First Antineutrino Oscillation Results from T2K

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for the T2K Collaboration

18 May 2015

Imperial College London

T2K

Outline

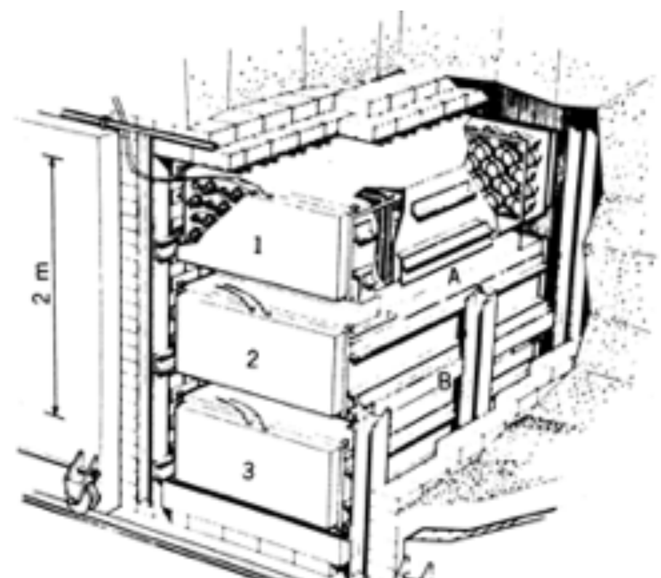
- Introduction to neutrino physics
- The T2K Experiment
- New results from anti-neutrino running

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



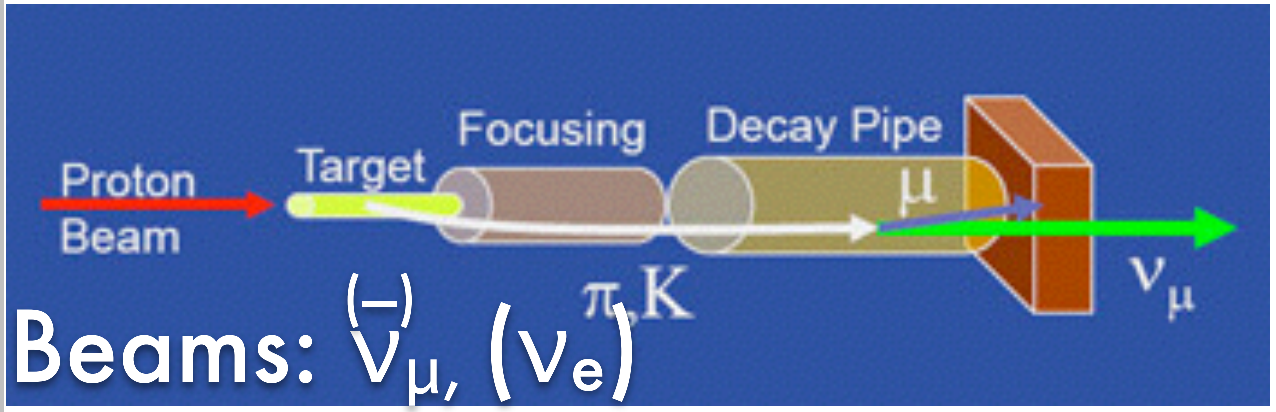
The experimental apparatus used by Reines and Cowan to detect the electron neutrino.

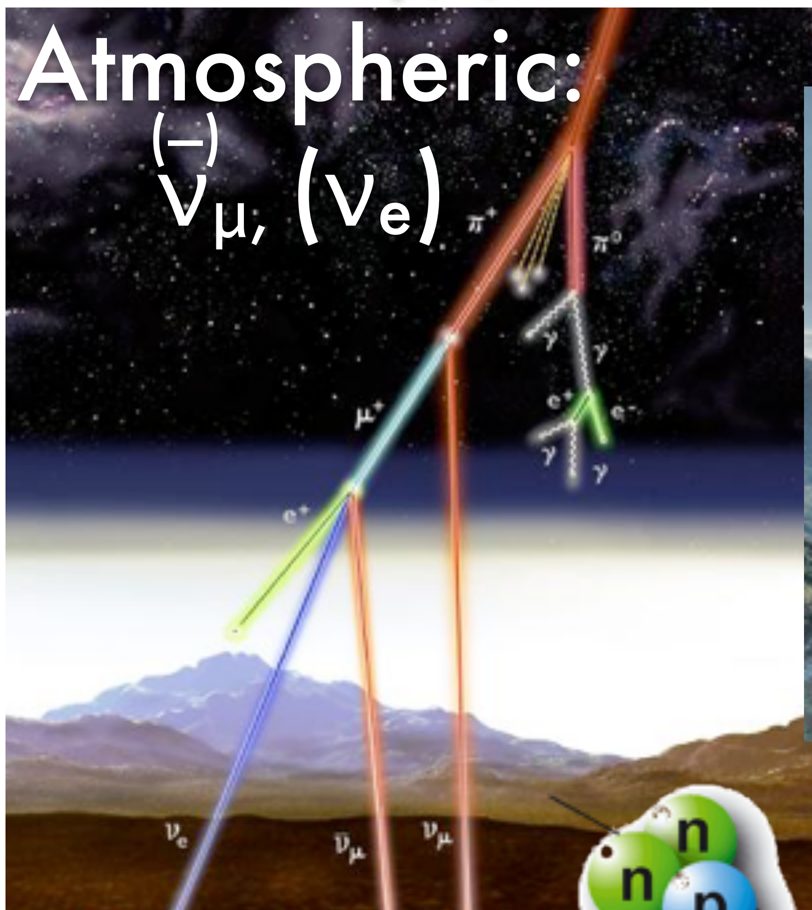
First detection by Reines and Cowen in 1956:

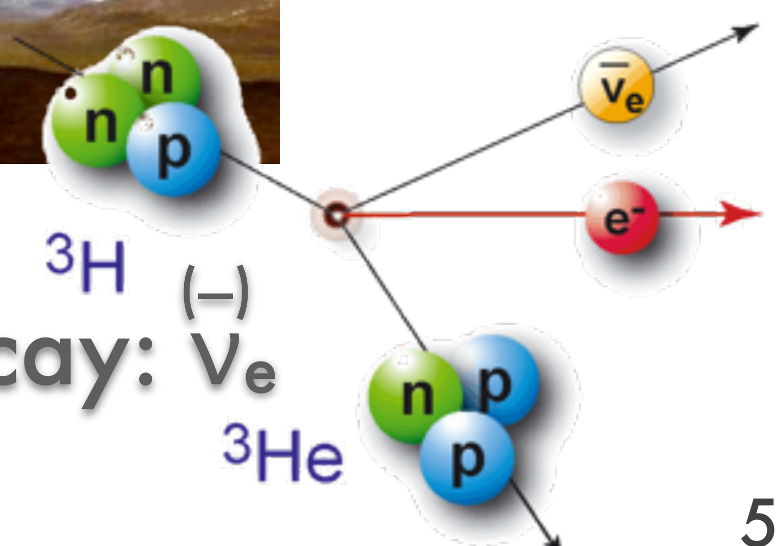
$\bar{\nu}_e + p \rightarrow n + e^+$

- Lightest particle in the standard model: <2.2 eV/c^2 (3.9x10^{-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







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

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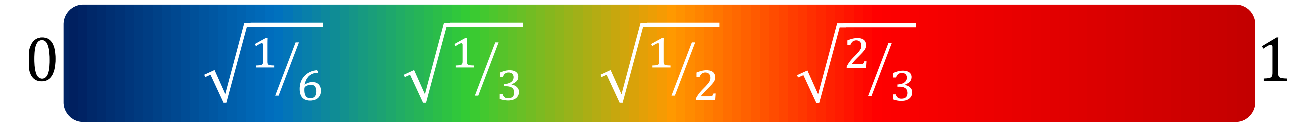
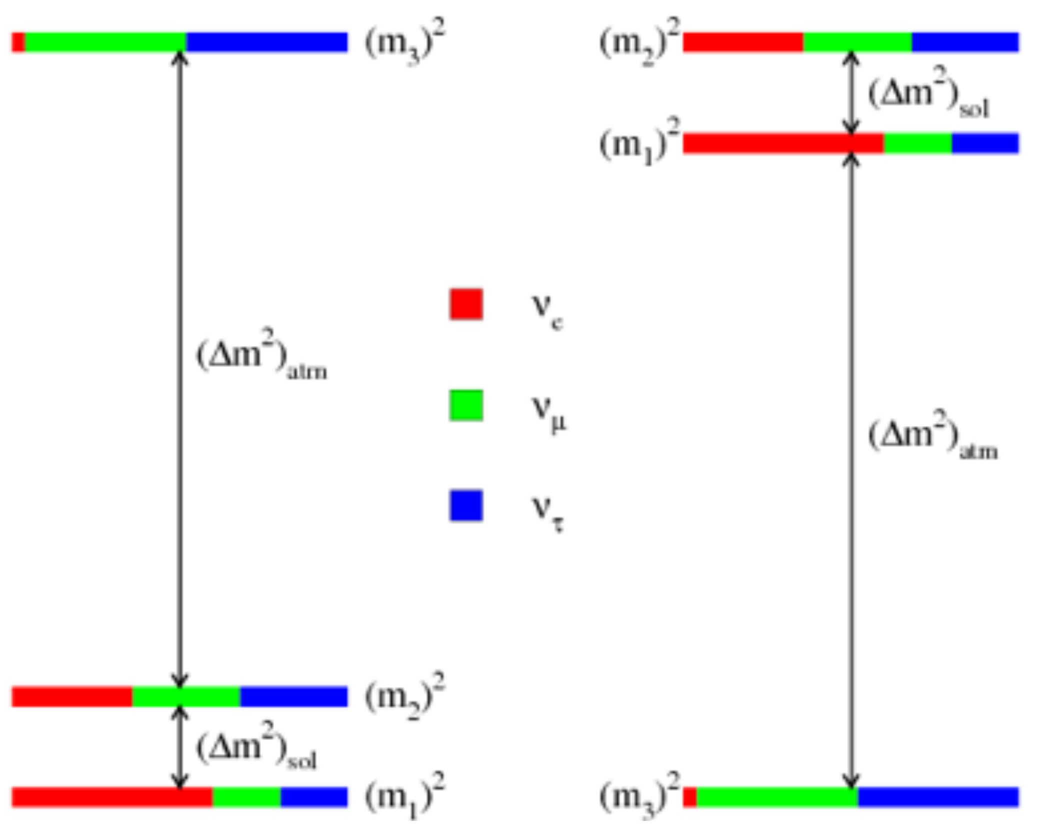
Neutrino Mixing

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

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





Normal Hierarchy Inverted Hierarchy

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

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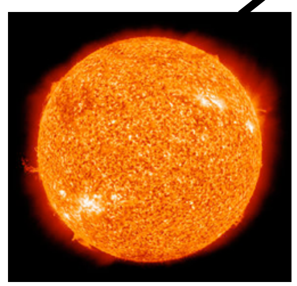
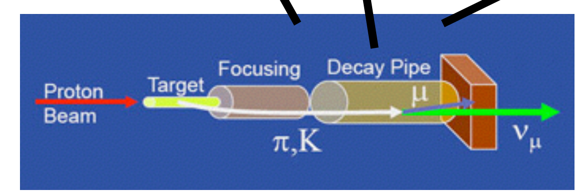
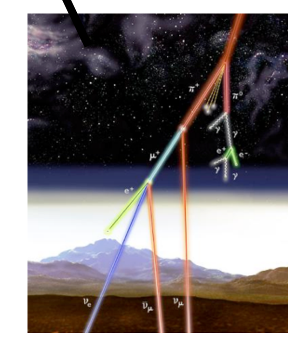
Neutrino Oscillation

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

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







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

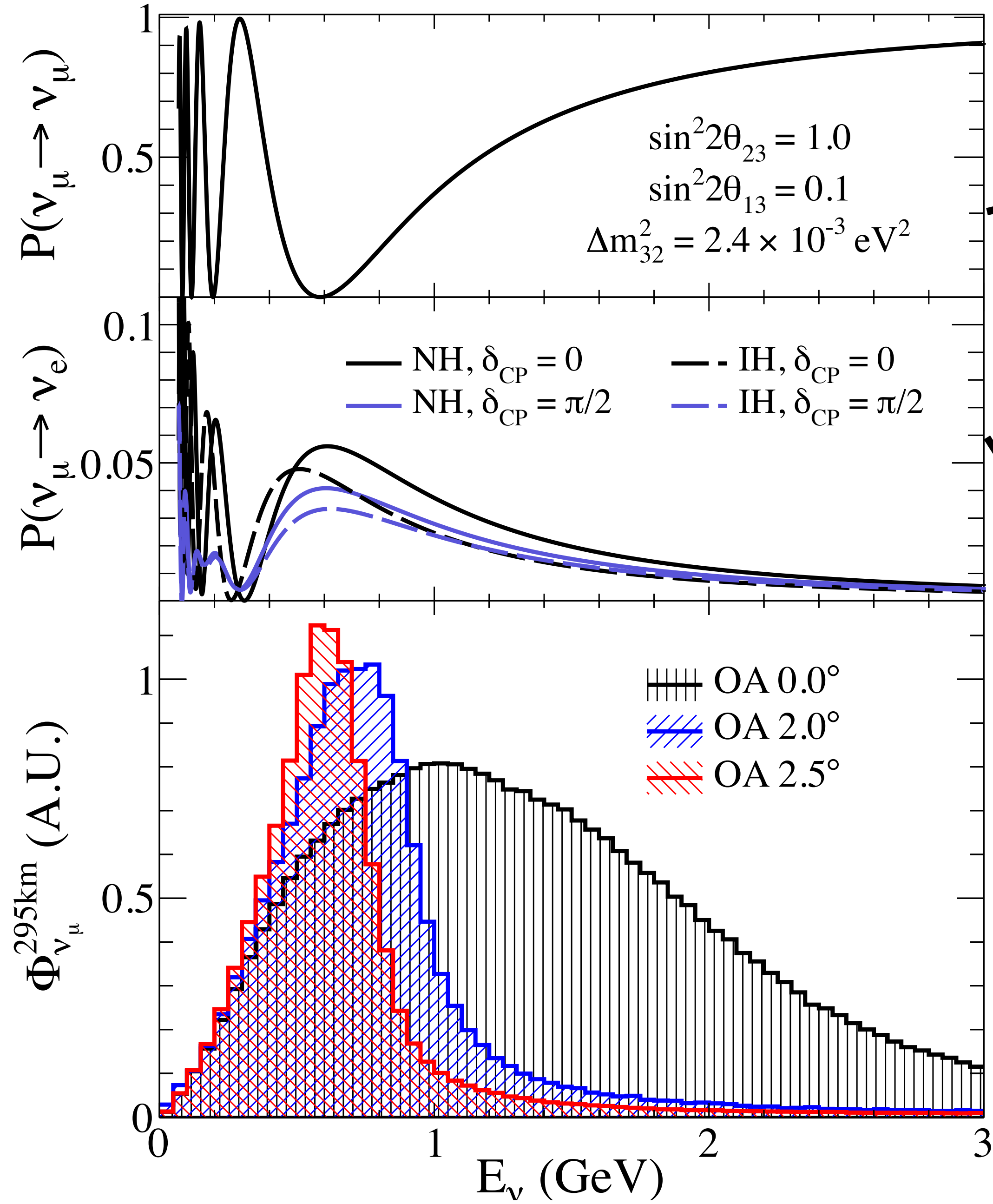
$\theta_{23}=45.8\pm3.2°$
$\theta_{12}=33.4\pm0.85°$
$\theta_{13}=8.88\pm0.39°$

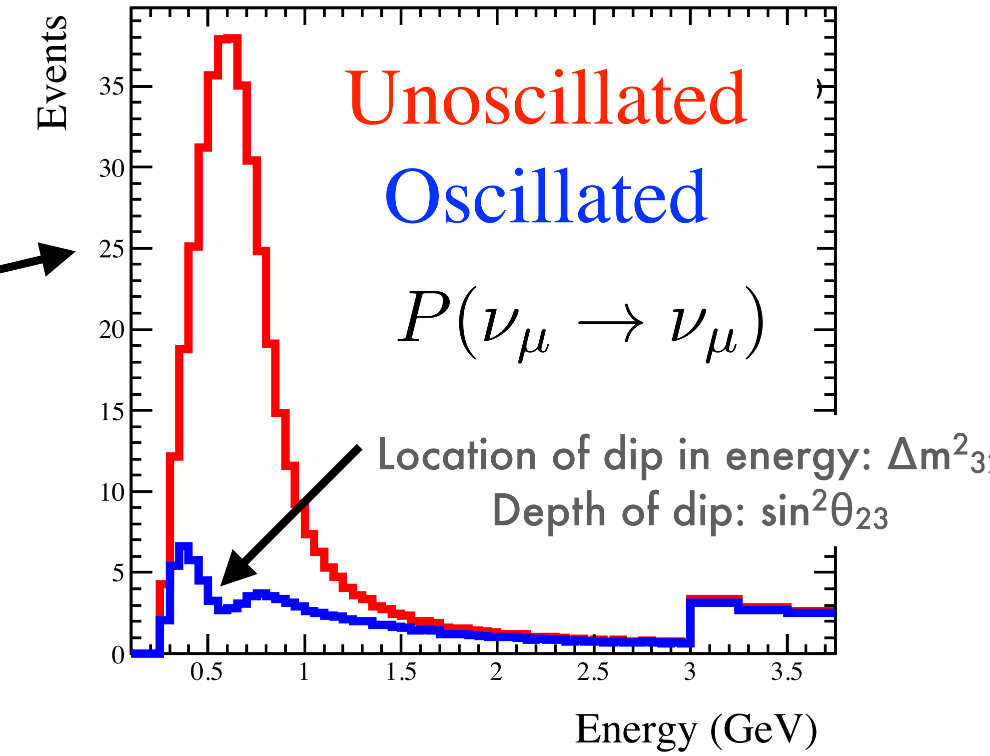
PDG 2014

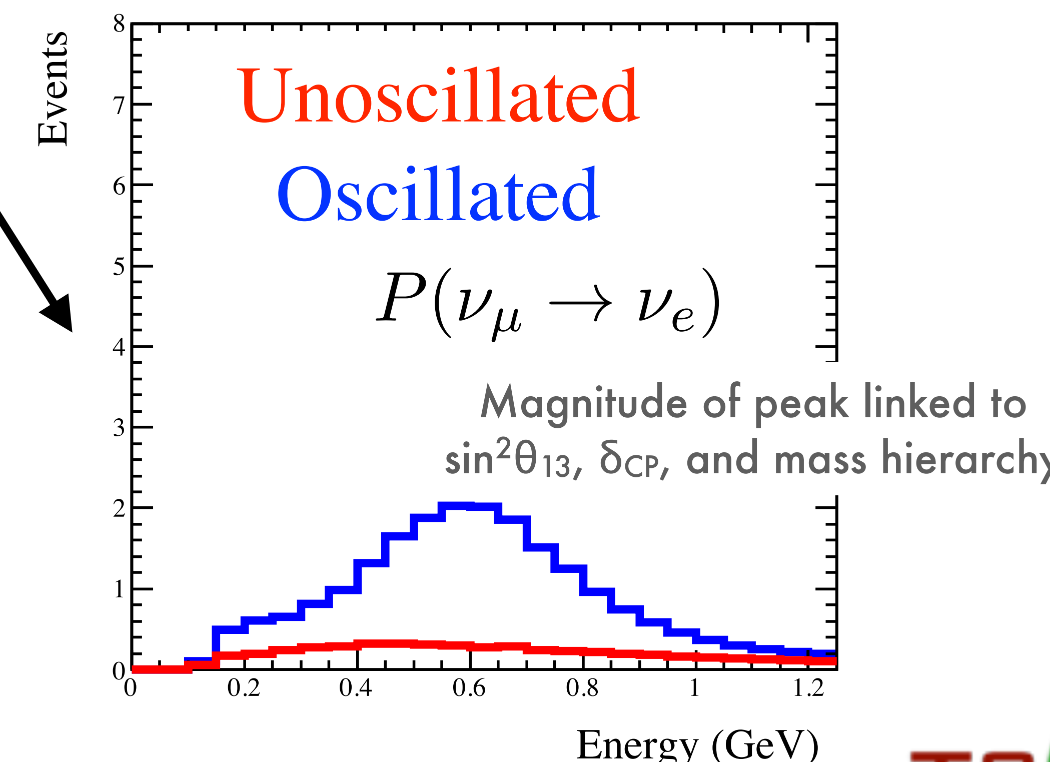
$\Delta m^2_{21} = 7.53\pm0.18\times10^{-5}\ \mathrm{eV}^2$
$|\Delta m^2_{32}| = 2.44\pm0.06\times10^{-3}\ \mathrm{eV}^2$
δ_{CP} = [-π–0.14π] and [0.87π–π] (90% interval)

Long-Baseline Neutrino Oscillation

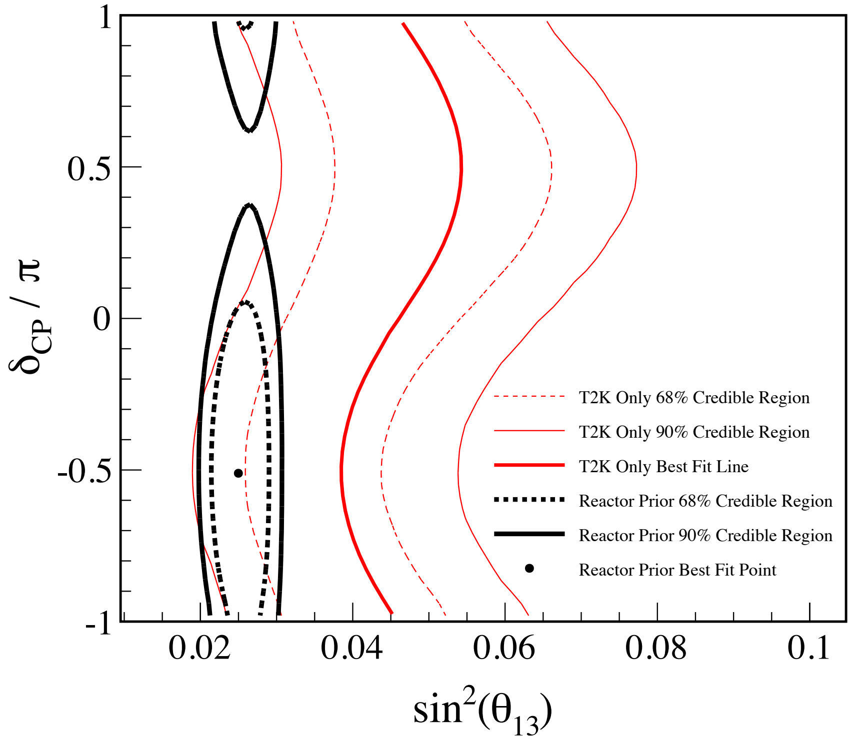
$$P(\nu_\mu \to \nu_\mu) \approx 1 - 4\cos^2(\theta_{13})\sin^2(\theta_{23})[1-\cos^2(\theta_{13})\sin^2(\theta_{23})]\sin^2\left(\frac{\Delta m^2_{31} L}{E_\nu}\right)$$

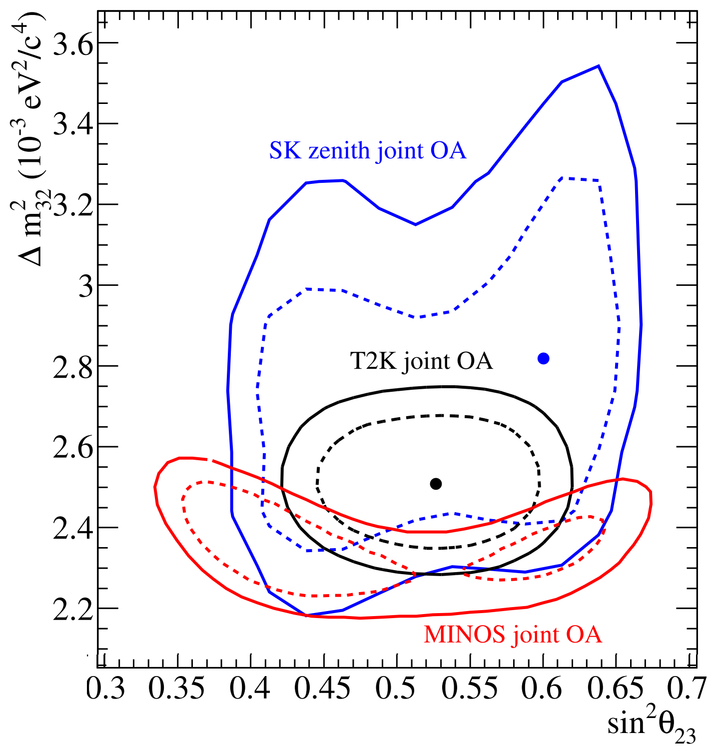




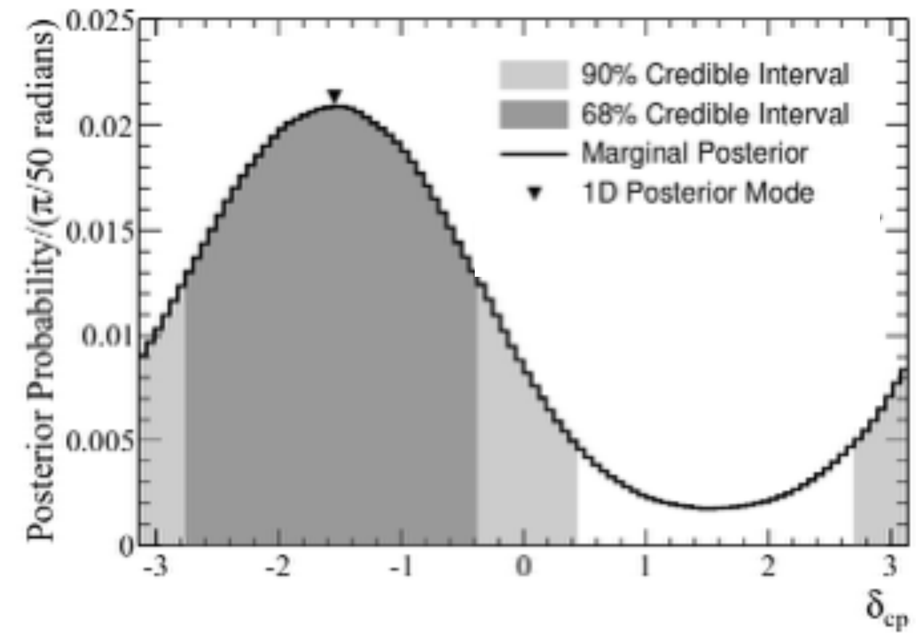


T2K Measurements





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



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}

First constraint of δ_{CP}

Parameters measured by T2K

$\theta_{23}=45.8\pm3.2°$

$\theta_{12}=33.4\pm0.85°$

$\theta_{13}=8.88\pm0.39°$

$\Delta m^2_{21} = 7.53\pm0.18\times10^{-5}\ eV^2$

$|\Delta m^2_{32}| = 2.44\pm0.06\times10^{-3}\ eV^2$

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

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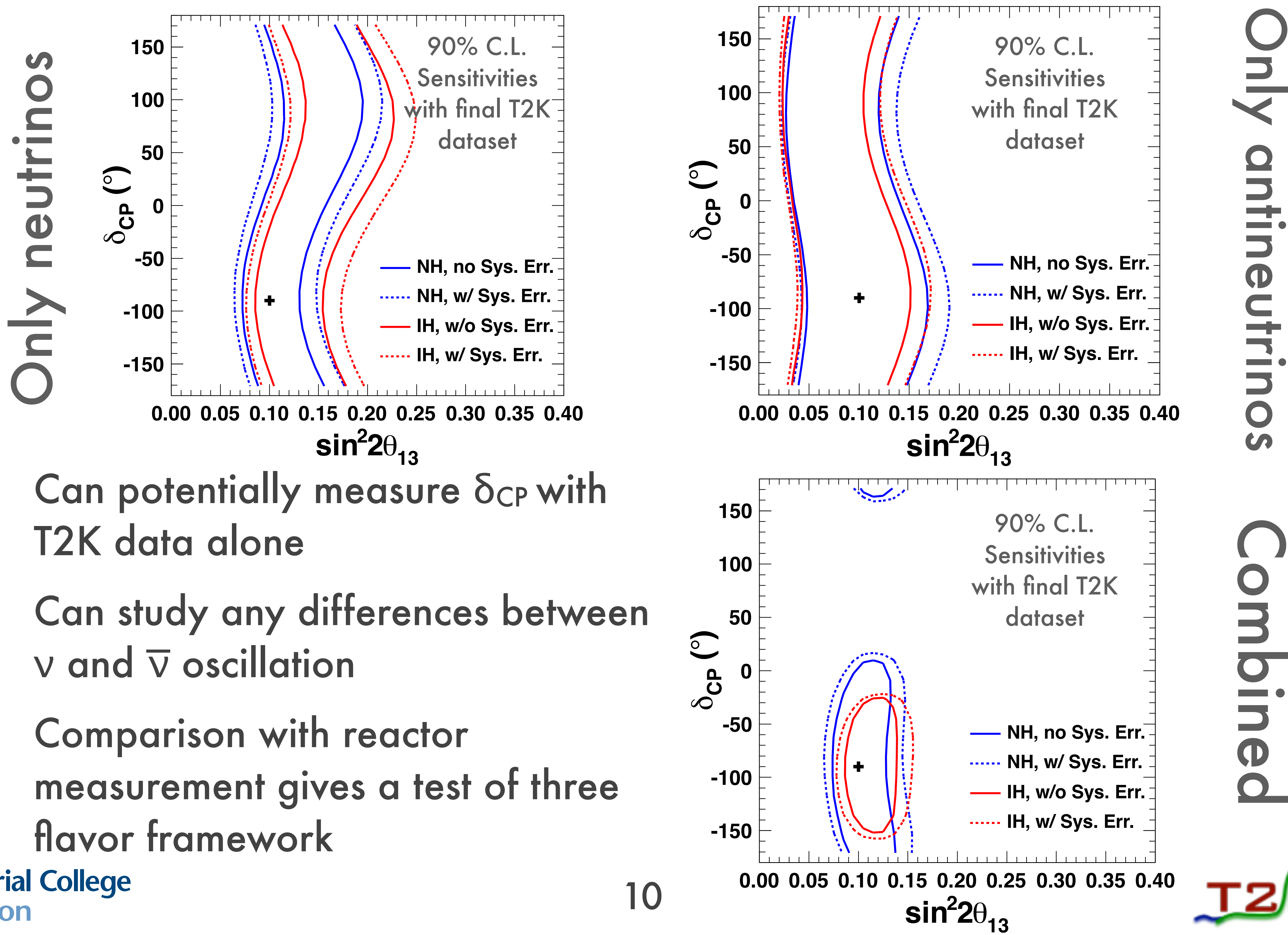
Why Antineutrinos?

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



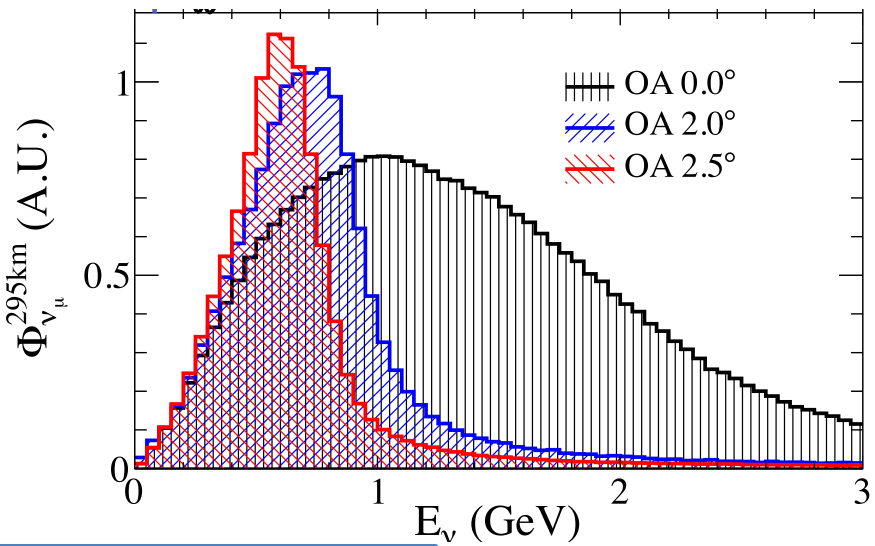
- Can potentially measure δ_{CP} with T2K data alone
- Can study any differences between ν and $\bar{\nu}$ oscillation
- Comparison with reactor measurement gives a test of three flavor framework

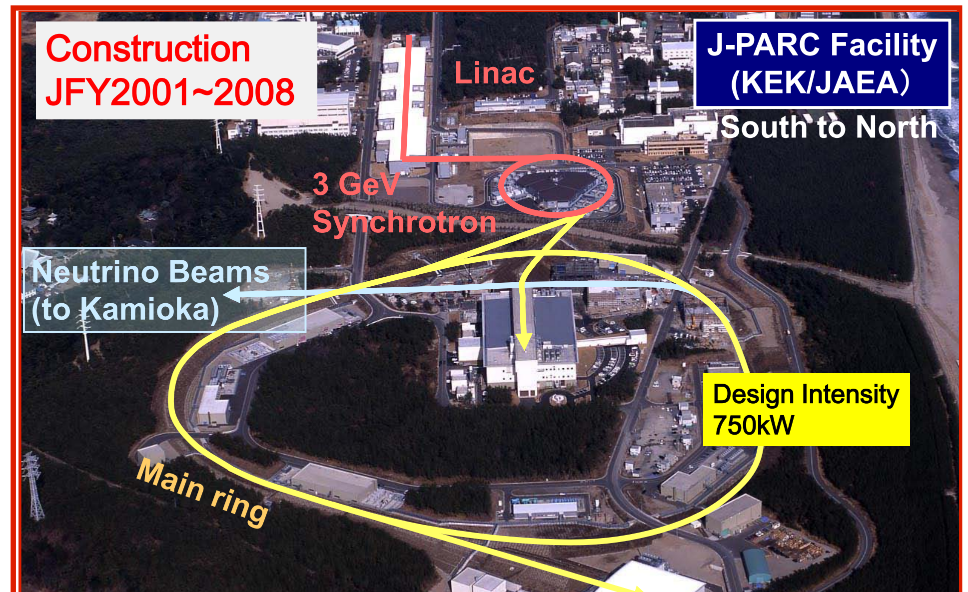
$\bar{\nu}_\mu$ Disappearance

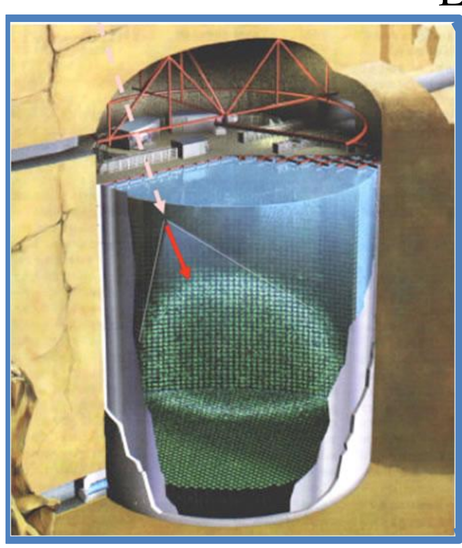
- Physics is interesting: investigate if neutrinos and antineutrinos behave differently:
  - CPT theorem implies that neutrino and antineutrino disappearance probability should be the same
  - Nonstandard matter interactions as the neutrinos/ antineutrinos pass through the Earth could change disappearance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

