By Craig Nagy

Latest T2K Neutrino Oscillation Results

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on behalf of the T2K Collaboration

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Beijing, 2 September 2017

Outline

- Neutrino oscillations and the T2K experiment
- Joint oscillation analysis with ν_μ, ν_e, $\bar{\nu}_\mu$, and $\bar{\nu}_e$ samples
- Summary

Neutrino Oscillations

$c_{ij} = \cos\theta_{ij}$

$s_{ij} = \sin\theta_{ij}$

PMNS matrix

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

$\theta_{ij} \neq 0$, δ_{CP}-phase irreducible → leptonic CP violation

Neutrino Oscillations

Neutrino (flavor) oscillations depend on mixing angles, δ_{CP}-phase and mass differences.

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$$\Delta_{ij} \equiv \frac{\Delta m^2_{ij} L}{4E}$$

$$\Delta m^2_{ij} \equiv m^2_i - m^2_j$$

With a ν_μ beam

$$P(\nu_\mu \to \nu_e) \simeq \sin^2 2\theta_{13} \sin^2 \Delta_{32} \left(\sin^2 \theta_{23} - \frac{\sin 2\theta_{12} \sin 2\theta_{23}}{2 \sin \theta_{13}} \sin \delta_{\rm CP} \sin \Delta_{21} \right)$$

$$P(\nu_\mu \to \nu_\mu) \simeq 1 - \sin^2 2\theta_{23} \sin^2 \Delta_{32}$$

"CP-odd term"

* neglecting matter effects

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With a $\bar{\nu}_\mu$ beam

flip sign

$$P(\bar{\nu}_\mu \to \bar{\nu}_e) \simeq \sin^2 2\theta_{13} \sin^2 \Delta_{32} \left(\sin^2 \theta_{23} + \frac{\sin 2\theta_{12} \sin 2\theta_{23}}{2 \sin \theta_{13}} \sin \delta_{CP} \sin \Delta_{21} \right)$$

$P(\bar{\nu}_\mu \to \bar{\nu}_\mu) = P(\nu_\mu \to \nu_\mu)$ by CPT symmetry

CP-odd term in appearance channels allow extraction of δ_{CP} using neutrino and anti-neutrino beams, up to ±30% effect at T2K

* neglecting matter effects

The T2K Experiment

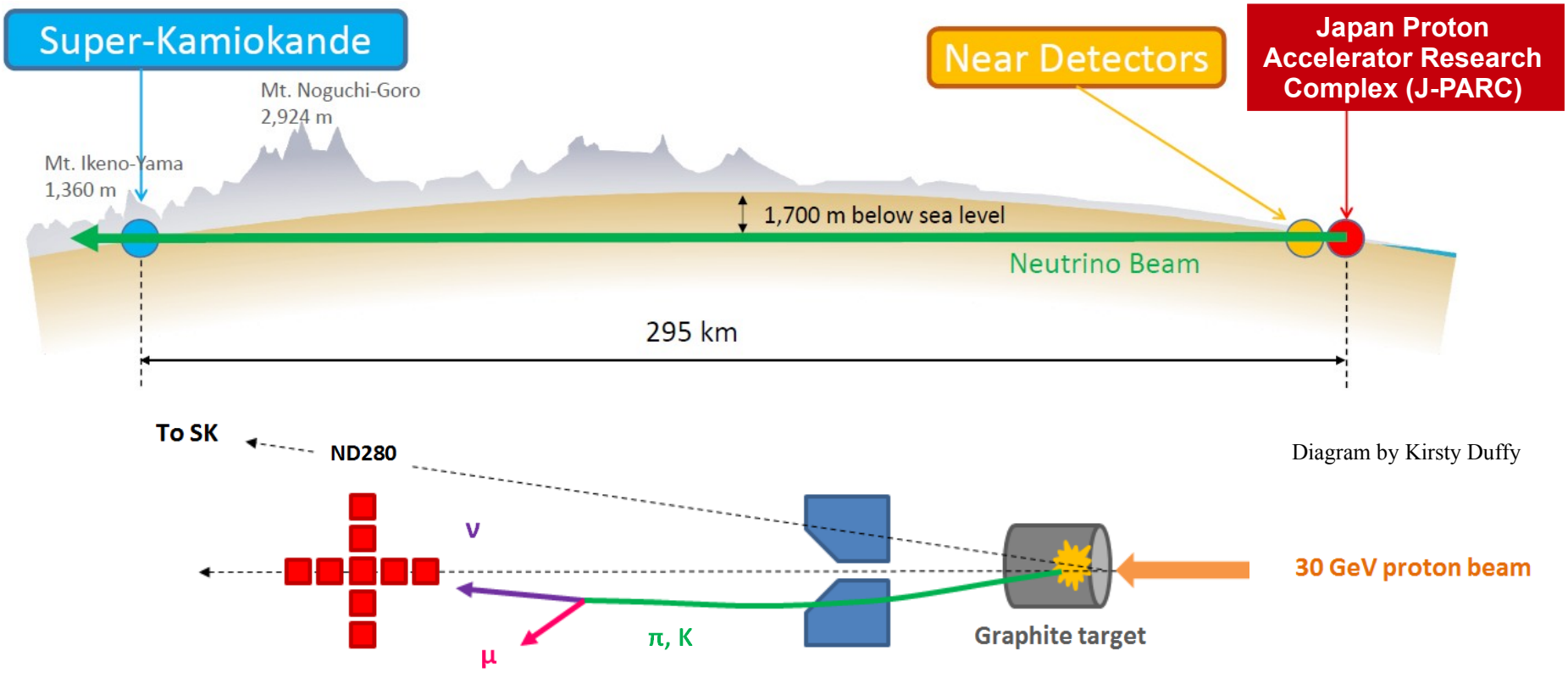

Diagram by Kirsty Duffy

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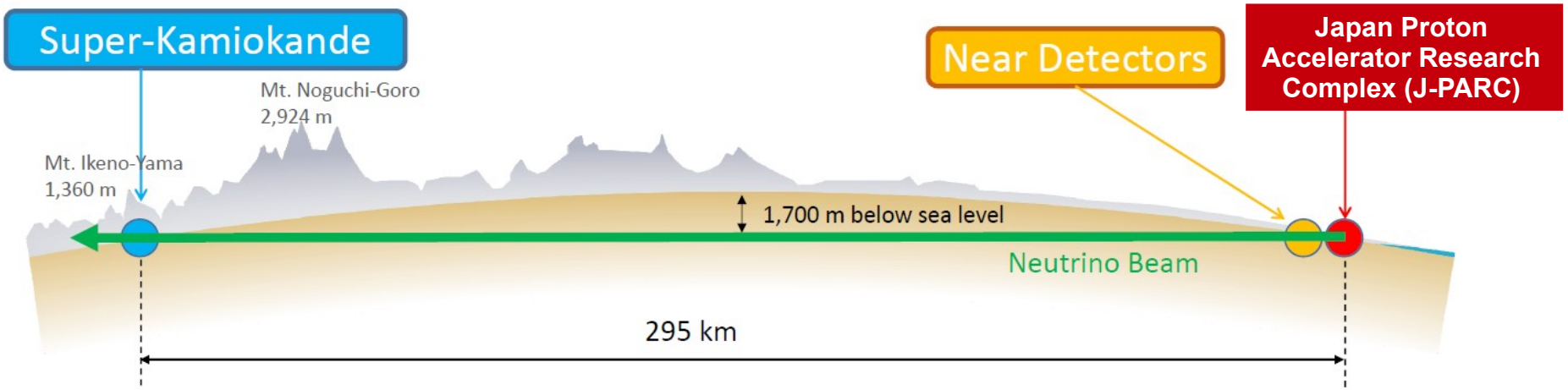

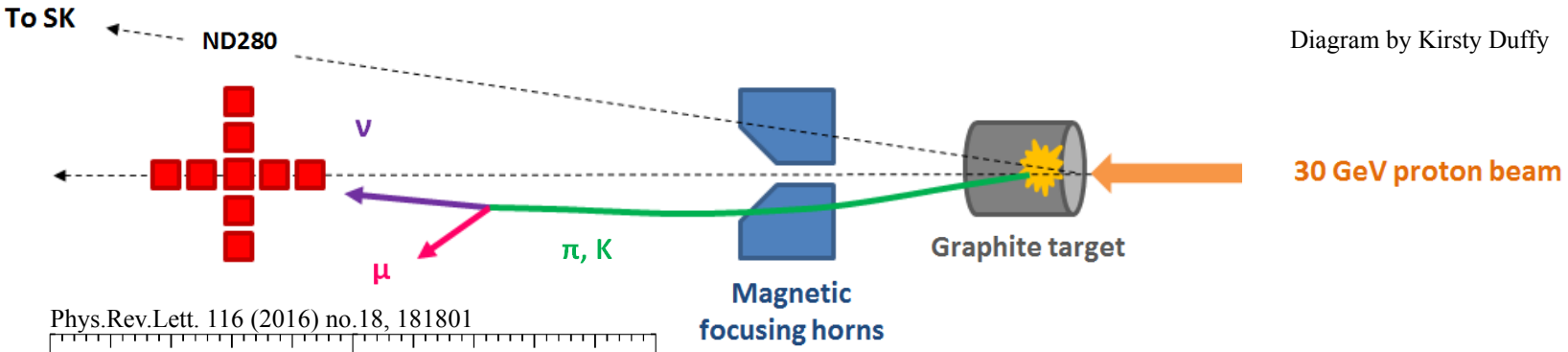

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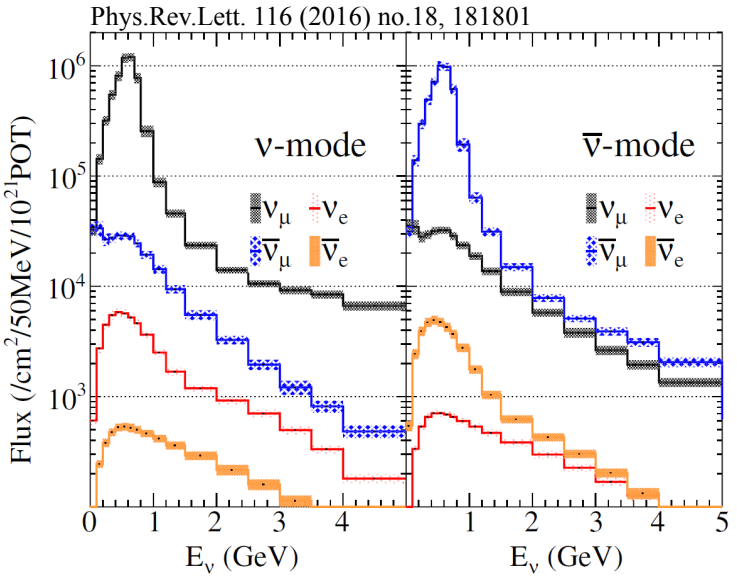
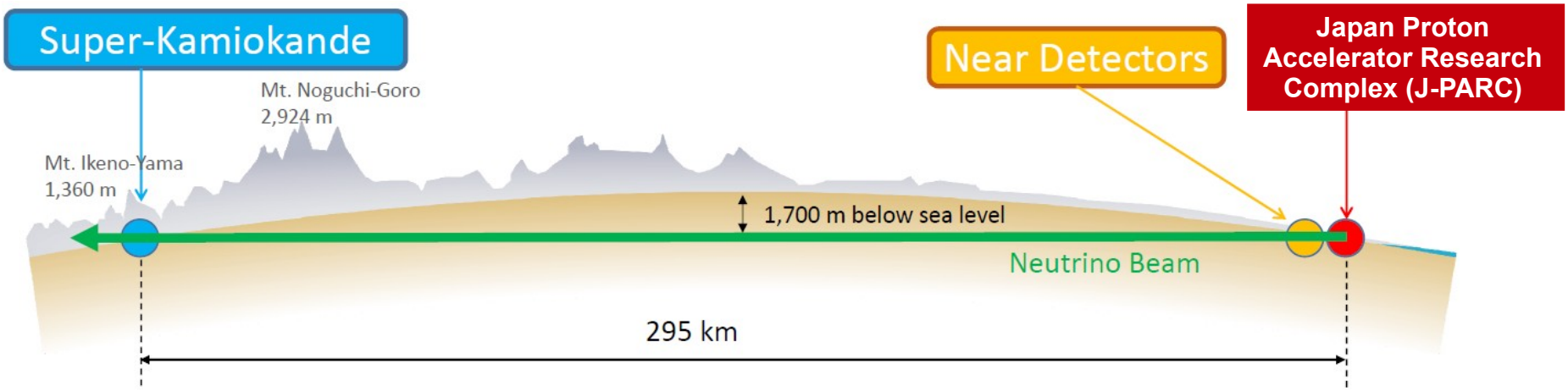
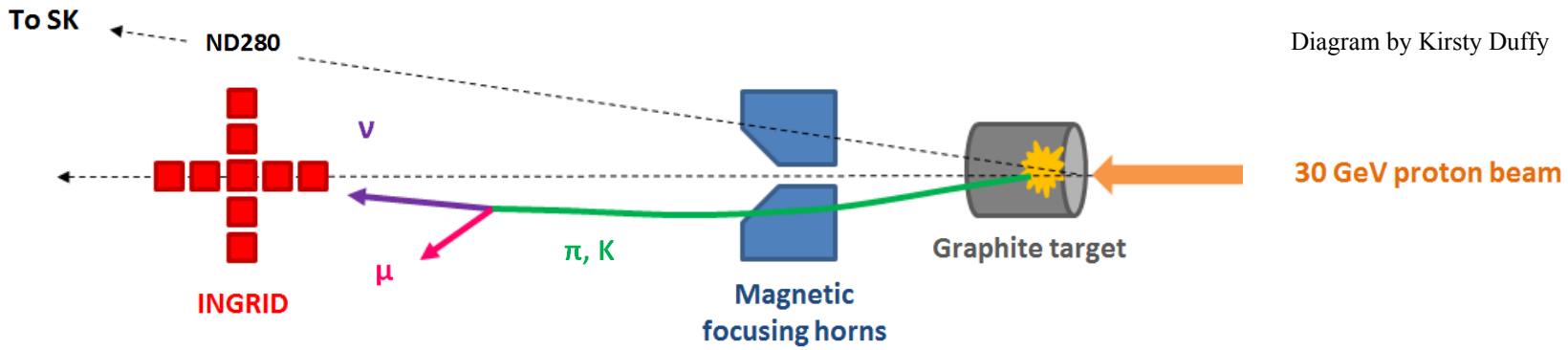


Charge selection on neutrino parents
→ ν or $\bar{\nu}$ mode

The T2K Experiment





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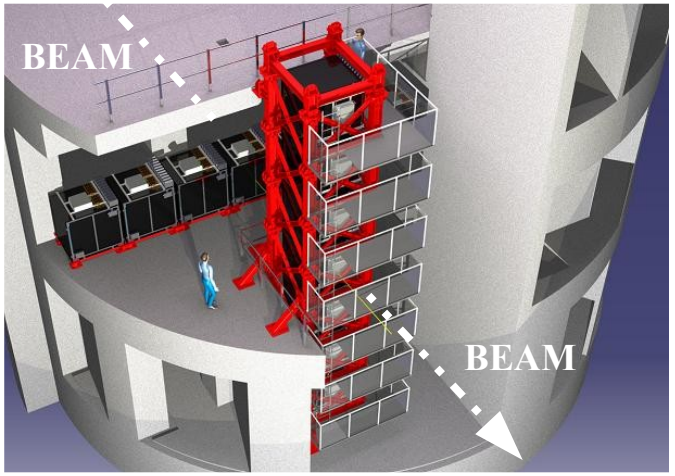


Crossed arrays of 9-ton iron-scintillator detectors

- Monitor neutrino beam stability and beam spatial profile
- estimate beam flux uncertainty
- stand-alone cross-section measurements

