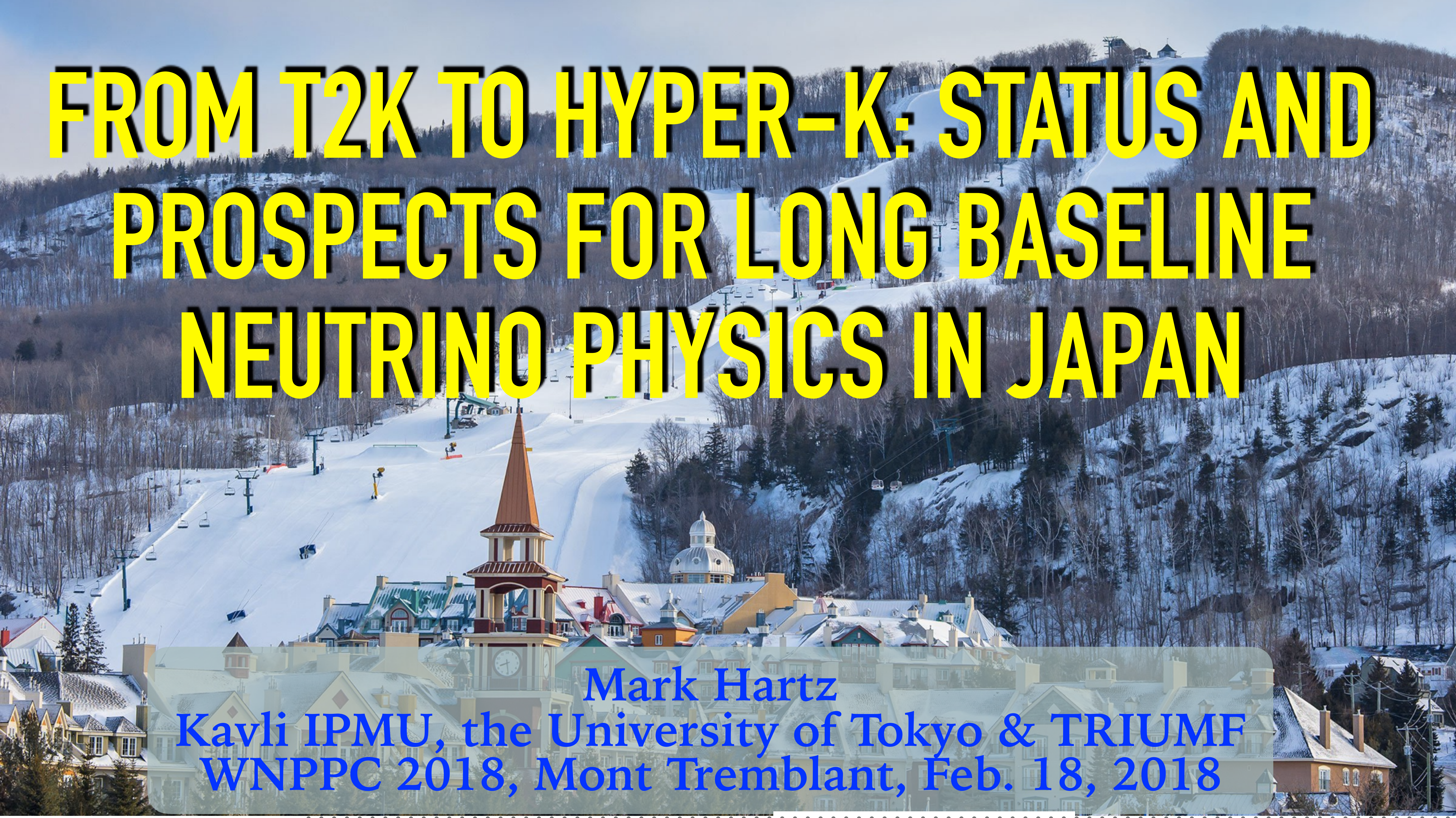

FROM T2K TO HYPER-K: STATUS AND PROSPECTS FOR LONG BASELINE NEUTRINO PHYSICS IN JAPAN

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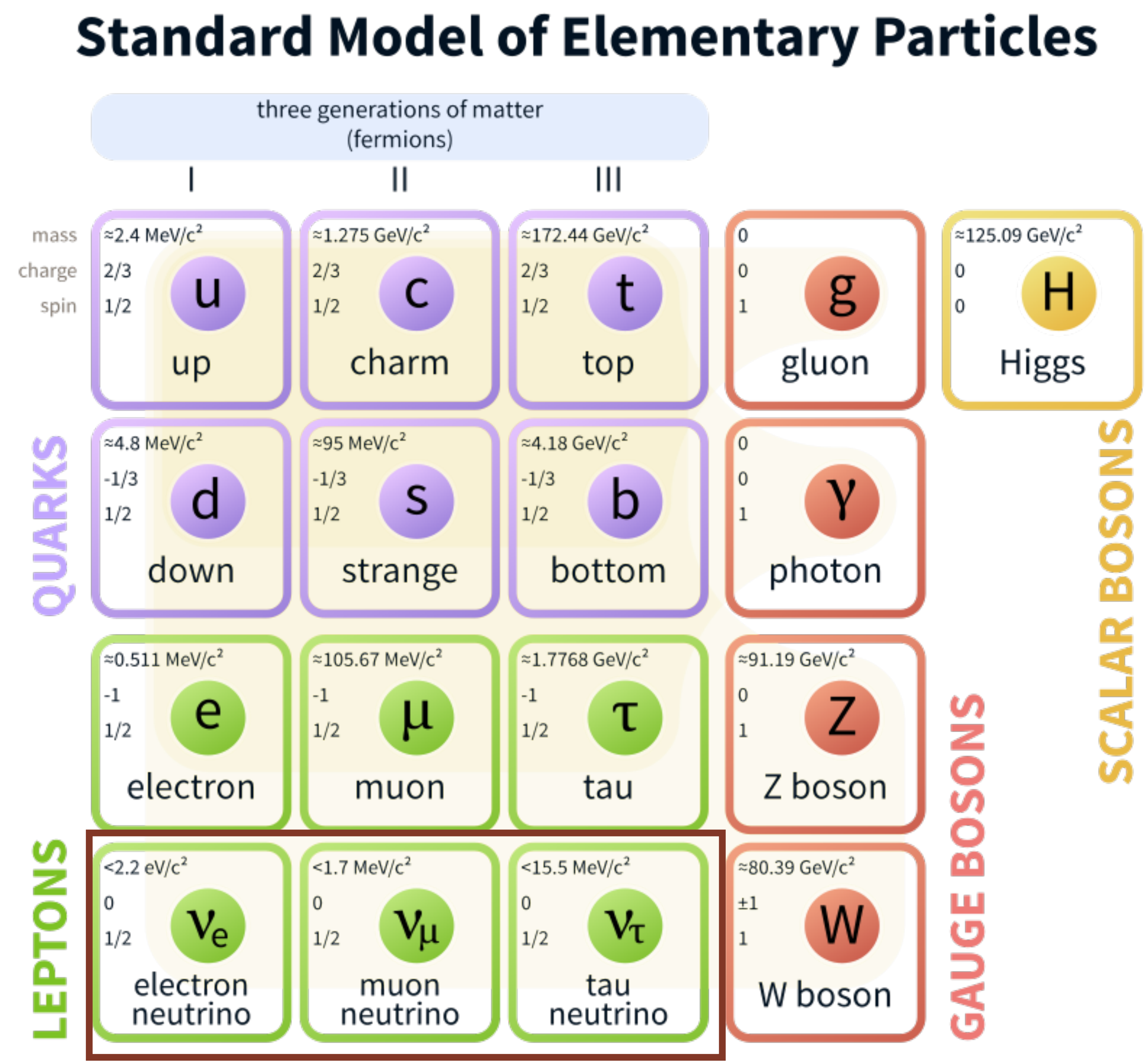
Kavli IPMU, the University of Tokyo & TRIUMF
WNPPC 2018, Mont Tremblant, Feb. 18, 2018

KAVLI IPMU
TRIUMF
T2K
Hyper-Kamiokande

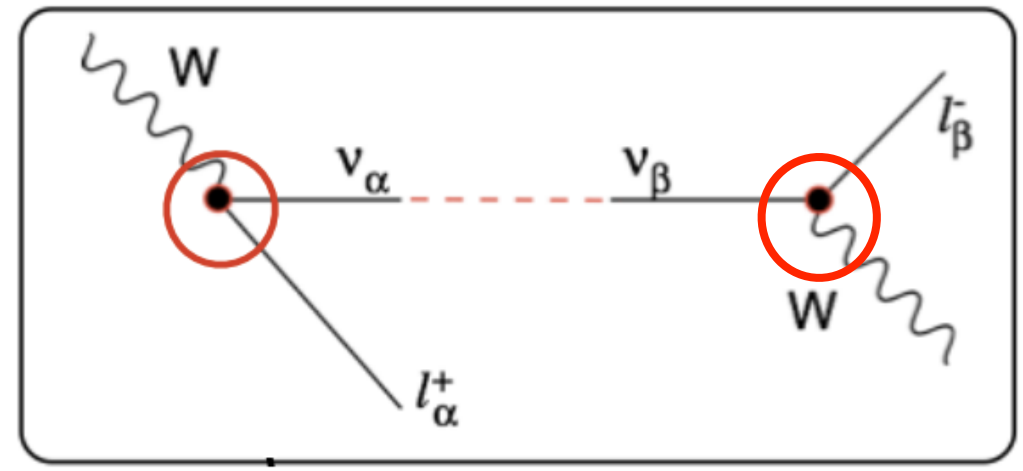
NEUTRINOS IN THE STANDARD MODEL

- **Neutrinos:**
  - Electrically neutral
  - Interact via Z, W bosons
  - 3 flavors, each associated with charged lepton
  - Very small mass, but not 0
    - Indicates physics beyond the standard model



NEUTRINO FLAVOR AND MASS

- Neutrinos are produced and interact via weak force in states of definite flavor



α = e, μ, τ

- Neutrinos propagate as states of definite mass.

- Flavor states are a linear superposition of mass states

$$|\nu_\alpha\rangle = \sum_{i=1}^{i=3} U^*_{\alpha i} |\nu_i\rangle$$

Mass states

- Unitary matrix *U* relates the flavor and mass states

- The relative phase of propagation depends on $\Delta m^2_{ji} = m_j^2 - m_i^2$

NEUTRINO MIXING & OSCILLATIONS

Neutrino mass and flavor states mix according to unitary matrix:

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s^{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_{21}/2} & 0 \\ 0 & 0 & e^{i\alpha_{31}/2} \end{pmatrix}$$

Accessible through neutrino oscillations ($s_{12} = \sin\theta_{12}$, etc.)

Majorana phases if neutrinos are Majorana particles

δ, α_{21} and α_{31} introduce new sources of CP violation

NEUTRINO MIXING & OSCILLATIONS

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Accessible through neutrino oscillations ($s_{12} = \sin\theta_{12}$, etc.)

Majorana phases if neutrinos are Majorana particles

δ, α_{21} and α_{31} introduce new sources of CP violation

The flavor content of neutrino states oscillate as they traverse matter or vacuum:

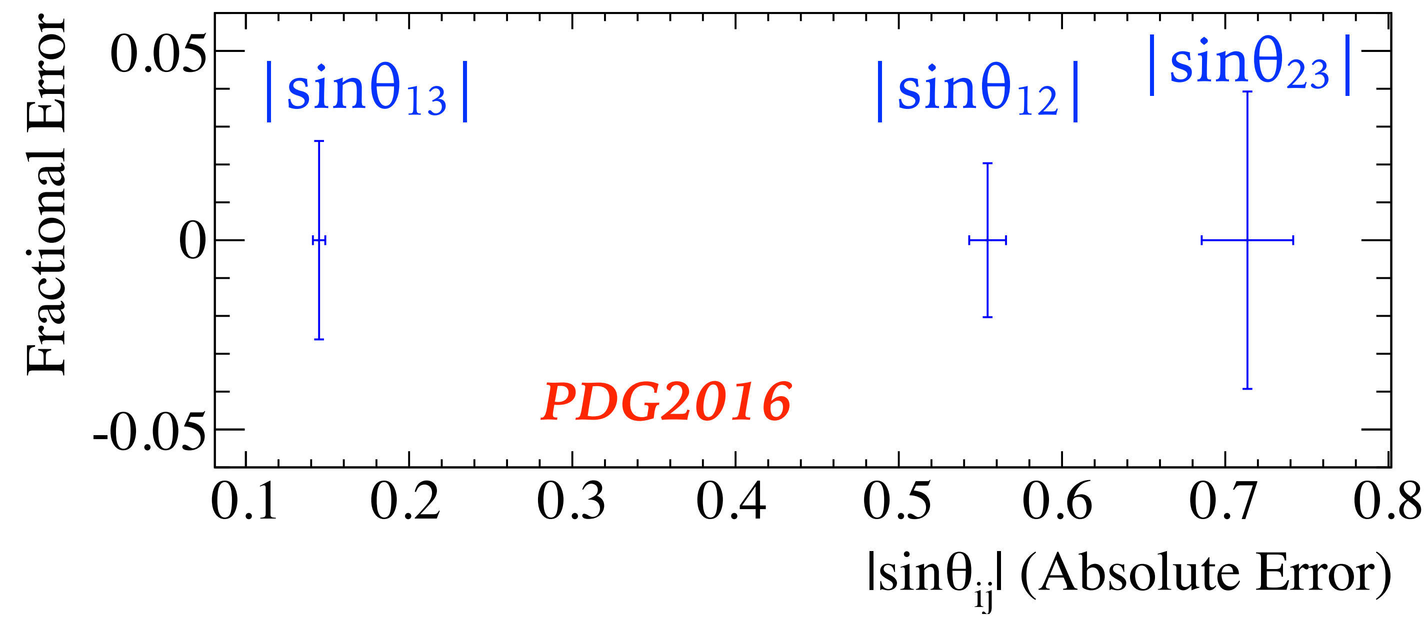
$$P_{\alpha\to\beta}=\delta_{\alpha\beta}-4\sum_{i>j}\mathrm{Re}\left(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}\right)\sin^2\left(\boxed{\frac{\Delta m^2_{ij}L}{4E}}\right)$$
$$+2\sum_{i>j}\mathrm{Im}\left(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}\right)\sin\left(\boxed{\frac{\Delta m^2_{ij}L}{2E}}\right)$$

Dependence on mass squared differences of mass states, distance and energy

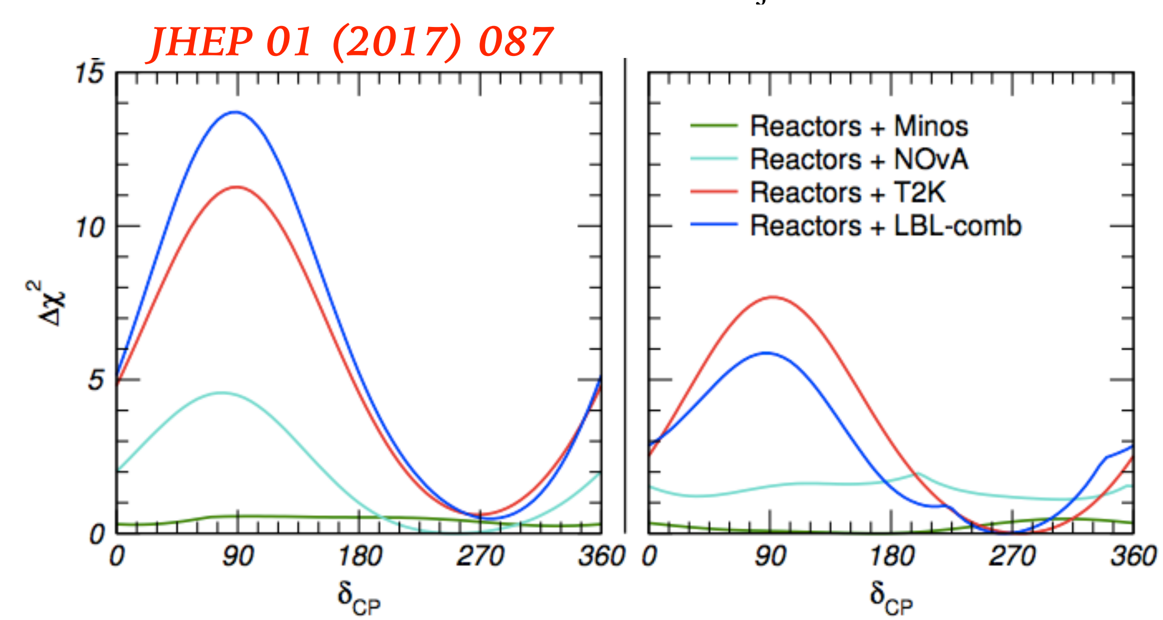
*Oscillations from flavor **α** to **β** in vacuum*

STATE OF OSCILLATION PARAMETER MEASUREMENTS

- **Mixing angles:**
  - Measured with ~5% precision
  - θ_{23} is consistent with 45°



- **CP violation:**
  - Weak global preference for δ_{cp} near 3π/2 (-π/2)



- **Masses:**
  - Whether the **m_3** state is heaviest (normal ordering) or lightest (inverted ordering) is still undetermined

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

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

or

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

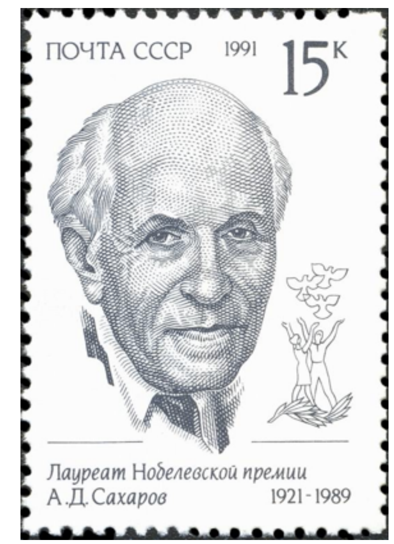
WHY IS CP VIOLATION IMPORTANT?

- Neutrino oscillations introduce a potential new source of CP violation
- Recall Sakharov's rules for explaining the baryogenesis:

  Baryon number violation.

  CP-symmetry violation.

  Interactions out of thermal equilibrium.

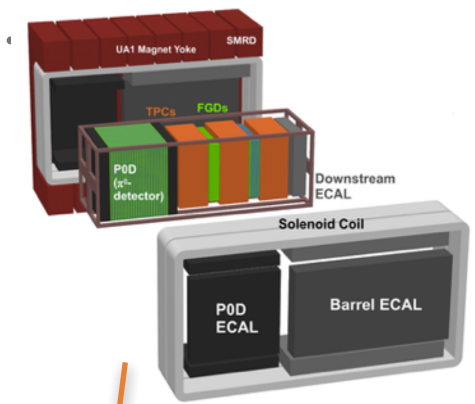


- Observed CP violation in the quark sector is not enough
- Leptogenesis is possible (**Fukugita & Yanagida, Phys. Lett. B 174, 45-47, 1986**):
  - First produce L $\neq$ 0 (lepton number violation)
  - Non-perturbative processes convert L $\neq$ 0 to B $\neq$ 0

A LONG-BASELINE NEUTRINO OSCILLATION EXPERIMENT

THE T2K EXPERIMENT

ND280 Near Detector



Generate beam of 99% muon neutrinos

THE T2K EXPERIMENT

ND280 Near Detector

Generate beam of 99% muon neutrinos

Muon (anti)neutrino survival:

$$P_{\mu\to\mu} = 1 - (\boxed{\sin^2 2\theta_{23}} - \sin^2\theta_{23}\cos 2\theta_{23}\sin^2 2\theta_{13})\sin^2\left(\frac{\boxed{\Delta m^2_{32}}L}{4E_\nu}\right) + \ldots$$

Electron (anti)neutrino appearance:

Discovery of $\nu_e \to \nu_\mu$ transition
Phys.Rev.Lett. 112 (2014) 061802

$$P_{\mu\to e} = \boxed{\sin^2\theta_{23}\sin^2 2\theta_{13}}\sin^2\left(\frac{\Delta m^2_{31}L}{4E_\nu}\right) \boxed{\mp} \frac{\sin 2\theta_{12}\sin 2\theta_{23}}{2\sin\theta_{13}}\sin^2 2\theta_{13}\sin\left(\frac{\Delta m^2_{21}L}{4E_\nu}\right)\sin^2\left(\frac{\Delta m^2_{31}L}{4E_\nu}\right)\boxed{\sin\delta_{CP}} + \ldots$$

sign flips for antineutrinos

The T2K Collaboration

～500 members, 64 Institutes, 12 countries

Canada
TRIUMF
U. B. Columbia
U. Regina
U. Toronto
U. Victoria
U. Winnipeg
York U.

France
CEA Saclay
LLR E. Poly.
LPNHE Paris

Germany
Aachen

Italy
INFN, U. Bari
INFN, U. Napoli
INFN, U. Padova
INFN, U. Roma

Japan
ICRR Kamioka
ICRR RCCN
Kavli IPMU
KEK
Kobe U.
Kyoto U.
Miyagi U. Edu.
Okayama U.
Osaka City U.
Tokyo Institute Tech
Tokyo Metropolitan U.
U. Tokyo
Tokyo U of Science
Yokohama National U.

Poland
IFJ PAN, Cracow
NCBJ, Warsaw
U. Silesia, Katowice
U. Warsaw
Warsaw U. T.
Wroclaw U.

Russia
INR

Spain
IFAE, Barcelona
IFIC, Valencia
U. Autonoma Madrid

Switzerland
ETH Zurich
U. Bern
U. Geneva

United Kingdom
Imperial C. London
Lancaster U.
Oxford U.
Queen Mary U. L.
Royal Holloway U.L.
STFC/Daresbury
STFC/RAL
U. Liverpool
U. Sheffield
U. Warwick

USA
Boston U.
Colorado S. U.
Duke U.
Louisiana State U.
Michigan S.U.
Stony Brook U.
U. C. Irvine
U. Colorado
U. Pittsburgh
U. Rochester
U. Washington

Vietnam
IFIRSE
IOP, VAST

OVERVIEW OF T2K EXPERIMENT

30 GeV proton beam

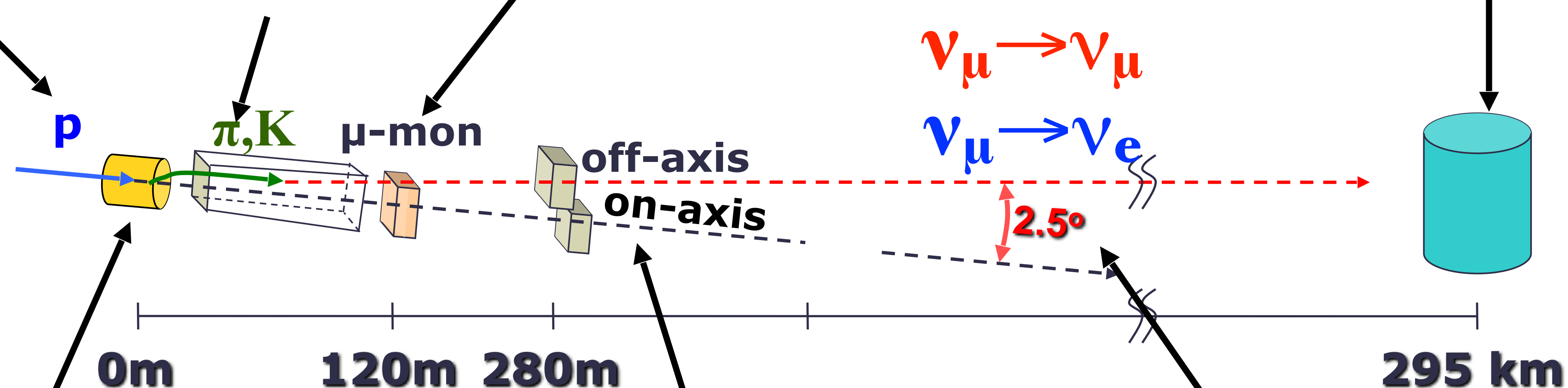
Decay volume:

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

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

MUMON measures muons from pion decay

Off-axis **far detector** at 295 km: SK Cherenkov detector measures event rates after oscillations



Off-axis = narrow band beam

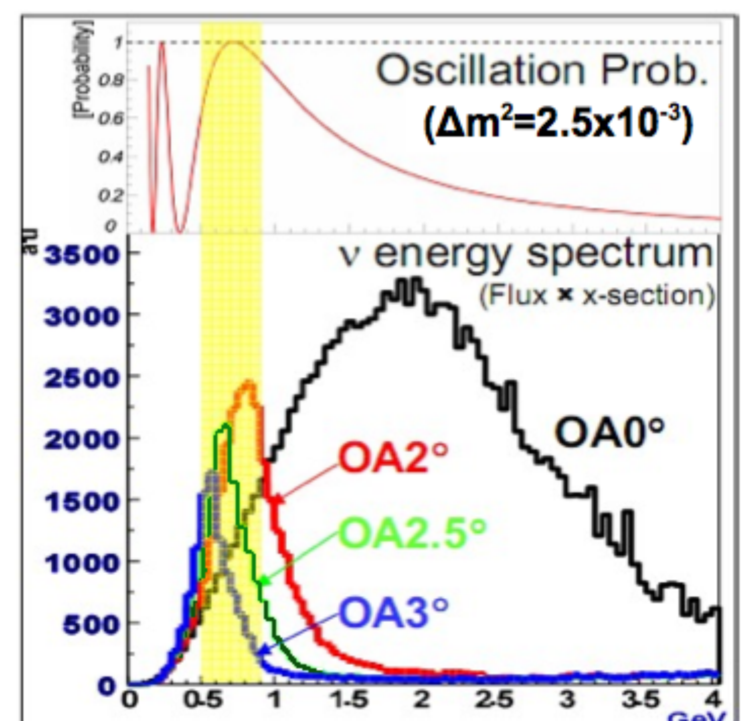
Beam on graphite target

3 magnetic horns focus:
π^+ for neutrino mode

π^- for antineutrino mode

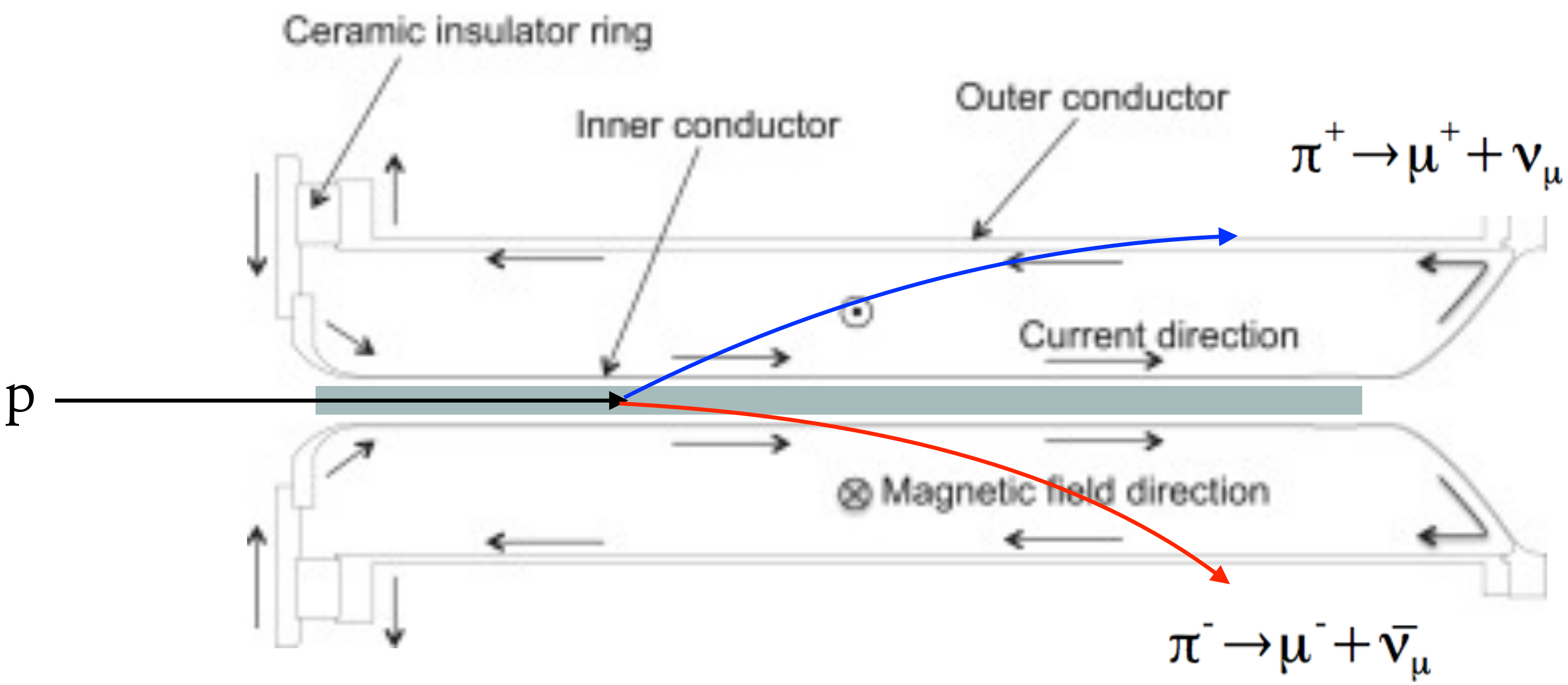
Off-axis **near detector**: ND280 detector measures spectra interactions

INGRID on-axis detector monitors beam direction and neutrino rate



NEUTRINO AND ANTINEUTRINO BEAMS

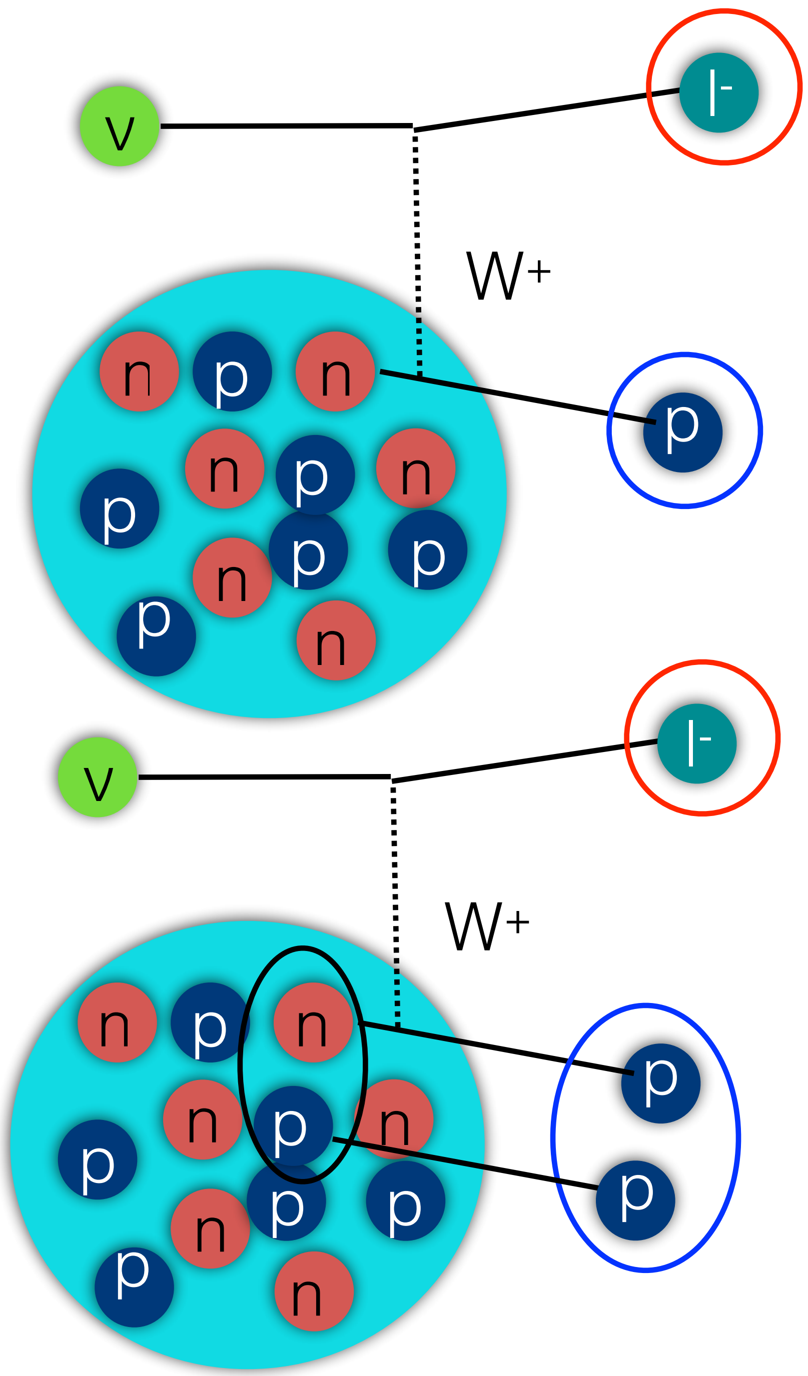
- Choose between neutrinos and antineutrinos by controlling polarity of horns



- Only horn polarity flips! **Beam, target and detector still made of matter.**
  - Expect ~4 times larger neutrino event rate even if CP is conserved
    - Must be accounted for in the analysis

DETECTING NEUTRINOS

- Detect neutrinos through the **charged-current interaction**
  - Energetic muon or electron in final state can be detected
  - Final state nucleon often undetectable



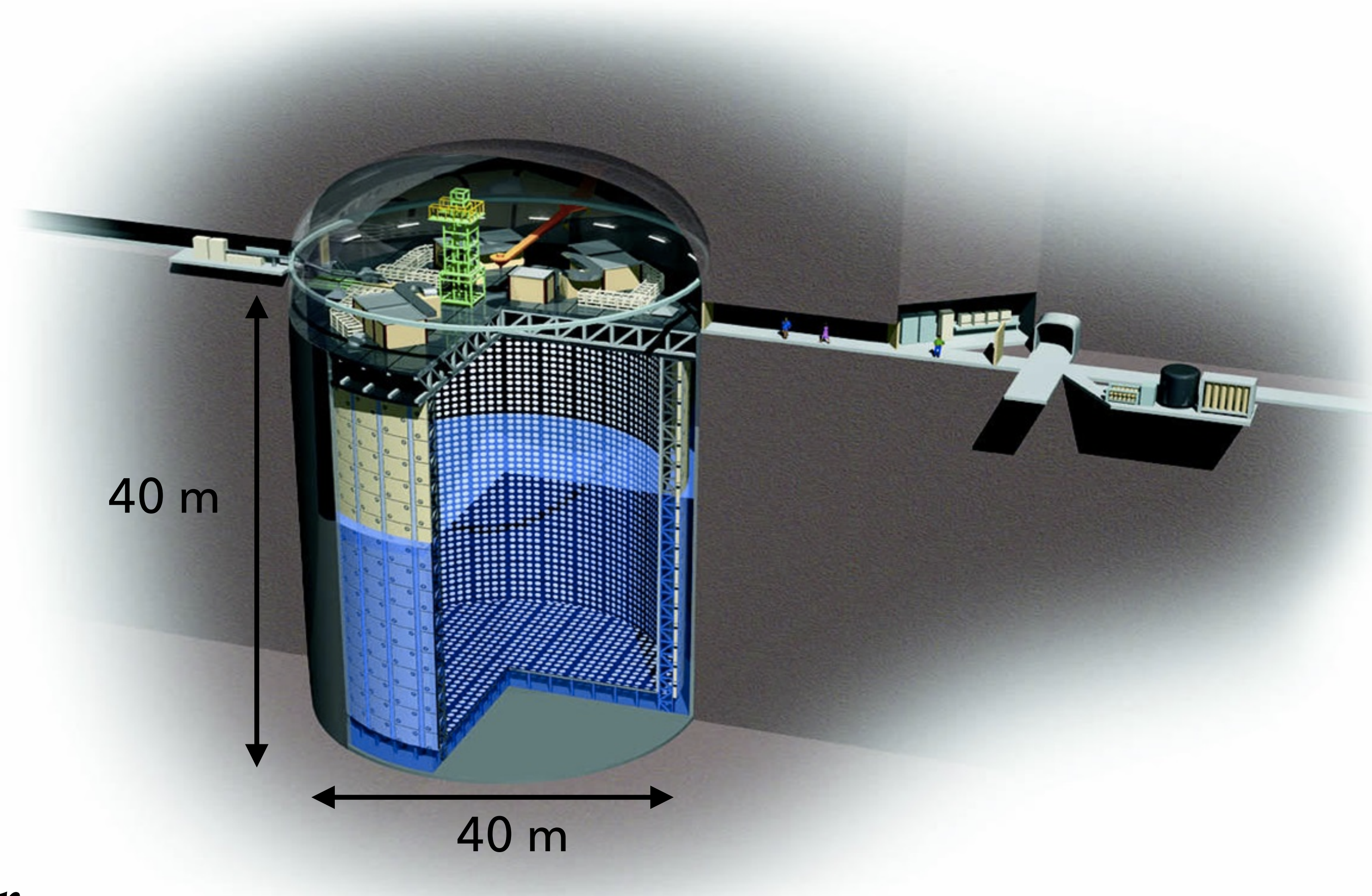
Approximation: scattering on single nucleon bound in nuclear potential

Reality: nuclear effects such as scattering on pairs of nucleons have a significant impact on the interaction cross section

Difficult model → source of systematic errors

SUPER-KAMIOKANDE

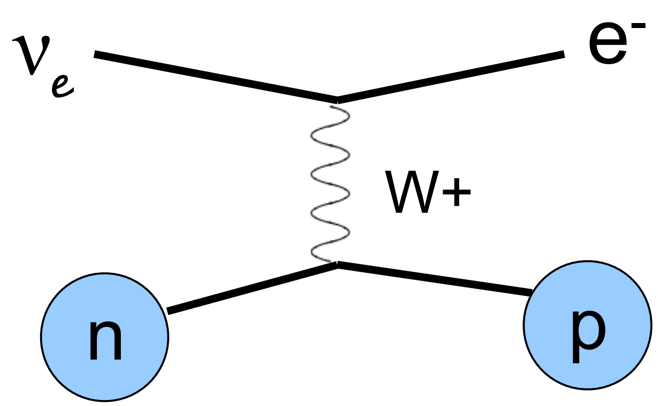
Ikenoyama near Kamioka



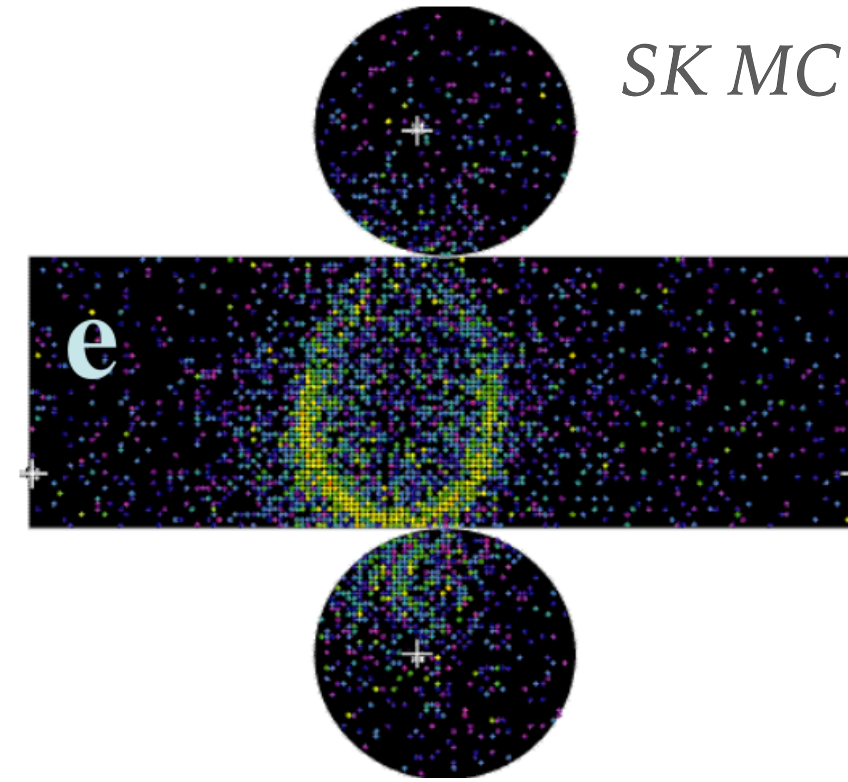
- 50 kton water-Cherenkov detector
- ~11,000 20" PMTs for inner detector (ID) (40% photo coverage)
- ~2,000 8" PMTs for outer detector (OD): veto cosmic muons, radioactivity, exiting particles
- Charged particles above Cherenkov threshold produce Cherenkov light detected by the PMTs

SIGNAL CHANNELS AT SUPER-K

Electron neutrino appearance signal:

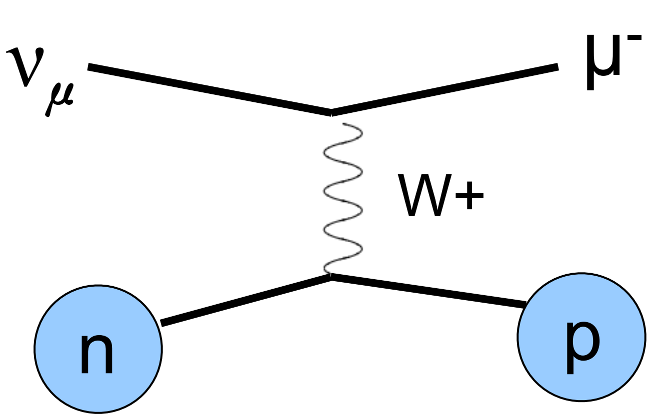


Detected electron produces a shower: "fuzzy" ring

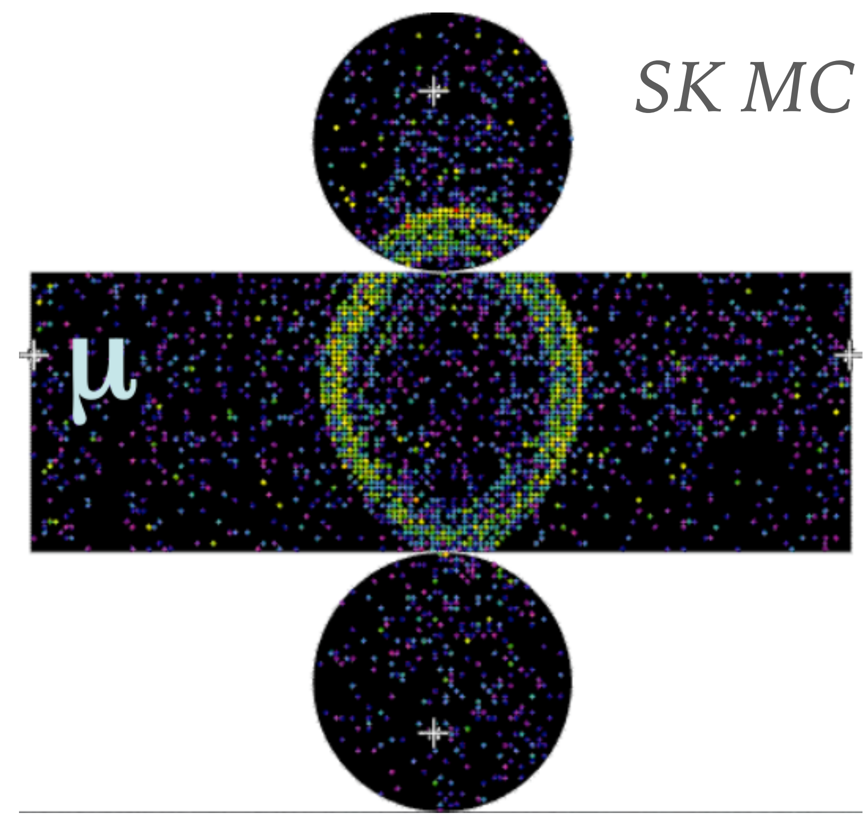


Target nucleon is bound in nucleus (more later)

Muon neutrino survival signal:



Detected muon produces a sharp ring

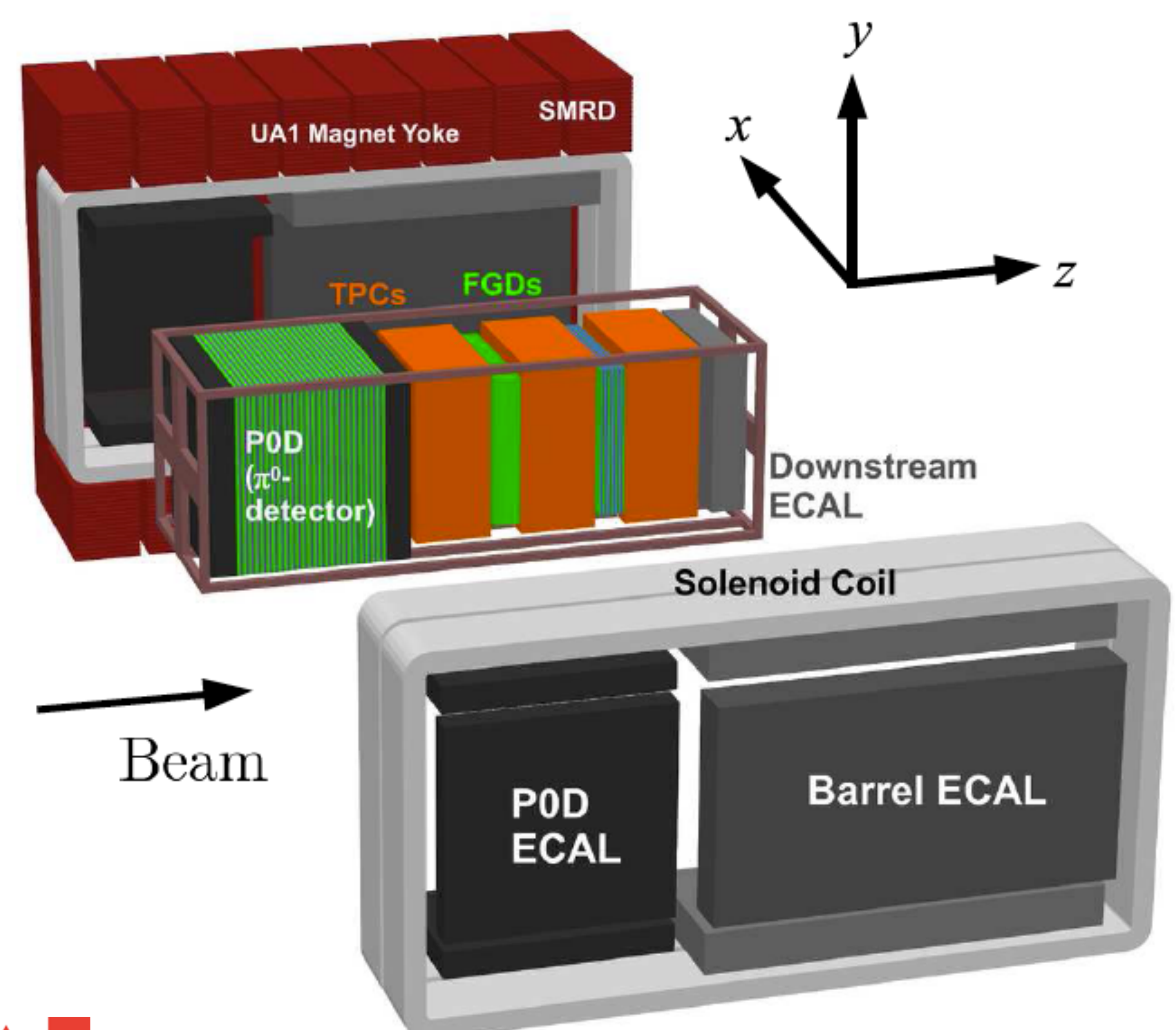


NEAR DETECTOR – ND280

- Detect neutrinos before they oscillate in the ND280 off-axis near detector
  - Place constraint on expected event rate at far detector
- Detector located in 0.2 T magnetic field