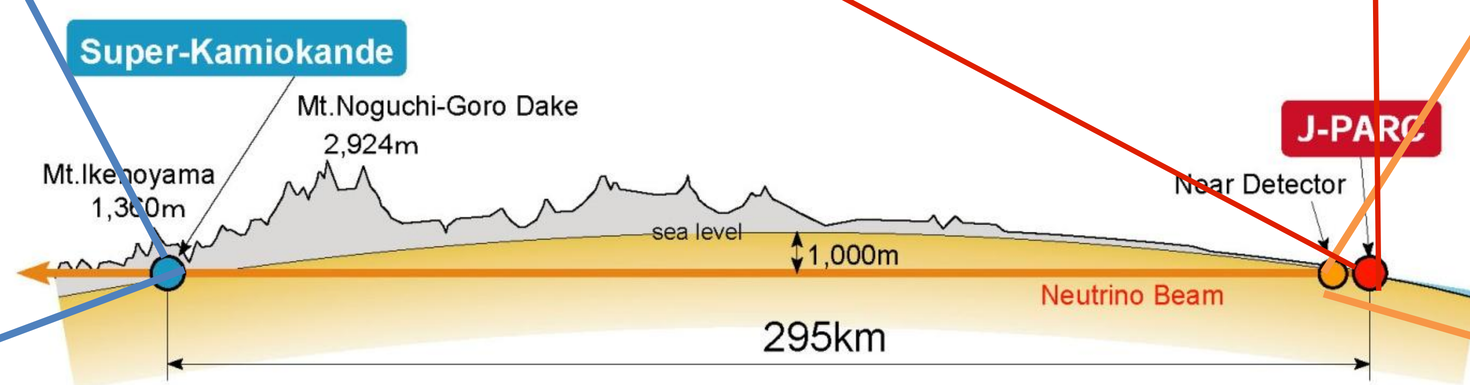
T2K

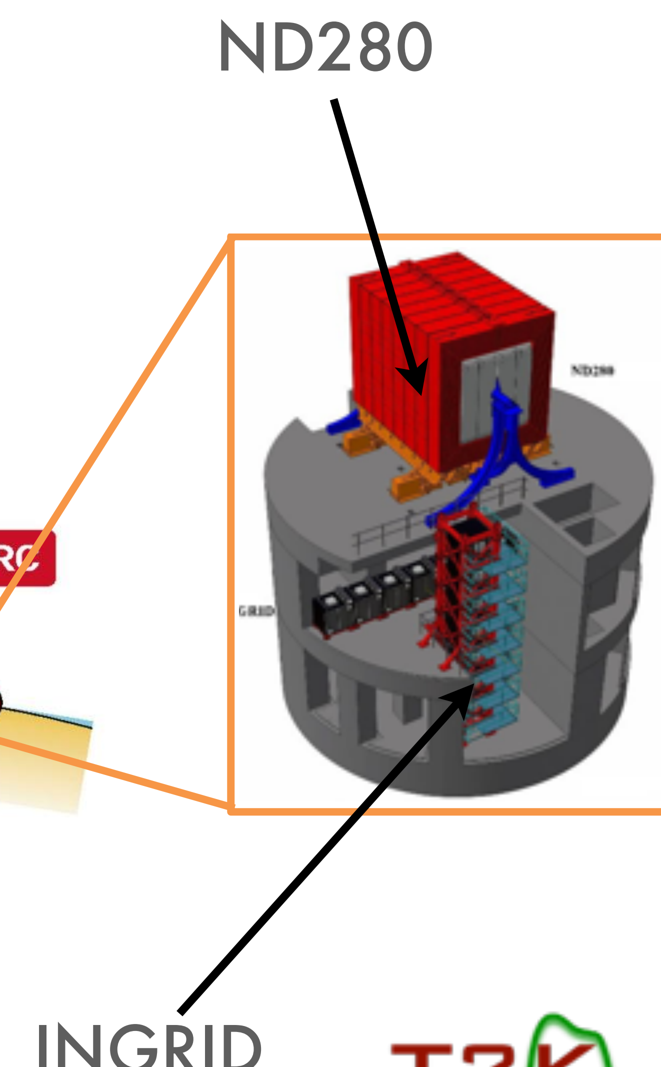
11 countries
60 institutions
~500 people

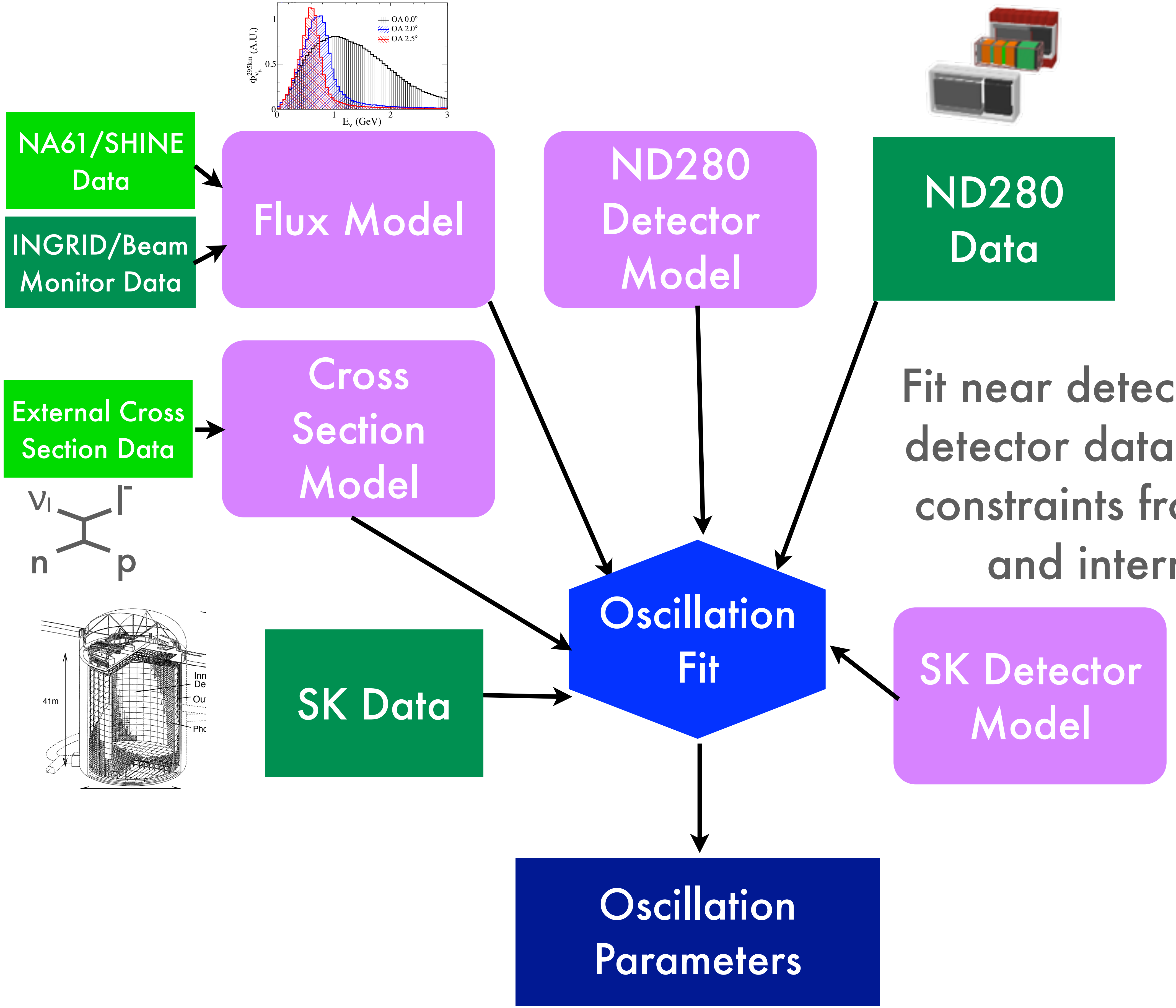












Fit near detector data, far detector data, and model constraints from external and internal data

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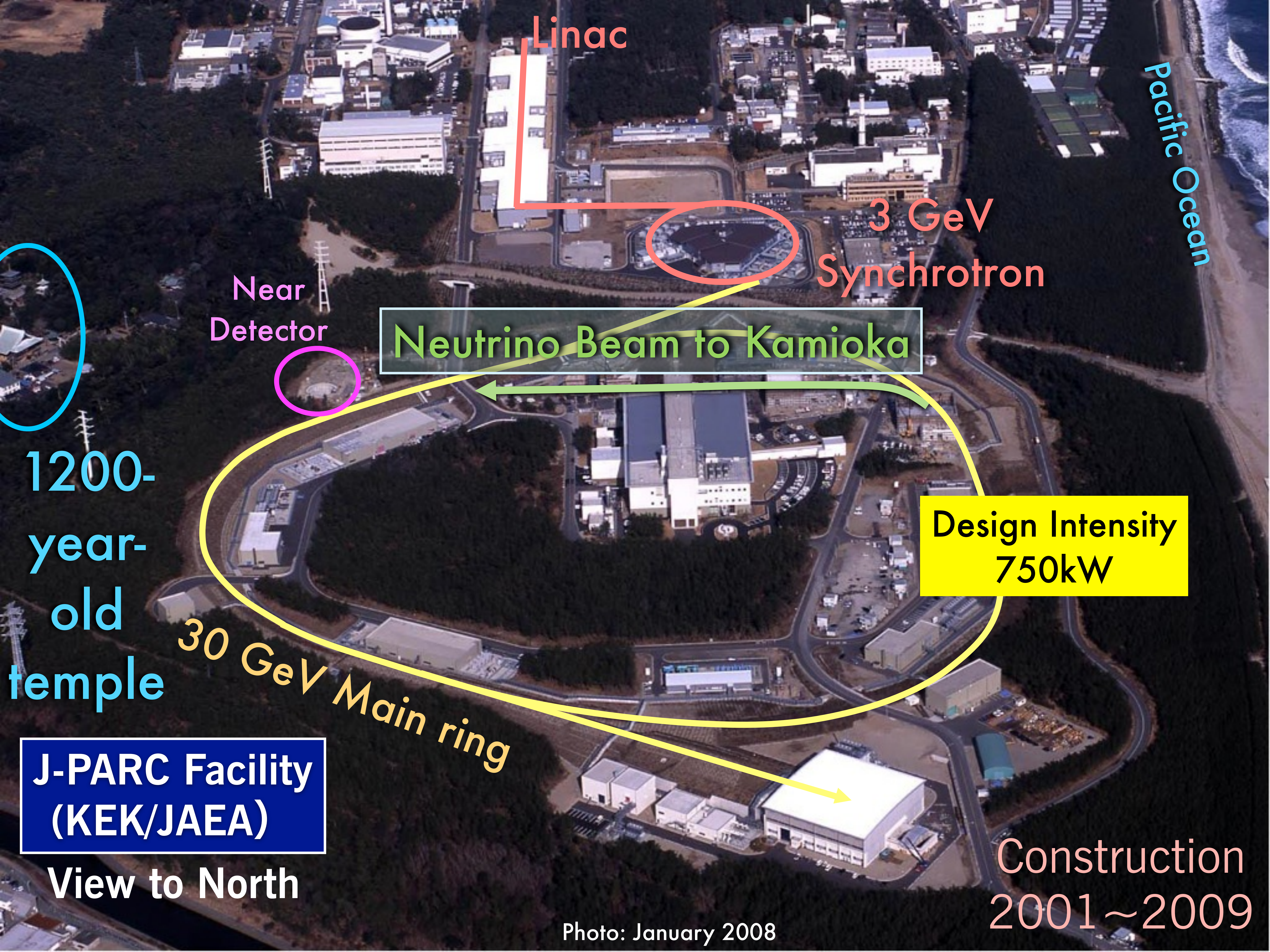
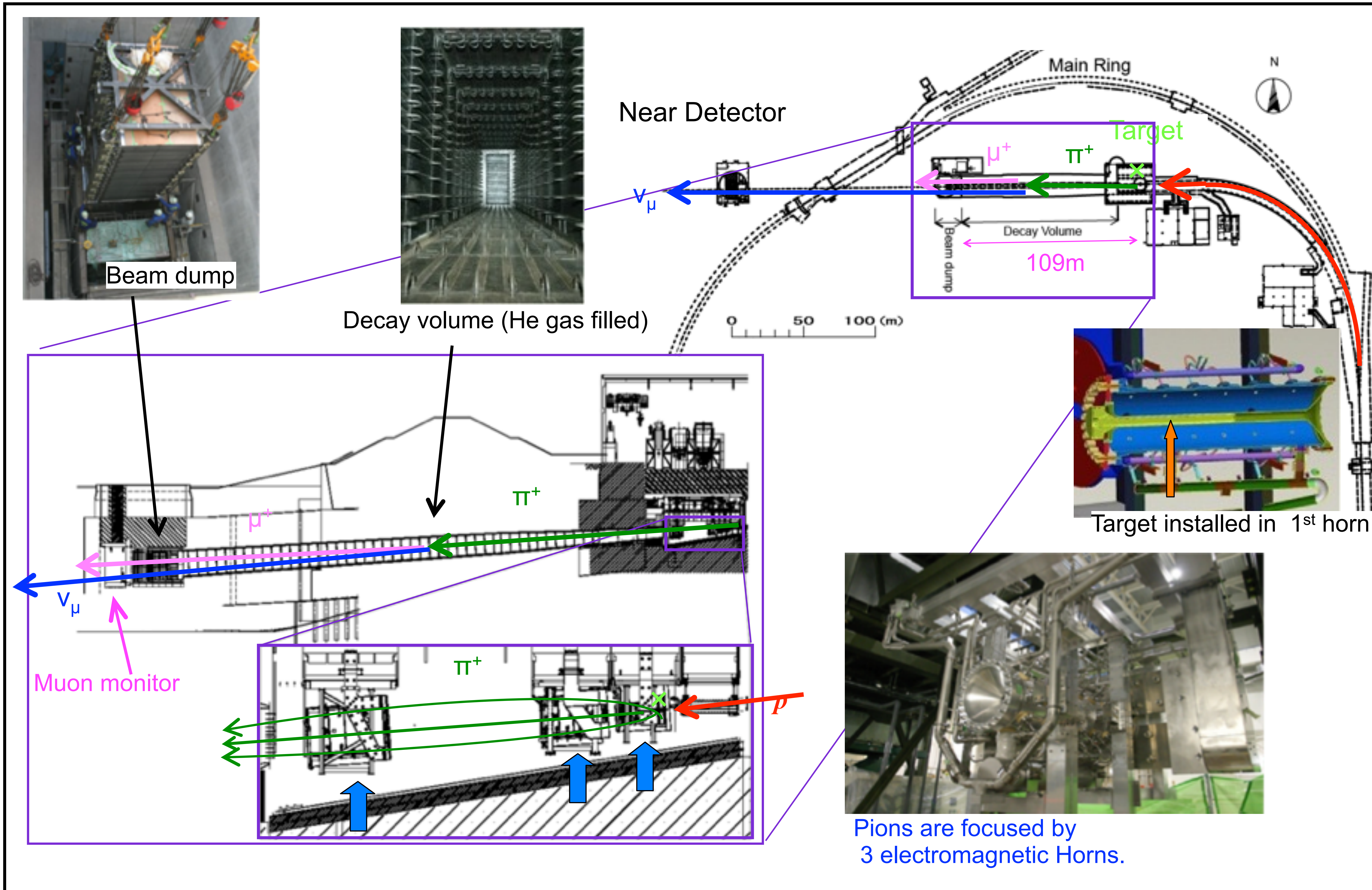
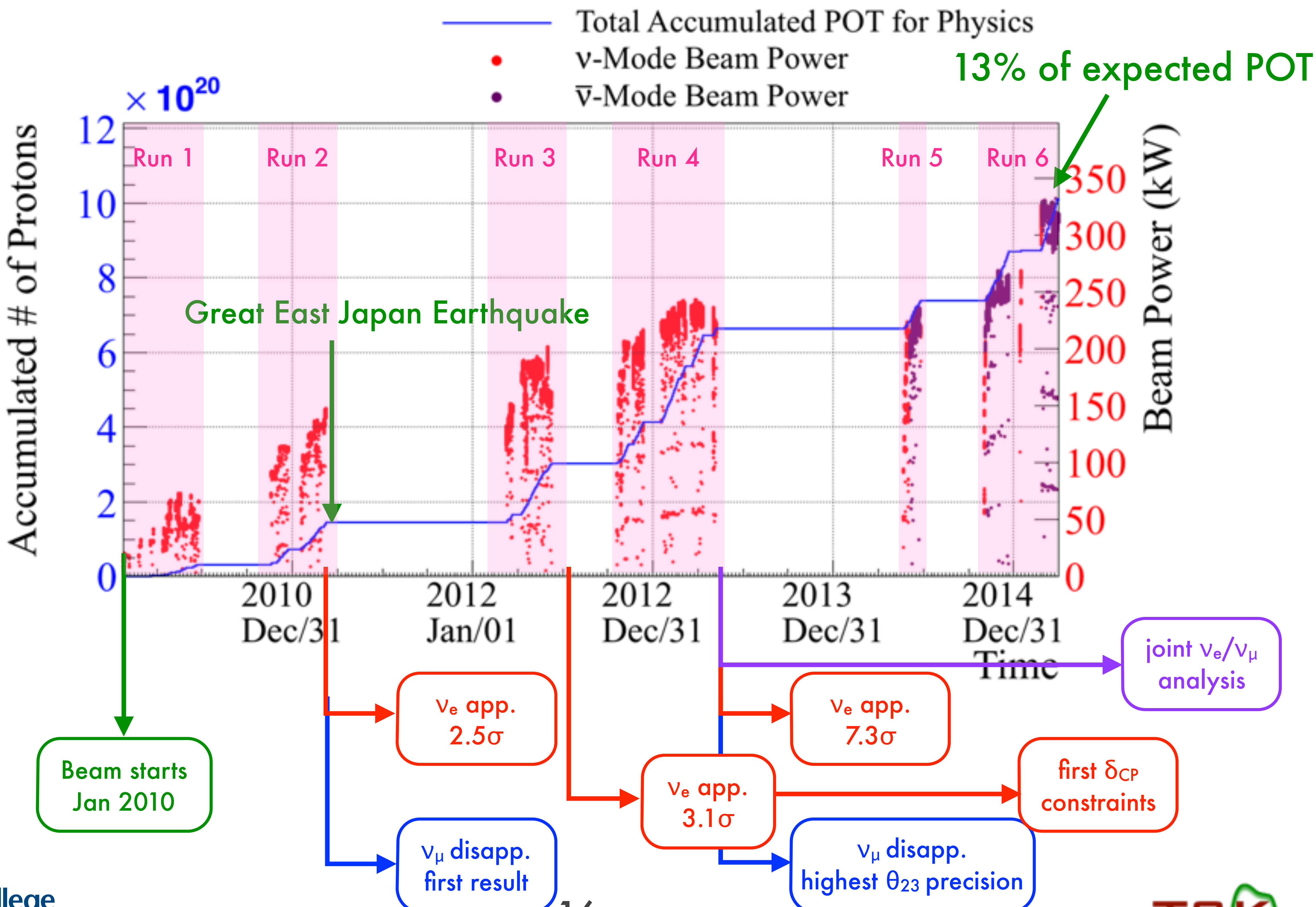

Linac
3 GeV
Synchrotron
Pacific Ocean
Near
Detector
Neutrino Beam to Kamioka
1200-
year-
old
temple
Design Intensity
750kW
30 GeV Main ring
J-PARC Facility
(KEK/JAEA)
View to North
Construction
2001~2009
Photo: January 2008

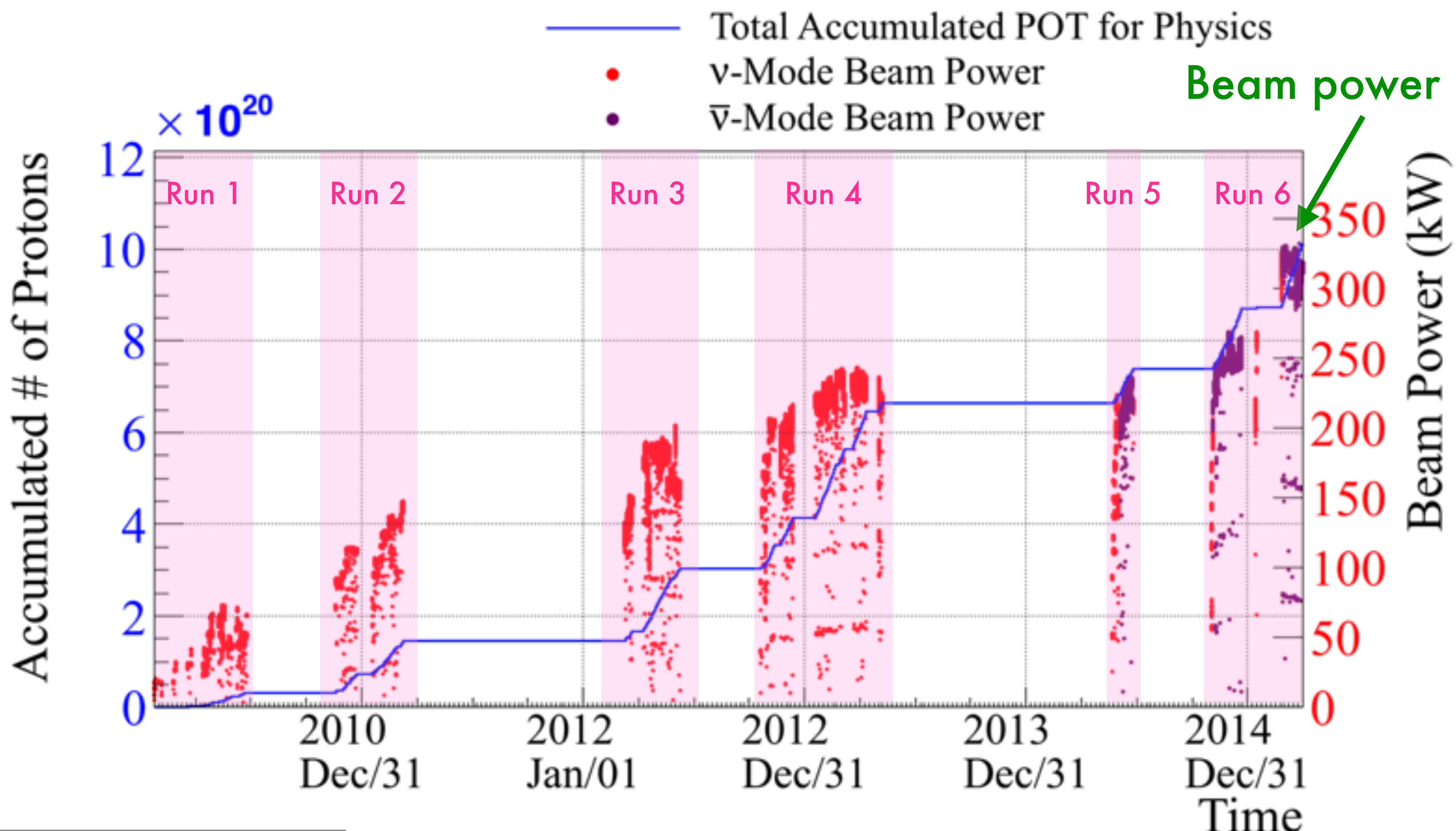
J-PARC neutrino beamline overview



Beam Operations



Beam Operations



POT	ND280	SK
ν mode	5.82x10	0
ν̄ mode	4.30x10	2.315x10

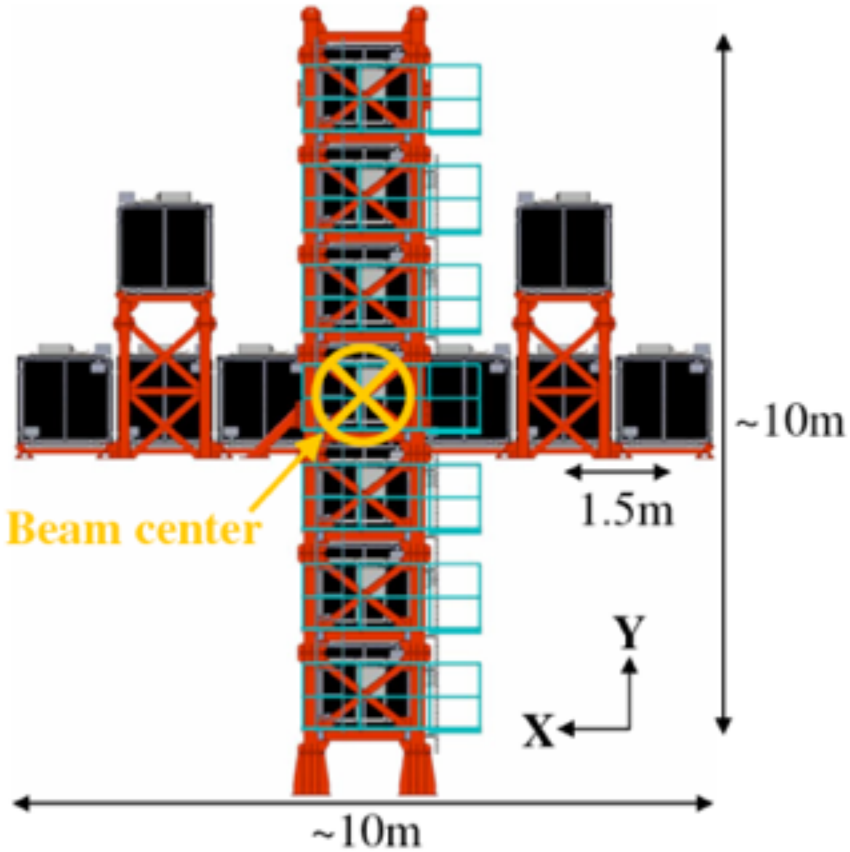
Used for this ND analysis: ν mode, Runs 2–4; ν̄ mode, Run 5

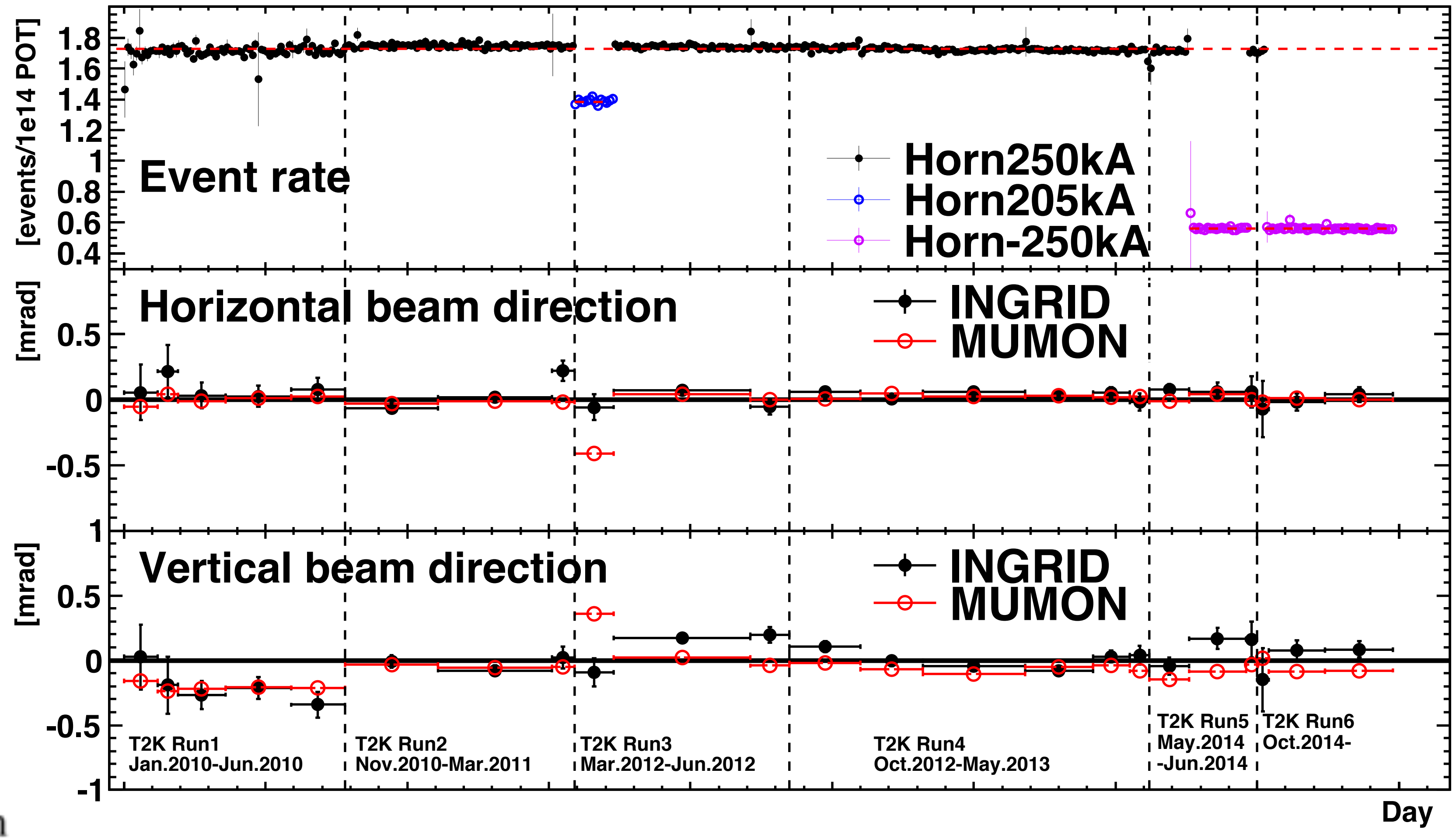
Used for this SK analysis: ν̄ mode, Run 5–6 (until 2015-03-12)

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

Beam Stability

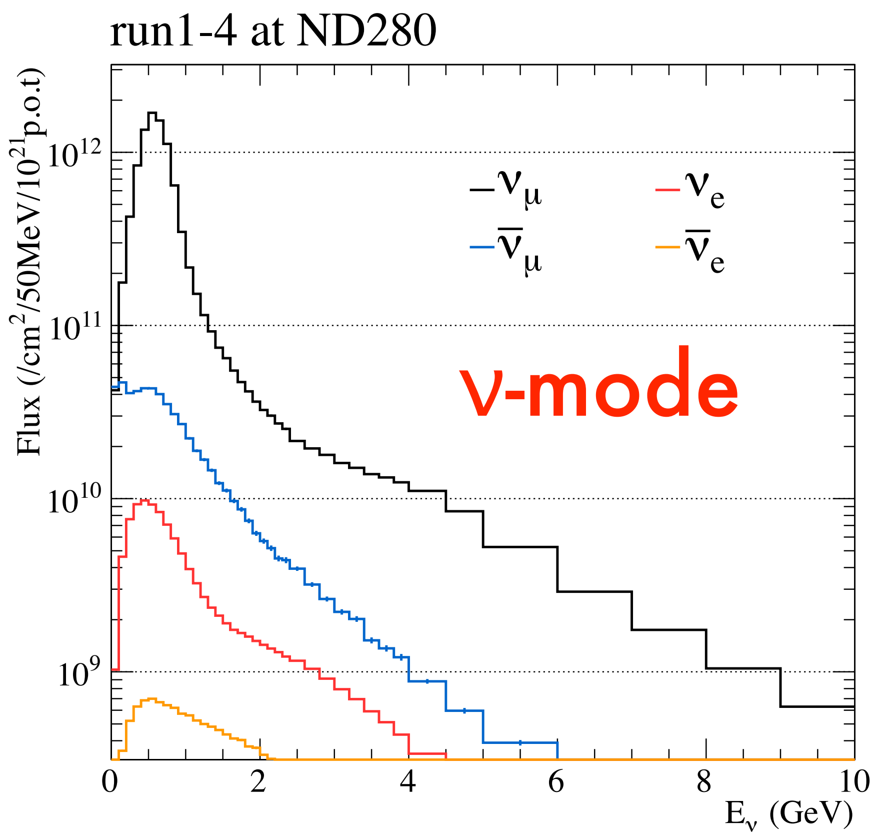
Use INGRID on-axis detector to measure beam stability

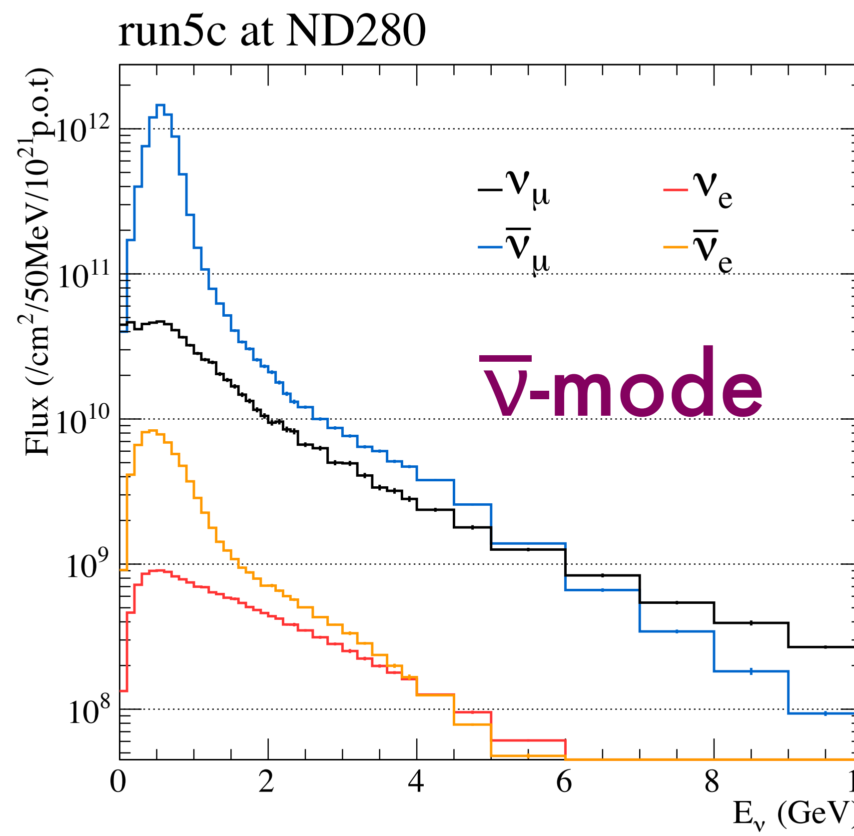




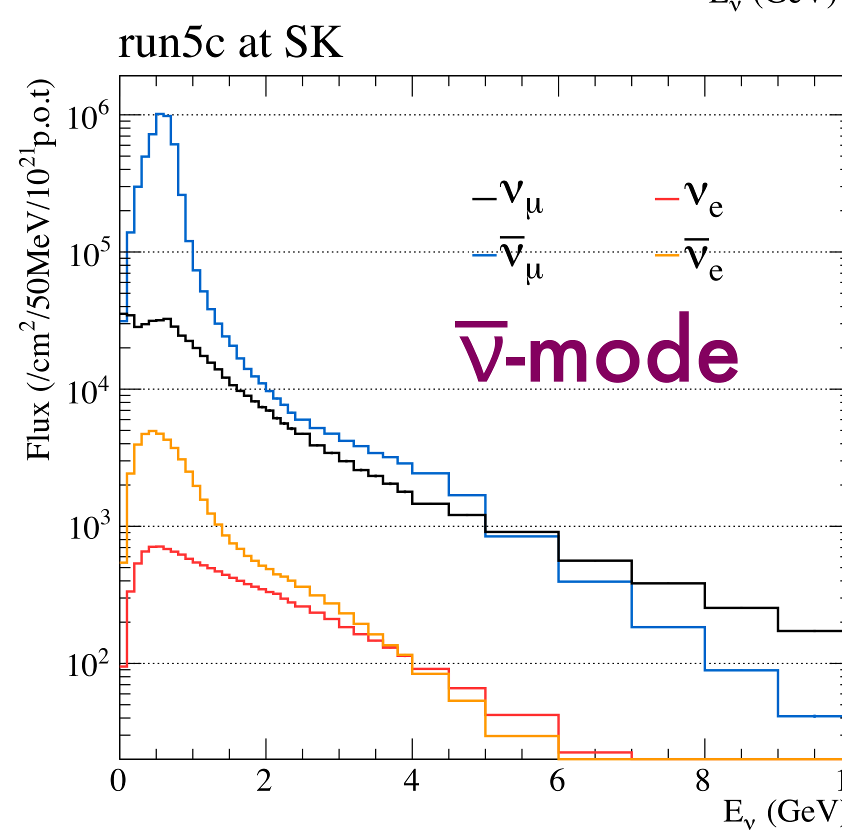
Beam rate and direction has been very stable in both neutrino and anti-neutrino modes

