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First Anti-Neutrino Oscillation Results from the T2K Experiment

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STFC/RAL

Overview

- Introduction
- The Experiments
  - Beam
  - Near Detectors
  - Super-Kamiokande
- Measurements
  - Disappearing muon anti-neutrinos
  - Appearing electron anti-neutrinos
  - Other measurements
- Summary

Neutrino Mixing
The PMNS Matrix

Pontecorvo-Maki-Nakagawa-Sakata

- Assume that neutrinos do have mass:
  - mass eigenstates ≠ weak interaction eigenstates
  - Analogue to CKM-Matrix in quark sector!

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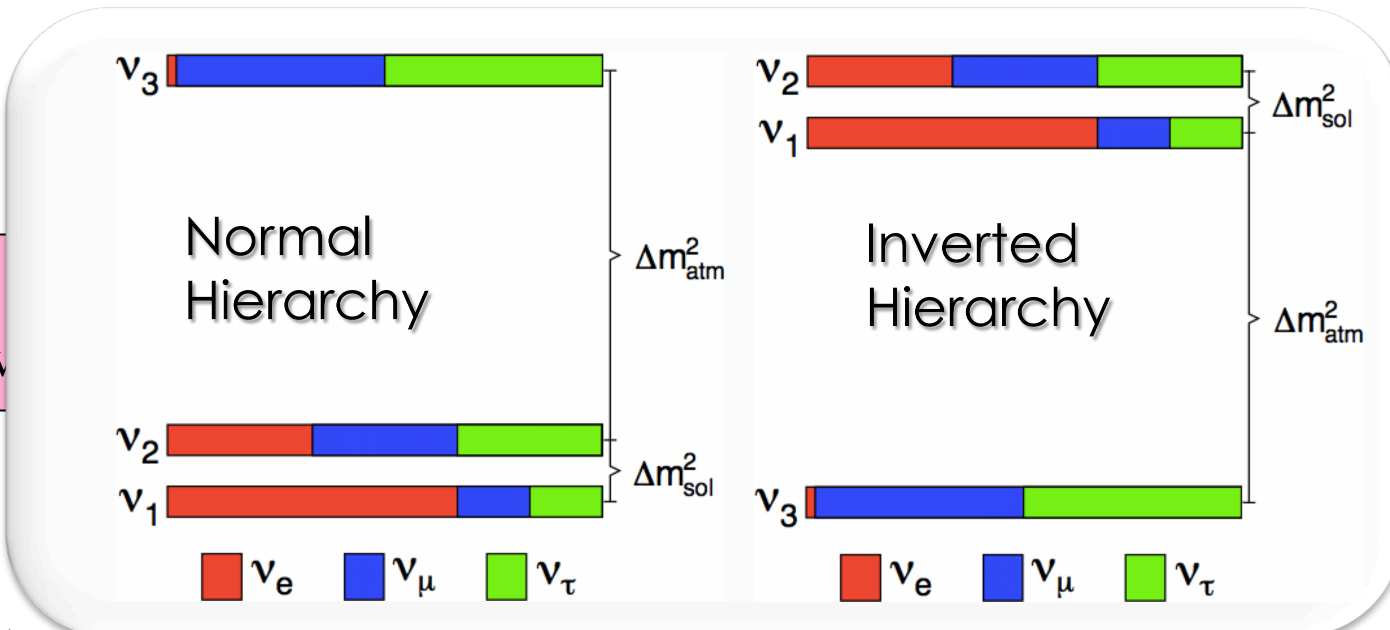

$$U = \begin{pmatrix} U_{e1} & \cdots & 0 \\ U_{\mu 1} & \cdots & 0 \\ U_{\tau 1} & \cdots & e^{i\delta_3} \end{pmatrix}$$

with $c_{ij} = \cos(\theta_{ij})$, $s_{ij} = \sin(\theta_{ij})$, θ_{ij} = mixing angle and Δm^2_{ij} = mass^2 difference

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Who is Who

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\delta_2} & 0 \\ 0 & 0 & e^{i\delta_3} \end{pmatrix}$$

beam ν_μ disappearance

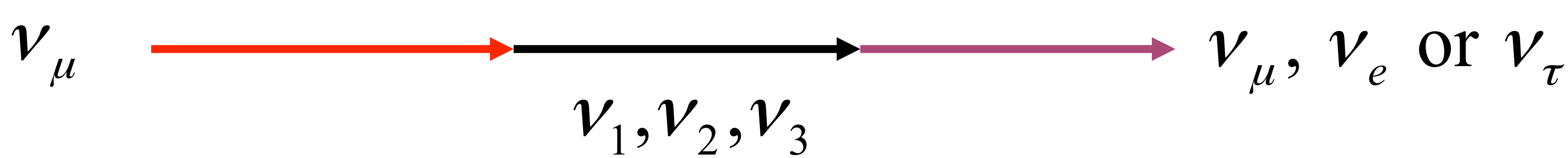
Solar & reactor

ν_e appearance in ν_μ beam
or
ν_e disappearance in reactor experiments

ν –less double beta decay

Neutrino Oscillations

- If mass and weak eigenstates are different:
  - Neutrino is produced in weak eigenstate
  - It travels a distance L as a mass eigenstate
  - It will be detected in a (possibly) different weak eigenstate



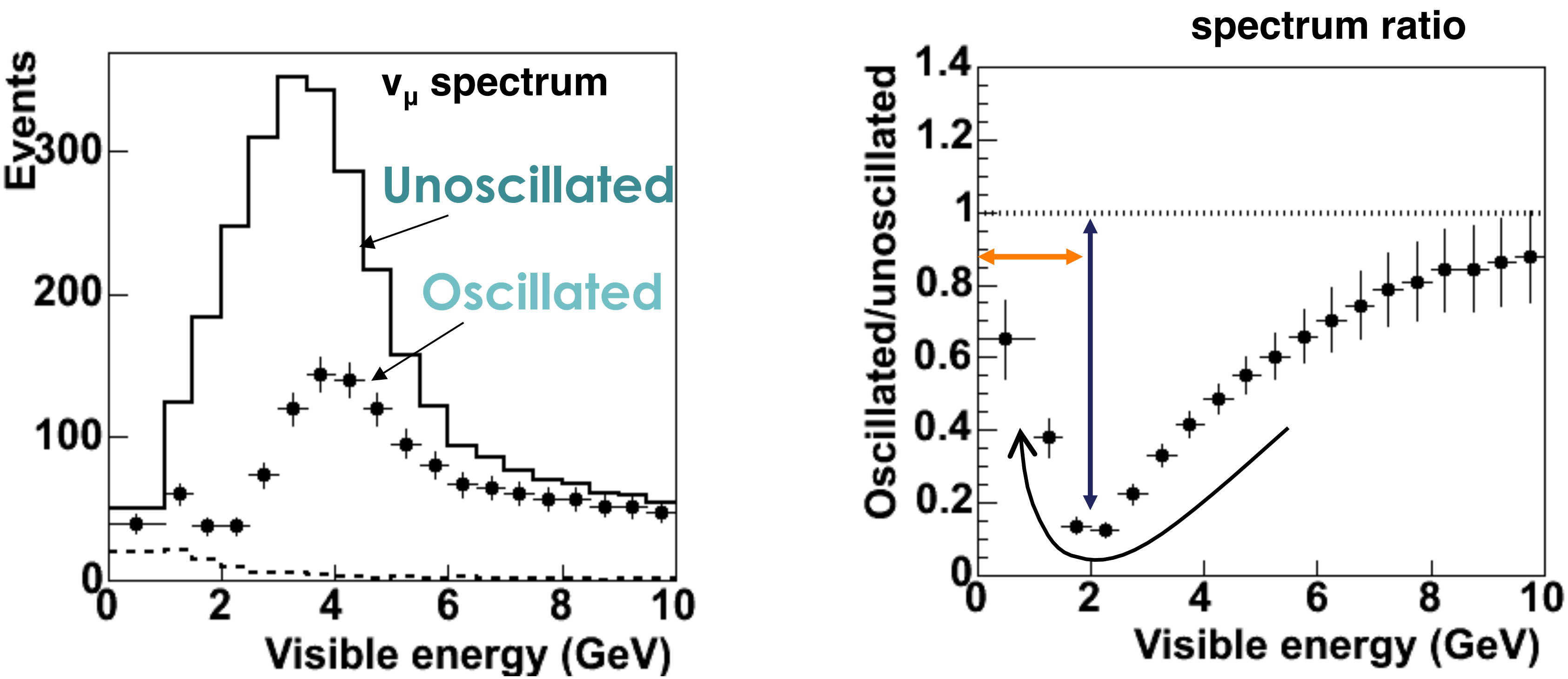
$$\begin{pmatrix} \nu_\mu \\ \nu_x \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} \qquad P(\nu_\mu \to \nu_x) = \sin^2(2\theta)\sin^2\left(\frac{1.27\Delta m^2 L}{E_\nu}\right)$$

Muon Neutrino Disappearance

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2(2\theta)\sin^2(1.27\Delta m^2 L / E)$$

Monte Carlo (MINOS Experiment)

(Input parameters: $\sin^2 2\theta = 1.0$, $\Delta m^2 = 3.35\text{x}10^{-3}$ eV^2)



A Little Bit of Math

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\delta_2} & 0 \\ 0 & 0 & e^{i\delta_3} \end{pmatrix}$$

with $c_{ij} = \cos(\theta_{ij})$, $s_{ij} = \sin(\theta_{ij})$, θ_{ij} = mixing angle and Δm^2_{ij} = mass^2 difference

$$P(\nu_\mu \to \nu_e) = 4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2 \frac{\Delta m^2_{31} L}{4E} \times \left(1 + \frac{2a}{\Delta m^2_{31}} \left(1 - 2S_{13}^2\right)\right)$$

$$+8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cos \frac{\Delta m^2_{32} L}{4E} \sin \frac{\Delta m^2_{31} L}{4E} \sin \frac{\Delta m^2_{21} L}{4E}$$

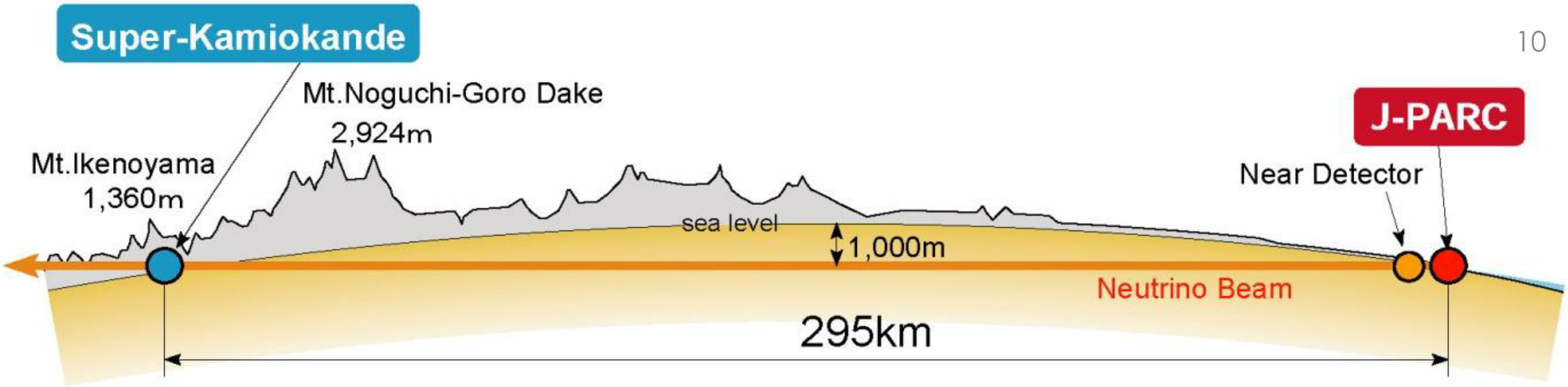
$$-8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \sin \frac{\Delta m^2_{32} L}{4E} \sin \frac{\Delta m^2_{31} L}{4E} \sin \frac{\Delta m^2_{21} L}{4E}$$

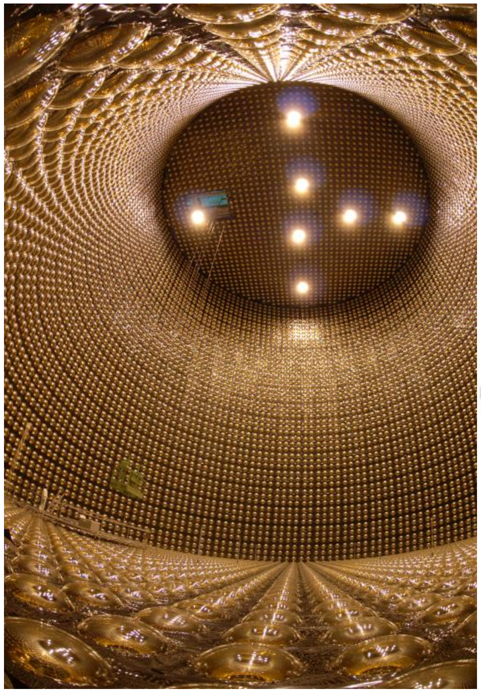
$$+4S_{12}^2 C_{13}^2 \left\{C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta\right\} \sin^2 \frac{\Delta m^2_{21} L}{4E}$$

$$-8C_{13}^2 S_{13}^2 S_{23}^2 \cos \frac{\Delta m^2_{32} L}{4E} \sin \frac{\Delta m^2_{31} L}{4E} \frac{aL}{4E} \left(1 - 2S_{13}^2\right)$$

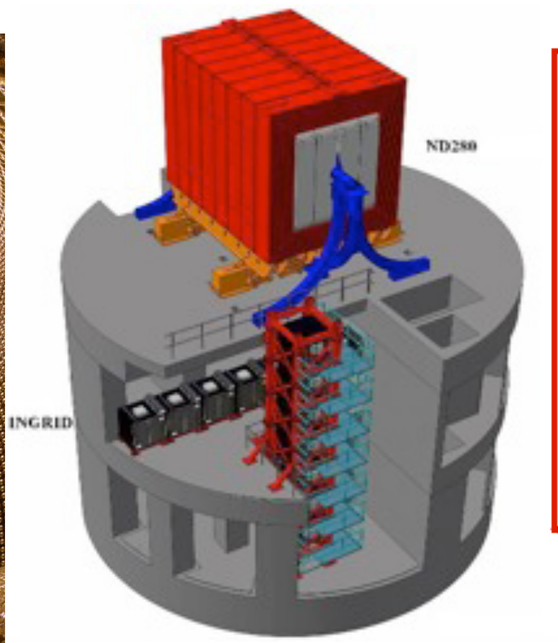

T2K Collaboration

T2K Experiment

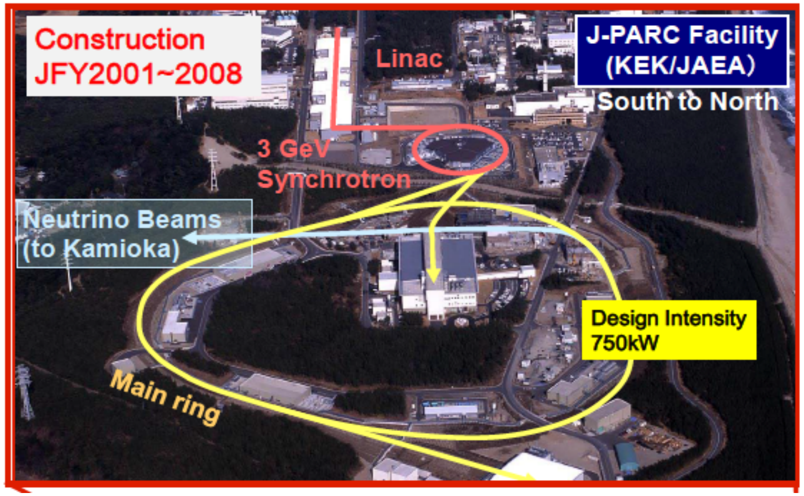




Far detector

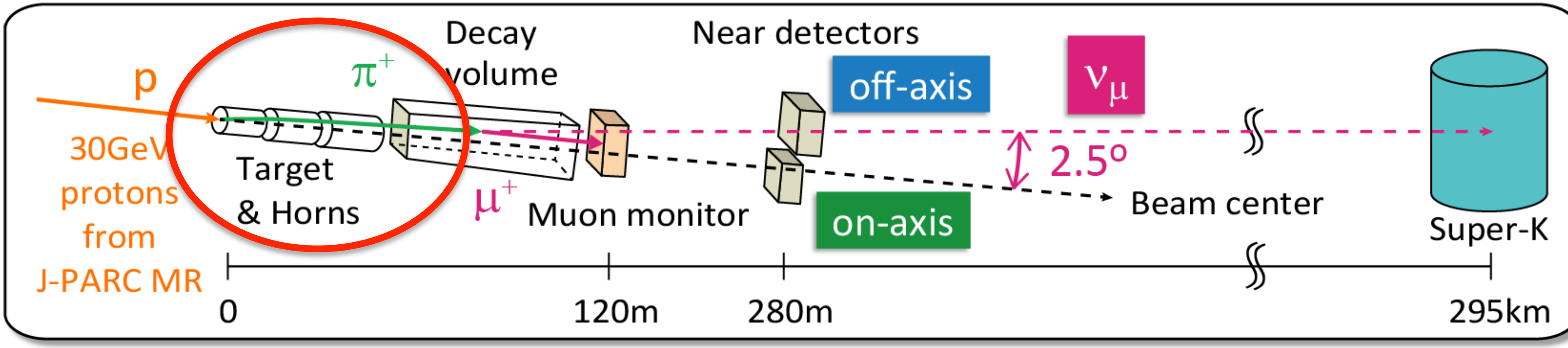


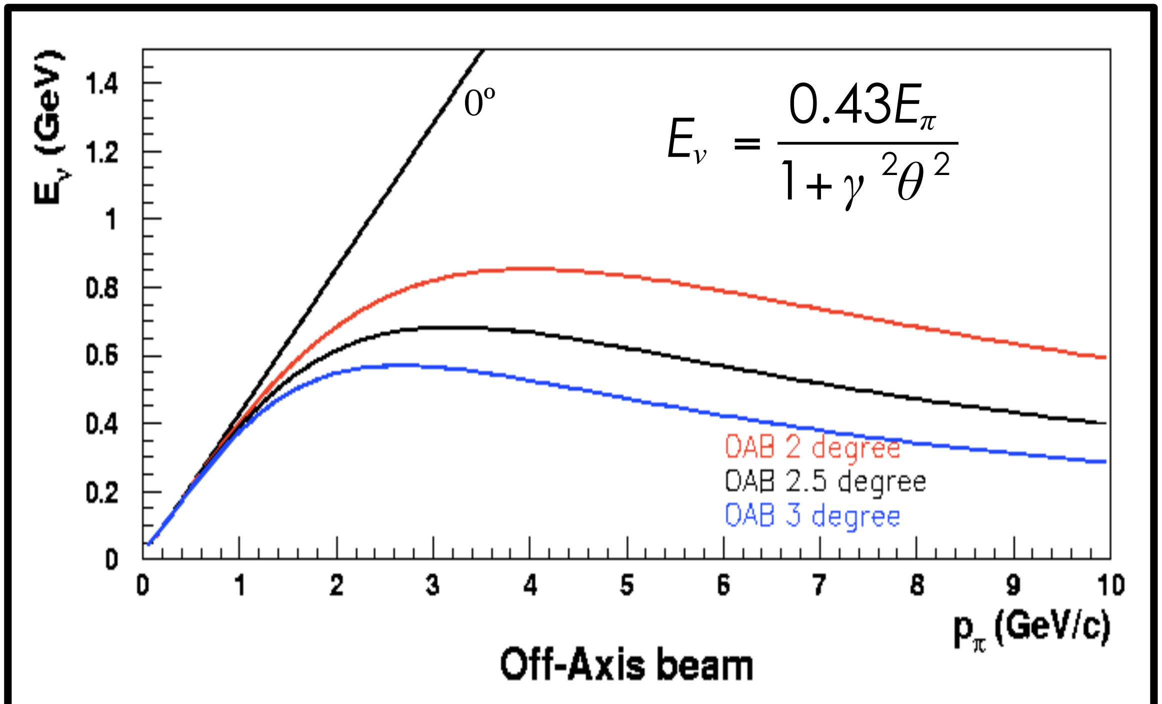
Near detectors
Off-axis: ND280
On-axis: INGRID