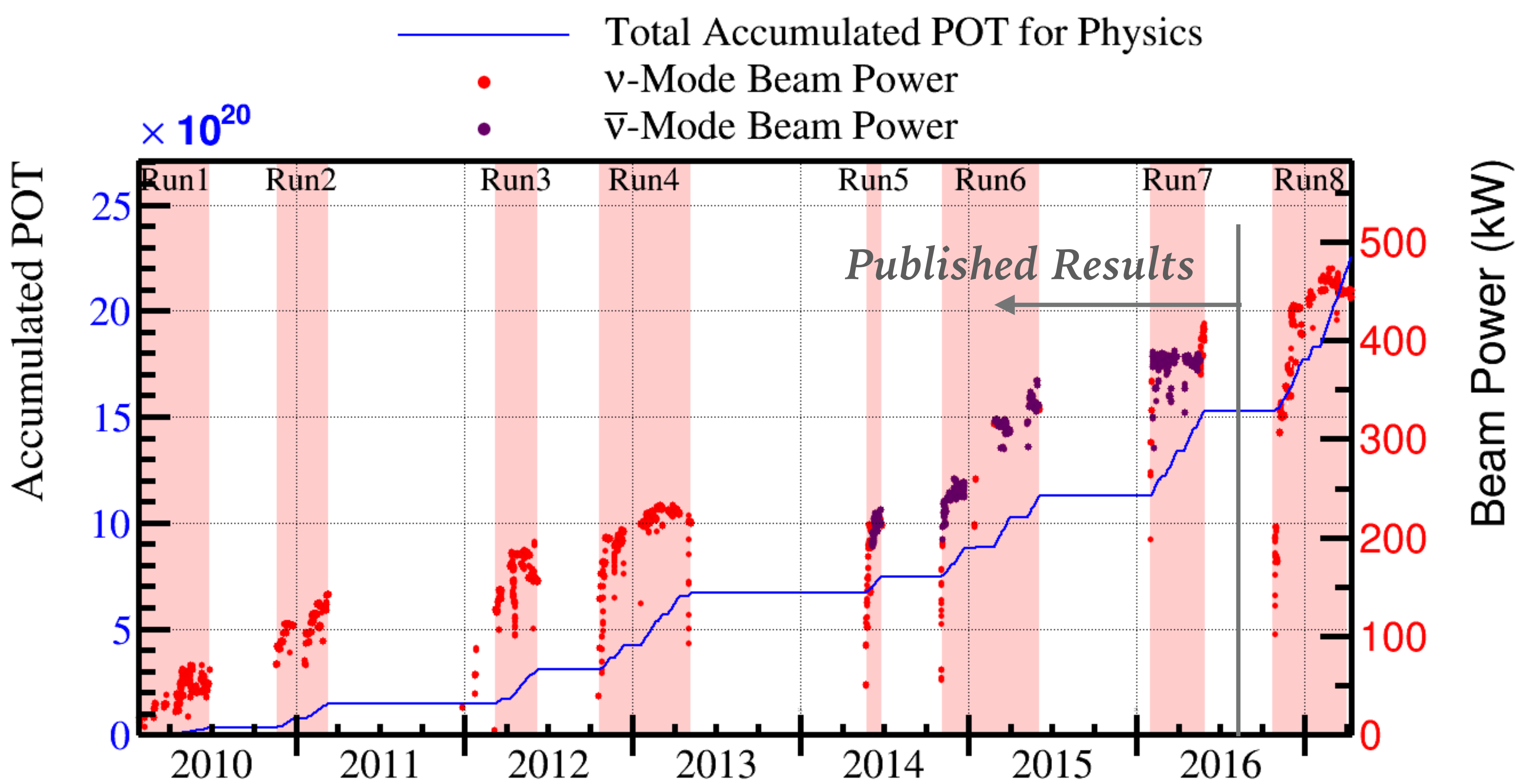
Key components:

- Fine-Grained Detectors (FGD)
  - Scintillator bars and water targets (FGD2)
  - Interaction mass and tracking
- Time Projection Chambers (TPC)
  - momentum and dE/dx measurements
- Construction and operation by: TRIUMF, UBC, U. Vic, Regina, U. Winnipeg



T2K RESULTS

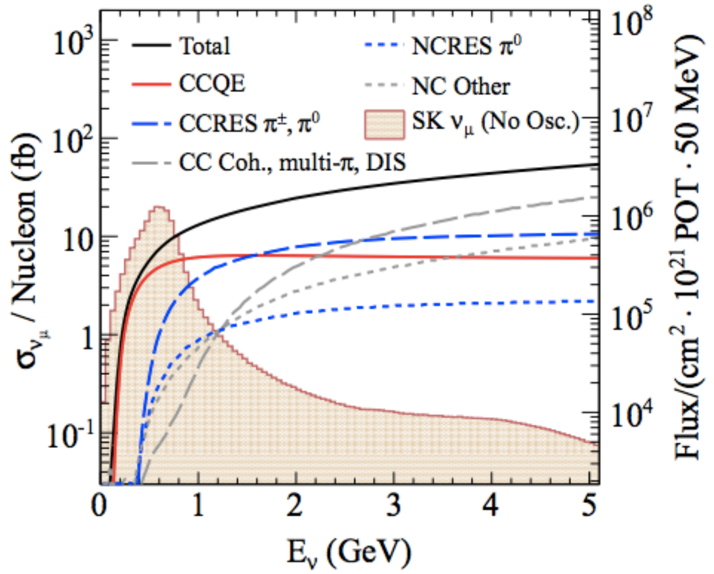
T2K DATA COLLECTION HISTORY



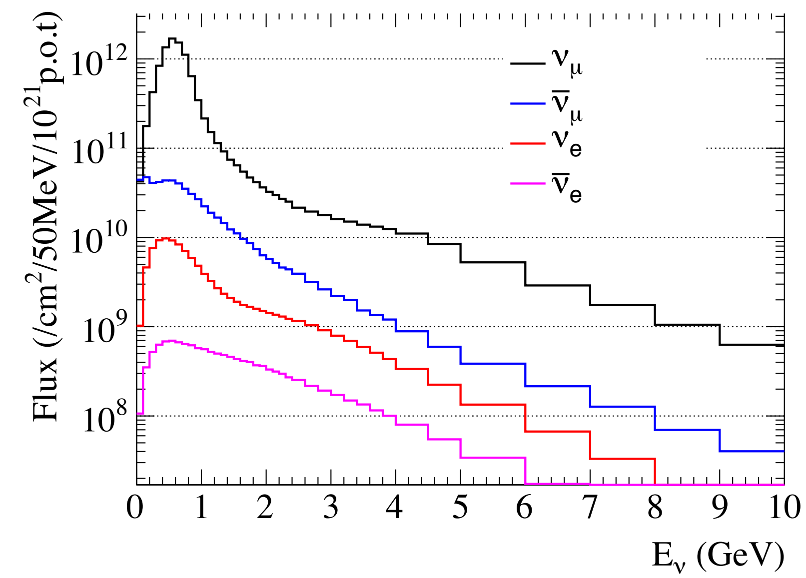
- Accumulated **14.7x10^{20}** protons-on-target (POT) in neutrino mode and **7.6x10^{20}** POT in antineutrino mode (additional antineutrino data not shown here)
  - **29% of the approved** T2K POT
  - 7.5x10^{20} neutrino mode, 7.5x10^{20} antineutrino mode for published results
    - **Phys. Rev. Lett. 118 (2017) no.15, 151801 - PRL Editor's Suggestion**
- Accelerator has achieved stable operation with **470 kW beam power**

CONSTRAINT FROM THE NEAR DETECTOR DATA

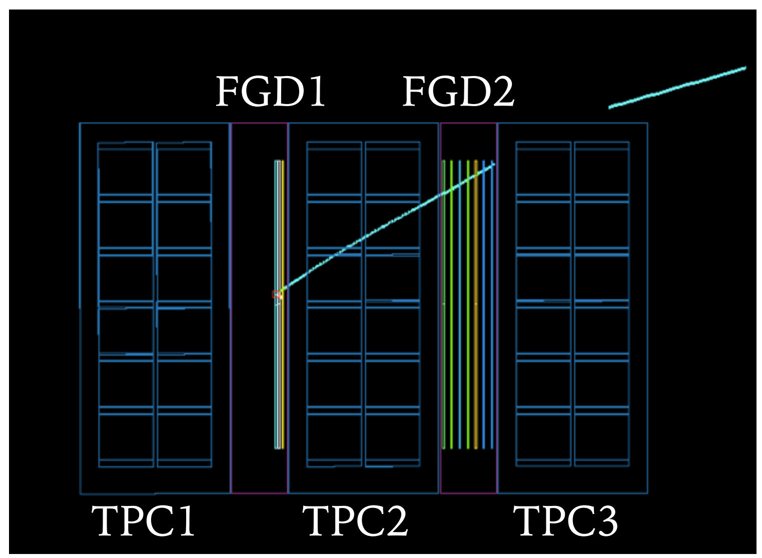
Neutrino-nucleus Interaction Model



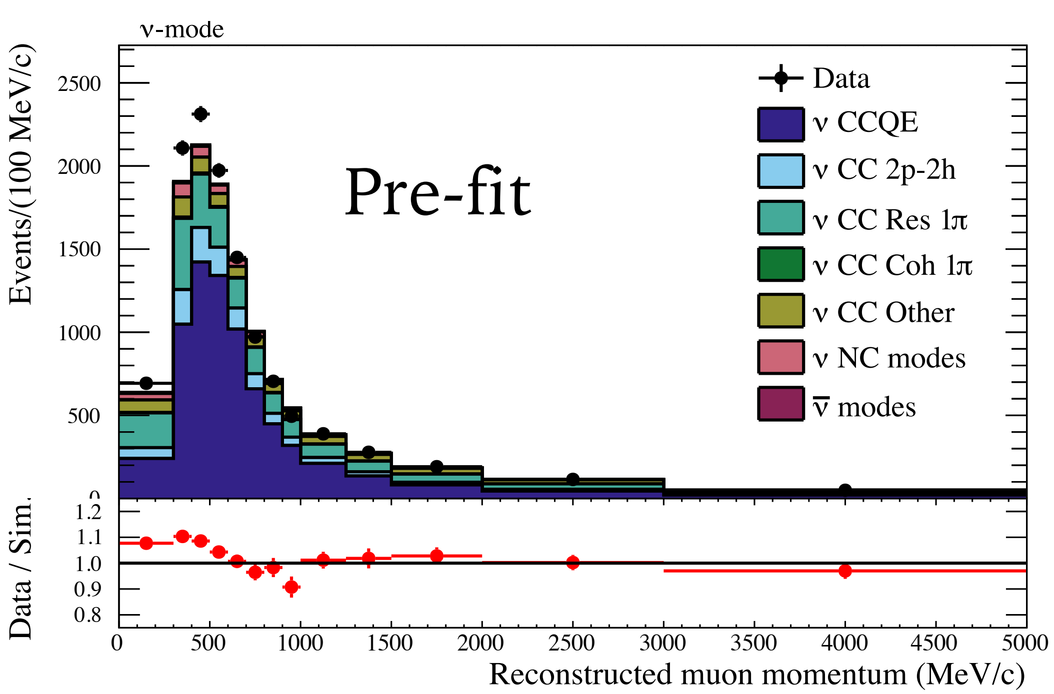
Neutrino Flux Model

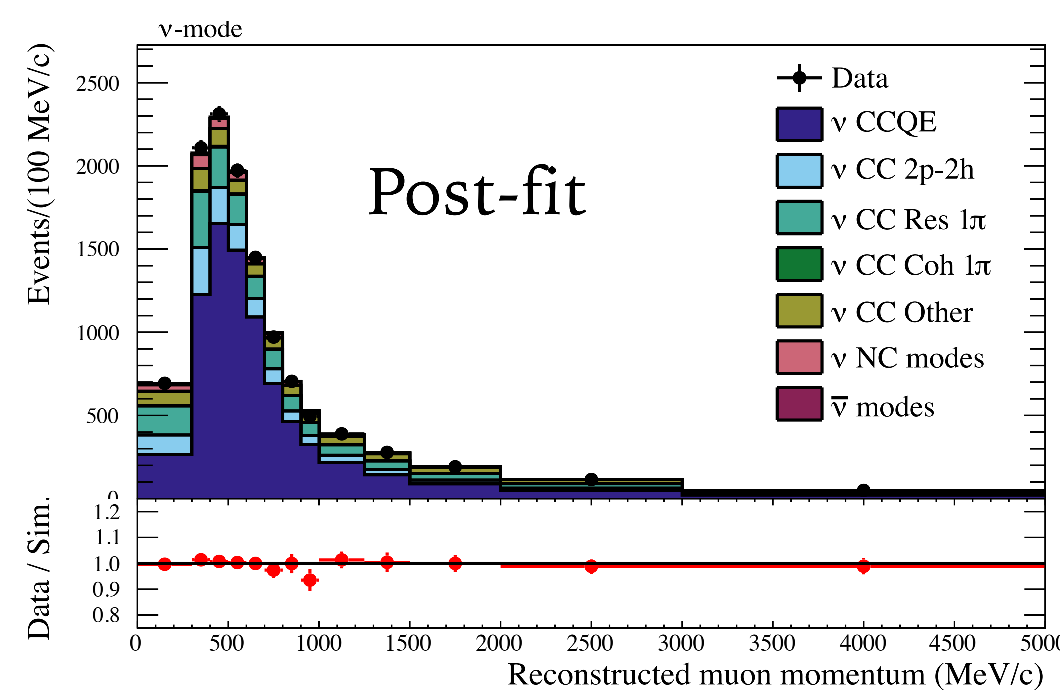


ND280 Data



Fit to ND280 data constrains neutrino flux parameters and interaction model parameters





PREDICTED AND OBSERVED EVENT RATES AT SK

	Predicted Rates				Observed
Sample	$\delta_{cp}=-\pi/2$	$\delta_{cp}=0$	$\delta_{cp}=\pi/2$	$\delta_{cp}=\pi$	Rates
CCQE 1-Ring e-like FHC	73.5	61.5	49.9	62.0	74
CC1π 1-Ring e-like FHC	6.92	6.01	4.87	5.78	15
CCQE 1-Ring e-like RHC	7.93	9.04	10.04	8.93	7
CCQE 1-Ring μ-like FHC	267.8	267.4	267.7	268.2	240
CCQE 1-Ring μ-like RHC	63.1	62.9	63.1	63.1	68

- The number of observed events are largely in line with the predictions after oscillations
    - The e-like samples have rates most consistent with the $\delta_{cp}=-\pi/2$ hypothesis
- The observed μ-like rate in neutrino mode is lower than prediction
    - Consistent within statistical and systematic errors

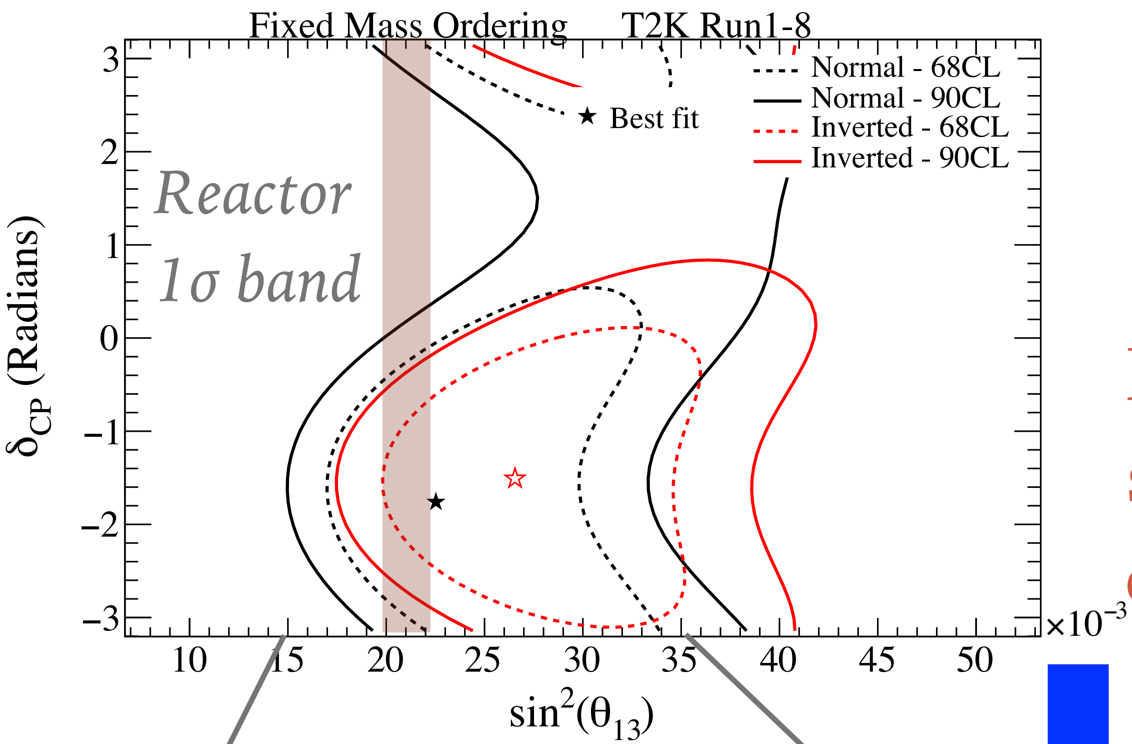
SYSTEMATIC ERRORS

	% Errors on Predicted Event Rates, Osc. Parameter Set A					
	1R μ-Like		1R e-Like			
Error Source	FHC	RHC	FHC	RHC	FHC CC1π	FHC/RHC
SK Detector	1.86	1.51	3.03	4.22	16.69	1.60
SK FSI+SI+PN	2.20	1.98	3.01	2.31	11.43	1.57
ND280 const. flux & xsec	3.22	2.72	3.22	2.88	4.05	2.50
$\sigma(\nu_e)/\sigma(\nu_\mu)$, $\sigma(\bar{\nu}_e)/\sigma(\bar{\nu}_\mu)$	0.00	0.00	2.63	1.46	2.62	3.03
NC1γ	0.00	0.00	1.08	2.59	0.33	1.49
NC Other	0.25	0.25	0.14	0.33	0.98	0.18
Total Systematic Error	**4.40**	**3.76**	**6.10**	**6.51**	**20.94**	**4.77**

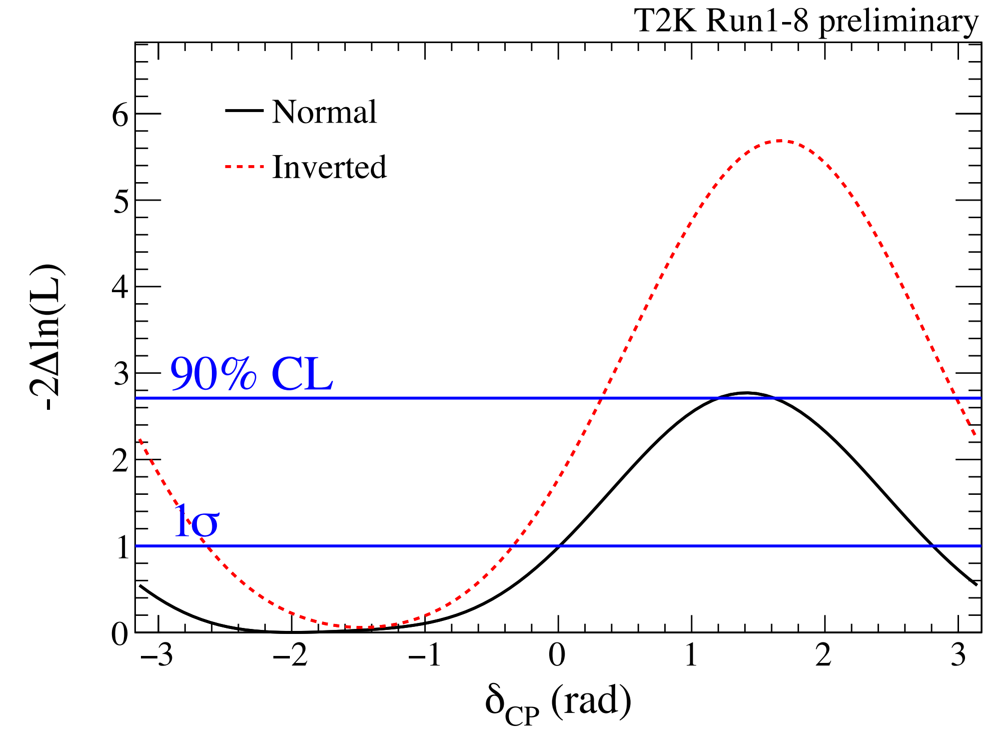
- Systematic errors arise in the neutrino flux, neutrino interaction and detector response modeling
- Errors of ~6% for the electron (anti)neutrino appearance channels

OSCILLATION PARAMETER SENSITIVITIES (2017)

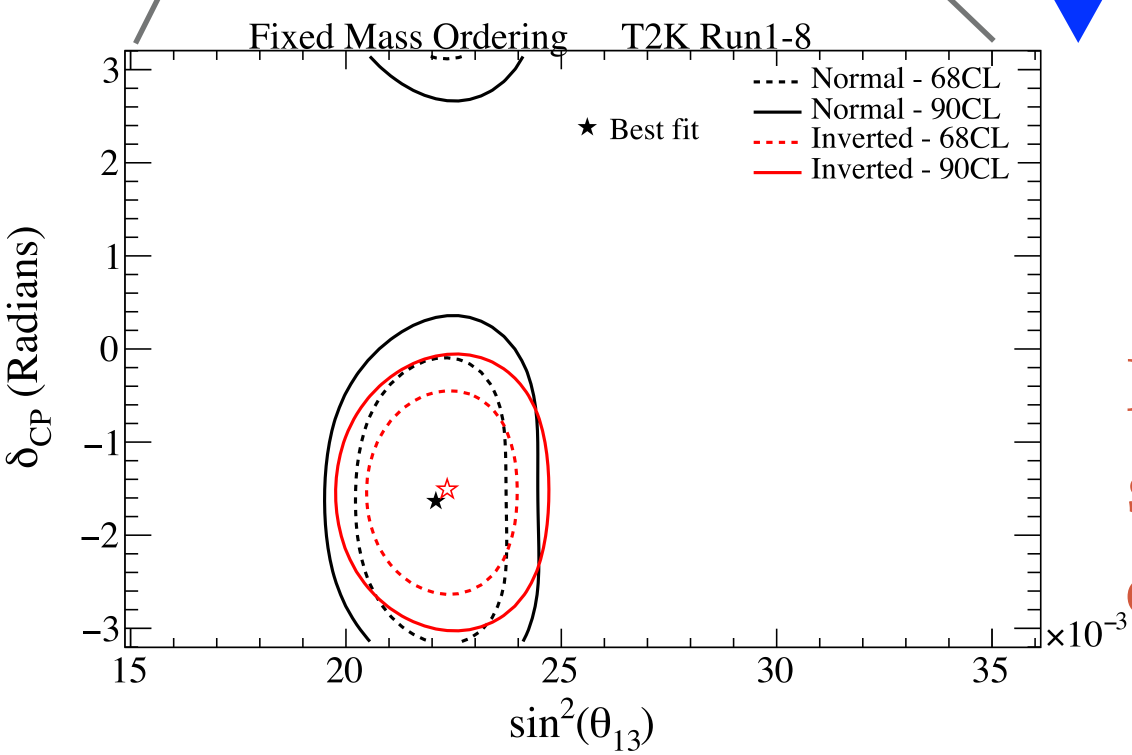
Without the reactor experiment constraint on $\sin^2 2\theta_{13}$



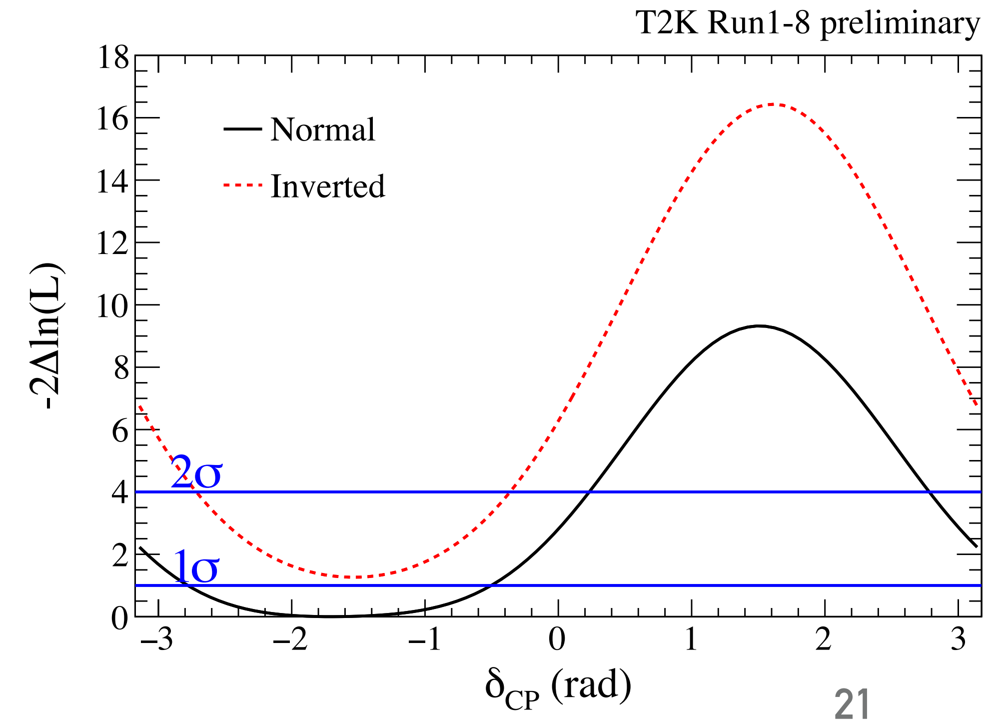
Integrate out $\sin^2\theta_{13}$ dependence



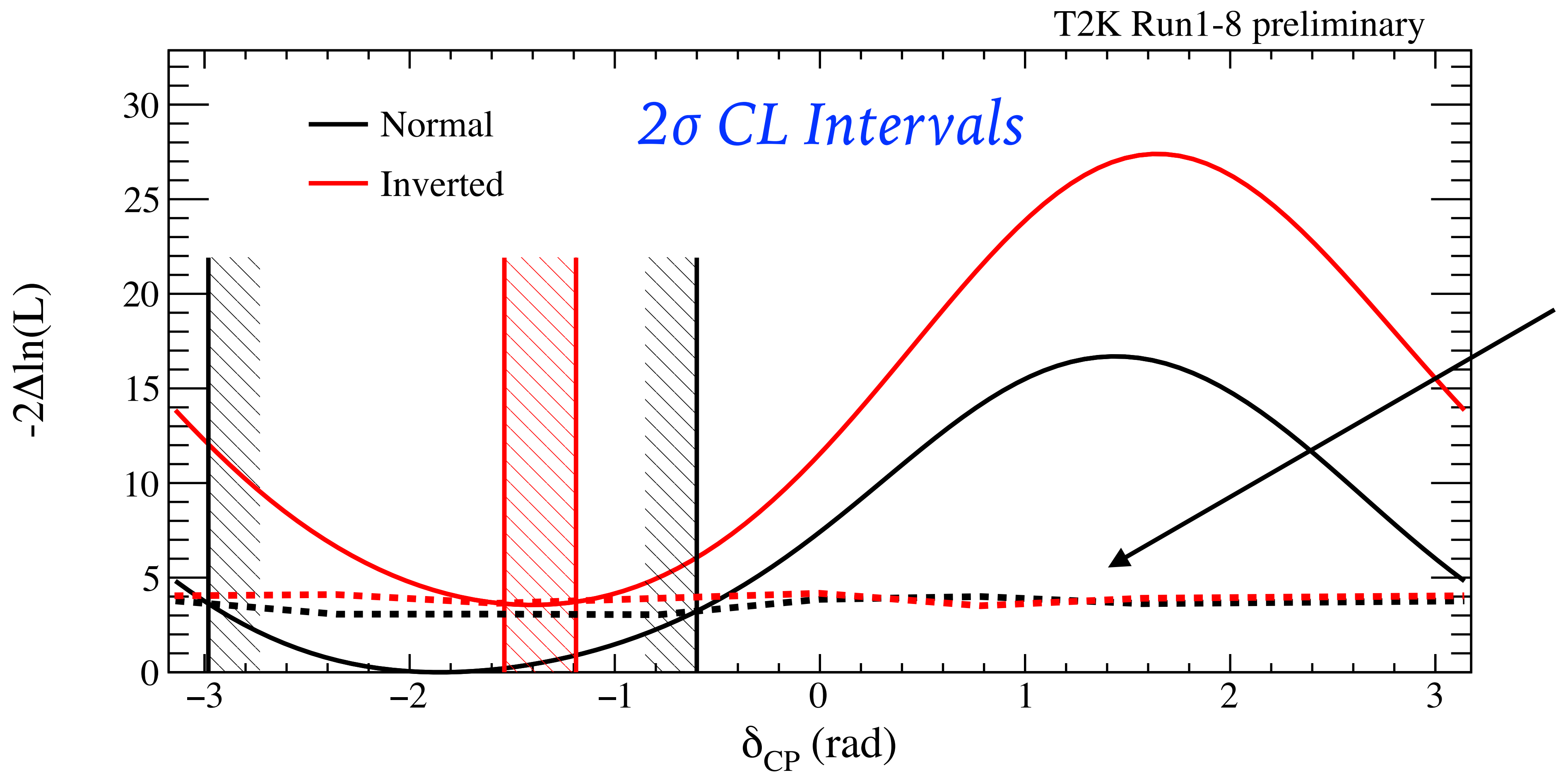
Reactor constraint on $\sin^2(2\theta)_{13}$ (PDG2016)



Integrate out $\sin^2\theta_{13}$ dependence



MEASUREMENT OF δ_{cp}



critical $\Delta\chi^2$ values for 2σ confidence level

Best fit point: **-1.83 radians in Normal Hierarchy**

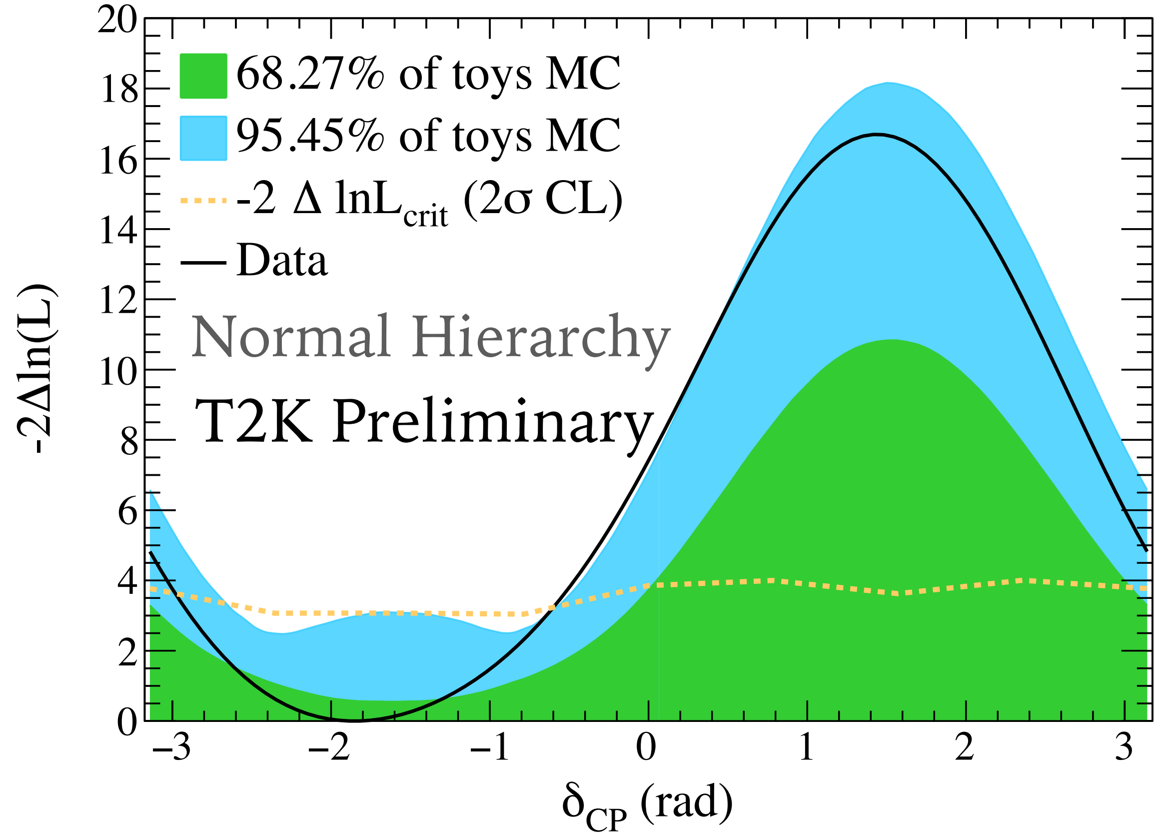
The 1σ CL confidence interval: Normal hierarchy: [-2.49, -1.23] radians

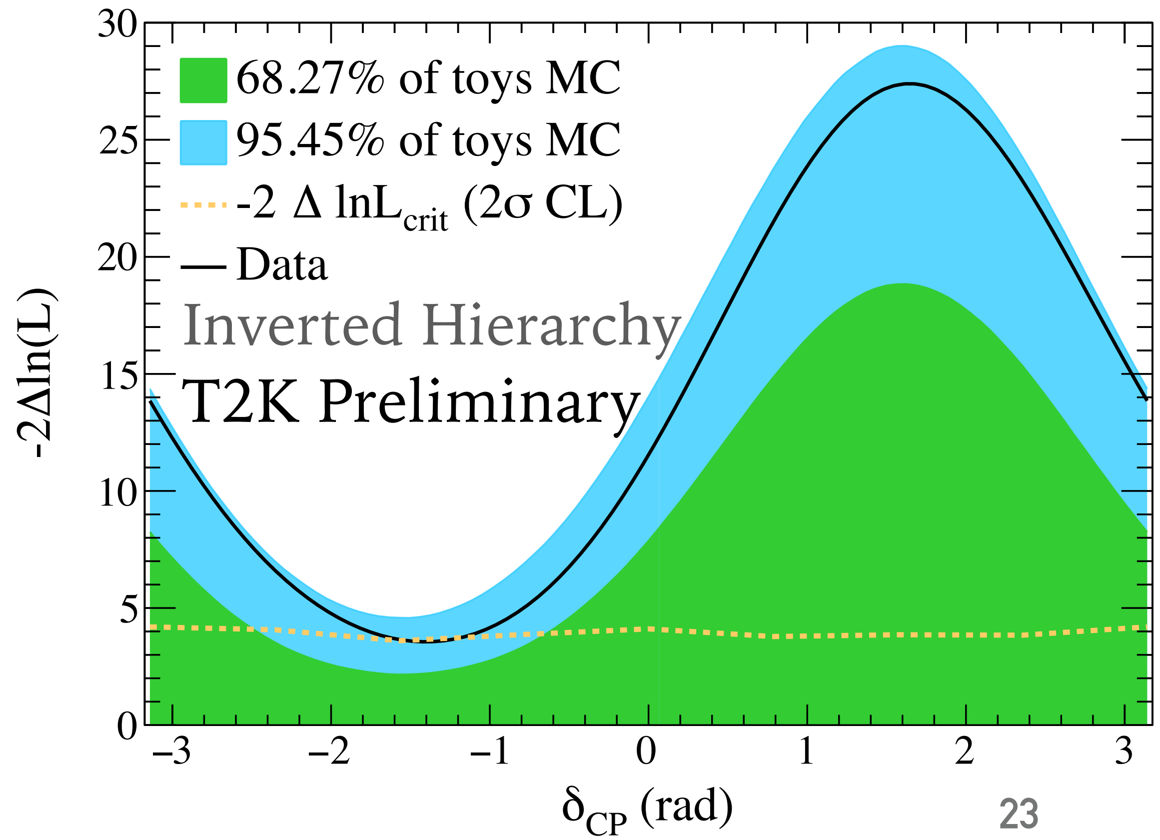
The 2σ CL confidence interval:
Normal hierarchy: [-2.98, -0.60] radians
Inverted hierarchy: [-1.54, -1.19] radians

CP conserving values (0,π) fall outside of the 2σ CL intervals

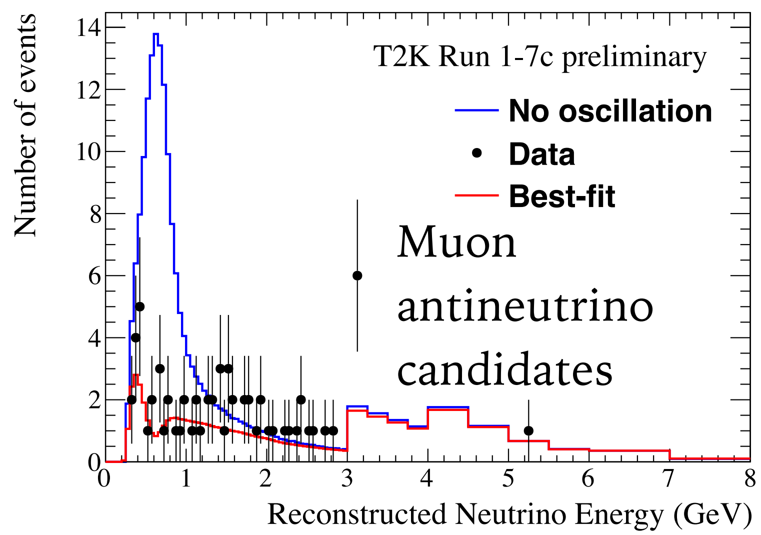
MEASURED CONSTRAINT VS. SENSITIVITY

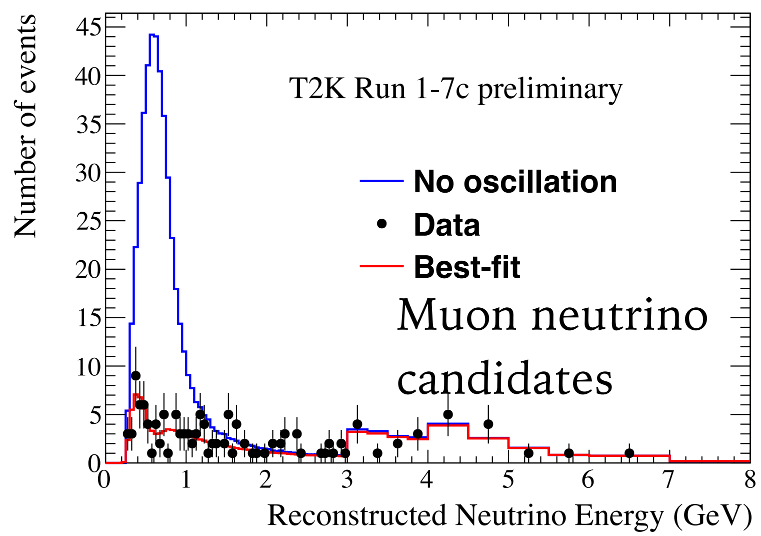
- Data constraint on δ_{cp} is stronger than the average sensitivity
  - Is it reasonable?
- Run many toy experiments with statistical and systematic fluctuations
  - δ_{cp}=-π/2, NH
- Data constraint falls within range for 95.45% of experiments for most δ_{cp} points
- 30% of experiments exclude δ_{cp}=0 at 2σ
- 25% of experiments exclude δ_{cp}=π at 2σ



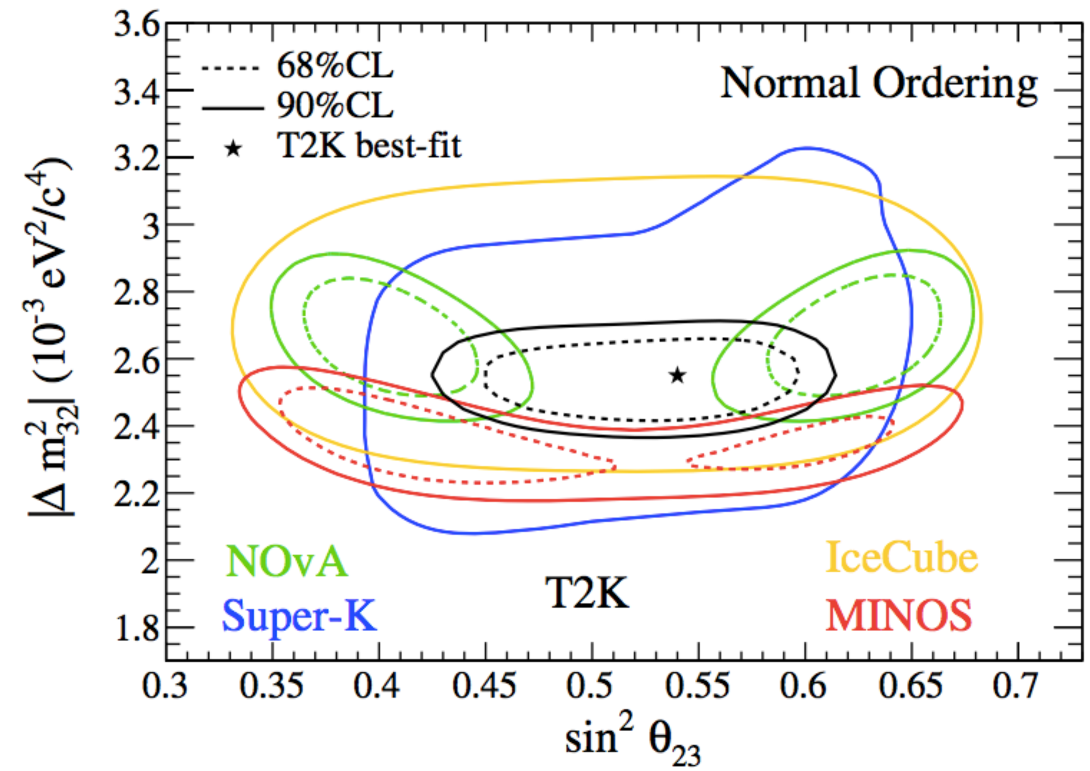


ATMOSPHERIC PARAMETERS PARAMETERS



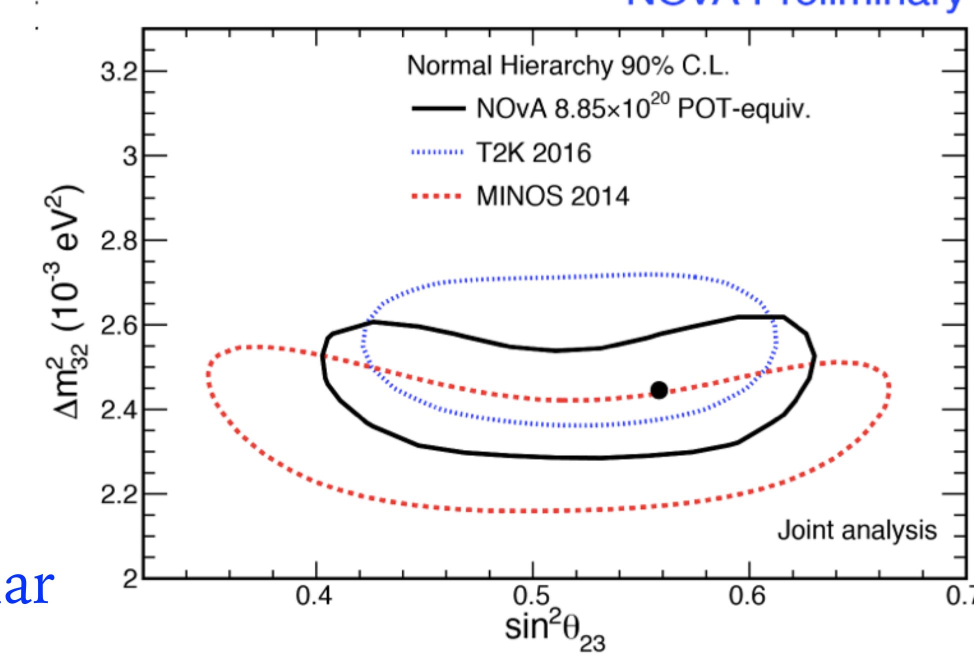


Results as of 2017



Slight tension between T2K and NOvA

NOvA Preliminary



NOvA showed new result in January 2018

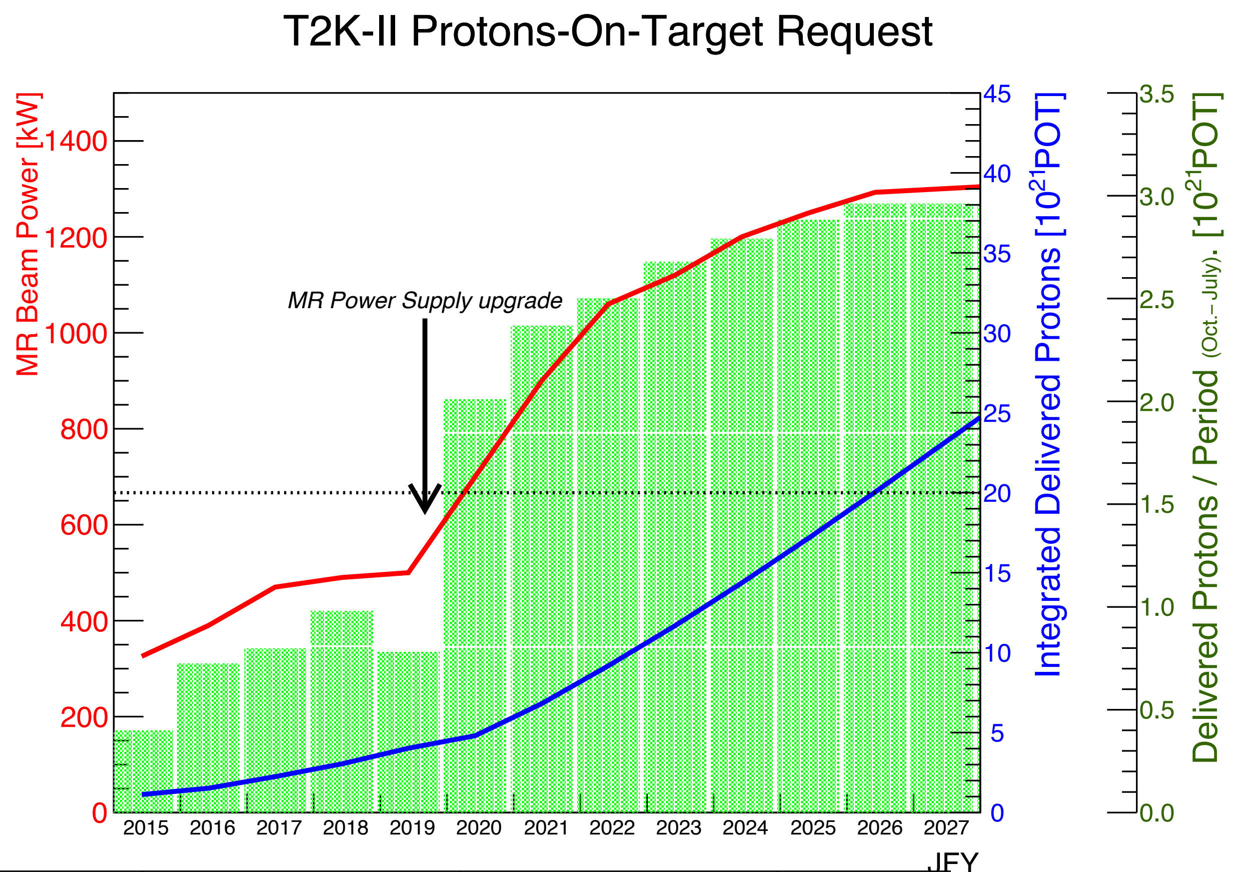
Now consistent with maximal mixing

A. Radovic, Fermilab JETP Seminar

THE FUTURE

T2K–II: EXTENDED T2K OPERATION

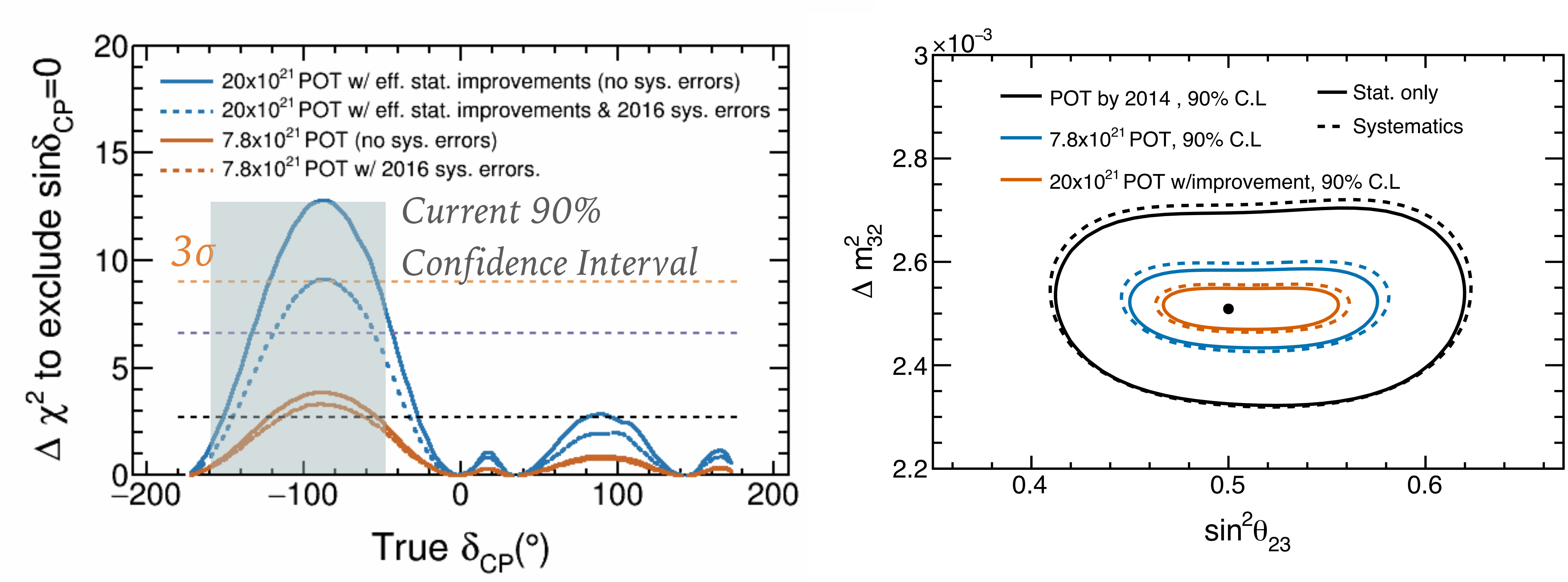
- T2K originally approved for 7.8×10^{21} POT
- Proposal to extend T2K operation to 2026 and collect 20.0×10^{21} POT
- Analysis and operation improvements to achieve another 50% improvement in experimental sensitivity
  - **~30% already achieved!**



