Antineutrino Results from T2K

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20150527
For the T2K Collaboration

Menu

- Introduce the T2K experiment and some recent results
- Muon Antineutrino Disappearance analysis ***(New!)***
- Future Prospects

Disappearance

$\nu_\mu \rightarrow \nu_x$

Oscillations

(predominantly ν_τ, Undetected)

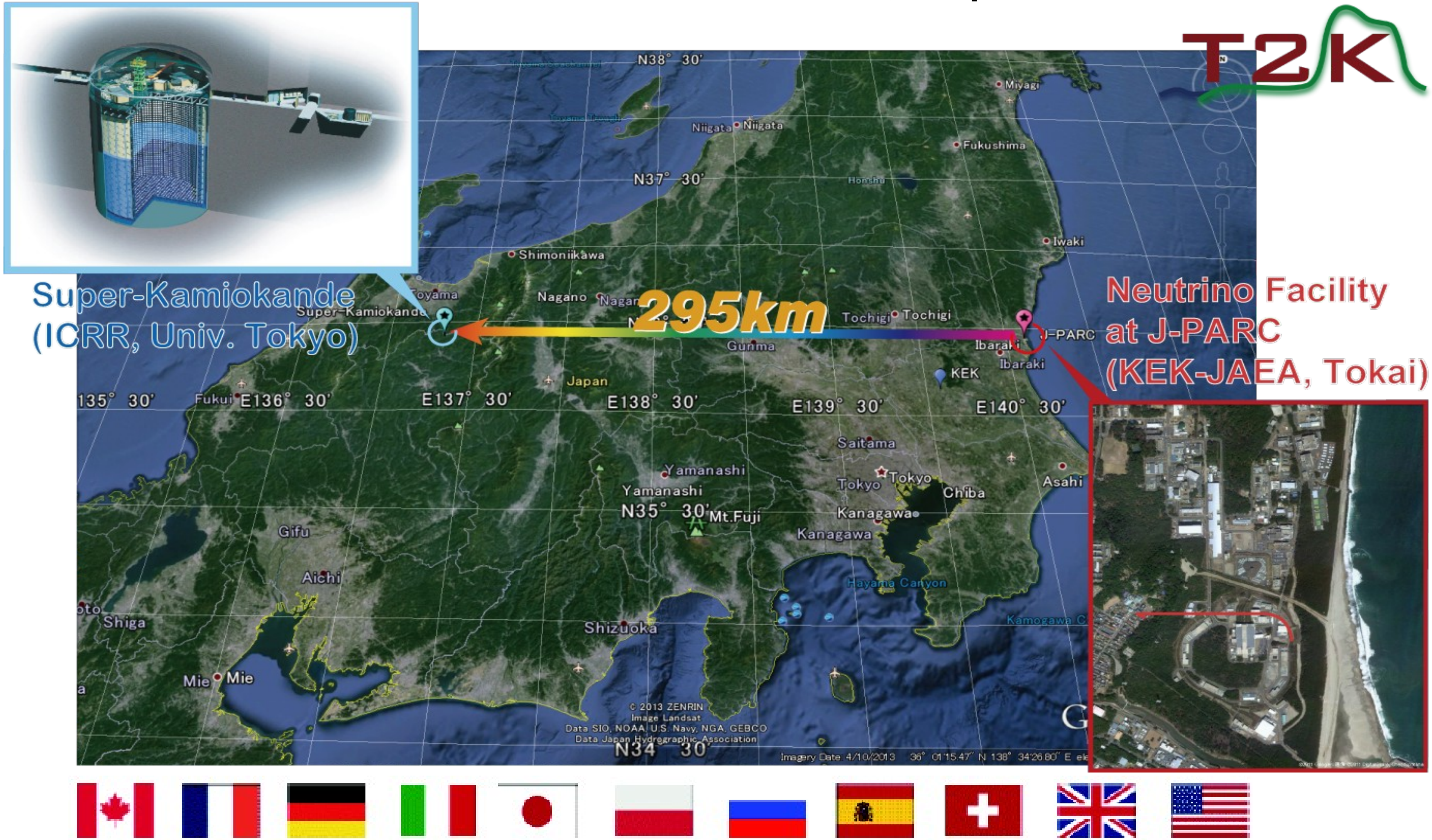
Disappearance

$\bar{\nu}_\mu \rightarrow \bar{\nu}_x$

Oscillations

(predominantly $\bar{\nu}_\tau$, Undetected)

The T2K (Tokai-to-Kamioka) experiment



Discovery of $\nu_\mu \rightarrow \nu_e$ oscillation

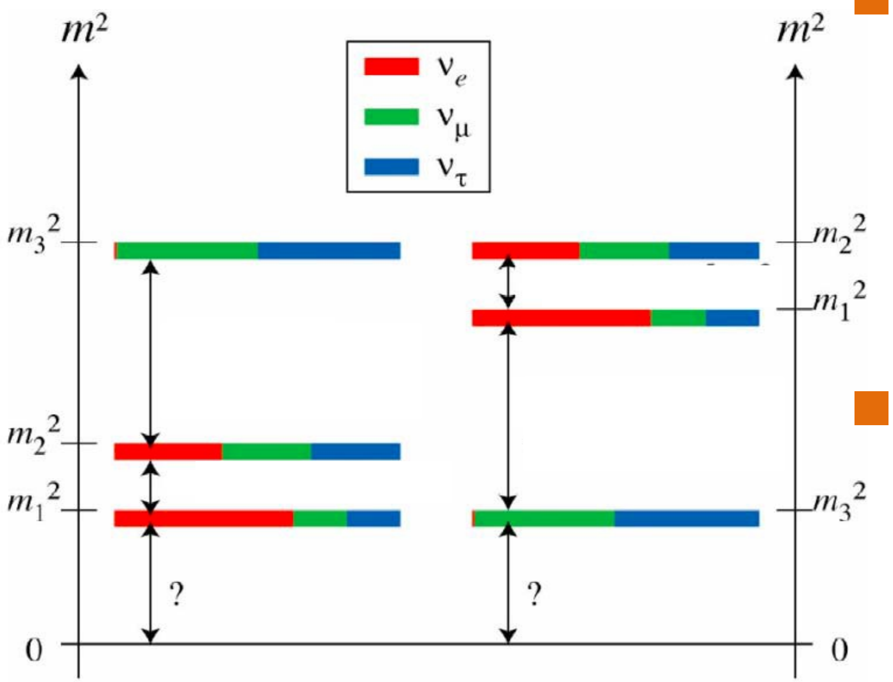
Precision measurements of $\nu_\mu \rightarrow \nu_\tau(x)$ oscillation

Cross - section measurements

Status of Neutrino Oscillations

Atmospheric   Solar

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



Normal Hierarchy   Inverted Hierarchy

- Mixing between all three neutrino flavors has been observed
  - θ_{12} = 33.4 ± 0.8°
  - θ_{13} = 8.8 ± 0.4°
  - θ_{23} = 45.8 ± 3.2° (octant?)
- Two Mass Differences
  - Δm^2_{12} ~ 7.5e-5 eV^2
  - $|\Delta m^2_{32}|$ ~ 2.4e-3 eV^2 (hierarchy?)
- CP-phase ,**δcp remains largely unkown**
  - [-1,-0.14] π and [0.87,1]π 90% C.L.
- Absolute value of mass states is unknown

Phenomenology Oscillations

- For a fixed baseline, L, energy, E, and a ν_μ source
- ν_e **appearance**

$$P(\nu_\mu \to \nu_e) = 4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2 \Phi_{31} \left(1 + \frac{2a}{\Delta m_{31}^2}(1 - 2S_{13}^2)\right) \quad \to \text{Leading, matter effect}$$

$$+ 8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cos\Phi_{32} \sin\Phi_{31} \sin\Phi_{21} \quad \to \text{CP conserving}$$

$$- 8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \sin\Phi_{32} \sin_{31} \sin\Phi_{21} \quad \to \text{CP violating}$$

$$+ 4S_{12}^2 C_{13}^2 (C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta) \sin^2\Phi_{21} \quad \to \text{Solar}$$

$$- 8C_{13}^2 S_{13}^2 S_{23}^2 (1 - 2S_{13}^2) \frac{aL}{4E} \cos\Phi_{32} \sin\Phi_{31} \quad \to \text{Matter effect}$$

  - Probability is coupled to ***all*** oscillation parameters
    - Atmospheric mixing parameters must also be well known!
  - *Possible to study CP violation in neutrinos!*

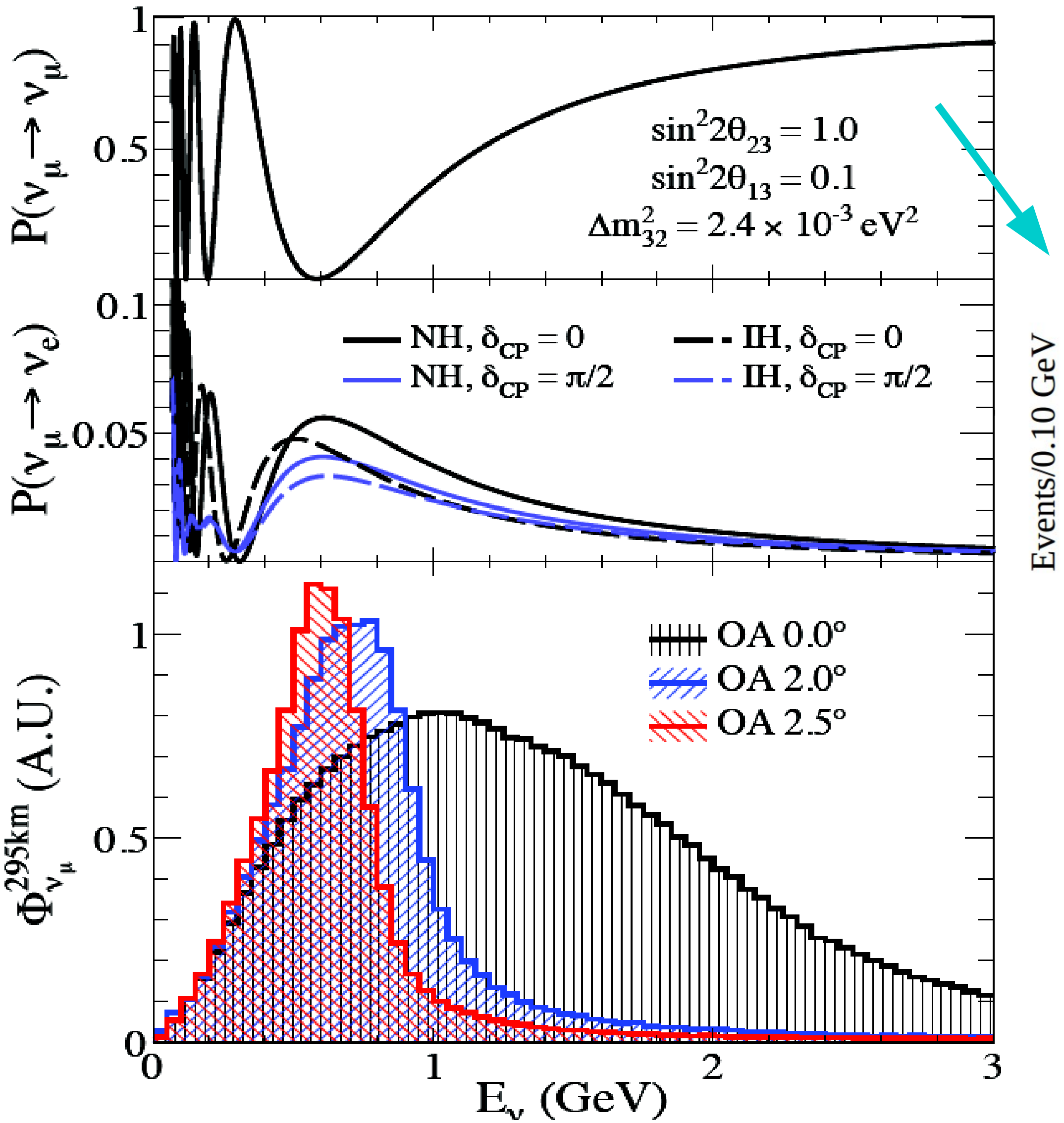
$$\Delta \equiv \frac{\Delta m_{31}^2 L}{4E}$$

- ν_μ **disappearance**

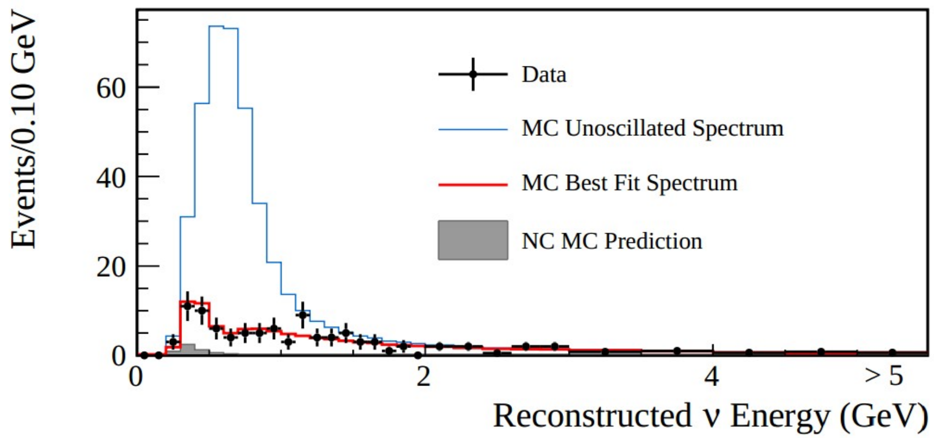
$$P(\nu_\mu \to \nu_\mu) \approx 1 - (\cos^4\theta_{13} \sin^2 2\theta_{23} + \sin^2 2\theta_{13} \sin^2\theta_{23}) \sin^2 \Delta$$

- T2K can observe ***both*** phenomena: Oscillation Maximum **~ 600 MeV**

Neutrino Oscillations : Neutrino Mode Disappearance

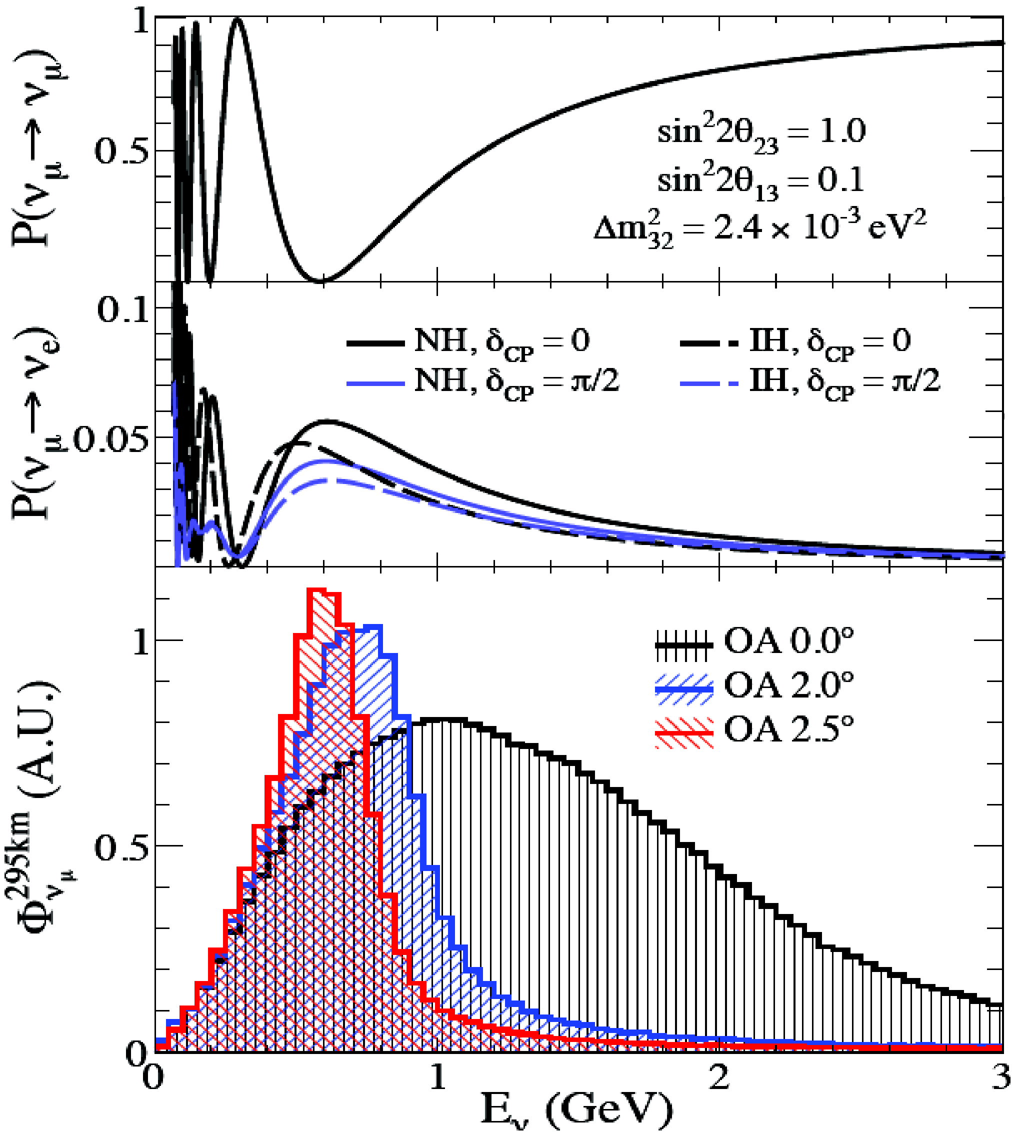


- Location and depth of oscillation "dip" determine mixing parameters, Δm^2_{23} and $\sin^2\theta_{23}$

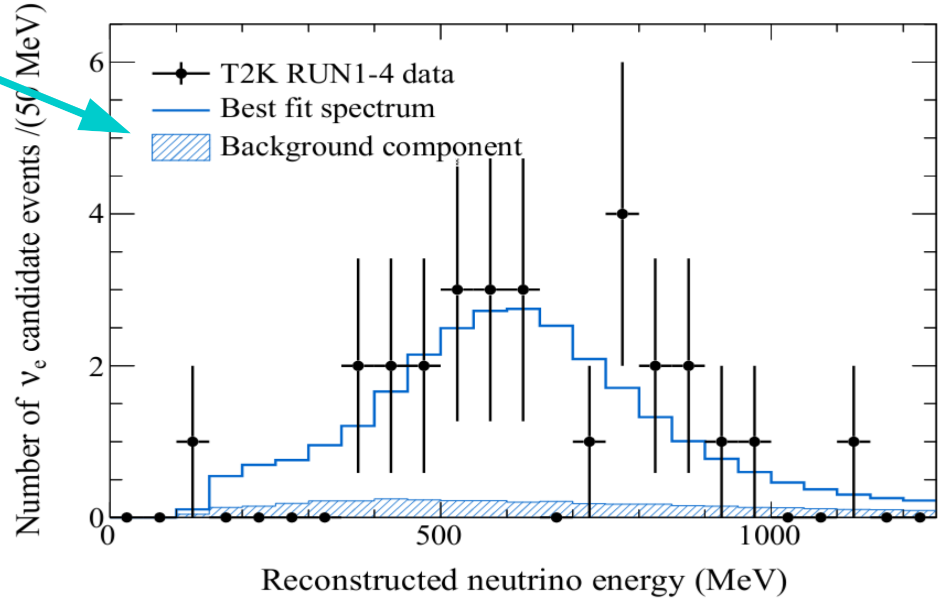


Type	Event Rate
MC Expectation	**124.98**
Observation	**120**
MC without Osc.	445.98

Neutrino Oscillations : Neutrino Mode Appearance



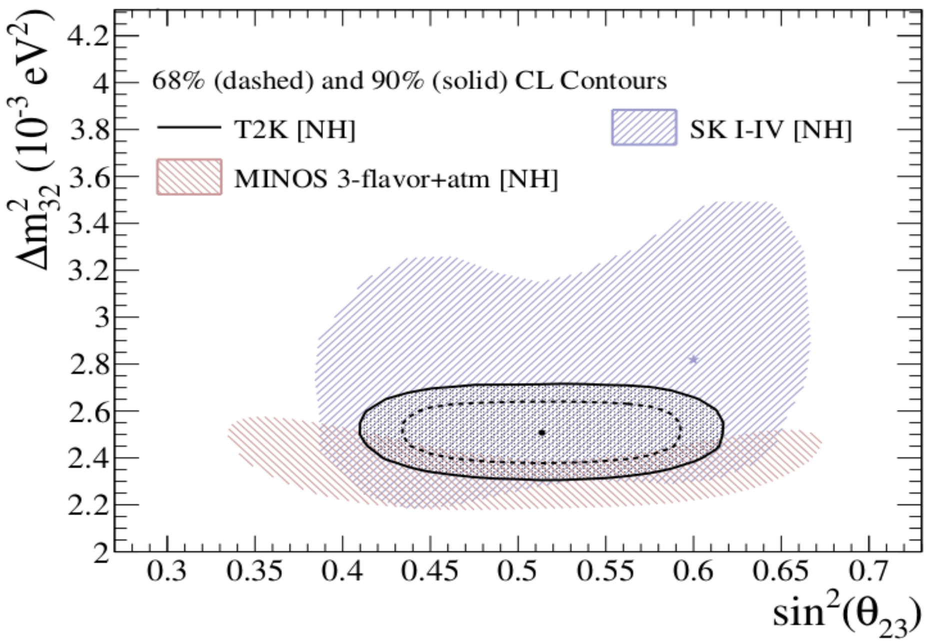
- Size of the appearance signal is sensitive to $\sin^2\theta_{13}$, δ_{cp}, and the mass hierarchy



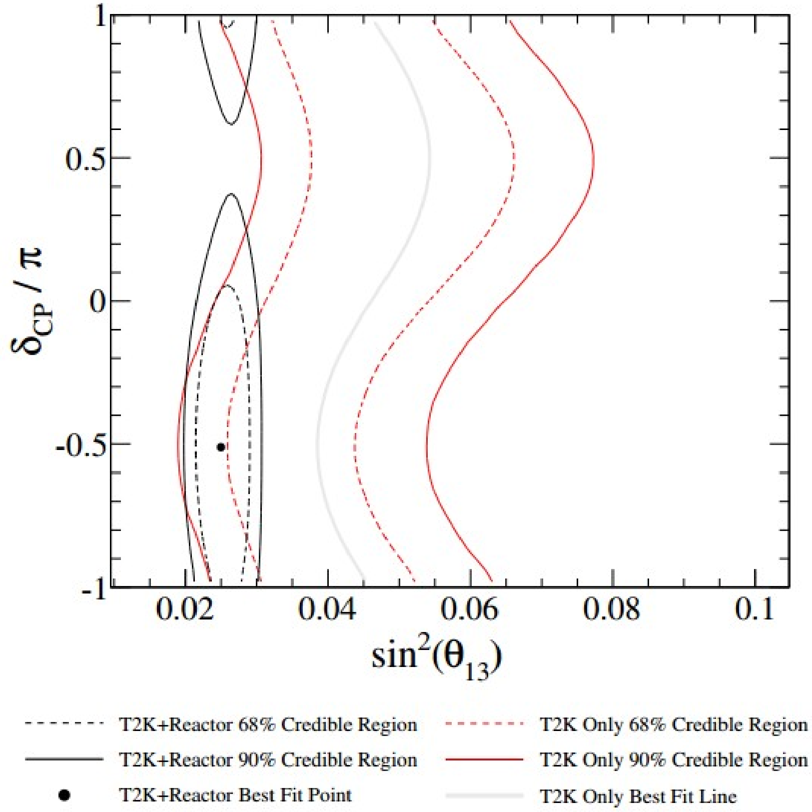
Type	Event Rate
MC Expectation	**21.06**
Observation	**28**
MC without Osc.	4.97

T2K Results: Run 1-4 (2014)

Disappearance



Appearance

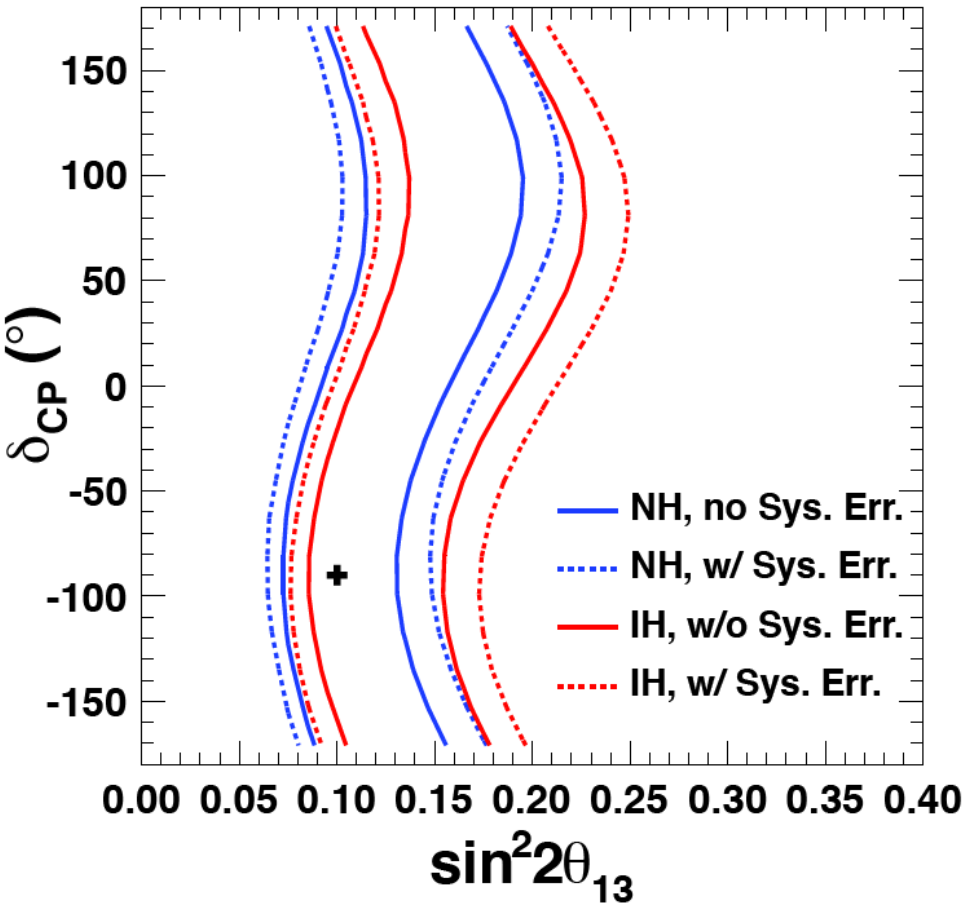


- T2K currently has the most precise measurement of the neutrino disappearance parameters
- 7.3σ observation of $\nu_\mu \rightarrow \nu_e$ appearance
- Combination with reactor neutrino measurements has provided first constraints on δ_{cp}