Beam Content

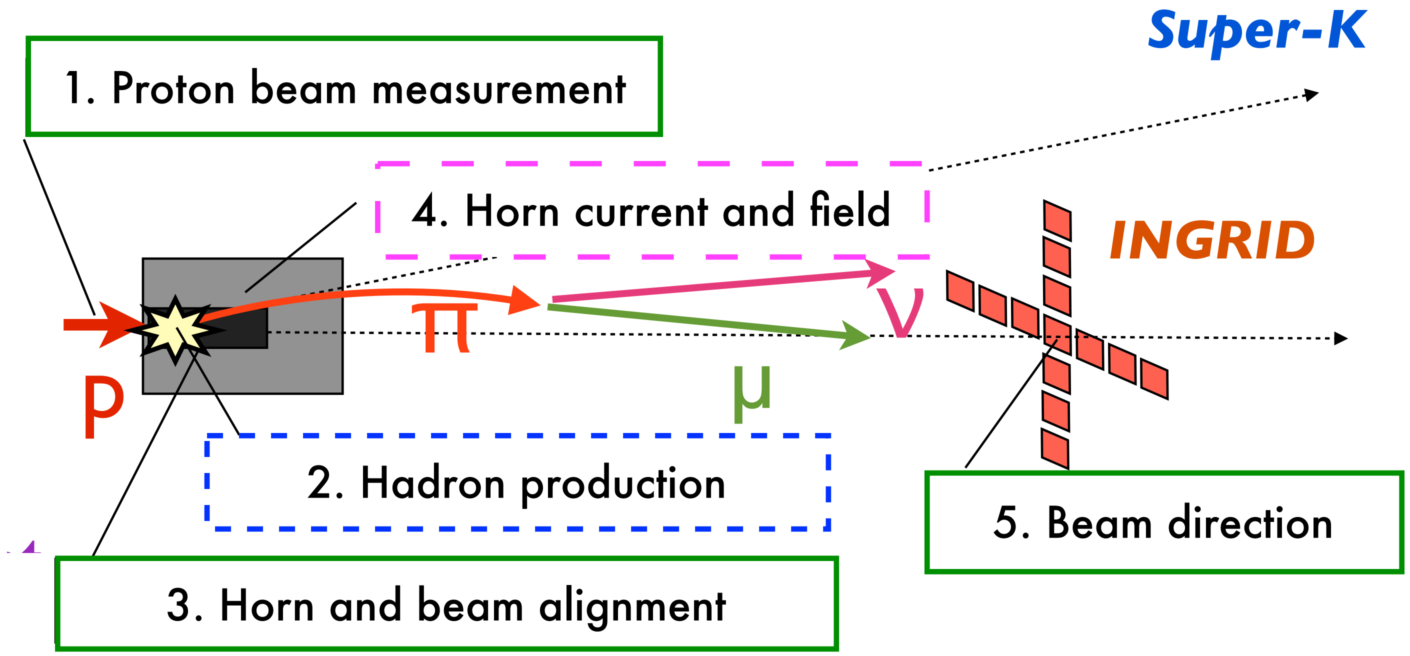


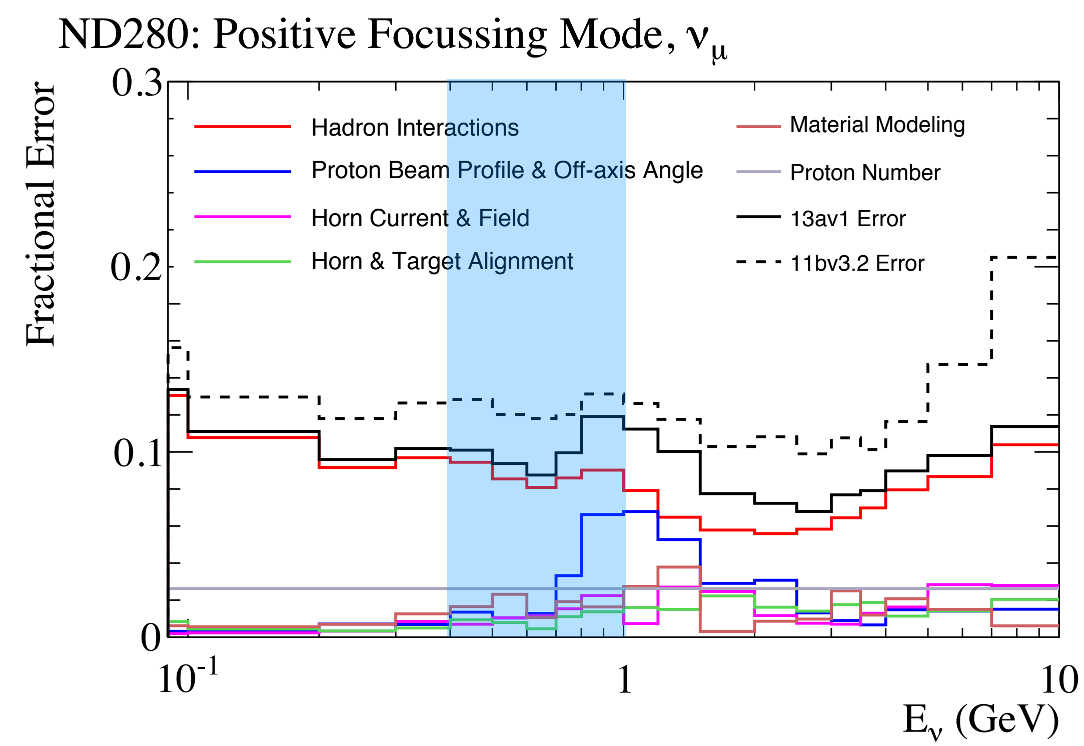


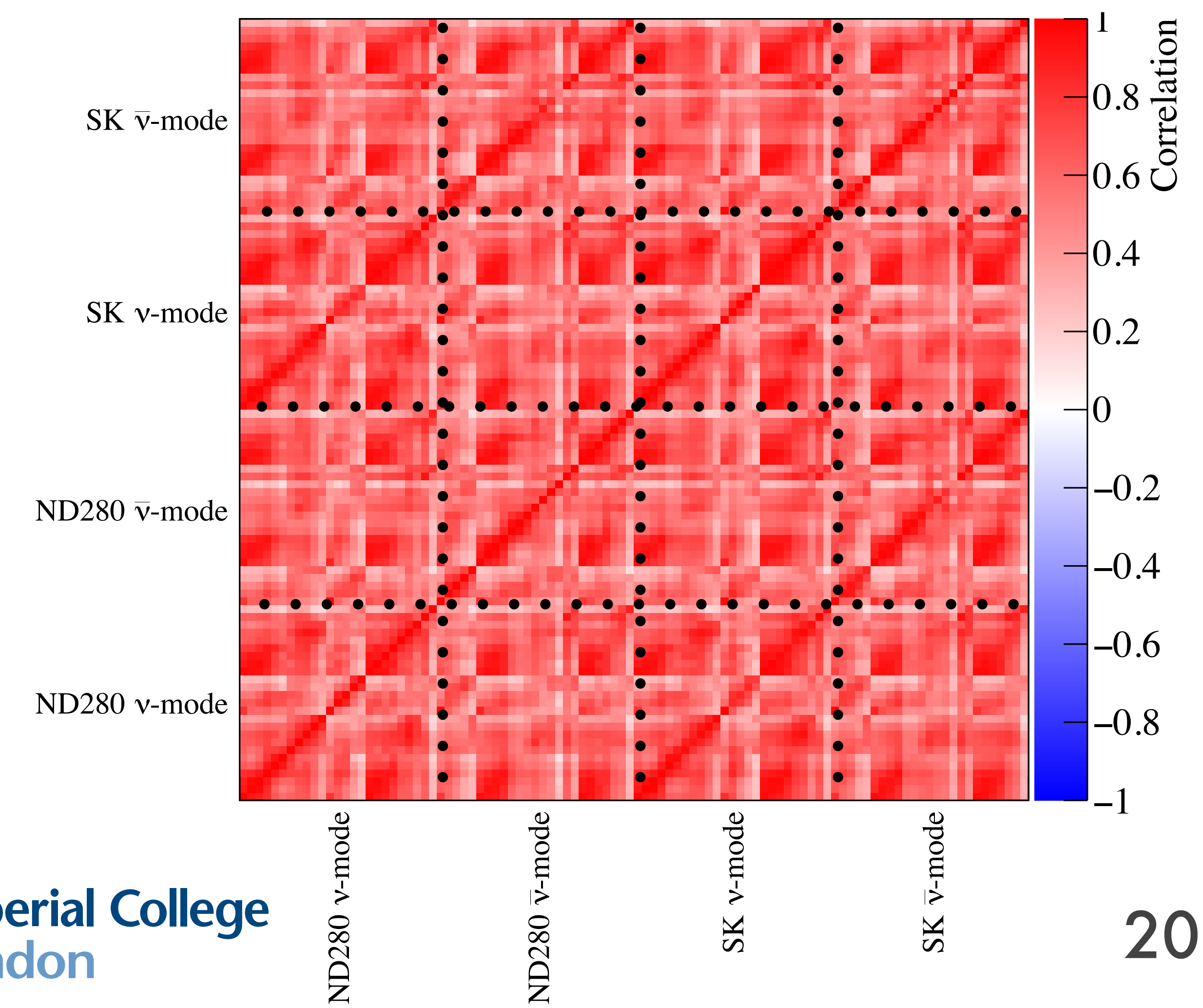
- Note that "wrong sign" backgrounds are much higher in $\bar{\nu}$ mode
- SK flux is highly correlated with ND280 flux

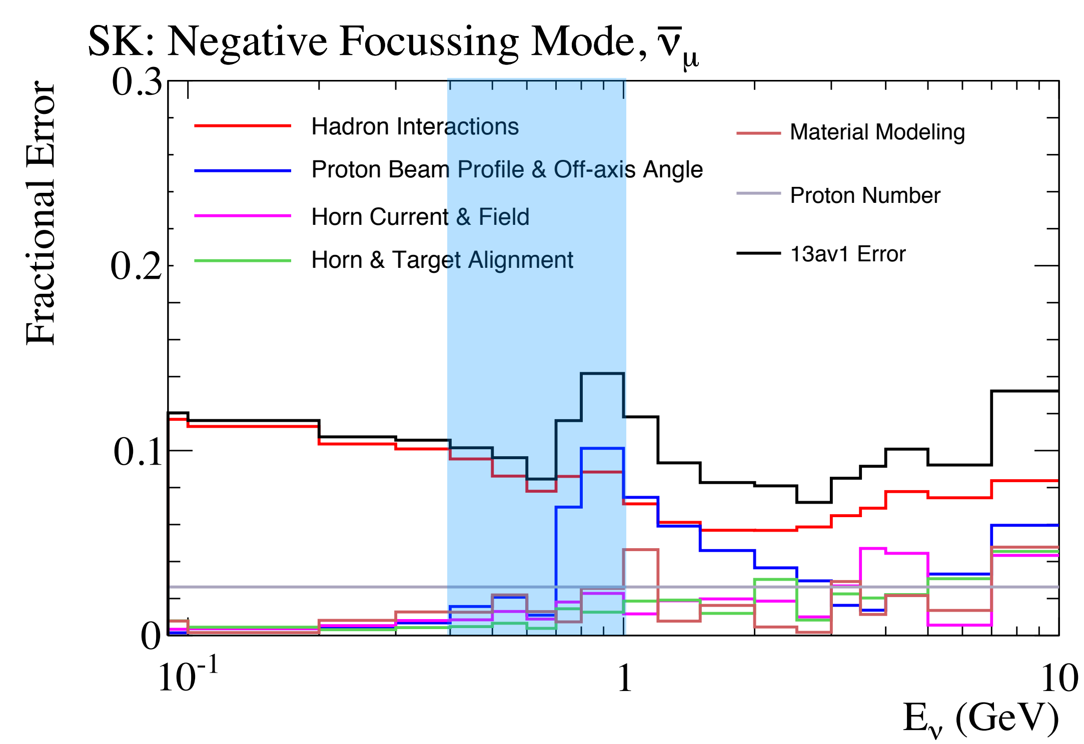


Beam Uncertainties









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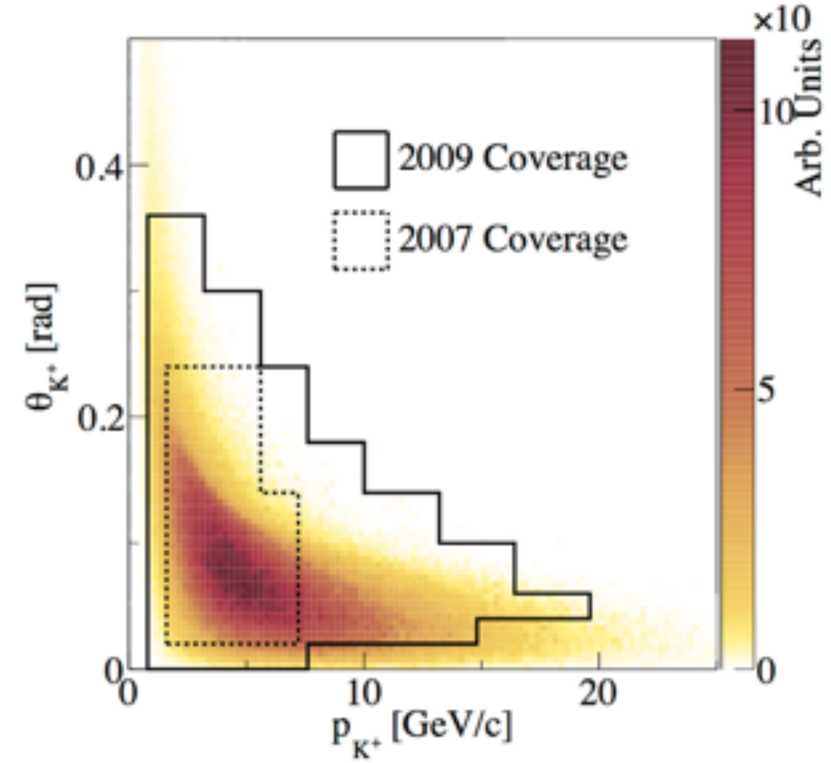
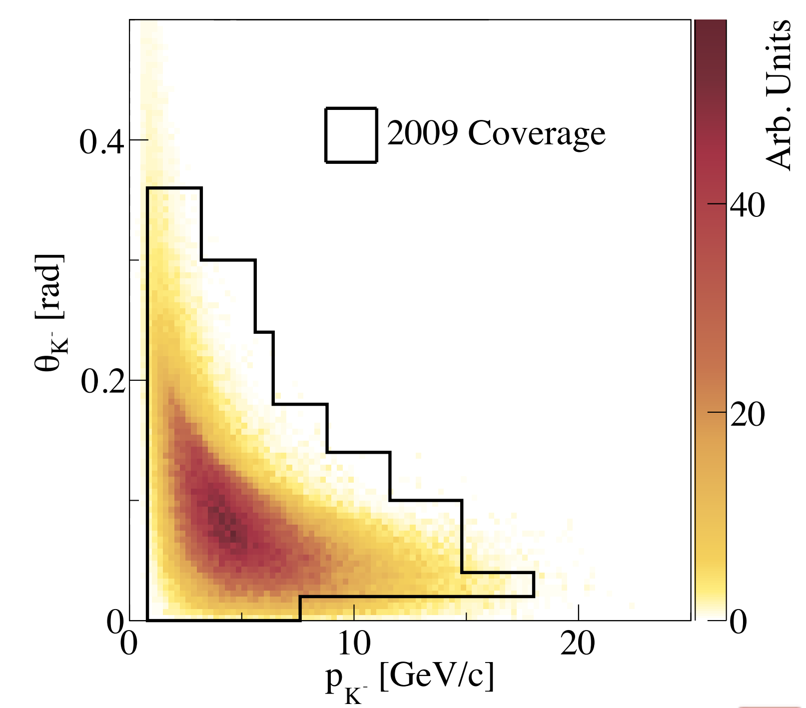
Hadronic Uncertainties

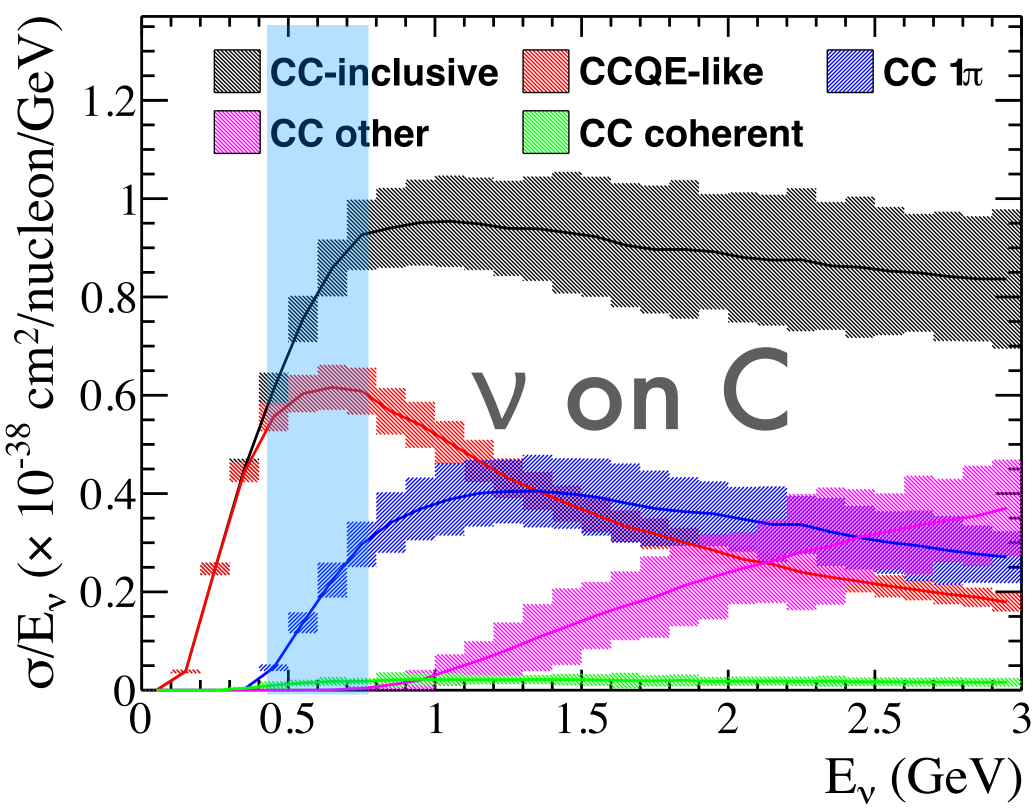
- This analysis has seen significant improvement in hadronic uncertainties through new data
  - NA61/SHINE (at CERN) measures the distributions of the pions and kaons that are produced from 30 GeV protons on a graphite target
  - T2K uses this information to tune the beam simulation
- The new data has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

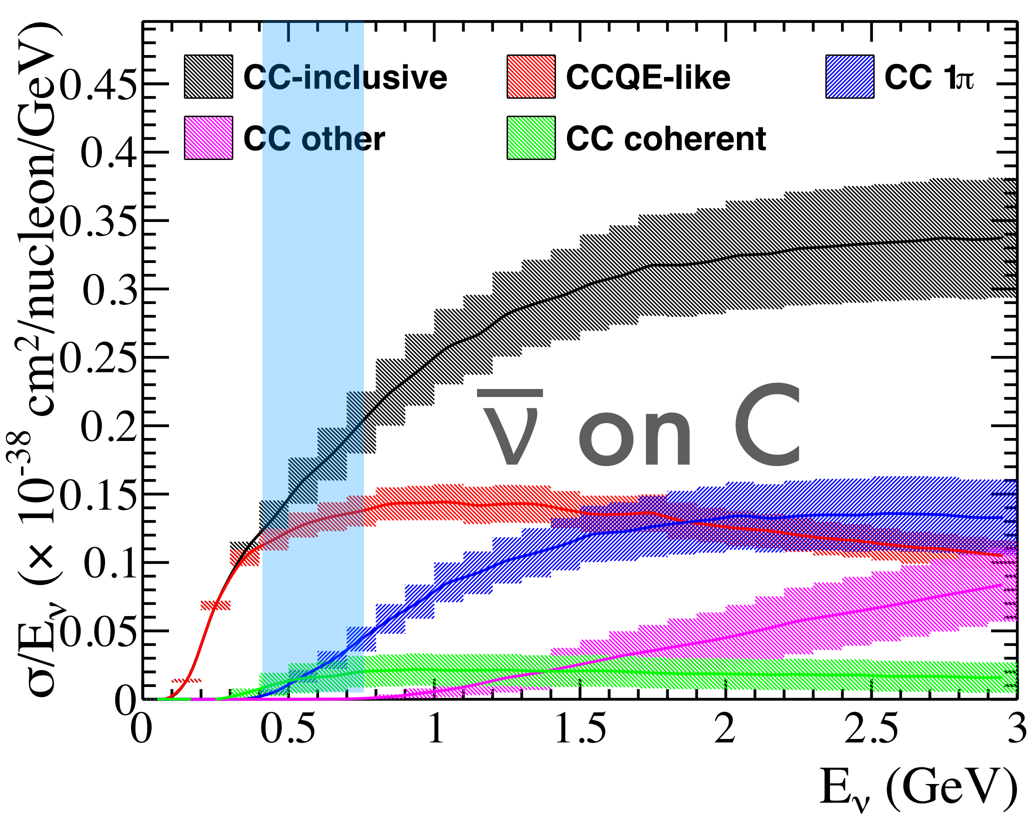




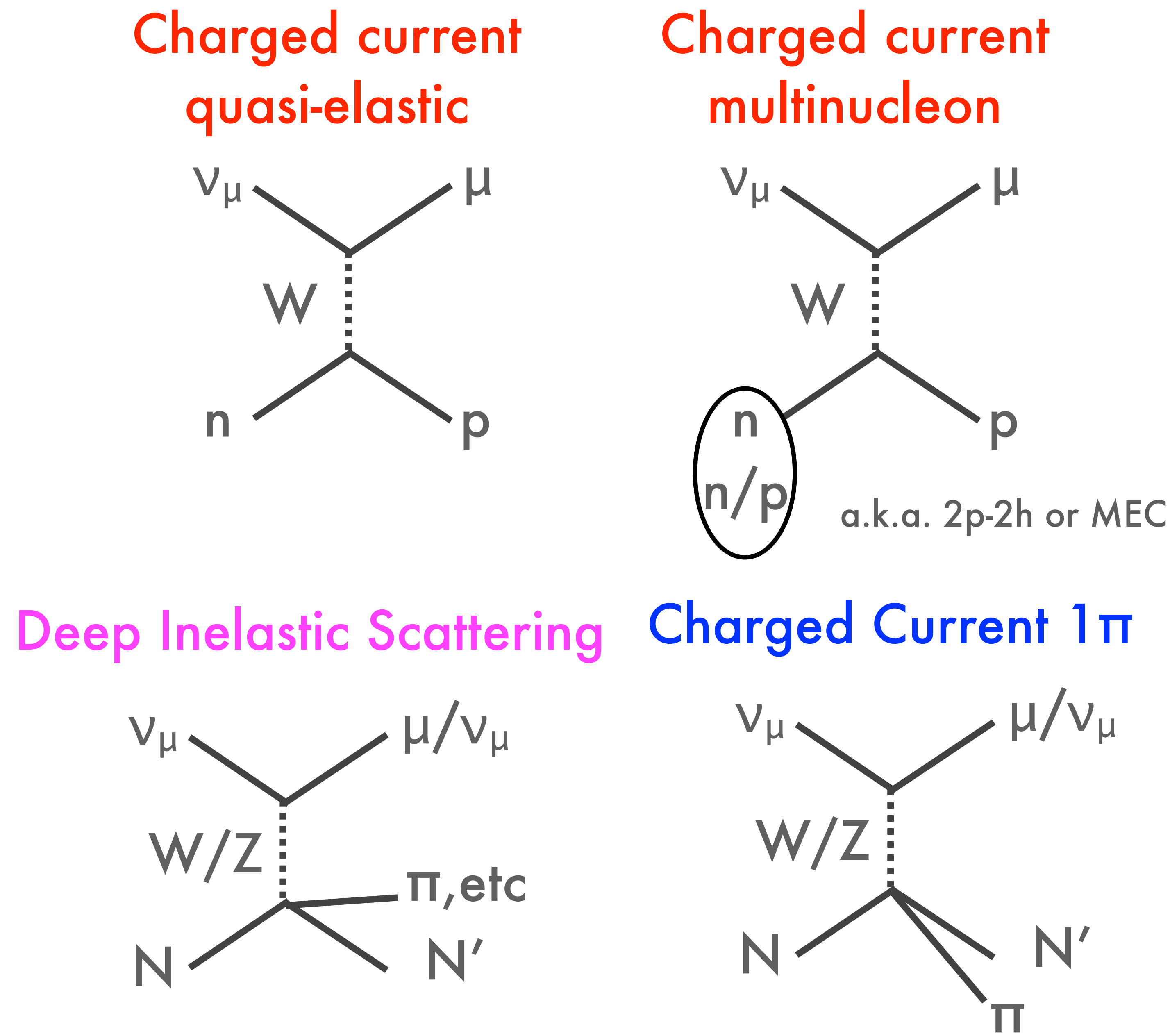
Reference

ν-N Cross Section Model



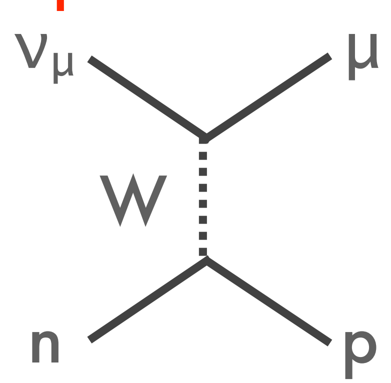


Uncertainties come from underlying model parameters and normalizations



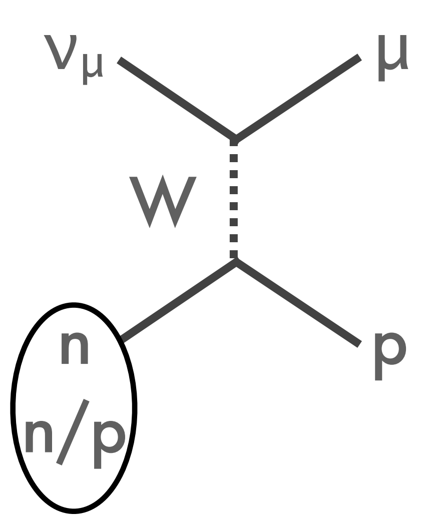
Why Multinucleon?

Charged current quasi-elastic

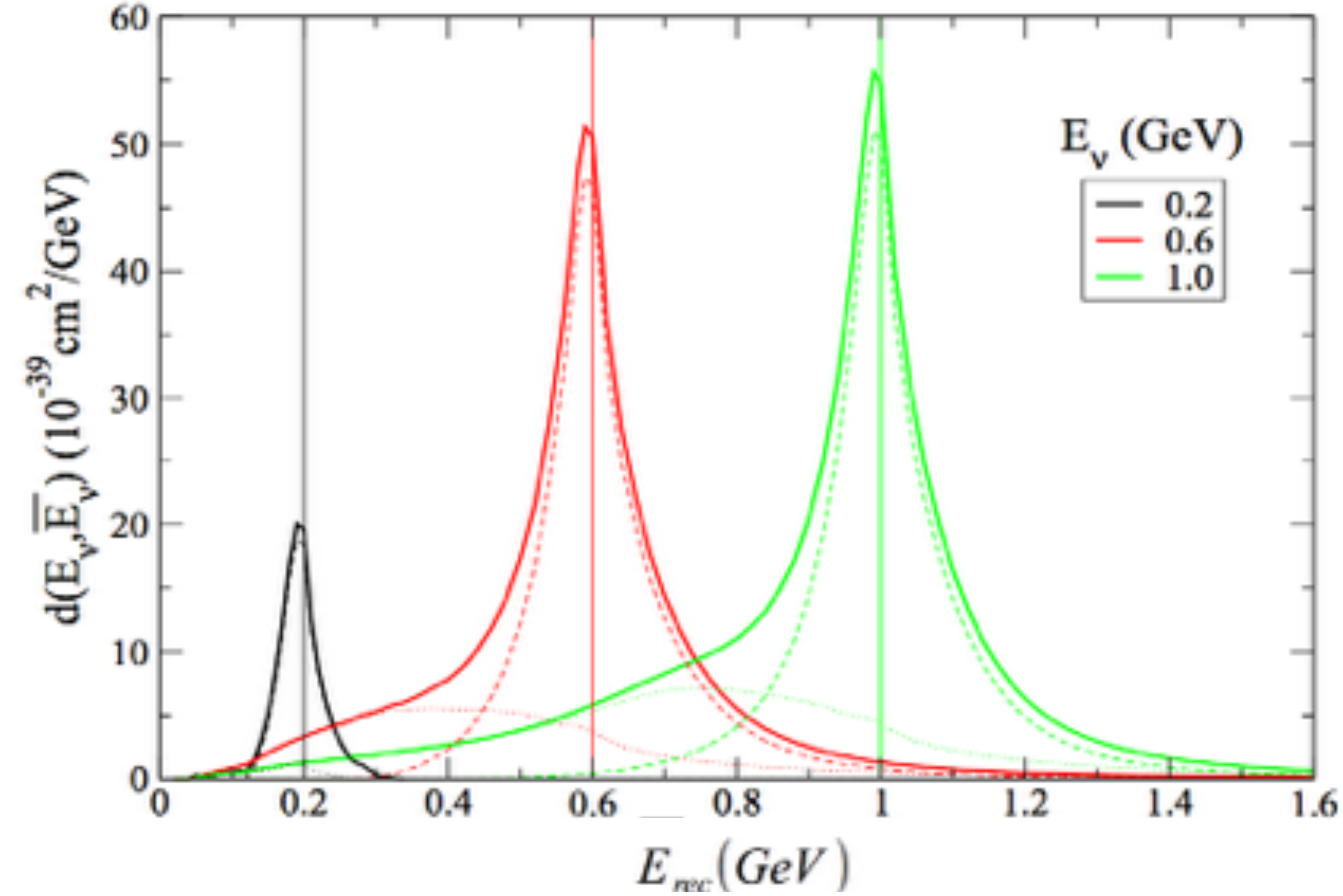


Charged current multinucleon

How does this change energy reconstruction?

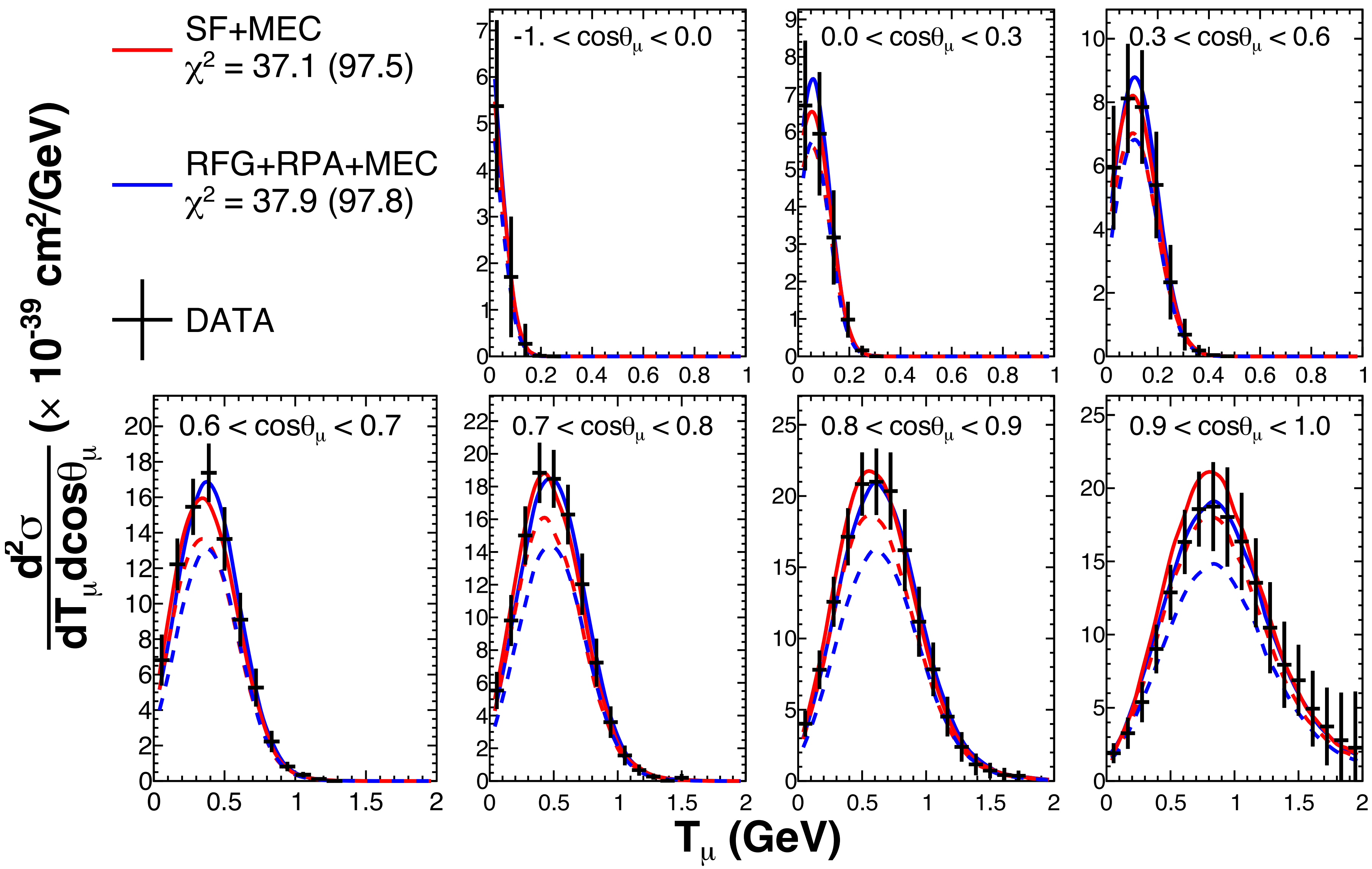


Martini et. al. Phys.Rev. D87 (2013) 013009



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

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

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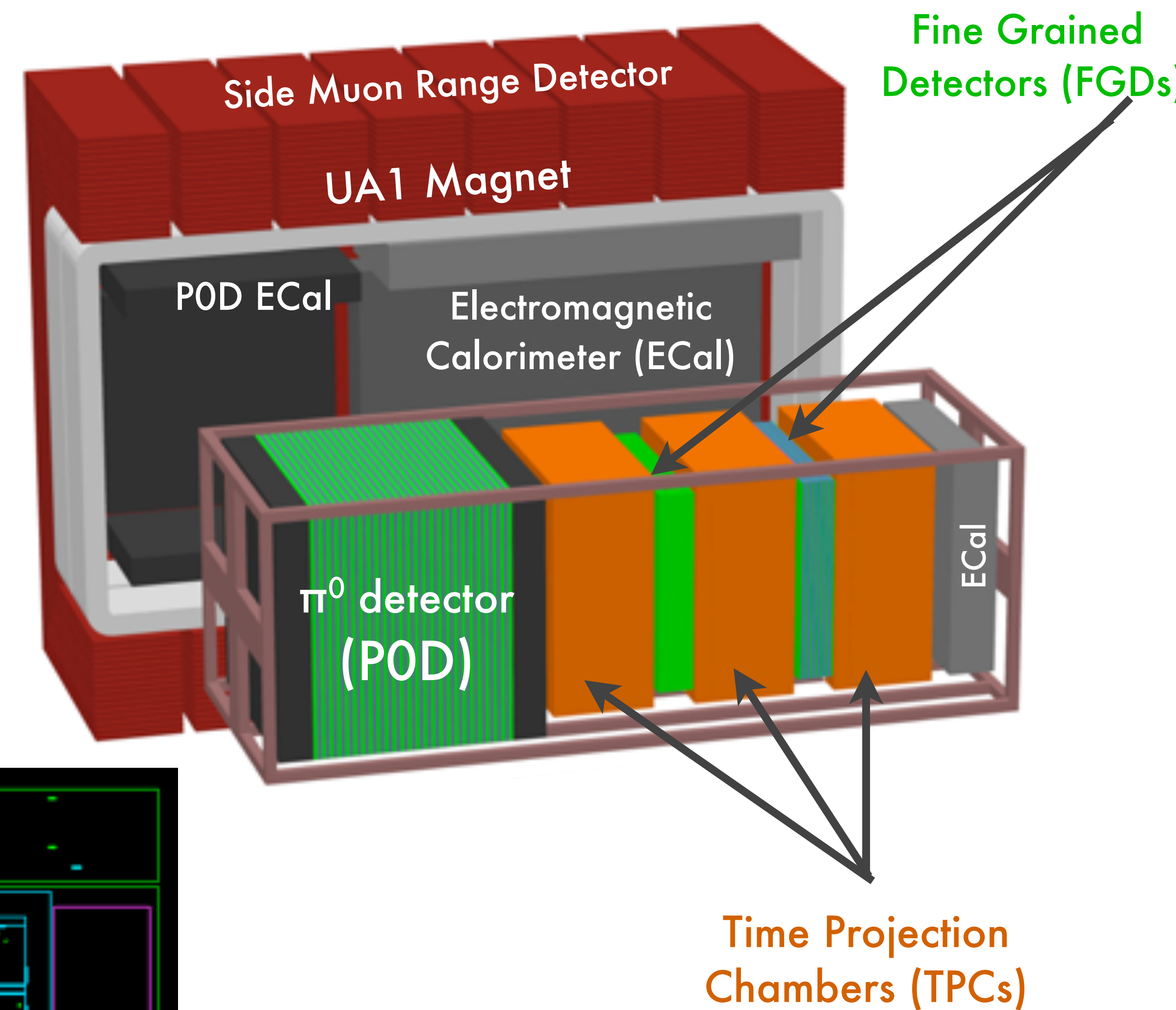
T2K Off-Axis Near Detector

