LOUISIANA STATE UNIVERSITY

T2K Latest Results On Muon Neutrino And Anti-Neutrino Disappearance

SIVA PRASAD K

On Behalf Of T2K Collaboration

XIX INTERNATIONAL WORKSHOP ON NEUTRINO TELESCOPES

18-26 FEBRUARY 2021

Outline

- The T2K Experiment
- Analysis Strategy
- Data Fit Results
- Summary and Outlook

Physics Goals

Neutrino mixing described by PMNS matrix, governed by
3 mixing angles and one CP-violation phase

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Atmospheric and accelerator
$\sin^2\theta_{23} \sim 0.512$
$|\Delta m_{32}^2| \sim 2.44\text{x}10^{-3}\ \text{eV}^2$

Reactor and accelerator
$\sin^2\theta_{13} \sim 2.18$
$\delta_{CP} \sim$??

Solar and reactor
$\sin^2\theta_{12} \sim 0.307$
$\Delta m_{12}^2 \sim 7.53\text{x}10^{-5}\ \text{eV}^2$

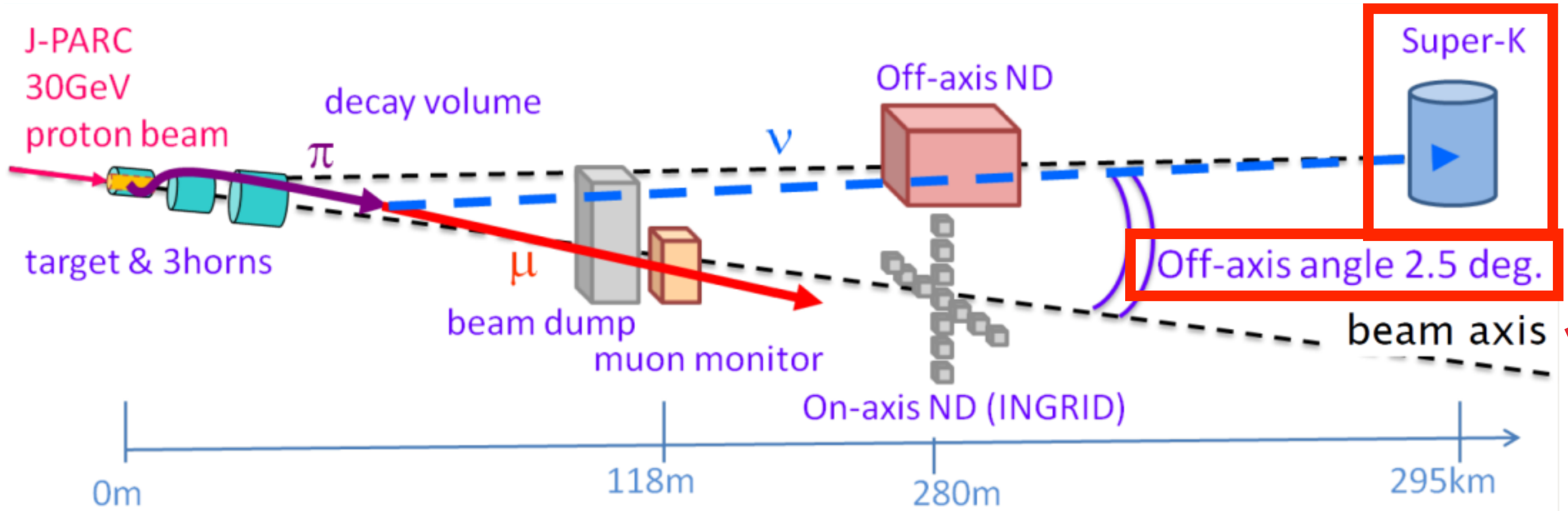
from PDG 2019

$\Delta m_{ji}^2 = m_j^2 - m_i^2 \quad c_{ij} = \cos\theta_{ij} \quad s_{ij} = \sin\theta_{ij}$

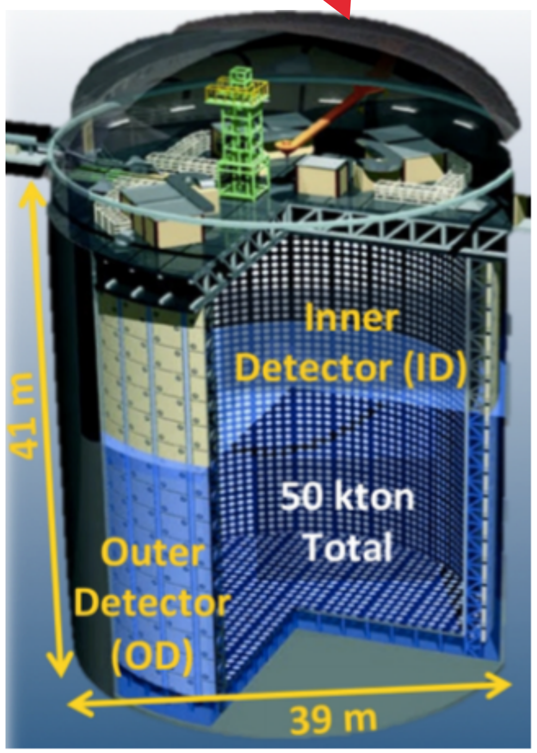
Physics goals of this analysis include

- ☑ Measurement of θ_{23}, Δm_{32}^2
- ☑ Test the consistency of PMNS oscillation model
  - ☑ Potential inconsistencies could be attributed to CPT violation, non-standard interactions (NSI)

The T2K Experiment



- A long-baseline accelerator based neutrino oscillation experiment.
- In T2K beam line, hadrons of either charge from the primary interactions (proton-on-carbon interaction) are focussed using magnetic horns by switching the horn current.
  - Focus positively charged hadrons produces neutrinos
  - Focus negatively charged hadrons produces anti-neutrinos
- T2K detectors can record data either in neutrino mode or anti-neutrino mode and this analysis takes advantage of such an ability.