The T2K Experiment

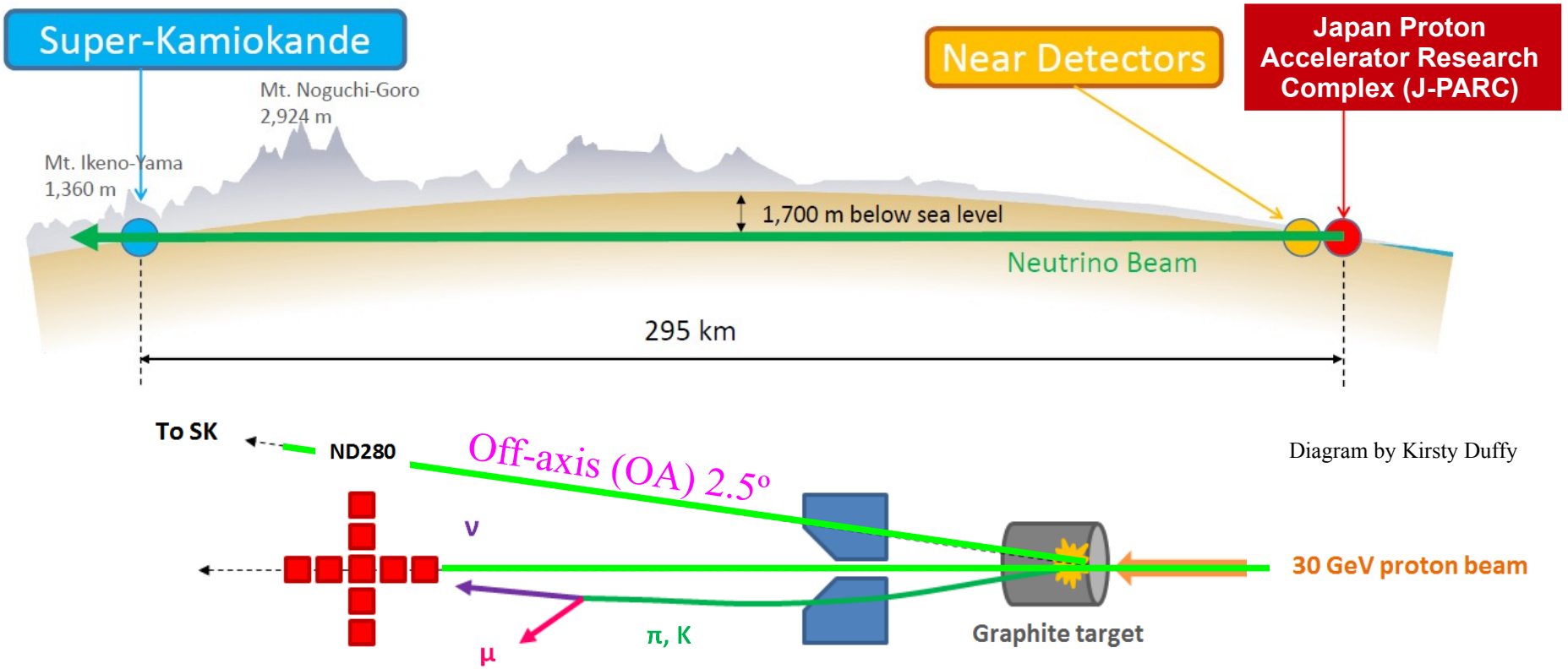
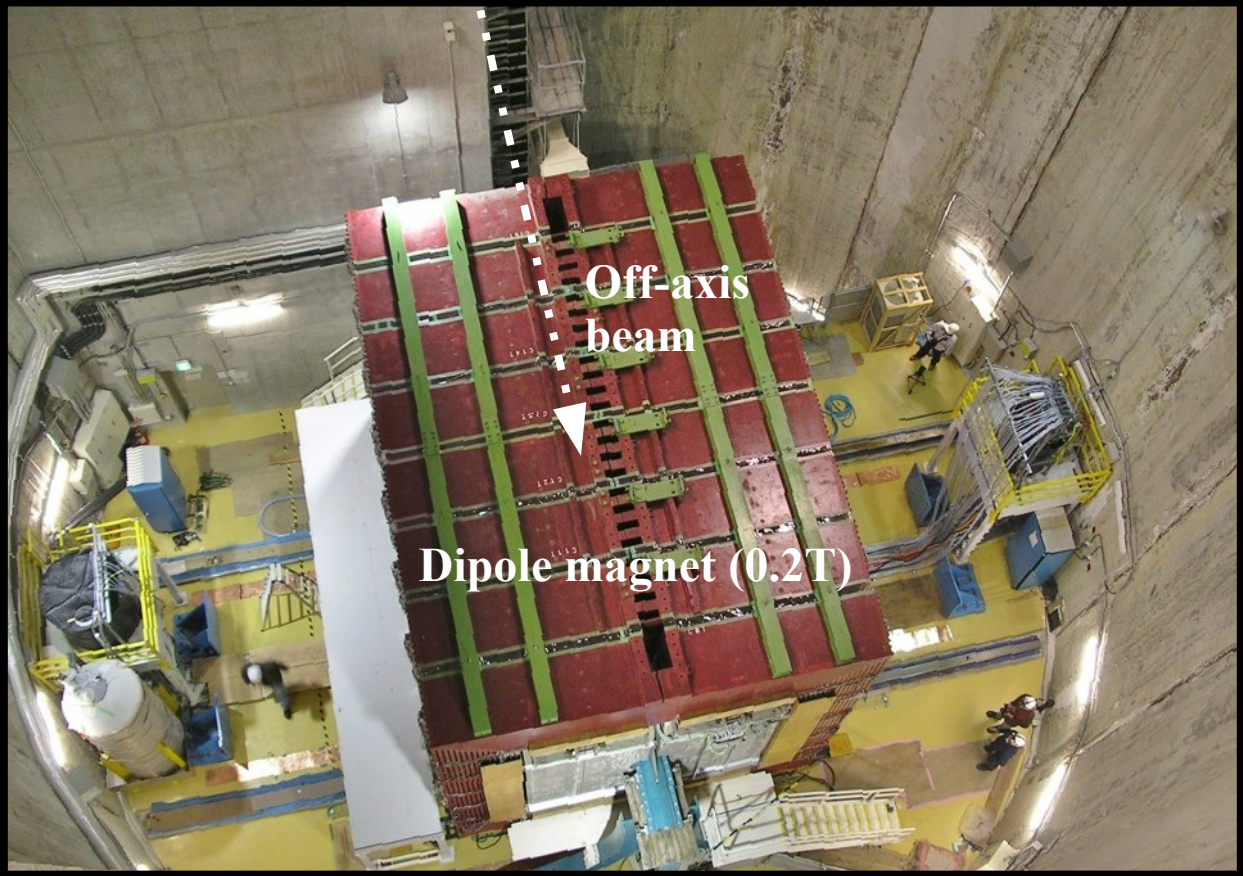


Diagram by Kirsty Duffy

Near detector: ND280
Far detector: SK

T2K off-axis near detector (ND280)



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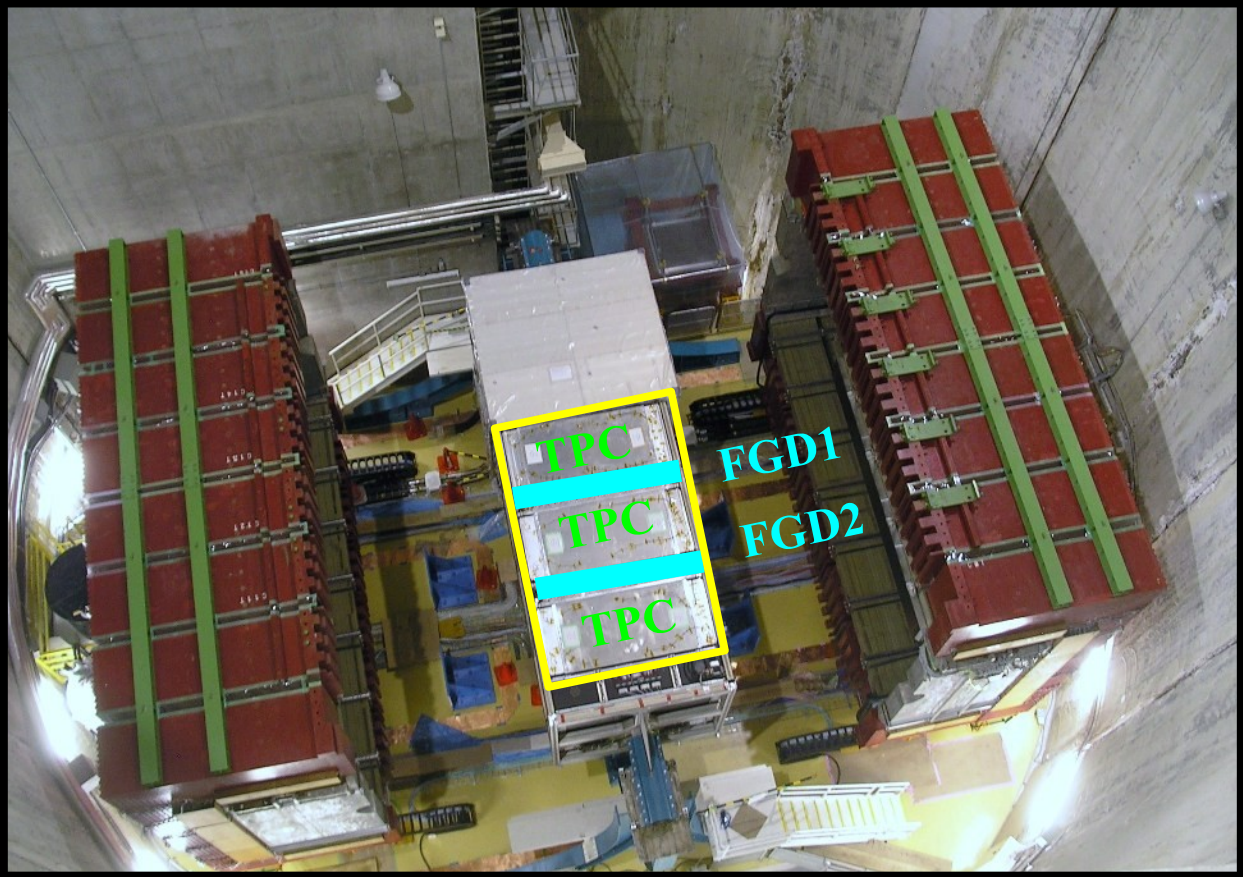
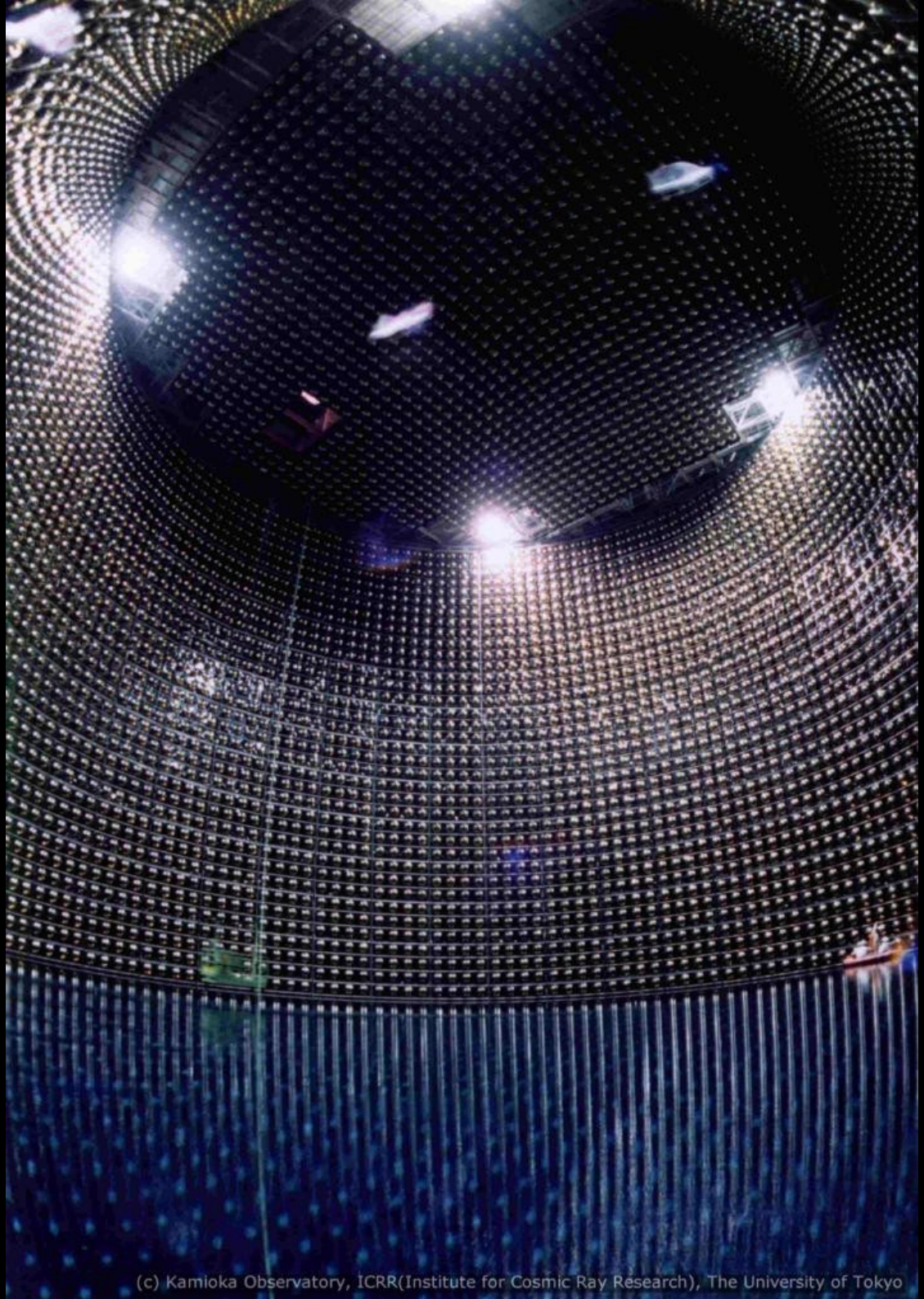


Tracker:

- FGD: Fine-Grained Detector
  1. plastic scintillator C_8H_8 target
  2. $C_8H_8 + H_2O$ target
- Time Projection Chamber (TPC)

- constrain beam flux and cross section for oscillation analysis
- stand-alone neutrino interaction measurements



T2K far detector: Super-Kamiokande

- 50 kt water-Cherenkov
- 11129 20-inch PMTs in inner detector; 1885 8-inch PMTs in outer veto detector
  → time and amplitude of Cherenkov light

Source: http://www-sk.icrr.u-tokyo.ac.jp/sk/detector/image-e.html

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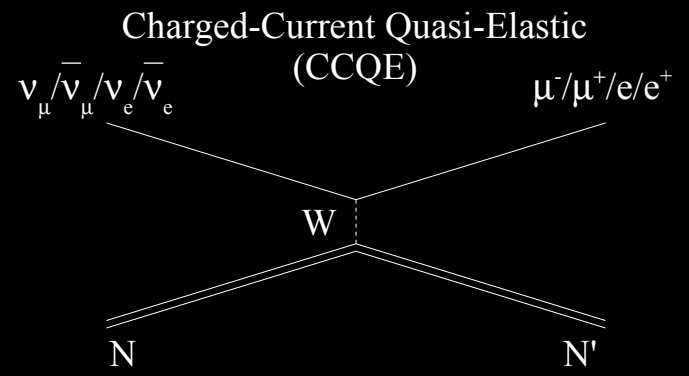

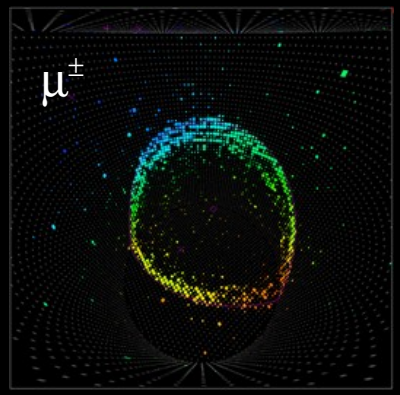

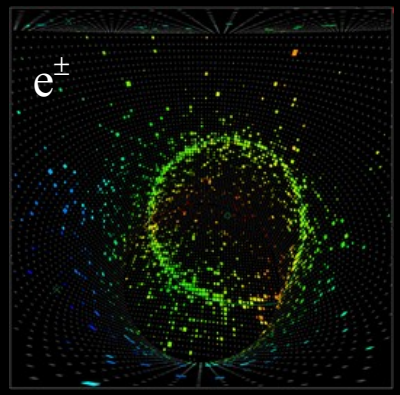

μ, e identification
→ detect propagated ν from J-PARC
→ E_ν rec. from μ/e kinematics