	True δ_{CP}	Total	Signal $\nu_\mu \to \nu_e$	Signal $\bar{\nu}_\mu \to \bar{\nu}_e$	Beam CC $\nu_e + \bar{\nu}_e$	Beam CC $\nu_\mu + \bar{\nu}_\mu$	NC
ν-mode ν_e sample	0	454.6	346.3	3.8	72.2	1.8	30.5
	$-\pi/2$	545.6	438.5	2.7	72.2	1.8	30.5
$\bar{\nu}$-mode $\bar{\nu}_e$ sample	0	129.2	16.1	71.0	28.4	0.4	13.3
	$-\pi/2$	111.8	19.2	50.5	28.4	0.4	13.3

	Total	Beam CC ν_μ	Beam CC $\bar{\nu}_\mu$	Beam CC $\nu_e + \bar{\nu}_e$	$\nu_\mu \to \nu_e +$ $\bar{\nu}_\mu \to \bar{\nu}_e$	NC
ν-mode ν_μ sample	2612.2	2290.5	150.0	1.6	7.0	163.1
$\bar{\nu}$-mode $\bar{\nu}_\mu$ sample	1217.5	482.1	672.5	0.6	1.0	61.3

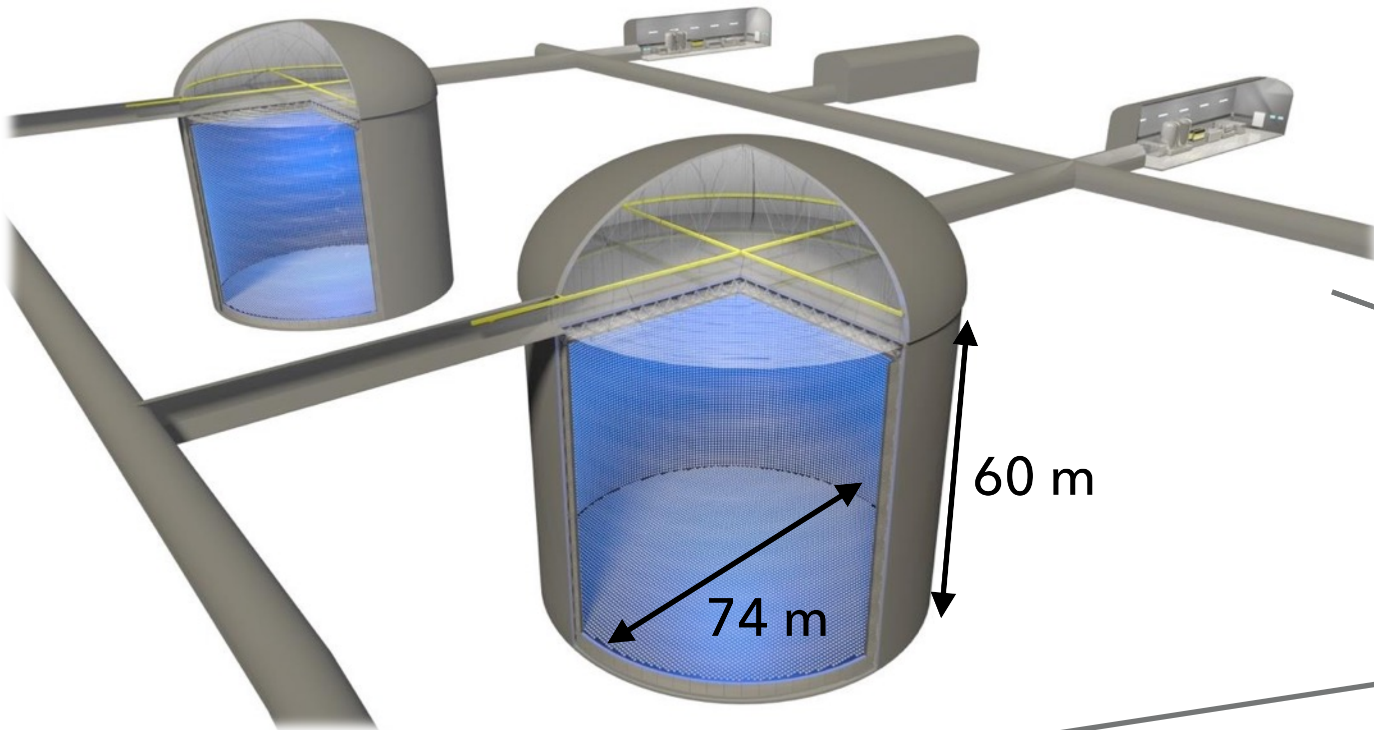
T2K-II SENSITIVITY

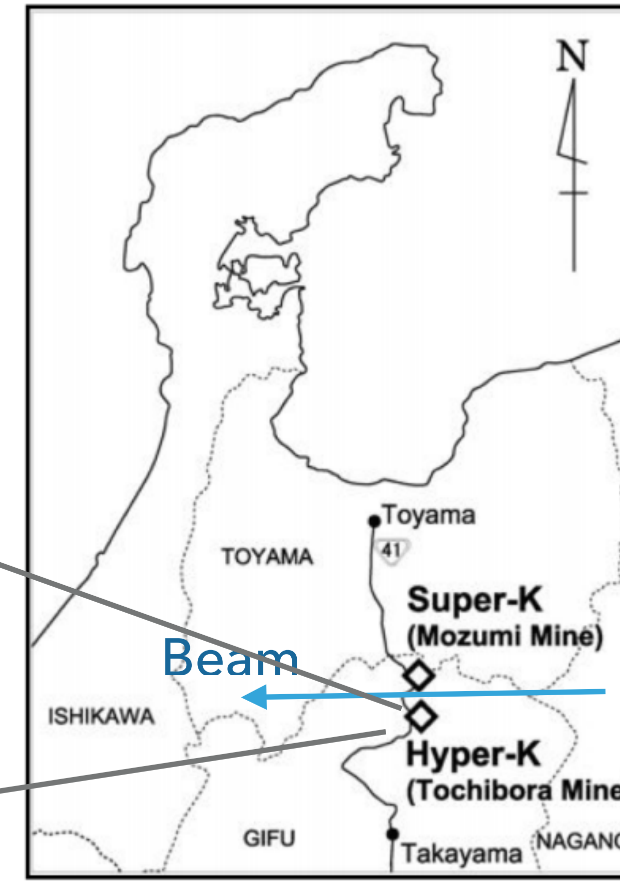


- If δ_{cp} is near current best fit, potential for a 3σ discovery of CP violation in T2K-II
  - The size of systematic errors has a large impact on the experimental sensitivity (dashed vs. solid lines) - we expect systematic uncertainties to improve
- Significant reduction of $\sin^2\theta_{23}$ and Δm^2_{32} intervals is also possible

HYPER-K

A new more massive water Cherenkov detector





Hyper-K Detector:

60 m tall x 74 m diameter tank

2 tanks with a staging approach (second tank 6 years later)

40,000 50cm ϕ PMTs → 40% photo-coverage

260 kton mass (187 kton fiducial volume is ~8x larger than Super-K)

Hyper-K Physics:

Long baseline neutrinos

Atmospheric neutrinos

Nucleon decay searches

Supernova neutrinos

Solar neutrinos

HYPER-K EVENT RATES & SPECTRA

Electron (anti)neutrino candidates

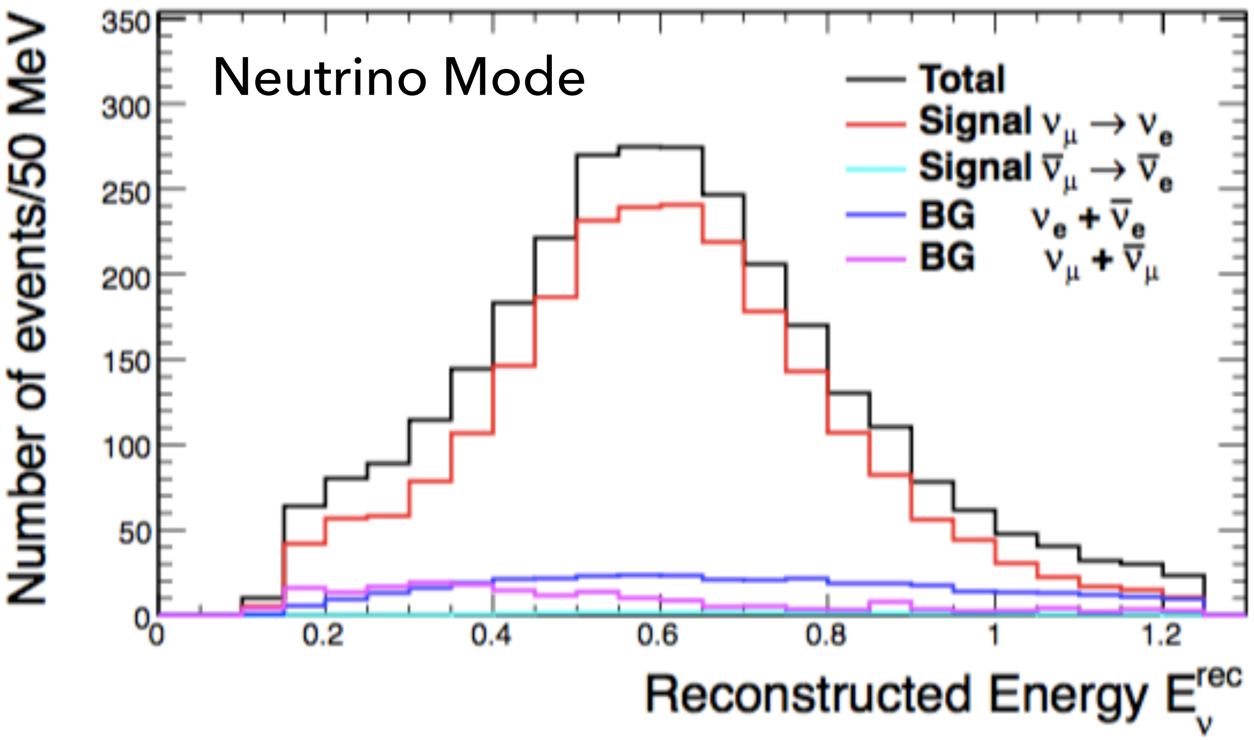
δ_{cp}=0	Signal	Wrong-sign appearance	CC ν_μ, $\bar{\nu}_\mu$	Intrinsic ν_e, $\bar{\nu}_e$	NC
ν beam	2300	21	10	362	188
$\bar{\nu}$ beam	1656	289	6	444	274

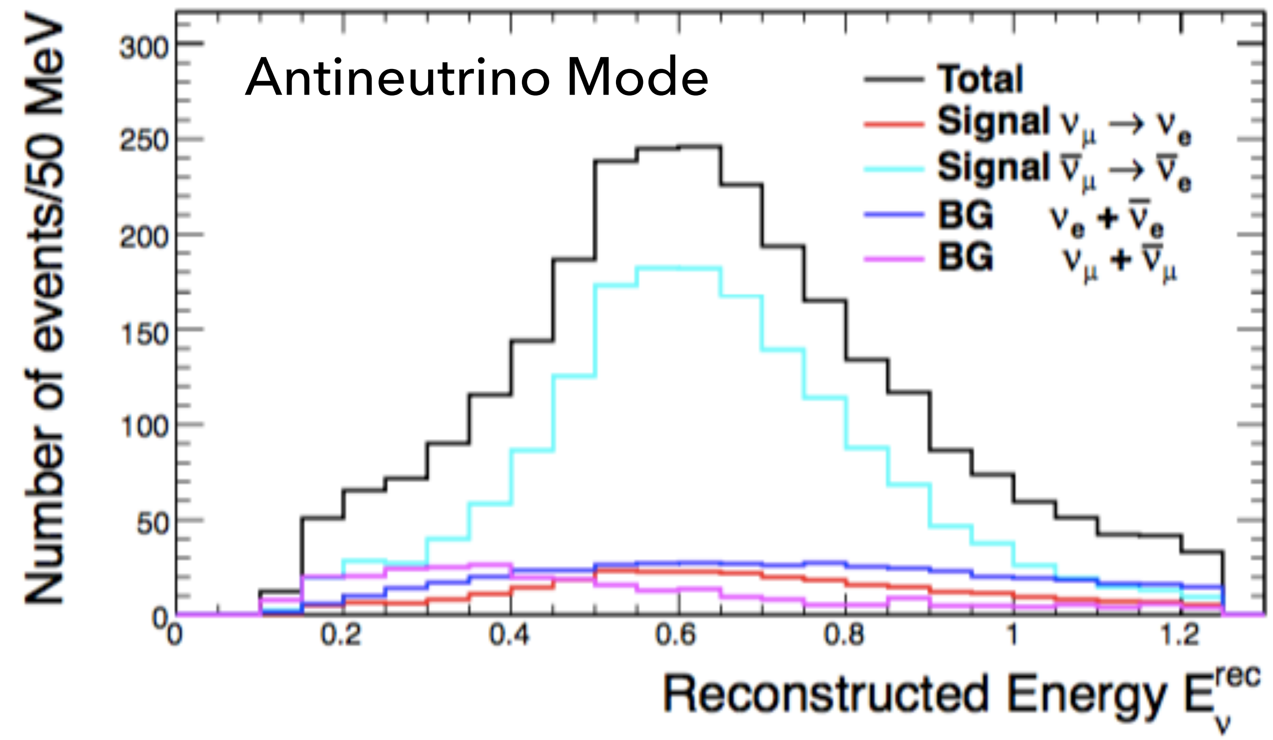
Statistical errors of 2%!!!

Muon (anti)neutrino candidates

	CCQE	CC non-QE	NC	Total
ν beam	8947	4444	672	14110
$\bar{\nu}$ beam	12317	6040	844	19214

HYPER-K EVENT RATES & SPECTRA





Muon (anti)neutrino candidates

	CCQE	CC non-QE	NC	Total
ν beam	8947	4444	672	14110
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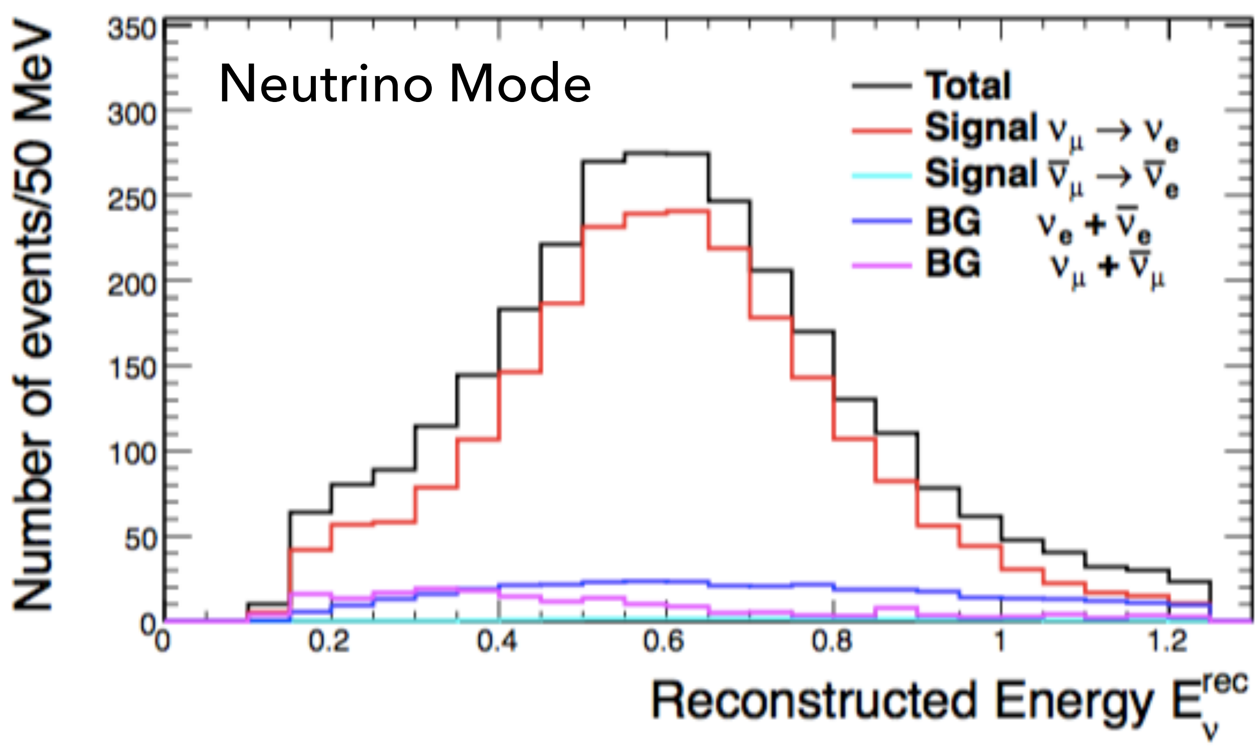
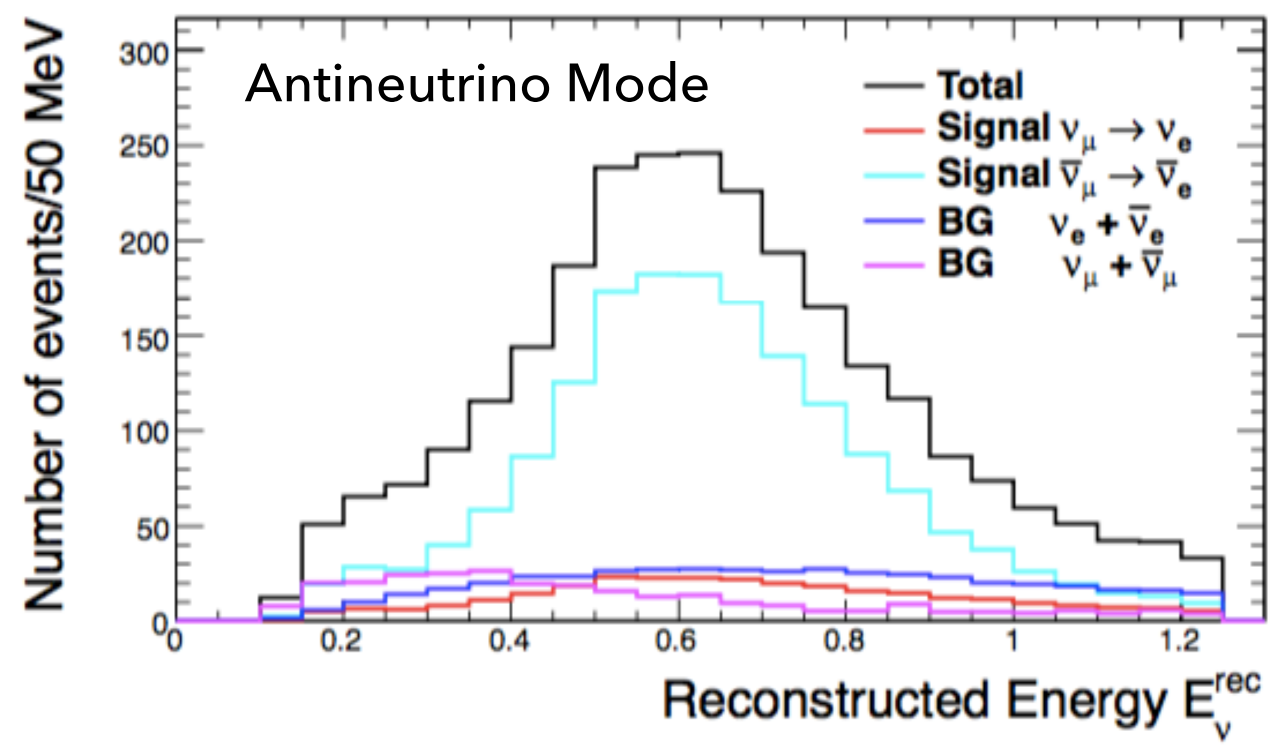
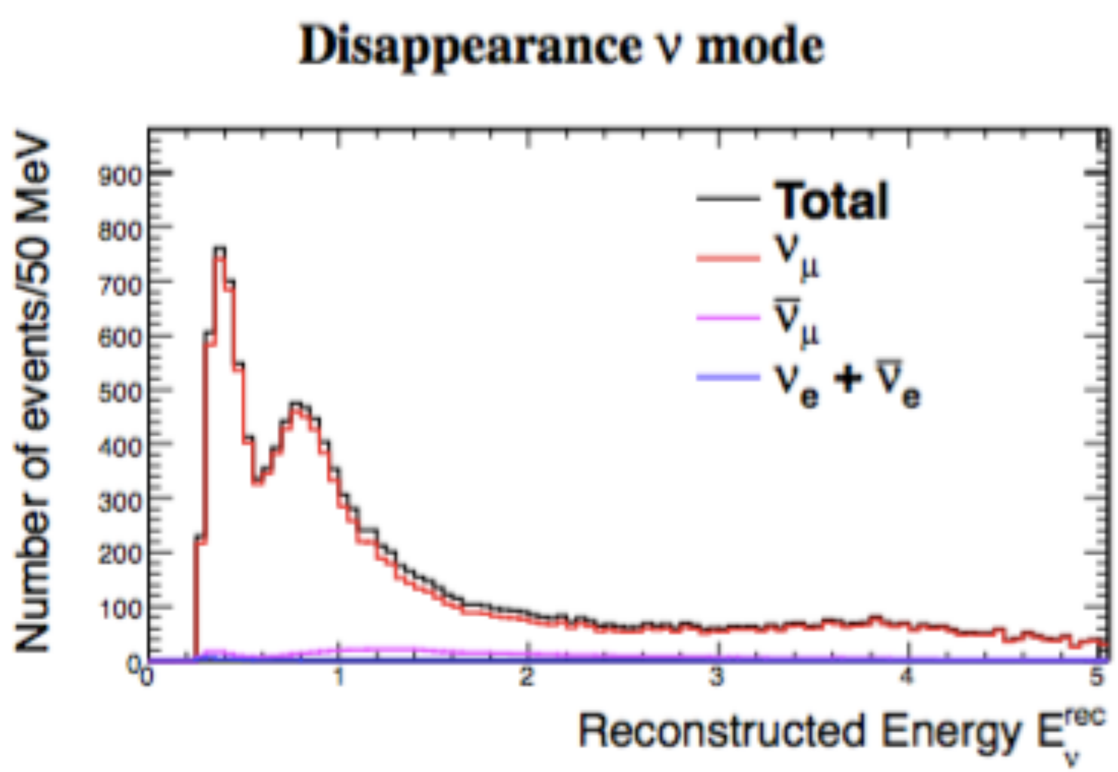
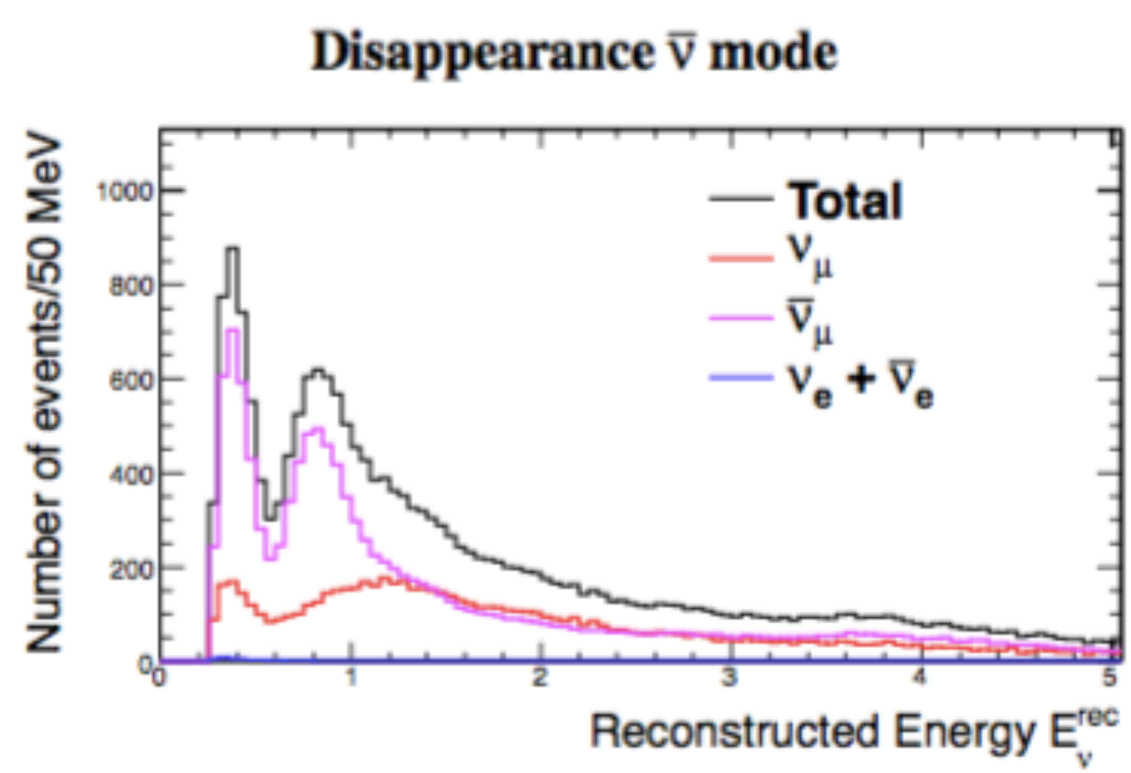
HYPER-K EVENT RATES & SPECTRA

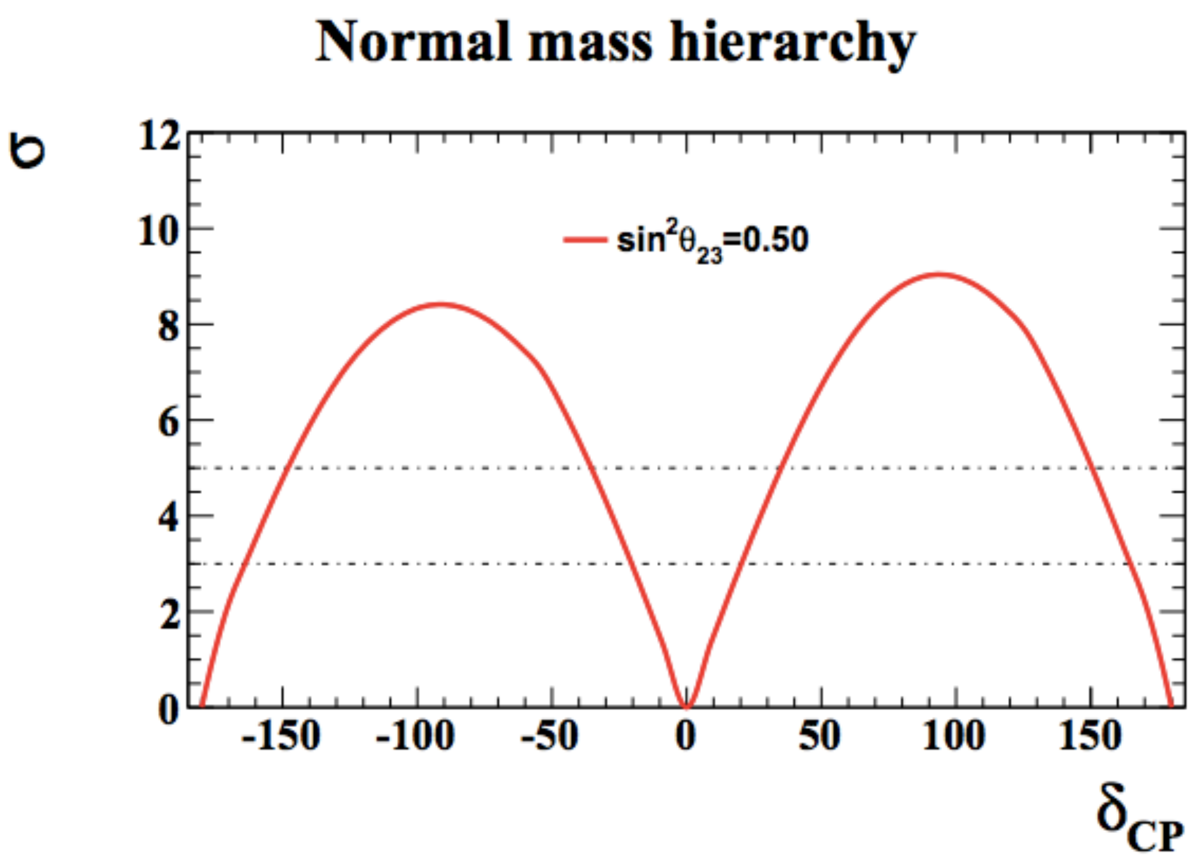


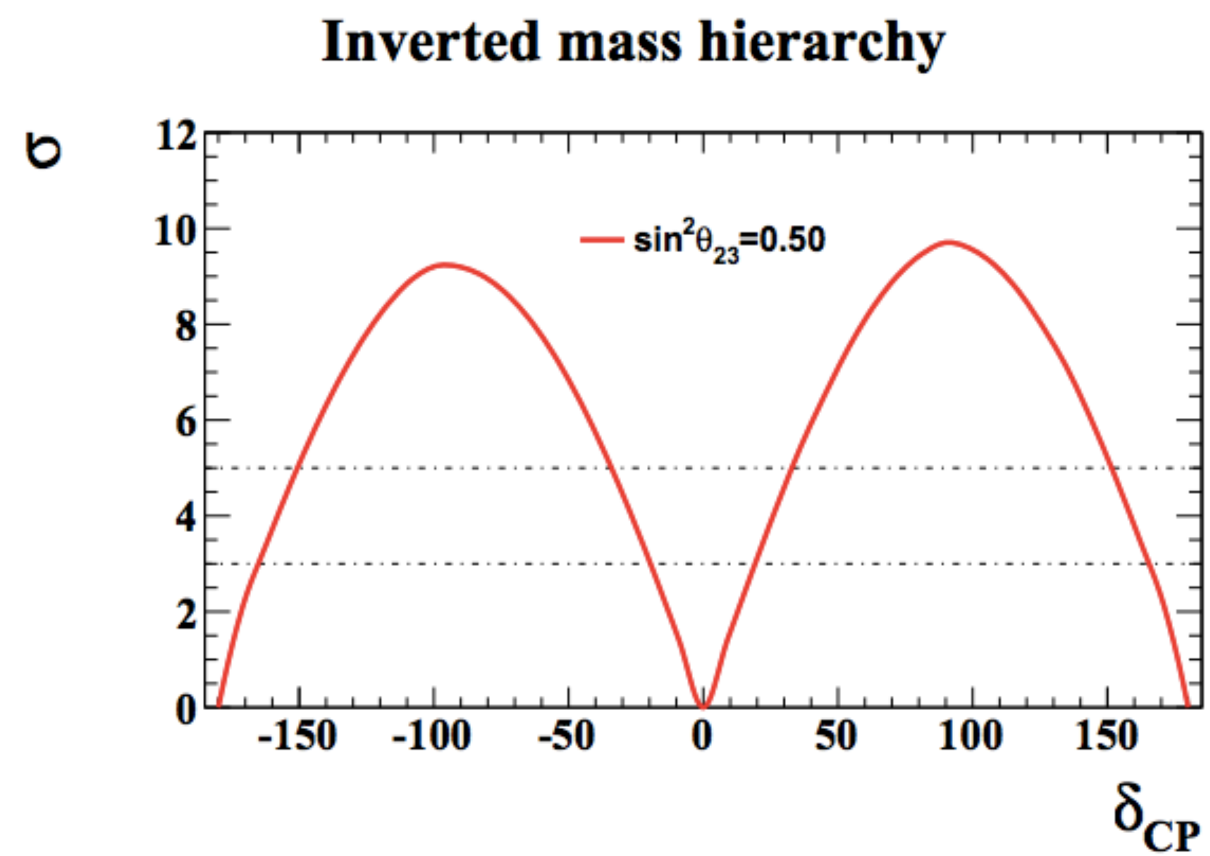






HYPER-K CPV SENSITIVITIES

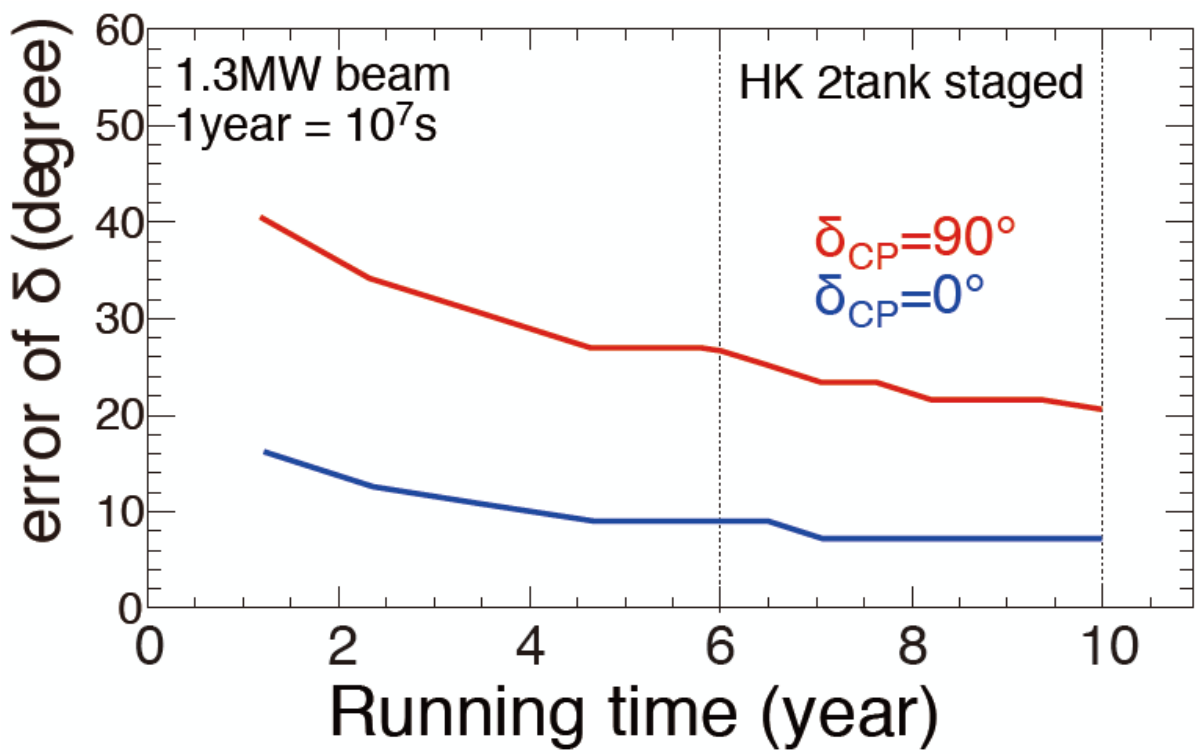




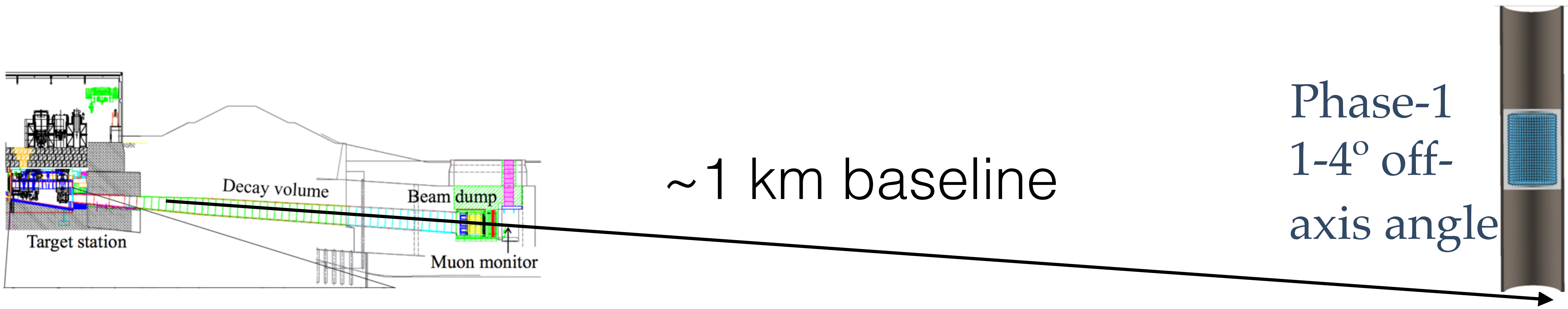
Exclusion of sin(δ_{cp})=0 at 3σ for 78% of δ_{cp} values at 5σ for 62%

21° precision at δ_{cp}=90°

7° precision at δ_{cp}=0°

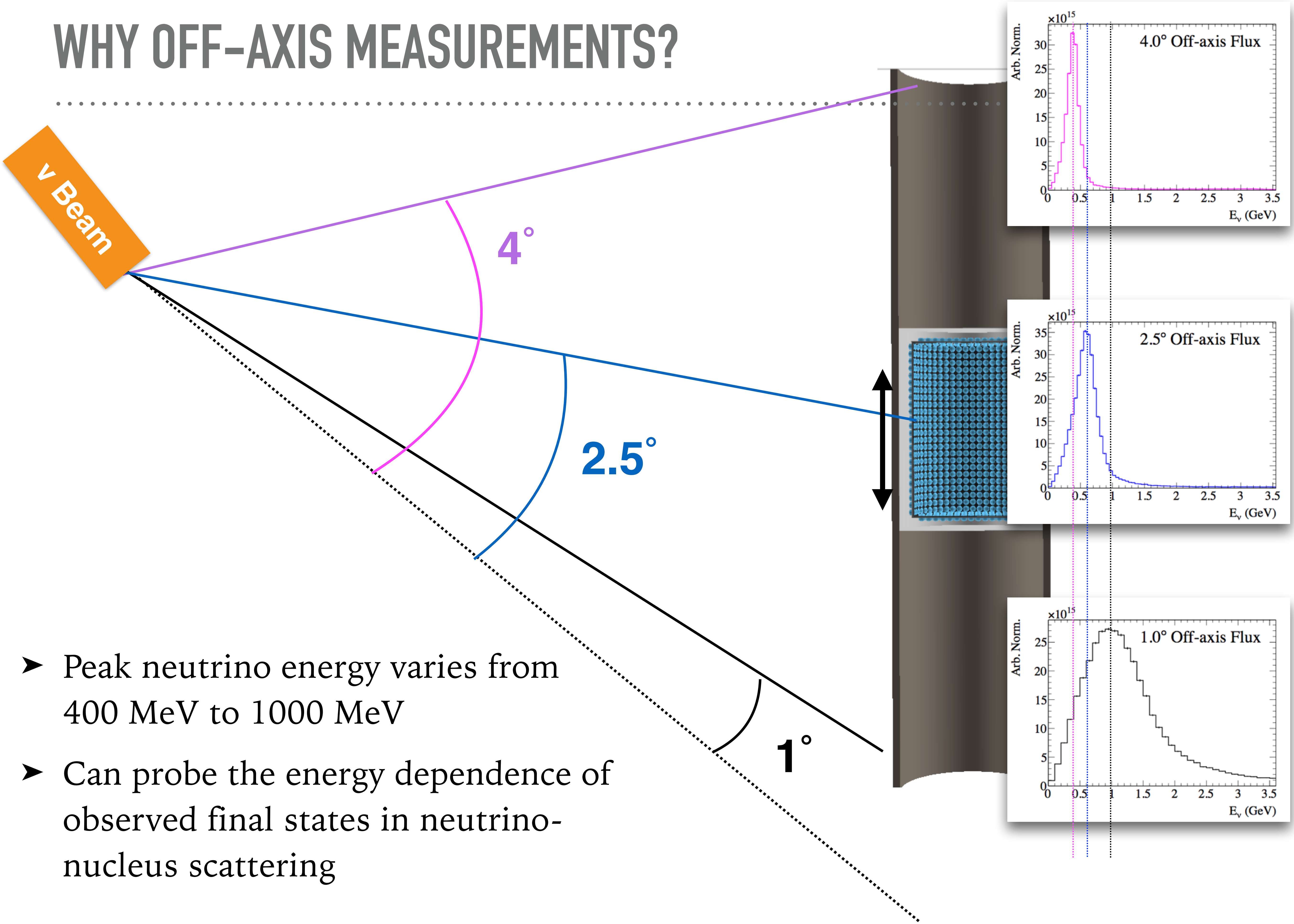


THE E61 EXPERIMENT



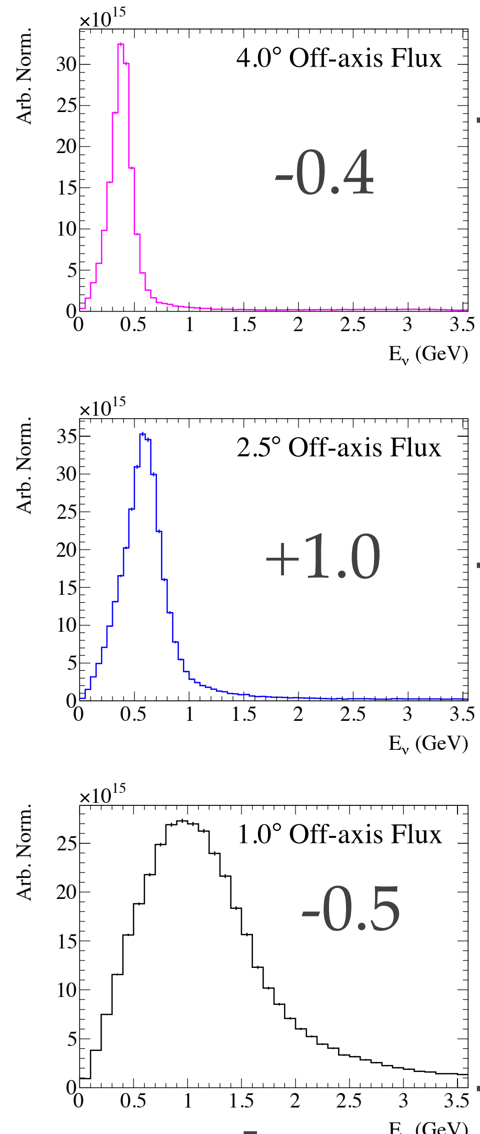
- E61 (NuPRISM): proposed intermediate detector for Hyper-K and later part of T2K experiment
- 1 kilo-ton scale water Cherenkov detector
- ~1 km from the neutrino source
- Instrumented part of detector moved in ~50 shaft
- **Address uncertainties on neutrino-nucleus scattering modeling for Hyper-K**

WHY OFF-AXIS MEASUREMENTS?

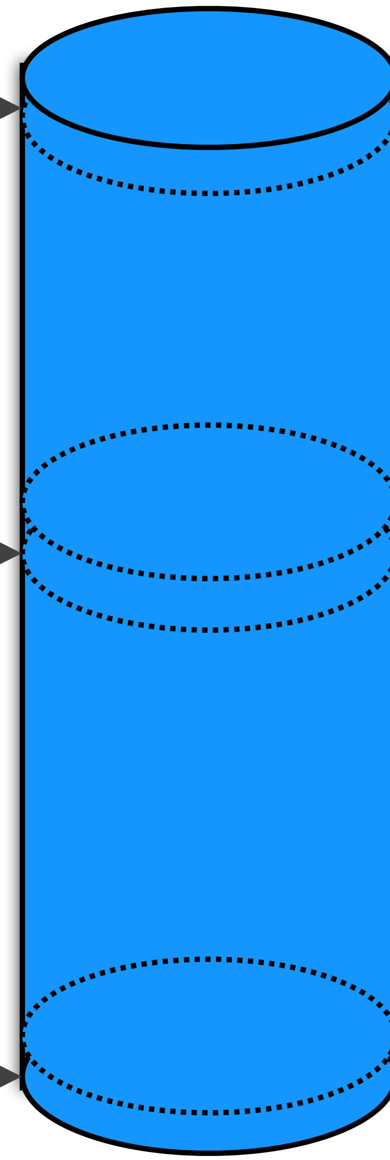


- Peak neutrino energy varies from 400 MeV to 1000 MeV
- Can probe the energy dependence of observed final states in neutrino-nucleus scattering

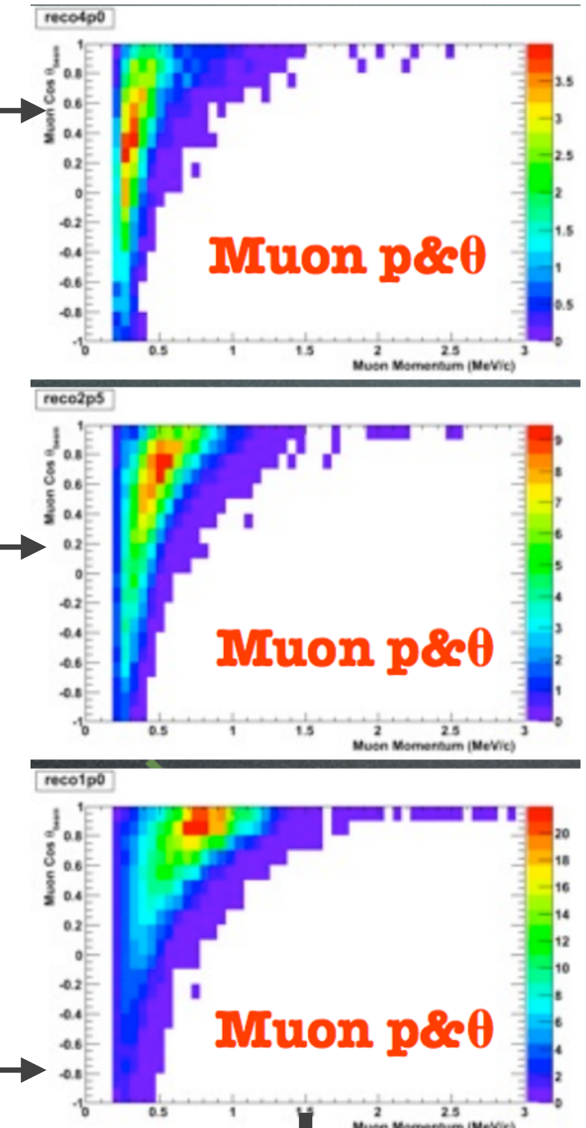
APPLICATION OFF-AXIS ANGLE MEASUREMENTS

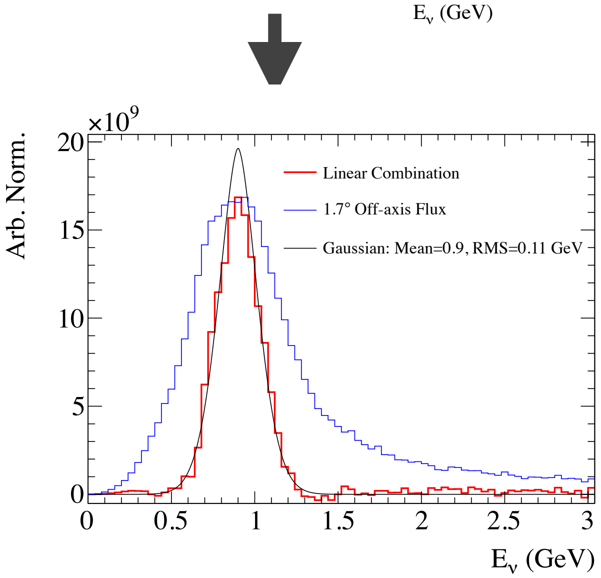


Spectra at at each off-axis bin

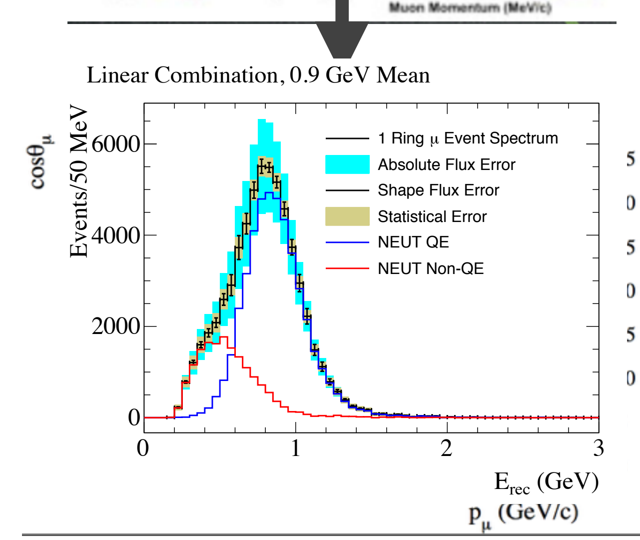


Observed muon kinematic distributions



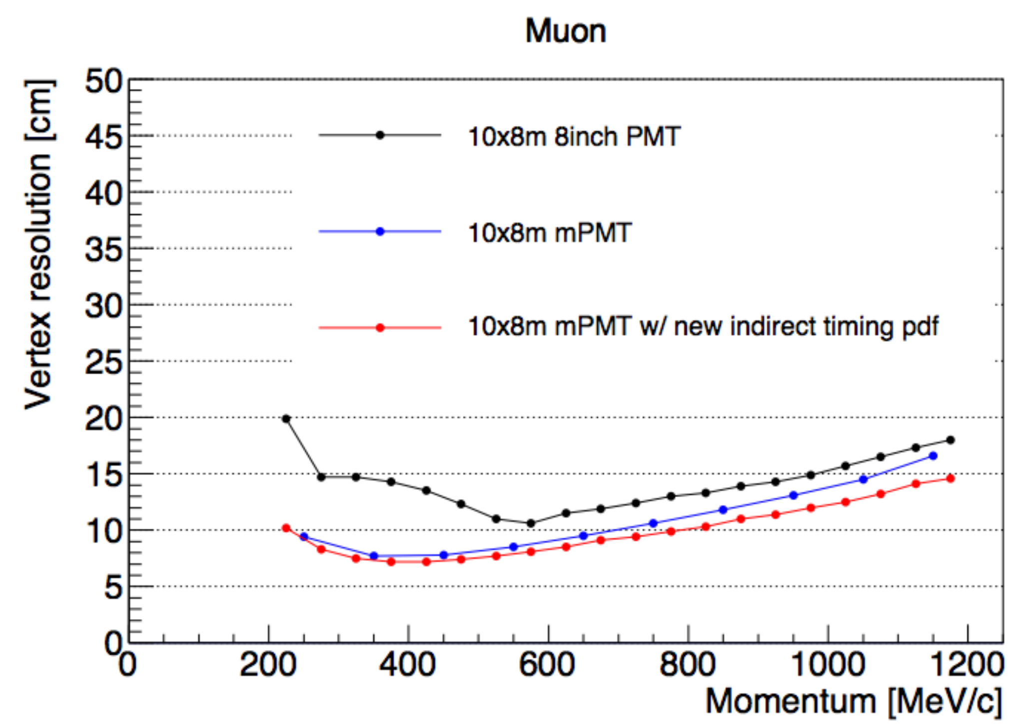


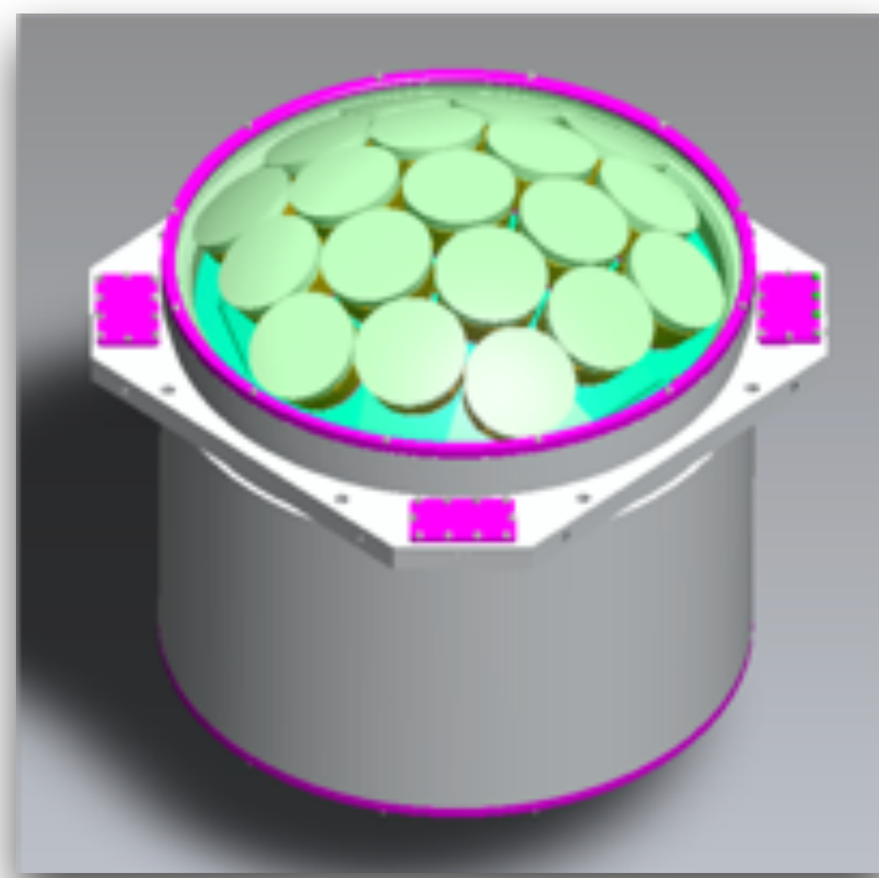
Subtract off low energy and high energy tails of flux → produce very narrow beam to measure energy response.



