First Antineutrino Oscillation Results from T2K

Asher Kaboth

for the T2K Collaboration

10 June 2015

Imperial College
London

T2K

Outline

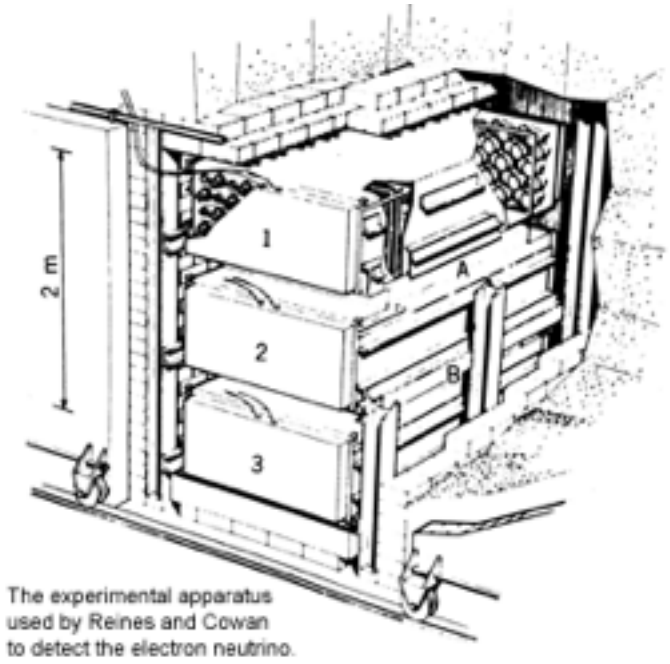
- Introduction to neutrino physics
- The T2K Experiment
- New results from anti-neutrino running

Why Neutrinos?

- Neutrino mass is a big piece of evidence of beyond-the-Standard-Model physics
- There are still many open questions about neutrino mass
  - Where does it come from? How does it relate to the Standard Model?
  - What does it mean for the early universe? Is it part of the matter-antimatter asymmetry puzzle?
- We need a full understanding of neutrino behavior to address these questions

Neutrinos

ν_e	ν_μ	ν_τ
e	μ	τ



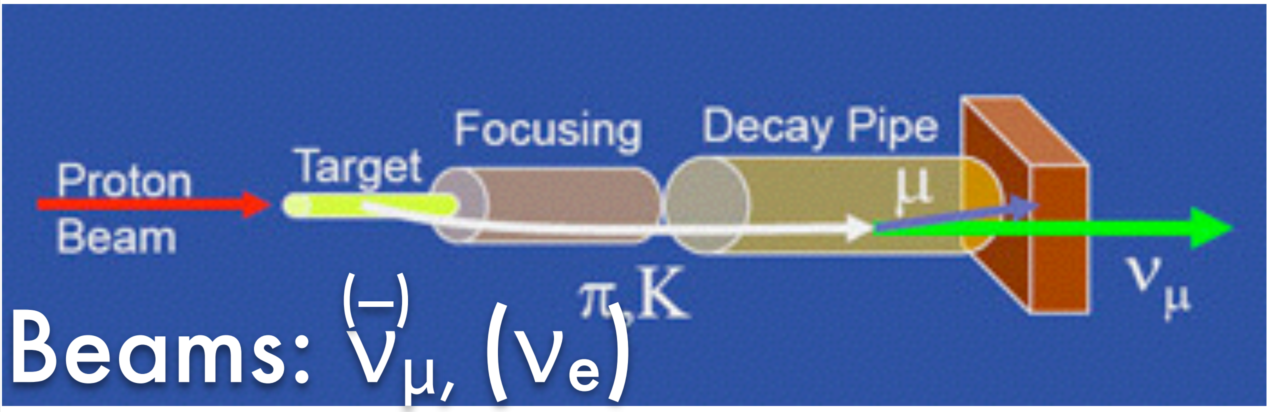
The experimental apparatus used by Reines and Cowan to detect the electron neutrino.

First detection by Reines and Cowen in 1956:

$\overline{\nu}_e + p \rightarrow n + e^+$

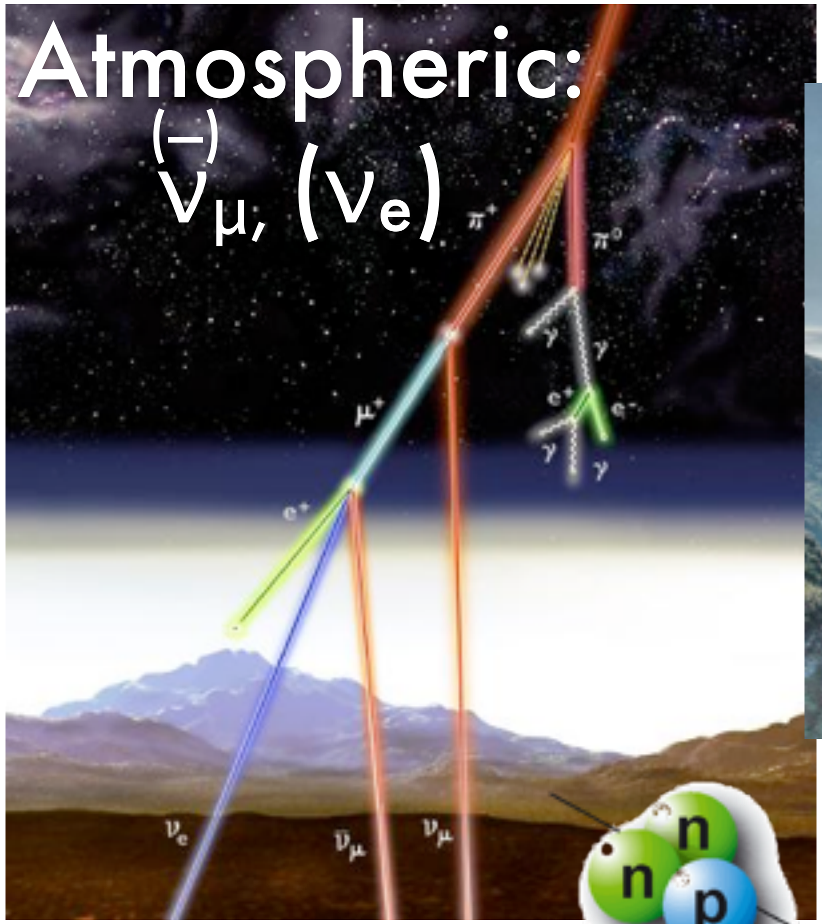
- Lightest particle in the standard model: <2.2 eV/c^2 (3.9×10^{-33} g)
- Interact only via the weak force and gravity; interaction rates are very, very small
- Each neutrino has a charged partner which determines its "flavor"

Sources of Neutrinos



Beams: $\overset{(-)}{\nu}_{\mu}$, (ν_e)

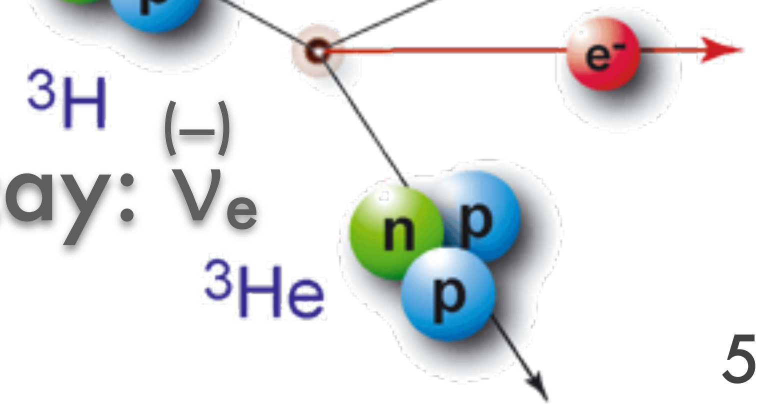
Solar: ν_e



Atmospheric: $\overset{(-)}{\nu}_{\mu}$, (ν_e)

Reactors: $\bar{\nu}_e$

Supernovae: all!



Nuclear Decay: $\overset{(-)}{\nu}_{e}$

Big Bang: all!

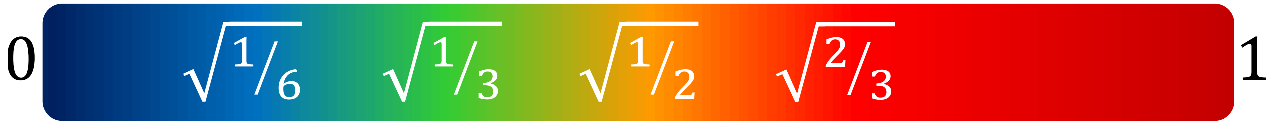
Imperial College
London

T2K

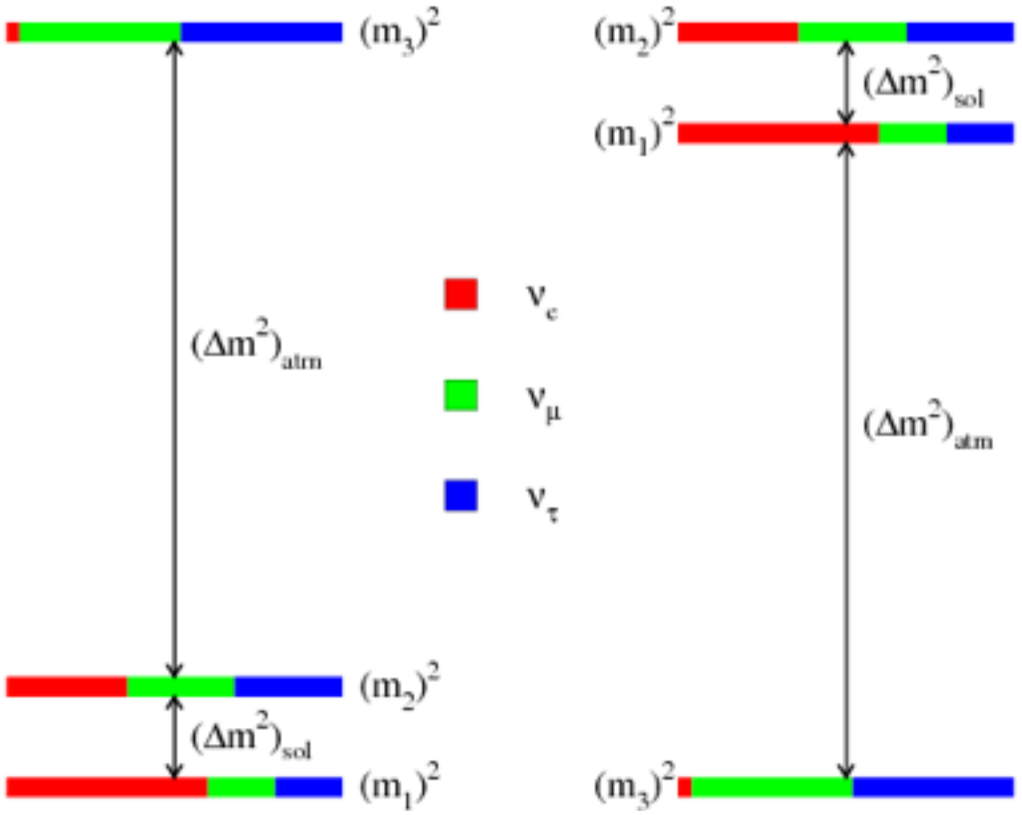
Neutrino Mixing

Neutrinos have two sets of eigenstates: mass (propagation) and flavor (detection)

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3}\\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$



PMNS mixing matrix tells us how mass and flavor eigenstates are related

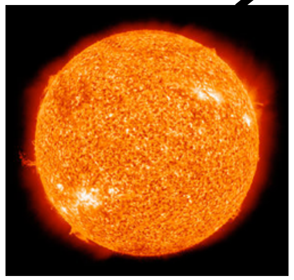


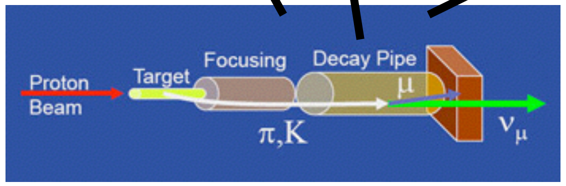
Normal Hierarchy Inverted Hierarchy

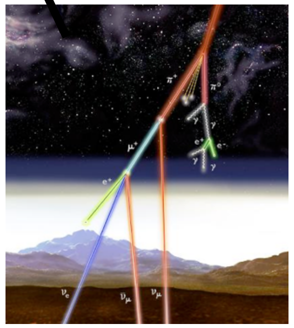
Neutrino Oscillation

$c_{ij}=\cos\theta_{ij}$ $s_{ij}=\sin\theta_{ij}$

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







Detection also depends on the mass splittings: $\sin^2\left(\frac{\Delta m^2 L}{E}\right)$ $\Delta m^2 = m_i^2 - m_j^2$

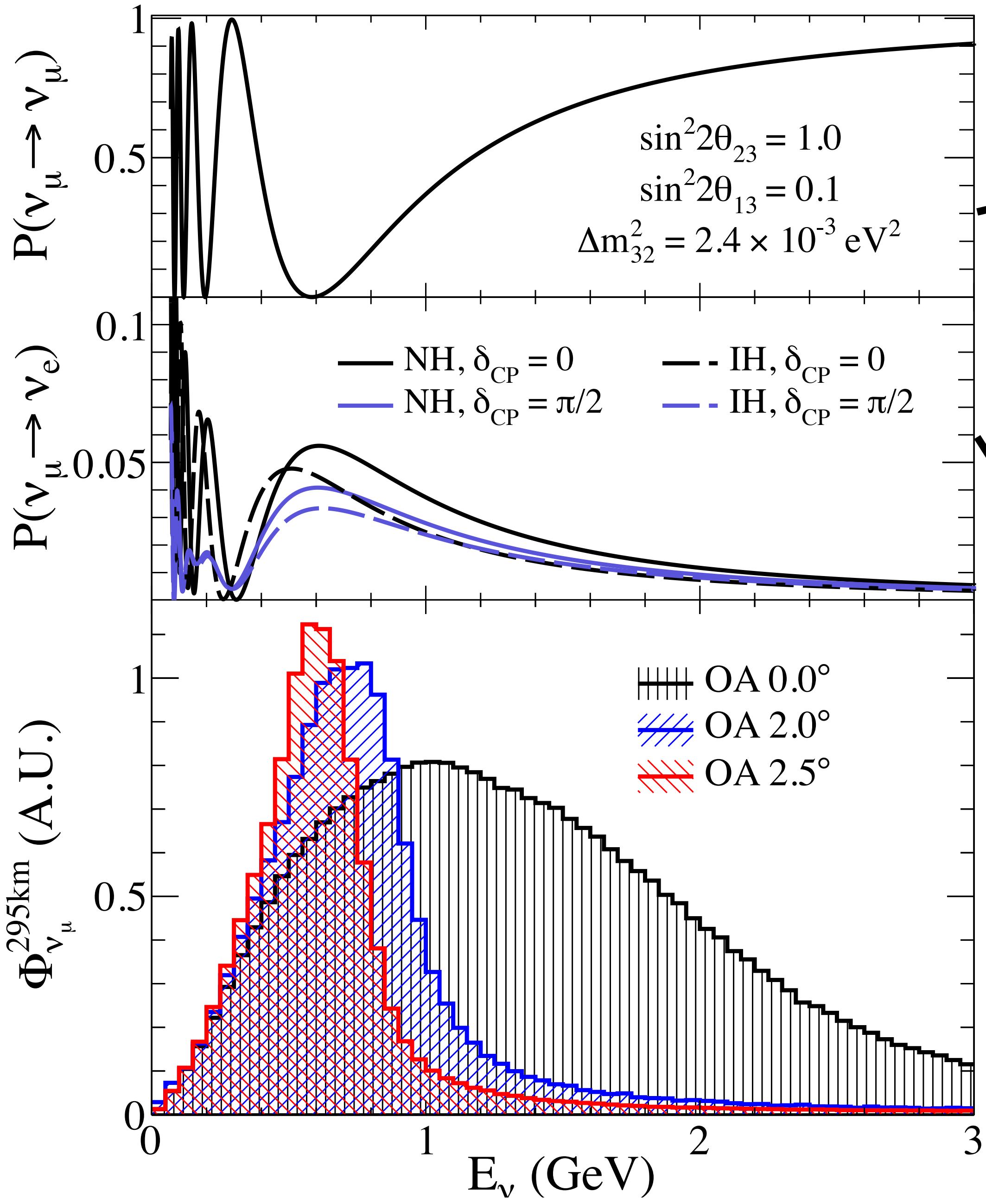
$\theta_{23}=45.8\pm3.2°$
$\theta_{12}=33.4\pm0.85°$
$\theta_{13}=8.88\pm0.39°$

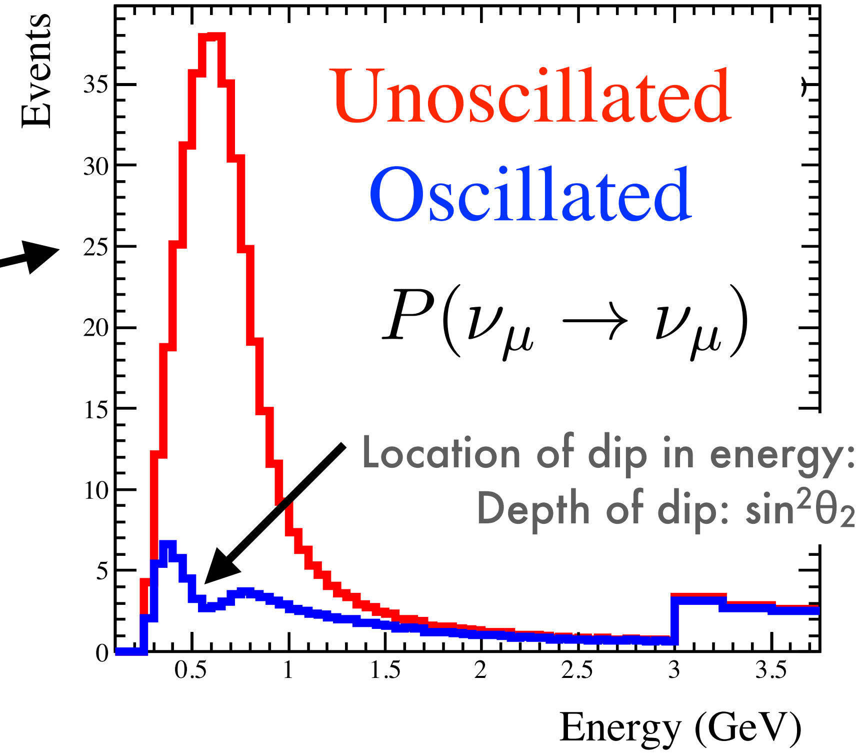
PDG 2014

$\Delta m^2_{21} = 7.53\pm0.18\times10^{-5}\ \mathrm{eV}^2$
$|\Delta m^2_{32}| = 2.44\pm0.06\times10^{-3}\ \mathrm{eV}^2$
δ_{CP} = [-π–0.14π] and [0.87π–π]
(90% interval)

Long-Baseline Neutrino Oscillation

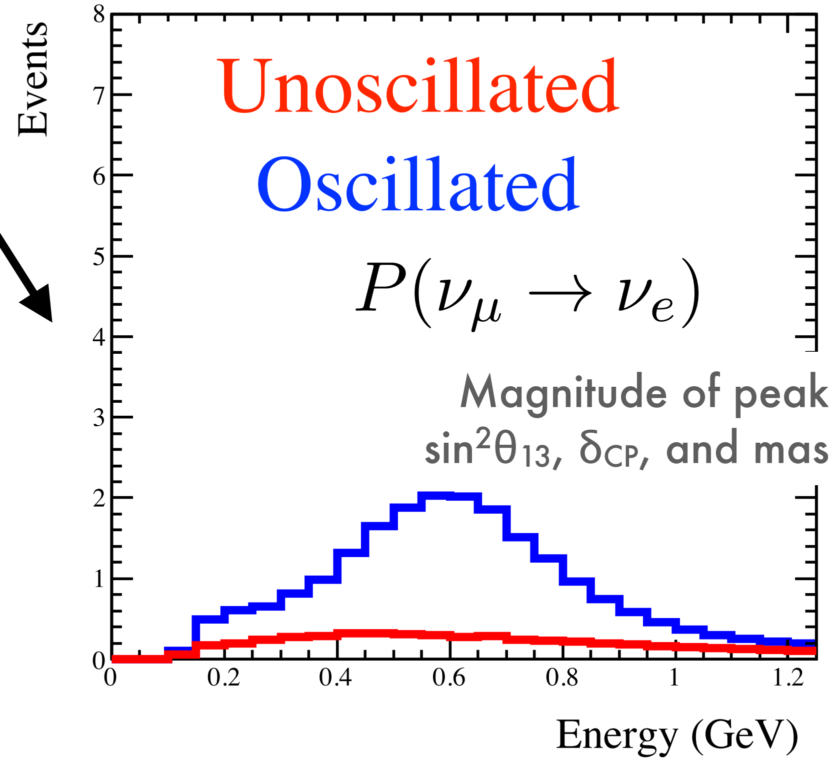
$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - 4\cos^2(\theta_{13})\sin^2(\theta_{23})[1-\cos^2(\theta_{13})\sin^2(\theta_{23})]\sin^2\left(\frac{\Delta m^2_{31} L}{E_\nu}\right)$$





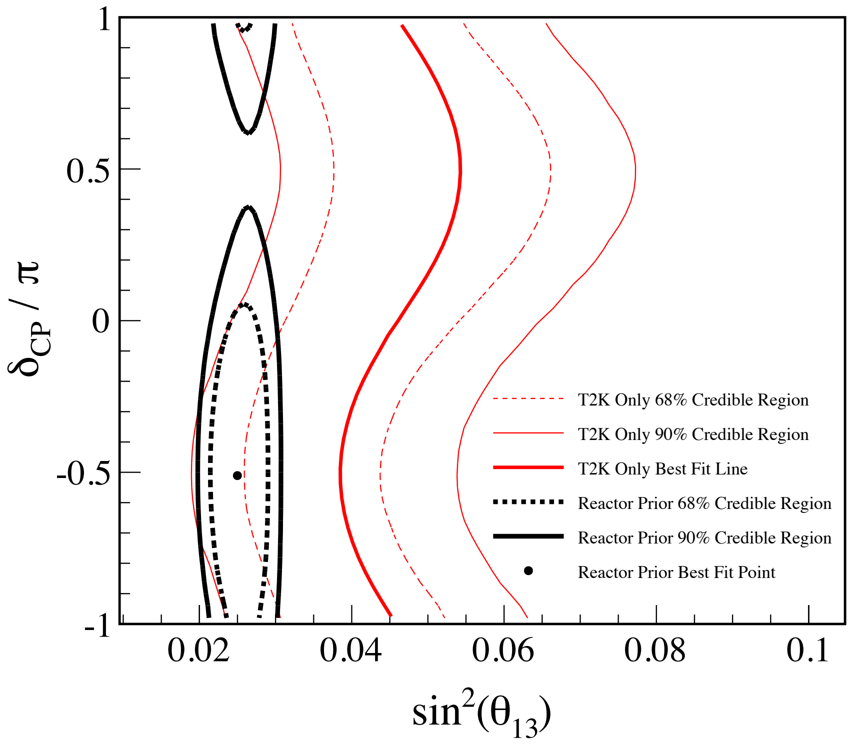
Location of dip in energy: Δm^2_{32}

Depth of dip: $\sin^2\theta_{23}$



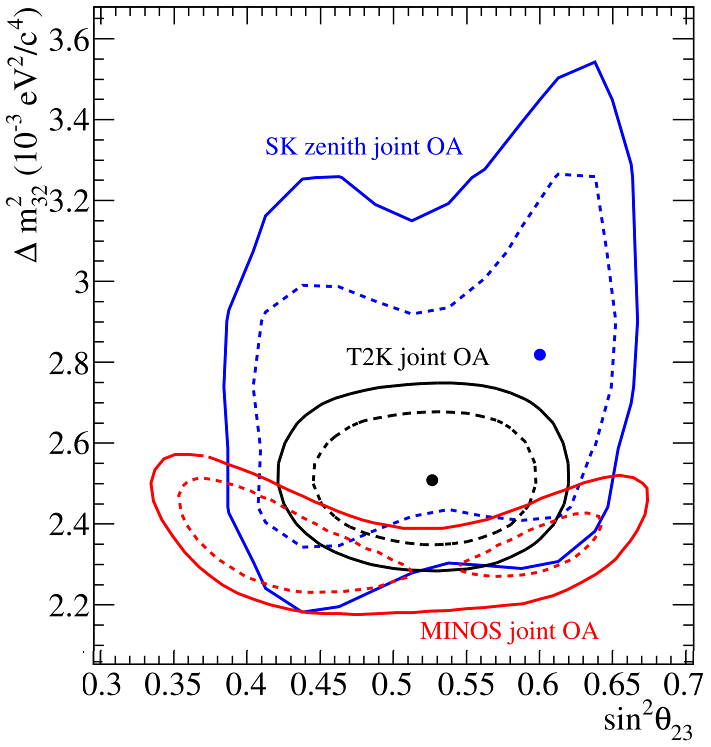
Magnitude of peak linked to $\sin^2\theta_{13}$, δ_{CP}, and mass hierarchy

T2K Measurements



First measurement of flavor appearance with 28 ν_e candidates

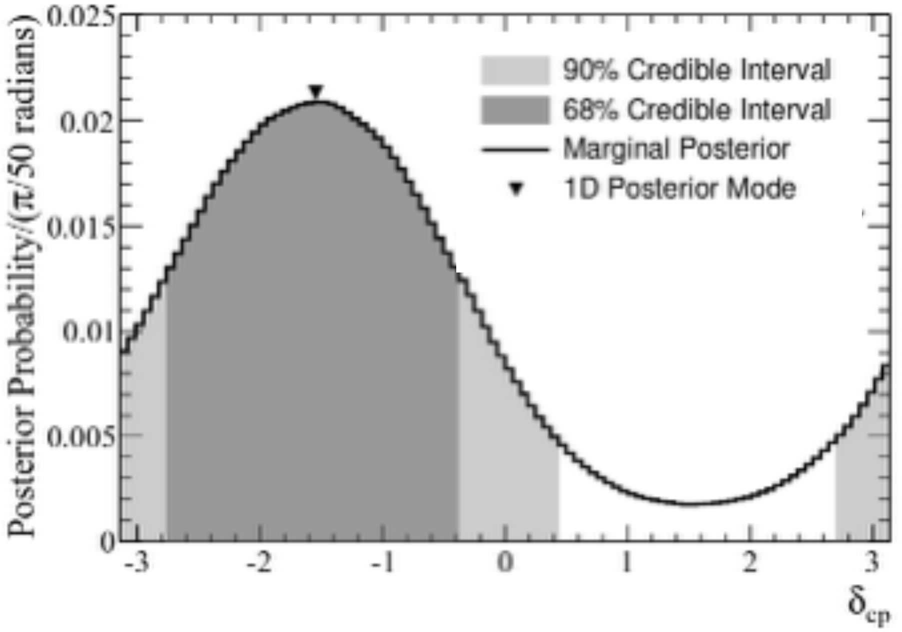
Independent measurement of θ_{13}



World-leading measurement of θ_{23}

Significant measurement of Δm^2_{32}

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



First constraint of δ_{CP}

Parameters measured by T2K

θ_{23}=45.8±3.2°

θ_{12}=33.4±0.85°

θ_{13}=8.88±0.39°

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

$|\Delta m^2_{32}| = 2.44 \pm 0.06 \times 10^{-3}$ eV^2

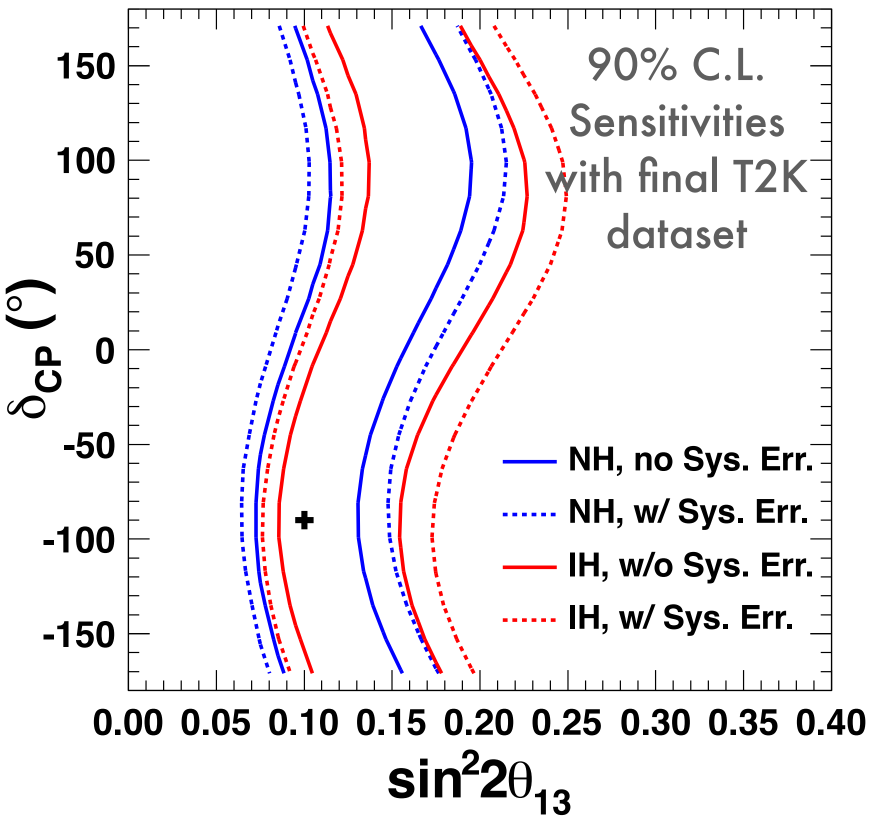
δ_{CP} = [-π–0.14π] and [0.87π–π] (90% interval)

Imperial College London

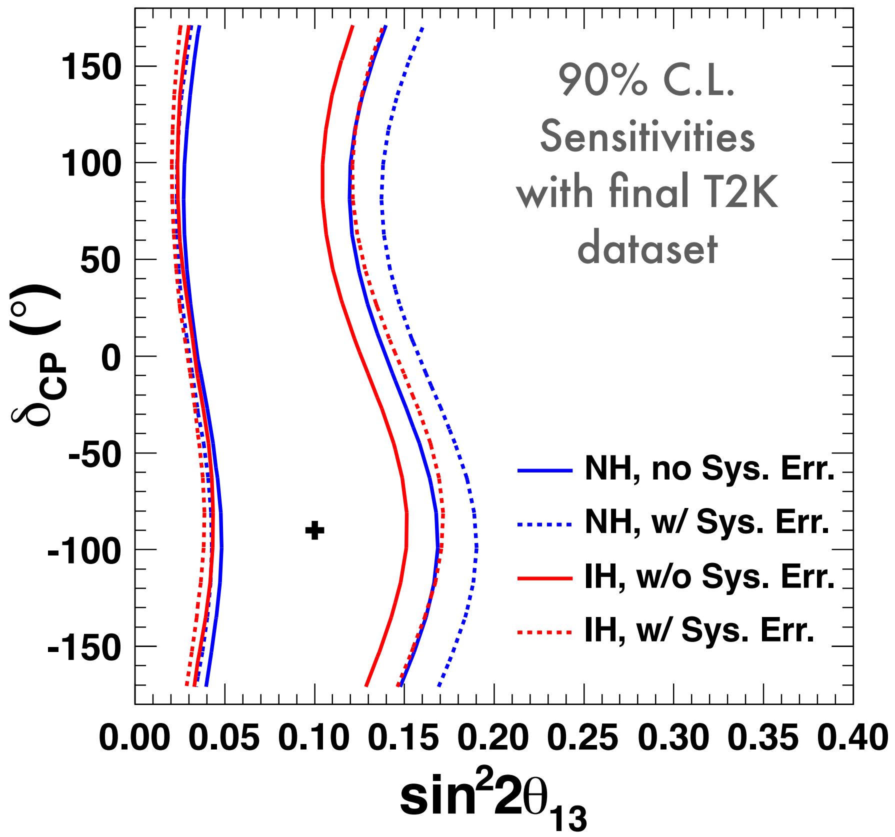
Why Antineutrinos?