Source: http://www.ps.uci.edu/~tomba/sk/tscan/th

SK event reconstruction

NEW since 2016 summer:
New reconstruction algorithm: fiTQun (likelihood-based)
Re-optimizing fiducial volume: ~30% increase in effective statistics

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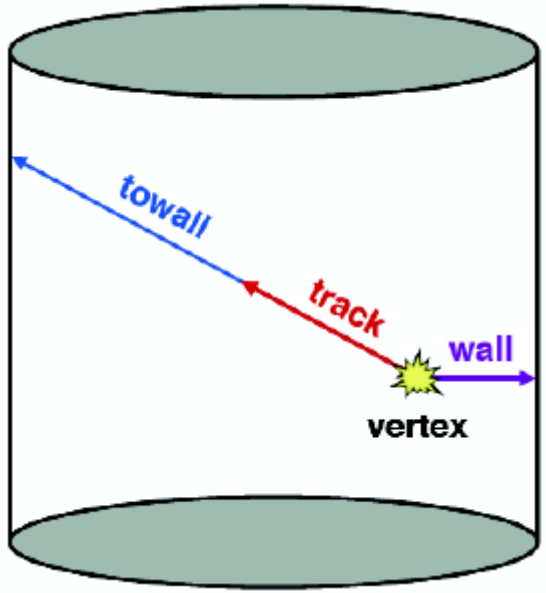
Distance to wall along particle trajectory



Minimum distance to wall

SK event reconstruction

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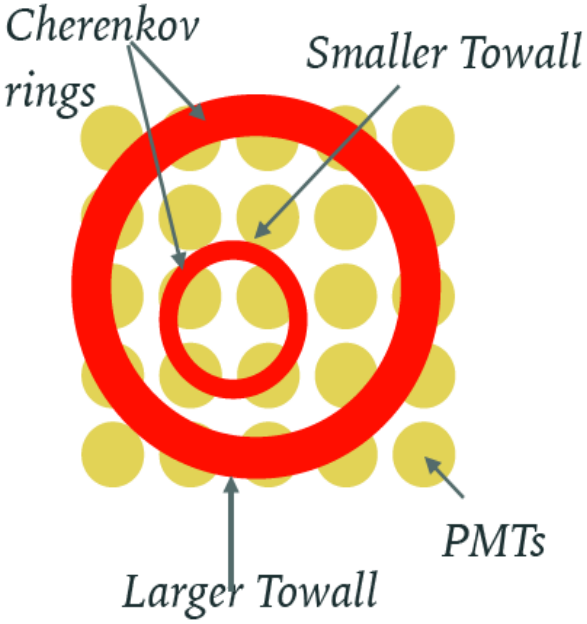
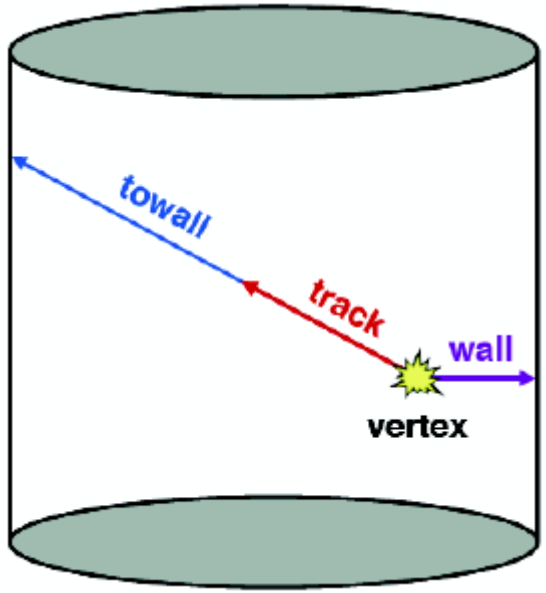
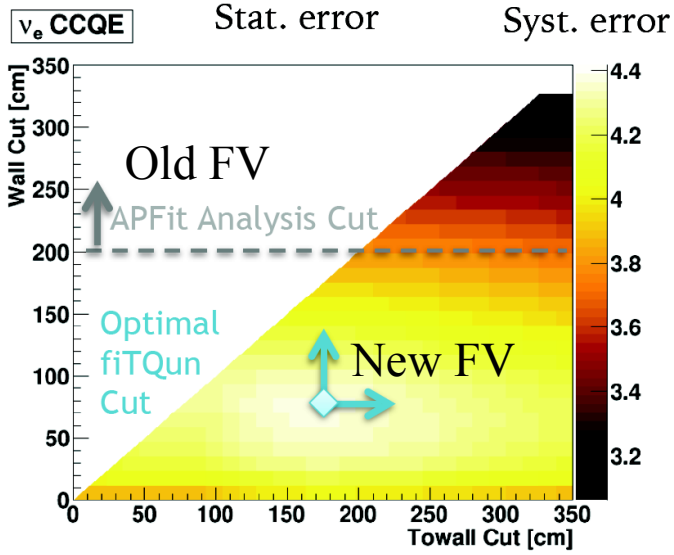
Re-optimizing fiducial volume: ~30% increase in effective statistics

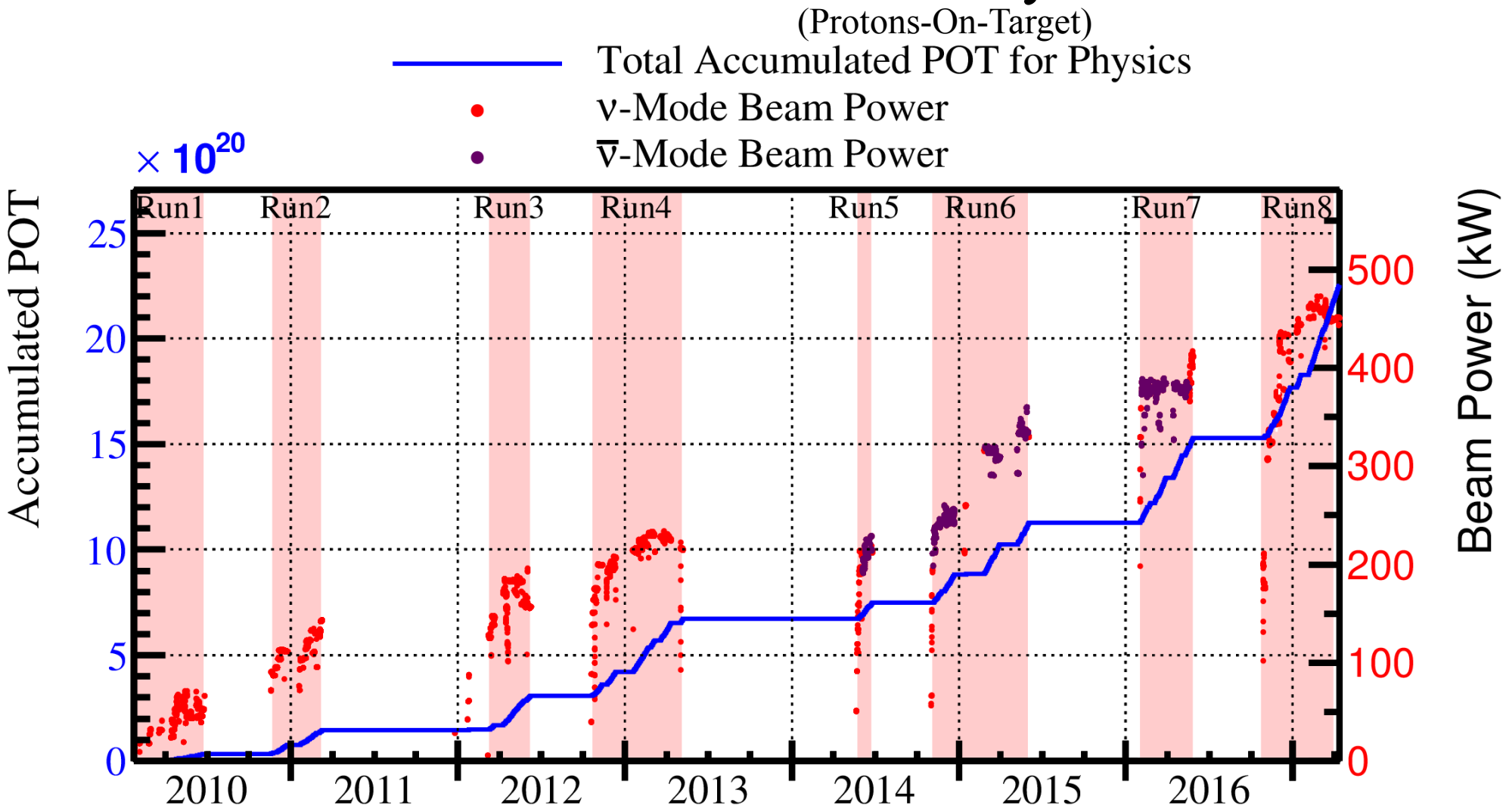






- Larger Towall = finer sampling of ring = better reconstruction
- Optimize cuts accounting for statistical and systematic errors

Data collection history



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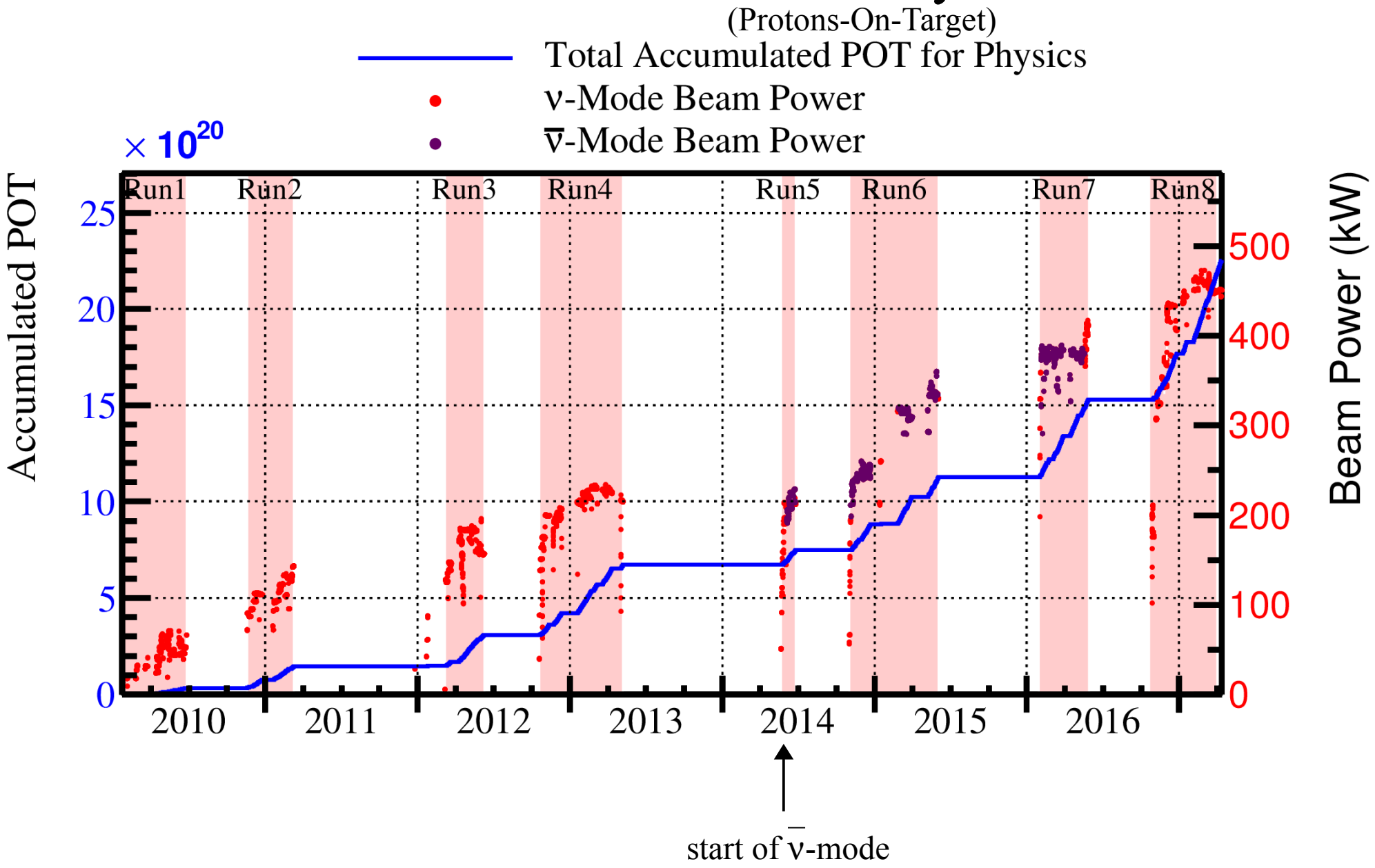

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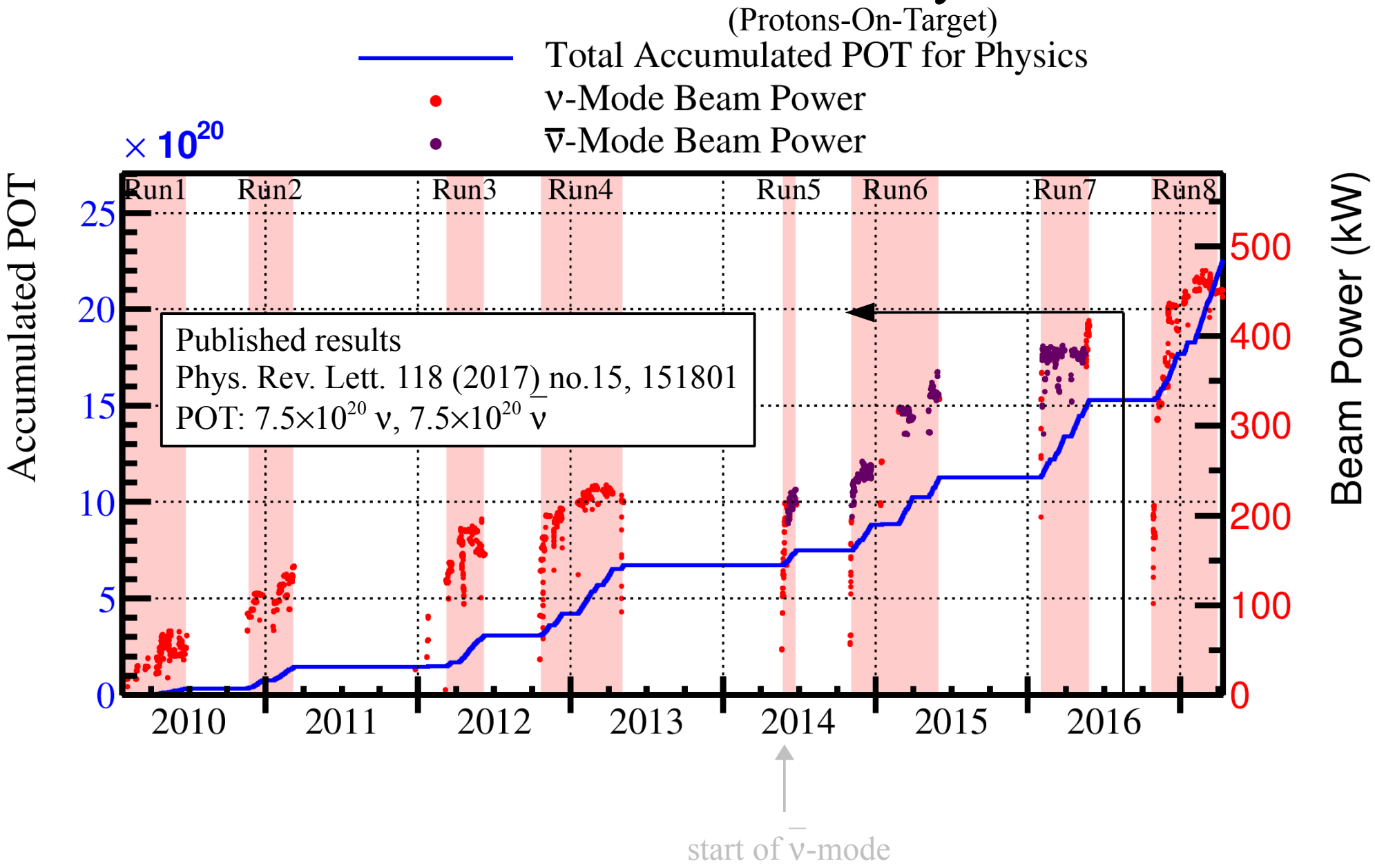