	90% CL Inclusion
NH	$\delta_{CP} \in [-1.18, 0.15]\pi$
IH	$\delta_{CP} \in [-0.91, -0.08]\pi$

T2K Future: The Case for Antineutrino Measurements

Neutrino Data Only



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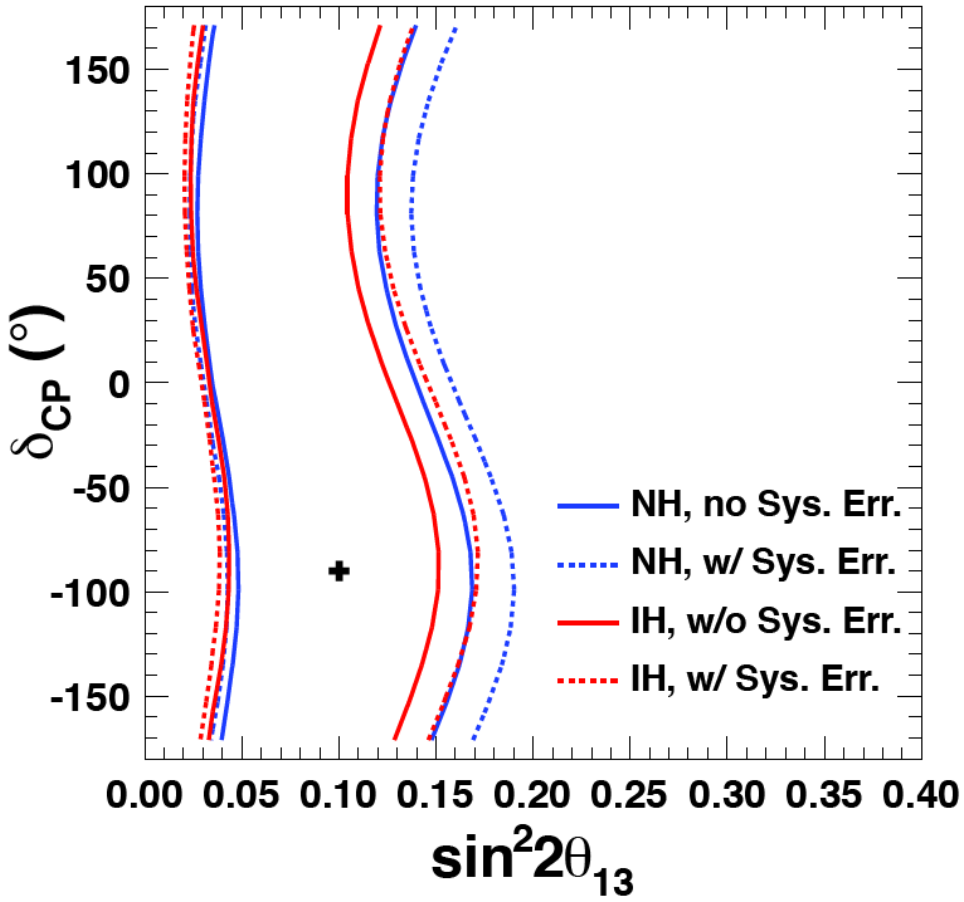
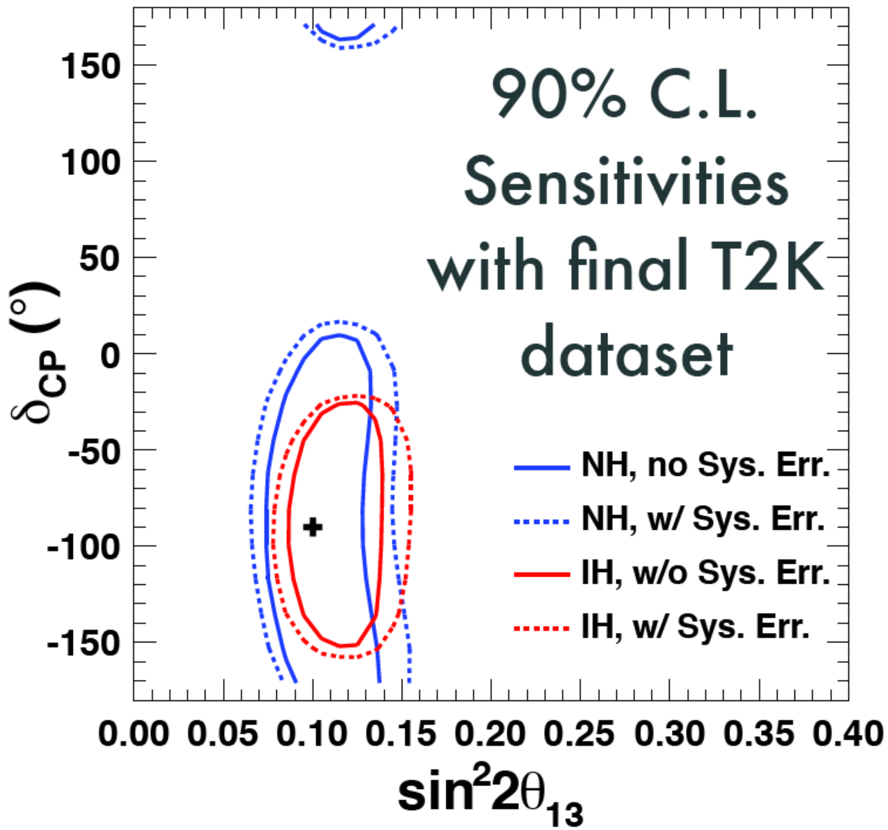


- No constraint on CP-violating parameter, δ_{cp}, using only neutrino or antineutrino mode data

T2K Future: The Case for Antineutrino Measurements

50:50
Neutrino : Antineutrino

7.8×10^{21} POT

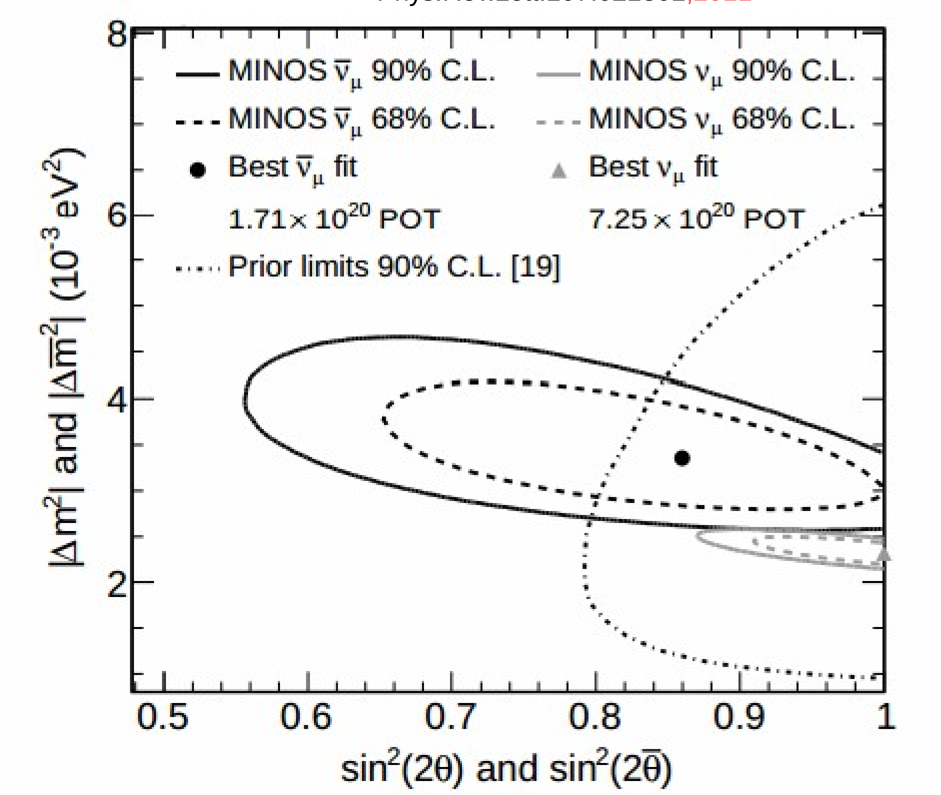


- However, T2K can make a 90% C.L. measurement of this parameter and even CP violation itself under fortunate scenarios

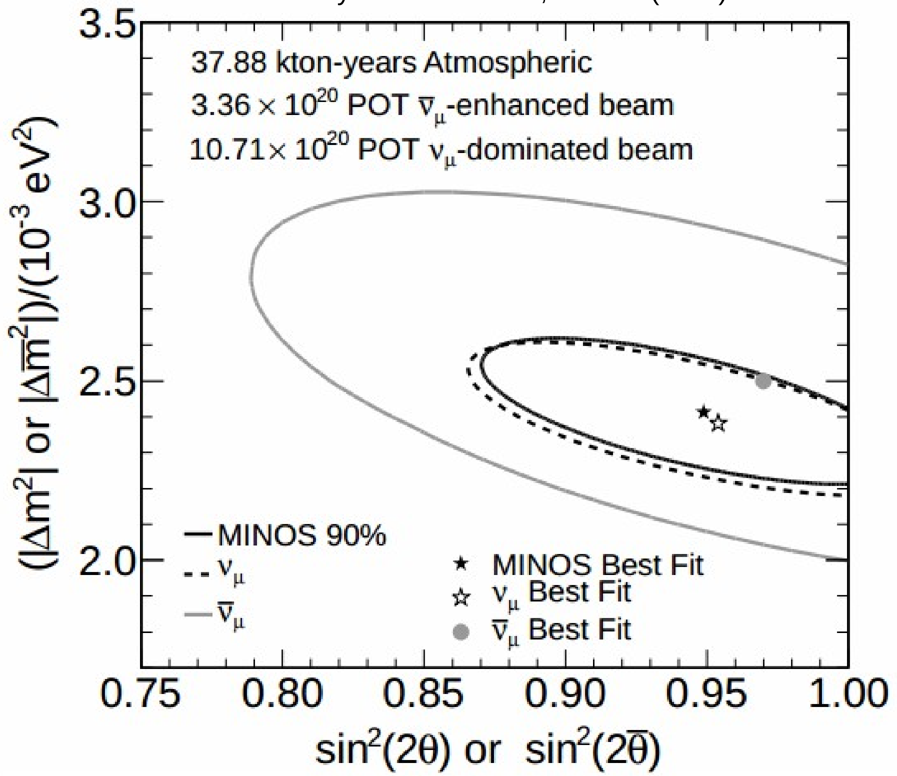
- Further, measurements of this sort at T2K are a baseline for future measurements envisioned by the high-statistics experiment, Hyper-K

T2K Present: The Case for Antineutrino Disappearance

Phys.Rev.Lett.107:021801,2011

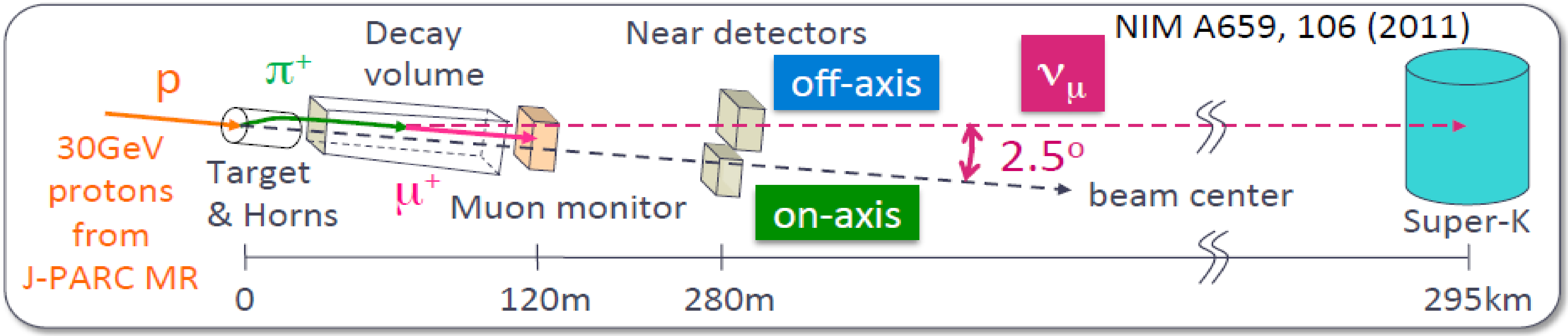


Phys. Rev. Lett. 110, 251801 (2013)

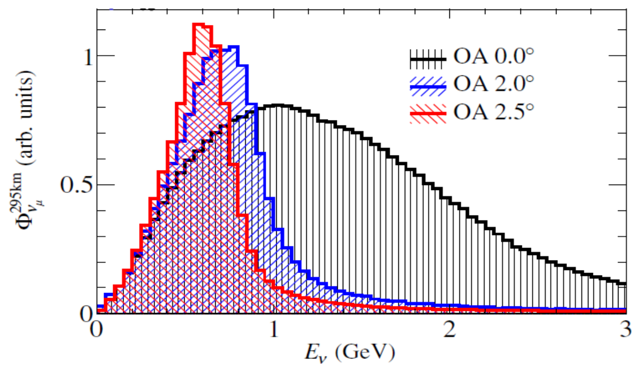


- Study the behavior of neutrino and antineutrino oscillations
  - Test of the CPT theorem
  - Probe of exotic oscillation models
- The antineutrino appearance probability is a strong function of the oscillation parameters disappearance experiments measure
  - Important input for future appearance studies

The Basic Idea of the Experiment



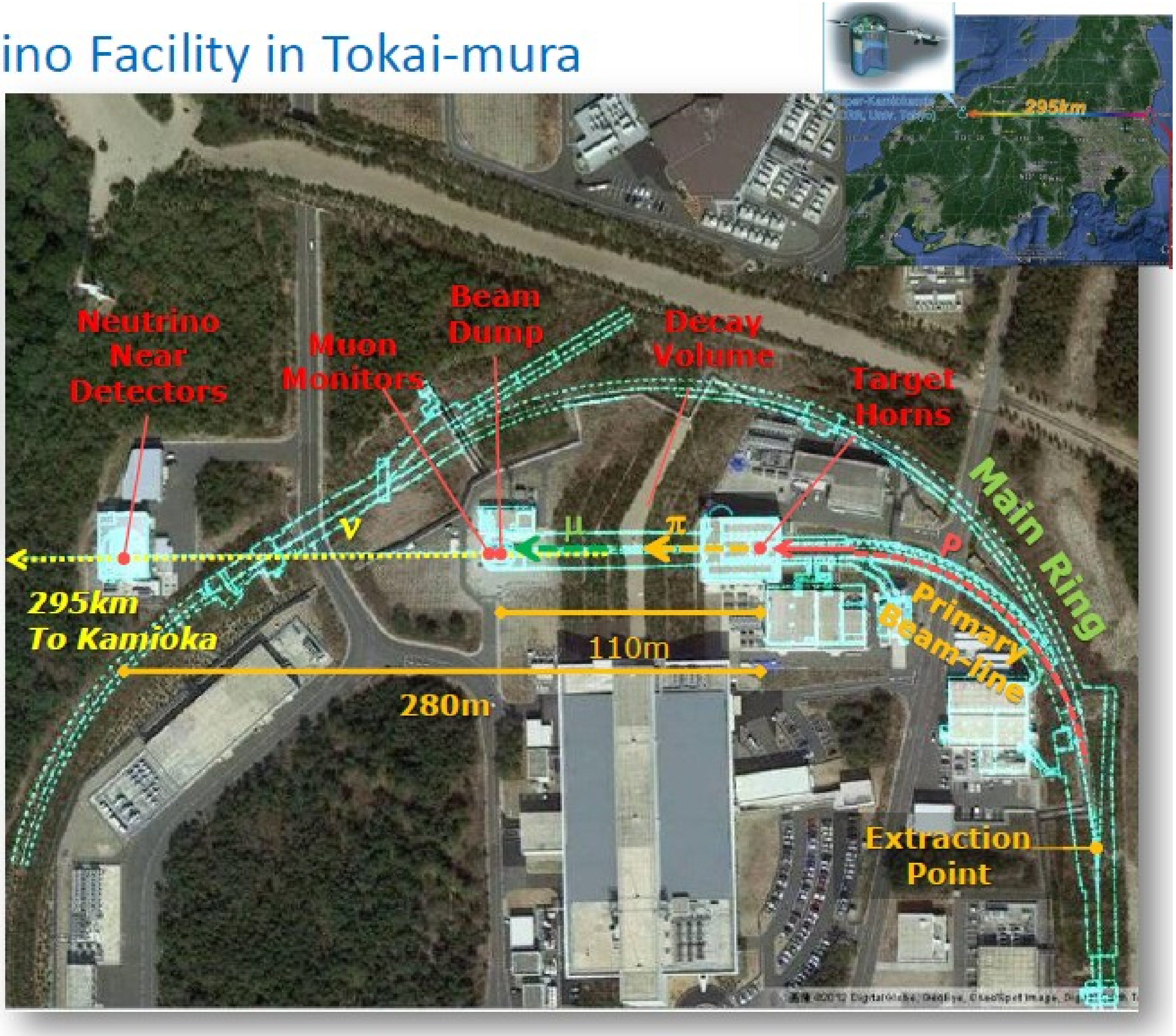
- T2K uses a 44 mrad off-axis beam to achieve a sharp ν energy profile peaked at 600 MeV (~oscillation maximum)



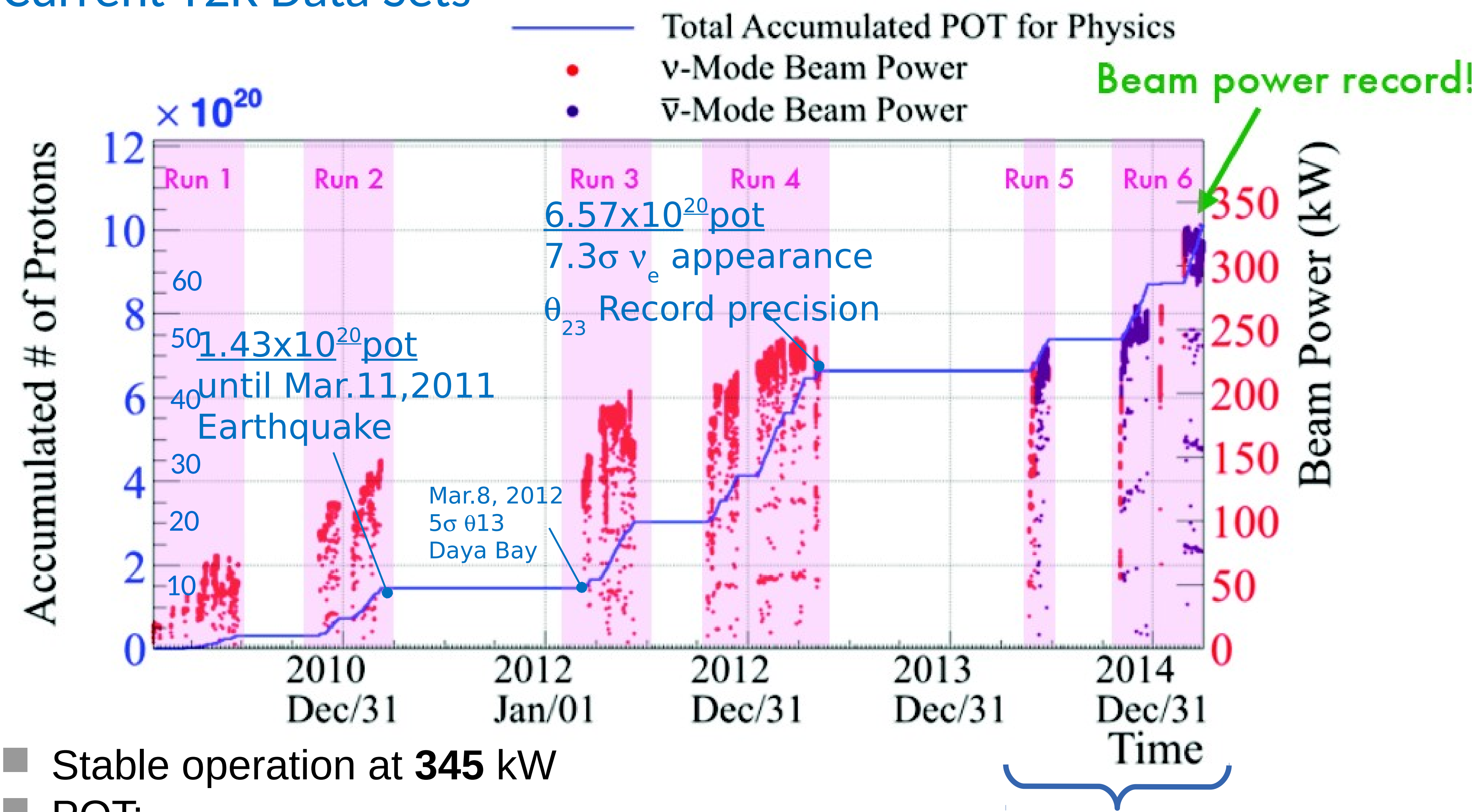
T2K Summary

- Beamline, Target, and Horns (L=0) : Create neutrino beam
- On-axis near detector (L=280m) : Measure beam direction precisely
- Off-axis near detector (L=280m) : Measure unoscillated flux
- Far detector (L=295**km**) : Measure oscillated flux

J-PARC Neutrino Facility in Tokai-mura



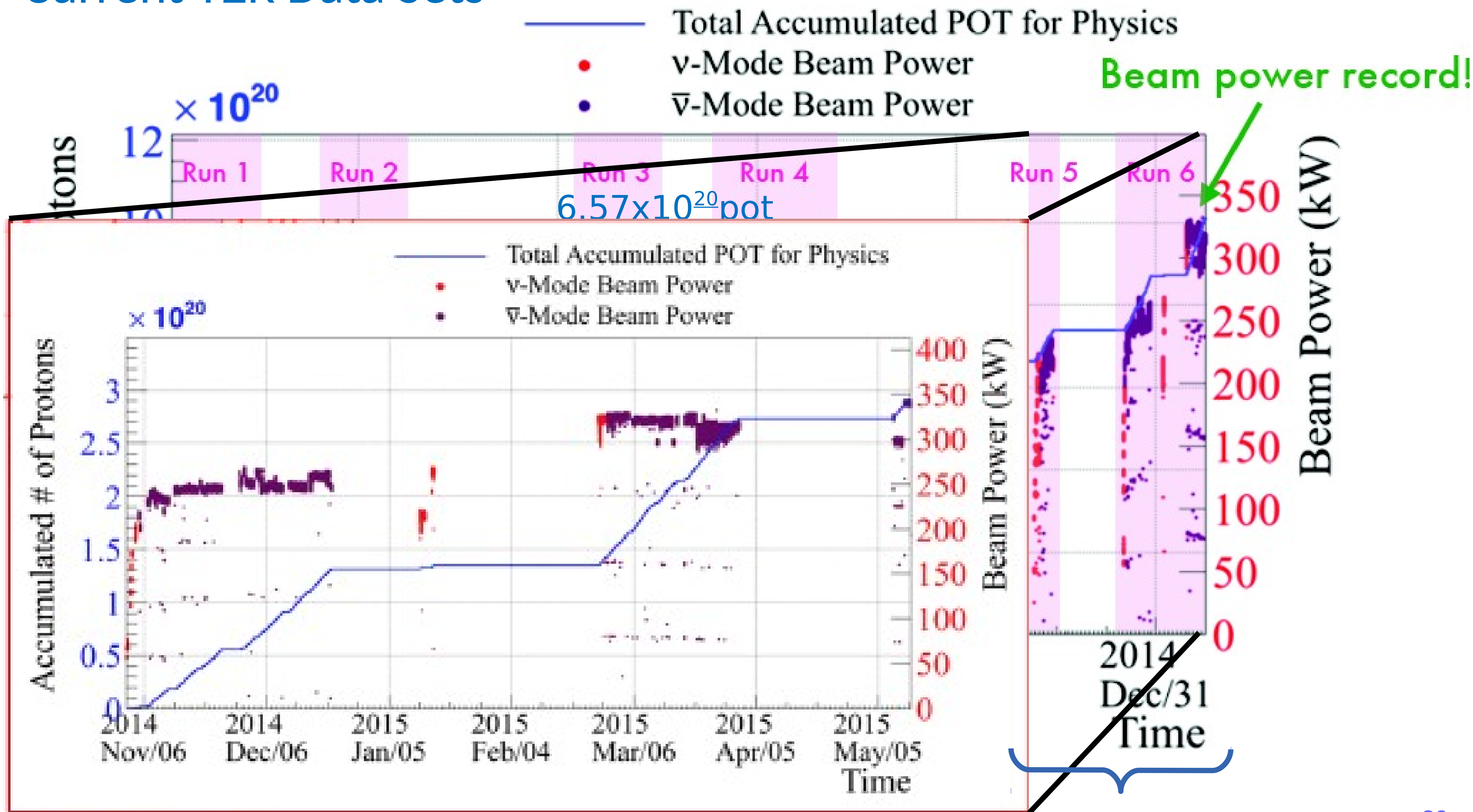
Current T2K Data Sets



- Stable operation at **345** kW
- POT:
  - **Neutrino Mode**: 7.0 × 10^{20}
  - **Antineutrino Mode**: 3.3 × 10^{20}