Prog. Theor. Exp. Phys. (2015) 043C01

Only neutrinos

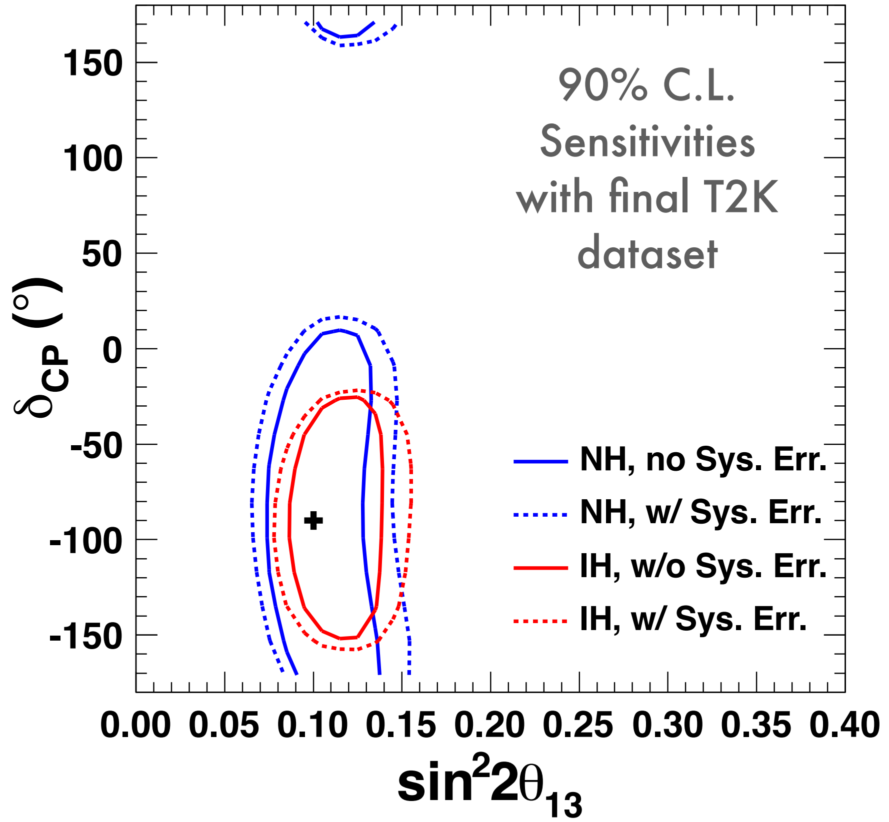


Only antineutrinos



- Can potentially measure δ_{CP} with T2K data alone
- Can study any differences between ν and $\bar{\nu}$ oscillation
- Comparison with reactor measurement gives a test of three flavor framework

Combined

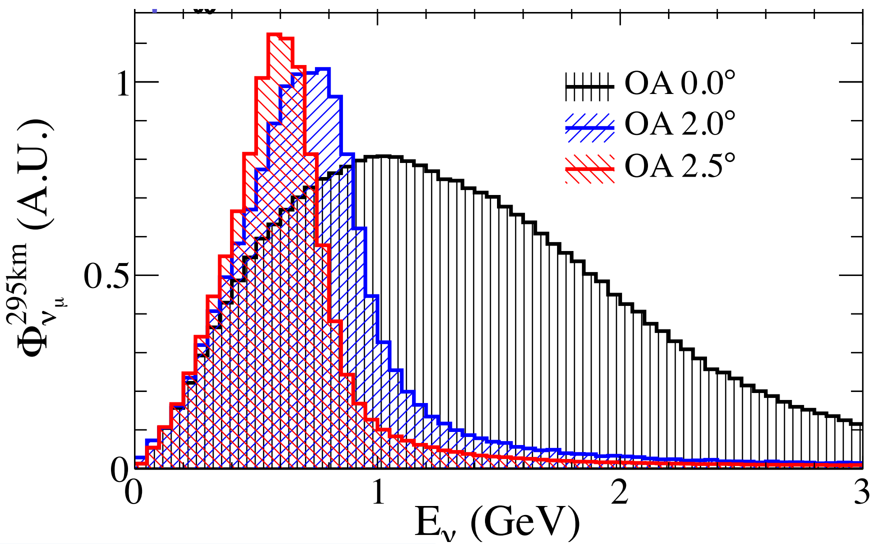


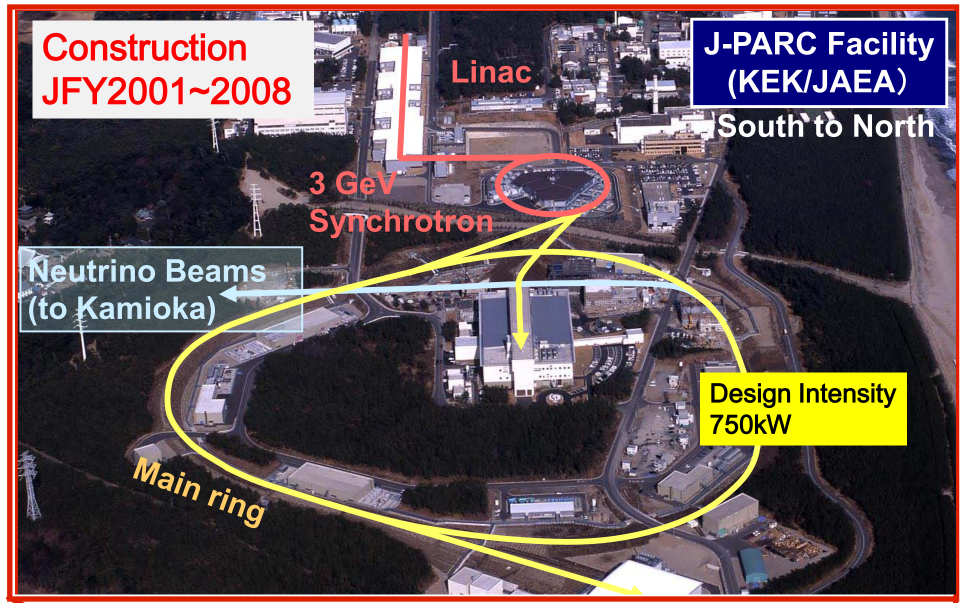
$\bar{\nu}_\mu$ Disappearance

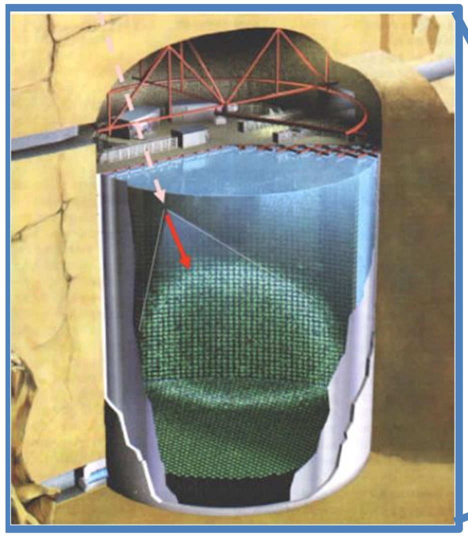
- Physics is interesting: investigate if neutrinos and antineutrinos behave differently:
  - CPT theorem implies that neutrino and antineutrino disappearance probability should be the same
  - Nonstandard matter interactions as the neutrinos/antineutrinos pass through the Earth could change disappearance probability
- Practical: understand the antineutrino beam before doing harder appearance measurement that depends on disappearance measurement

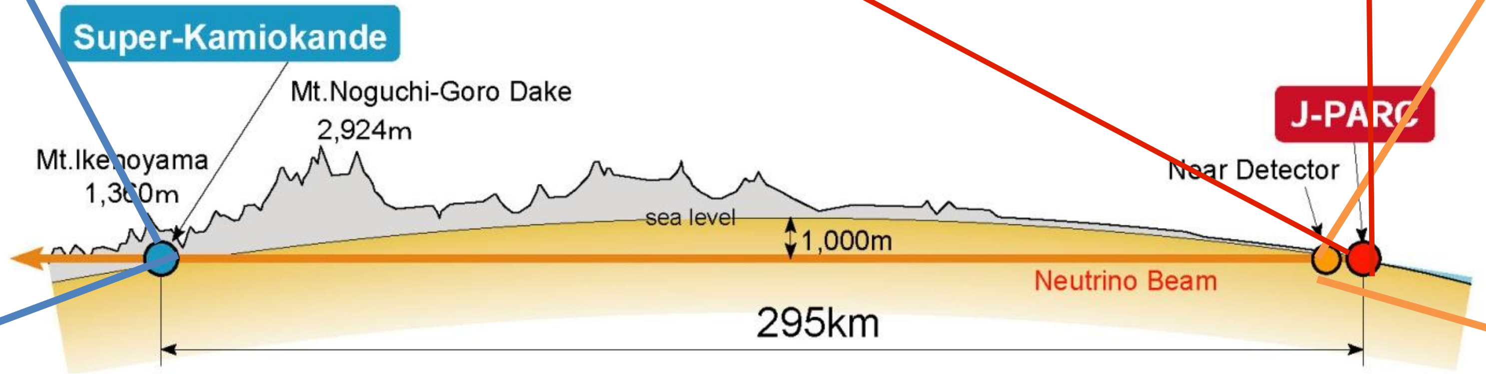
T2K

11 countries
60 institutions
~500 people

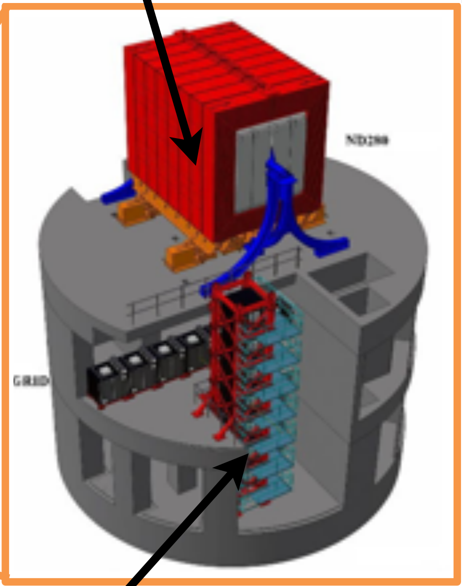




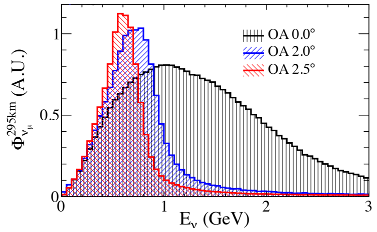




ND280



INGRID

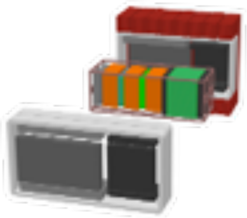


NA61/SHINE Data

INGRID/Beam Monitor Data

Flux Model

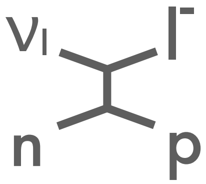
ND280 Detector Model

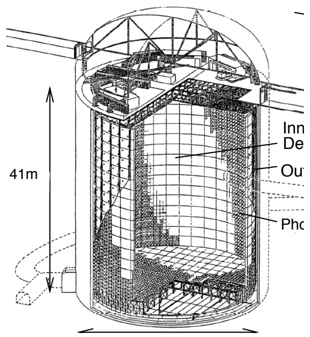


ND280 Data

External Cross Section Data

Cross Section Model





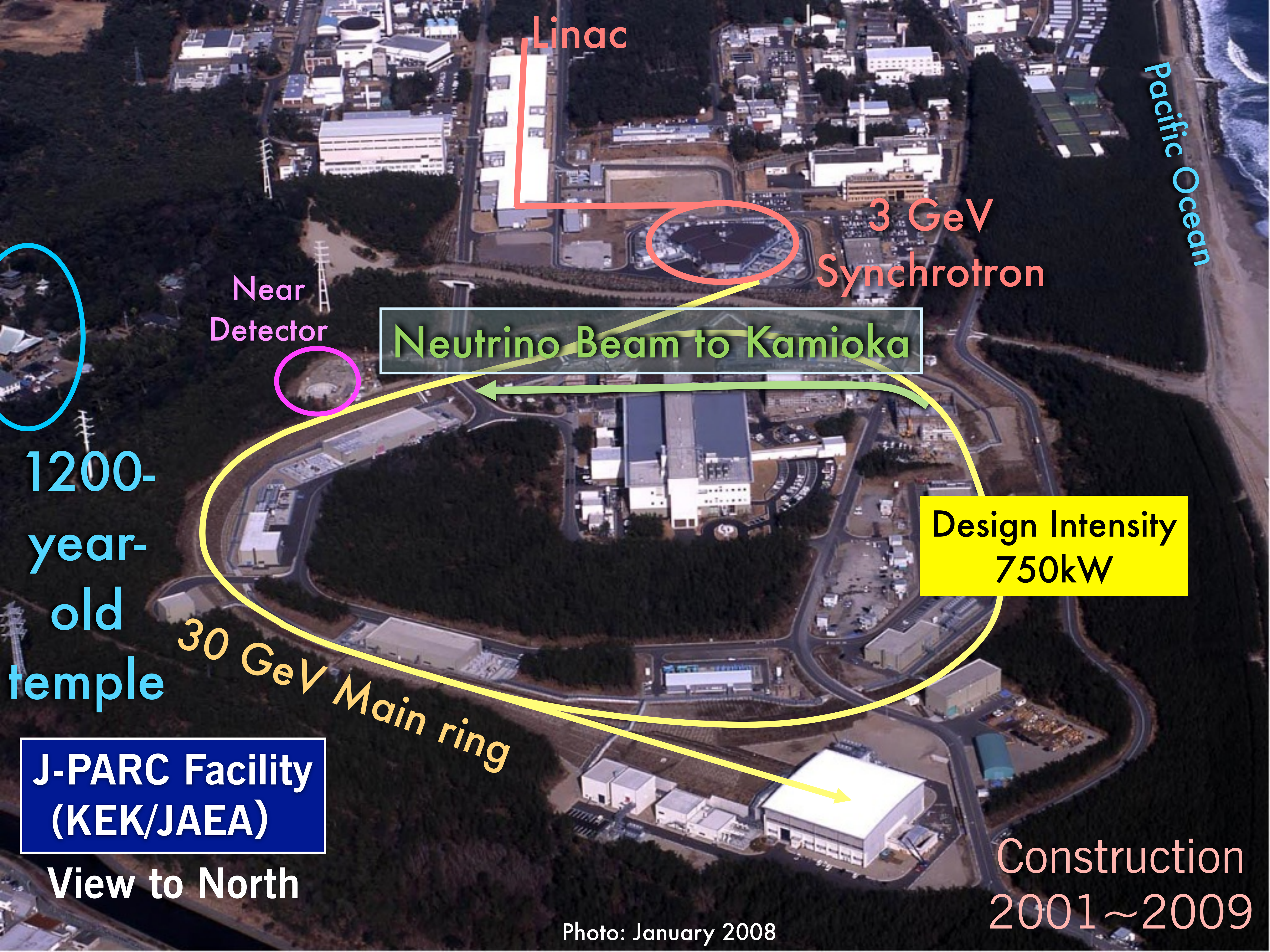
SK Data

Oscillation Fit

SK Detector Model

Fit near detector data, far detector data, and model constraints from external and internal data

Oscillation Parameters

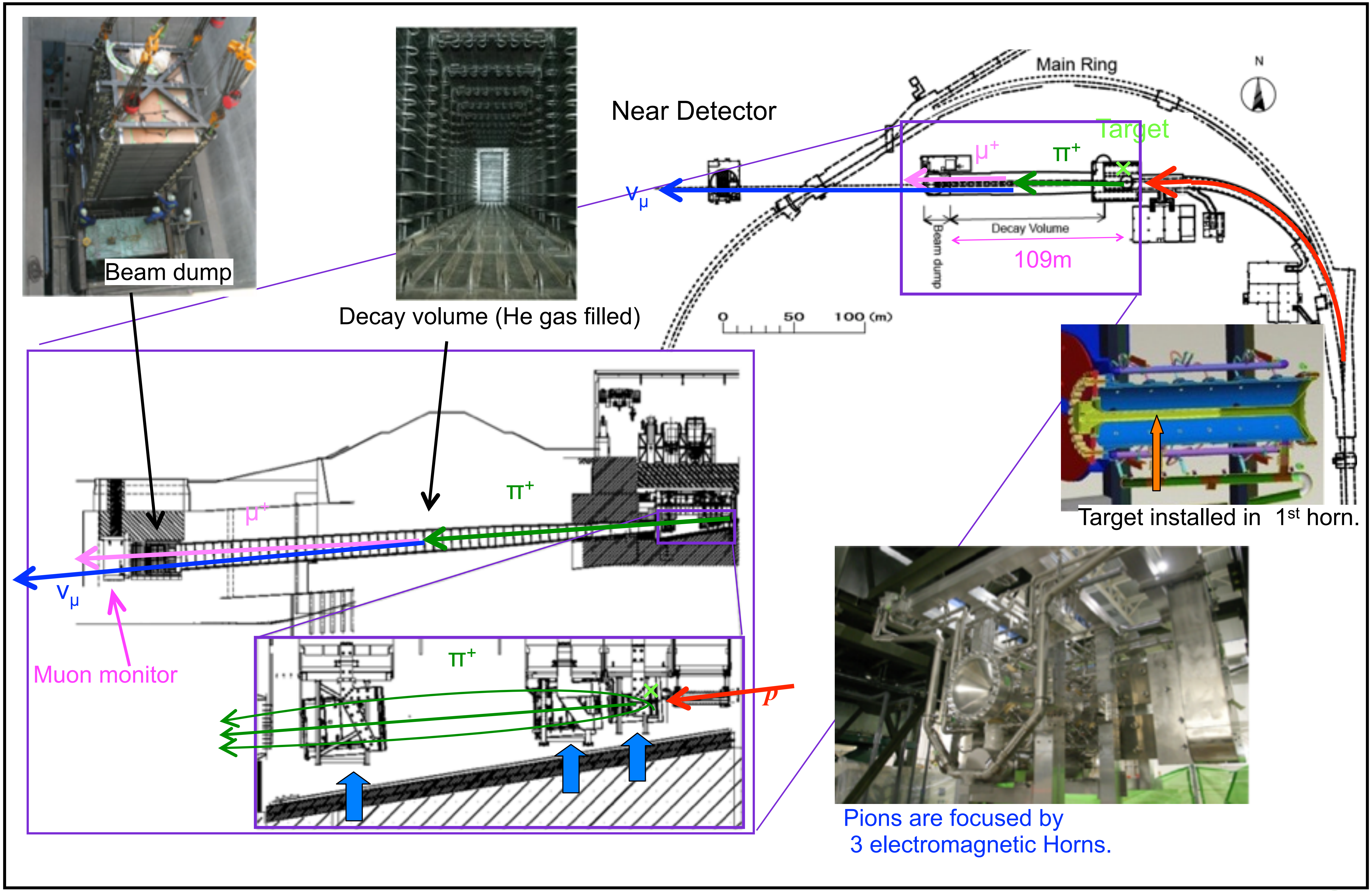


J-PARC Facility (KEK/JAEA)

View to North

Photo: January 2008

J-PARC neutrino beamline overview



Near Detector

Beam dump

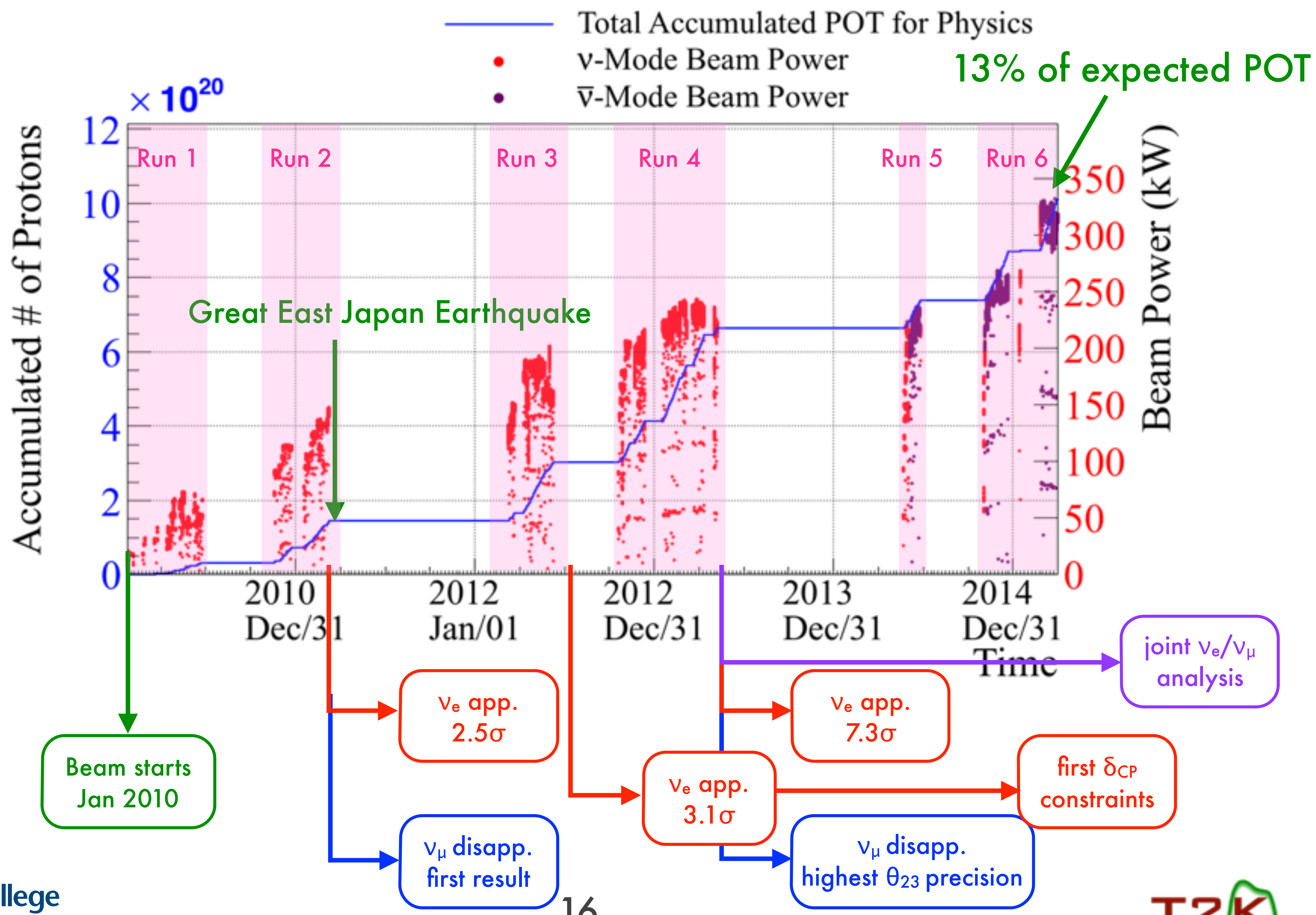
Decay volume (He gas filled)

Muon monitor

Target installed in 1st horn.

Pions are focused by
3 electromagnetic Horns.

Beam Operations



13% of expected POT

Great East Japan Earthquake

Beam starts Jan 2010

ν_e app. 2.5σ

ν_μ disapp. first result

ν_e app. 3.1σ

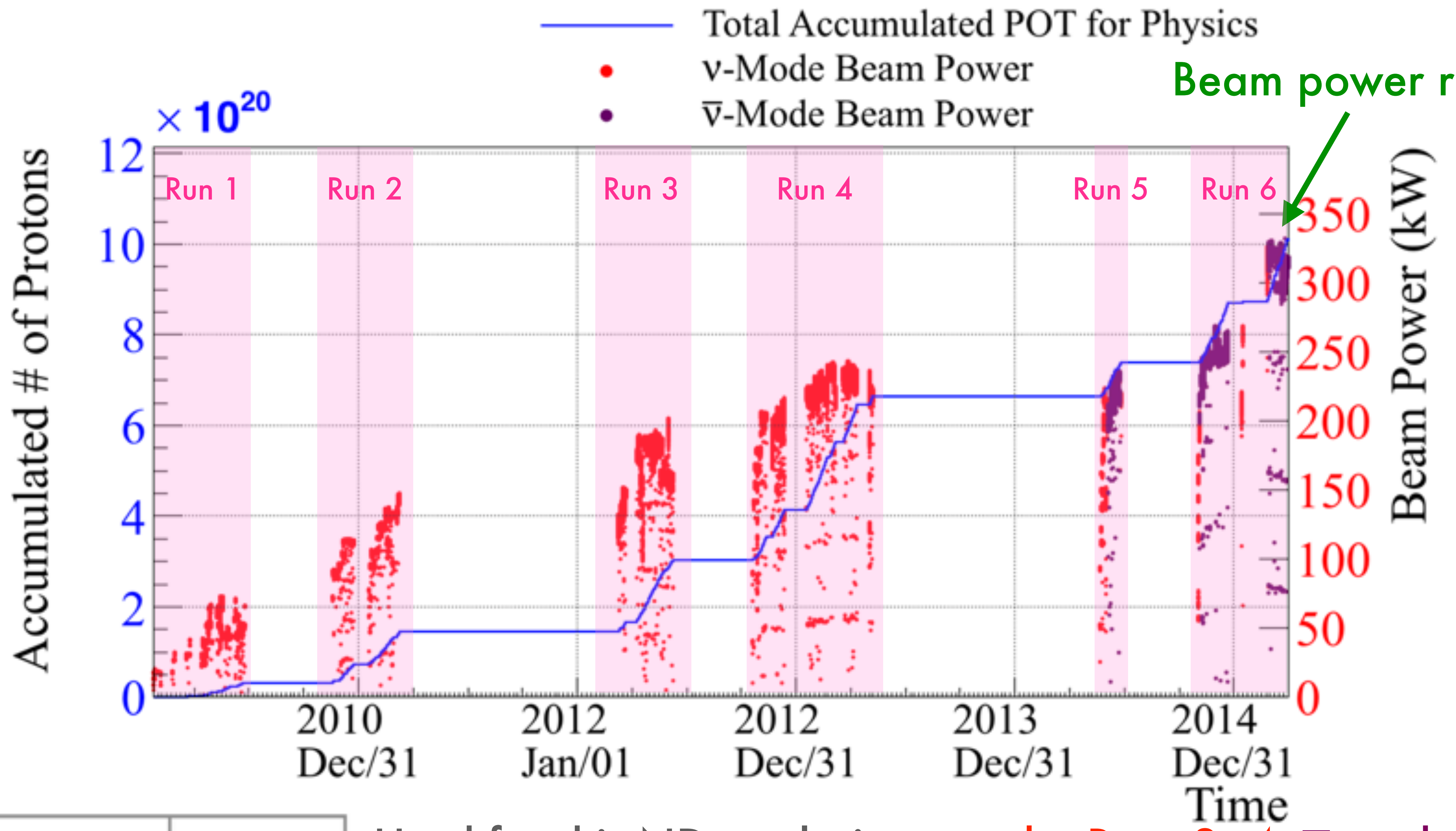
ν_e app. 7.3σ

ν_μ disapp. highest θ_{23} precision

first δ_{CP} constraints

joint ν_e/ν_μ analysis

Beam Operations



Beam power record!

