

Recent Results from T2K

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For T2K

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Outline

- Neutrino mixing review
- The T2K experiment
 - Near and Far Detectors
 - Constraining systematics with the Near Detector
- Nue Appearance Results
- NuMu Disappearance Results
 - New preliminary results!

Neutrino Mixing

Neutrino flavor states are not mass eigenstates: $|\nu_i\rangle = \sum U_{\alpha i} |\nu_\alpha\rangle$

Matrix U contains 3 angles ($\theta_{12}, \theta_{23}, \theta_{13}$) and one phase (δ)

A useful decomposition:

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

$$U_{\alpha i} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric: $38^\circ < \theta_{23} < 52^\circ$ Super-K, MINOS

CP sector: $\theta_{13} = (9 \pm 0.9)^\circ$ Daya Bay, Reno, T2K

Solar: $\theta_{12} = (34 \pm 1)^\circ$ SNO, KamLAND

Neutrino Mixing

Mass states interfere during neutrino propagation. Probability of observing flavor ν_β after making ν_α depends on :

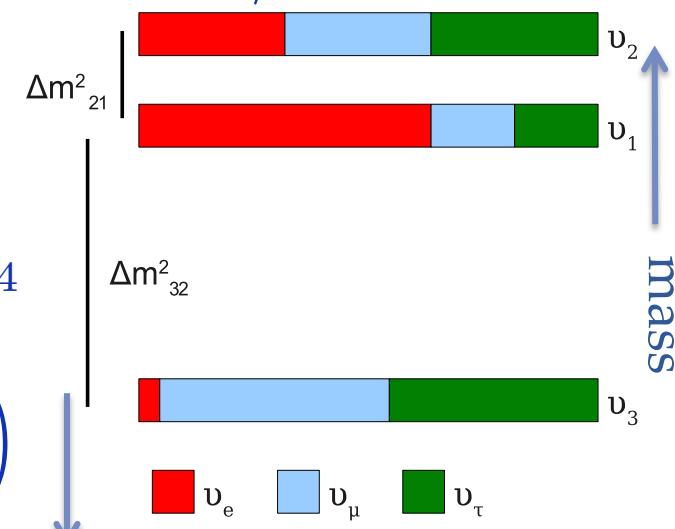
- L : The distance the neutrino has traveled (in km)
- E : The energy of the neutrino (in GeV)
- Δm_{ij}^2 : The mass splitting between the i and j mass eigenstates (in eV 2)

NuMu Disappearance:

$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \sin^2 \left(1.27 \frac{\Delta m_{32}^2 L}{E} \right) \approx 2.43 \times 10^{-3} \text{eV}^2/c^4$$

Nue Appearance:

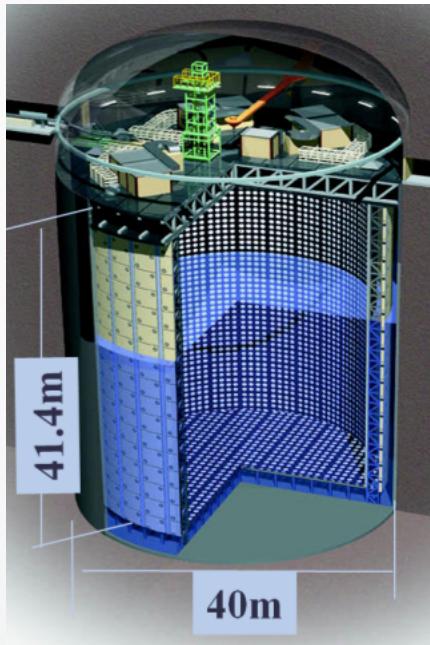
$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2 \theta_{23} \sin^2 2\theta_{13} \sin^2 \left(1.27 \frac{\Delta m_{31}^2 L}{E} \right) \approx 7.6 \times 10^{-5} \text{eV}^2/c^4$$



The T2K Experiment

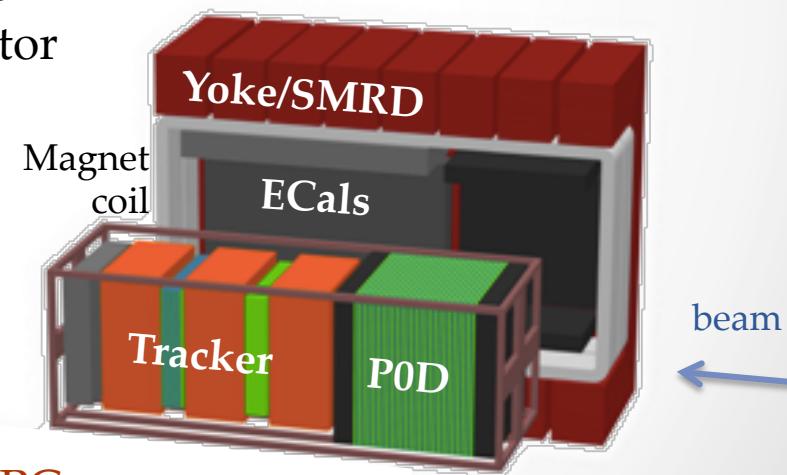
Measure ν_e appearance in a ν_μ beam (θ_{13}), as well as ν_μ disappearance (θ_{23})

Super-K

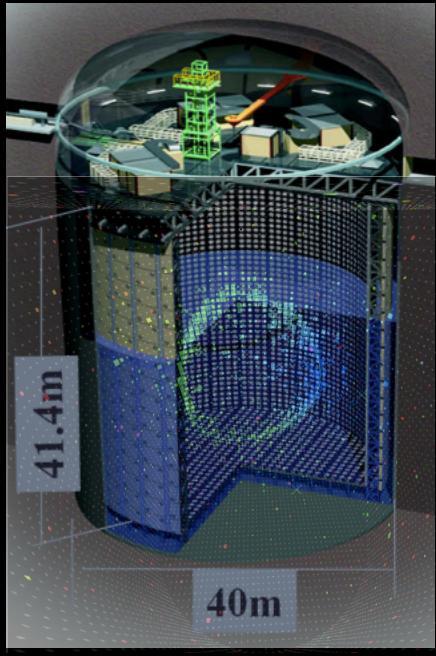


Muon neutrino beam from
JPARC to the Super-
Kamiokande detector

ND280



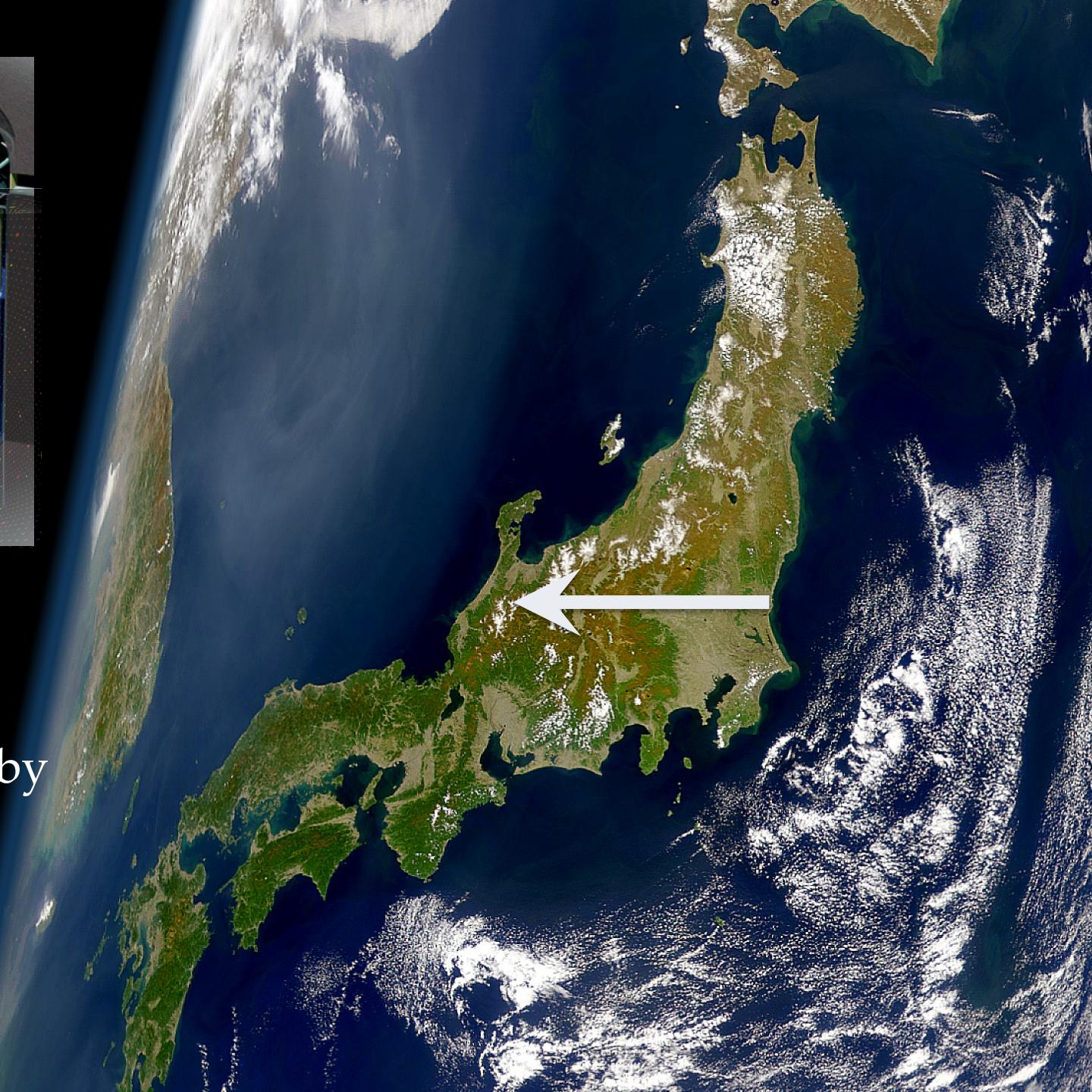
3 gas TPCs
2 fine-grained detectors w/
water, carbon targets



22.5 kT fiducial
volume

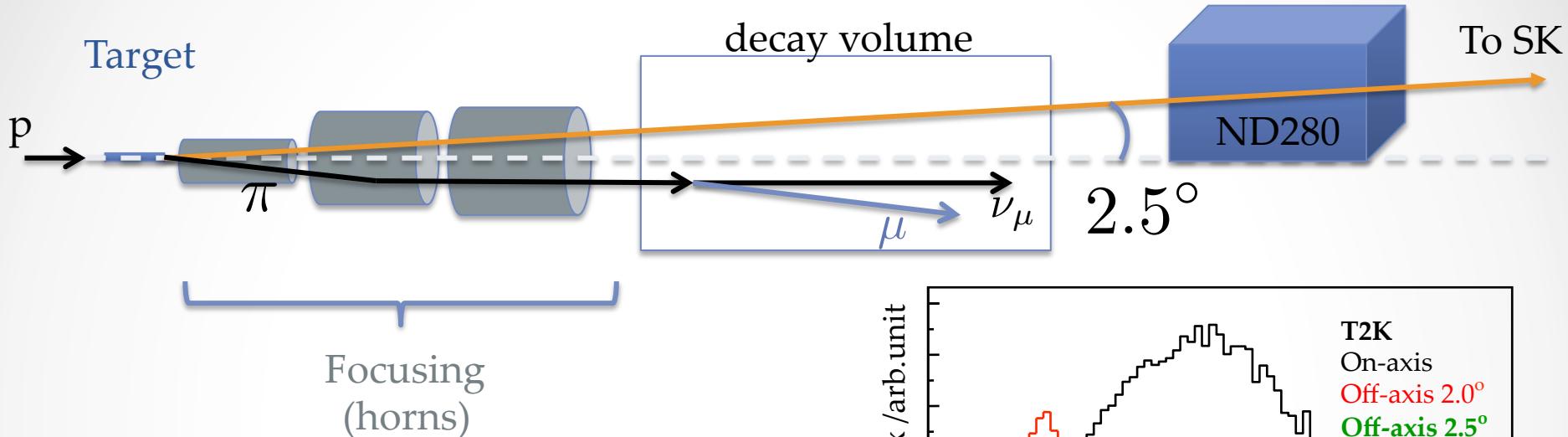
e - μ separation by
Cherenkov ring
topology