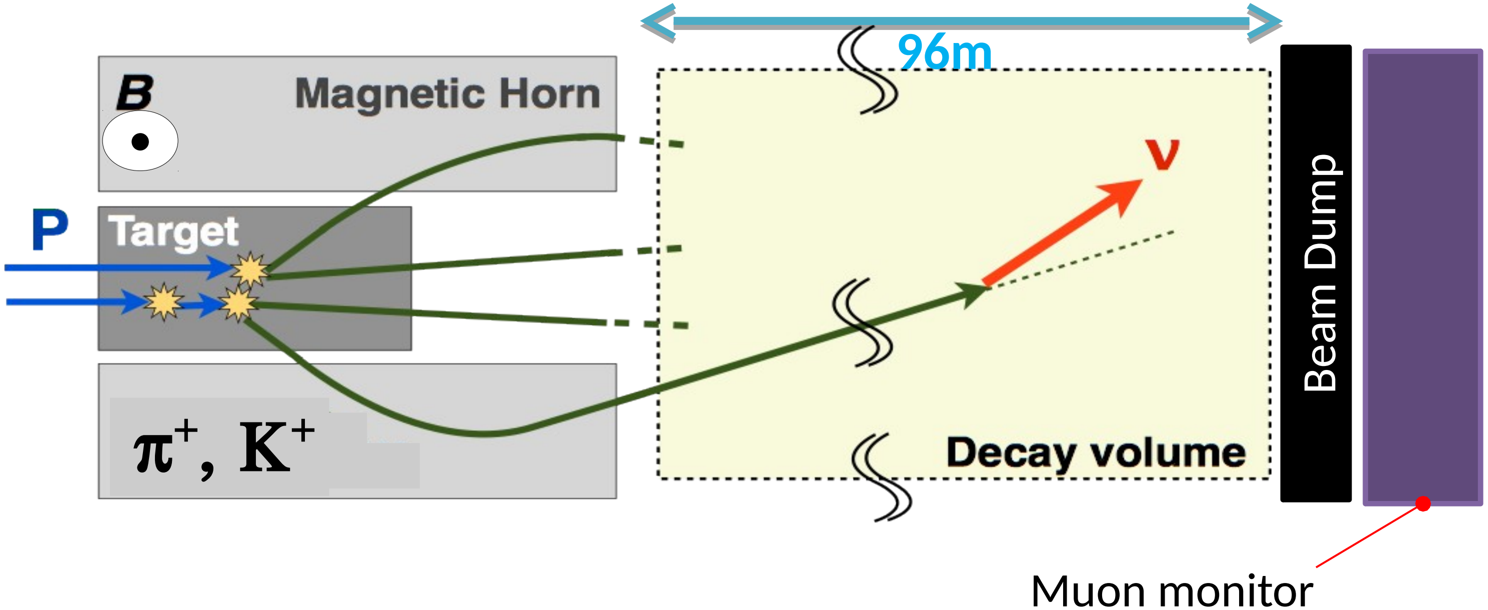
- **[Today's Results 2.3×10^{20}]**

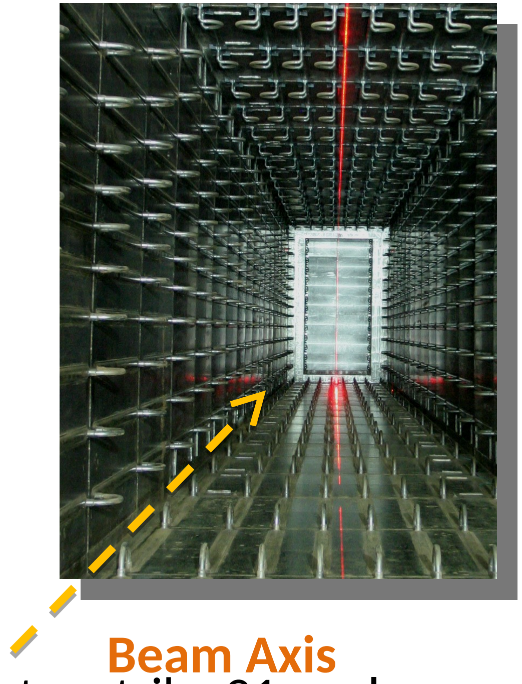
Current T2K Data Sets



- **Neutrino Mode**: 7.0×10^{20}
- **Antineutrino Mode**: 3.3×10^{20}
- [Today's Results 2.3×10^{20}]

Hadron Decay Into ν : Neturino Mode





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

$$\hookrightarrow e^+ \nu_e \bar{\nu}_\mu$$

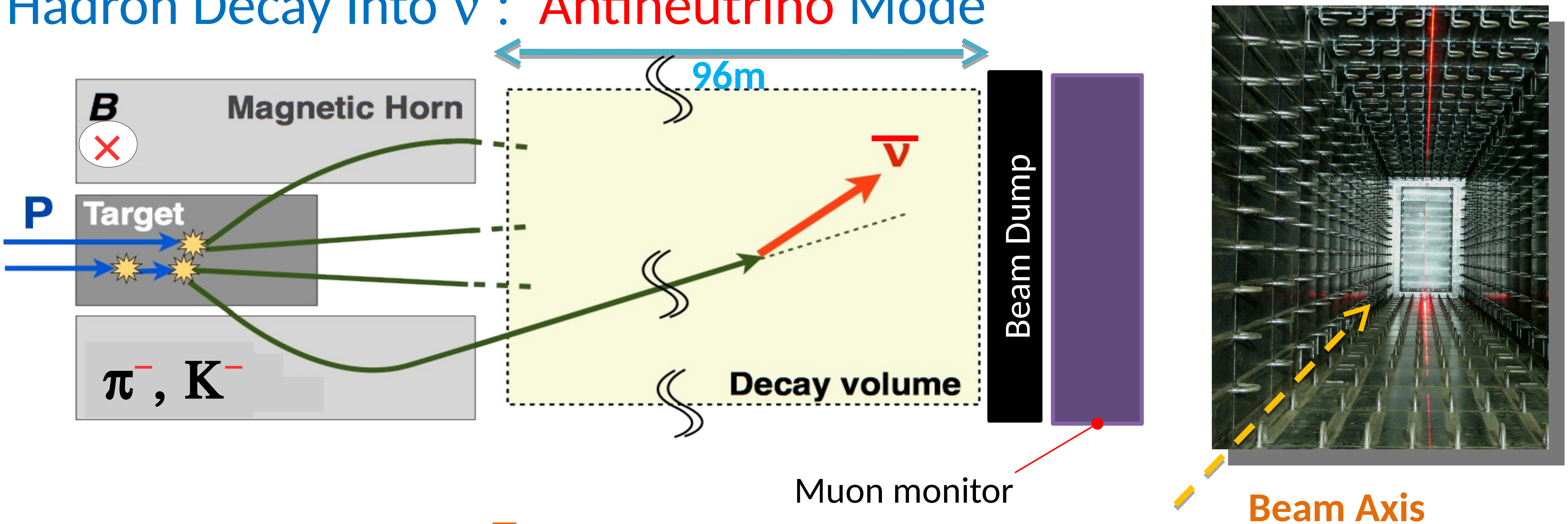
$$K^+ \rightarrow \mu^+ \nu_\mu$$

$$K^+ \rightarrow \pi^0 \mu^+ \nu_\mu$$

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

- 31 GeV/c protons from JPARC accelerator strike 91 cm long graphite target, neutrinos are produced from decays of emerging pions
- Resulting beam is almost entirely ν_μ
  - Intrinsic contamination of ν_e from muon decays, a background for appearance search
- Protons and other hadrons that have not decayed are stopped in a beam dump if p < 5 GeV/c
- Higher energy muons are observed by a downstream muon monitor

Hadron Decay Into ν : Antineutrino Mode



$$\pi^- \rightarrow \mu^- \ \bar{\nu}_\mu$$

$$\hookrightarrow e^- \ \bar{\nu}_e \ \nu_\mu$$

$$K^- \rightarrow \mu^- \ \bar{\nu}_\mu$$

$$K^- \rightarrow \pi^0 \mu^- \ \bar{\nu}_\mu$$

$$K^- \rightarrow \pi^0 e^- \ \bar{\nu}_e$$

- 31 GeV/c protons from JPARC accelerator strike 91 cm long graphite target, neutrinos are produced from decays of emerging pions
- Resulting beam is almost entirely $\bar{\nu}_\mu$
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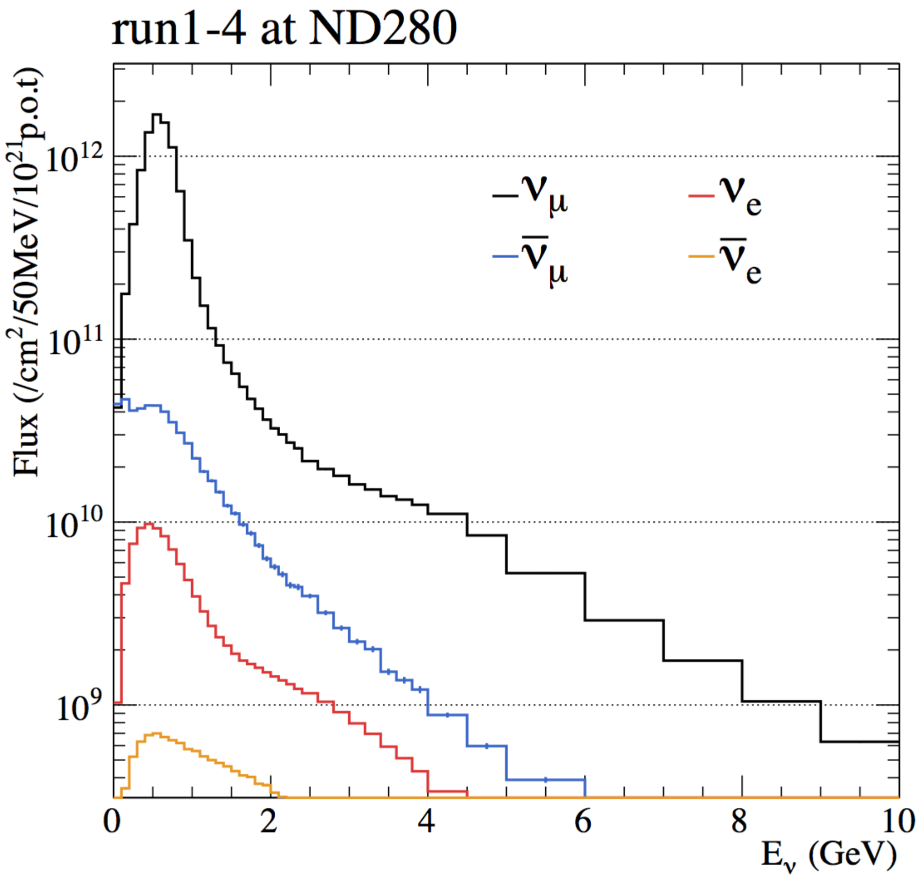
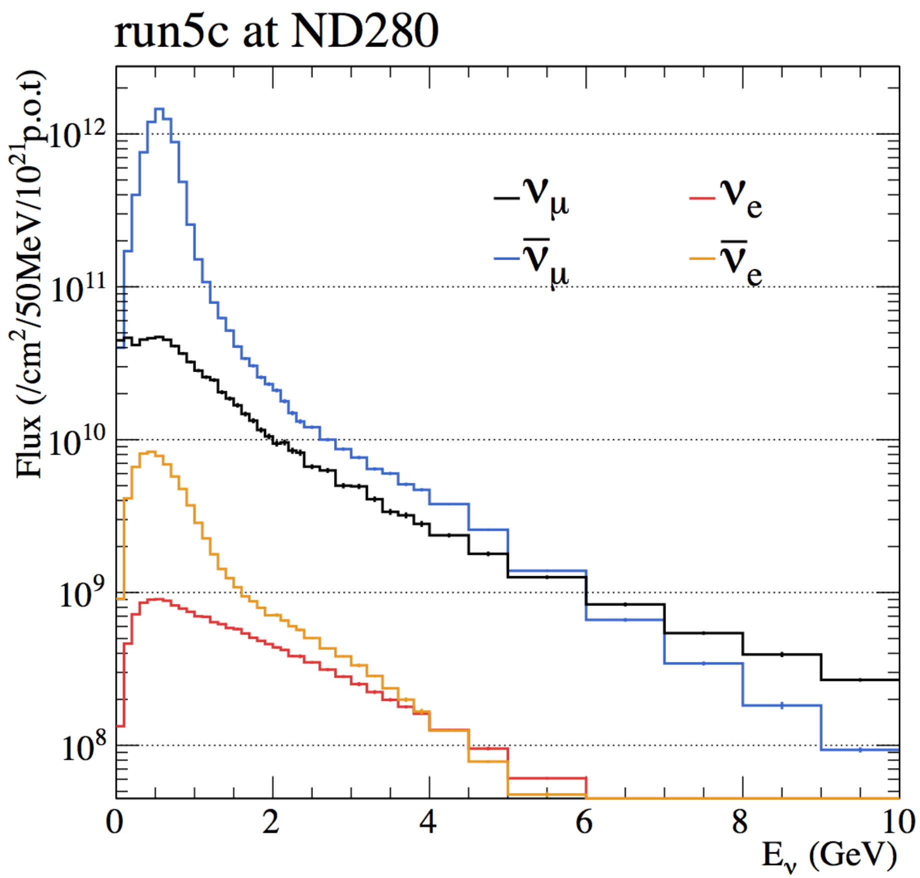
Beam Composition

Neutrino Mode

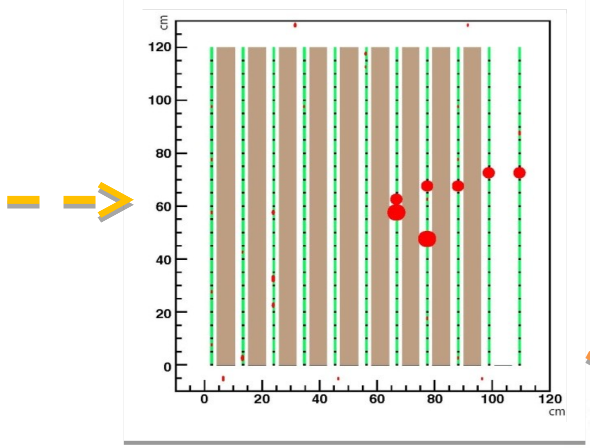


Antineutrino Mode

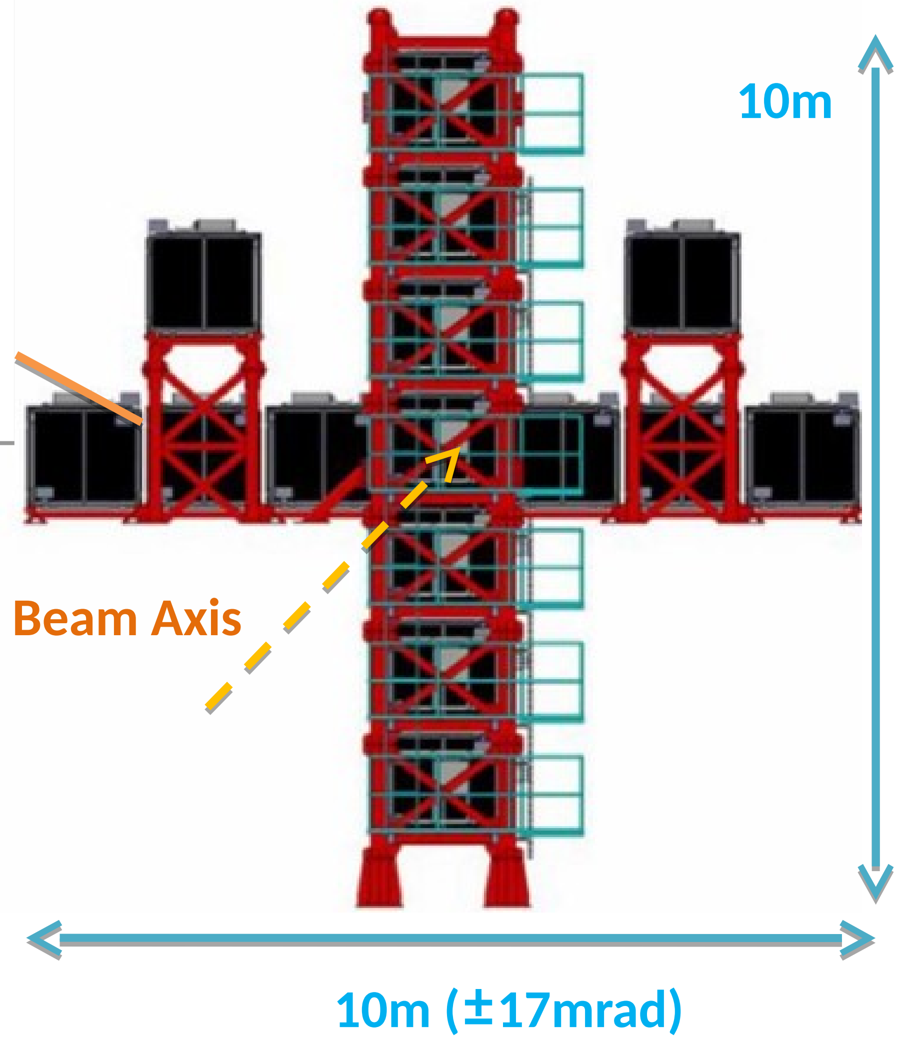


- Wrong sign component of antineutrino mode flux is larger than that of the neutrino mode flux
- Muonic neutrinos comprise the majority of the flux

On-Axis Near Detector, INGRID (L=280m)

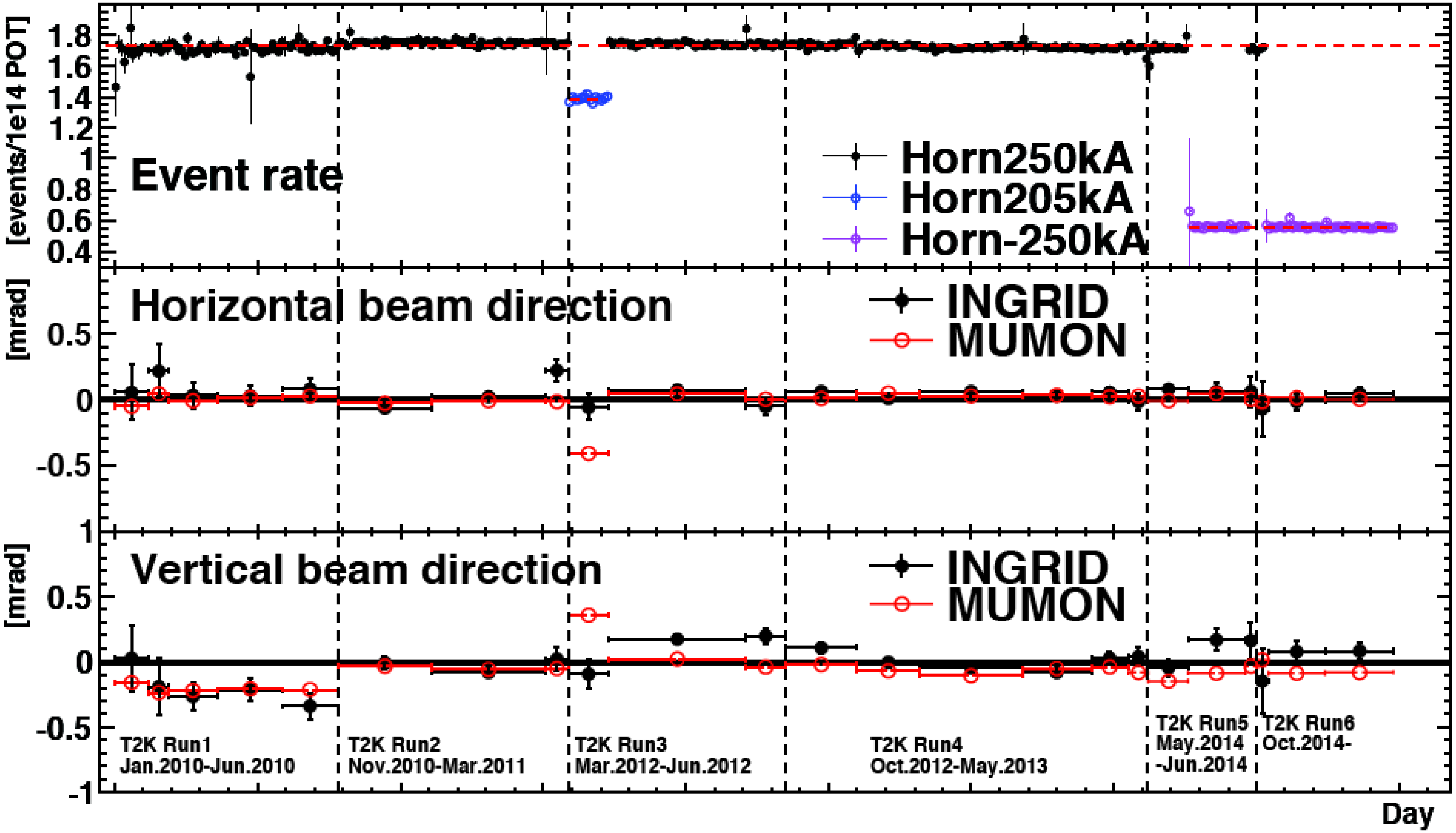


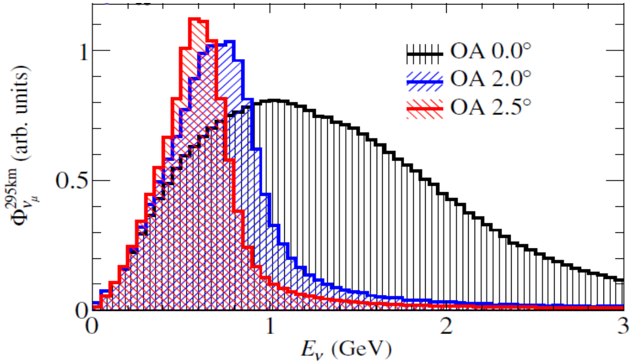
- Composed of 16 modules
- Modules are alternating sheets of iron target and plastic scintillator
  - 11 tracking planes surrounded by veto planes to reject external particles
- Measures beam direction and profile
- Muons as a function of angle from the beam axis



- Select events with long tracks in each module, fit for the beam rate and position

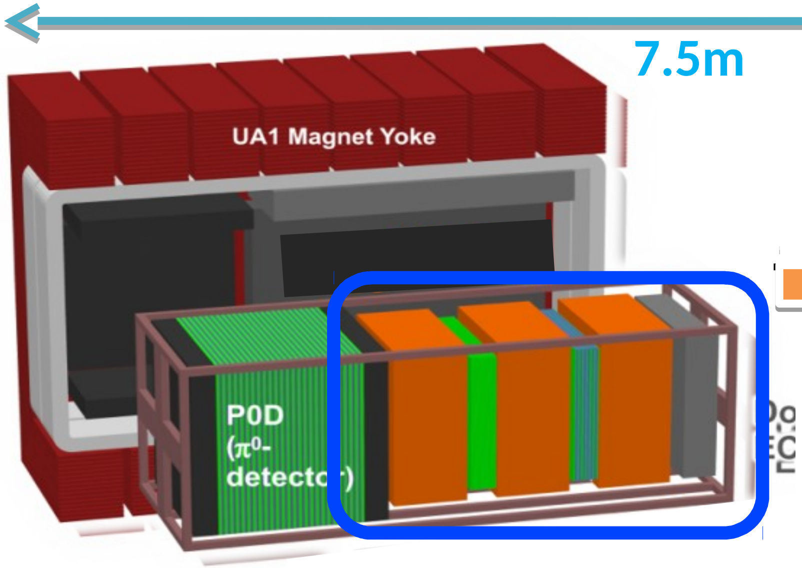
Beam Stability With INGRID

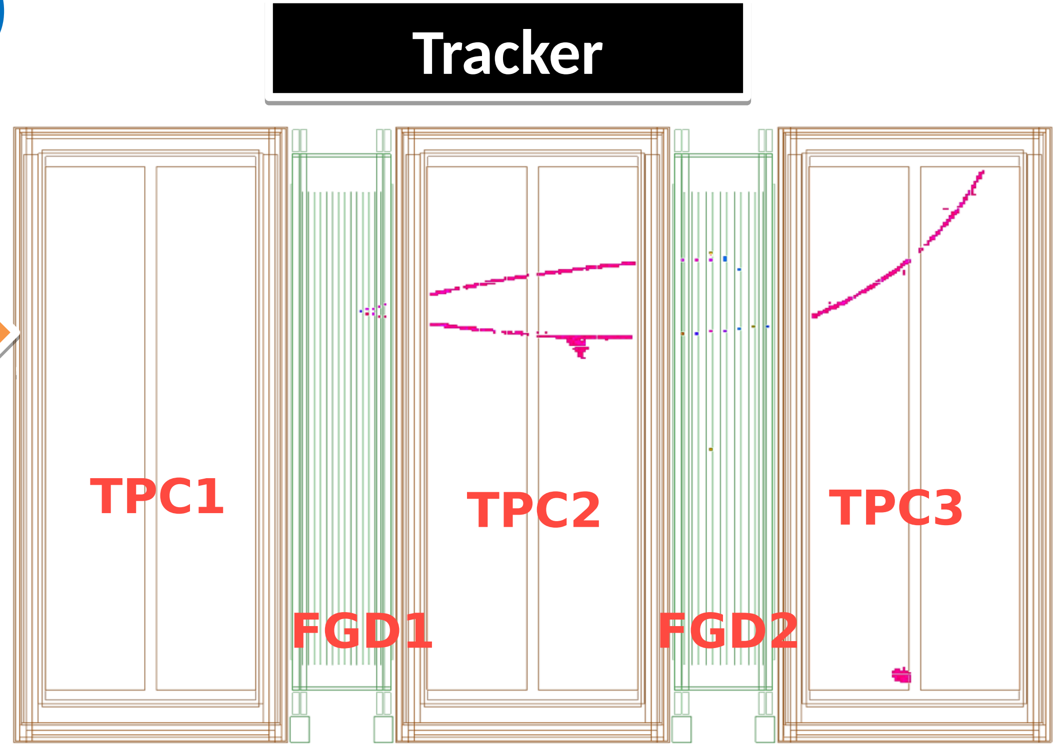




- POT normalized event rate stable to less than 1%
- Beam direction is stable to within 1mrad
  - **1 mrad** shift → **2%** shift in ν peak energy

Off-Axis Near Detector (L=280m)