POT	ND280	SK
ν mode	5.82×10^{20}	0
ν̅ mode	4.30×10^{19}	2.315×10^{20}

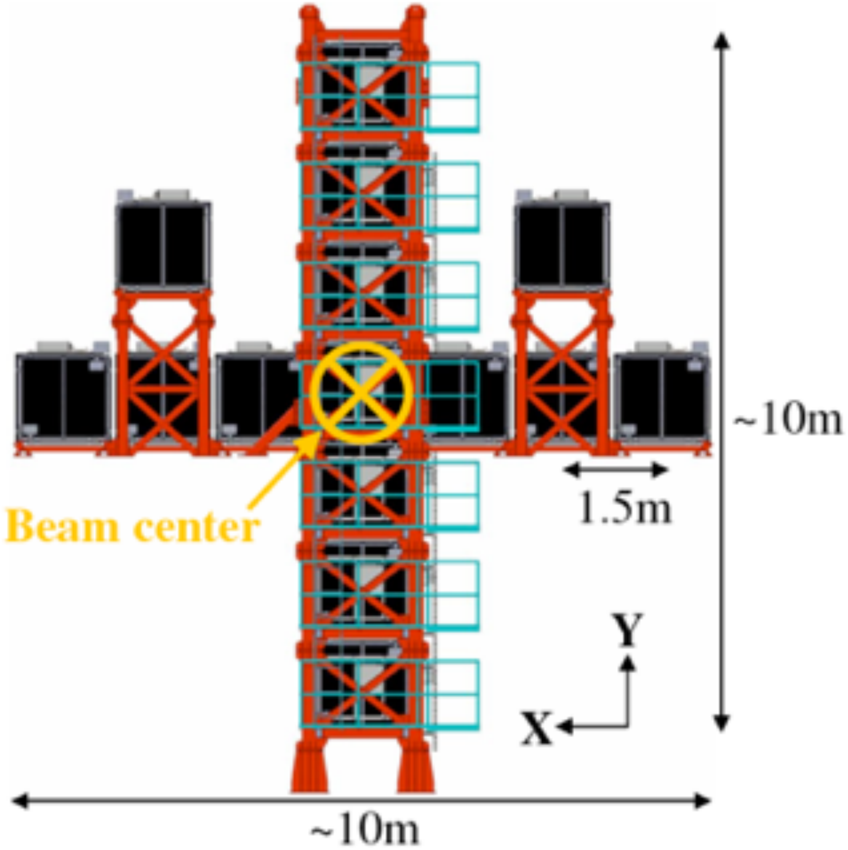
Used for this ND analysis: ν mode, Runs 2–4; ν̅ mode, Run 5

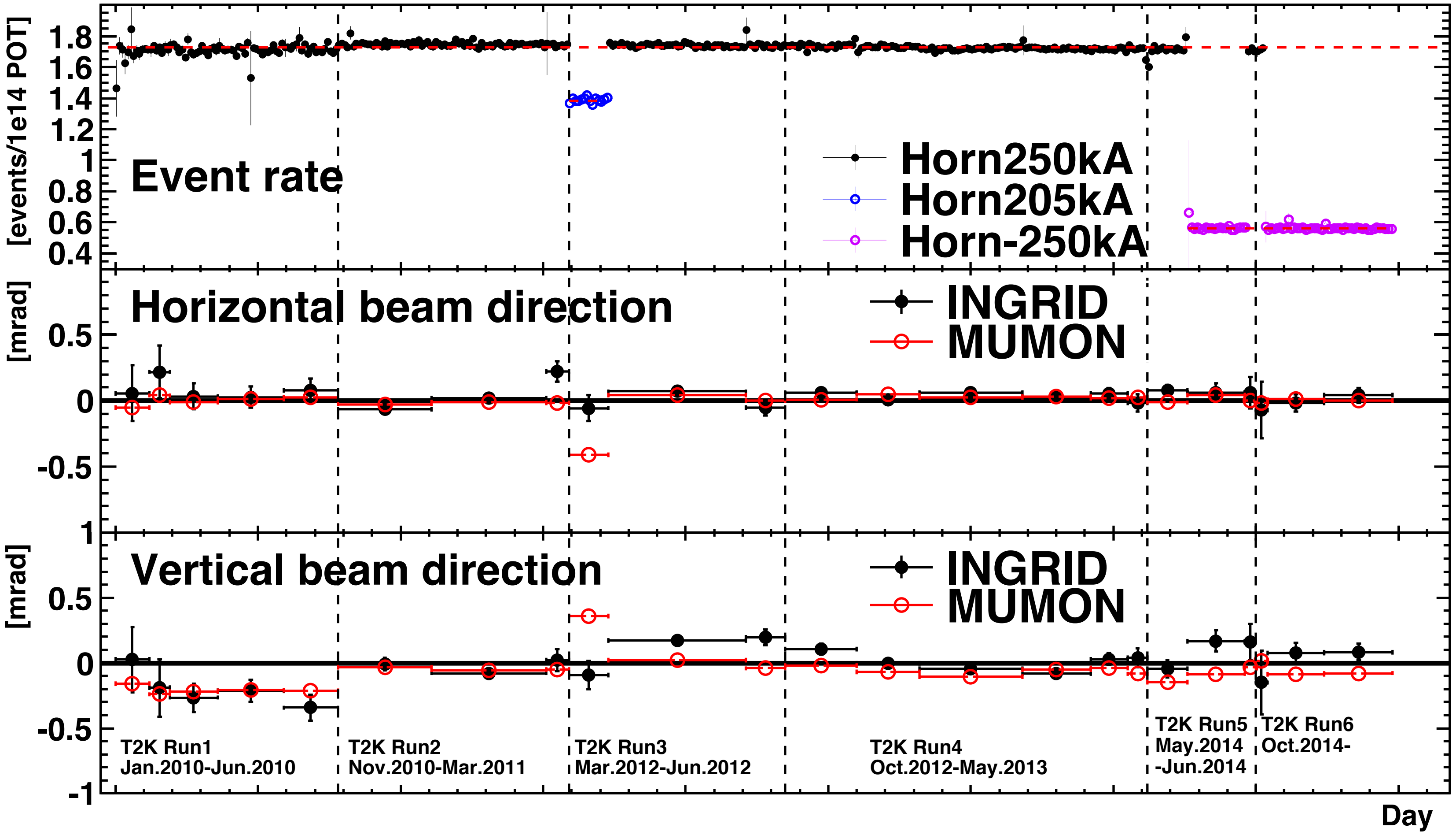
Used for this SK analysis: ν̅ mode, Run 5–6 (until 2015-03-12)

ν-mode is also known as "forward horn current" (FHC) or "positive focusing" (PF)
ν̅-mode is also known as "reverse horn current" (RHC) or "negative focusing" (NF)

Beam Stability

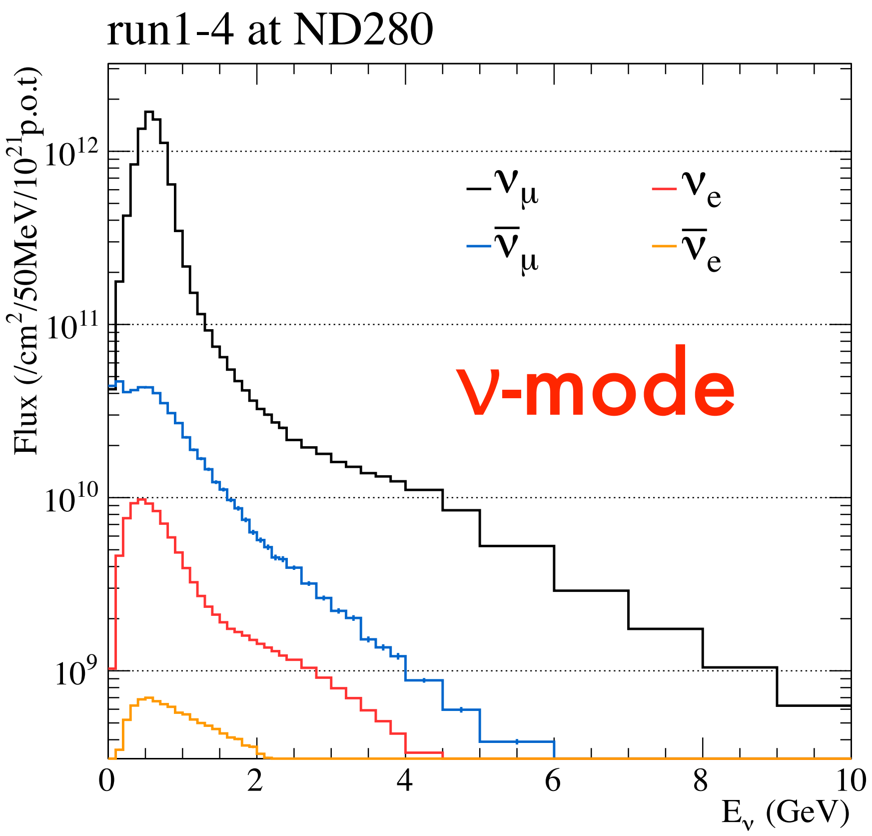
Use INGRID on-axis detector to measure beam stability

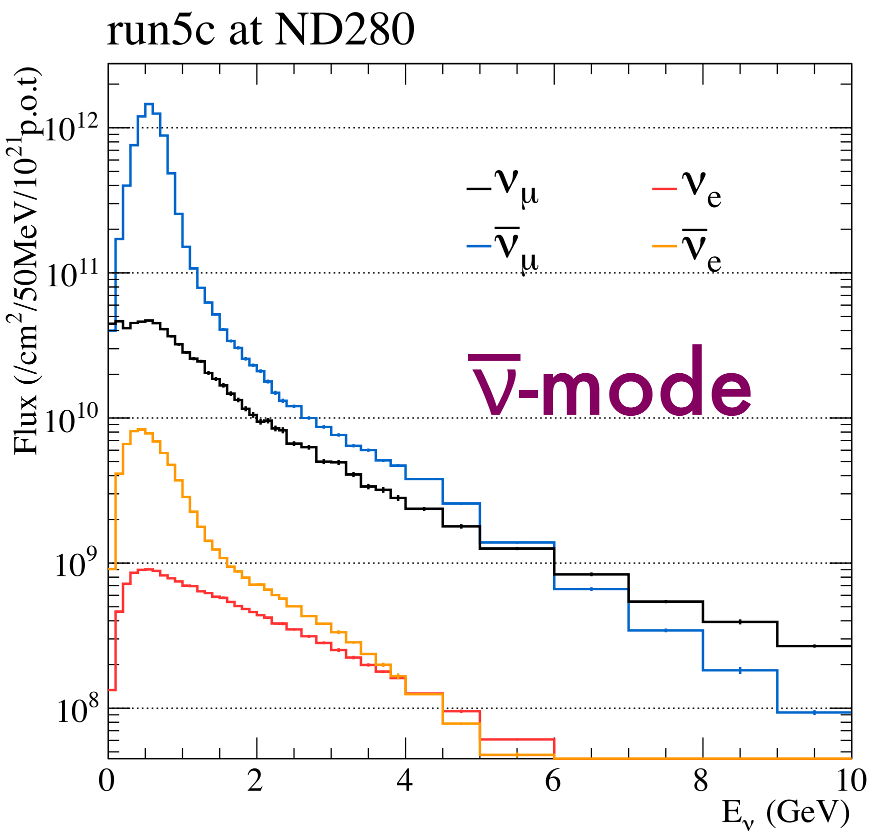


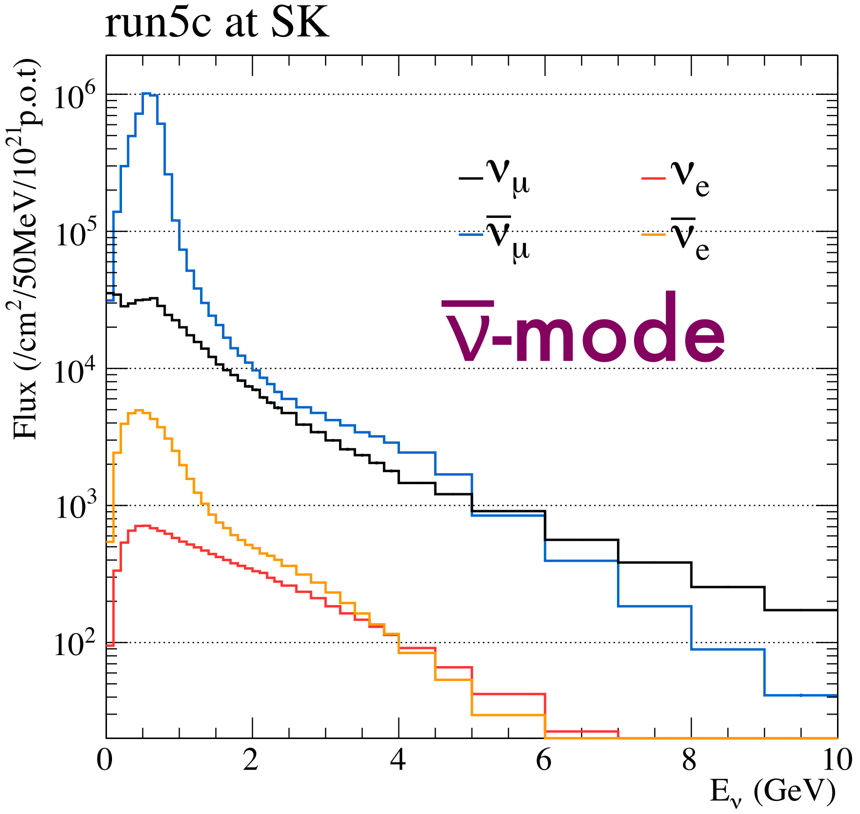


Beam rate and direction has been very stable in both neutrino and anti-neutrino modes

Beam Content

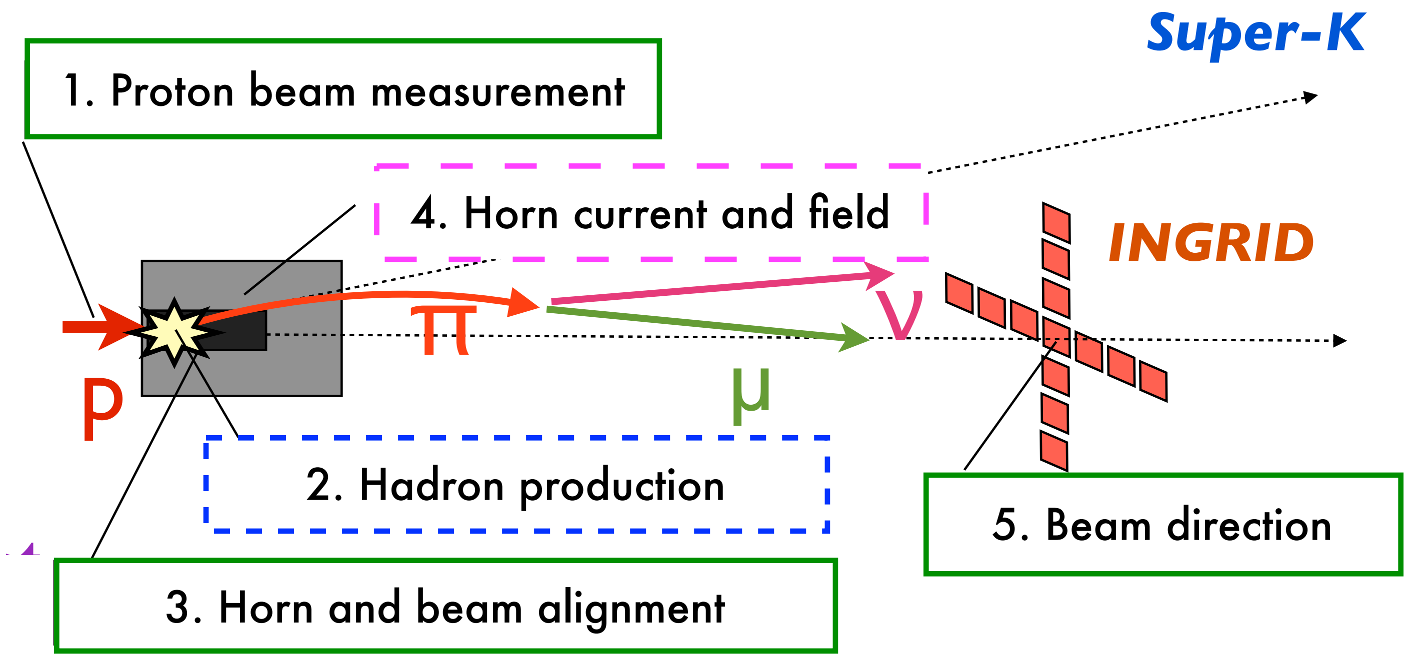

run1-4 at ND280


run5c at ND280


run5c at SK

- Note that "wrong sign" backgrounds are much higher in $\bar{\nu}$ mode
- SK flux is highly correlated with ND280 flux

Beam Uncertainties



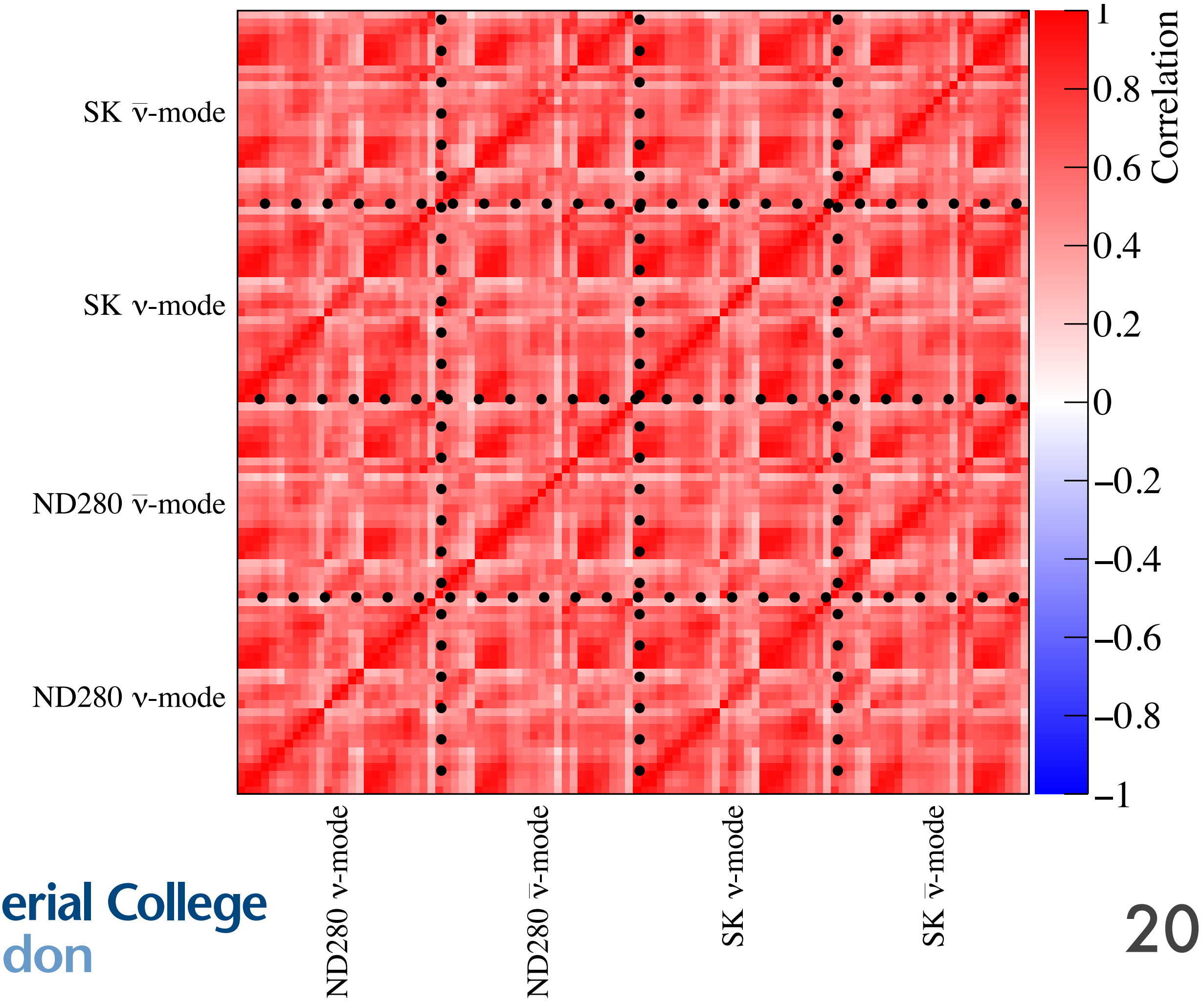
1. Proton beam measurement

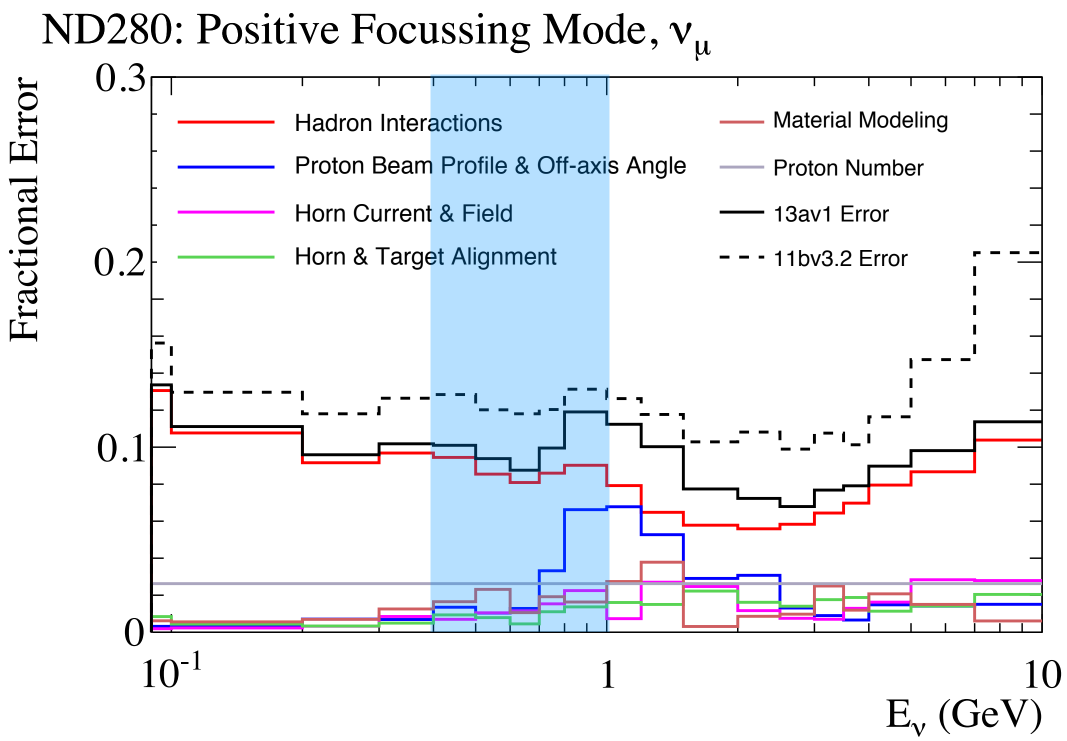
2. Hadron production

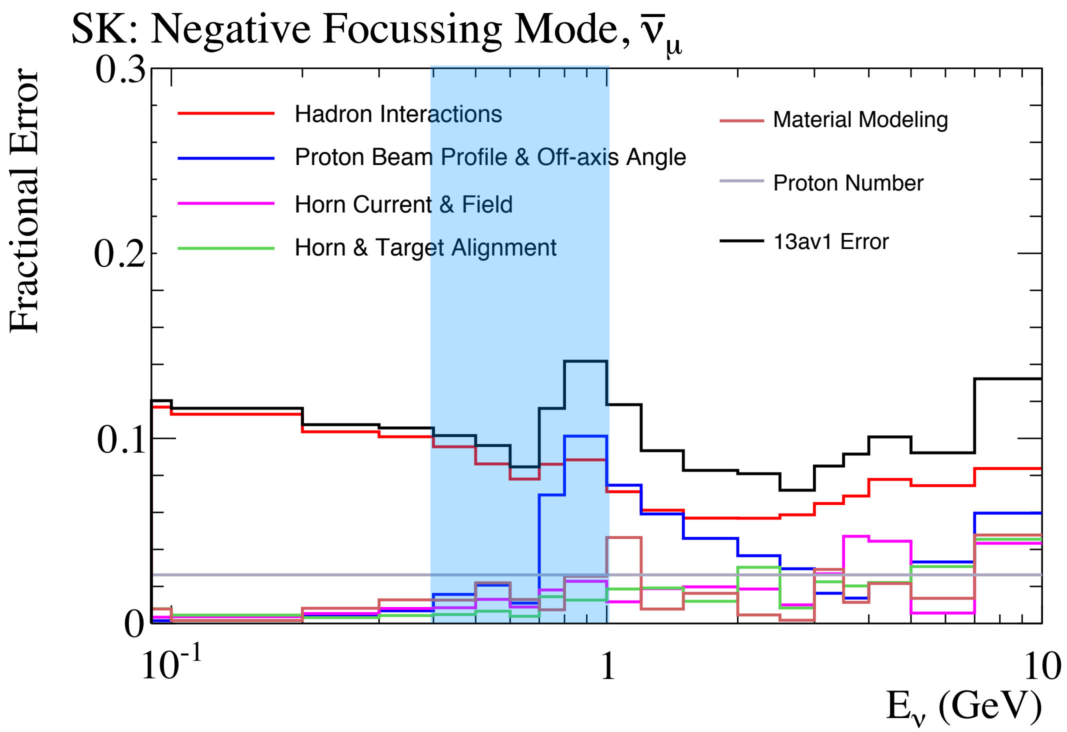
3. Horn and beam alignment

4. Horn current and field

5. Beam direction

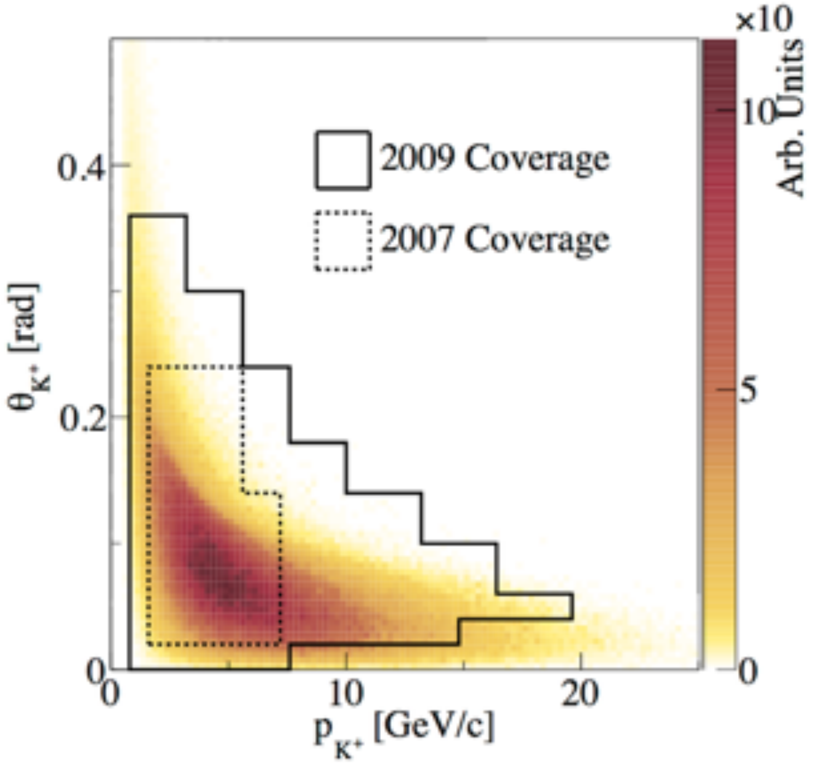


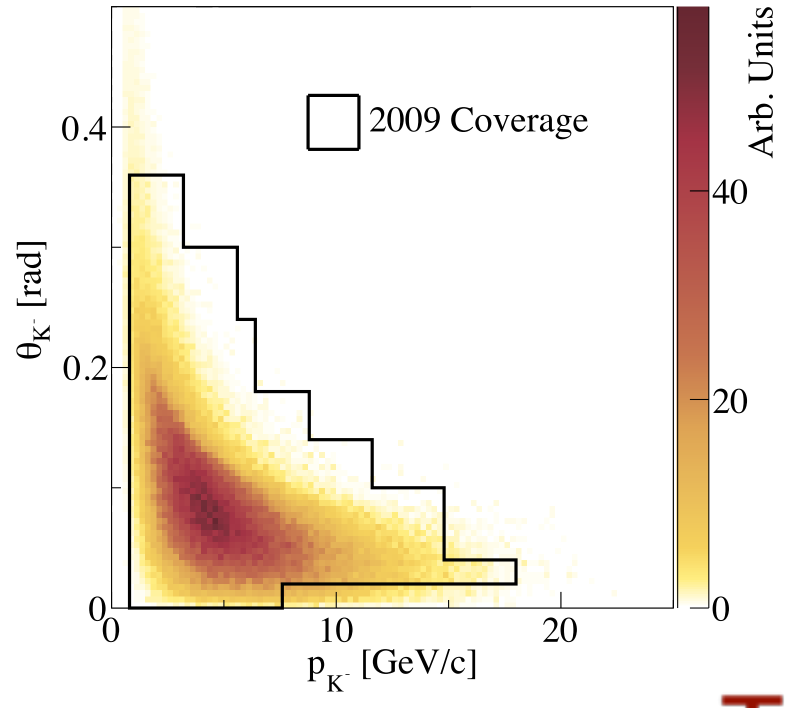




Hadronic Uncertainties

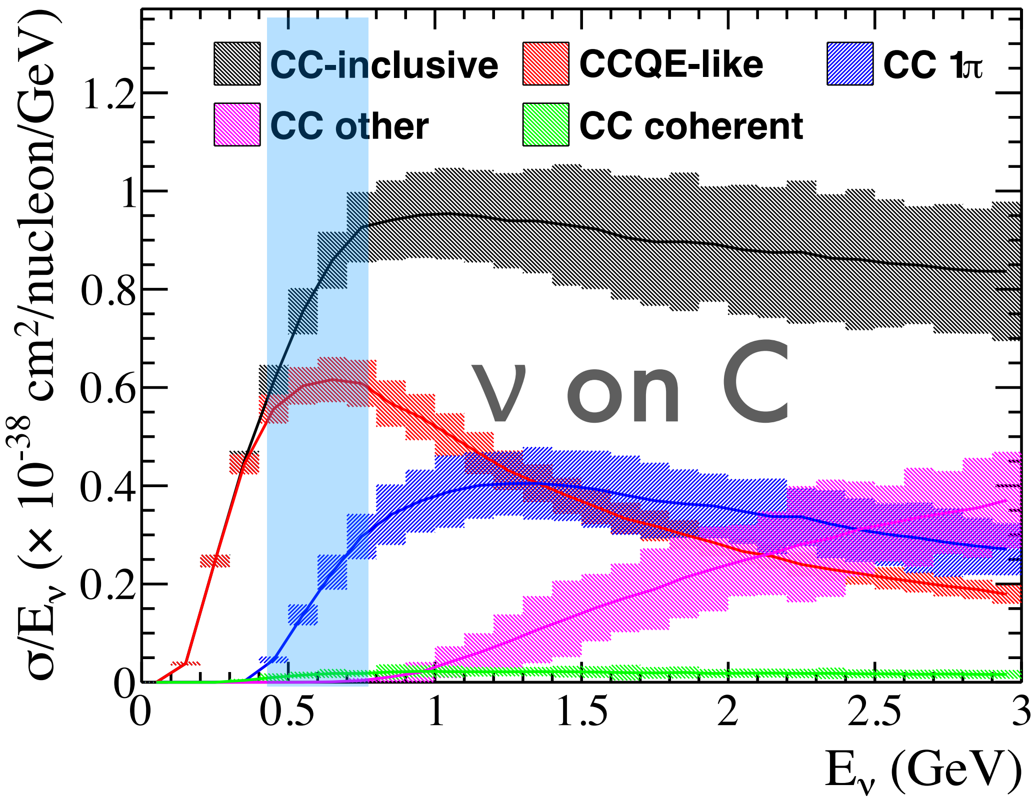
- This analysis has seen significant improvement in hadronic uncertainties through new data
  - NA61/SHINE (at CERN) measures the distributions of the pions and kaons that are produced from 30 GeV protons on a graphite target
  - T2K uses this information to tune the beam simulation
- The new data has both improved the beam prediction and reduced the uncertainty by ~4% in the beam peak

