New Results from the T2K Experiment:

Observation of ν_e Appearance from a ν_μ Beam

Michael Wilking, TRIUMF
on behalf of the T2K Collaboration

EPS Conference

19-July-2013

Overview

- Neutrino oscillations
- Introduction to T2K
- Near detector analysis improvements for 2013
    - T2K cross section measurements
- Far detector analysis improvements for 2013
    - A New Reconstruction algorithm for Super-Kamiokande (**fiTQun**)
- **New result** (today): ν_e appearance
- **Recent result** (winter, 2013): ν_μ disappearance

Neutrino Mixing

Flavor States | Mass States

Note: $c_{ij} = \cos(\theta_{ij})$, $s_{ij} = \sin(\theta_{ij})$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} e^{i\alpha_1}/2 & 0 & 0 \\ 0 & e^{i\alpha_2}/2 & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

"Atmospheric ν" (Super-K, K2K, MINOS) $\sin^2 2\theta_{23} > 0.95$ (90% C.L.)	"Reactor/Acc. ν" (Daya Bay, RENO, Double Chooz, T2K, NOνA) $\sin^2 2\theta_{13} = 0.098 \pm 0.013$	"Solar ν" (SNO, Super-K, KamLAND) $\sin^2 2\theta_{12} = 0.857 \pm 0.024$	Majorana phases; Not yet observed

- **θ_{13} is now precisely known**, and relatively large
- It may now be possible to put **constraints on δ_{CP}** (Long-baseline experiments only: T2K & NOνA)
- However, the **large uncertainty on θ_{23}** is now limiting the information that can be extracted from ν_e appearance measurements
- Precise measurements of **all the mixing angles** will be needed to maximize sensitivity to CP violation

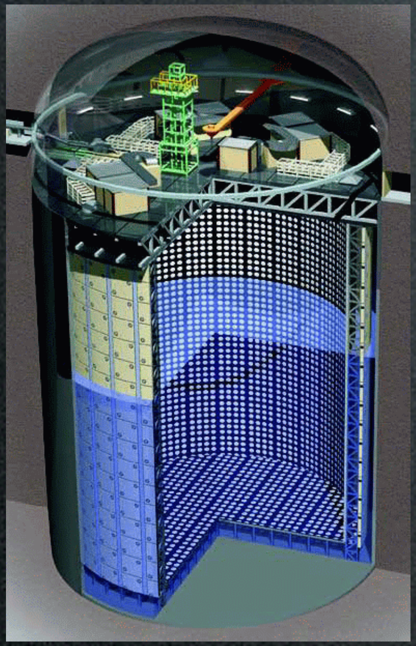
Oscillation Probabilities

$$P_{\mu\to\mu} \approx 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)$$
+ (subleading terms)

$$P_{\mu\to e} \approx \sin^2 2\theta_{13} \sin^2\theta_{23} \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)$$
+ (CPV term) + (matter term) + ...

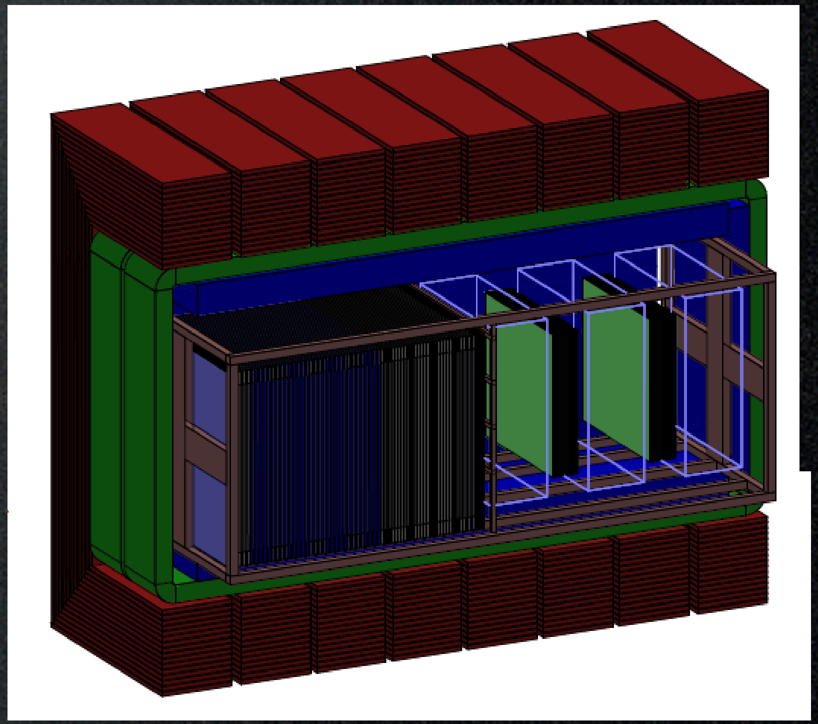
The T2K Experiment

Super-K Detector



J-PARC Accelerator

Near Detector



- The T2K experiment searches for neutrino oscillations in a **high purity ν_μ beam**
- A near detector located 280 m downstream of the target measures the unoscillated neutrino spectrum
- The neutrinos travel 295 km to the Super-Kamiokande water Cherenkov detector
  - ν_e appearance (sensitive to θ_{13} & δ_{CP})
  - ν_μ disappearance (sensitive to θ_{23} & Δm^2_{32})

The T2K Collaboration

~500 members, 59 Institutes, 11 countries

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

France
CEA Saclay
IPN Lyon
LLR E. Poly.
LPNHE Paris

Germany
Aachen U.

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.
Osaka City U.
Okayama U.
Tokyo Metropolitan U.
U. Tokyo

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

Russia
INR

Spain
IFAE, Barcelona
IFIC, Valencia

Switzerland
ETH Zurich
U. Bern
U. Geneva

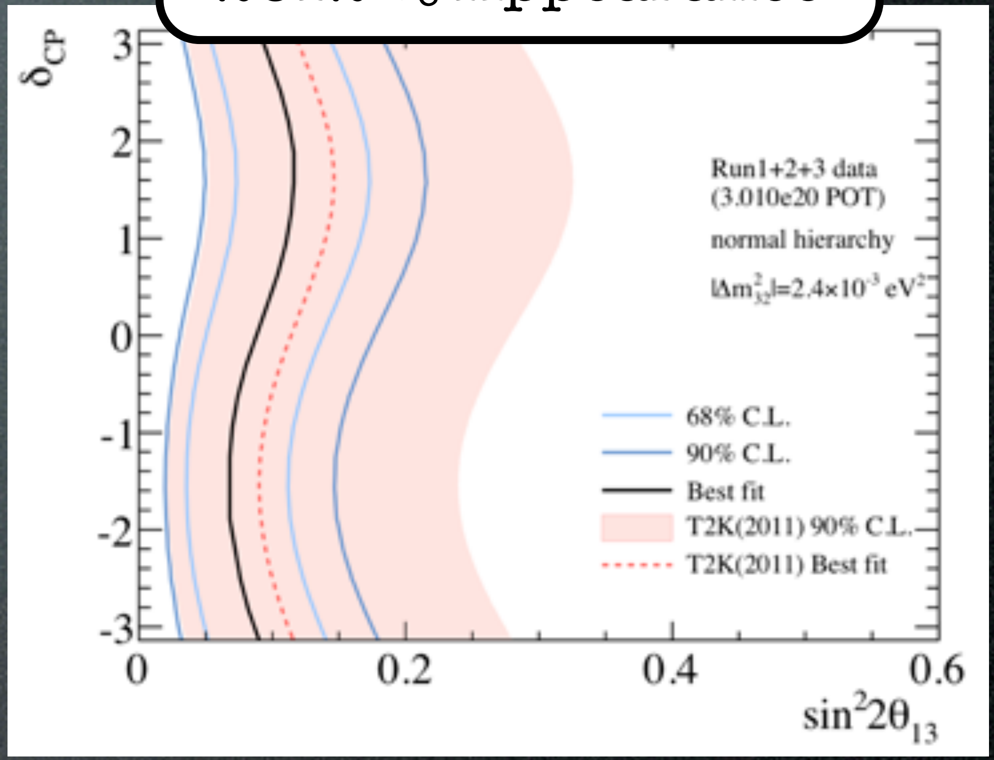
United Kingdom
Imperial C. London
Lancaster U.
Oxford U.
Queen Mary U. L.
STFC/Daresbury
STFC/RAL
U. Liverpool
U. Sheffield
U. Warwick

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

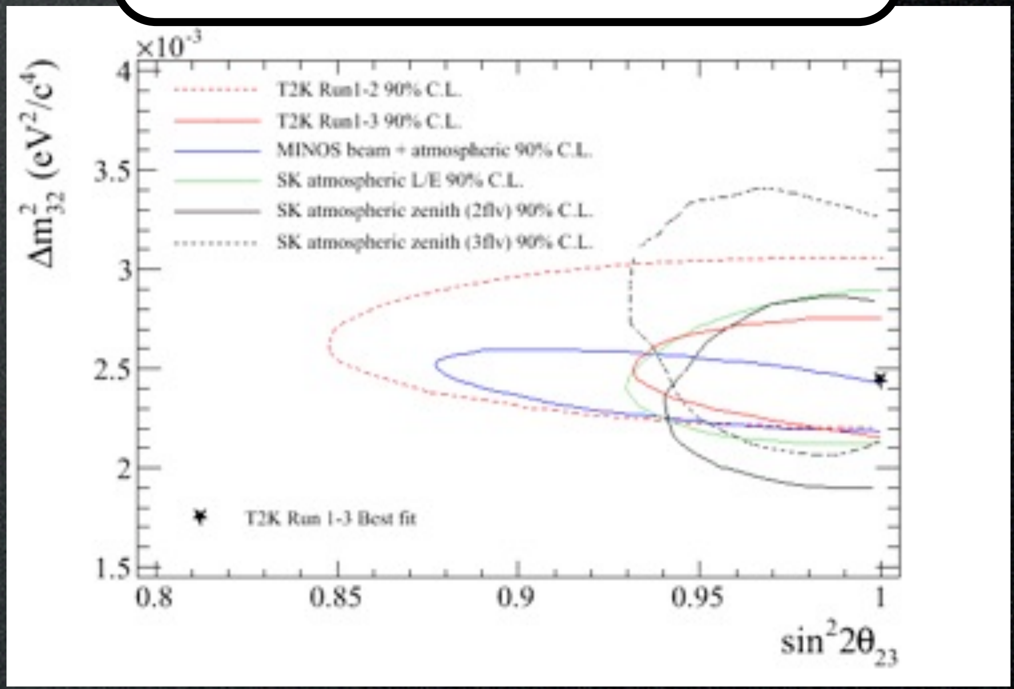
Previous T2K Results

- **2011 ν_e appearance**
  - Observed 6 events (background: 1.5 ± 0.3 events)
  - First indication of **non-zero θ_{13} at 2.5σ** significance
  - Phys. Rev. Lett. 107, 041801 (2011)
- **2012 ν_e appearance**
  - Observed 11 events (background: 3.3 ± 0.4 events)
  - **3.1σ exclusion non-zero θ_{13}**
  - arXiv:1304.0841 (accepted by PRD)
- **2013 ν_μ disappearance**

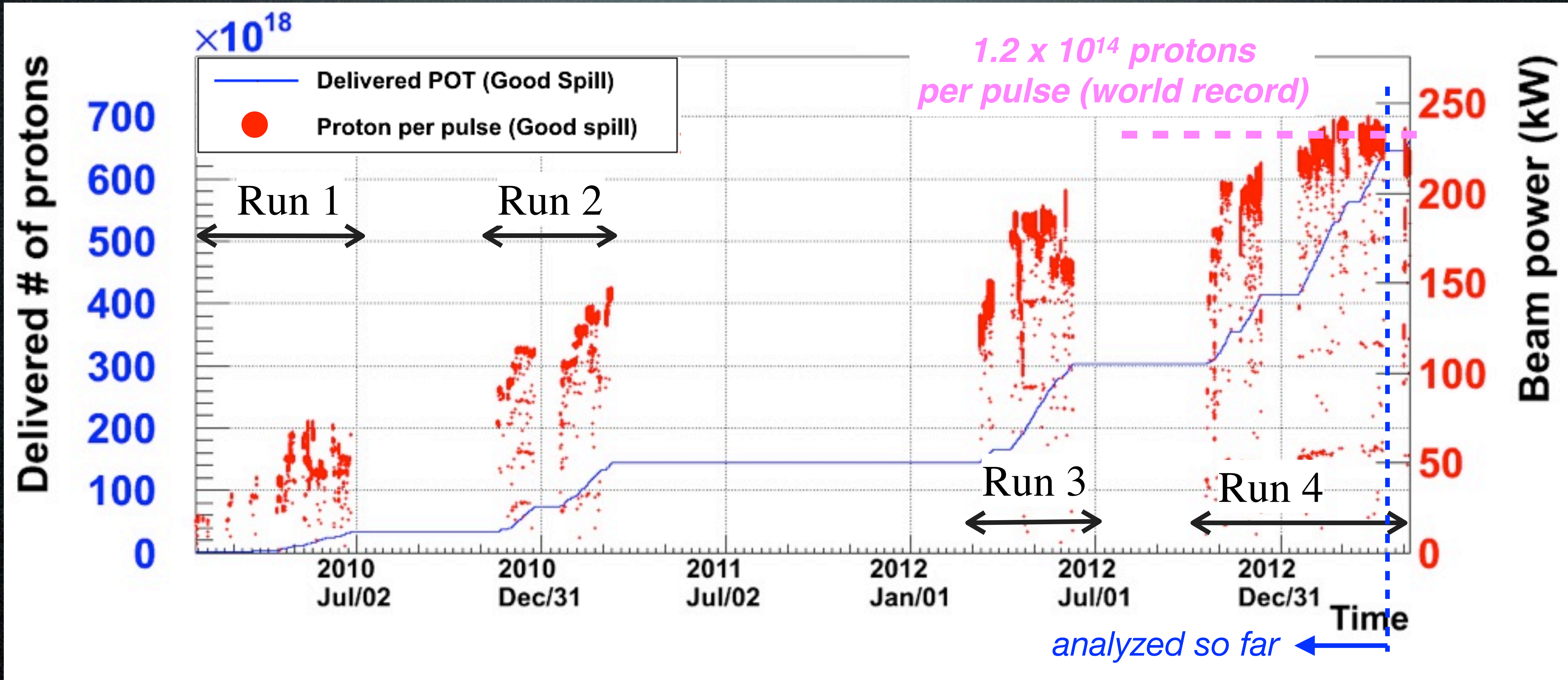
2012 ν_e Appearance



2013 ν_μ Disappearance



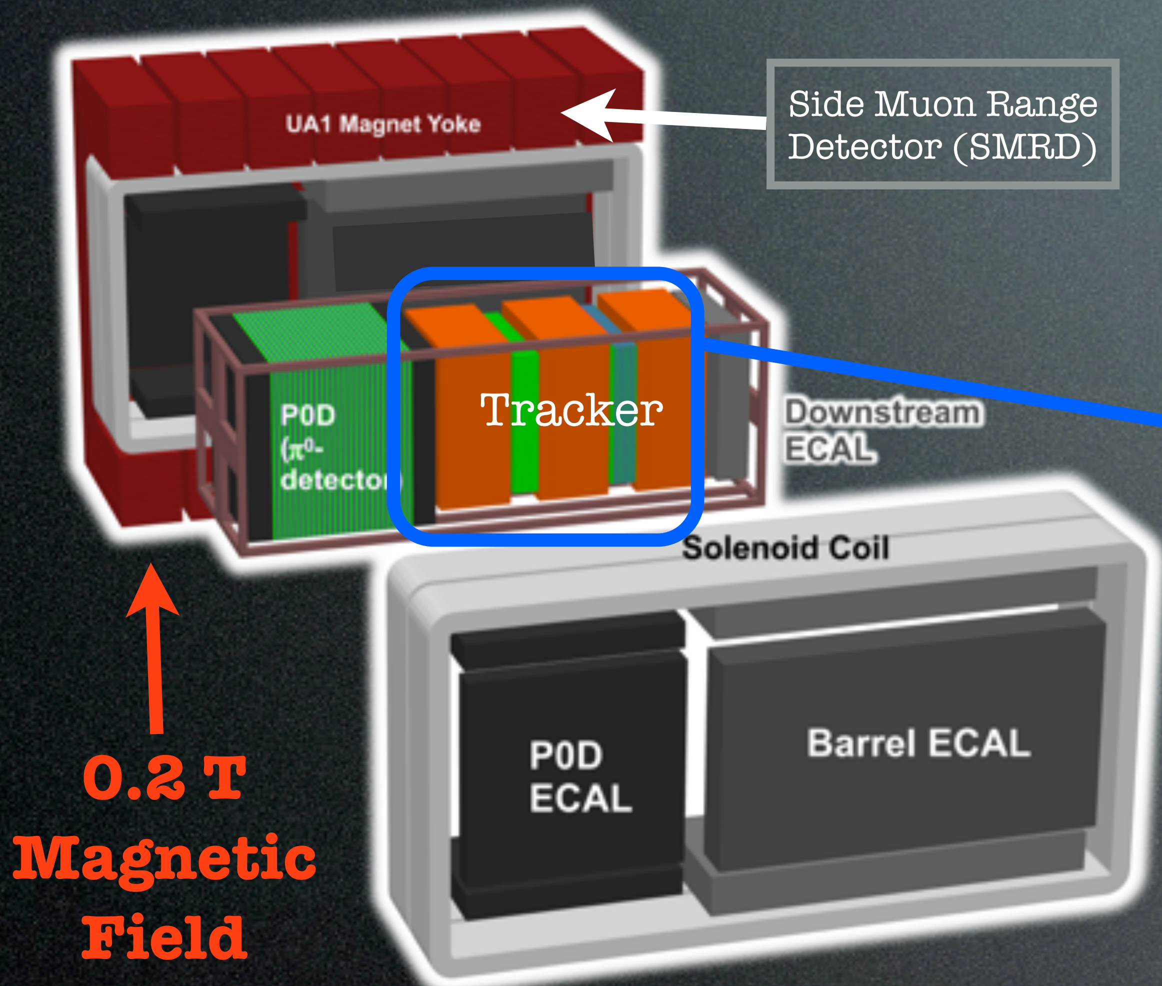
Data Taking (Run 1-4)



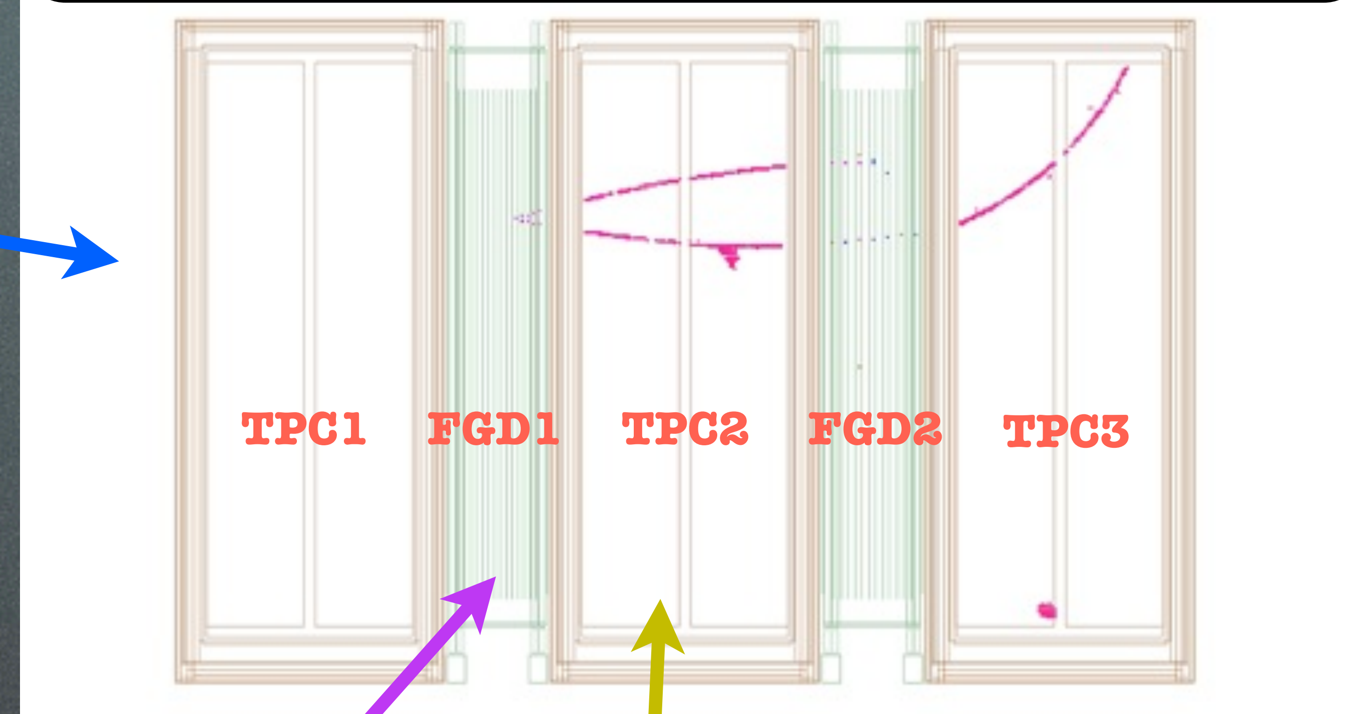
- Today's results are possible due to the efforts of J-PARC accelerator division and other related people.
  - Consistent running at 220 kW for much of Run 4 (**world record protons per pulse**)
- 6.39 * 10^{20} POT analyzed through April 12th (6.63 * 10^{20} through May)
- Previous ν_e appearance result: 3.01 * 10^{20} POT ➜ **Factor of 2.1 increase in statistics**