295 km from
J-PARC to SK





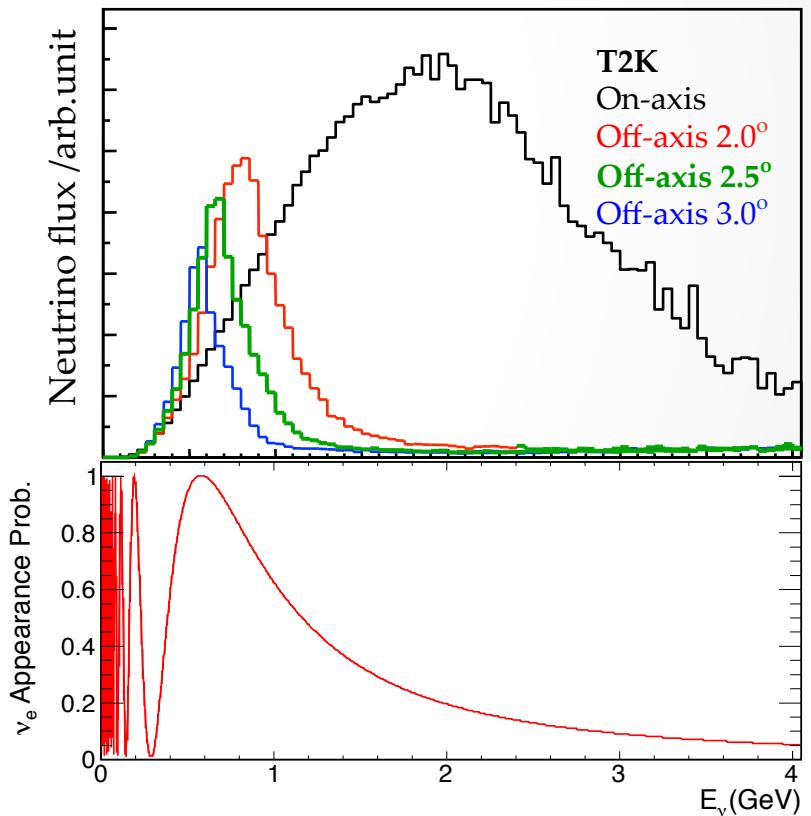
Off-axis neutrino beam



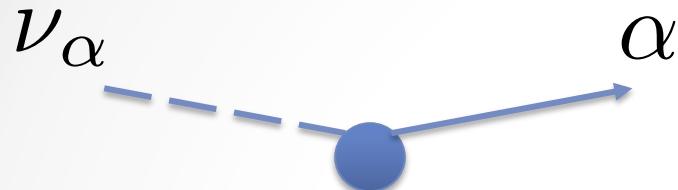
30 GeV protons strike a graphite target producing secondary mesons (π, K) which produce a tertiary neutrino beam

Pion decay kinematics gives a narrow-band neutrino beam off-axis that can be tuned to maximum oscillations

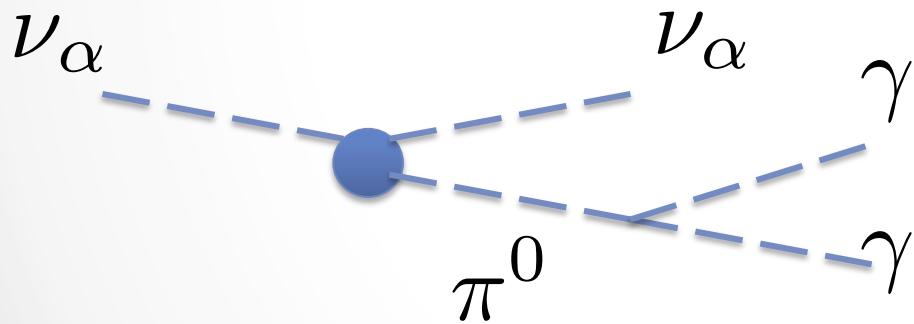
3×10^{20} protons-on-target delivered through Run 3



Neutrino interactions



Charged-Current quasi-elastic:
Neutrino interacts, lepton exits.
1 ring is reconstructed in
Super-K.

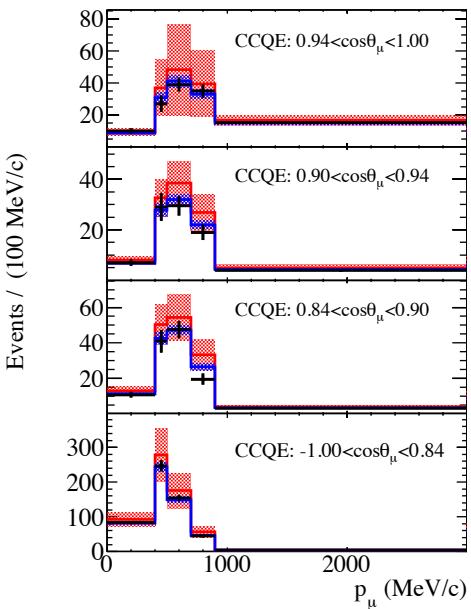


Neutral-Current: Neutrino
interacts, neutrino exits.

Single π^0 with missing γ looks
like an electron. 1 ring is
reconstructed.
This is background.

Constraining Systematics

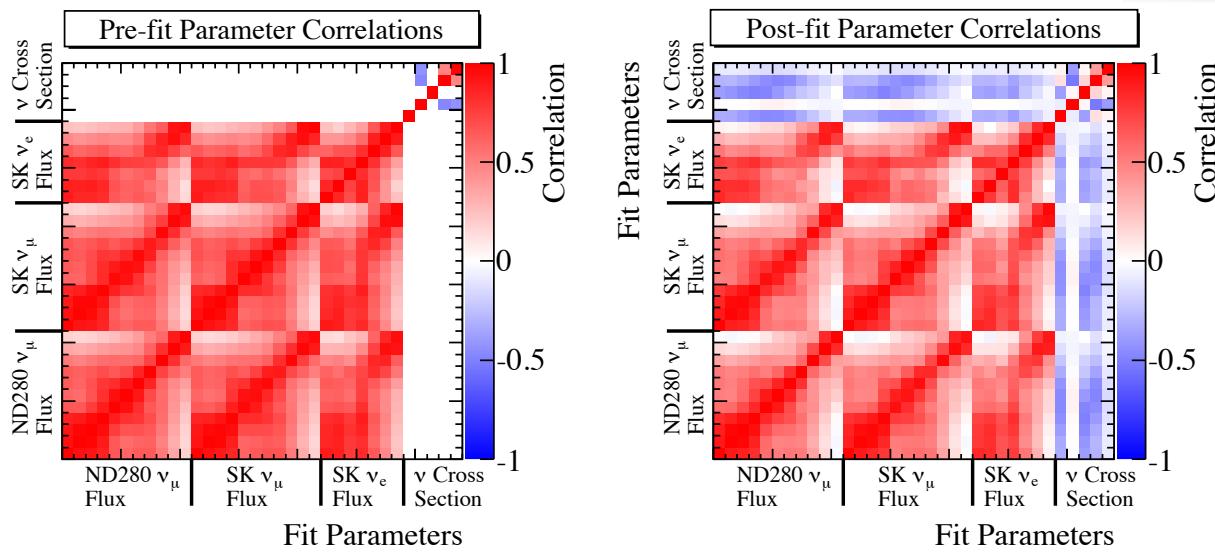
Fit ND280 tracker ν_μ sample in bins of p and θ with all systematic parameters :



Data
With ND280 information
Without ND280 information

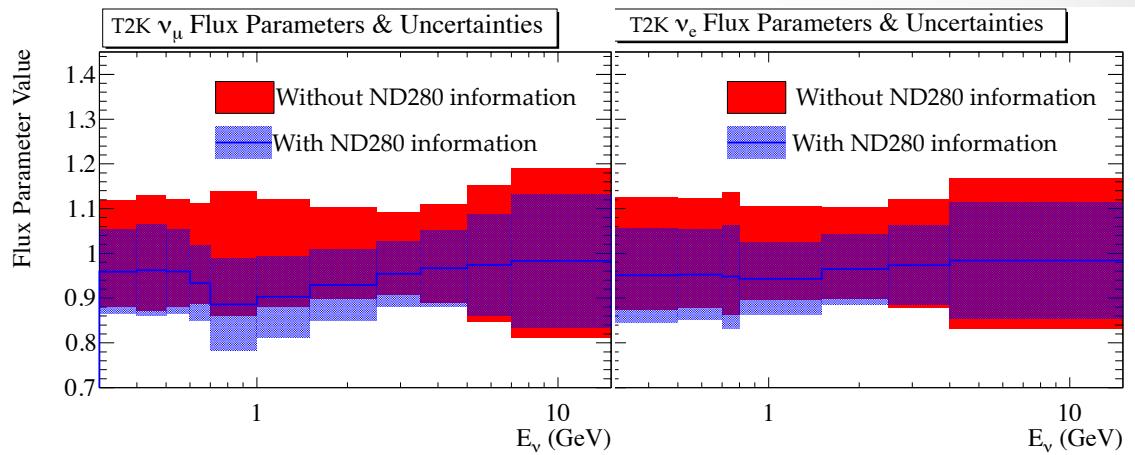
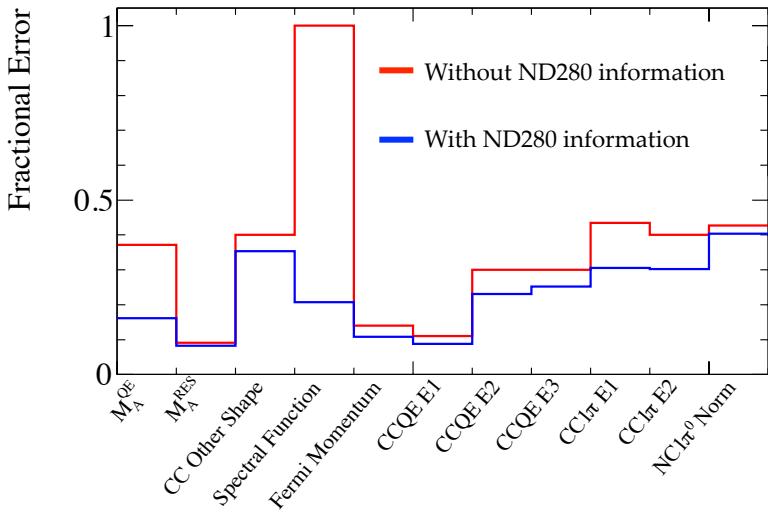
	Prior Value and Uncertainty	Fitted Value and Uncertainty
M_A^{QE} (GeV)	1.21 ± 0.45	1.19 ± 0.19
M_A^{RES} (GeV)	1.162 ± 0.110	1.137 ± 0.095
CCQE Norm. 0-1.5 GeV	1.000 ± 0.110	0.941 ± 0.087
CC1 π Norm. 0-2.5 GeV	1.63 ± 0.43	1.67 ± 0.28
NC1 π^0 Norm.	1.19 ± 0.43	1.22 ± 0.40