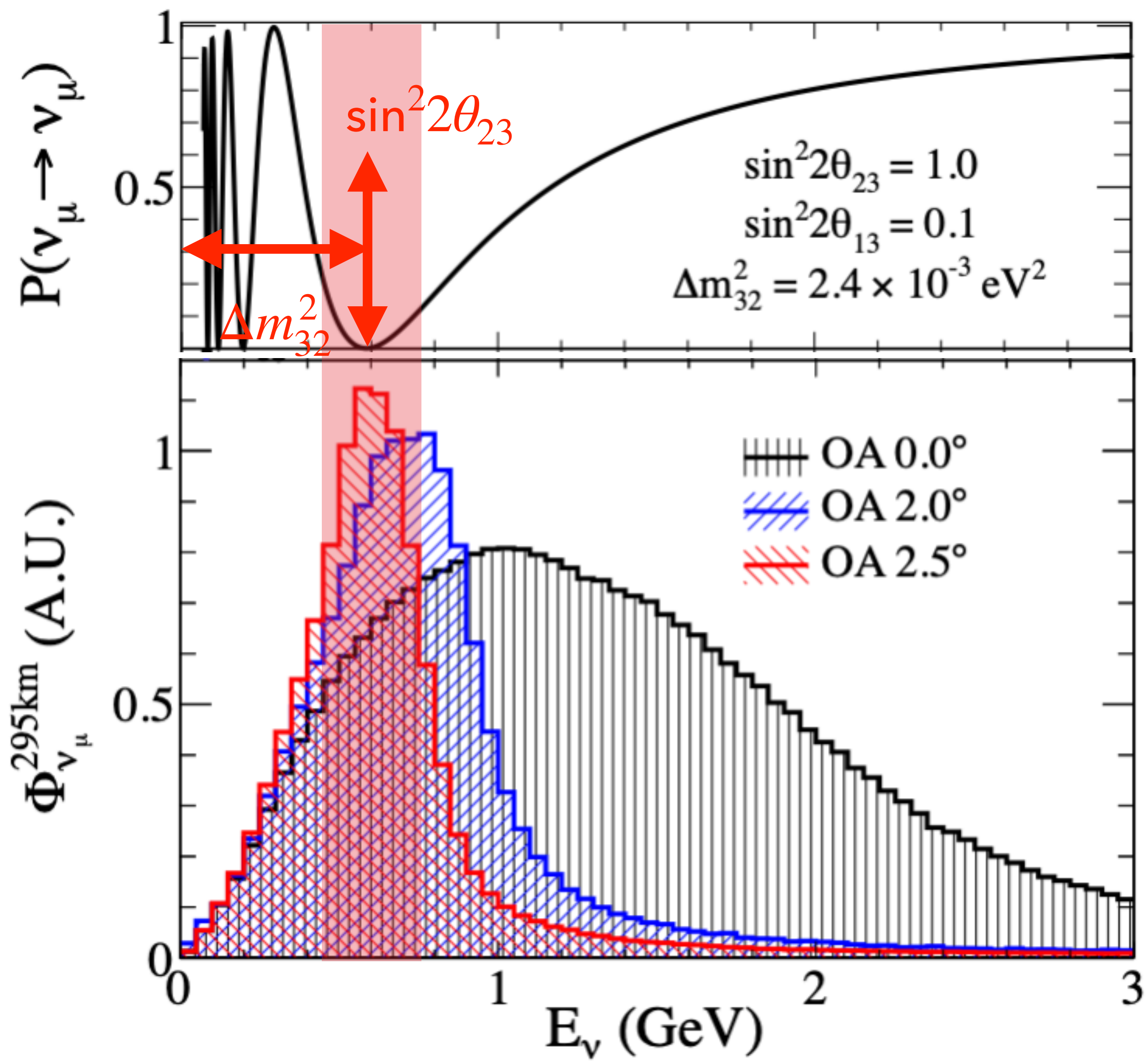


See Mathieu Guigue Plenary talk

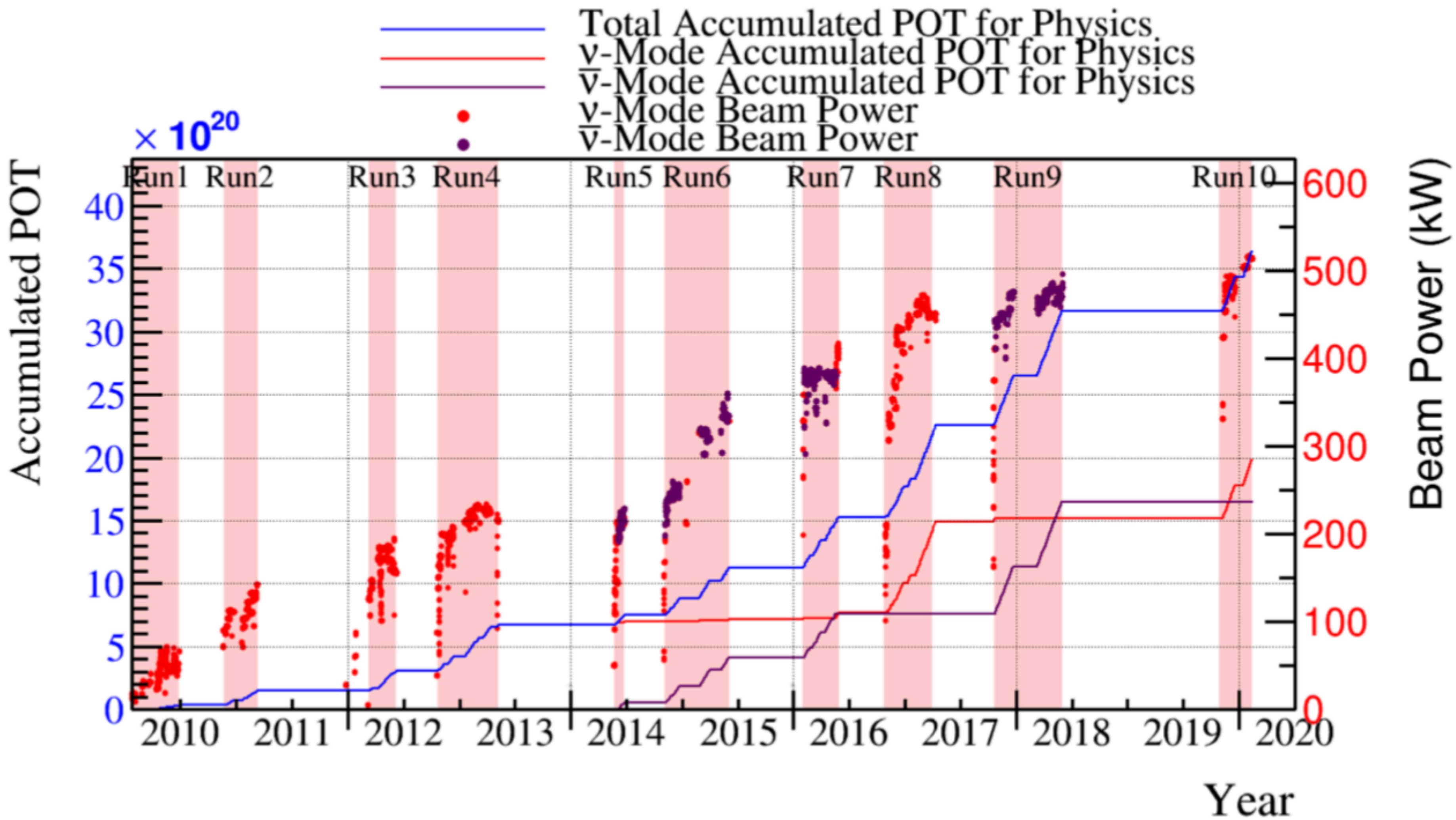
Off-axis Configuration

$$P(\nu_\mu \rightarrow \nu_\mu) \simeq 1 - (\cos^4\theta_{13} \, . \, \sin^2 2\theta_{23} + \sin^2 2\theta_{13} \, . \, \sin^2\theta_{23}) \, . \, \sin^2 \frac{\Delta m^2_{32} \, . \, L}{4E}$$

- An off-axis angle 2.5^o makes ν_μ beam more narrow and peak around 0.6 GeV which allows us to observe maximum oscillation probability for a baseline of 295 km.
- Maximize signal and reduce high energy backgrounds.
- For ν_μ disappearance
  - depth of dip ~ $\sin^2 2\theta_{23}$
  - location of dip ~ Δm^2_{32}