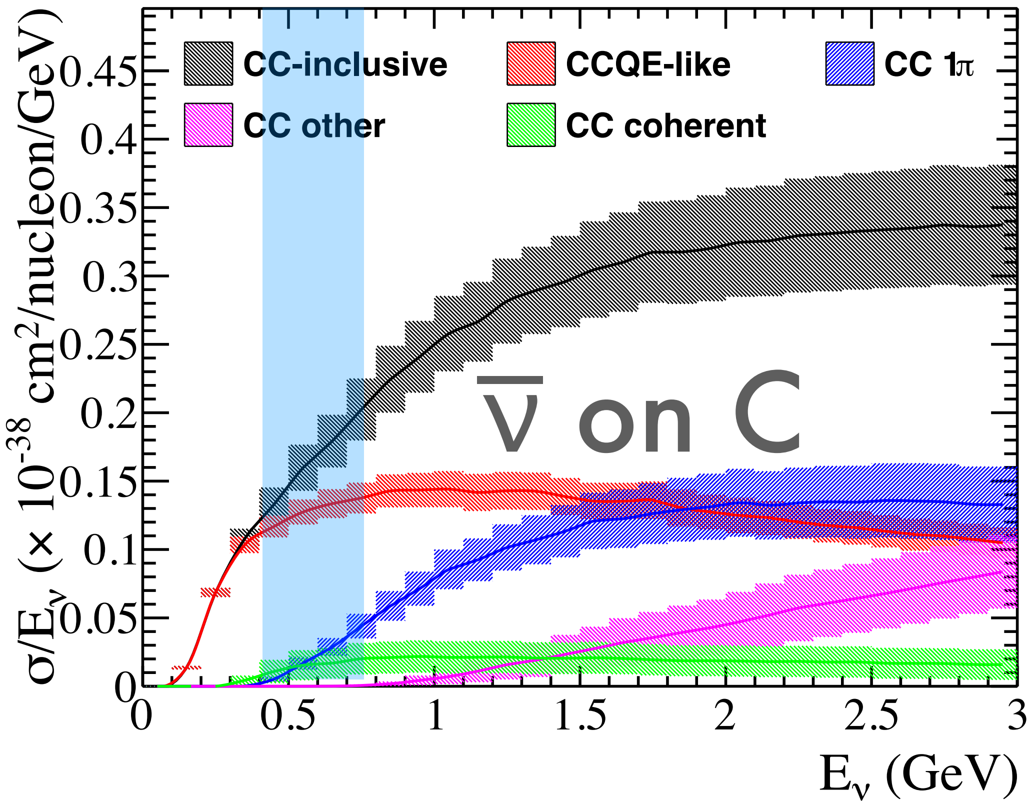




Reference

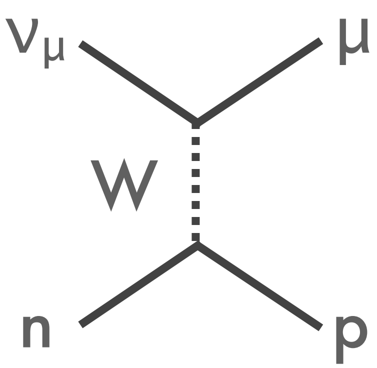
ν-N Cross Section Model



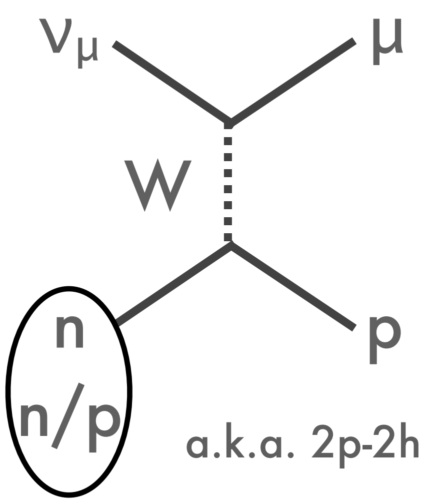


Uncertainties come from underlying model parameters and normalizations

Charged current quasi-elastic

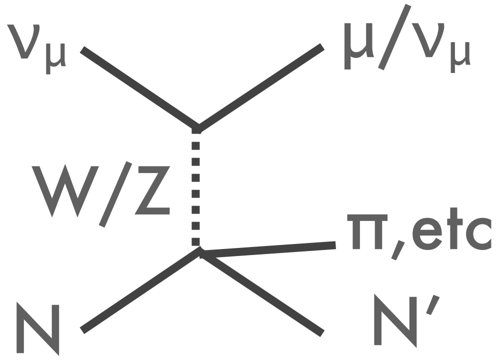


Charged current multinucleon

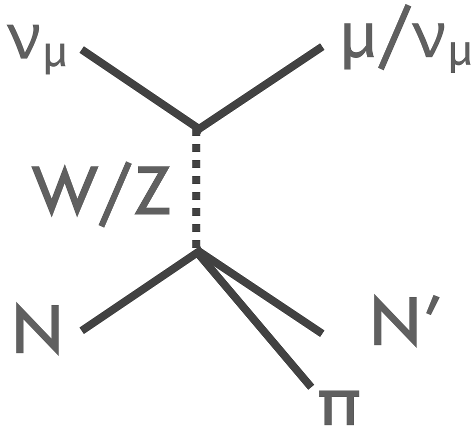


a.k.a. 2p-2h or MEC

Deep Inelastic Scattering

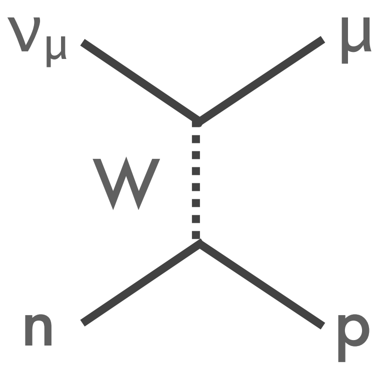


Charged Current 1π



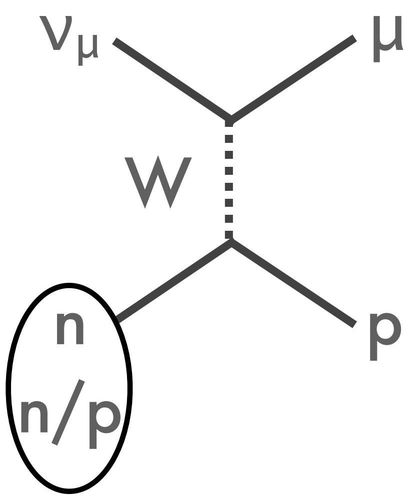
Why Multinucleon?

Charged current quasi-elastic

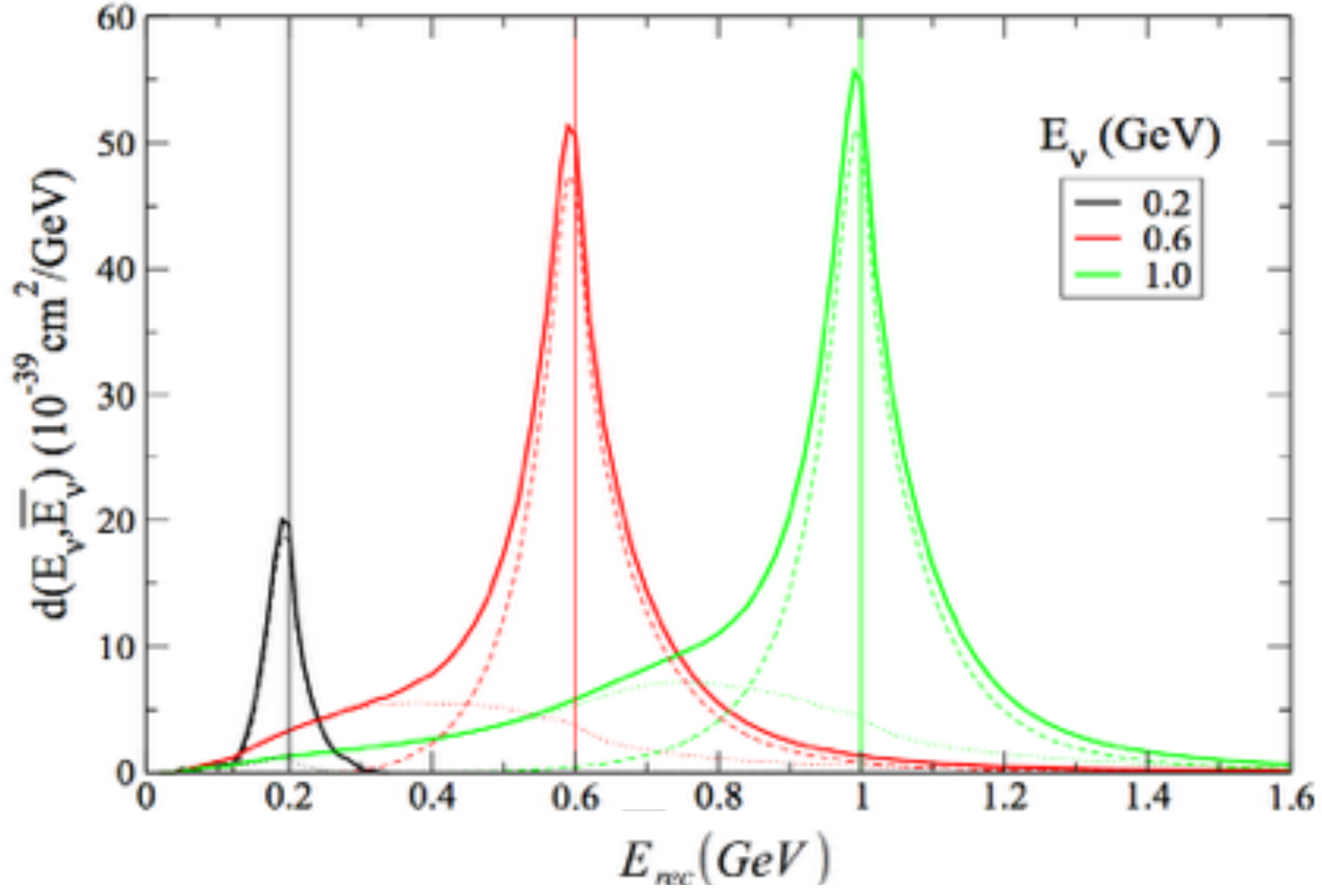


Charged current multinucleon

How does this change energy reconstruction?

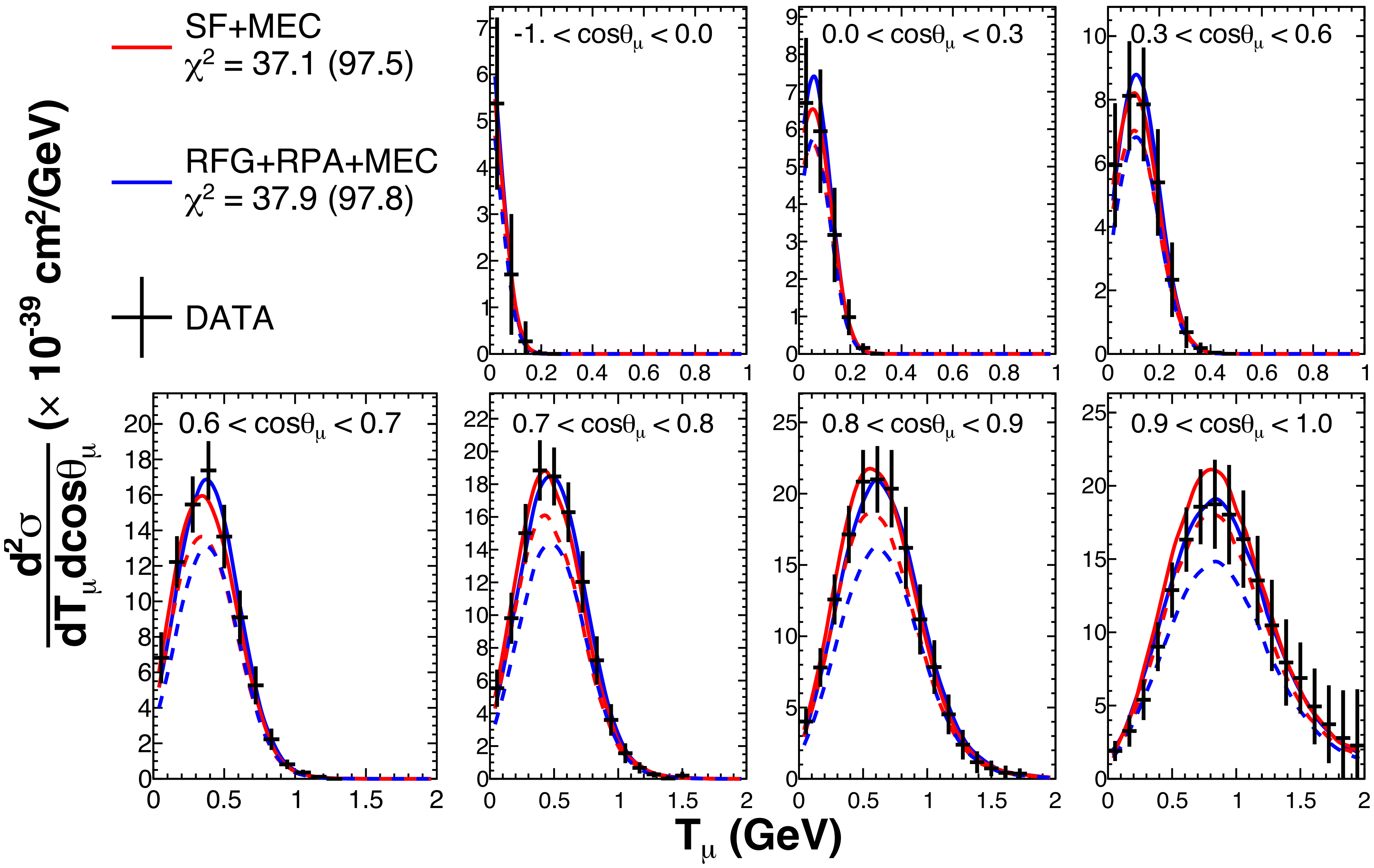


Martini et. al. Phys.Rev. D87 (2013) 013009



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

External CCQE Fit



MiniBooNE
neutrino
dataset

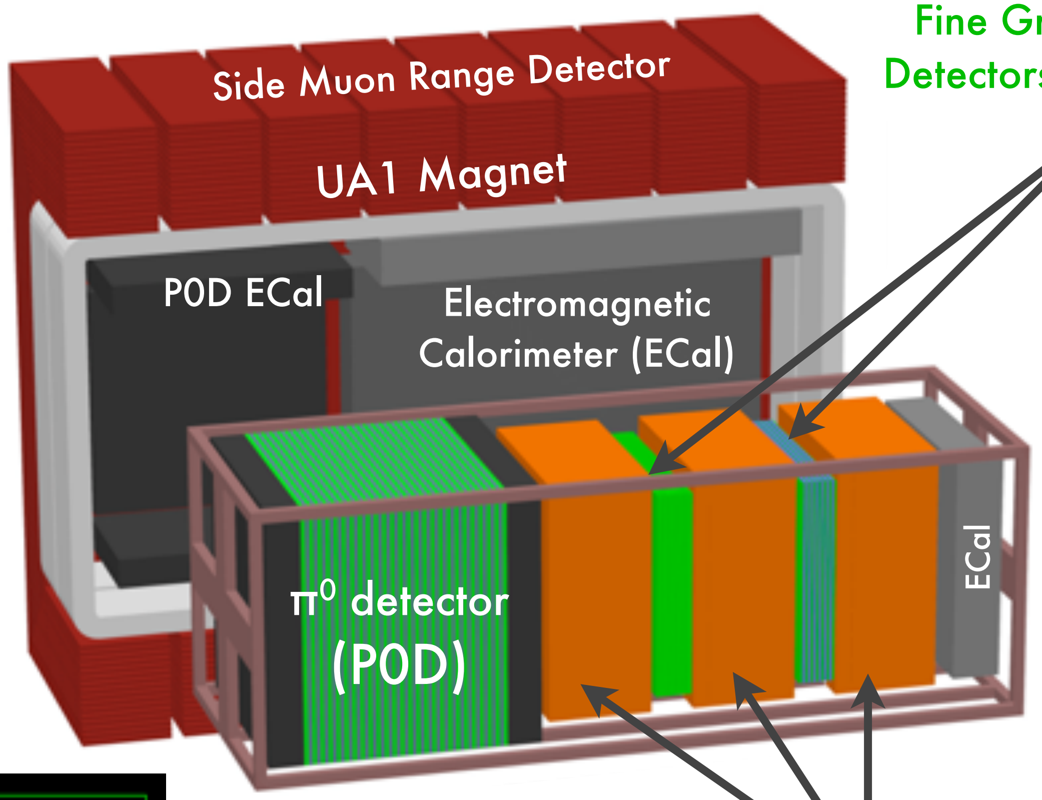
- Use CCQE-like data from the MiniBooNE and MINERVA experiments to select a cross section model and tune parameters
- External data is somewhat in tension, so errors are inflated to account for that tension

T2K Off-Axis Near Detector

Primary Interaction Material: Carbon

Secondary Interaction Materials:
Oxygen, Lead, Brass, Argon

Beam

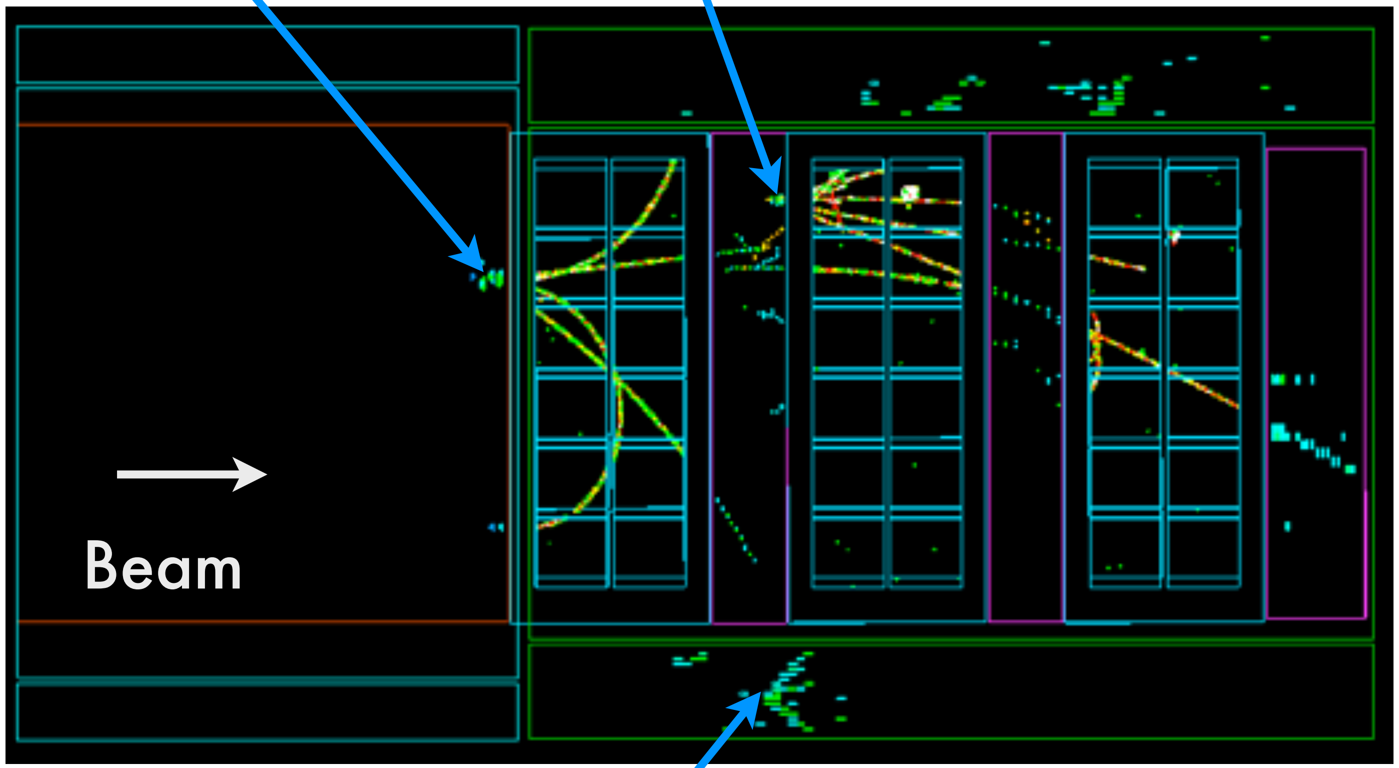


Fine Grained Detectors (FGDs)

Time Projection Chambers (TPCs)