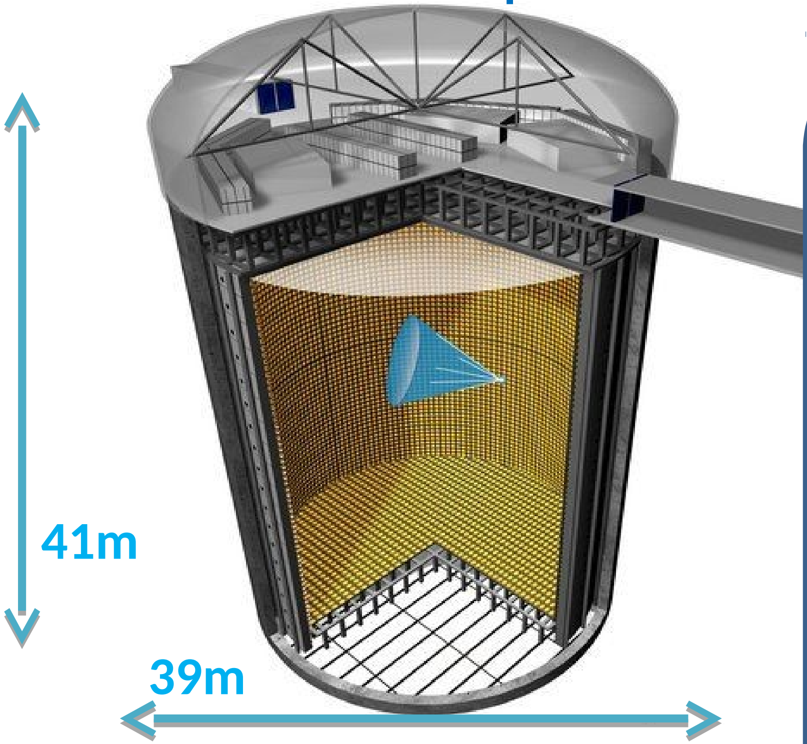


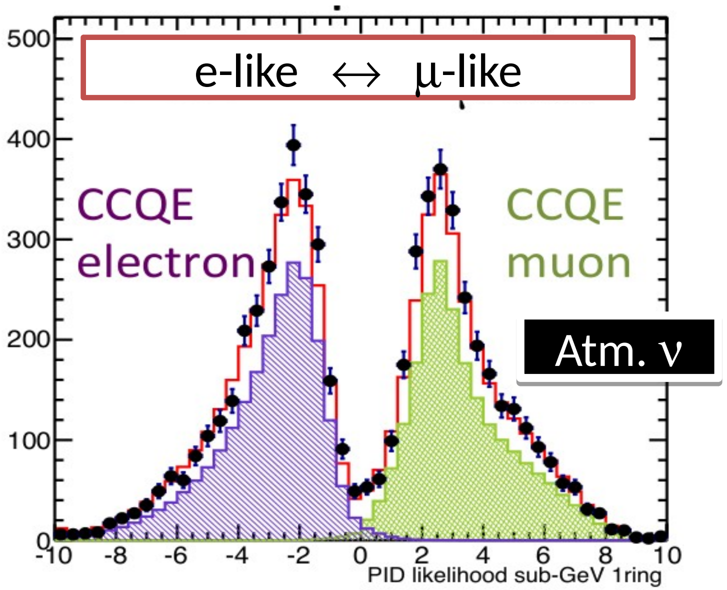
0.2 T Magnetic Field

Situated 2.5° (44mrad) off-axis, same as far detector

- Several sub-detectors, target nuclei (ν cross section measurements, etc.)
- "Tracker" used in this analysis
- Two Fine Grained Detectors (FGDs)
  - Scintillator Trips, 1.6t neutrino target (C) , Precise vertex information
- Three Time Projection Chambers (TPCs)
  - Gas Ionization, Momentum by curvature, PID by dE/dx

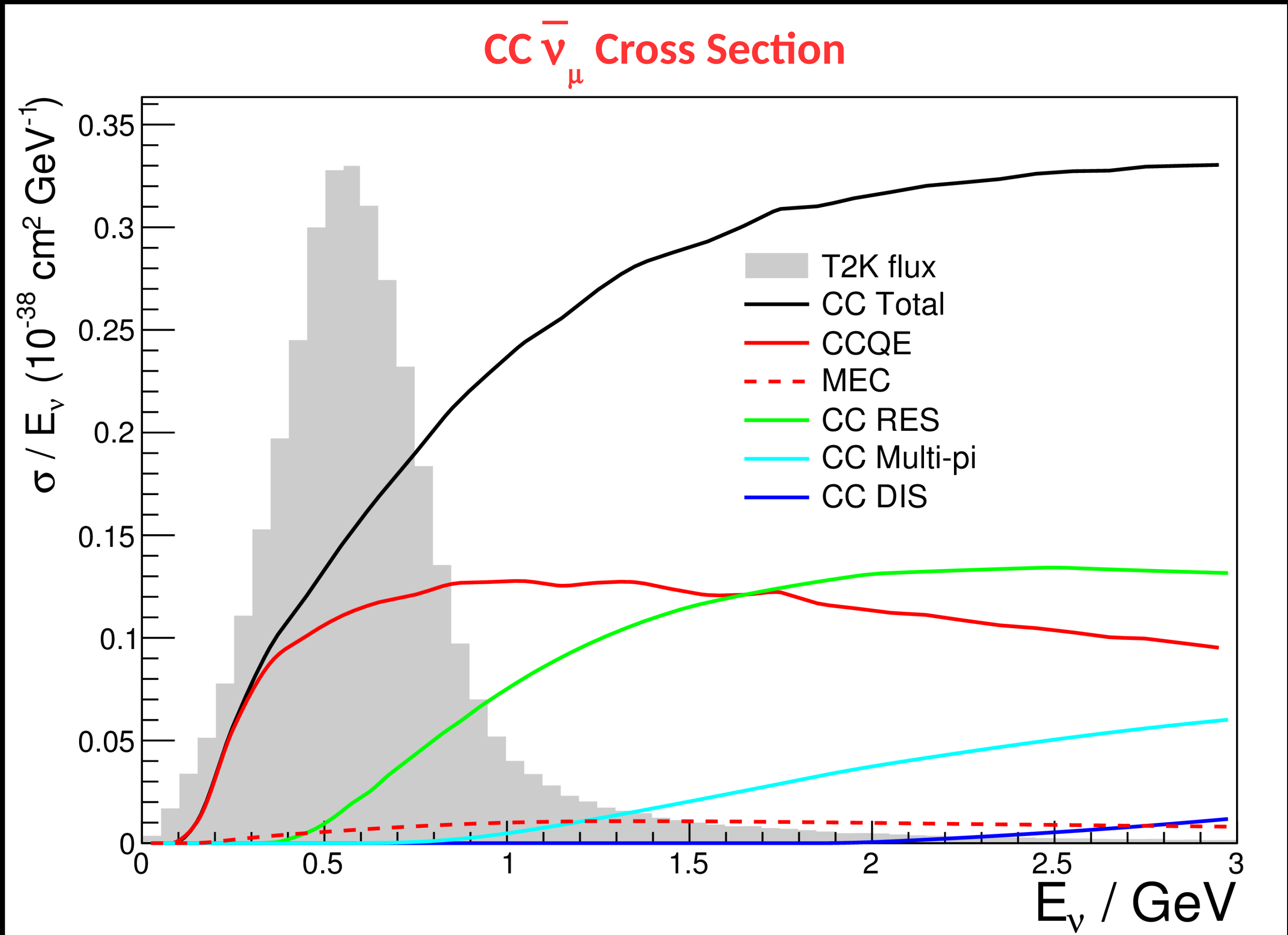
Far Detector Super-Kamiokande (L=295 **km**)



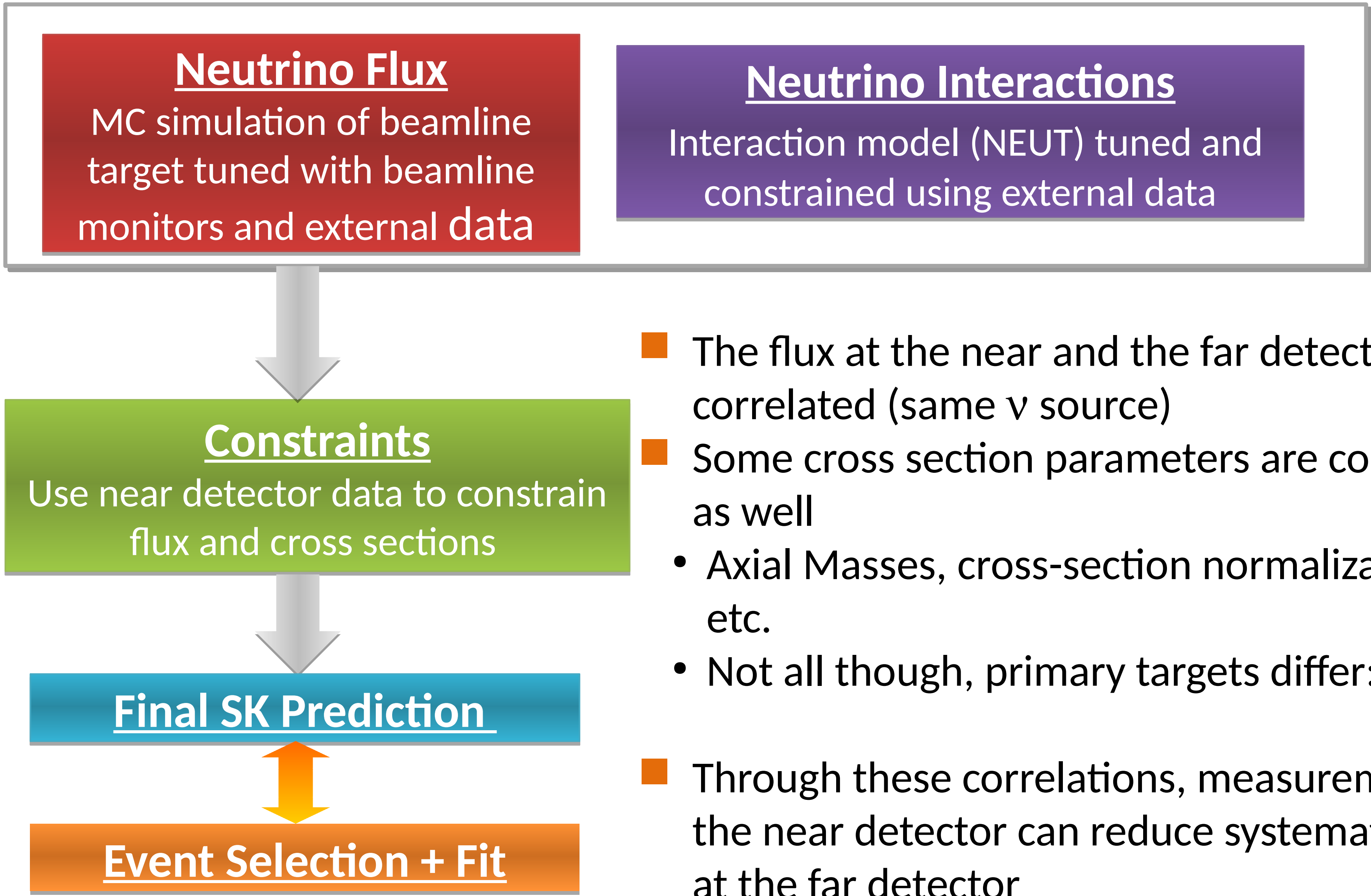


- 50 kton water cherenkov detector
  - 22.5 kton fiducial volume
  - Charged particles produce “cherenkov rings”
  - No net magnetic fields
- Inner detector : 11,146 50cm PMTs
- Outer detector (veto) : 1,885 20cm PMTs
- Excellent particle identification (efficient separation of μ and e)
  - 0.6% MIS-ID below 1 GeV
  - **1,632** days of atmospheric neutrino data control samples
- T2K trigger records all PMT hits within ±500 μs of the beam arrival time

Analysis Methodology

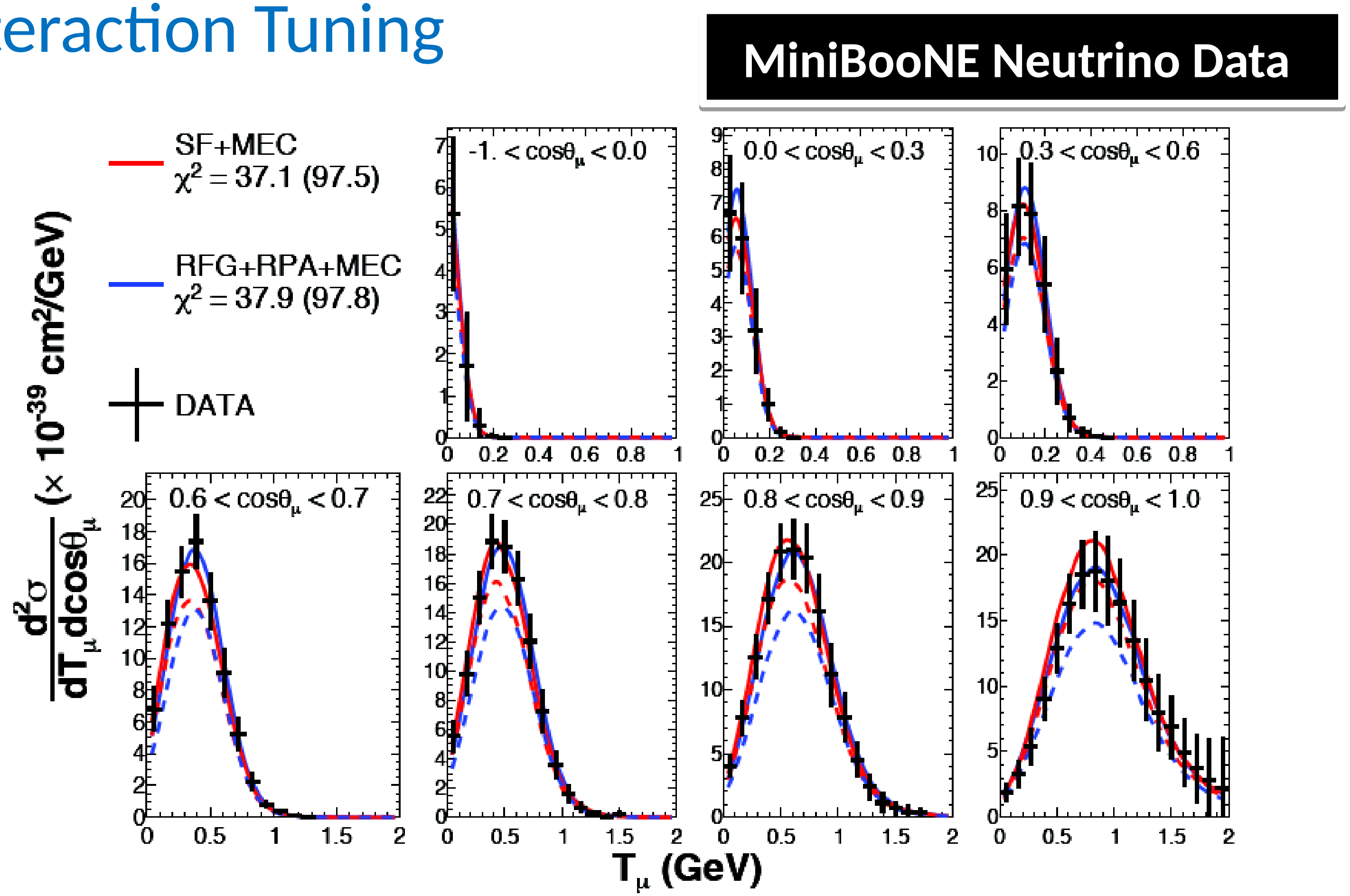


Oscillation Analysis Strategy



- The flux at the near and the far detectors are correlated (same ν source)
- Some cross section parameters are correlated as well
  - Axial Masses, cross-section normalizations etc.
  - Not all though, primary targets differ: O vs. C
- Through these correlations, measurements at the near detector can reduce systematic errors at the far detector

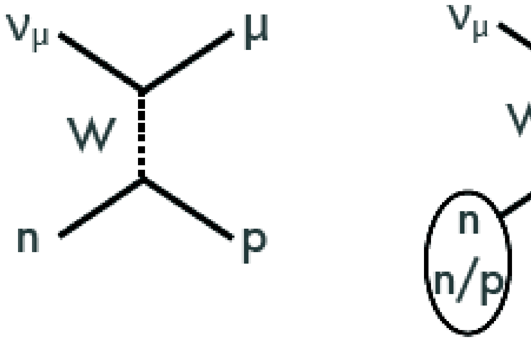
Neutrino Interaction Tuning

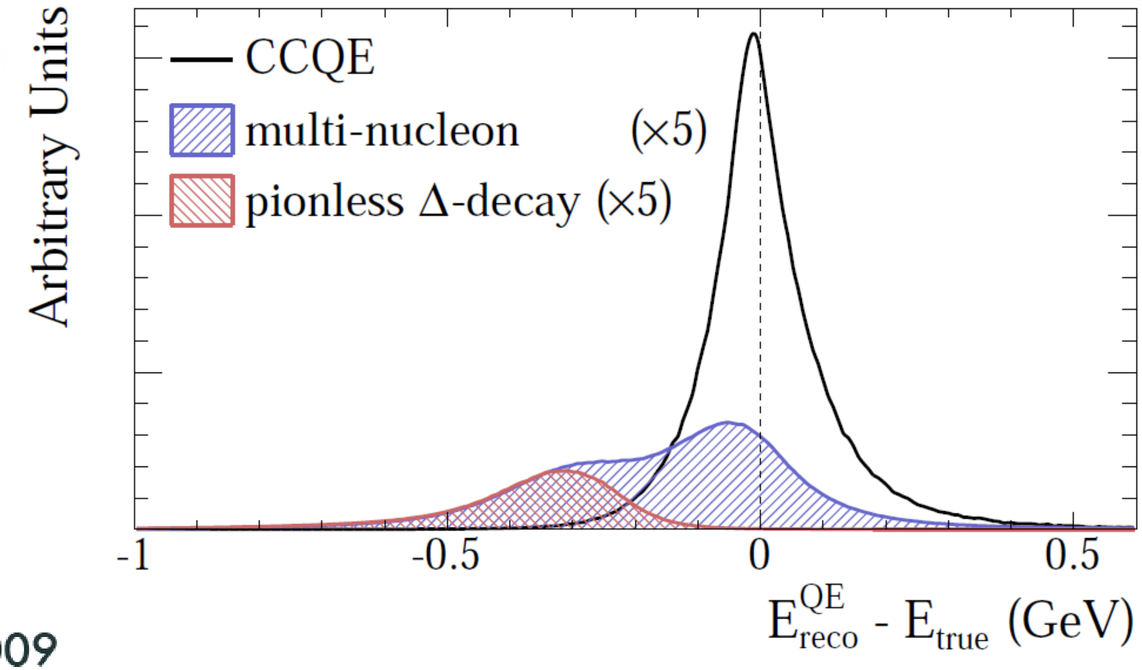


- Neutrino interaction model tuned using fits to external data sets, MiniBooNE and MINERVA CCQE-like data
- Data sets are not completely compatible, systematic errors have been inflated to cover the discrepancies
- Final state interactions and secondary interaction cross sections are tuned using pion-nucleus scattering data

New to the Model: Multinucleon Interactions

$$E_{reco} = \frac{m_p^2 - (m_n - E_b)^2 - m_\mu^2 + 2(m_n - E_b)E_\mu}{2(m_n - E_b - E_\mu + p_\mu \cos\theta_\mu)}$$



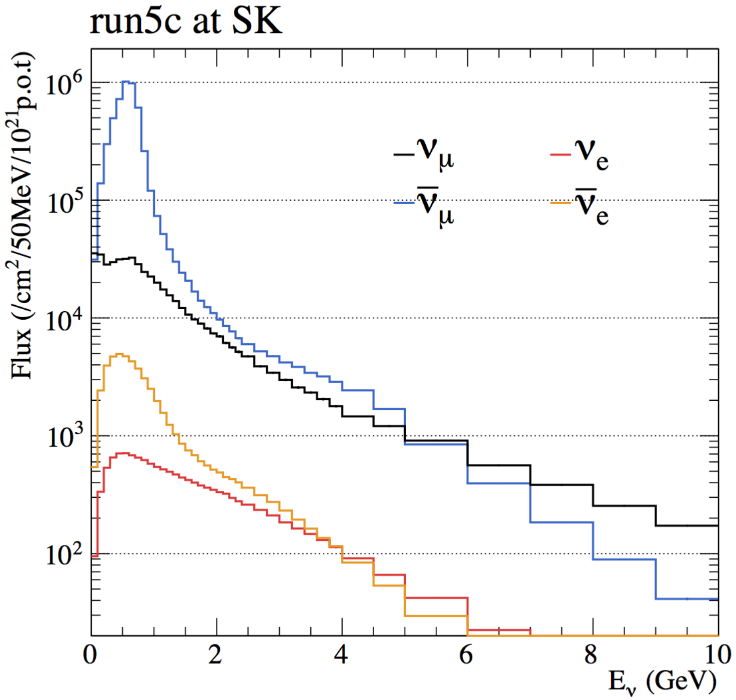


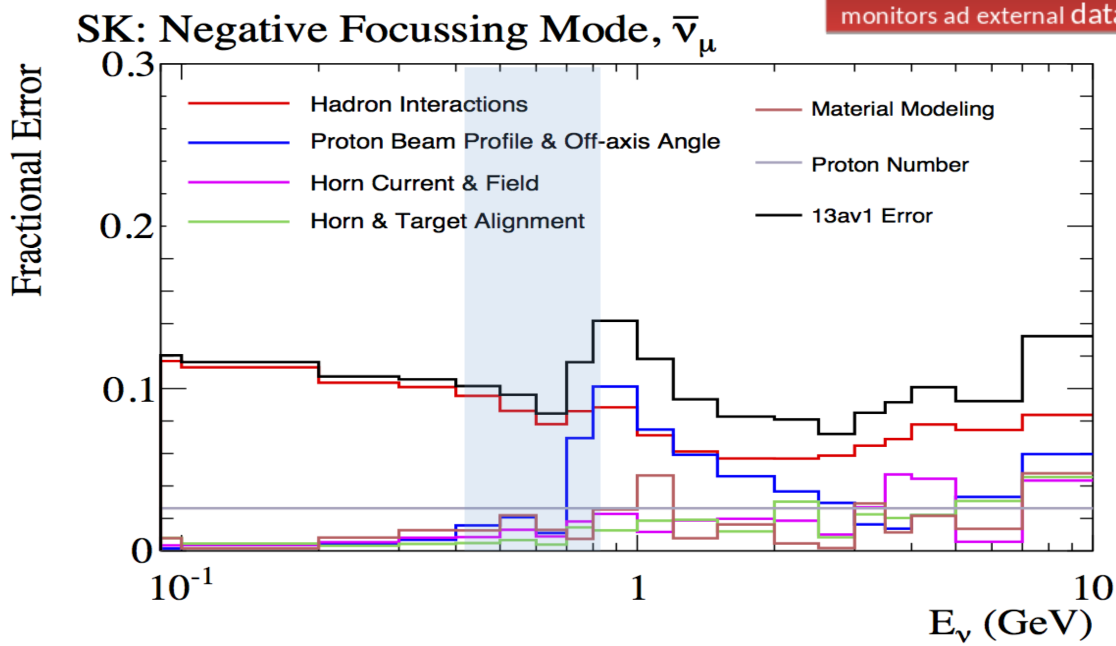
Martini et. al. Phys.Rev. D87 (2013) 013009

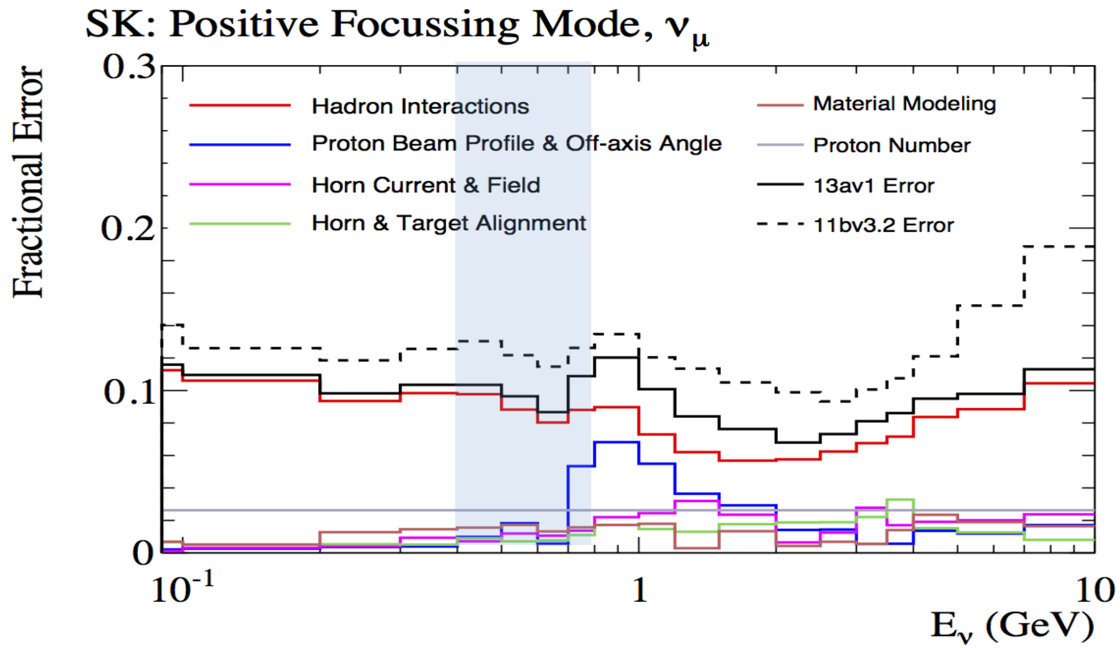
- T2K assumes CCQE interactions to reconstruct the parent neutrino energy
- Recently several theories predict multinucleon interactions are a sizeable fraction of the total cross section below a few GeV
- Interactions off a correlated pair of nucleons leave less energy is the outgoing lepton
  - Systematic bias towards lower reconstructed energies

Flux Systematics

Neutrino Flux
MC simulation of beamline target tuned with beamline monitors ad external data