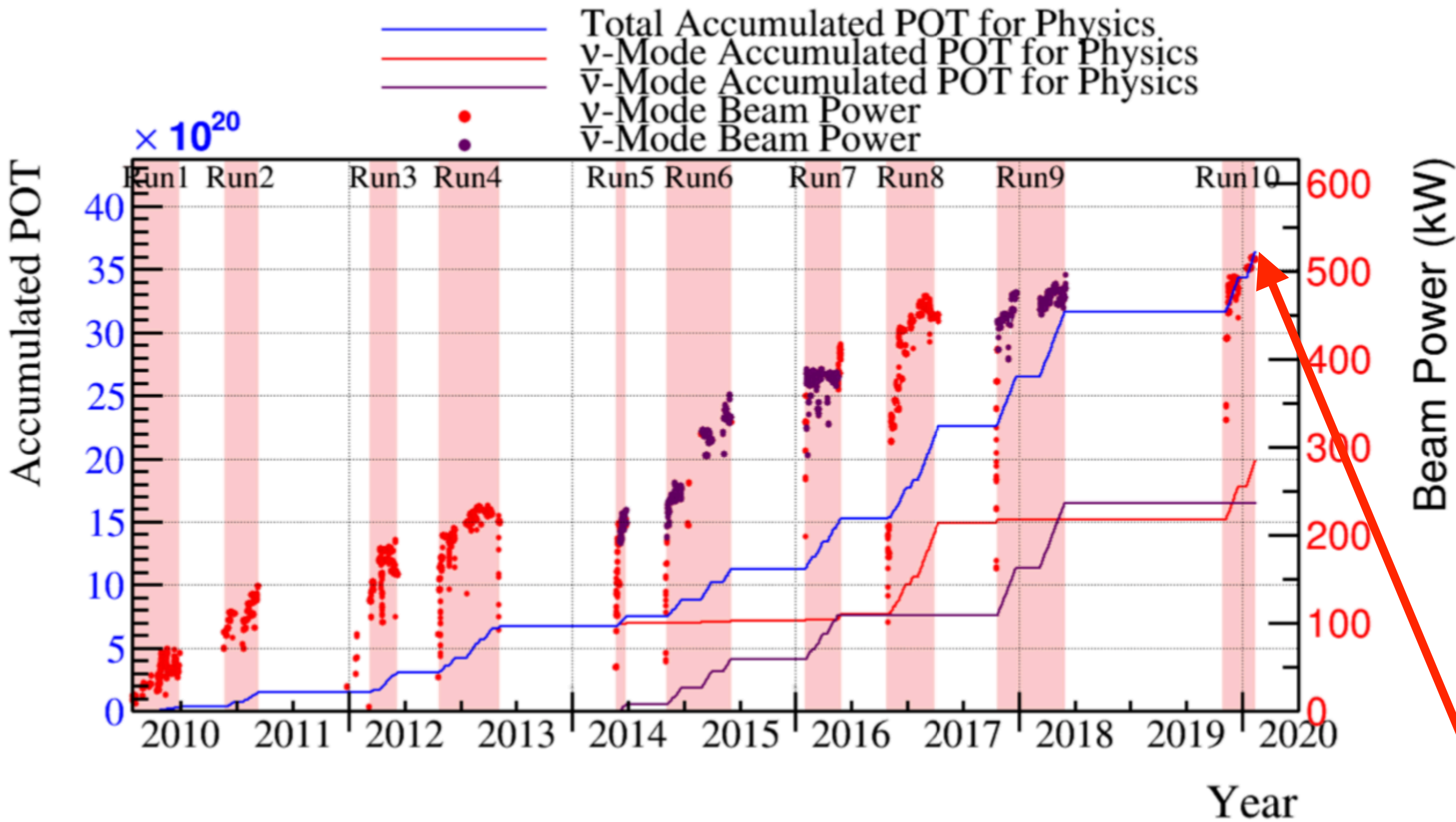


Data Accumulation to Date



*POT = Protons On Target

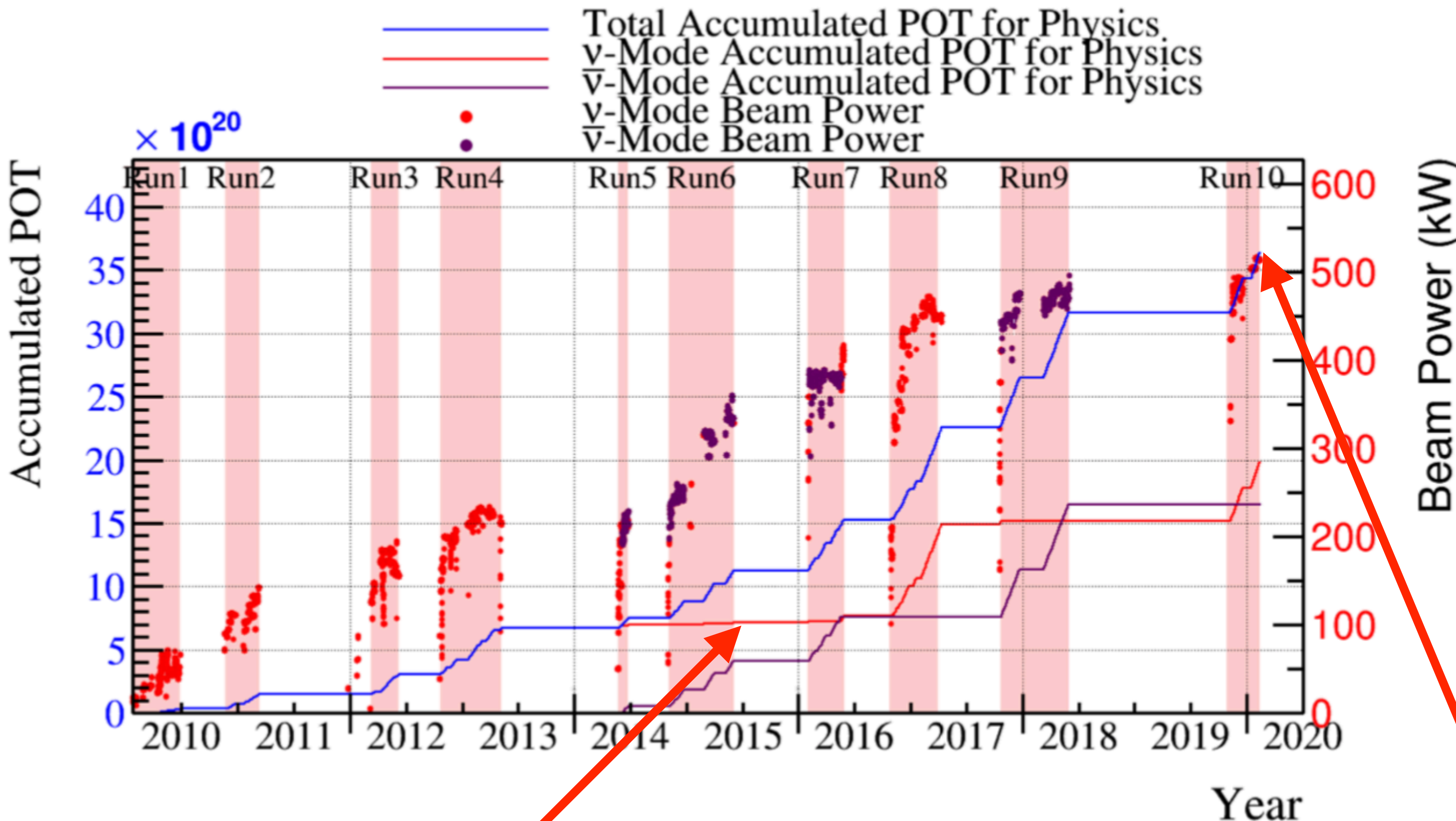
Data Accumulation to Date



*POT = Protons On Target

Stable operation at 515 kW beam power

Data Accumulation to Date



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- Total of 1.97×10^{21} POT in ν-mode
  - Additional 33% POT collected since 2018

Stable operation at 515 kW beam power

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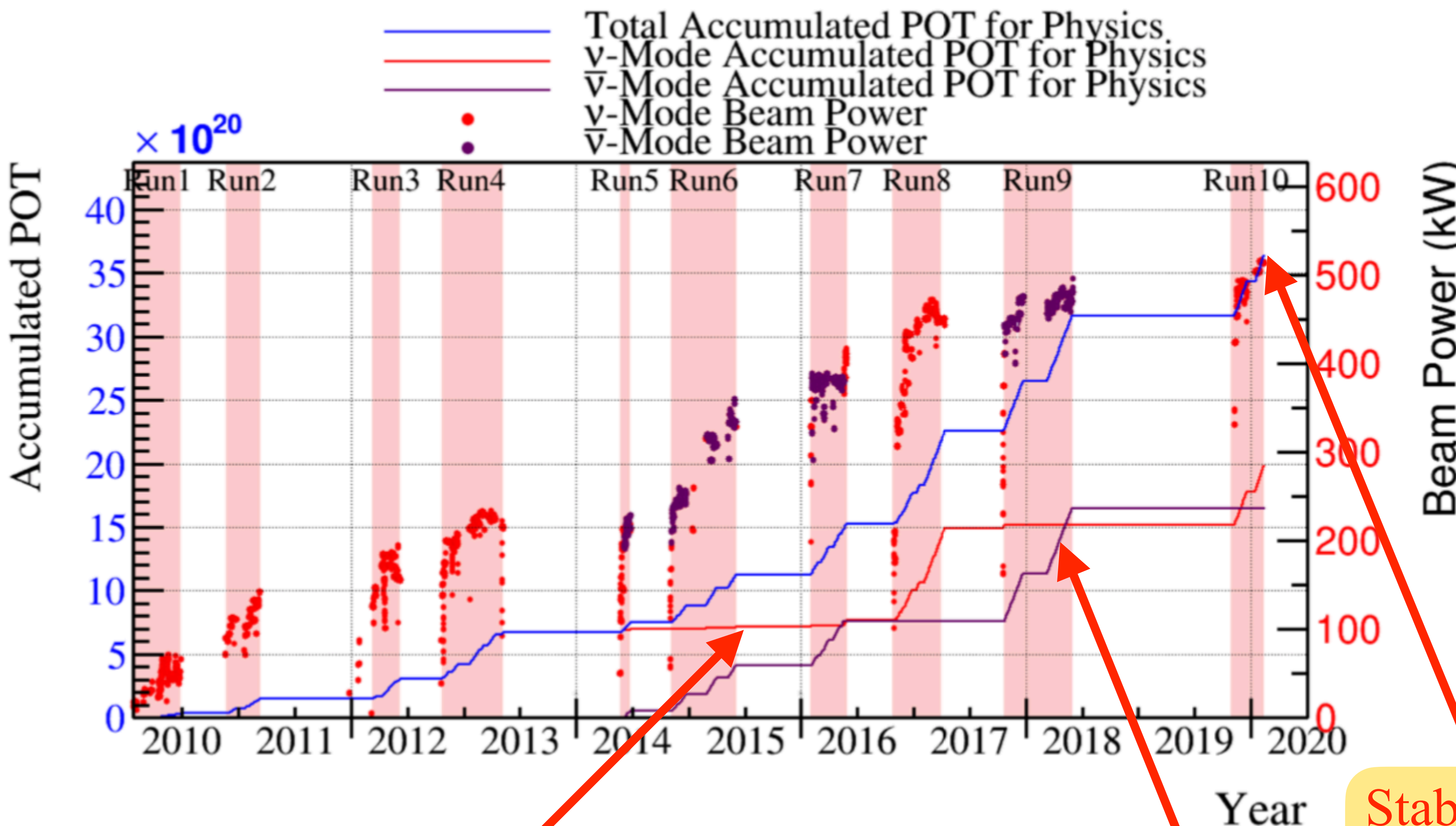

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- Total of 1.97×10^{21} POT in ν-mode
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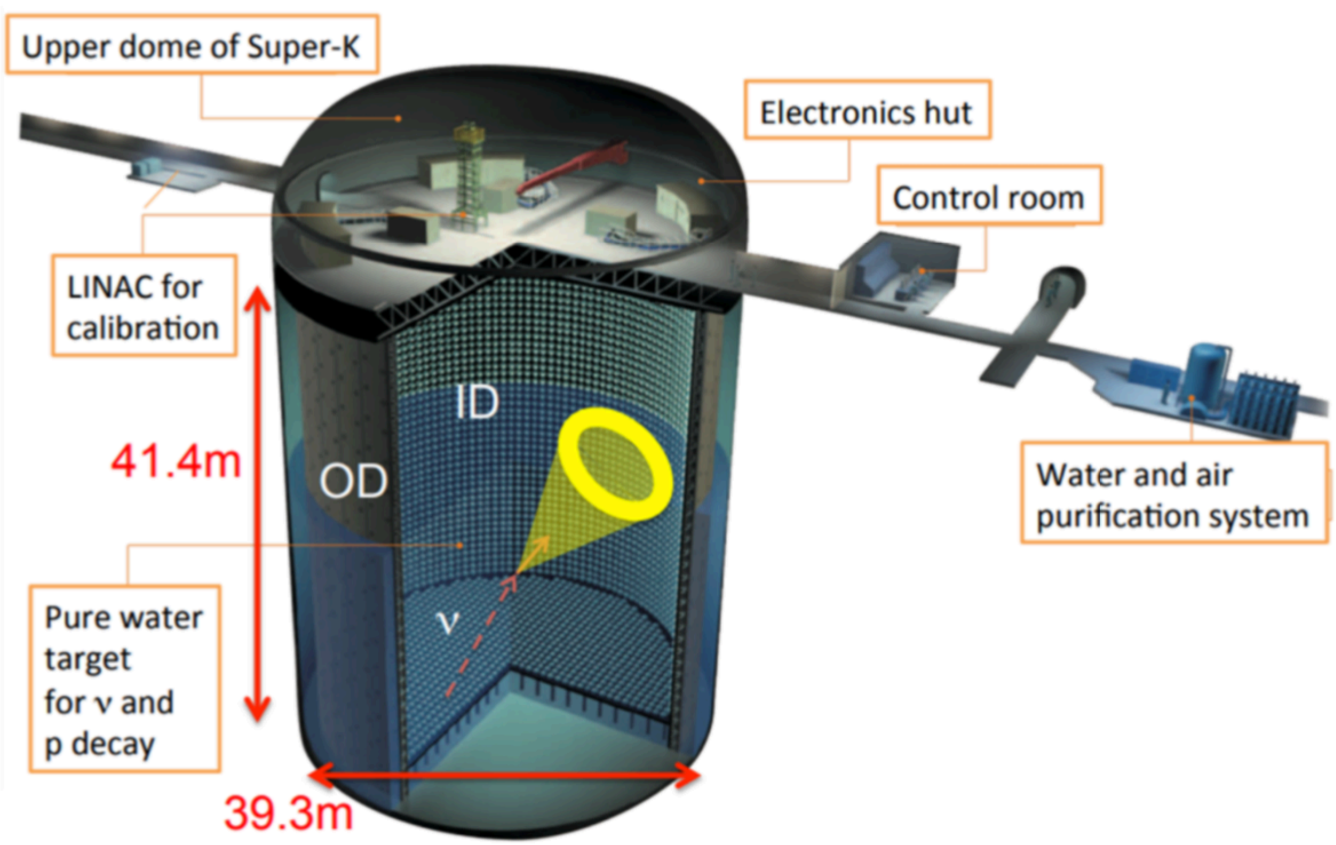
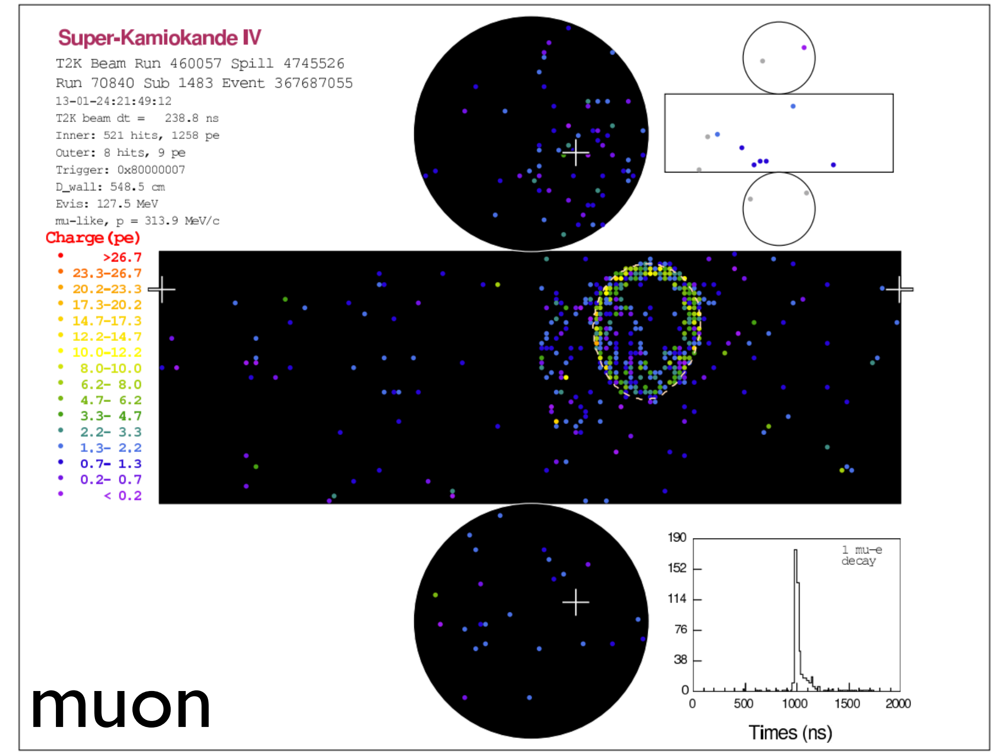
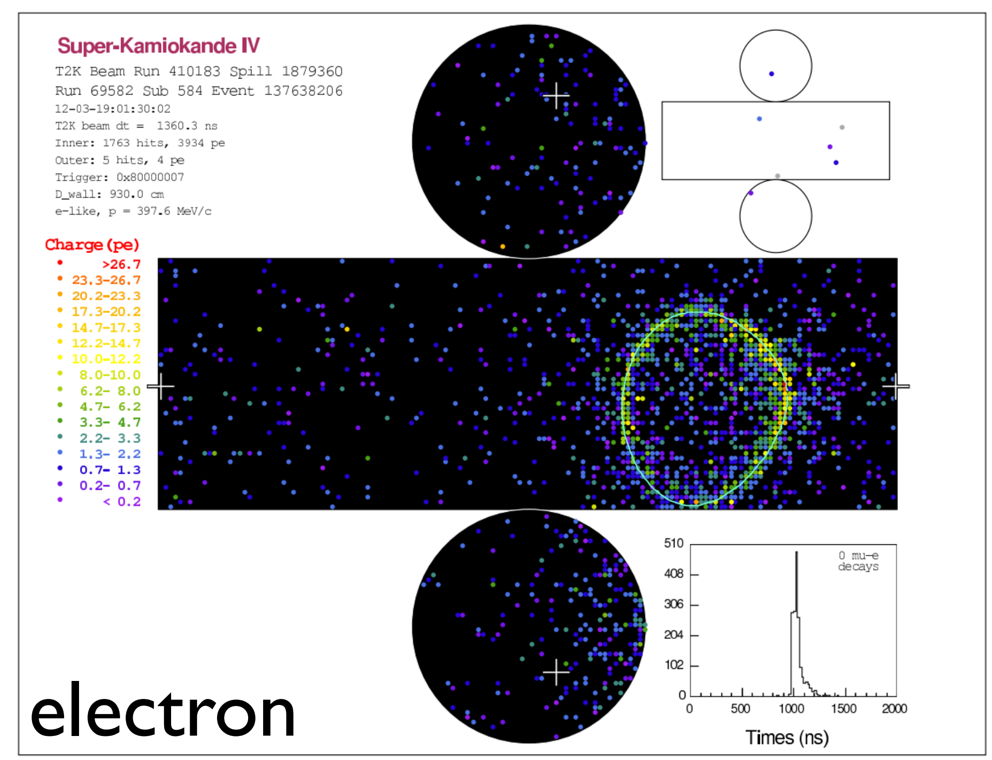
Total of 1.63×10^{21} POT in $\bar{\nu}$-mode