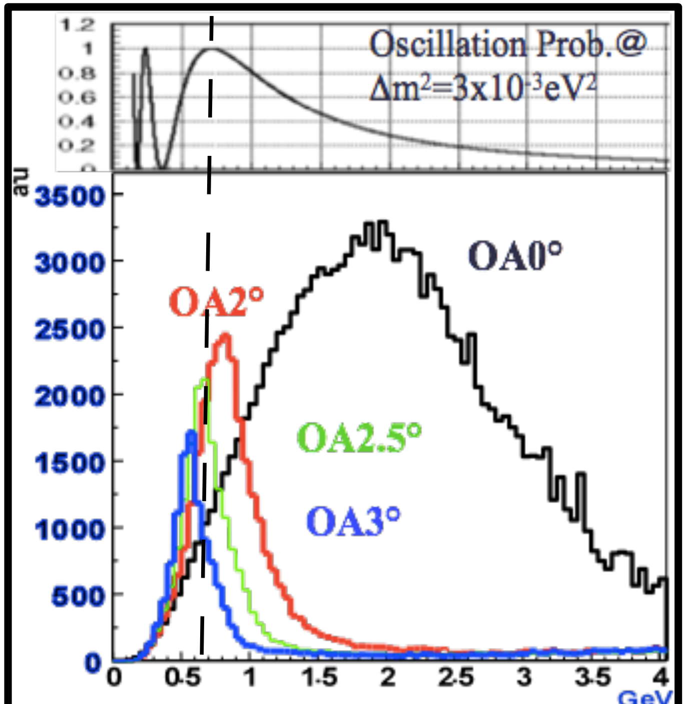


J-PARC accelerator

Design Principle

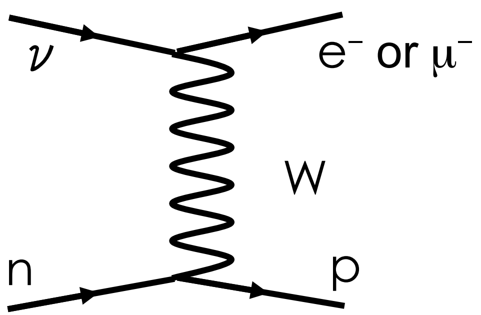






Neutrino Interactions

Charged Current Quasi-Elastic (CCQE)

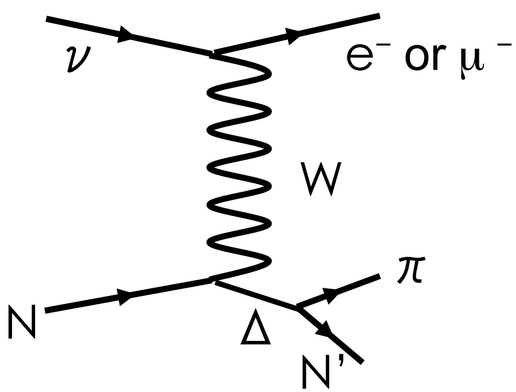


Neutrino energy from lepton momentum and angle:

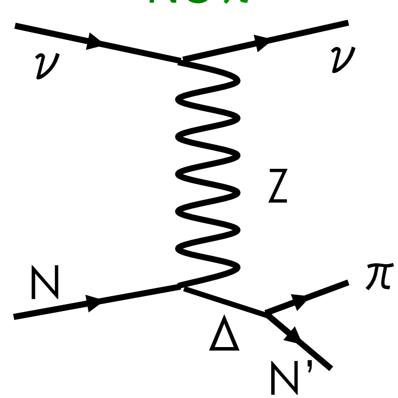
$$E_\nu^{QE} = \frac{m_p^2 - {m'}_n^2 - m_\mu^2 + 2{m'}_n E_\mu}{2({m'}_n - E_\mu + p_\mu \cos\theta_\mu)}$$

2 body kinematics and assumes the target nucleon is at rest

CC π



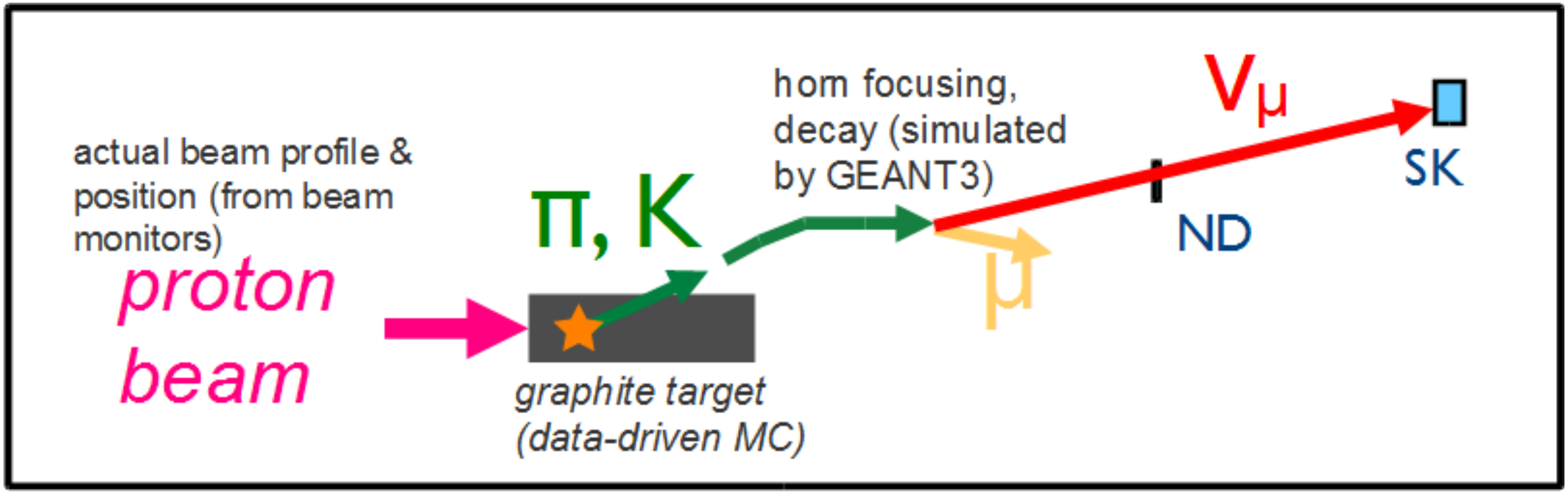
NC π



Additional significant processes:

- CCQE-like multinucleon interaction
- Charged current single pion production (CC π)
- Neutral current single pion production (NC π)

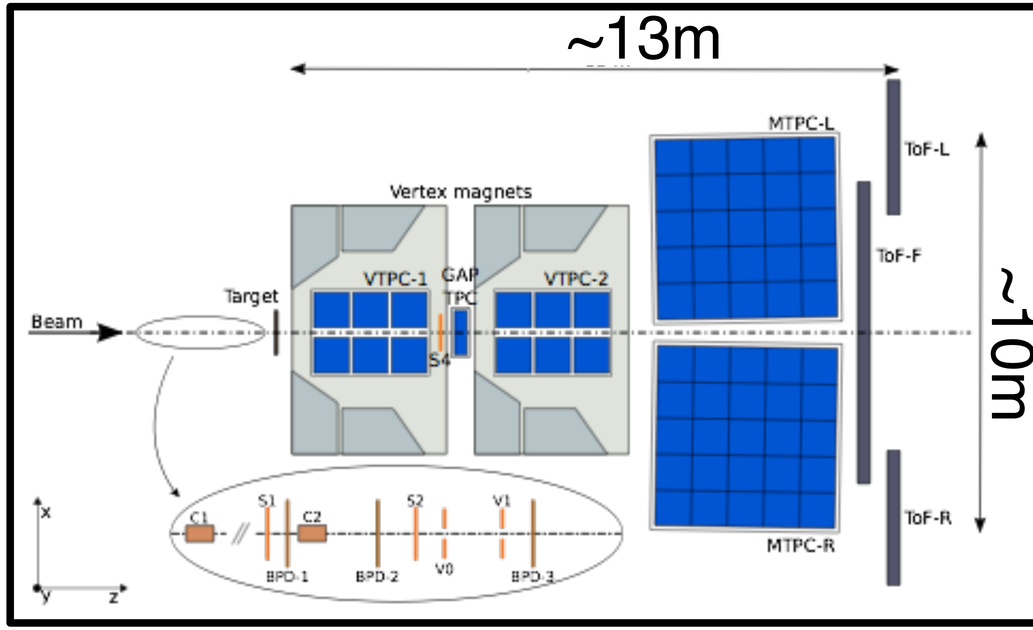
Beamline MC



- Hadronic interactions
  - Pions/Kaons - use **CERN NA61/SHINE pion measurement (large acceptance: >95% coverage of ν parent pions)**
  - Pions outside NA61 acceptance, other interaction use **FLUKA simulation**
  - Secondary interactions outside the target based on experimentally measured cross-sections
- **GEANT3 transport simulation used downstream of target**

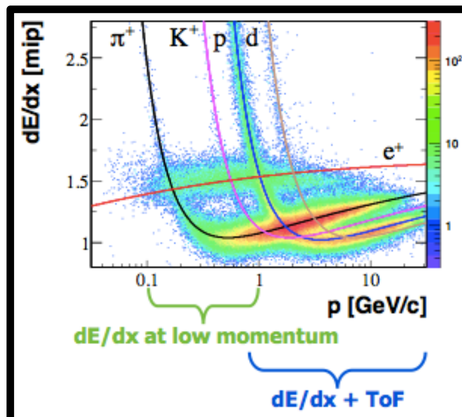
NA61/SHINE @ CERN

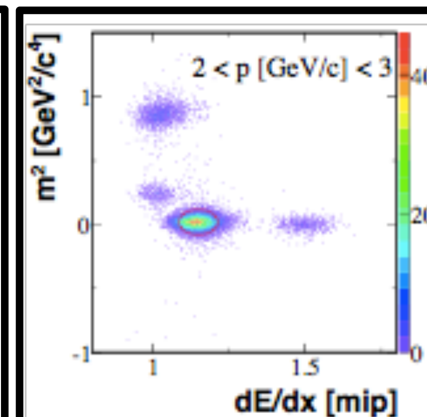
- Hadron(π, K) yield measurement
  - 30 GeV proton
- High-acceptance ToFs and spectrometers
- Measurement program
  - 2 cm thin target - 4%λ_I
  - T2K Replica target



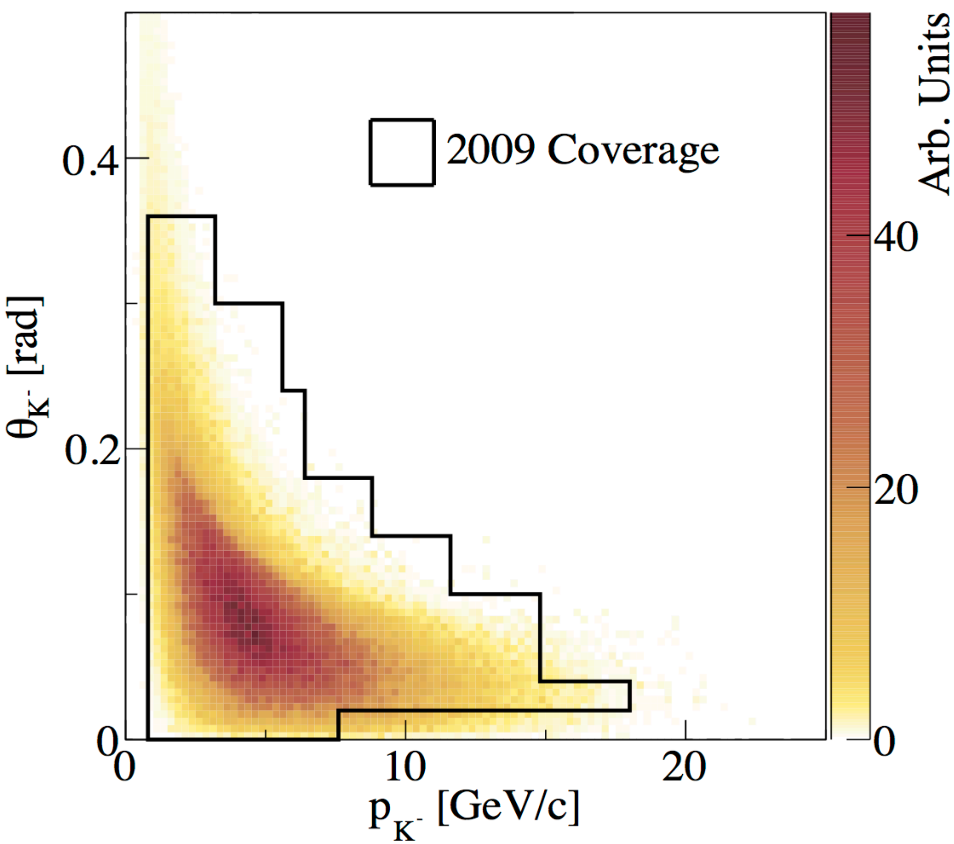
$$\sigma(p)/p^2 \approx 2\times10^{-3},\ 7\times10^{-3},\ 3\times10^{-2}(\mathrm{GeV/c})^{-1}$$
$$\text{for } p>5,\ p=2,\ p=1\ \mathrm{GeV/c}$$

$$\sigma(\mathrm{dE/dx})/\langle\mathrm{dE/dx}\rangle \approx 0.04$$
$$\sigma(\text{TOF-F}) \approx 115\ \mathrm{ps}$$





Flux Prediction



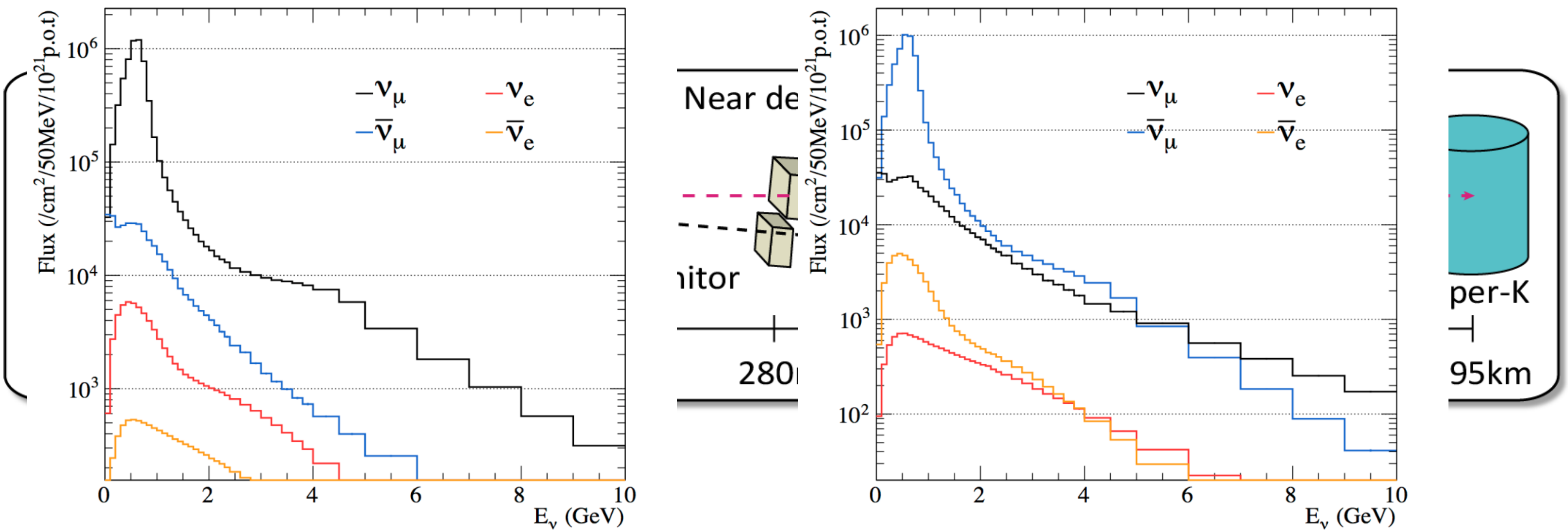
- Flux prediction
  - external or in-situ measurements
  - p-C data
  - alignment and off-axis angle
  - $\pi^{\pm}$, $K^{\pm}$ production from NA61/SHINE

Uncertainties are comparable for neutrino or antineutrino mode operation (10-15%)

Flux Prediction II

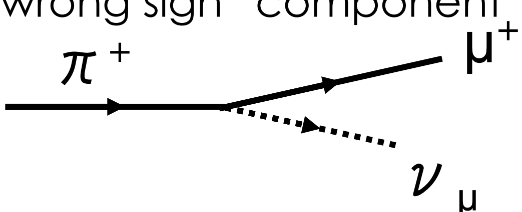
Neutrino mode operation

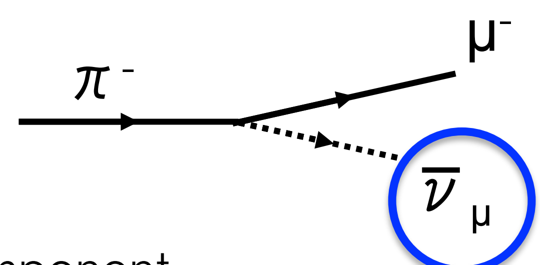
Antineutrino mode operation



FLUKA/Geant3-based neutrino beam simulation (PRD 87, 012001)

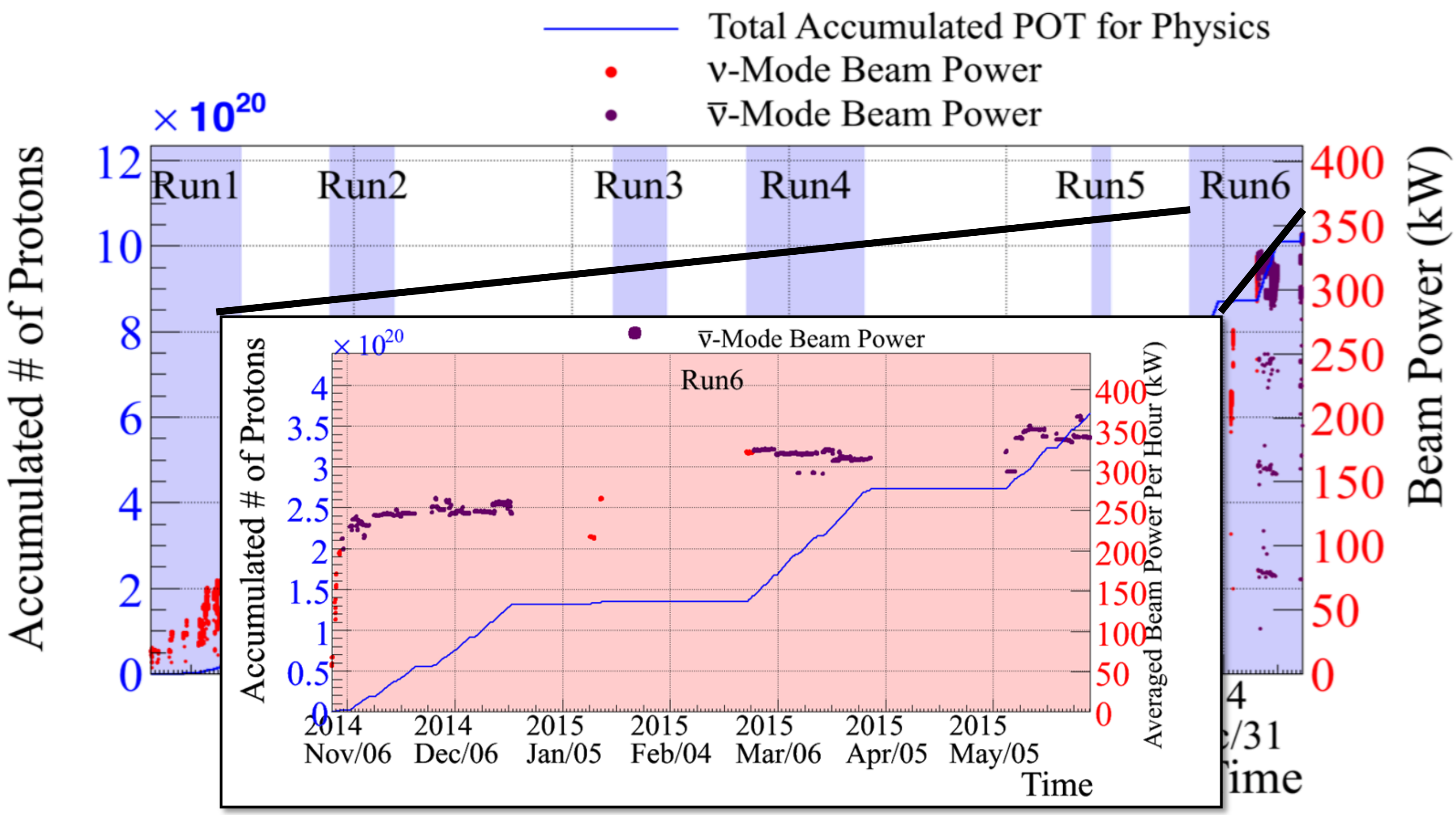
- Significant neutrino component to antineutrino mode beam
  - Increases in event rate due to lower antineutrino cross section
- "wrong sign" component