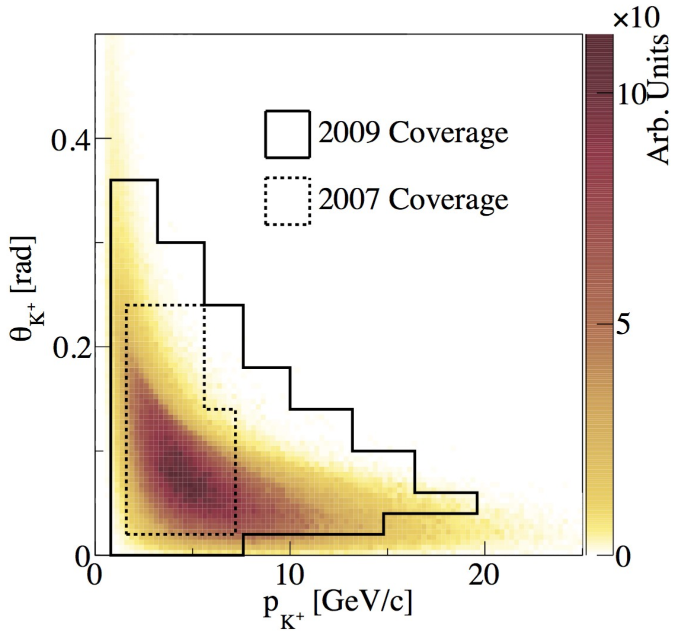


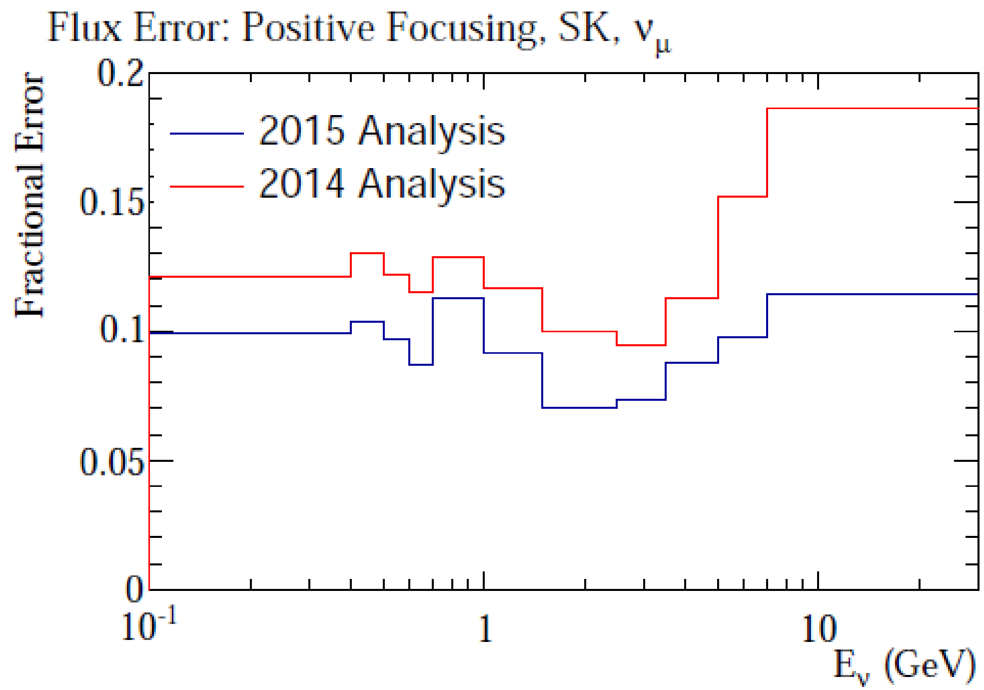


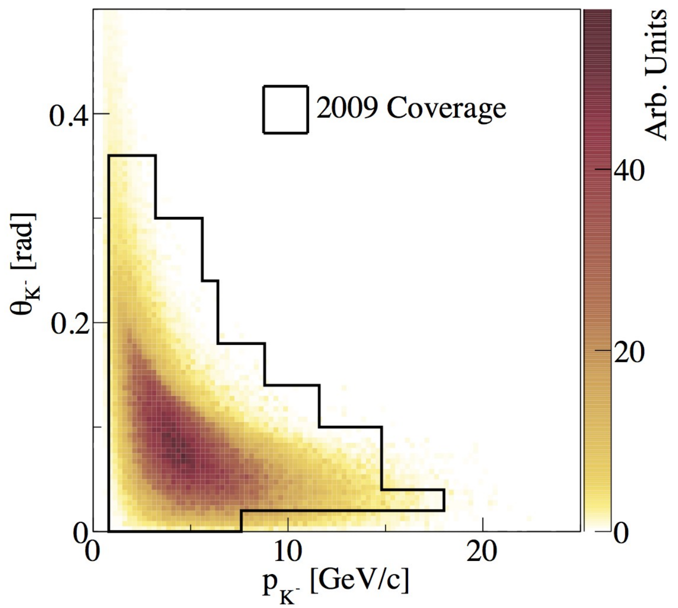


- Hadron production model tuned using NA61 data on a thin carbon target
- Overall flux uncertainty is between **10% - 15%**

Hadronic Uncertainties



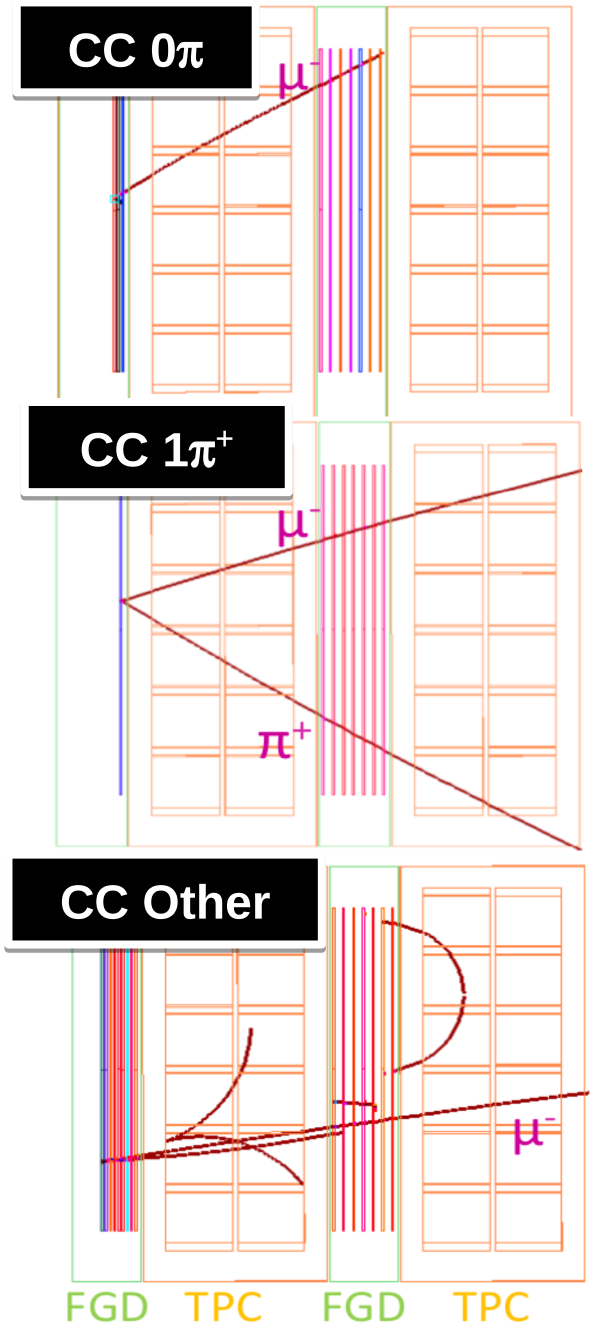




- T2K neutrino flux is tuned using hadron multiplicity measurements from the NA61/SHINE collaboration
- NA61 uses 31 GeV protons and a carbon target to replicate conditions at T2K
- Updated measurements have reduced the uncertainty in the flux by 4% at its peak

Fit To the Near Detector Tracker Neutrino Data

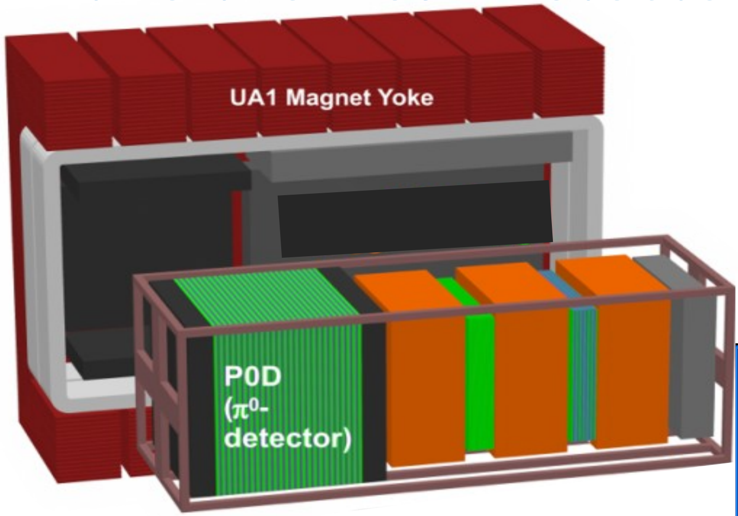
Constraints
Use near detector data to constrain flux and cross sections



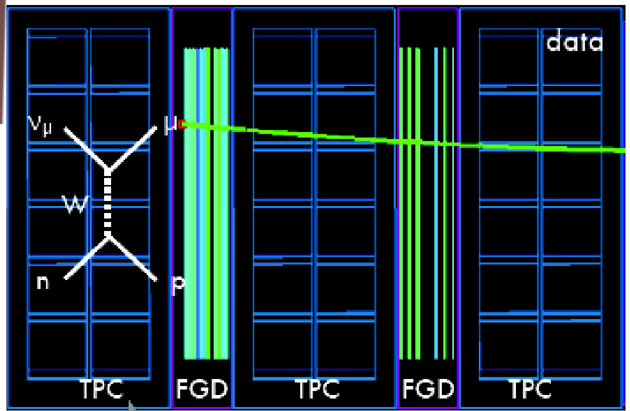
- **Goal** : Constrain flux at SK by fitting ND data
  - Fit analysis samples in p_μ, θ_μ
- **Seven** samples used in the fit
  - Focus on measured final states
  - CC-0 π , CC-1 π+, and CC-Other (neutrino mode)
  - 4 antineutrino mode (next slide)
- Neutrino mode data has high statistics constraint for flux and cross section model

Interaction	CC-0π	CC-1π⁺	CC Other
CCQE	63.5%	5.3%	3.9%
Resonant π	20.2%	39.5%	14.3%
DIS	7.5%	31.3%	67.8%
Coherent π	1.4%	10.6%	1.4%
Other	7.4%	13.3%	12.6%

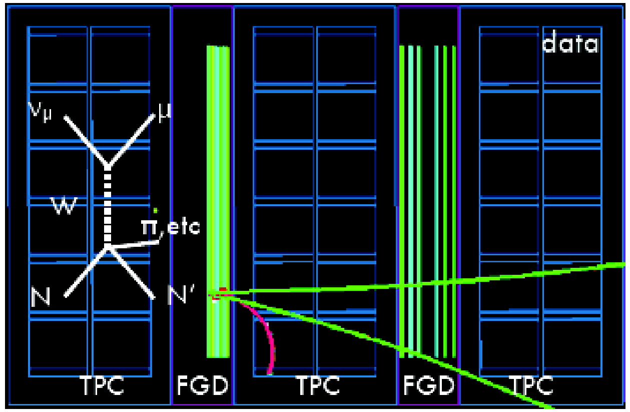
Fit To the Near Detector Tracker Antineutrino Data



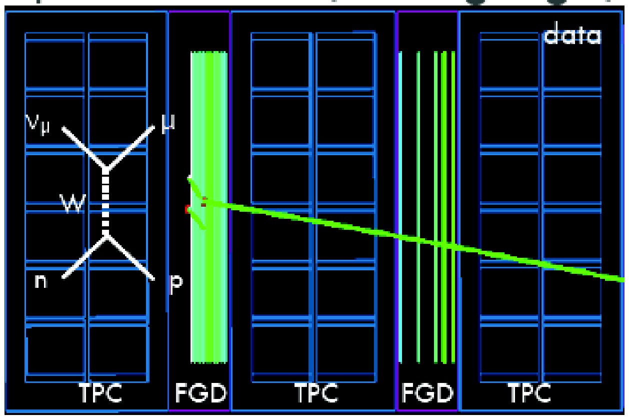
$\bar{\nu}_\mu$ CC-1Track



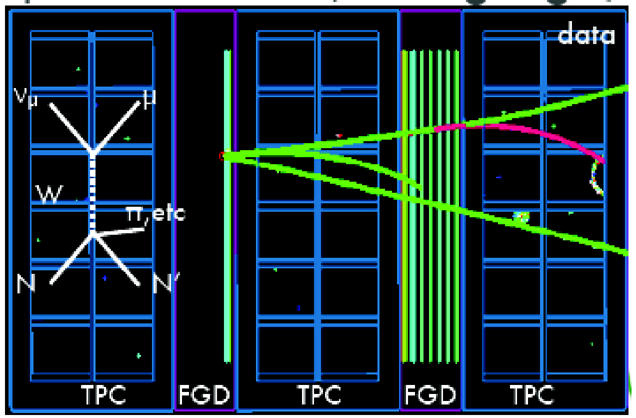
$\bar{\nu}_\mu$ CC-NTrack



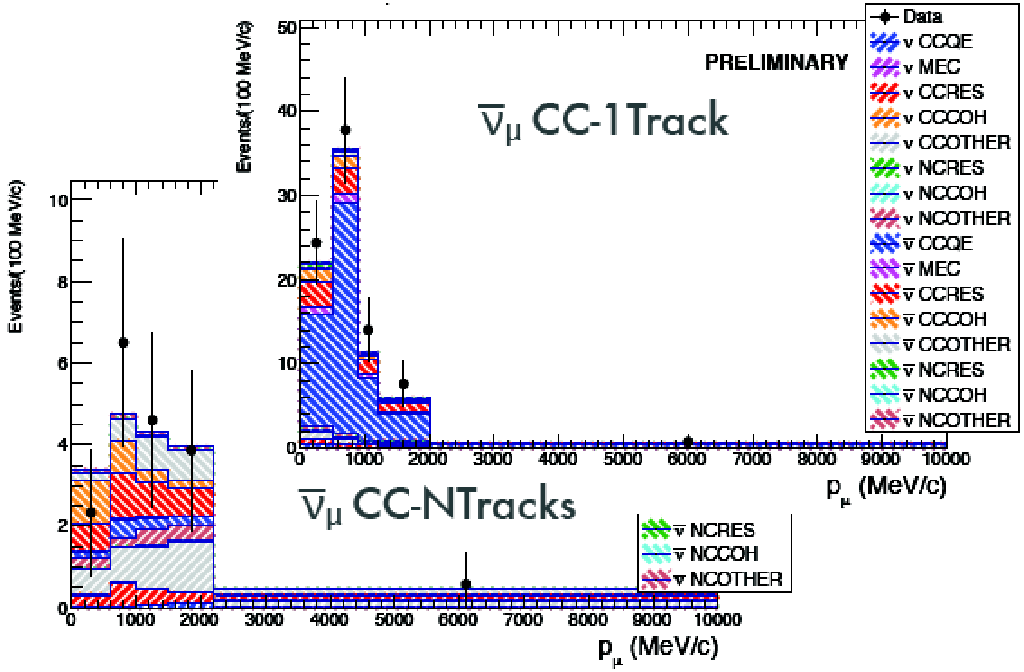
ν_μ CC-1Track (wrong sign)

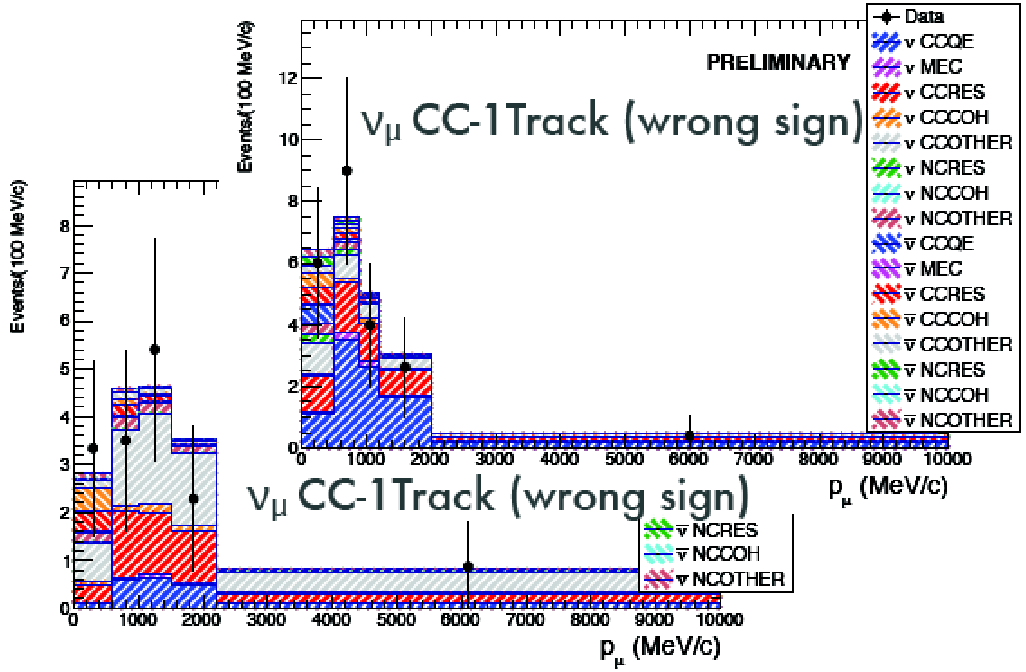


ν_μ CC-NTrack (wrong sign)



Fit To the Near Detector Tracker Antineutrino Data

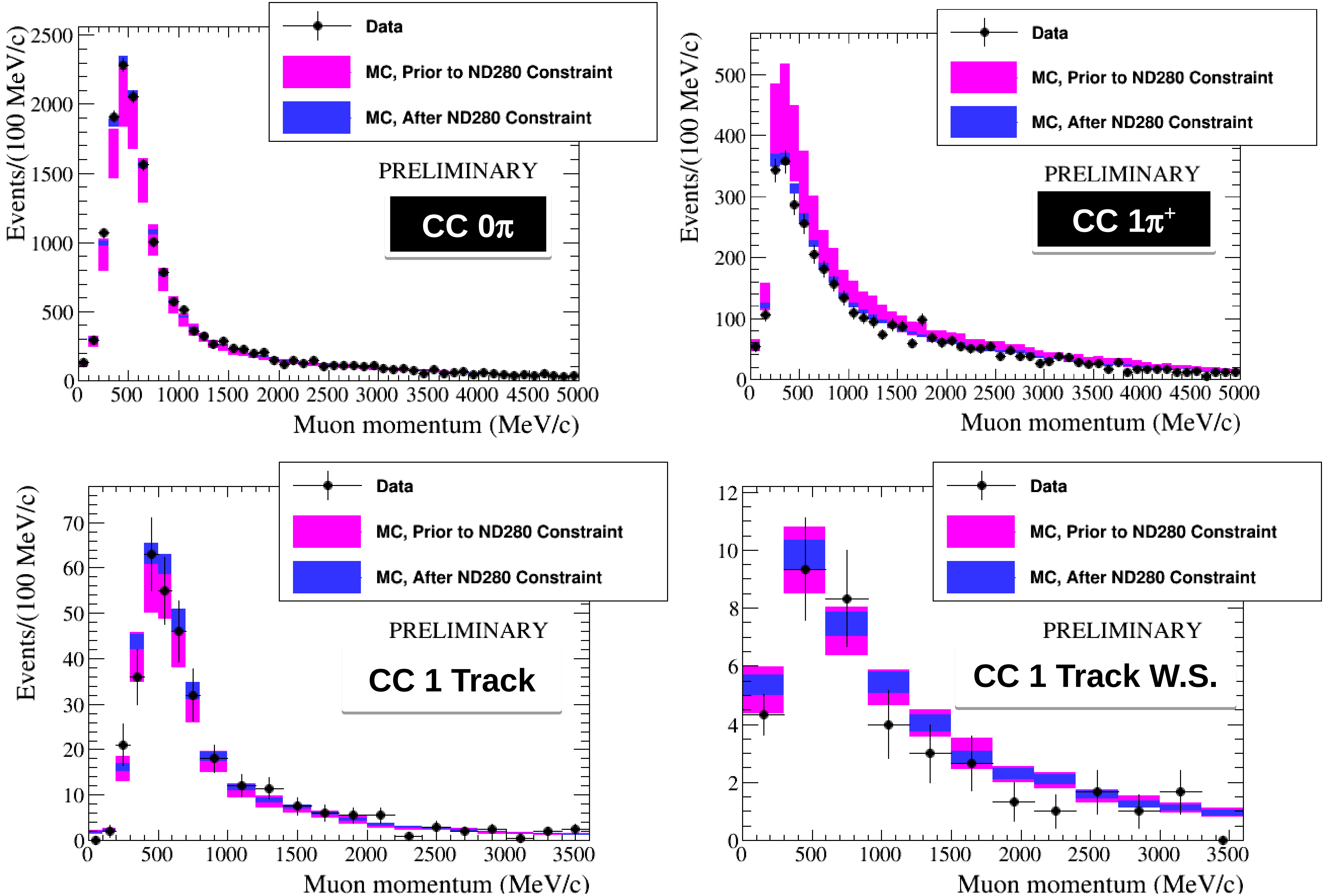




Interaction	CC-0π	CC-Nπ	BKG	External
CC-1 Track	73.4%	15.8%	5.5%	5.3%
CC-N Track	8.8%	46.8%	36.7%	7.5%
CC-1 Track W.S.	50.6%	27.8%	9.3%	12.3%
CC-N Track W.S.	15.2%	66.3%	12.3%	6.2%

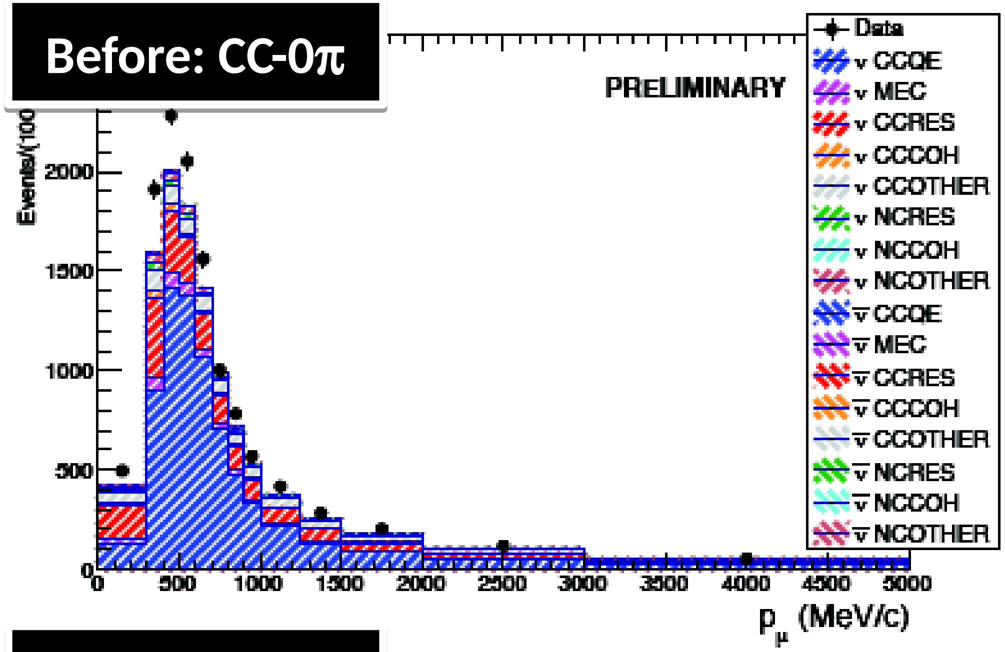
- Antineutrino data is statistically limited: Using 4.3×10^{19} POT

Fit To the Near Detector Data

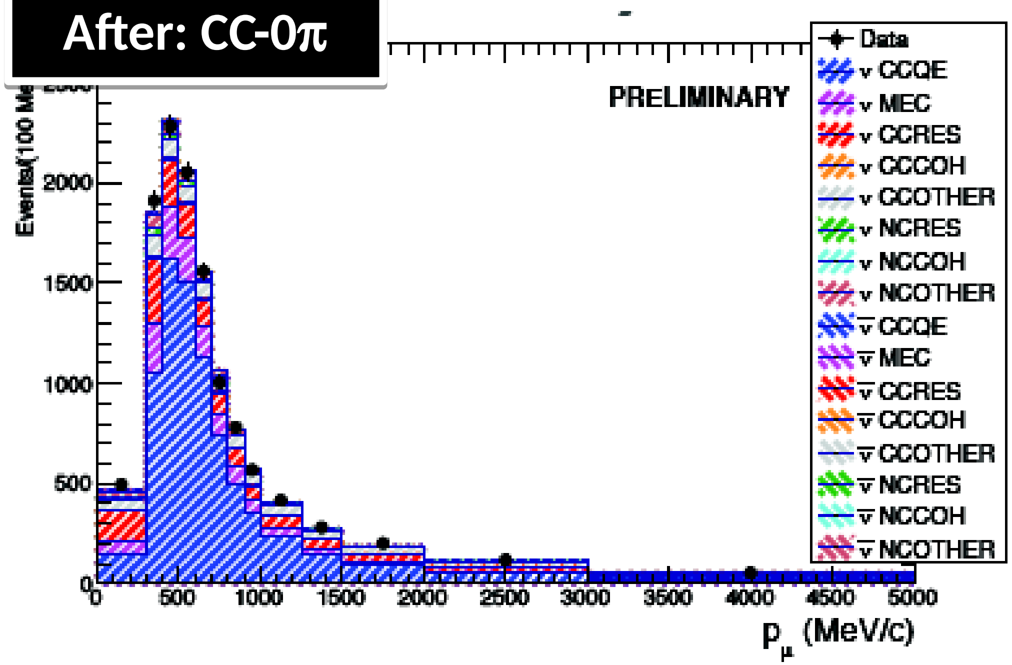


Fit To the Near Detector Data

Before: CC-0π



After: CC-0π



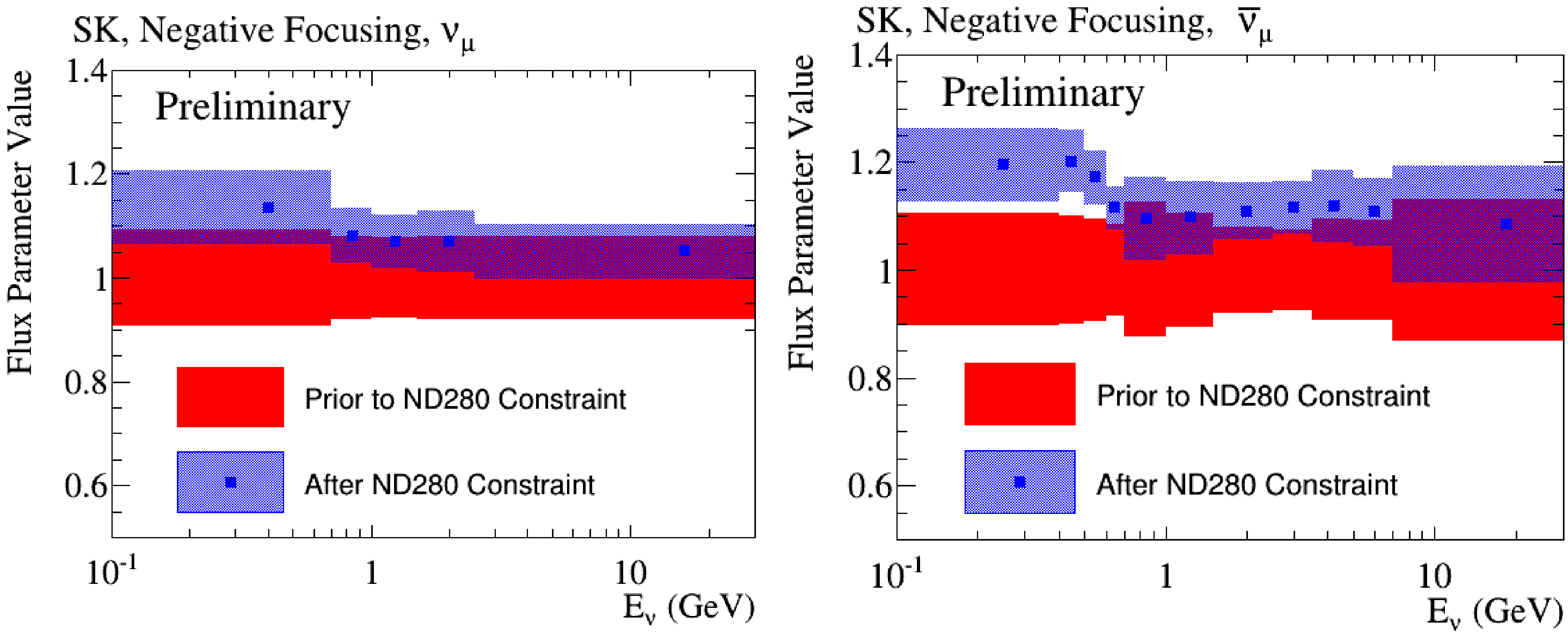
- Improved Data/MC agreement after the fit
  - Multinucleon component increased
- Constraints on the underlying cross section parameters and **reduced errors:**