(relative to 2012 analysis)

The Near Detector



CC Interaction in the Tracker



Fine-Grained Detectors (FGDs)

- Scintillator strips
- Provides neutrino target
- Detailed vertex information

Time Projection Chambers (TPCs)

- Gas ionization chambers
- Track momentum from curvature
- Particle ID from dE/dx

Near Detector Constraints

Goal: Constrain ν-flux and cross section parameters (used for T2K far detector MC prediction)

ν-Flux

ν_μ and ν_e fluxes are correlated

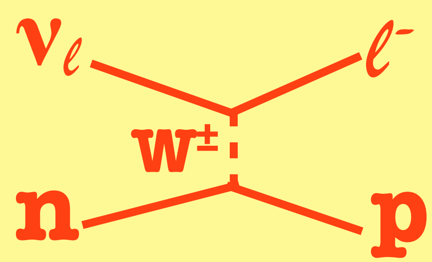
$$\pi^+ \rightarrow \mu^+ \, \nu_\mu$$
$$\hookrightarrow e^+ \, \nu_e \, \bar{\nu}_\mu$$

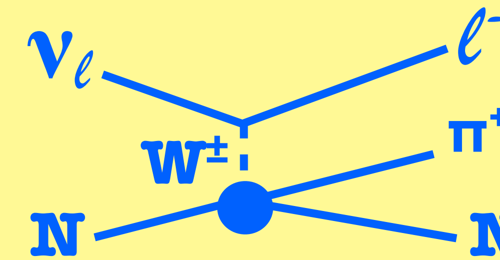
Can use ν_μ measurement to constrain the ν_e flux

External constraints from **NA61** (see talk later in this session)

Cross Sections

Main CC interactions relevant to T2K are **CCQE** and **CCπ^+**



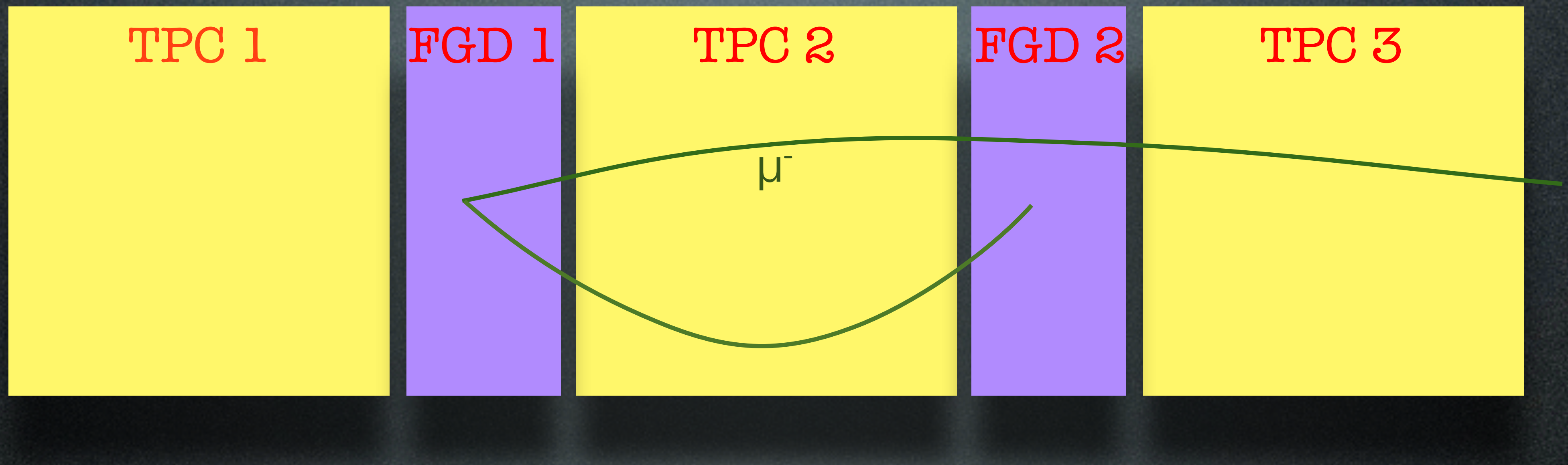


Need to constrain the parameters of these interactions: M_A^{QE}, M_A^{RES}, etc.

External constraints from **MiniBooNE**

The ν_μ spectrum at the near detector is fit to extract flux and cross section constraints at the far detector

2012 Event Selection



- Charged-Current events were separated into 2 categories:
  - **CCQE-like sample** (1-track events)
    - 70% CCQE purity (95% at osc. max)
    - **CCQE parameters are well constrained**
  - **CCnonQE-like sample** (>1-track events)
    - 29% $CC\pi^+$ purity
    - **$CC\pi^+$ parameters are poorly constrained**

Limitations of the 2012 Near Detector Analysis

- Doubling the data statistics produced only a small reduction in the error on the far detector event rate

Error on T2K ν_e Candidate Prediction (After Near Detector Constraint)

$\sin^2 2\theta_{13}$	Using Data from Runs 1-2	Using Data from Runs 1-3
0.1	5.7% →	4.7%
0.0	6.7% →	6.1%

Statistics doubled

- The diagonal error on the cross section parameters were unchanged
  - (some small improvement in the correlated error)

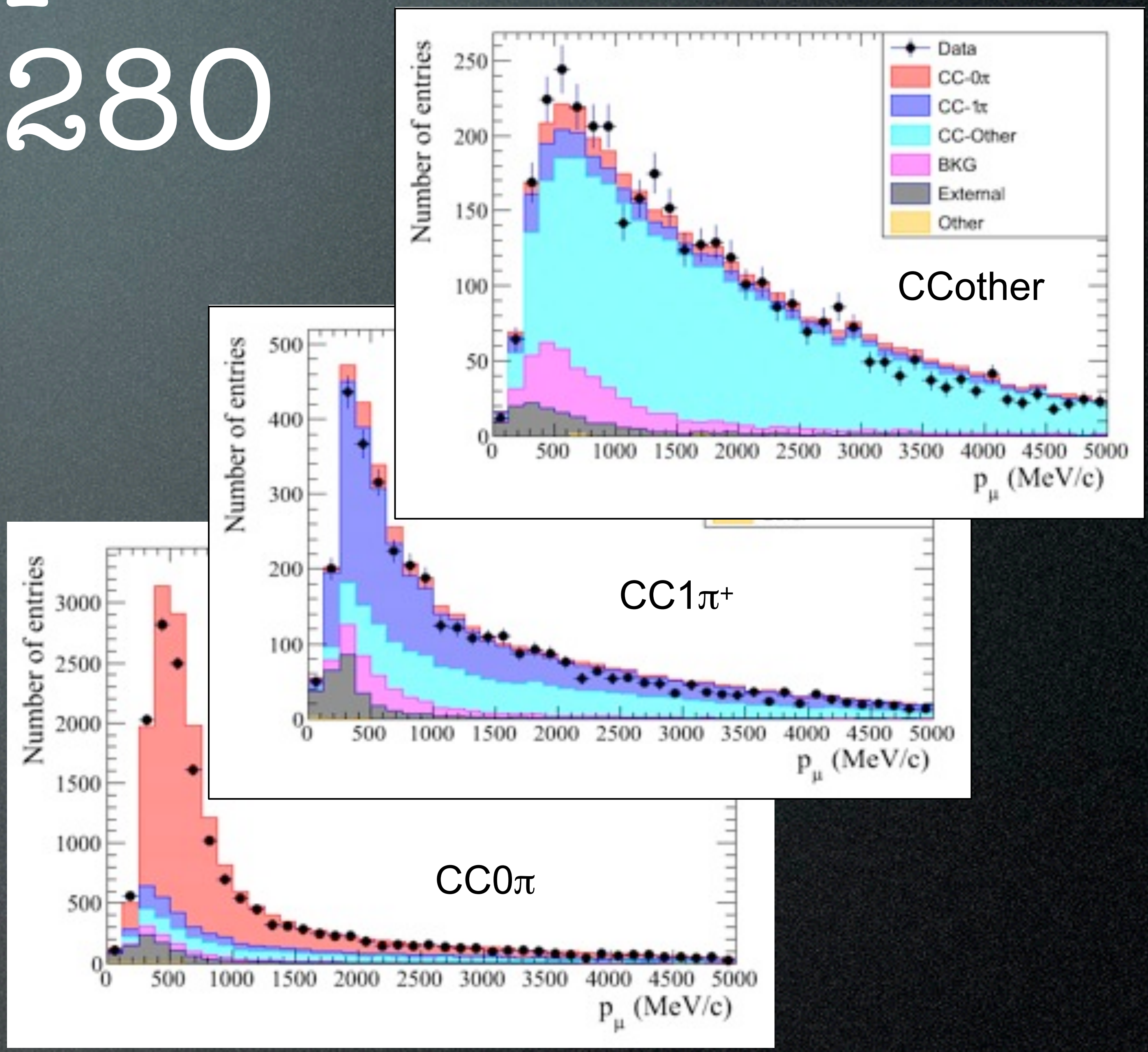
Error on Cross Section Parameters (After Near Detector Constraint)

Parameter	Run 1-2 Data	Runs 1-3 Data
M_A^{QE} (GeV/c²)	1.17 ± 0.19 →	1.27 ± 0.19
M_A^{RES} (GeV/c²)	1.25 ± 0.14 →	1.22 ± 0.13
CCQE Norm.	0.95 ± 0.09 →	0.95 ± 0.09
CC1π Norm.	1.33 ± 0.22 →	1.37 ± 0.20

Statistics doubled

Analysis Improvements: ND280

- Separate the CC sample into three subsamples:
  - CC0π: **no pions** in the final state
  - CC1π$^+$: exactly **1 π$^+$** in the final state
  - CCother: **>1 π$^+$** OR **>0 π$^-$** OR **>0 tagged photons**
- Higher purities for all 3 samples, relative to the 2012 analysis
  - Much better samples for constraining CCQE and CCπ$^+$ cross section parameters
- See poster by Raquel Castillo



	CC0π purities	CC1π purities	CCother purities
CC0π	72.6%	6.4%	5.8%
CC1π	8.6%	49.4%	7.8%
CCother	11.4%	31%	73.8%
Bkg(NC+anti-ν)	2.3%	6.8%	8.7%
Out FGD1 FV	5.1%	6.5%	3.9%

2013 Near Detector Constraint

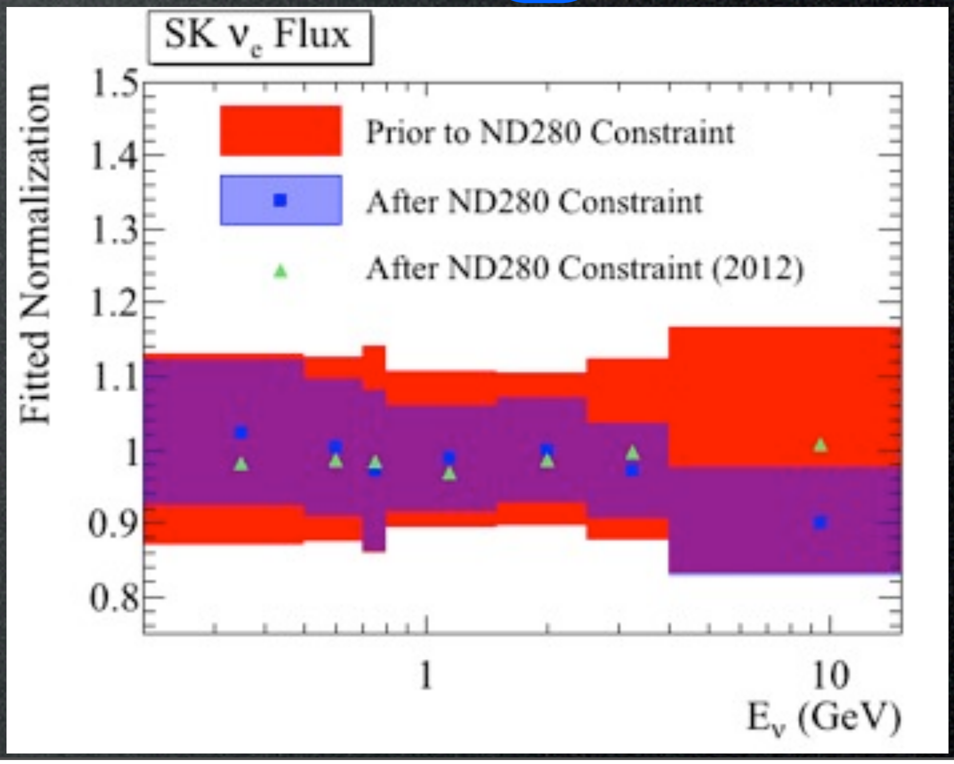
- Significant reduction in the far detector event rate errors
- Uncertainties on the cross section parameters have been reduced
- Uncertainties on the flux parameters are also reduced

Error on Far Detector ν_e Prediction (After Near Detector Constraint)

	Runs 1-3 (2012)	Runs 1-3 (2013)	Runs 1-4 (2013)
$\sin^2 2\theta_{13}=0.1$	4.7%	3.5%	3.0%
$\sin^2 2\theta_{13}=0.0$	6.1%	5.2%	4.9%

Error on Cross Section Parameters (After Near Detector Constraint)

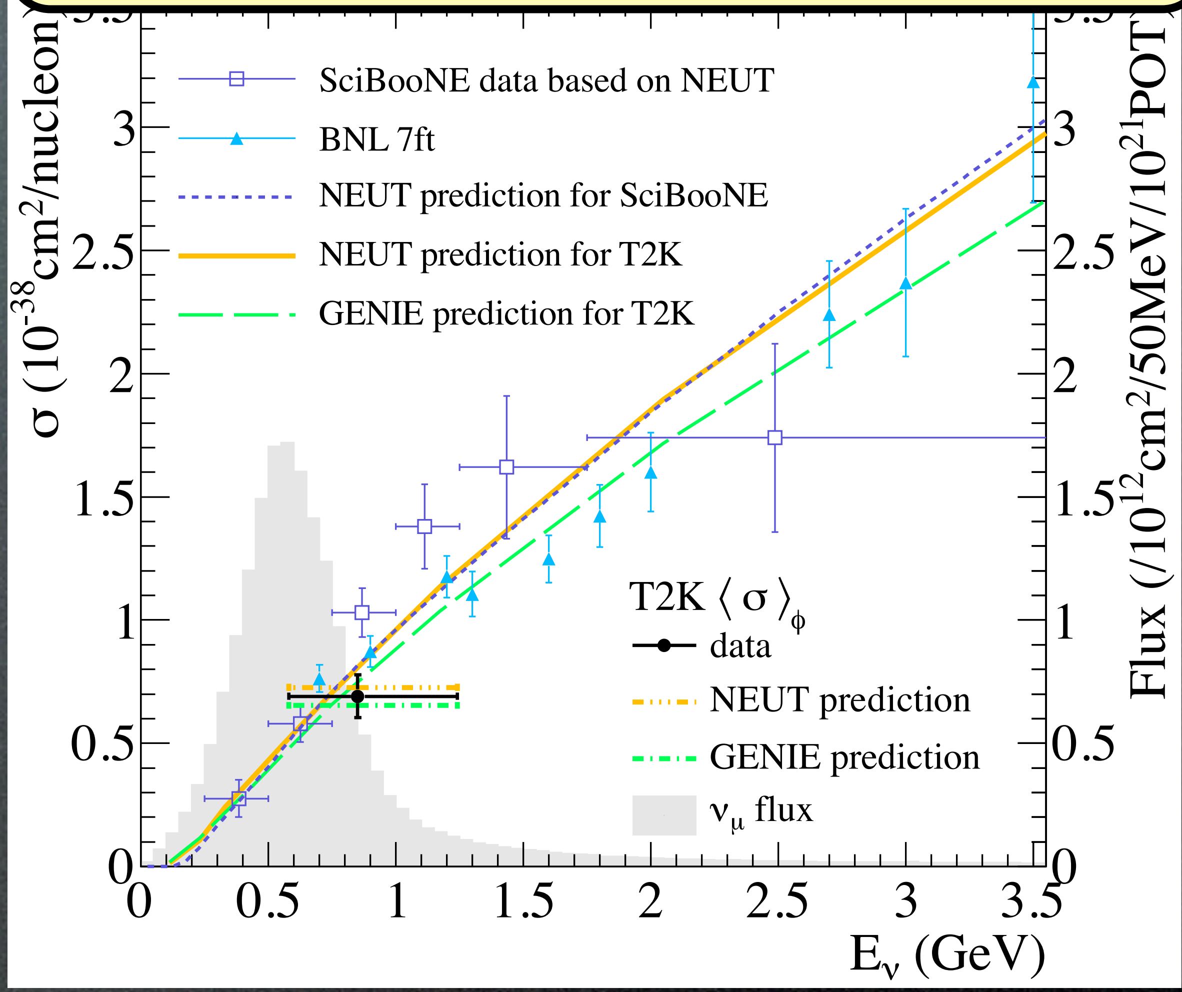
Parameter	Runs 1-3 (2012)	Runs 1-4 (2013)
M_A^{QE} (GeV/c²)	1.27 ± 0.19	1.22 ± 0.07
M_A^{RES} (GeV/c²)	1.22 ± 0.13	0.96 ± 0.06
CCQE Norm.	0.95 ± 0.09	0.96 ± 0.08
CC1π Norm.	1.37 ± 0.20	1.22 ± 0.16



T2K Cross Section Measurements

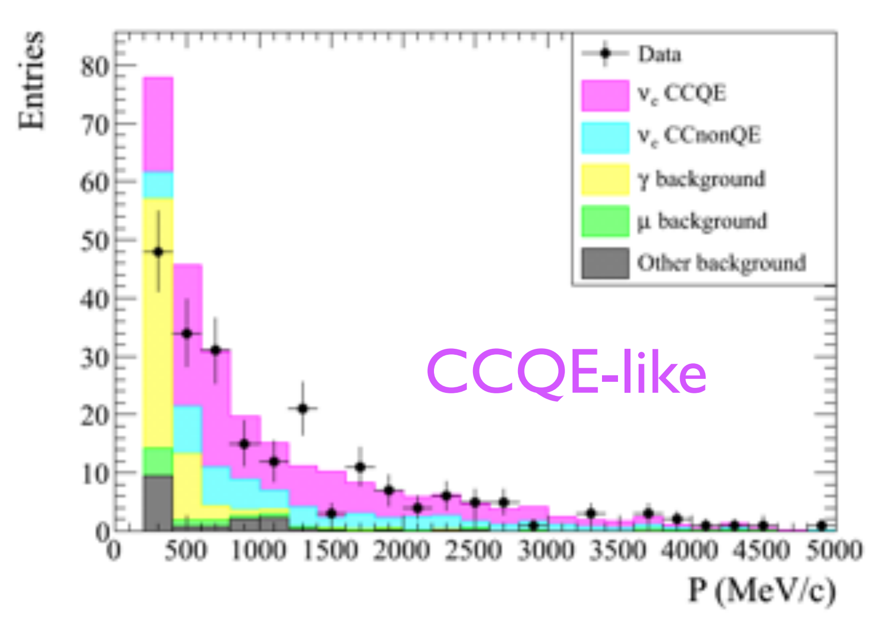
- The near detector oscillation analysis can be repurposed for cross section measurements
  - Event selection and detector systematic uncertainties are the same
- The T2K CC-Inclusive cross section measurement has now been published
  - Uses the same near detector event selection as the 2012 oscillation analysis
  - Phys. Rev. D 87, 092003 (2013)
- The CCQE sample from the 2012 oscillation analysis has been used to measure $\sigma_{CCQE}(E_\nu)$
  - See poster by David Hadley
- Additional cross section results are expected later this year