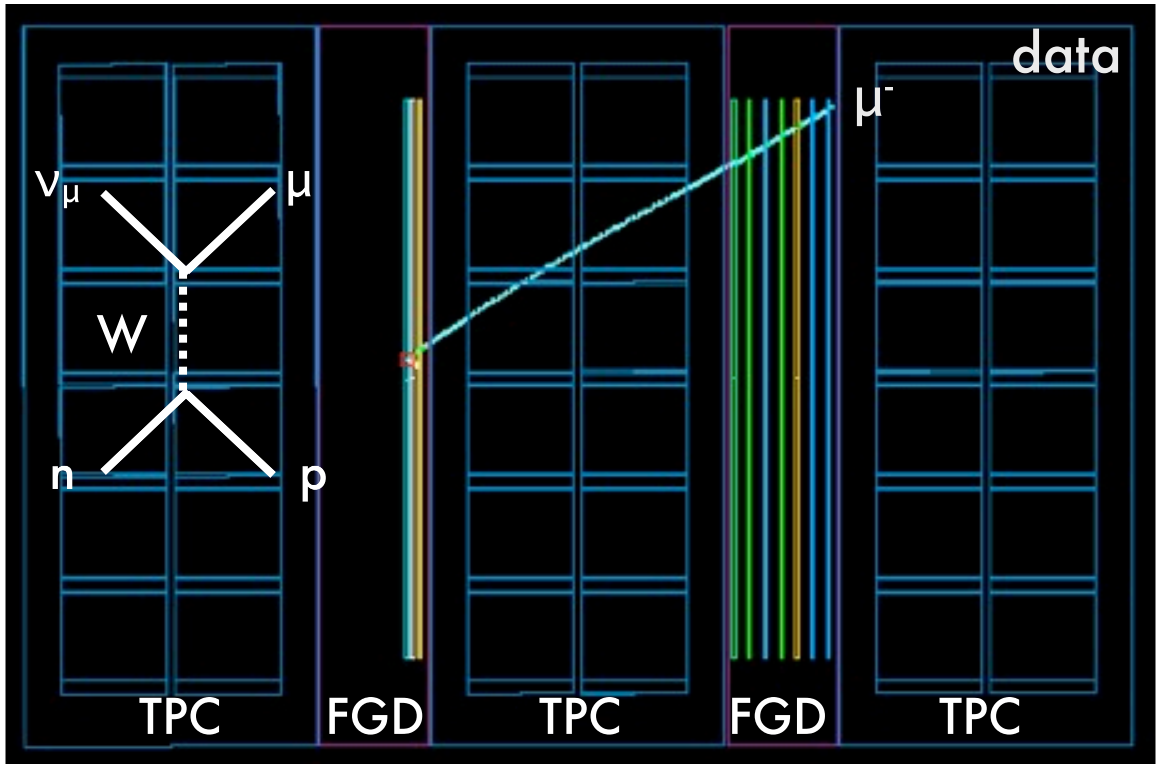
Interaction in P0D

Interaction in FGD1

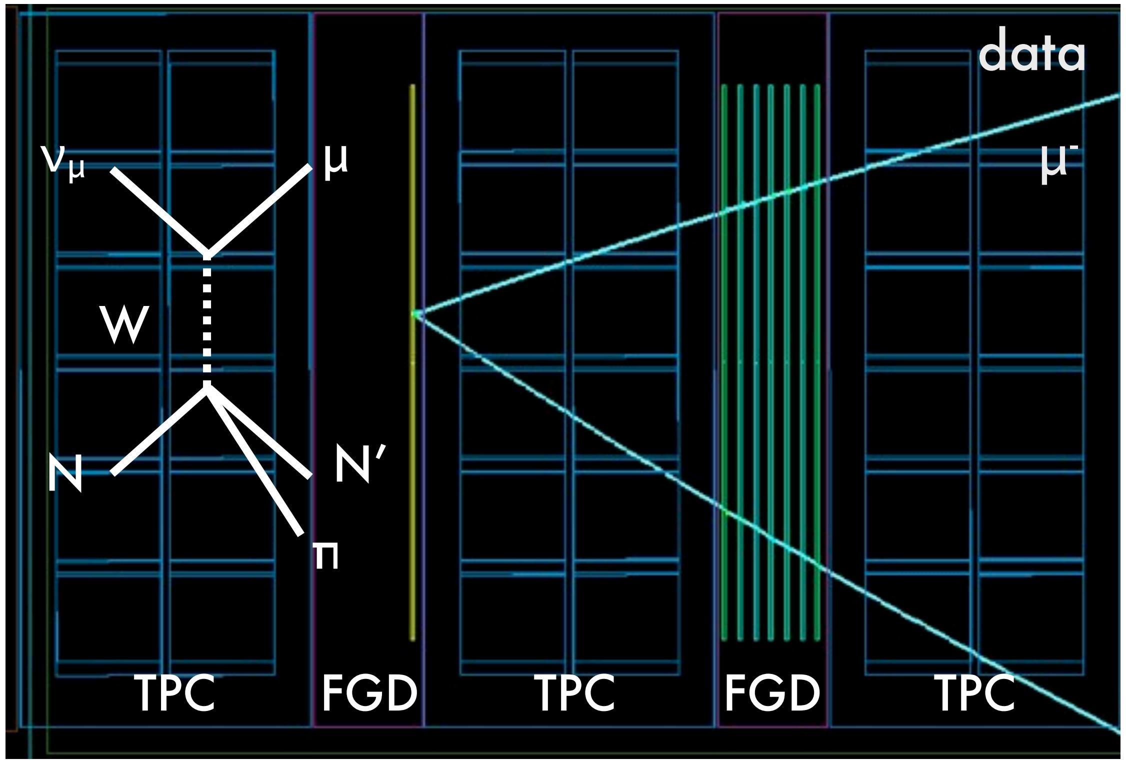


Interaction in ECal

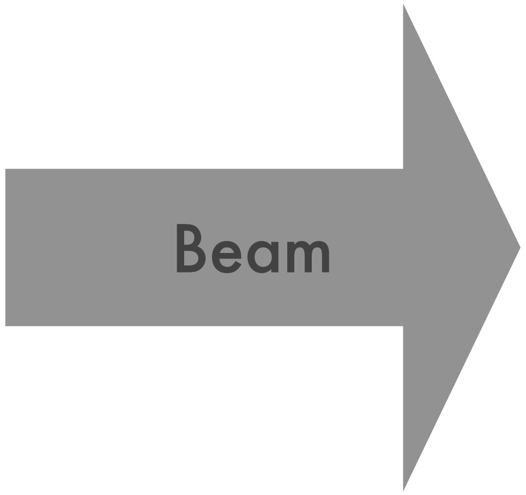
CC0π

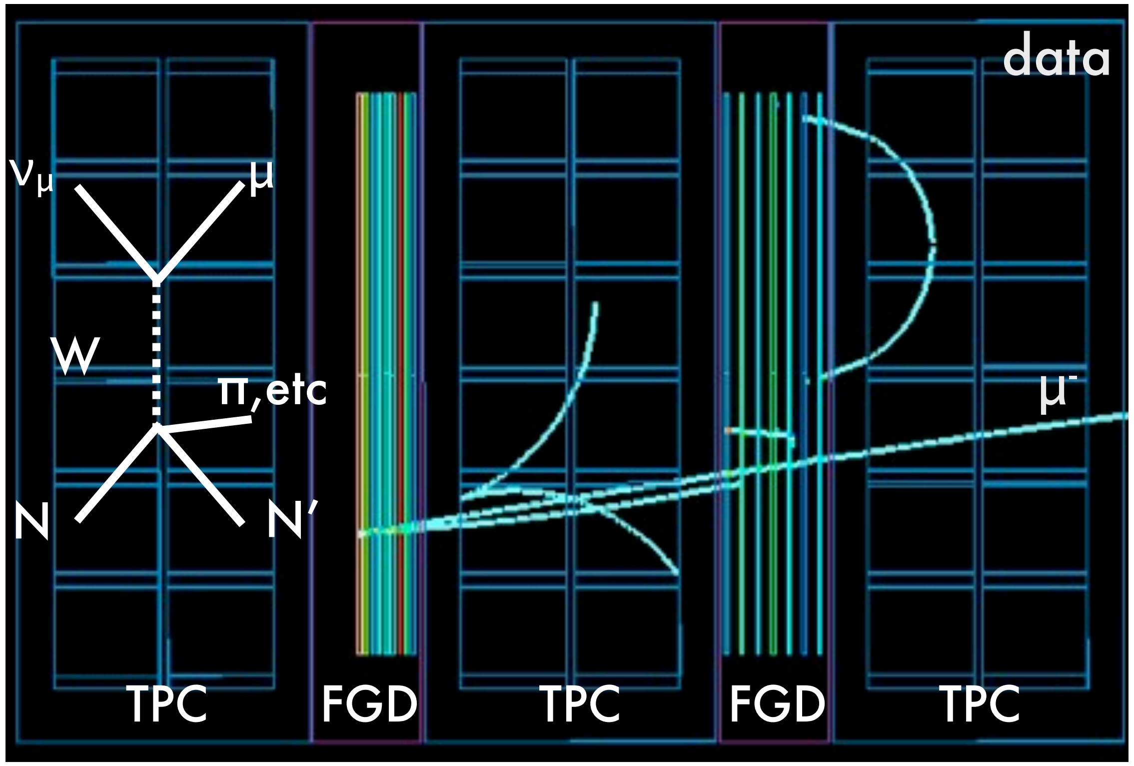


CC1π^+



CC other

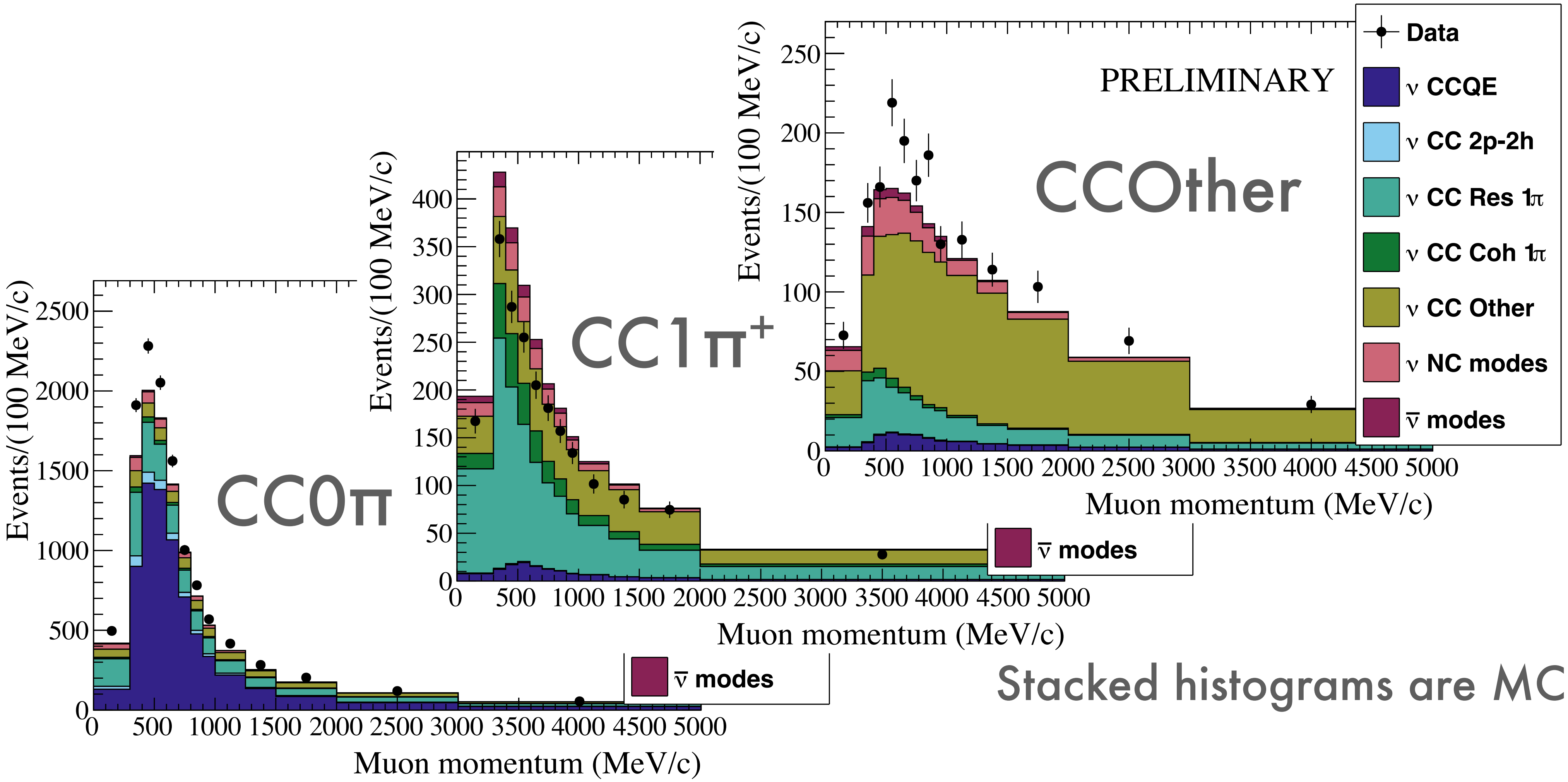




Imperial College London

T2K

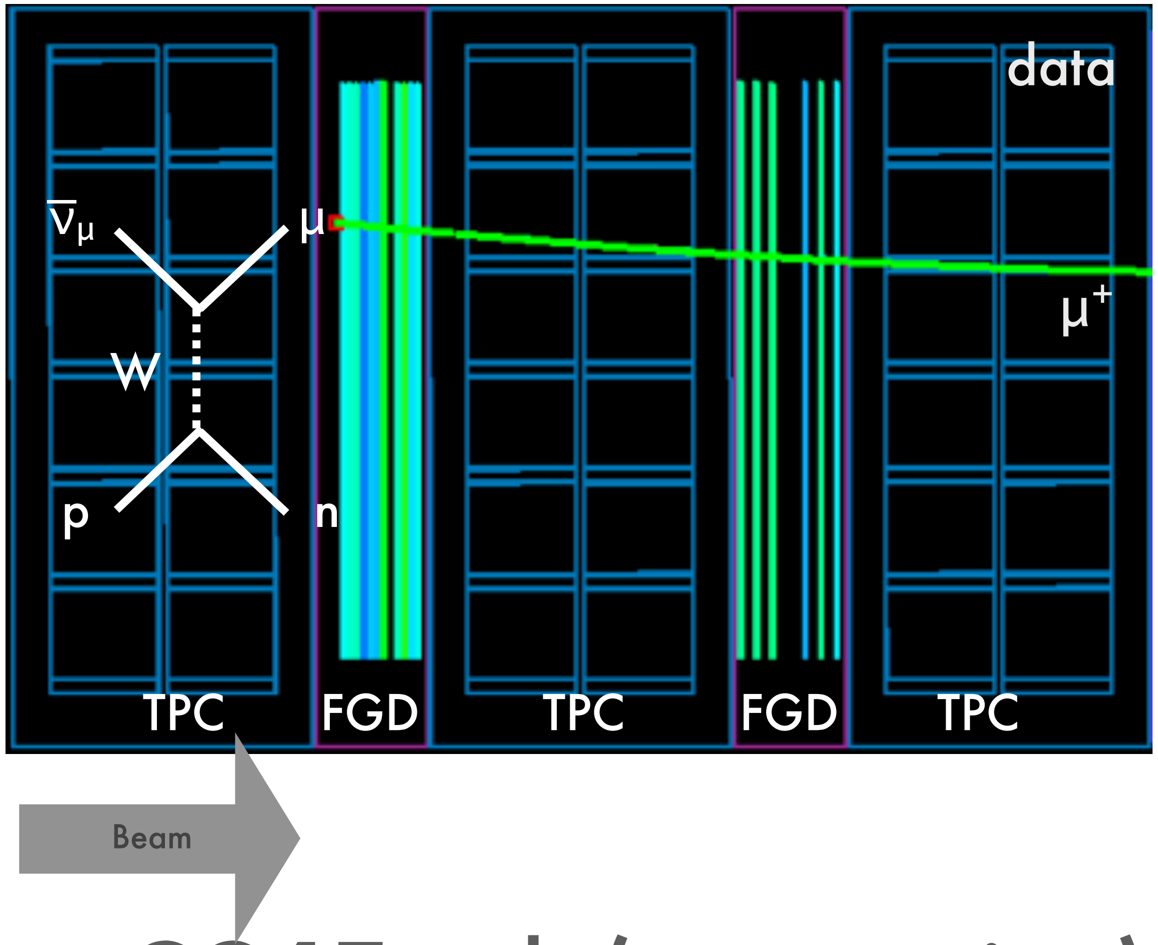
ND280 ν-mode samples



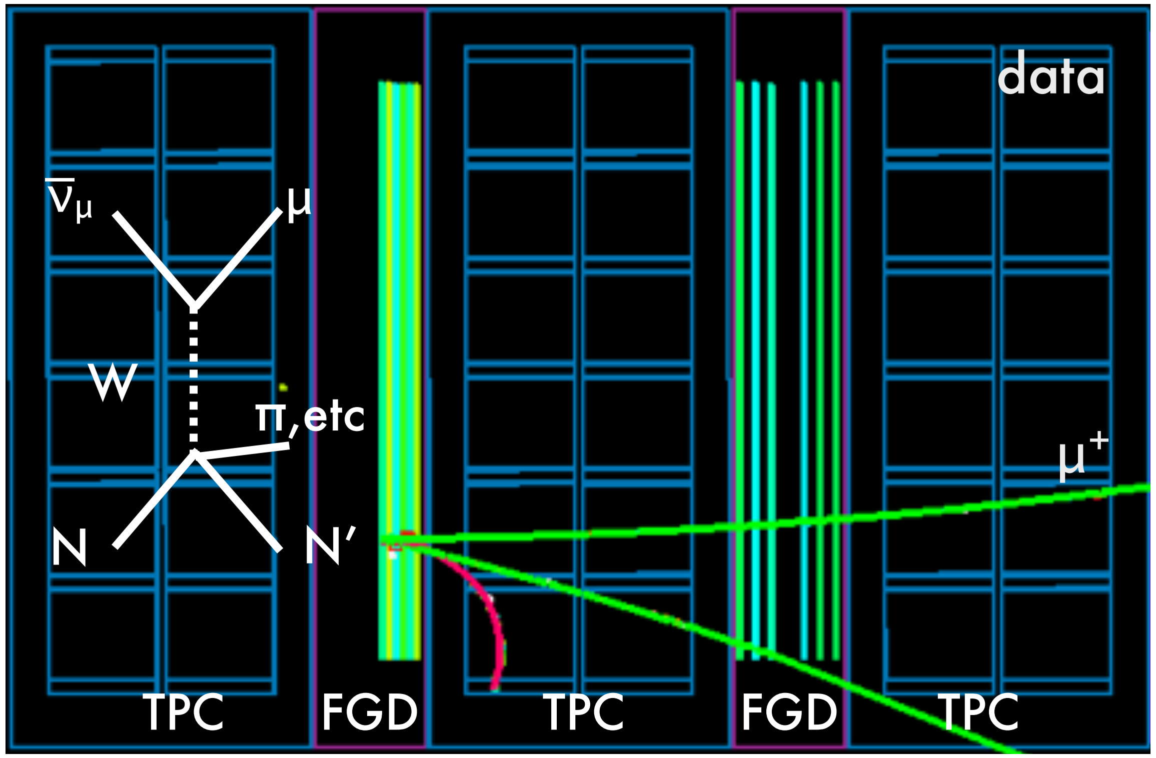
Stacked histograms are MC prefit

- Three samples allow sensitivity to different beam energies and cross section interaction modes
- High statistics in neutrino mode provide strong constraints
- CC0π and CC Other samples are underestimated by model; CC1π$^+$ is overestimated

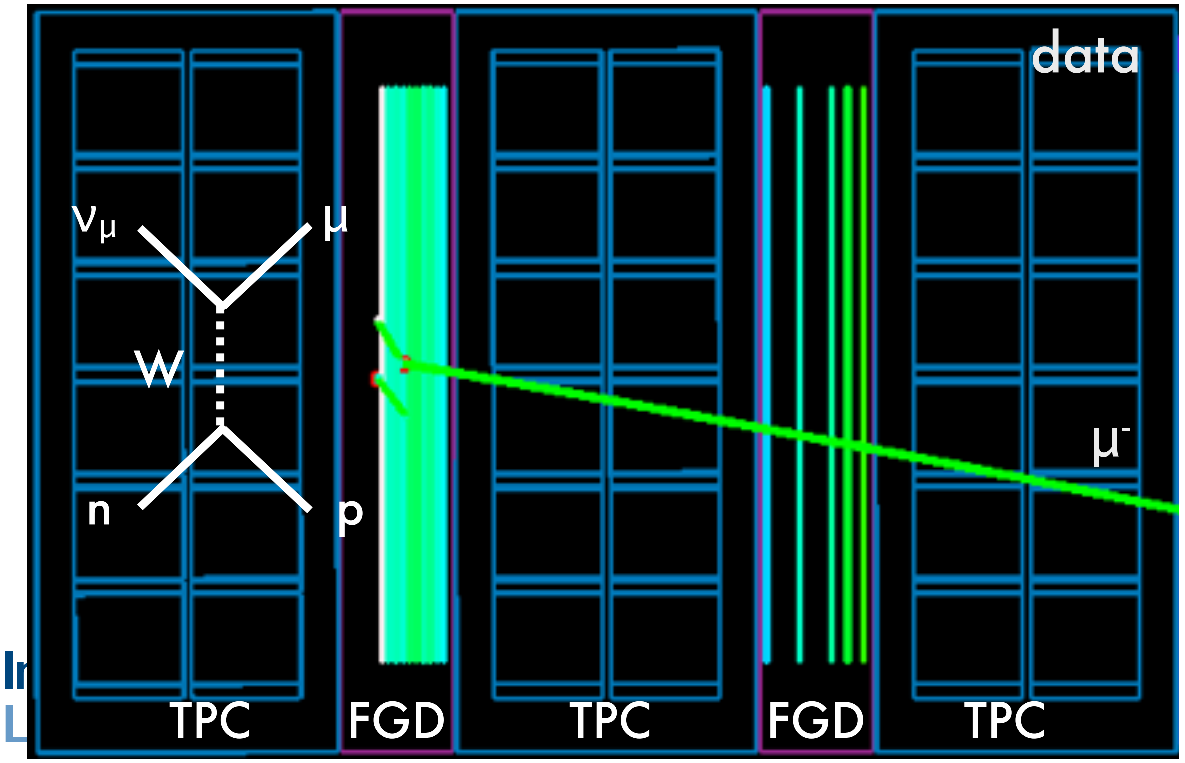
$\overline{\nu}_\mu$ CC-1Track



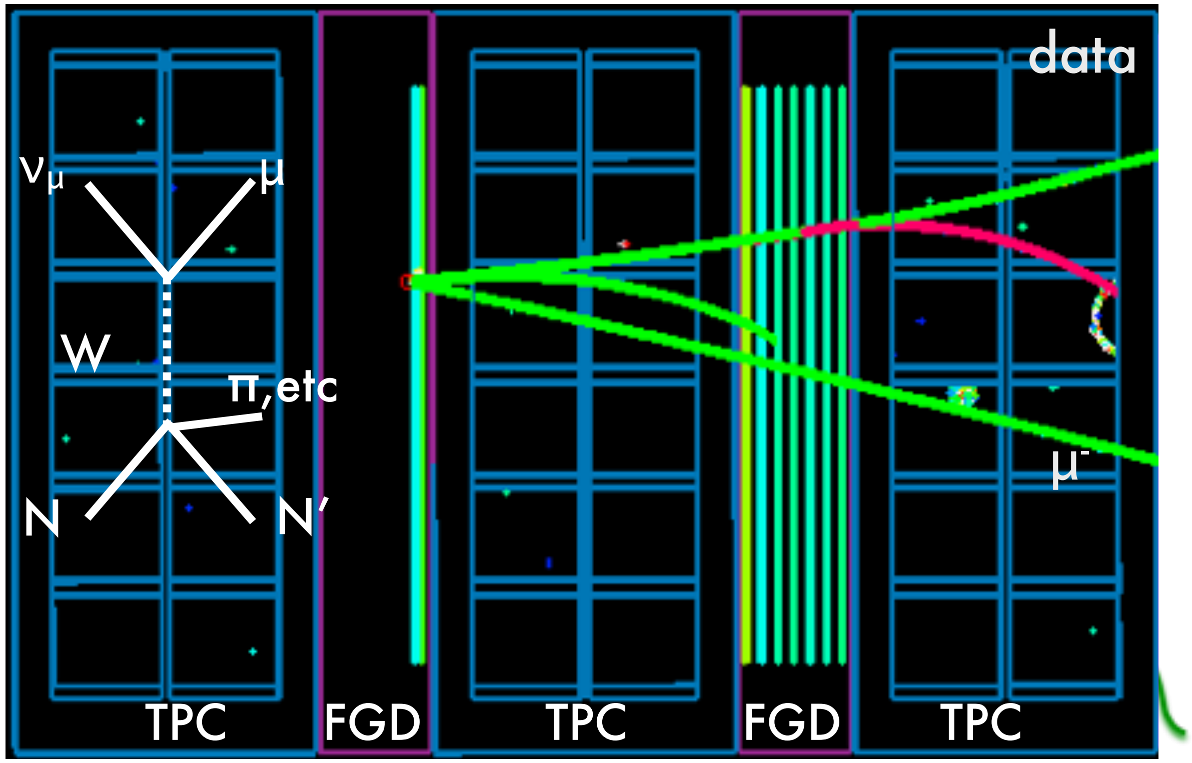
$\overline{\nu}_\mu$ CC-NTrack



ν_μ CC-1Track (wrong sign)

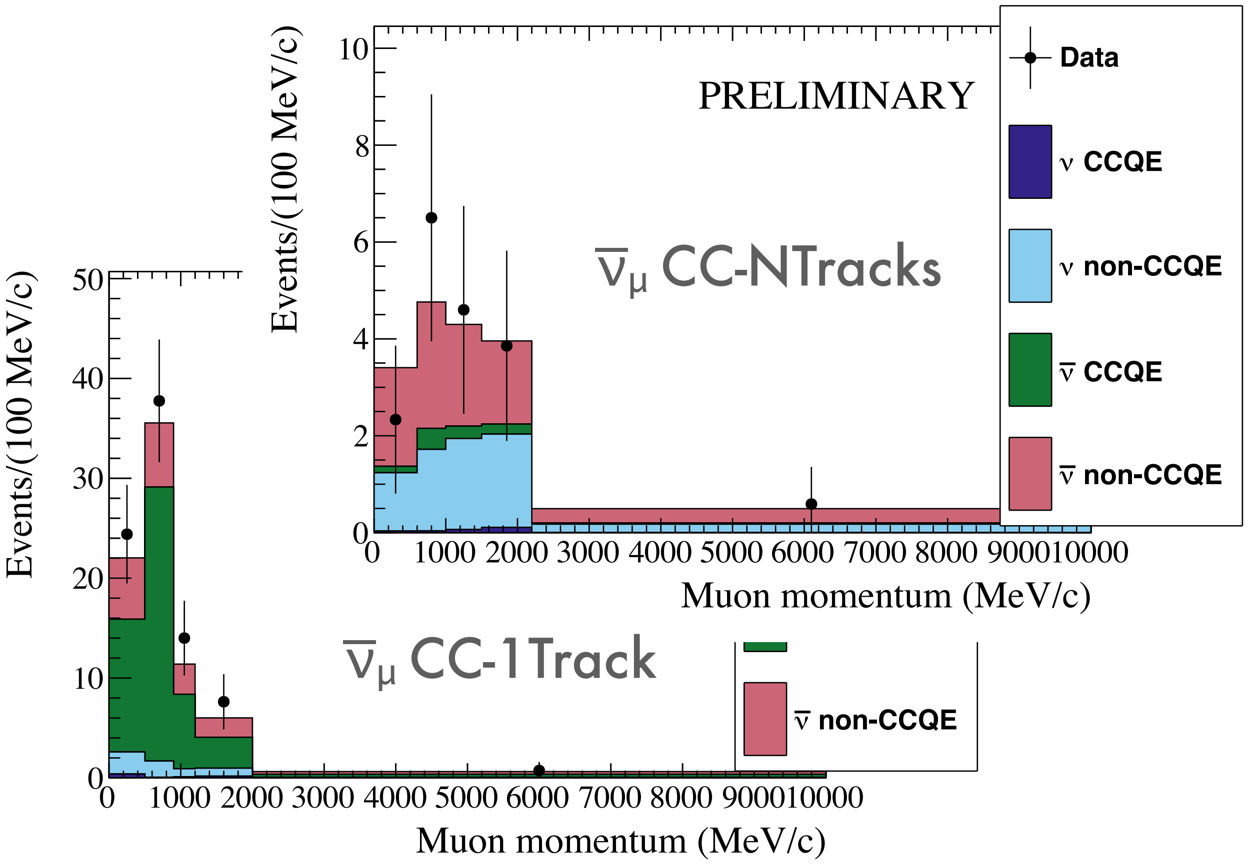


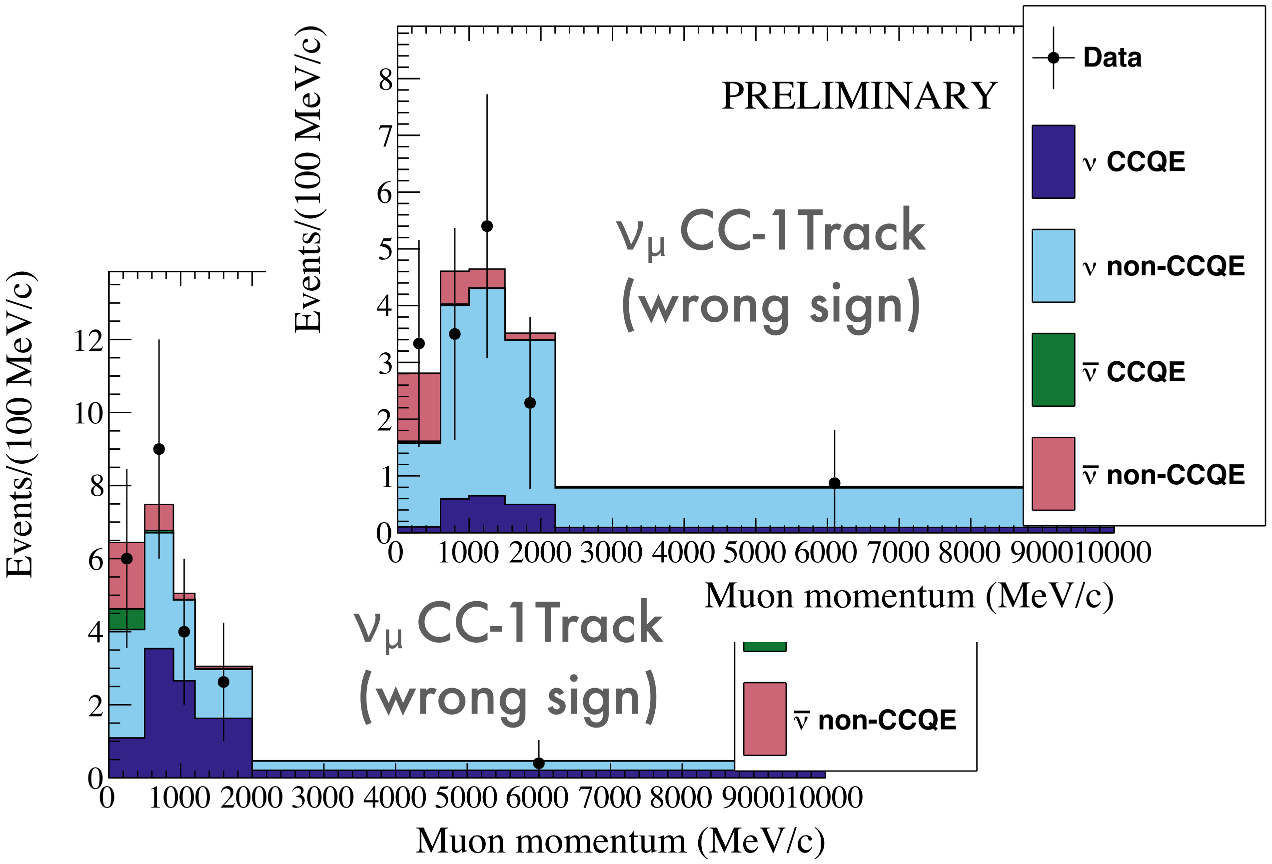
ν_μ CC-NTrack (wrong sign)



ND280 $\bar{\nu}$-mode Samples

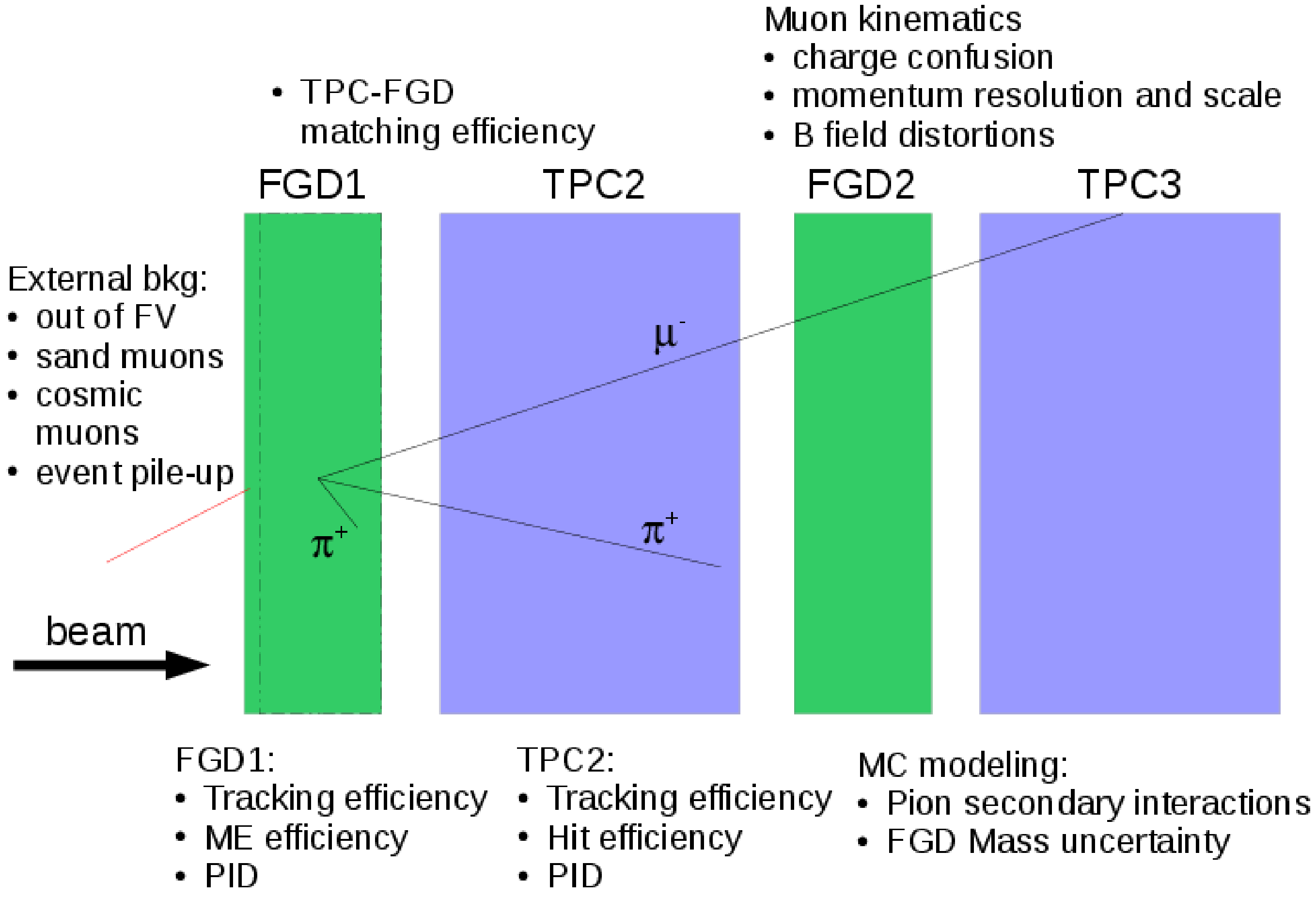
Stacked histograms are MC prefit





- Samples are still statistically small compared to ν-mode
- Important look into what ND280 will do with $\bar{\nu}$ data

ND280 Detector Model



- TPC-FGD matching efficiency

Muon kinematics
- charge confusion
- momentum resolution and scale
- B field distortions

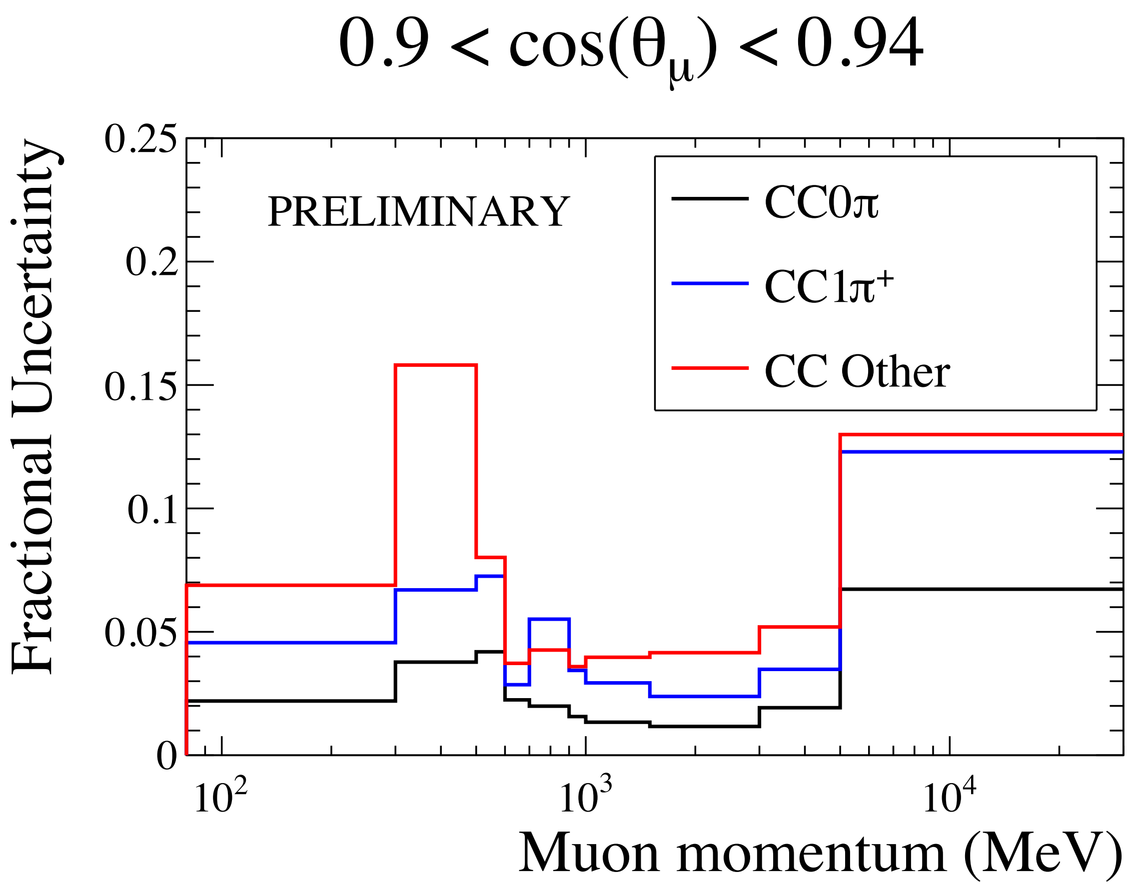
External bkg:
- out of FV
- sand muons
- cosmic muons
- event pile-up

FGD1:
- Tracking efficiency
- ME efficiency
- PID

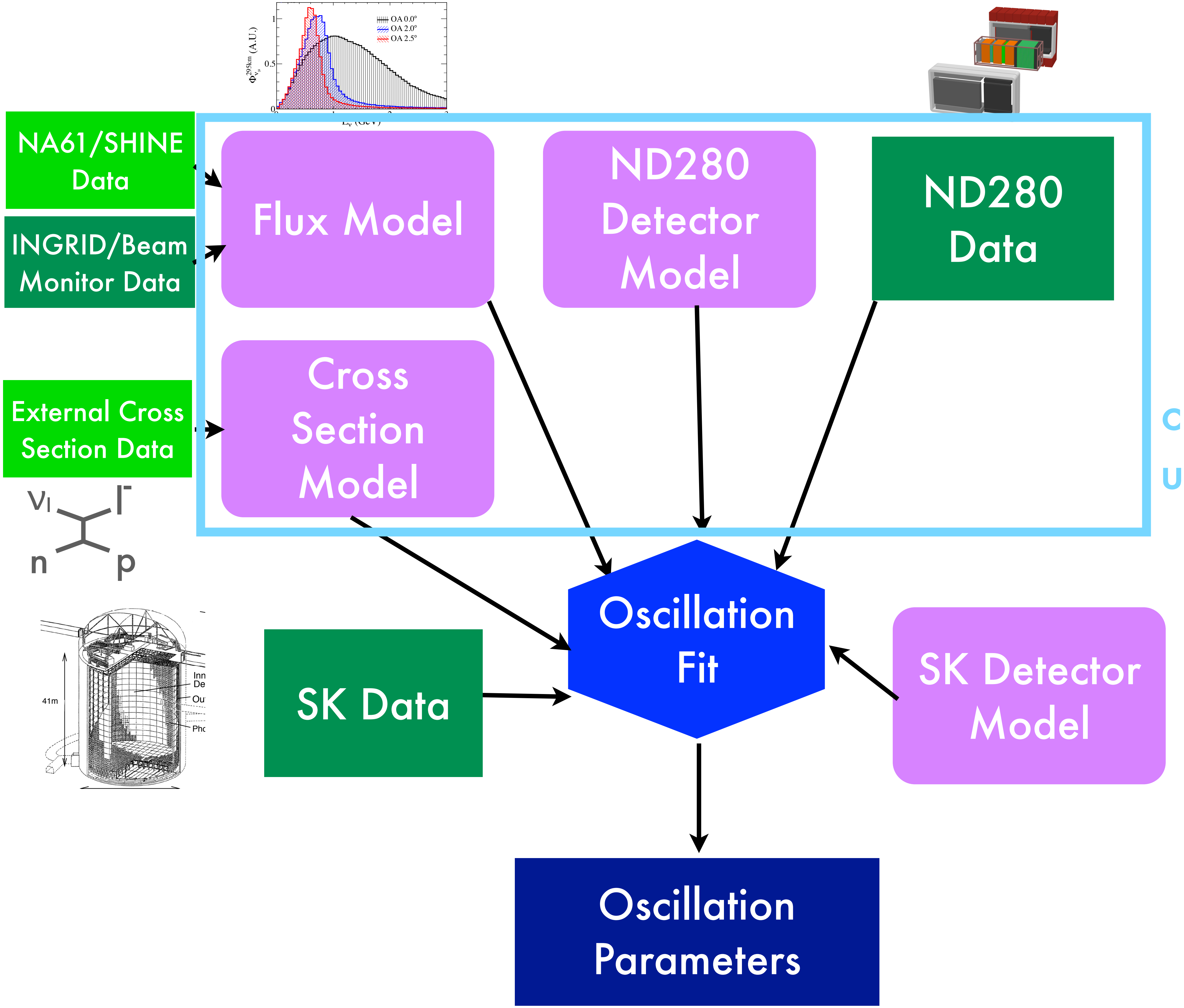
TPC2:
- Tracking efficiency
- Hit efficiency
- PID