Stable operation at 515 kW beam power

Super-K Detector







- Off-axis at 2.5^o angle, with 50 kilo ton pure water
- About 11k inner detector PMTs (20")
- About 1880 outer detector PMTs (8")
- Particle ID based on Cherenkov ring pattern, not charge based
  - Sharp ring - muons
  - Fuzzy rings - electrons
  - $\mu \rightarrow e$ mis-ID ~ 1%

Motivation

- To test the consistency of PMNS oscillation model with data by comparing ν_μ and $\bar{\nu}_\mu$ disappearance.
  - Negligible matter effects on ν_μ survival probability at T2K baseline.
  - CPT violation, non-standard interactions (NSI) etc. may cause inconsistency between ν_μ and $\bar{\nu}_\mu$.

Motivation

- To test the consistency of PMNS oscillation model with data by comparing ν_μ and $\bar{\nu}_\mu$ disappearance.
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  - CPT violation, non-standard interactions (NSI) etc. may cause inconsistency between ν_μ and $\bar{\nu}_\mu$.
- How do we do it?
- Perform ν-disappearance analysis at Super-K detector using both neutrino mode and anti-neutrino mode μ-like samples.
- Joint fit between these two samples allowing ν_μ and $\bar{\nu}_\mu$ oscillations governed by separate PMNS oscillation parameters $(\sin^2\theta_{23}, \Delta m^2_{32}) \neq (\sin^2\bar{\theta}_{23}, \Delta\bar{m}^2_{32})$.
- Joint fit allows us to constrain the wrong-sign background in neutrino and anti-neutrino μ-like sample.

Analysis Strategy

- Analysis strategy is to define a model that gives predictions at near and far detectors, and constrain it with either external experimental data or T2K data or both.
  - e.g. Flux model is constrained with both NA61/SHINE data and INGRID data.

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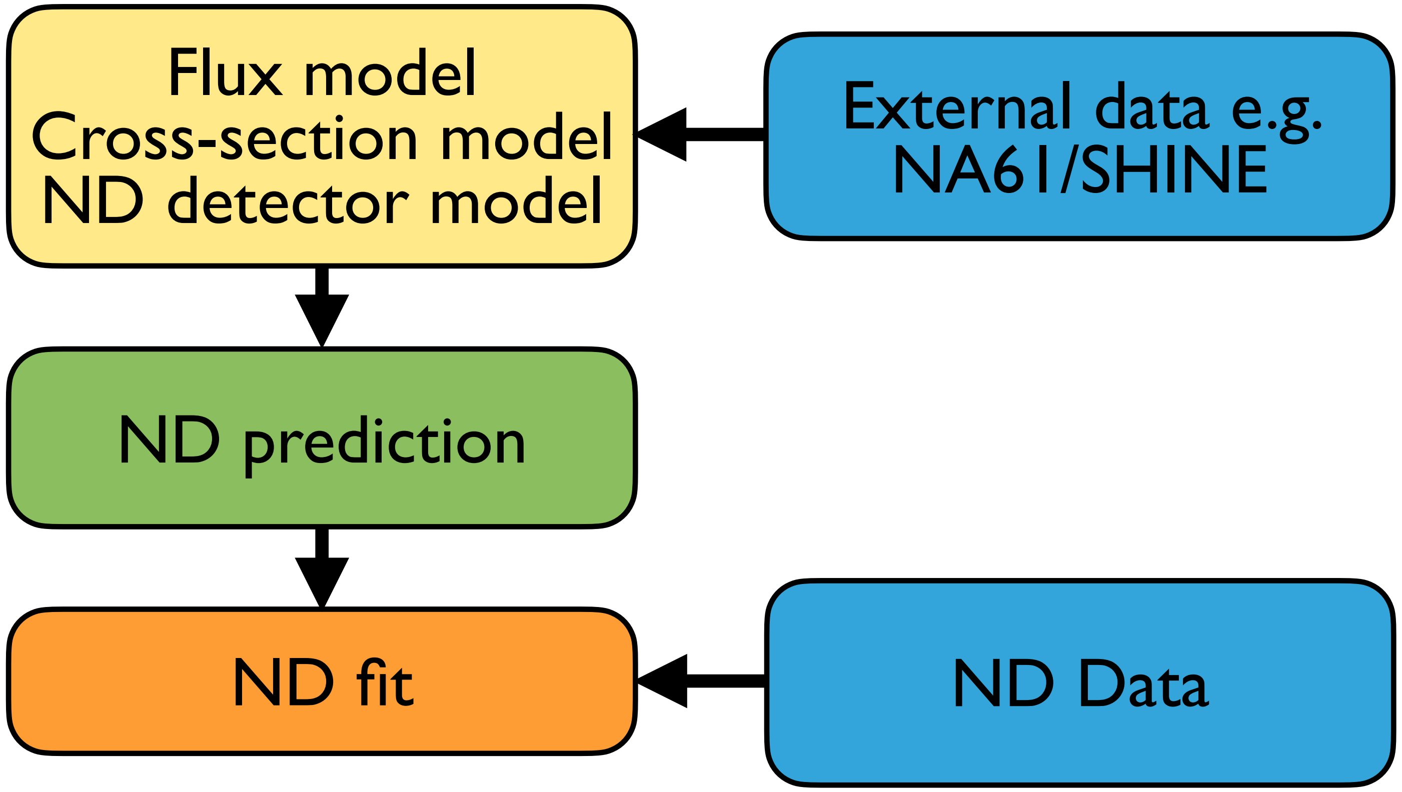