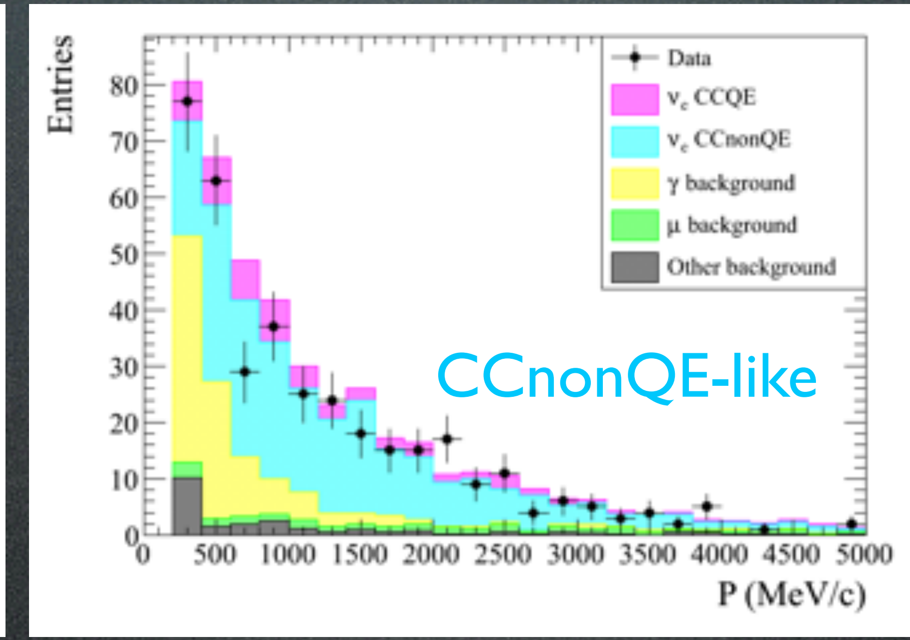
T2K CC-Inclusive Cross Section Measurement

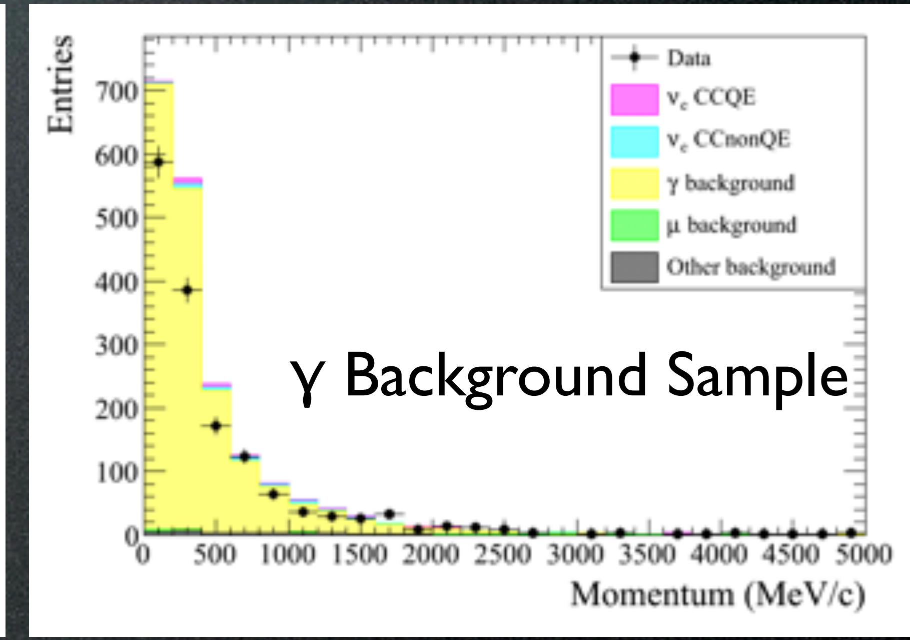


Near Detector Beam ν_e Measurement

- For ν_e appearance, the largest background is from the intrinsic ν_e contamination in the beam
- The intrinsic ν_e rate can be measured in the near detector
- Details are given in a poster by Davide Sgalaberna

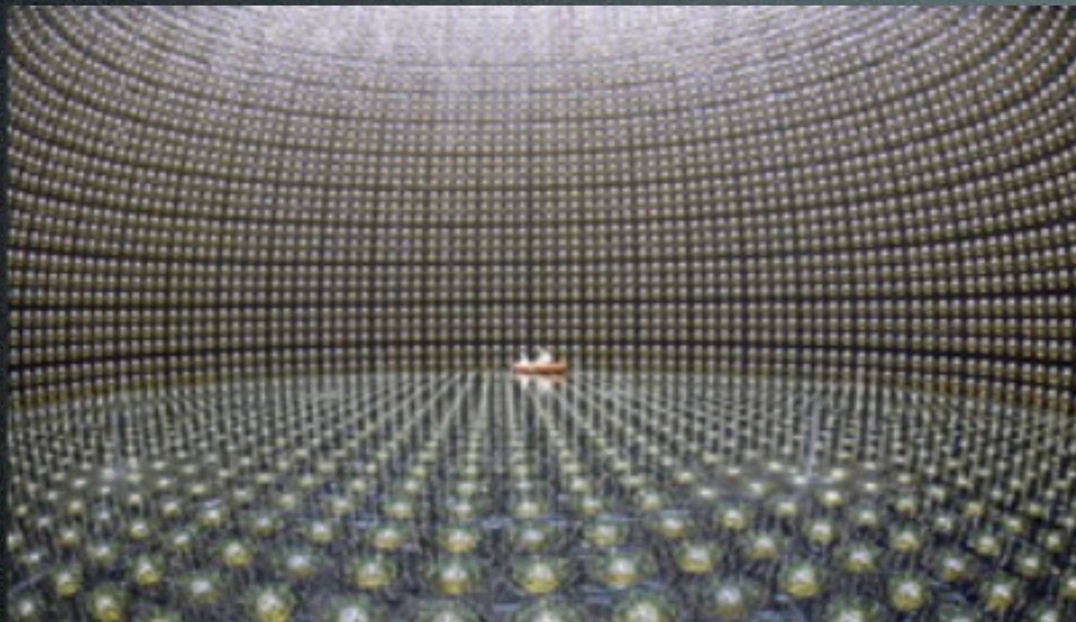


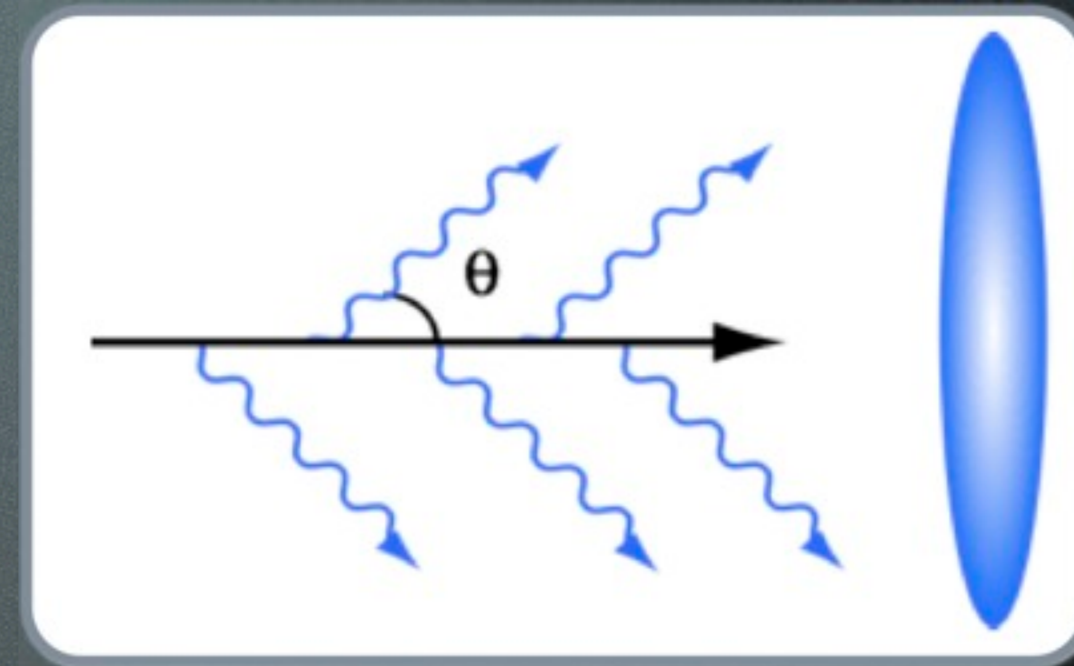




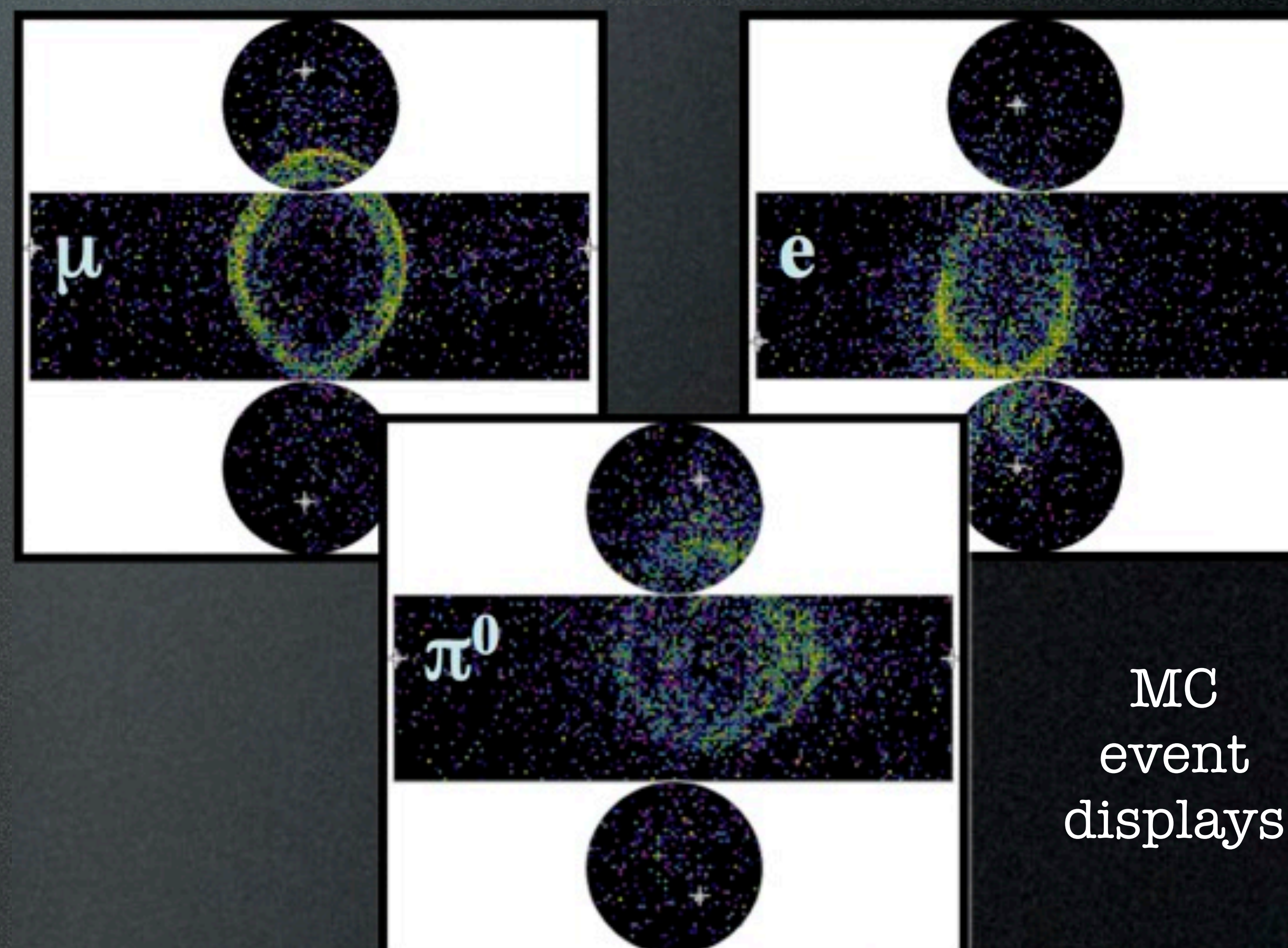
- Short-baseline ν_e's can also be used to search for sterile neutrinos
- Details about T2K's sensitivity for such a measurement are given in another poster by Davide Sgalaberna

The Super-K Detector





- 50 kton water Cherenkov detector
- **μ detection**
  - Less scattering ⇒ sharp rings
- **e detection**
  - More scattering ⇒ fuzzy rings
- **π^0 detection**
  - 2 electron rings ($\pi^0 \rightarrow 2\gamma$)
  - To separate from electrons, **MUST detect 2nd ring**



MC event displays

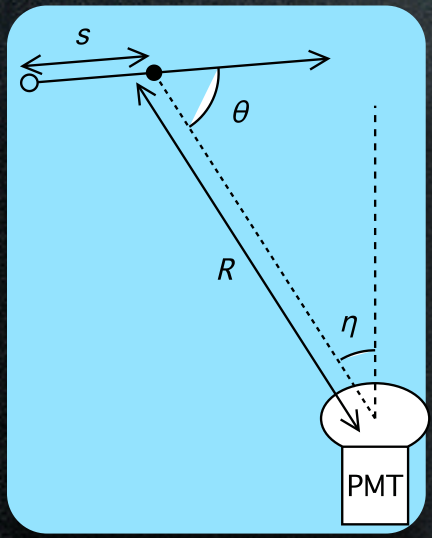
Far Detector Oscillation Analysis Improvements

- The strength of T2K thus far has been relying on well-established event reconstruction tools at Super-K
    - After 15 years of operation, is there still room for improvement?
- 2012 T2K Signal/background ratio **2.7** (for $\sin^2 2\theta_{13}=0.1$)
    - Significant gains in ν_e appearance sensitivity from any additional background reduction
- 2012 Total background = **3.22 ± 0.43 events**
    - Beam ν_e background = **1.56 ± 0.20 events** (irreducible)
    - Neutral current (mostly π^0) = **1.26 ± 0.35 events** (reducible?)

fiTQun: A New Event Reconstruction Algorithm for Super-K

- For each Super-K event we have, for every hit PMT
  - **A measured charge**
  - **A measured time**
- For a given event topology hypothesis, it is possible to produce a **charge and time PDF for each PMT**
  - Main challenge is to predict the number of photons at the PMT (**predicted charge, μ** -- see next slide)
  - Based on the algorithm used by MiniBooNE (NIM A608, 206 (2009))
- Framework can handle **any number of reconstructed tracks**
  - Same fit machinery used for all event topologies (e.g. e^- and π^0)
- Event hypotheses are distinguished by **comparing best-fit likelihoods**
  - electron vs muon
  - 1-ring vs 2-ring vs 3-ring ...

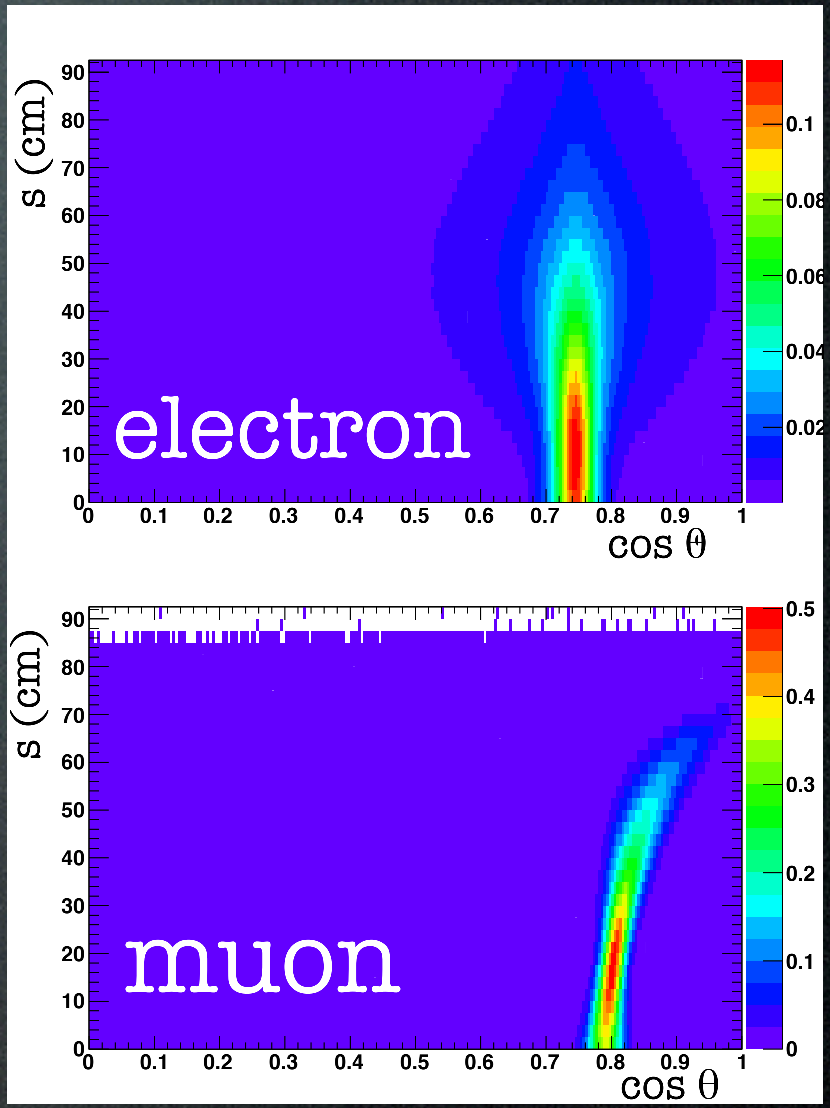
Predicted Charge (μ)



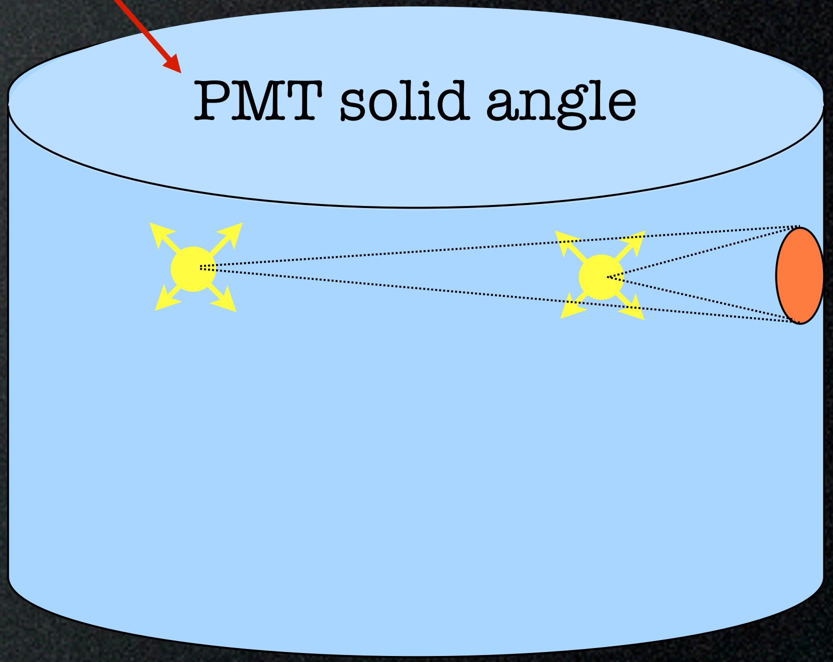
$$\mu^{\rm dir} = \Phi(p)\int ds g(s,\cos\theta)\Omega(R)T(R)\epsilon(\eta)$$

Light Yield — Integral over track length — PMT solid angle — Water attenuation — PMT angular response