MC modeling:
- Pion secondary interactions
- FGD Mass uncertainty

As far as possible, use data to constrain systematics; e.g. use cosmic samples to evaluate interdetector matching



Dominant systematics are pion secondary interactions, MC statistics, and out of fiducial volume events



NA61/SHINE Data

INGRID/Beam Monitor Data

External Cross Section Data

Flux Model

ND280 Detector Model

ND280 Data

Cross Section Model

Oscillation Fit

SK Data

SK Detector Model

Oscillation Parameters

ND data primarily constrains flux and cross section uncertainties

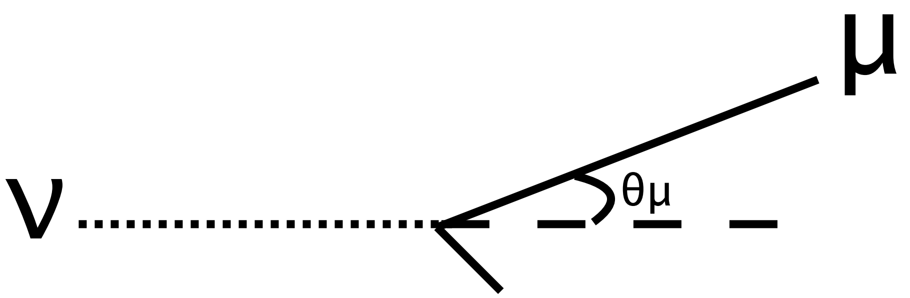
Imperial College London

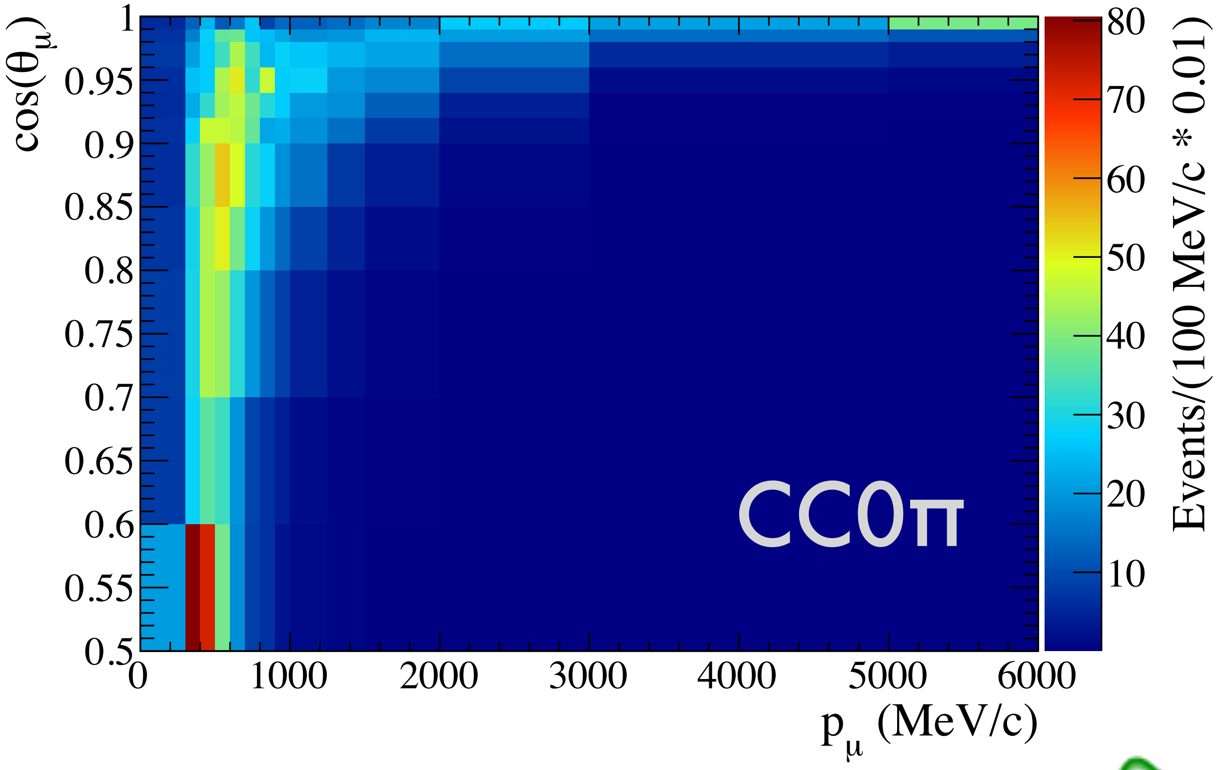
T2K

Near Detector Analysis

$$\mathcal{L} = \mathcal{L}_{\mathrm{Poisson}} \times \mathcal{L}_{\mathrm{Syst}}$$

Maximize a likelihood which is the product of a Poisson term comparing the predicted spectrum to the data and a term incorporating the systematics

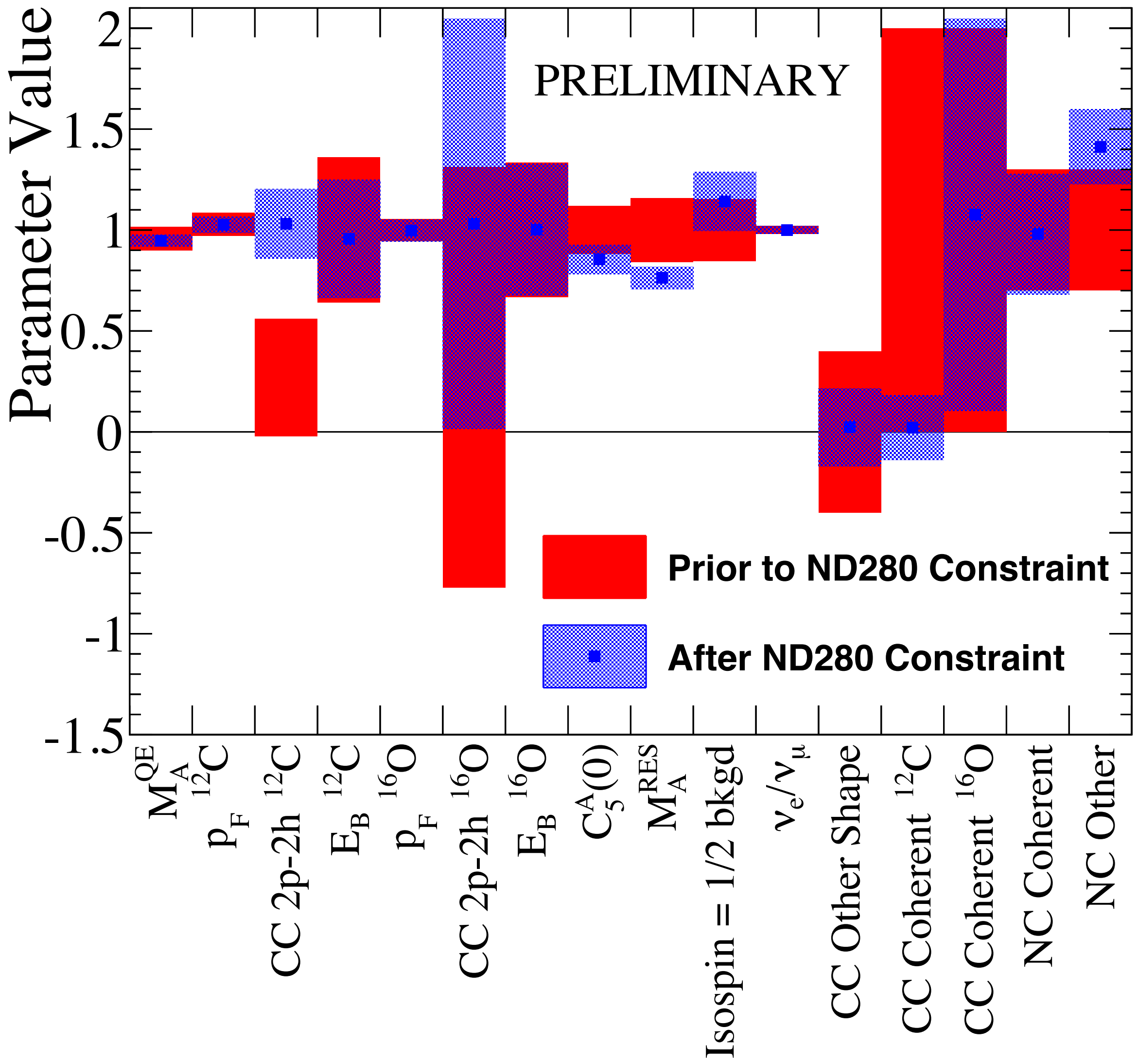


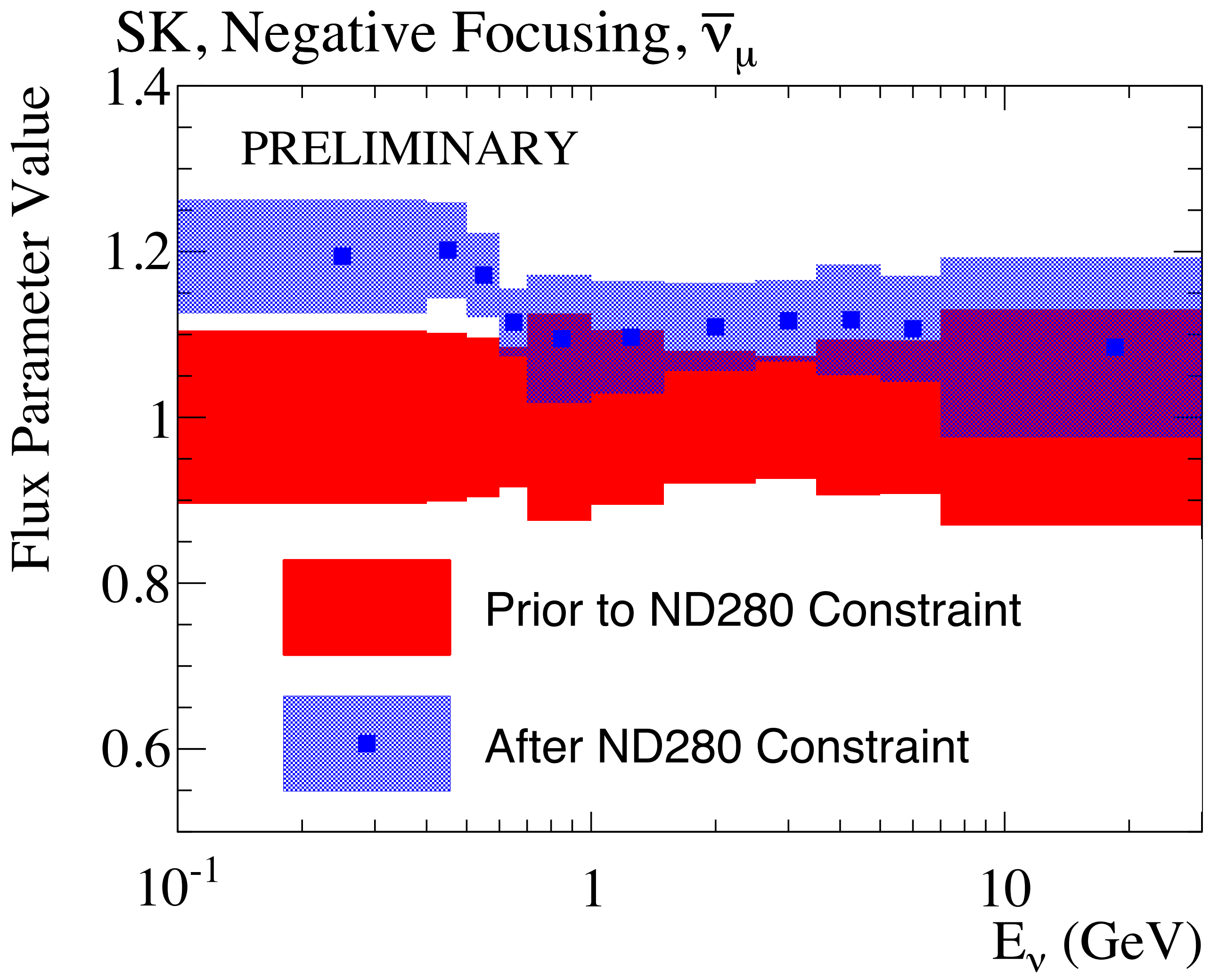


Data is binned in muon candidate momentum and angle with respect to the incoming neutrino beam

Near Detector Results

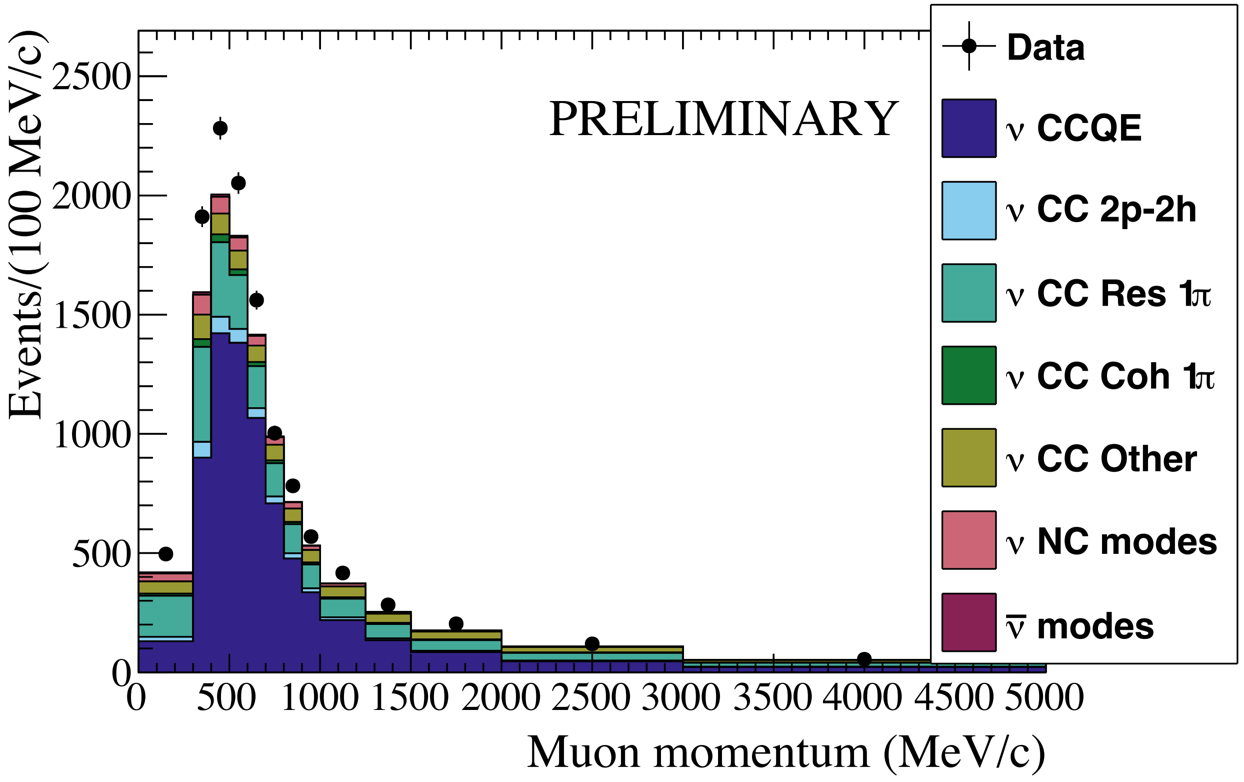
- Flux parameters are generally increased
- Some cross section parameters—especially the carbon multinucleon parameter—are changed significantly from prior values



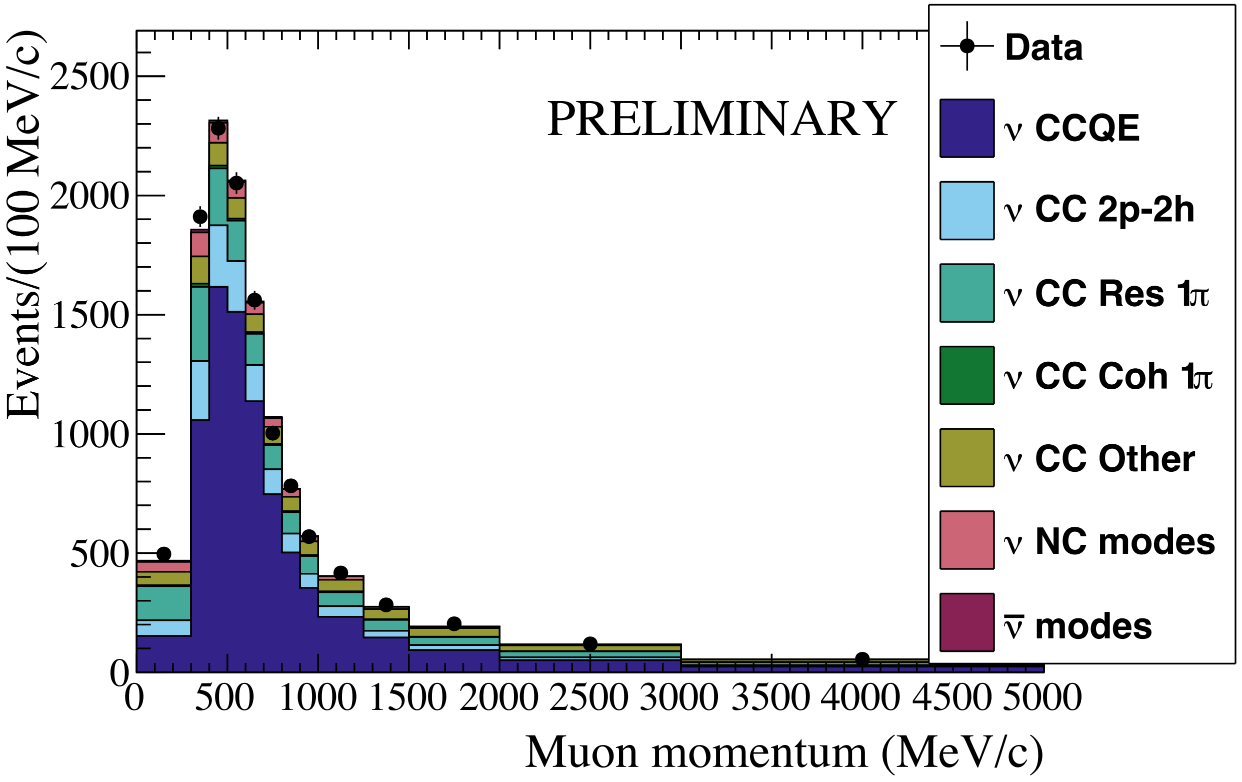


CC0π Samples

Before analysis

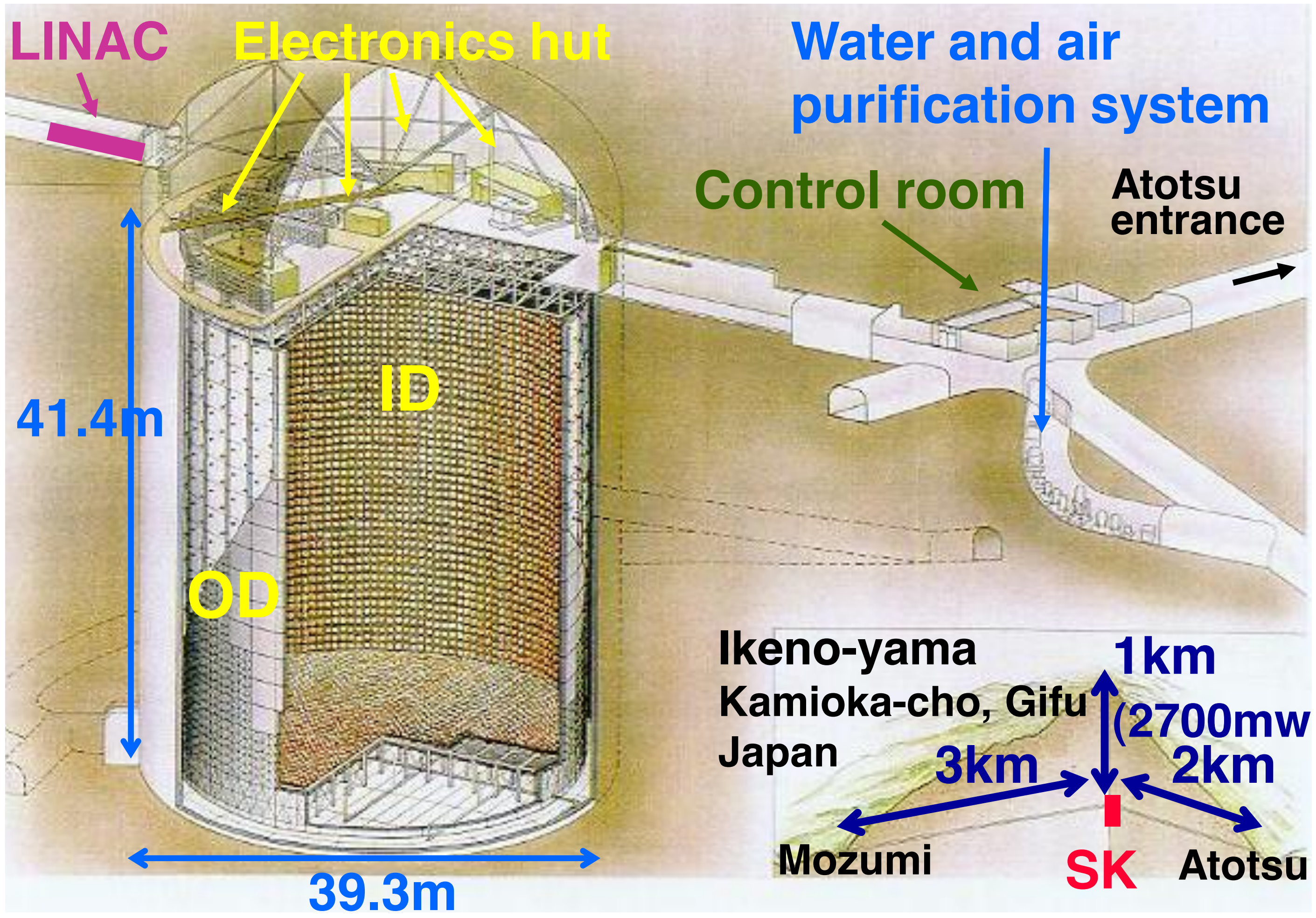


After analysis



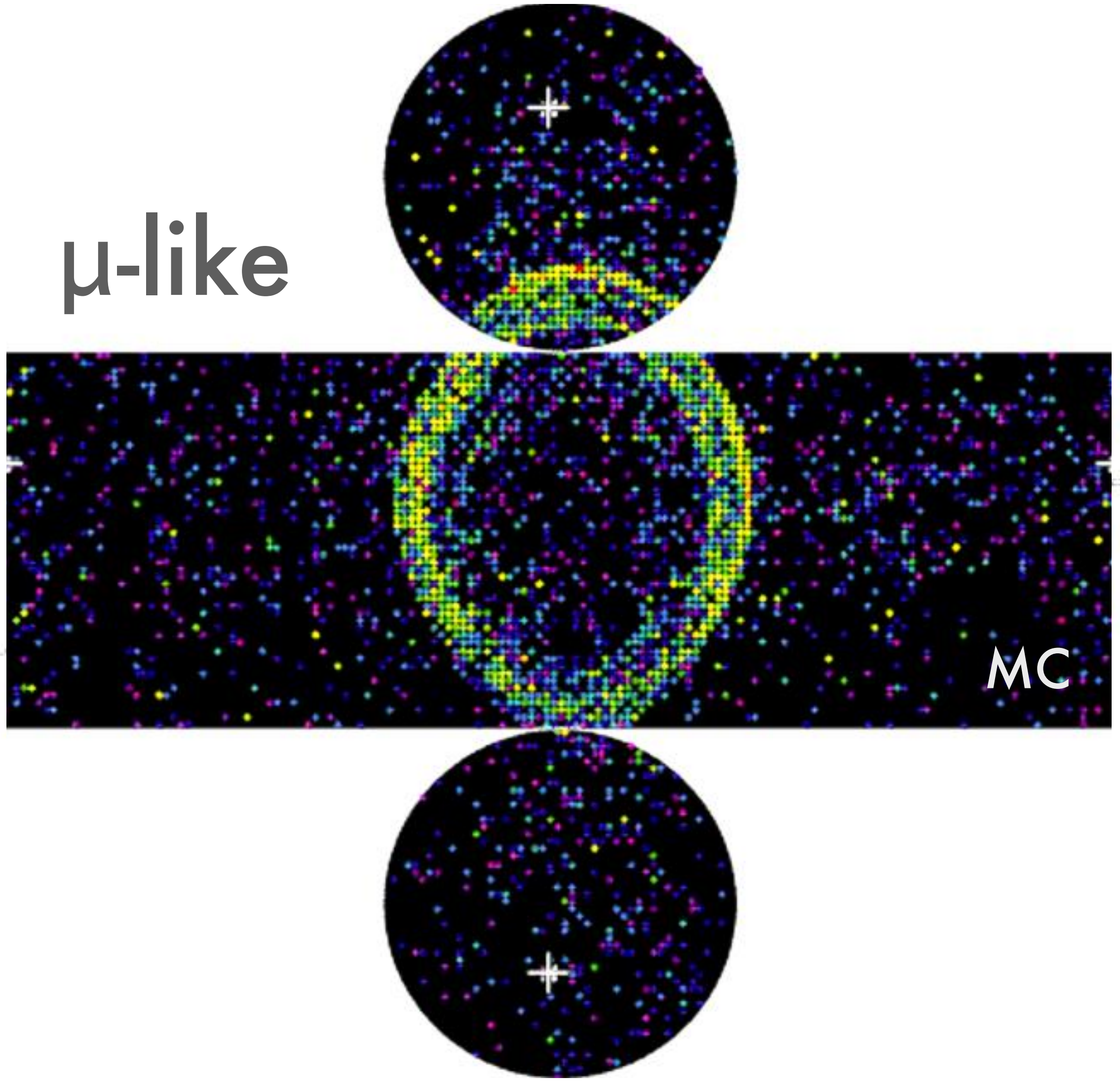
- Clear that data is in better agreement after the analysis
- Multinucleon component of distribution is noticeably increased

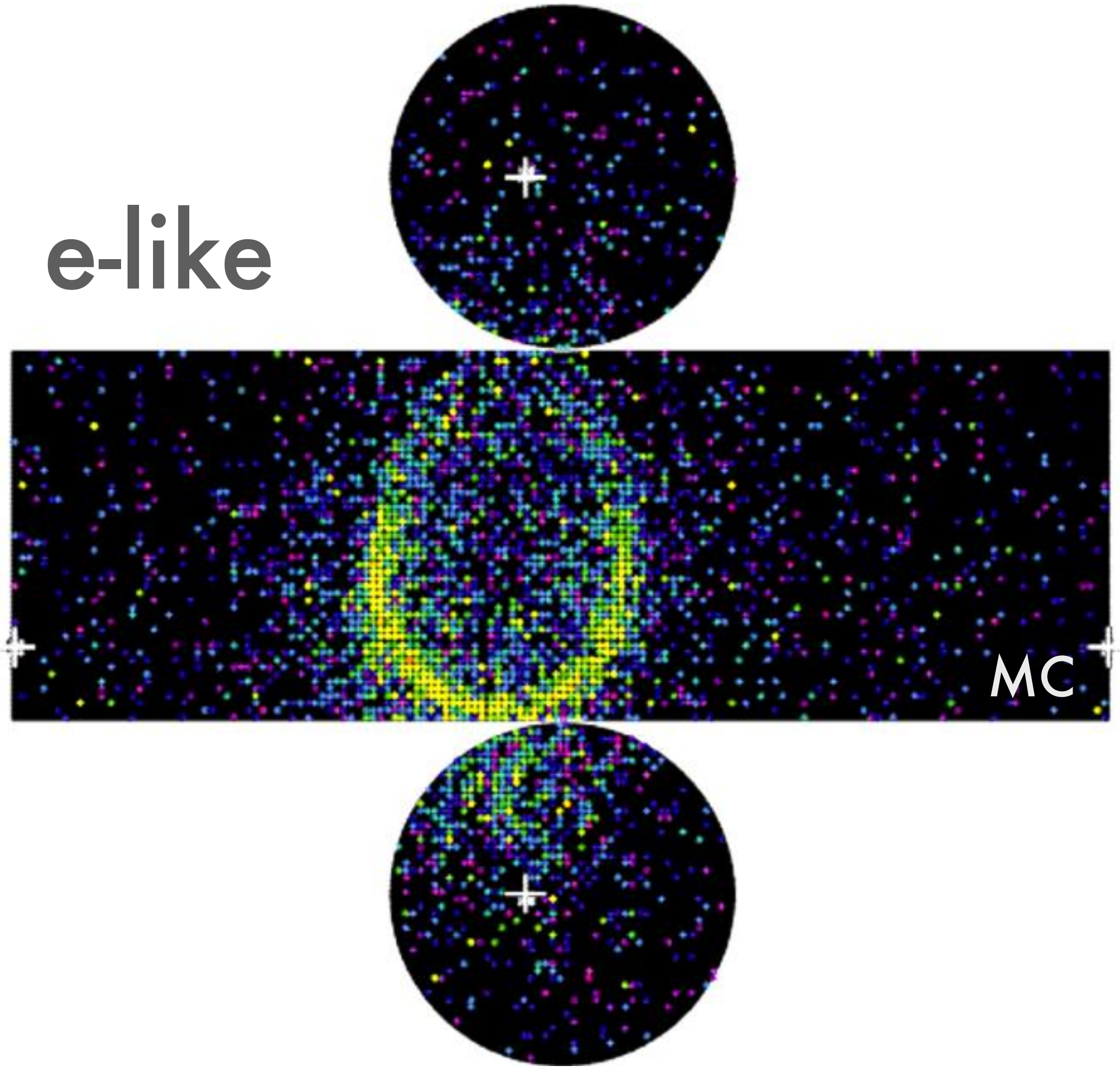
Super-Kamiokande



- 50 kton (22.5 kton fiducial volume) water Cherenkov detector
- ~11,000 20" PMT for inner detector (ID) (40% photo coverage)
- ~2,000 outward facing 8" PMT for outer detector (OD): veto cosmics, radioactivity, exiting events