Prior value and uncertainty from fit to MiniBooNE single pion samples

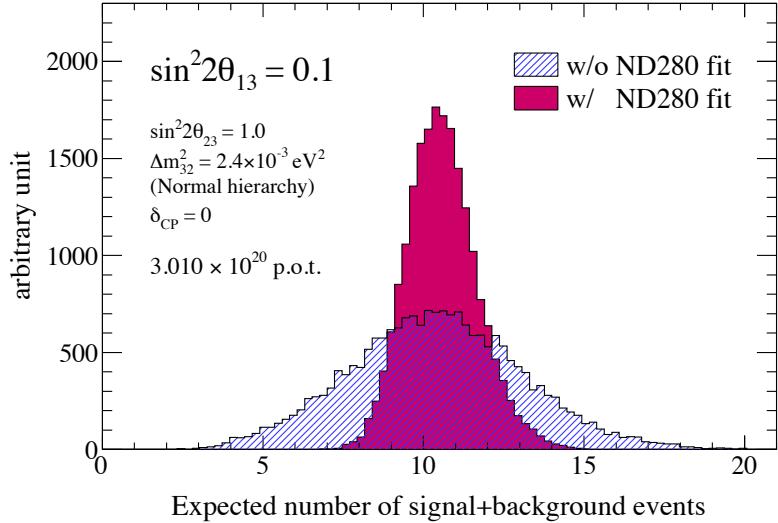


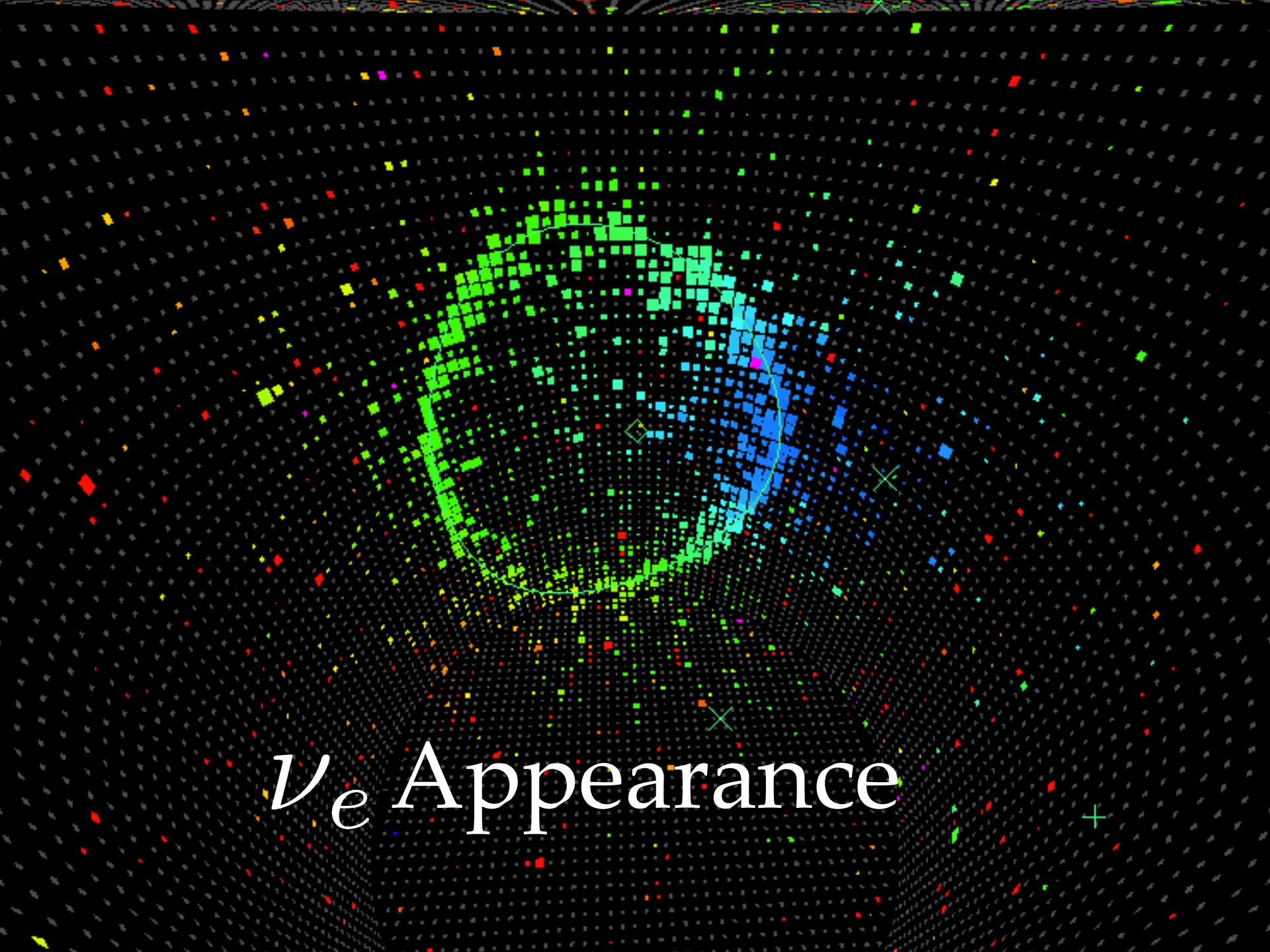
Constraining Systematics

Propagating ND280
parameters and
covariance to the Far
Detector prediction



Reduce uncertainty in Super-K expectation:





ν_e Appearance

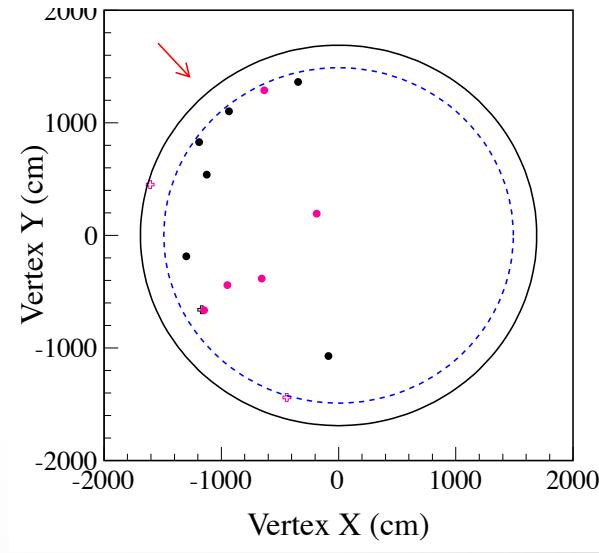
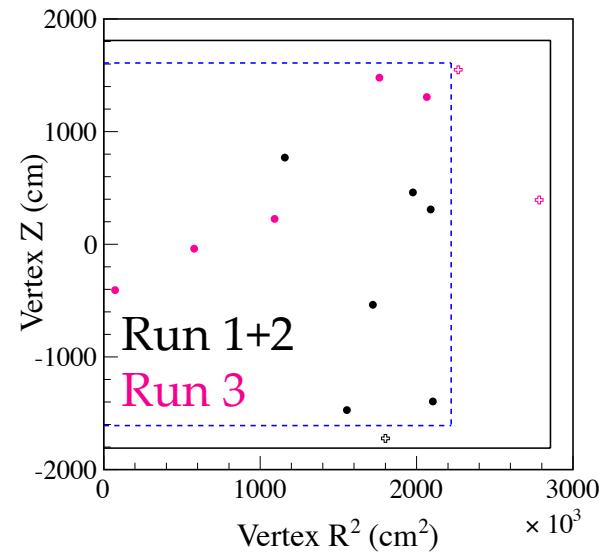
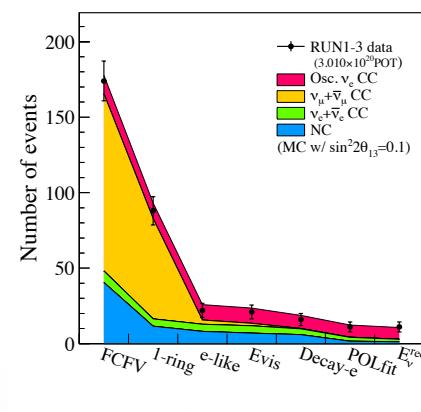
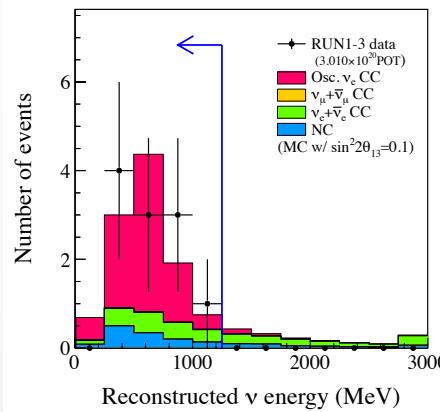
Event Selection

Select fully-contained events with:

- 1 electron-like ring
- No decay electron (from muon bkg.)
- No pi0-like invariant mass from 2nd ring
- 100 MeV < Energy < 1250 MeV (shown)

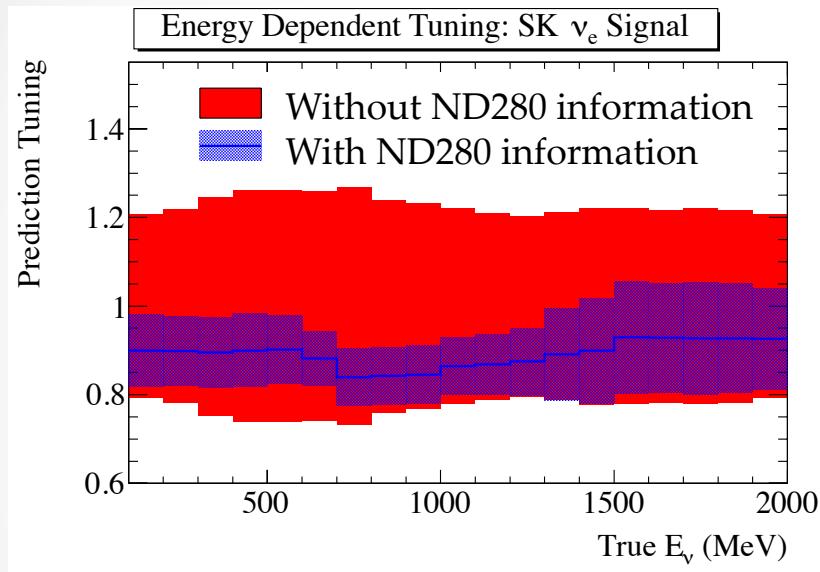
Event category	The predicted number of events	
	$\sin^2 2\theta_{13} = 0.0$	$\sin^2 2\theta_{13} = 0.1$
Total	3.22	10.71
ν_e signal	0.18	7.79
ν_e background	1.67	1.56
ν_μ background	1.21	1.21
$\bar{\nu}_\mu$ background	0.07	0.07
$\bar{\nu}_e$ background	0.09	0.09

Observed 11
events!