Beam →

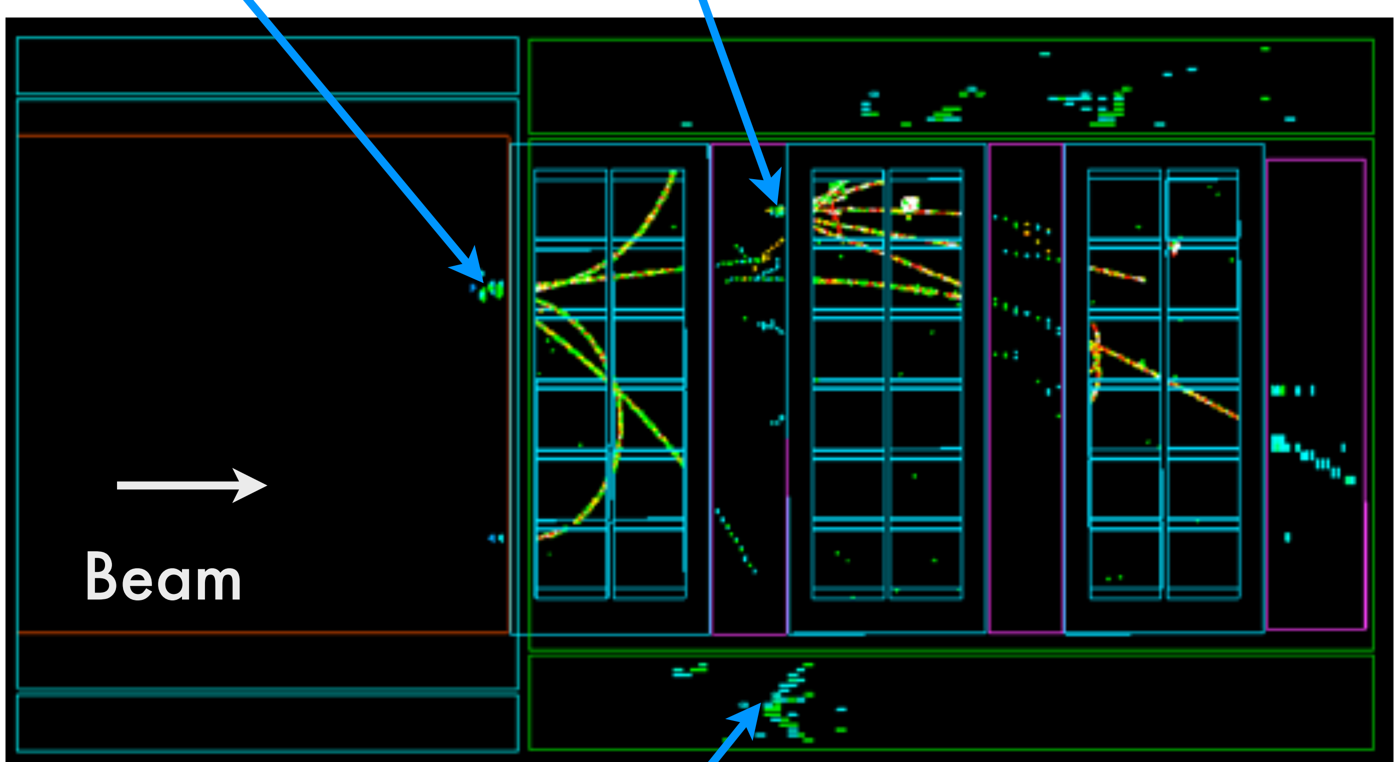


Primary Interaction Material: Carbon

Secondary Interaction Materials:
Oxygen, Lead, Brass, Argon

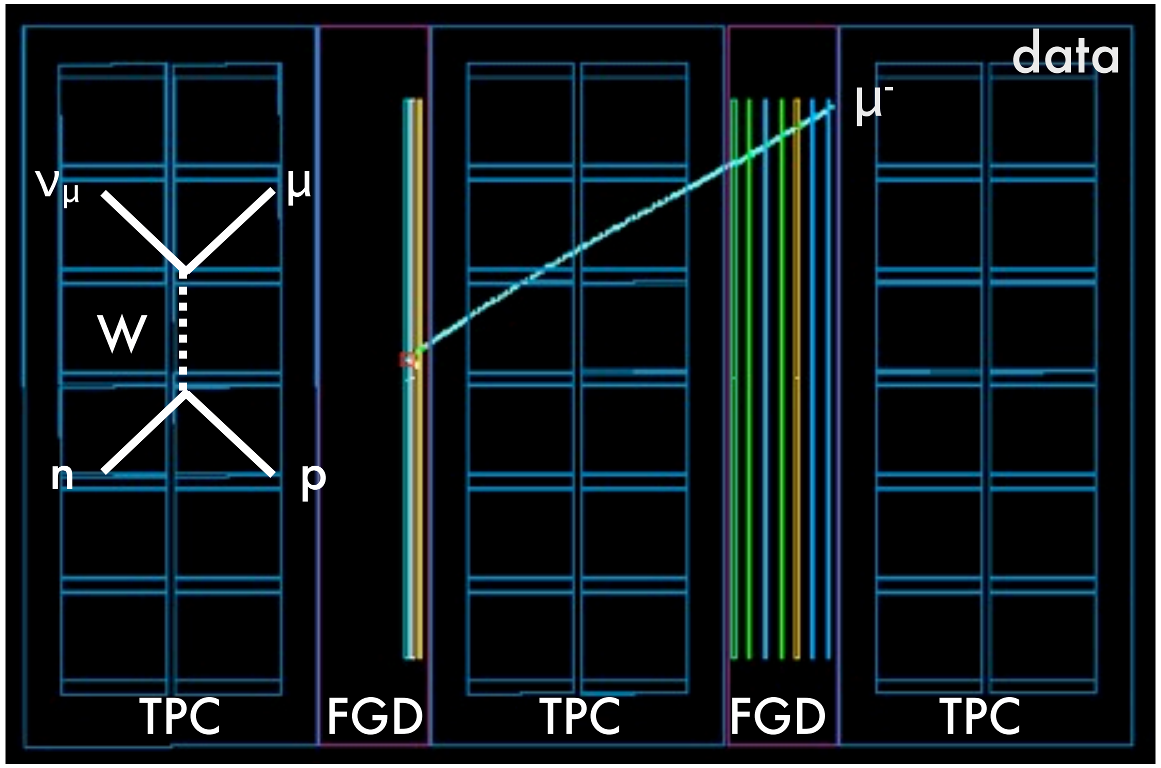
Interaction in P0D

Interaction in FGD1

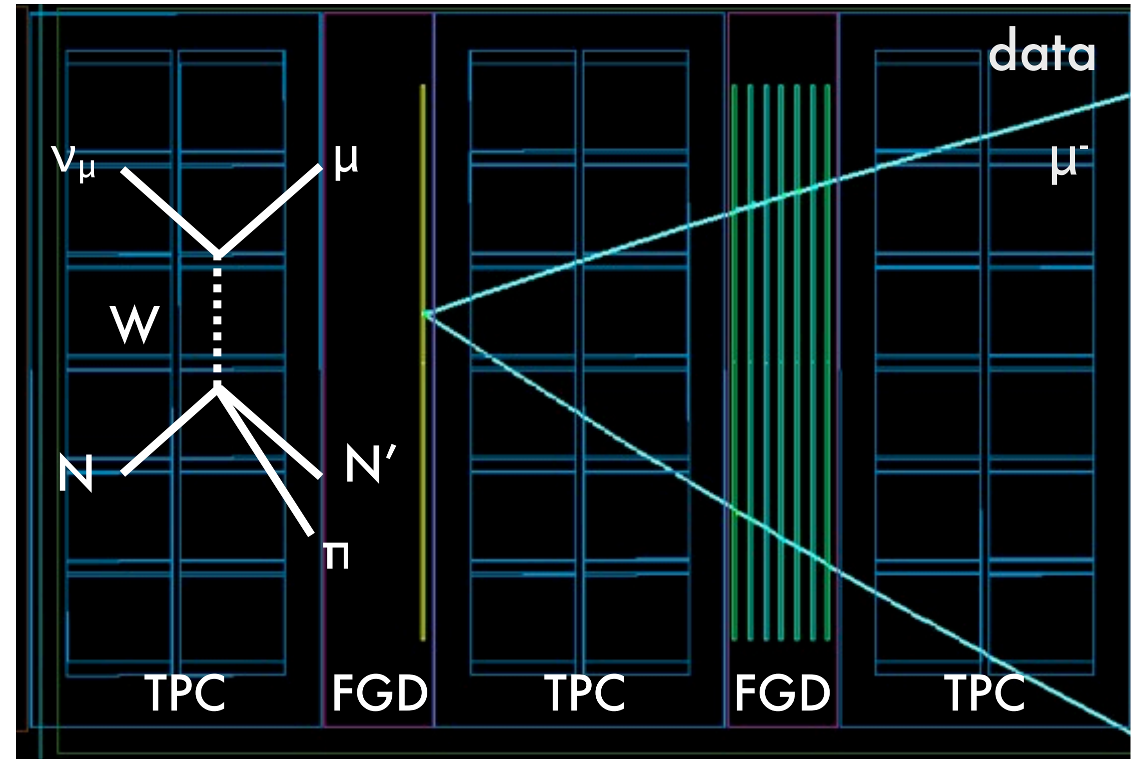


Interaction in ECal

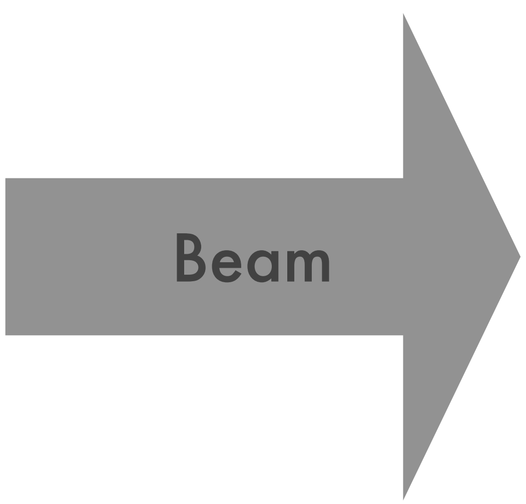
CC0π

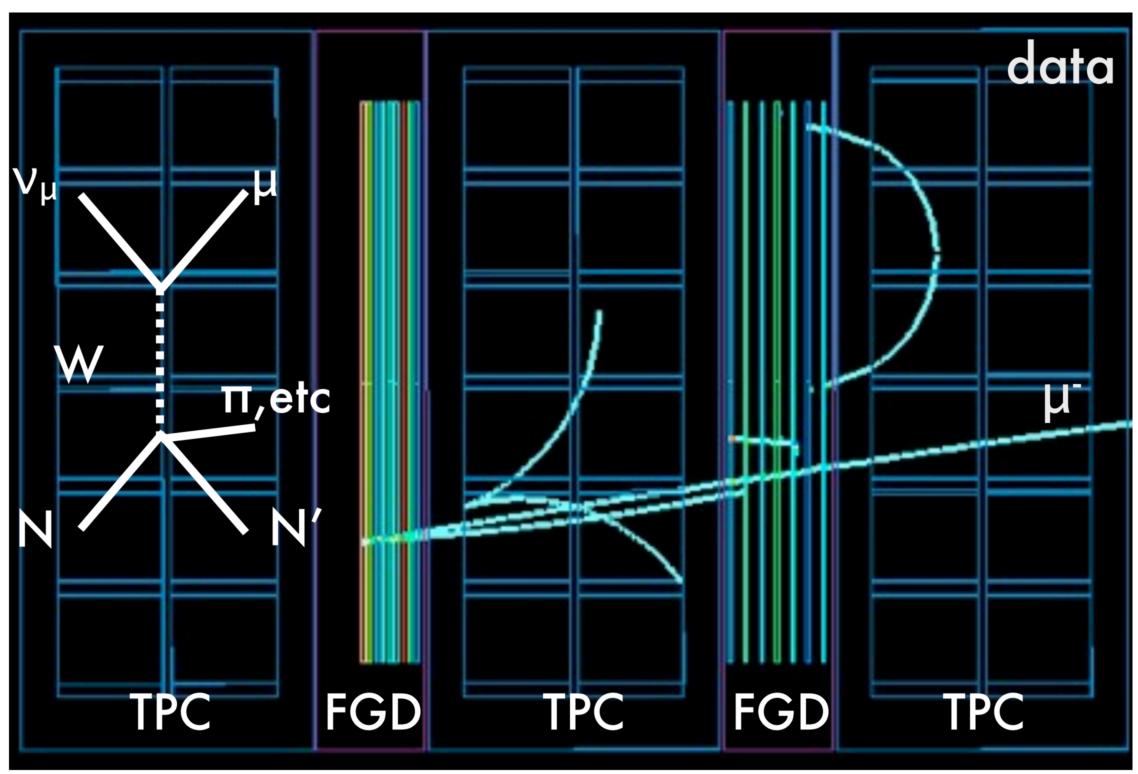


CC1π$^+$

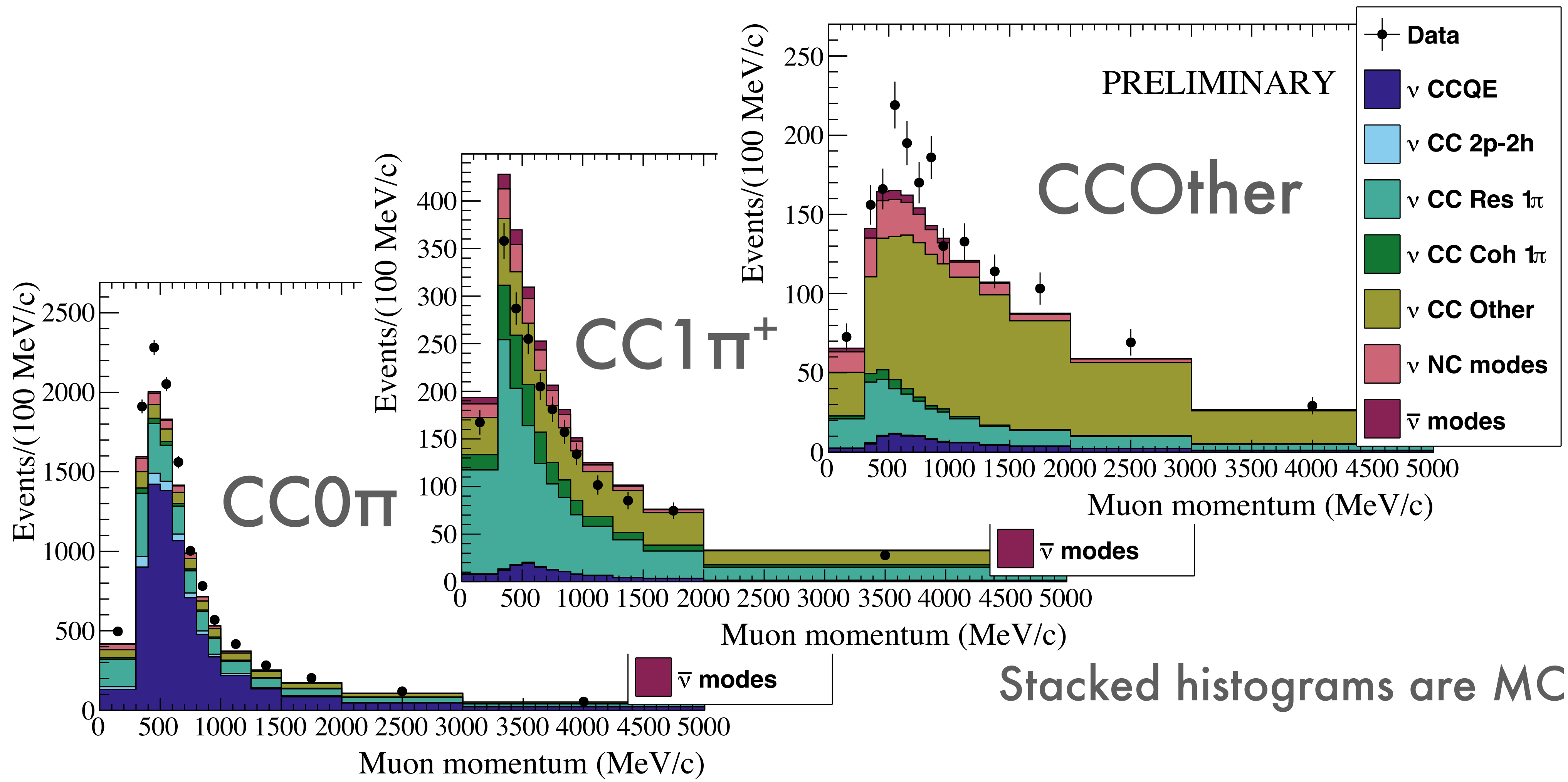


CC other





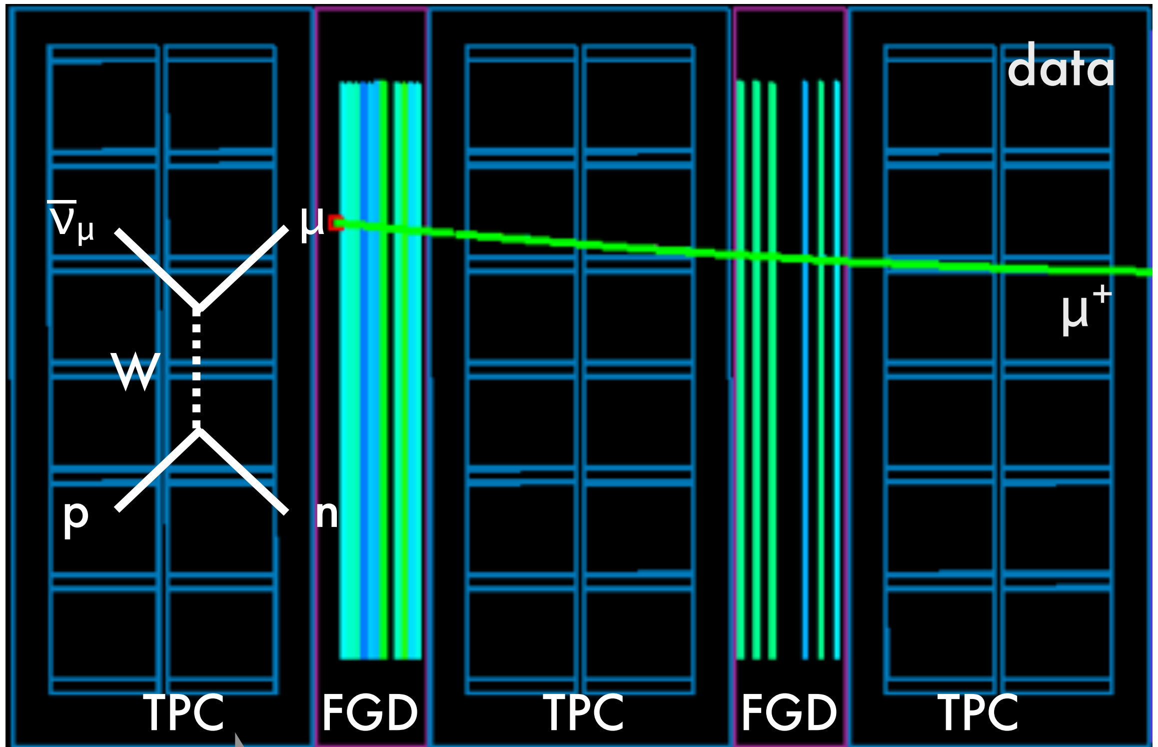
ND280 ν-mode samples



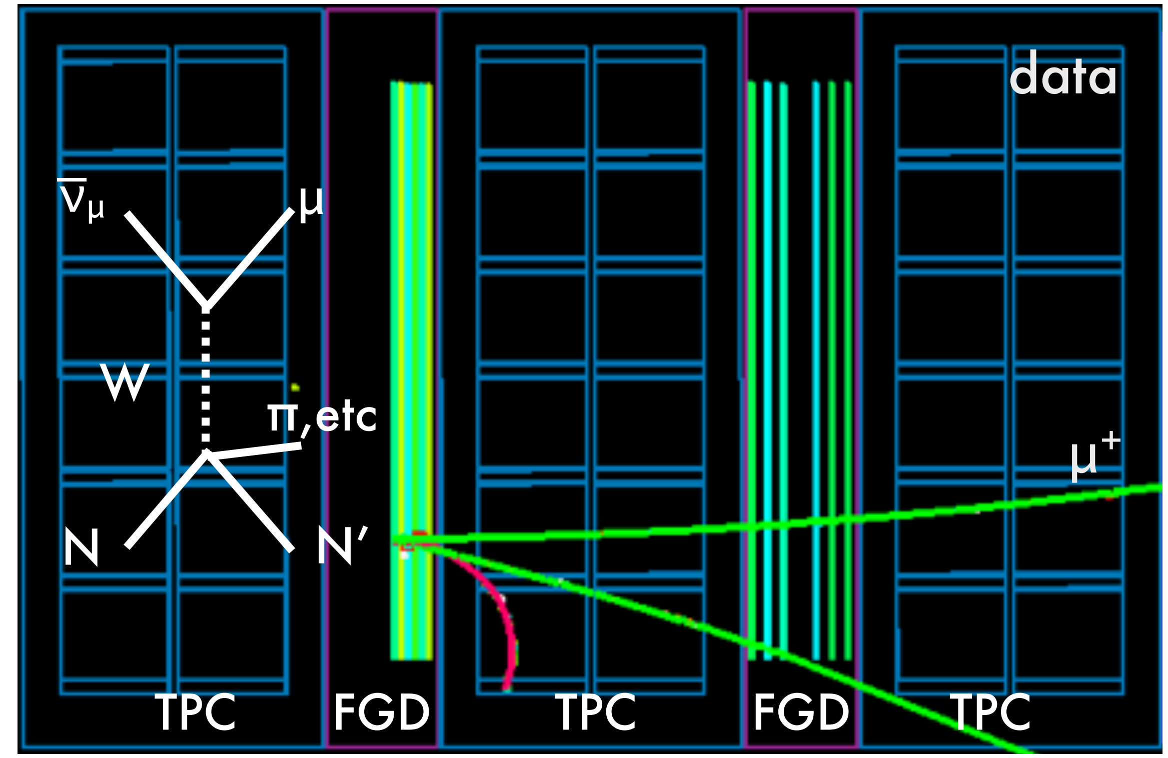
Stacked histograms are MC prefit

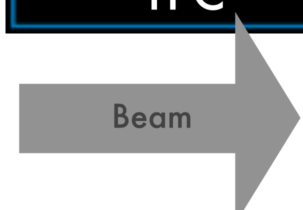
- Three samples allow sensitivity to different beam energies and cross section interaction modes
- High statistics in neutrino mode provide strong constraints
- CC0π and CC Other samples are underestimated by model; CC1π$^+$ is overestimated

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

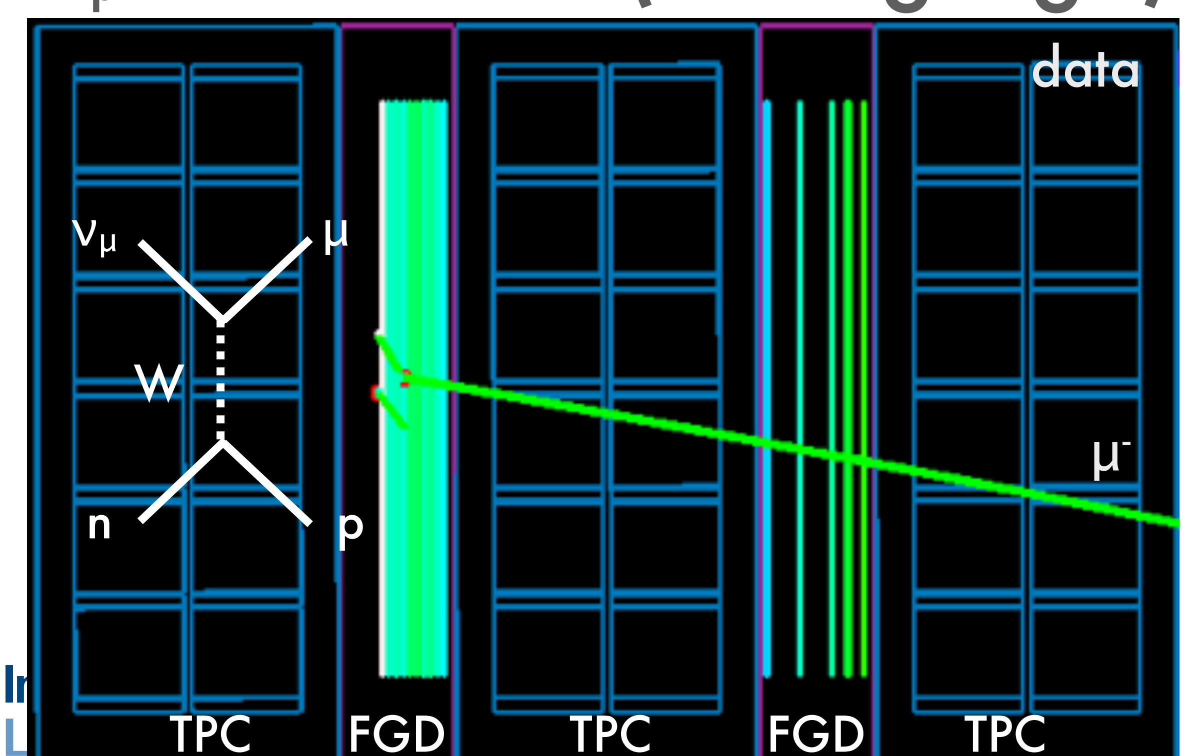


$\bar{\nu}_\mu$ CC-NTrack

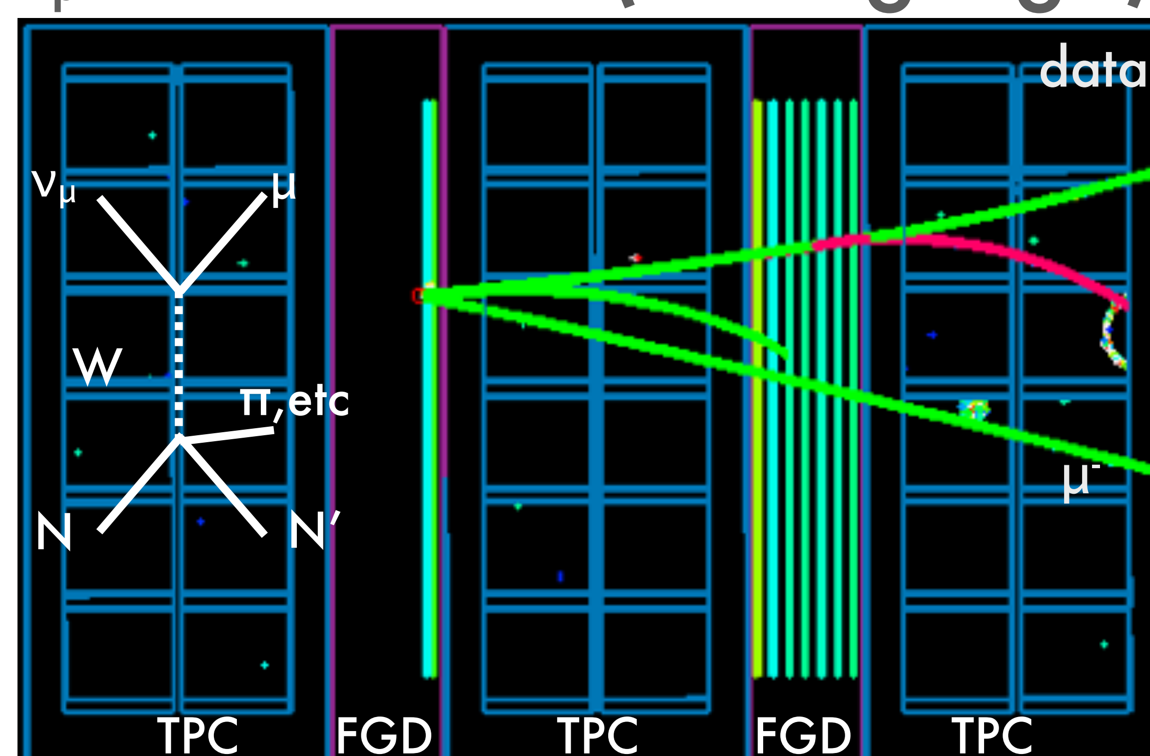




ν_μ CC-1Track (wrong sign)

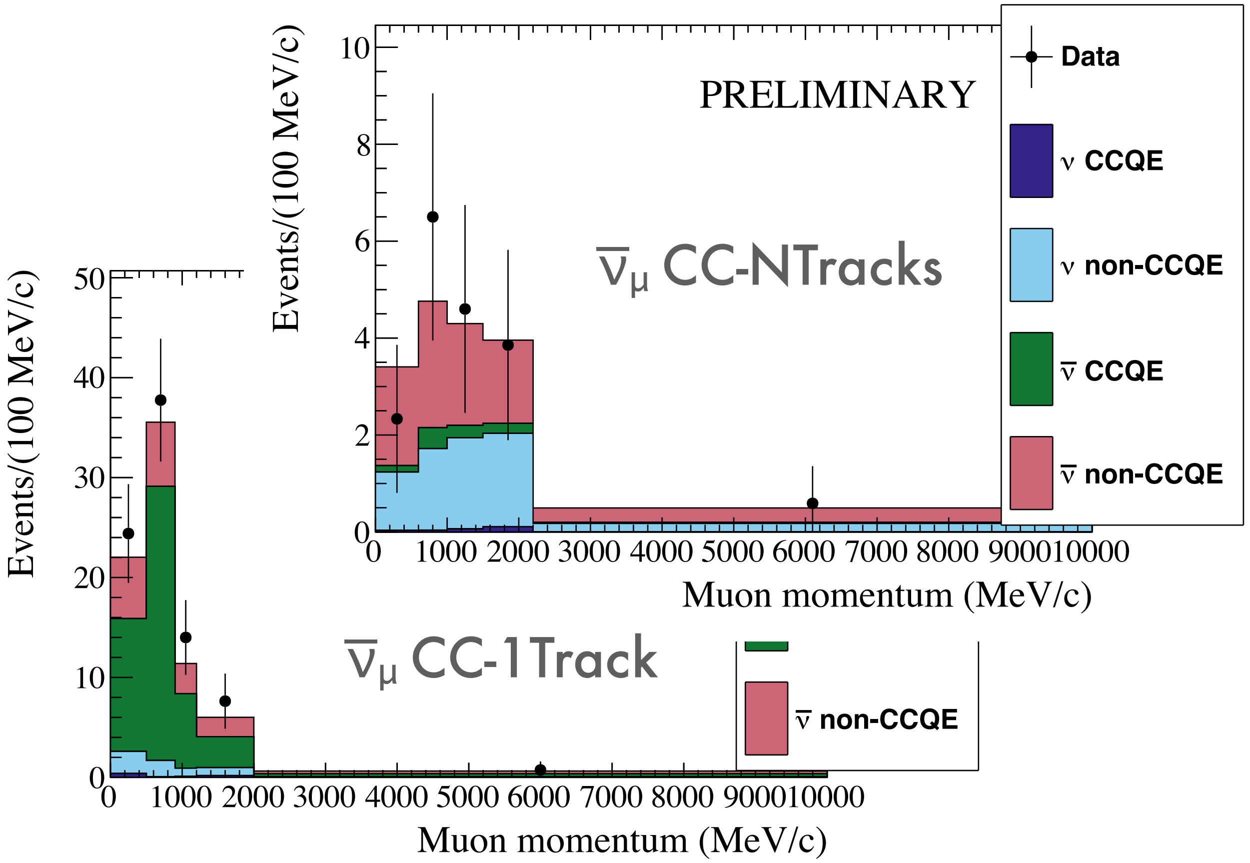


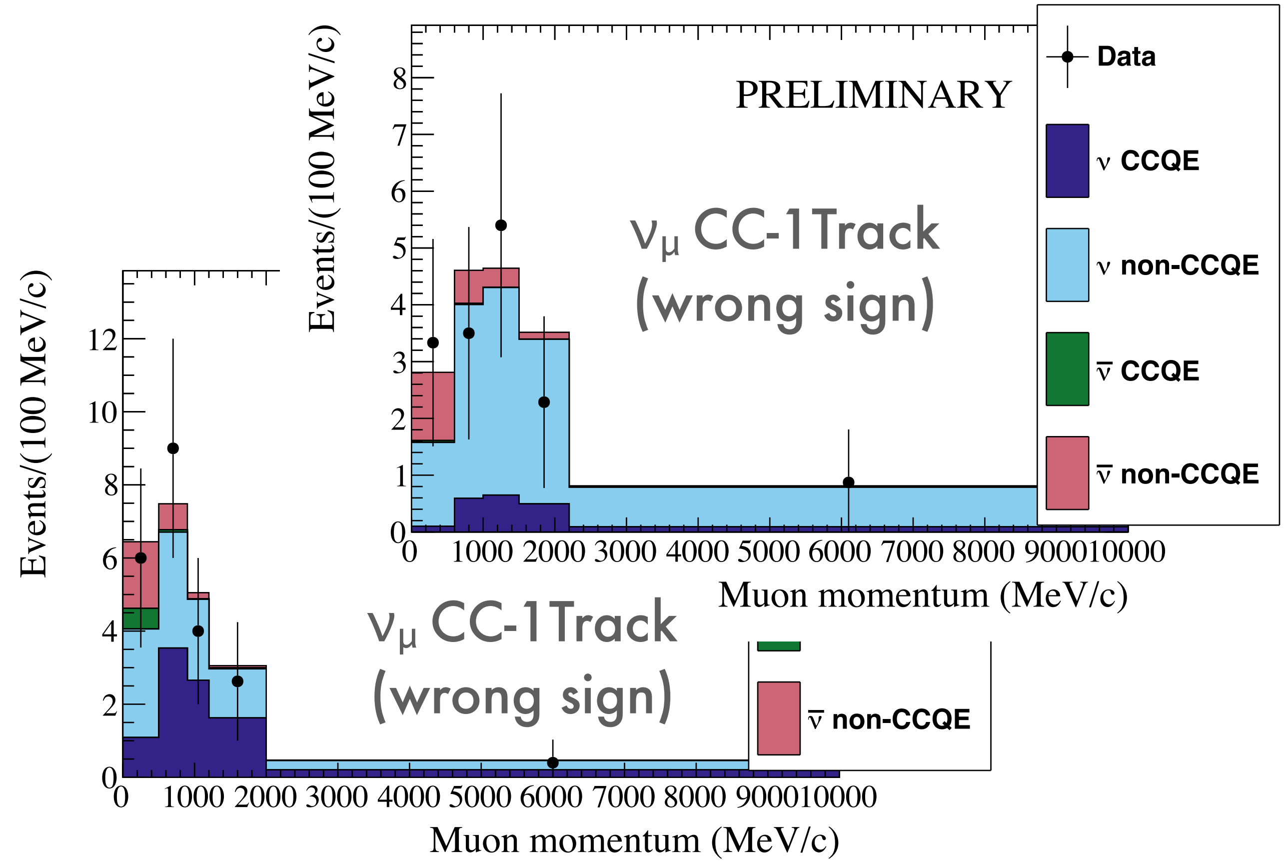
ν_μ CC-NTrack (wrong sign)