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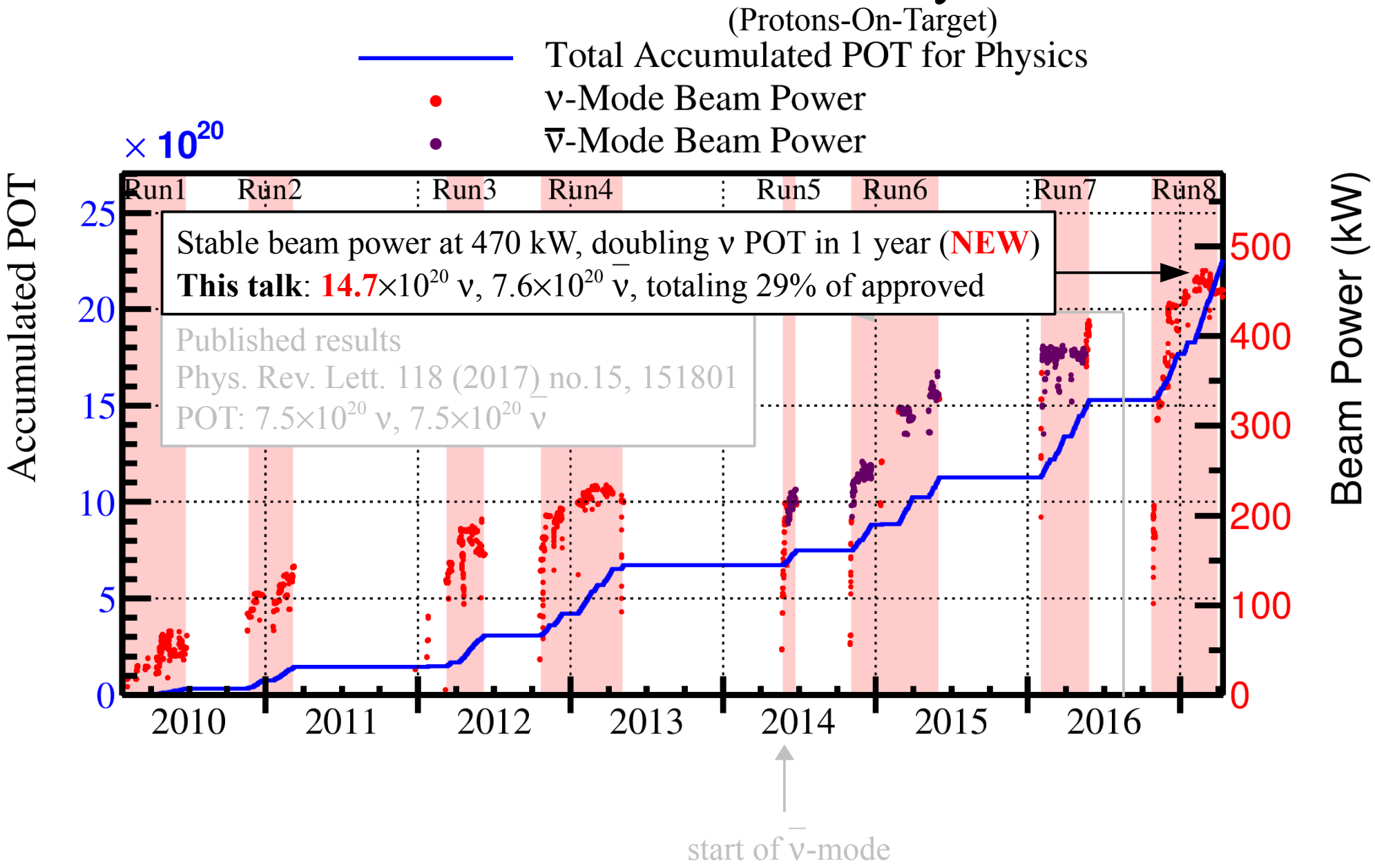

Outline

- Neutrino oscillations and the T2K experiment
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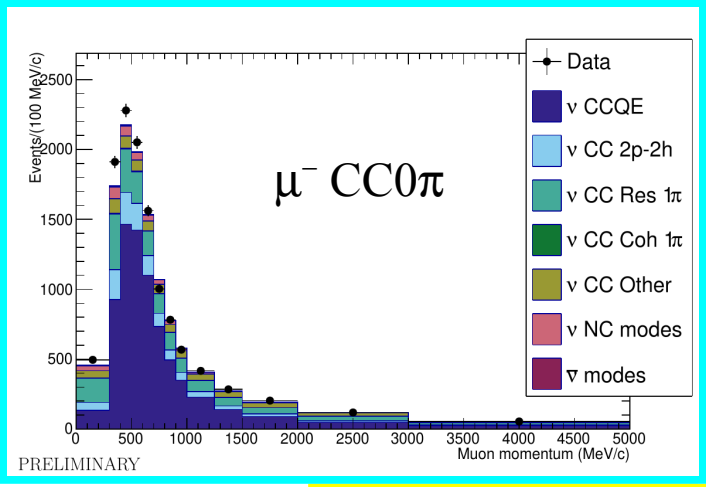
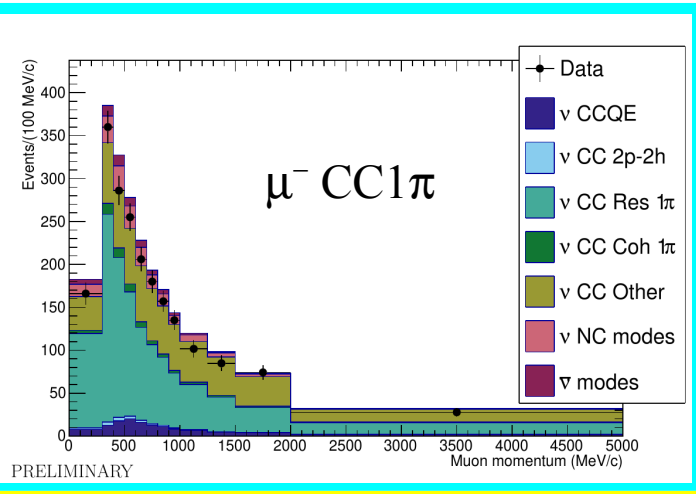
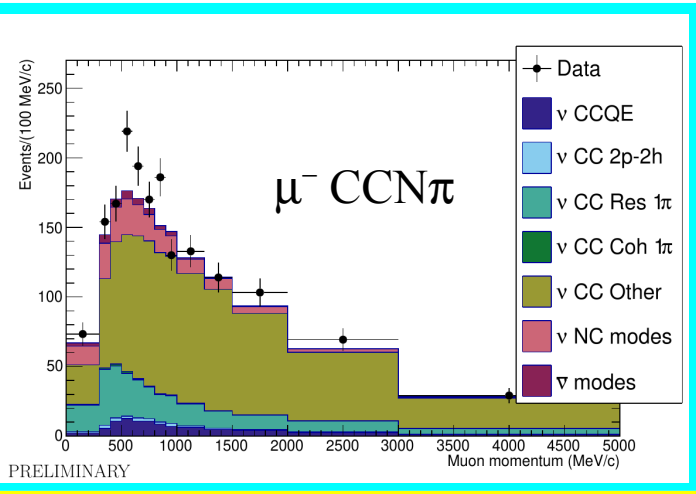
- Summary

Near Detector Samples

ν-mode FGD1 p_μ

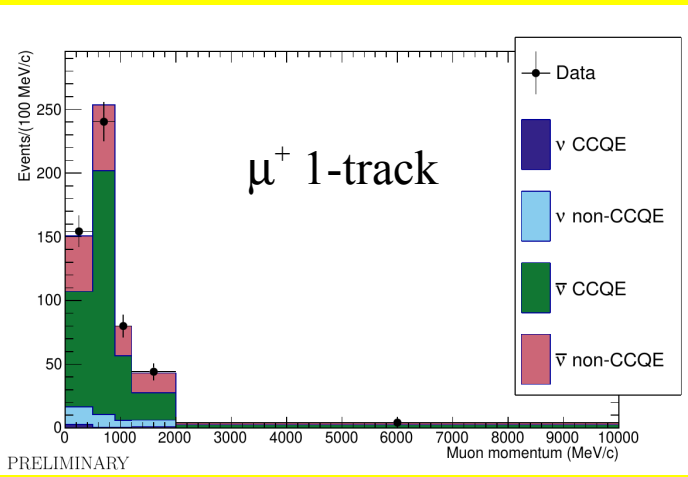


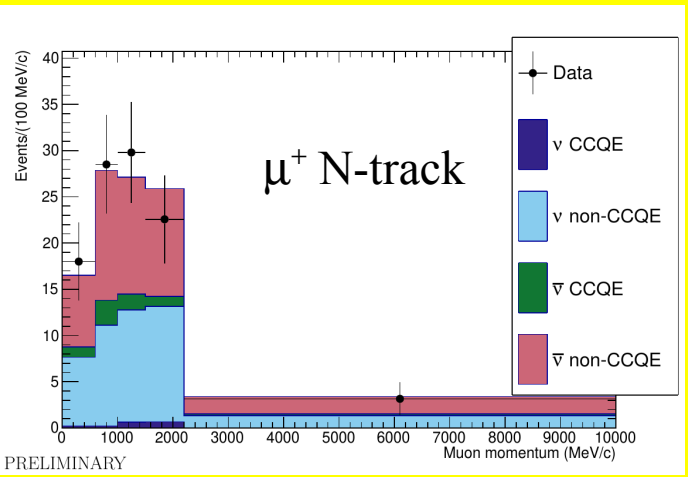


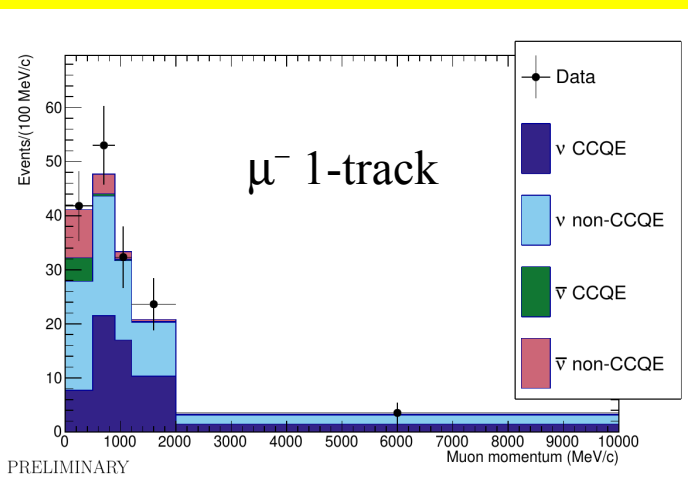


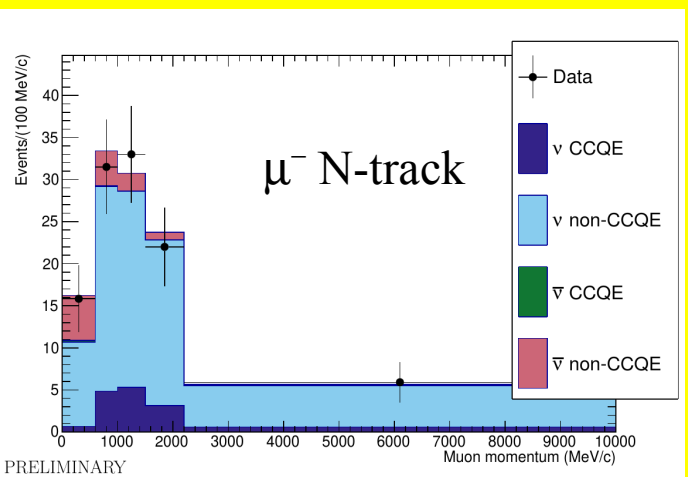
$\bar{\nu}$-mode FGD1 p_μ

- Data
  - ➔ 6 ν-mode samples (FGD1,2)
  - ➔ 8 $\bar{\nu}$-mode samples (FGD1,2)
- Model
  - ➔ Flux prediction: beamline MC tuned with ext. data (NA61) + beam monitor, INGRID
  - ➔ Cross-section models tuned to ext. measurements.