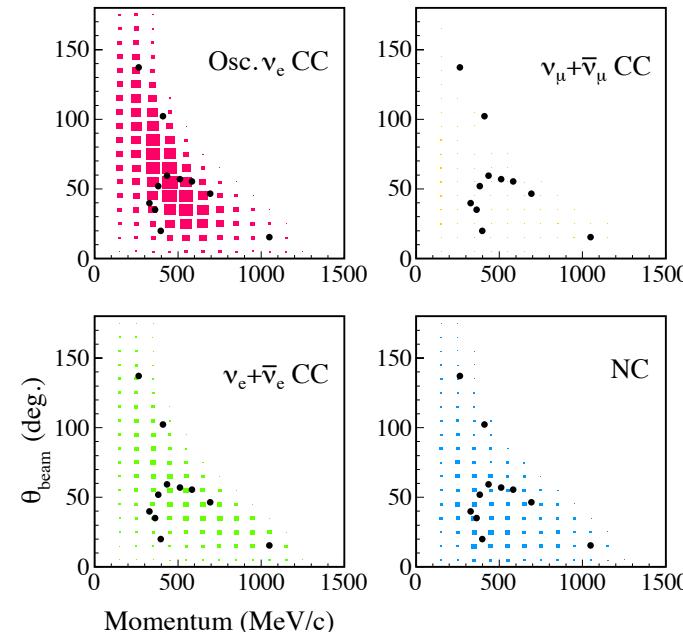
Analysis

Near detector information significantly reduces systematic errors

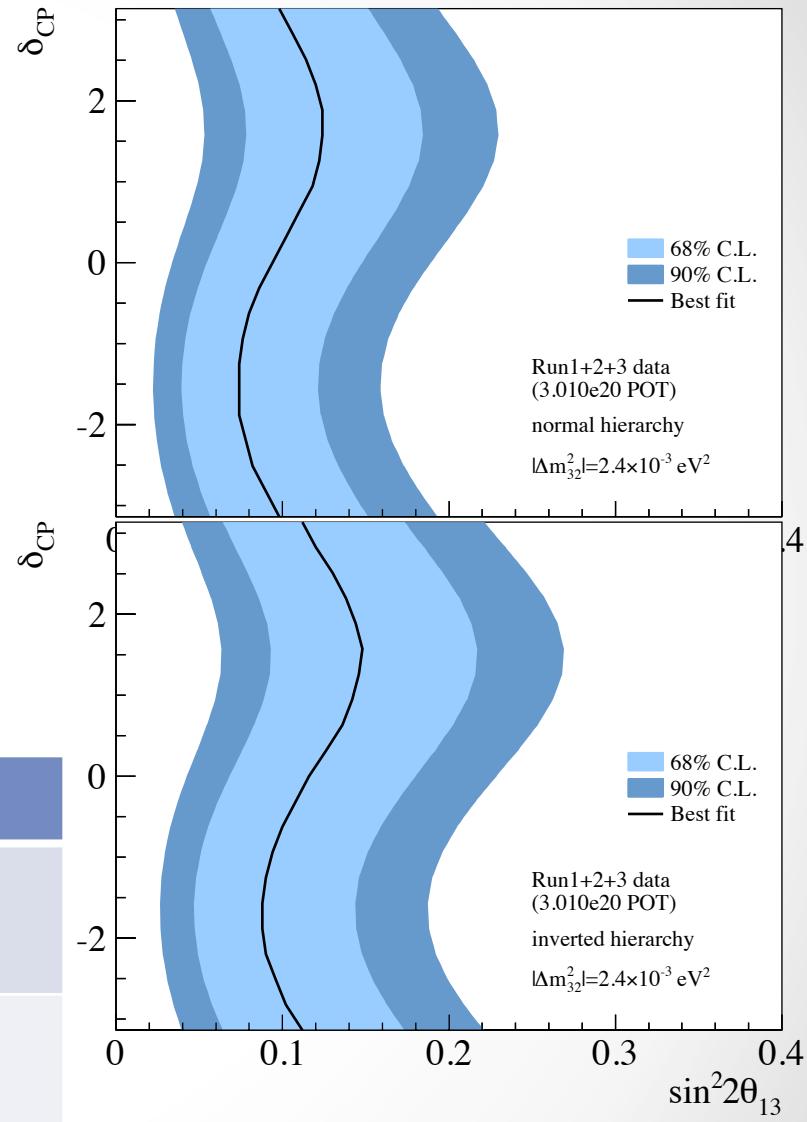
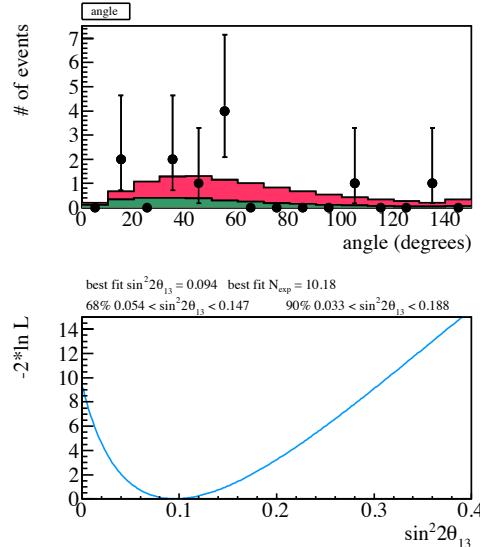
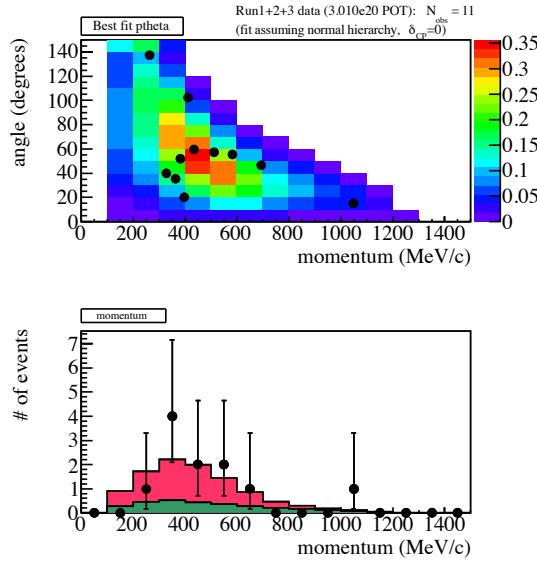


Fit in bins of p and θ
with respect to the
beam direction

Error source	$\sin^2 2\theta_{13} =$	
	0	0.1
Beam flux+ ν int. in T2K fit	8.7 %	5.7 %
ν int. (from other exp.)	5.9 %	7.5 %
Final state interaction	3.1 %	2.4 %
Far detector	7.1 %	3.1 %
Total	13.4 %	10.3 %



Fit data in bins of p and θ with respect to the beam direction



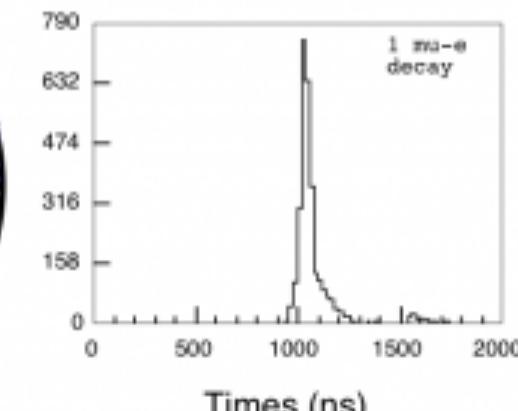
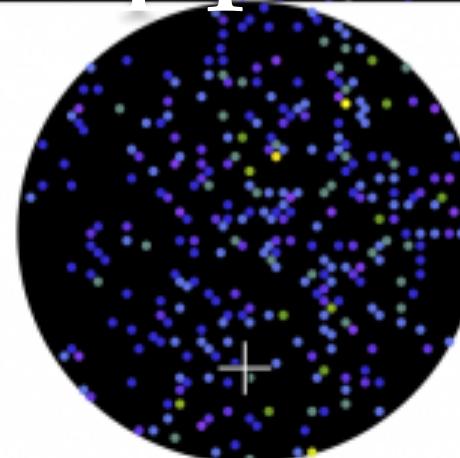
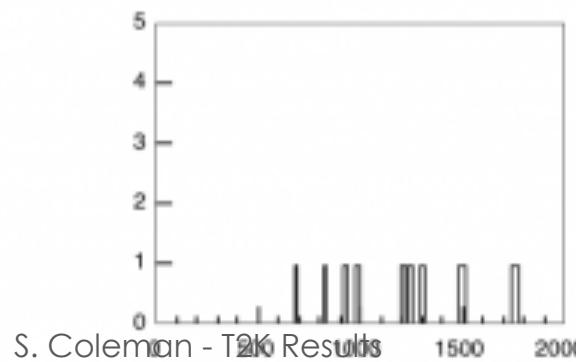
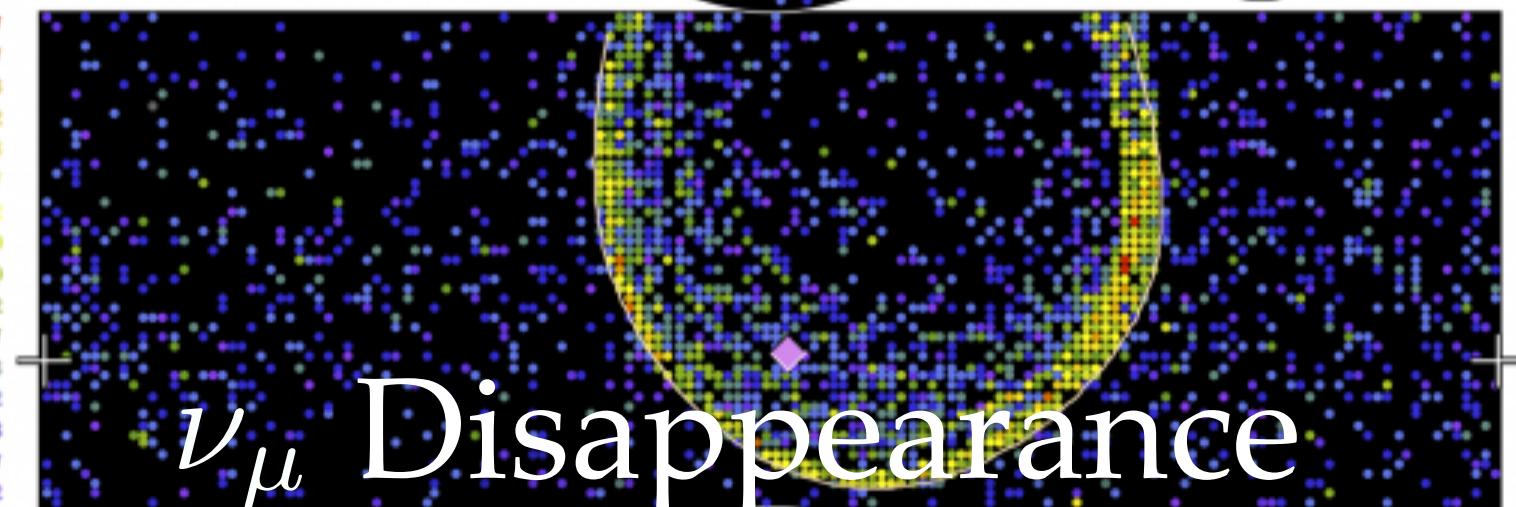
3.2σ significance