- "Intrinsic" ~0.5% electron (anti)neutrino component

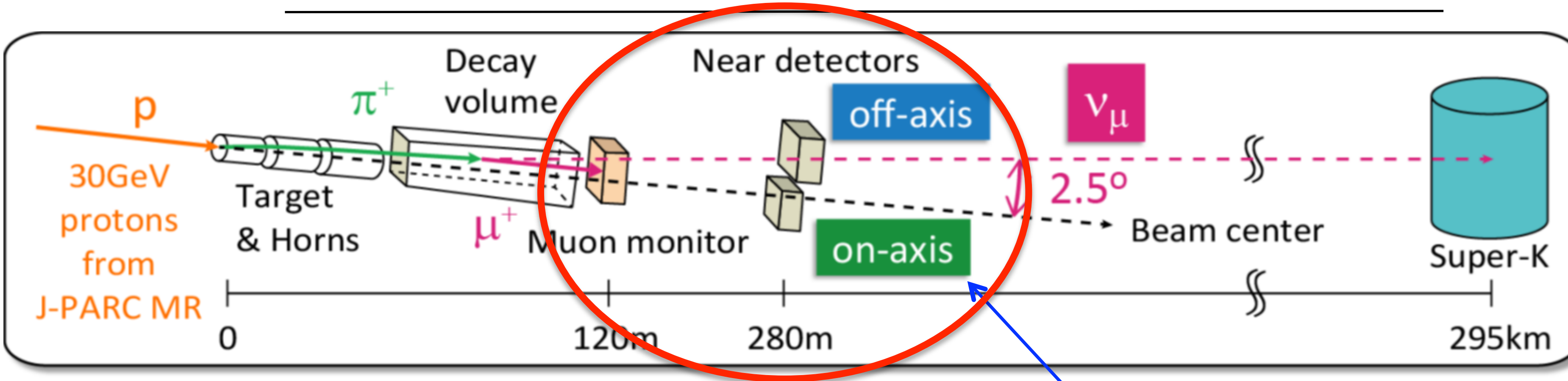
Data Taking



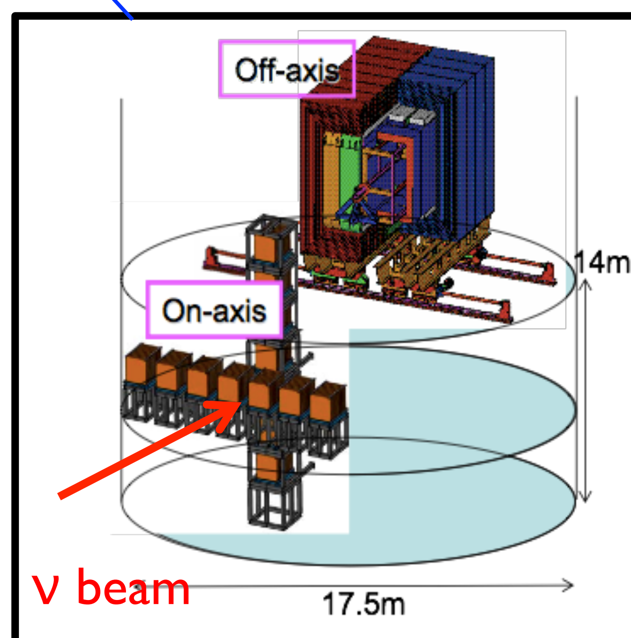
Protons on Target (POT) for the antineutrino analyses today:

- Run 5c+6 datasets for far detector, Super-K: 4.0 x 10^{20} POT
- Run 5c datasets for off-axis near detector, ND280: 4.3 x 10^{19} POT

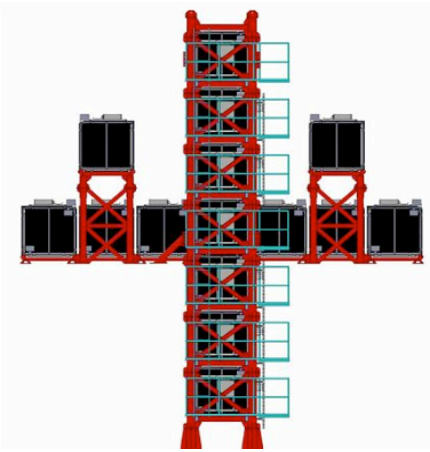
Near detectors

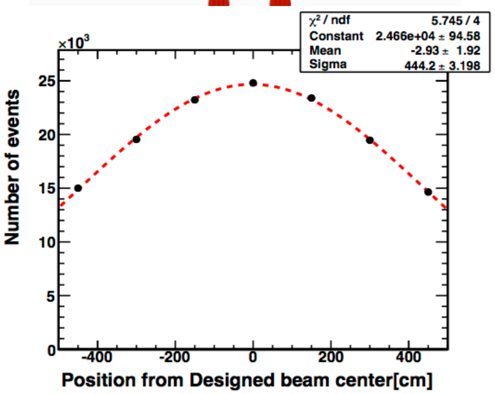


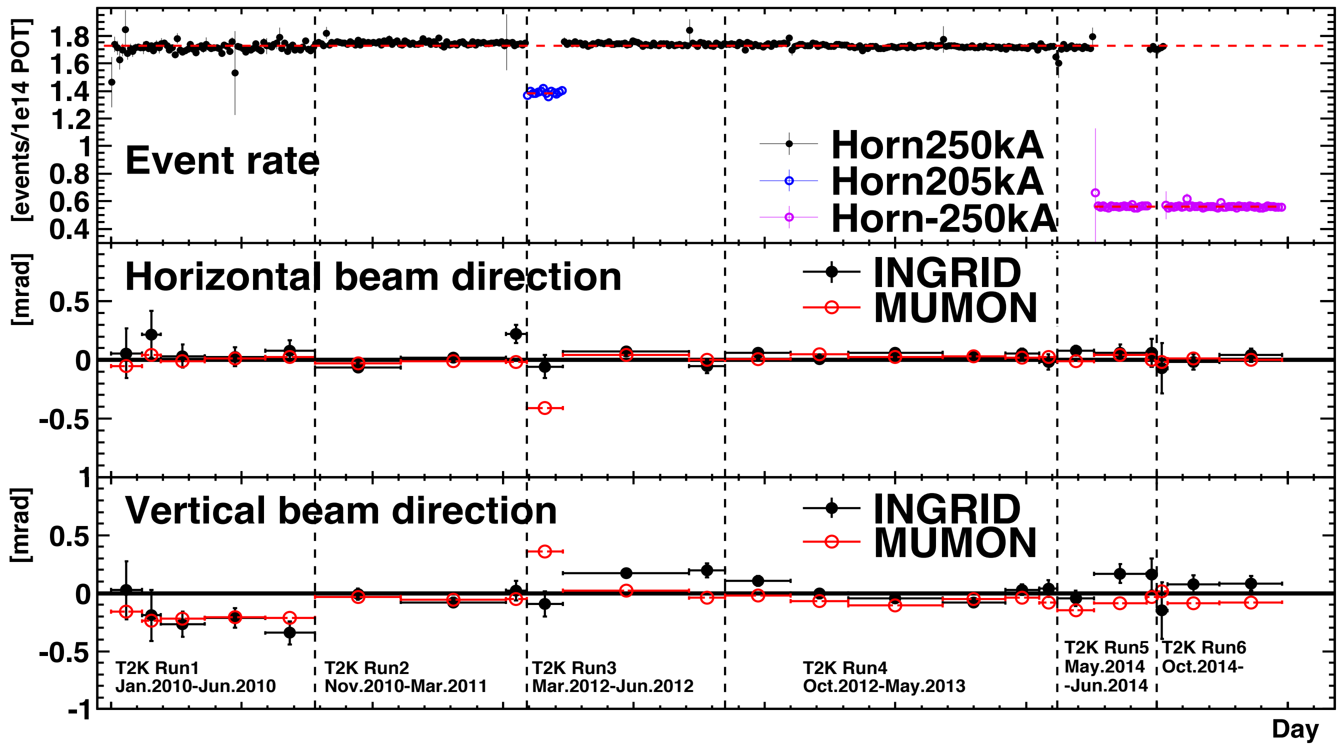
- **Muon monitor**
  - spill-by-spill monitoring
- **INGRID** (On-axis detector)
  - measures beam intensity/direction
  - **1 mrad** precision in 1 day
- **ND280** (same off-axis angle as SK)
  - Detailed flux measurement
  - Exclusive cross-section measurements



Beam Stability



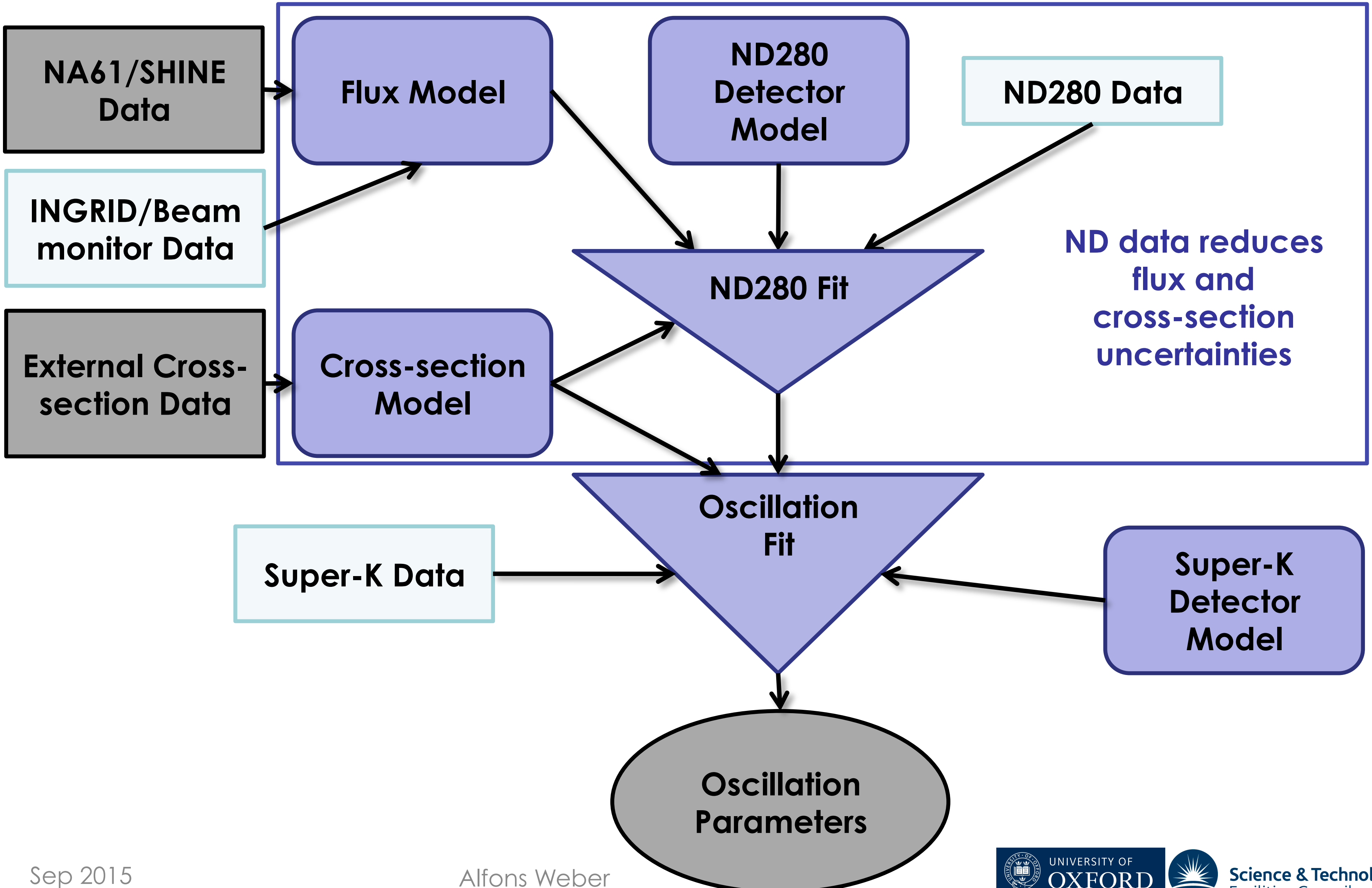




neutrino beam profile measured with INGRID

- scintillator/iron tracking detectors (0-0.9 degrees off-axis)
- POT normalized event rate stable to better than 1%
- Beam direction is stable to within 1 mrad
  - corresponds to a 2% shift to peak in off-axis neutrino energy

Analysis Strategy



Reducing Uncertainties

$$N_{FD} \sim \Phi(E_\nu)\sigma(E_\nu)\epsilon_{FD}P(\nu_\mu \to \nu_e)$$

Neutrino flux prediction

Neutrino cross section model

Far Detector selection, efficiency

$$N_{ND} \sim \Phi(E_\nu)\sigma(E_\nu)\epsilon_{ND}$$

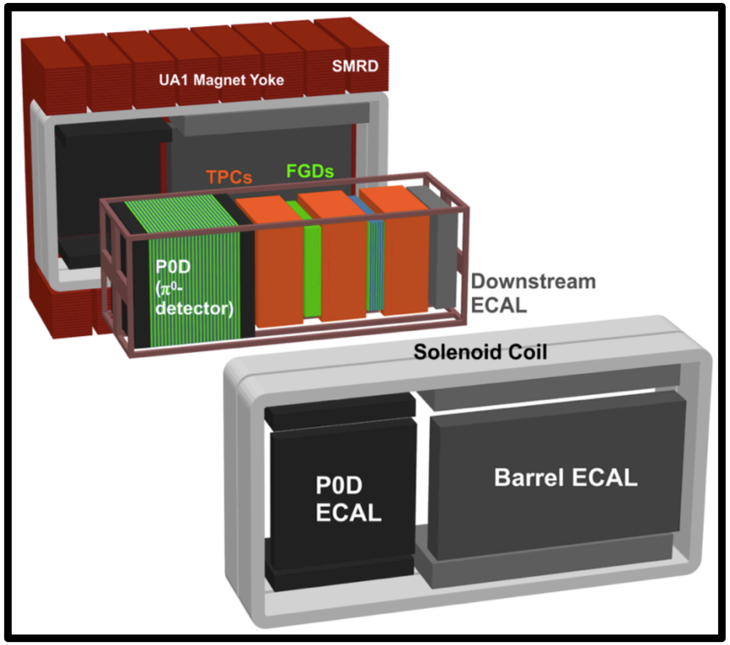
Neutrino flux prediction

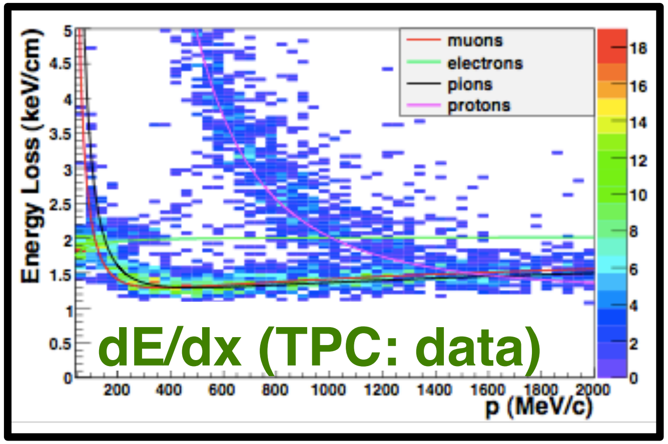
Neutrino cross section model

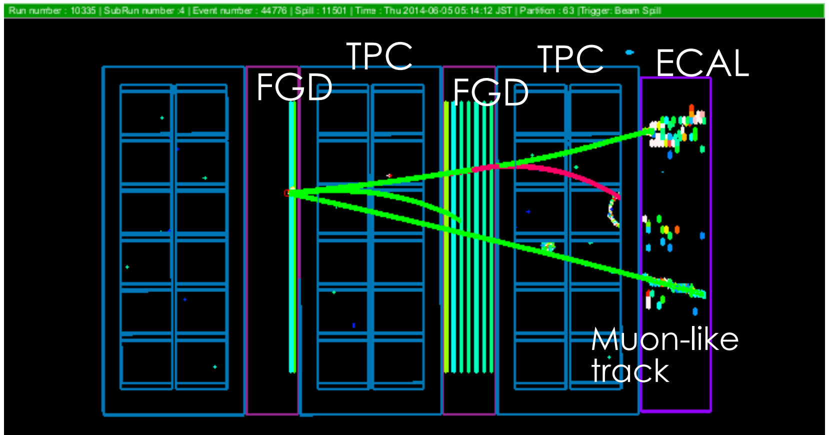
Near Detector selection, efficiency

ND280 Detector

- 0.2 T magnet
  - Recycled from UA1@ CERN
  - Recycled from NOMAD @ CERN
- Plastic scintillator detectors:
  - Fine Grained Detector (FGD)
    - 1.6 ton fiducial mass for analysis
  - π^0 detector (P0D)
  - ECals and SMRD
- Time projection chambers (TPC)
  - better than 10% dE/dx resolution
  - 10% p resolution at 1GeV/c
  - Micromegas from CERN

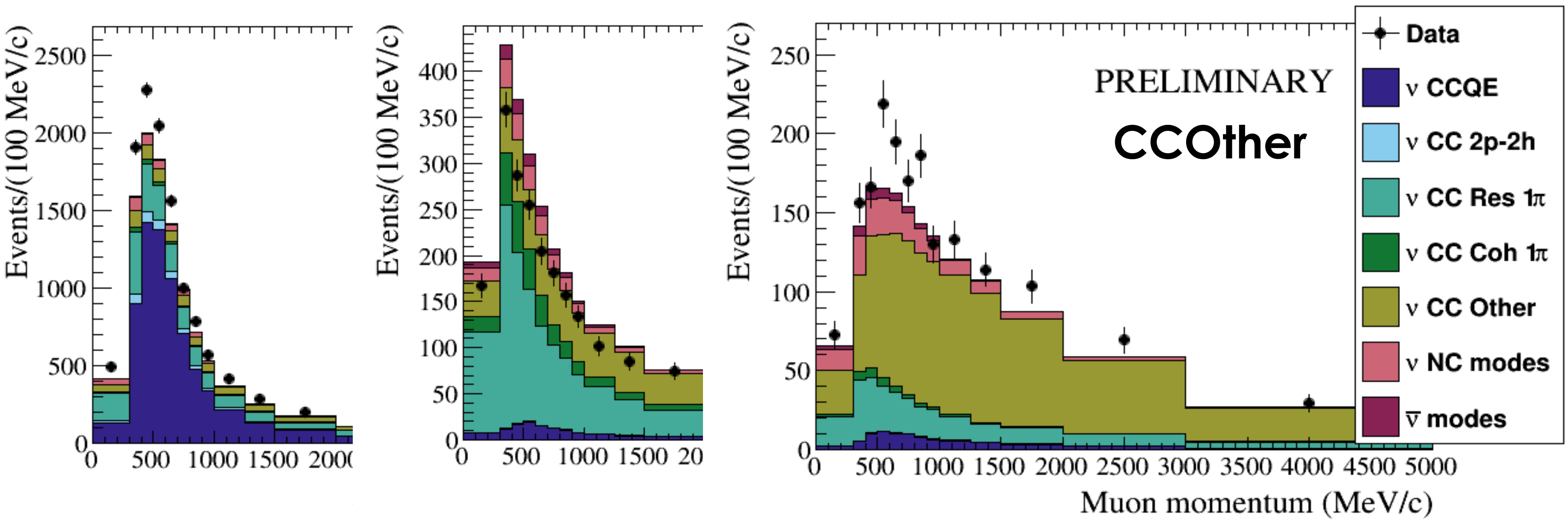






Example: neutrino candidate in antineutrino mode

ND Event Samples (I)