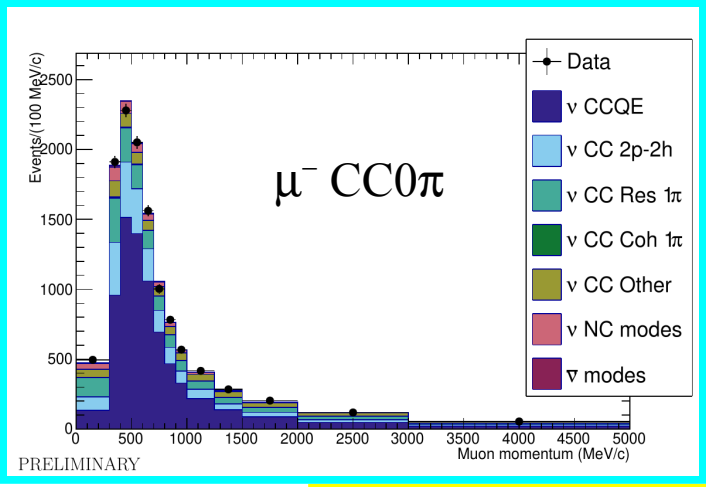


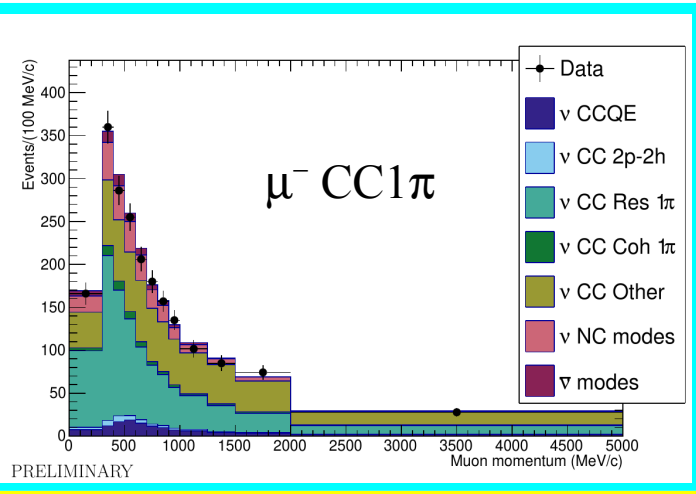


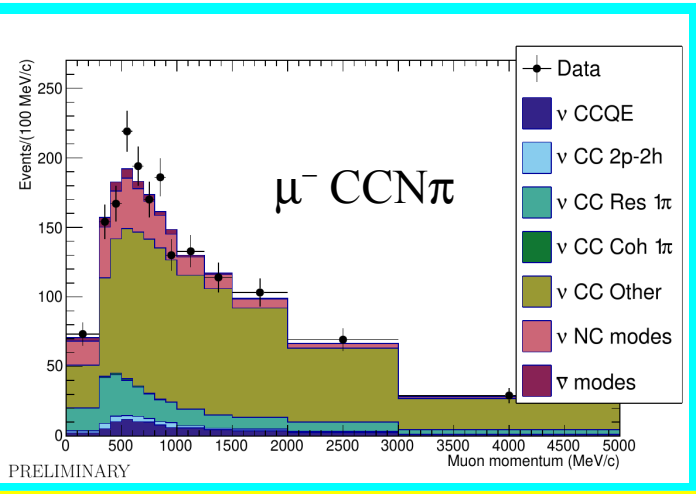


Near Detector Fit – *post*-fit

ν-mode FGD1 p_μ

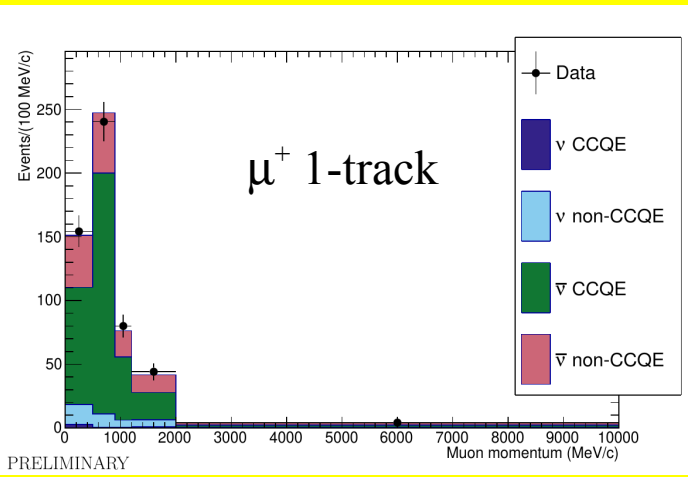


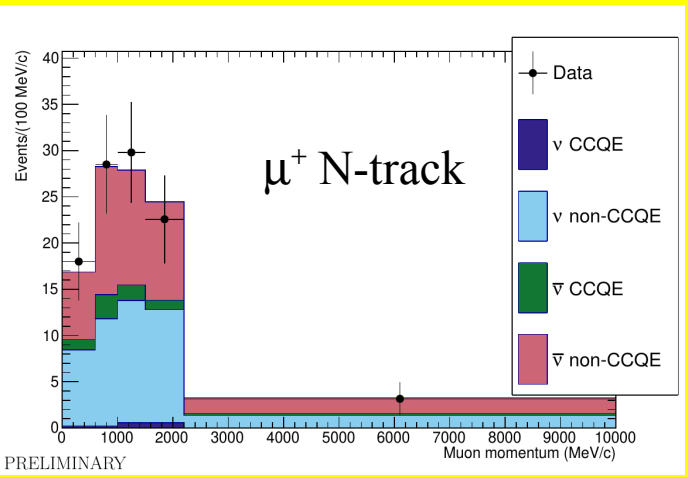


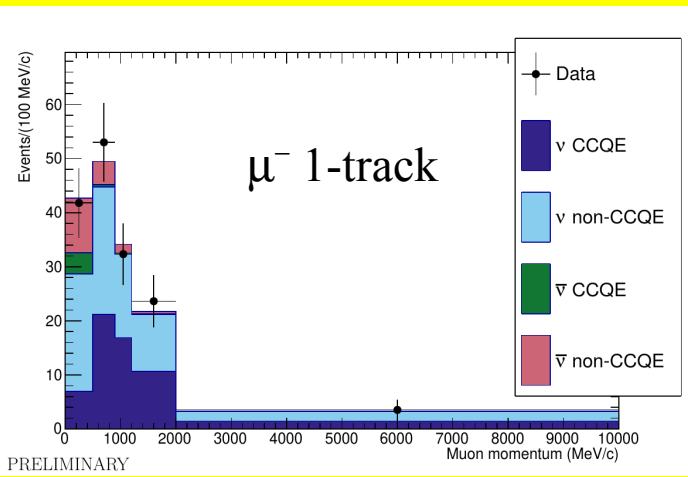


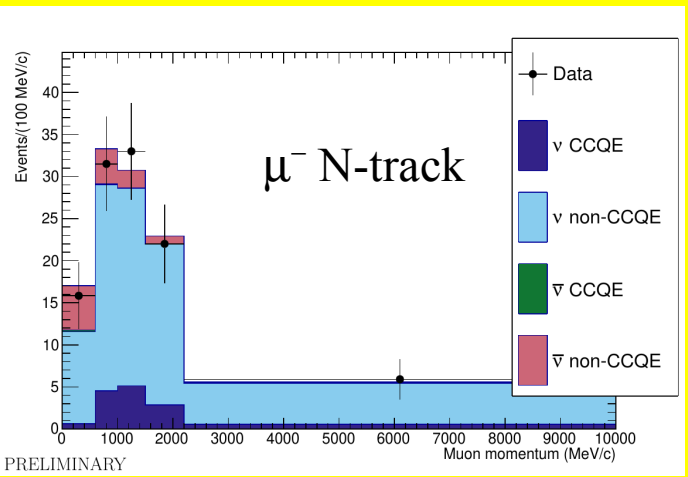
$\bar{\nu}$-mode FGD1 p_μ

- Data
  - 6 ν-mode samples (FGD1,2)
  - 8 $\bar{\nu}$-mode samples (FGD1,2)
- Simultaneous fit of p_μ, θ_μ
  - Data well reproduced: p-value 0.47
  - Fitted flux parameters near nominal, most within 1σ prior uncertainty
  - Nucleon correlations (**NEW**): 2p2h, RPA effects significantly adjusted
  - flux × cross section at SK sys. error 13% → 3 %.



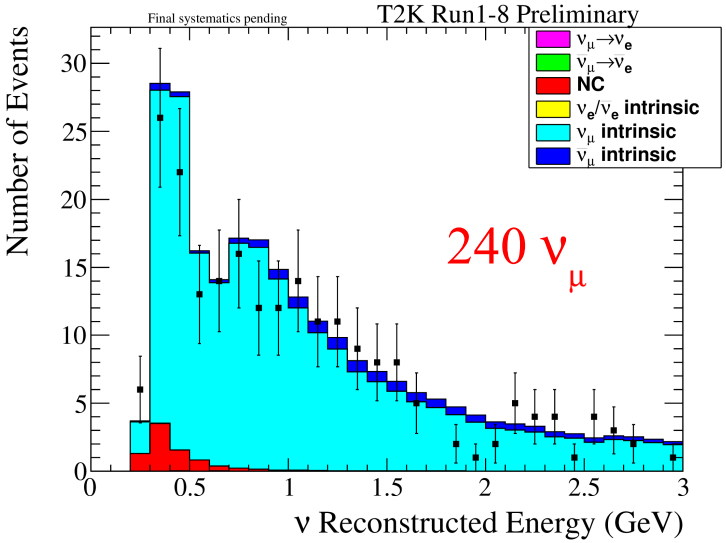


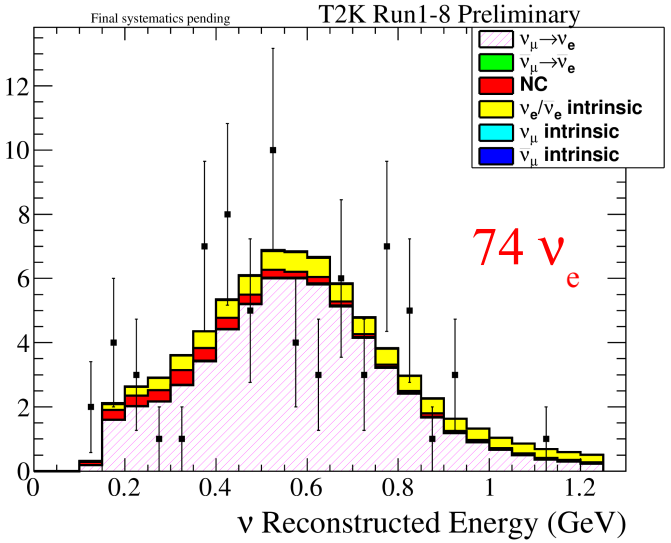




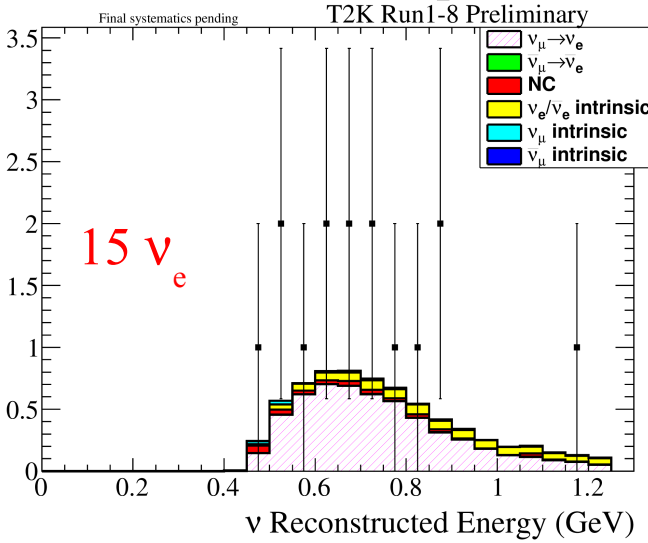
Event distributions and oscillation fit

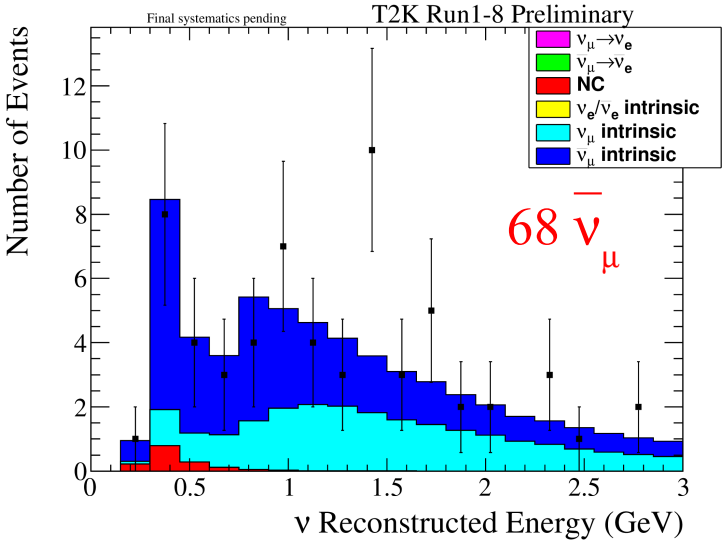
CCQE-like sample

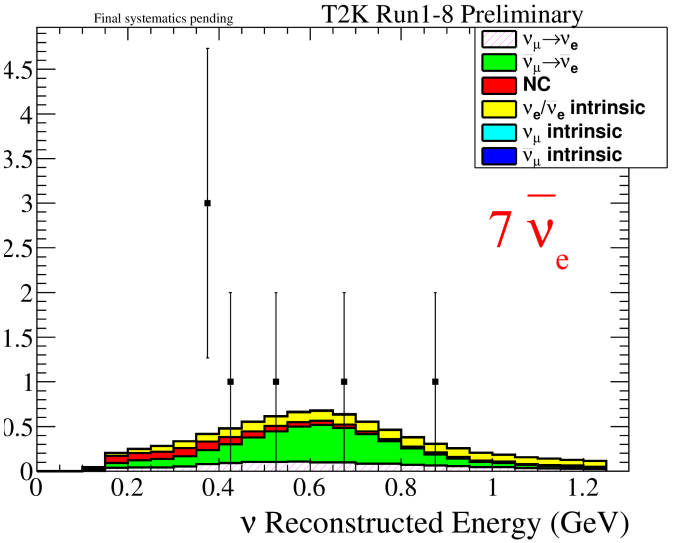


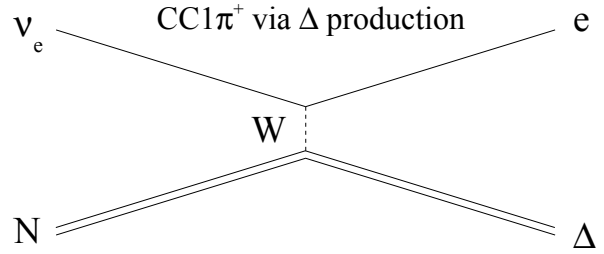


CC1π^+ sample









(No CC1π^- sample due to π^- absorption)

- Reconstructed neutrino energy distributions at Super-Kamiokande
  - Dotted: data; histogram: oscillation fit results, p-value 0.42

Event distributions and oscillation fit

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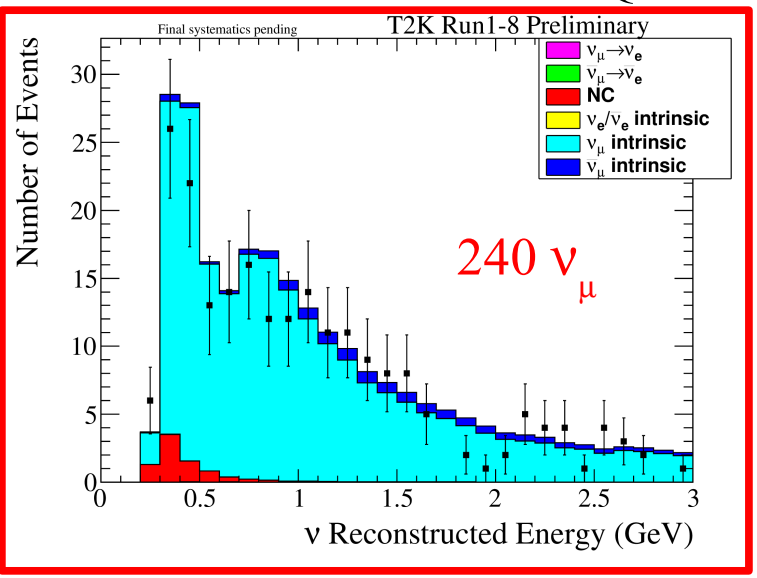
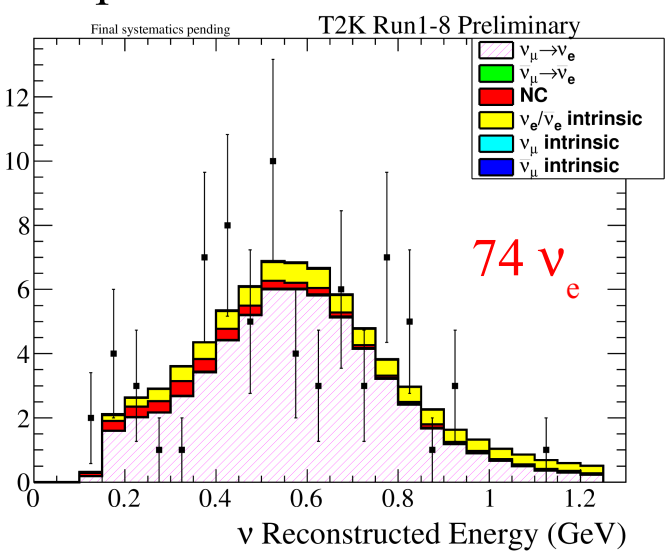
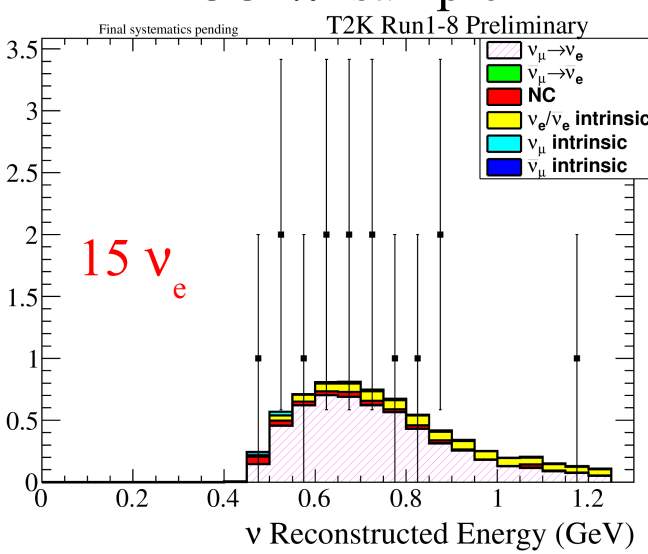
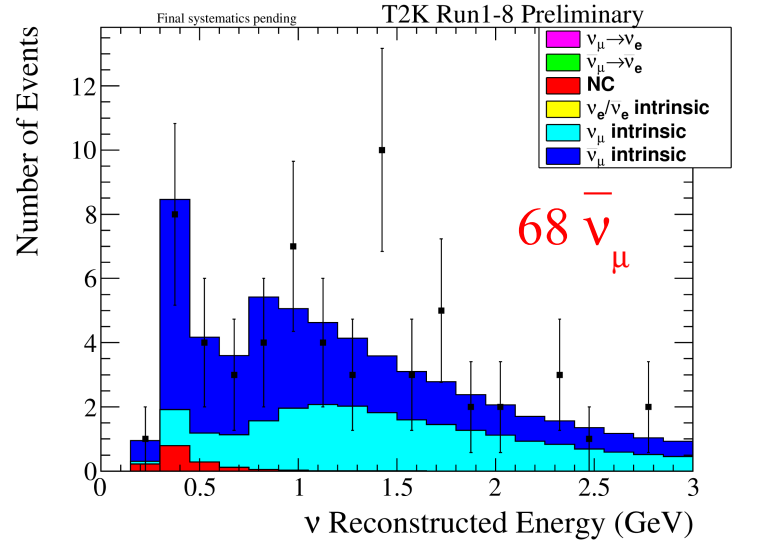
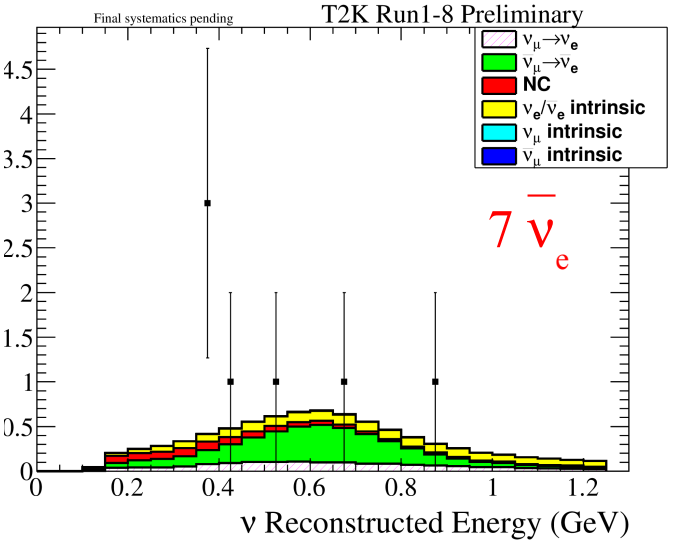