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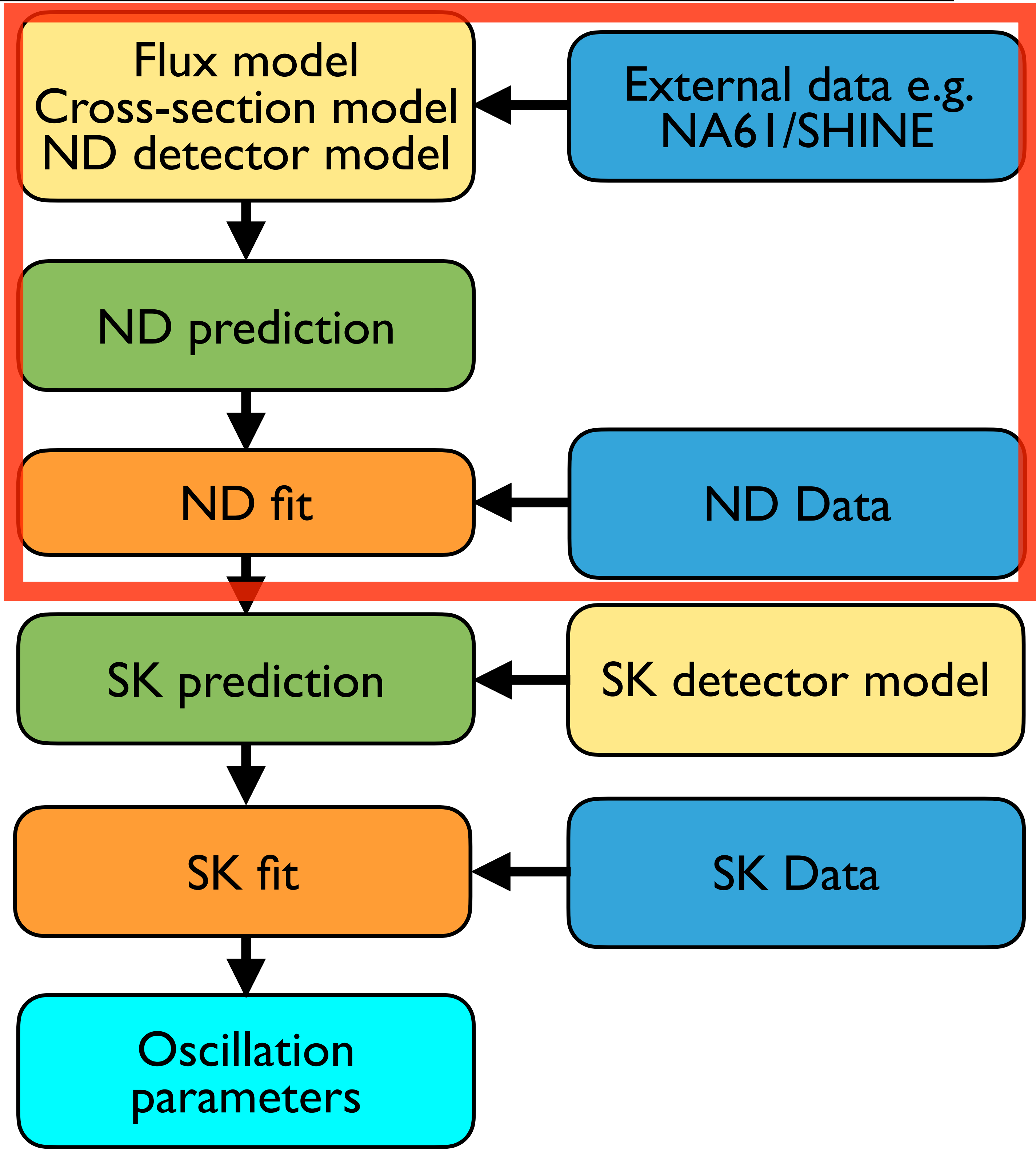
- Near detector fit provides constraints on both flux and cross-section uncertainties (covariance matrix) which is used to get SK prediction.



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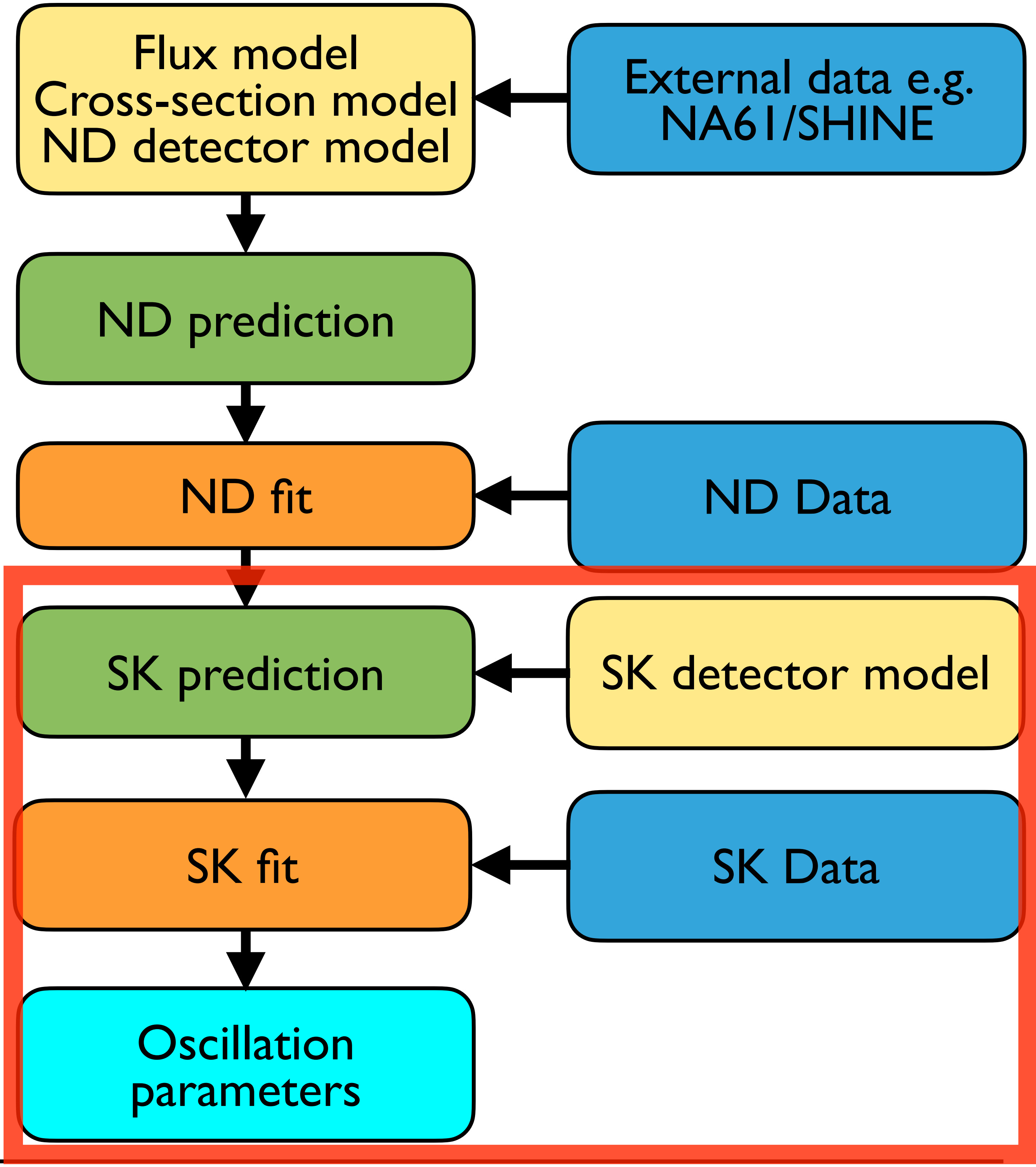
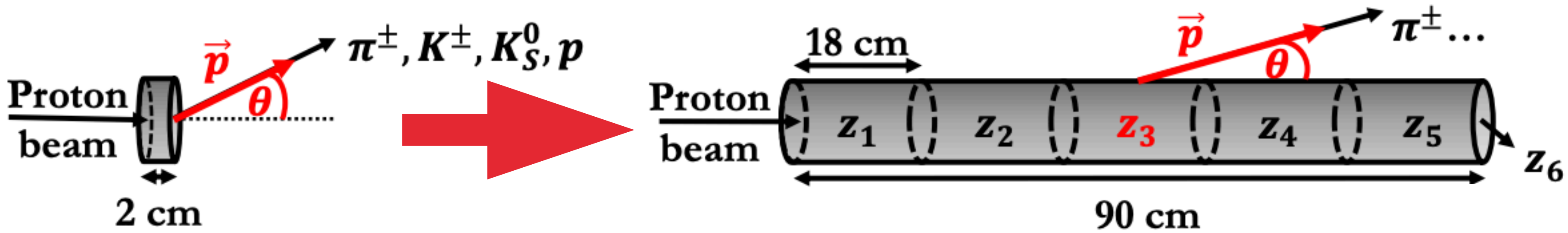
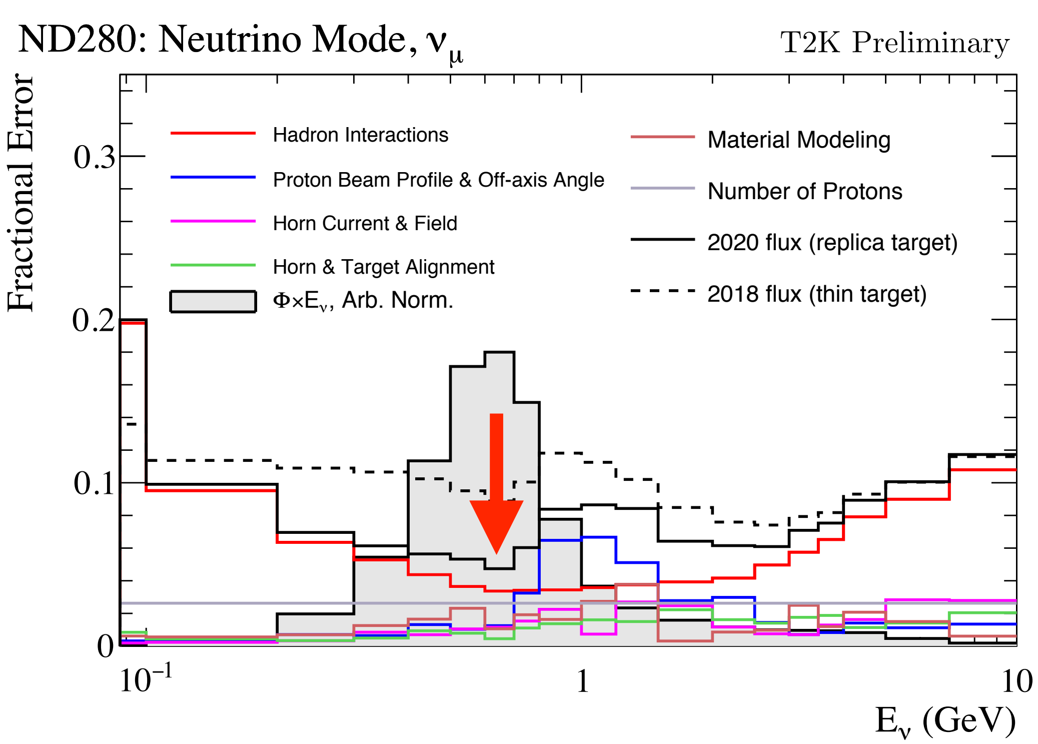
  - e.g. Flux model is constrained with both NA61/SHINE data and INGRID data.
- Near detector fit provides constraints on both flux and cross-section uncertainties (covariance matrix) which is used to get SK prediction.
- This analysis uses inputs from ND fit and then independently performs fits to SK data.