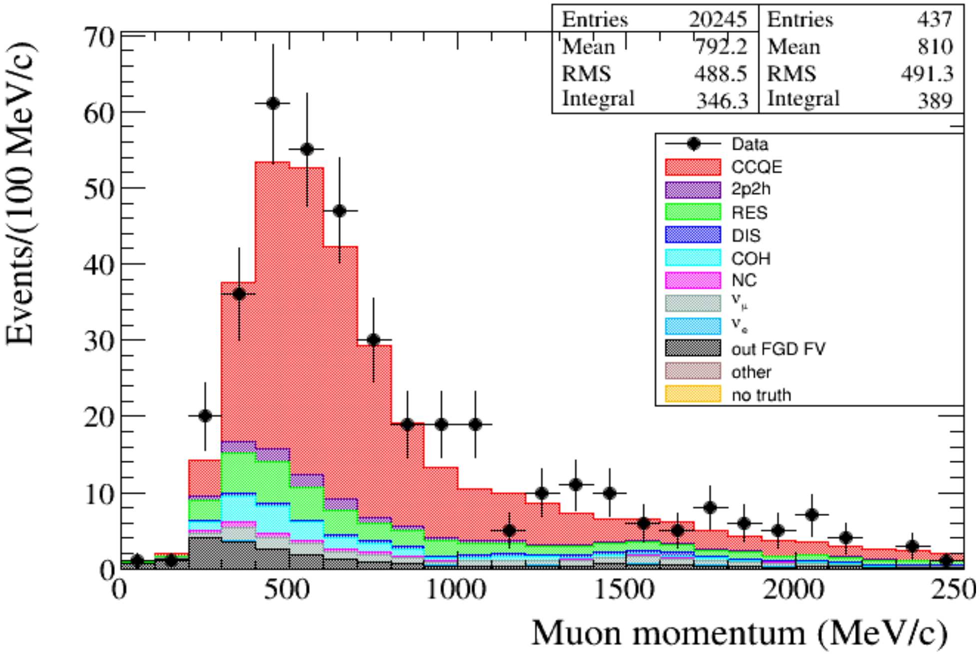
- Select CC ν_μ candidates based on interactions with μ^-
  - Select highest momentum track with negative charge, and PID consistent with a muon
  - Event samples provide information on flux, cross section model
  - Separated based on presence of charged pion in final state (CC0π, CC1π, CC Other)
  - Pions identified using track multiplicity, dE/dx in TPCs, photons in ECALs

ND Event Samples (II)

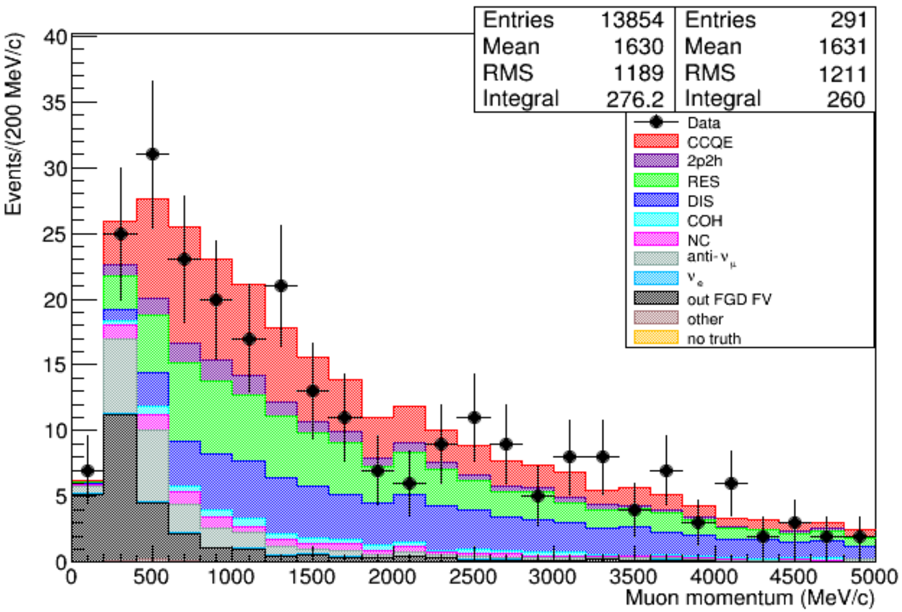
Select CC $\bar{\nu}_\mu$ candidates based on interactions with μ^+

- highest momentum track, positive charge, and PID consistent with muon
- Two sub-samples based on track multiplicity:
  - CC1-Track,
  - CC>1 Track
- Complementary selection of neutrino candidates in antineutrino mode

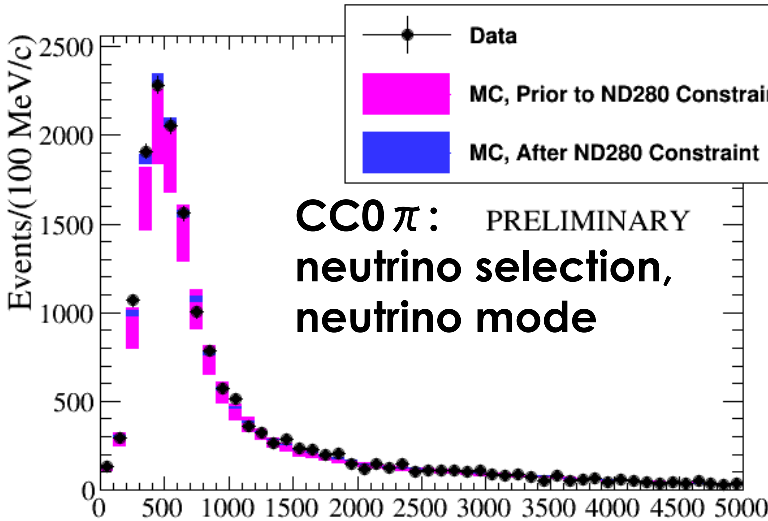
CC1Track: antineutrino selection, antineutrino mode

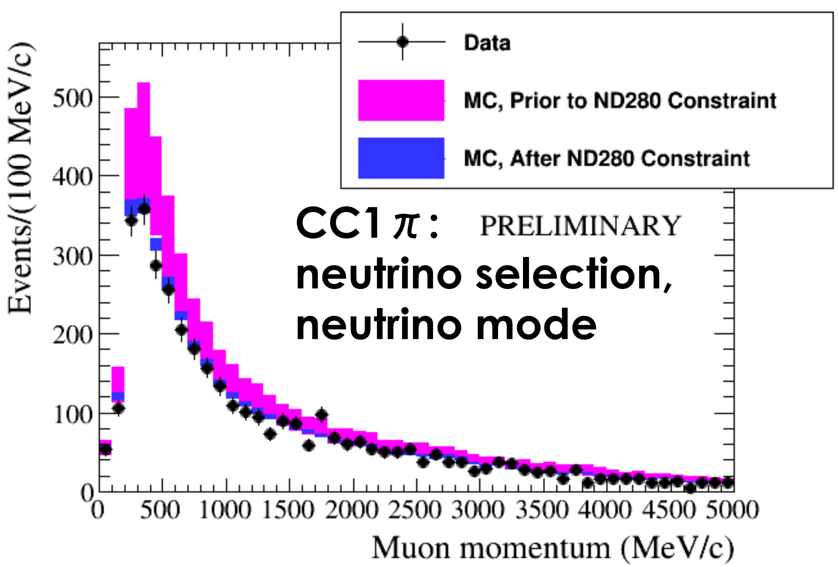


CC inclusive: neutrino selection, antineutrino mode



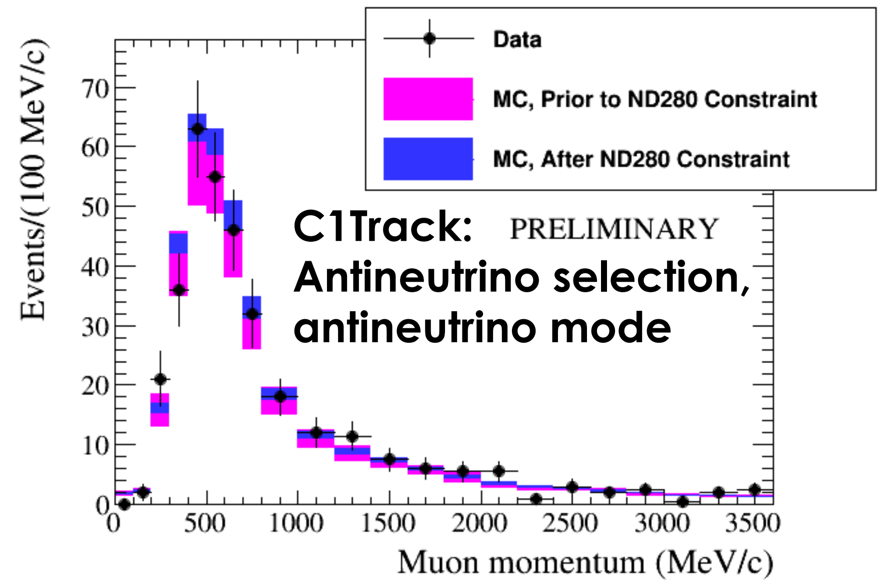
Near Detector Fit (I)





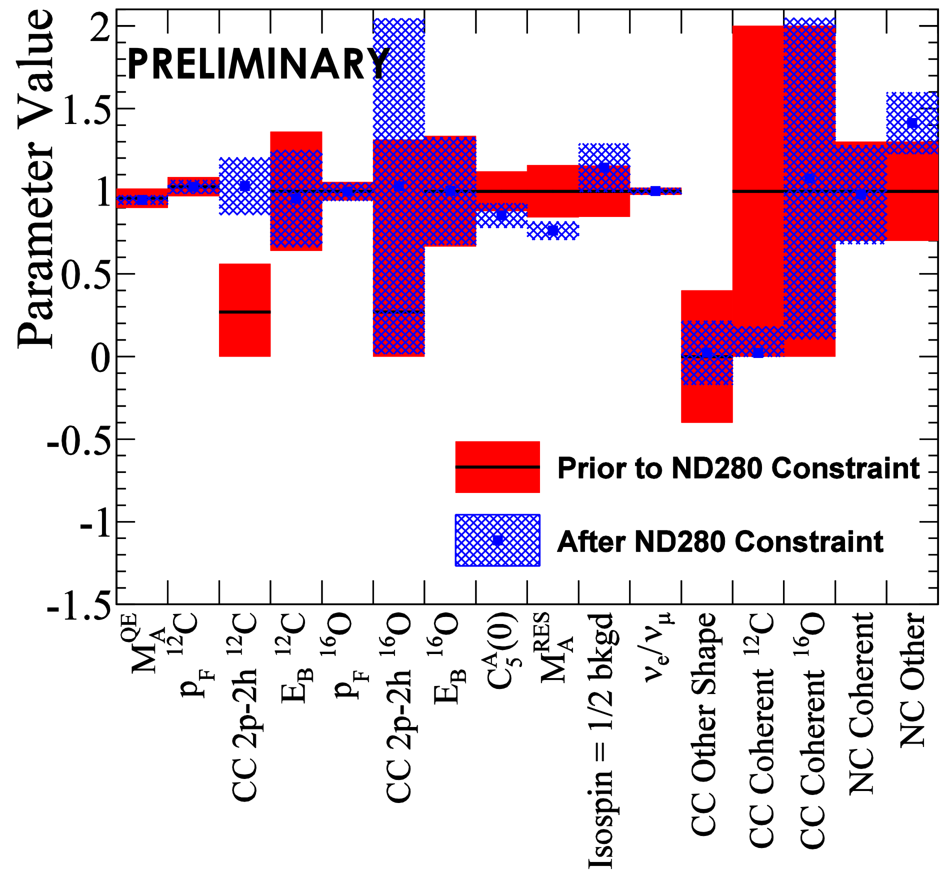
Far detector expectations tuned with fit to ND samples (p,θ)

- (Anti-)Neutrino fluxes highly correlated between ND and FD
- Cross sections highly correlated
- Significant reduction to overall uncertainties

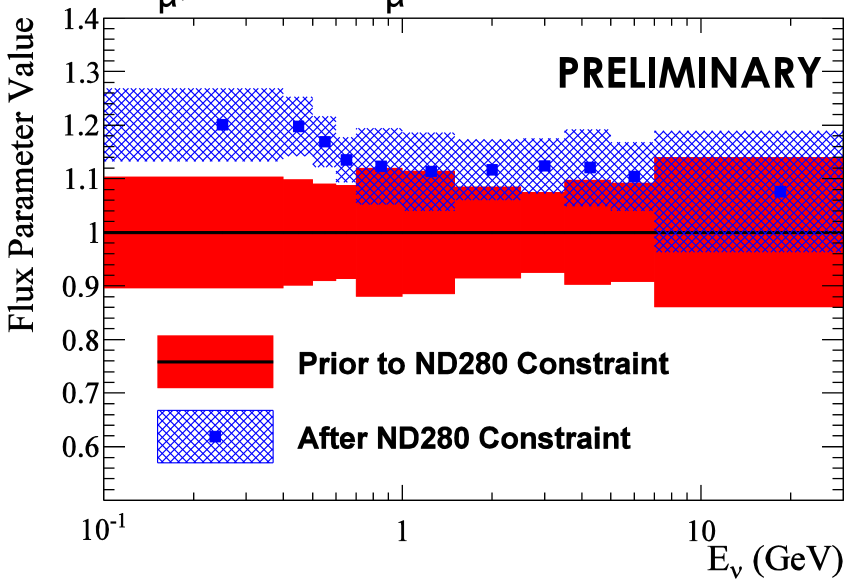


Near Detector Fit (II)

- Predicted flux at FD is generally increased
- Some cross-section parameters are significantly different to prior values
- In general error on parameters is decreased