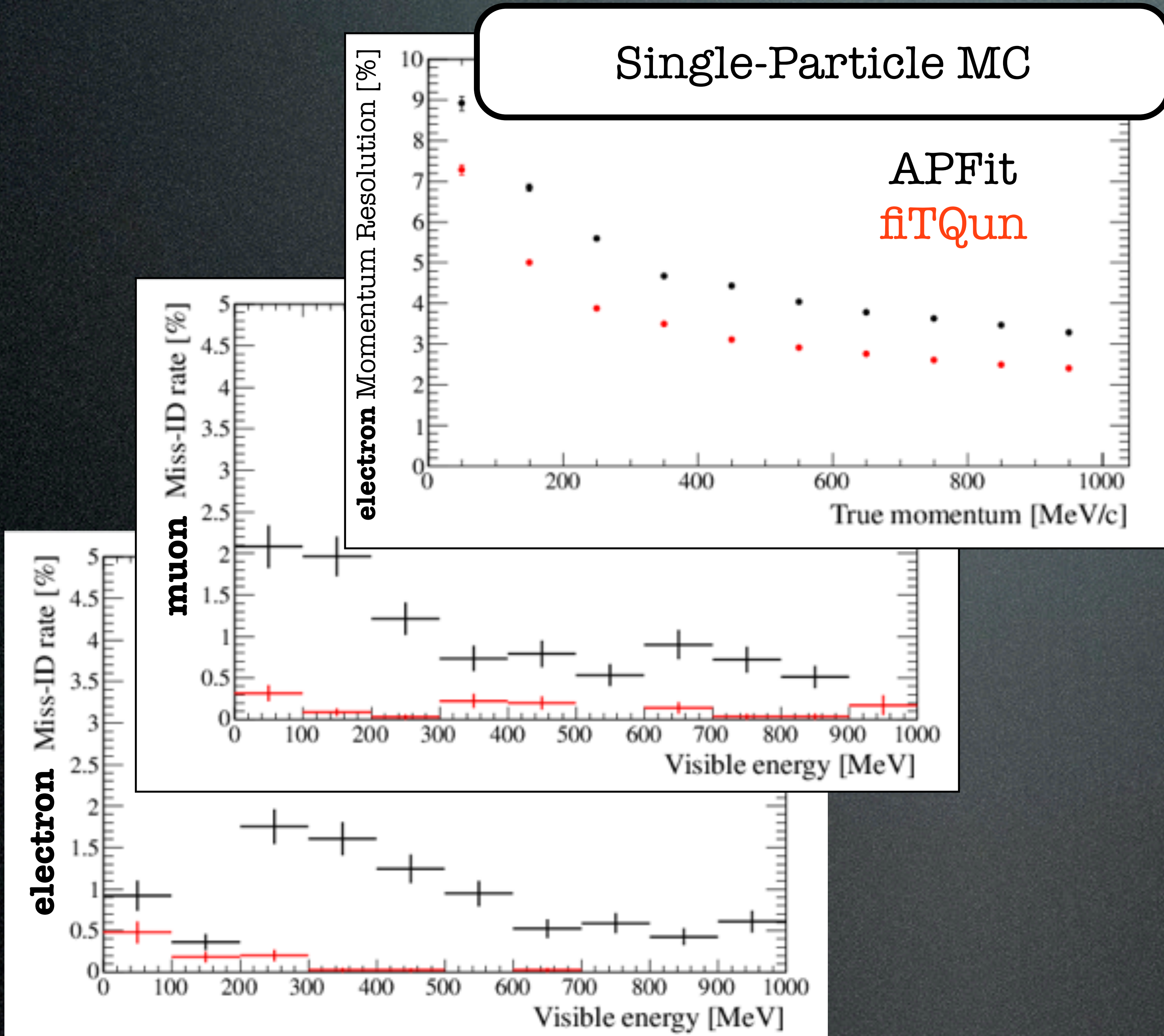
Cherenkov light emission profile

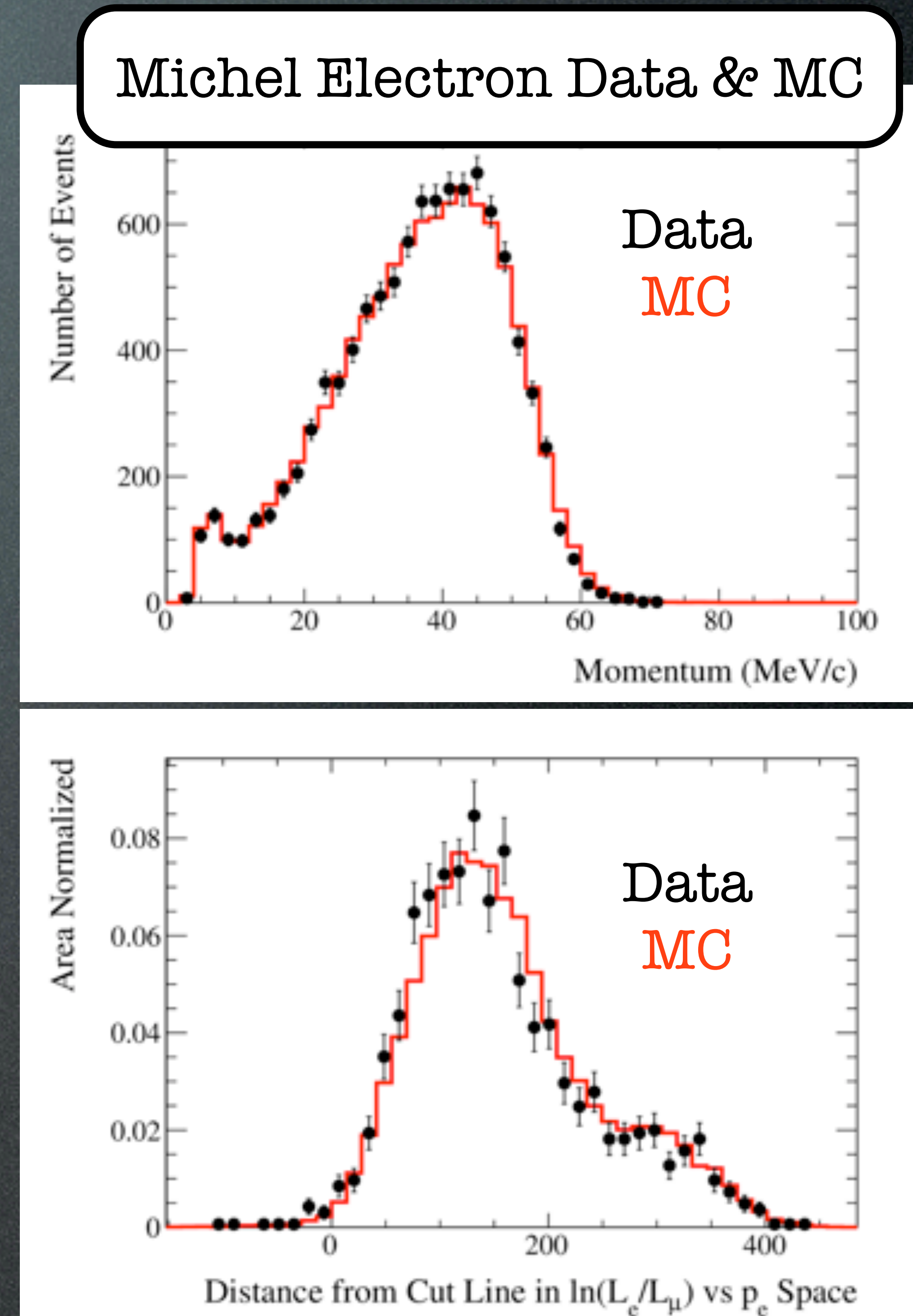


- $\mu^{\rm dir}$ is the predicted charge due to "direct light" only (scattered light is handled separately)
- μ is an integral over the length of the track (parameterized by the momentum, p)
- Cherenkov light emission is characterized by g(s,cosθ)
  - These functions must be generated separately for each particle type
  - All particle ID comes from these distributions
- Ω, T, and ε depend on the geometry and detector properties
  - Can be used for all particle hypotheses



One-Ring-Fit Performance

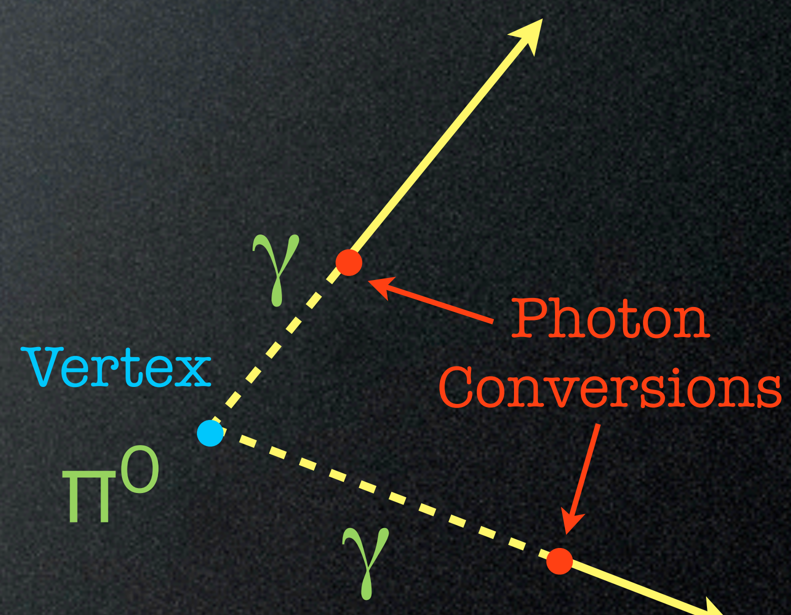




- Significantly better particle ID and momentum reconstruction than previous Super-K reconstruction (APFit)
- Good data/MC agreement in Michel electron sample

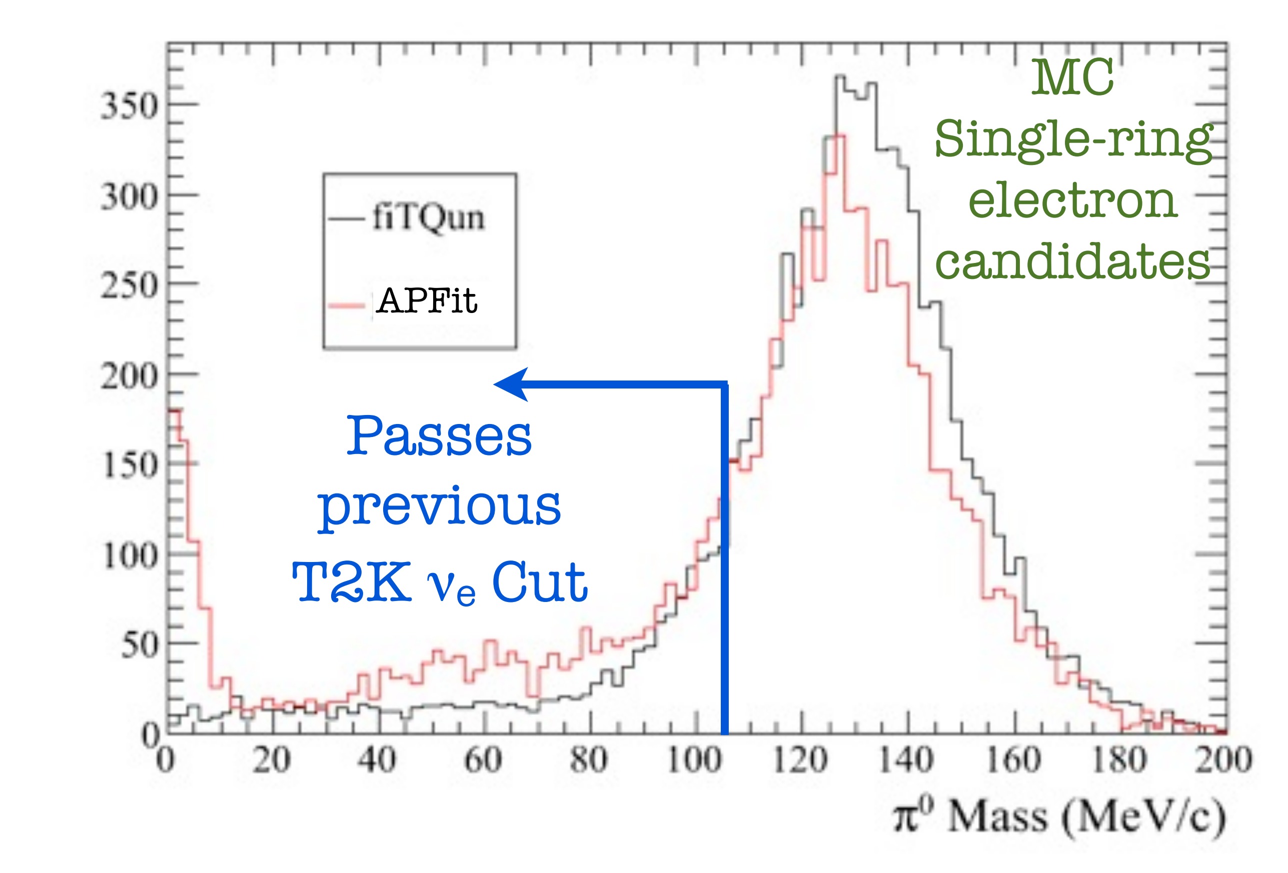
π^0 Fitter

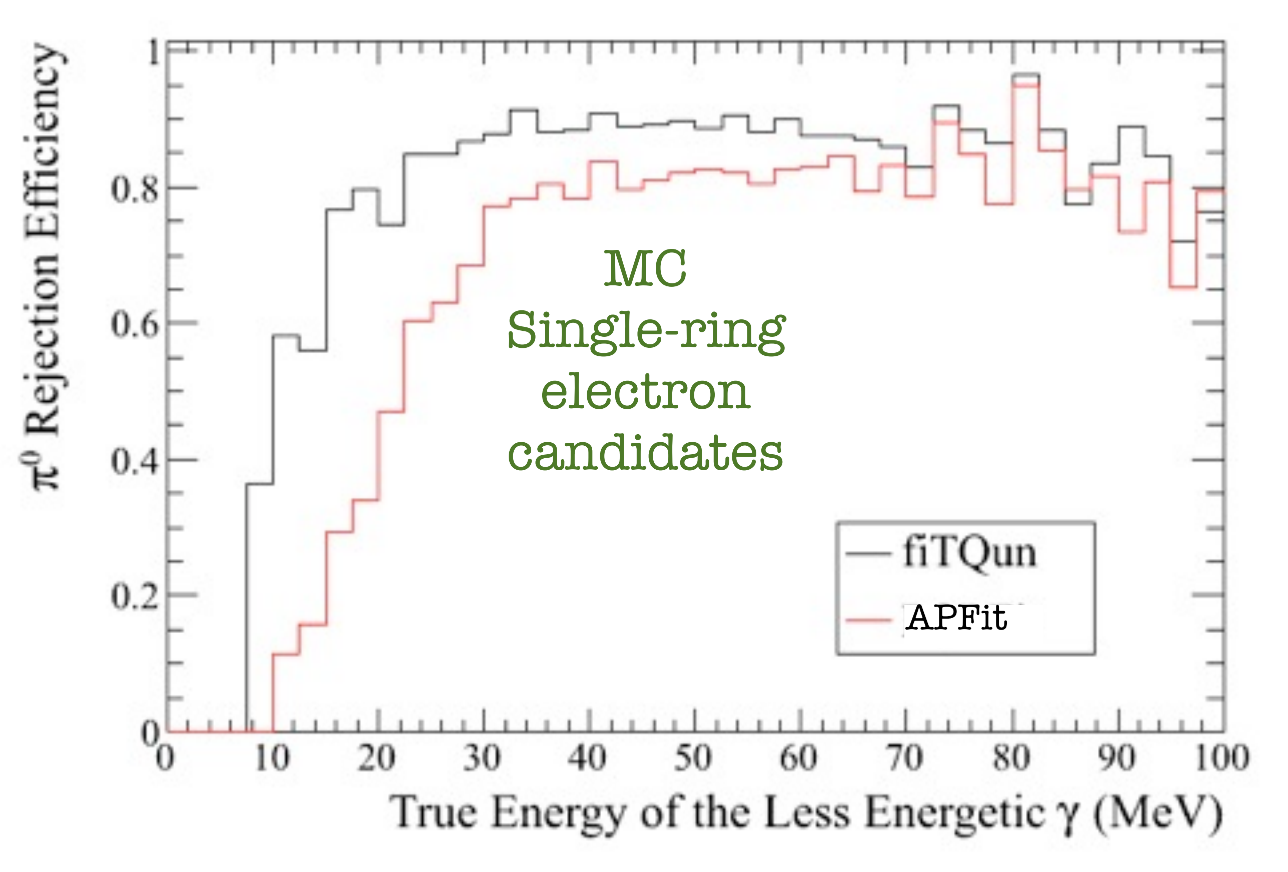
- Assumes two electron-like rings produced at a common vertex
- **12 parameters** (single track fit had 7)
  - Vertex (X, Y, Z, T)
  - Directions (θ_1, ϕ_1, θ_2, ϕ_2)
  - Momenta (p_1, p_2)
  - Conversion lengths (c_1, c_2)
- **All 12 parameters are varied simultaneously**



π^0 Fit Performance

- Previous T2K ν_e appearance cut:
  $m_{\pi 0} < 105$ MeV/c^2
- The π^0 mass tail is much smaller for fiTQun
  - Significant spike at zero mass in previous fitting algorithm (**APFit**)
- **Lower plot:**
  π^0 rejection efficiency vs lower photon energy
  - fiTQun is more sensitive to lower energy photons

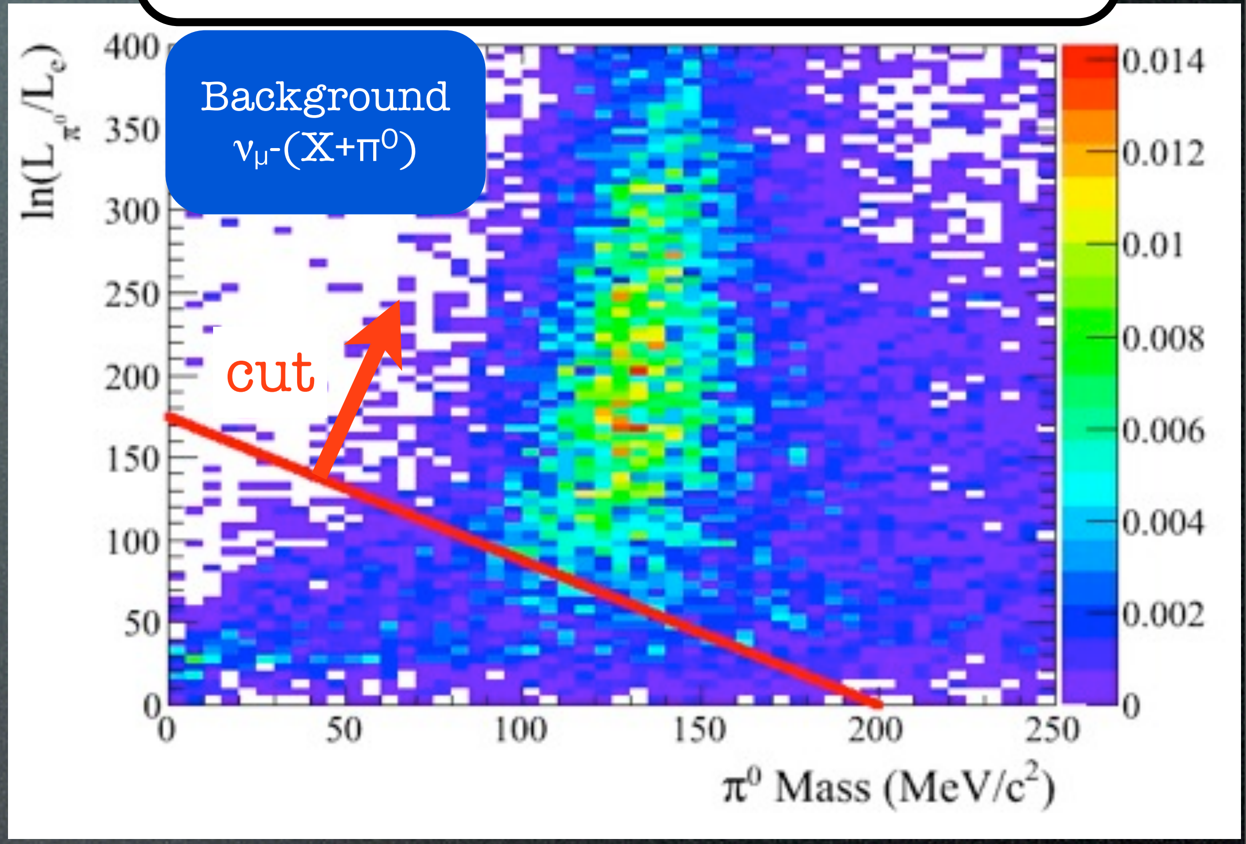


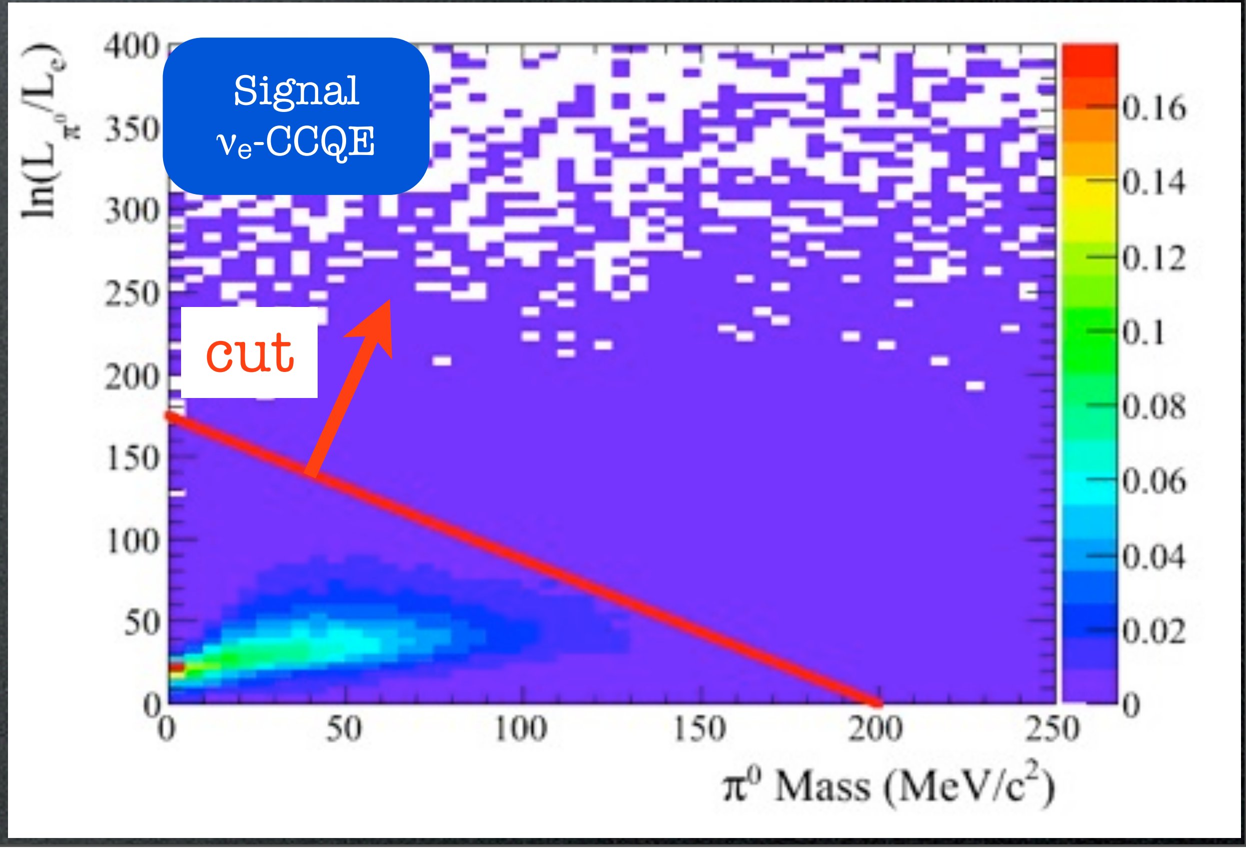


Enhanced π^0 Rejection

- fiTQun can also use the best-fit **likelihood ratio** to distinguish e^- from π^0
- 2D cut **removes 70% of the remaining π^0 background** allowed by APFit for the same signal efficiency
  - Beam ν_e background does not change significantly
- Total background is reduced by 27%
  - 6.36 events → 4.64 events (for full Run 1-4 dataset)