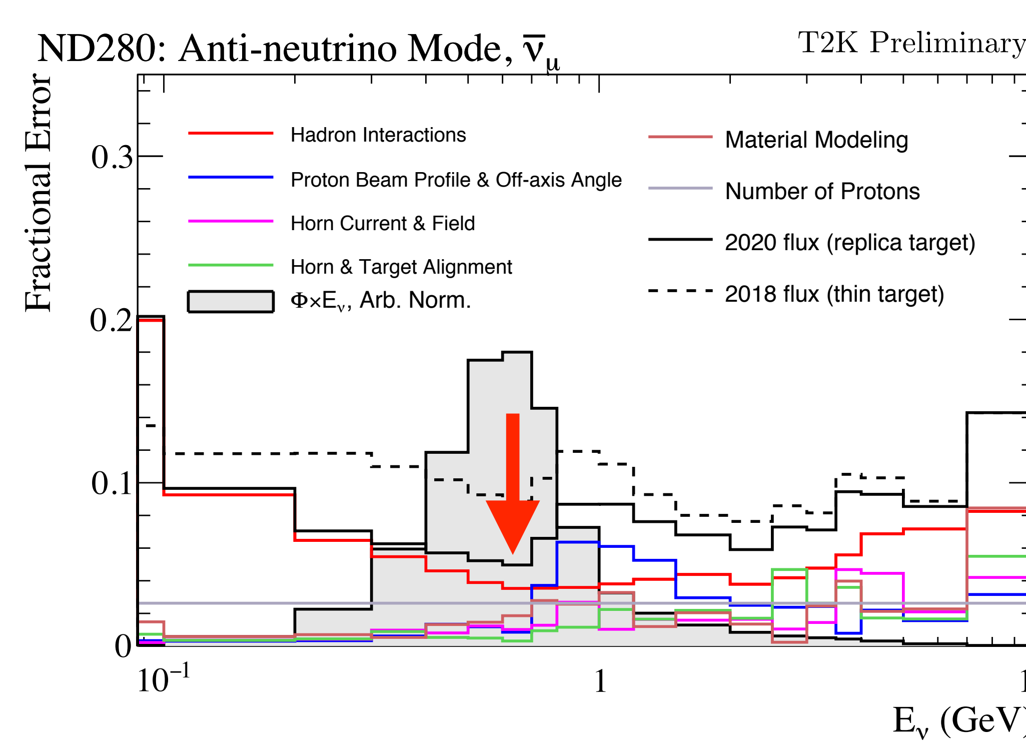


Neutrino Flux Model

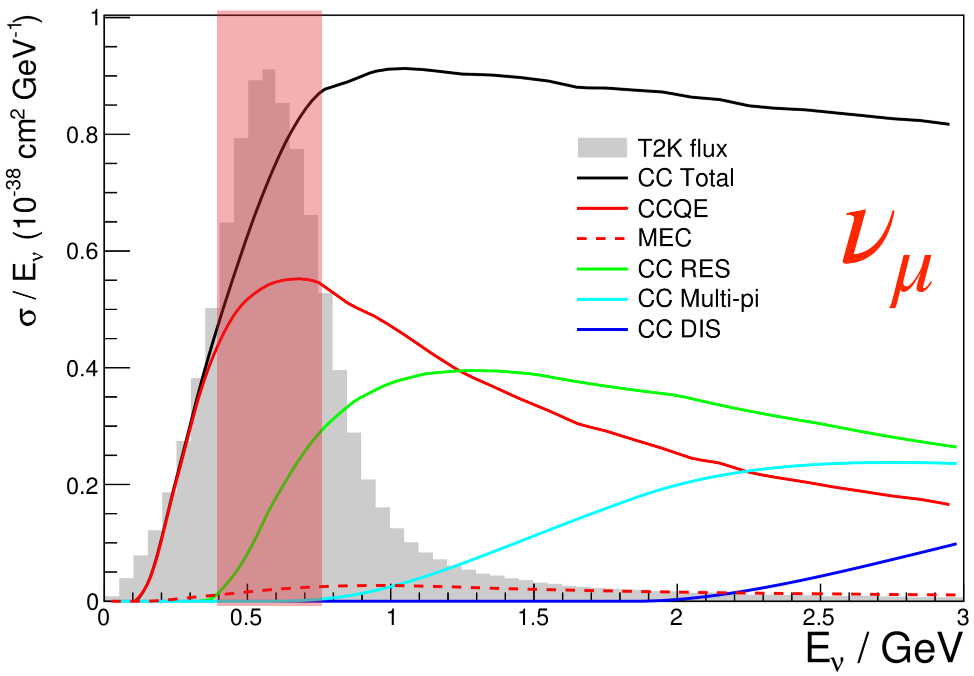


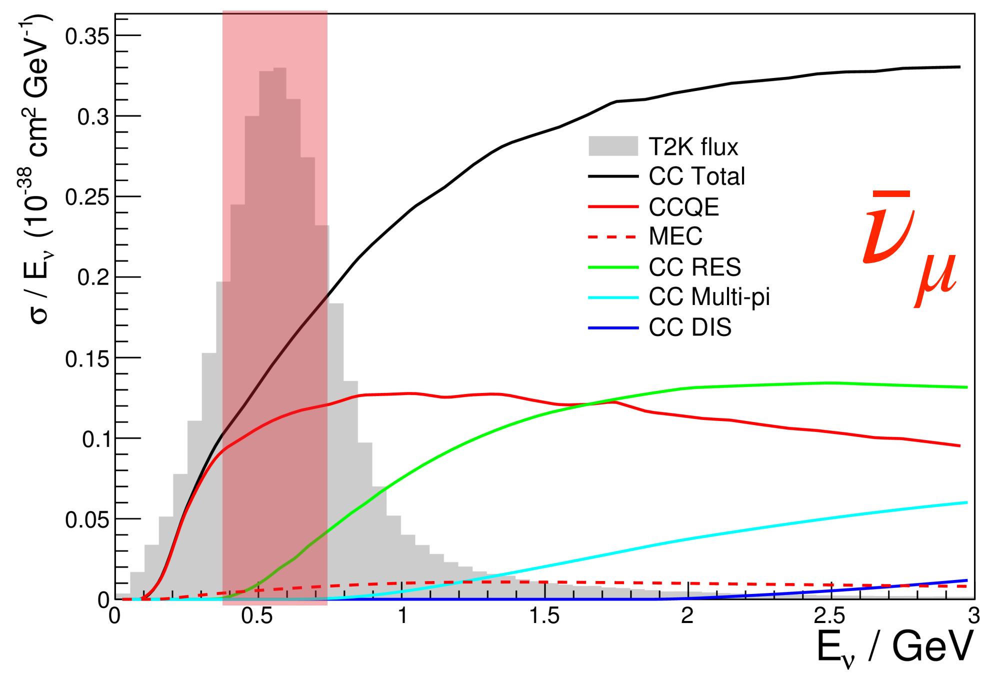
- Neutrino flux at T2K is tuned to NA61/SHINE T2K replica target [EPJC 76, 84 (2016)].
  - In the previous analysis, flux was tuned to NA61/SHINE thin target data.
- Flux uncertainty from 8% to 5%.



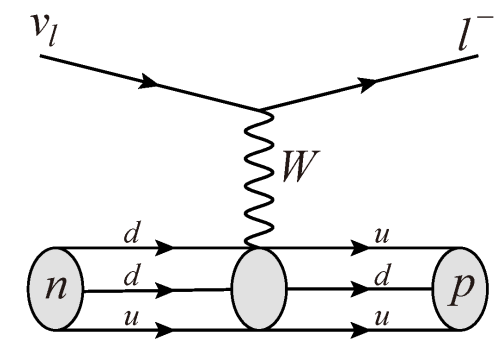


Neutrino Interaction Model

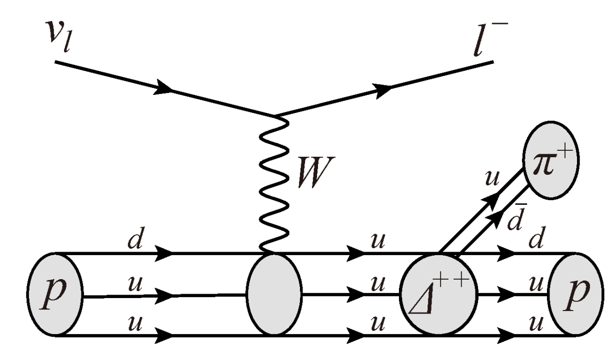




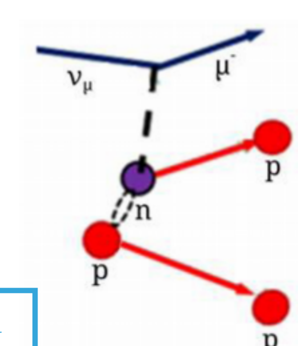
Charged Current Quasi-Elastic (CCQE) interaction