Super-Kamiokande IV

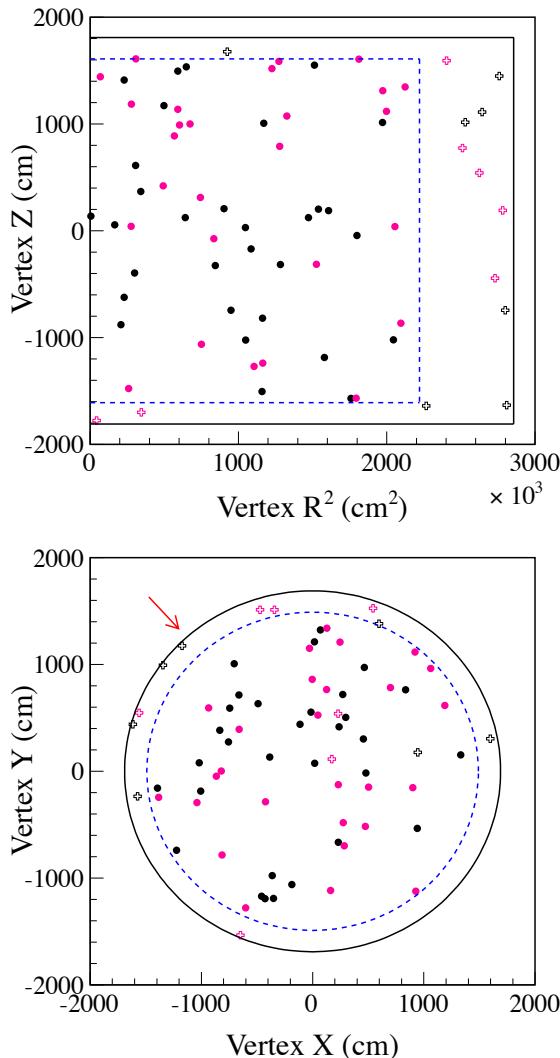
T2K Beam Run 0 Spill 952106
Run 66831 Sub 410 Event 96851432
10-05-18:18:33:08
T2K beam dt = 1879.5 ns
Inner: 2949 hits, 8030 pe
Outer: 3 hits, 2 pe
Trigger: 0x800000007
 D_{wall} : 709.7 cm
mu-like, $p = 1024.6 \text{ MeV}/c$

Charge (pe)

- >26.7
- 23.3-26.7
- 20.2-23.3
- 17.3-20.2
- 14.7-17.3
- 12.2-14.7
- 10.0-12.2
- 8.0-10.0
- 6.2- 8.0
- 4.7- 6.2
- 3.3- 4.7
- 2.2- 3.3
- 1.3- 2.2
- 0.7- 1.3
- 0.2- 0.7
- < 0.2

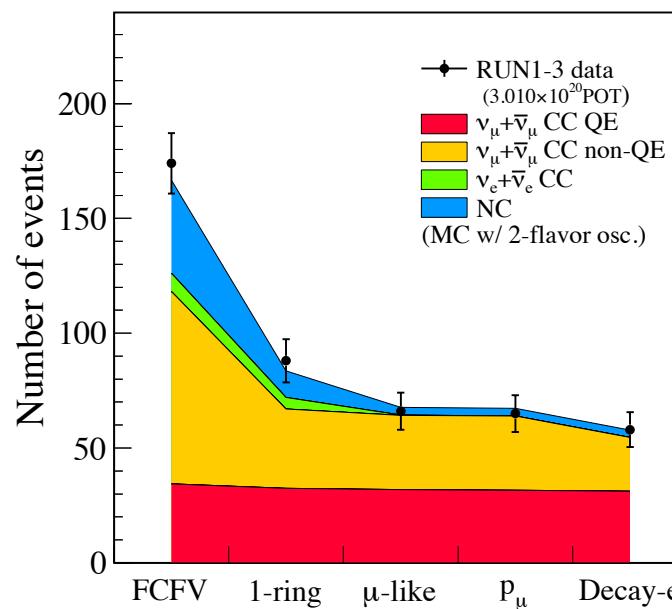


Event Selection



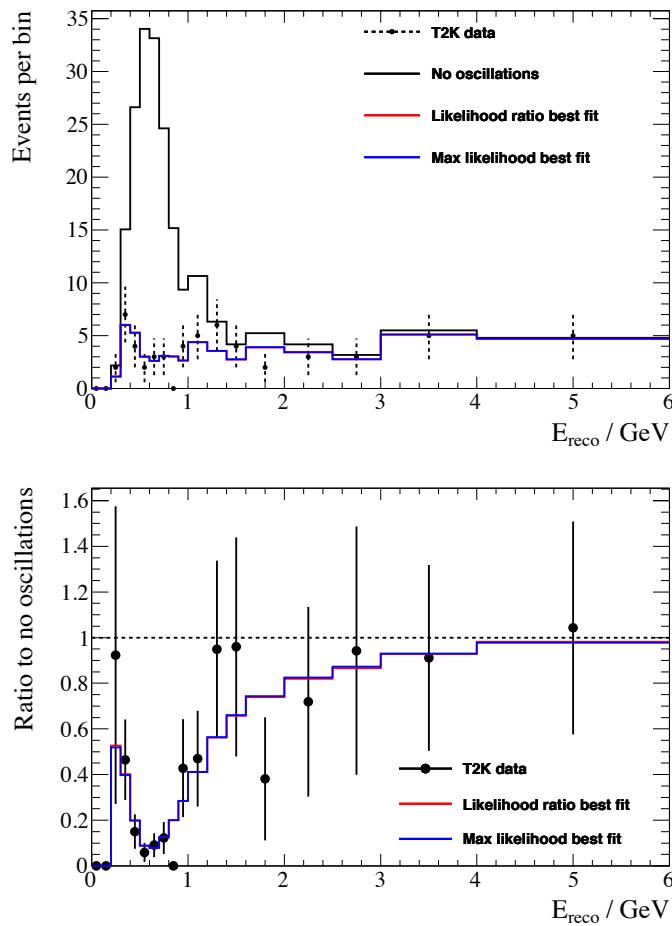
Select fully-contained events with:

- 1 muon-like ring
- Momentum > 200 MeV
- No more than 1 decay- e ring



58 events pass
selection cuts

Analysis

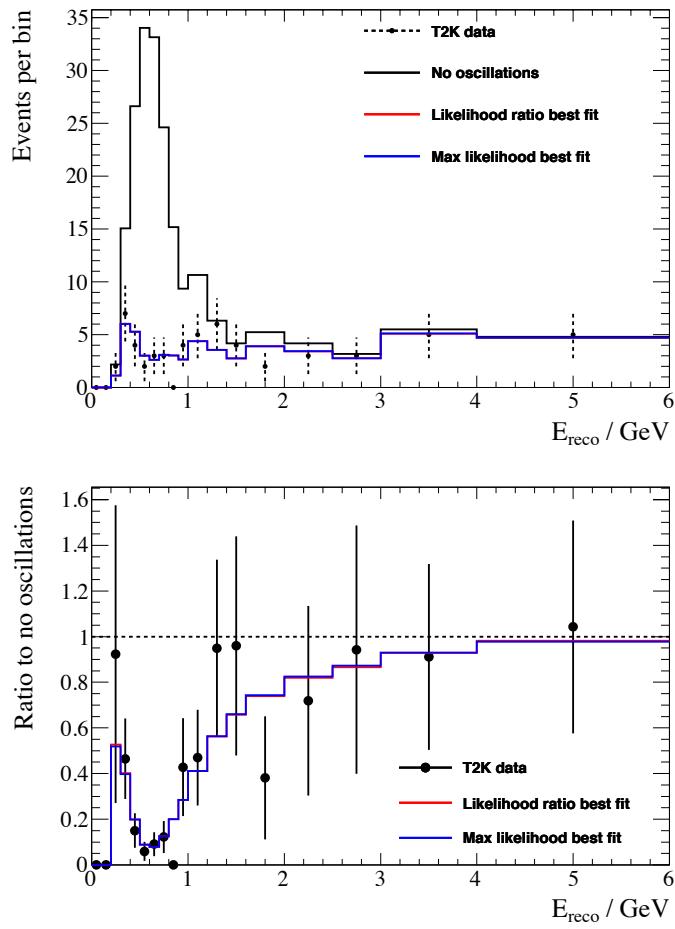


Systematic	Before fit	After fit
Flux and x-sec	21.8	4.2
Uncorrelated x-sec		6.3
SK detector		10.1
SI-FSI		3.5
Total	25.1	13.0

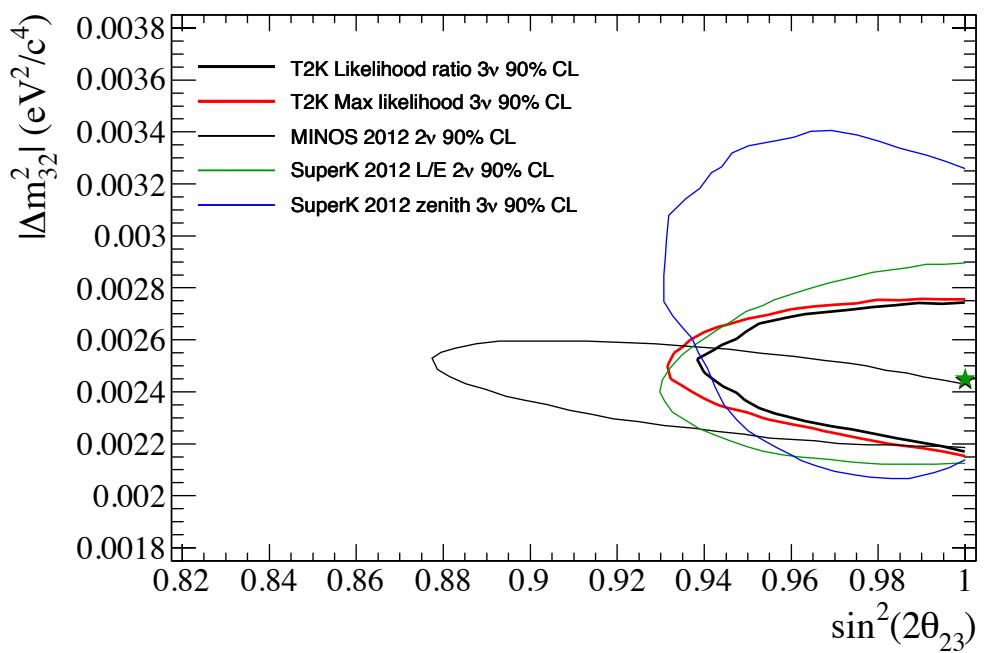
Two independent analysis methods:

- Maximum likelihood
- Likelihood ratio

Results



Method	$\Delta m^2_{32} (\times 10^{-3} \text{ eV}^2/\text{c}^4)$	$\sin^2(2\theta_{23})$
Likelihood Ratio	2.443	1.0
Max. Likelihood	2.45	1.0



Conclusion

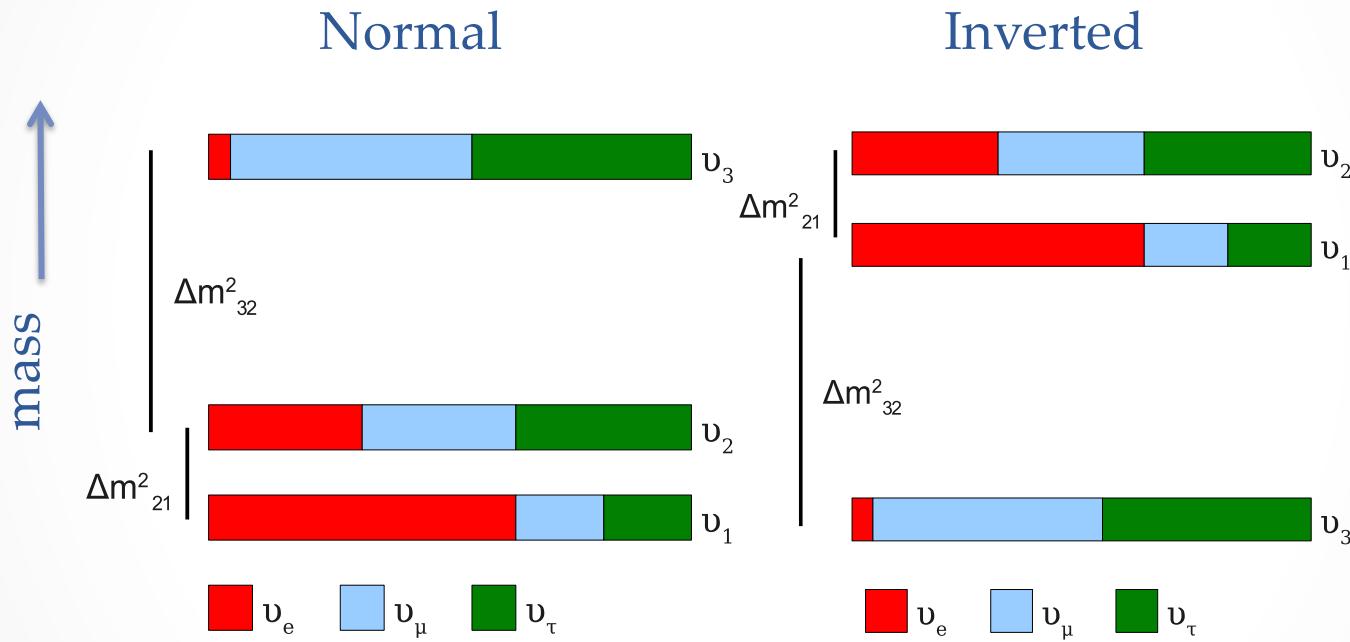
With only 4% of data goal (3.01×10^{20} POT):

- First direct observation of ν_e appearance
 - 3.2σ evidence for non-zero θ_{13} with 11 events
 - Consistent with reactor experiments Daya Bay, RENO, etc.
- Competitive limits on θ_{23}
 - Maximal mixing consistent with MINOS, Super-K
- On track to add 5×10^{20} POT by July 2013

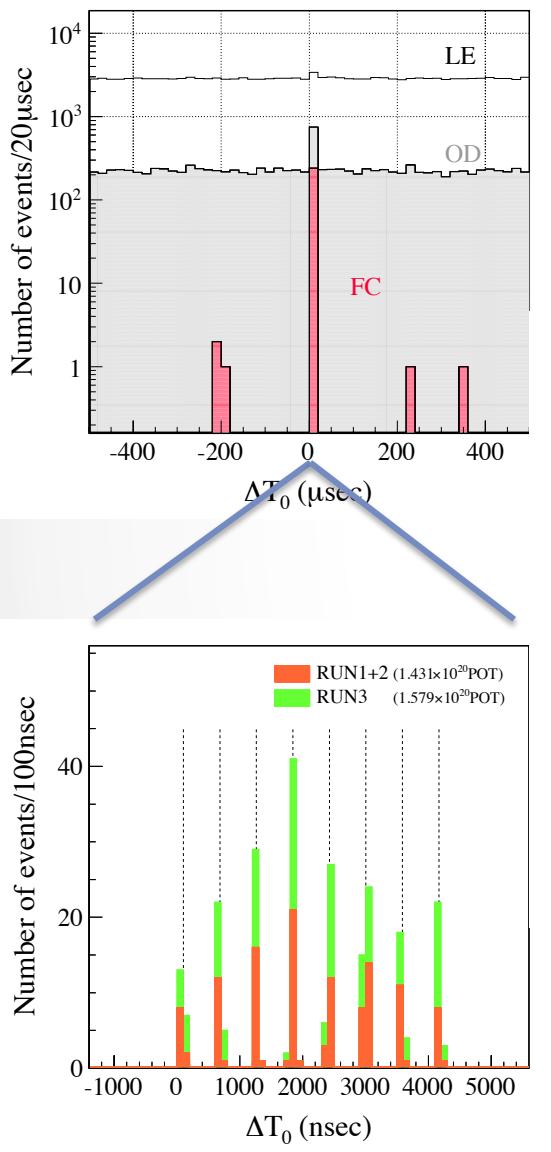
With more data, T2K will play a part in determining δ
and hopefully the mass hierarchy