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

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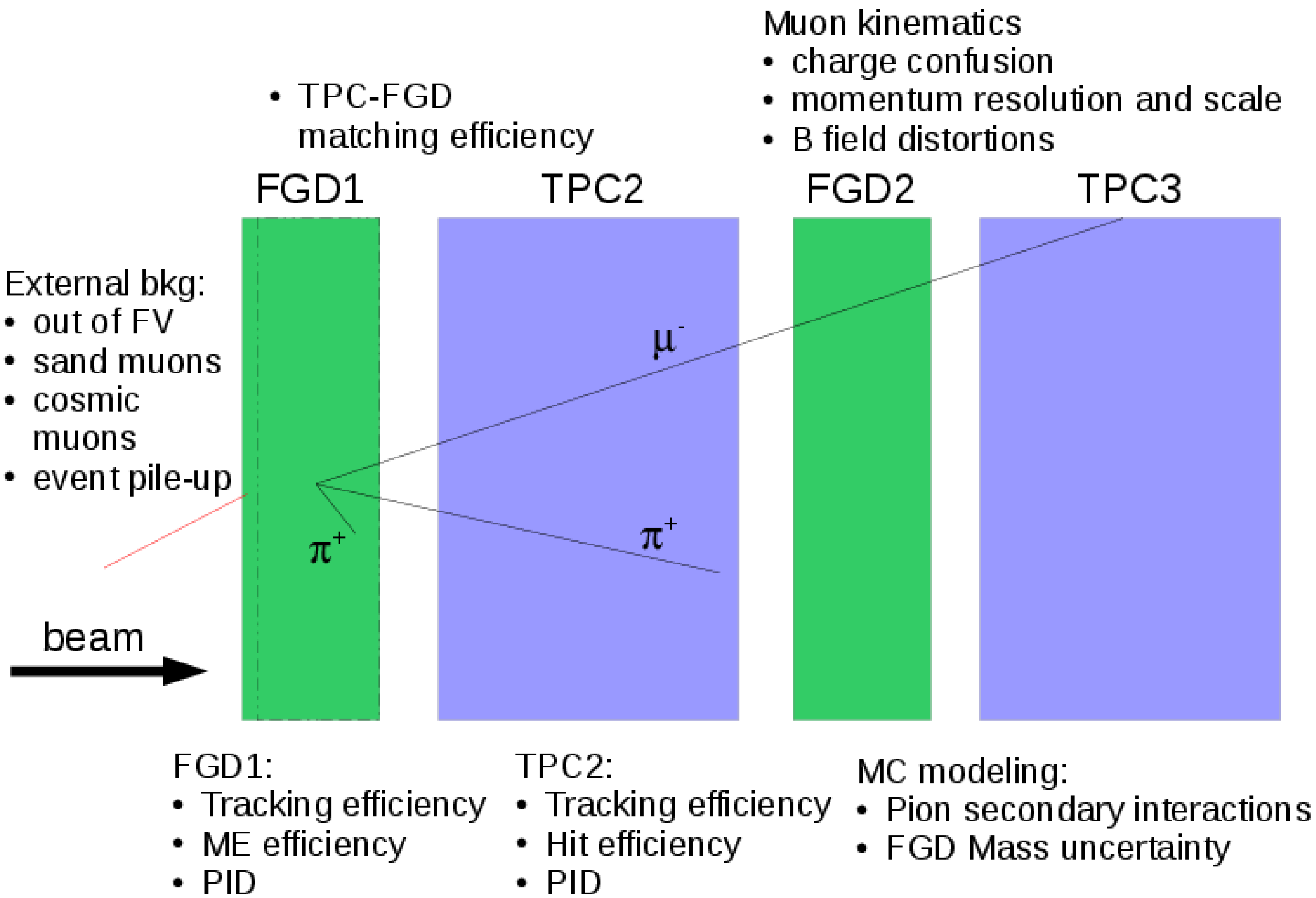
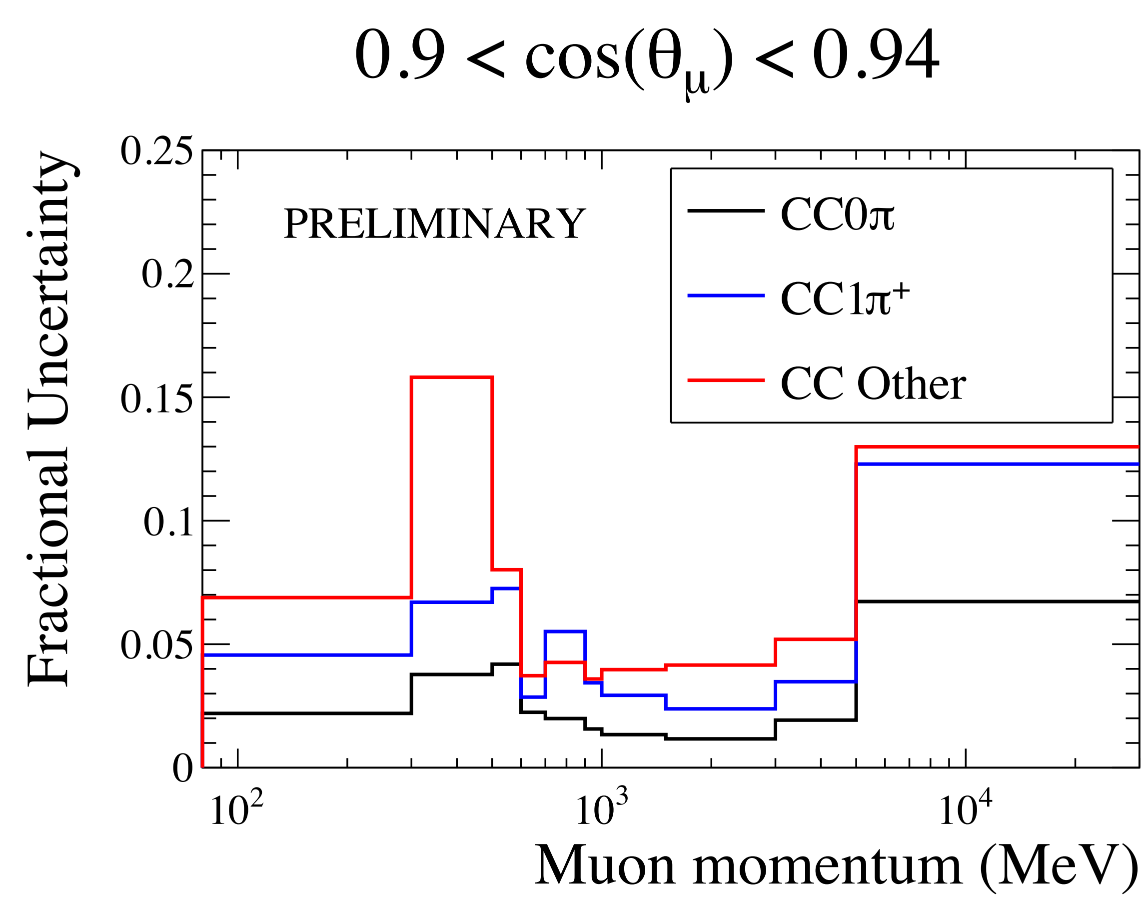
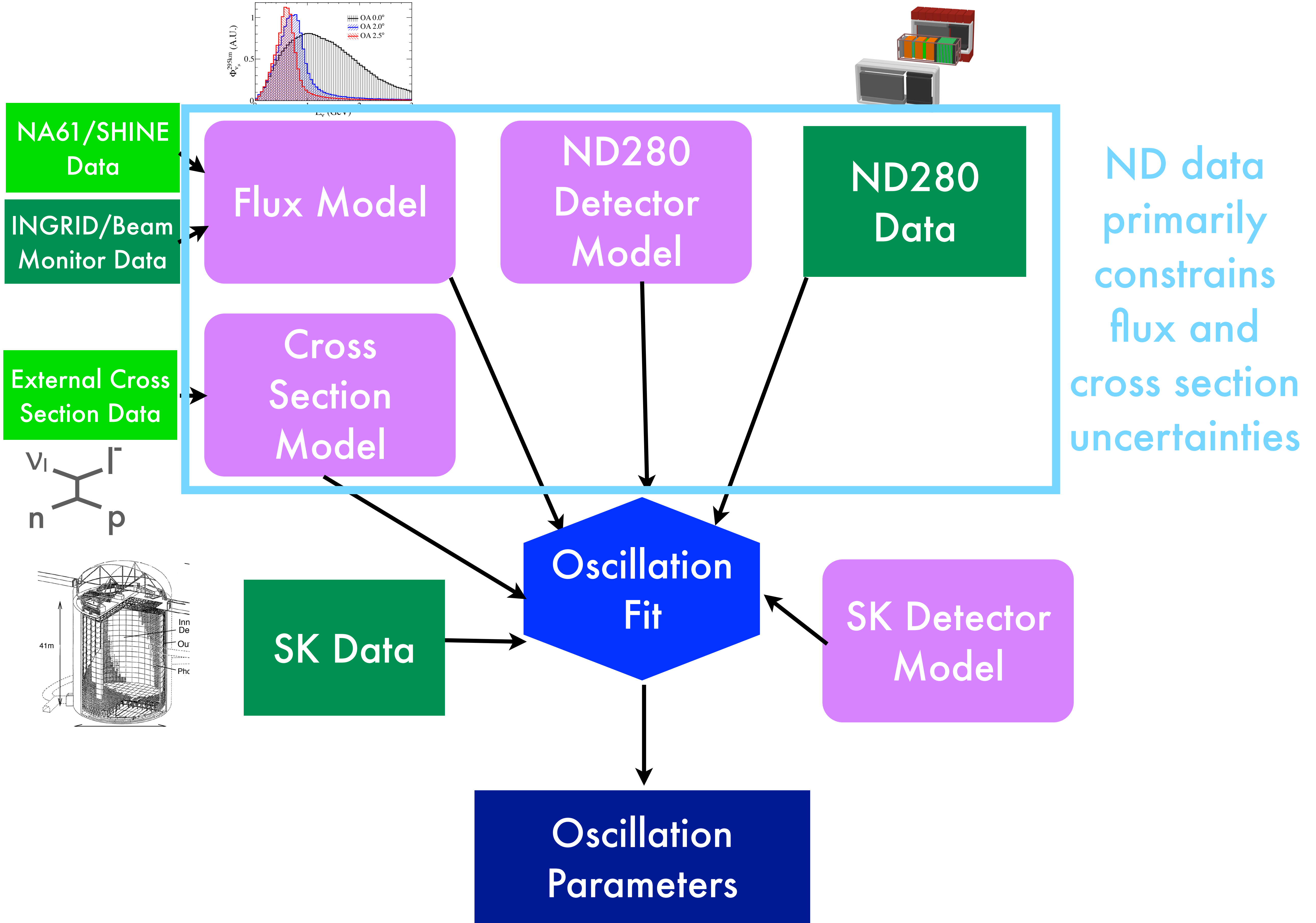
ND280 Detector Model



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

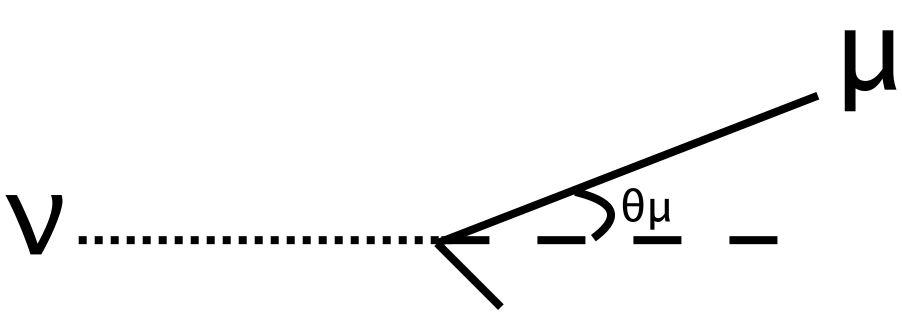


Dominant systematics are pion secondary interactions, MC statistics, and out of fiducial volume events


NA61/SHINE Data
INGRID/Beam Monitor Data
External Cross Section Data
Flux Model
ND280 Detector Model
ND280 Data
Cross Section Model
ND data primarily constrains flux and cross section uncertainties
OA 0.0°
OA 2.0°
OA 2.5°
Oscillation Fit
SK Data
SK Detector Model
Oscillation Parameters

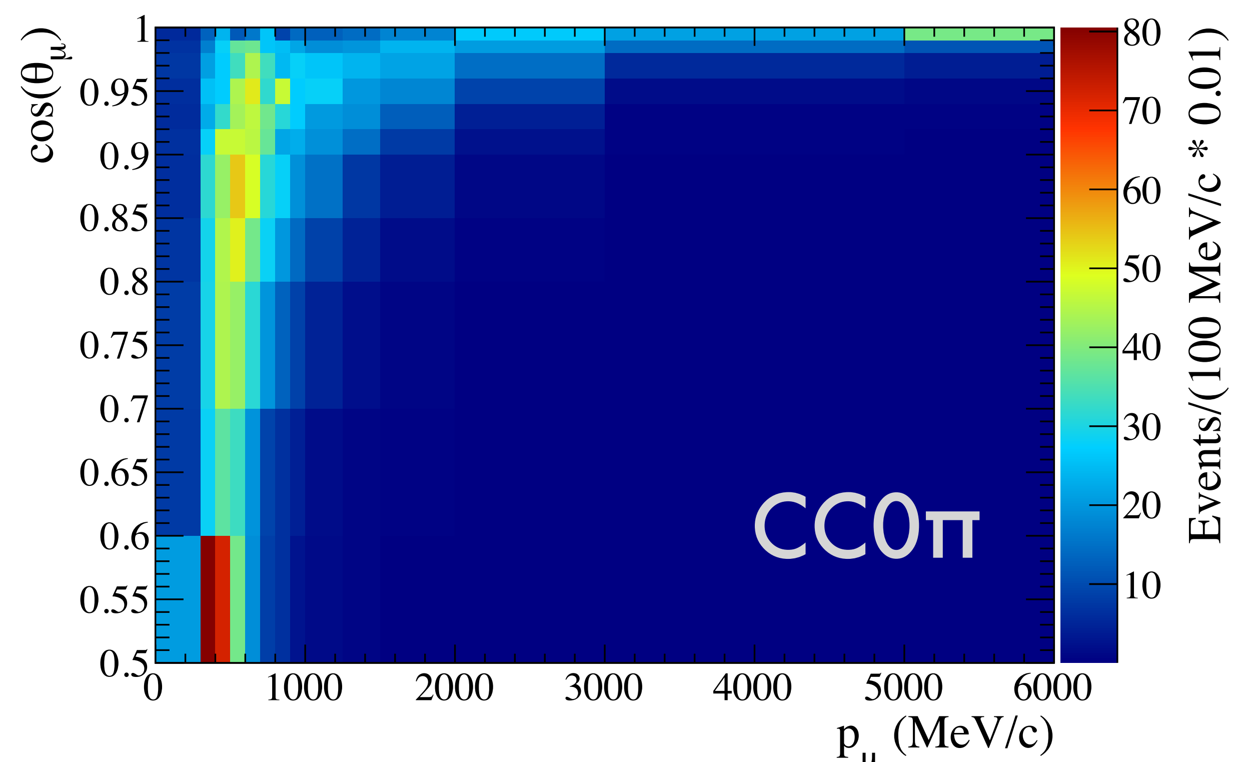
Near Detector Analysis

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



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



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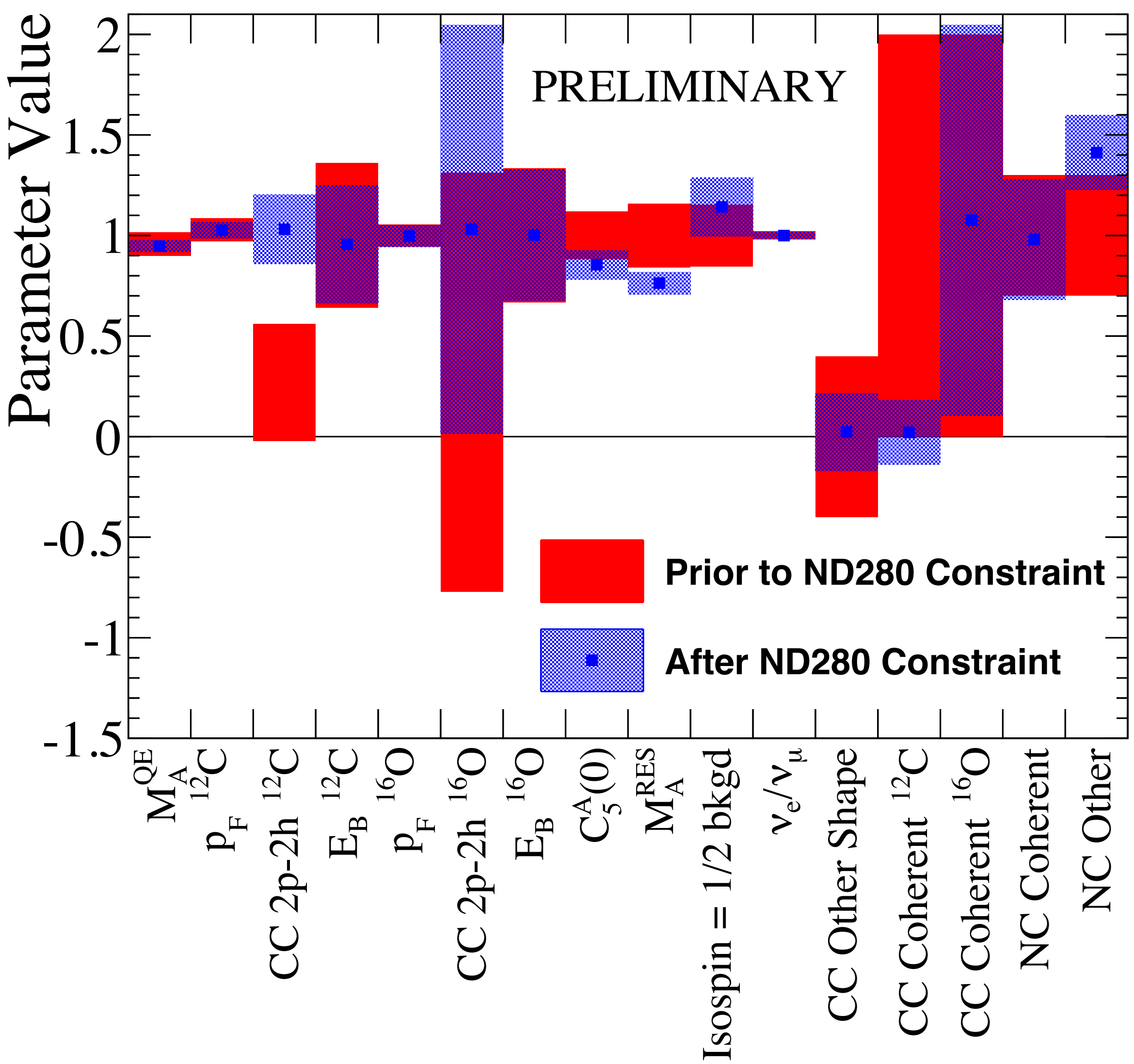
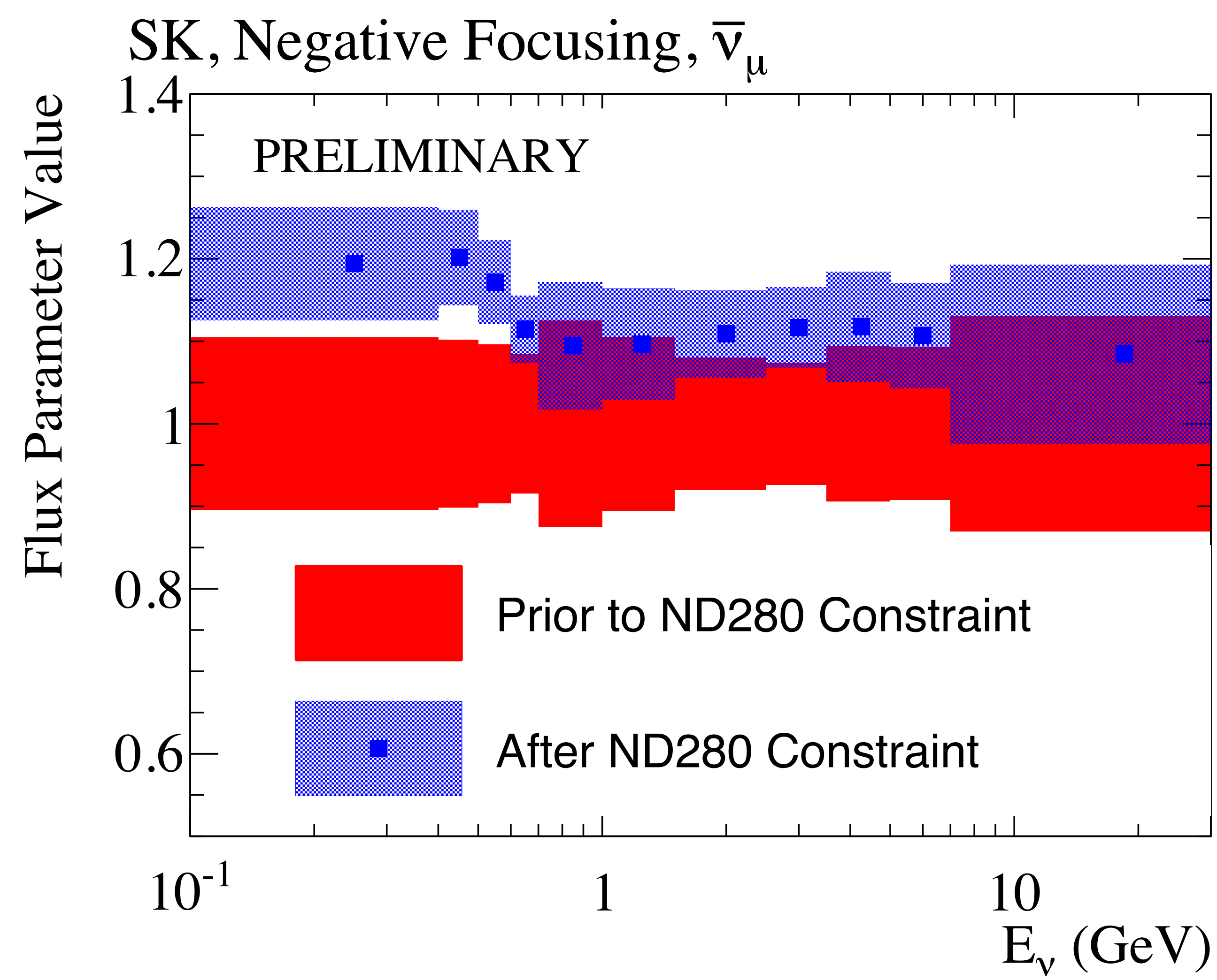
Near Detector Results

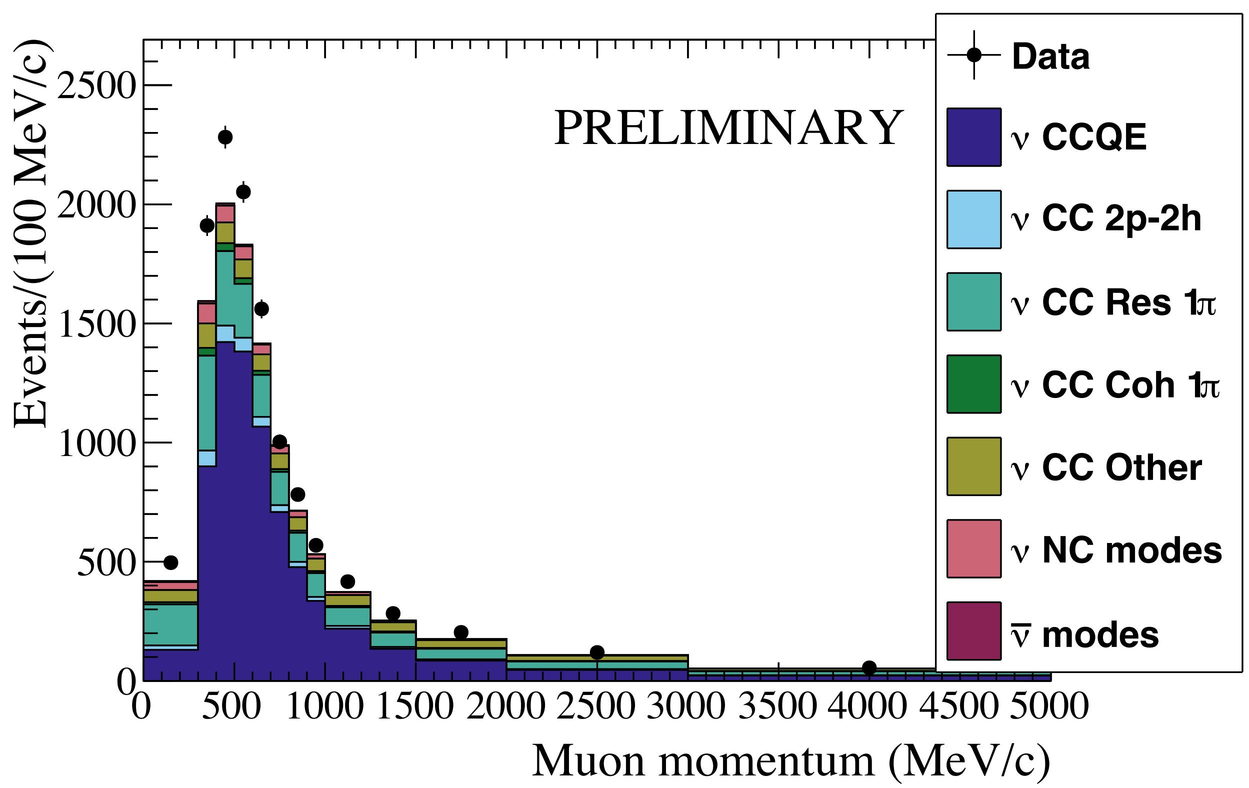
- Flux parameters are generally increased
- Some cross section parameters—especially the carbon multinucleon parameter—are changed significantly from prior values



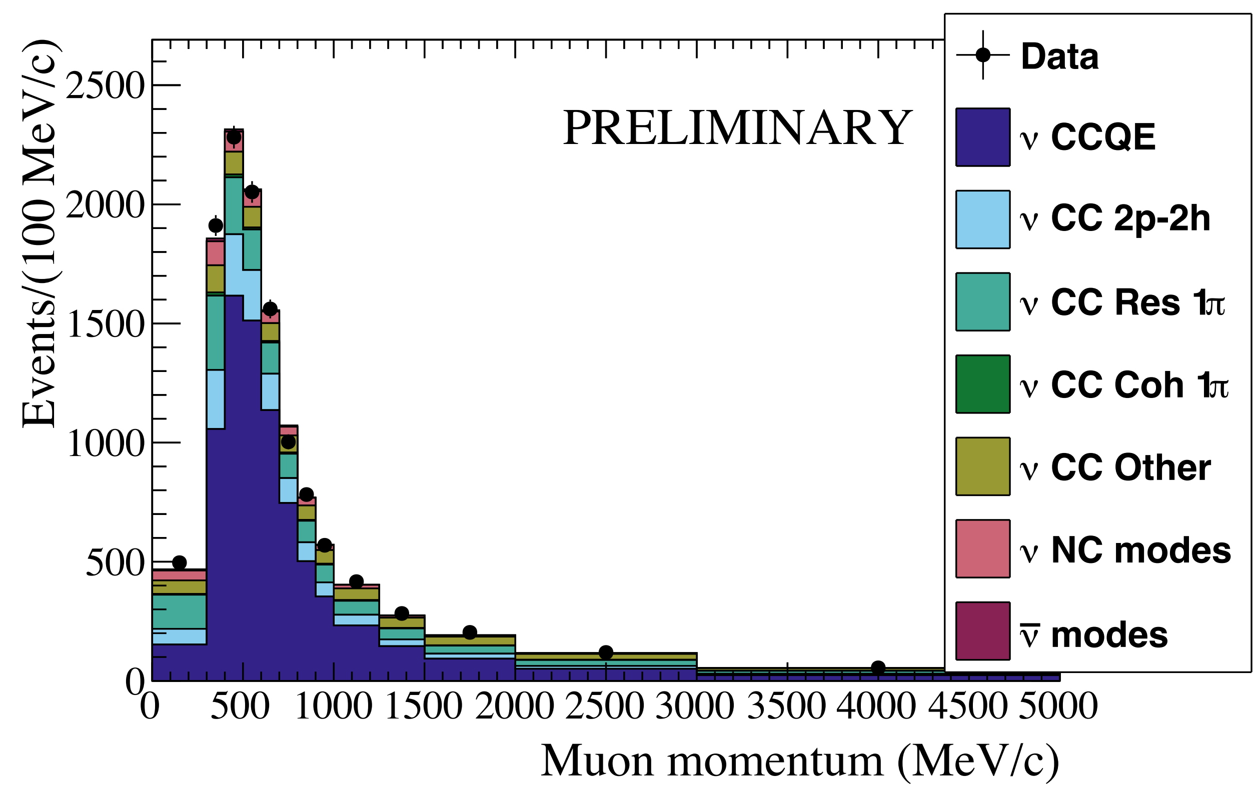


CC0π Samples

Before analysis

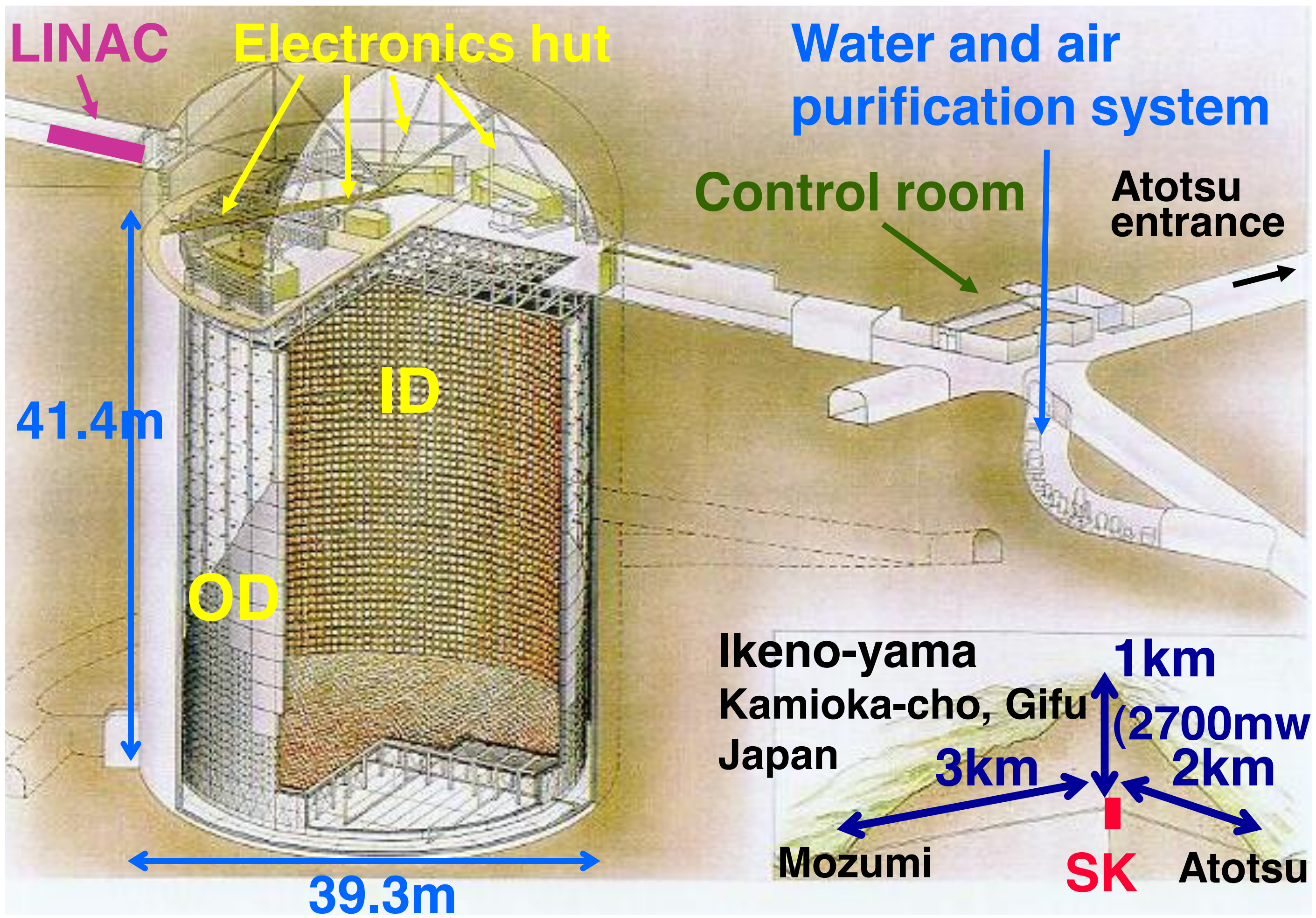


After analysis



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

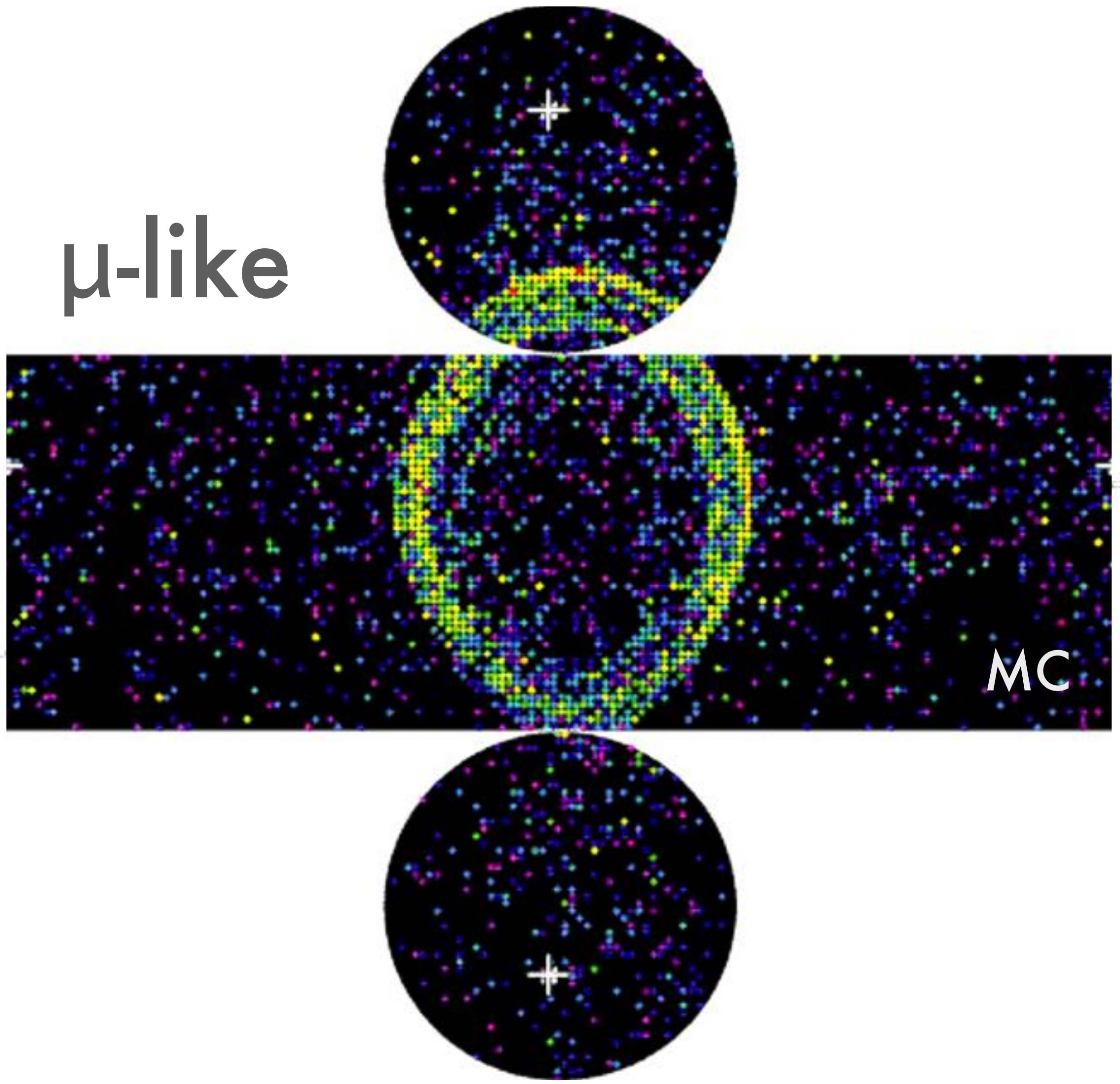
Super-Kamiokande



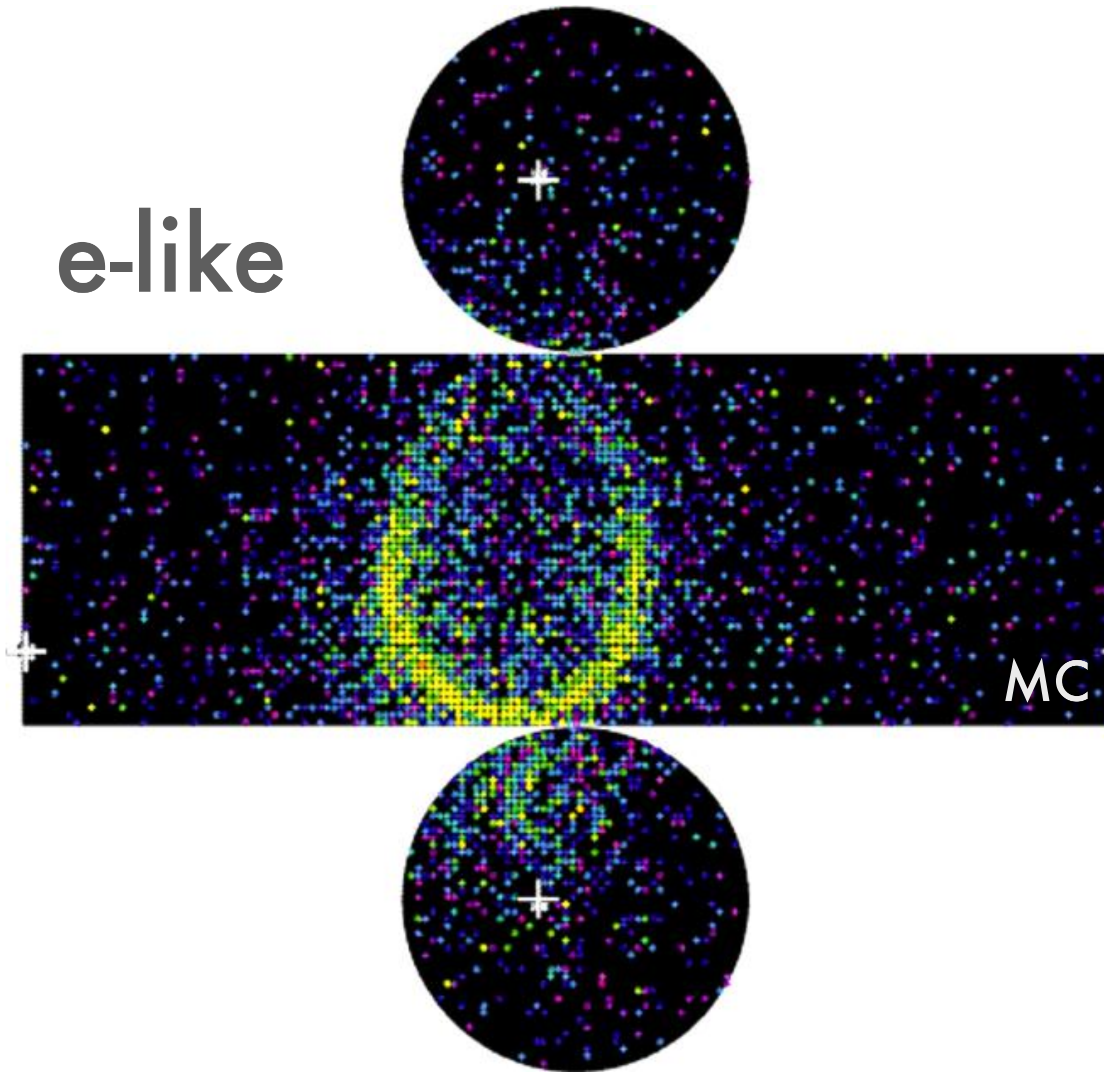
- 50 kton (22.5 kton fiducial volume) water Cherenkov detector
- ~11,000 20" PMT for inner detector (ID) (40% photo coverage)
- ~2,000 outward facing 8" PMT for outer detector (OD): veto cosmics, radioactivity, exiting events