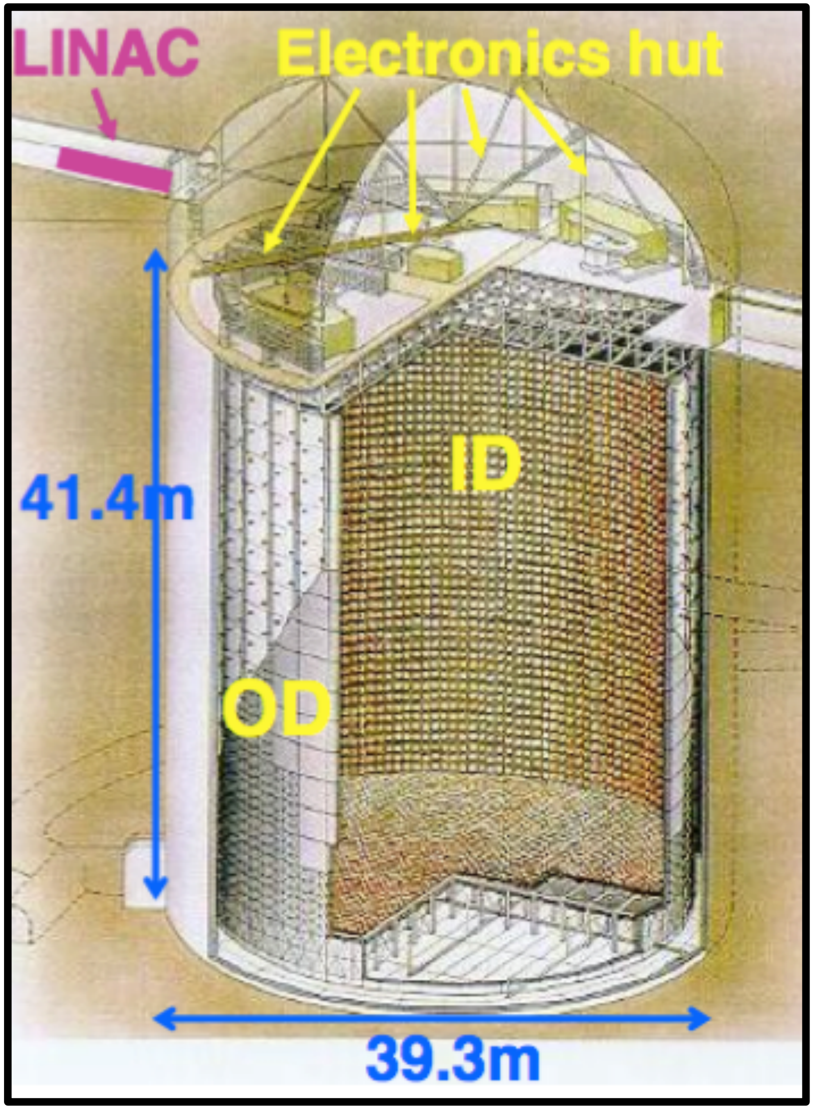


$\bar{\nu}_\mu$-flux in $\bar{\nu}_\mu$-mode beam

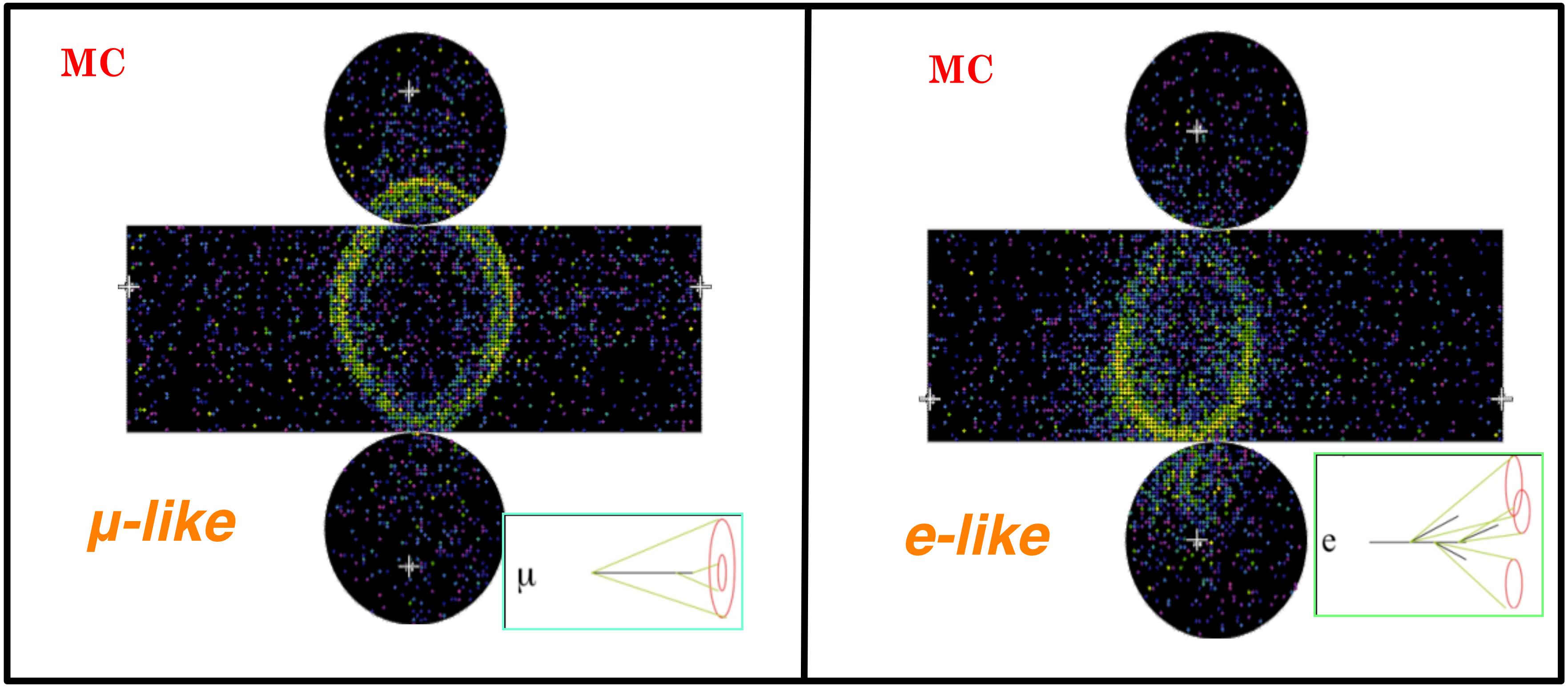


Super-K Detector

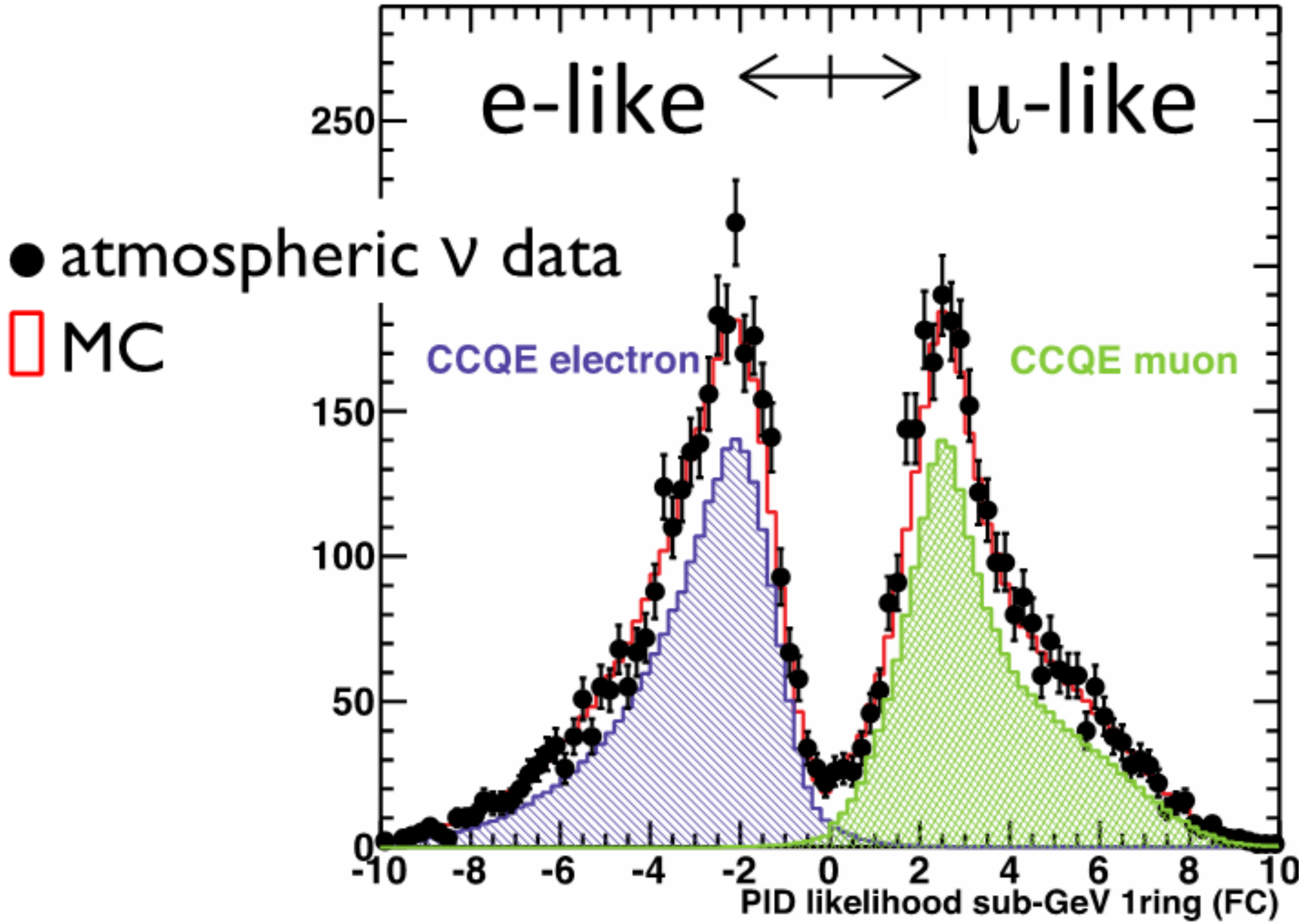
- Located in Mozumi mine
  - 2700 m.w.e. overburden
- Water Cherenkov detector
  - 22.5 kt fiducial mass
- Inner detector
  - 11000 20-inch PMTs
- Outer veto
  - 1900 8-inch PMTs
- New DAQ system
  - No deadtime
- Excellent μ /e separation
  - Probability to reconstruct μ as e ~1%



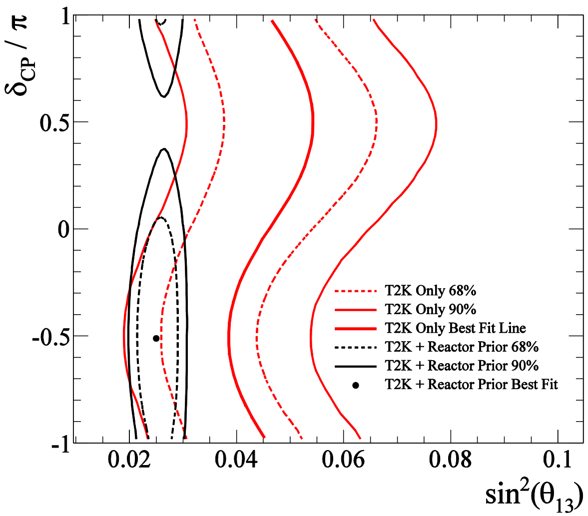
Particle Identification

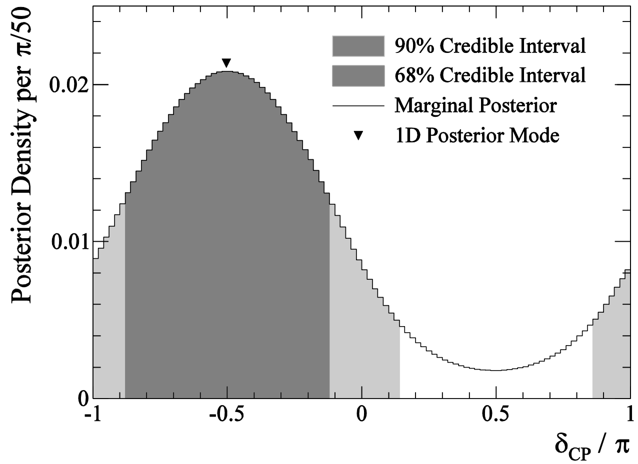


PID (II)

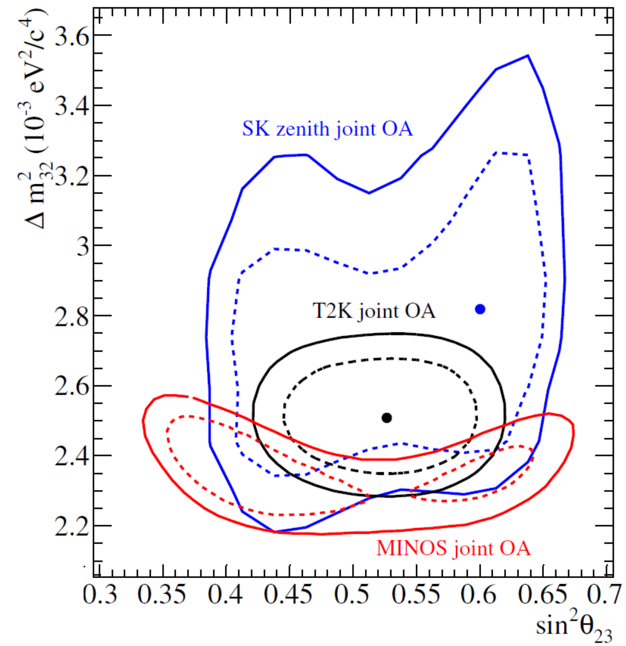

e-like
μ-like
● atmospheric ν data
MC
CCQE electron
CCQE muon
250
150
100
50
0
-10
-8
-6
-4
-2
0
2
4
6
8
10
PID likelihood sub-GeV 1ring (FC)

Previous T2K Measurements





90% CL constrain on δ_{CP}



First measurement ν_e appearance (7.3 σ)

Measurement of θ_{13} (w/ & w/o reactor constrain $\sin^2\theta_{13}$=0.095±0.001)

Open Questions
- Mass Hierarchy
- CP Phase δ_{CP}

World-leading measurement of θ_{23}
Significant measurement of Δm^2_{23}

Abe, K. et al, Physical Review D 91.7 (2015): 072010

T2K Oscillation Analysis

Muon antineutrino disappearance

- Fit for $\bar{\theta}_{23}$ and $\overline{\Delta m^2}_{32}$
- Use separate parameters for neutrino interactions
- Other oscillation parameters fixed to T2K neutrino data and PDG2014
- Test of NSI or CPT theorem

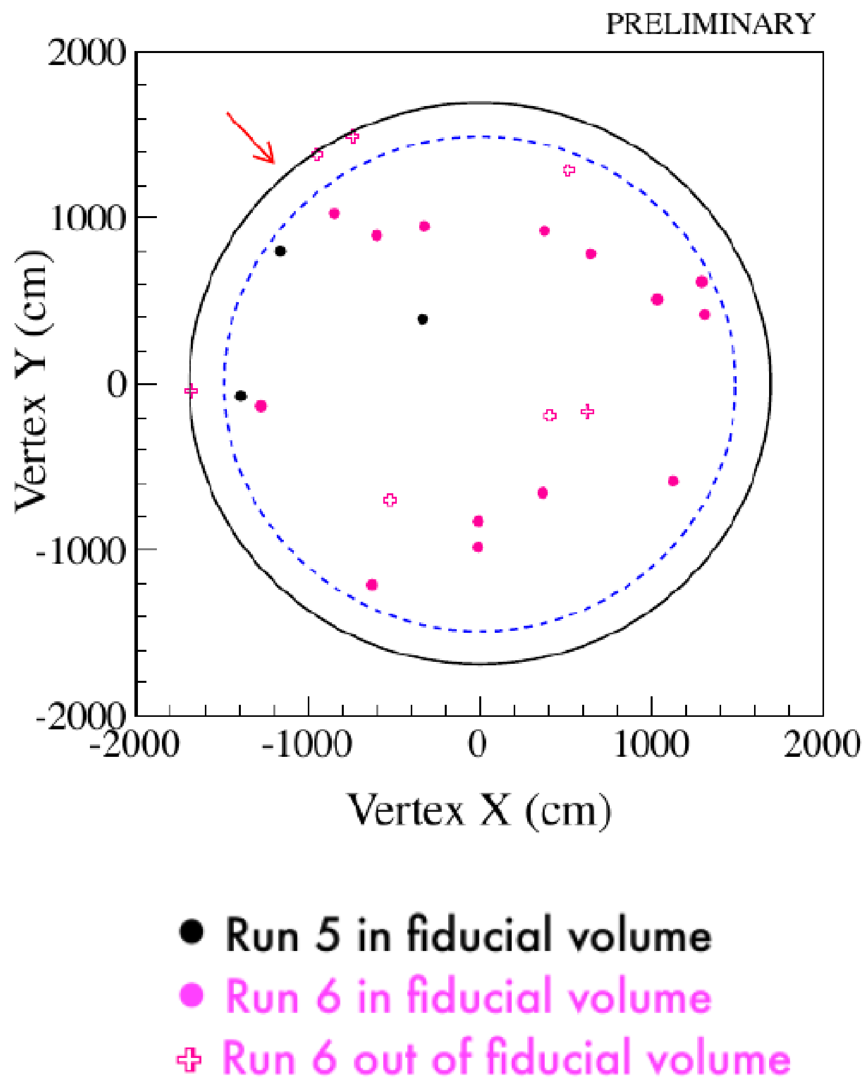
Electron antineutrino appearance

- Search for presence of appearance with antineutrinos
- Necessary step toward future CPV searches

T2K SEARCH FOR MUON NEUTRINOS

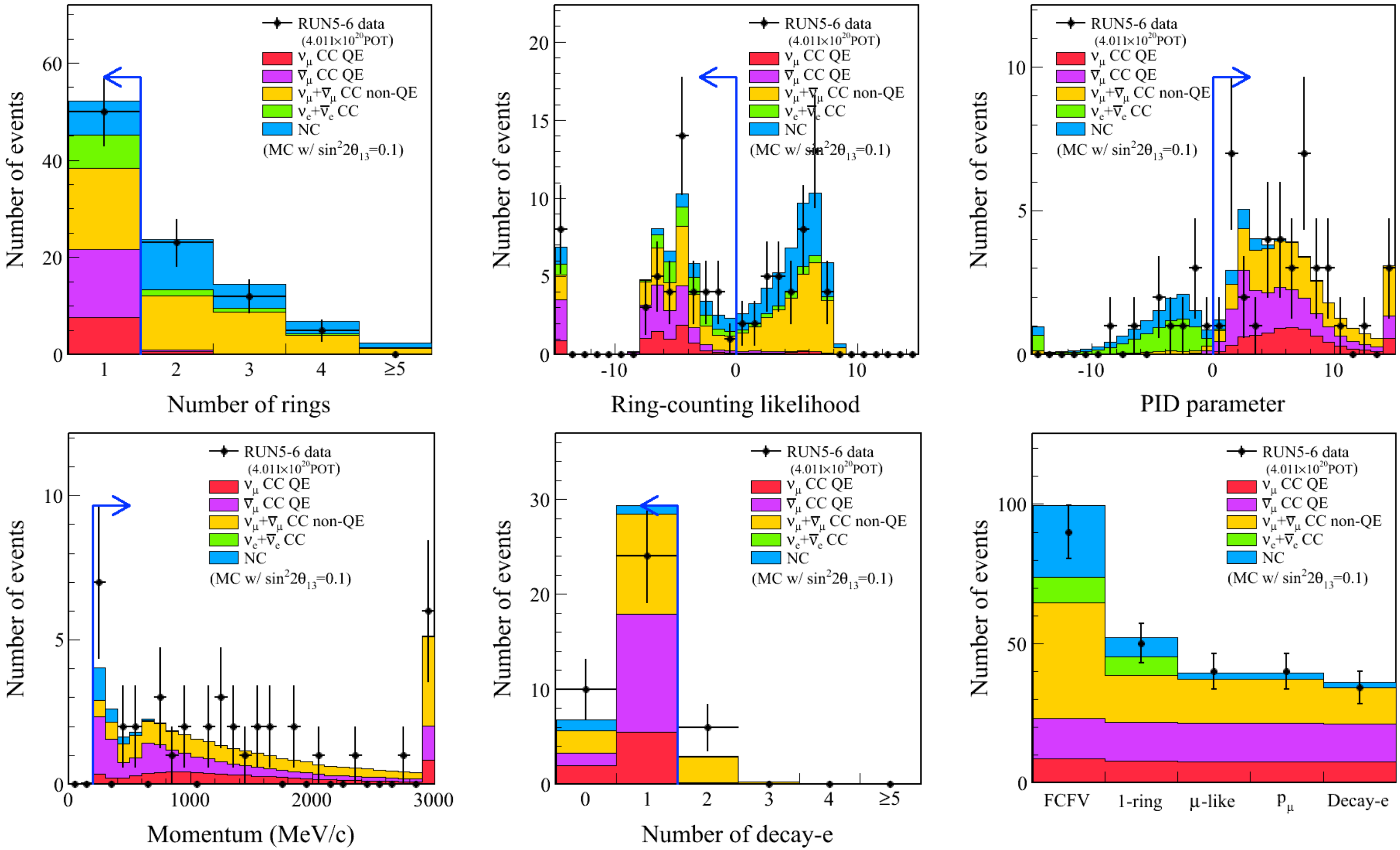
$\bar{\nu}_\mu$ Selection (I)

FD Event selection
- Muon-like PID
- Fully contained in fiducial volume
- 1 ring
- ≤1 decay electron(s)
- p_μ > 200 MeV

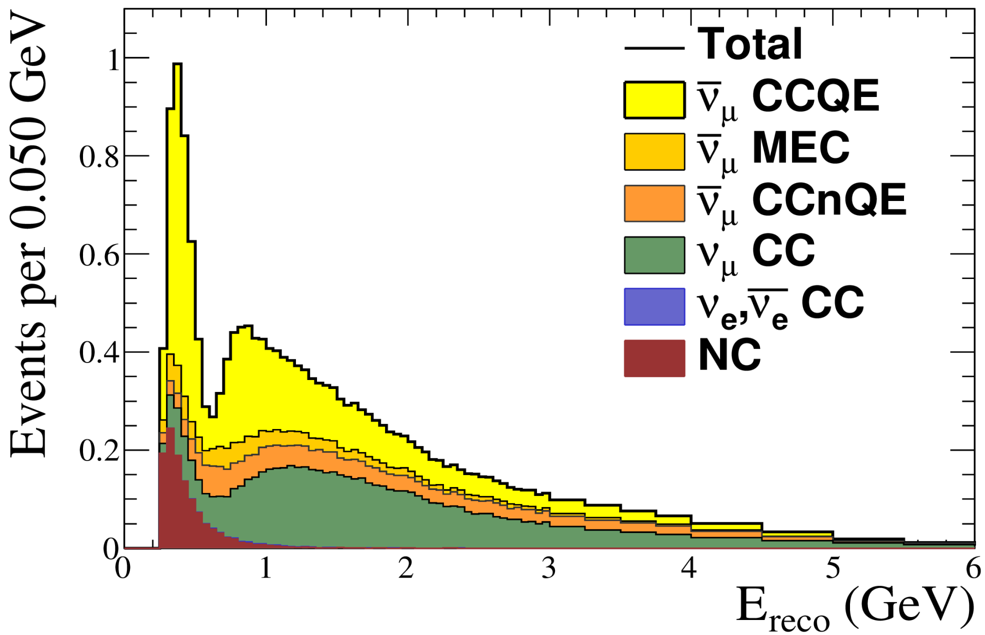


- Beam direction
- Fiducial volume boundary
- Events during run 5
- Events during run 6
- Out of fiducial volume events

$\bar{\nu}_\mu$ Selection (II)



Predicted Event Rates



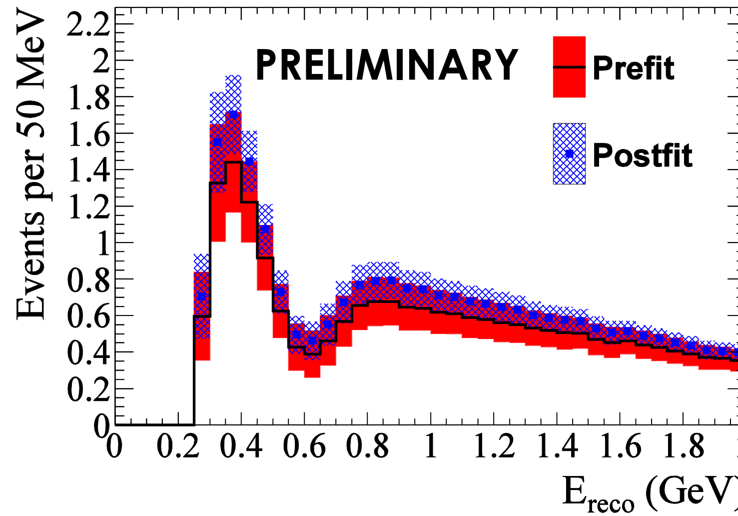
Predominantly antineutrino interactions, but significant components from other channels