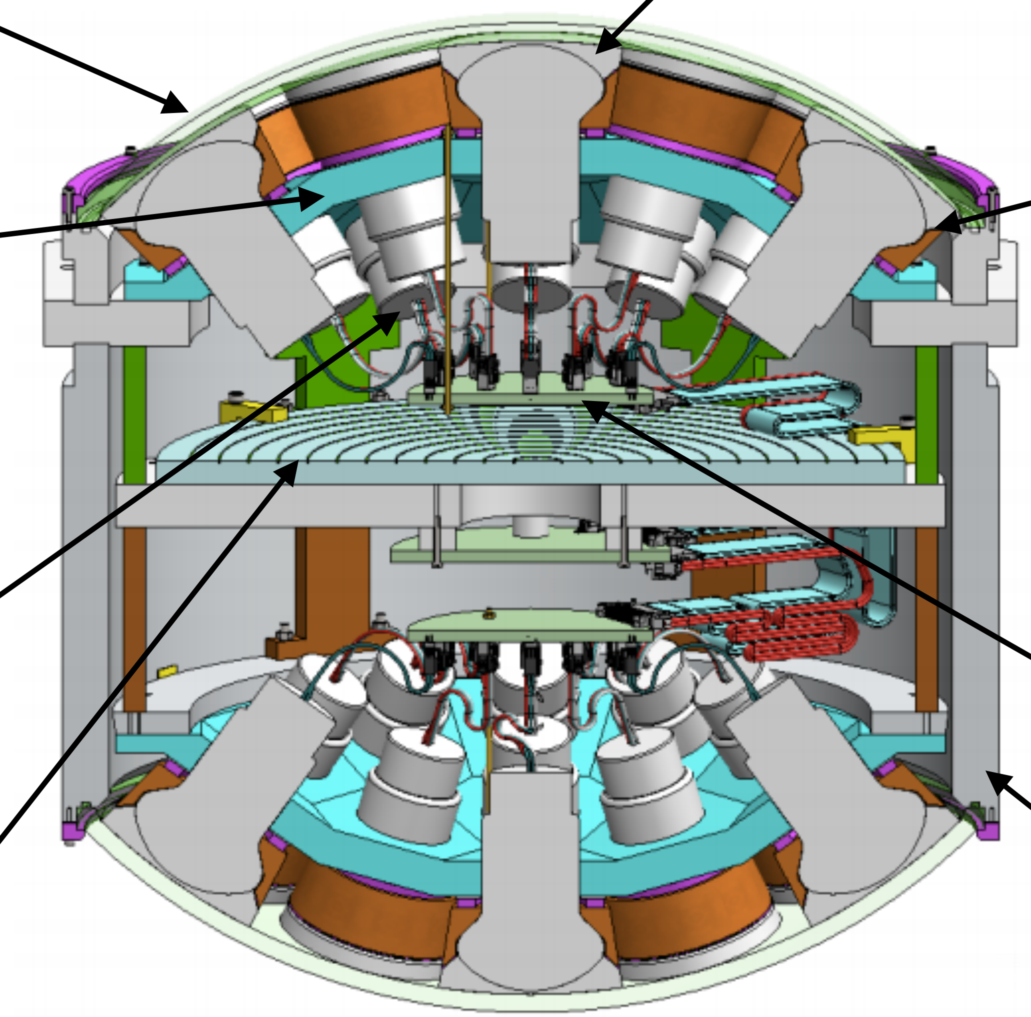
MULTI-PMTS IN E61

- Simulation studies show that the detector performance is improved with smaller photo-multiplier tubes with better timing resolution
- Building on the KM3NeT approach, deploy multi-PMT modules with 3 inch PMTs
- 19 PMTs view the inner detector
- 7 or fewer PMTs view the outer detector
- Modules contain high voltage generation and readout electronics





MULTI-PMT MODULE DESIGN



Canadian institutes involved in the development of most components for the mPMT

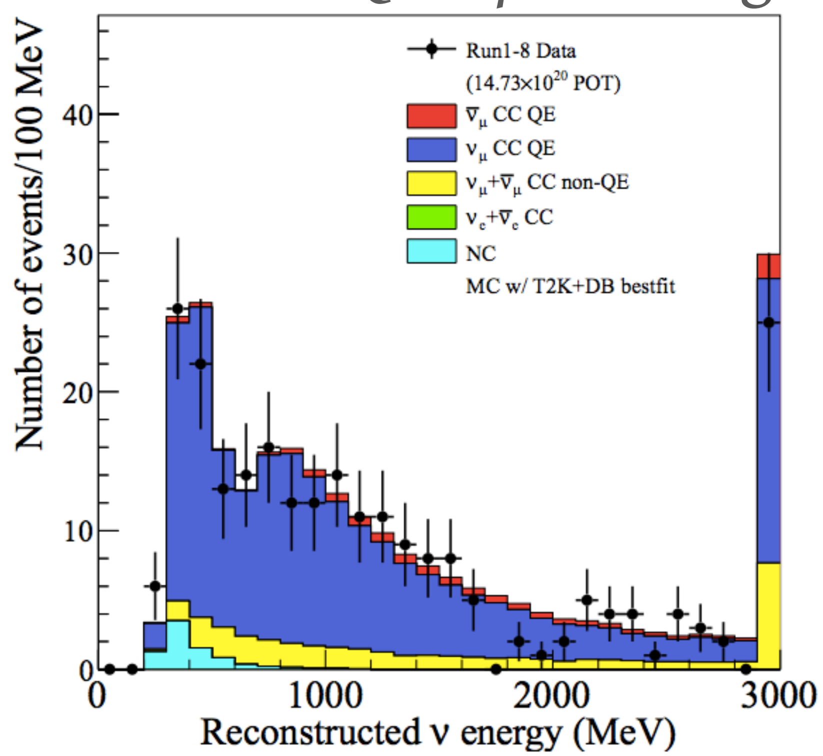
SUMMARY

- With new data and analysis T2K has updated oscillation parameter estimates
  - CP conserving values of δ_{cp} are excluded at 2σ in both confidence intervals and credible intervals
- T2K proposes an extended program to collect 20×10^{21} POT and achieve 3σ sensitivity to exclude CP conserving values for favorable true values of δ_{cp}
- Hyper-K will see the construction of a new detector 8 times larger than Super-K
- Systematic error reduction for Hyper-K is critical. E61 (NuPRISM) aimed at reduce systematic errors on neutrino interaction modeling.

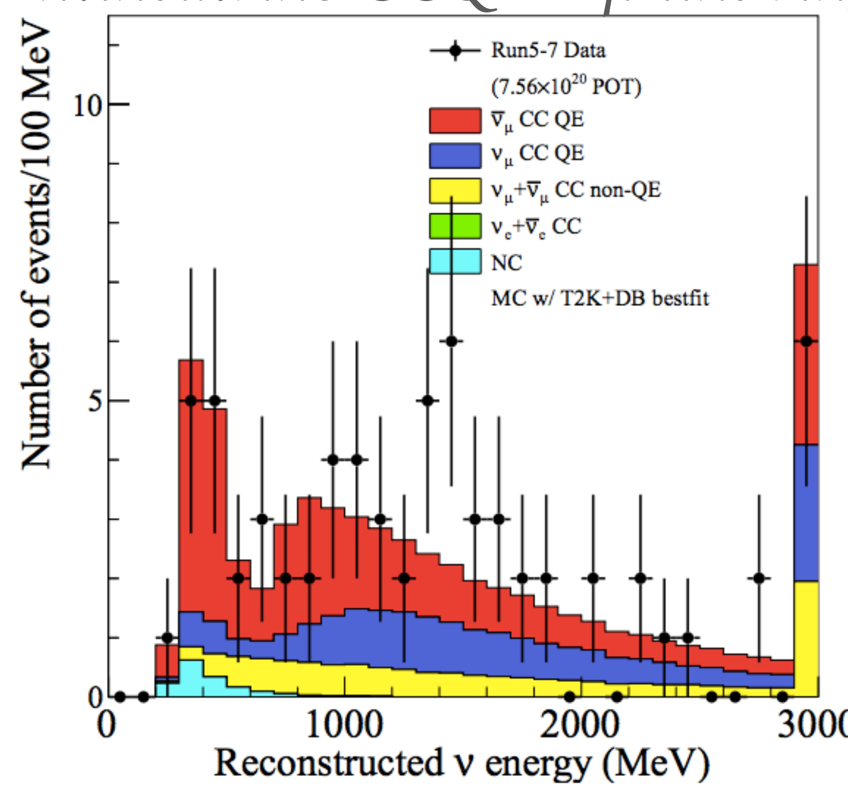
THANK YOU!

OBSERVED SPECTRA

Neutrino CCQE 1 μ-like ring

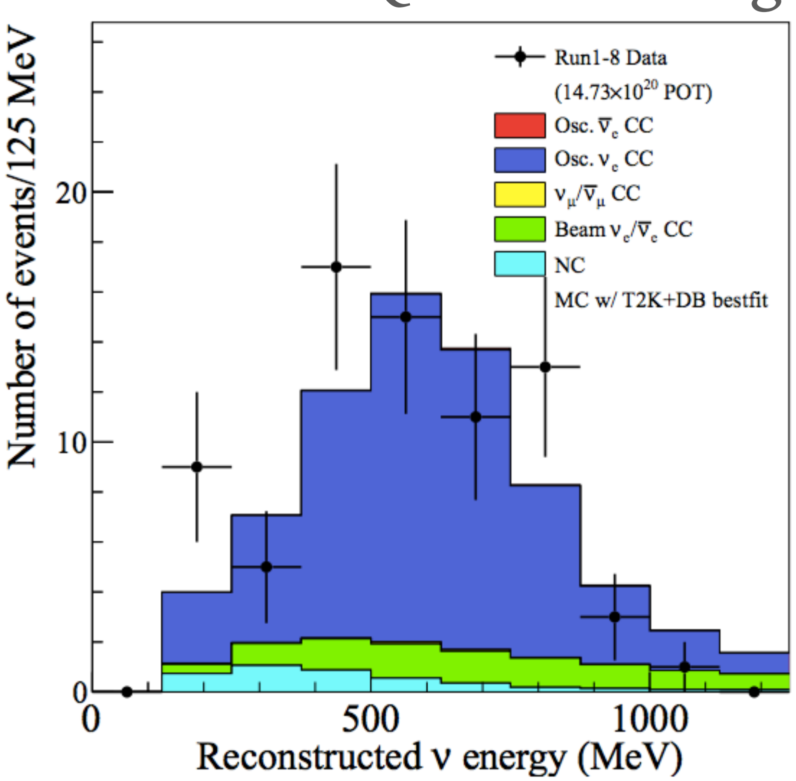


Antineutrino CCQE 1 μ-like ring

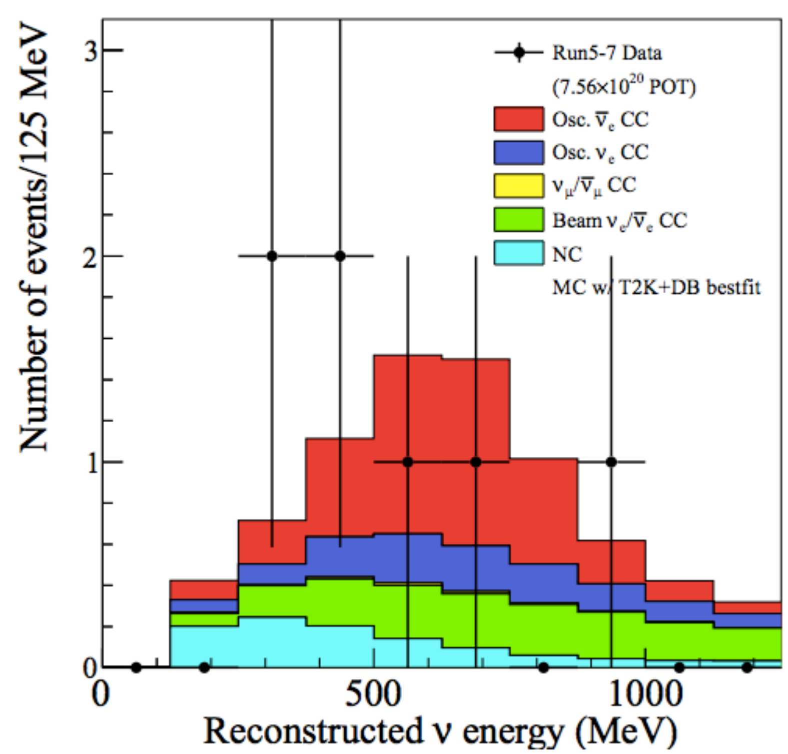


T2K Preliminary

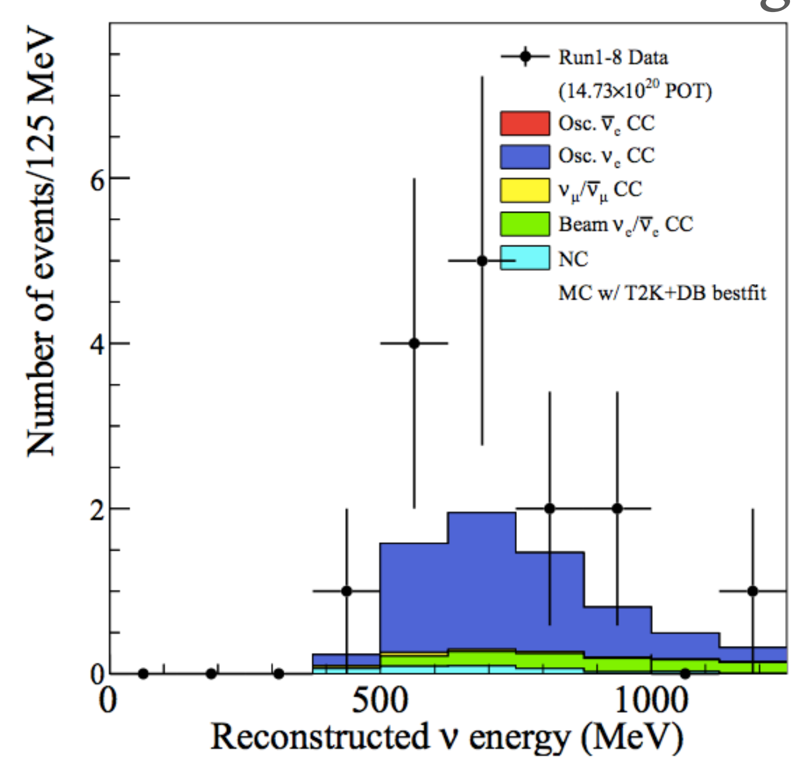
Neutrino CCQE 1 e-like ring



Antineutrino CCQE 1e-like ring

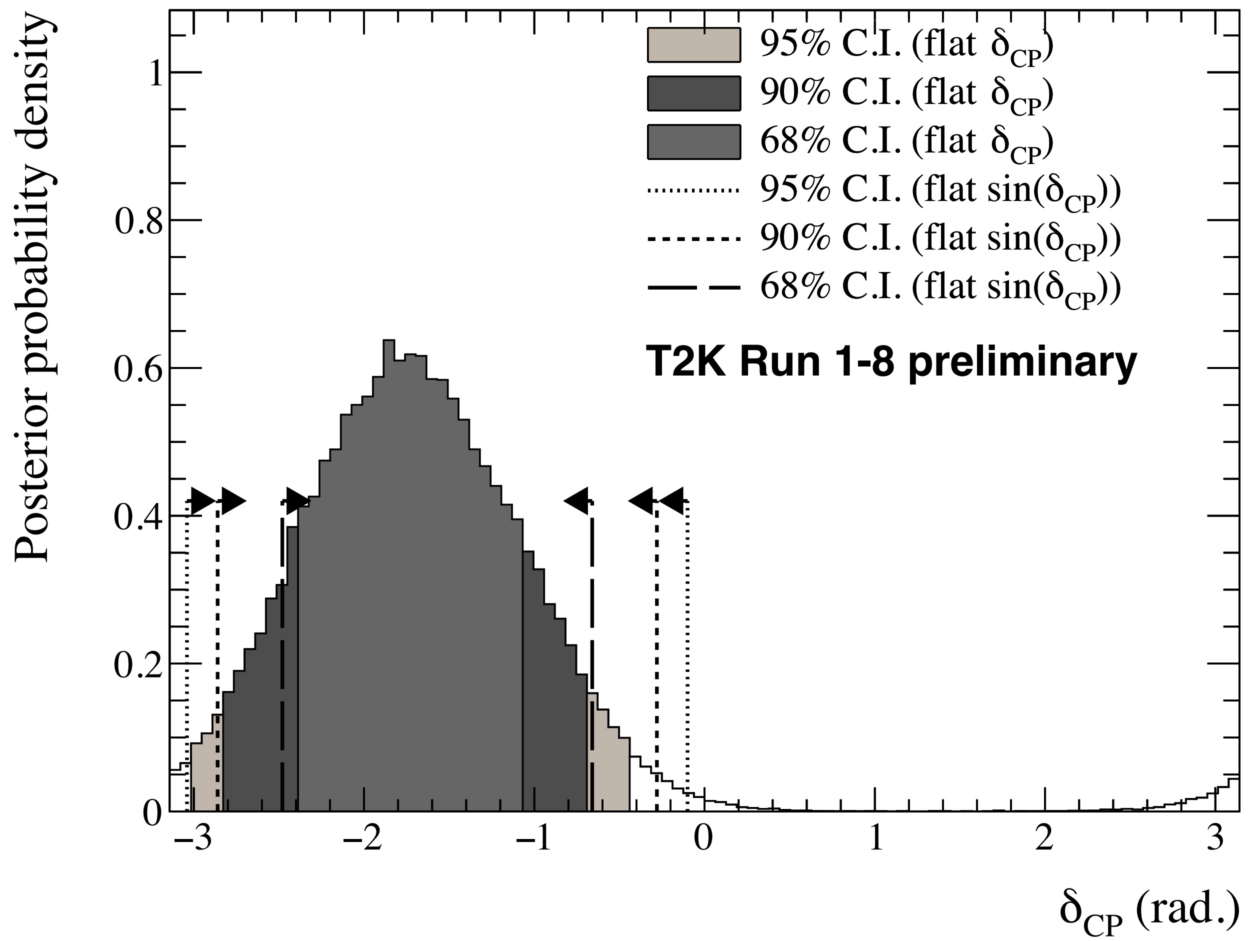


Neutrino CC1π 1e-like ring



COMPARISON TO BAYESIAN CREDIBLE INTERVALS

- Produce posterior probability distributions and credible intervals in Bayesian analysis
- Two choices for priors: flat in δ_{cp} and flat in $\sin(\delta_{cp})$



The 2σ confidence interval:

Flat prior on δ_{cp}: [-3.02, -0.44] radians

Flat prior on $\sin(\delta_{cp})$: [-3.04, -0.10] radians

CP conserving values $(0,\pi)$ fall outside of the 2σ intervals

OCTANT AND HIERARCHY PREFERENCES

- Bayesian analysis: natural way to infer data preference for **θ_{23} octant** or **mass hierarchy**
- Assume equal prior probability for both octant and hierarchy hypotheses
- Fraction of steps from Markov Chain in each octant/hierarchy is posterior probability for the octant/hierarchy hypothesis

Posterior probabilities (with reactor constraint)

	$\sin^2\theta_{23} < 0.5$	$\sin^2\theta_{23} > 0.5$	Sum
NH ($\Delta m^2_{32} > 0$)	0.193	0.674	0.868
IH ($\Delta m^2_{32} < 0$)	0.026	0.106	0.132
Sum	0.219	0.781	

- T2K data prefers the normal hierarchy and upper octant
  - No conclusive statement yet

BINNED LIKELIHOOD

- Define a binned likelihood for our data:

$$-ln(L) = \sum_{i}^{N_{SKbins}} N_i^{SK}(\vec{o},\vec{p}) - M_i^{SK} + M_i^{SK} ln[M_i^{SK}/N^{SK}(\vec{o},\vec{p})]$$
$$+ \frac{1}{2}\sum_{i}^{N_o^{const}}\sum_{j}^{N_o^{const}} \Delta o_i (V_{ij}^{o})^{-1} \Delta o_j + \frac{1}{2}\sum_{i}^{N_p}\sum_{j}^{N_p} \Delta p_i (V_{ij}^{p})^{-1} \Delta p_j.$$

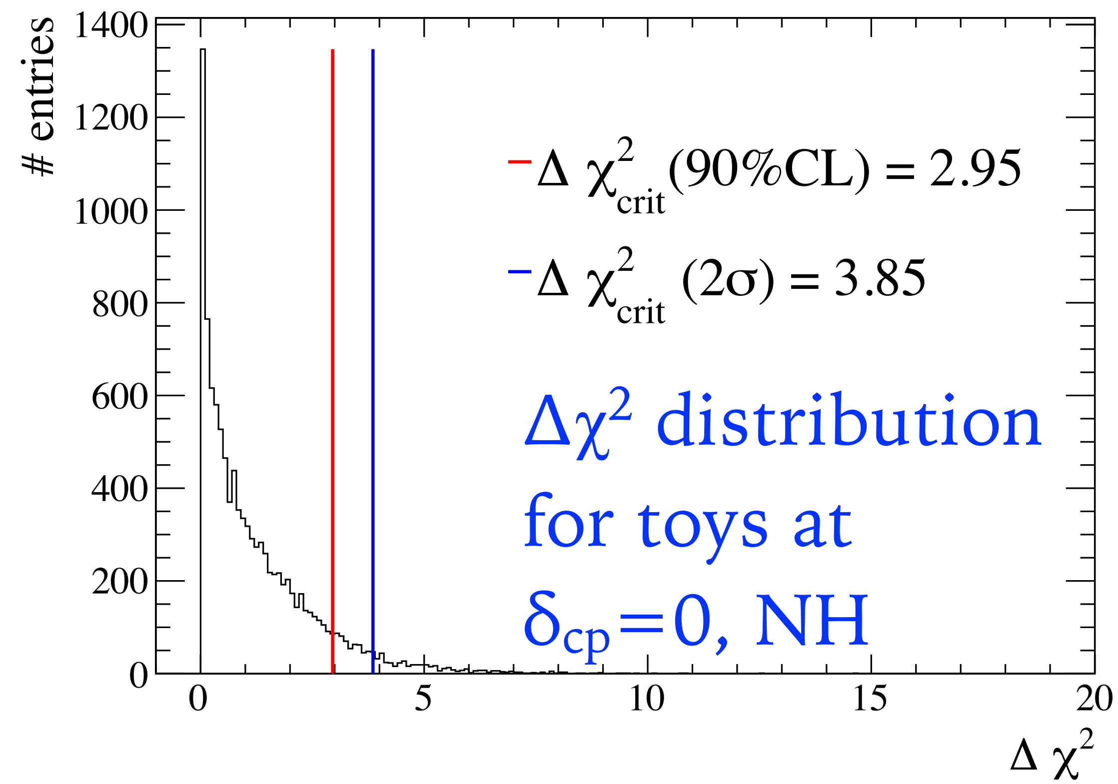
- M^{SK}_i : observed number of events in the i^{th} bin (all SK samples)
- N^{SK}_i : is the predicted number of events in the i^{th} bin
  - Depends on oscillation (**o**) and systematic (**p**) parameters
  - Oscillation and systematic parameters can have prior constraints
- Marginal likelihood formed by integrating out the dependence on all **p** and **o** that are not being plotted

FREQUENTIST VS. BAYESIAN ANALYSES

- Calculate intervals for parameters using two statistical approaches

- Scan the $\Delta[-2\ln(L_{marg})]=\Delta\chi^2$ surface for oscillation parameters and construct frequentist confidence intervals

  - For the 1-D δ_{cp} interval, perform a Feldman-Cousins construction to calculate the critical $\Delta\chi^2$ for given confidence levels



- Perform a **Markov Chain Monte Carlo (MCMC)** where step acceptance is based on the likelihood. Produce Bayesian credible intervals

  - MCMC method uses a likelihood that includes the near detector data

T2K SENSITIVITY INPUTS

- Evaluate sensitivity to oscillation parameters: run fits on Monte Carlo sets generated with no systematic or statistical throws

- Generated at two sets of oscillation parameter values:

Parameter	Set A value	Set B value
$\sin^2\theta_{12}$	0.304	0.304
$\sin^2\theta_{23}$	0.528	0.45
$\sin^2\theta_{13}$	0.0217	0.0217
Δm^2_{21}	7.53×10^{-5} eV^2	7.53×10^{-5} eV^2
Δm^2_{32}	2.509×10^{-3} eV^2	2.509×10^{-3} eV^2
δ_{CP}	-1.601	0

Near-maximal in A, non-maximal in B

CP violation in A, CP conservation in B

FITQUN RECONSTRUCTION ALGORITHM

- Previous T2K analyses have used the event reconstruction algorithm **APFit**
- For this result, event reconstruction at Super-K updated to use the **fiTQun** algorithm
- **fiTQun** uses a charge and time likelihood for a given ring(s) hypotheses
  - Maximizes likelihood for each event
  - Complete charge and time information in the likelihood leads to improved event reconstruction
- **fiTQun** previously used in T2K analyses for the rejection of π^0 from electron neutrino candidates

THE FIVE SAMPLES

- Using the reconstructed fiTQun quantities, five samples are selected:

Neutrino Mode (forward horn current FHC):

(CCQE) 1 Muon-like Ring, ≤1 decay electron

$$\nu_\mu(\bar{\nu}_\mu) + N \rightarrow \mu^-(\mu^+) + X$$

$$\downarrow$$

$$e^-(e^+) + \bar{\nu}_e(\nu_e) + \nu_\mu(\bar{\nu}_\mu)$$

(CCQE) 1 Electron-like Ring, 0 decay electrons

$$\nu_e(\bar{\nu}_e) + N \rightarrow e^-(e^+) + X$$

(CC1π) 1 Electron-like Ring, 1 decay electron

$$\nu_e + N \rightarrow e^- + \pi^+ + X$$

$$\downarrow$$

$$\mu^+ + \nu_\mu$$

$$\downarrow$$

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

Antineutrino Mode (reverse horn current RHC):

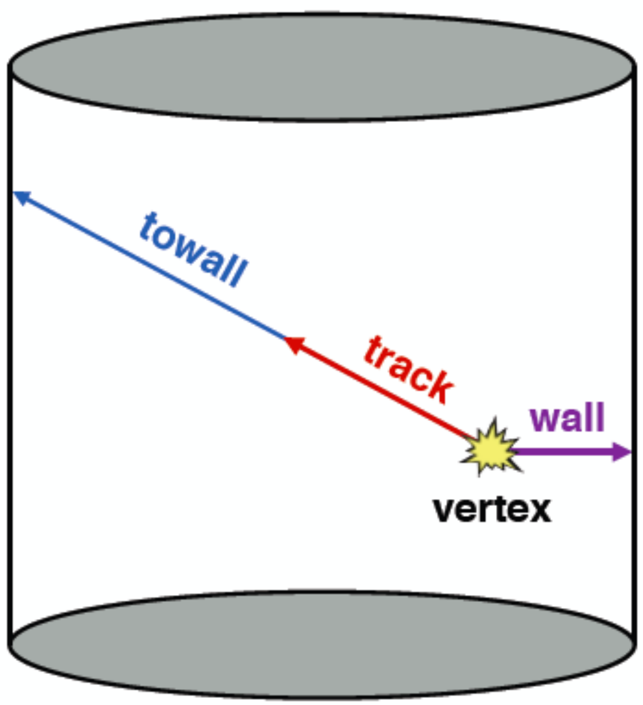
(CCQE) 1 Muon-like Ring, ≤1 decay electron

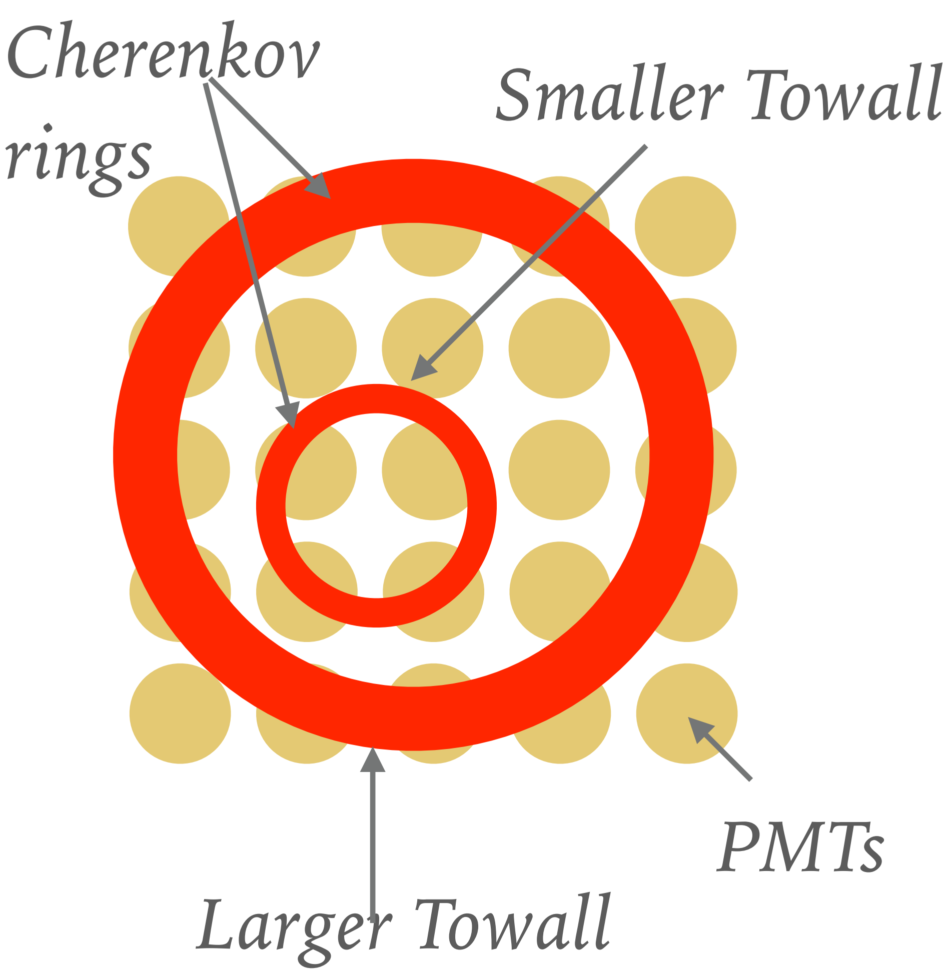
(CCQE) 1 Electron-like Ring, 0 decay electrons

No antineutrino mode CC1π sample due to π^- absorption

= *detected particles*

EXPANSION OF THE FIDUCIAL VOLUME





- APFit based fiducial volume: reconstructed vertex > 2 m from the detector wall
- With fiTQun, fiducial volume cut is re-optimized
  - Cut on two variables:
    - Distance of vertex from wall (Wall)
      - Minimum distance to exclude external backgrounds
    - Distance to the wall along the particle trajectory (Towall)
      - Larger Towall = finer sampling of ring = better reconstruction
  - Optimize cuts accounting for statistical and systematic errors

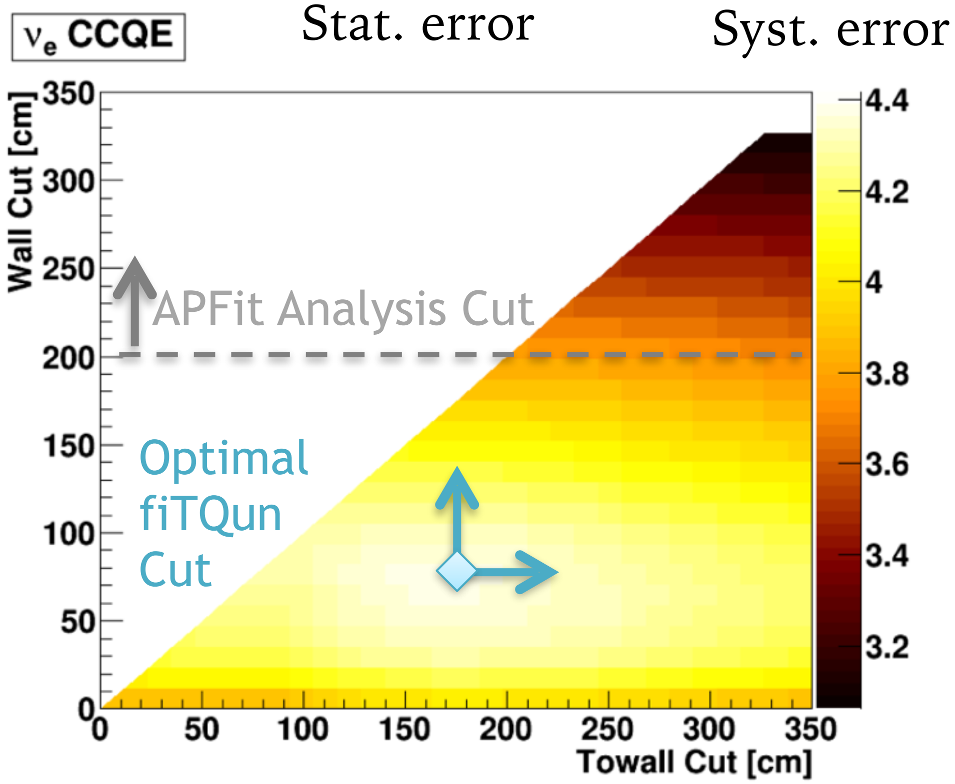
OPTIMIZATION OF FIDUCIAL VOLUME CUTS

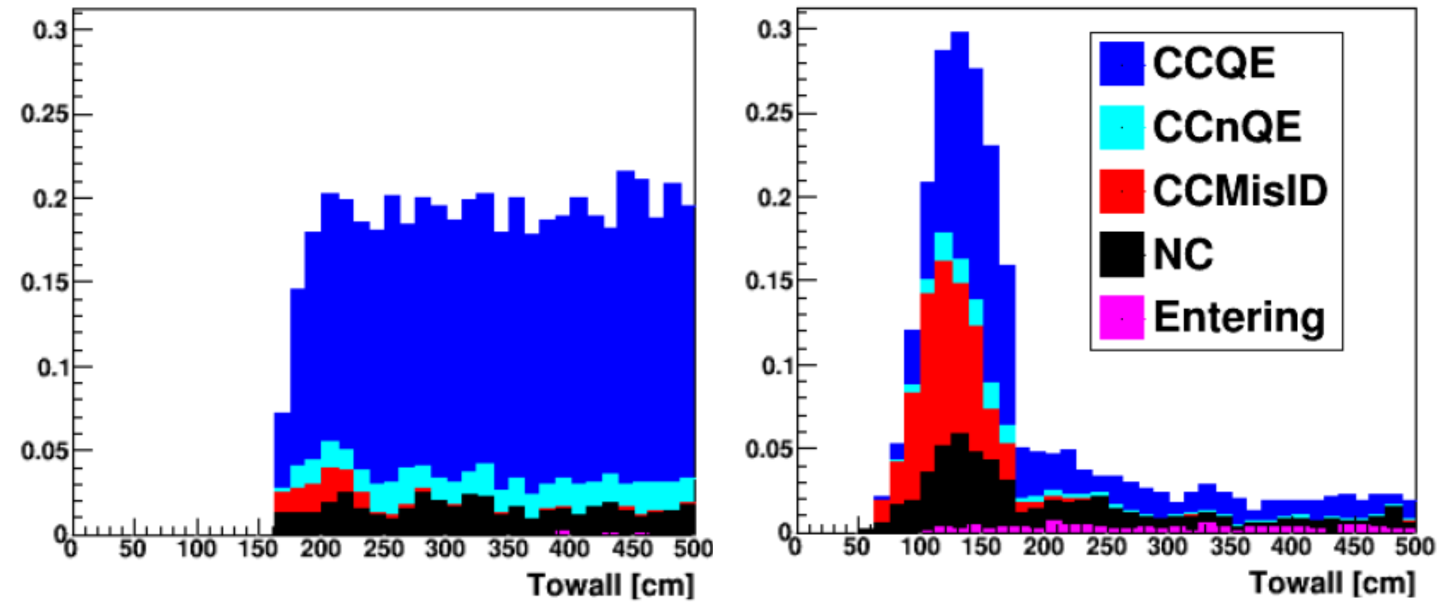
Derivative with respect to oscillation parameter θ

$$\text{Sensitivity Metric} = \frac{\left(\frac{\partial \hat{N}}{\partial \theta}\right)^2}{\hat{N} + \sigma_{syst}^2}$$

Stat. error

Syst. error





Accepted Events

Rejected Events

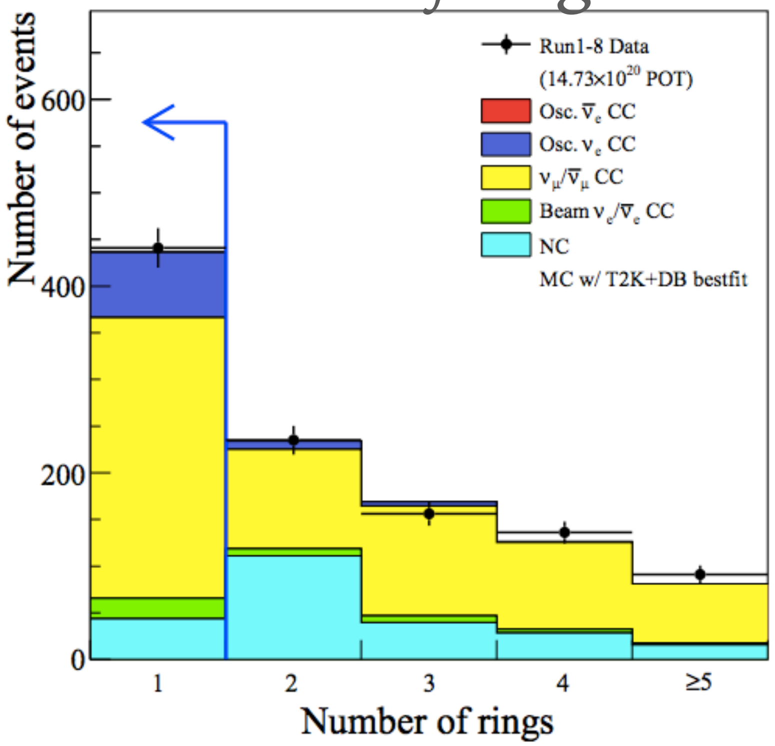
➤ Systematic parameters evaluated in a fit to atmospheric neutrino and cosmic muon control samples

➤ For each of the 5 samples, position of the Towall and Wall cuts selected by maximizing the sensitivity metric

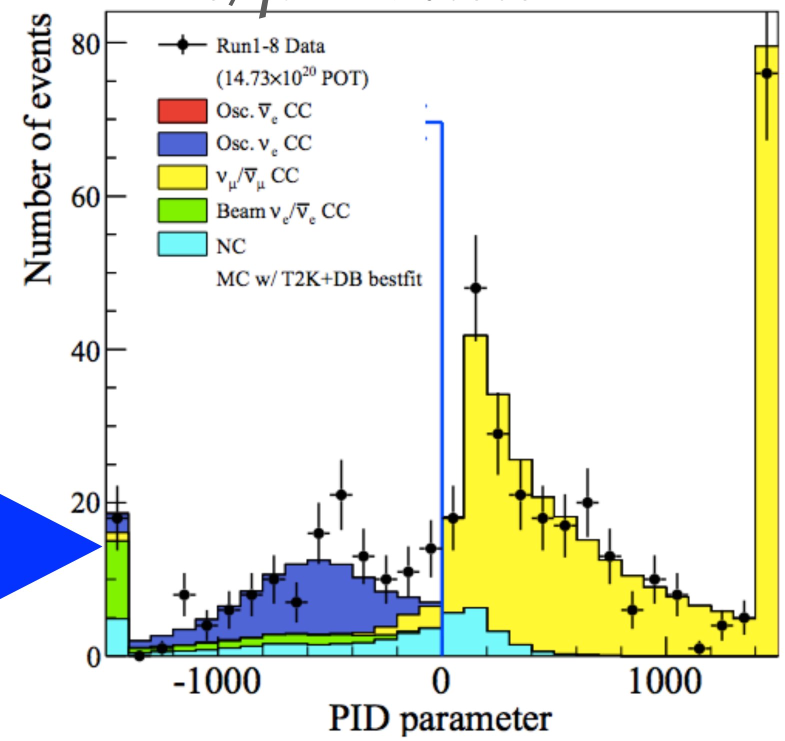
Sample	Towall Cut	Wall Cut
CCQE 1-Ring e-like FHC	170 cm	80 cm
CCQE 1-Ring μ-like FHC	250 cm	50 cm
CC1π 1-Ring e-like FHC	270 cm	50 cm
CCQE 1-Ring e-like RHC	170 cm	80 cm
CCQE 1-Ring μ-like RHC	250 cm	50 cm