SK Particle Identification

μ-like



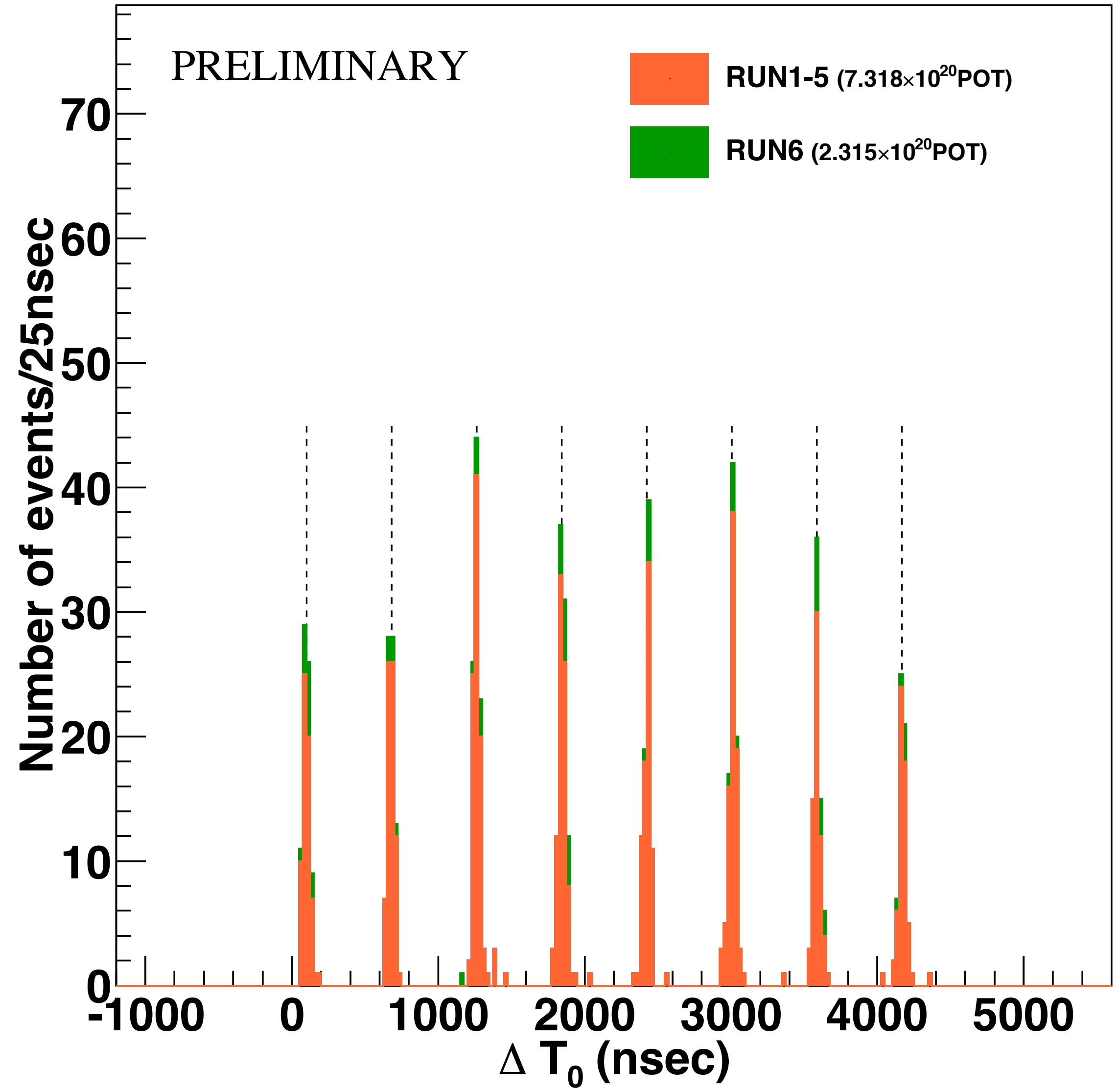
e-like



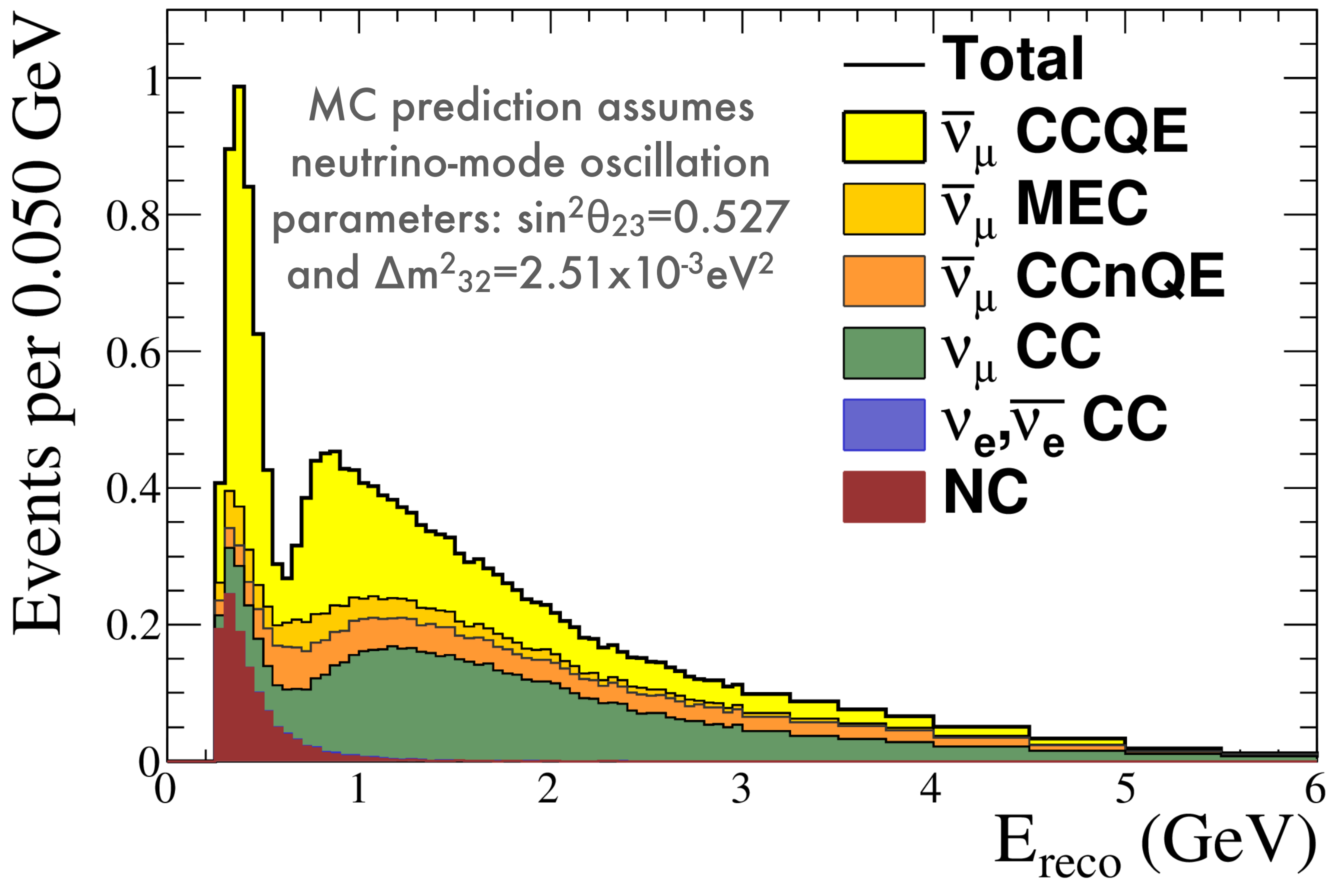
Choose rings which are sharp and clear

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



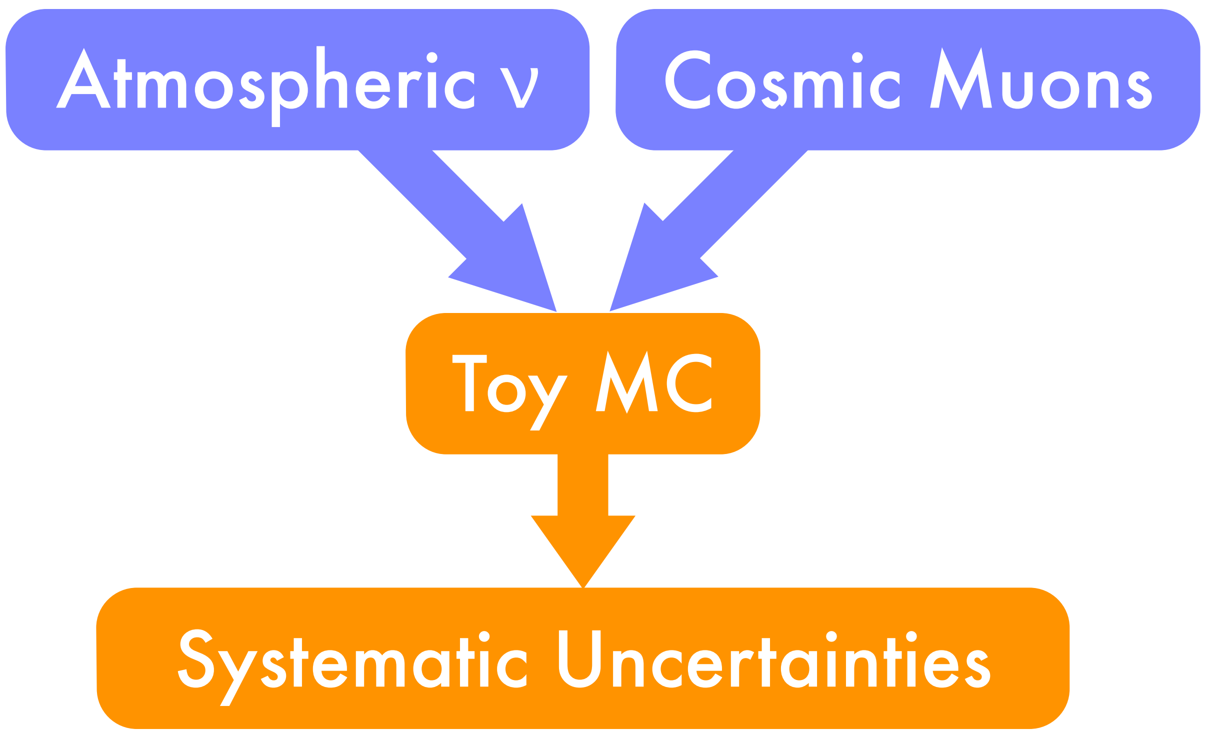
Predicted SK Spectra

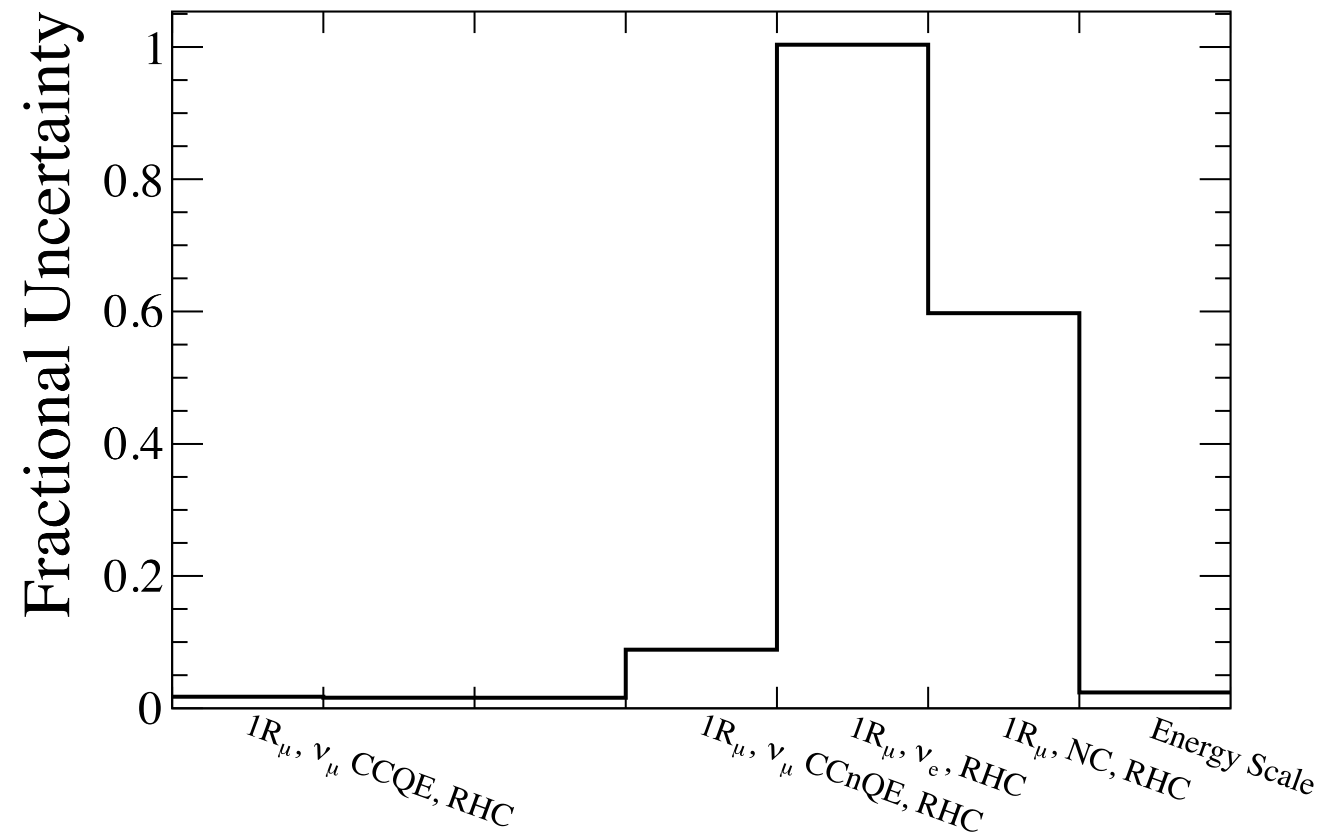


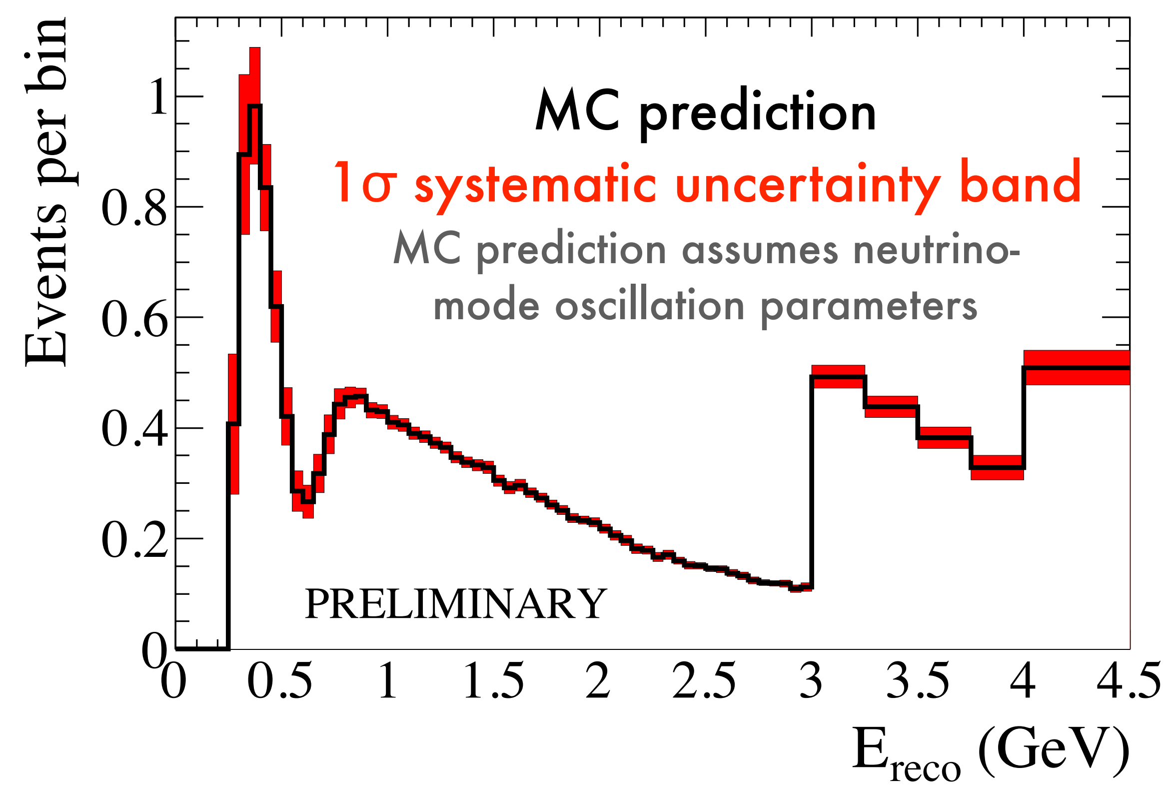
1. Fully contained within the fiducial volume of SK
2. Have one and only one reconstructed ring
3. Have μ-like PID
4. Have muon momentum >200 MeV/c
5. Have one or fewer decay electron

- Predict the expected spectrum at SK using neutrino-mode oscillation parameters
- Dominated by $\bar{\nu}$ CCQE events, but many other contributions—this is why cross section model is so important
- Predict 19.9 events with oscillation and 58.9 without oscillation

SK Detector Systematics



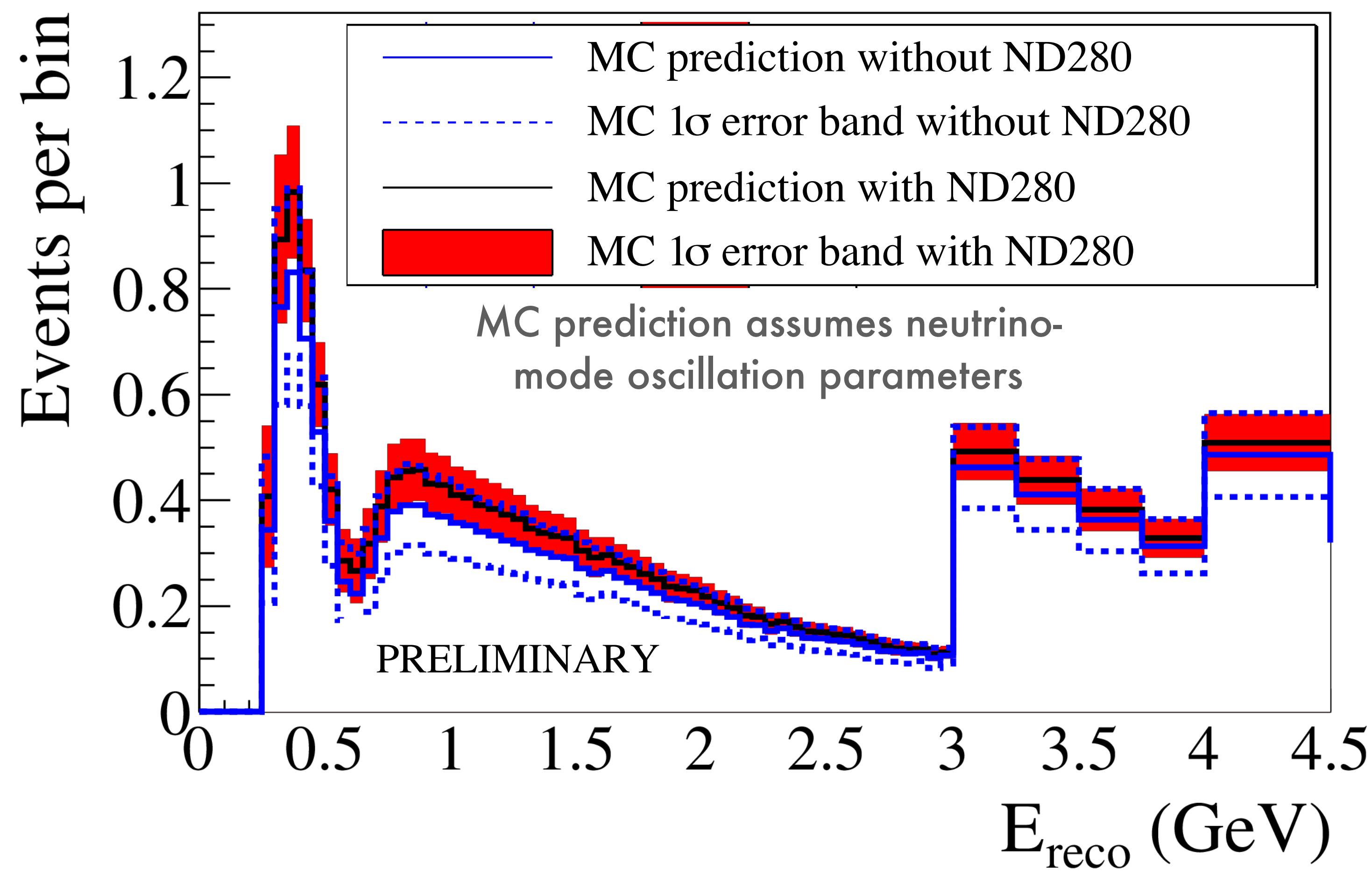




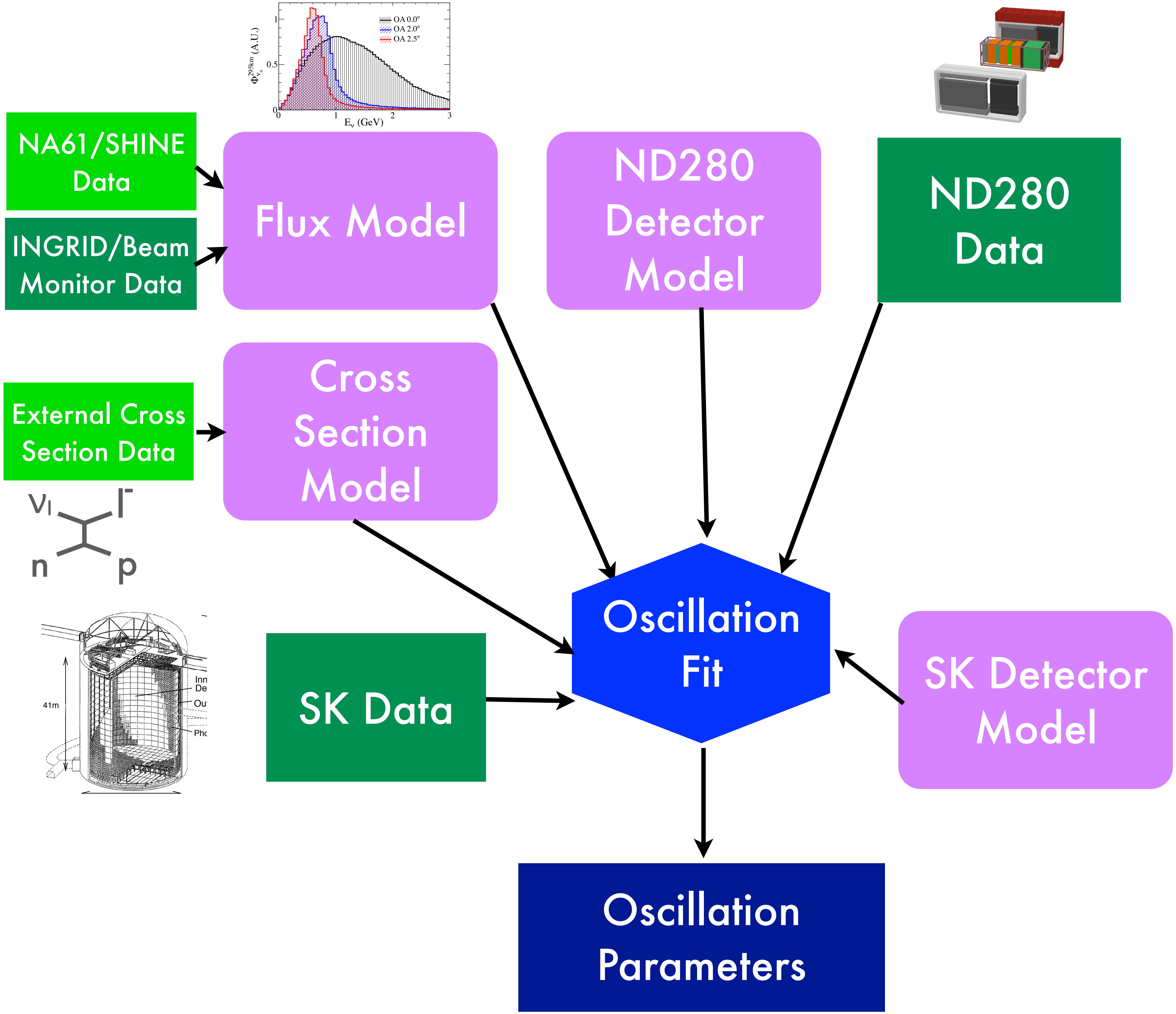
- ν_e uncertainty is largest—but these events are rare
- Neutral current uncertainty dominates at low energy
- Effects are small elsewhere

Total Systematic Uncertainties

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



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%


OA 0.0°
OA 2.0°
OA 2.5°
E_ν (GeV)
NA61/SHINE Data
INGRID/Beam Monitor Data
Flux Model
ND280 Detector Model
ND280 Data
External Cross Section Data
Cross Section Model
ν_l
l⁻
n
p
41m
SK Data
Oscillation Fit
SK Detector Model
Oscillation Parameters

Analysis Method

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

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

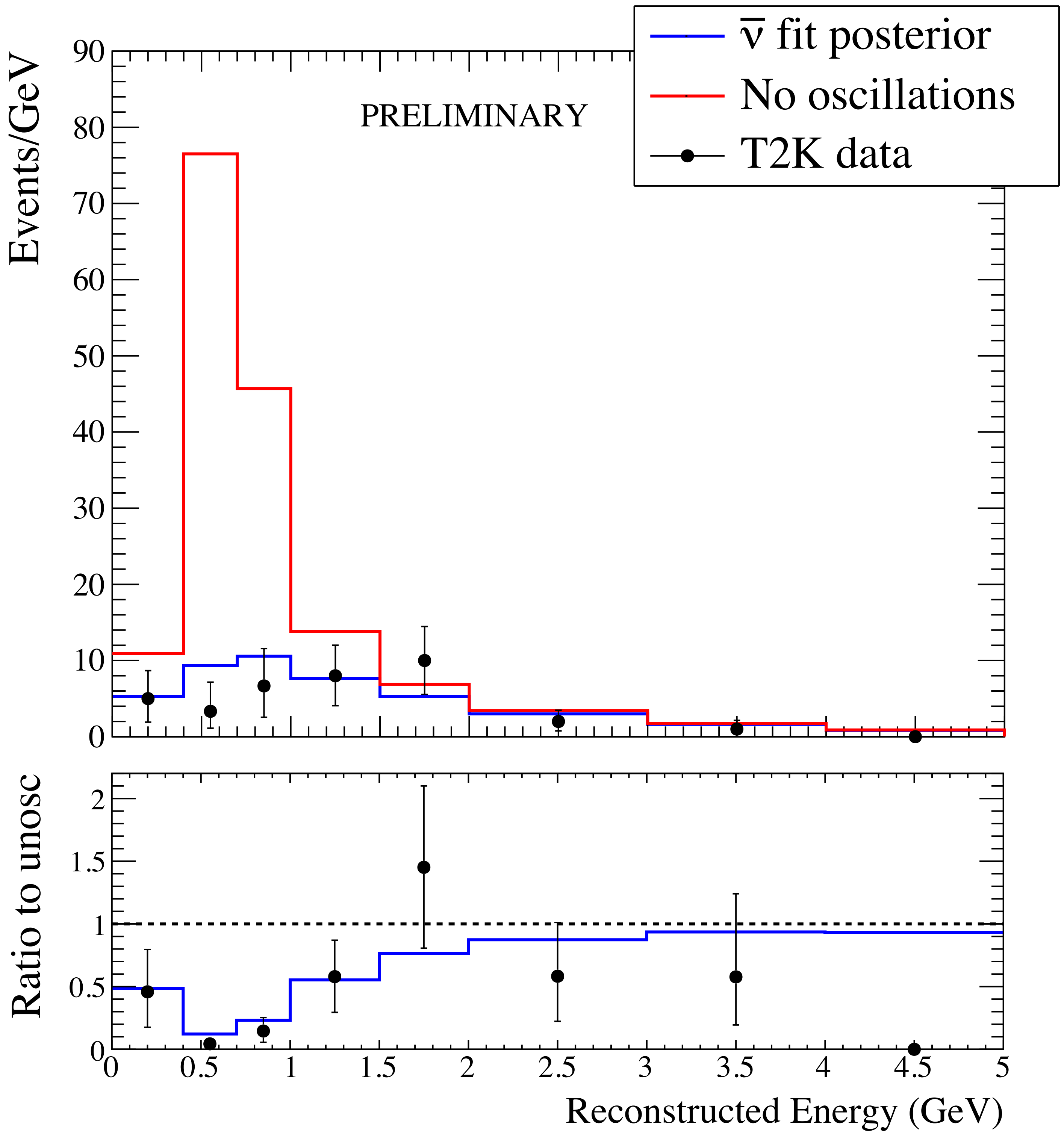
Fix all oscillation parameters except $\sin^2\bar{\theta}_{23}$ and $\Delta\bar{m}^2_{32}$ using T2K neutrino data and PDG 2014

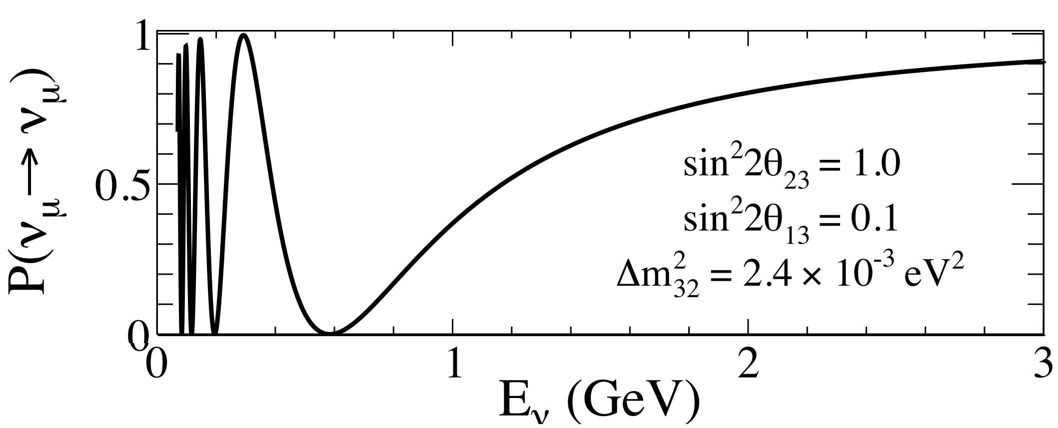
$\sin^2\theta_{23}$	0.527	$\sin^2\bar{\theta}_{23}$	0–1
Δm^2_{32}	2.51×10^{-3} eV^2	$\Delta\bar{m}^2_{32}$	0–0.02 eV^2
$\sin^2\theta_{13}$	0.0248	$\sin^2\bar{\theta}_{13}$	0.0248
$\sin^2\theta_{12}$	0.304	$\sin^2\bar{\theta}_{12}$	0.304
Δm^2_{21}	7.53×10^{-5} eV^2	$\Delta\bar{m}^2_{21}$	7.53×10^{-5}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

Results!