Charged Current Resonance (CCRES) interaction



multi-nucleon or 2p2h interaction

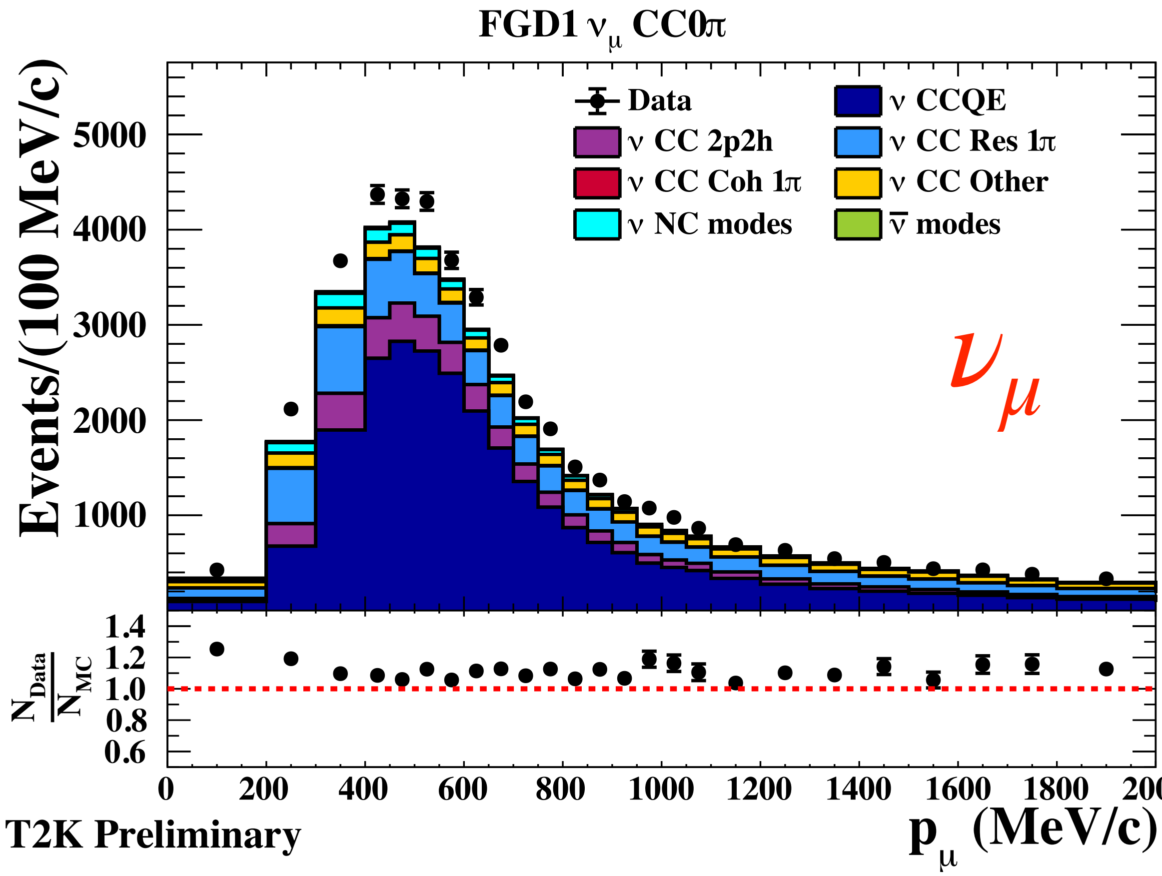


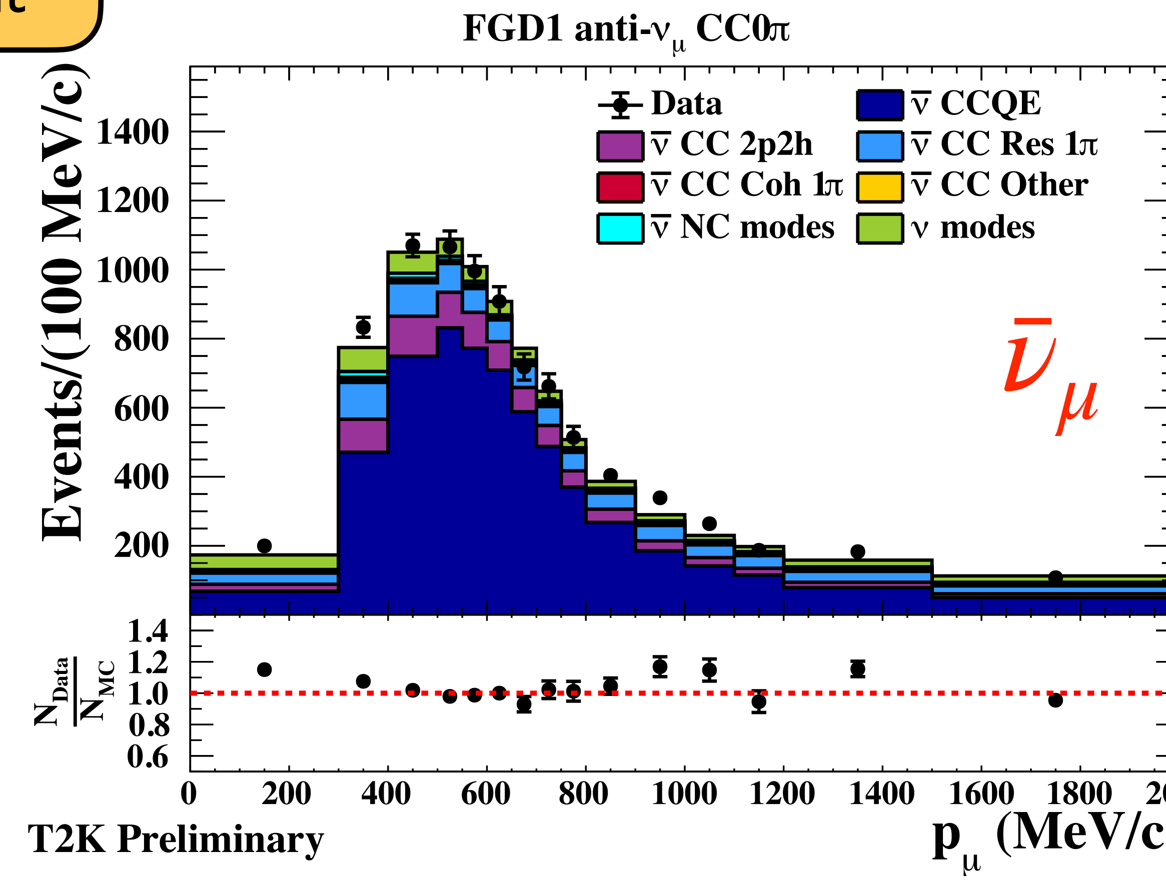
- At T2K energies, CCQE and CCRES are the dominant scattering processes.
- Some highlights of cross-section systematics
  - Separate 2p2h normalization parameters for neutrino and anti-neutrino - independently varied.
  - Binding energy is correlated between neutrino and anti-neutrino.
  - Axial mass parameter (M_A^{QE}) is correlated neutrino and anti-neutrino.

See Mathieu Guigue Plenary talk

Near Detector Fit

Pre-fit



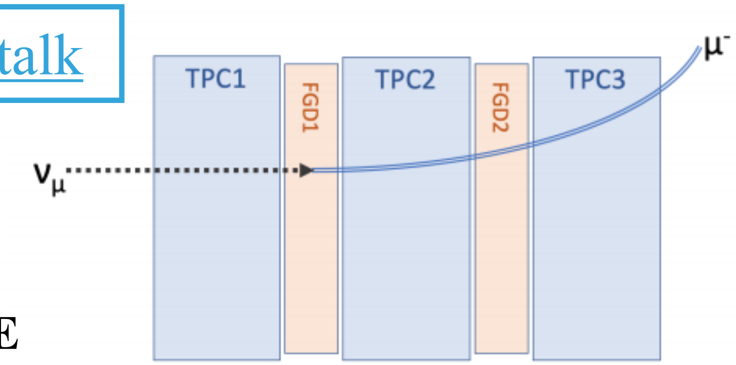


- Near detector (ND280) fit to data constrains both flux and cross-section systematics uncertainties - about twice as much data 1.15 (0.8) $\times 10^{21}$ POT in ν ($\bar{\nu}$) mode.
- Total of 18 samples based on number of reconstructed π's, in FGD1/FGD2 and in neutrino/anti-neutrino mode .

See Joe Walsh Parallel talk

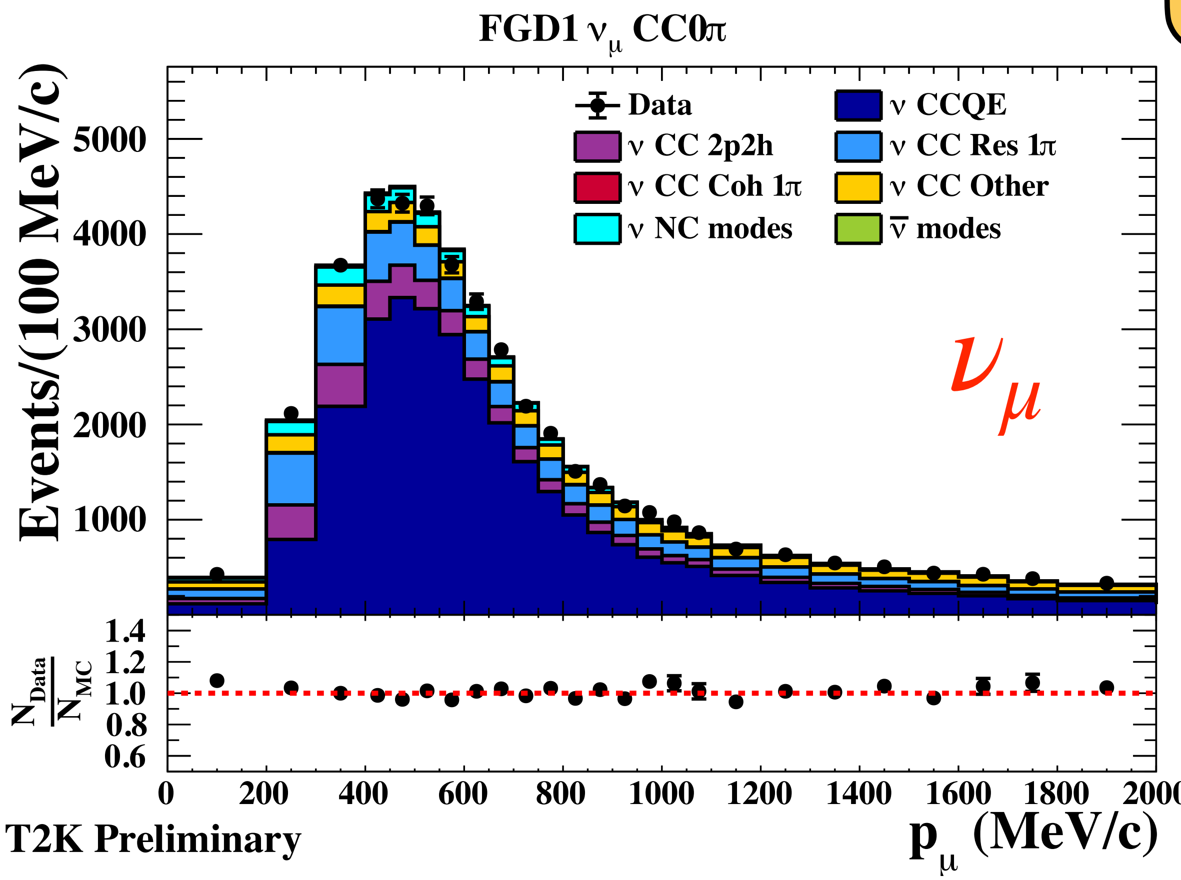
	FGD1			FGD2		
ν events in neutrino mode	CC0π	CC1π	CCNπ	CC0π	CC1π	CCNπ
$\bar{\nu}$ events in antineutrino mode	CC0π	CC1π	CCNπ	CC0π	CC1π	CCNπ
ν events in antineutrino mode	CC0π	CC1π	CCNπ	CC0π	CC1π	CCNπ