Likelihood Ratio vs π^0 Mass
(T2K Monte Carlo)

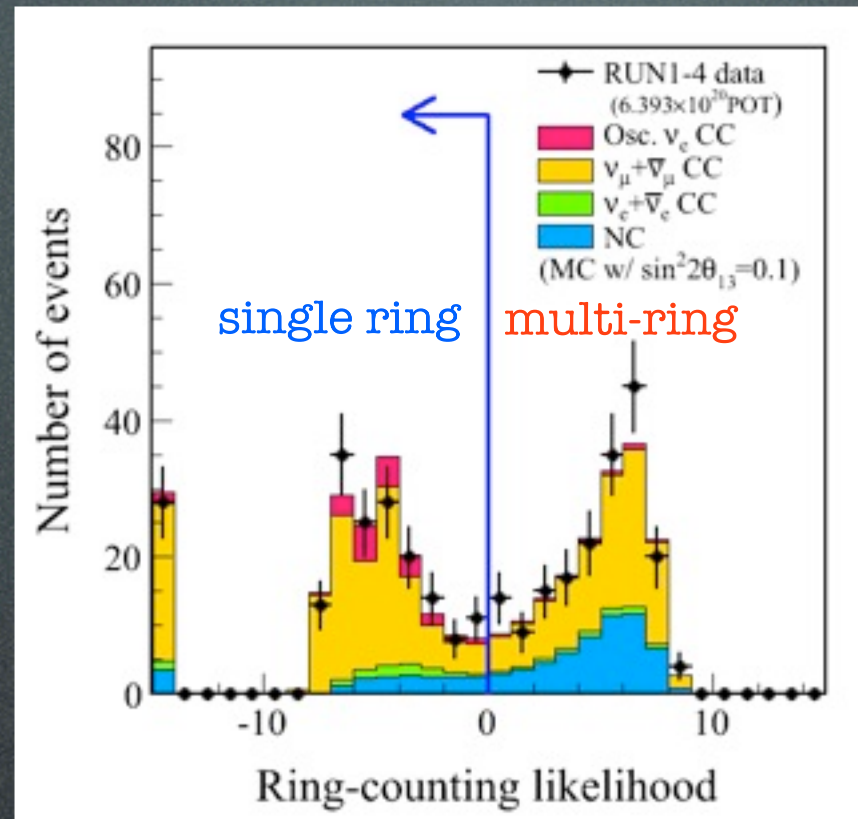


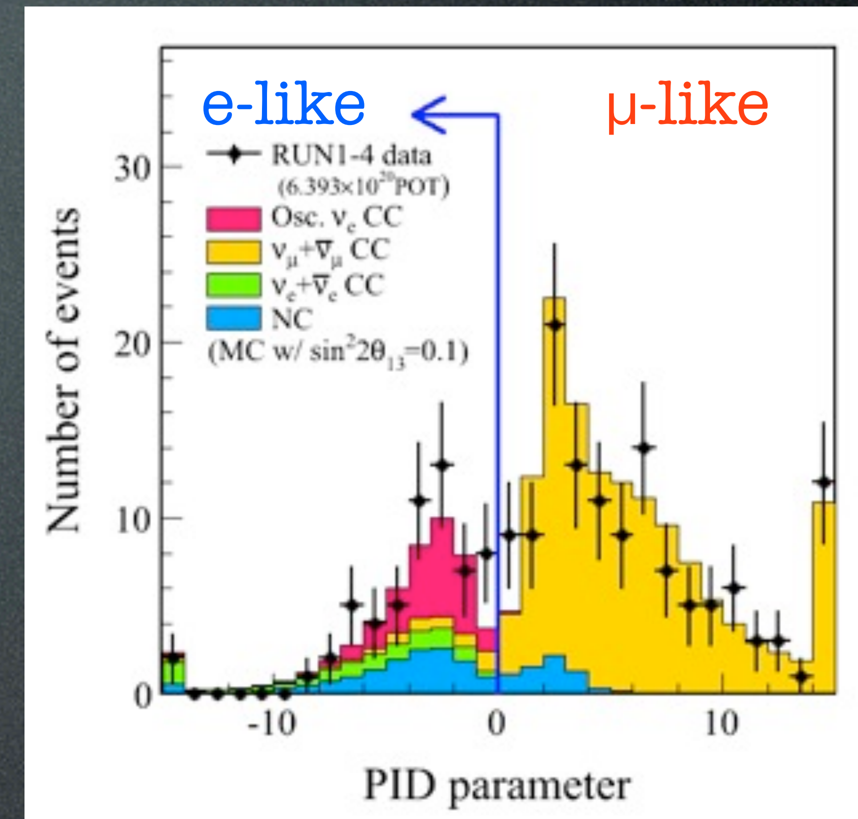


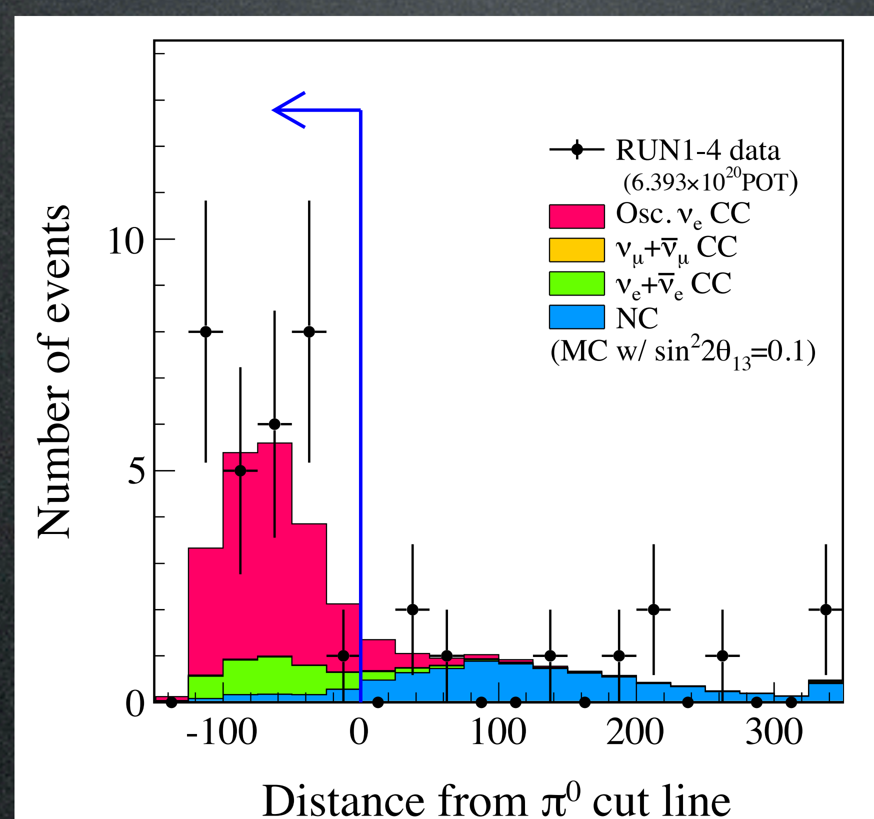
T2K ν_e Event Selection

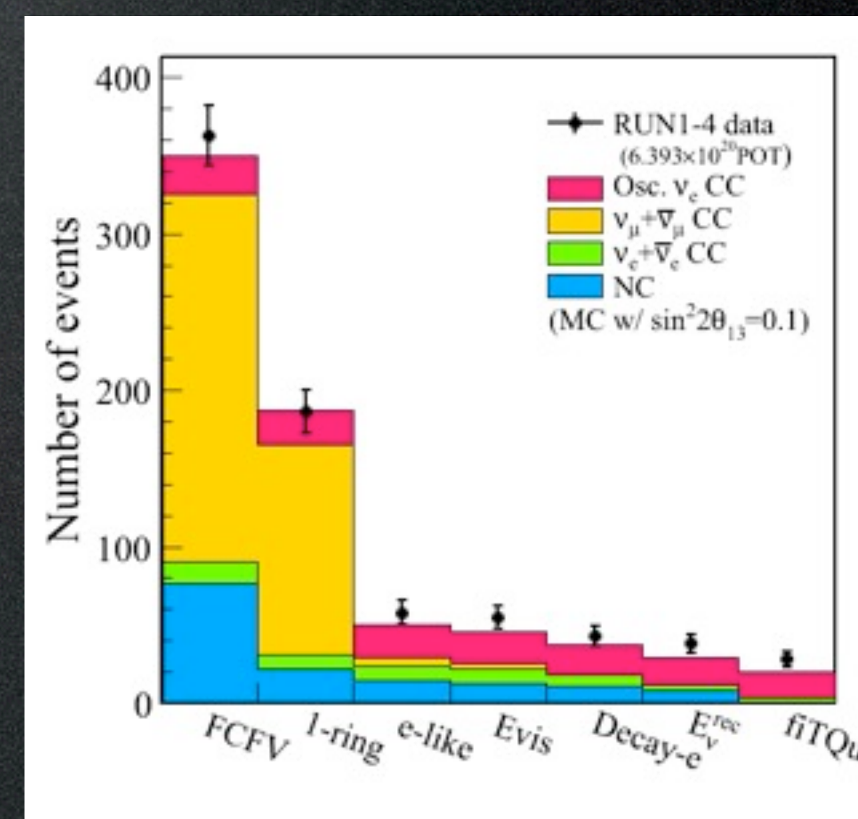
ν_e Selection Cuts

- # veto hits < 16
- Fid. Vol. = 200 cm
- # of rings = 1
- Ring is e-like
- $E_{visible}$ > 100 MeV
- no Michel electrons
- fiTQun π^0 cut
- 0 < E_ν < 1250 MeV



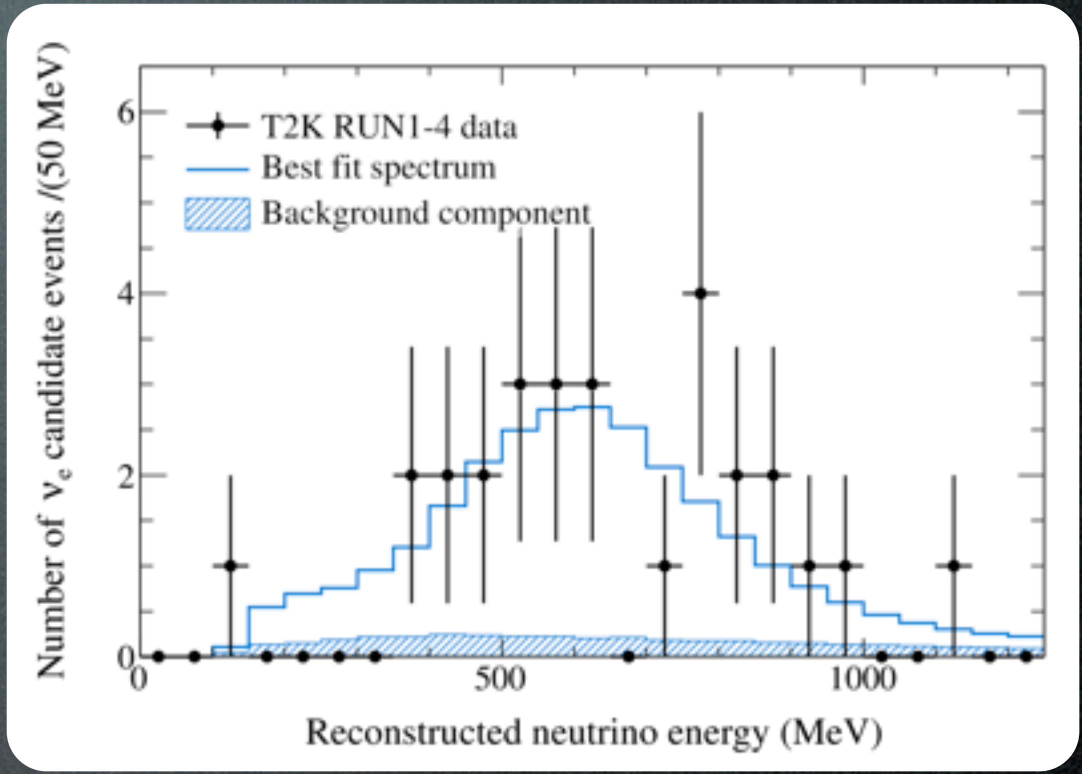


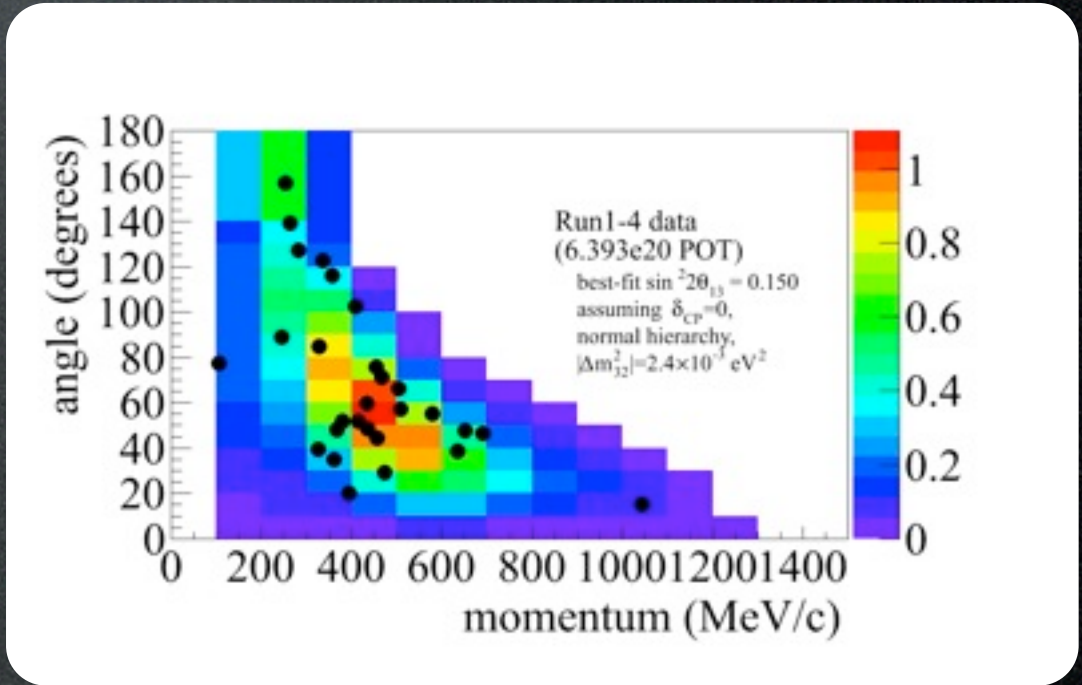




ν_e Appearance Analysis

- 4.64 ± 0.53 background events
- 20.4 ± 1.8 events expected
  - For $\sin^2 2\theta_{13}=0.1$, $\sin^2 2\theta_{23}=1$, $\delta_{CP}=0$, and normal mass hierarchy
  - **5.5σ sensitivity to exclude $\theta_{13} = 0$**
- Oscillation parameters were extracted in 2 different ways:
  - using the E_ν distribution
  - using the p-θ distribution