T2K Preliminary

Cross-section Model Parameter	Prior to ND280 Constraint	After ND280 Constraint
M_A^{QE} (GeV/c^2)	1.150 ± 0.070	1.137 ± 0.034
CC 2p-2h ^{12}C	0.27 ± 0.29	1.03 ± 0.17
CC 2p-2h ^{16}O	0.27 ± 1.04	1.03 ± 1.01
p_F ^{12}C (MeV/c)	223.0 ± 12.3	222.7 ± 8.8
E_B ^{12}C (MeV)	25.0 ± 9.0	23.9 ± 7.3
$C^A_5(0)$	1.01 ± 0.12	0.862 ± 0.074
M_A^{RES} (GeV/c^2)	0.95 ± 0.15	0.724 ± 0.052
I=1/2 Background	1.3 ± 0.2	1.49 ± 0.19
CC Coherent ^{12}C	1.0 ± 1.0	0.02 ± 0.16
CC Other Shape	0.0 ± 0.4	0.02 ± 0.19

Fit To the Near Detector Tracker Data: Results

Final SK Prediction



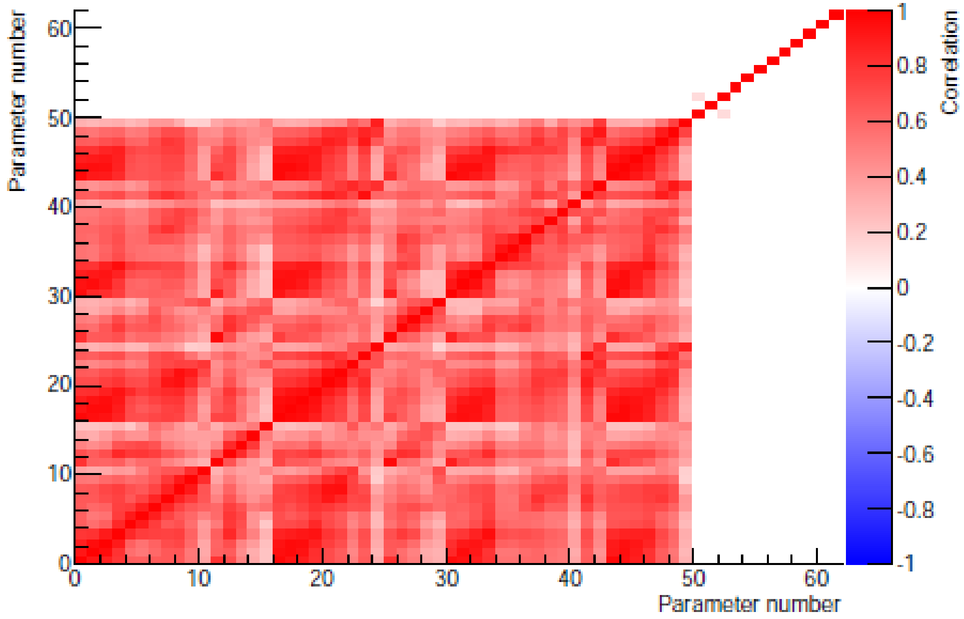
- Flux parameters fit higher than the default model in general
  - true for both neutrino and antineutrino mode

- Uncertainty on flux parameters is reduced after the fit

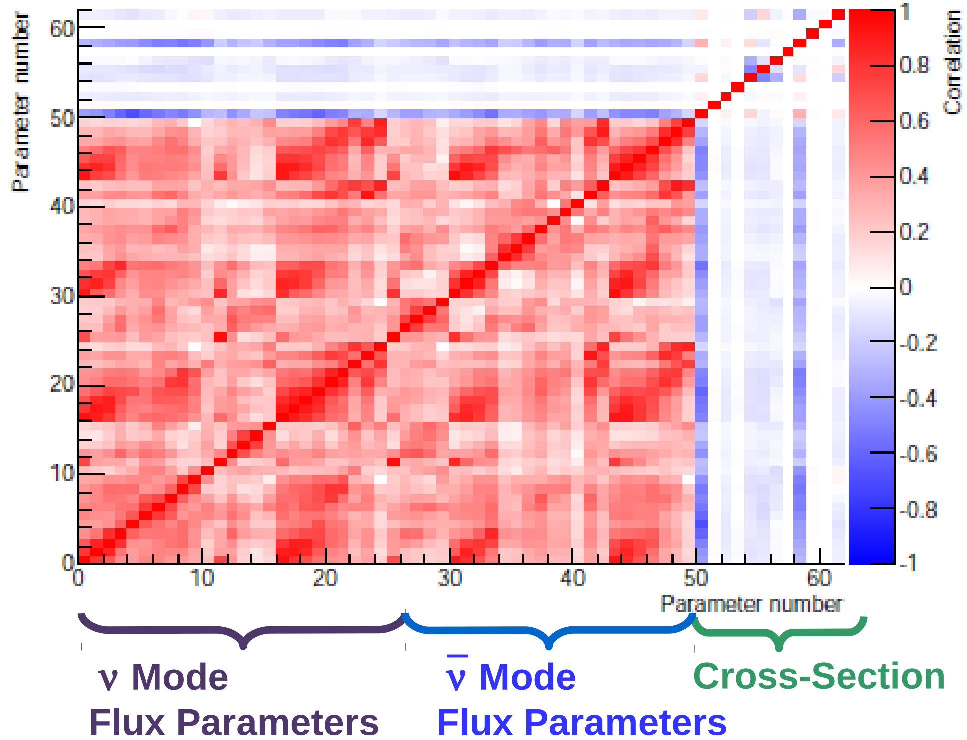
Fit To the Near Detector Tracker Data: Results

Final SK Prediction

Before ND Fit

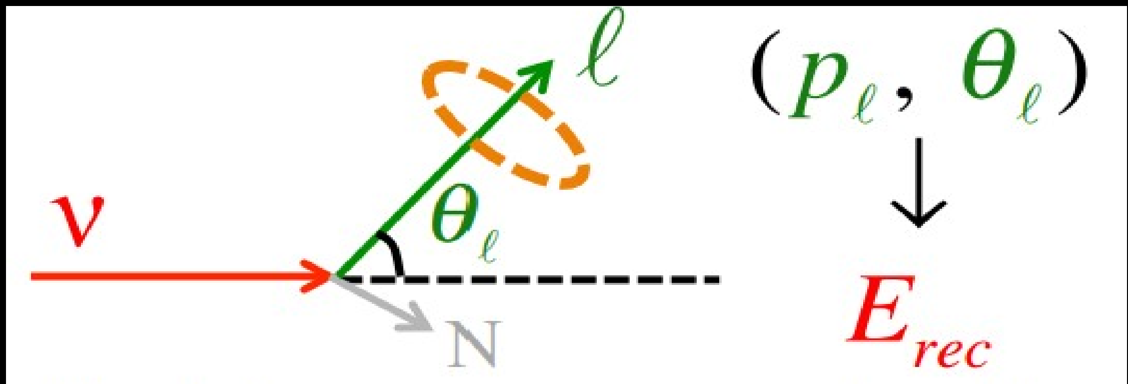


After ND Fit



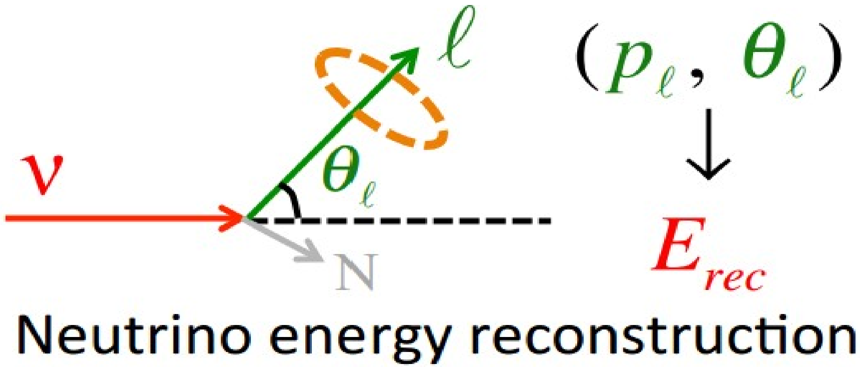
- ND280 fit introduces further correlations and anticorrelations between the flux and cross section models
- This correlation matrix is propagated in the oscillation analysis to introduce the constraint from ND280 on the SK data

Super-K Event Selection



Super-Kamiokande Event Selection

- **Strategy** : Select interactions consistent with a single out-going lepton
  - Enables reconstruction of the neutrino energy assuming CCQE interactions

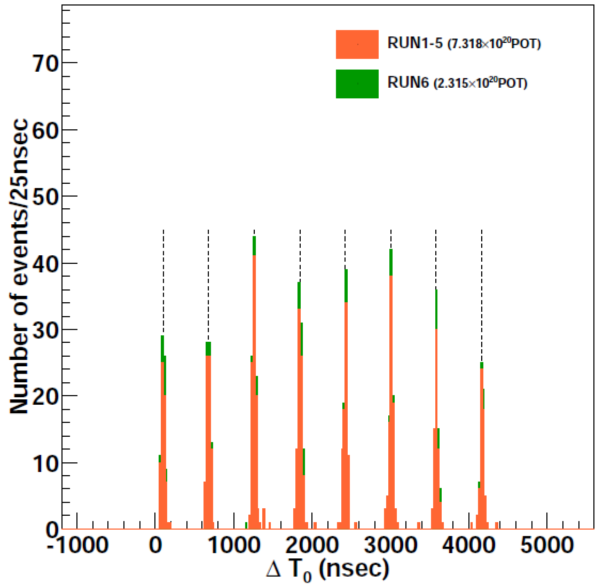


$$E_\nu^{\mathrm{rec}} = \frac{(M_n - V_{nuc}) \cdot E_e - m_e^2/2 + M_n \cdot V_{nuc} - V_{nuc}^2/2 + \left(M_p^2 - M_n^2\right)/2}{M_n - V_{nuc} - E_e + P_e \cos\theta_{\mathrm{beam}}}$$

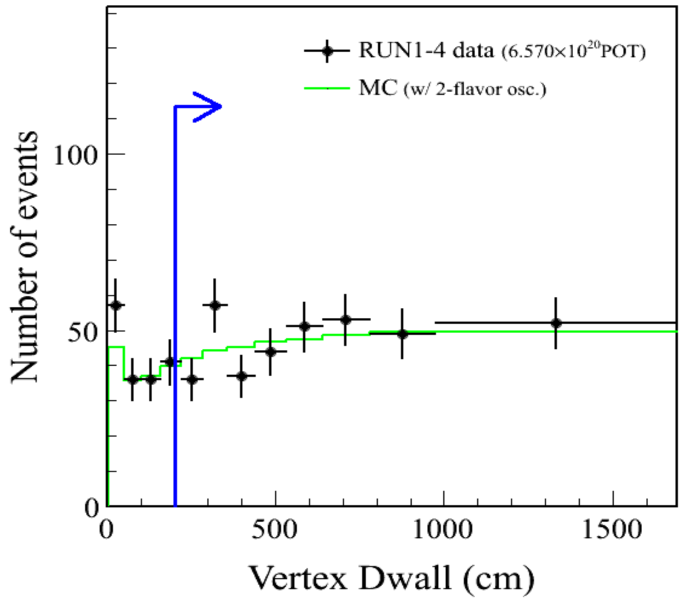
- At T2K energies the outgoing nucleon is often unseen at Super-K
  - CC neutrino interactions produce neutrons
  - CC antineutrino interactions produce protons below Cherenkov threshold

Primary Event selection

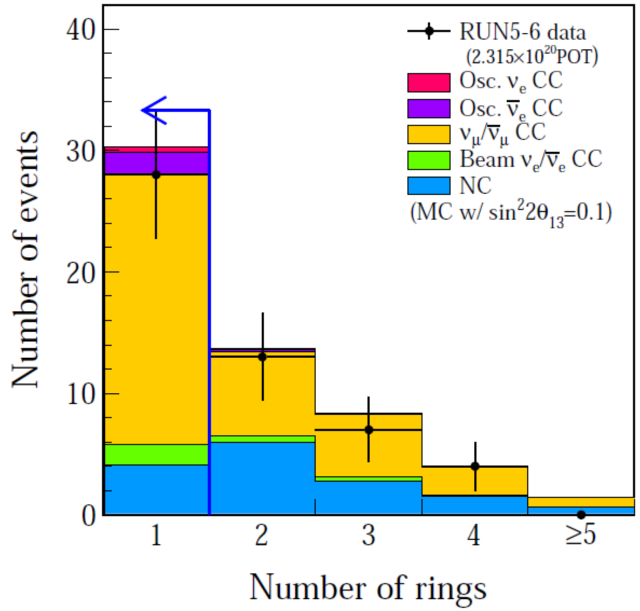
Beam Timing



FC Fiducial Vol.

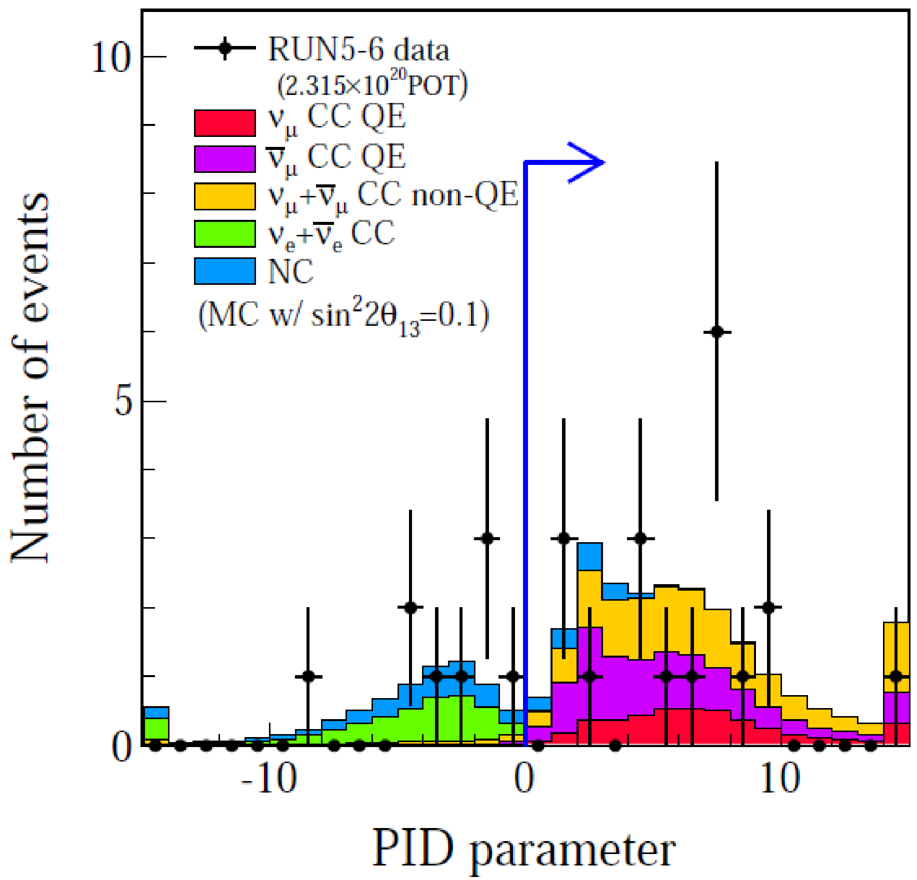


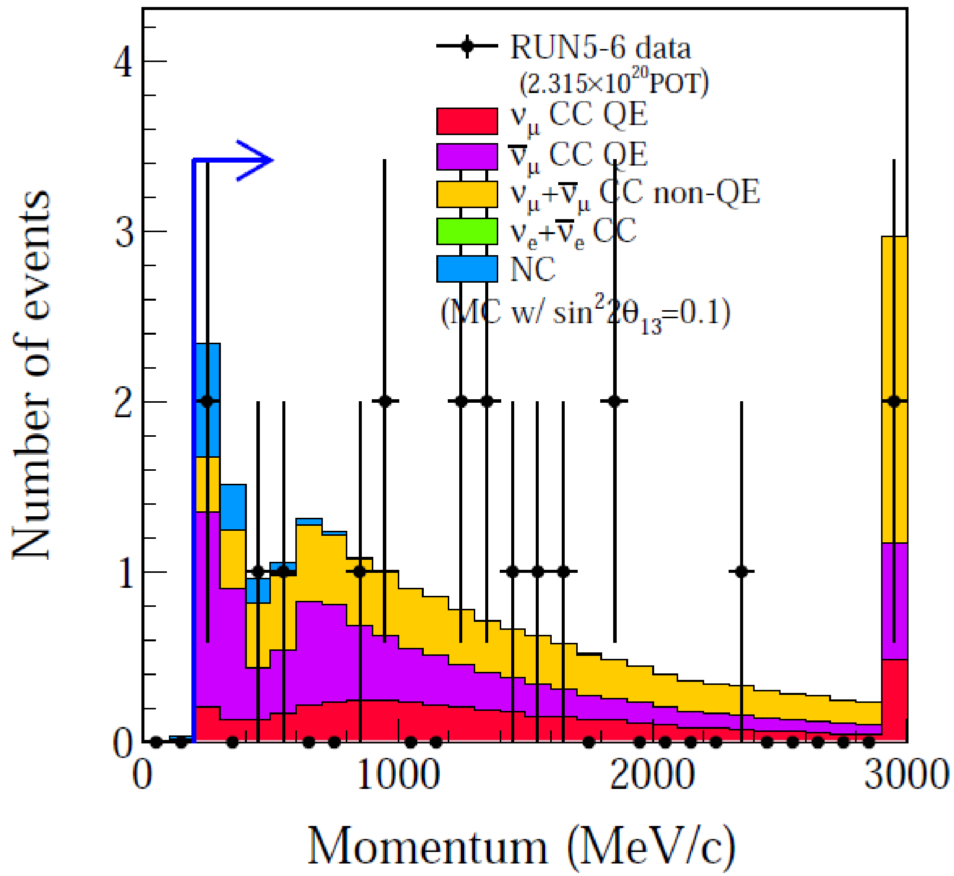
Single Ring



- Select interactions consistent with the accelerator timing
  - 8 bunch structure of the beam is clearly visible at SK
- Select interactions in the 22.5 kton fiducial volume defined as the region offset from the ID wall be 200 cm
- Select Single Ring interactions

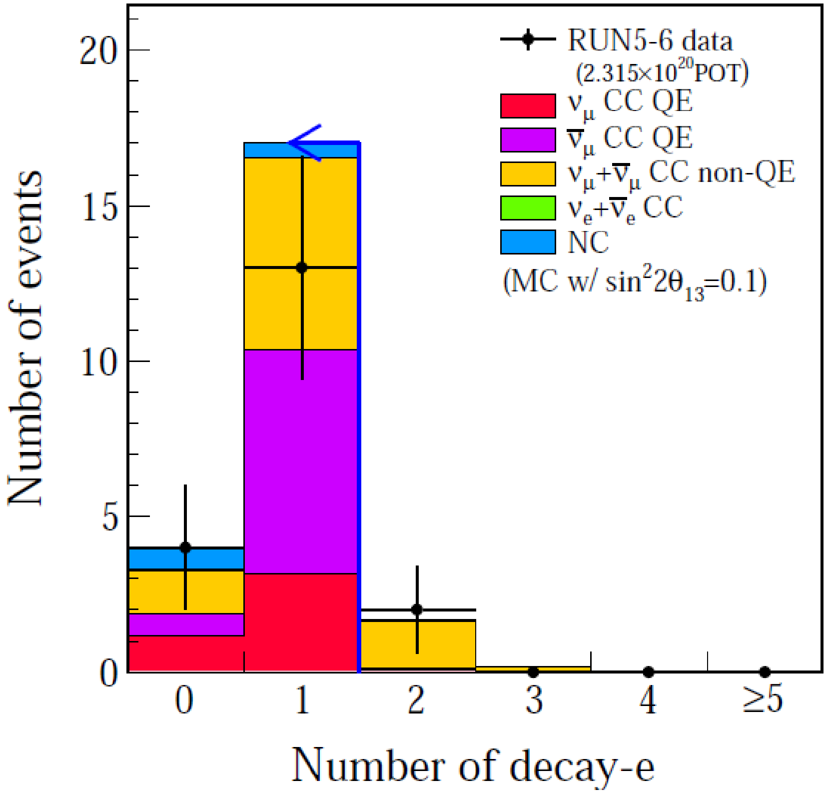
Muon-like Sample Definitions

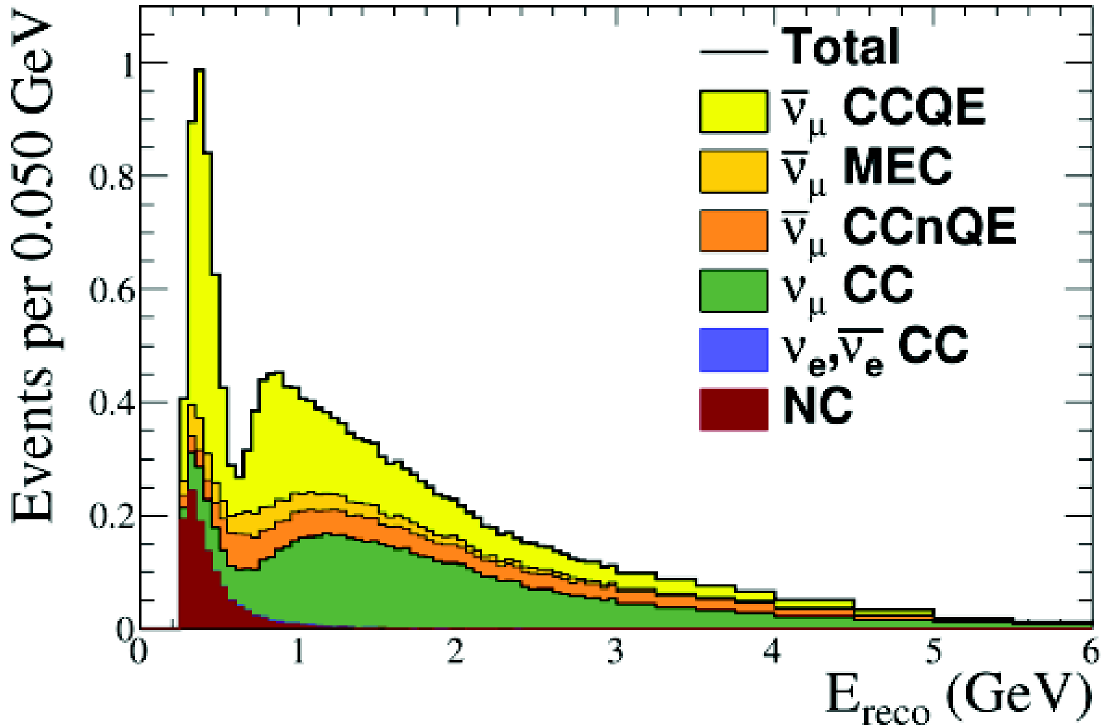




- PID selection to reduce contamination from NC and νe interactions
- Select events with a reconstructed lepton momentum greater than 200 MeV

Muon-like Sample Definitions

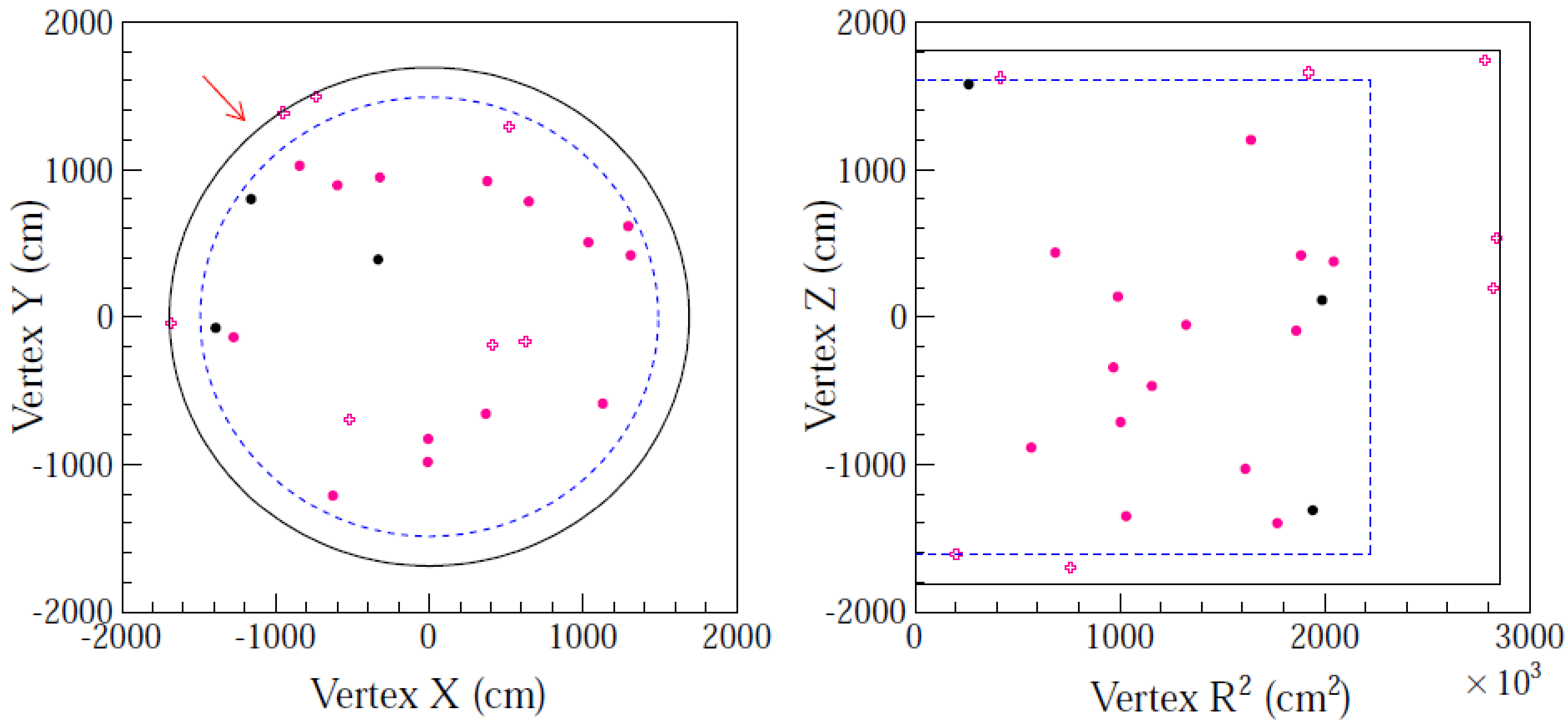




- N.B. So far no attempt to separate ν and $\bar{\nu}$
- After these selections **17** candidates remain
- Final MC prediction
  - **58.9** events without oscillations
  - **19.9** events with oscillations