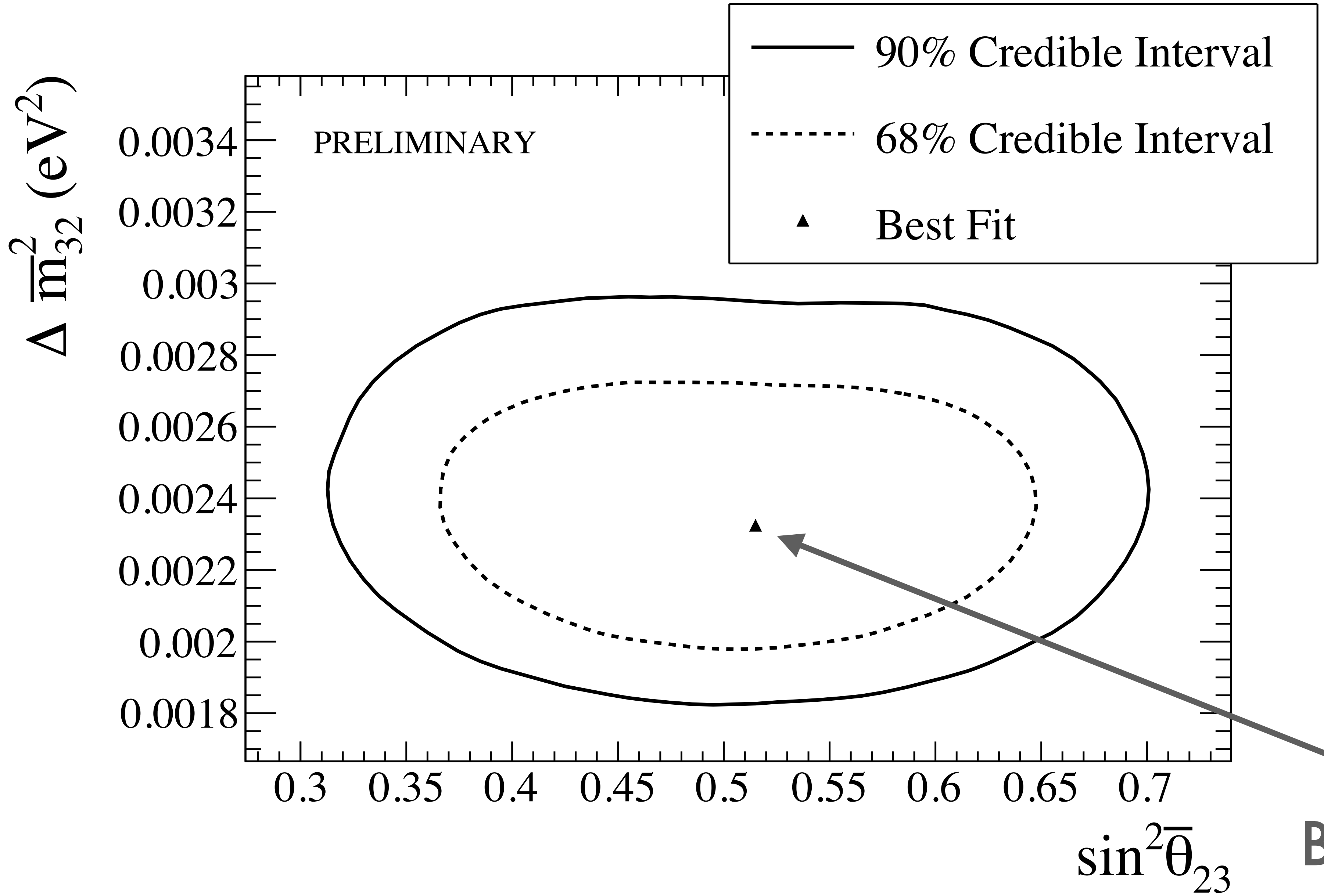
Best Fit Spectrum

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





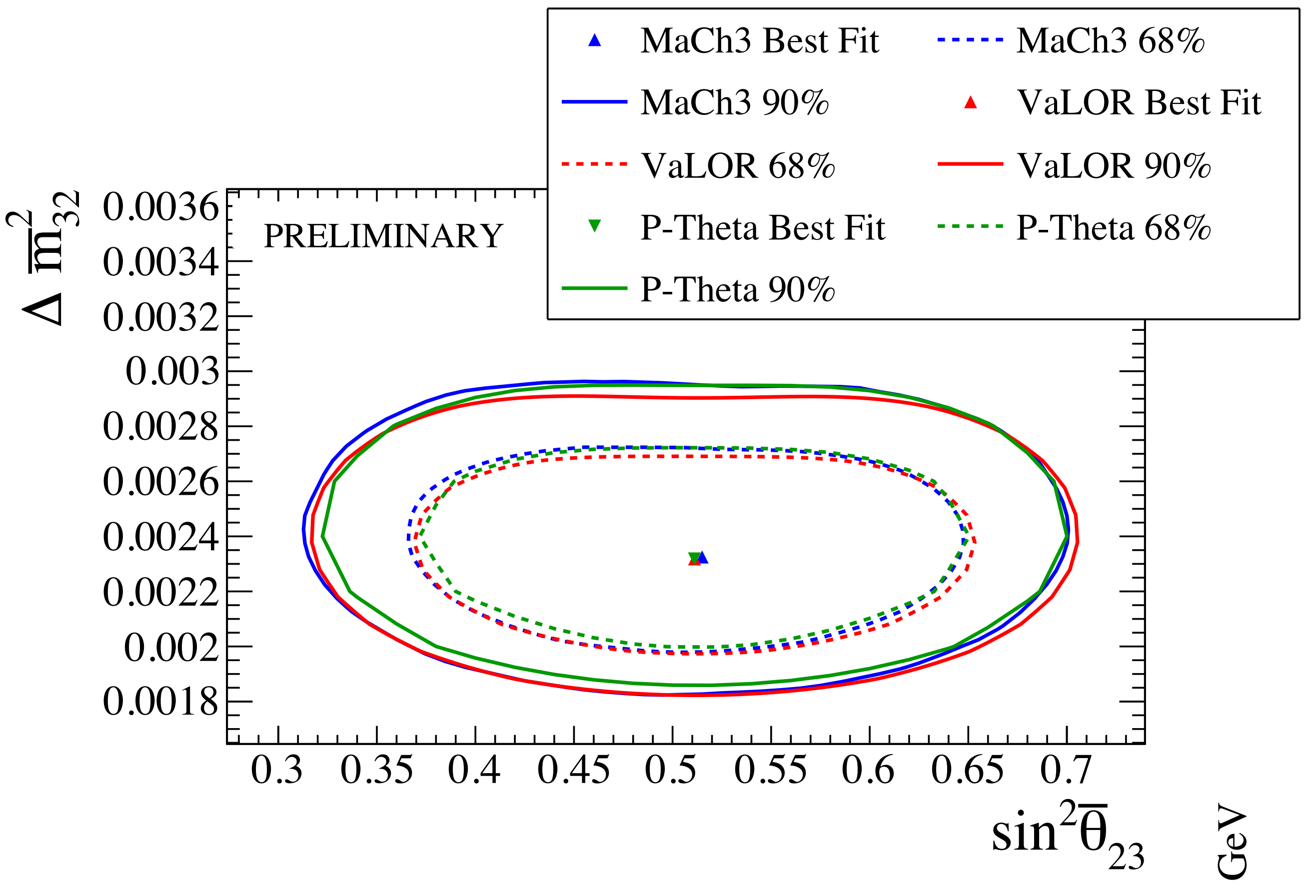
Oscillation Parameters



Best fit is near maximal disappearance

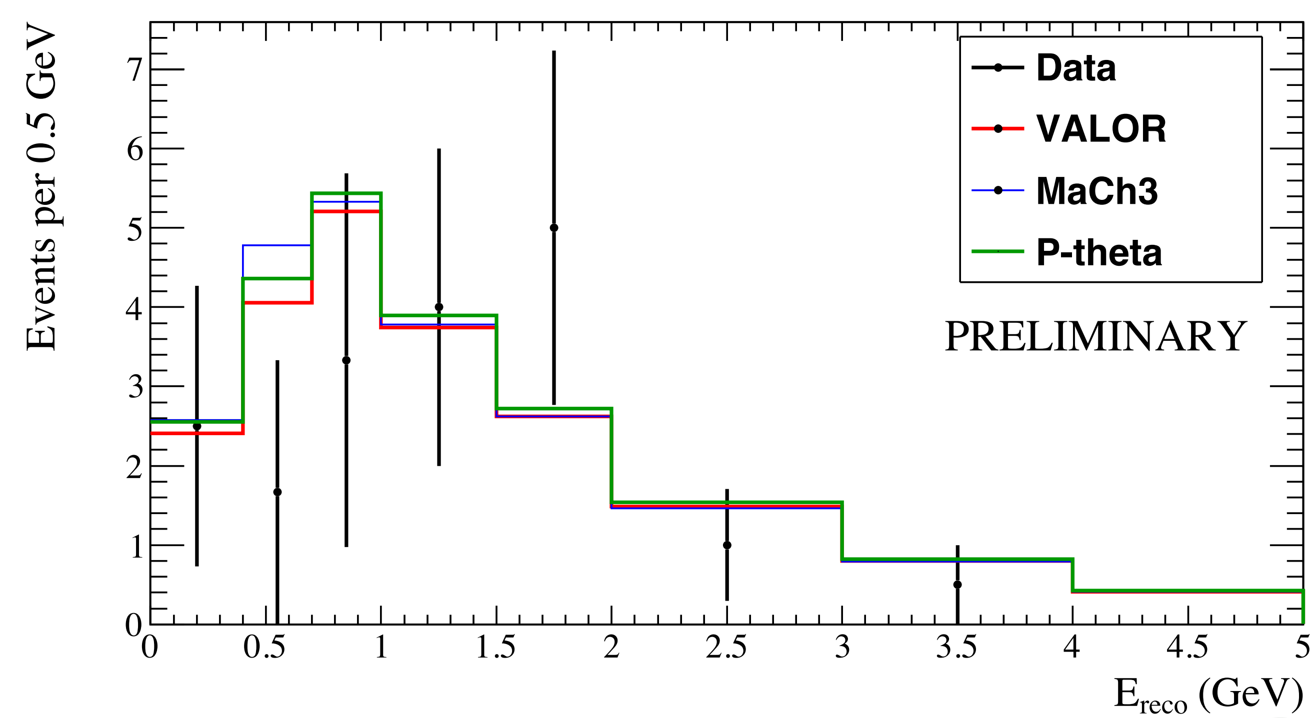
$\lvert\Delta\bar{m}^2_{32}\rvert$	$\sin^2(\bar{\theta}_{23})$
$2.33^{+0.27}_{-0.23}\ \times 10^{-3}\ \text{eV}^2$	$0.515^{+0.085}_{-0.095}$

Analysis Comparison



T2K performs three different analyses with different methods of maximizing likelihood

Analyses are in good agreement



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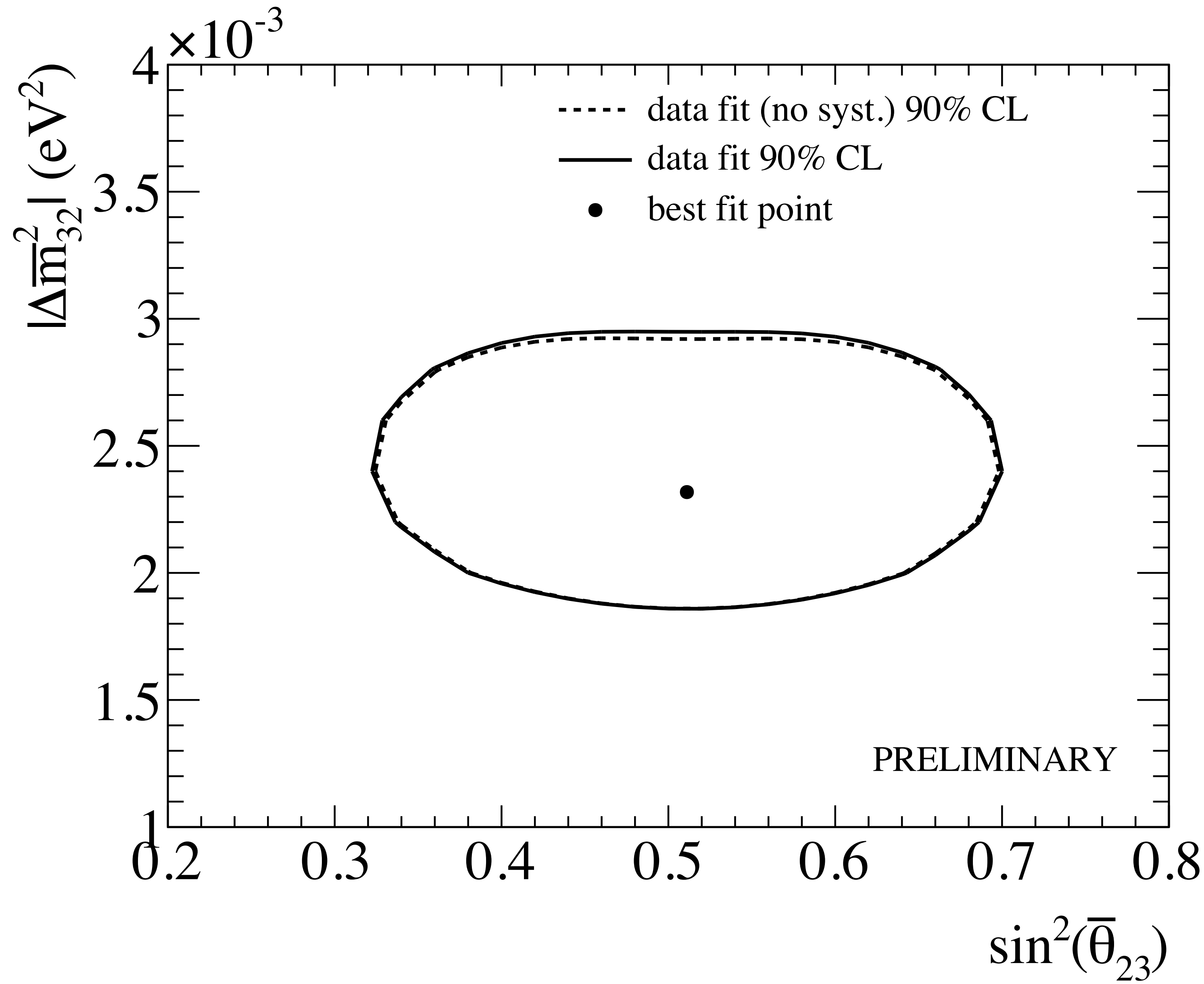
Impact of Systematic Uncertainty

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



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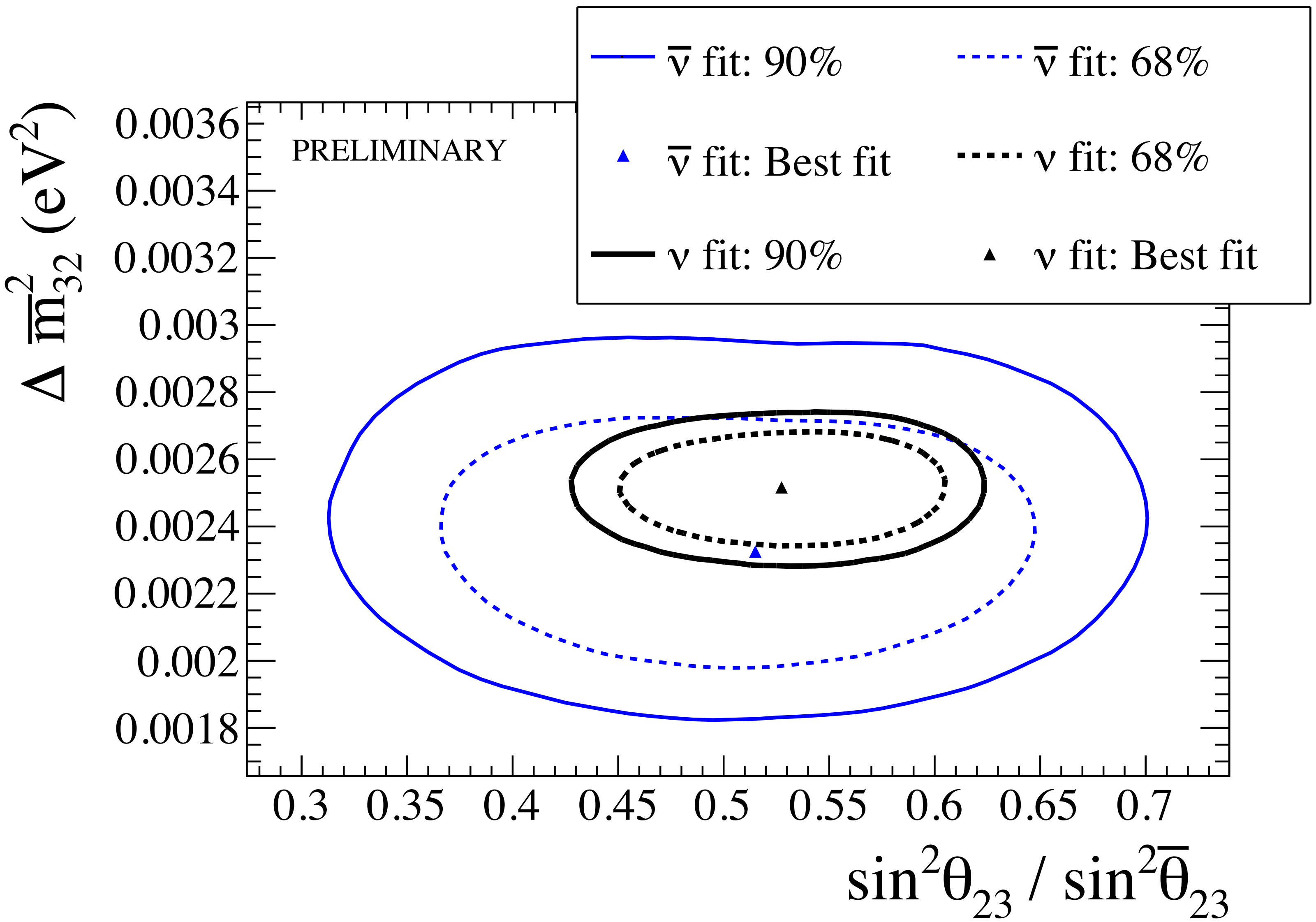
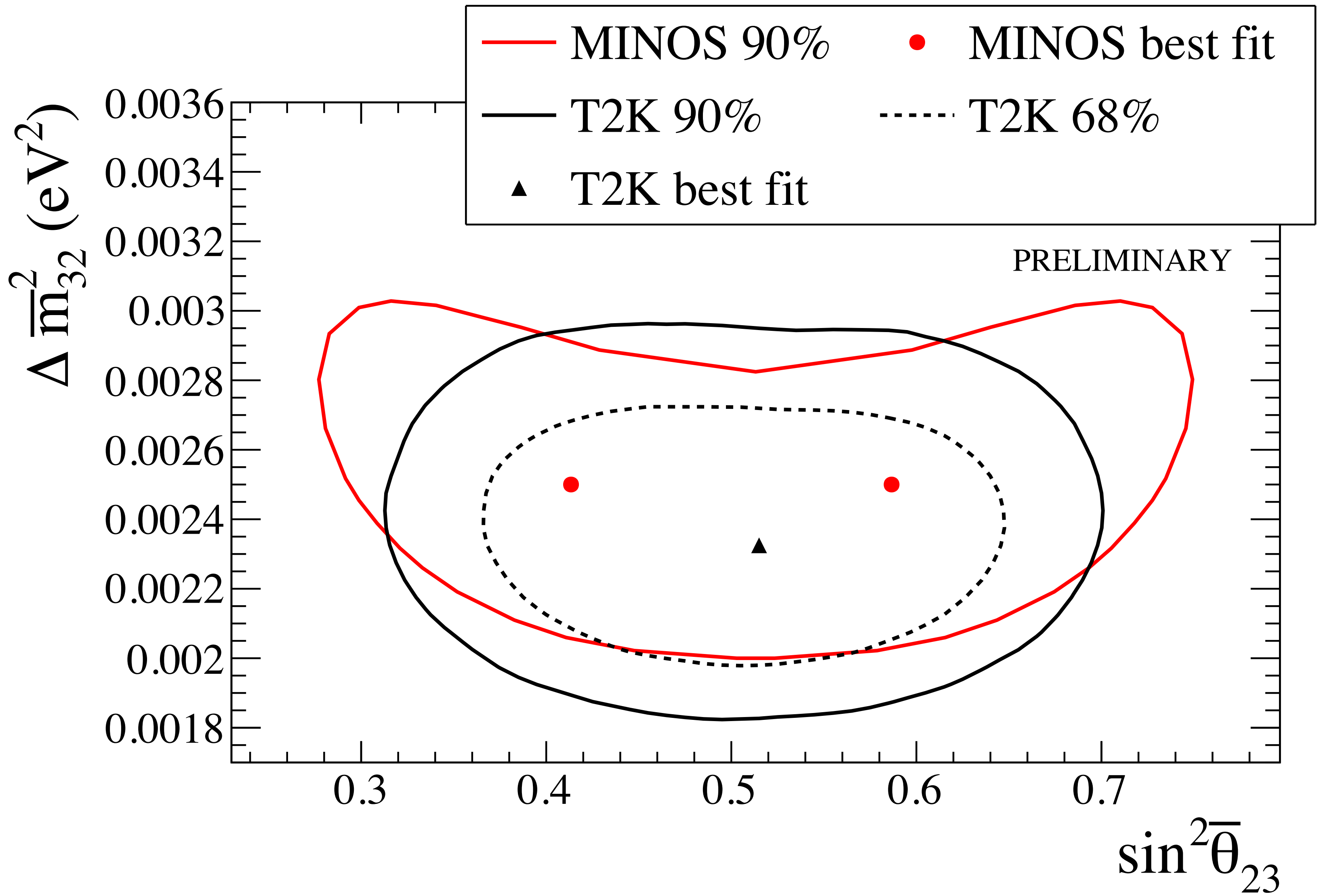
Comparison to Neutrino Results



- 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



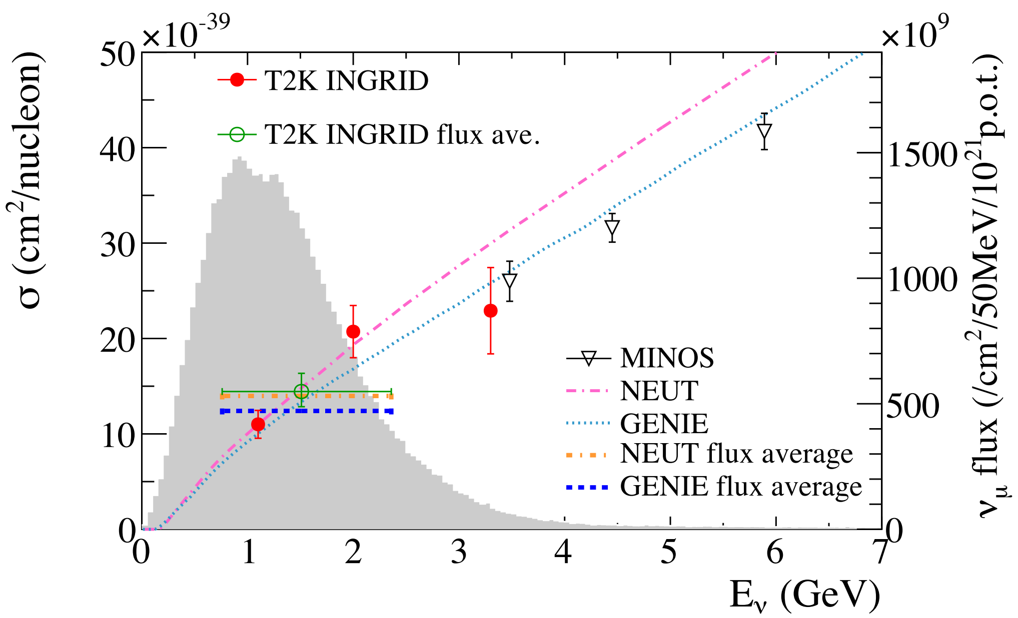
MINOS data is beam and cosmic combined

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

Future Work

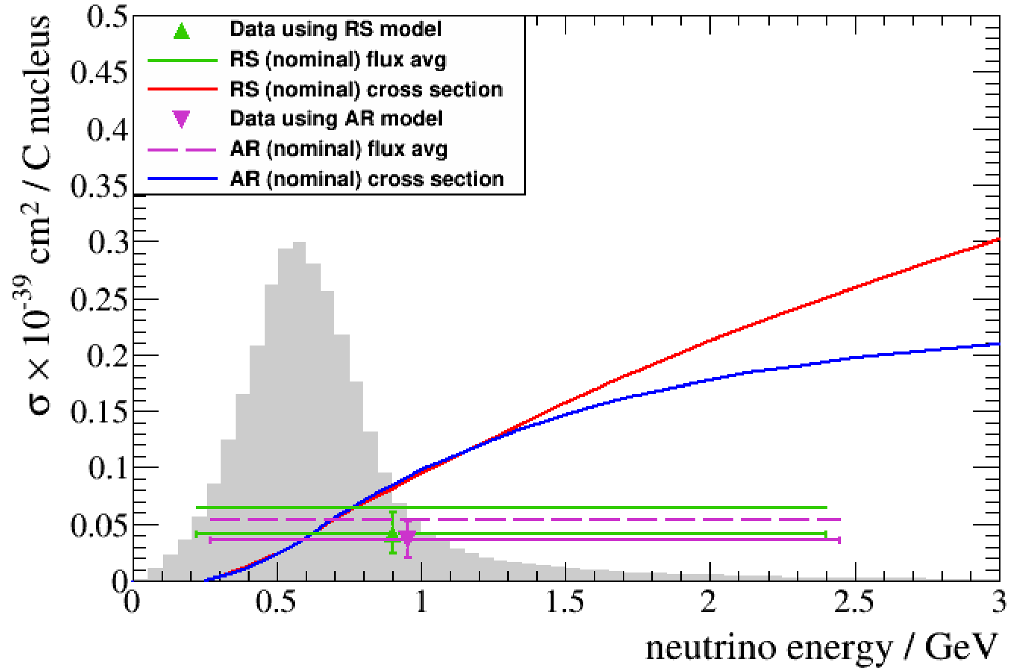
- Anti-neutrino running is ongoing—expected POT at the end of May is 4.5×10^{20}, nearly twice as large as this dataset
- Anti-neutrino analysis of $\bar{\nu}_e$ appearance is underway

Other T2K results

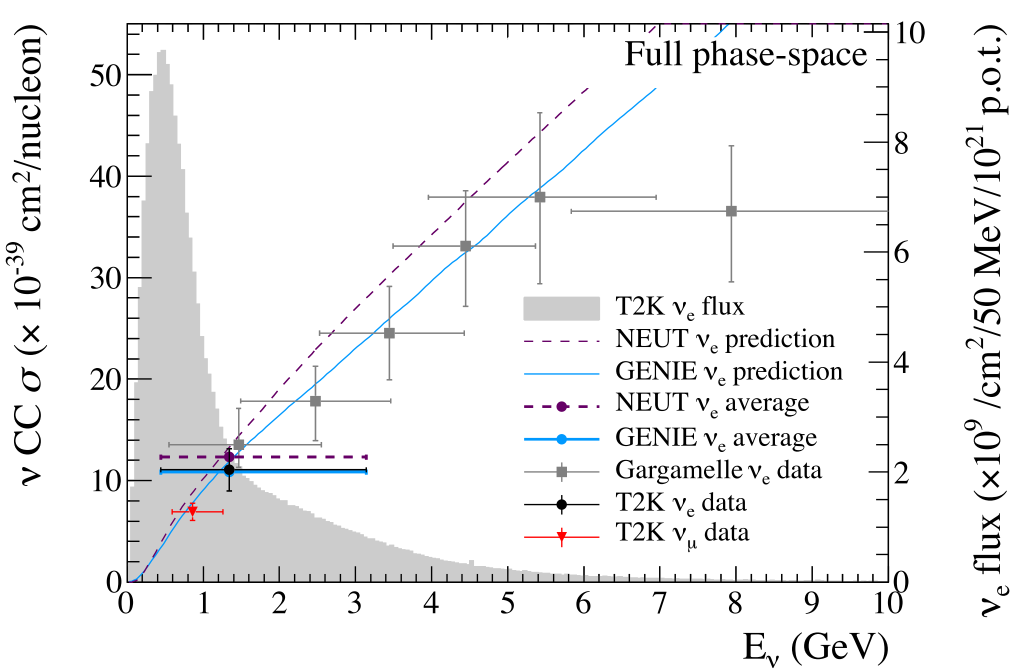


Cross section measurements at INGRID

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

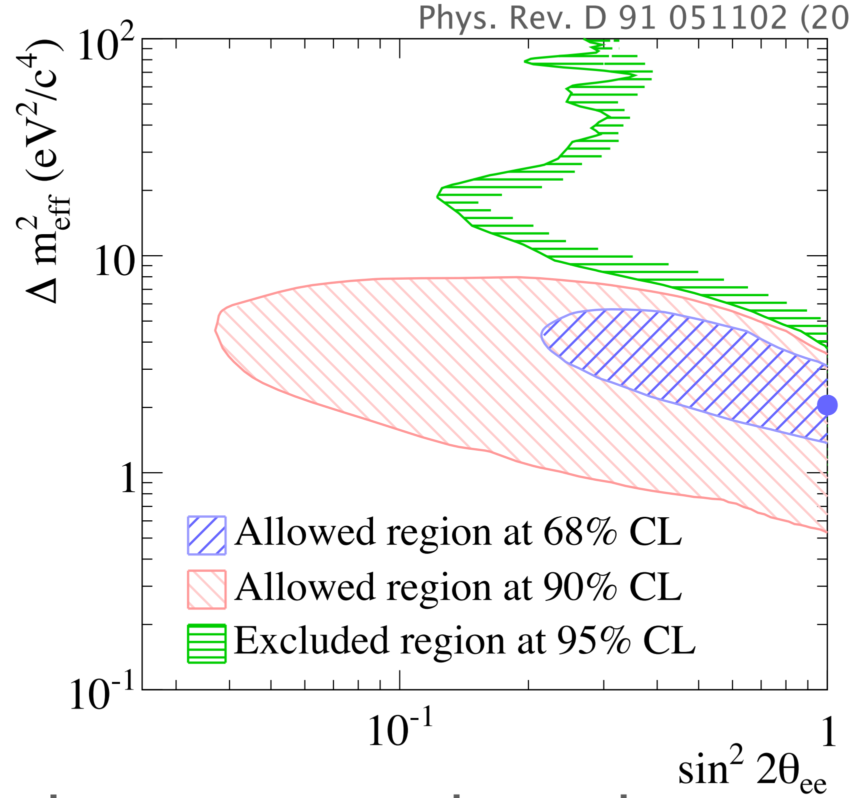


Charged current coherent cross sections at ND280



ν_e cross section measurements at ND280

Phys. Rev. D 91 051102 (2015)



Sterile neutrino searches with ν_e

T2K Papers in 2014–2015

PMNS Oscillation	Measurements of neutrino oscillation in appearance and disappearance channels by the T2K experiment with 6.6E20 protons on target	Phys. Rev. D 91, 072010 (2015)
PMNS Oscillation	Neutrino Oscillation Physics Potential of the T2K Experiment	Prog. Theor. Exp. Phys. 043C01 (2015)
PMNS Oscillation	Precise Measurement of the Neutrino Mixing Parameter θ_{23} from Muon Neutrino Disappearance in an Off-axis Beam	Phys. Rev. Lett. 112, 181801 (2014)
PMNS Oscillation	Observation of Electron Neutrino Appearance in a Muon Neutrino Beam	Phys.Rev.Lett. 112,061802 (2014)
Cross Section	Measurement of the Electron Neutrino Charged-current Interaction Rate on Water with the T2K ND280 pi-zero Detector	Accepted in PRD
Cross Section	Measurement of the ν_μ charged current quasi-elastic cross-section on carbon with the T2K on-axis neutrino beam	submitted to PRD
Cross Section	Measurement of the ν_μ CCQE cross section on carbon with the ND280 detector at T2K	submitted to PRD
Cross Section	Measurement of the Inclusive Electron Neutrino Charged Current Cross Section on Carbon with the T2K Near Detector	Phys. Rev. Lett. 113, 241803 (2014)
Cross Section	Measurement of the inclusive numu charged current cross section on iron and hydrocarbon in the T2K on-axis neutrino beam	Phys. Rev. D, 90, 052010 (2014)
Cross Section	Measurement of the intrinsic electron neutrino component in the T2K neutrino beam with the ND280 detector	Phys. Rev. D 89, 092003 (2014)
Cross Section	Measurement of the neutrino-oxygen neutral-current interaction cross section by observing nuclear deexcitation γ rays	Phys. Rev. D 90, 072012 (2014)
Neutrino Mass	Upper bound on neutrino mass based on T2K neutrino timing measurements	submitted to PRD
Sterile Oscillation	Search for short baseline νe disappearance with the T2K near detector	Phys. Rev. D 91 051102 (2015)

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 the J-PARC facility for providing us with such excellent beam for this physics!