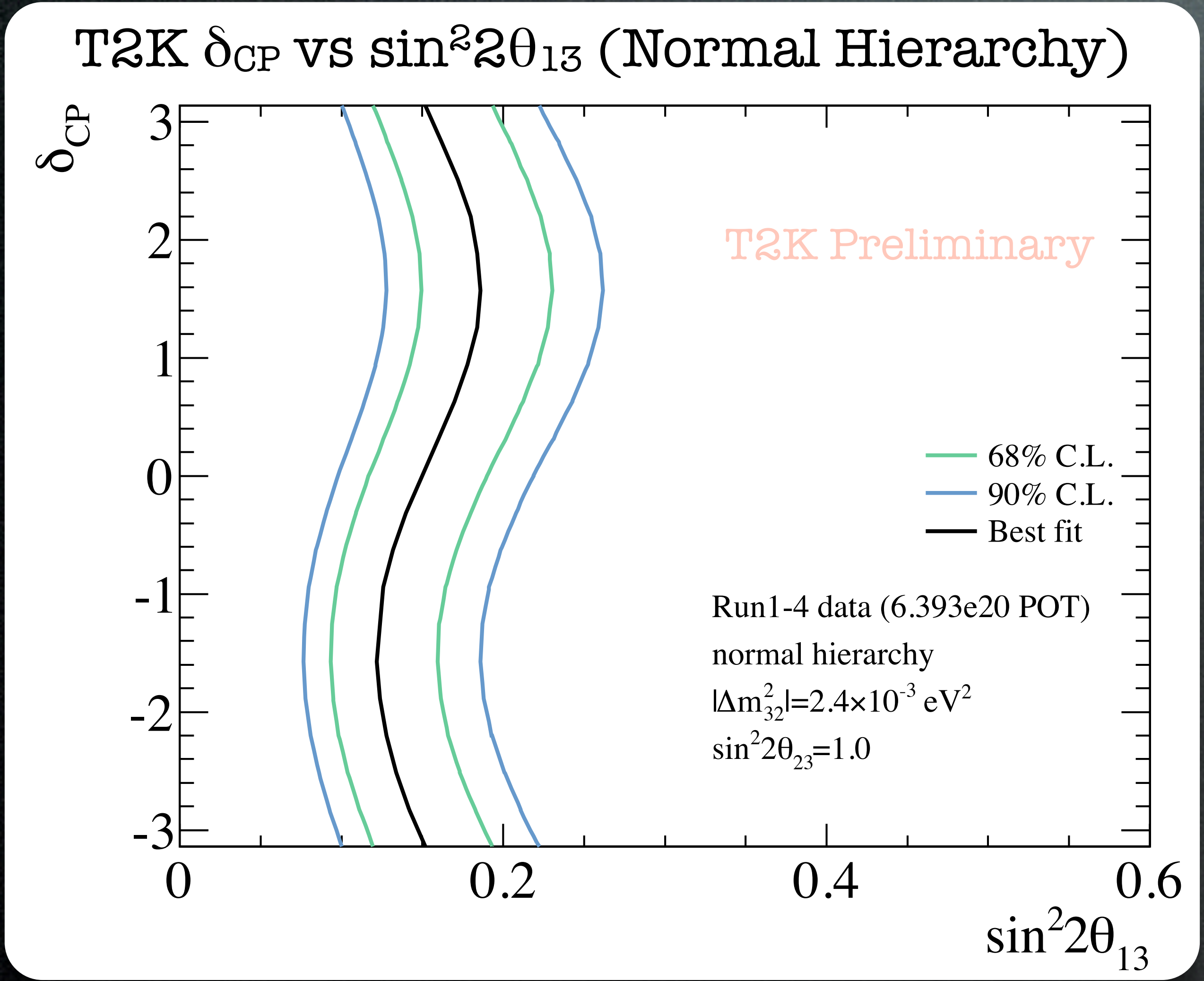


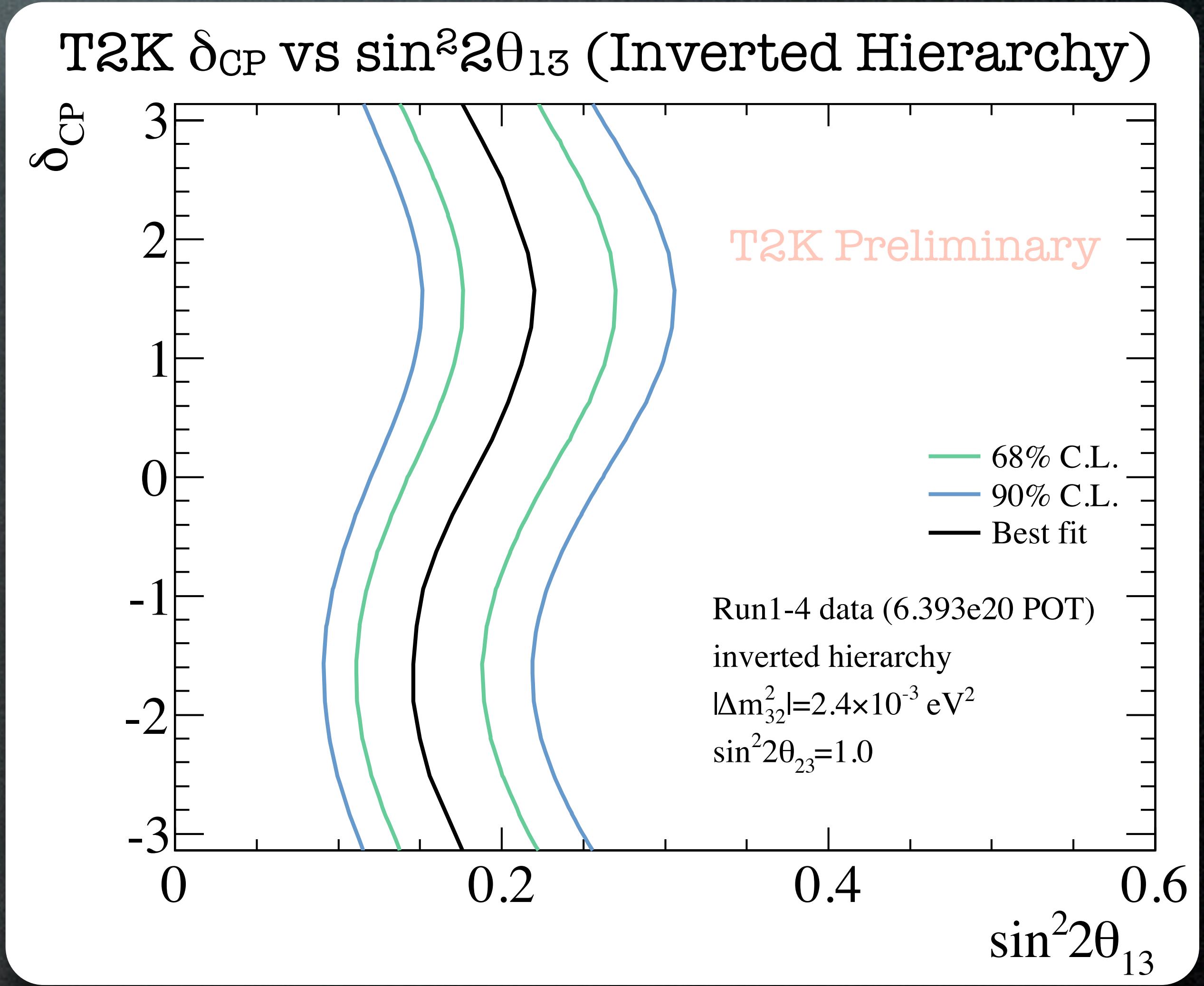


ν_e Appearance Results

- **Observed 28 events** (expected 20.4 ± 1.8 for $\sin^2 2\theta_{13}$=0.1)
- Comparing the best p-θ fit likelihood to null hypothesis gives a **7.5σ significance for non-zero θ_{13}**

(For $\sin^2 2\theta_{23}$=1, δ_{CP}=0, and normal mass hierarchy)



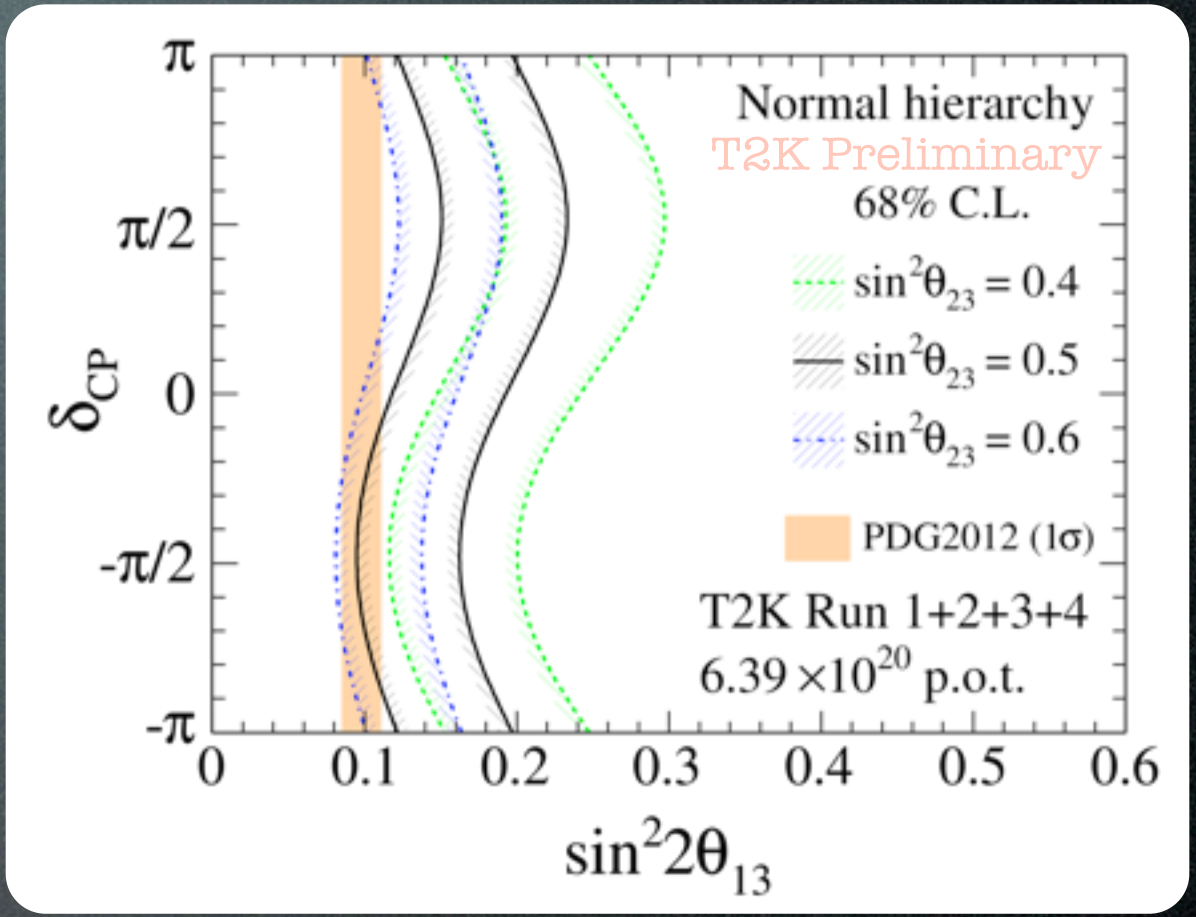


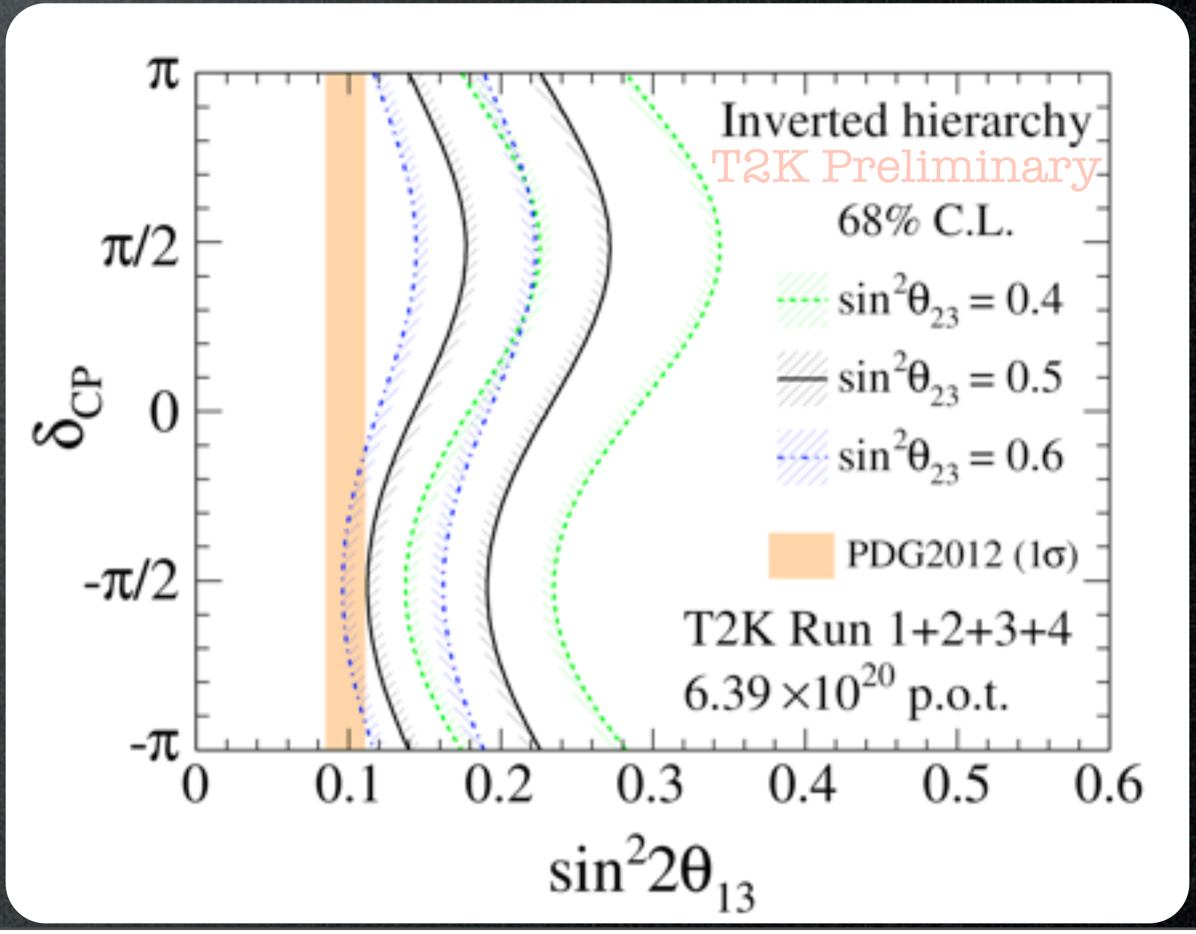
First ever observation (>5σ) of an explicit ν appearance channel

Effect of θ_{23} Uncertainty

- ν_e appearance probability also depends on the value of θ_{23}
- If θ_{23} is fixed at values near the edge of the current allowed region, the fit contours shift
- Future improved measurements of θ_{23} will be important to extract information about other oscillation parameters (including δ_{CP}) in long-baseline experiments
  - A T2K combined ν_e+ν_μ analysis is underway

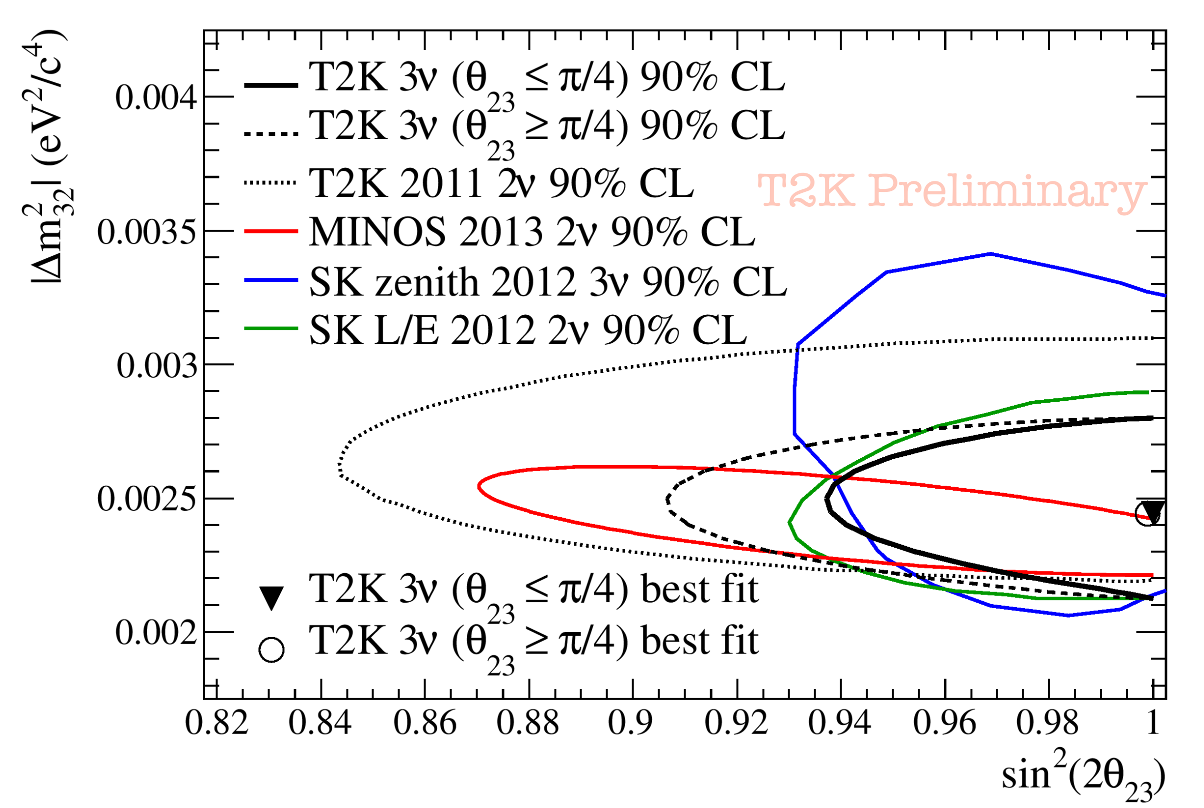
Note: these are 1D contours for various values of δ_{CP}, not 2D contours

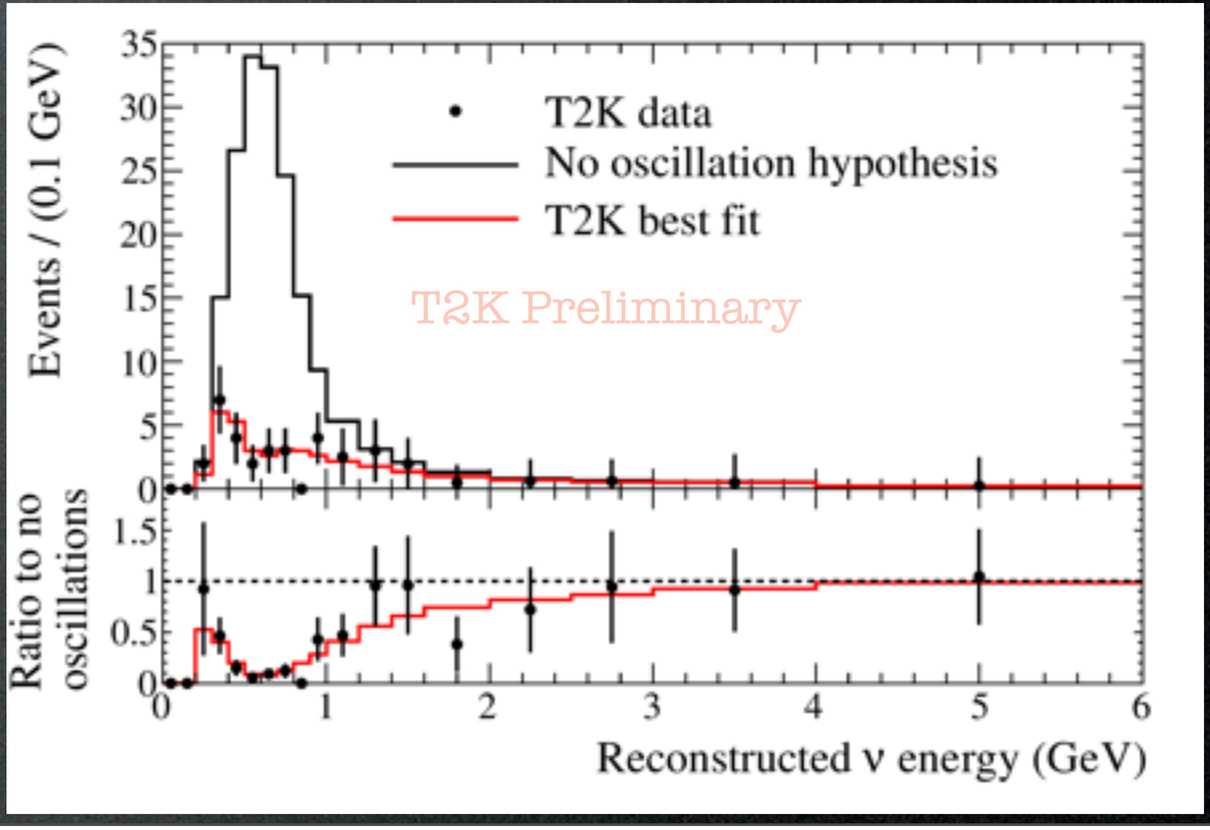




Updated ν_μ Disappearance Results

- Preliminary results using Run 1-3 data ($3.01 * 10^{20}$ POT) were first shown earlier this year
- Previous contours for $\sin^2 2\theta_{23}$ assumed $\theta_{23} < \pi/4$ (first octant)
    - However, octant choice can significantly affect the shape of the 90% C.L. contour
- Contours for both octants are now provided (below)
- In the future, results will be reported in $\sin^2\theta_{23}$ rather than $\sin^2 2\theta_{23}$