CUT PROGRESSION FOR CCQE 1-RING E-LIKE

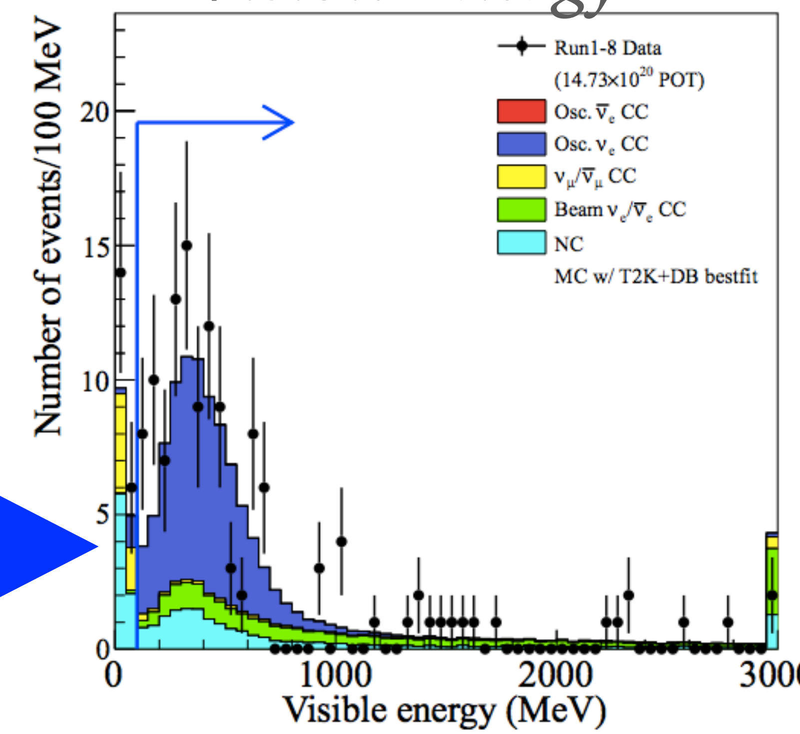
Number of rings



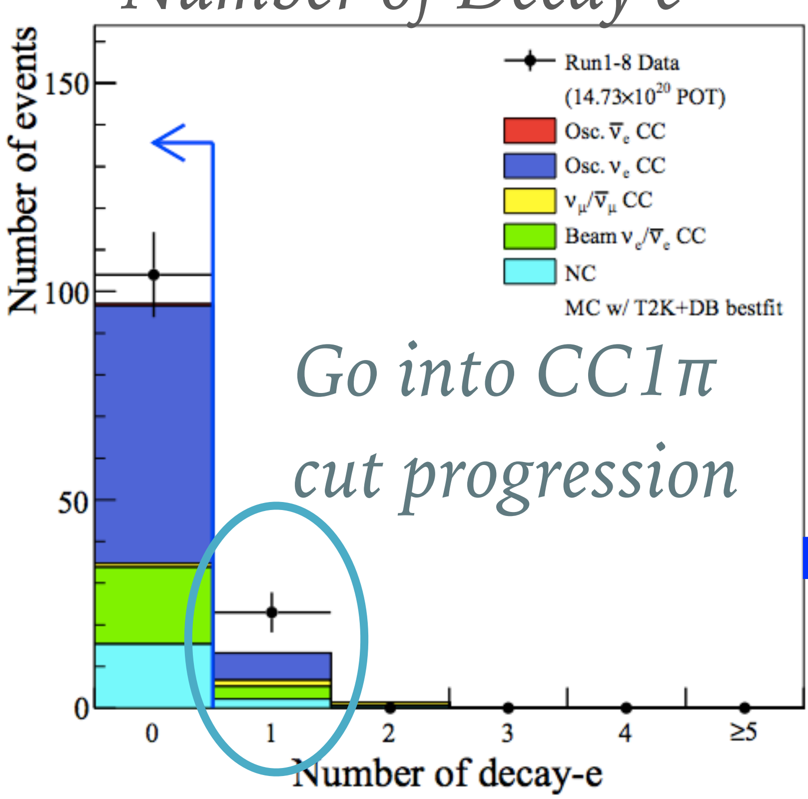
e/μ Particle ID



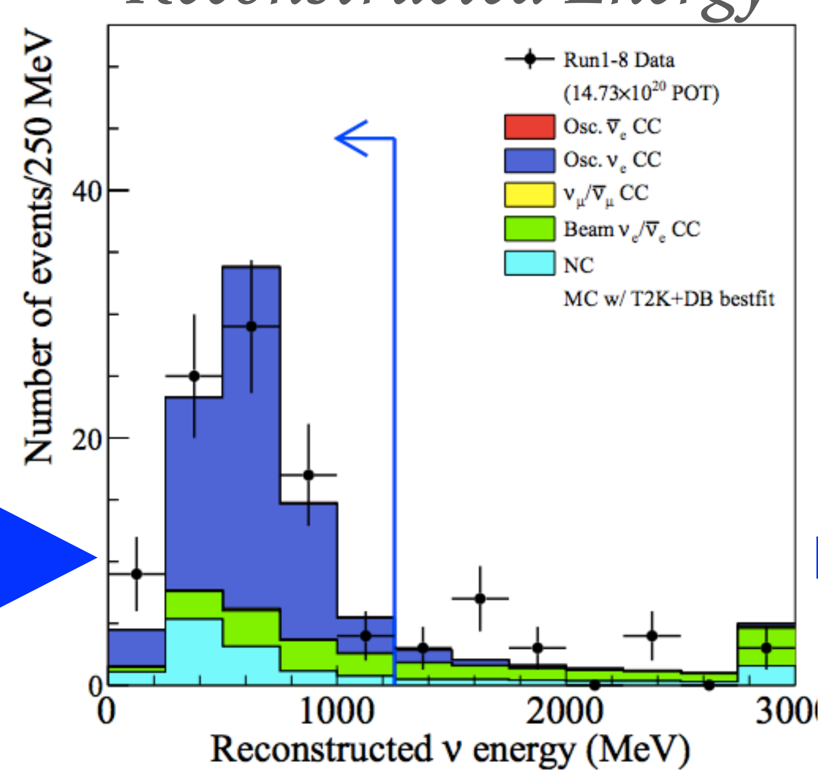
Visible Energy



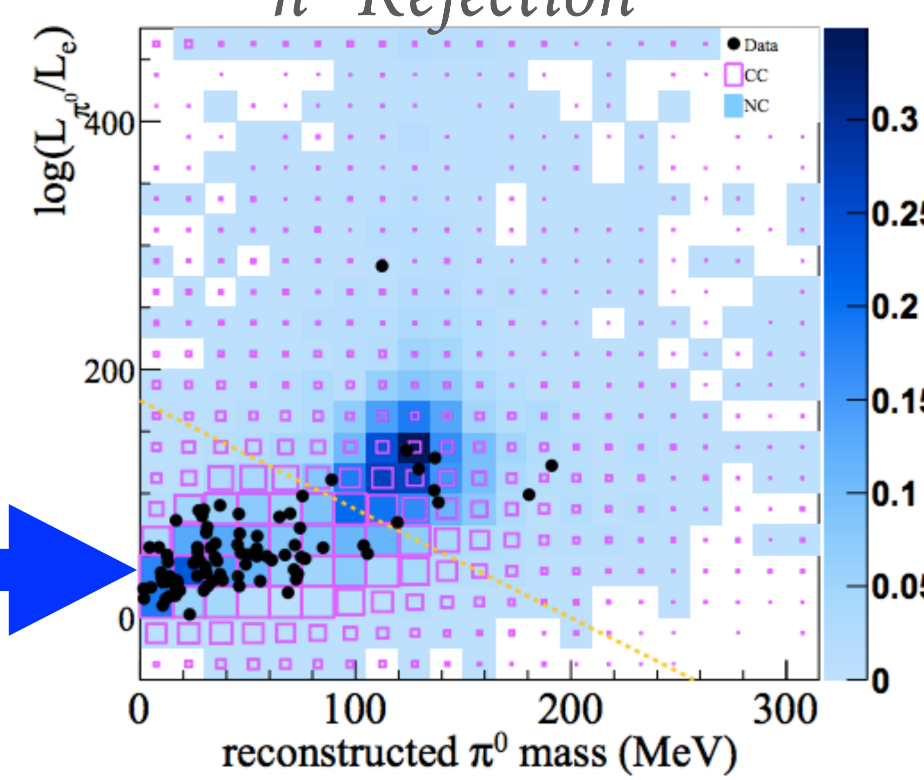
Number of Decay e



Reconstructed Energy



π^0 Rejection



IMPROVEMENTS FROM APFIT TO FITQUN

	fiTQun Selection		APFit Selection	
Sample	Candidates	Purity	Candidates	Purity
CCQE 1-Ring e-like FHC	69.5	81.2%	56.5	81.4%
CCQE 1-Ring μ-like FHC	261.6	79.7%	268.7	68.1%
CC1π 1-Ring e-like FHC	6.9	78.8%	5.6	72.0%
CCQE 1-Ring e-like RHC	7.6	62.0%	6.1	63.7%
CCQE 1-Ring μ-like RHC	62.0	79.7%	65.4	70.5%

- CCQE 1-Ring e-like samples: efficiency increases (due to new fiducial cuts) while purity remains the same
- CCQE 1-Ring μ-like samples: improvement in signal efficiency and purity
  - Reduction of NCπ and CCπ backgrounds
- CC1π 1-Ring e-like: improvement in signal efficiency and purity
  - Improved PID = less muon ring contamination

IMPROVEMENTS FROM APFIT TO FITQUN

	fiTQun Selection		APFit Selection	
Sample	Candidates	Purity	Candidates	Purity
CCQE 1-Ring e-like FHC	69.5	81.2%	56.5	81.4%
CCQE 1				.1%
CC1π 1-				.0%
CCQE 1-				.7%
CCQE 1-				.5%

With new fiTQun reconstruction and CC1π e-like sample, significant statistical improvement for same beam exposure since last summer:

30% increase for neutrino mode e-like selection
20% increase for antineutrino mode e-like selection

- CCQE ... ucial cuts)
- CCQE ... nd purity
    - Reduction of NCπ and CCπ backgrounds
- CC1π 1-Ring e-like: improvement in signal efficiency and purity
    - Improved PID = less muon ring contamination

OBSERVED EVENT RATES AT SUPER-K

PREDICTED AND OBSERVED EVENT RATES AT SK

	Predicted Rates				Observed
Sample	δ_{cp}=-π/2	δ_{cp}=0	δ_{cp}=π/2	δ_{cp}=π	Rates
CCQE 1-Ring e-like FHC	73.5	61.5	49.9	62.0	74
CC1π 1-Ring e-like FHC	6.92	6.01	4.87	5.78	15
CCQE 1-Ring e-like RHC	7.93	9.04	10.04	8.93	7
CCQE 1-Ring μ-like FHC	267.8	267.4	267.7	268.2	240
CCQE 1-Ring μ-like RHC	63.1	62.9	63.1	63.1	68

- The number of observed events are largely in line with the predictions after oscillations
  - The e-like samples have rates most consistent with the δ_{cp}=-π/2 hypothesis
- The observed μ-like rate in neutrino mode is lower than prediction
  - Consistent within statistical and systematic errors

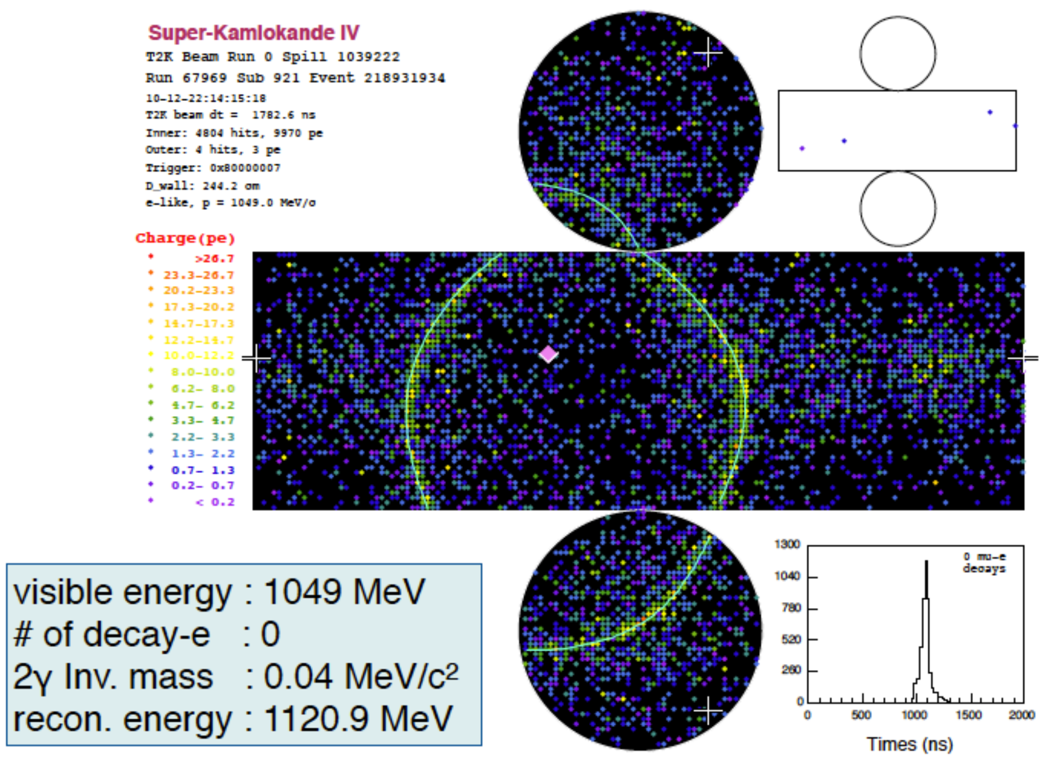
EXTRACTING OSCILLATION PARAMETERS, STEP 2

Prediction at Super-K

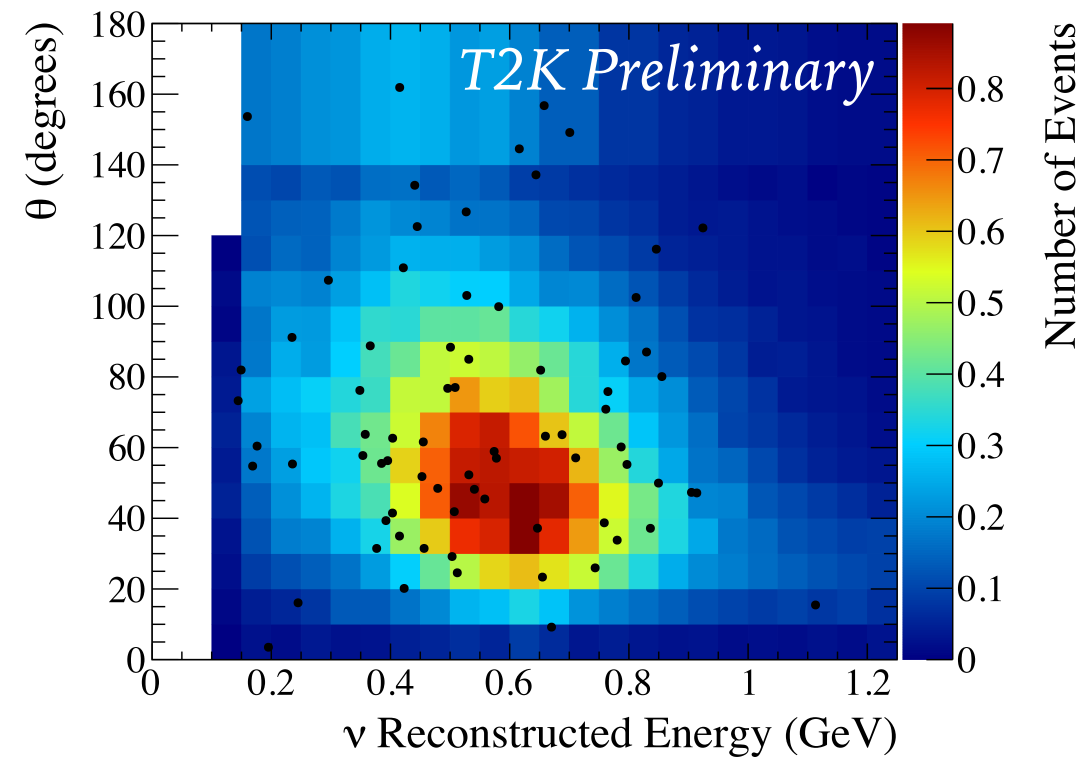
Oscillation Probability — Constrained by near detector fit

$$N(p_k,\theta_k;\theta_{23},\Delta m^2_{32},\delta_{CP}\ldots)=\sum_i^{E_\nu\text{ bins}}\sum_j^{flavors}\boxed{P_{\nu_j\rightarrow\nu_k}(E_{\nu,i};\theta_{23},\Delta m^2_{32},\delta_{CP}\ldots)}\boxed{\Phi_j^{far}(E_{\nu,i})\sigma_k(E_{\nu,i},p_k,\theta_k)}\epsilon(p_k,\theta_k)M_{det}$$

T2K Super-K Data



Fit to SK data to extract oscillation parameter intervals



ν Mode ν_e Candidates

EXTRACTING OSCILLATION PARAMETERS, STEP 2

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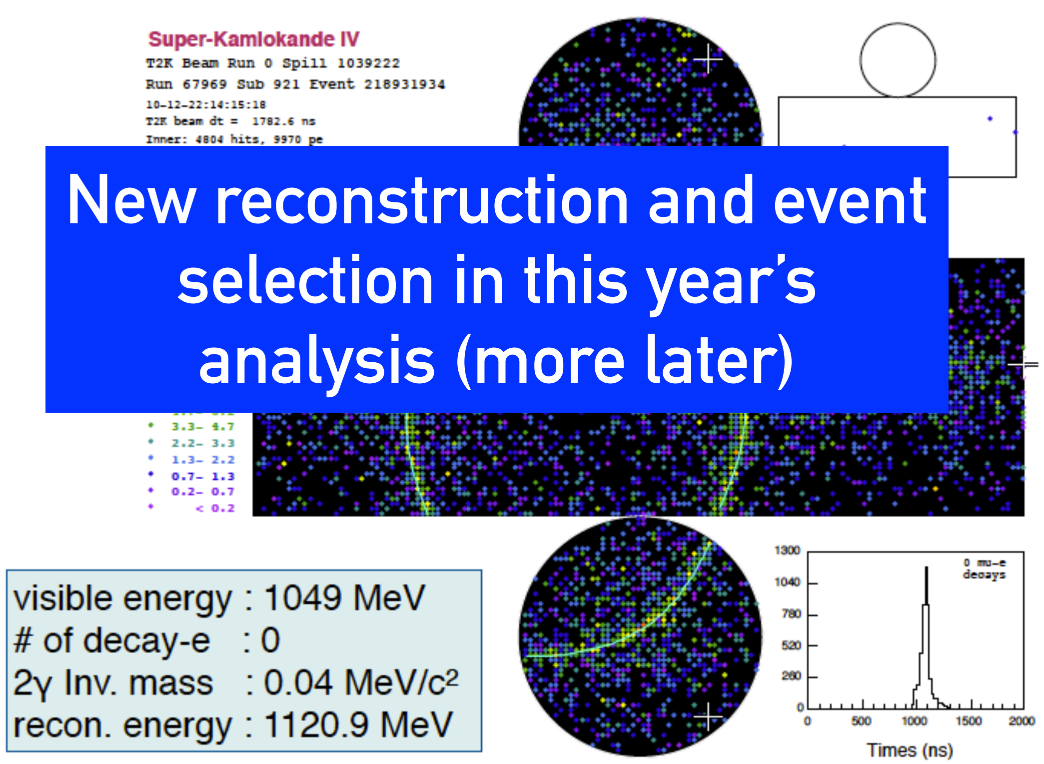
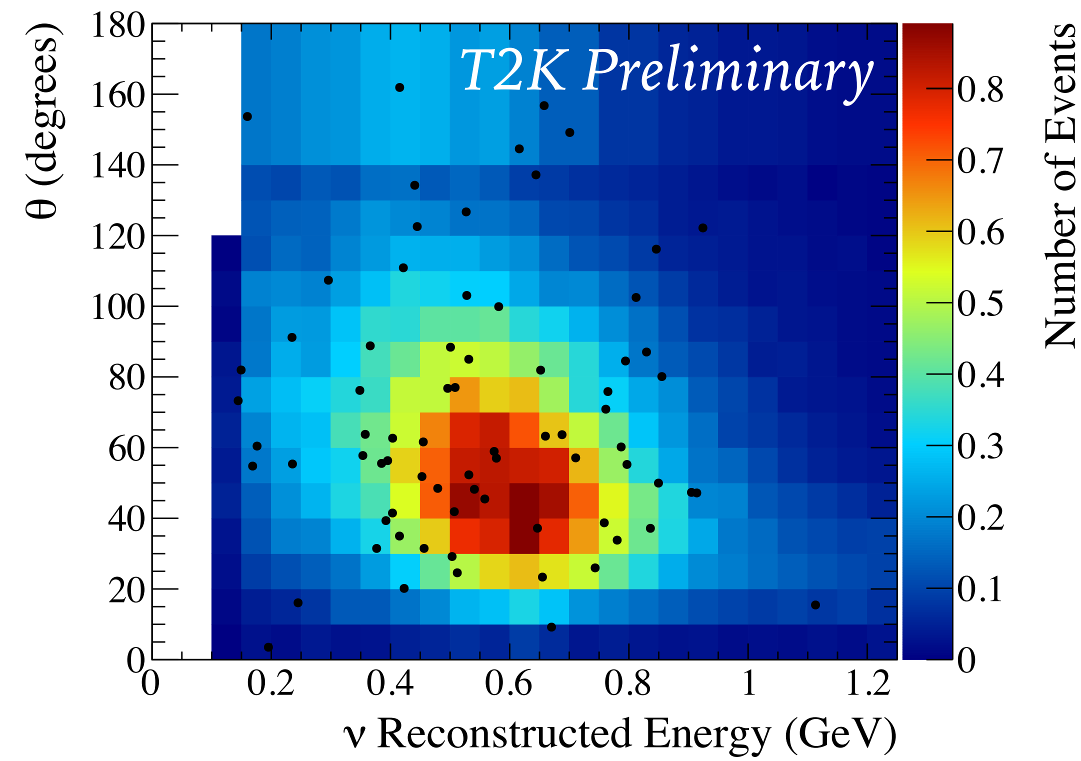


New reconstruction and event selection in this year's analysis (more later)

Fit to SK data to extract oscillation parameter intervals



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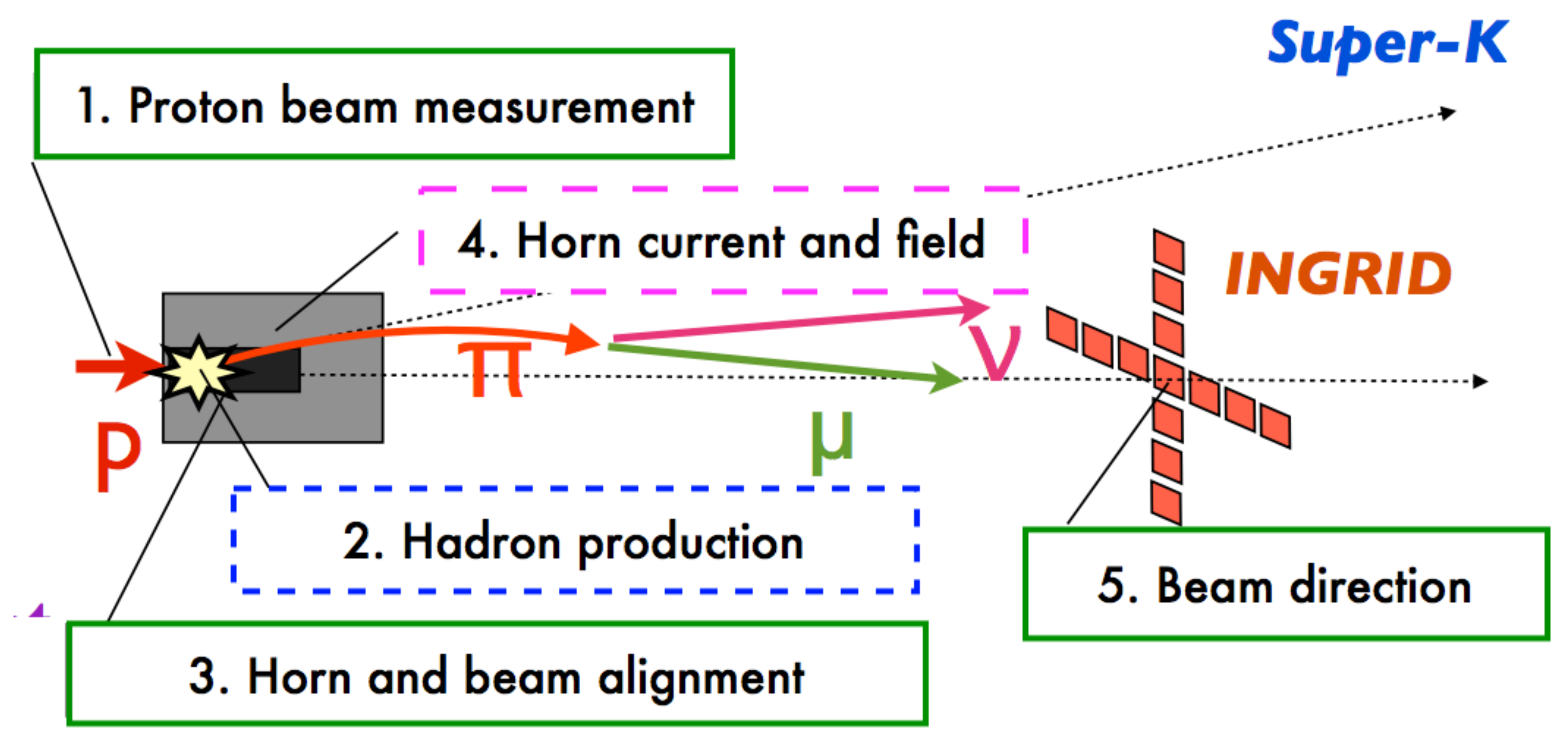
FLUX AND INTERACTION MODELING + ND280 CONSTRAINT

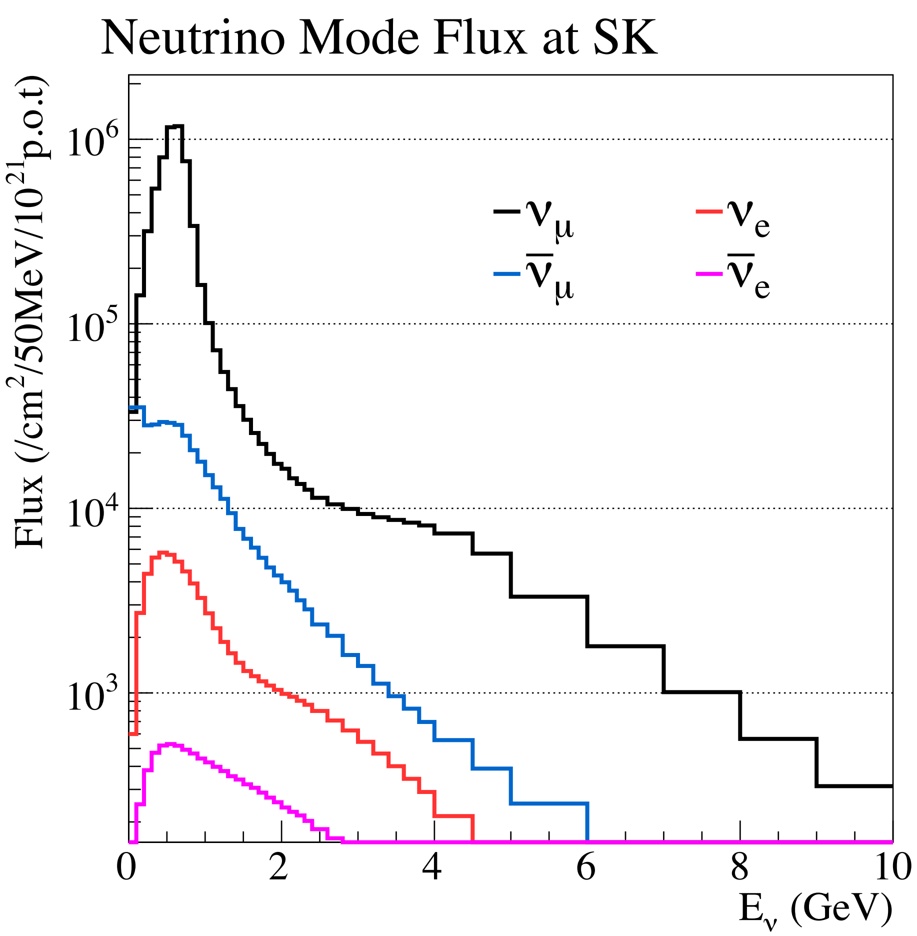
NEUTRINO PRODUCTION SIMULATION

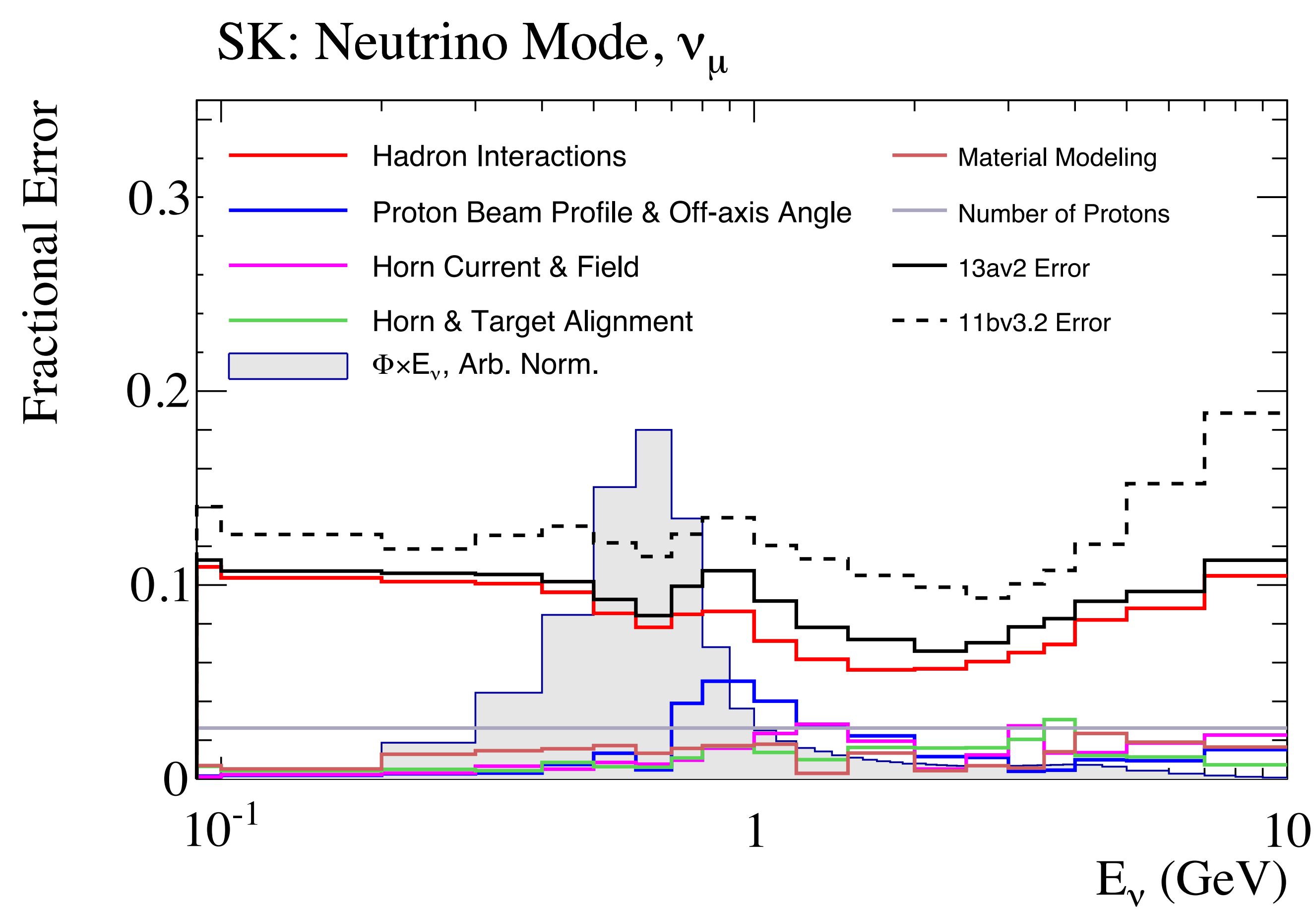


- Beam monitors measure the proton beam current and trajectory - input to flux simulation
- Interactions in 90 cm long graphite target produce hadrons (π,K…) - simulated with FLUKA2011
  - Interaction rate and particle production tuned with NA61/SHINE thin (2 cm) target data (Eur. Phys. J. C76 (2016) no.2, 84)
- Propagation through magnetic horns and decay to neutrinos simulated in GEANT3

THE NEUTRINO FLUX PREDICTION

➤ Flux predictions and error bands derived from data-driven simulation:





➤ **Flux prediction uncertainty is 8-12%**

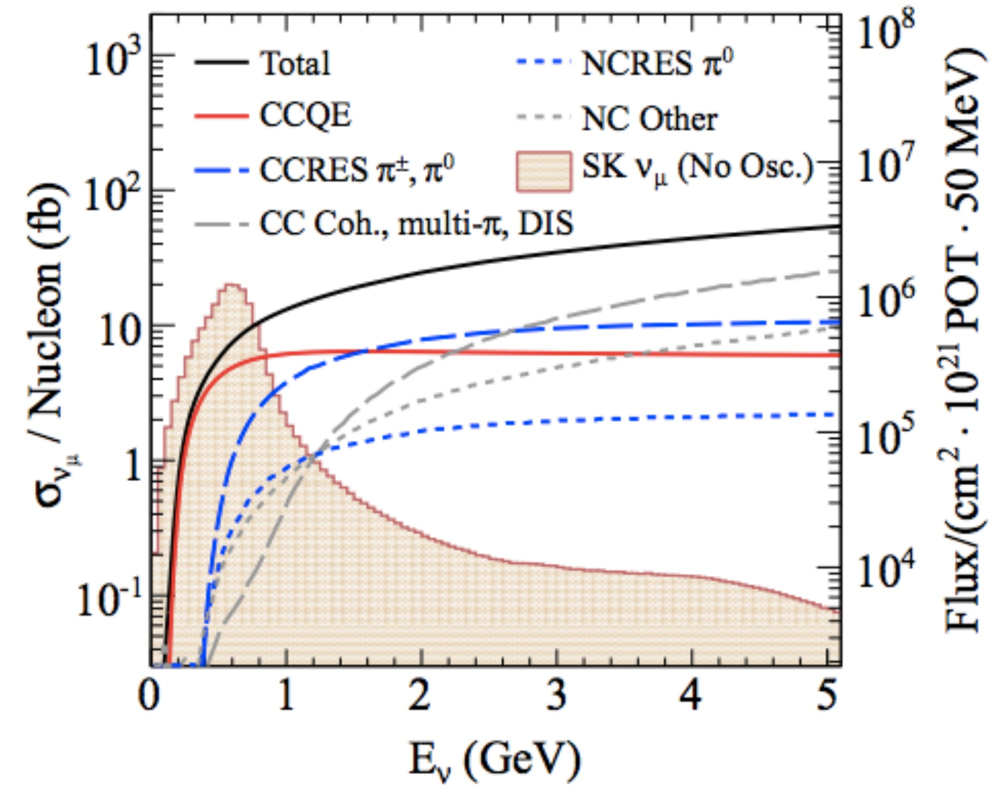
➤ Uncertainties on hadronic interaction modeling are largest

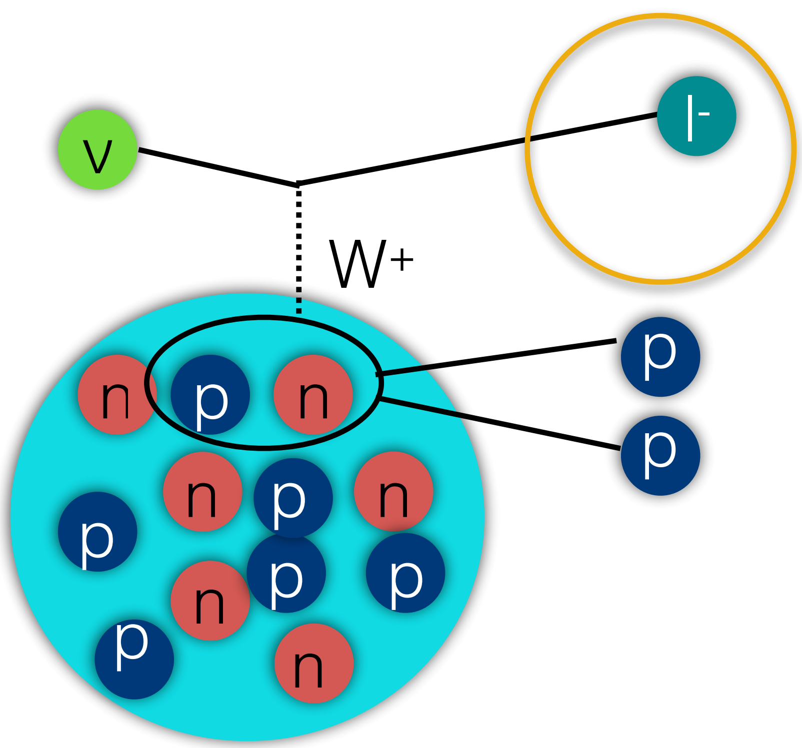
➤ NA61/SHINE data taken with **replica T2K target** is being incorporated for future analyses

  ➤ Expect reduction of flux calculation uncertainty

NEUTRINO INTERACTION MODELING

- At T2K's energy dominant contribution: charged-current quasi-elastic CCQE interactions
  - Also interactions producing one or more pions
  - Nuclear effects: interactions that mimic a CCQE interaction





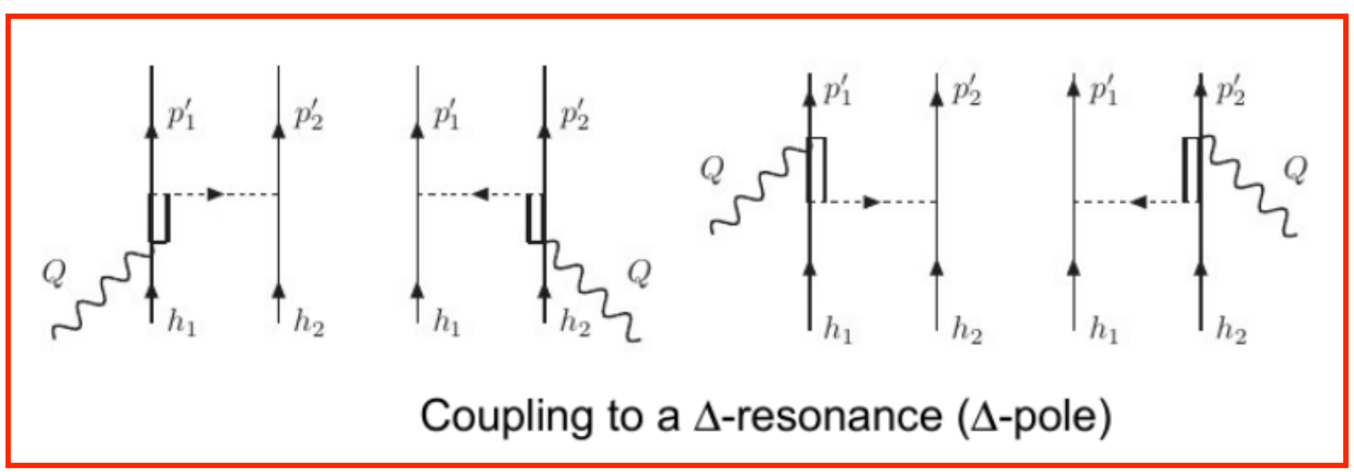
- Mimic CCQE interactions:
  - Neutrino scatters on a correlated pair of nucleons (left) (called multi-nucleon or 2 particle-2 hole, 2p-2h)
  - Neutrino scatter produces a pion, which is re-absorbed in the nucleus
  - Neutrino scatter produces a pion, which is absorbed in the detector

INTERACTION MODEL IMPROVEMENTS

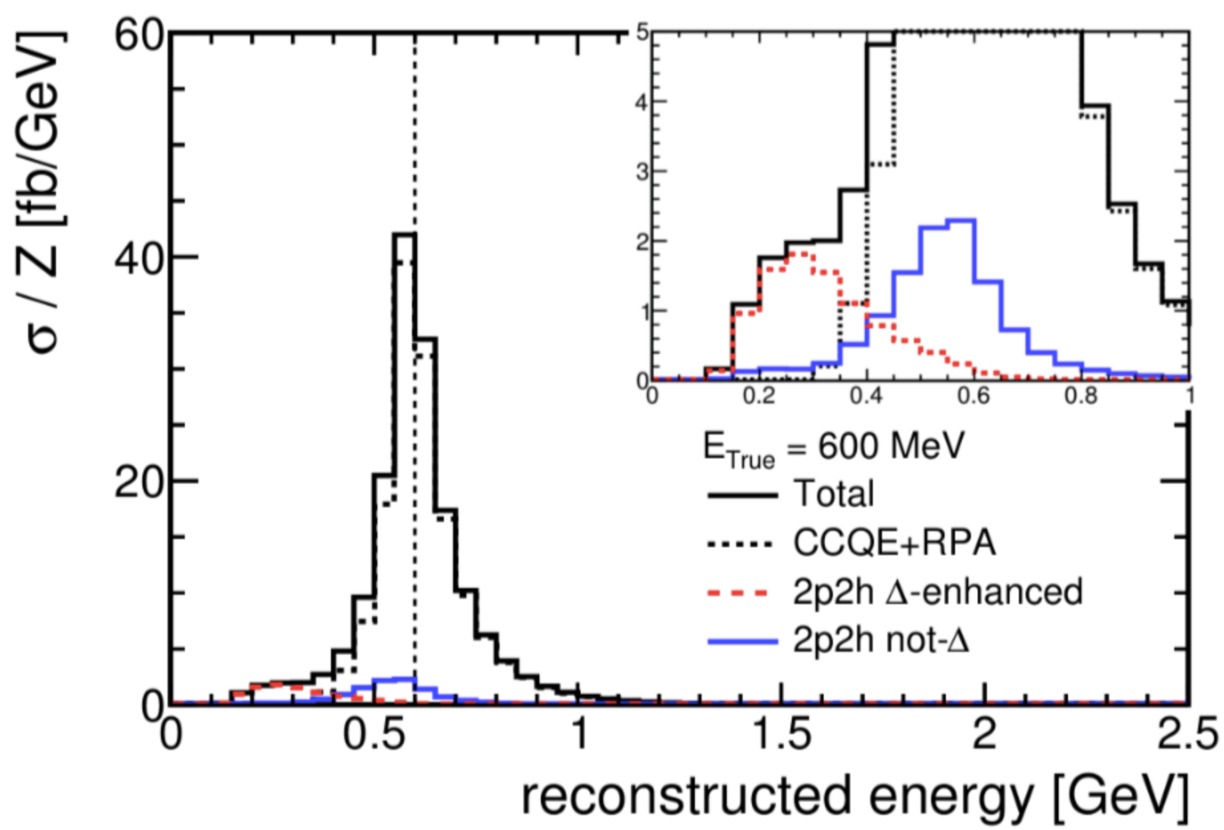
- In recent years, T2K made significant progress to improve the neutrino interaction model in NEUT (neutrino interaction generator):
  - Improved pion production model with tuning to data on hydrogen and deuterium
  - Inclusion of a model for multi-nucleon scattering processes: Valencia 2p-2h model (Phys. Rev. C83 (2011) 045501)
  - Improved the CCQE model by including the effect of long-range correlations in the nucleus (calculation technique called random phase approximation, RPA)
- This analysis: developed new parameterizations of the uncertainties in multi-nucleon and RPA modeling

MULTINUCLEON (2P-2H) MODELING ERROR

- 2p-2h processes can produce events with biased reconstructed energy
  - Energy mis-reconstruction largest in processes involving coupling to a **Δ resonance**
- Model the energy reconstruction error: allow strength of the 2p-2h cross-section to vary between all Δ-enhanced and all not-Δ-enhanced
- Also allow normalization for 2p-2h to vary separately for neutrinos and antineutrinos



Coupling to a Δ-resonance (Δ-pole)

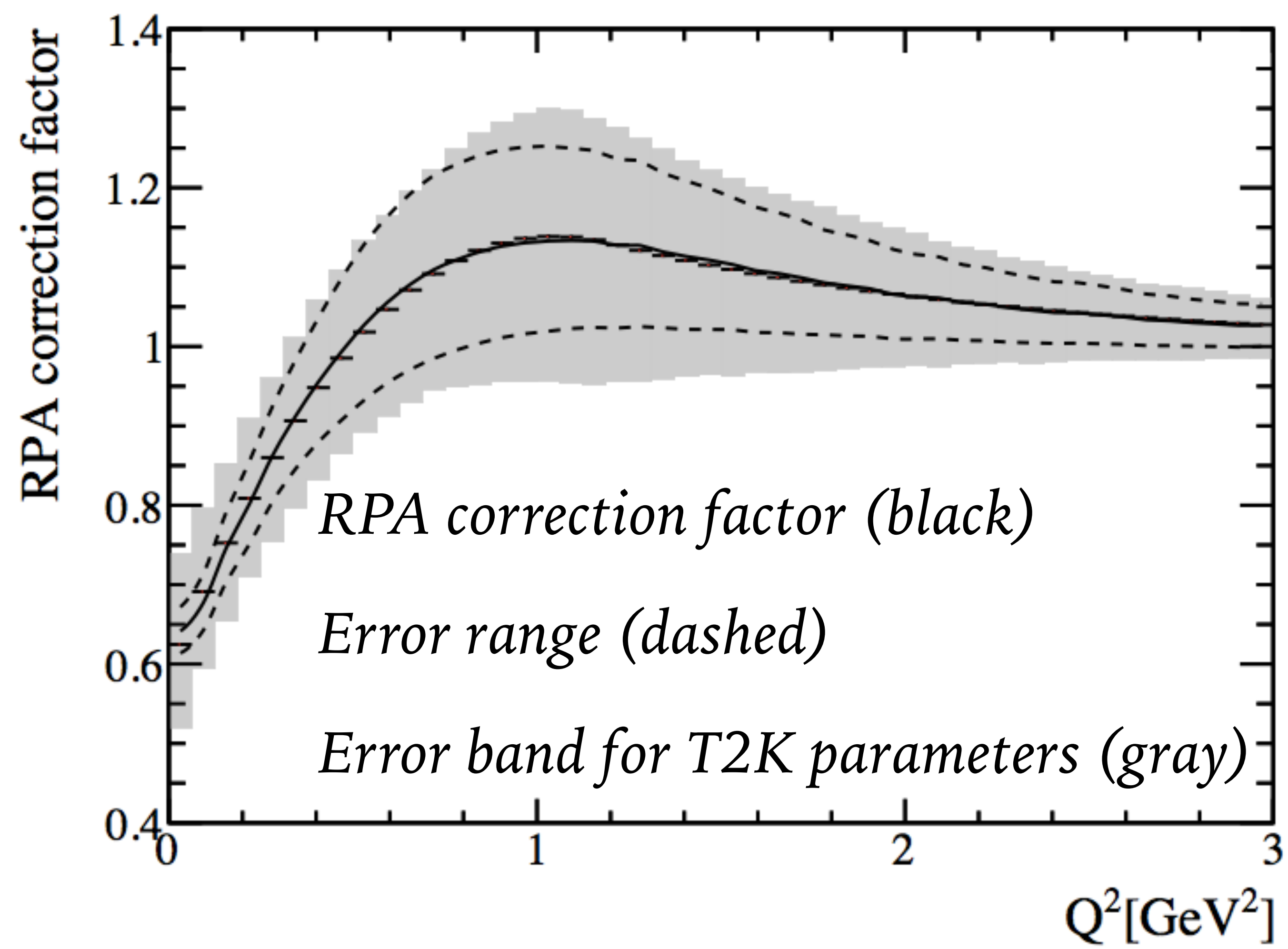


RPA CORRECTION UNCERTAINTY

- Correction for long-range correlations in the nucleus modifies Q^2 dependence of CCQE cross section
- Introduce a parametrization of this correction:

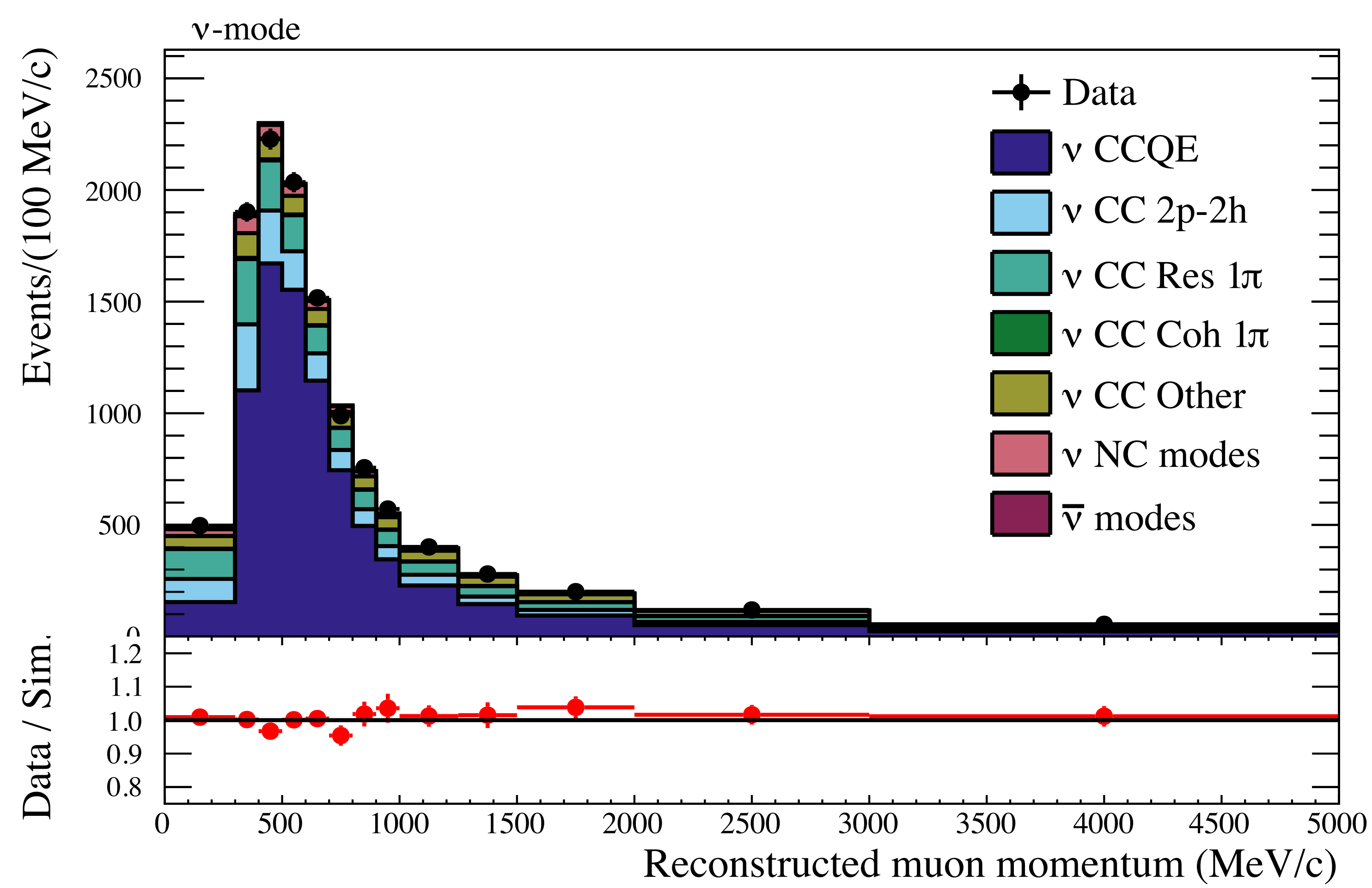
$$f(x) = \begin{cases} A(1-x')^3 + 3B(1-x')^2x' + 3p_1(1-x')x'^2 + Cx'^3, & x < U \\ 1 + p_2 \exp(-D(x-U)), & x > U \end{cases} \qquad x = Q^2$$