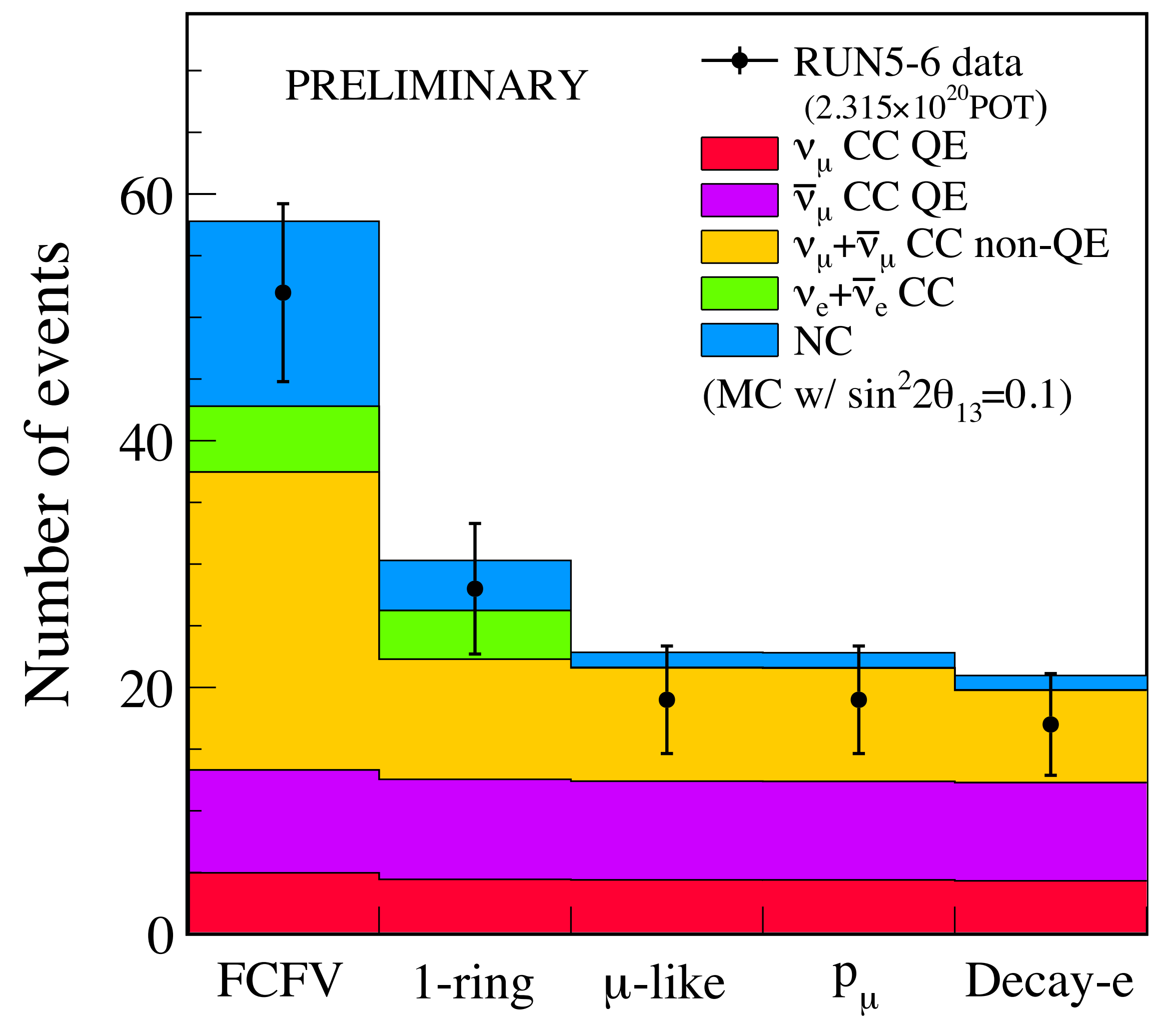
Supplementary

Cross Section Model

- Charged Current Quasi-Elastic (CCQE)
  - Llewellyn-Smith base model
  - Smith-Moniz fermi gas model for nucleus
  - Random Phase Approximation
- Multinucleon scattering (2p-2h)
- Single Pion Production (CC/NC1π)
  - Rein-Seghal resonance model
  - Retuned using new form factors and reanalyzed data
  - Remove pionless delta decay (more complete model in 2p-2h)
- Deep Inelastic Scattering (DIS) and Charged Current multi-π
  - GRV98 PDF
  - Bodek-Yang correction
- Final State Interactions (FSI)
  - Cascade model—track secondary particles until they exit the nucleus
  - Separate models used for low (<500 MeV) and high momentum

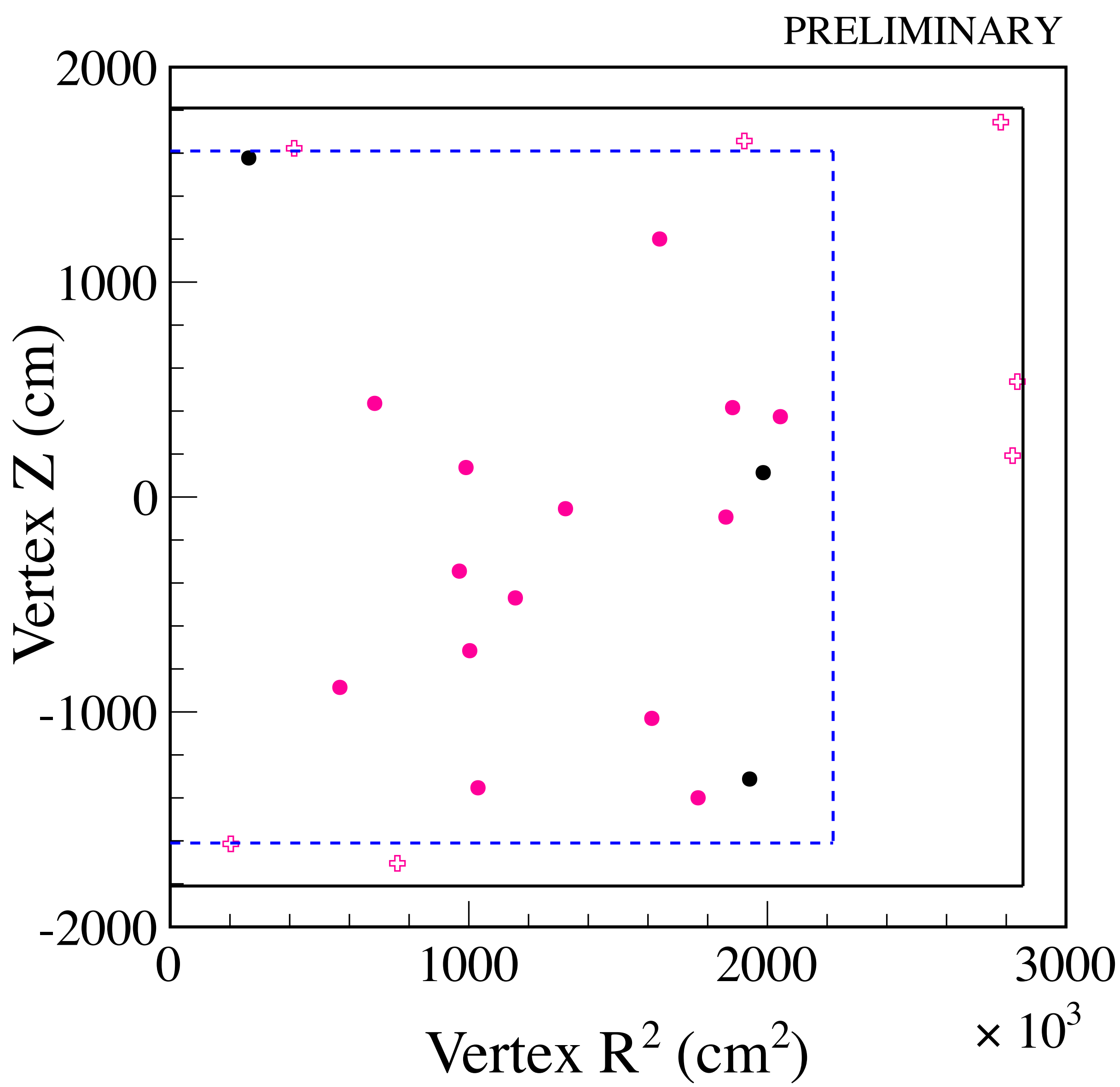
SK $1R_\mu$ Selection

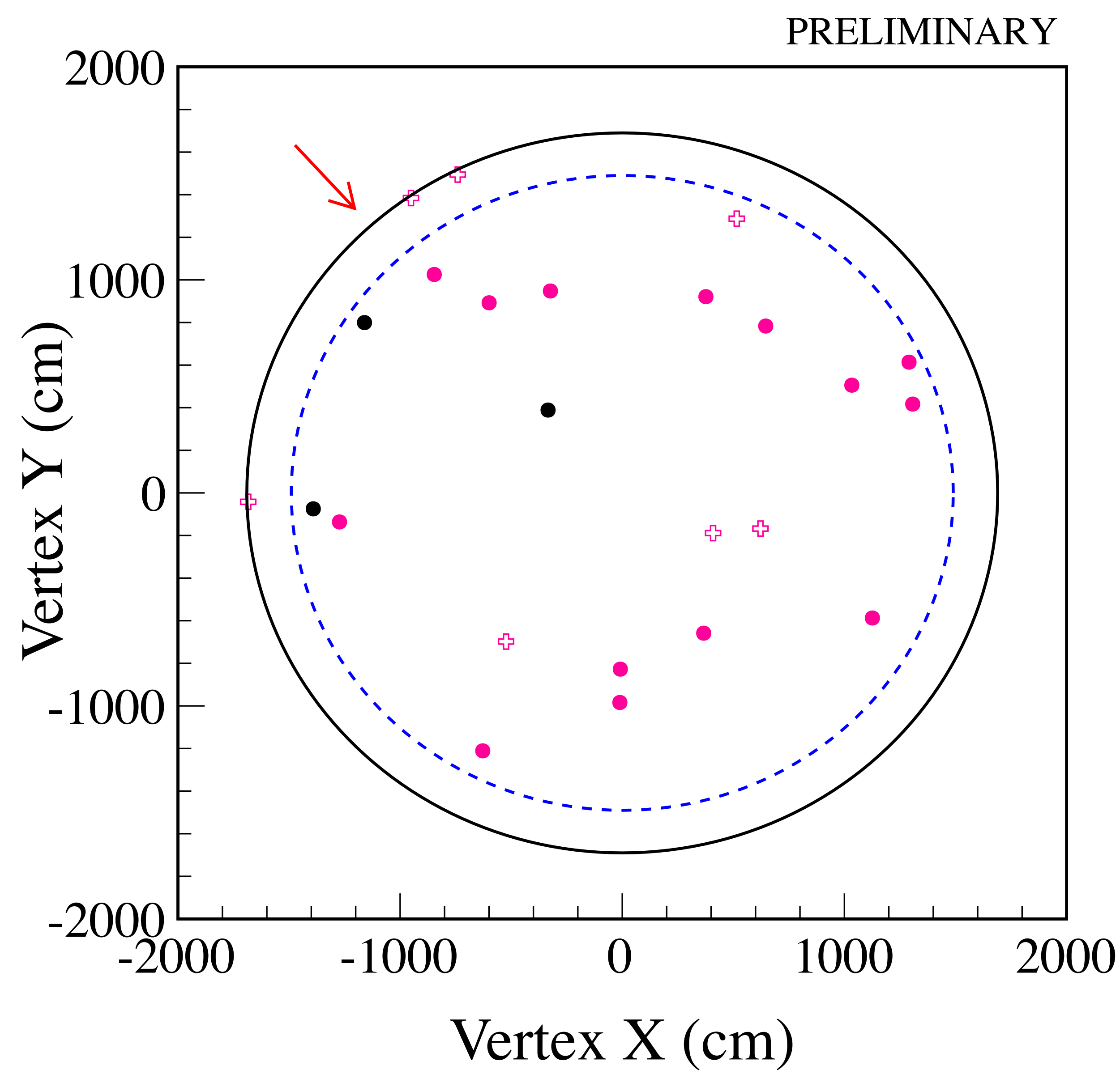
1. Fully contained within the fiducial volume of SK (52 events)
2. Have one and only one reconstructed ring (28 events)
3. Have μ-like PID (19 events)
4. Have muon momentum >200 MeV/c (19 events)
5. Have one or fewer decay electron (17 events)



MC prediction uses neutrino-mode oscillation parameters: $\sin^2\theta_{23}$=0.527 and Δm^2_{32}=2.51x10^{-3}eV^2

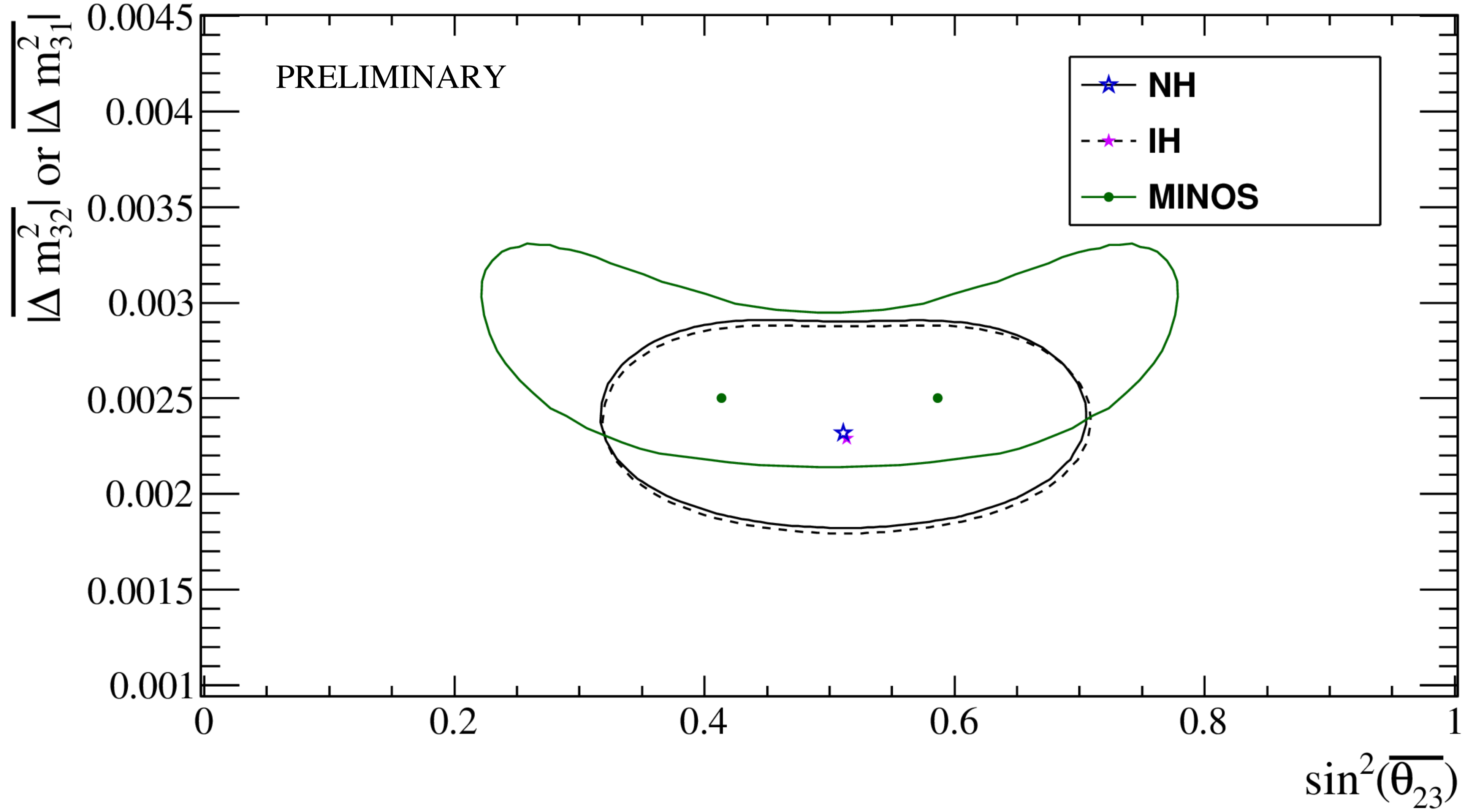
Event Distribution





- Run 5 in fiducial volume
- Run 6 in fiducial volume
- Run 6 out of fiducial volume

Normal vs Inverted



No significant difference between hierarchies in this analysis

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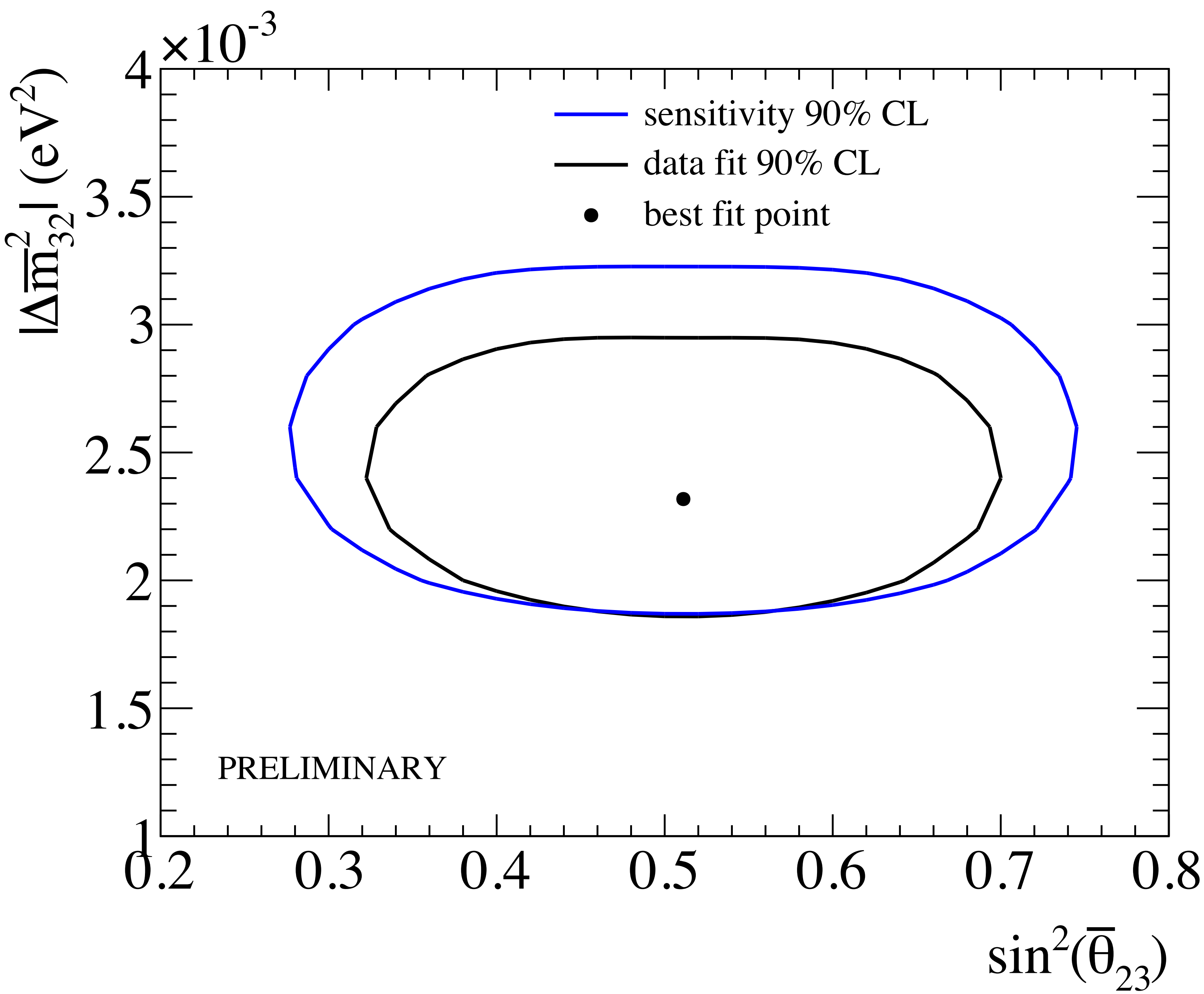
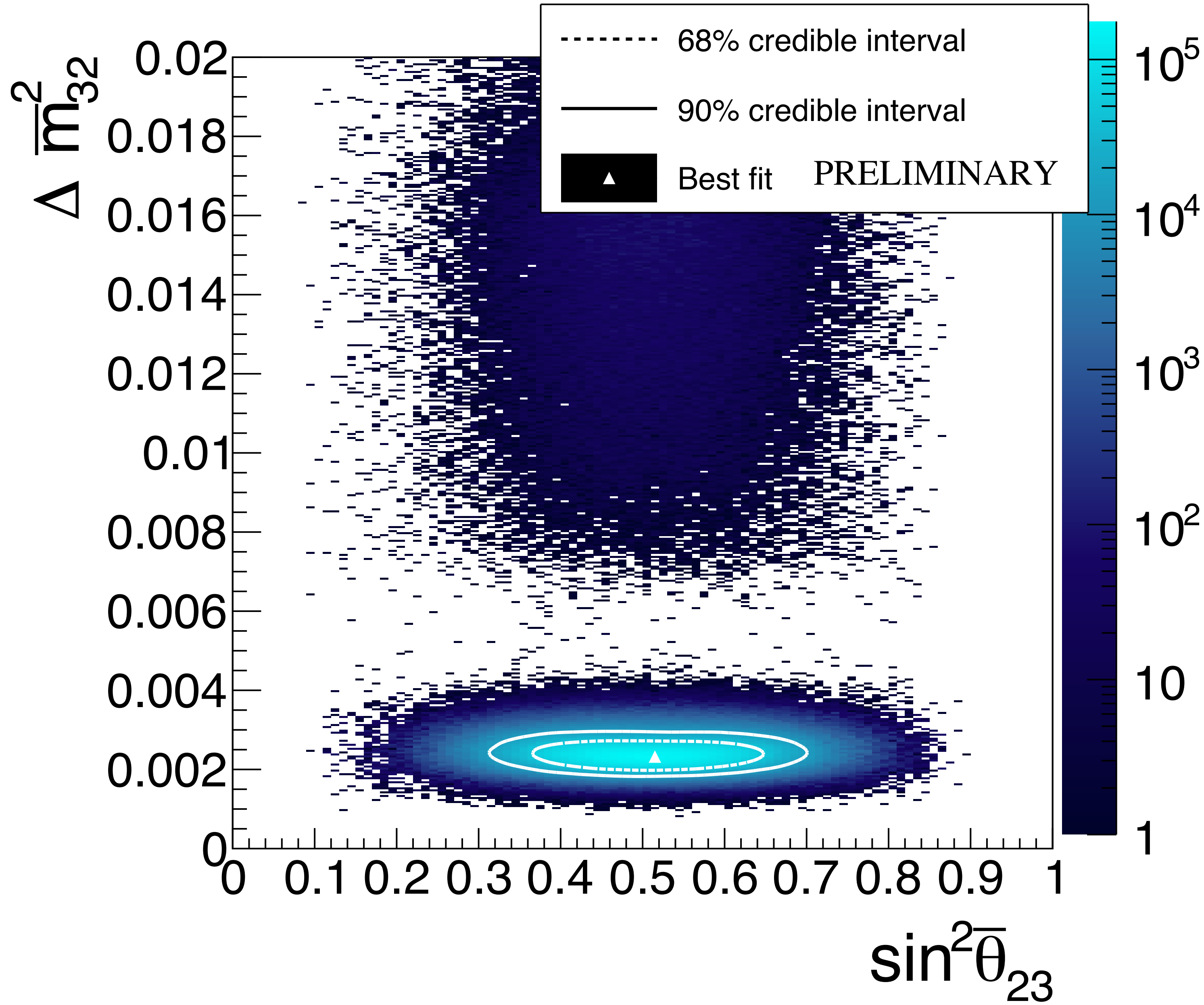
Data vs Sensitivity



T2K sees fewer events than predicted, which produces tighter contours

High Mass Region



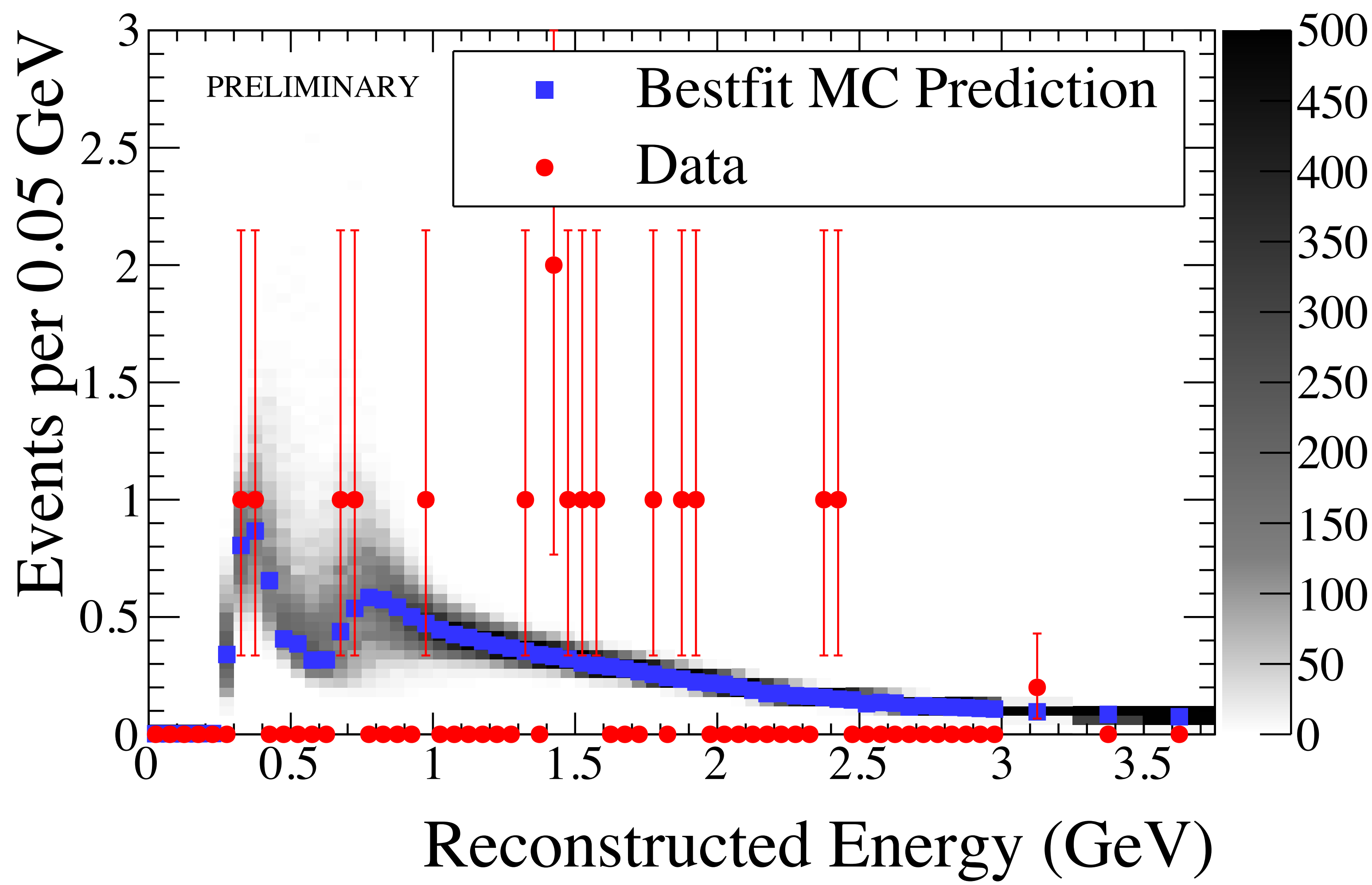
- Less than 0.6% of probability is in the region $\Delta m^2 > 6\text{x}10^{-3}$ eV^2

Analysis Comparison

T2K Name	Method	Systematic Uncertainies	ND280 Constraint	Contour Type
MaCh3	Markov Chain Mone Carlo	Marginalized	Simultaneous Fit	Bayesian Credible Interval
Valor	MINUIT	Minimized	Matrix Propagation	Constant Δ
p-θ	MINUIT with internal syst. marginalization	Marginalized	Matrix Propagation	Constant Δ

Fine Binned Best Fit

Greyscale shows results of toys thrown from post-fitting distributions; blue square is mode of this distribution in each bin



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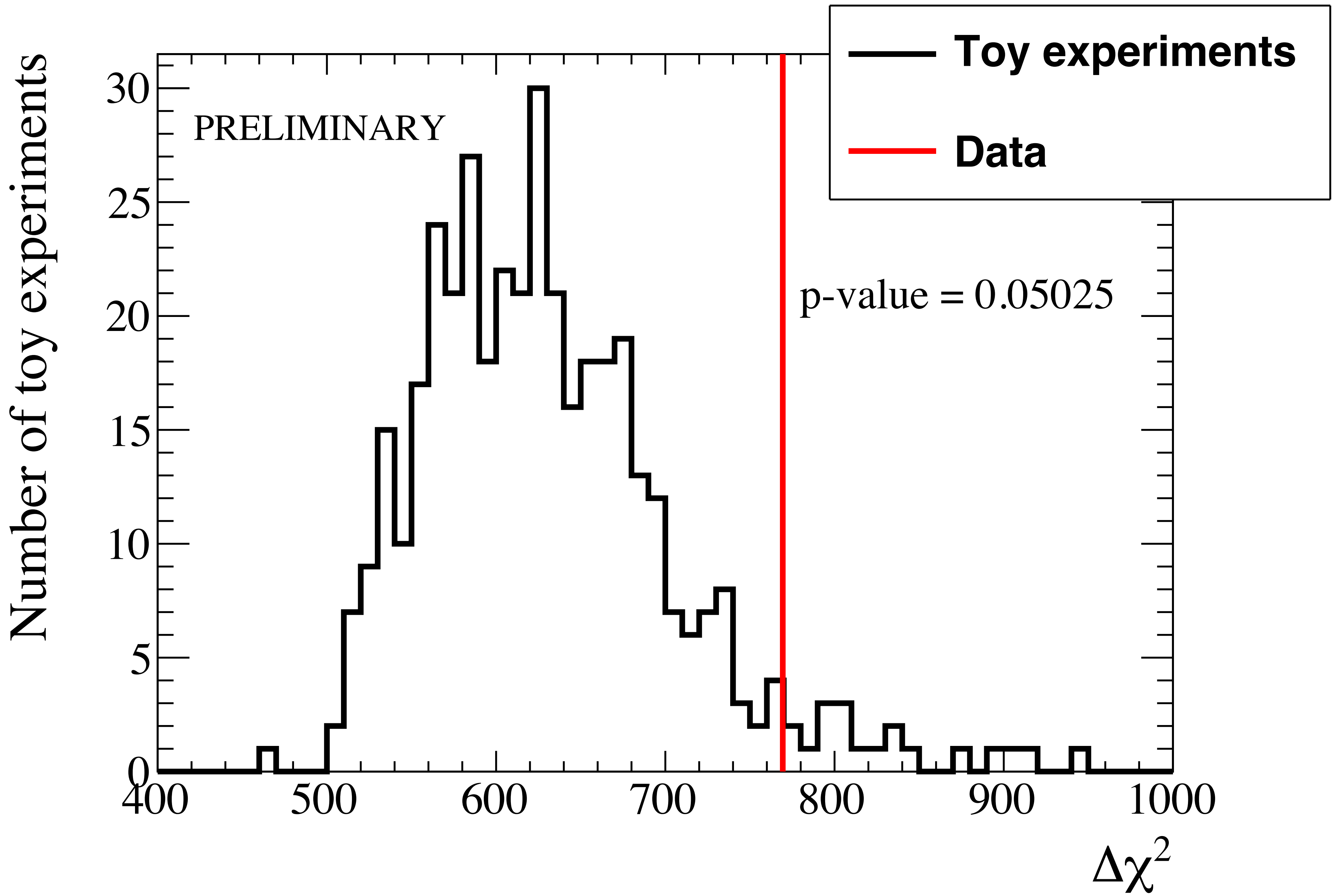
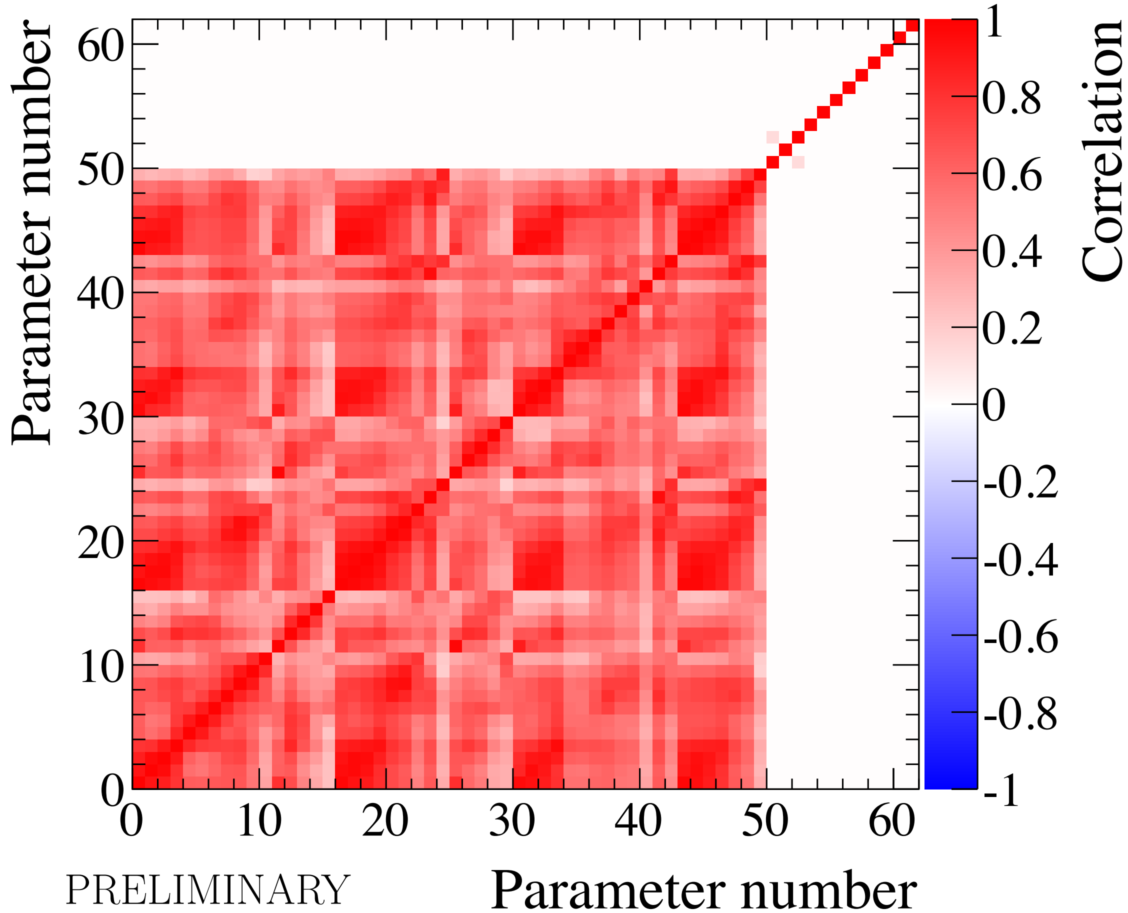
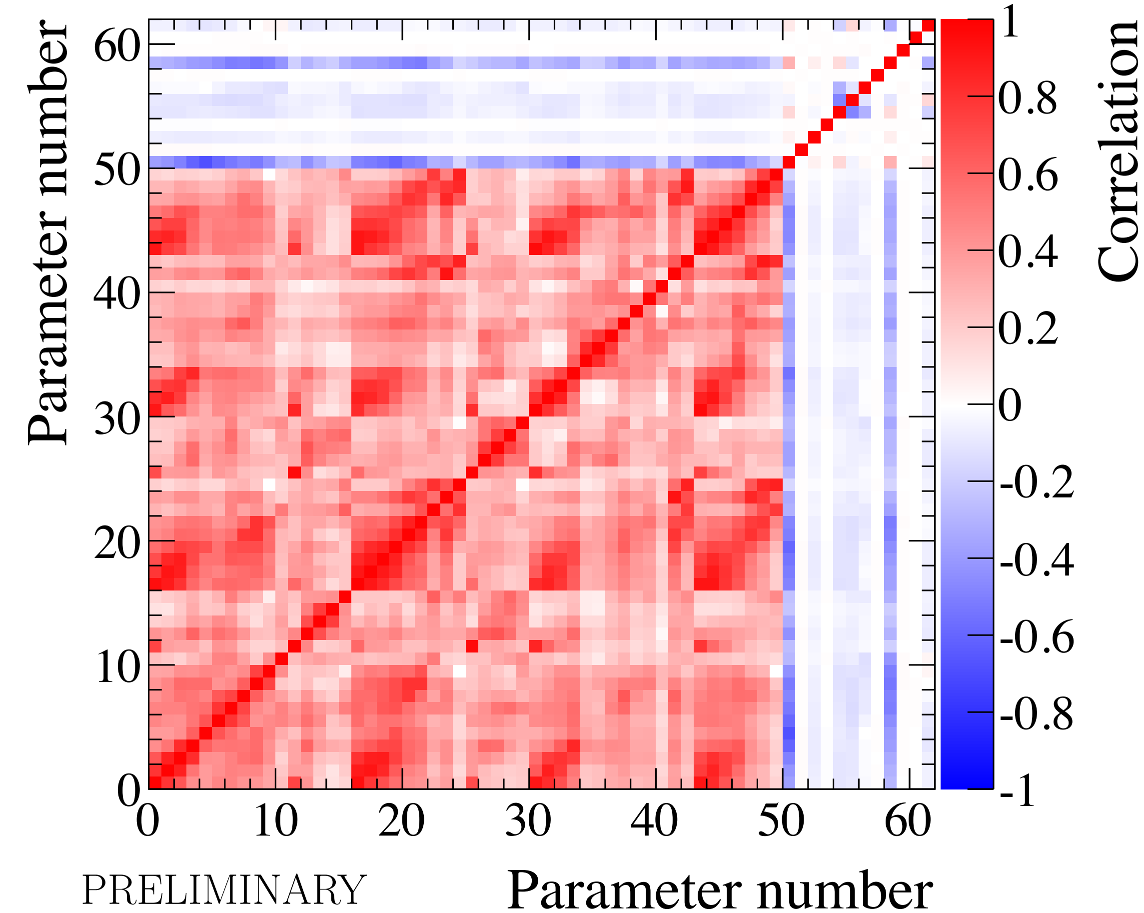
ND280 GOF



Toy experiments
Data
PRELIMINARY
p-value = 0.05025
Number of toy experiments
0
5
10
15
20
25
30
400
500
600
700
800
900
1000
$\Delta\chi^2$

Flux/Cross Section Correlations





Parameters	Parameter number(s)
SK, Positive Focusing, ν_μ	0 – 10
SK, Positive Focusing, $\bar{\nu}_\mu$	11 – 15
SK, Positive Focusing, ν_e	16 – 22
SK, Positive Focusing, $\bar{\nu}_e$	23 – 24
SK, Negative Focusing, ν_μ	25 – 29
SK, Negative Focusing, $\bar{\nu}_\mu$	30 – 40
SK, Negative Focusing, ν_e	41 – 42
SK, Negative Focusing, $\bar{\nu}_e$	43 – 49
M_A^{QE} (GeV/c^2)	50
p_F ^{16}O (MeV/c)	51

CC 2p-2h ^{16}O	52
E_B ^{16}O (MeV)	53
$C_5^A(0)$	54
M_A^{RES} (GeV/c^2)	55
Isospin=$\frac{1}{2}$ Background	56
ν_e/ν_μ	57
CC Other Shape	58
CC Coherent ^{16}O	59
NC Coherent	60
NC Other	61

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T2K

ND280 Fit Comparison