- Expect 34.6 events w/ oscillation
- Expect 103.6 events w/o oscillation

	$\nu_\mu \to \nu_\mu$	$\overline{\nu}_\mu \to \overline{\nu}_\mu$	$\nu_e \to \nu_e$	$\overline{\nu}_e \to \overline{\nu}_e$	$\nu_\mu \to \nu_e$	$\overline{\nu}_\mu \to \overline{\nu}_e$
CCQE	6.870	13.258	0.004	0.005	0.007	0.017
MEC	1.578	2.347	0.001	0.001	0.001	0.003
CC1π	2.414	3.046	0.003	0.002	0.003	0.003
CC coherent	0.167	0.696	0.000	0.000	0.000	0.002
CC other	1.222	0.880	0.001	0.000	0.000	0.000
NC1π	0.391	0.428	0.016	0.012	-	-
NC other	0.707	0.420	0.035	0.017	-	-
subtotal	13.349	21.076	0.059	0.038	0.011	0.025
total	34.559					

Systematics

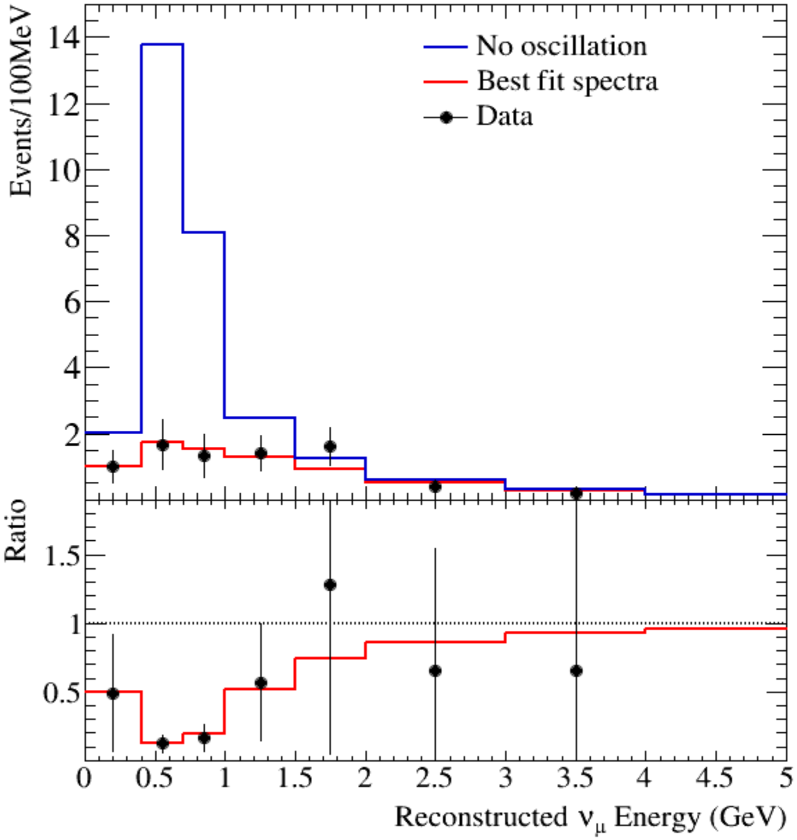
The near detector significantly reduces the systematic uncertainty in the predicted event rate at far detector



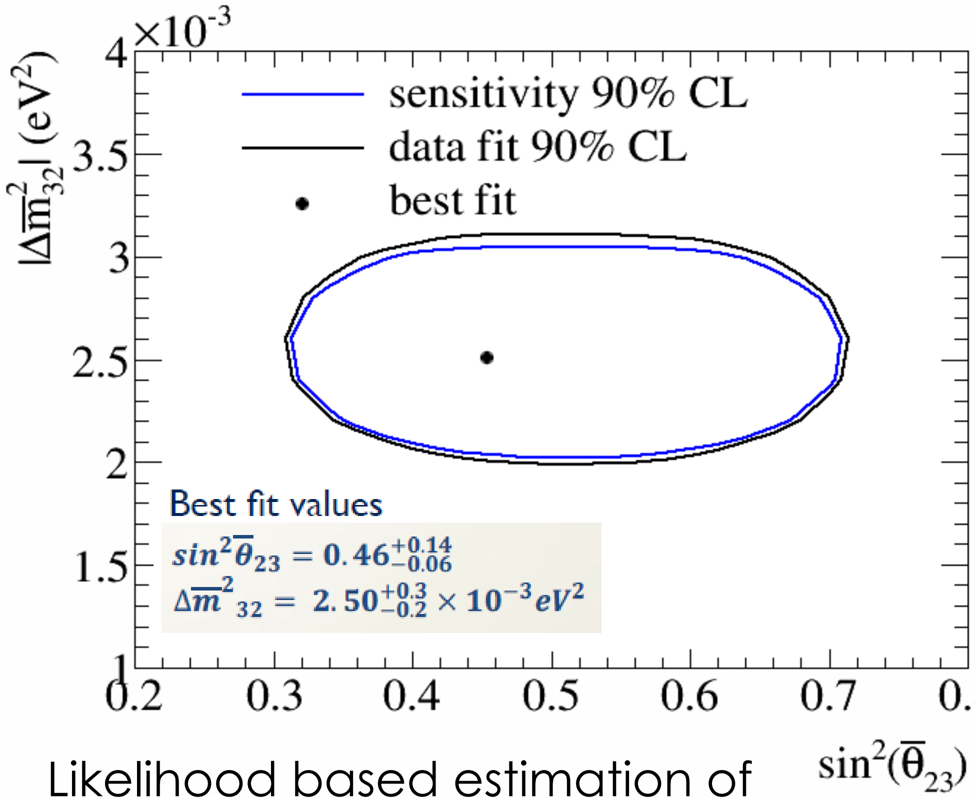
Systematic			Without ND	With ND
Flux and Cross-section	Common to ND280/SK		9.2%	3.4%
	Super-K Only	Multi-nucleon effect on oxygen	9.5%	
		All Super-K Only	10.0%	
	All		13.0%	10.1%
Final State Interaction/Secondary Interaction at Super-K			2.1%	
Super-K Detector			3.8%	
Total			14.4%	11.6%

ND Measurements on water not jet included

Antineutrino Disappearance



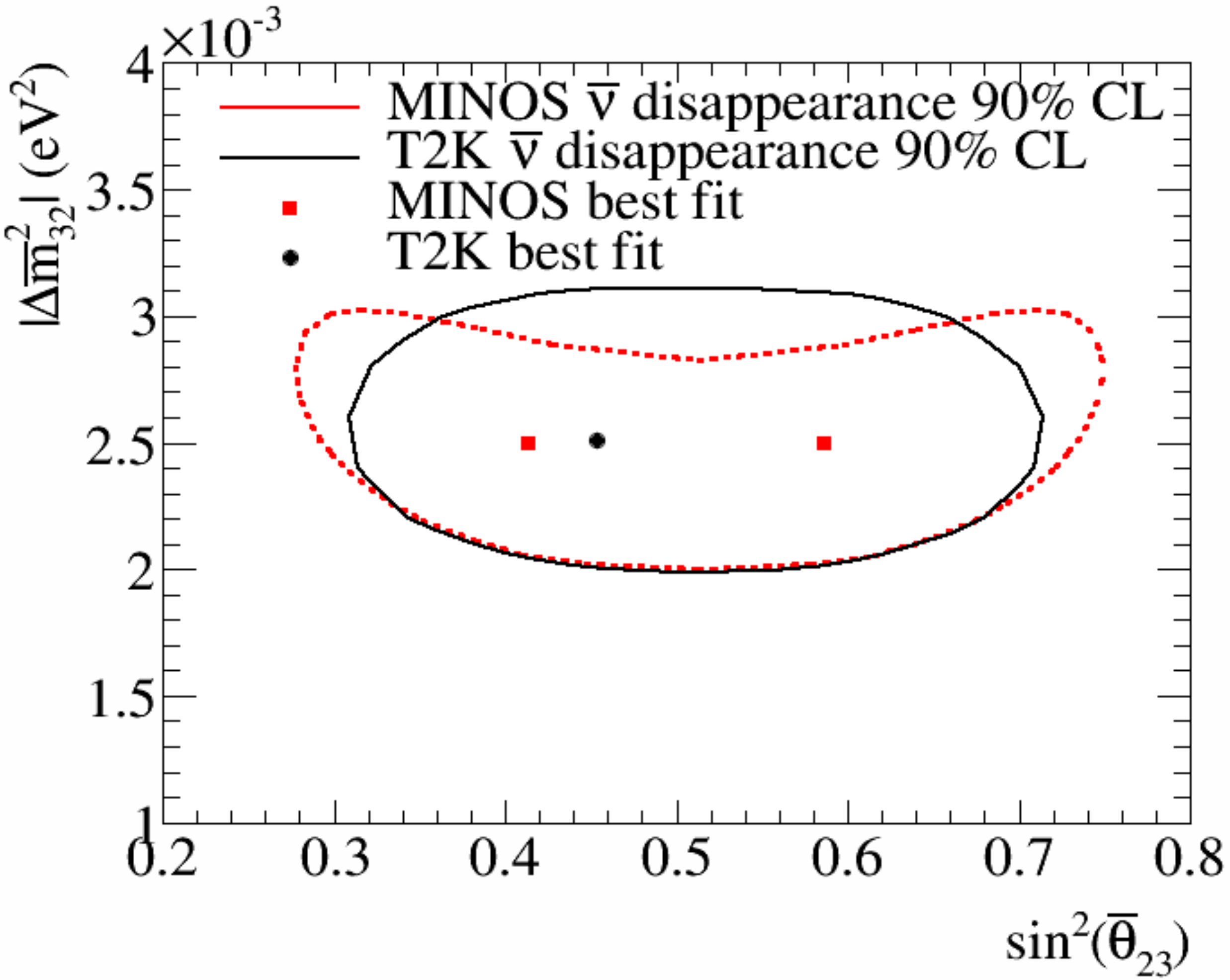
34 events observed
103.6 expected (w/o osc.)



Likelihood based estimation of oscillation parameters

- Binned in reconstructed neutrino energy
- Other oscillation parameters fixed to T2K neutrino data and PDG2014

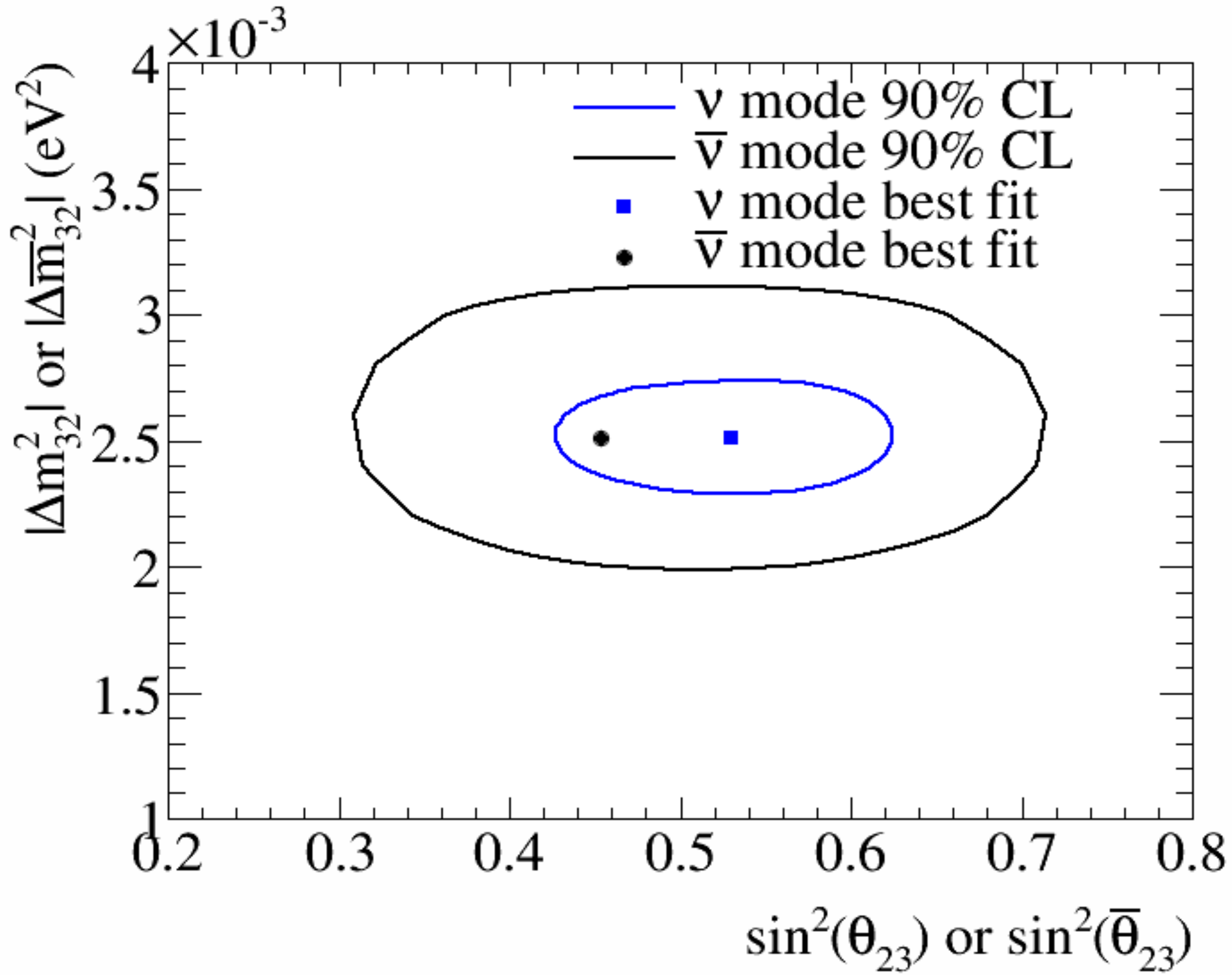
Comparison with MINOS



Results compatible with MINOS combined beam+atm

- P. Adamson et al., Phys. Rev. Lett. 110 (2013) 25, 251801

Comparison with Neutrino Result

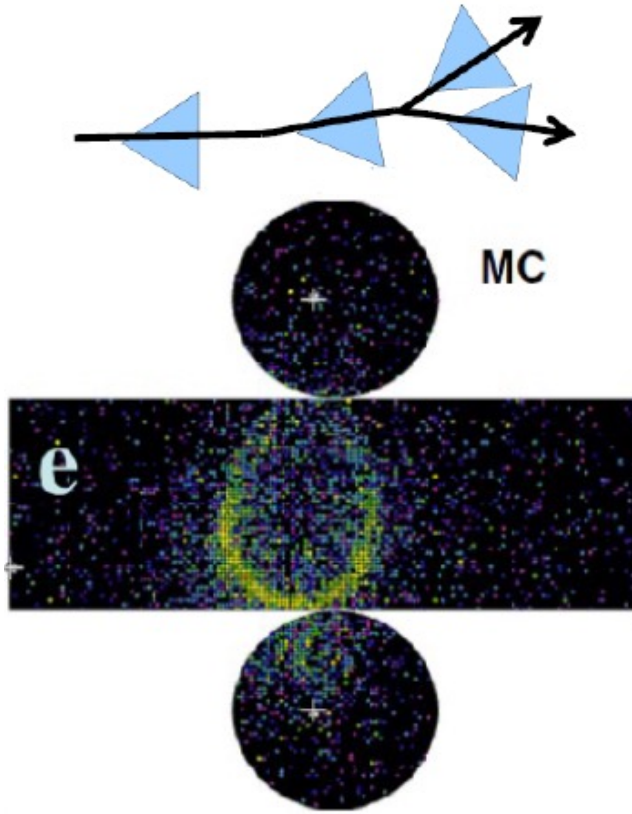


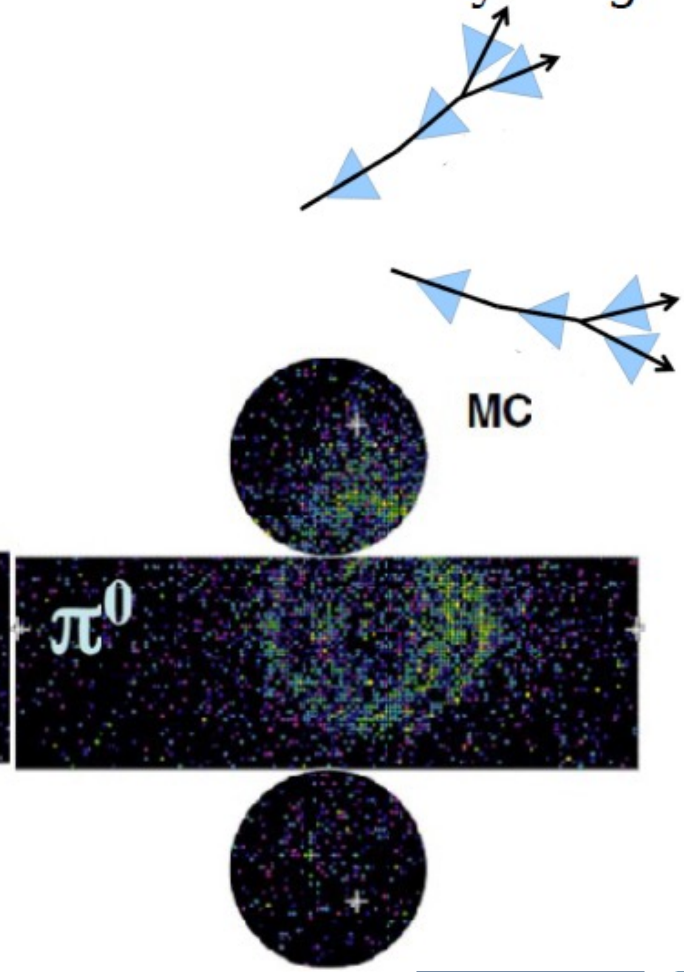
T2K SEARCH FOR ELECTRON NEUTRINOS

Identifying ν_e

EM Shower:
Fuzzy Ring

2 EM Showers:
> 1 Fuzzy Ring





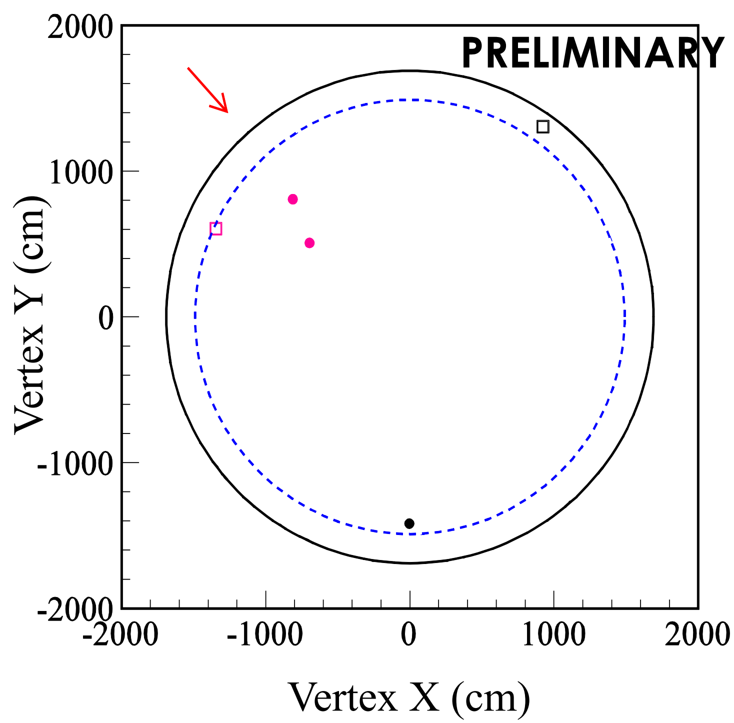
$\bar{\nu}_e$ Events

FD Event Selection

- Electron-like PID
- In fiducial volume
- 1 ring
- No decay electrons
- p_e > 100 MeV
- E_ν < 1250 MeV
- Pass π^0-rejection

Beam direction
Fiducial volume boundary
Events during run 5
Events during run 6
Out of fiducial volume events