	Efficiency
NC	2.2
CCQE νμ	65.7
CCQE $\bar{\nu}\mu$	77.1
CC-nonQE νμ	22.9
CC νe	0.6

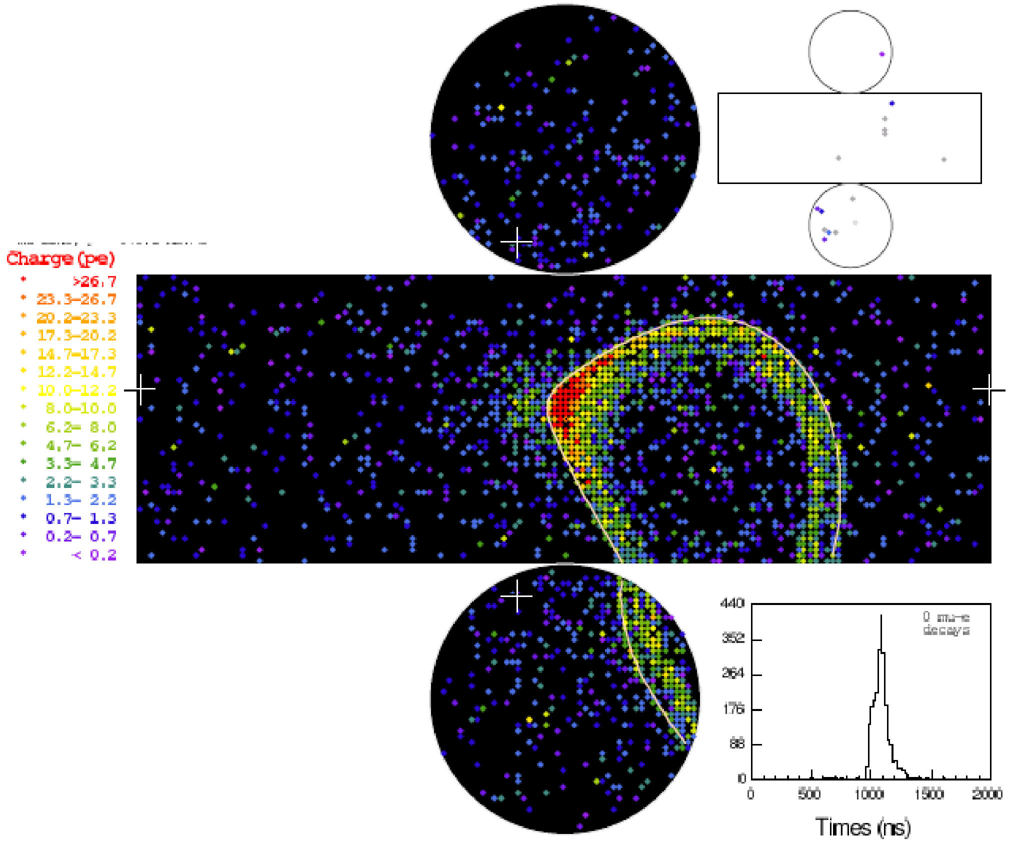
Muon-like Sample Vertex Distribution

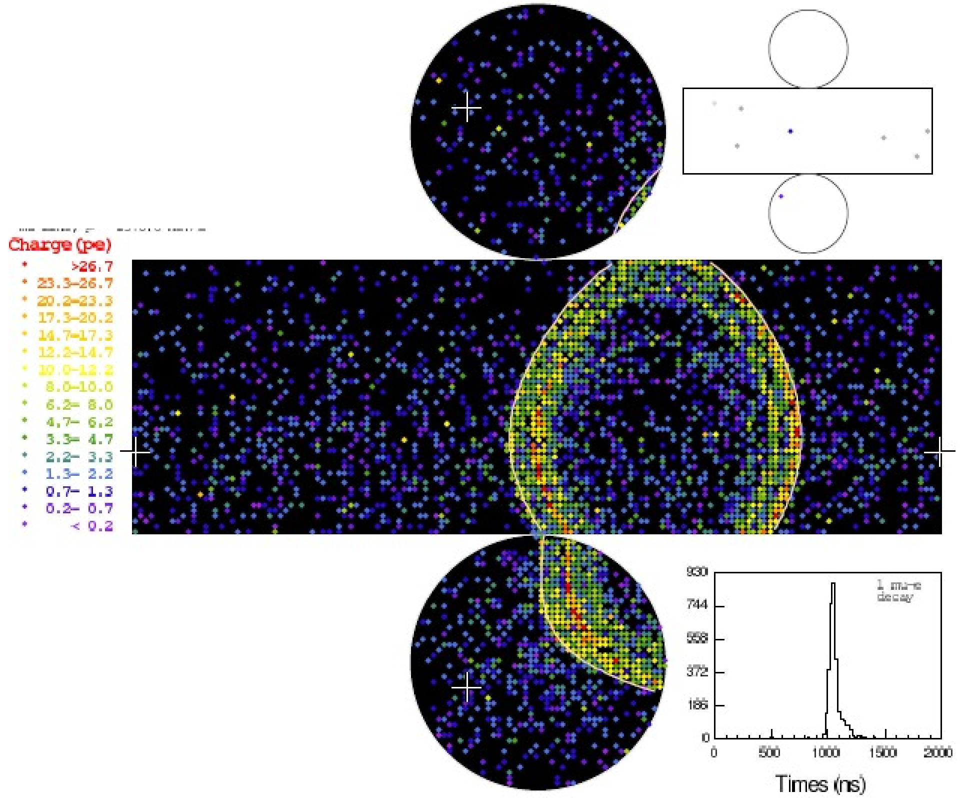


- After these selections **17** candidates remain
- Vertex distribution appears uniform

● Run 5 in fiducial volume
● Run 6 in fiducial volume
✣ Run 6 out of fiducial volume

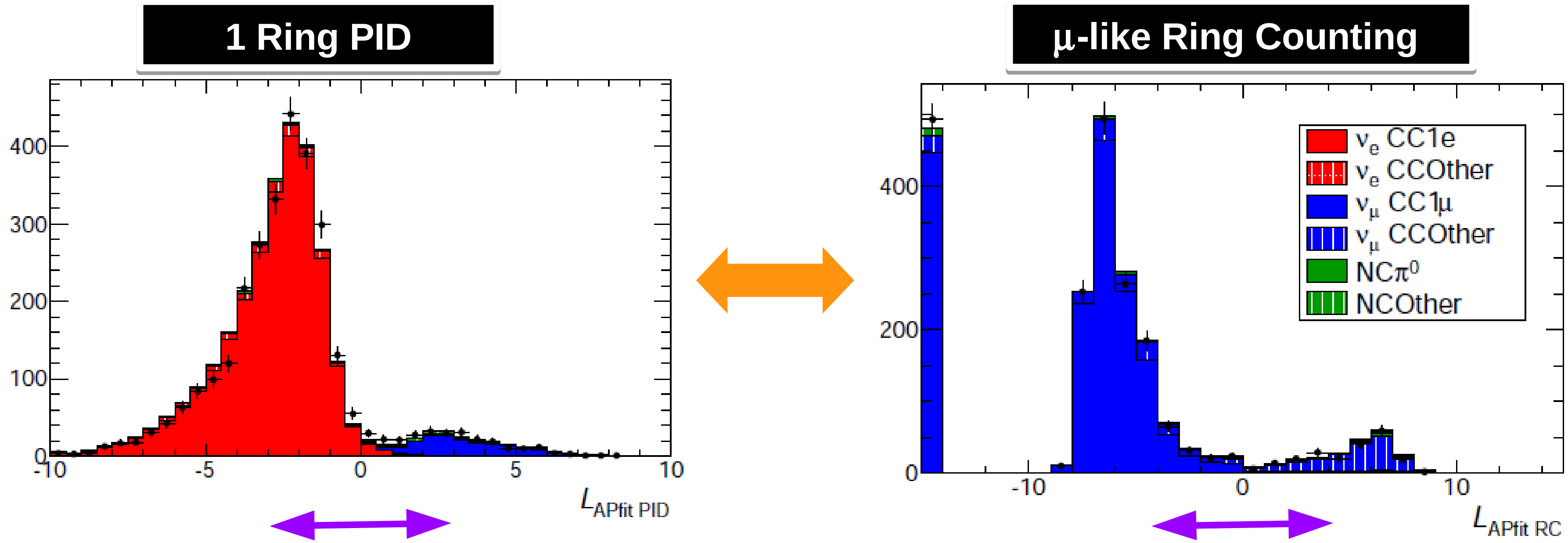
Antineutrino Mode Disappearance Sample Candidates



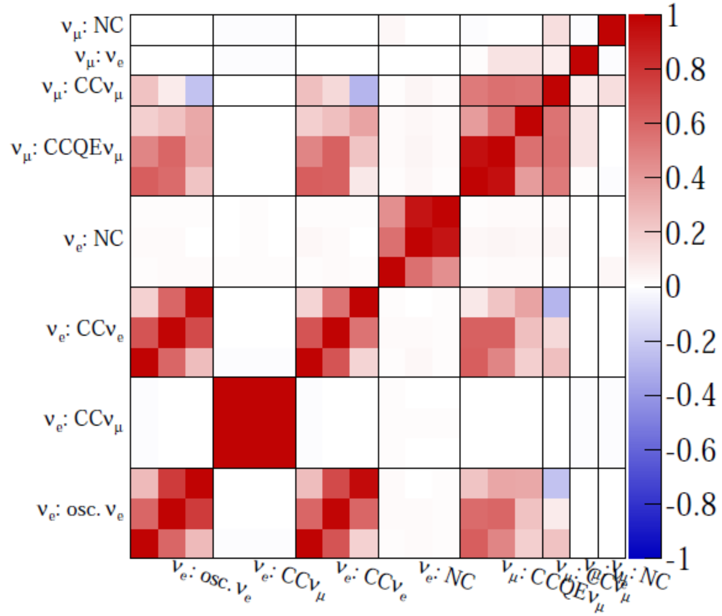


- Two events passing the event selection for the analysis sample

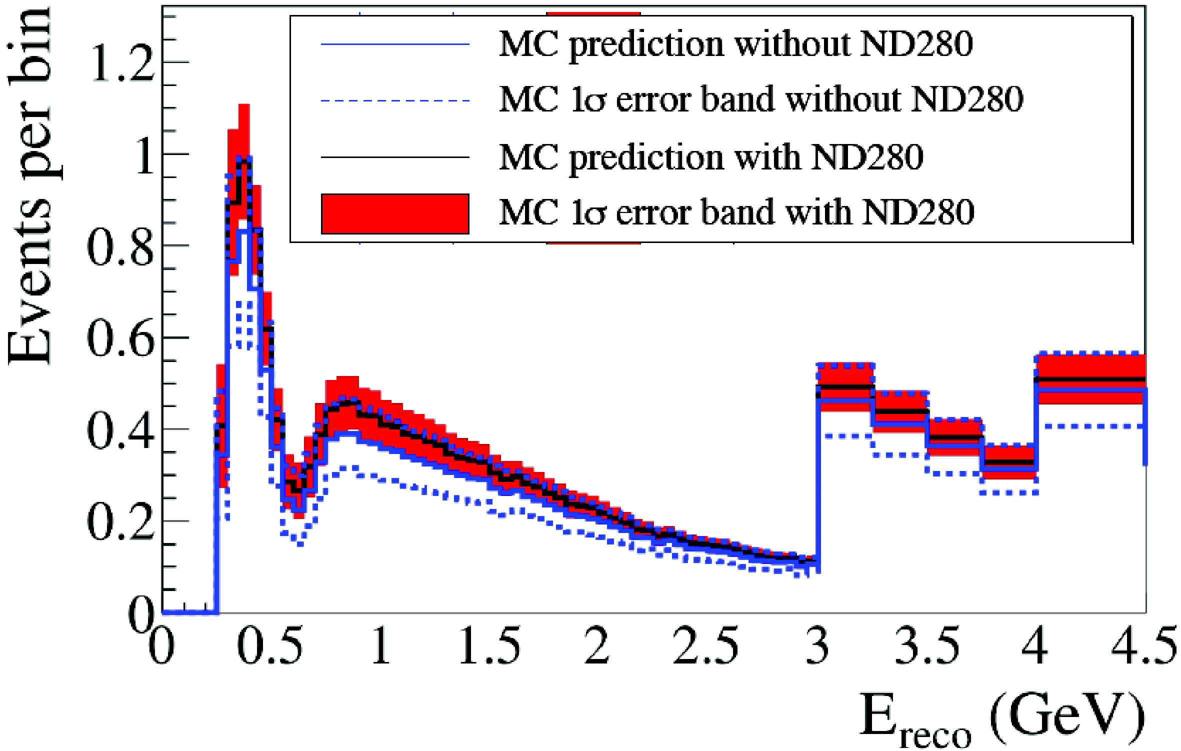
Super-K Detector Systematics



- Evaluated using SK atmospheric neutrino data binned in visible energy
  - 12 analysis samples containing e-like, μ-like, and NC-like interactions used to study uncertainty in selection efficiency
- Data are fit to MC allowing event migration between the various samples
  - Construct correlated errors for propagation to the oscillation analysis

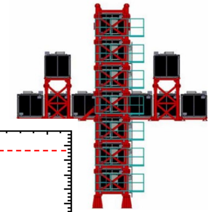


Systematic Error on the SK Event Rate

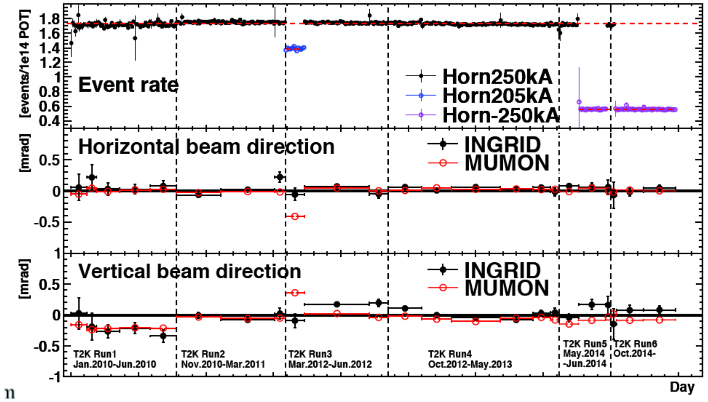


Systematic		Without ND	With ND measurement
Flux and Cross Section	Common to ND280/SK	9.2% →	3.4%
	SK only	10%	
	All	13.0% →	10.0%
Final State Interaction/Secondary Interaction		2.1%	
SK Detector		3.8%	
Total		14.4% →	11.6%

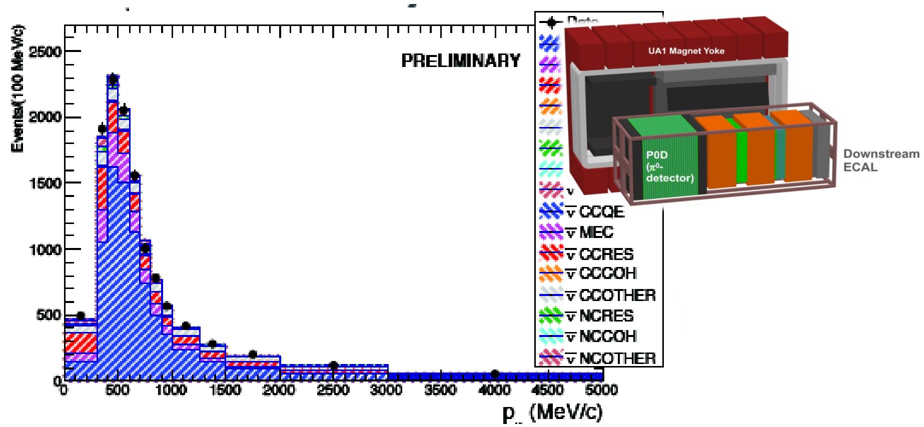
Key Point Summary



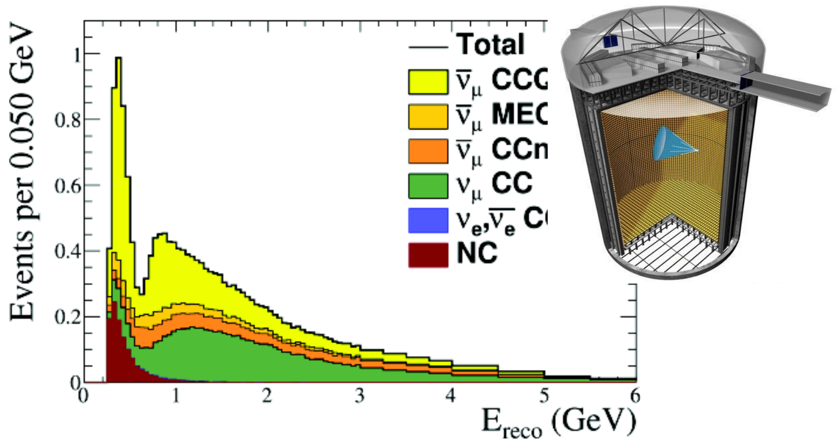
- Off-axis beam peaked at ~600 MeV
  - Stable operation in both neutrino and antineutrino mode
  - Beam direction stable throughout



- Flux and interaction model constrained using measurements at the T2K near detector, ND280
  - Precise understanding of the expected distribution at at Super-K
  - Model constraints are propagated to Super-K for analysis



- Robust event selection at Super-K
  - Systematics understood using atmospheric and cosmic ray muon control samples



Oscillation Analysis

Vary these as part of the likelihood maximization

(predominantly $\bar{\nu}_\tau$, Undetected)

Disappearance

$\bar{\nu}_\mu \rightarrow \bar{\nu}_x$

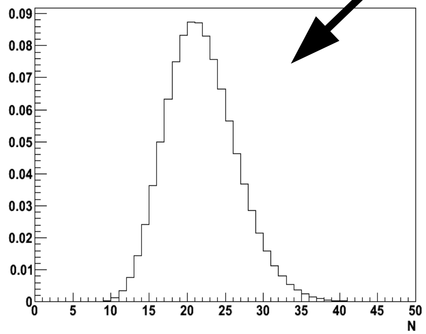
Oscillations

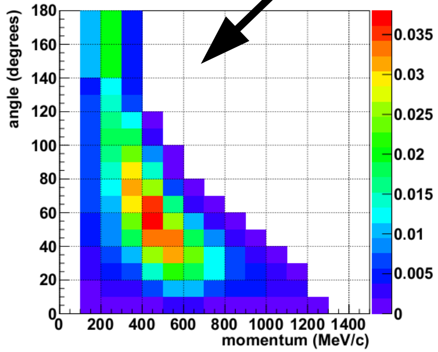
$\sin^2\theta_{23}$	0.527	$\sin^2\bar{\theta}_{23}$	0–1
Δm^2_{32}	2.51×10^{-3} eV^2	$\Delta \bar{m}^2_{32}$	0–0.02 eV^2
$\sin^2\theta_{13}$	0.0248	$\sin^2\bar{\theta}_{13}$	0.0248
$\sin^2\theta_{12}$	0.304	$\sin^2\bar{\theta}_{12}$	0.304
Δm^2_{21}	7.53×10^{-5} eV^2	$\Delta \bar{m}^2_{21}$	7.53×10^{-5} eV^2
δ	−1.55 rad	$\bar{\delta}$	−1.55 rad

Fixed parameters based on T2K neutrino mode measurements and PDG2014

Disappearance Analysis

$$\mathcal{L}(N_{obs}, \boldsymbol{x}, \boldsymbol{o}, \boldsymbol{f}) = \mathcal{L}_{norm}(N_{\mathrm{obs}}, \boldsymbol{o}, \boldsymbol{f}) \times \mathcal{L}_{shape}(N_{\mathrm{obs}}, \boldsymbol{x}, \boldsymbol{o}, \boldsymbol{f}) \times \mathcal{L}_{\mathrm{syst}}(\boldsymbol{f})$$





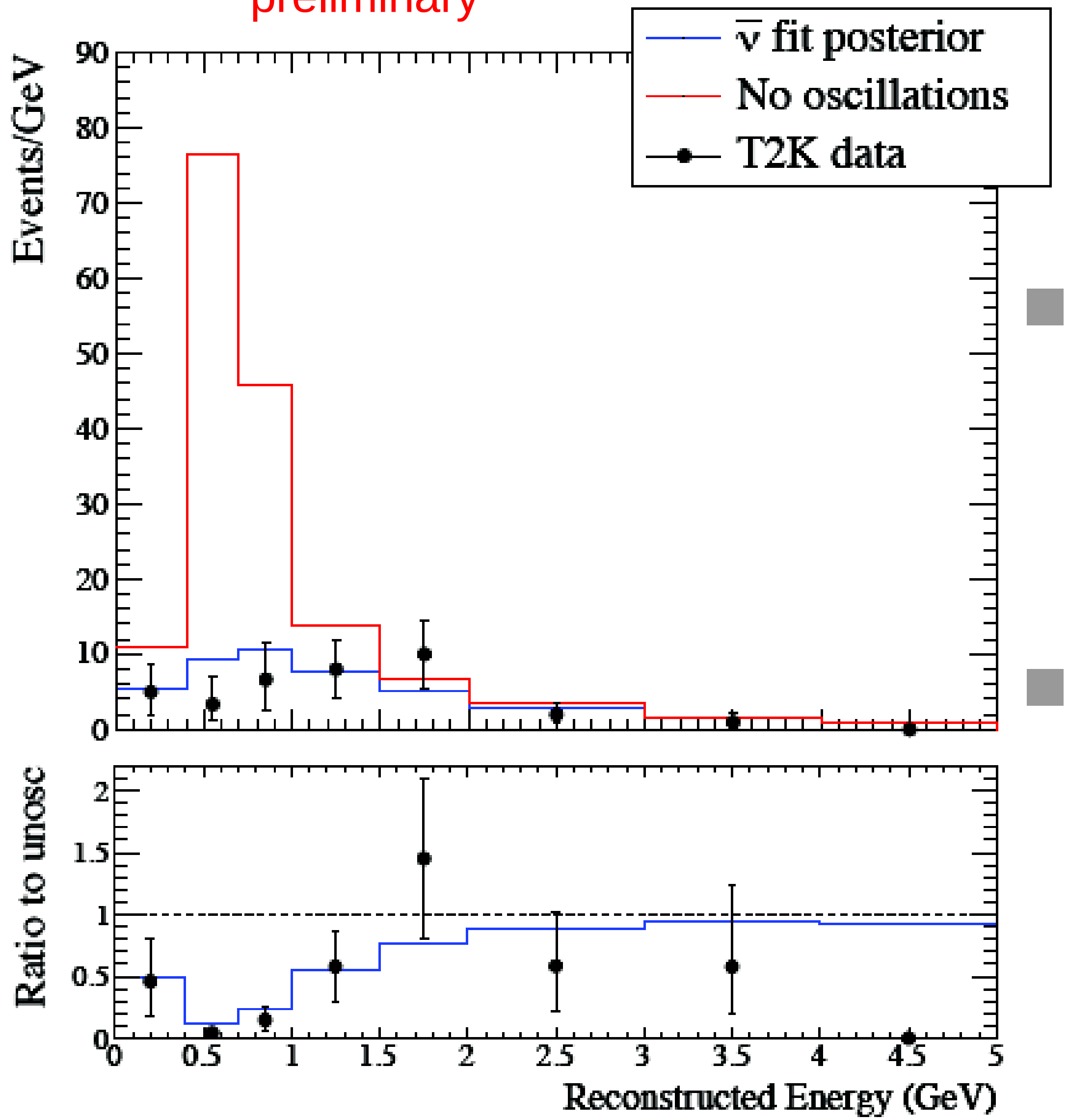
$$\mathcal{L}_{\mathrm{syst}} = \exp(-0.5 \sum_{i,j} v_i M_{ij} v_j)$$

Analysis	Method	Systematics	ND Constraint	Shape Term
MaCH3	MCMC	Marginalize	Fit	E^{rec}
Valor	MINUIT	Minimize	Cov. Matrix	E^{rec}
p-θ	MINUIT	Marginalize	Cov. Matrix	(p_μ, θ_μ)

- Three separate oscillation analyses with different techniques
- All maximize a likelihood function against the data incorporating correlated systematic uncertainties