- Uncertainties on the parameters cover the theoretical uncertainty on the RPA correction factor

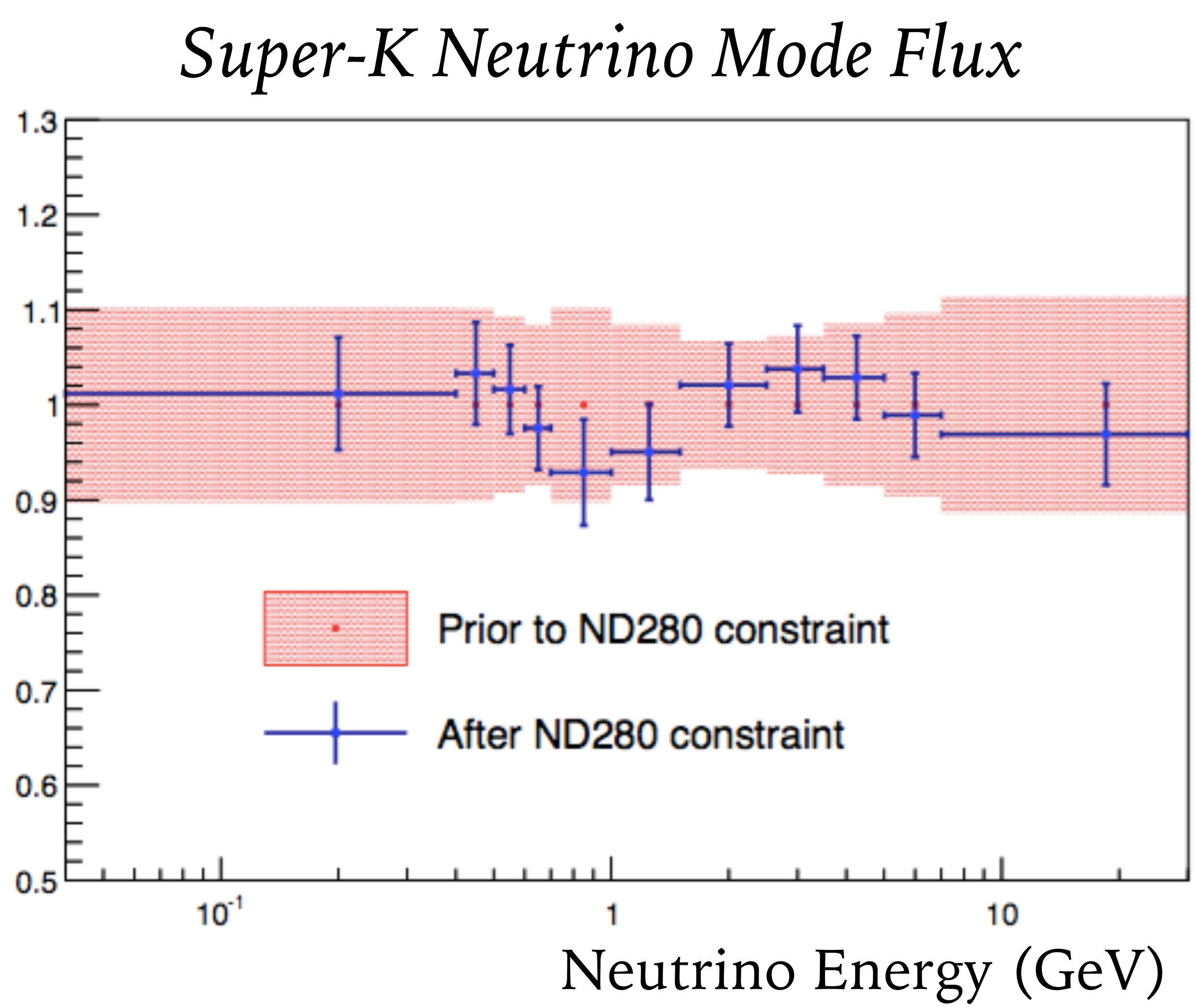


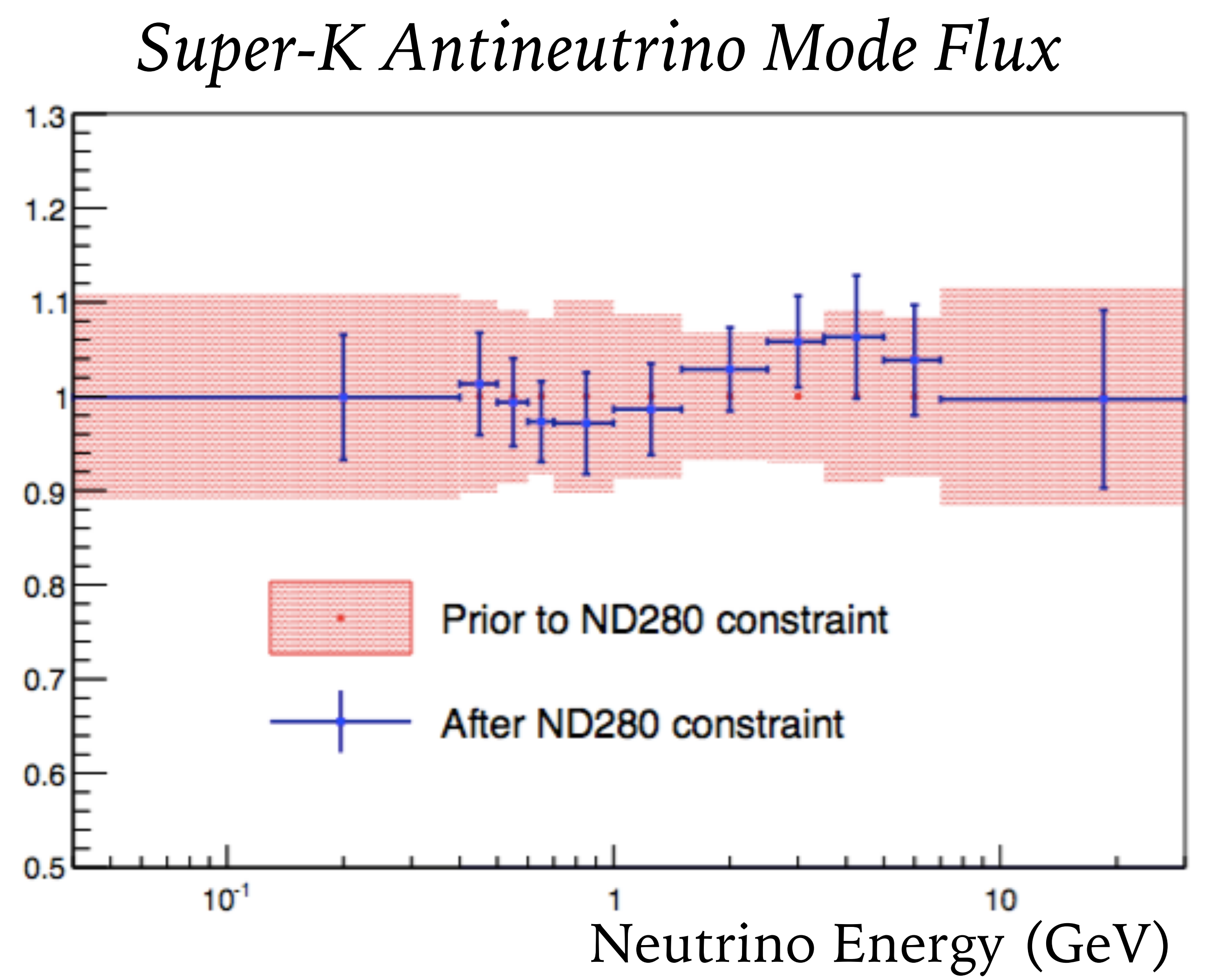
FITTING ND280 DATA

- Since 2016, include FGD2 (water targets) to include interactions on H_2O
    - Separate data sets in FGD1 and FGD2
- Neutrino mode separated by number of charged pions: **CC-0π, CC-1π, CC-Other**
- Antineutrino mode separate by number of TPC tracks: **CC-1Track, CC-NTrack**
    - In antineutrino mode, separate samples for μ^+ and μ^- candidates
- Example fitted FGD2 CC-0π muon momentum (left)
- The fit reproduces the data well with a p-value of 0.47



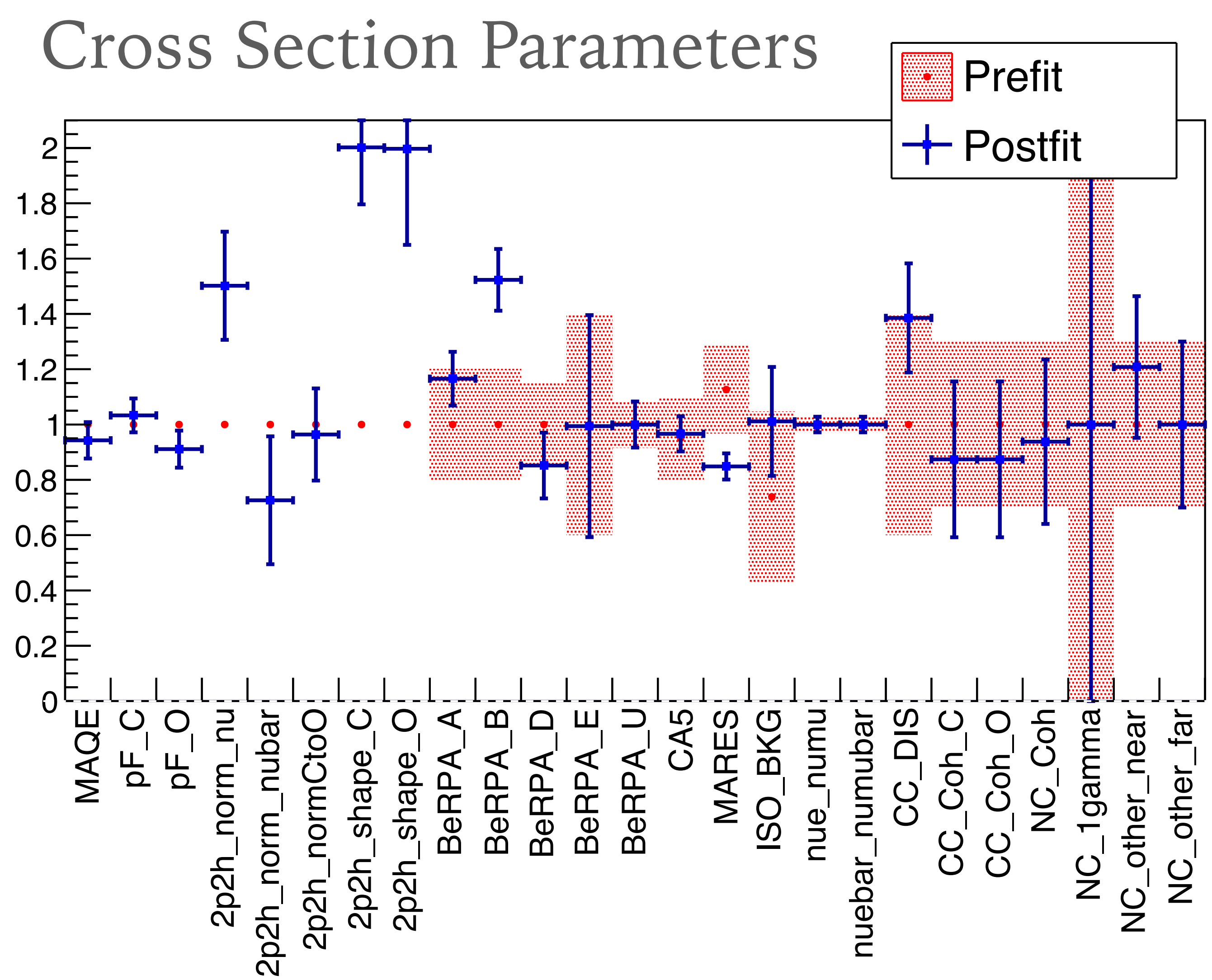
FITTED FLUX PARAMETERS





- Fitted flux parameters are generally near their nominal value of 1.0
- Most of the fitted flux parameters fall within their assigned 1 sigma prior uncertainty

FITTED INTERACTION MODEL PARAMETERS



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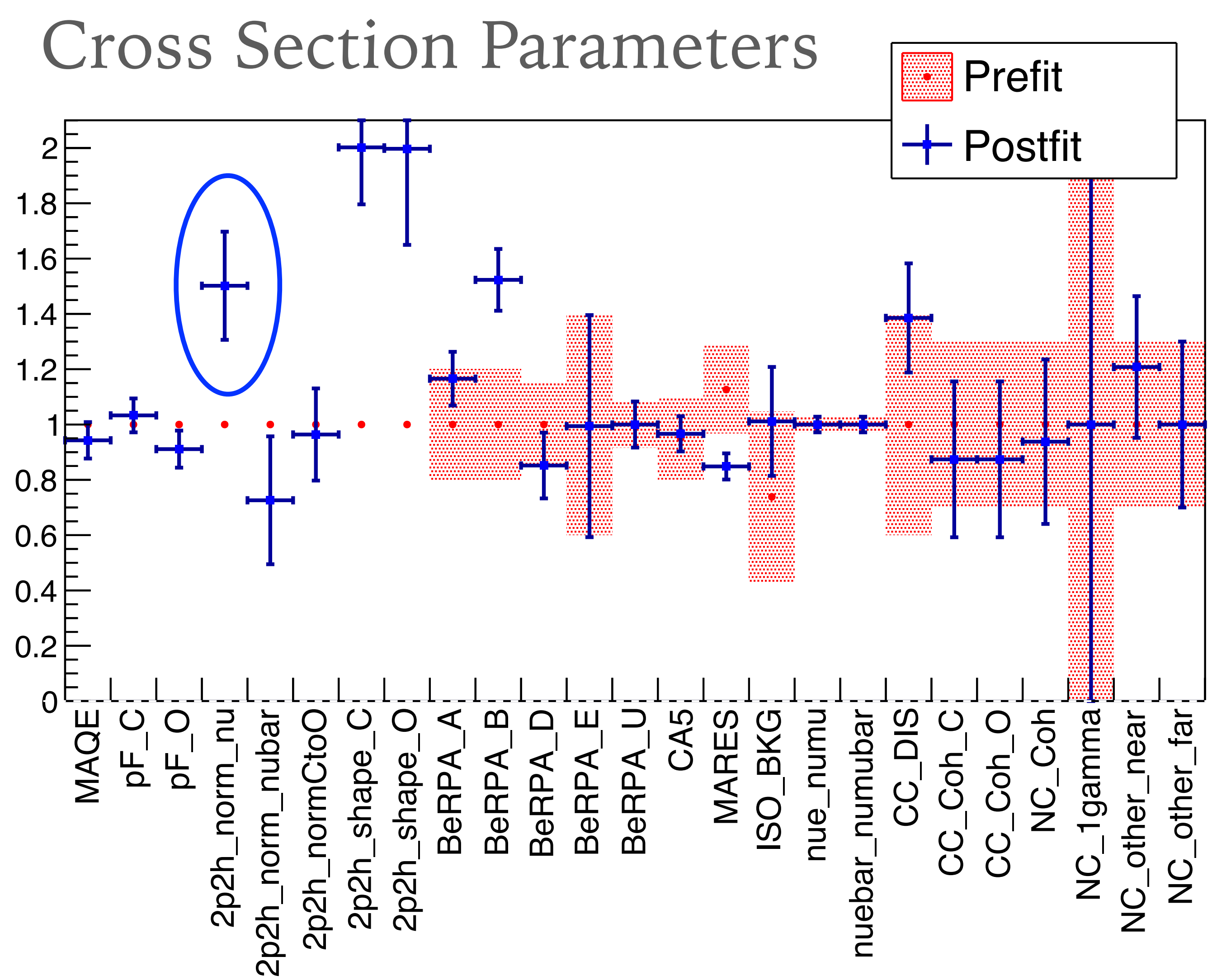

➤ The 2p-2h for neutrinos is enhanced by 50%

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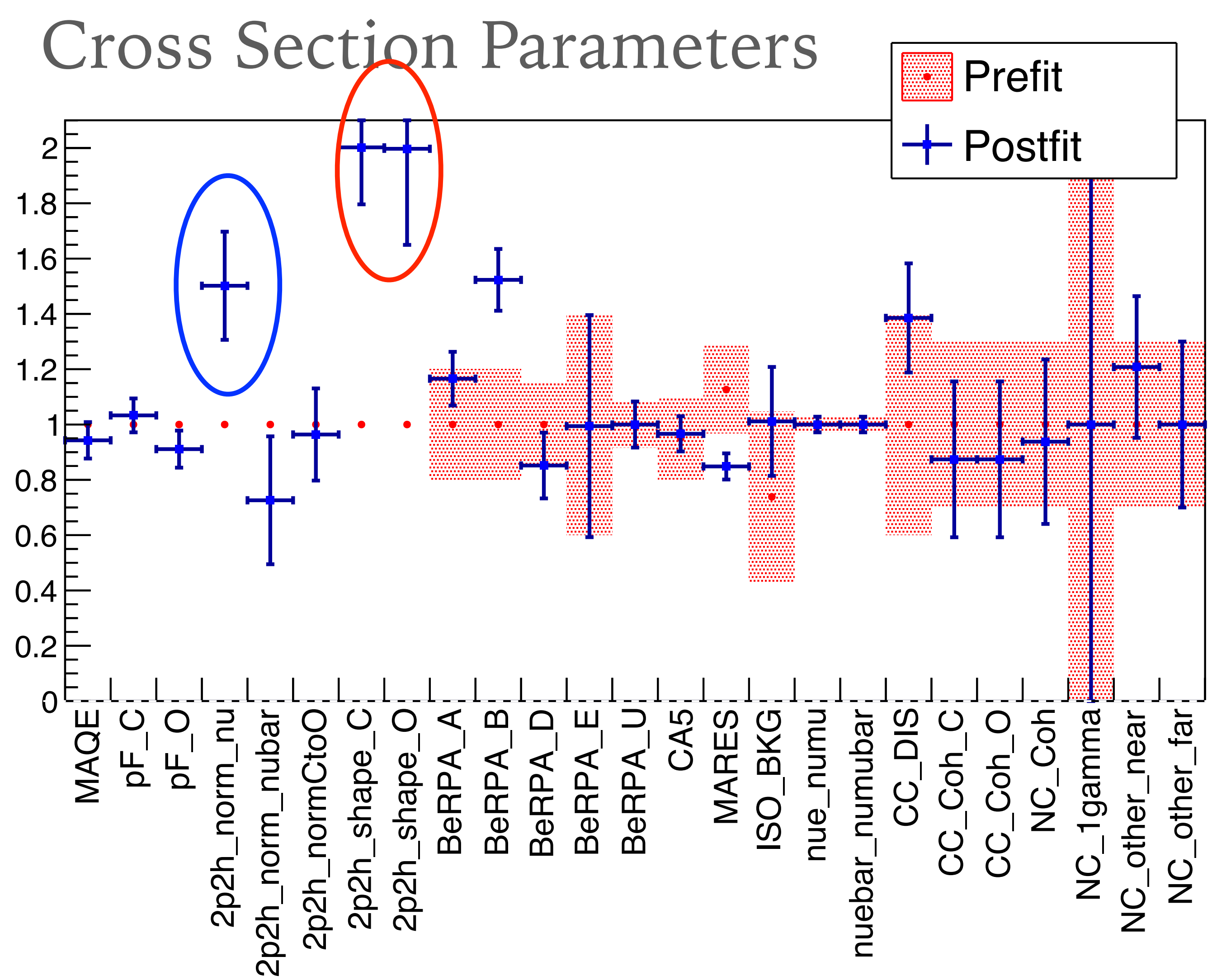

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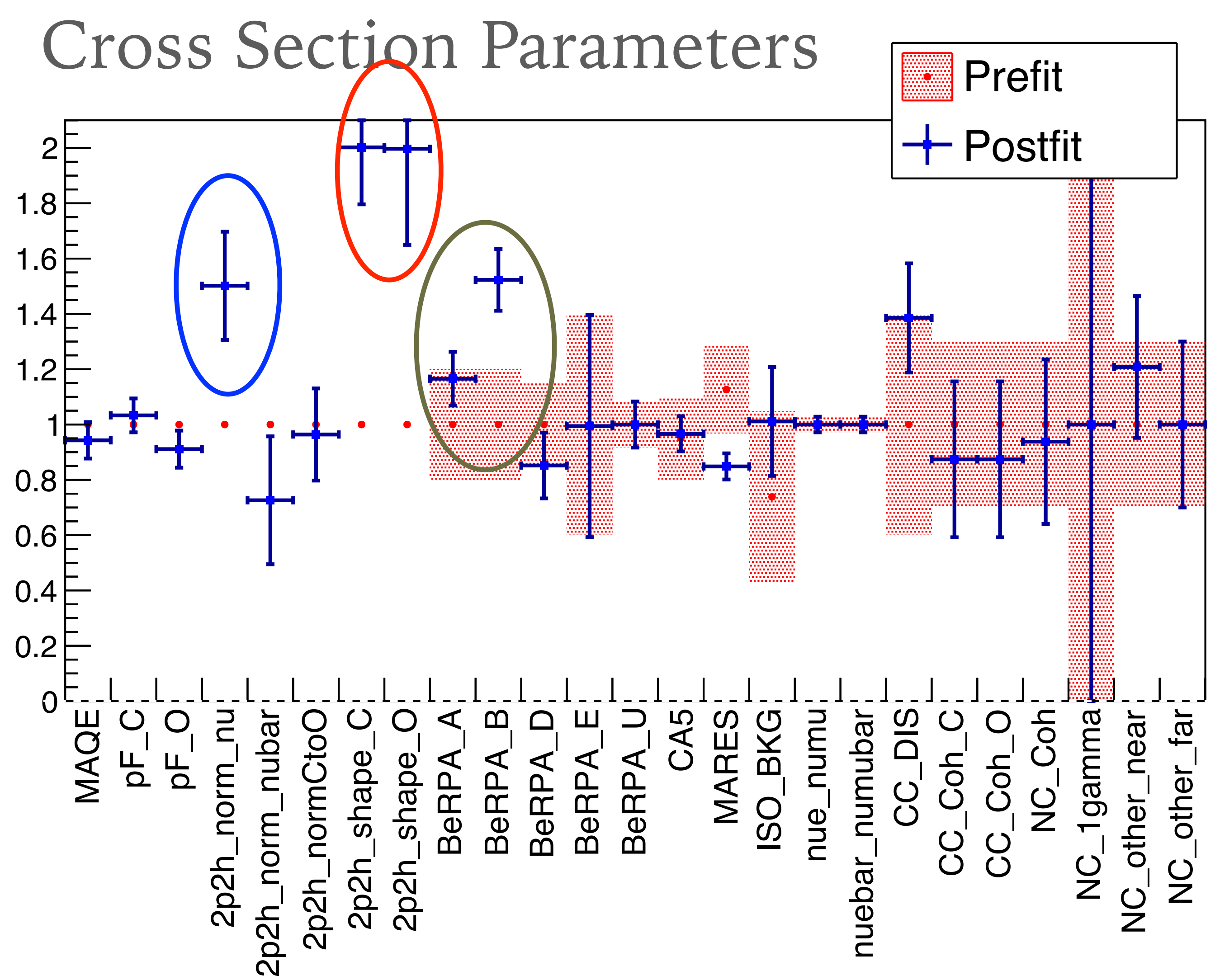

- The 2p-2h for neutrinos is enhanced by 50%
- The 2p-2h shape is shifted so that the Δ-enhanced component of the cross section is increased to maximum
- The RPA parameters for Q^2 below 1 GeV^2 are increased, enhancing the cross section in that region

MEASURING OSCILLATION PARAMETERS

- Compare observed rates at SK to predictions under oscillation hypotheses:

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

- Prediction depends on modeling: neutrino flux, neutrino interaction cross sections and detection efficiency
  - Systematic errors enter here
- To reduce errors on the flux and interaction models, use measurements in ND280

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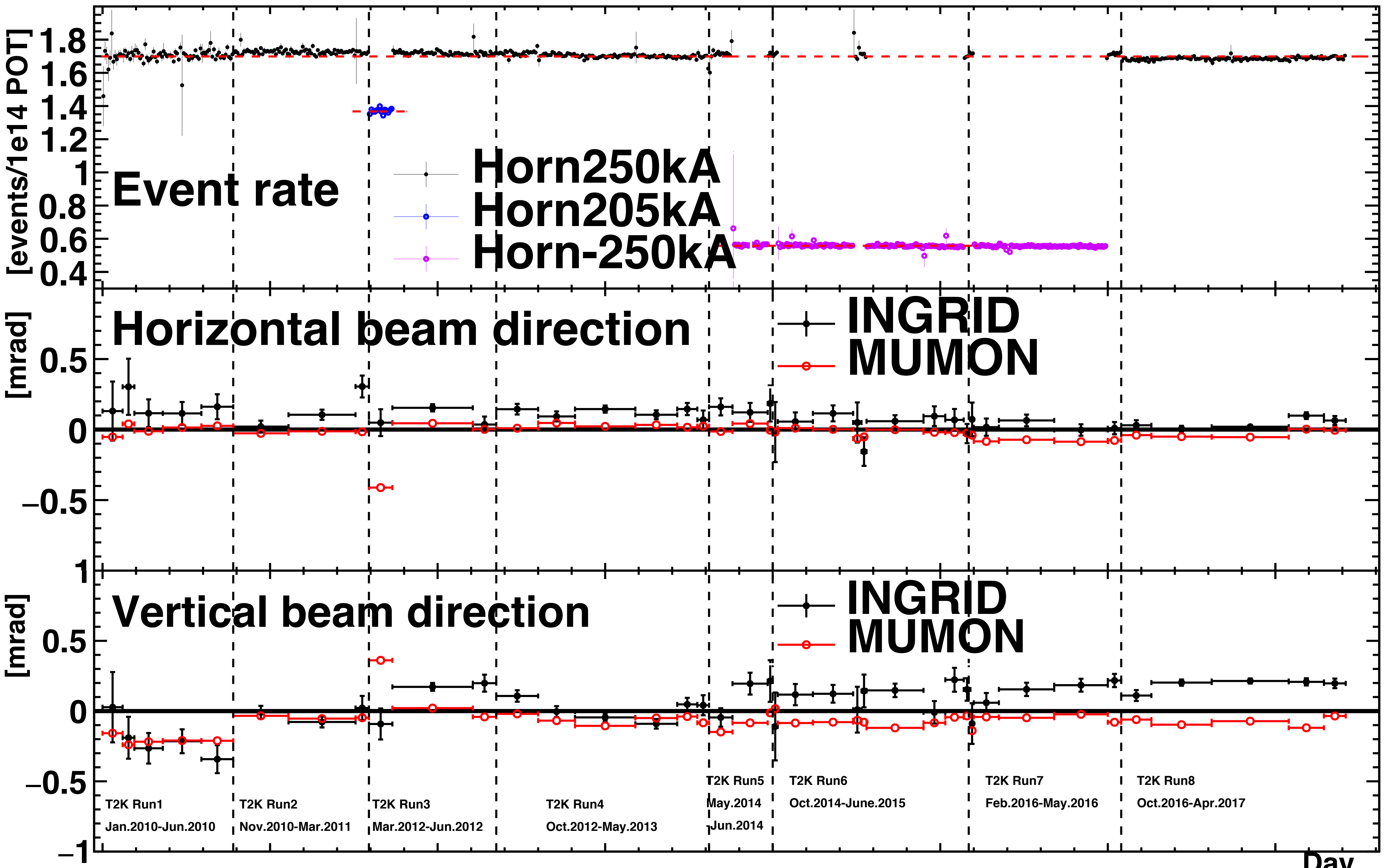
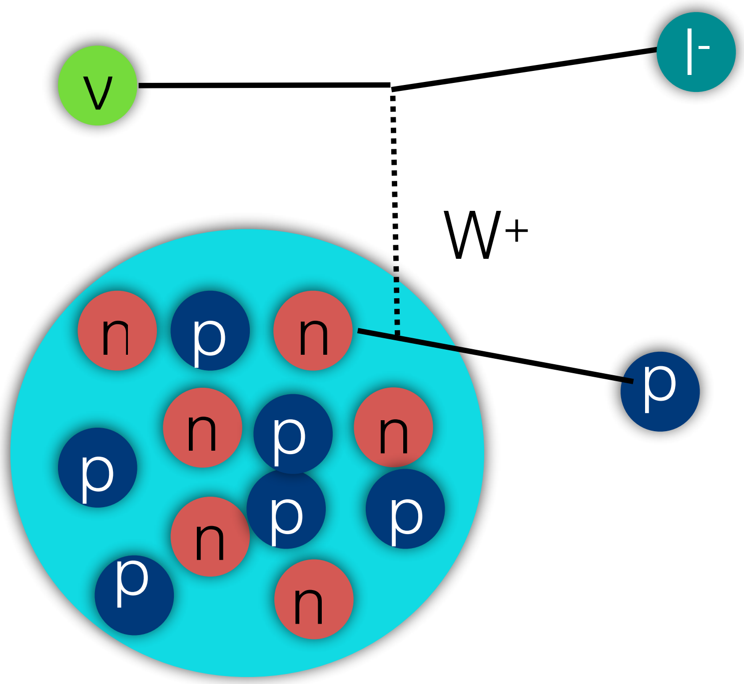
BEAM STABILITY IN T2K

- Stable neutrino event rate monitored by INGRID on-axis detector
- Stable beam direction monitored using neutrinos (INGRID) and muons from neutrino parent particle decays (MUMON)



DETECTING NEUTRINOS

- Detect neutrinos through the **charged-current interaction**
  - Energetic muon or electron in final state can be detected



Scattering on nucleons bound in nucleus

Recoil hadrons may be below detection threshold

Scattering on single bound nucleon called charged-current quasi-elastic **(CCQE)** scattering

- Signal mode: no detectable recoil hadrons in a water-Cherenkov detector
- Reconstruct energy assuming CCQE:

$$E_\nu^{\mathrm{rec}} = \frac{m_p^2 - (m_n - E_b)^2 - m_e^2 + 2(m_n - E_b)E_e}{2(m_n - E_b - E_e + p_e \cos\theta_e)}$$

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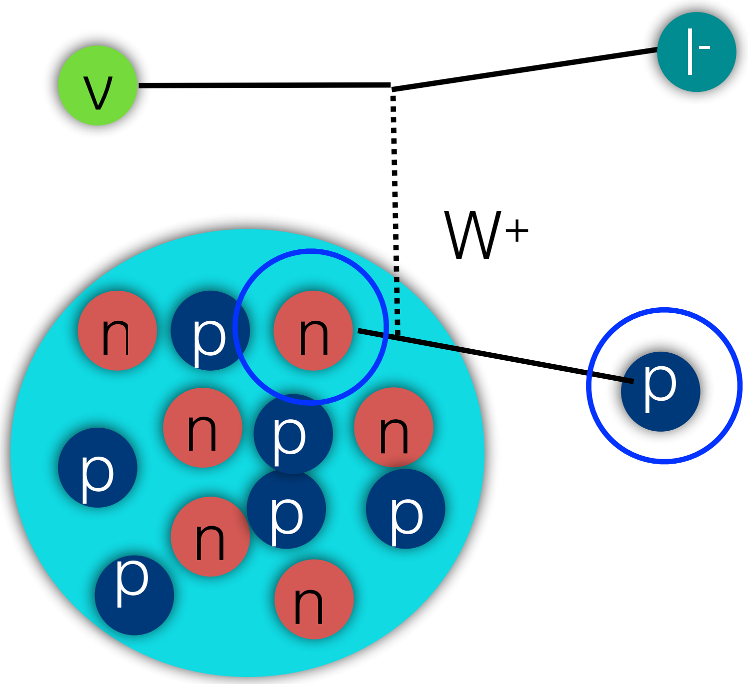

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Mass of target and recoil nucleons

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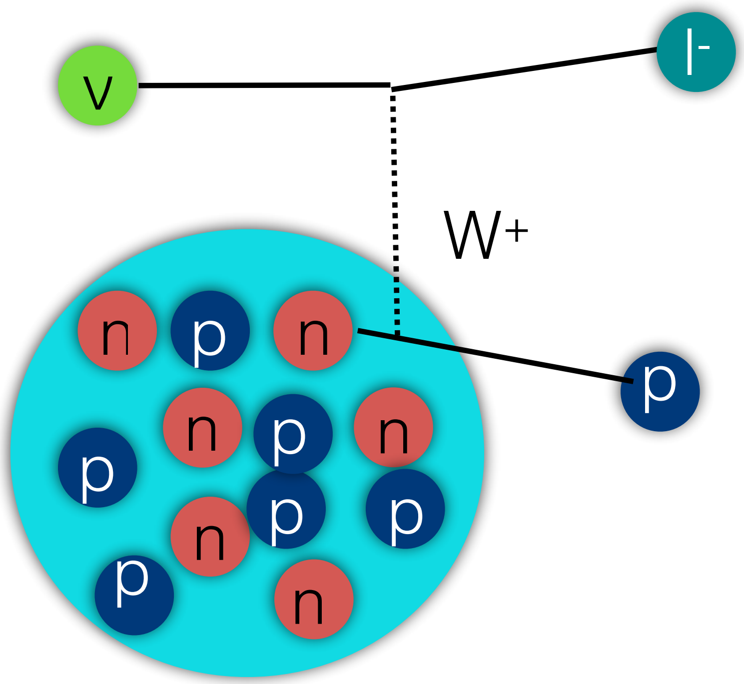

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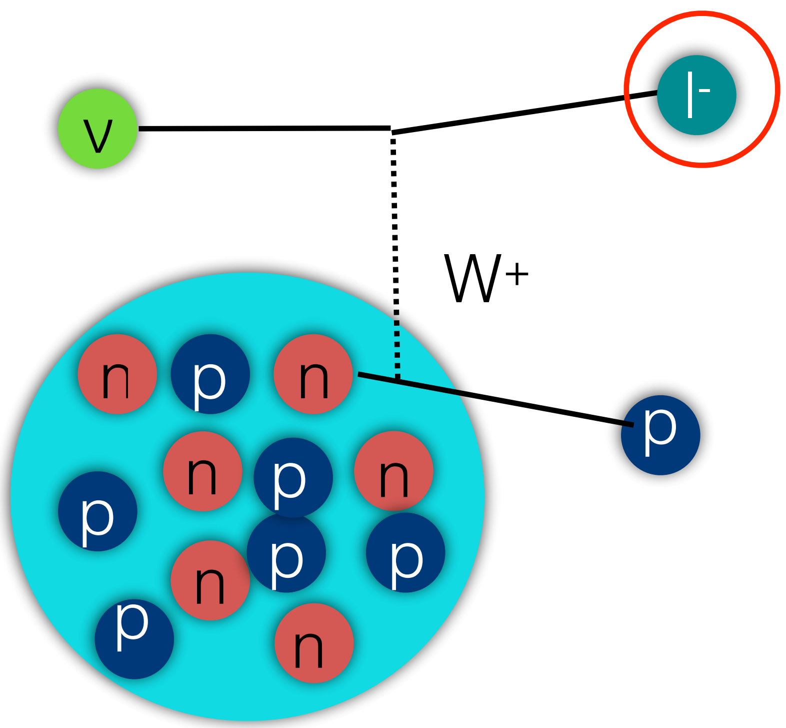

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Mass, energy, momentum, scattering angle of charged lepton

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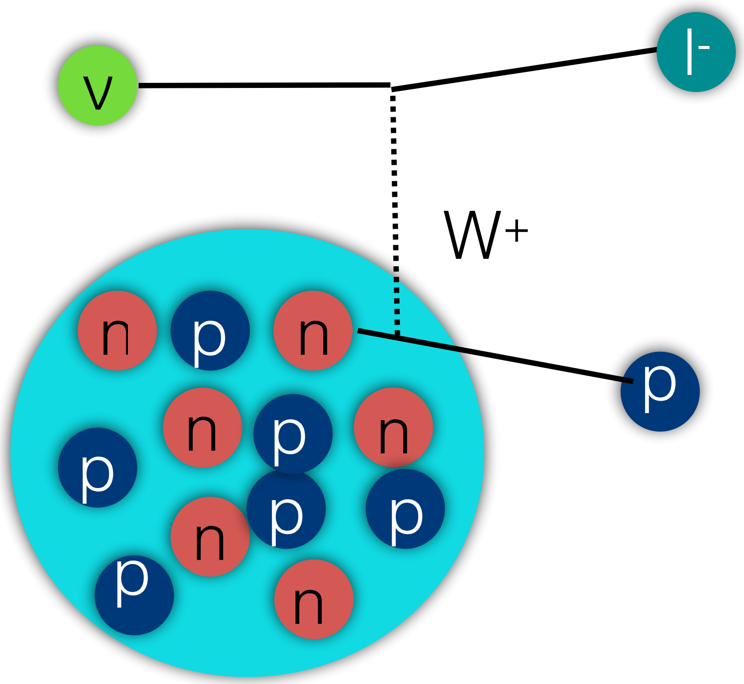

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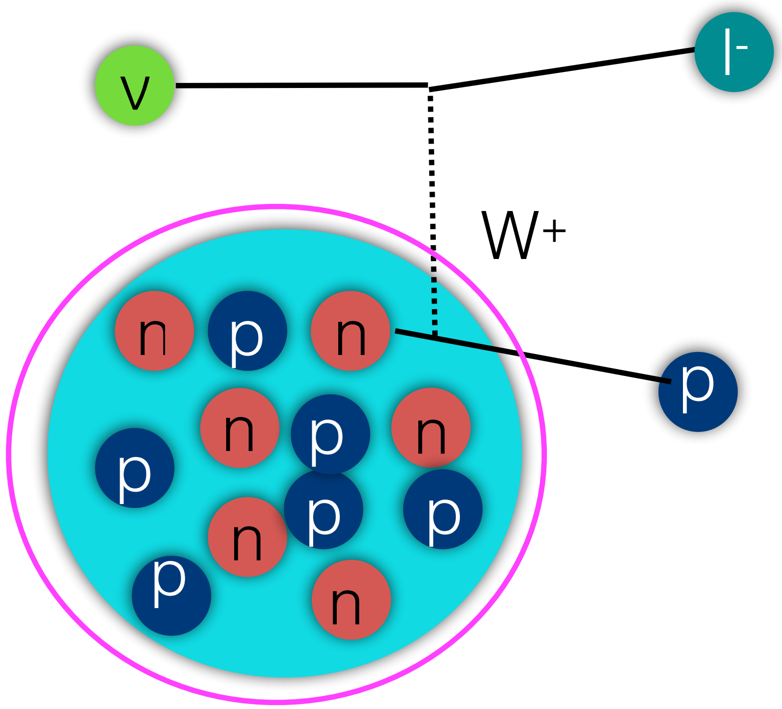

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Nuclear binding energy

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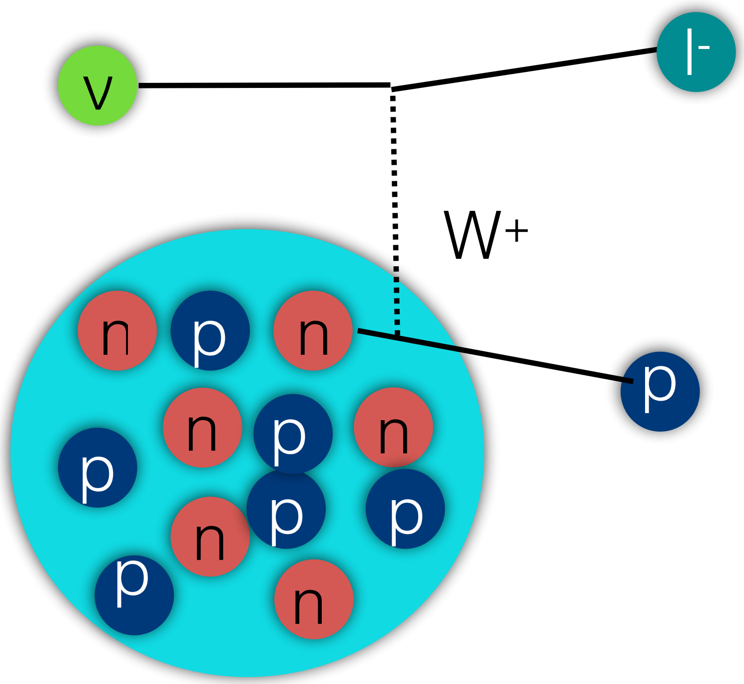

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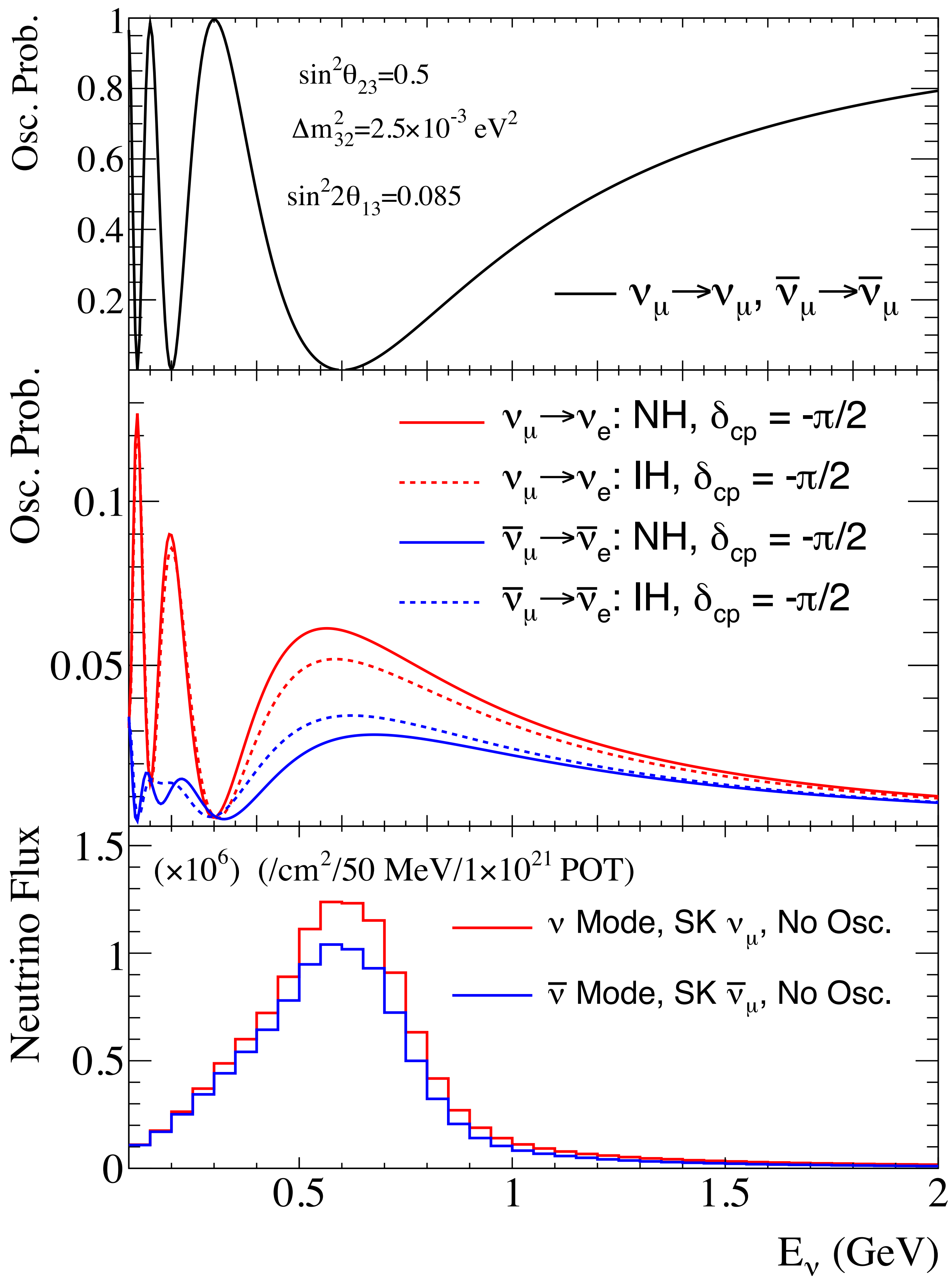
NEUTRINO OSCILLATION AT T2K



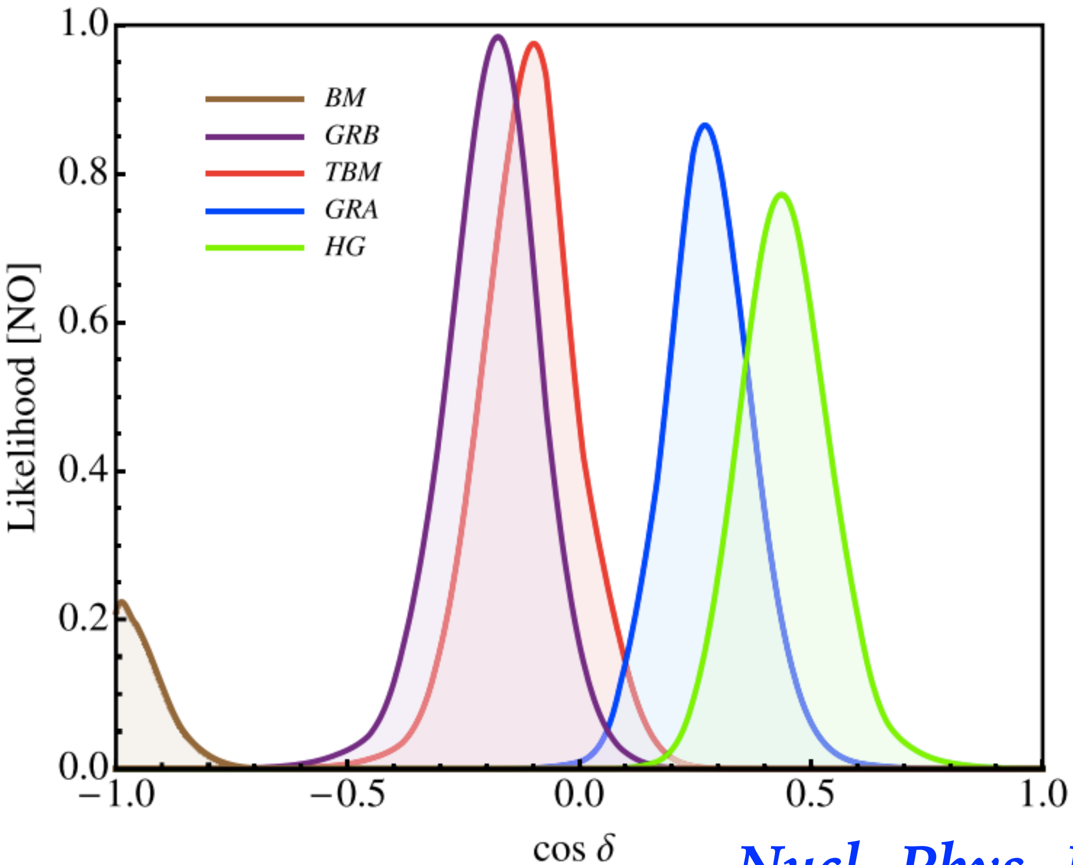
- **Muon (anti)neutrino survival** depends on $\sin^2(2\theta_{23})$ and Δm^2_{32}
- **Electron (anti)neutrino appearance**
  - $\sin^2(\theta_{23})$, $\sin^2(2\theta_{13})$ and Δm^2_{32} in leading term
  - Sub-leading dependence on δ_{cp}
    - CP conservation at $\delta_{cp}=0,\pi$
    - Maximal CP violation at $\delta_{cp}=-\pi/2,\pi/2$
  - Matter effect → dependence on the mass hierarchy
    - Normal Hierarchy (NH): enhanced rate for neutrinos, decreased for antineutrinos

WHY MEASURE THESE PARAMETERS?