Anti-neutrino e-like selection
3 events



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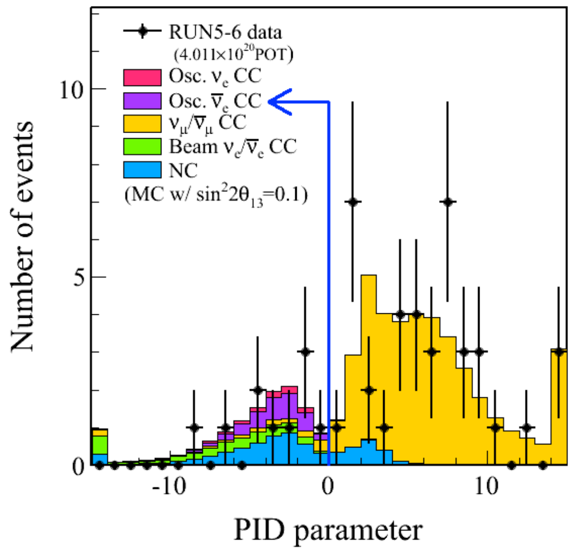
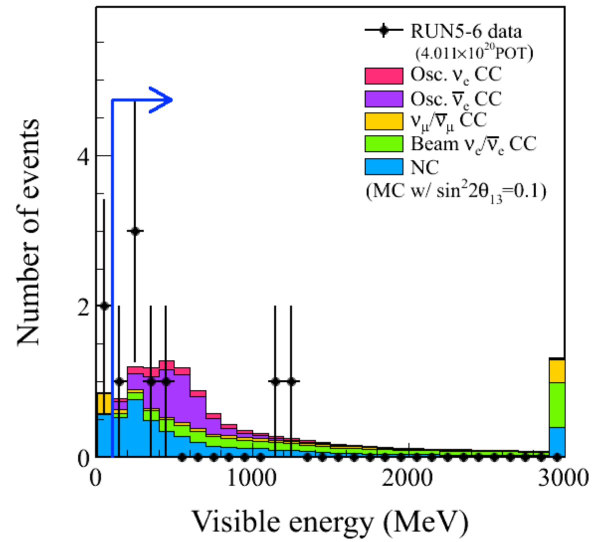
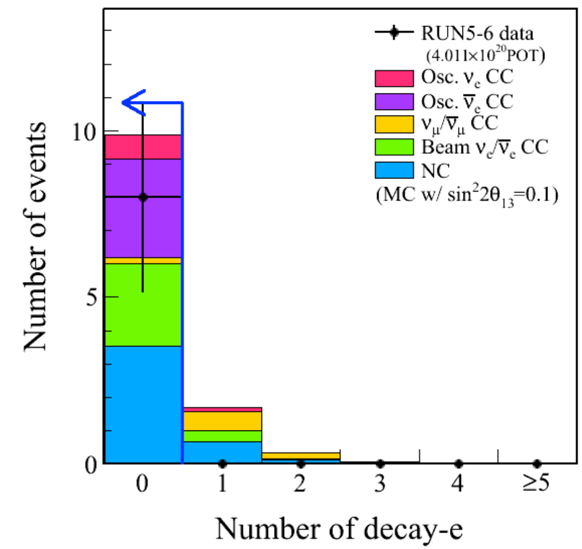
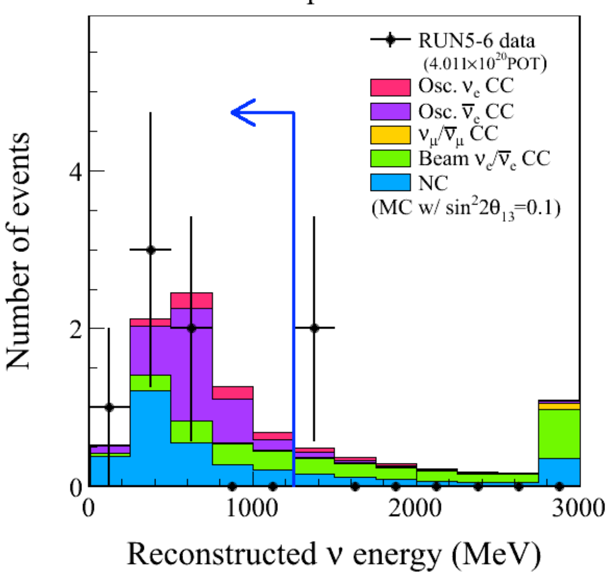
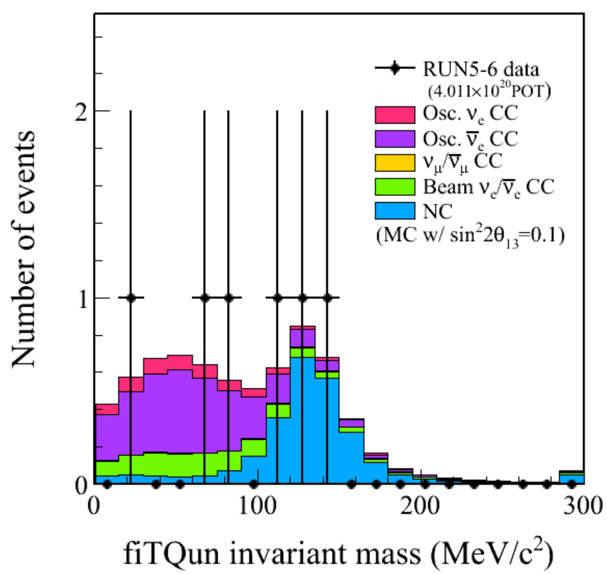
$\overline{\nu}_e$ Selection

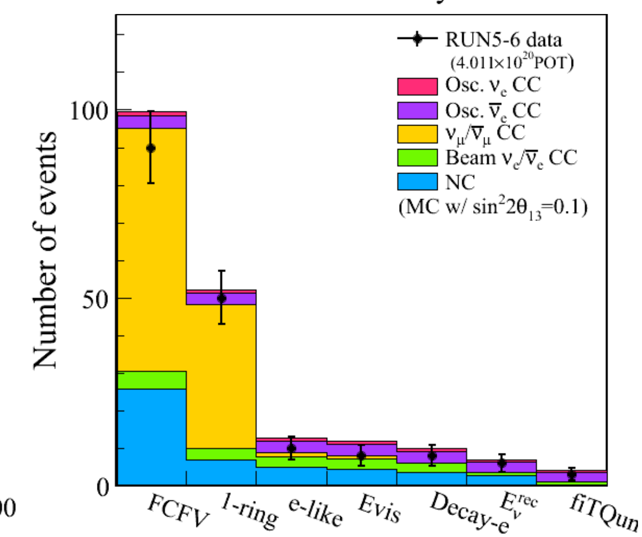








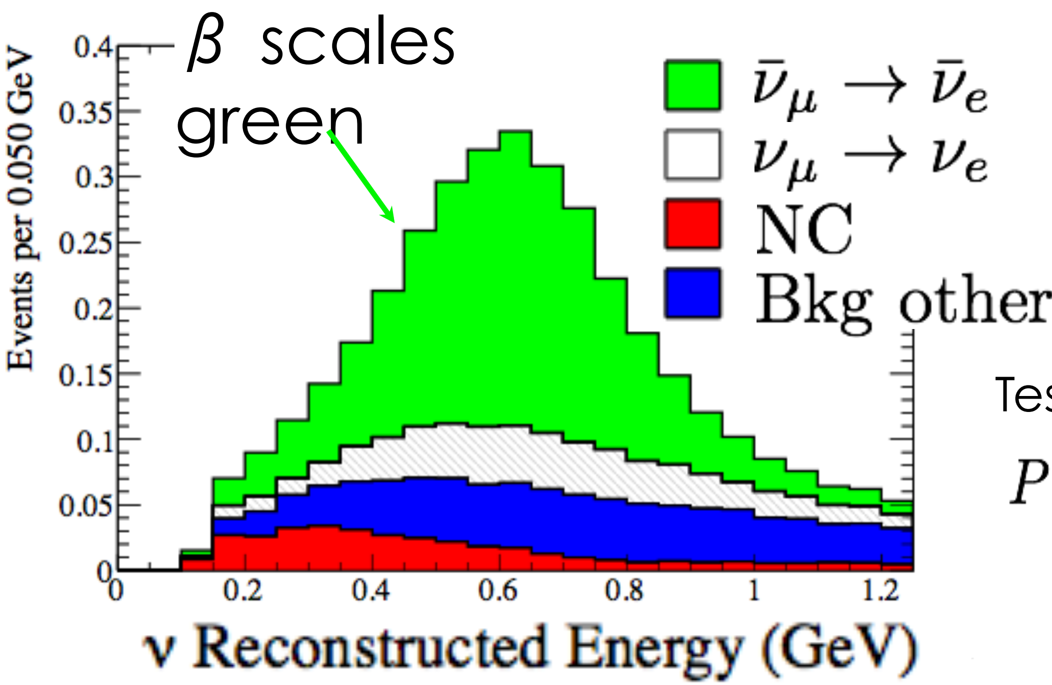




Appearance Analysis

	NH $\delta_{CP}=-\pi/2$	NH $\delta_{CP}=0$	NH $\delta_{CP}=+\pi/2$	IH $\delta_{CP}=-\pi/2$	IH $\delta_{CP}=0$	IH $\delta_{CP}=+\pi/2$
Sig $\bar{\nu}_\mu \to \bar{\nu}_e$	1.961	2.636	3.288	2.481	3.254	3.939
Bkg $\nu_\mu \to \nu_e$	0.592	0.505	0.389	0.531	0.423	0.341
Bkg NC	0.349	0.349	0.349	0.349	0.349	0.349
Bkg other	0.826	0.826	0.826	0.821	0.821	0.821
Total	3.729	4.315	4.851	4.181	4.848	5.450

Normal hierarchy — Inverted hierarchy



Test of no $\bar{\nu}_e$ appearance hypothesis:

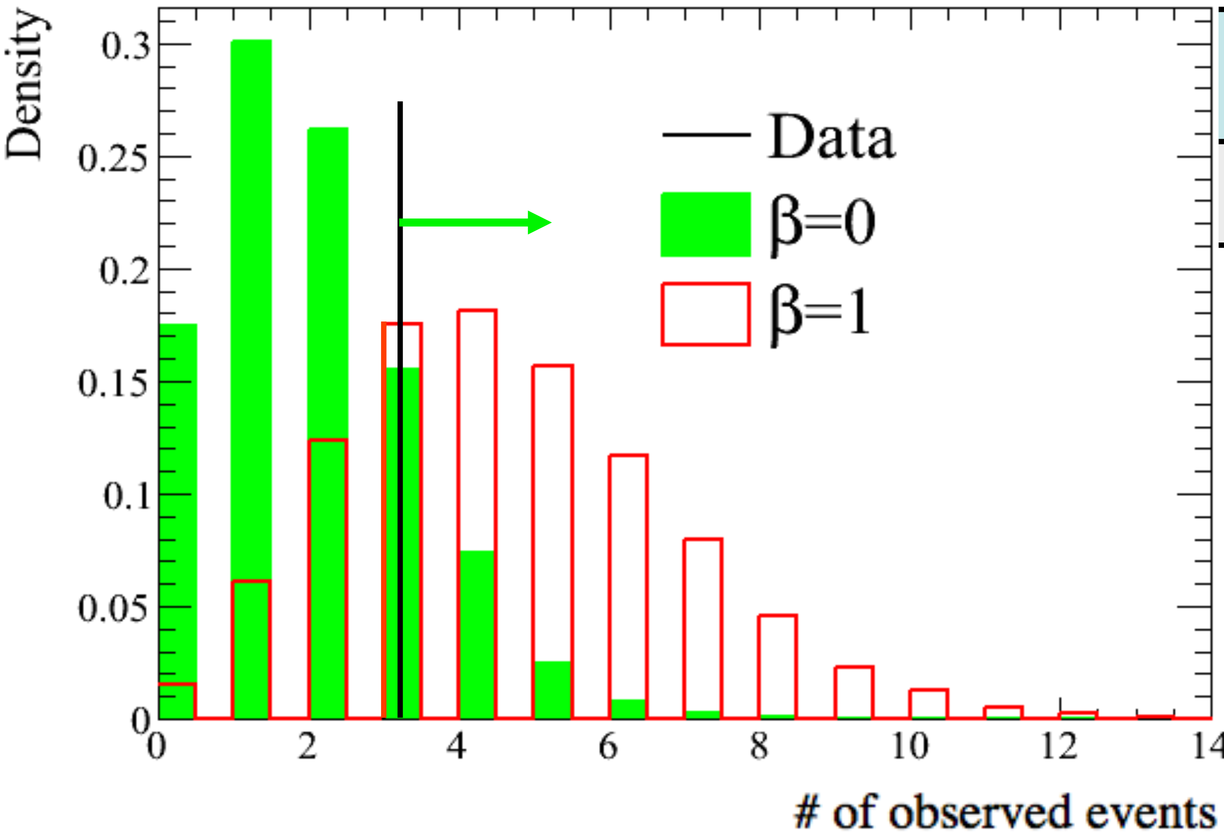
$$P(\bar{\nu}_\mu \to \bar{\nu}_e) = \beta \times P_{\mathrm{PMNS}}(\bar{\nu}_\mu \to \bar{\nu}_e)$$

β = 0 or 1

Rate Measurement

Generate an ensemble of test experiments with β =0 (no $\bar{\nu}_e$ appearance)

- p-value: fraction of test experiments that have as many or more candidate events as T2K data
- Sensitivity:
  mean p-value for an ensemble of fake data experiments with β =1

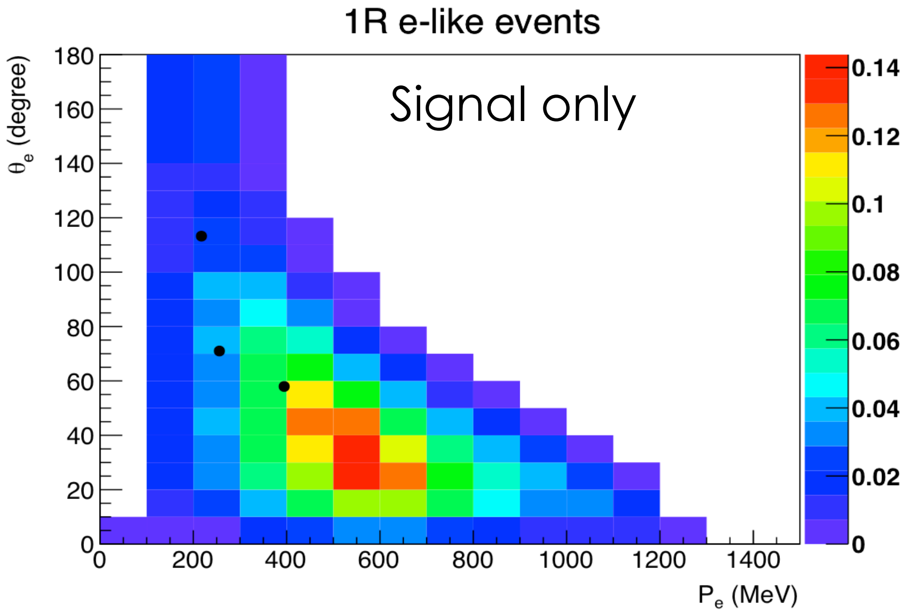


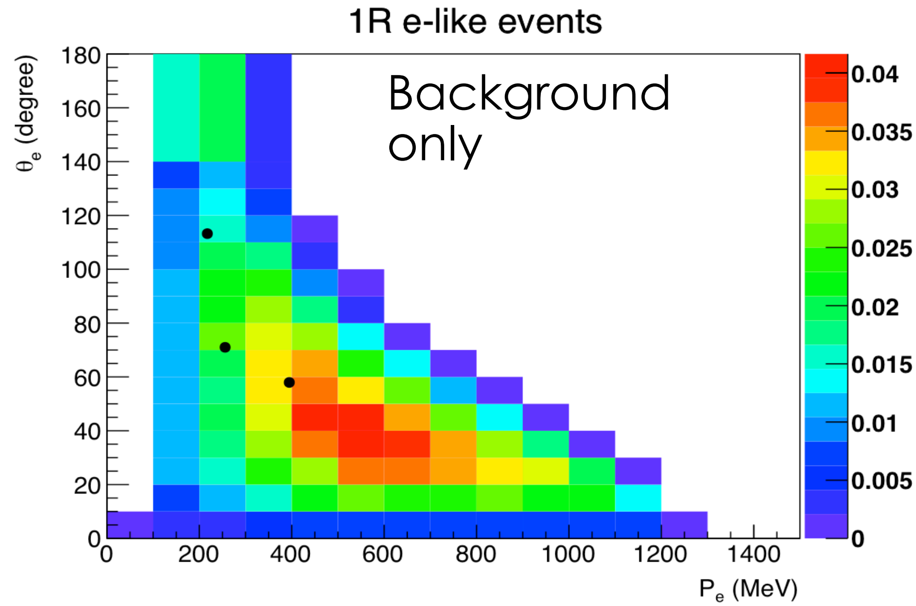
Rate only	p-value	Likelihood ratio
3 evts	0.26	0.9

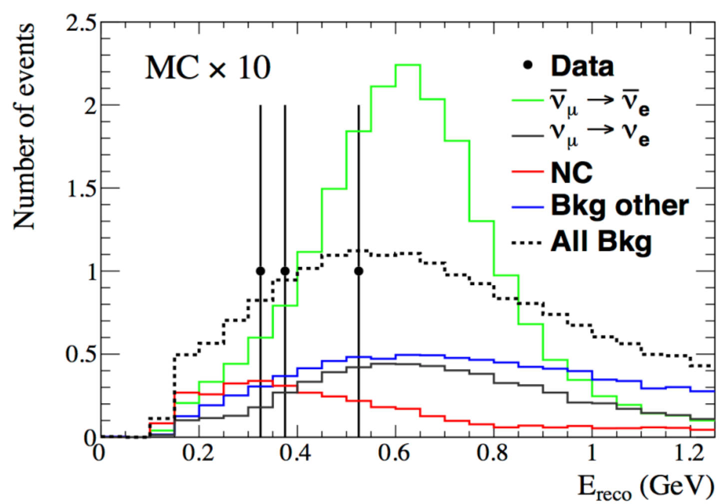
Likelihood ratio:
L(β =0)/L(β =1) is close to 1

Data does not favor or disfavor $\bar{\nu}_e$ appearance

Rate & Shape


1R e-like events
Signal only
θe (degree)
Pe (MeV)
0
200
400
600
800
1000
1200
1400
20
40
60
80
100
120
140
160
180
0.02
0.04
0.06
0.08
0.1
0.12
0.14

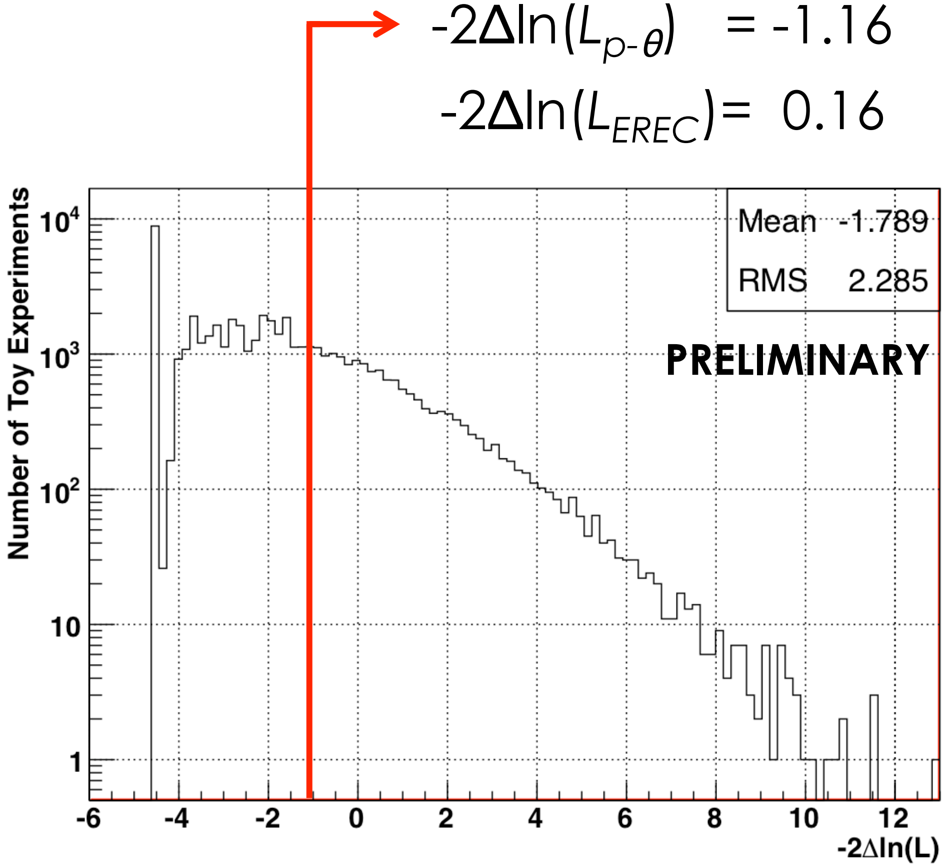

1R e-like events
Background only
θe (degree)
Pe (MeV)
0
200
400
600
800
1000
1200
1400
20
40
60
80
100
120
140
160
180
0.005
0.01
0.015
0.02
0.025
0.03
0.035
0.04