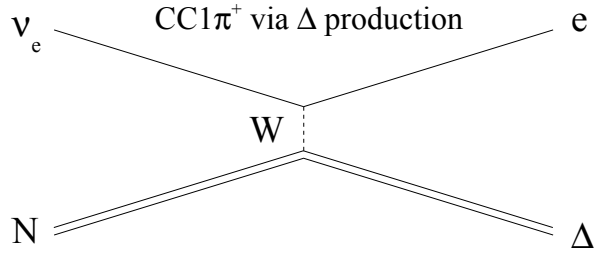


$CC1\pi^+$ sample







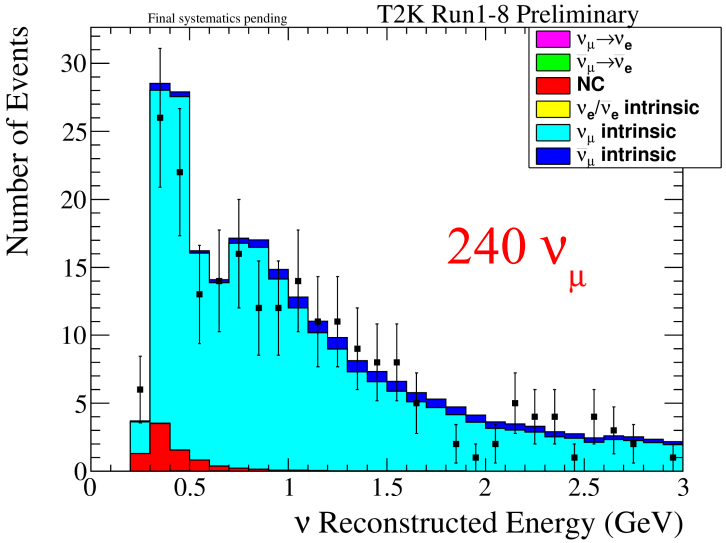


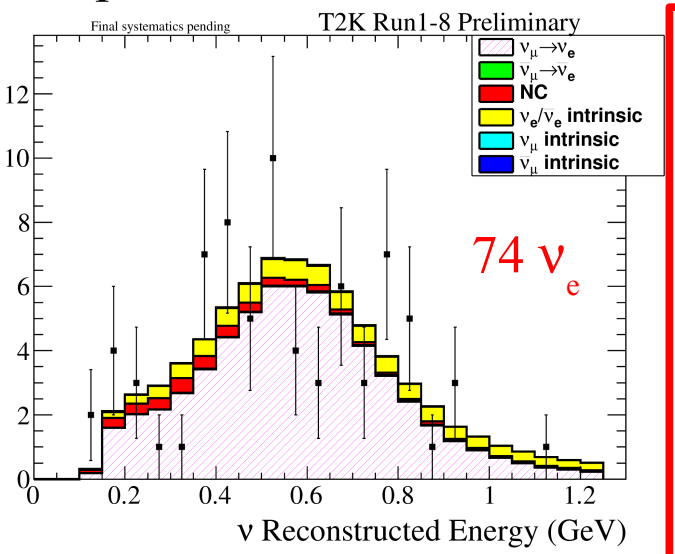
(No $CC1\pi^-$ sample due to π^- absorption)

- ν_μ rate lower than fit, consistent with uncertainties.

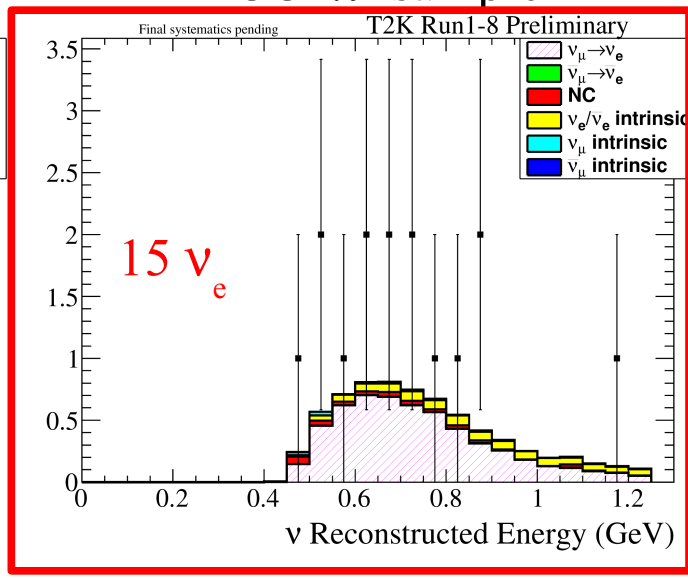
Event distributions and oscillation fit

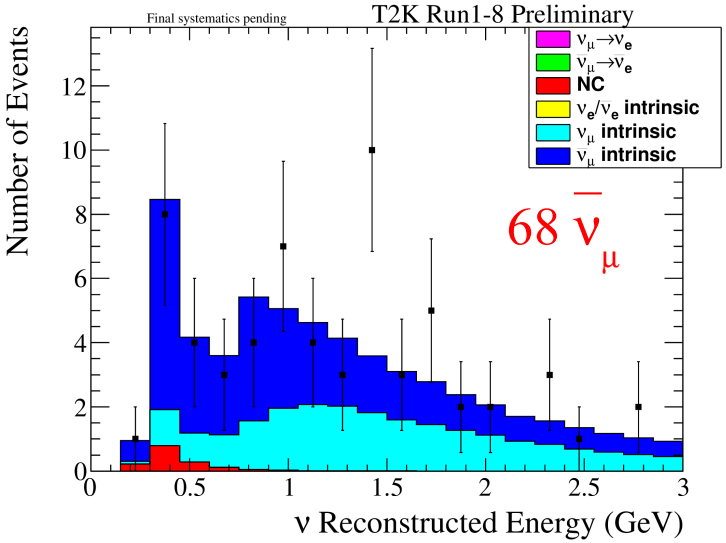
CCQE-like sample

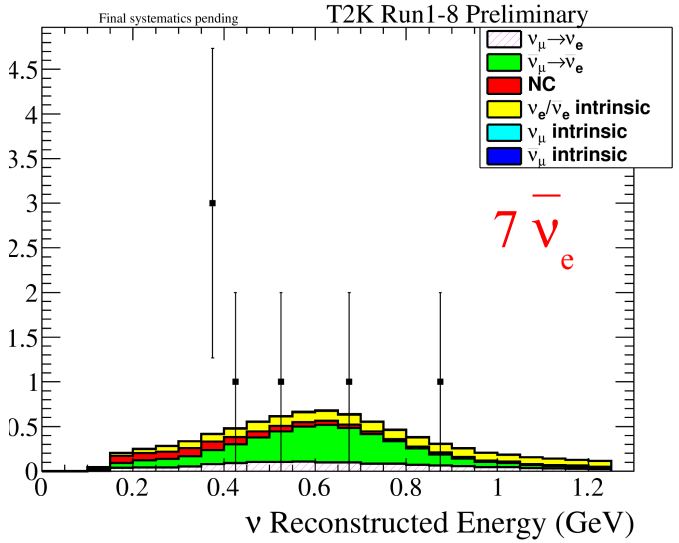


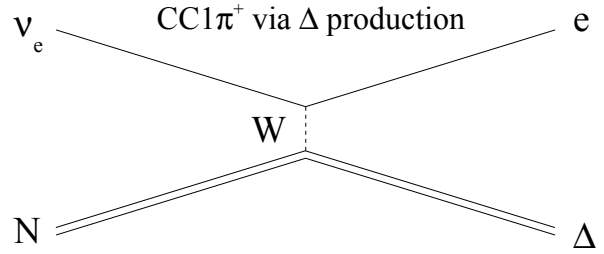


$CC1\pi^+$ sample





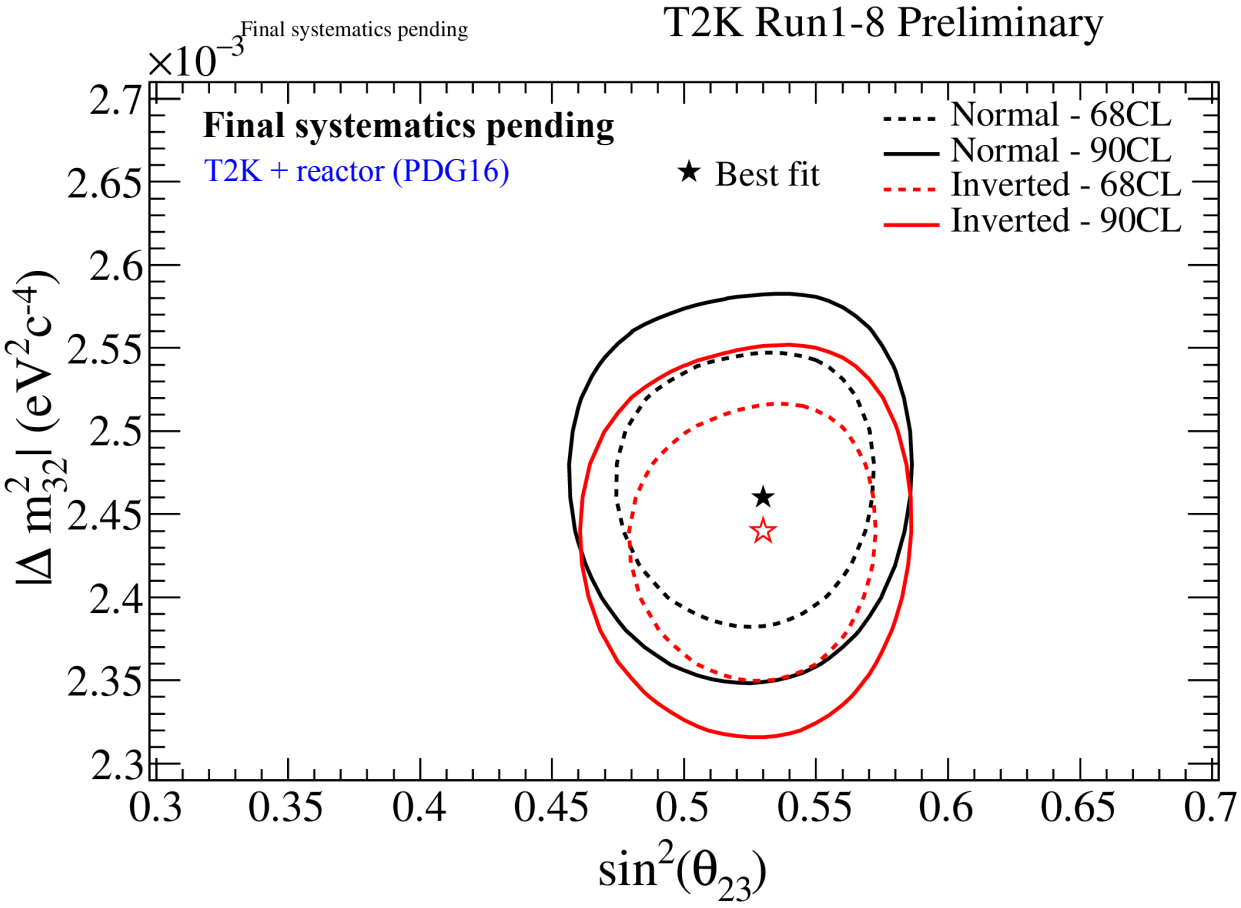




(No $CC1\pi^-$ sample due to π^- absorption)

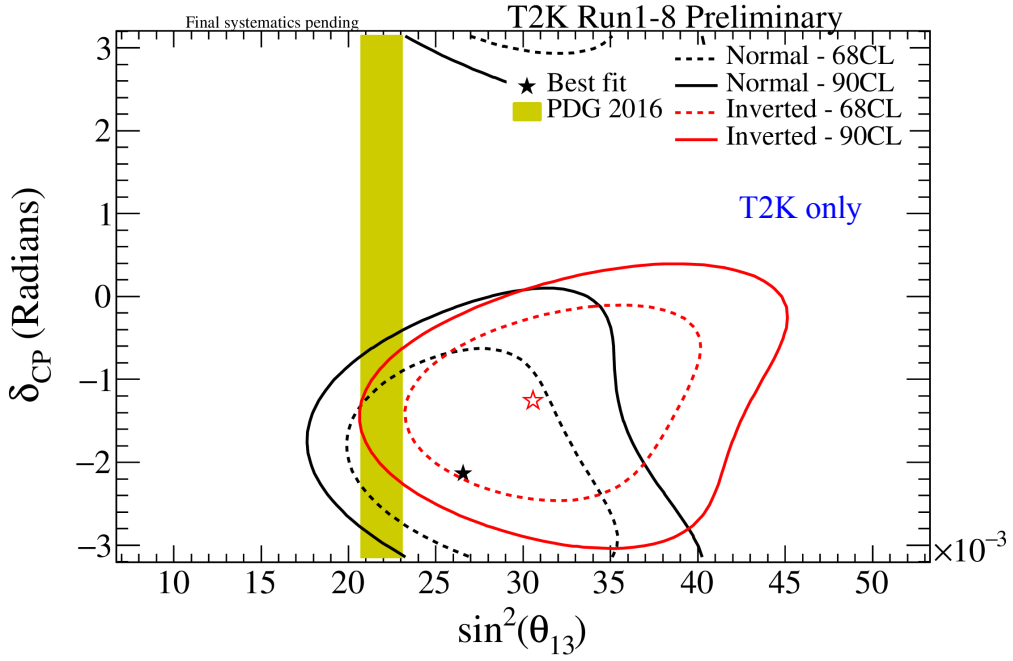
- $CC1\pi$ ν_e rate: 15 events observed vs. 6.92 maximum prediction
  - P-value 0.12 for upward or downward fluctuation in at least 1 of 5 samples