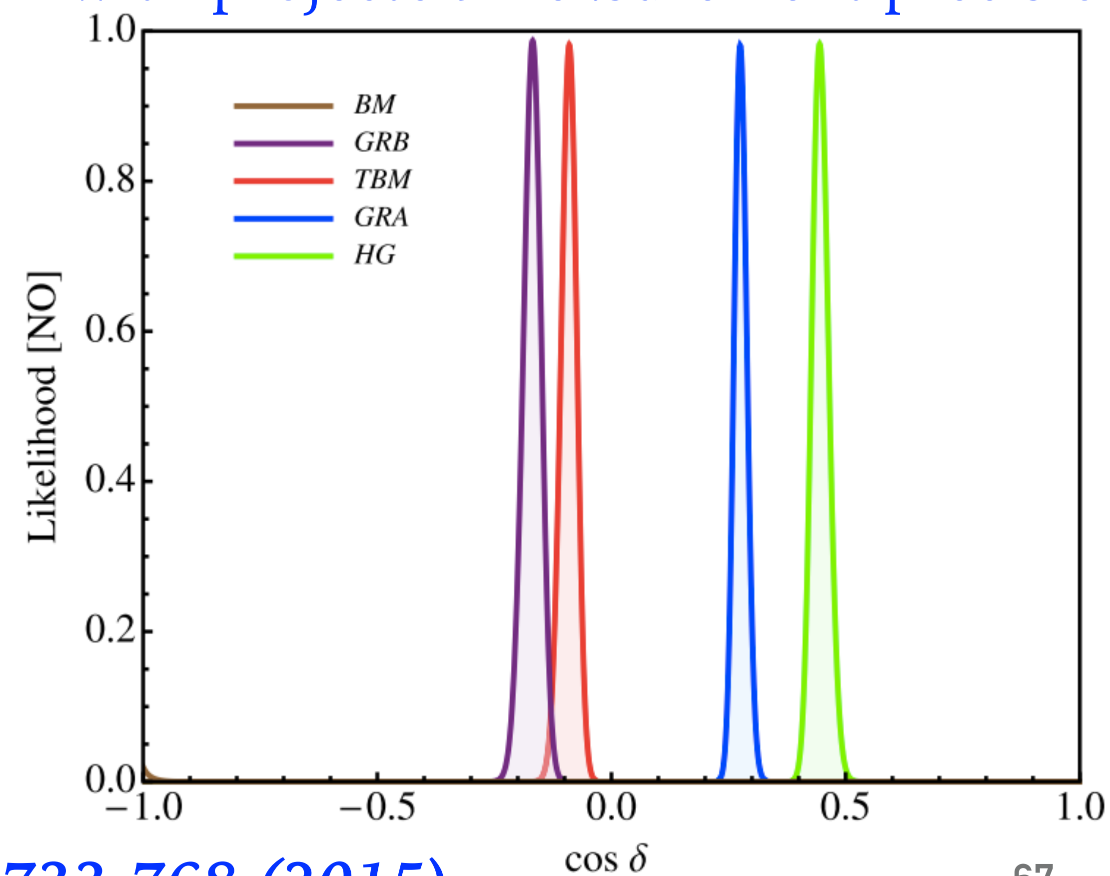
- Lepton mixing allows for a **new source of CP violation** that can be studied with neutrinos
  - CPV through δ_{cp} may be sufficient source for **leptogenesis** **(Nucl. Phys. B774 (2007) 1)**
- Neutrino masses indicate new physics beyond the standard model and electroweak scale
  - **Precise values** of the mixing parameters may indicate or disfavor models of **flavor symmetries**

Predictions from cosδ sum rules for discrete symmetries:

Predictions from flavor symmetry forms with current measurement precision



Predictions of flavor symmetry forms with projected measurement precision



Nucl. Phys. B, Vol. 894, 733-768 (2015)

A BRIEF HISTORY OF NEUTRINO EXPERIMENTS

- **1930** - Proposal by Wolfgang Pauli that beta decay spectrum could be explained by light neutral spin 1/2 particle

- **1956** - Cowan and Reines directly detect the electron (anti)neutrino

- **1962** - Brookhaven AGS neutrino experiment discovers muon neutrinos with accelerator-based neutrino source

- **1960s-1980s** - Ray Davis's Homestake Experiment observes a deficit of neutrinos from the sun

- **1980s-1990s** - Nucleon decay experiments such as Kamiokande and IMB observe deficits of neutrinos from cosmic rays

- **1987** - Observation of neutrinos from 1987a supernova at Kamiokande and others

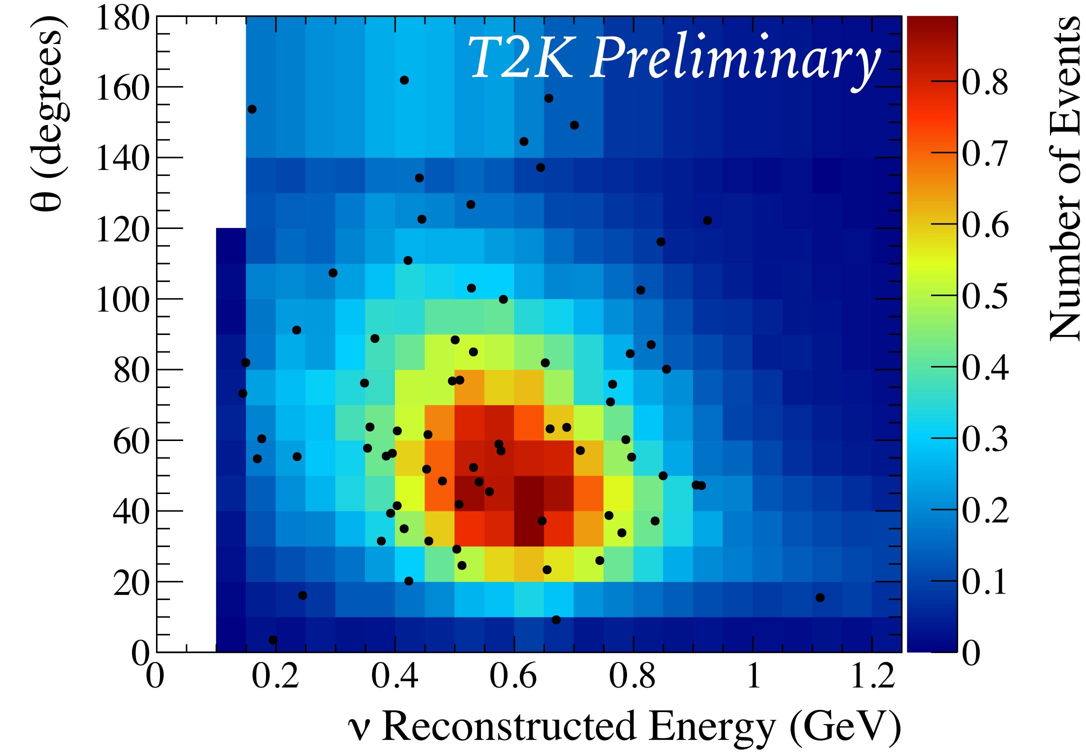
- **1998** - Super-Kamiokande presents strong evidence that atmospheric neutrino deficit is due to oscillations

- **2001** - SNO and Super-K show that solar neutrino deficit is due to oscillations, confirmed by KamLAND

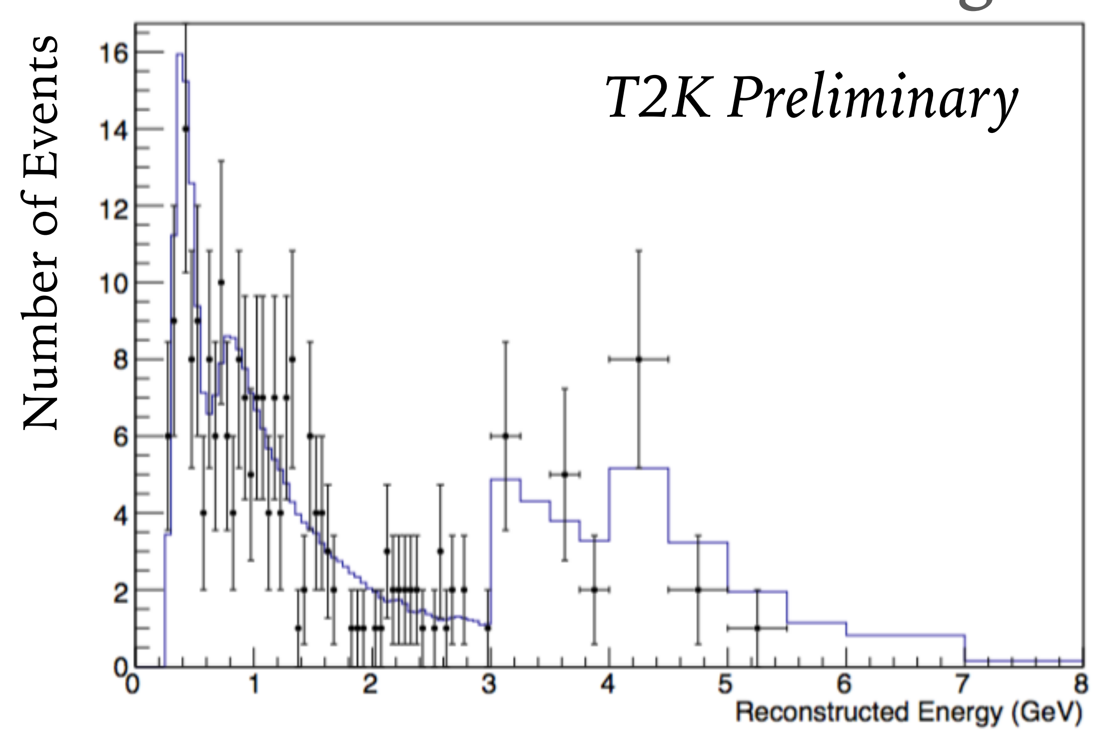
BINNING OF THE DATA

- The electron-like data are binned in 2 dimensions
  - θ = angle of the electron candidate relative to beam direction
  - E_{rec} = reconstructed energy assuming QE kinematics or p = momentum of the electron candidate
    - Sensitivity is the same whether we use E_{rec} or p
- The muon-like data are binned in E_{rec} only

Neutrino Mode 1 Electron-like Ring



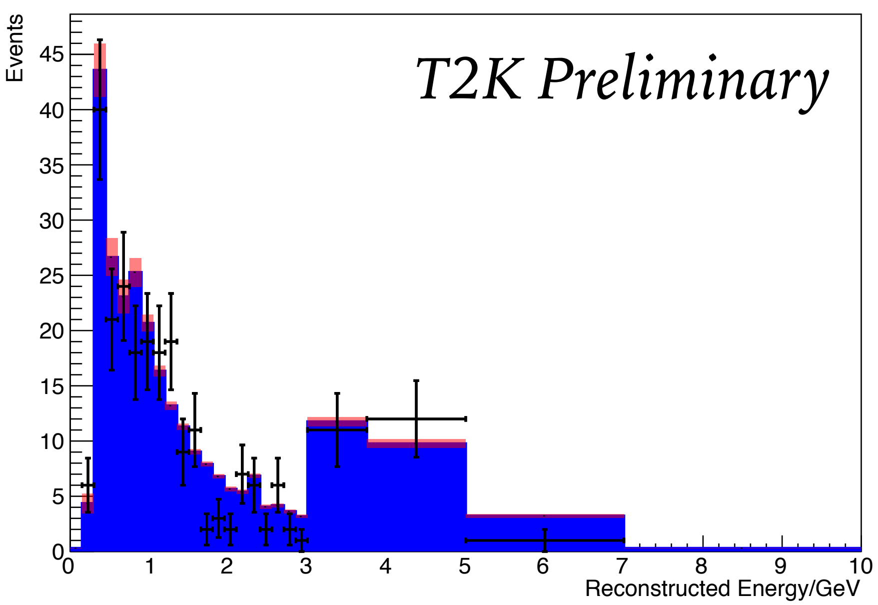
Neutrino Mode 1 Muon-like Ring



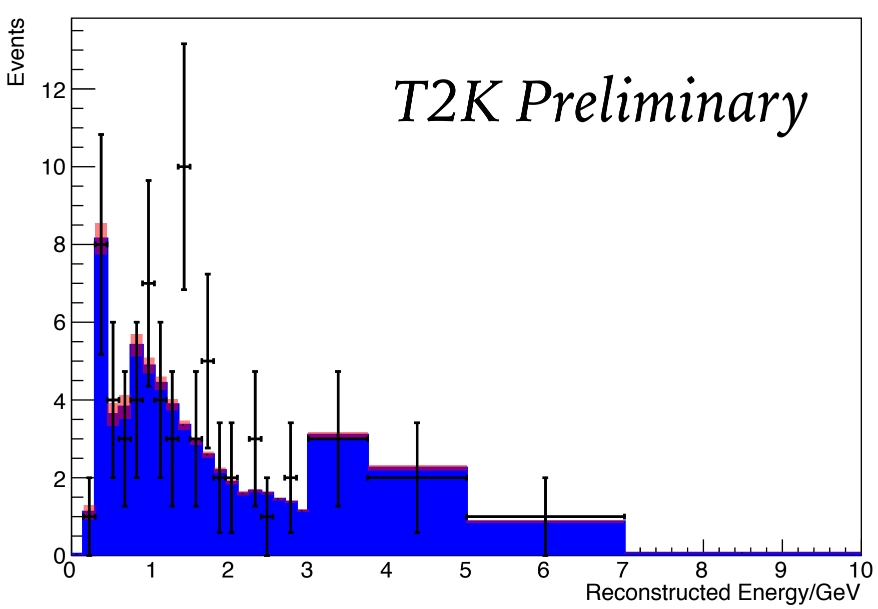
FITTED DATA DISTRIBUTIONS

CCQE 1μ Ring

Neutrino mode

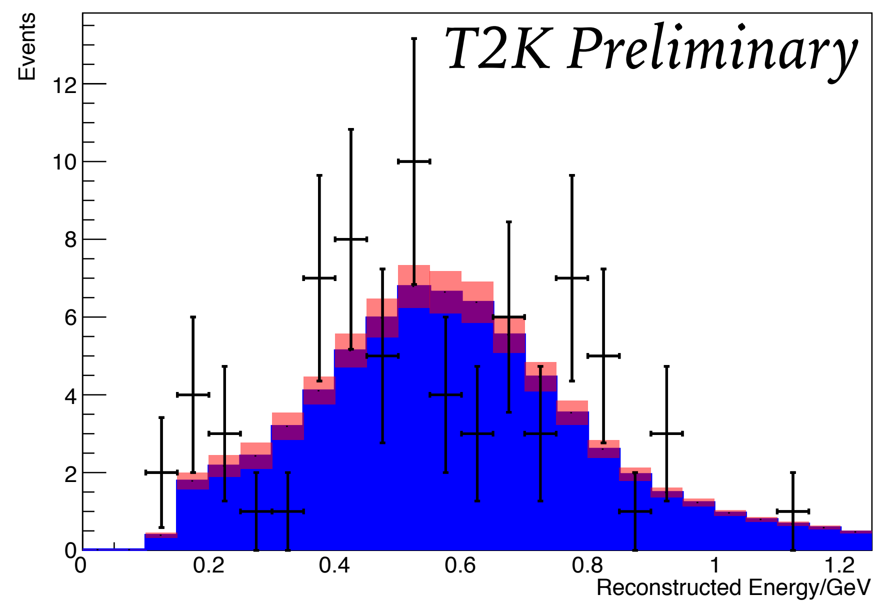


Antineutrino mode

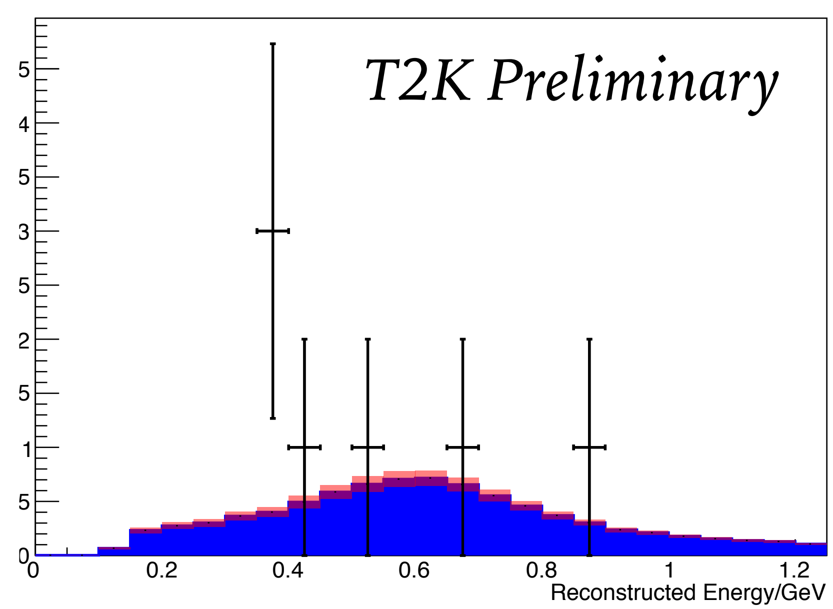


CCQE 1e Ring

Neutrino mode

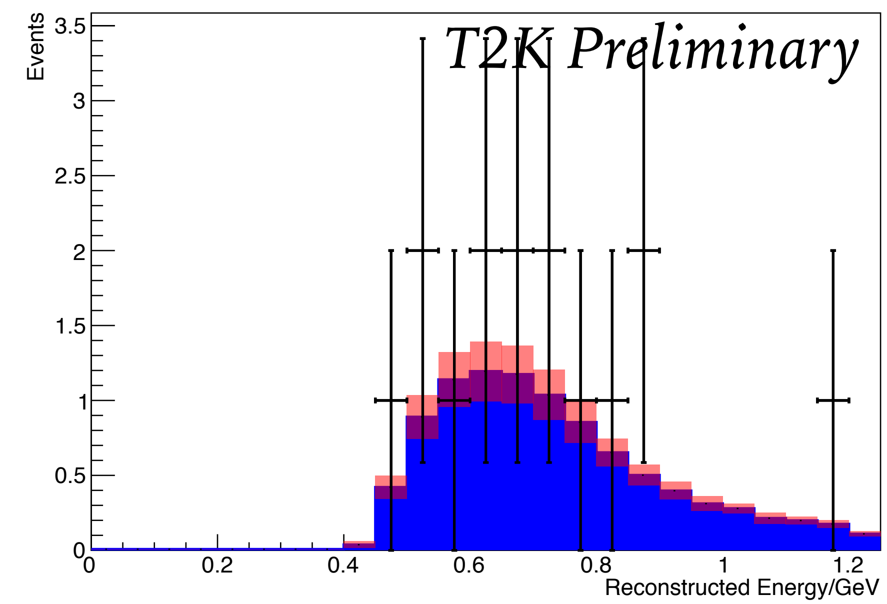


Antineutrino mode



CC1π 1e Ring

Neutrino mode

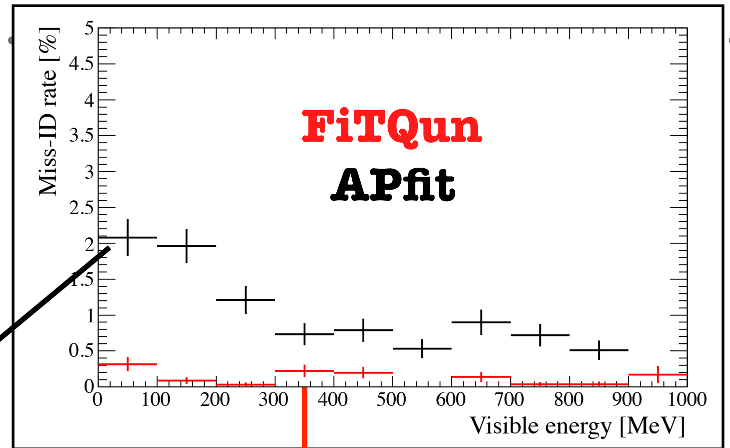


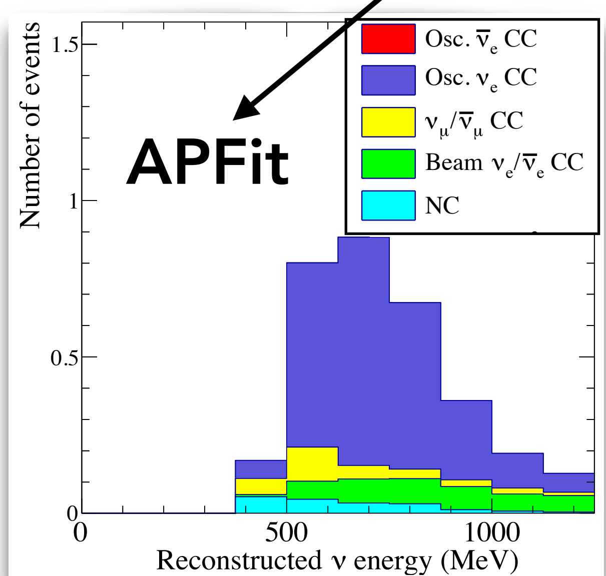
p-value = 0.42

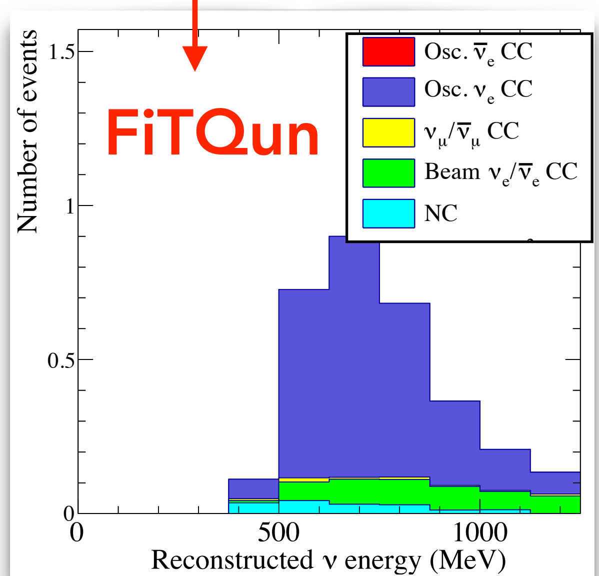
calculated using posterior predictive method

ADVANTAGES OF FITQUN

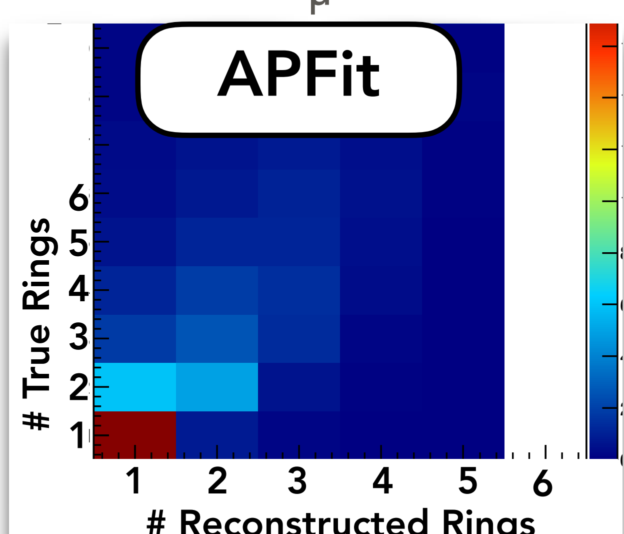
Improved particle ID reduces μ^- contamination of 1-ring CCπ^+ sample

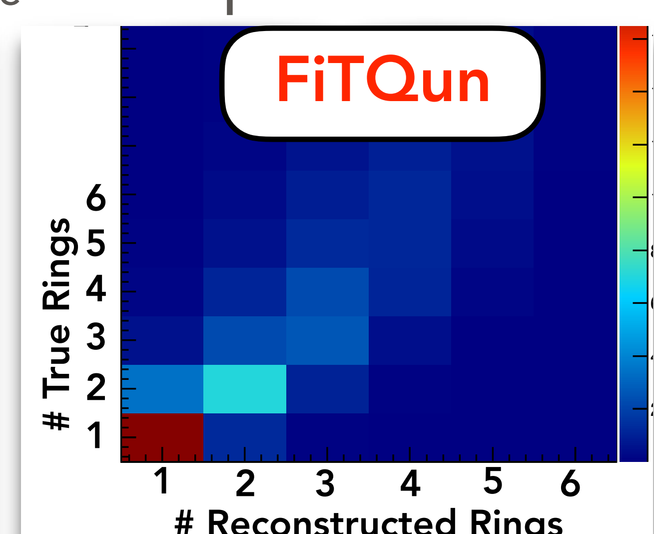




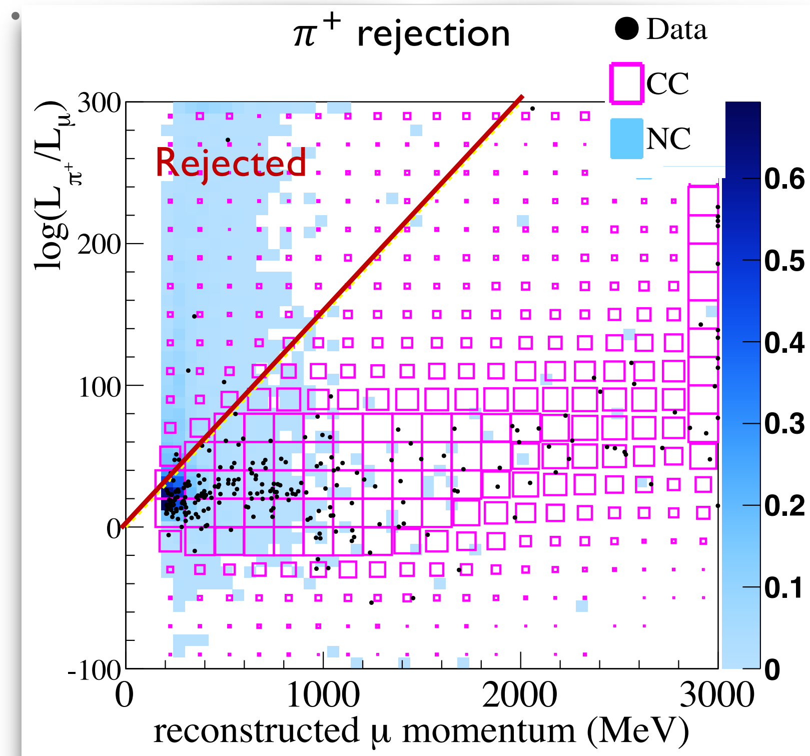


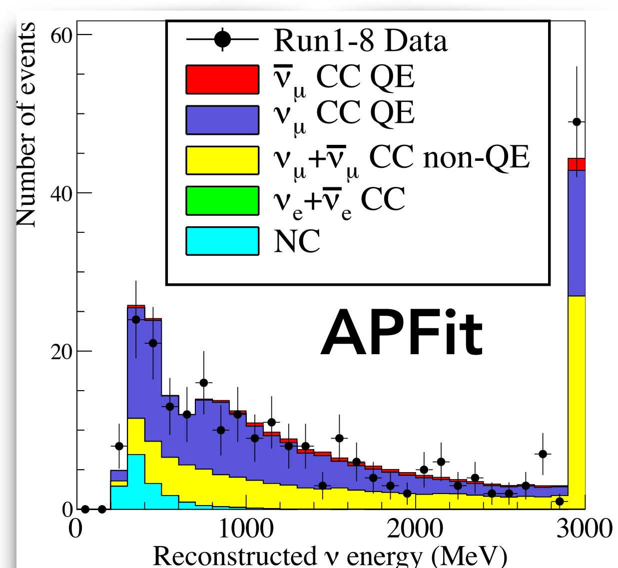
Improved ring counting increases ν_μ-CC0π & ν_e-CC1π purities

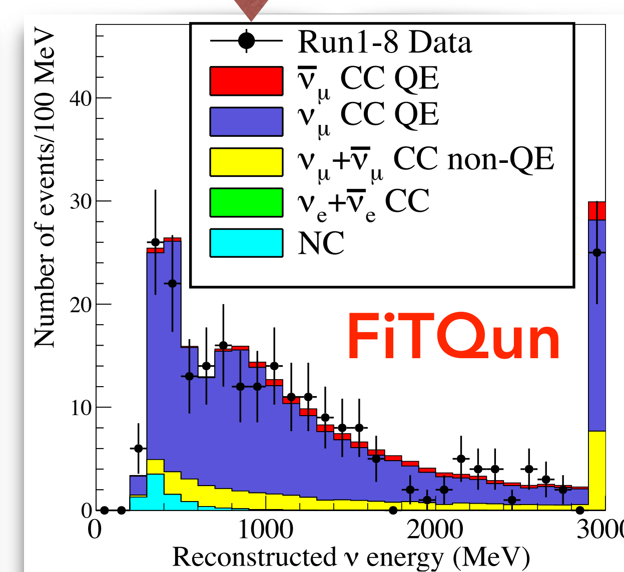




Unlike APFit, FiTQun can distinguish muons from charged pions:







Note: FiTQun π^0 rejection has been applied to "APFit" results since 2013

OSCILLATION MODES IN T2K

- *Start with a beam of 99% muon (anti)neutrinos*
- *How many of the muon (anti)neutrinos survive:*

$$P_{\mu\rightarrow\mu} = 1 - \left(\sin^2 2\theta_{23} - \sin^2\theta_{23}\cos 2\theta_{23}\sin^2 2\theta_{13}\right)\sin^2\left(\frac{\Delta m^2_{32} L}{4E_\nu}\right) + \ldots$$

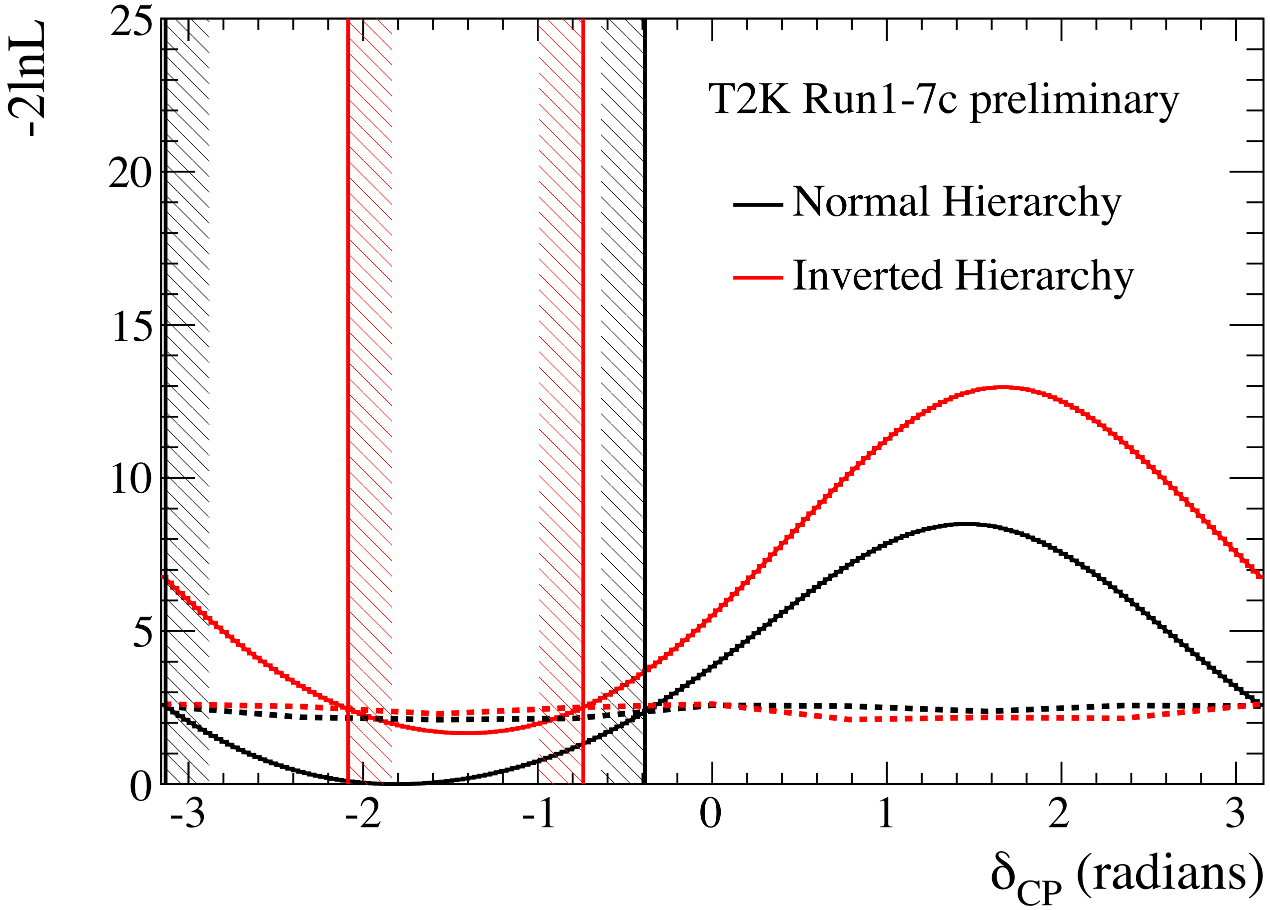
- *How many of the muon (anti)neutrinos oscillate to electron (anti)neutrinos:*

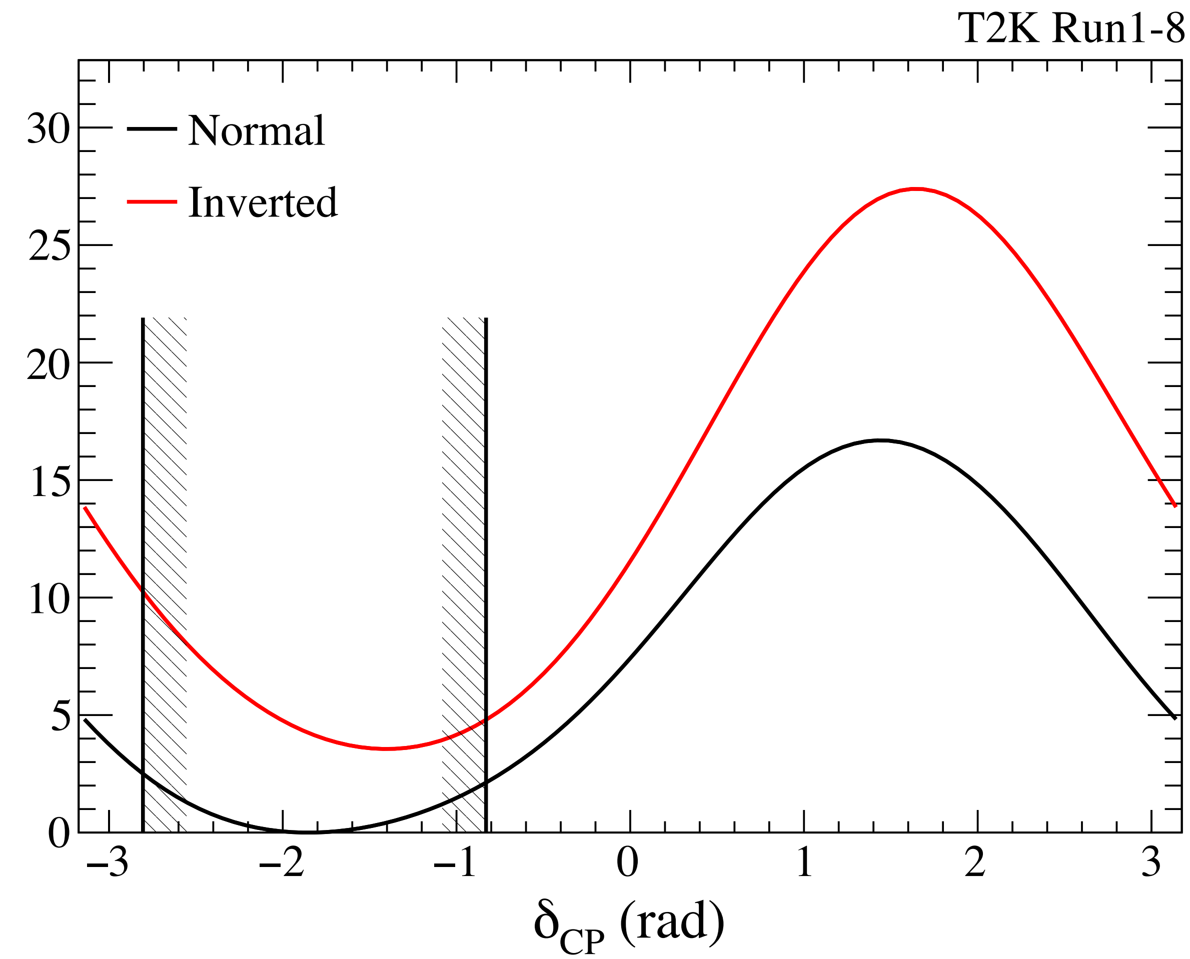
$$P_{\mu\rightarrow e} = \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{31} L}{4E_\nu}\right) \mp \frac{\sin 2\theta_{12}\sin 2\theta_{23}}{2\sin\theta_{13}}\sin^2 2\theta_{13}\sin\left(\frac{\Delta m^2_{21} L}{4E_\nu}\right)\sin^2\left(\frac{\Delta m^2_{31} L}{4E_\nu}\right)\sin\delta_{CP} + \ldots$$

sign flips for antineutrinos

- *The appearance of the electron (anti)neutrinos*
  - *Dependence on $\sin^2\theta_{23}$ can allow for determination if θ_{23} is $>45^o$ or $<45^o$*
  - *Matter effects give some sensitivity to the mass hierarchy*
  - *Sign flip in sub-leading term gives different probability for neutrinos and antineutrinos - CP violation!*

2016 VS. 2017 RESULTS





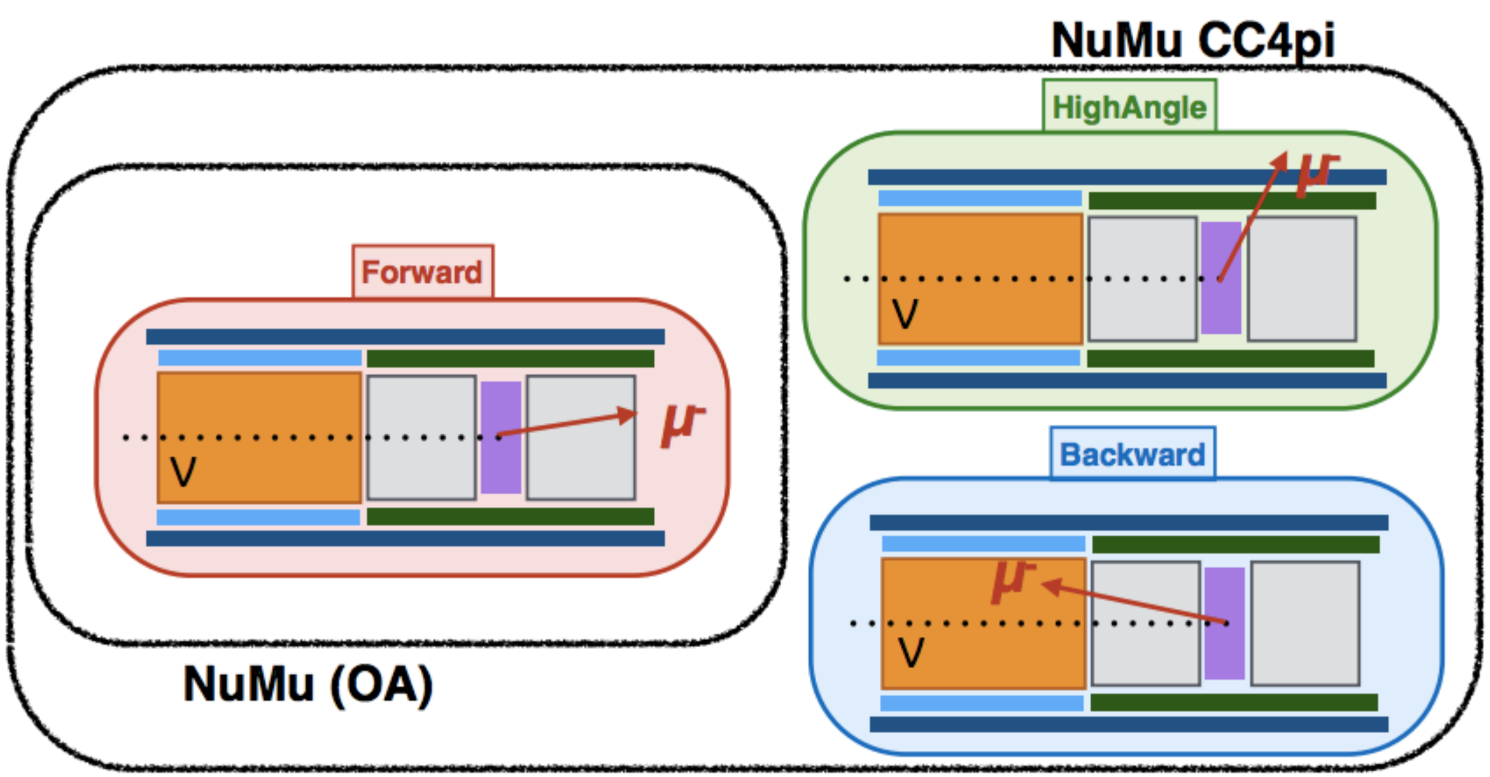
90% confidence intervals:

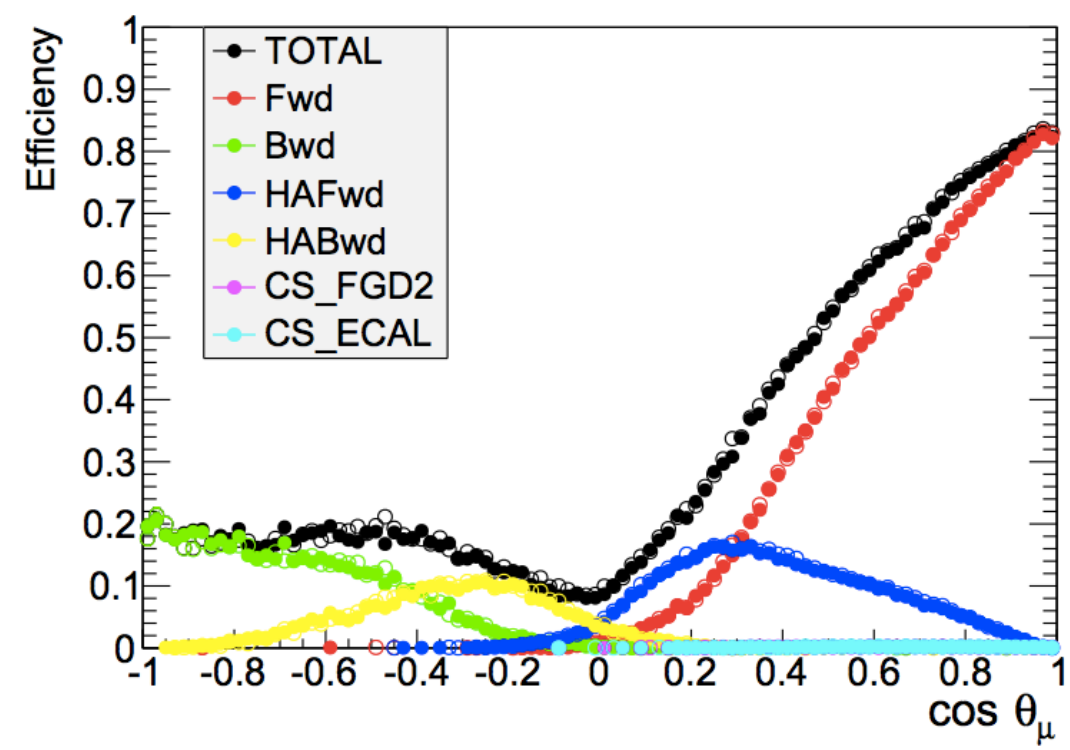
Run 1-7c: Normal hierarchy: [-3.13, -0.39] radians
Inverted hierarchy: [-2.09, -0.74] radians

Run 1-8: Normal hierarchy: [-2.80, -0.83] radians

ND280 HIGH ANGLE/BACKWARD RECONSTRUCTION

- *New ND280 samples with high-angle and backward tracks have been developed*
- *Have 10-20% efficiency in the high-angle and backward regions*
- *Will be included in future fits to ND280 data*

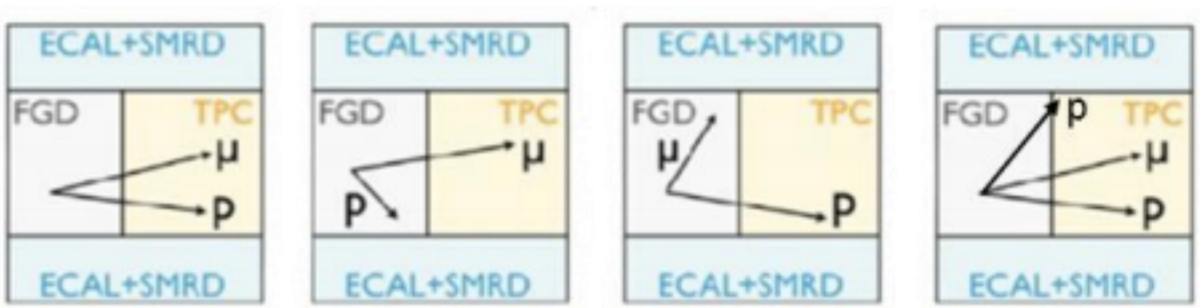




PROTON RECONSTRUCTION IN ND280

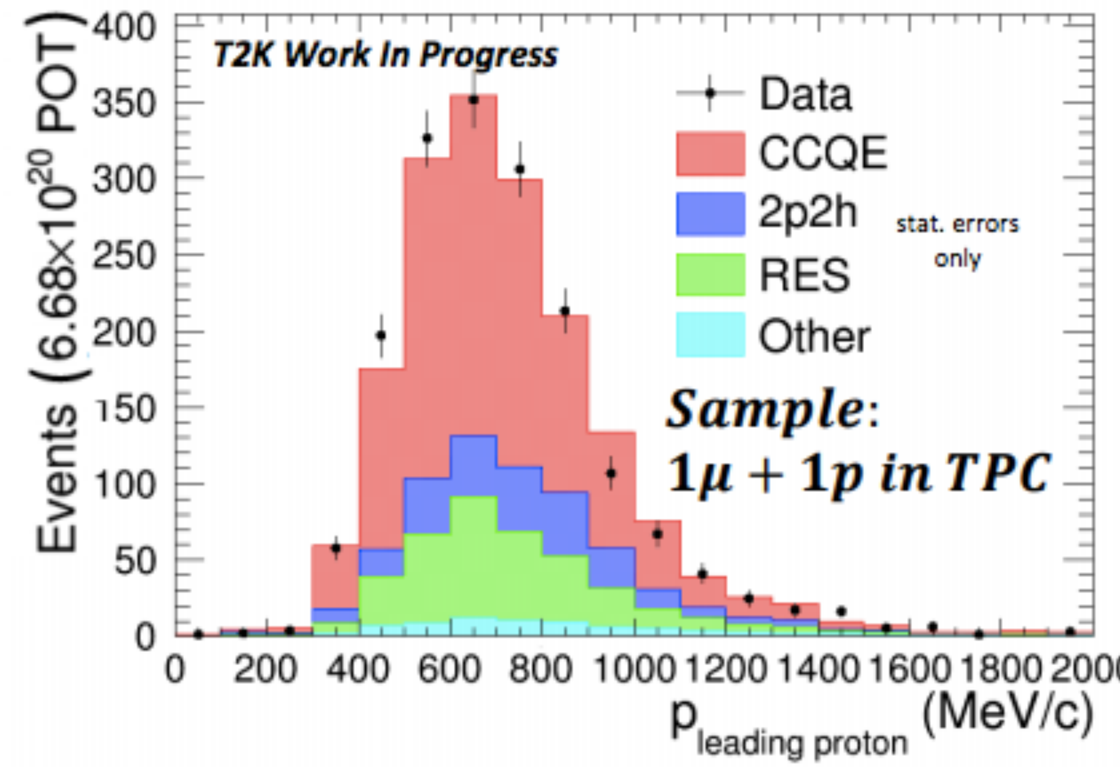
Now developing event selections that include final states with reconstructed protons