MC × 10
Data
$\bar{\nu}_\mu \to \bar{\nu}_e$
$\nu_\mu \to \nu_e$
NC
Bkg other
All Bkg
Number of events
E_{reco} (GeV)
0
0.2
0.4
0.6
0.8
1
1.2
0.5
1.5
2
2.5

Rate & Shape

$-2\Delta\ln(L_{p\text{-}\theta}) = -1.16$

$-2\Delta\ln(L_{EREC}) = 0.16$



Distribution of test statistic for $\beta = 0$ using Lepton P-θ shape information

P-values from data

Shape term	P-value
E_{rec}	0.16
Lepton P-θ	0.34

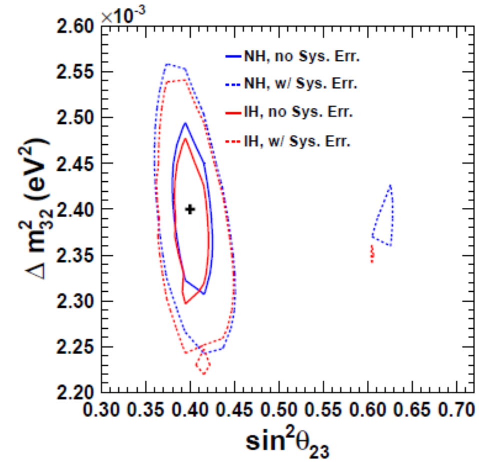
Likelihood ratio

Shape term	B_{10}
E_{rec}	1.1
Lepton P-θ	0.6

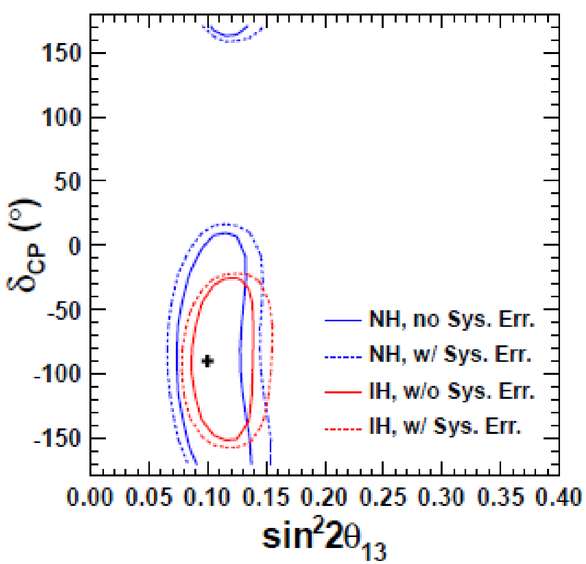
No evidence for $\beta = 1$ over $\beta = 0$

T2K Potential

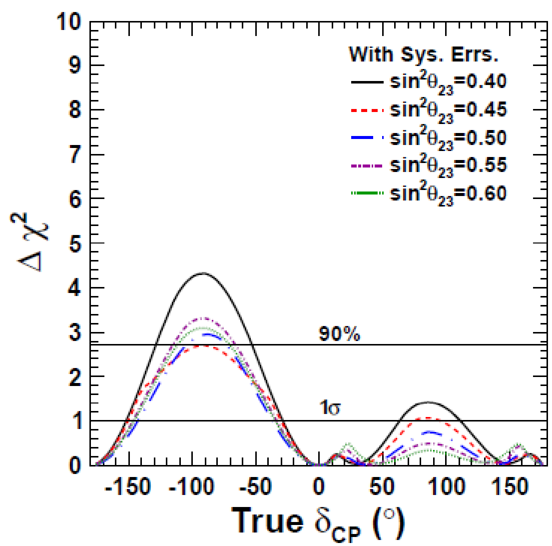
- So far, 14% of T2K design POT taken
  - ν-mode: 6.9 x 10^{20} POT;
  - $\bar{\nu}$-mode: 4.0 x 10^{20} POT
- Final sensitivity may be sufficient to find indication for
  - CPV and/or octant (combined with others)



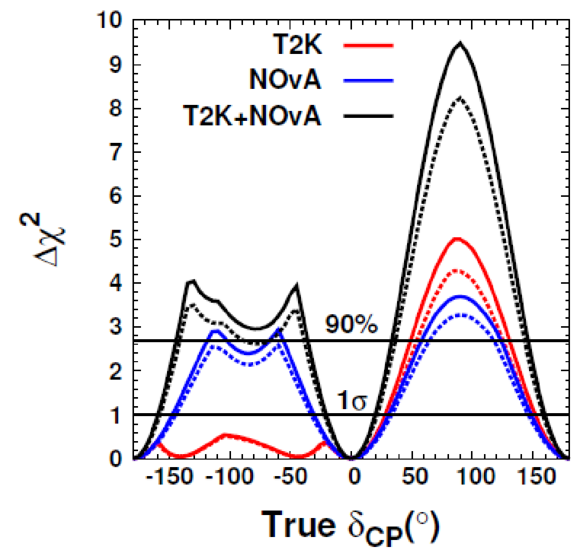
(d) 50% ν-, 50% $\bar{\nu}$-mode, with ultimate reactor error.



(c) 50% ν-, 50% $\bar{\nu}$-mode.



(d) 50% ν-, 50% $\bar{\nu}$-mode, with the 2012 systematic errors.



(d) 1:1 T2K, 1:1 NOνA ν:$\bar{\nu}$, IH

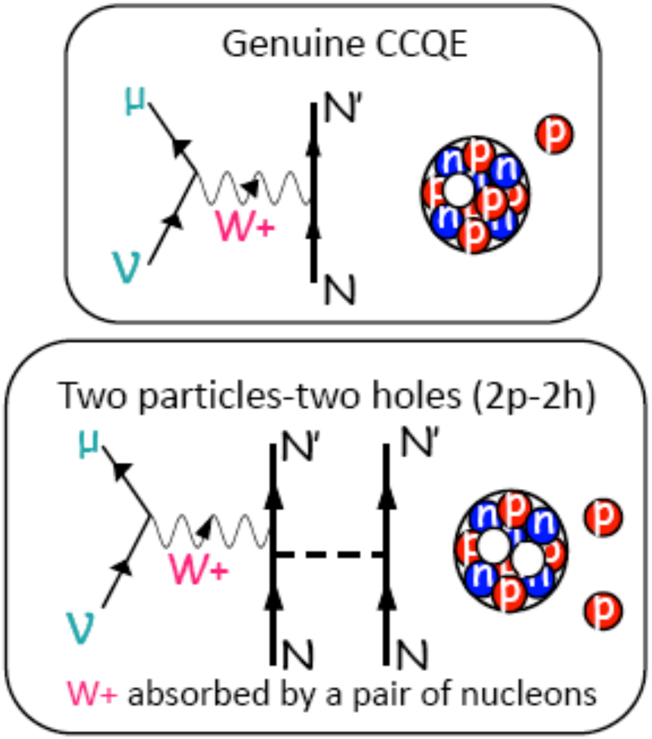
Future Systematics

Nuclear effects can enhanced "CCQE" cross section and change reconstructed energy

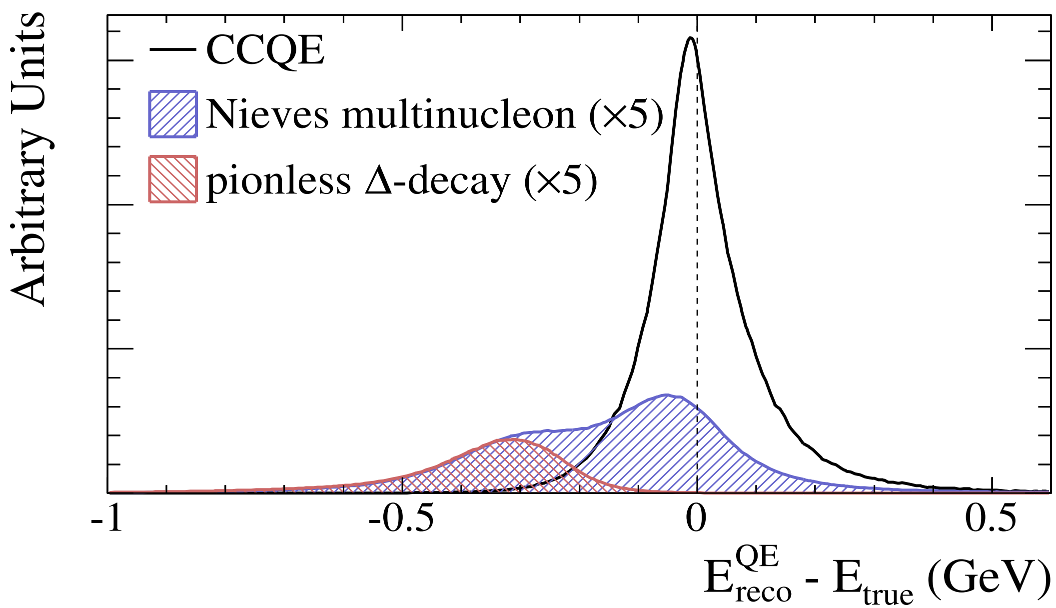
- CCQE interaction simulated on single nucleon (1p1h)
- But contribution from correlated pair of nucleons (2p2h)

J. Nieves, I. Ruiz Simo, and M. J. Vicente Vacas, PRC 83 045501 (2011)

G. Chanfray, and J. Marteau, PRC 80 065501

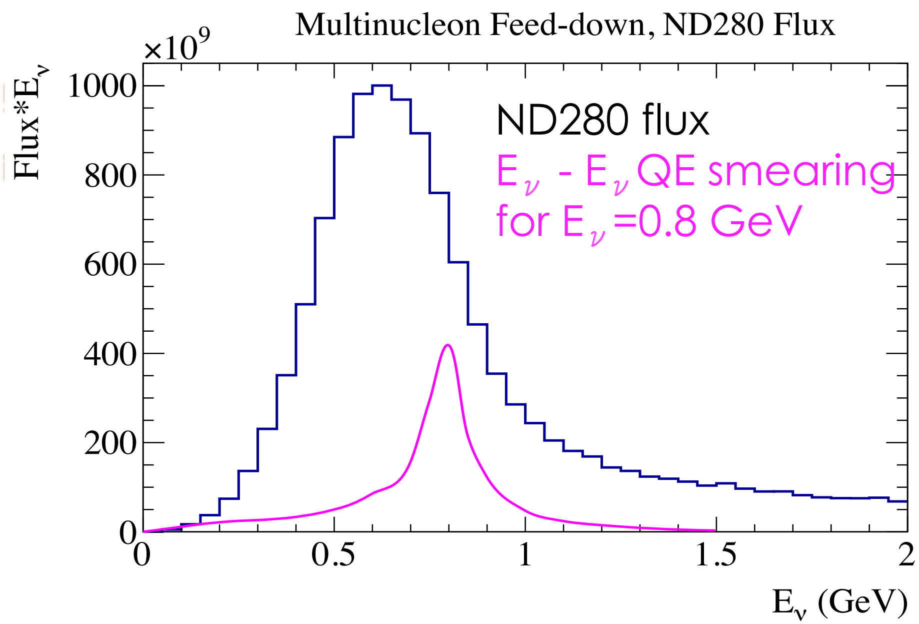


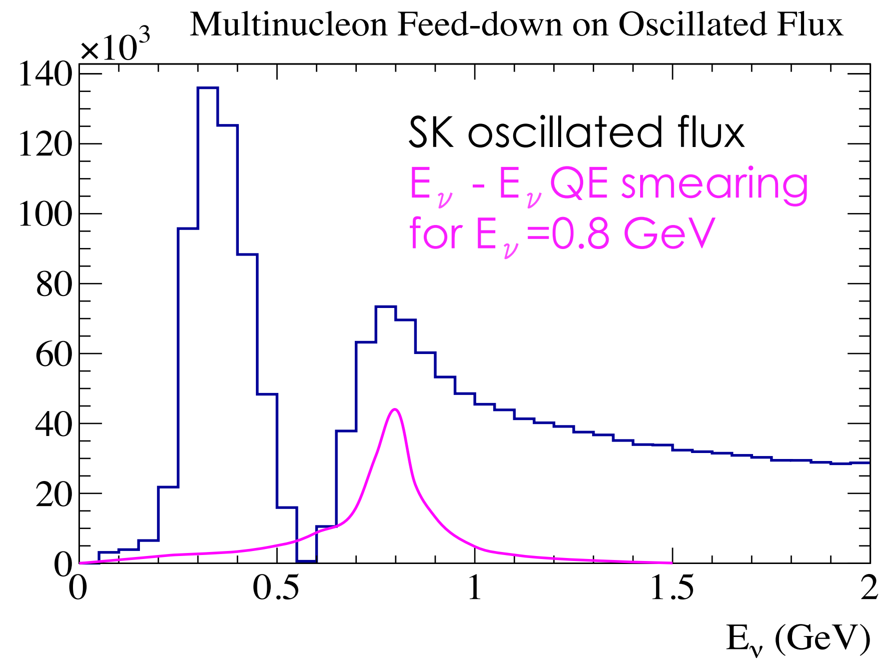
Picture by M. Martini



T2K collab PRL 112, 181801 (2014)

Cross Section Systematics





$$FD(\nu_e) = \boxed{\Phi \times \sigma} \times \epsilon \times P(\nu_\mu \rightarrow \nu_e)$$
$$ND(\nu_\mu) = \boxed{\Phi \times \sigma} \times \epsilon_{ND}$$

$$E_\nu^{QE} = \frac{m_p^2 - {m'}_n^2 - m_\mu^2 + 2{m'}_n E_\mu}{2({m'}_n - E_\mu + p_\mu \cos\theta_\mu)}$$

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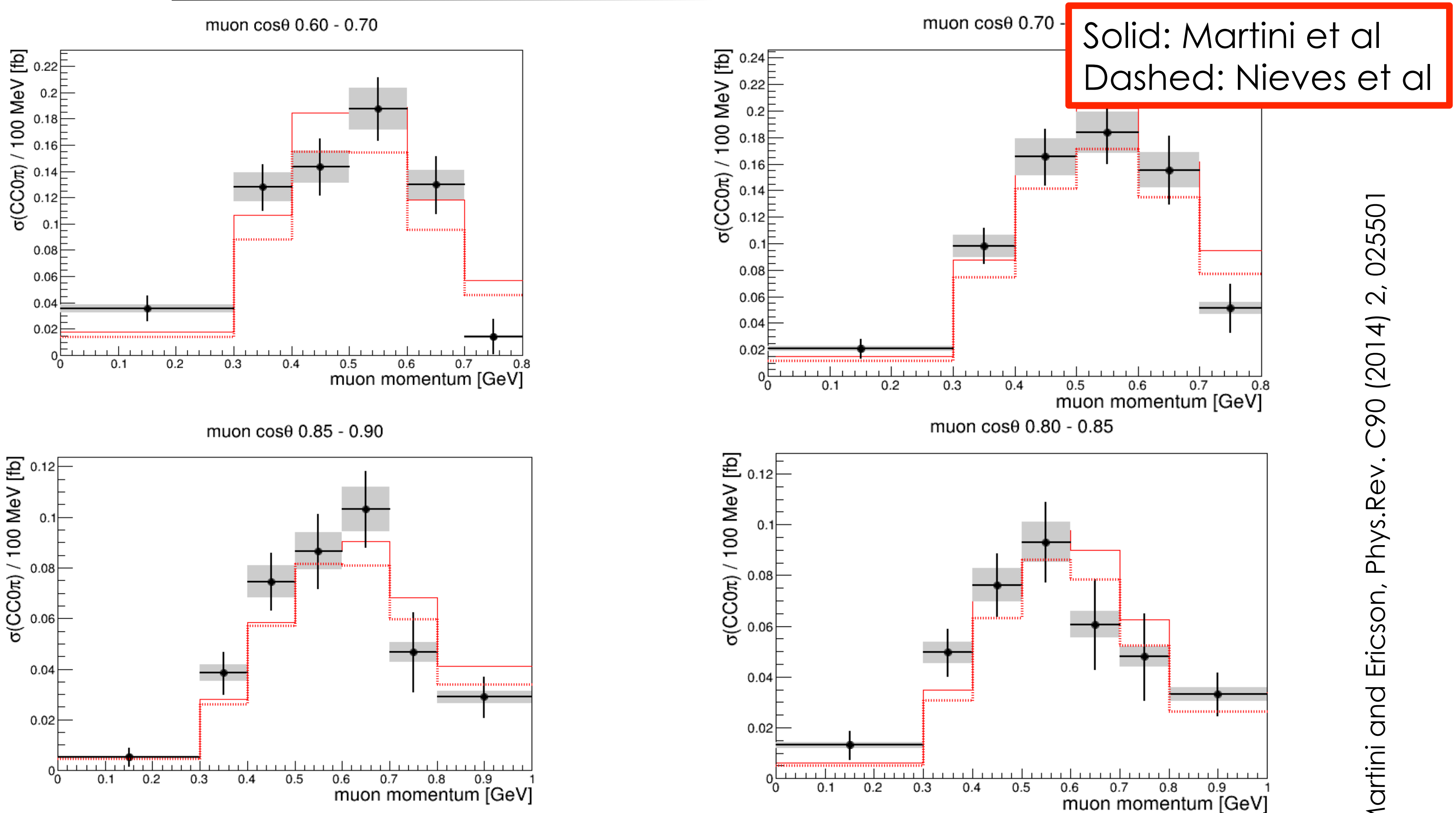
CC 0π Final State



Martini and Ericson, Phys.Rev. C90 (2014) 2, 025501

New measurement muon kinematics for muon, muon + proton, both with no pion in final state from ND280 off-axis beam

T2K Cross Sections

Cross section measurements	Target	Reported in	Detector
ν_μ CC inclusive	CH	PRD 87, 092003 (2013)	ND280, Tracker
ν_μ CCQE	CH	Accepted by PRD	ND280, Tracker
ν_e CC inclusive	CH	PRL 113, 241803 (2014)	ND280, Tracker
ν_μ NC π^0	CH/Water	Publication in progress	ND280, P0D
ν_μ NC elastic	Water	PRD 90, 072012 (2014)	SK
ν_μ CC inclusive	CH/Fe	PRD 90, 052010 (2014)	INGRID
ν_μ CCQE	CH	PRD 91, 112002 (2015)	INGRID
ν_μ CC coherent	CH	Publication in progress	INGRID
ν_μ CC coherent	CH	Publication in progress	ND280, Tracker
ν_μ CC π^+	Water	Publication in progress	ND280, Tracker
ν_μ CC0 π	CH	Publication in progress	ND280, Tracker

Thank You!

CERN contributions to T2K

- UA1/NOMAD magnet
  - And infrastructure
- Production and testing of micromegas
  - TS/DEM group
- NA61/SHINE experiment
  - Hadron production
- CERN-KEK cooperation on superconducting magnets
  - For neutrino beam line
- Test beams
  - For ND detector components

Summary & Conclusion

- T2K made its first measurement using an anti-neutrino beam
- Clear measurement of muon anti-neutrino disappearance
- No clear signal for electron neutrino appearance
  - Statistics very low
- Anti-neutrino measurements are statistically limited
  - And will be for foreseeable future
- More anti-neutrino running is planned
- Much more data expected
  - May have first indication for CP-Violation

Back-up