Summary

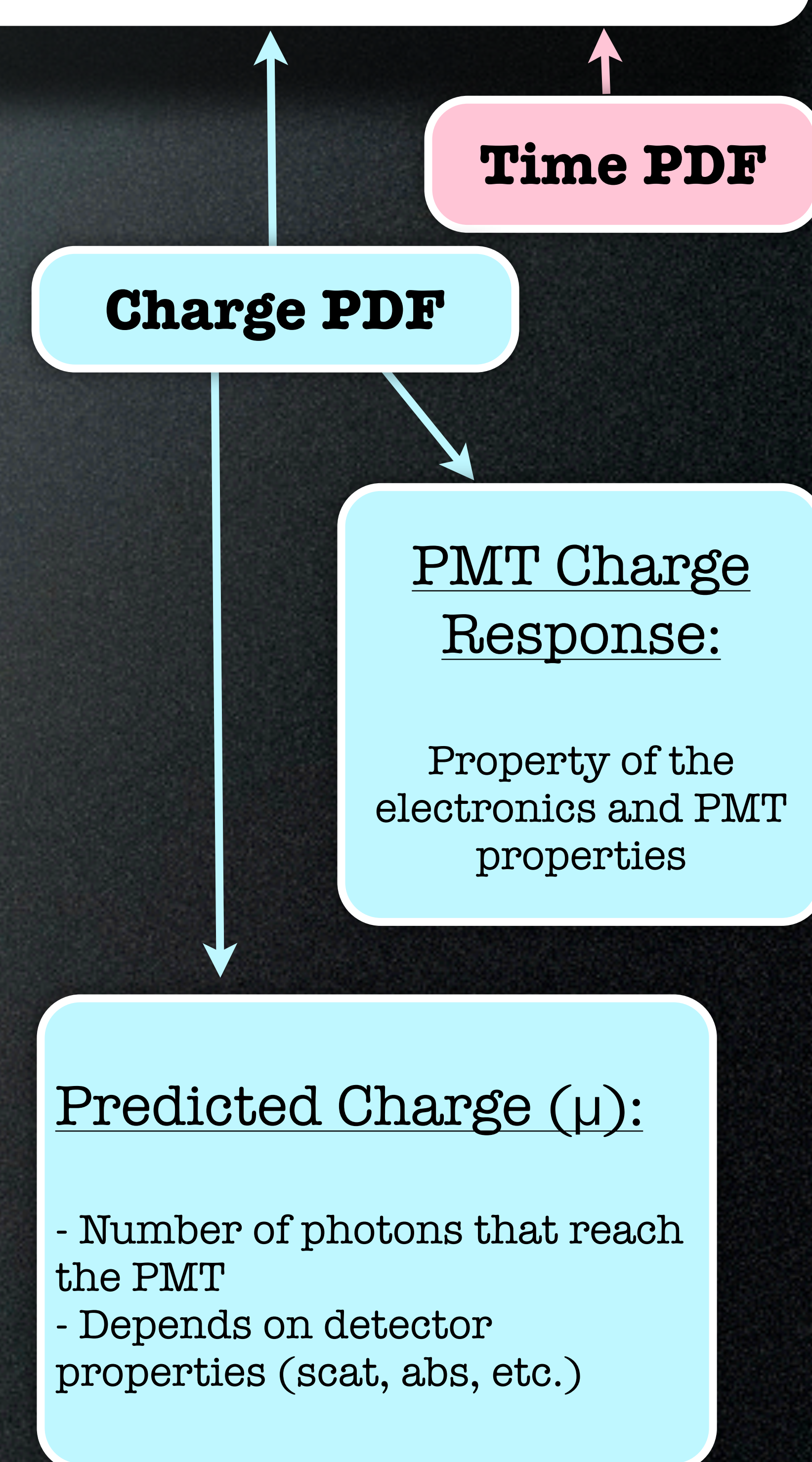
- **T2K has made an observation of ν_e appearance from a ν_μ beam**
  - **θ_{13}=0 is excluded with a significance of 7.5σ (δ_{CP}=0, $\sin^2 2\theta_{23}$=1)**
- J-PARC achieved steady operation at 220 kW for much of Run 4
- We have now analyzed $6.39 * 10^{20}$ POT accumulated by April 12th, 2013
  - This is 2.1 times the Run 1-3 data used for the 2012 analysis
- Analysis improvements have significantly enhanced the sensitivity to ν_e appearance (from below 5σ to 5.5σ)
  - Near detector event selection now contains a CC1π^+ sample
  - The new fiTQun reconstruction algorithm removes 70% of the π^0 background relative to the previous analysis
    - More improvement is expected as fiTQun becomes more fully integrated into T2K analyses
- The ν_μ disappearance contours are sensitive to the octant chosen
  - Both contours are now provided

Supplemental Slides

The fiTQun Likelihood Fit

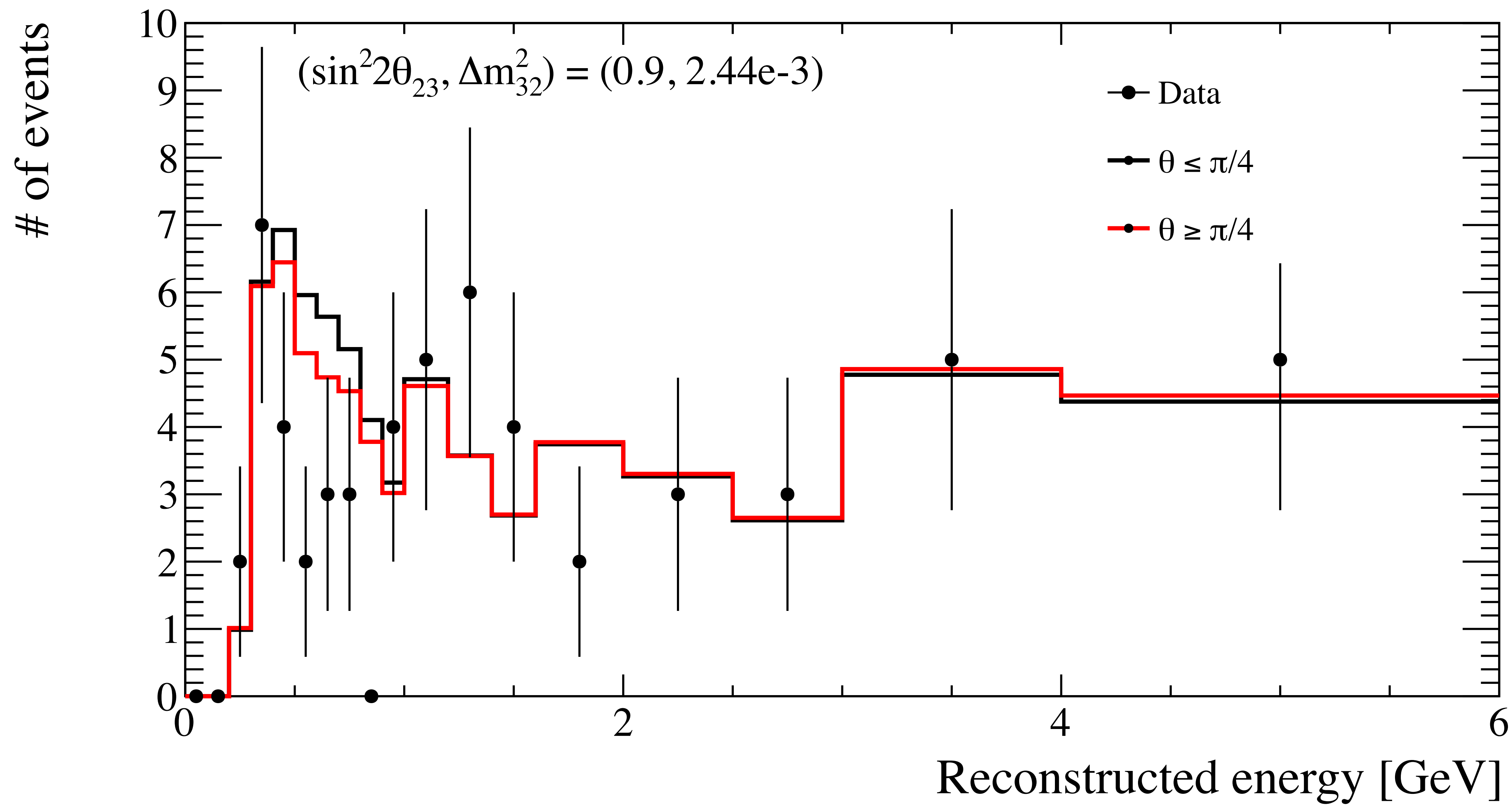
$$L(\mathbf{x}) = \prod_{\text{unhit}} P(i\text{unhit}; \mathbf{x}) \prod_{\text{hit}} P(i\text{hit}; \mathbf{x}) f_q(q_i; \mathbf{x}) f_t(t_i; \mathbf{x})$$

- A single track in the detector can be specified by a **particle type**, and **7 kinematic variables** (represented above as the vector **x**):
  - A vertex position **(X, Y, Z, T)**
  - A track momentum **(p)**
  - A track direction **(θ, φ)**
- For a given **x**, a charge and time probability distribution function (PDF) is produced for every PMT
- All 7 track parameters **fit simultaneously**
- **For particle ID**: compare final likelihoods for different particle hypotheses



ν_μ disappearance results using 3.01×10^{21} POT

Fit spectra @ $(\sin^2 2\theta_{23}, \Delta m_{32}^2) = (0.9, 2.44\text{e-}3)$

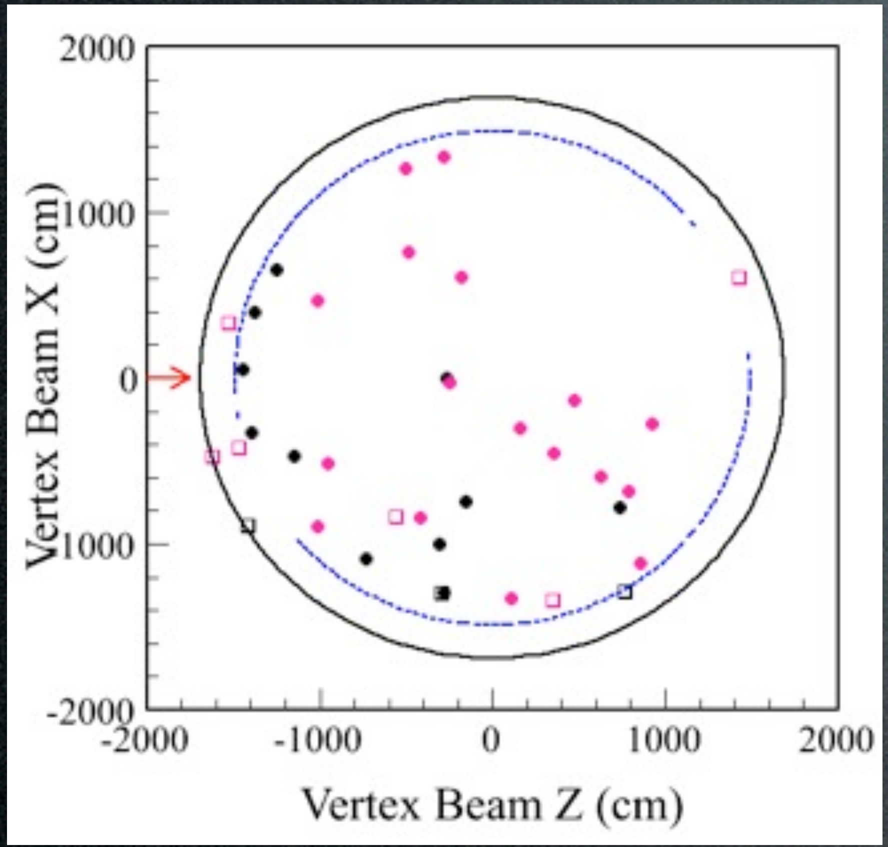


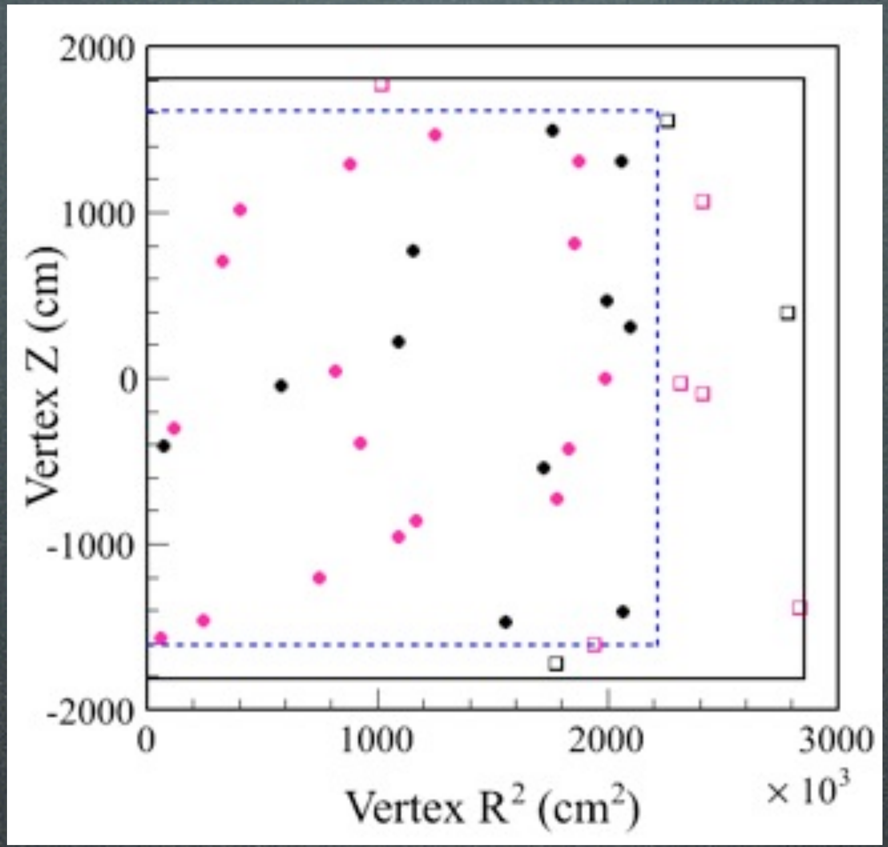
$$P(\nu_\mu \rightarrow \nu_\mu) \sim 1 - \left(\cos^4\theta_{13}\cdot\sin^2 2\theta_{23} + \sin^2 2\theta_{13}\cdot\sin^2\theta_{23}\right)\cdot\sin^2\frac{\Delta m^2_{31}\cdot L}{4E}$$