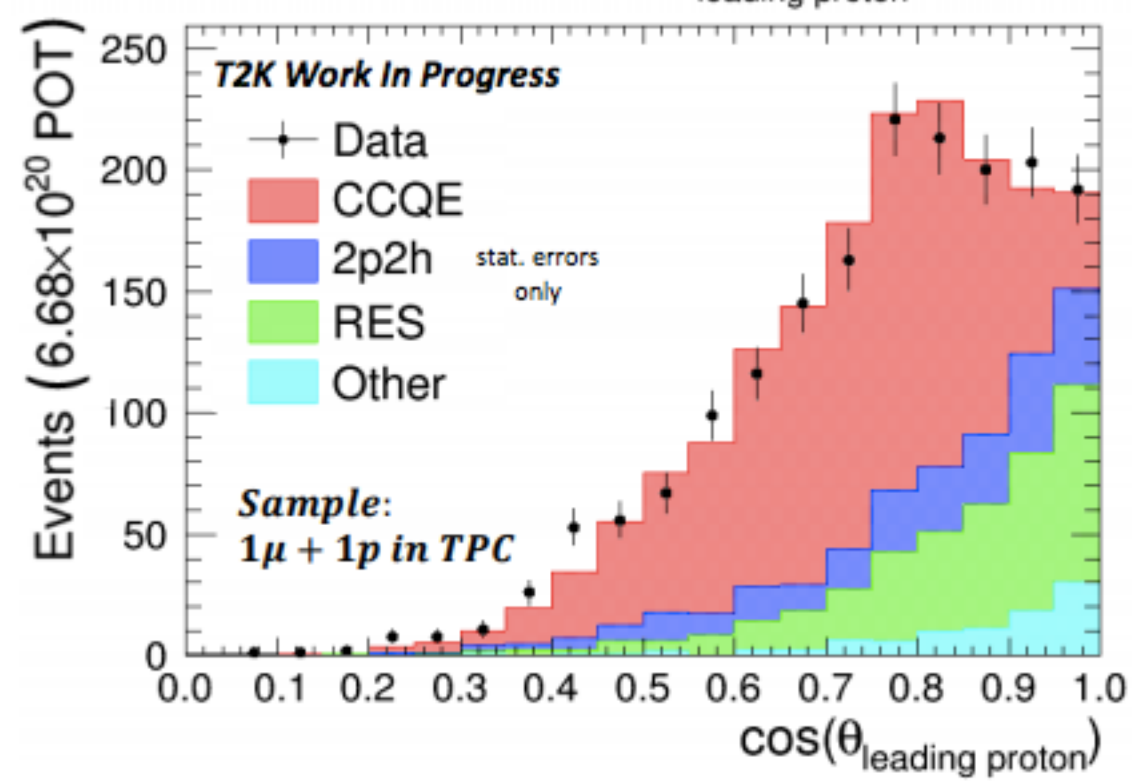
Signal



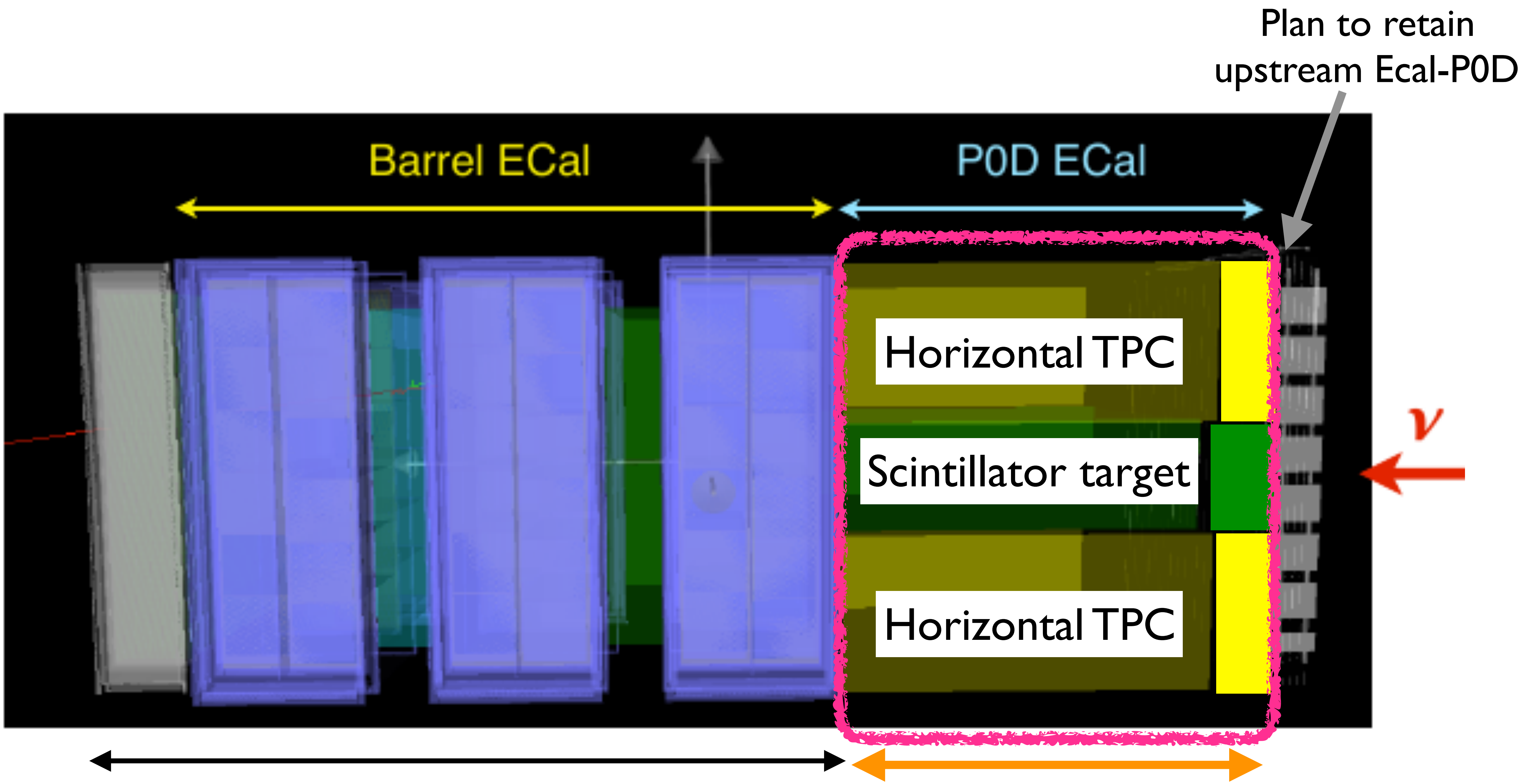
- Require one μ-like and p-like track(s) starting in FGD1 (CH target)
- Use a Michel electron tag and ECal EM shower veto to reject 1π backgrounds
- Use of many samples gives wide kinematic acceptance

Reconstructed kinematics





ND280 UPGRADE



Keep current tracker + DS Ecal

New detectors

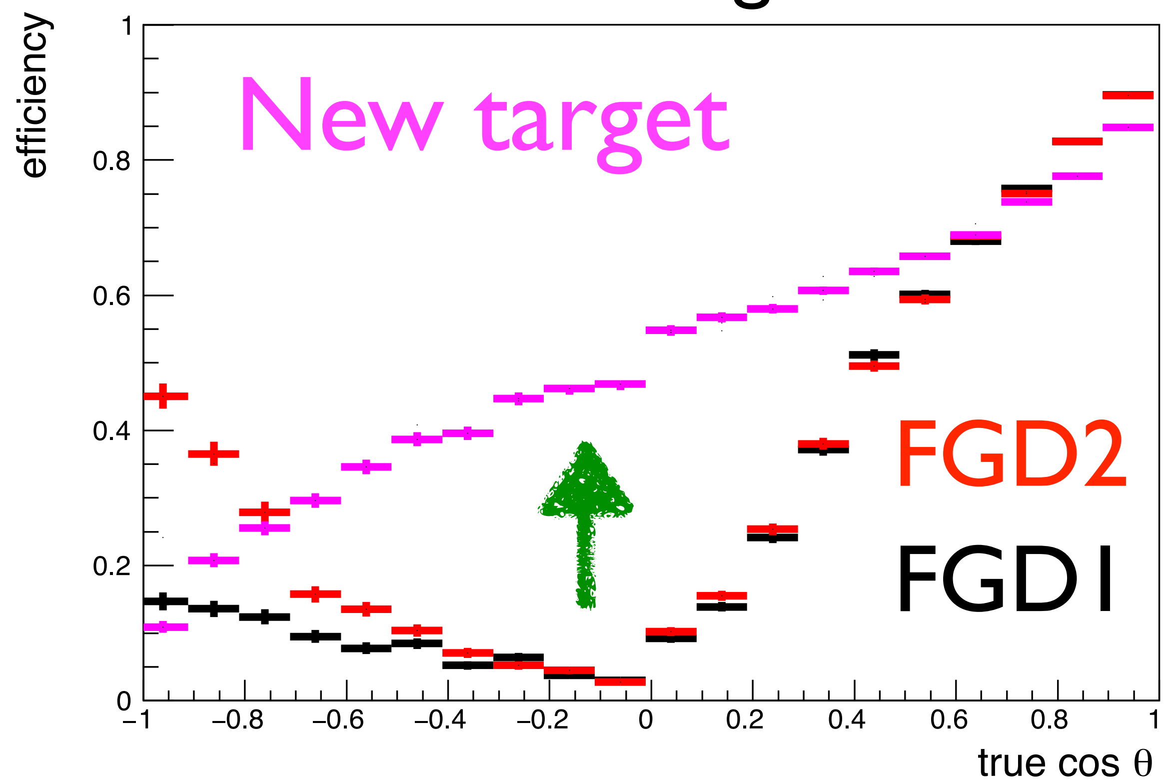
Magnet and surrounding Ecal also preserved

Two TPCs
Scintillator target
TOF detectors

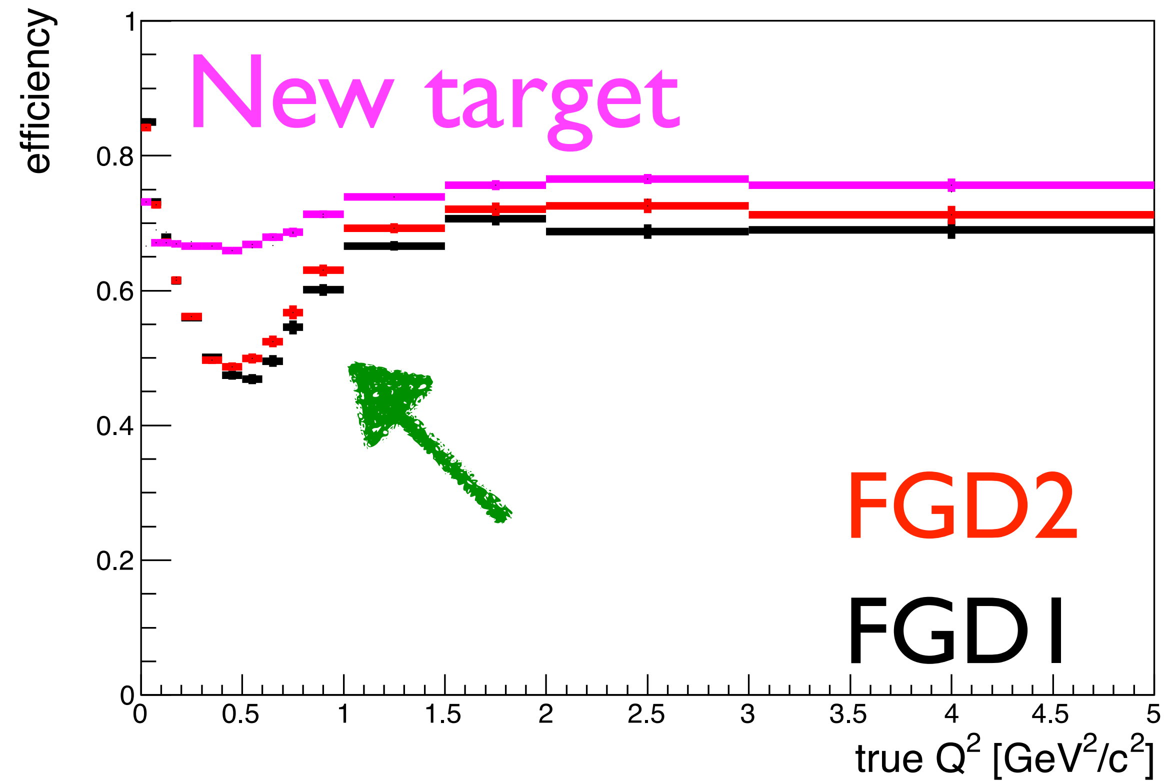
Efficiency estimated with GEANT simulation

Example: ν_μ CC inclusive selection

Muon angle



Q^2

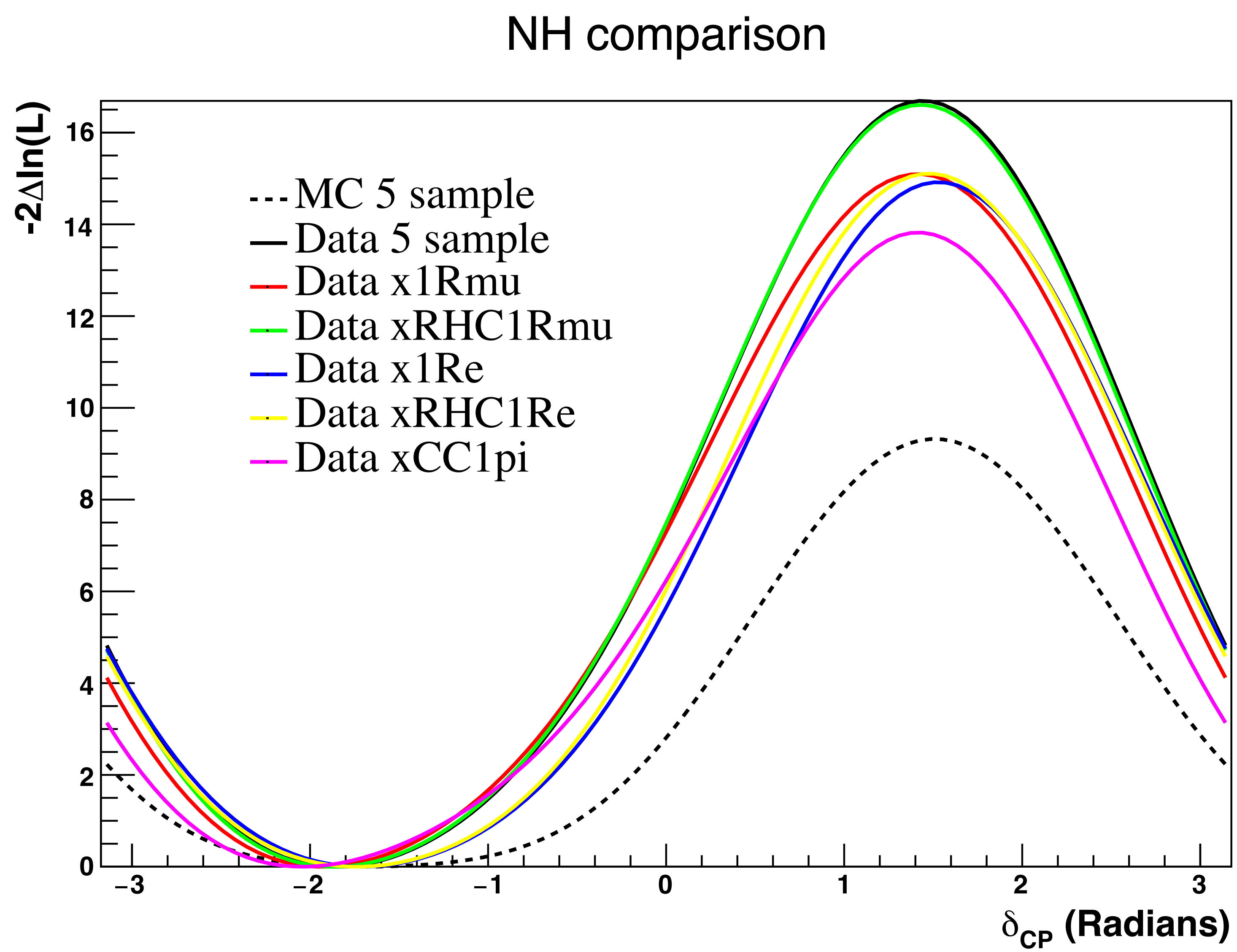


Large angle efficiency is improved as expected.

(preliminary: optimization still ongoing)

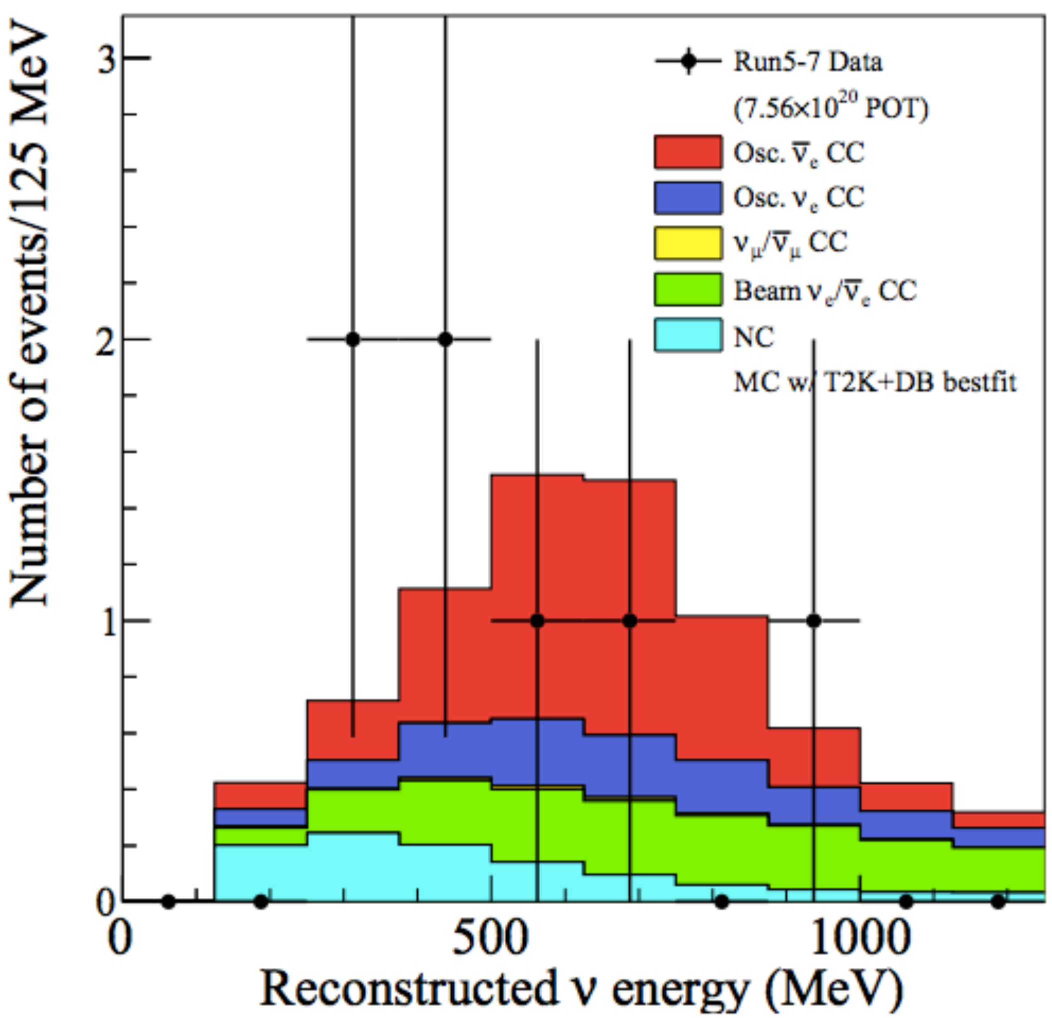
SAMPLES CONSTRAINTING THE CP PHASE

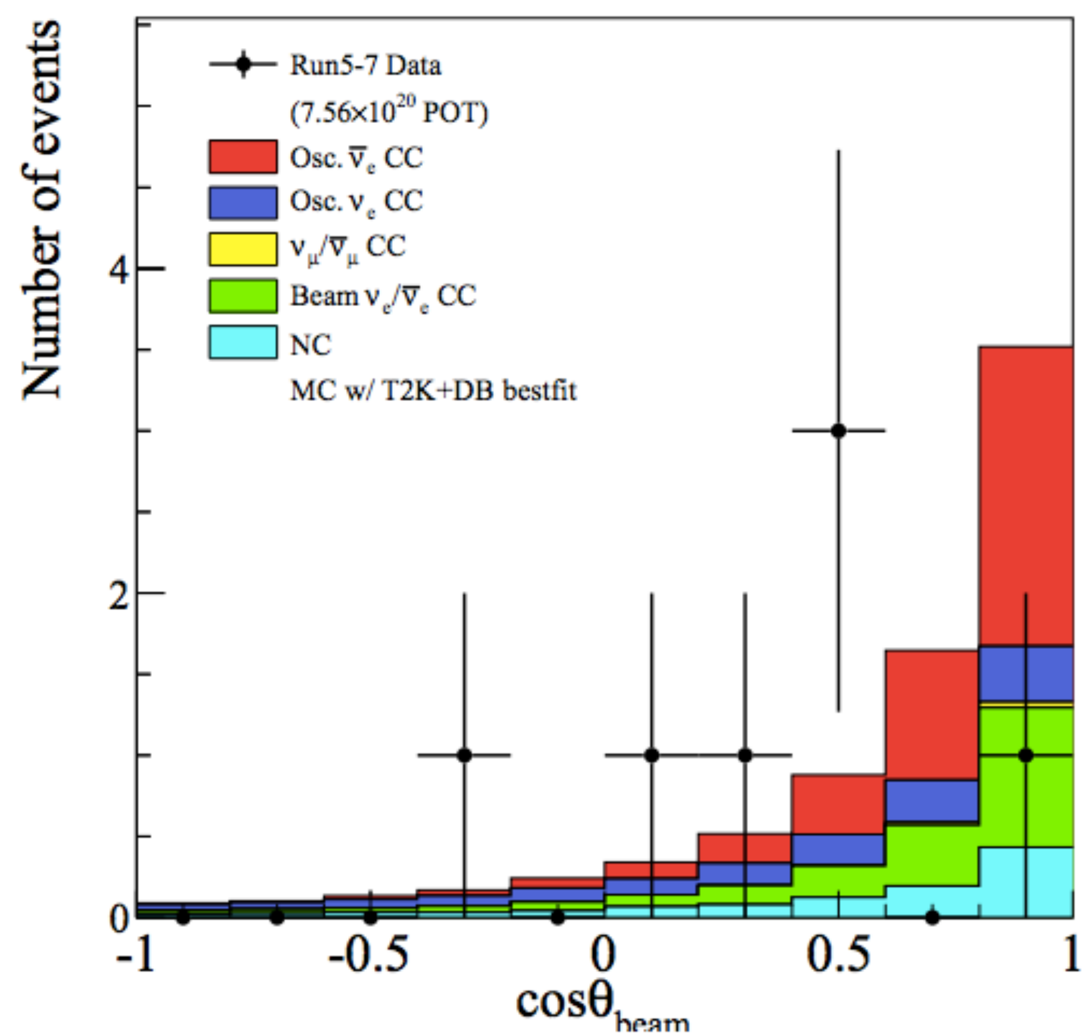
- Data constraint is stronger than average sensitivity - what is driving it?
- Take data samples out 1 at a time and replace with nominal Monte Carlo prediction
- Check how constraint changes



- Largest effect is the CC1π 1-Ring e-like sample
- Contributions from other samples except for CCQE 1-Ring μ-like in antineutrino-mode

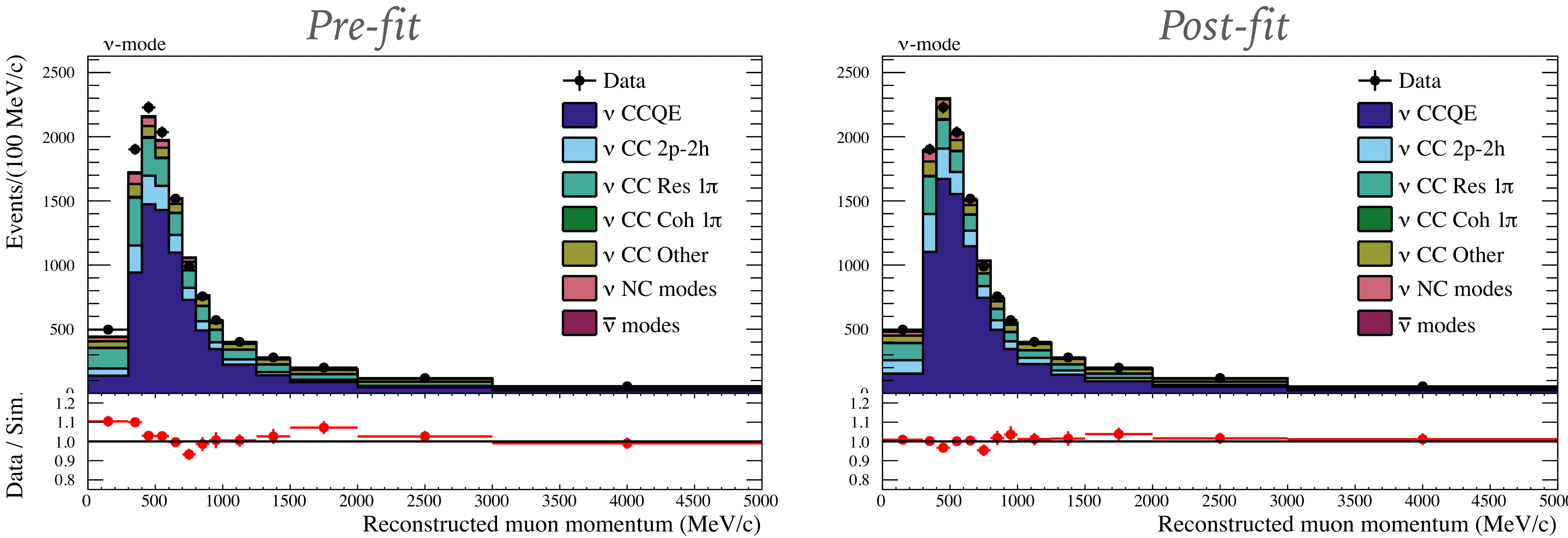
ANTINEUTRINO MODE 1R E-LIKE ANGULAR DIST.





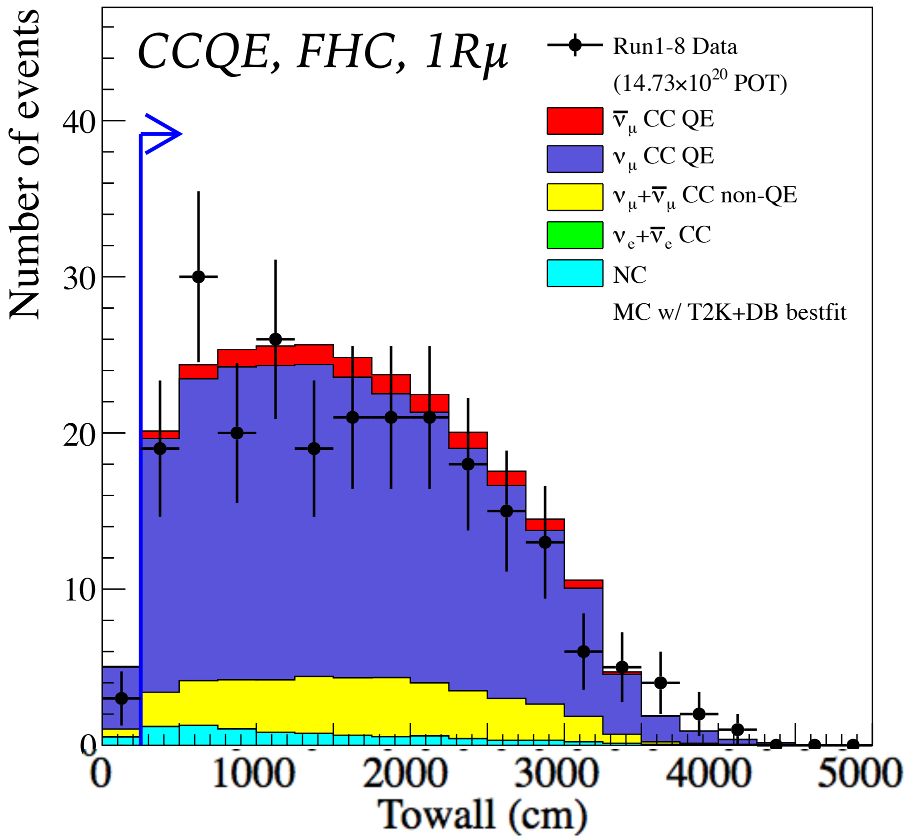
- Observed events are distributed at lower energy and higher angle where the the signal prediction is relatively small
- Stronger preference against δ_{cp}=0 which predicts a harder spectrum

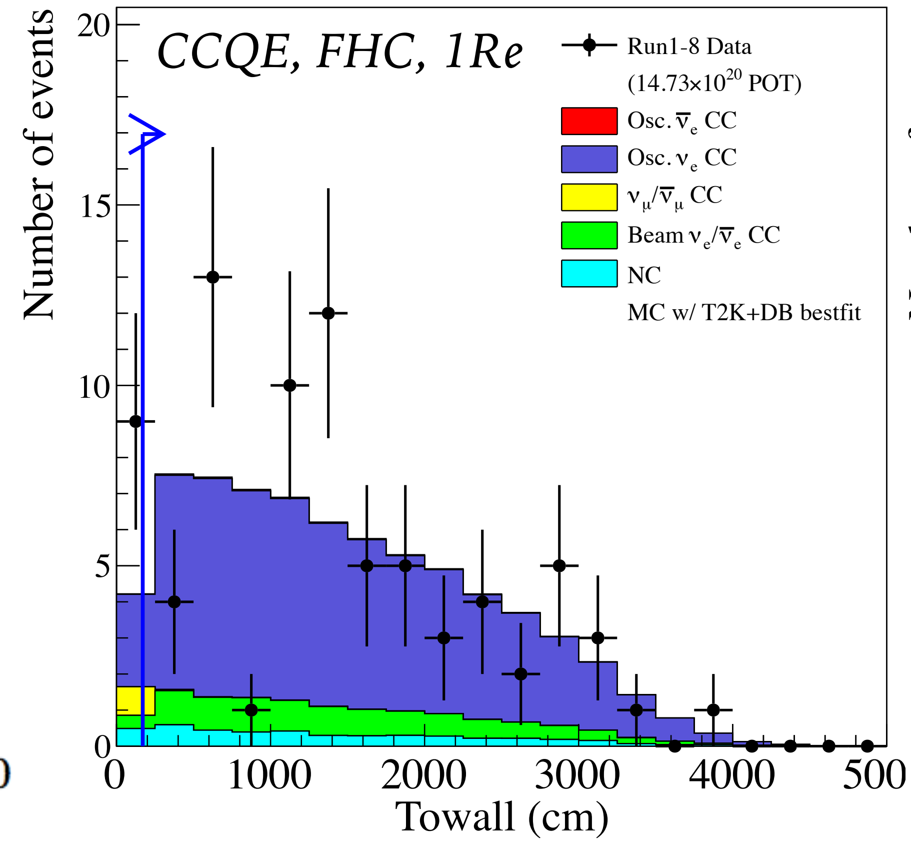
ND280 PRE AND POST-FIT (NEUTRINO MODE)

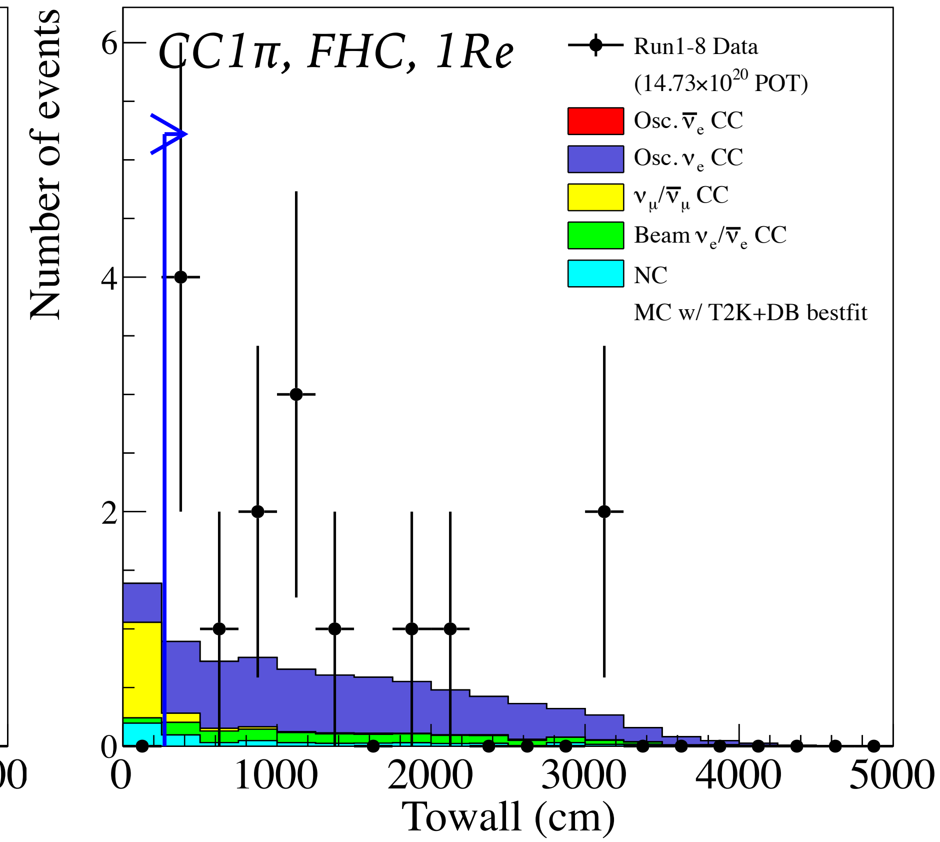


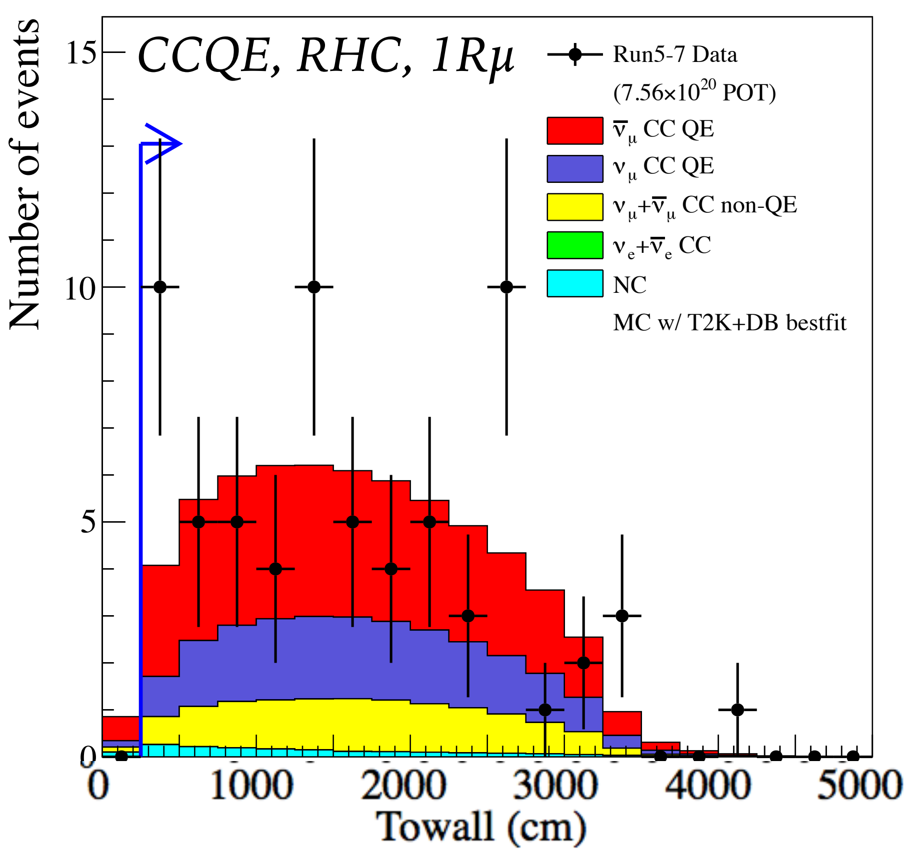
- ND280 fit to neutrino mode CC0π data
- Significant improvement in data/simulation residuals from fit

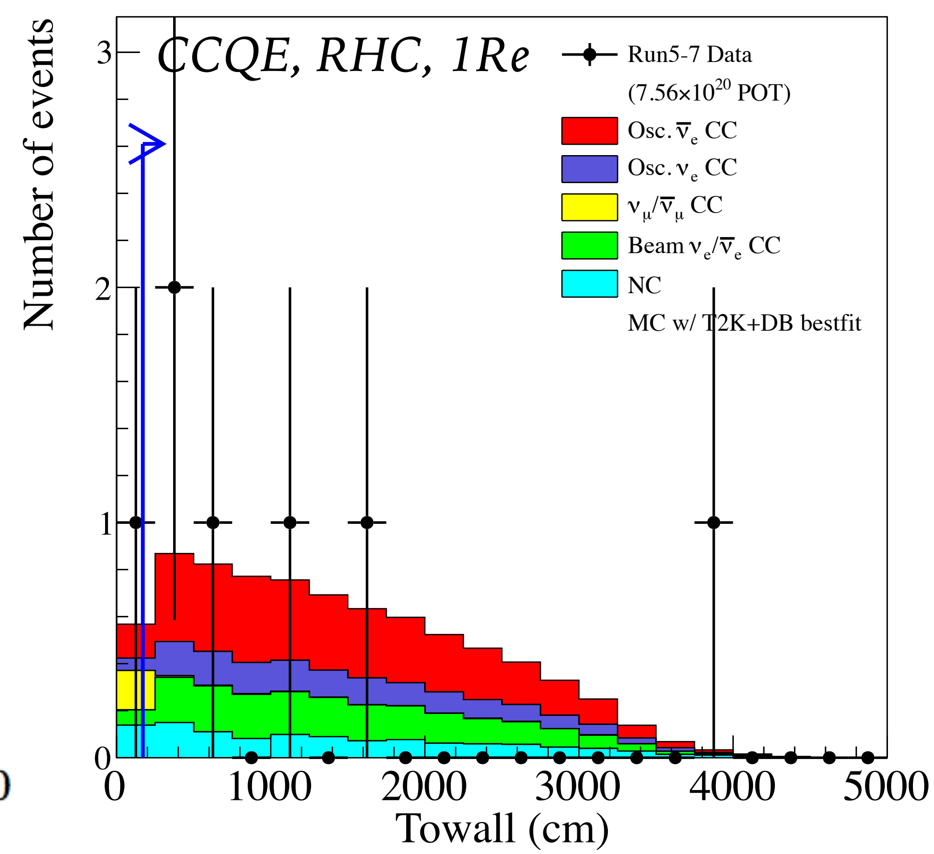
TOWALL DISTRIBUTIONS







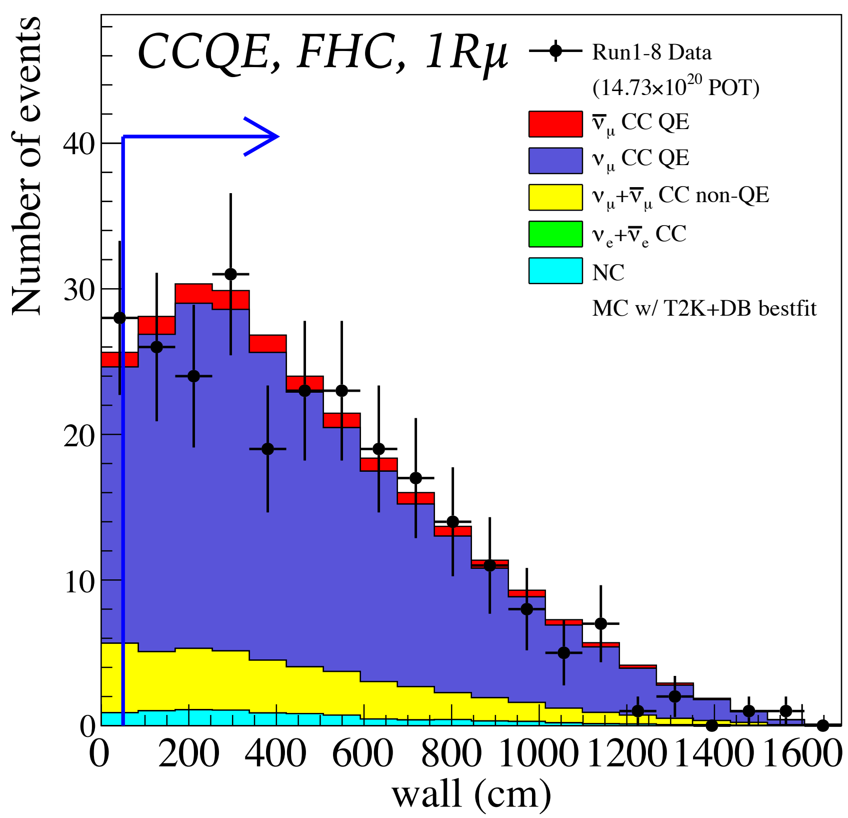


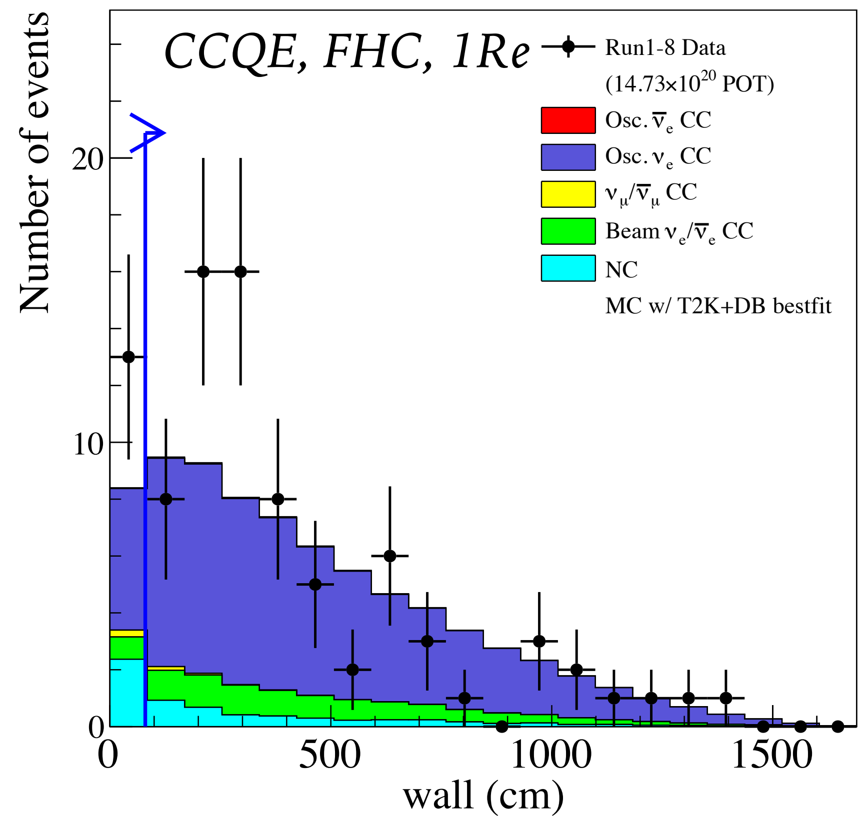


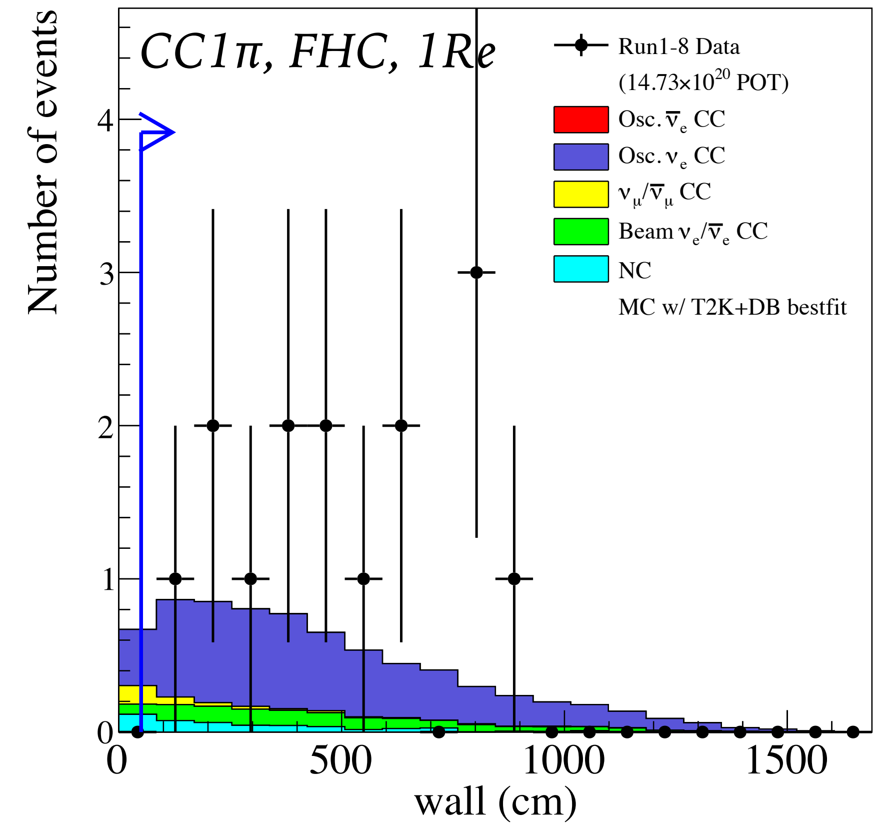
T2K Preliminary

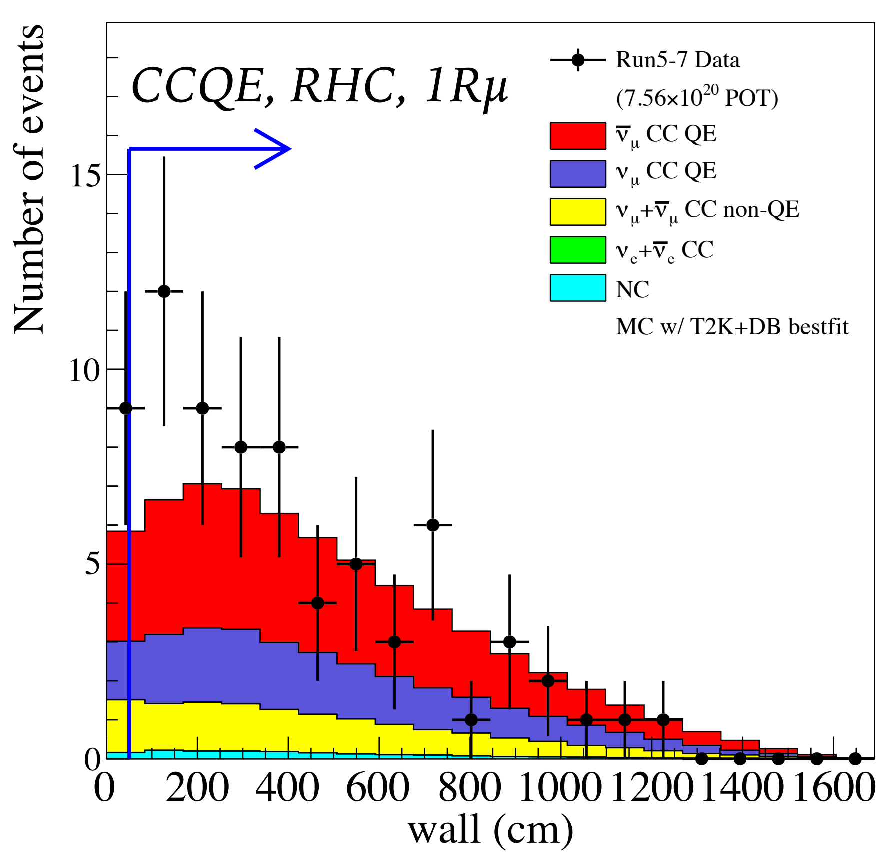
Towall = distance to wall along the lepton candidate direction.

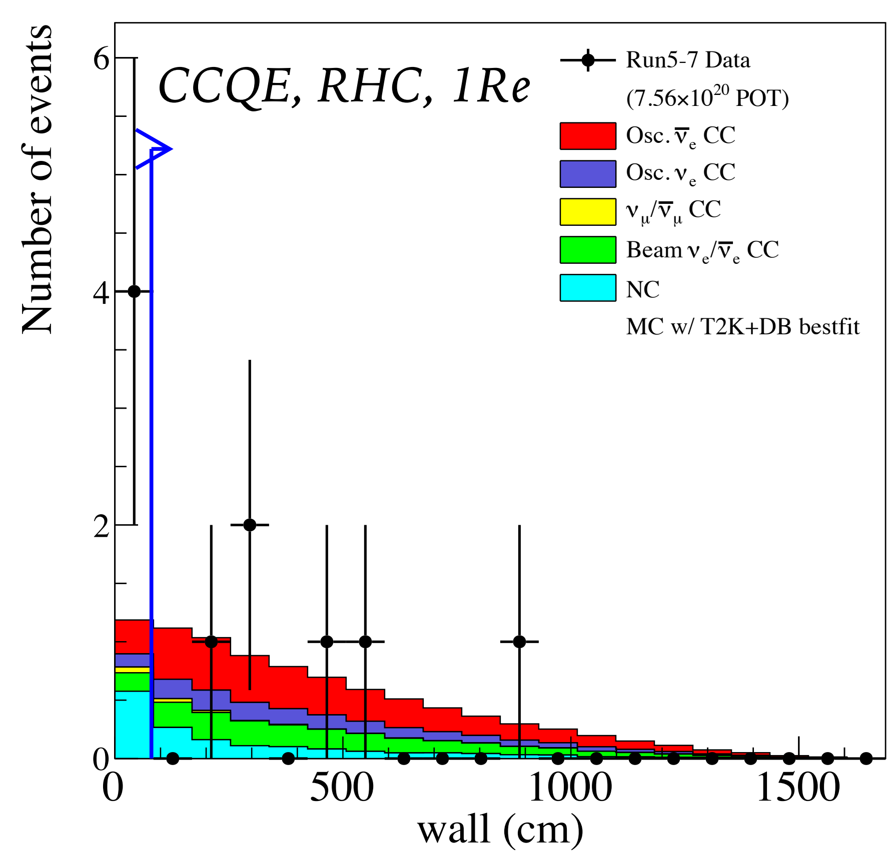
WALL DISTRIBUTIONS











T2K Preliminary

wall = shortest distance of the vertex from the detector wall