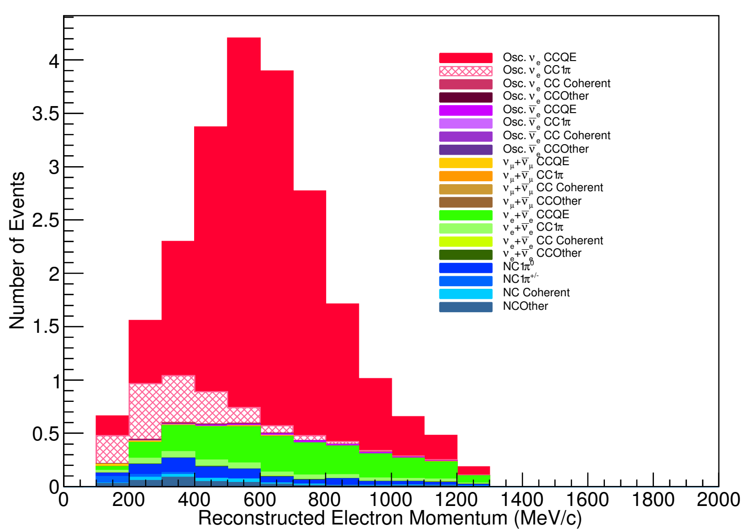
Matter effect: $< \pm$10% effect

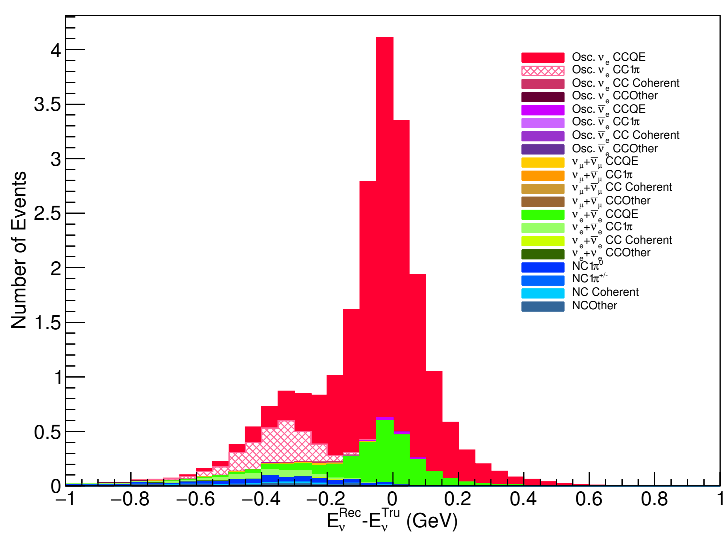
ν_e Energy Reconstruction at SK

Neutrino energy at SK reconstructed by considering two body process with proton recoil:

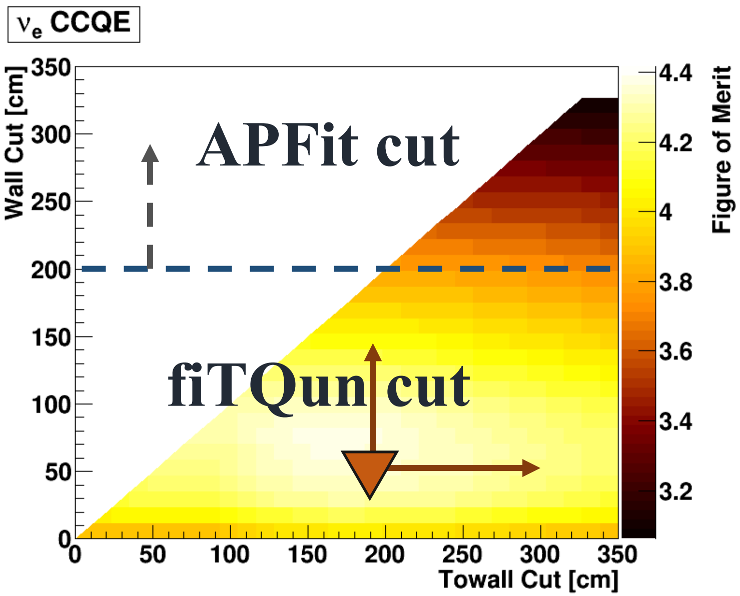
$$E_{rec} = \frac{2(M_n - V_{nuc})E_e + M_p^2 - (M_n - V_{nuc})^2 - M_e^2}{2((M_n - V_{nuc}) - E_e + p_e \cos\theta_e)}$$