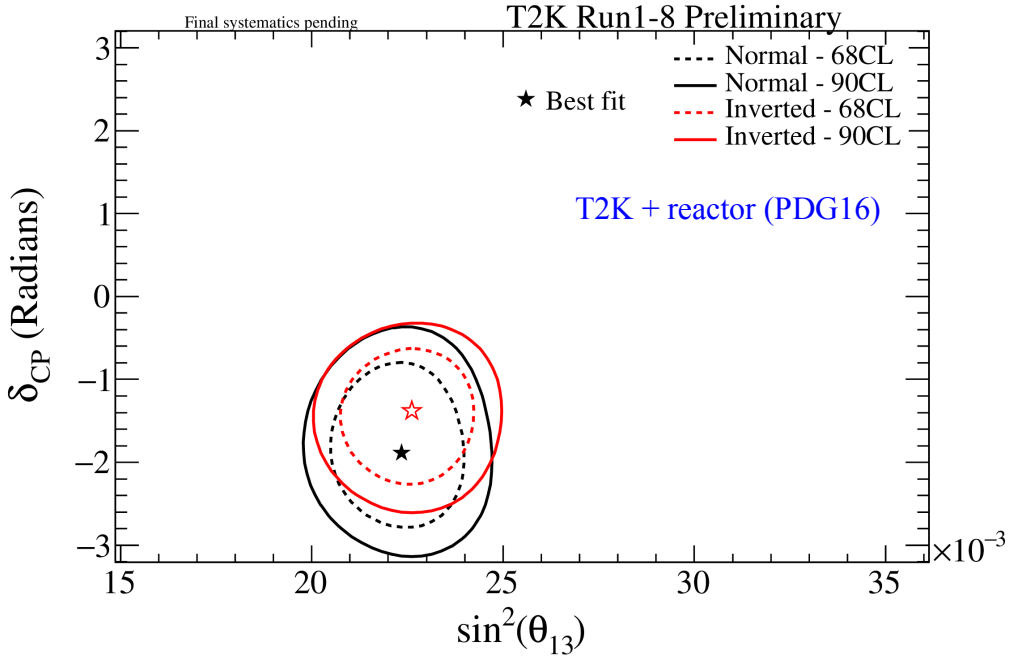
Atmospheric parameter constraints



- Fit normal and inverted hierarchies separately
- Final systematics pending, possible additional contribution from interaction models (no significant impact on δ_{CP})

Appearance parameter constraints

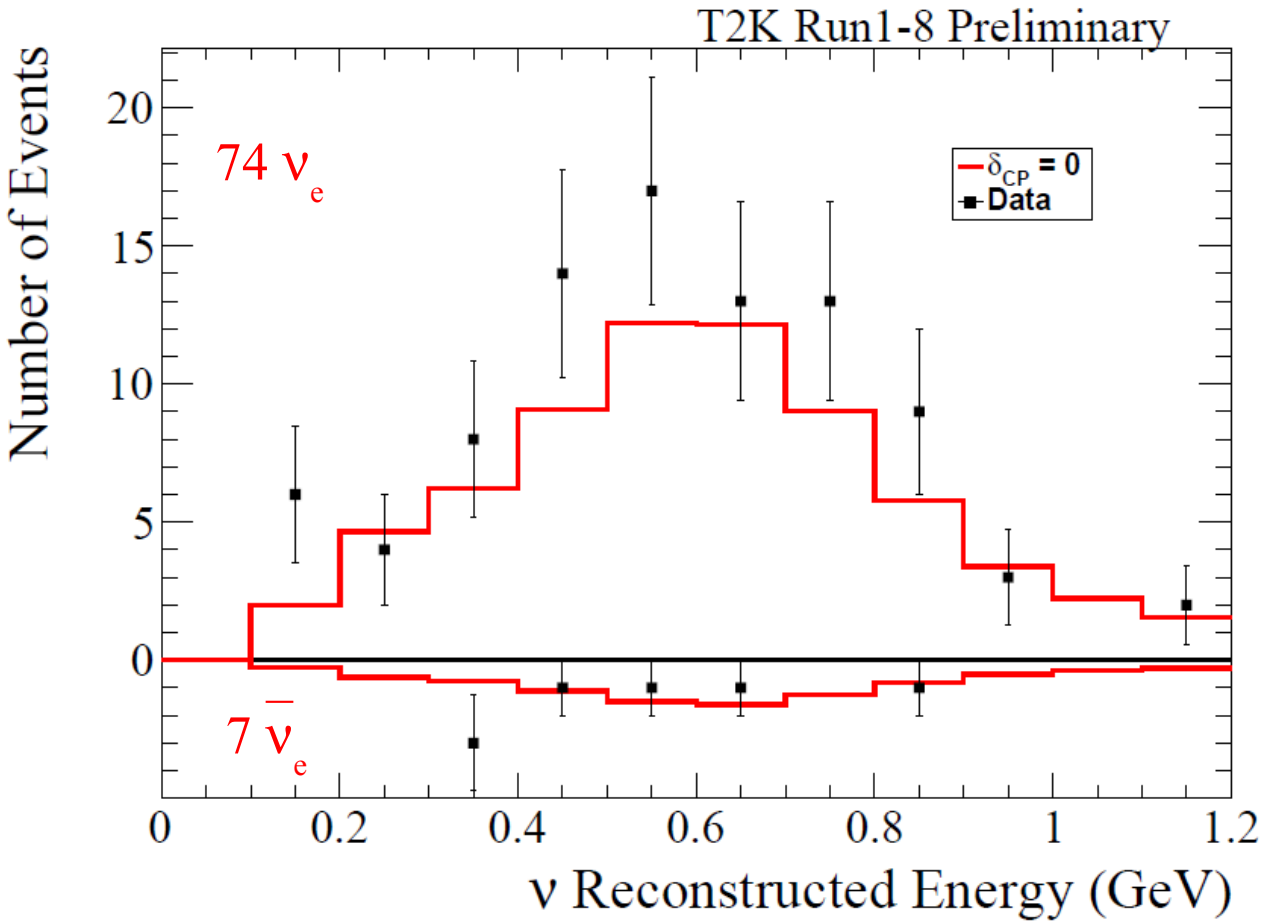




scale

- Left: T2K best-fit result and confidence intervals compared to PDG 2016: consistent
  - $\bar{\nu}$ data bring in δ_{CP}-sensitivity
- Right: T2K results with reactor constraint (PDG 2016), contour range much reduced.

Measurement of δ_{CP}



CCQE-like ν_e and $\bar{\nu}_e$ rate compared to δ_{CP}=0 predictions:

- Excess in neutrino (top)
- Deficit in antineutrino (bottom)

Measurement of δ_{CP}

Percentage errors on predicted <u>event rate ratio</u> between ν_e and $\bar{\nu}_e$ samples:
relevant for δ_{CP} extraction

SK detector	SK FSI+SI+PN	ND280 constrained flux & xsec	$\sigma(\nu_e)/\sigma(\bar{\nu}_e)$	NC1γ	NC other	Oscillation parameter variation	Total systematic error
1.60	1.57	2.50	3.03	1.49	0.18	0.79	4.85

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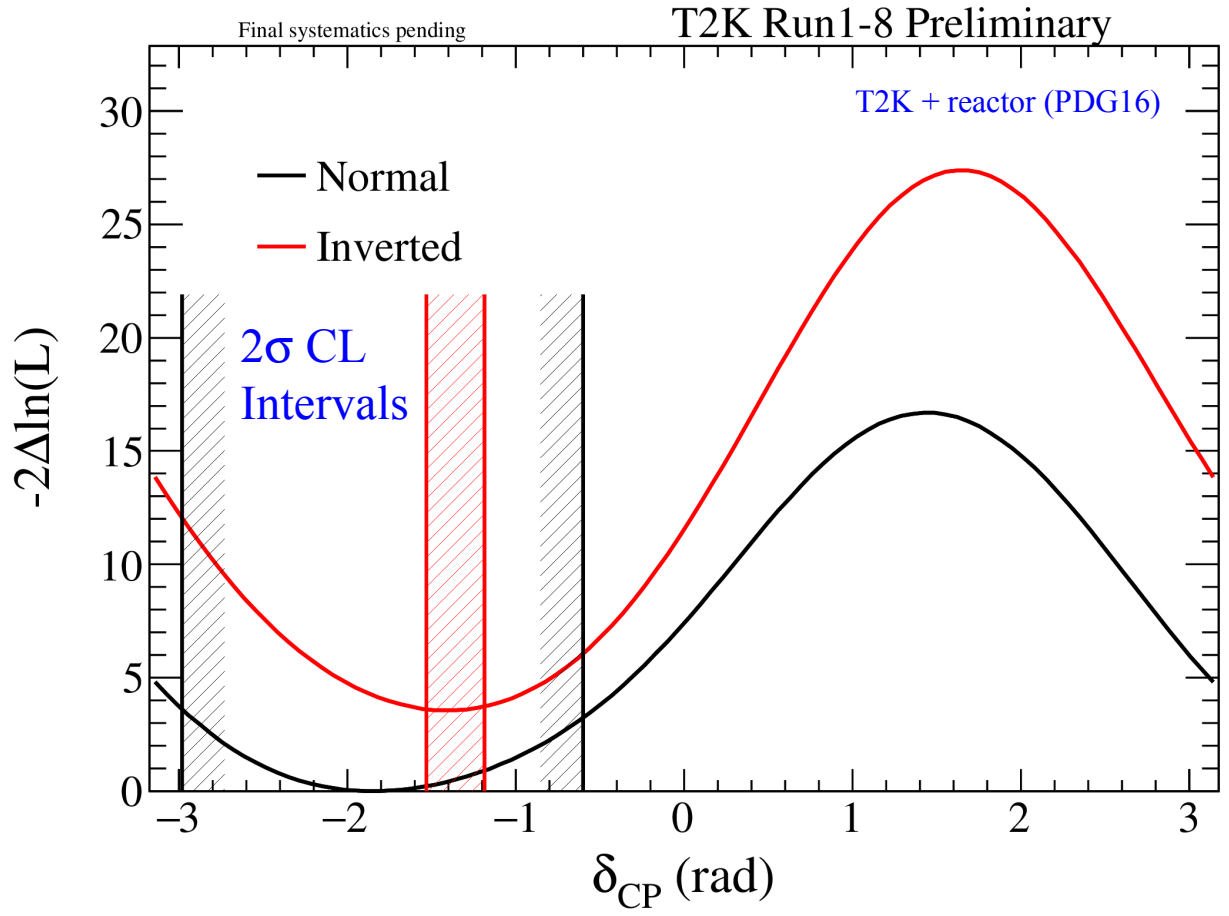
Neutral current (NC) interactions not constrained by ND280. Theoretical models constrained by external measurements.

Total error 4.85% on event rate ratio ν_e / $\bar{\nu}_e$ (10% by design).

Measurement of δ_{CP}



Best fit point: -1.83 radians in Normal Hierarchy

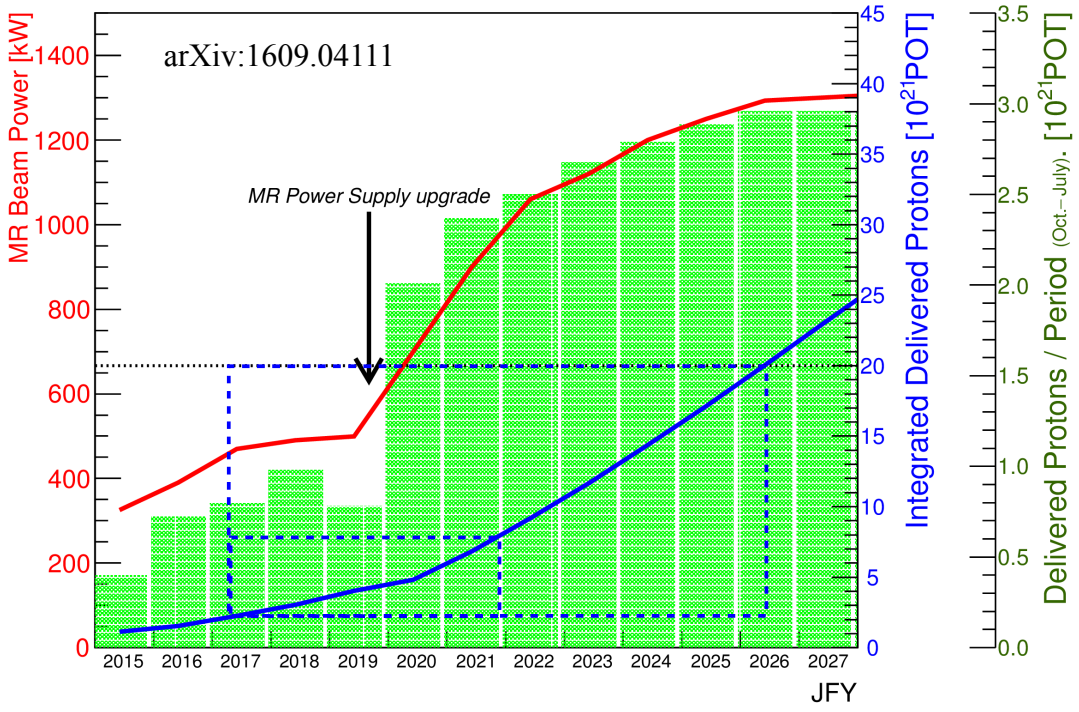
2σ CL interval:

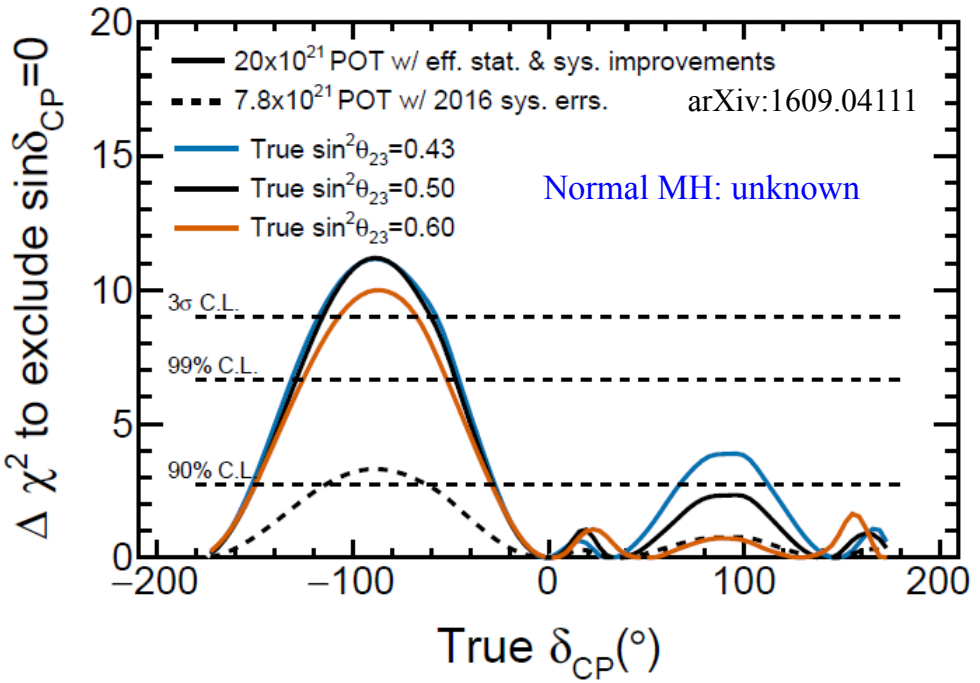
Normal Hierarchy: [-2.98, -0.60] radians