SK Particle Identification

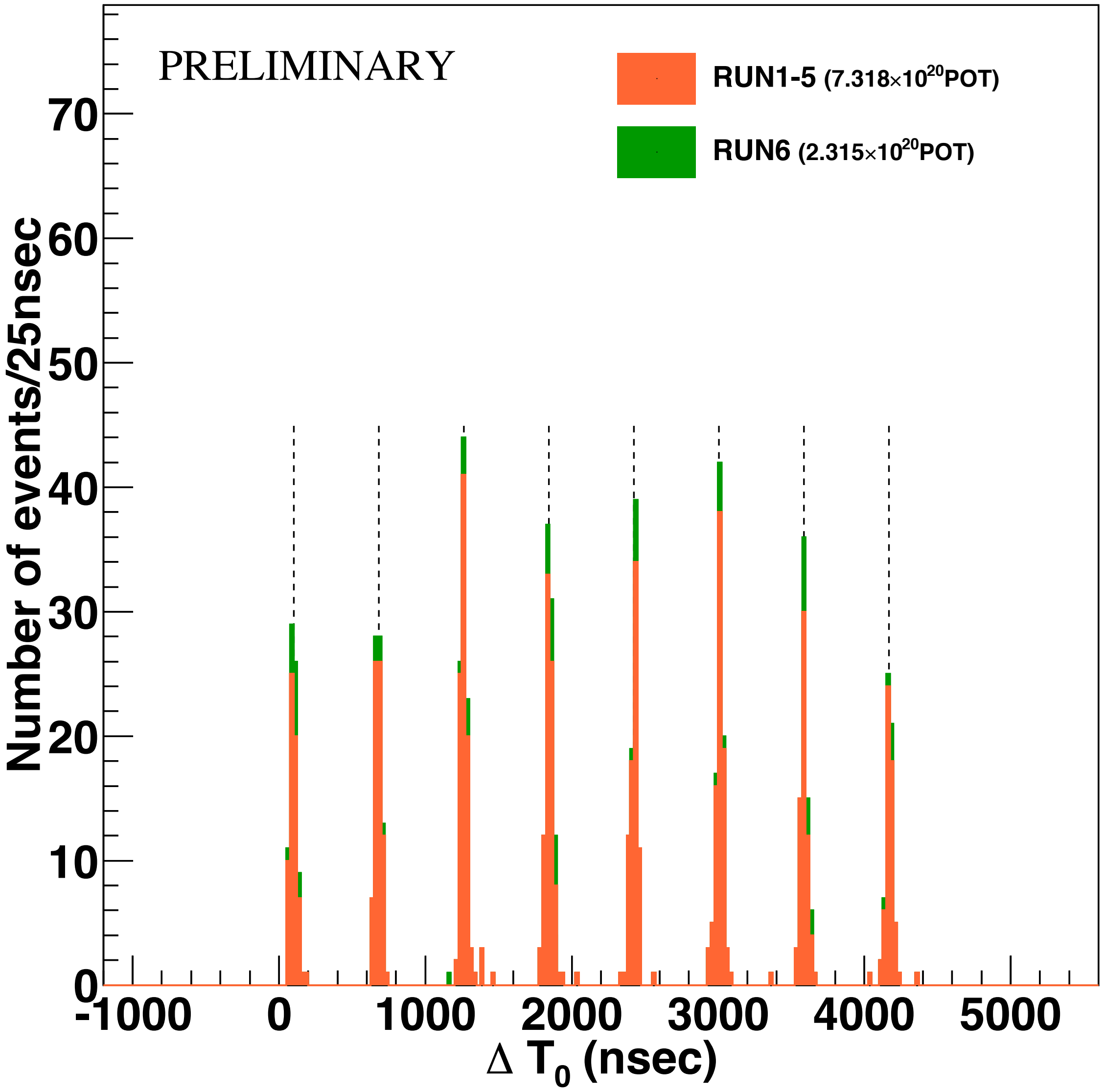




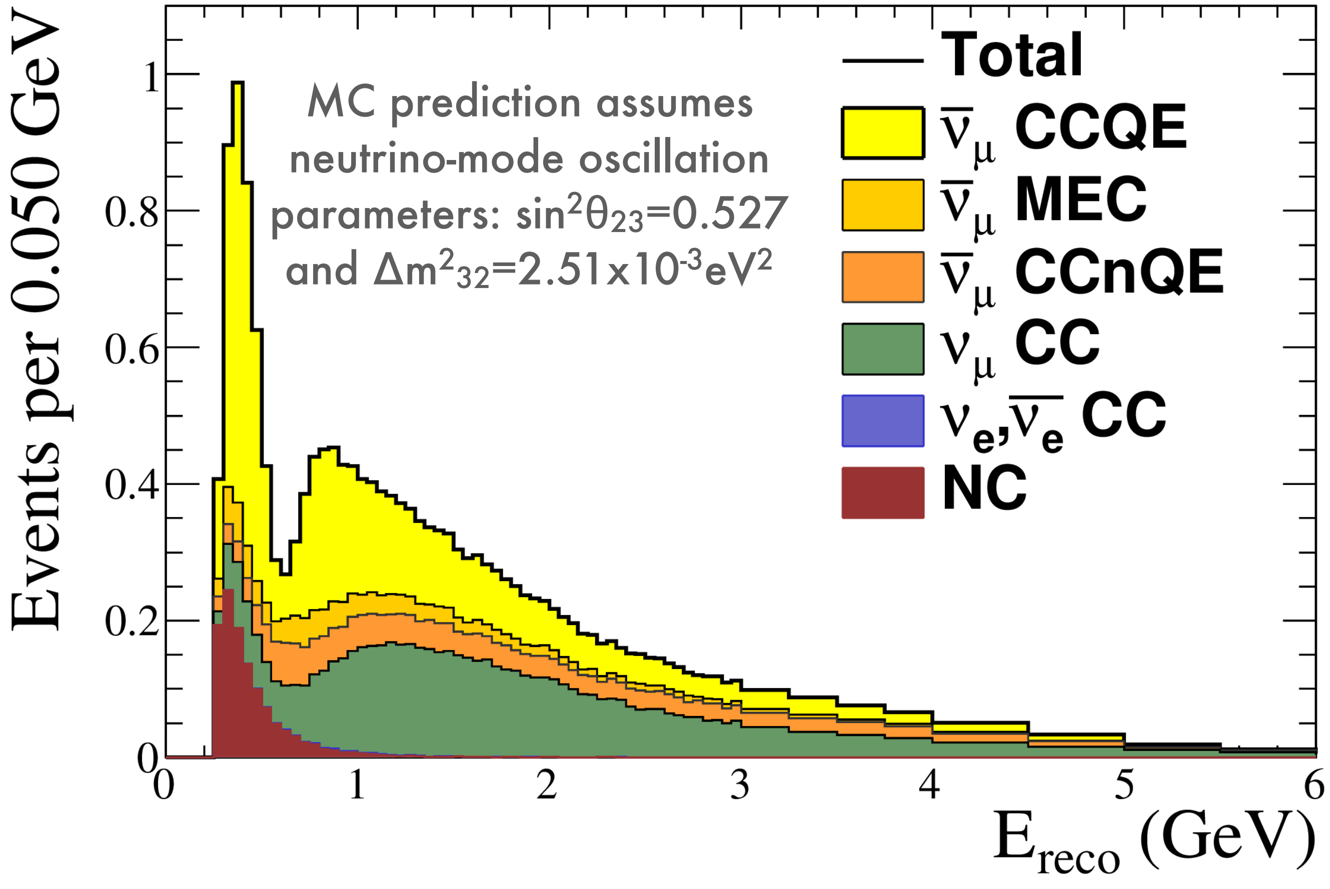
Choose rings which are sharp and clear

Beam Timing at SK

- Fully contained events in the SK fiducial volume appear in time with the T2K beam
- Both ν-mode and $\bar{\nu}$-mode events have good beam timing



Predicted SK Spectra

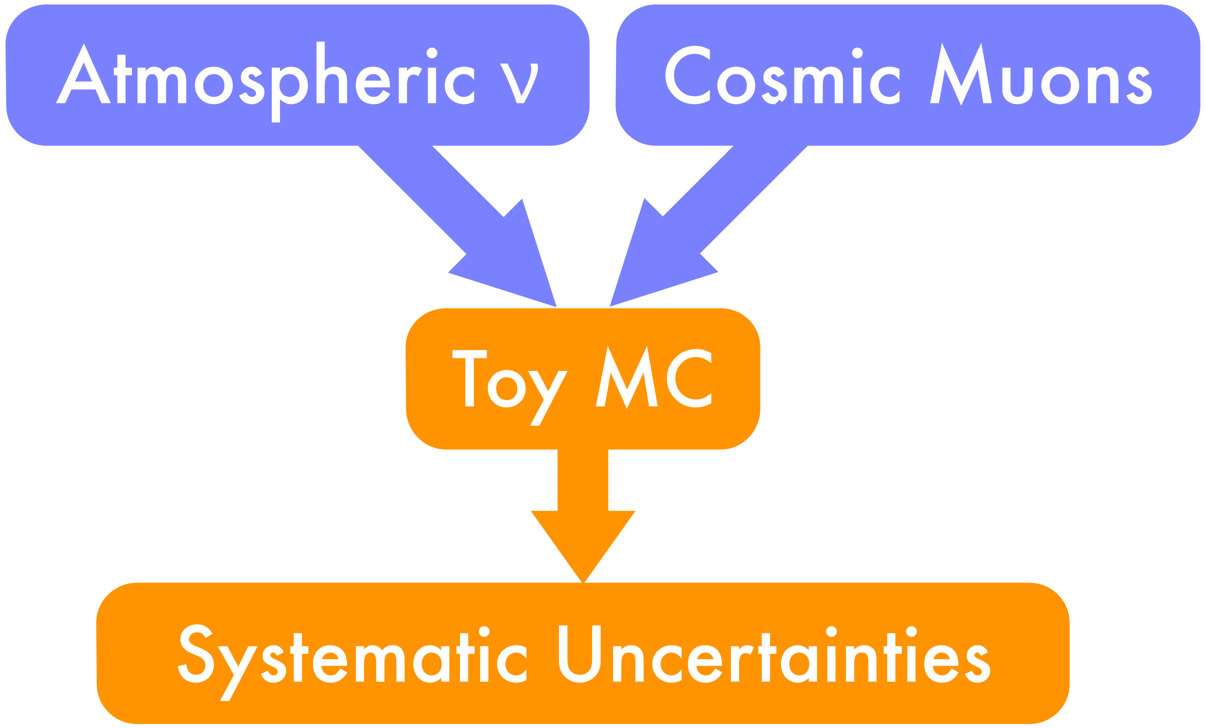


MC prediction assumes neutrino-mode oscillation parameters: $\sin^2\theta_{23}=0.527$ and $\Delta m^2_{32}=2.51\times10^{-3}\text{eV}^2$

1. Fully contained within the fiducial volume of SK
2. Have one and only one reconstructed ring
3. Have μ-like PID
4. Have muon momentum >200 MeV/c
5. Have one or fewer decay electron

- Predict the expected spectrum at SK using neutrino-mode oscillation parameters
- Dominated by $\overline{\nu}$ CCQE events, but many other contributions—this is why cross section model is so important
- Predict 19.9 events with oscillation and 59.8 without oscillation

SK Detector Systematics

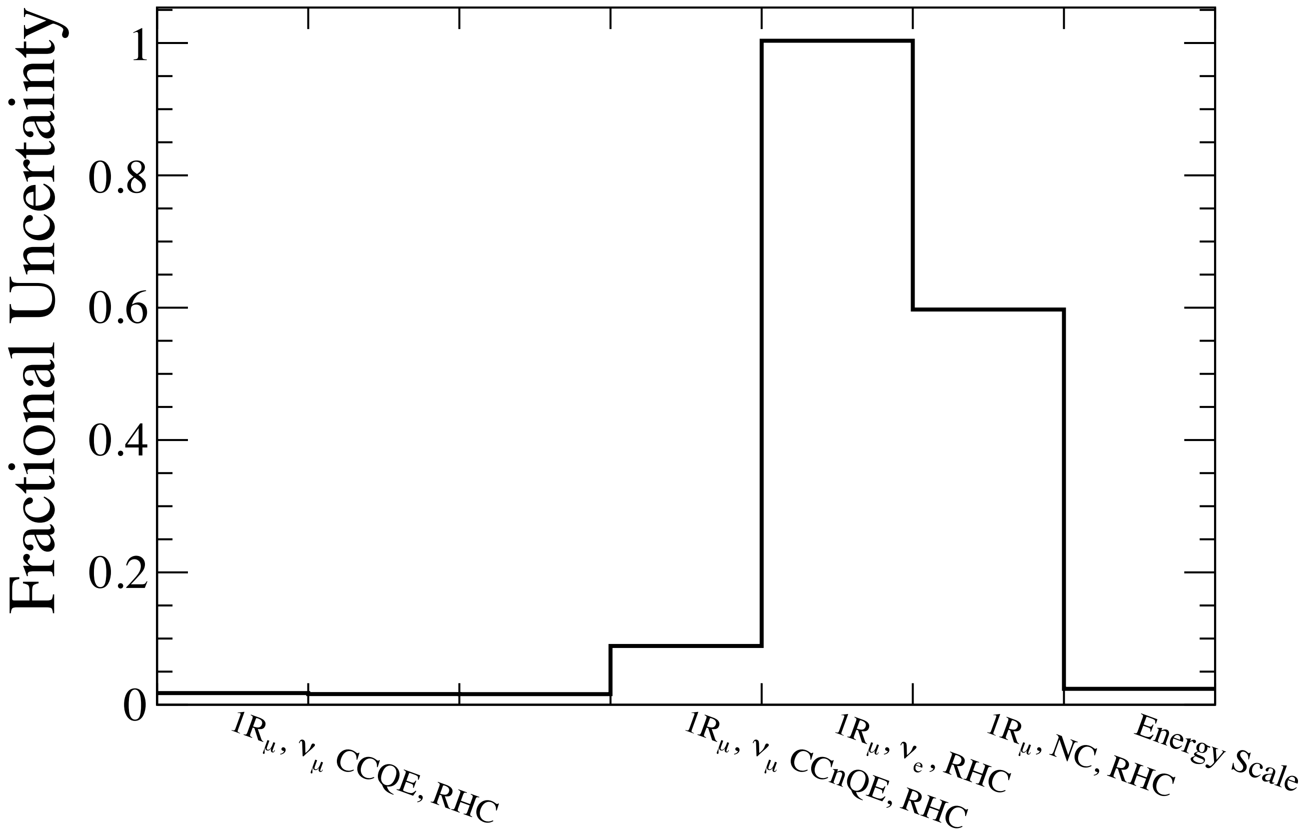


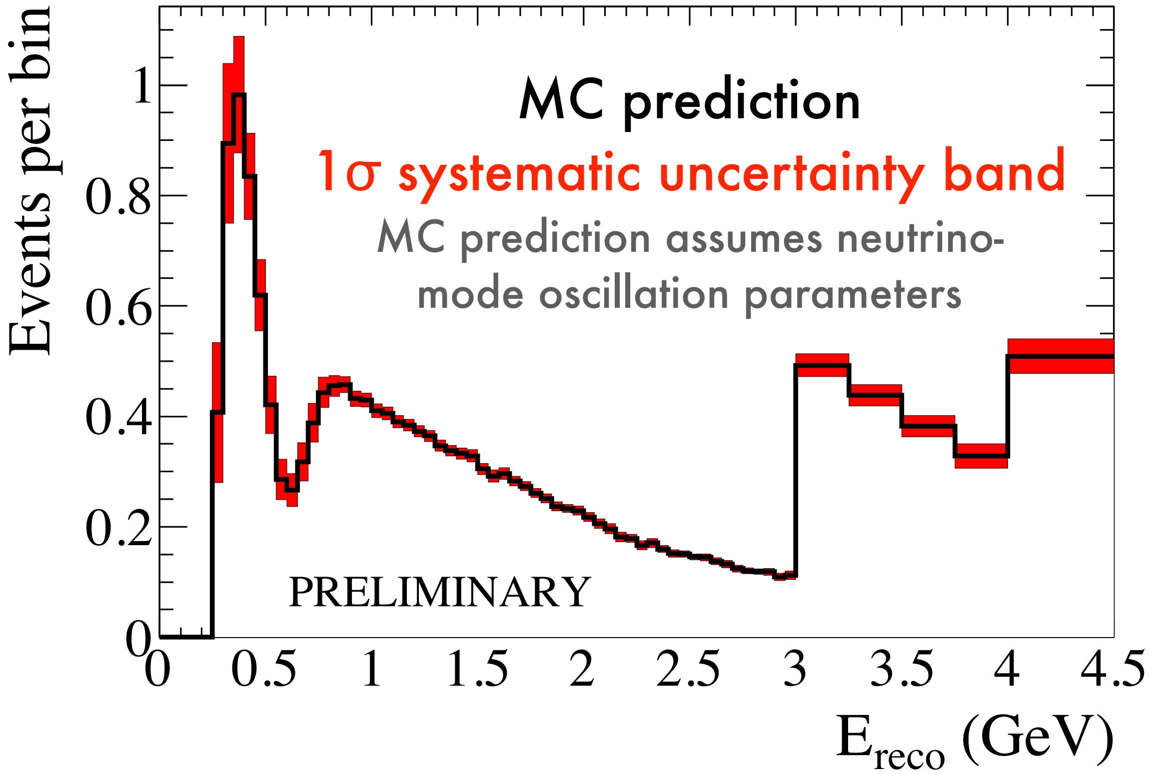
Atmospheric ν

Cosmic Muons

Toy MC

Systematic Uncertainties



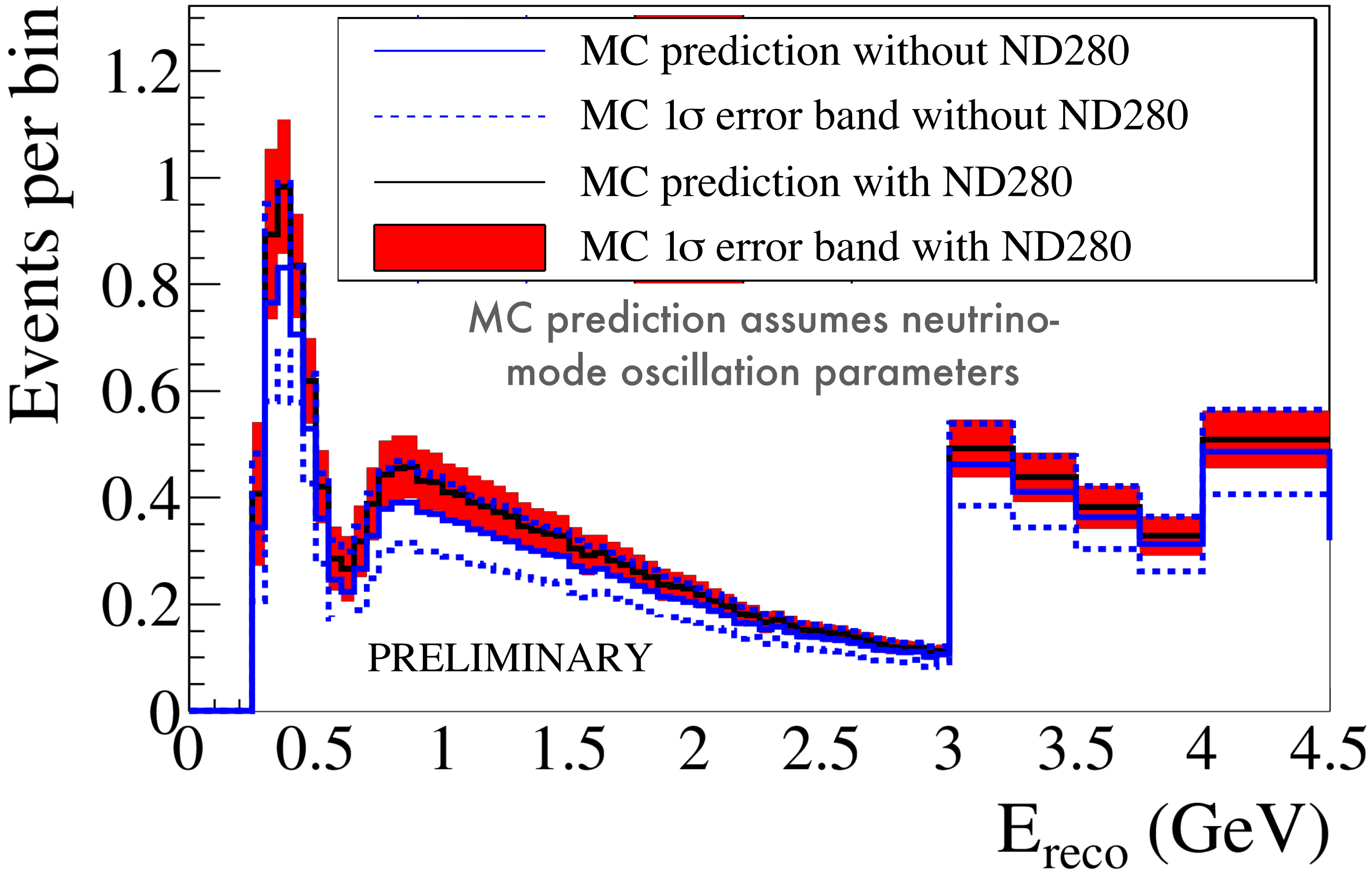


- ν_e uncertainty is largest—but these events are rare
- Neutral current uncertainty dominates at low energy
- Effects are small elsewhere

Imperial College London

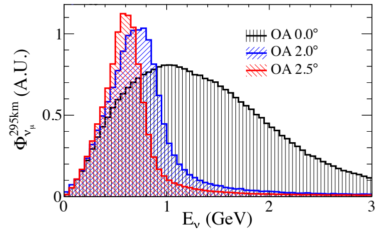
Total Systematic Uncertainties

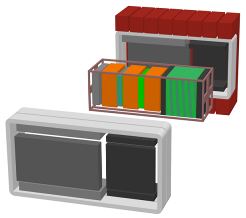
Flux and cross section uncertainties are dominated by uncertainties on the difference between interactions on C and O

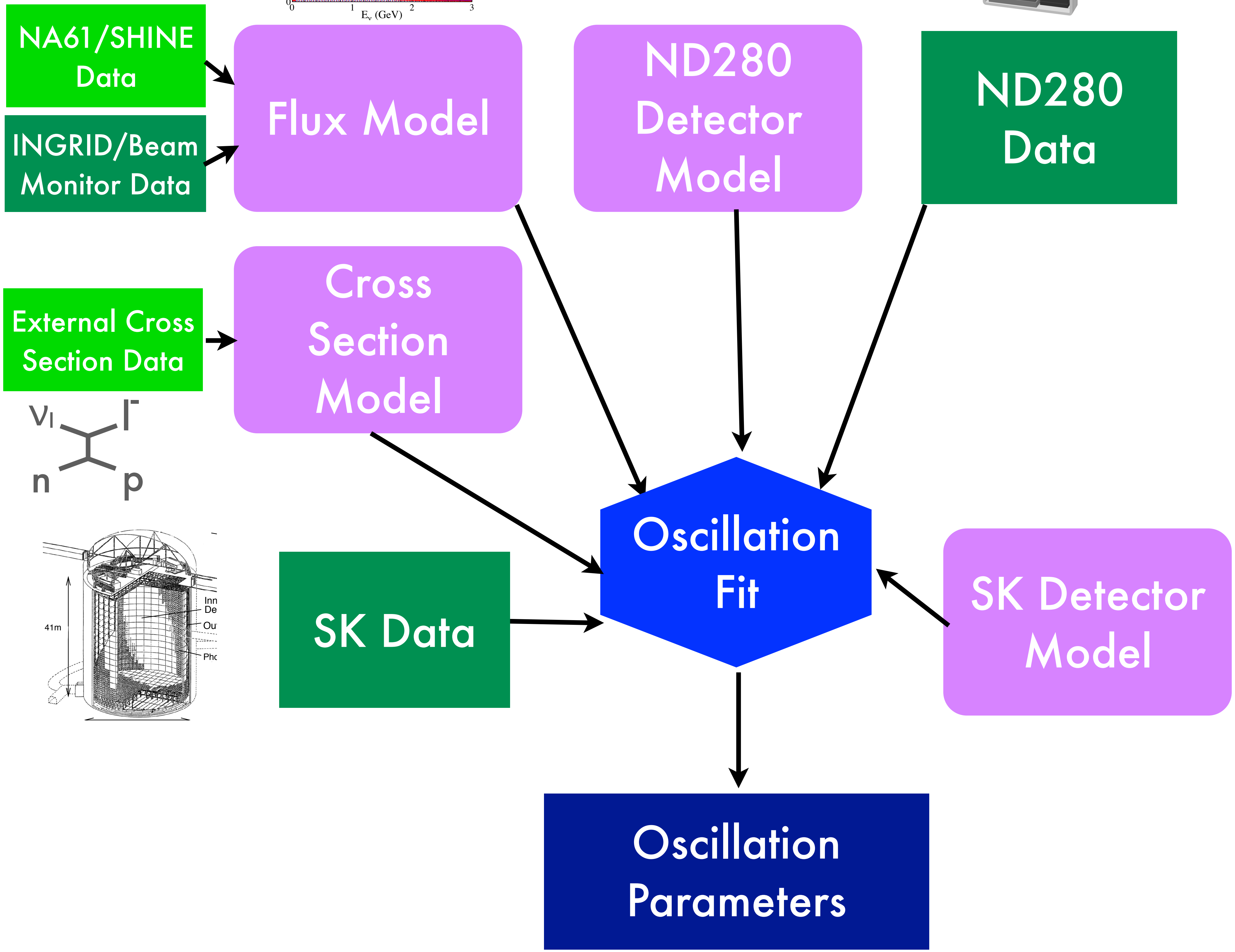


MC prediction assumes neutrino-mode oscillation parameters

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







NA61/SHINE Data

INGRID/Beam Monitor Data

Flux Model

ND280 Detector Model

ND280 Data

External Cross Section Data

Cross Section Model

SK Data

Oscillation Fit

SK Detector Model

Oscillation Parameters

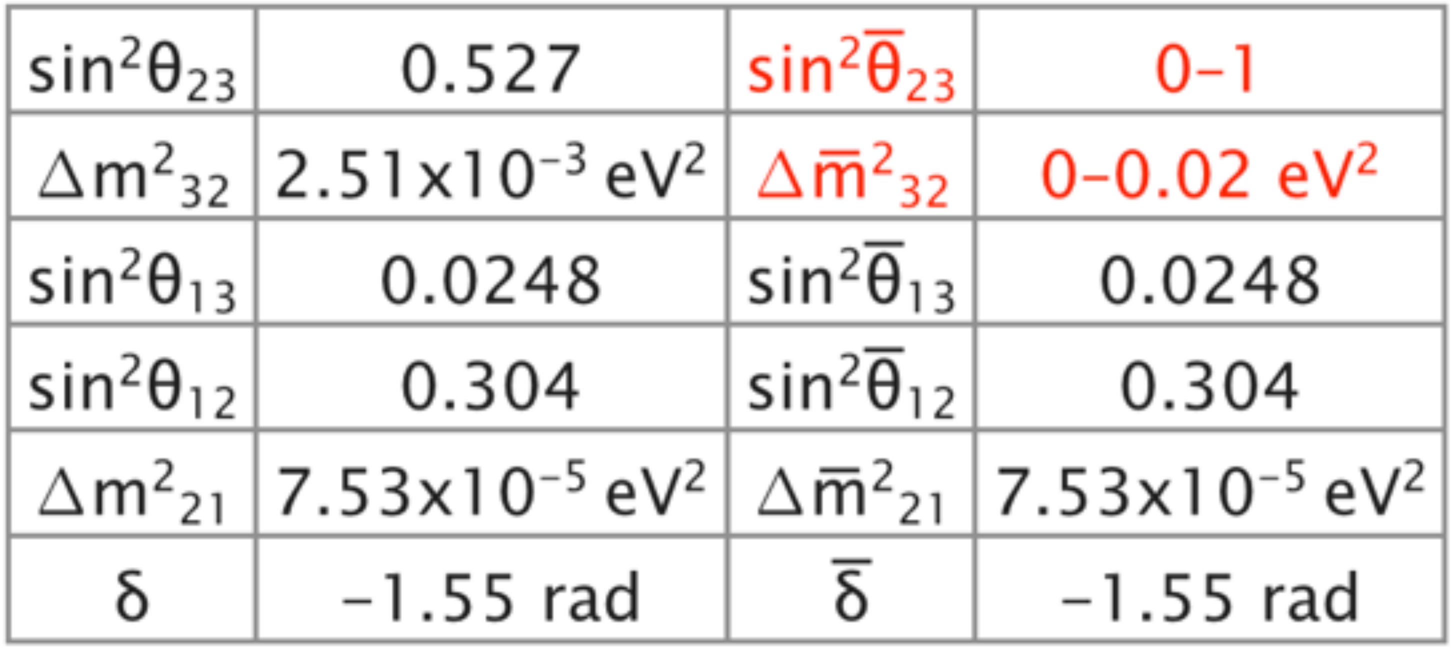
Analysis Method

$$\mathcal{L} = \mathcal{L}_{\mathrm{Poisson}} \times \mathcal{L}_{\mathrm{Syst}}$$

Maximize a likelihood which is the product of a Poisson term comparing the predicted spectrum to the data and a term incorporating the systematics

Data is binned in reconstructed neutrino energy

Fix all oscillation parameters except $\sin^2\bar{\theta}_{23}$ and $\Delta\bar{m}^2_{32}$ using T2K neutrino data and PDG 2014