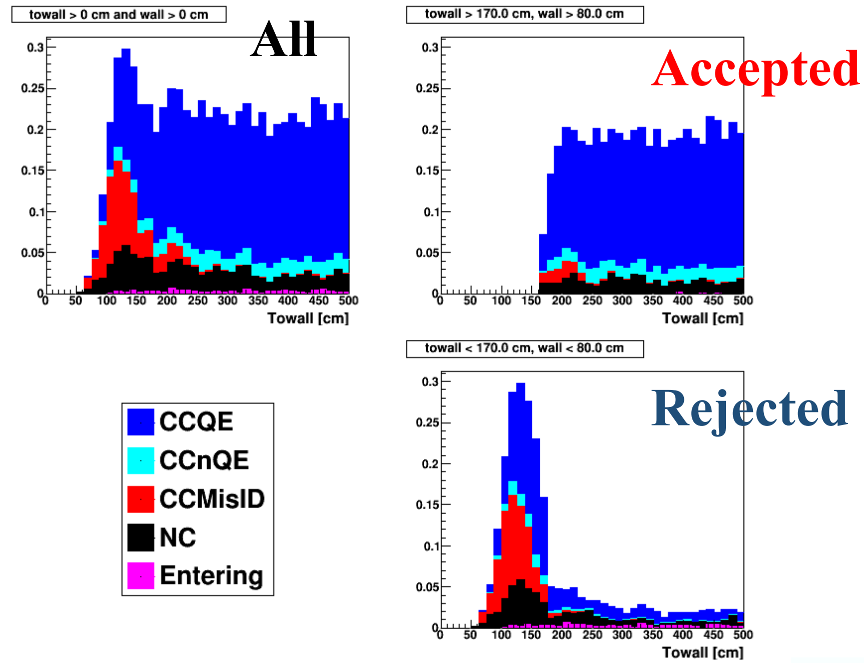
M_x = x mass
V_{nuc} = Nuclear binding potential (27.0 MeV/c^2)
E_e/p_e = Reconstructed electron energy/momentum
θ_e = Angle between neutrino and electron



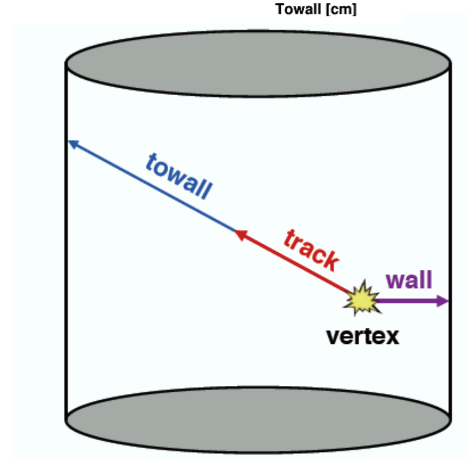


fiTQun Fiducial Volume Re-Optimization





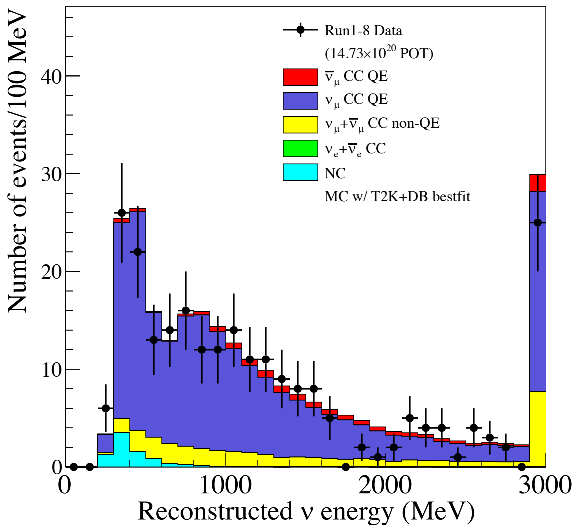
Sample	towall	wall
ν_μ CC0π	250 cm	50 cm
$\bar{\nu}_\mu$ CC0π	250 cm	50 cm
ν_e CC0π	170 cm	80 cm
ν_e CC1π^+	270 cm	50 cm
$\bar{\nu}_e$ CC0π	170 cm	80 cm