Backup Slides

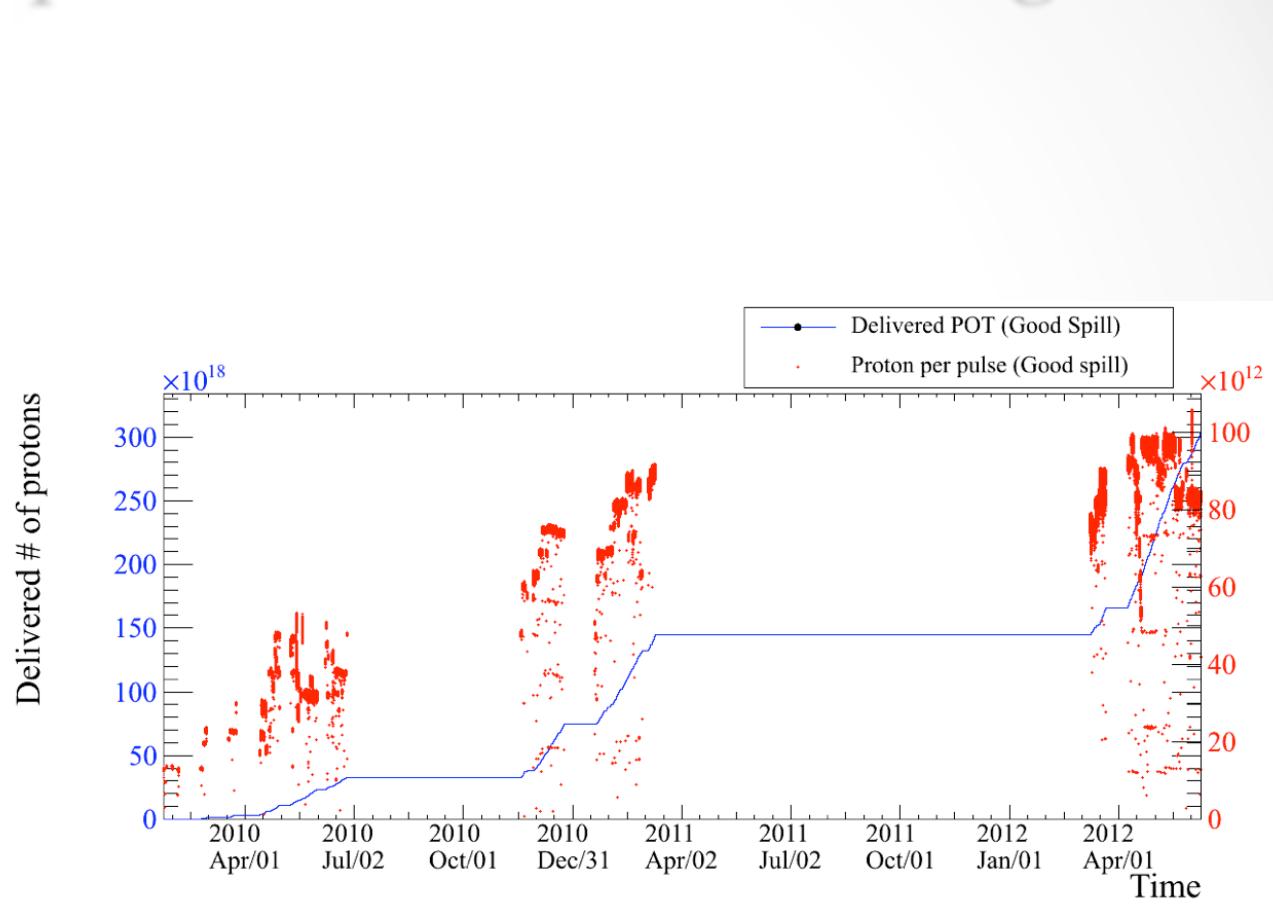
Mass Hierarchy



Beam performance and timing

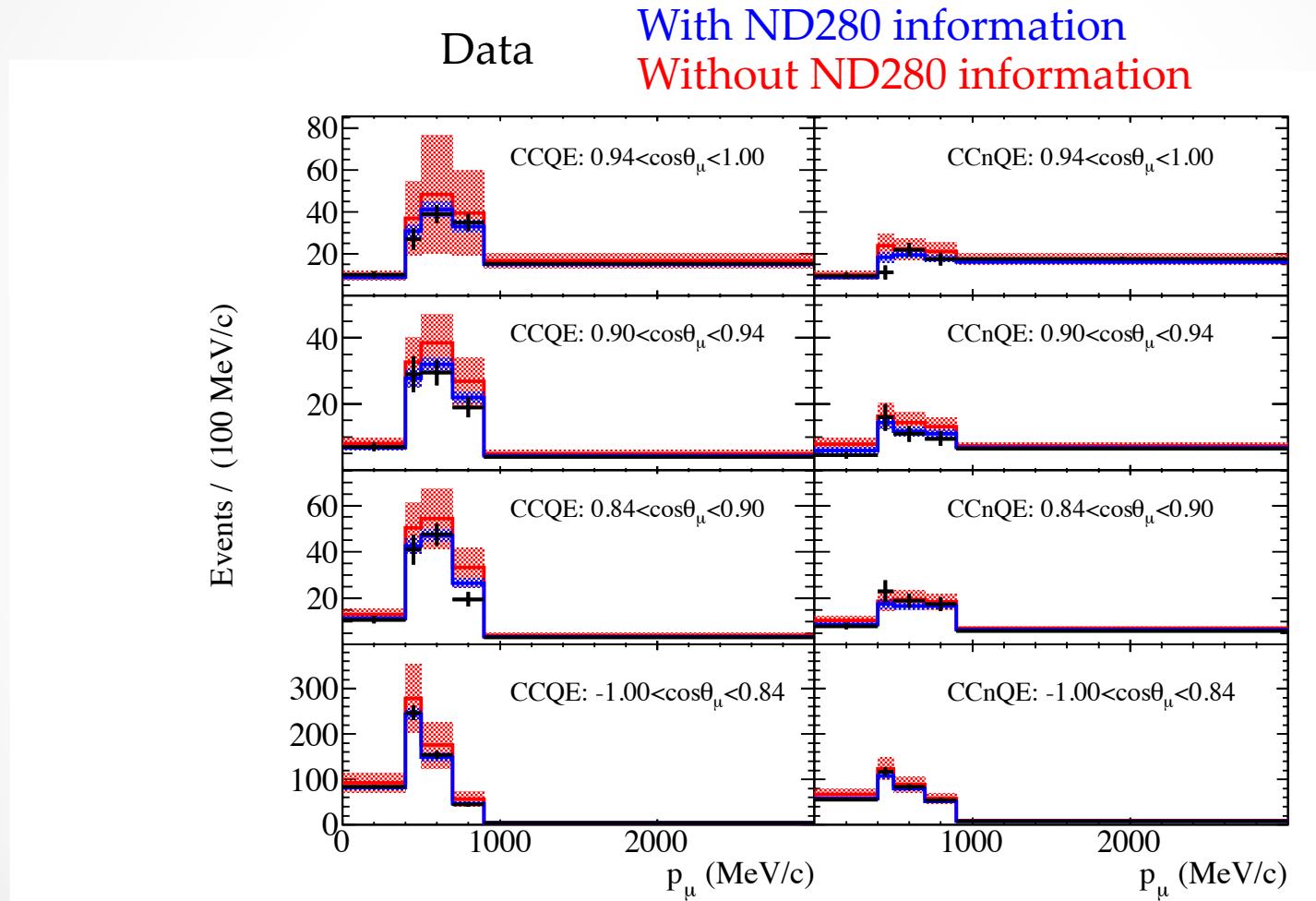


Delivered # of protons

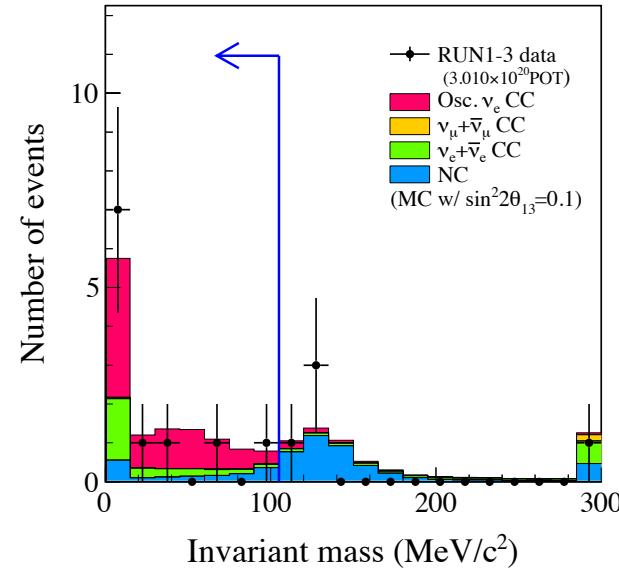
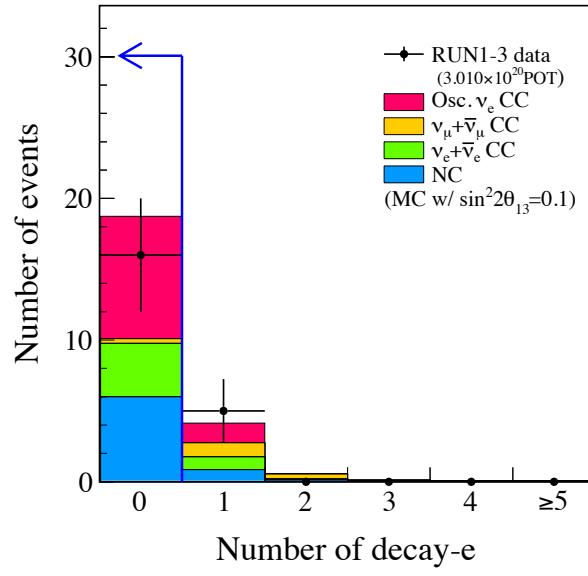
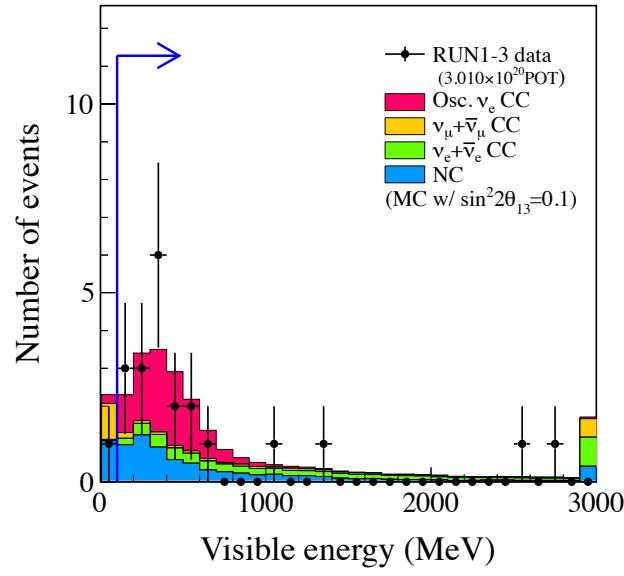
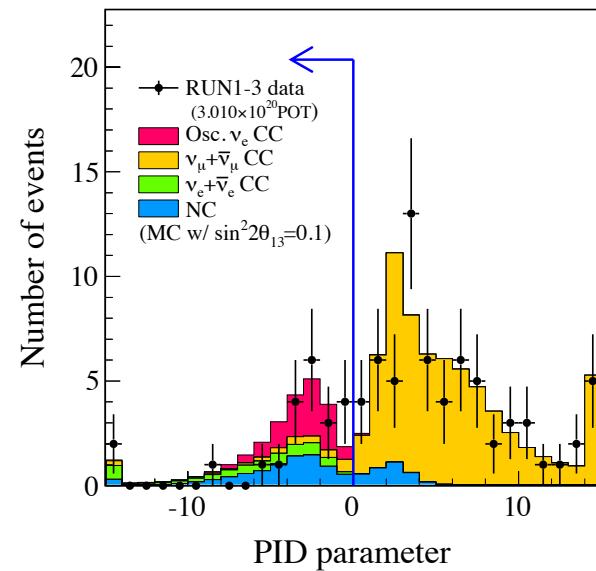
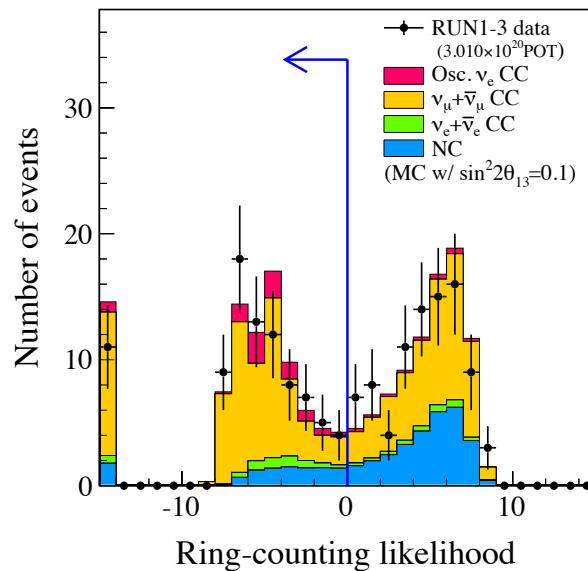
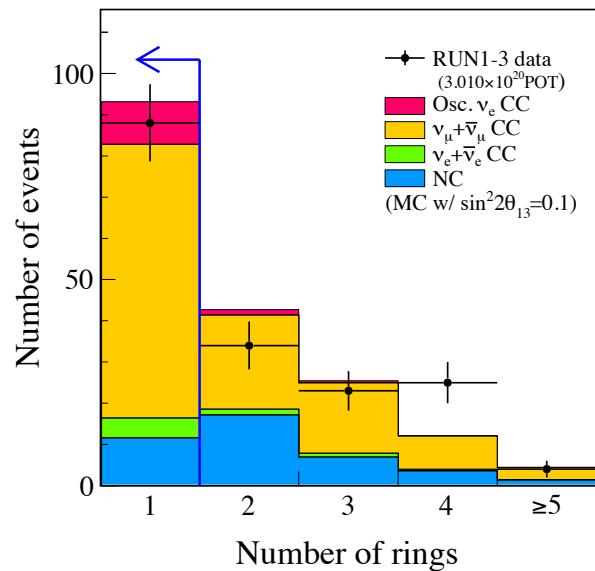