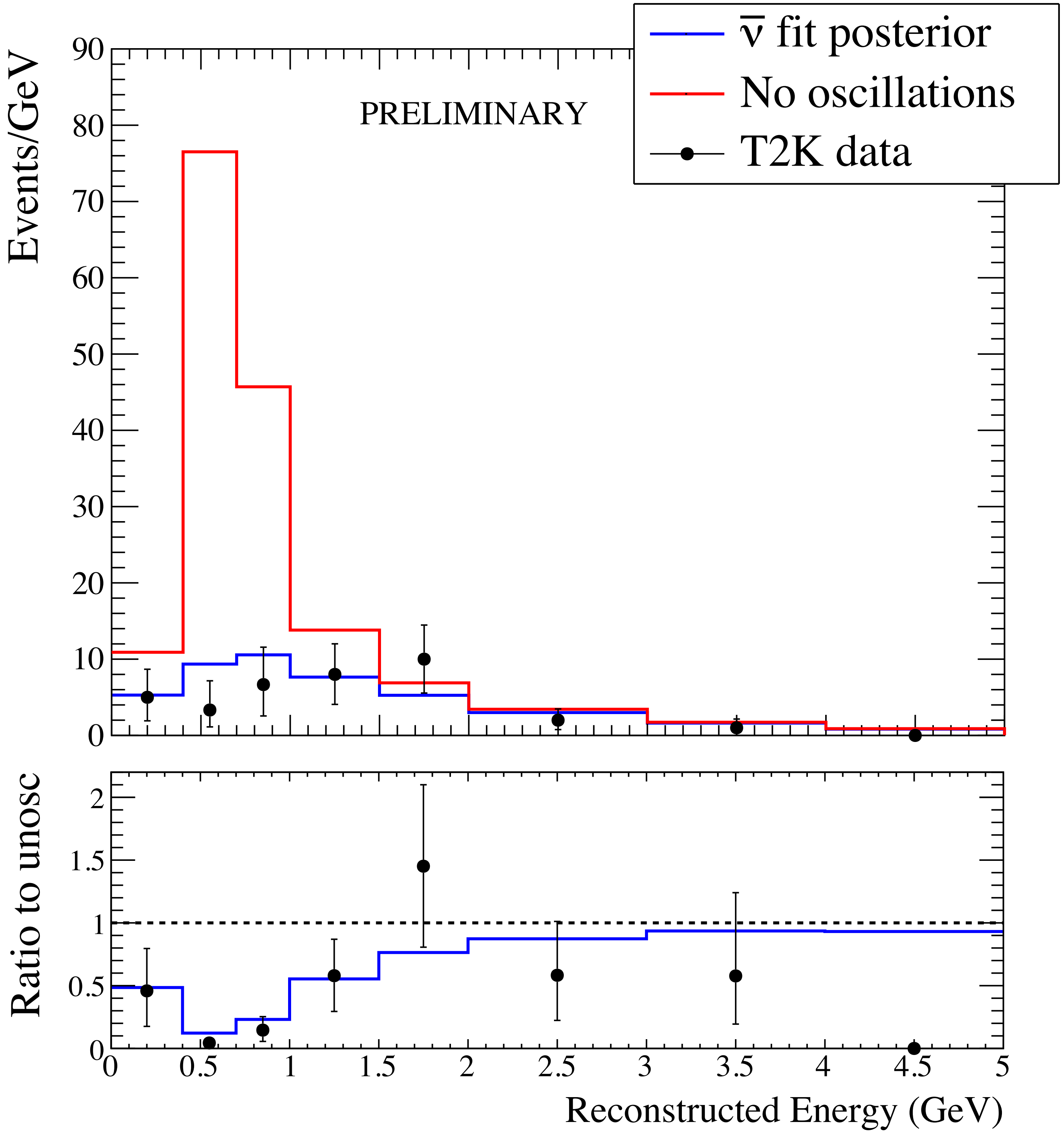


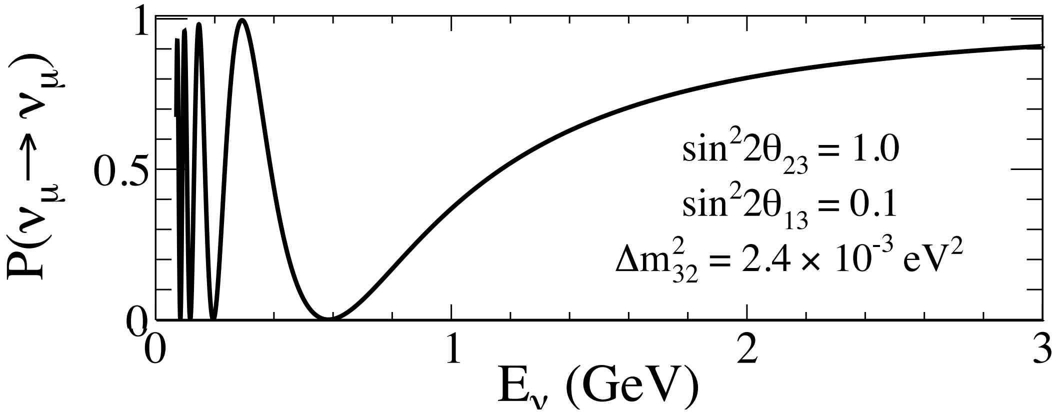
$\sin^2\theta_{23}$	0.527	$\sin^2\bar{\theta}_{23}$	0–1
Δm^2_{32}	2.51×10^{-3} eV^2	$\Delta\bar{m}^2_{32}$	0–0.02 eV^2
$\sin^2\theta_{13}$	0.0248	$\sin^2\bar{\theta}_{13}$	0.0248
$\sin^2\theta_{12}$	0.304	$\sin^2\bar{\theta}_{12}$	0.304
Δm^2_{21}	7.53×10^{-5} eV^2	$\Delta\bar{m}^2_{21}$	7.53×10^{-5}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

Results!

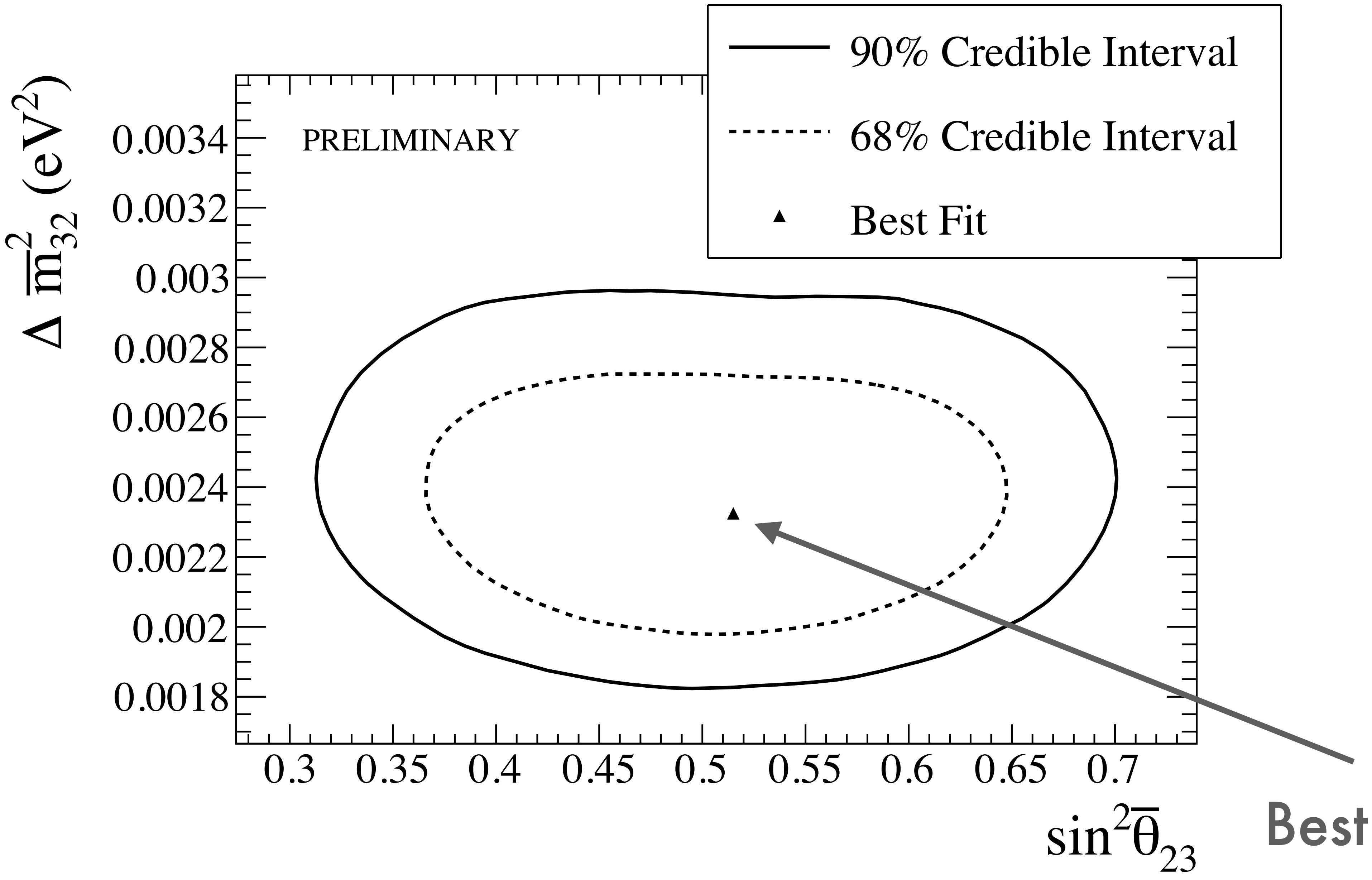
Best Fit Spectrum

- Data show clear evidence of oscillation
- Clear, visible oscillation "dip" in the data





Oscillation Parameters



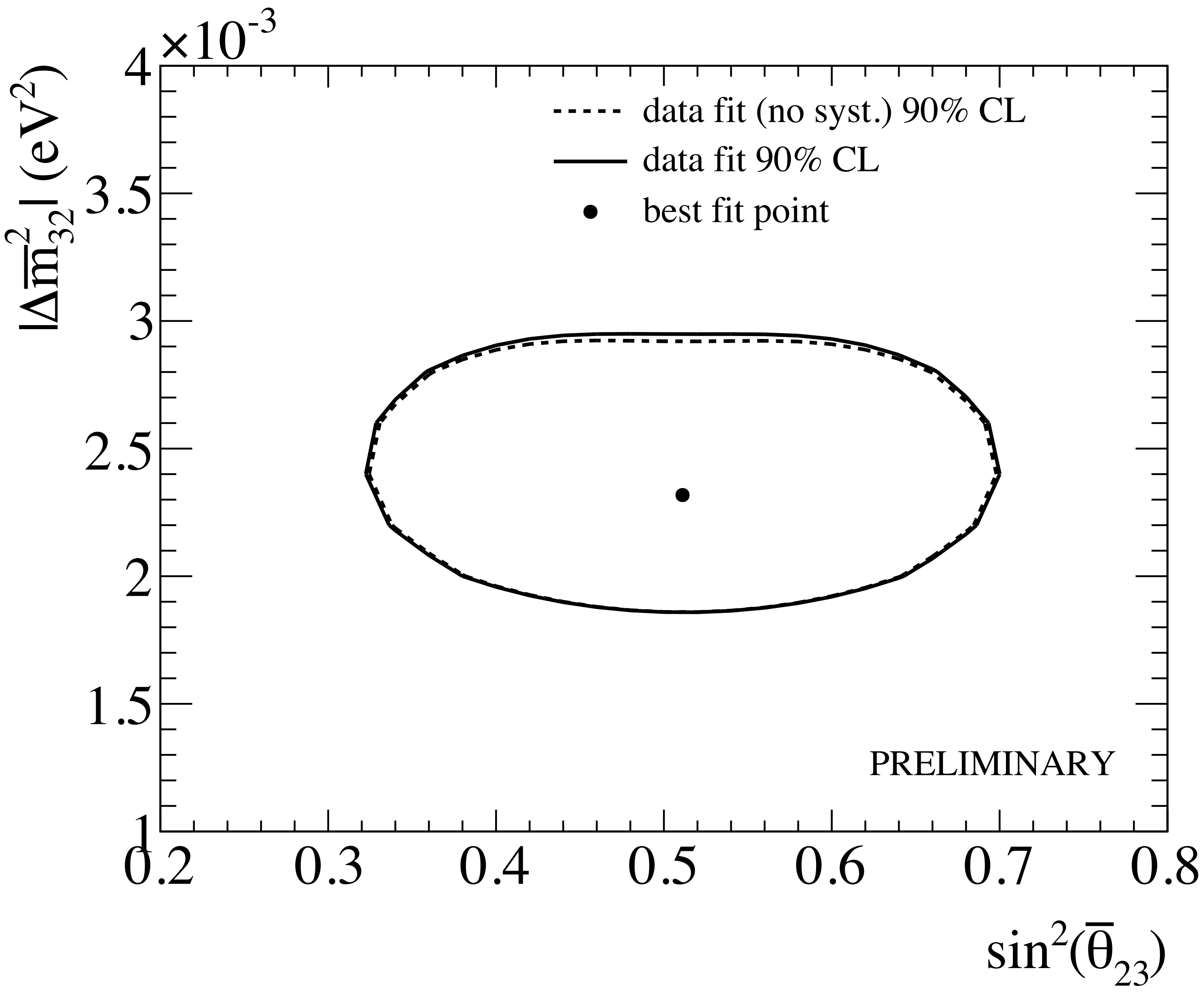
$\lvert\Delta\bar{m}^2_{32}\rvert$	$\sin^2(\bar{\theta}_{23})$
$2.33^{+0.27}_{-0.23} \times 10^{-3}$ eV^2	$0.515^{+0.085}_{-0.095}$

Best fit is near maximal disappearance

Imperial College London

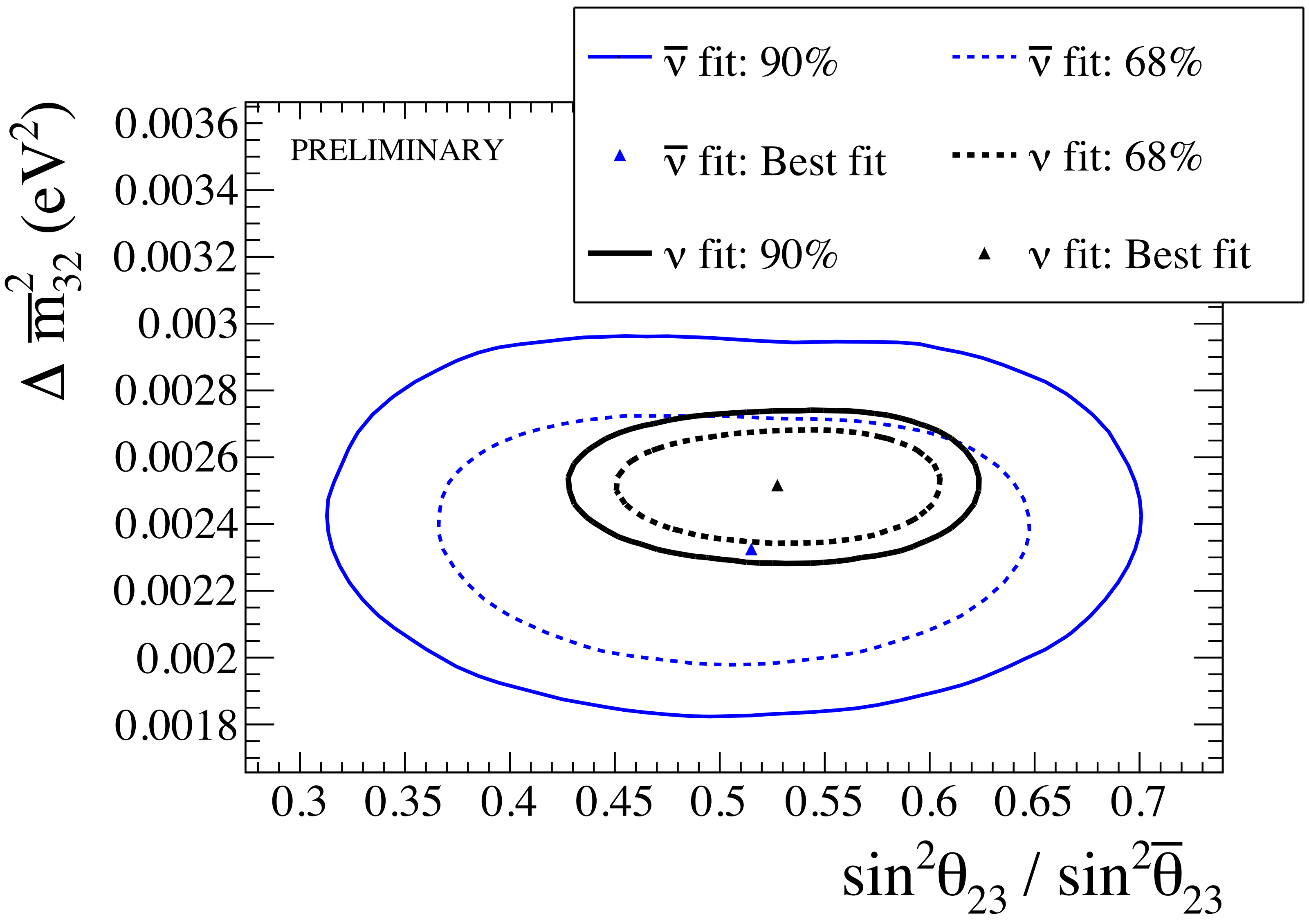
Impact of Systematic Uncertainty

- Fitting without including systematic uncertainties produces nearly identical contours
- This analysis is statistics dominated



Imperial College London

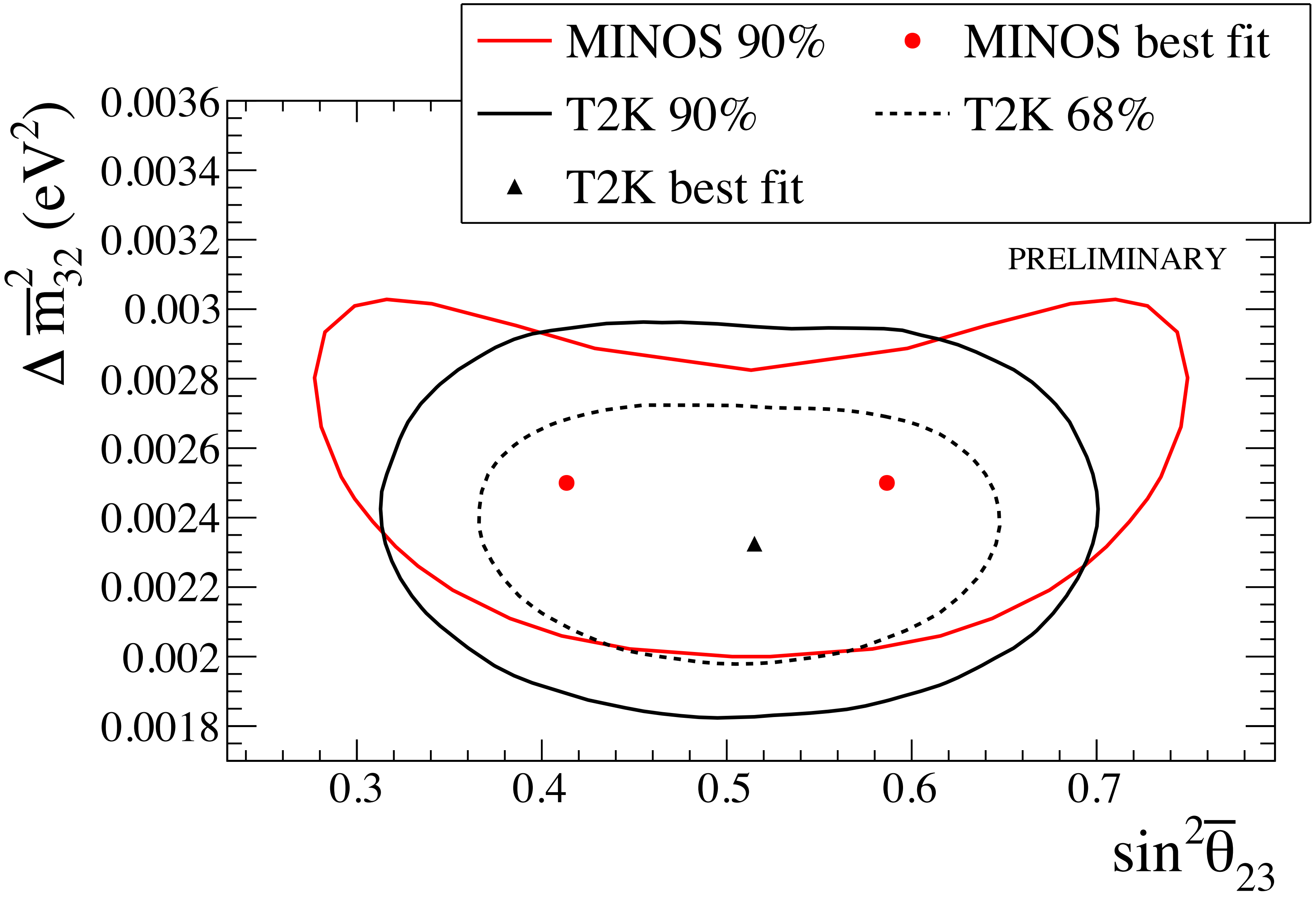
Comparison to Neutrino Results



- Antineutrino analysis has much larger contours than neutrino analysis
- Two analyses are consistent with no difference between neutrinos and antineutrinos

Comparison to MINOS

- T2K contours are smaller in $\sin^2\bar{\theta}_{23}$, though MINOS saw a non-maximal best fit point
- Results are completely compatible



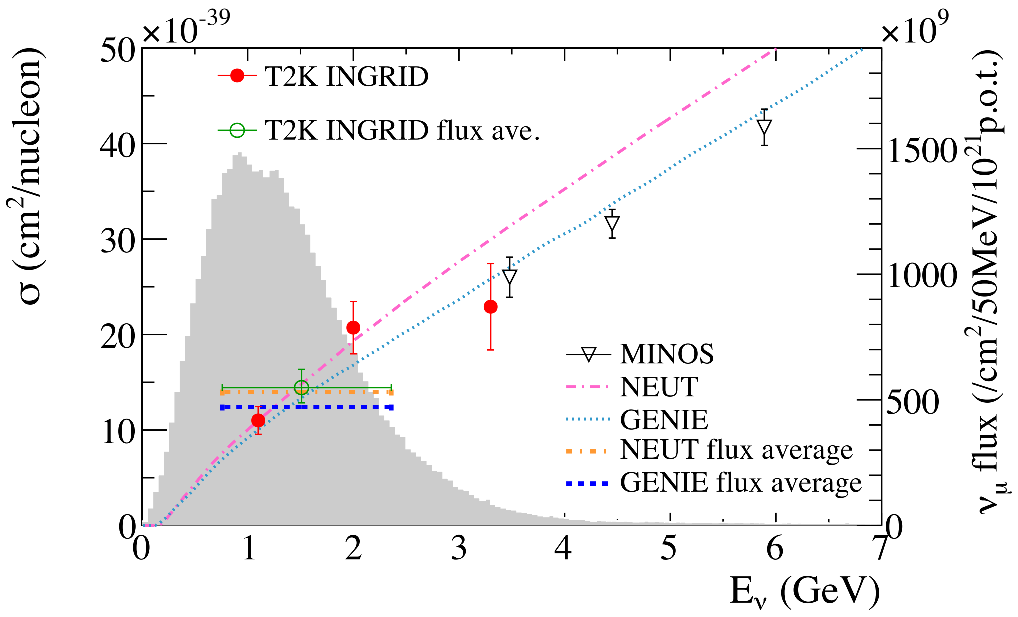
MINOS data is beam and cosmic combined

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

Future Work

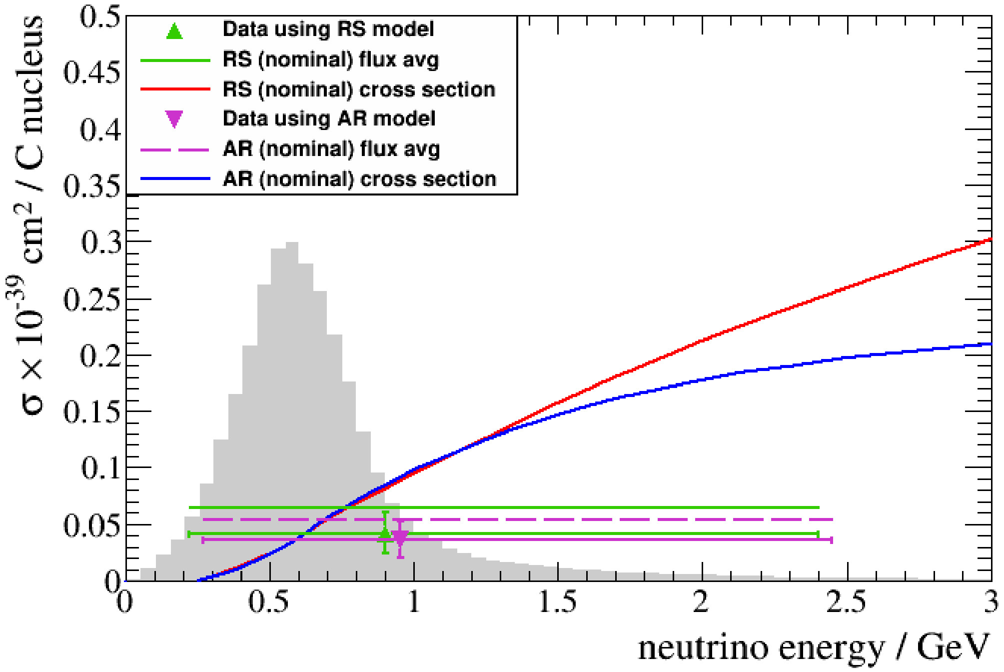
- Anti-neutrino running is ongoing– POT at the end of May is 4.0×10^{20}, nearly twice as large as this dataset
- Anti-neutrino analysis of $\overline{\nu}_e$ appearance is underway
- Expect to release these results in late summer

Other T2K results



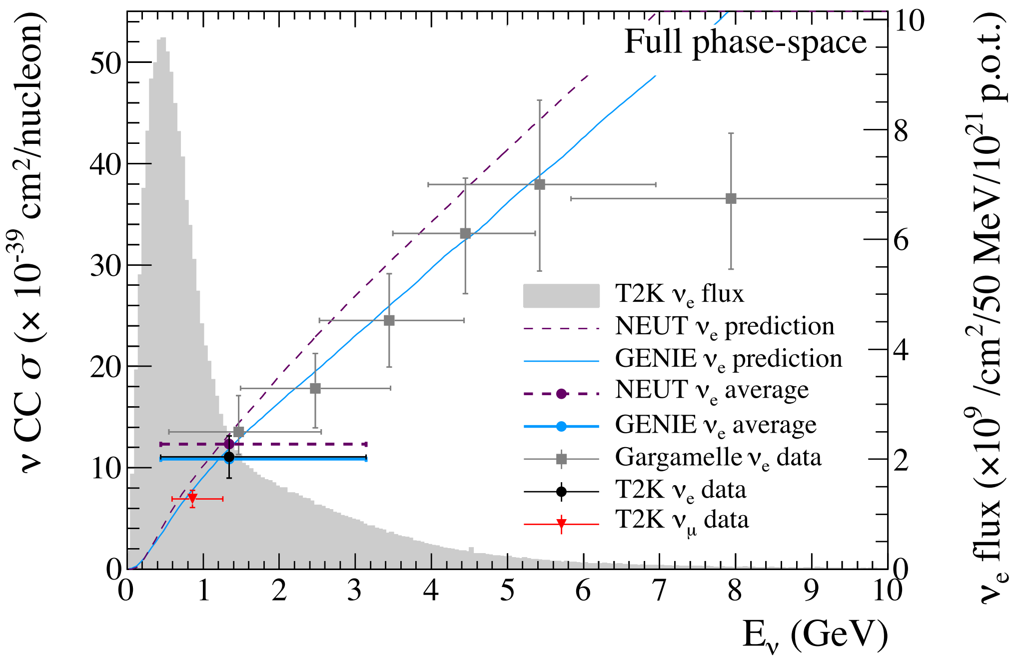
Cross section measurements at INGRID

Phys. Rev. Lett. 113, 241803 (2014)

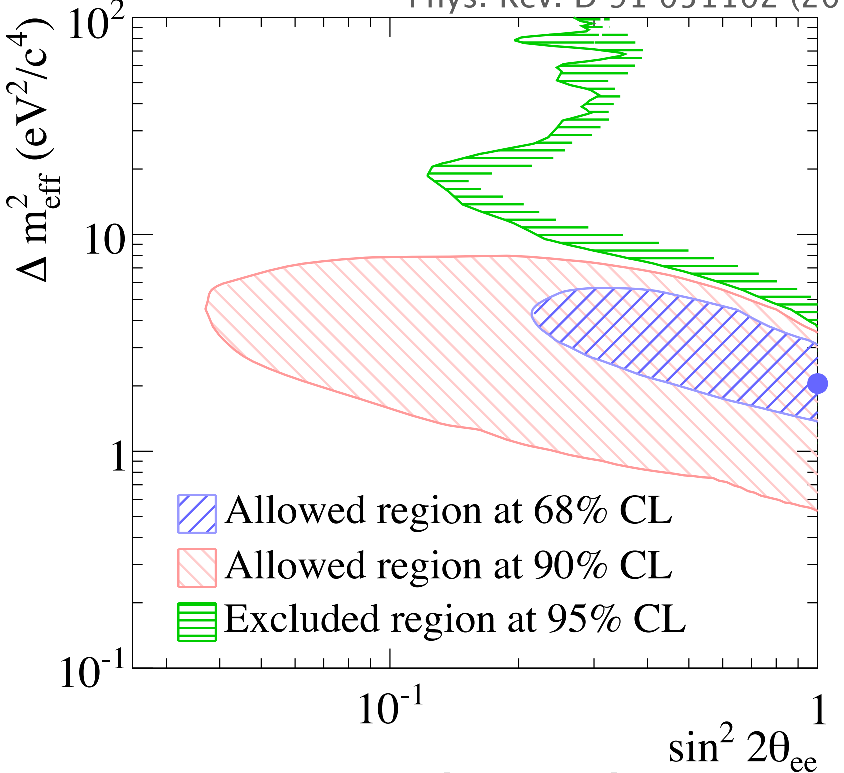


Charged current coherent cross sections at ND280

Phys. Rev. D 91 051102 (2015)



ν_e cross section measurements at ND280



Sterile neutrino searches with ν_e

Conclusions

- T2K has performed its first analysis with anti-neutrino data
- In a study of muon anti-neutrino disappearance, T2K observes 17 events in the far detector and has set a world-leading limit on the $\bar{\theta}_{23}$ parameter—but we are limited by statistics!
- T2K continues to take data and more anti-neutrino results are coming soon!
- Thank you to RAL for hosting Emerald, which was used for most of the computing for this analysis!

Supplementary