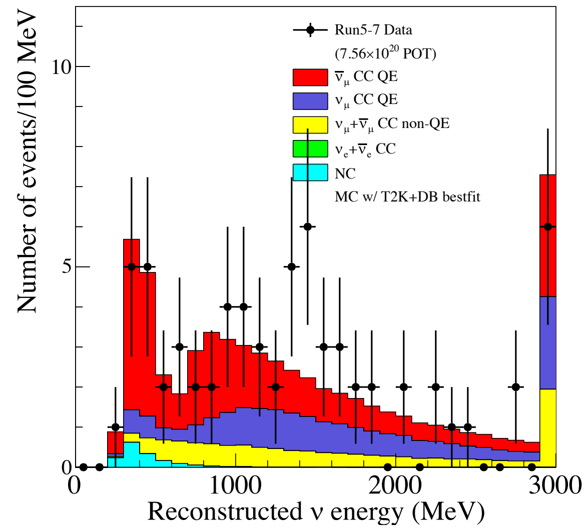
towall = distance to the wall along the trajectory

T2K Observed Events

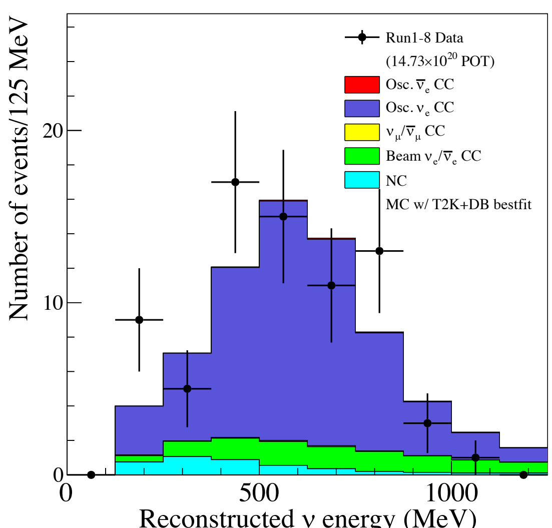
1-ring, μ-like, ν_μ CC0π



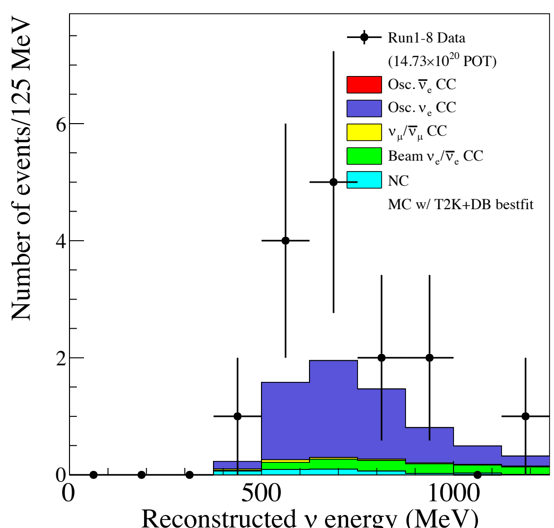
1-ring, μ-like, $\bar{\nu}_\mu$ CC0π



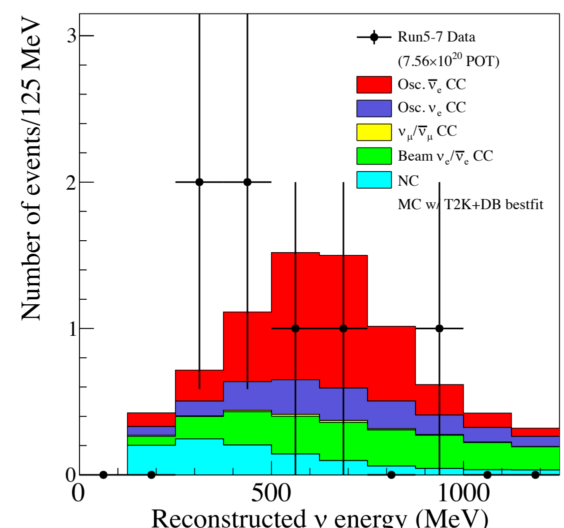
1-ring, e-like, ν_e CC0π



1-ring, e-like, ν_e CC1π^+



1-ring, e-like, $\bar{\nu}_e$ CC0π



NOνA Analysis Update

- **Continuous usage of deep learning inspired ν_e and ν_μ PID**
  - Previously only used for ν_e analysis
- **Modified Energy resolution bins**
  - Different energy resolution variations based on hadronic energy fraction
- **Retuned cross section models**
  - RPA and 2p2h tuning