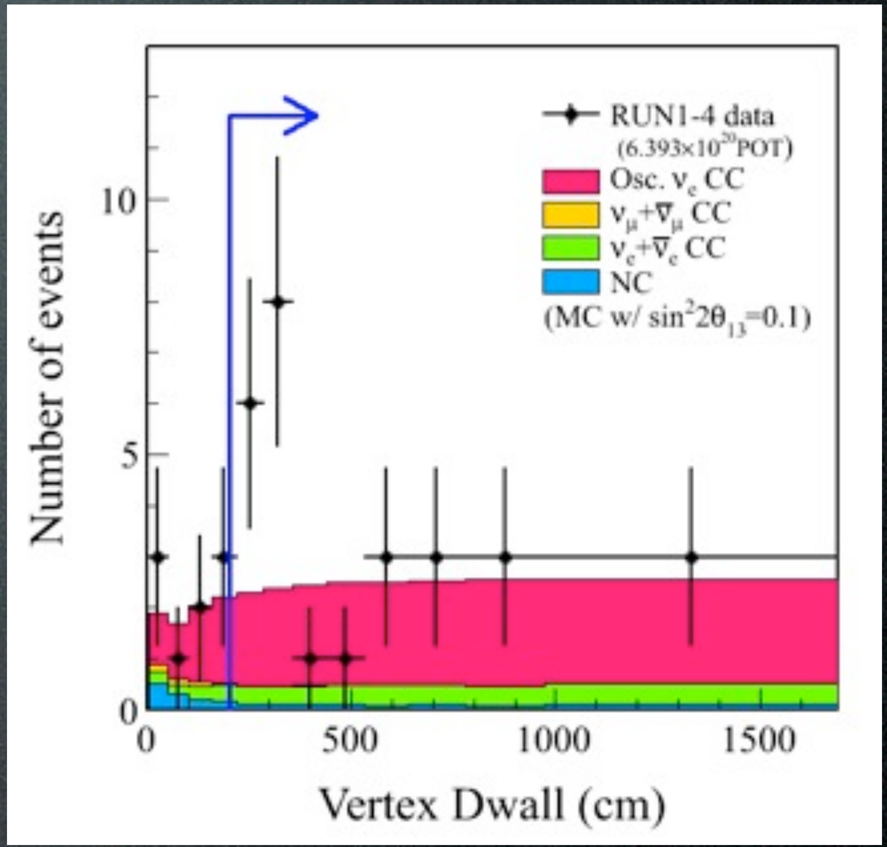
Leading

Next-to-leading

Far Detector ν_e Vertex Distribution



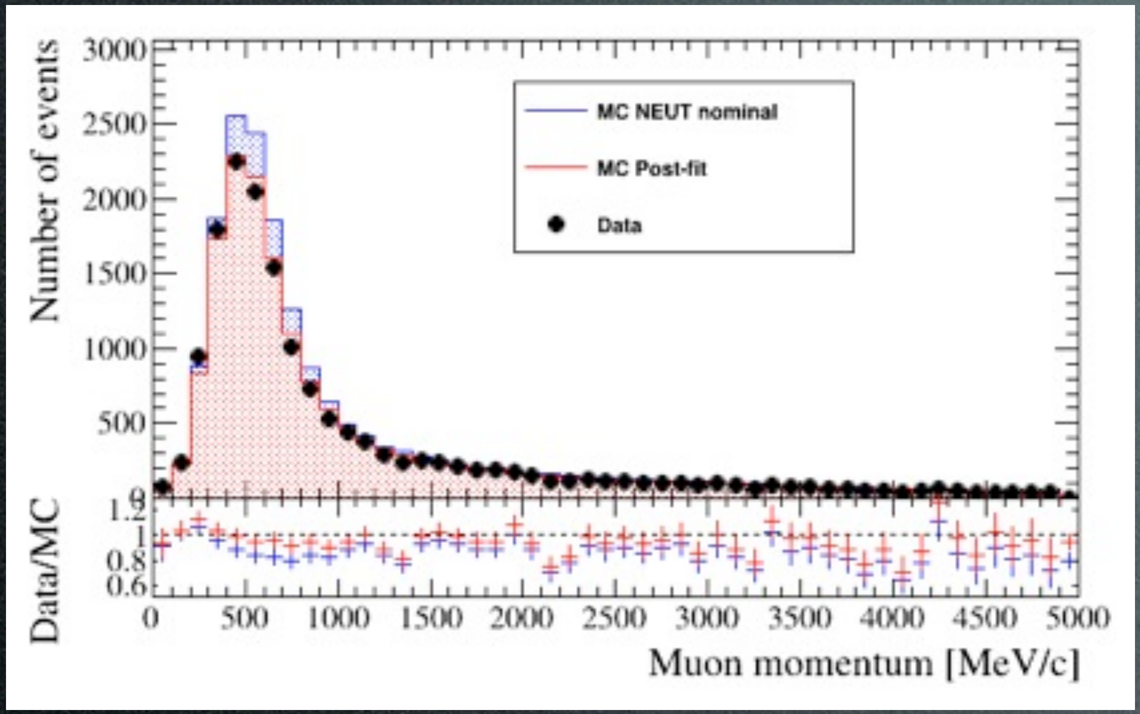


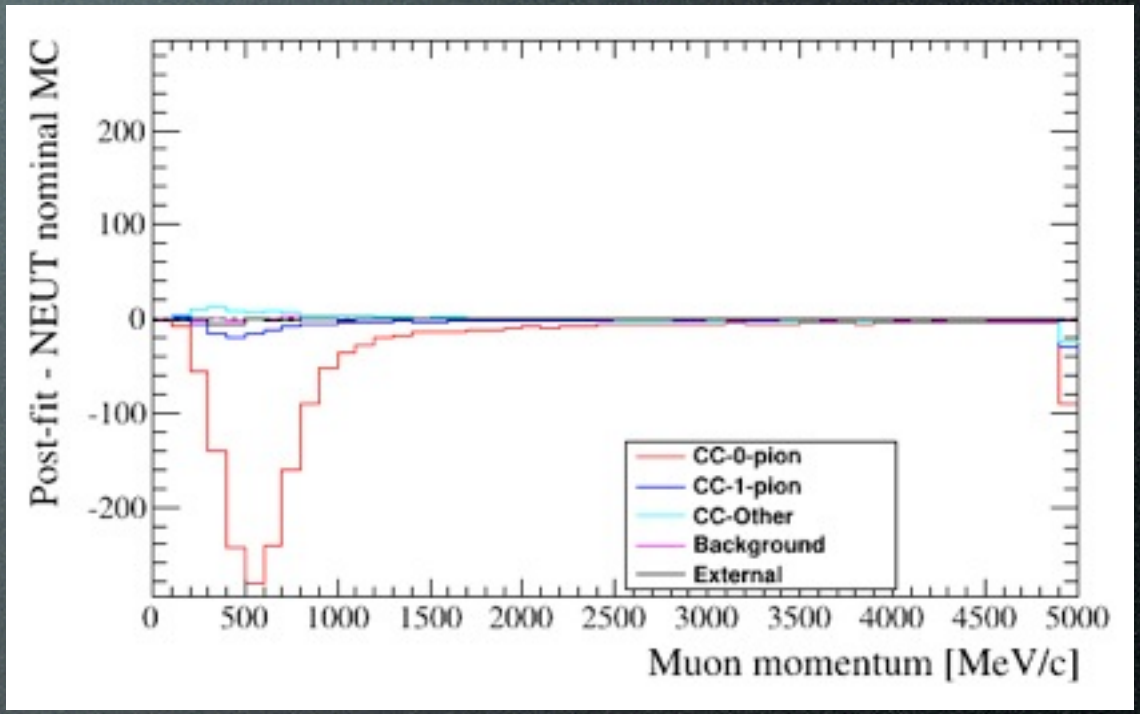


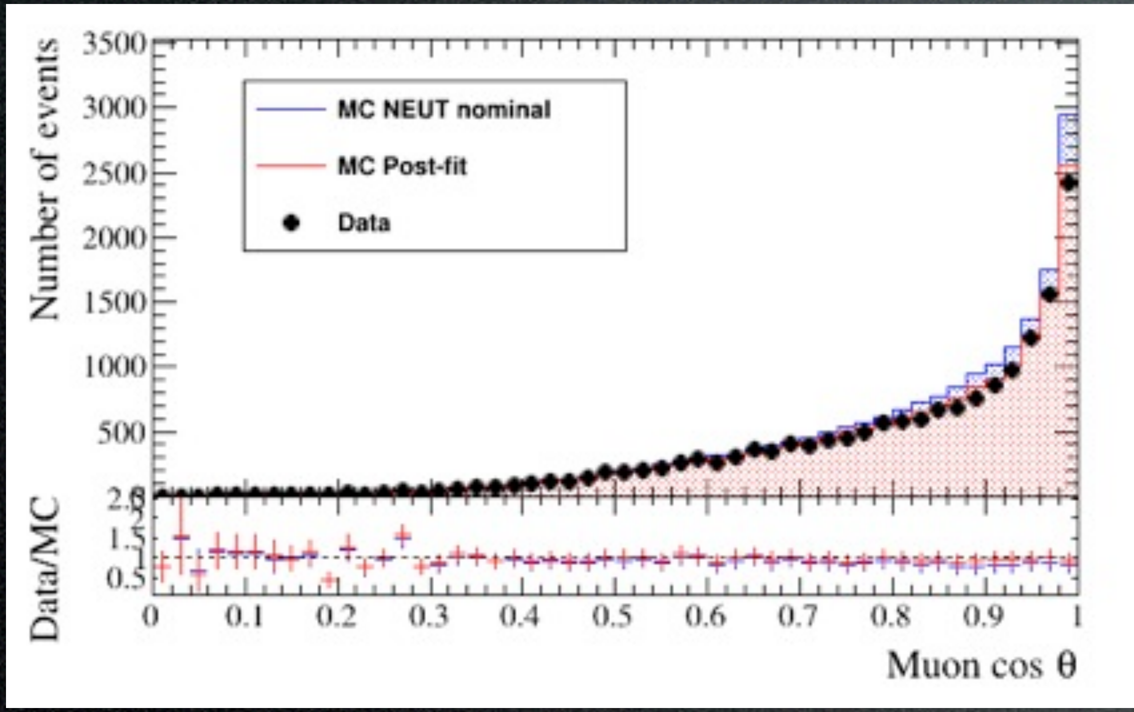
	RUN1+2+3	RUN4	RUN1+2+3+4
Dwall	34.4%	54.7%	20.9%
Fromwall beam$_{\|\|}$	6.04%	85.6%	8.93%
$R^2 + Z$	32.4%	98.1%	64.5%

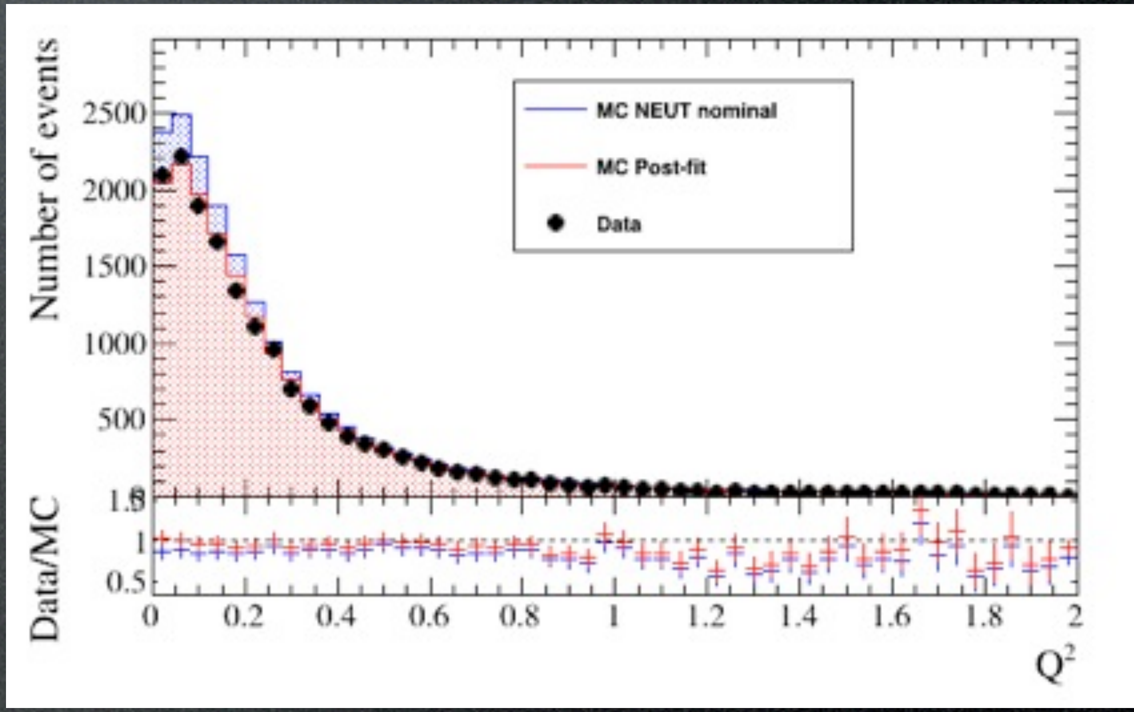
- With increased statistics, the p-values for the test distributions have increased

Near Detector CC0pi Post-Fit



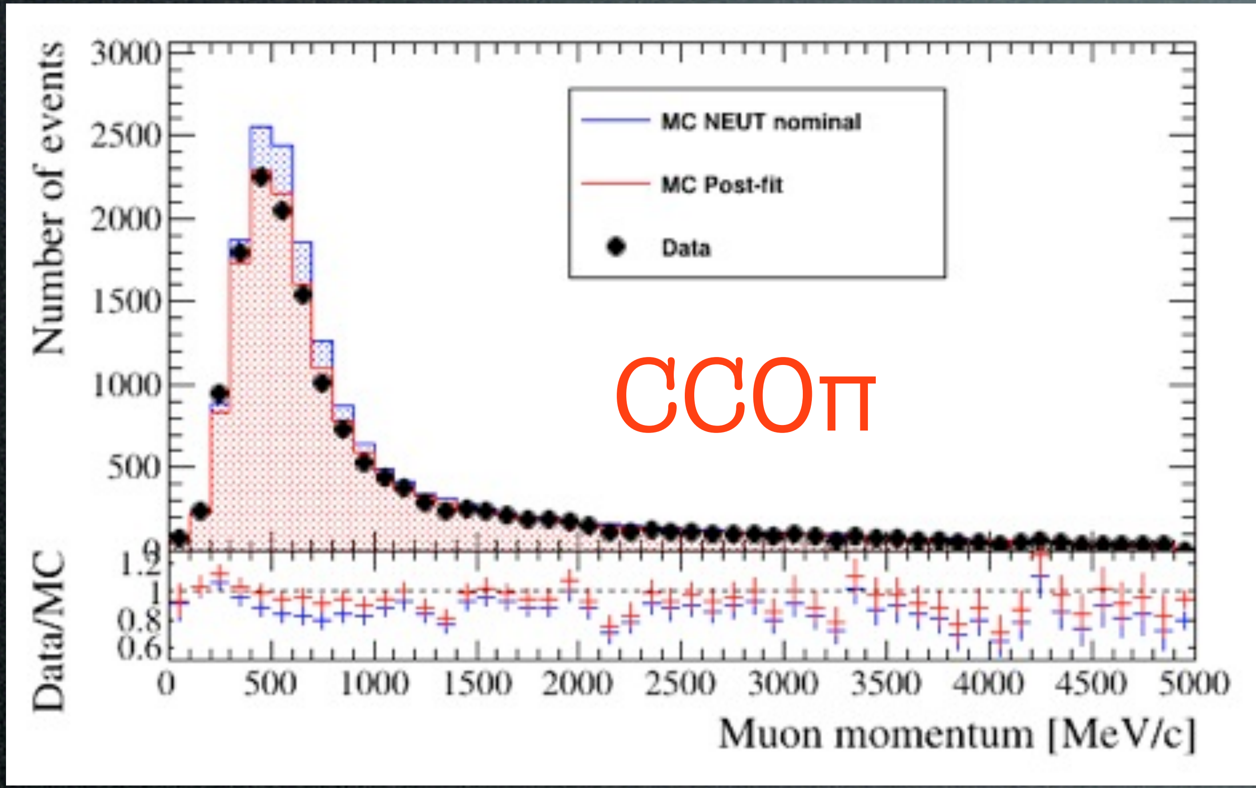


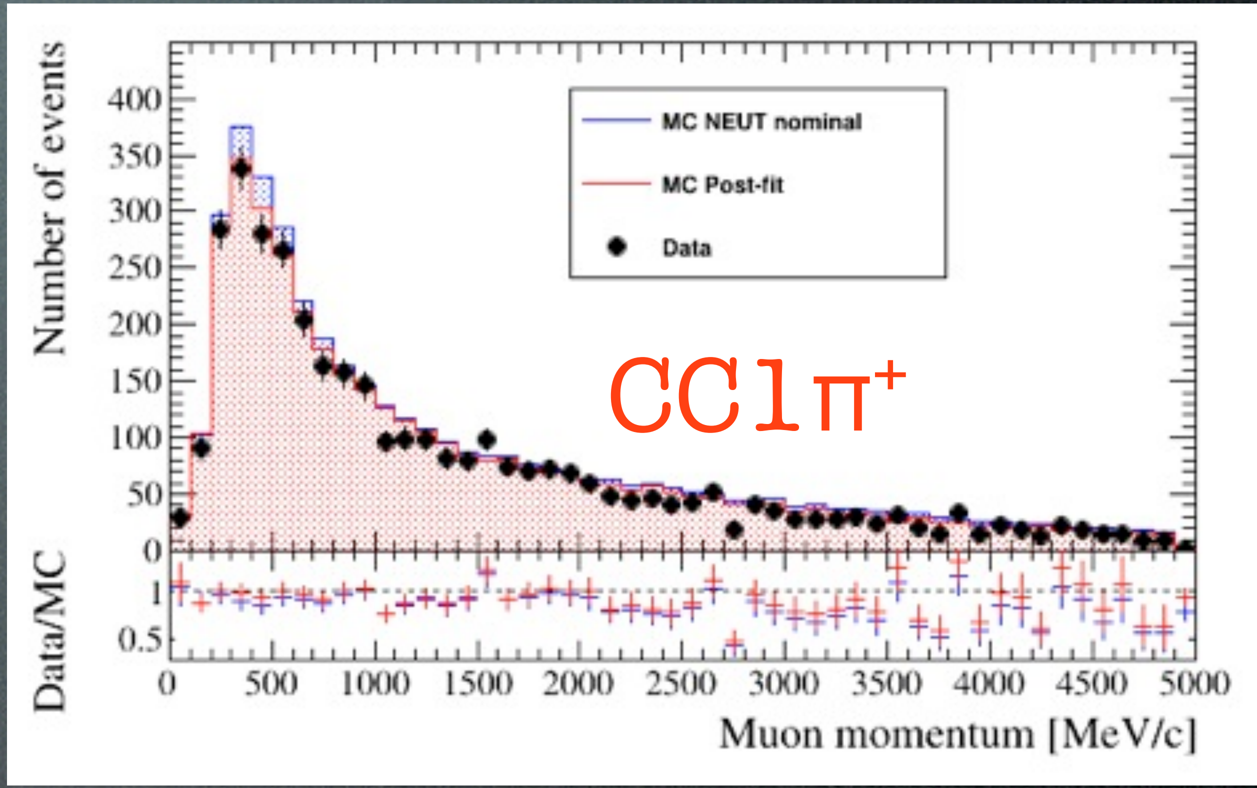


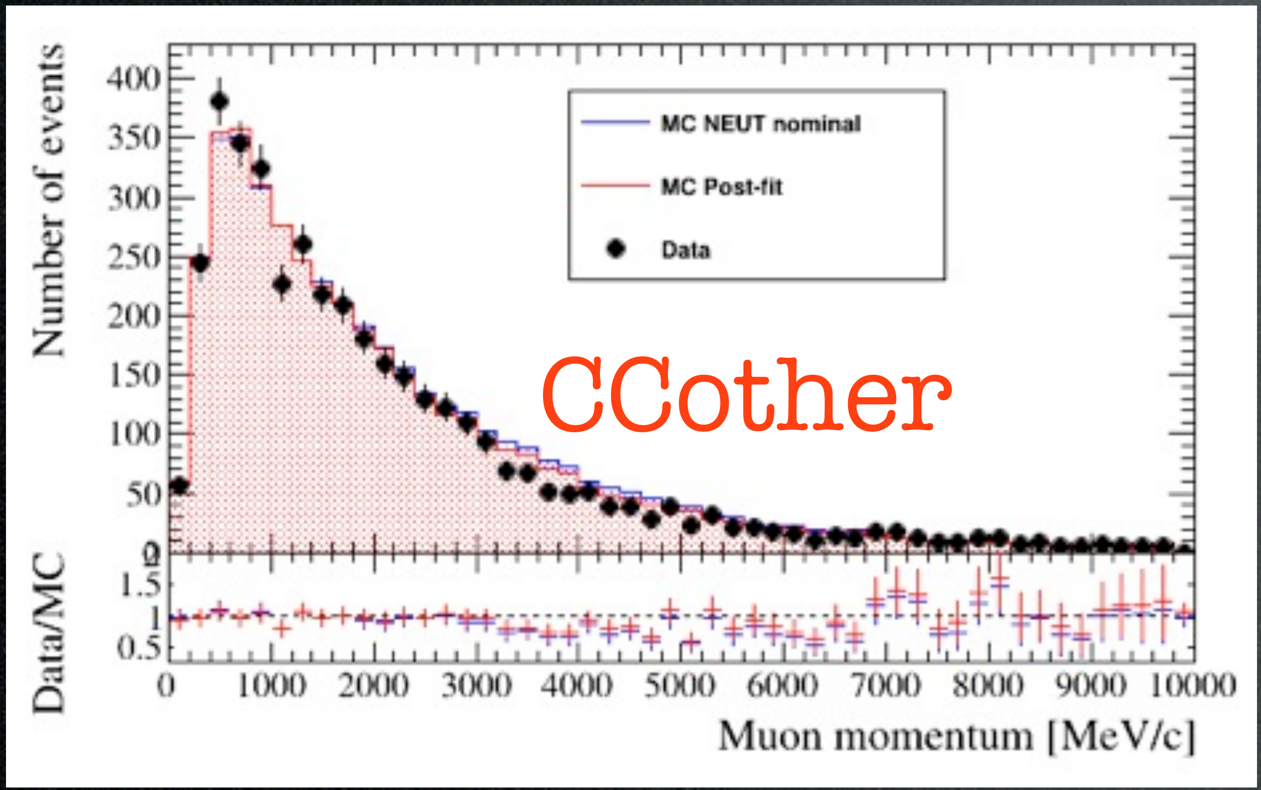


- Agreement between data and MC is significantly improved by the near detector constraint

Near Detector Post-Fit: All Samples

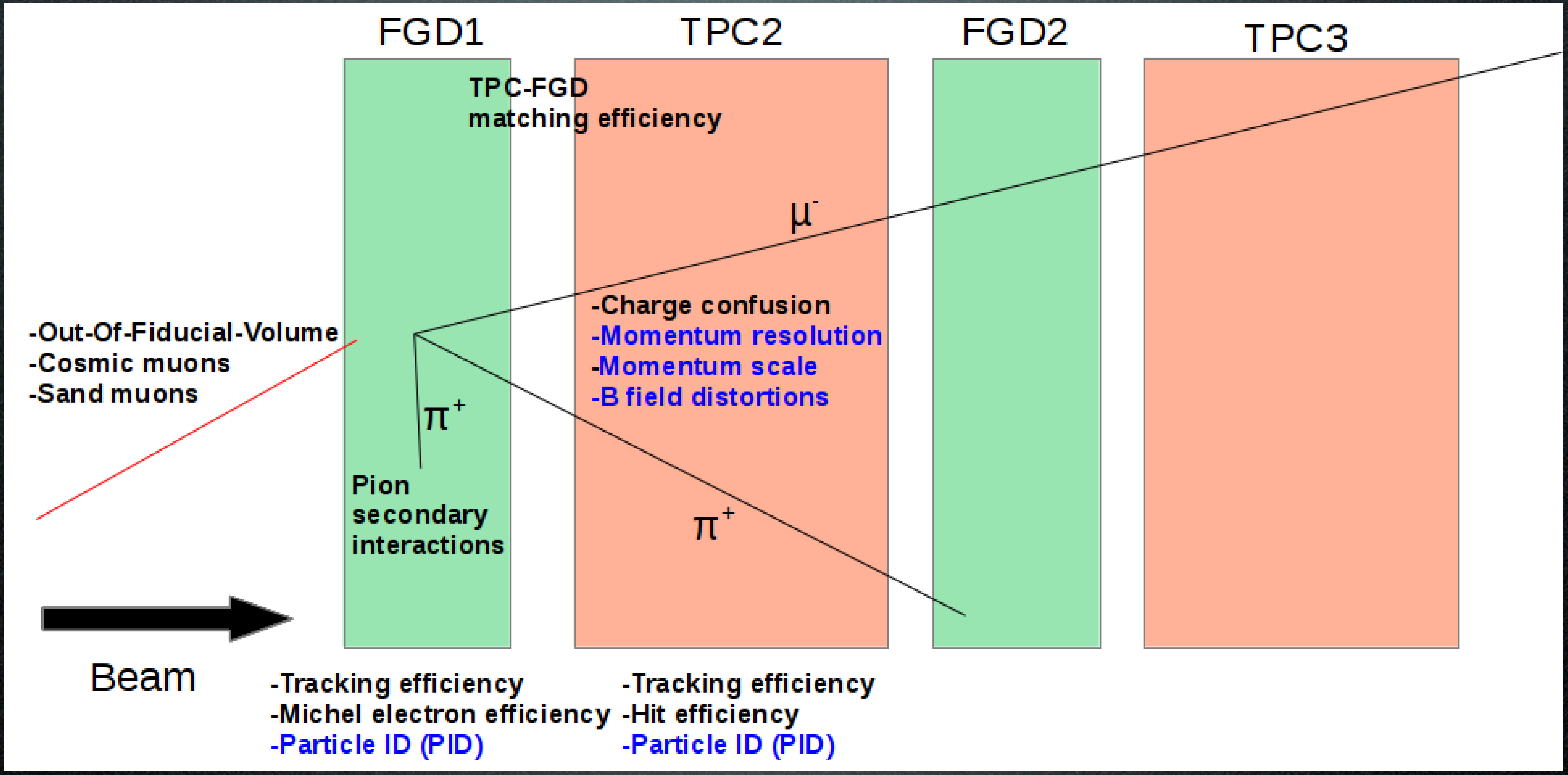






data/MC agreement is improved by the near detector constraint

ND280 Systematic Errors



Matter Effects and δ_{CP}

$$P(\nu_\mu \rightarrow \nu_e) \cong \sin^2 2\theta_{13}\, T_1 - \alpha \sin 2\theta_{13}\, T_2 + \alpha \sin 2\theta_{13}\, T_3 + \alpha^2\, T_4$$

$$T_1 = \sin^2\theta_{23} \sin^2[(1-x_\nu)\Delta]/(1-x_\nu)^2$$
$$T_2 = \sin\delta \sin 2\theta_{12} \sin 2\theta_{23} \sin\Delta \sin(x_\nu\Delta)/x_\nu \sin[(1-x_\nu)\Delta]/(1-x_\nu)$$
$$T_3 = \cos\delta \sin 2\theta_{12} \sin 2\theta_{23} \cos\Delta \sin(x_\nu\Delta)/x_\nu \sin[(1-x_\nu)\Delta]/(1-x_\nu)$$
$$T_4 = \cos^2\theta_{23} \sin^2 2\theta_{12} \sin^2(x_\nu\Delta)/x_\nu^2$$

$$\Delta \equiv \Delta m^2_{31} L/4E, \quad \alpha \equiv \Delta m^2_{21}/\Delta m^2_{31} \sim 1/30, \quad x_\nu \equiv 2\sqrt{2} G_F N_e E/\Delta m^2_{31}$$