Proton per pulse

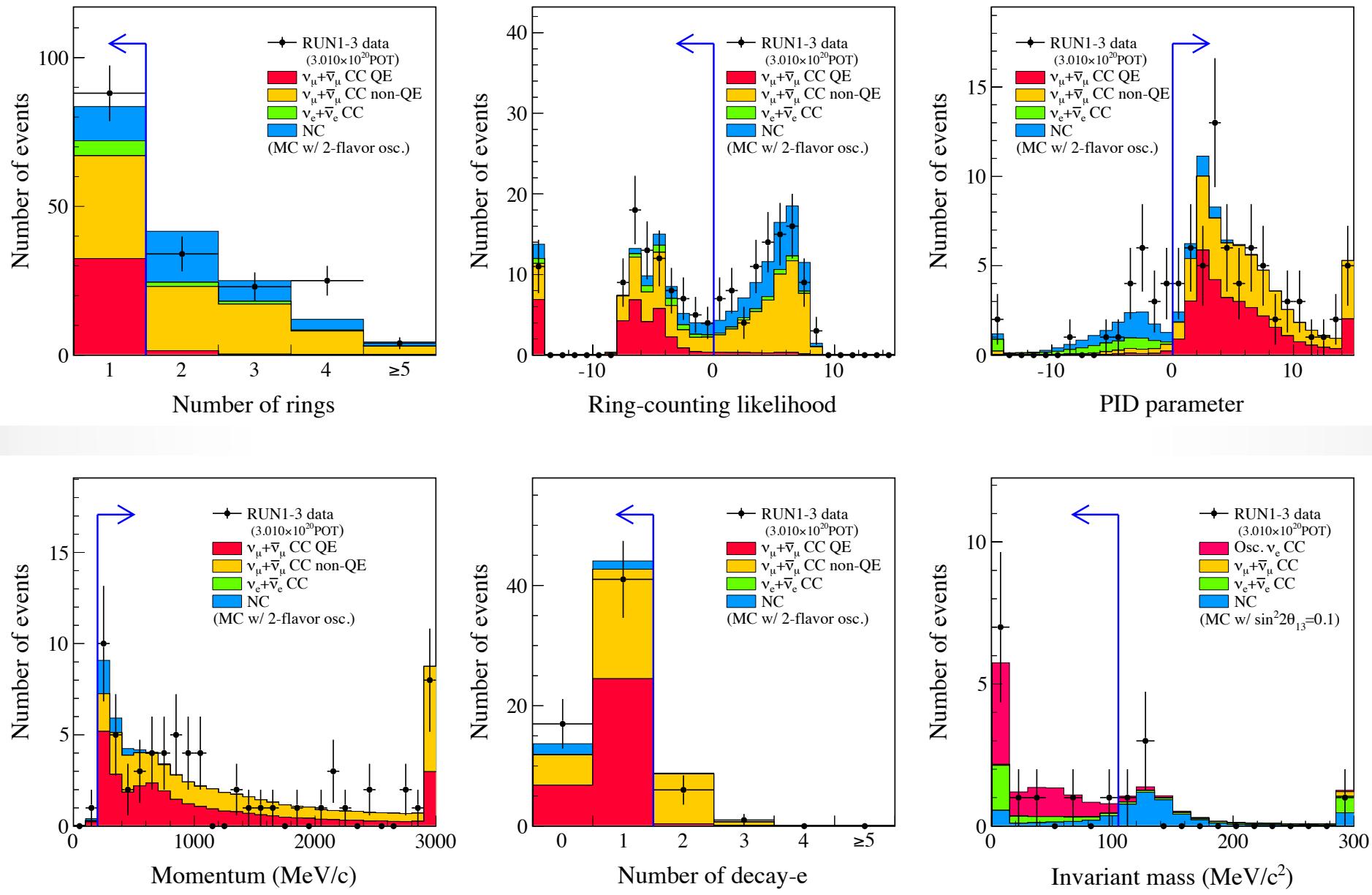
ND280 fit – CCQE and CC non-QE



Nue Selection

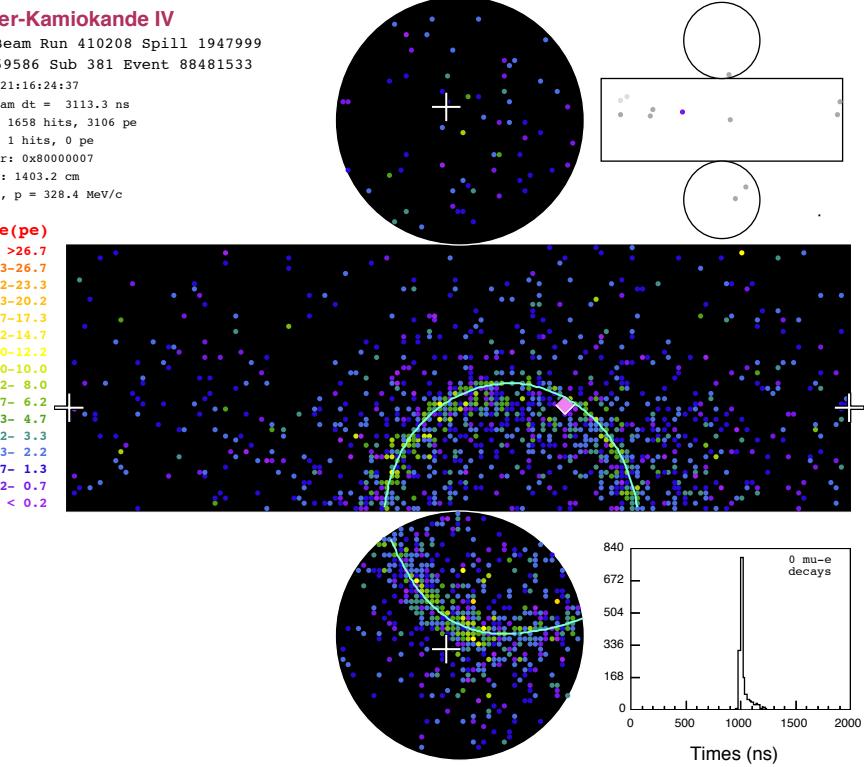


NuMu Selection

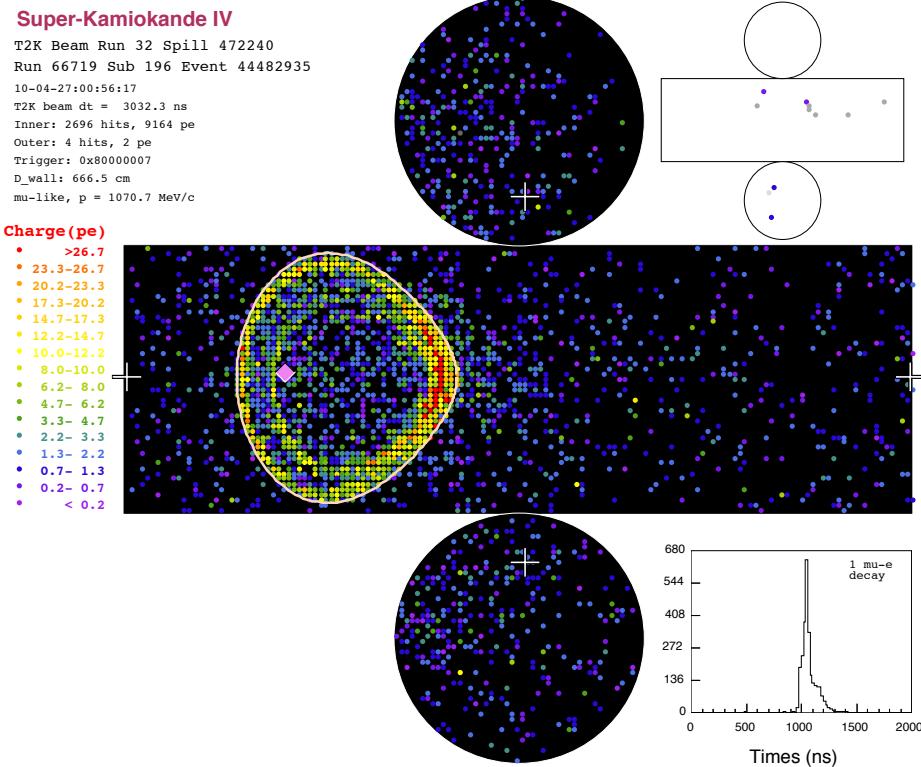


Ring ID

Electron-like:

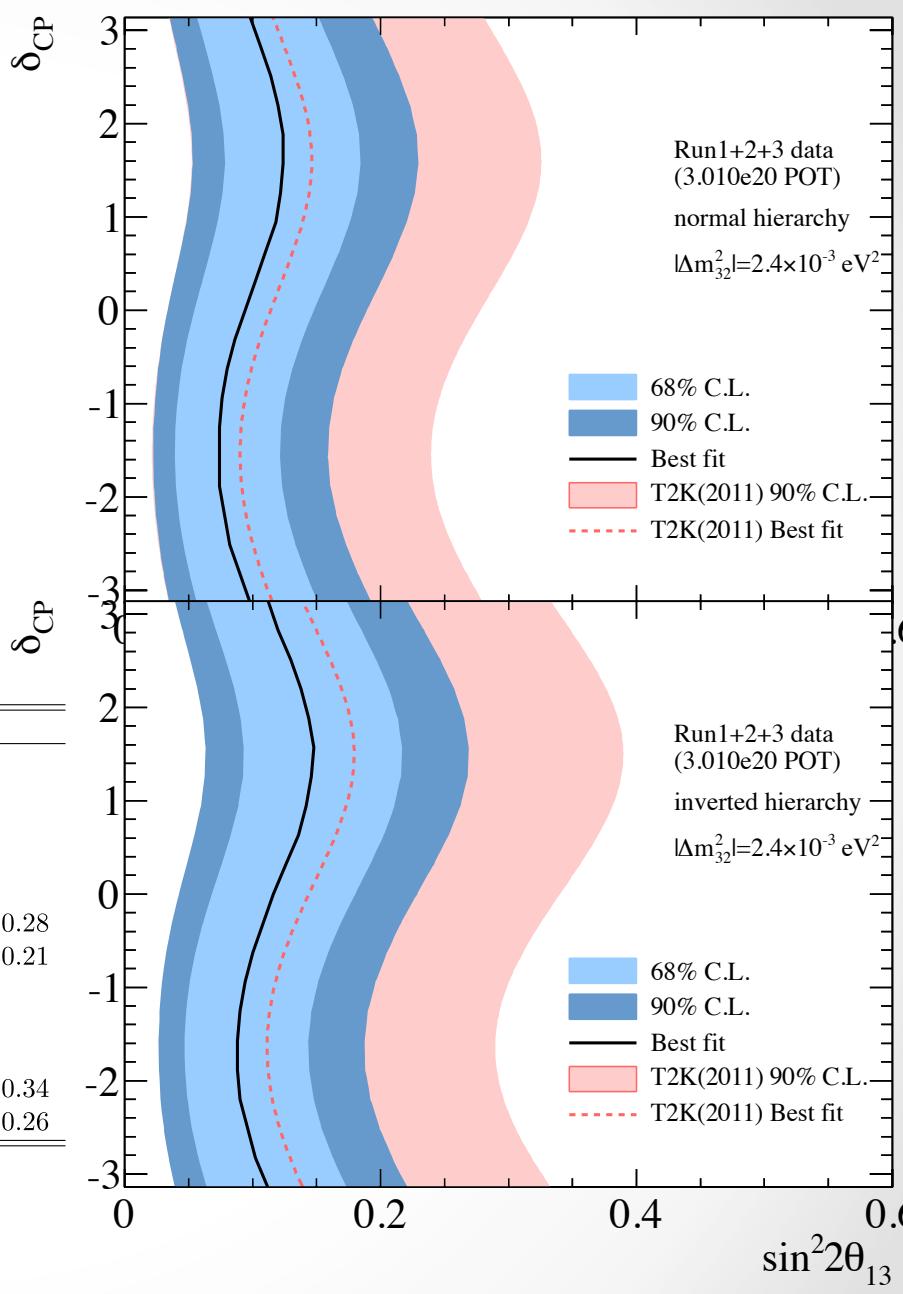


Muon-like:



Comparison to previous results

Result	This analysis	2010a analysis
POT	3.010×10^{20}	1.431×10^{20}
The observed number of events	11	6
Normal hierarchy		
Best fit value of $\sin^2 2\theta_{13}$	0.094	0.11
90 % C.L. allowed region	$0.033 < \sin^2 2\theta_{13} < 0.188$	$0.03 < \sin^2 2\theta_{13} < 0.28$
68 % C.L. allowed region	$0.054 < \sin^2 2\theta_{13} < 0.147$	$0.05 < \sin^2 2\theta_{13} < 0.21$
Inverted hierarchy		
Best fit value of $\sin^2 2\theta_{13}$	0.116	0.14
90 % C.L. allowed region	$0.041 < \sin^2 2\theta_{13} < 0.228$	$0.04 < \sin^2 2\theta_{13} < 0.34$
68 % C.L. allowed region	$0.067 < \sin^2 2\theta_{13} < 0.179$	$0.07 < \sin^2 2\theta_{13} < 0.26$



Comparison to previous results (ν_μ)