- **Improved detector simulation**
  - Addition of Cherenkov light in detector simulation to model the response to hadronic activity
- **Data driven flux estimates**
  - NuMI beam flux prediction developed by MINERνA

NOνA Analysis Update

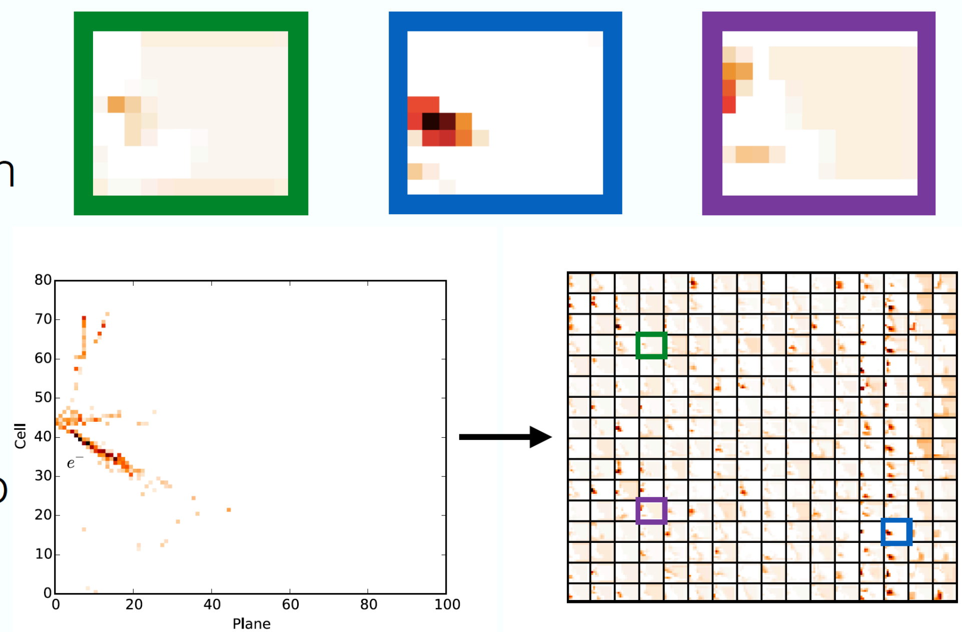
- **Continuous usage of deep learning inspired ν_e and ν_μ PID**
  - Previously only used for ν_e analysis

Deep Learning Inspired PID: ν_e & ν_μ Selection

21 A. Radovic, JETP January 2018

Previously only used for our ν_e analysis, now our ν_μ analysis also features the same event selection technique based on ideas from computer vision and deep learning.

Additionally now used to reclaim a new class of previously rejected ν_e events.