Inverted Hierarchy: [-1.54, -1.19] radians

CP conserving values 0, π both fall outside 2σ CL intervals

T2K-II Protons-On-Target Request

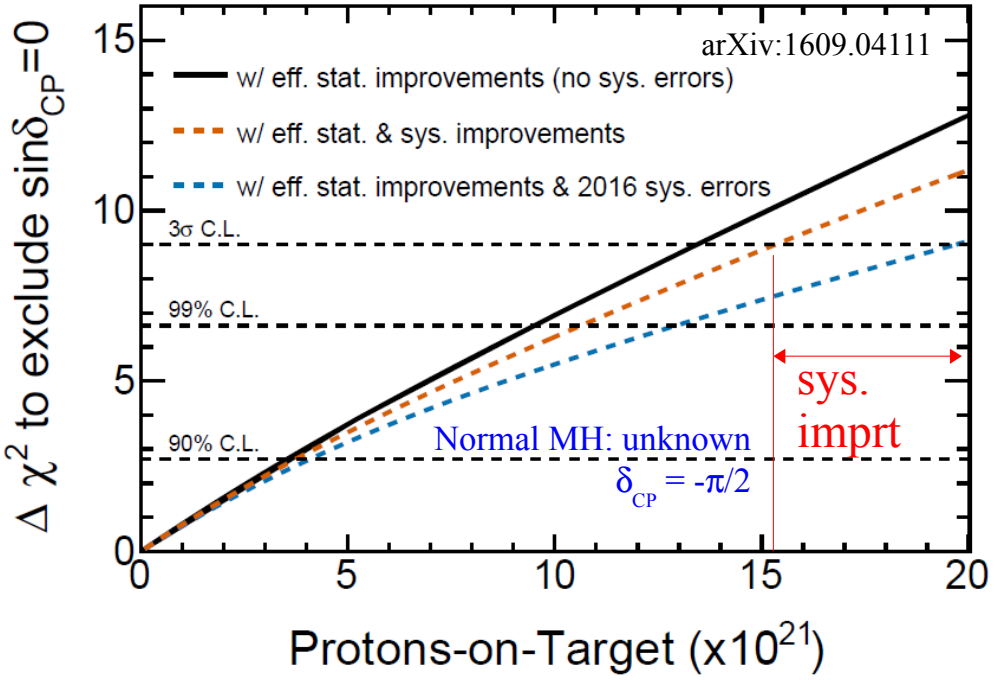




- Extension of T2K run to 20×10^{21} POT (~2026)
- Currently approved for 7.8×10^{21} POT (~2021)
- Accelerator and beam-line upgrades to 1.3 MW

3-σ sensitivity for CP violation for favorable parameters, if

- ✓ Full T2K-II exposure 20×10^{21} POT
- ✓ 50% improvement in effective statistics: horn current, SK event reconstruction
- ✓ Systematic uncertainties down to 2/3 of current size: ND upgrade



Outline

- Neutrino oscillations and the T2K experiment
- Joint oscillation analysis with ν_μ, ν_e, $\bar{\nu}_\mu$, and $\bar{\nu}_e$ samples
- Summary

Summary

- NEW since 2016 summer:
  - Doubled neutrino-mode statistics
  - New reconstruction and event selection at SK: effective improvement in statistics by ~30%
  - Improvements to neutrino interaction model
- Updated oscillation parameter estimates
  - CP conserving values of δ_{CP} are disfavored at 2σ level.
- T2K upgrade to collect 20×10^{21} POT and achieve 3σ (in case of favorable true values of δ_{CP}) sensitivity to exclude CP conserving values.

谢谢！

BACKUP

Neutrino Oscillations

Neutrino (flavor) oscillations depend on mixing angles, δ_{CP}-phase and mass differences.

$c_{ij} = \cos\theta_{ij}$

$s_{ij} = \sin\theta_{ij}$

PMNS matrix

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

$\theta_{ij} \neq 0$, δ_{CP}-phase irreducible → leptonic CP violation

$$\Delta_{ij} \equiv \frac{\Delta m^2_{ij} L}{4E}$$

With a $\bar{\nu}_\mu$ beam

flip sign

solar + KamLAND *et al.*

$$\Delta m^2_{ij} \equiv m^2_i - m^2_j$$

$$P(\bar{\nu}_\mu \to \bar{\nu}_e) \simeq \sin^2 2\theta_{13} \sin^2 \Delta_{32} \left(\sin^2\theta_{23} + \frac{\sin 2\theta_{12} \sin 2\theta_{23}}{2\sin\theta_{13}} \sin\delta_{CP} \sin\Delta_{21}\right)$$

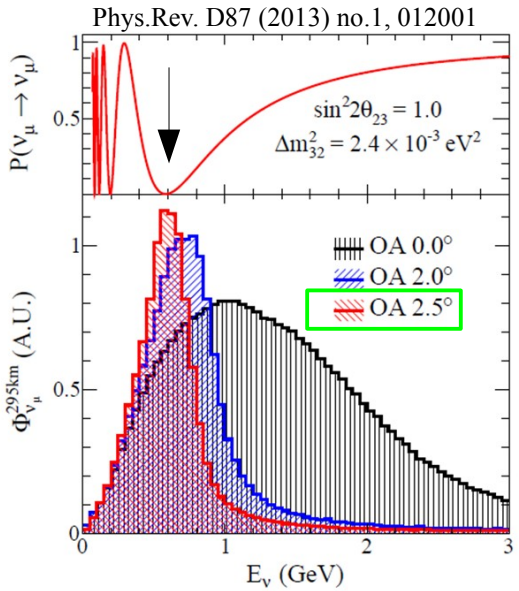
$$P(\bar{\nu}_\mu \to \bar{\nu}_\mu) = P(\nu_\mu \to \nu_\mu) \text{ by CPT symmetry}$$

CP-odd term in appearance channels allow extraction of δ_{CP} using neutrino and anti-neutrino beams, up to ±30% effect at T2K – unique opportunities for experiments with accelerator neutrinos

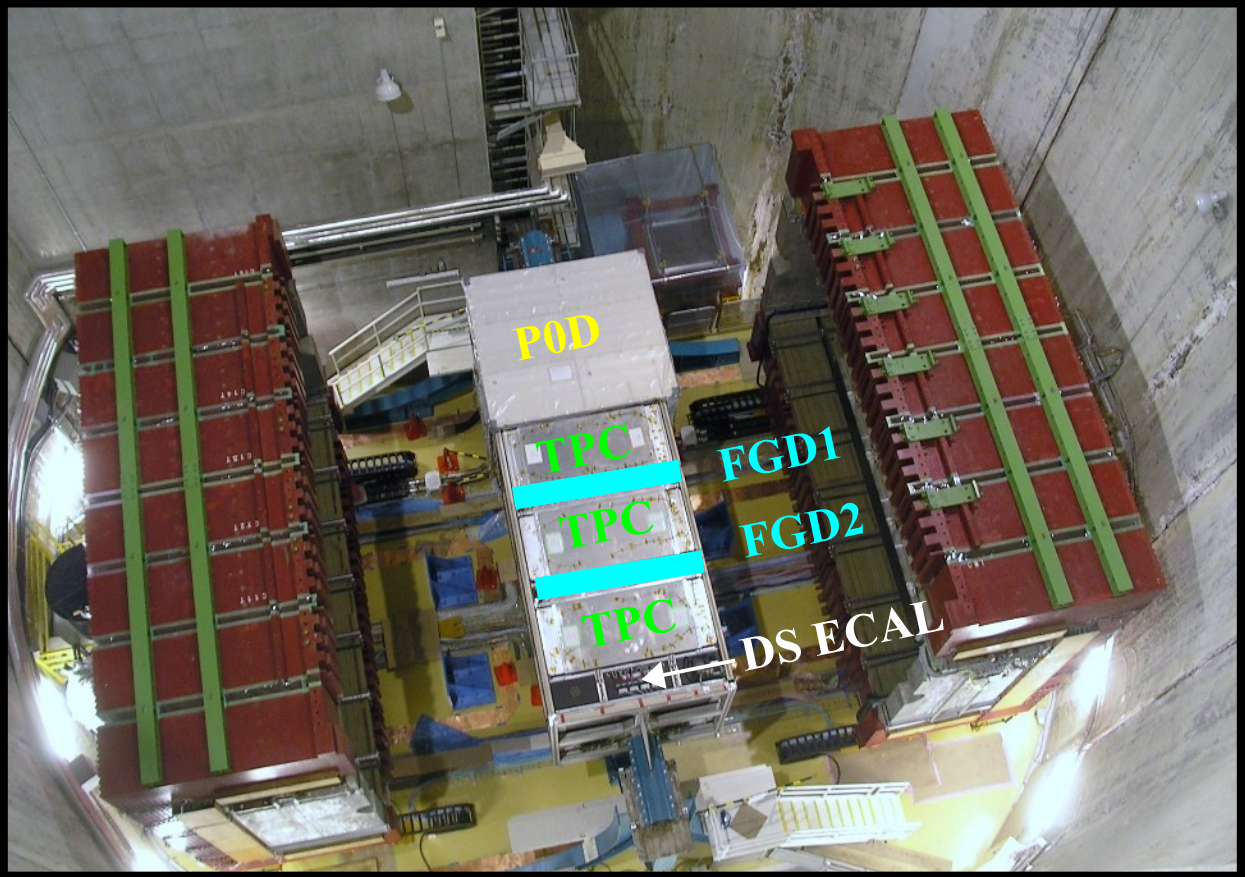
* neglecting matter effects

Off-axis neutrino beams:
Reduce dependence on pion energy → narrow-band

Spectrum peak at maximum disappearance @SK



T2K off-axis near detector (ND280)



P0D: Pi0 Detector
contains H_2O targets

Tracker:
- FGD: Fine-Grained Detector
  1. plastic scintillator C_8H_8 target
  2. $C_8H_8 + H_2O$ target
- Time Projection Chamber (TPC)

Electromagnetic Calorimeter (ECAL):
surrounding P0D and tracker

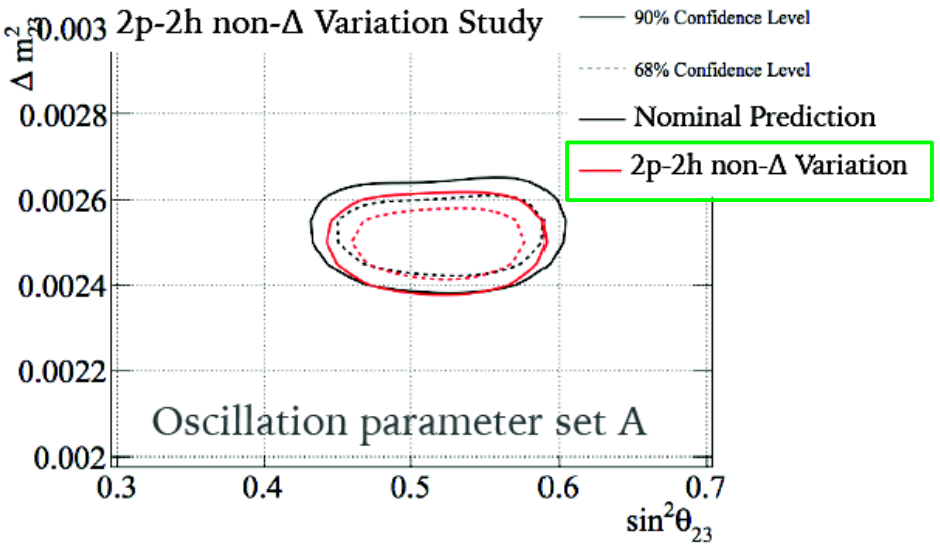
Side Muon Range Detector:
in magnet yokes

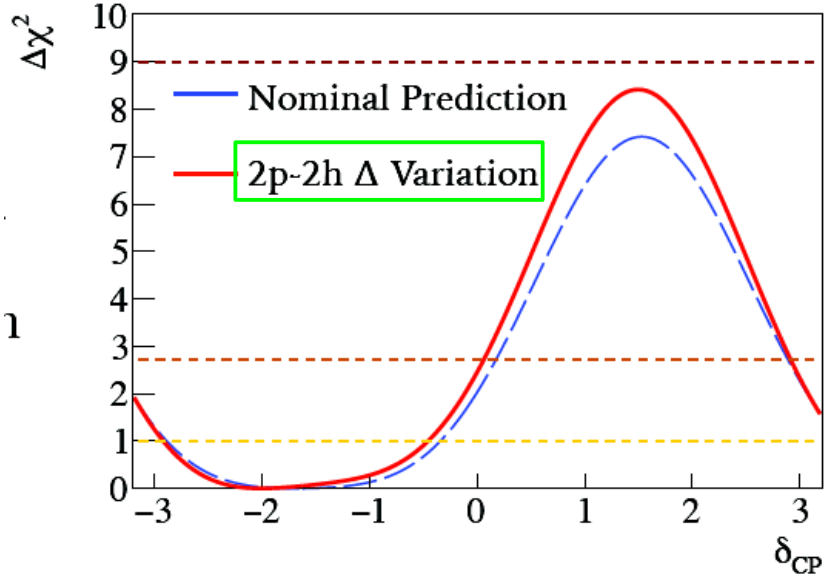
- constrain beam flux and cross section for oscillation analysis
- stand-alone neutrino interaction measurements

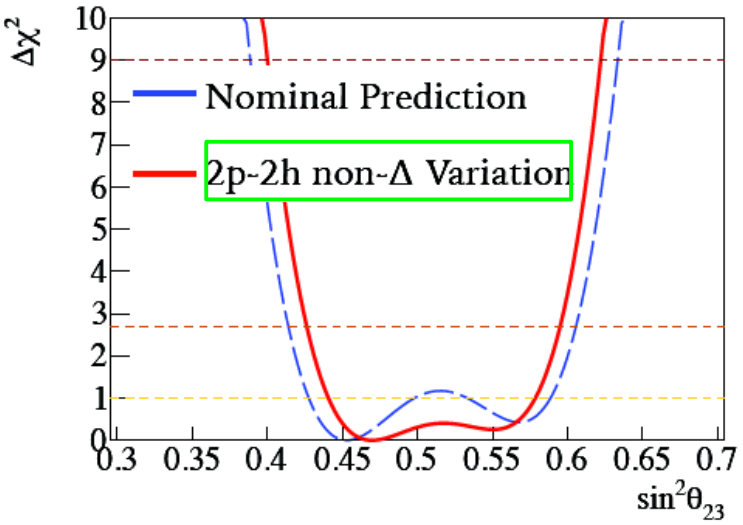
Impact of data-driven variation on sensitivity:

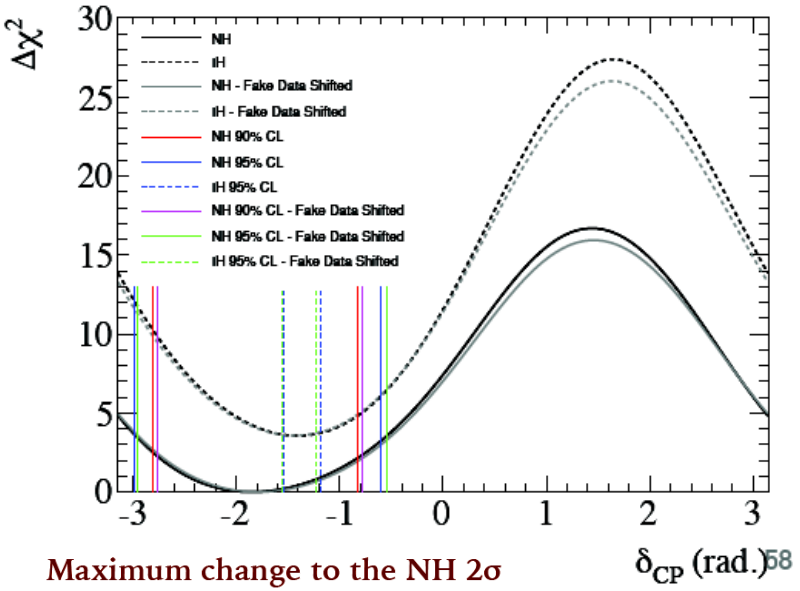
variation = pre-fit/model prediction difference at ND280

Shift $\Delta\chi^2$ observed in data (bottom plot) by difference observed in systematic study (top plot)









Maximum change to the NH 2σ confidence interval was 2.3%

Effect seen on $\sin^2\theta_{23}$ and Δm^2_{32}

Impact on δ_{cp} intervals is small

Will be addressed in future by 4π sample, hadronic recoil, ND upgrade

END