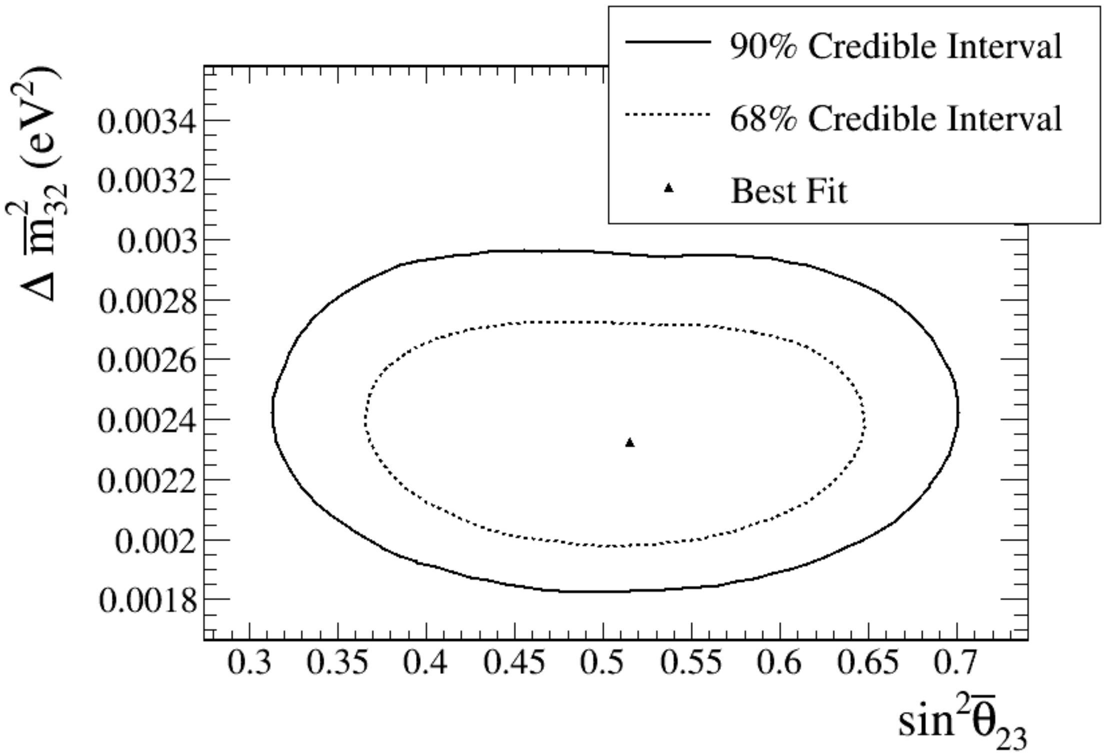
Super-K muon-like data (antineutino mode)

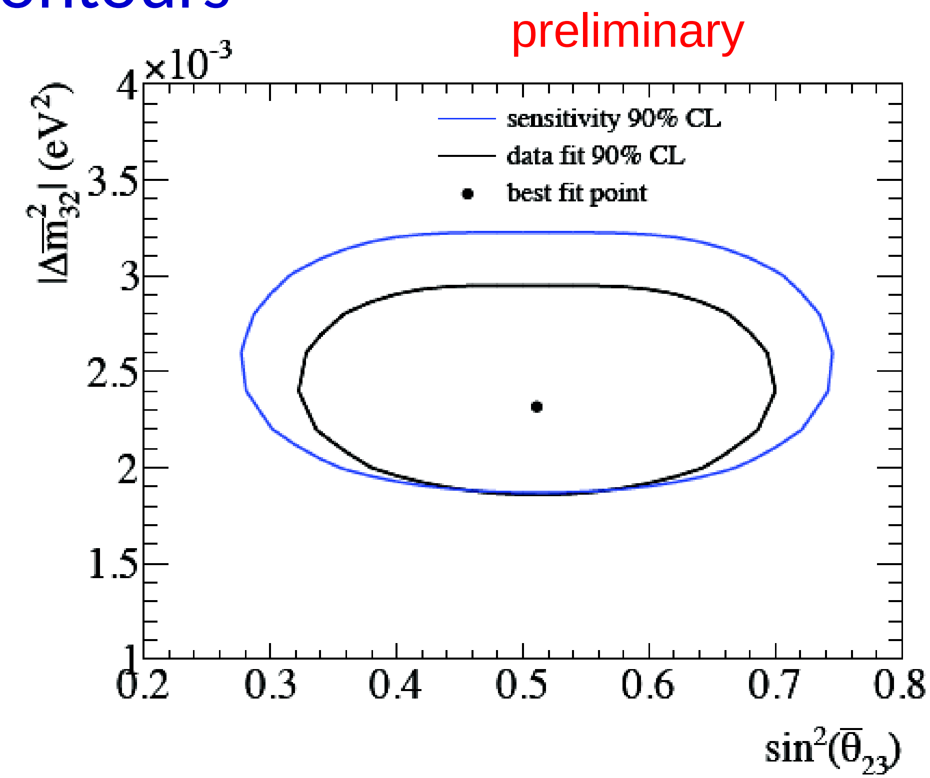
preliminary



- Data clearly disfavor the no oscillation hypothesis
- Oscillation dip, which is used to determine $\overline{\Delta m}^2$ and $\sin\bar{\theta}_{23}$, is clearly visible

Muon Antineutrino Disappearance Contours



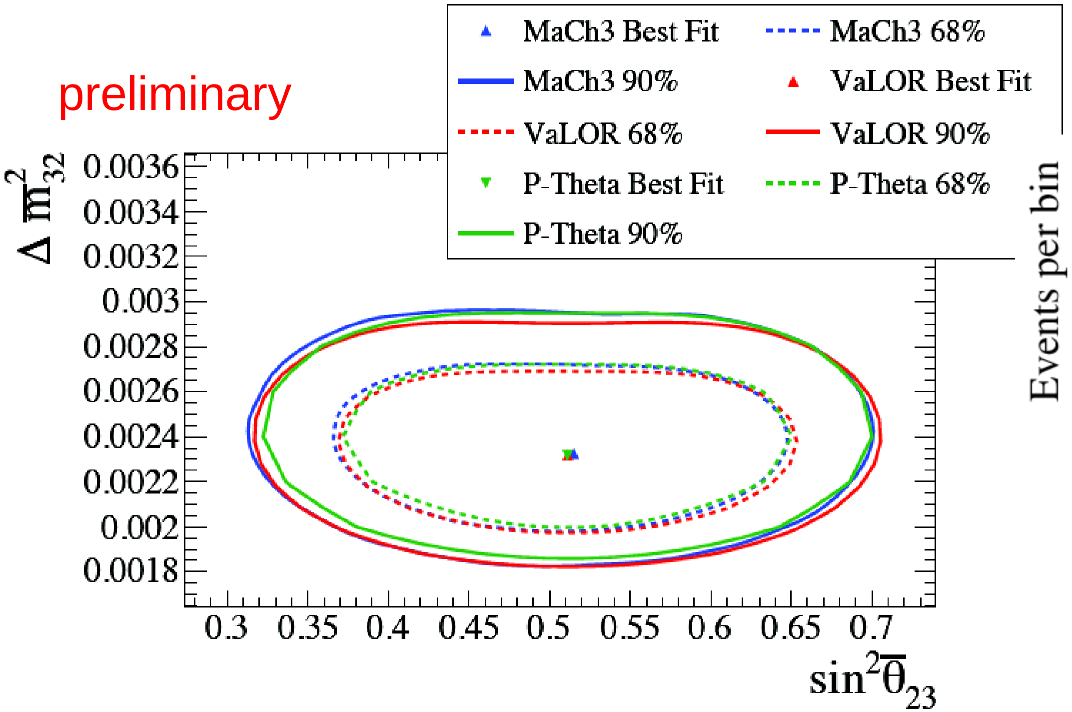


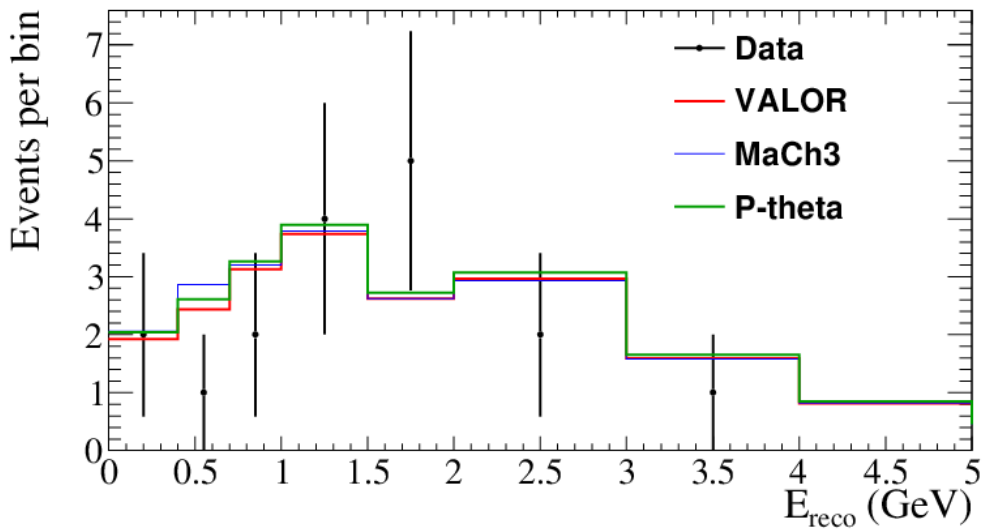
$\lvert\Delta\bar{m}^2_{32}\rvert$	$\sin^2(\bar{\theta}_{23})$
$2.33^{+0.27}_{-0.23}\ \times10^{-3}\ \mathrm{eV}^2$	$0.515^{+0.085}_{-0.095}$

- Tight constraints on the antineutrino mixing parameters
  - Normal hierarchy assumed
- Data result is slightly more constraining than expected sensitivity

Cross Analysis Comparison

preliminary

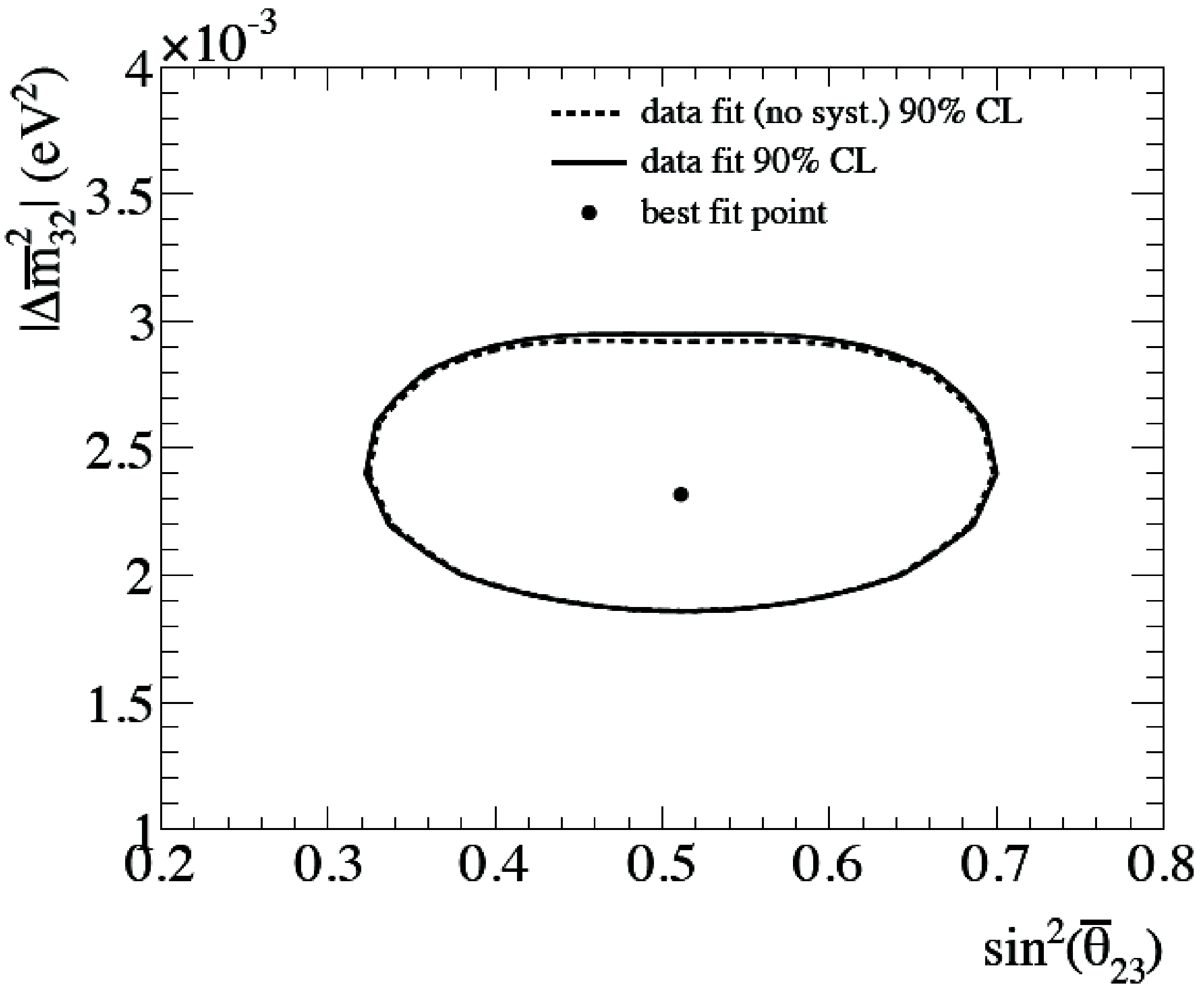




- Very good agreement among the three different analyses
- Results from fit to the normal mass hierarchy

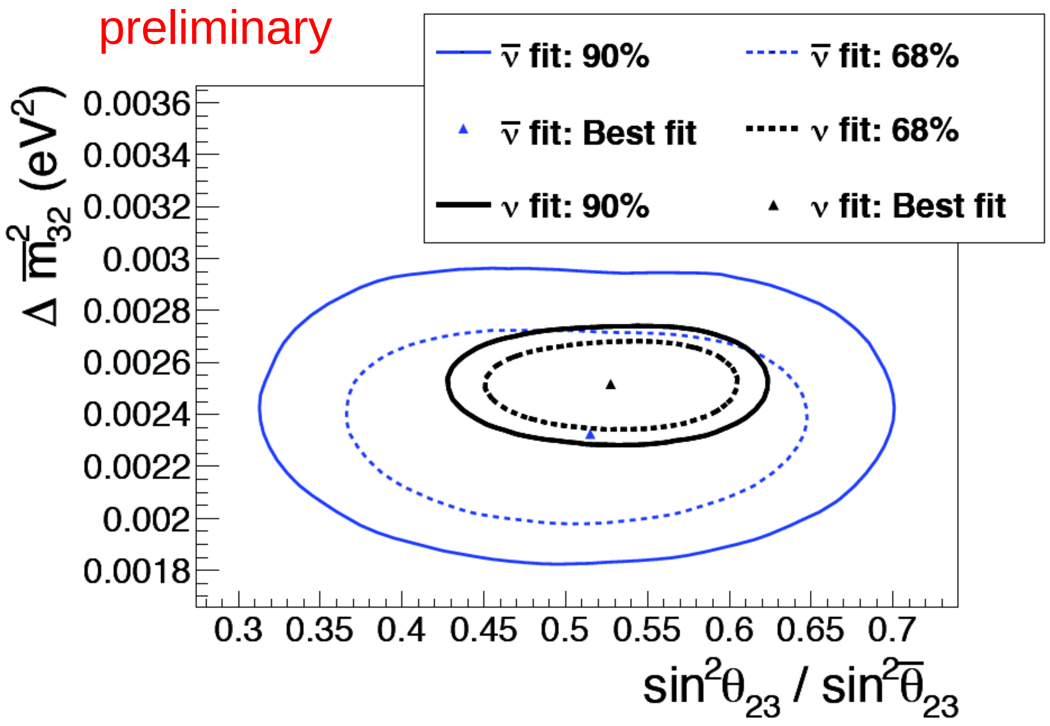
Impact of Systematic Errors

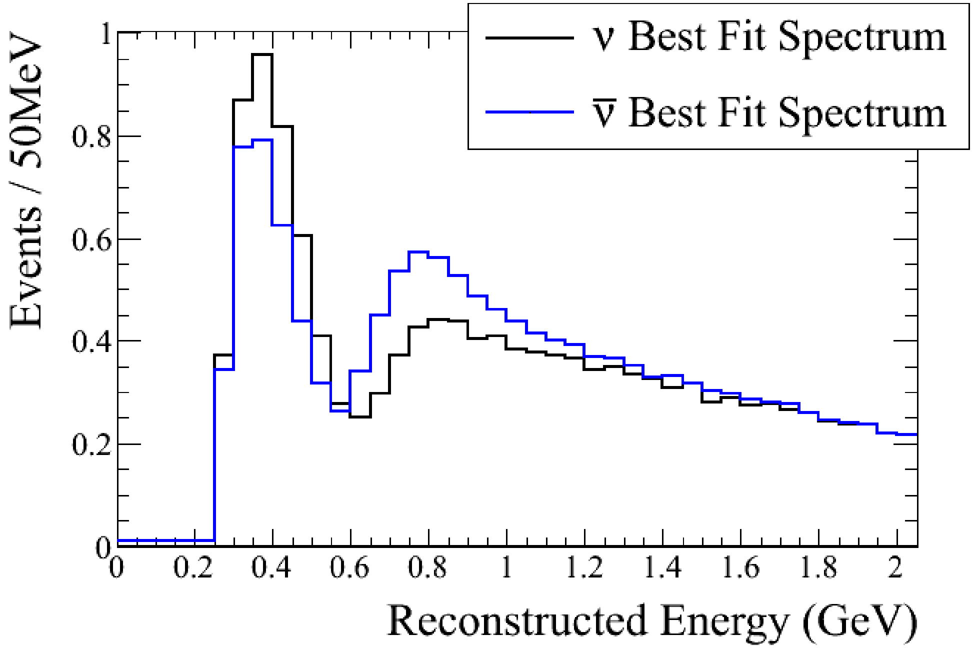
preliminary



- No change is best fit point and only minimal change to the allowed region
- Analysis is heavily dominated by statistical uncertainty
  - Systematic uncertainties have little impact

Comparison with Neutrino Mode Result

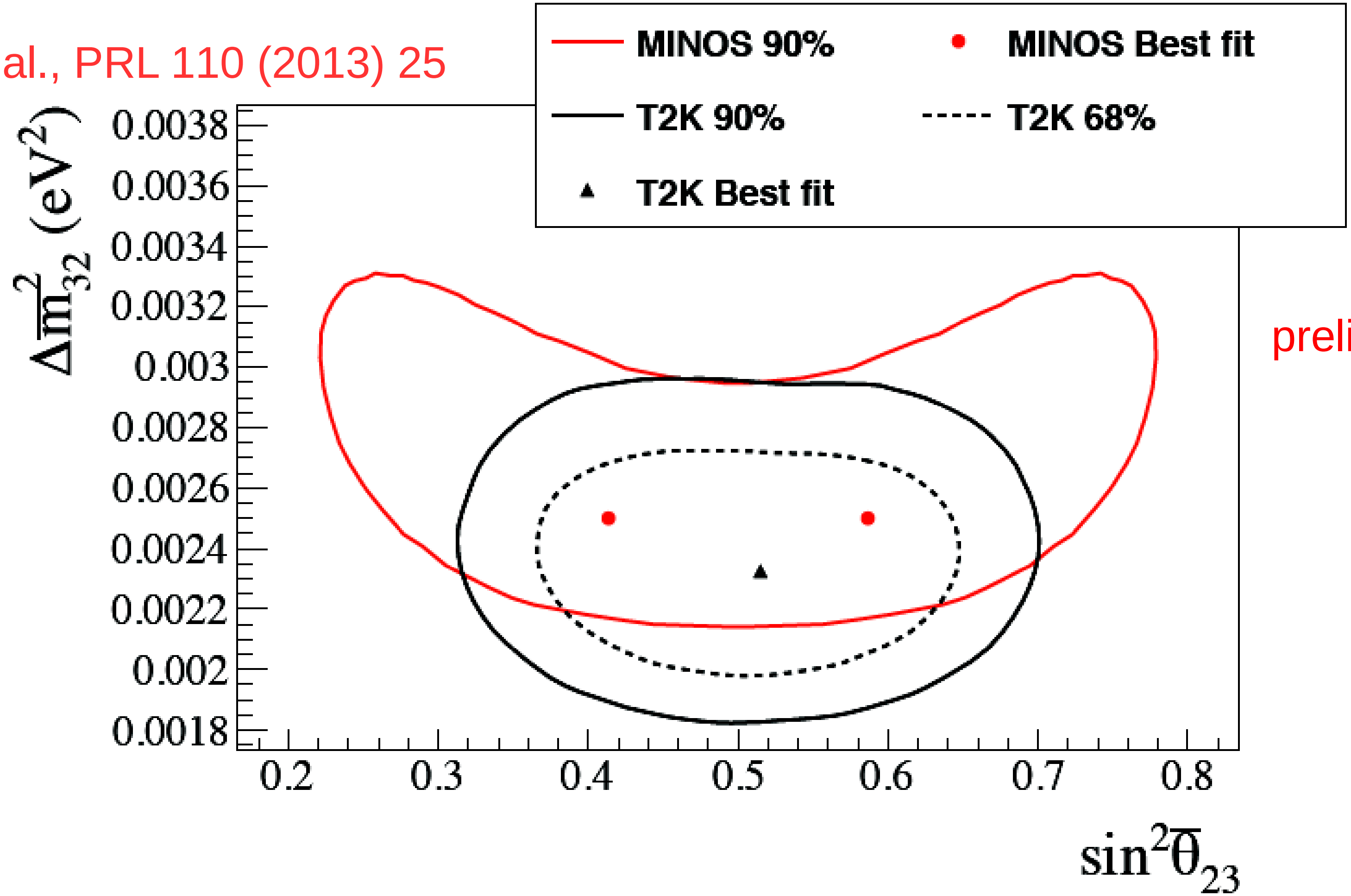




- Neutrino mode data shows a tighter contour than the antineutrino mode data
  - Large POT in the former and larger cross section for neutrinos

Comparison with MINOS Antineutrino Mode Result

P.Adamson et al., PRL 110 (2013) 25



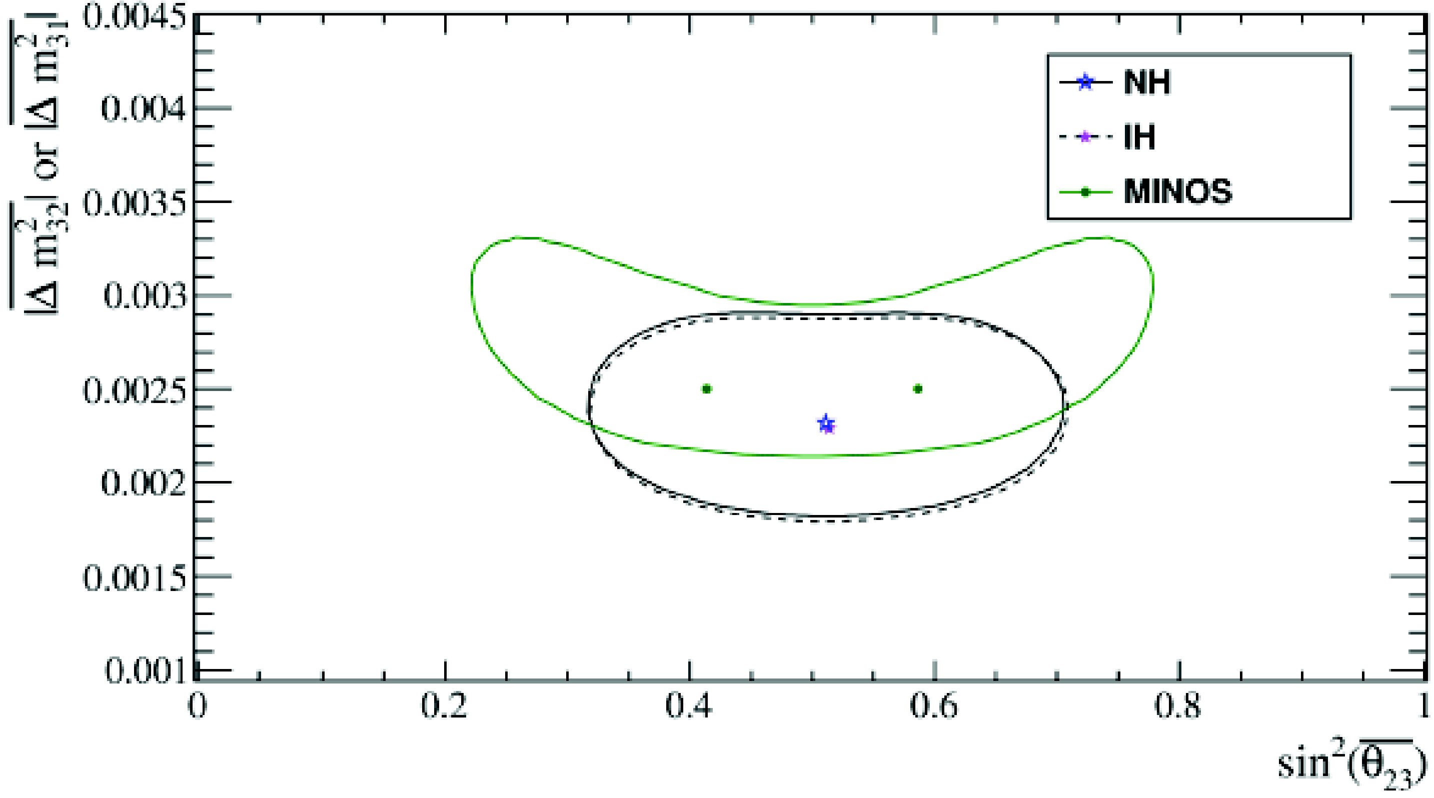
preliminary

- T2K's accumulated POT is less than MINOS's but the measured contour is smaller
  - 2.3×10^{20} vs. 3.3×10^{20}
  - Nice demonstration of the off-axis oscillation technique

Hierarchy Comparison

P.Adamson et al., PRL 110 (2013) 25

preliminary



- Changing the assumed mass hierarchy similarly has no large effect on the analysis result

Summary

- First measurement of muon antineutrino disappearance using the off-axis beam technique has been performed using an off-axis beam

$\lvert\Delta\bar{m}^2_{32}\rvert$	$\sin^2(\bar{\theta}_{23})$
$2.33^{+0.27}_{-0.23}\ \times 10^{-3}\ \mathrm{eV}^2$	$0.515^{+0.085}_{-0.095}$

preliminary
(MCMC Analysis)

- Currently has world-leading measurement of the antineutrino mixing angle $\sin^2\theta_{23}$

- So far T2K has accumulated only 13% of its total allocated POT
  - More physics to come!

- Antineutrino mode data is still being accumulated
  - Expect 4.5×10^{20} POT by summer, about twice the current statistics)

- Search for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance now underway
  - Aiming for a first result this summer – stay tuned!

Thank You!

Please continue to enjoy oscillation measurements from T2K!