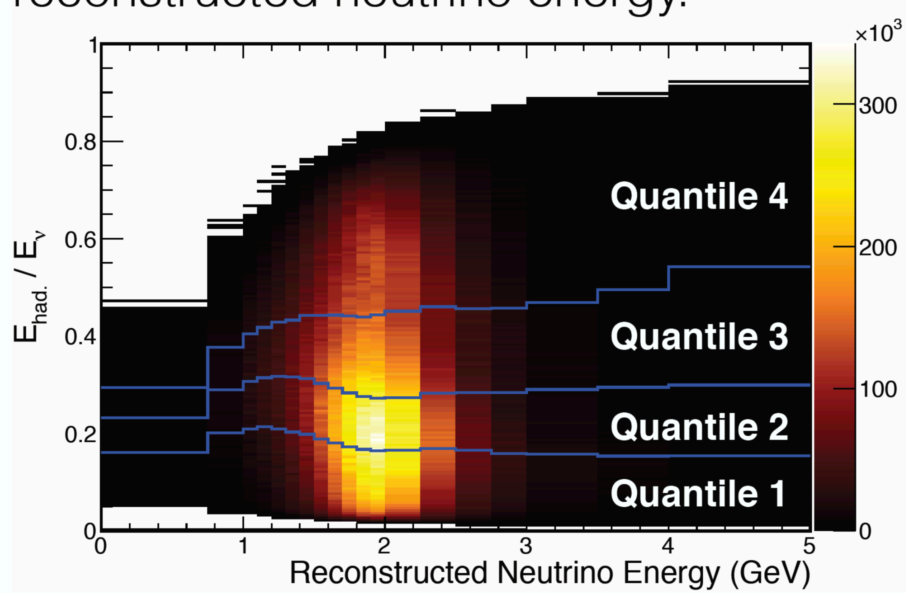
"A Convolutional Neural Network Neutrino Event Classifier"
A. Aurisano, A. Radovic, and D. Rocco et al
Journal of Instrumentation, Volume 11, September 2016

NOνA Analysis Update

- **Modified Energy resolution bins**
  - Different energy resolution variations based on hadronic energy fraction

Resolution Bins

- Four bins of equal populations in FD, split in hadronic energy fraction as a function of reconstructed neutrino energy.
- Resolution varies from ~6% to ~12% from the best to worst resolution bins.



NOνA Analysis Update

- **Improved detector simulation**
  - Addition of Cherenkov light in detector simulation to model the response to hadronic activity

Improved Detector Simulation

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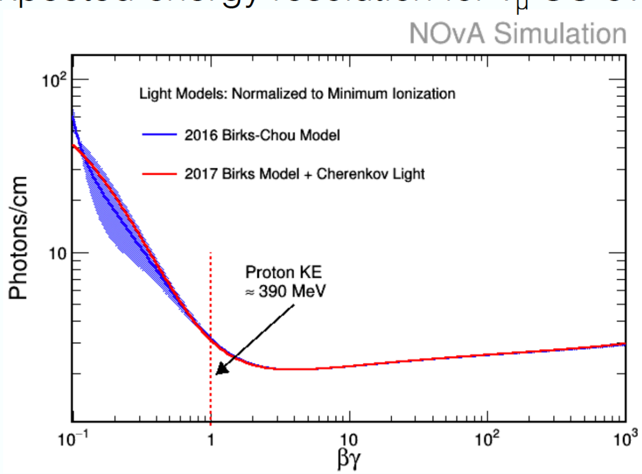
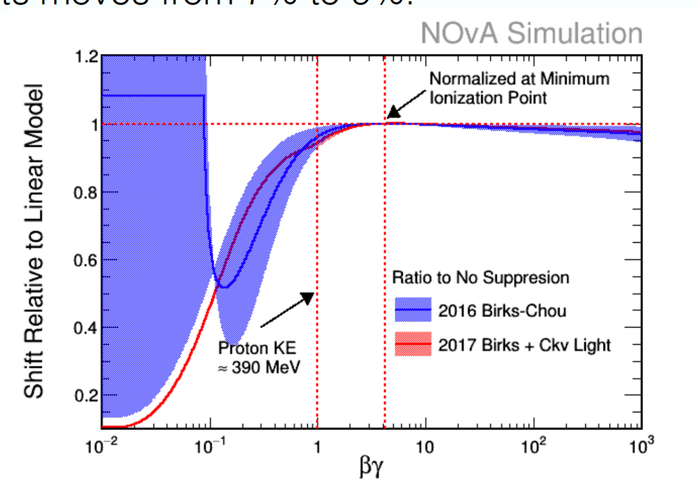
- Previously detector response uncertainties were some of our largest. Reduced by an order of magnitude in new detector simulation, driven by addition of cherenkov light.
- Absorbed and re-emitted Cherenkov light is a small but important in modeling the detector response to hadronic activity.
- Expected energy resolution for ν_μ CC events moves from 7% to 9%.





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