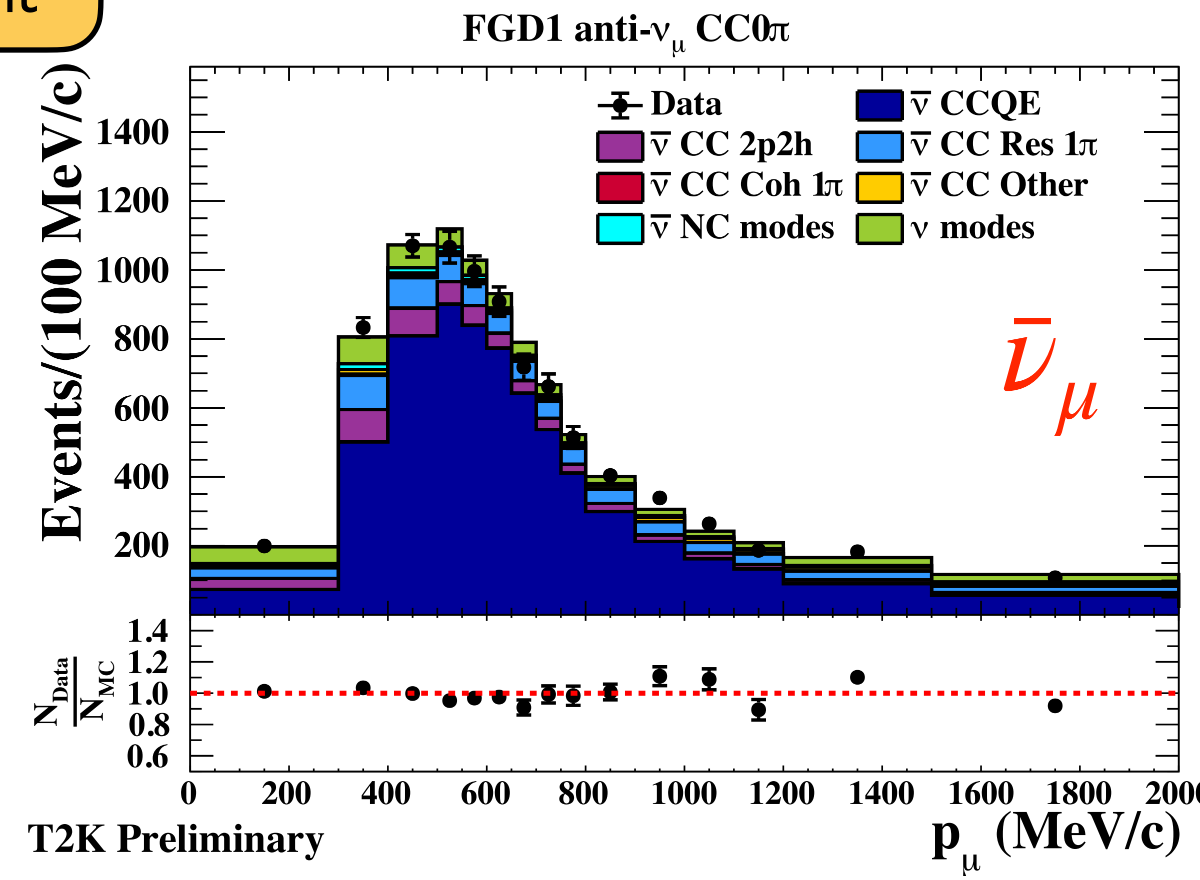
ν_μ CC0π: No π's in final state mostly CCQE



Near Detector Fit

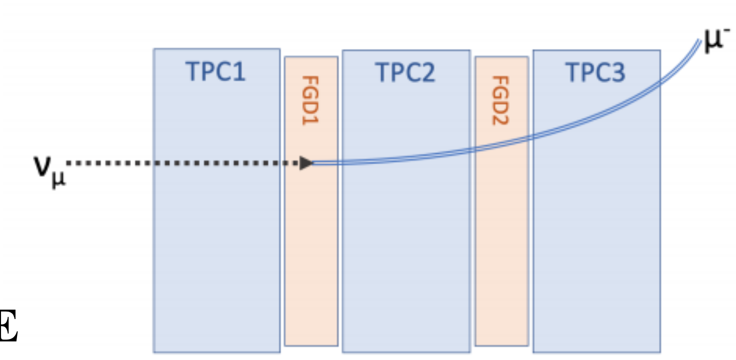
Post-fit





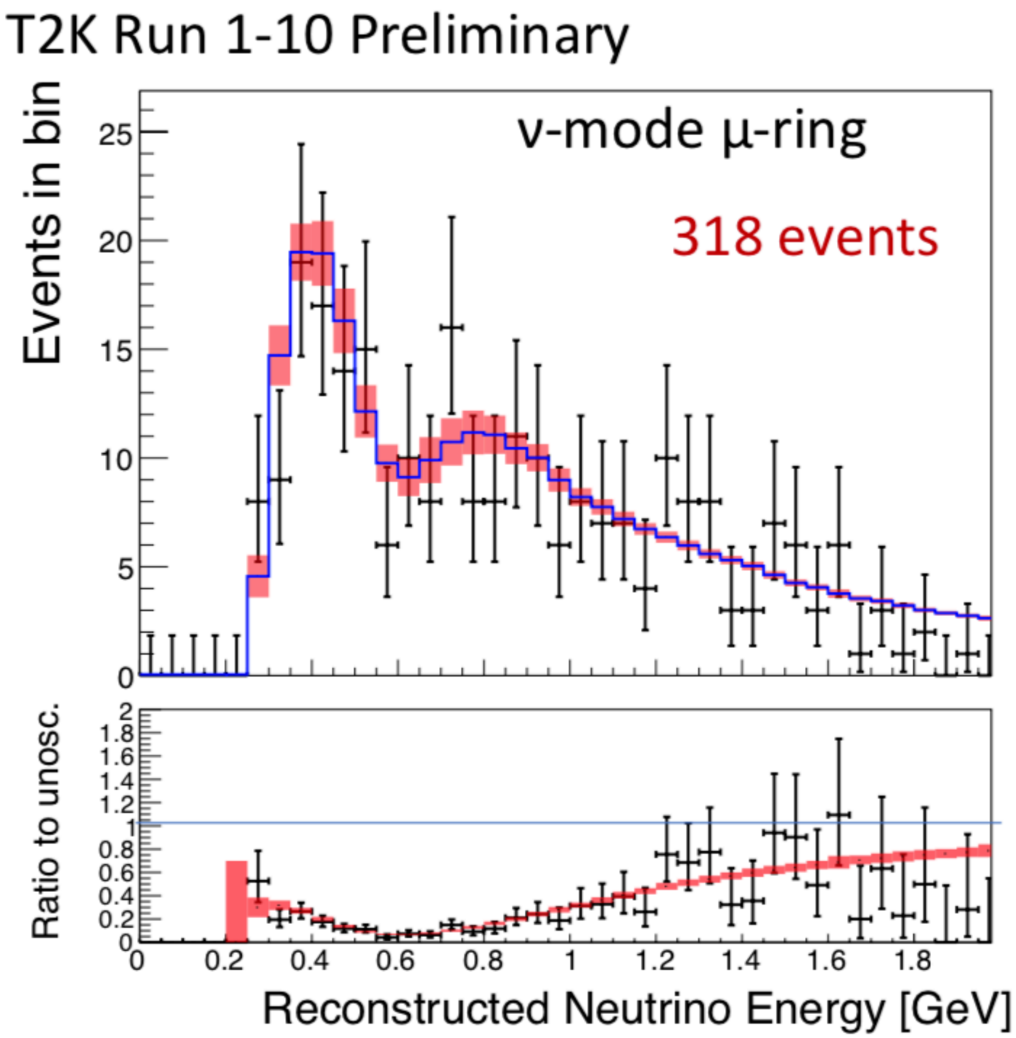
- Near detector (ND280) fit to data constrains both flux and cross-section systematics uncertainties - about twice as much data 1.15 (0.8) $\times 10^{21}$ POT in ν ($\bar{\nu}$) mode.
- ND fit introduces anti-correlations between flux and cross-section uncertainties.
  - Reduced uncertainties on event rates at SK.
- SK pre-fit uncertainty reduced
  - ν_μ sample - 11.1% to 3.0%.
  - $\bar{\nu}_\mu$ sample - 11.3% to 4.0%

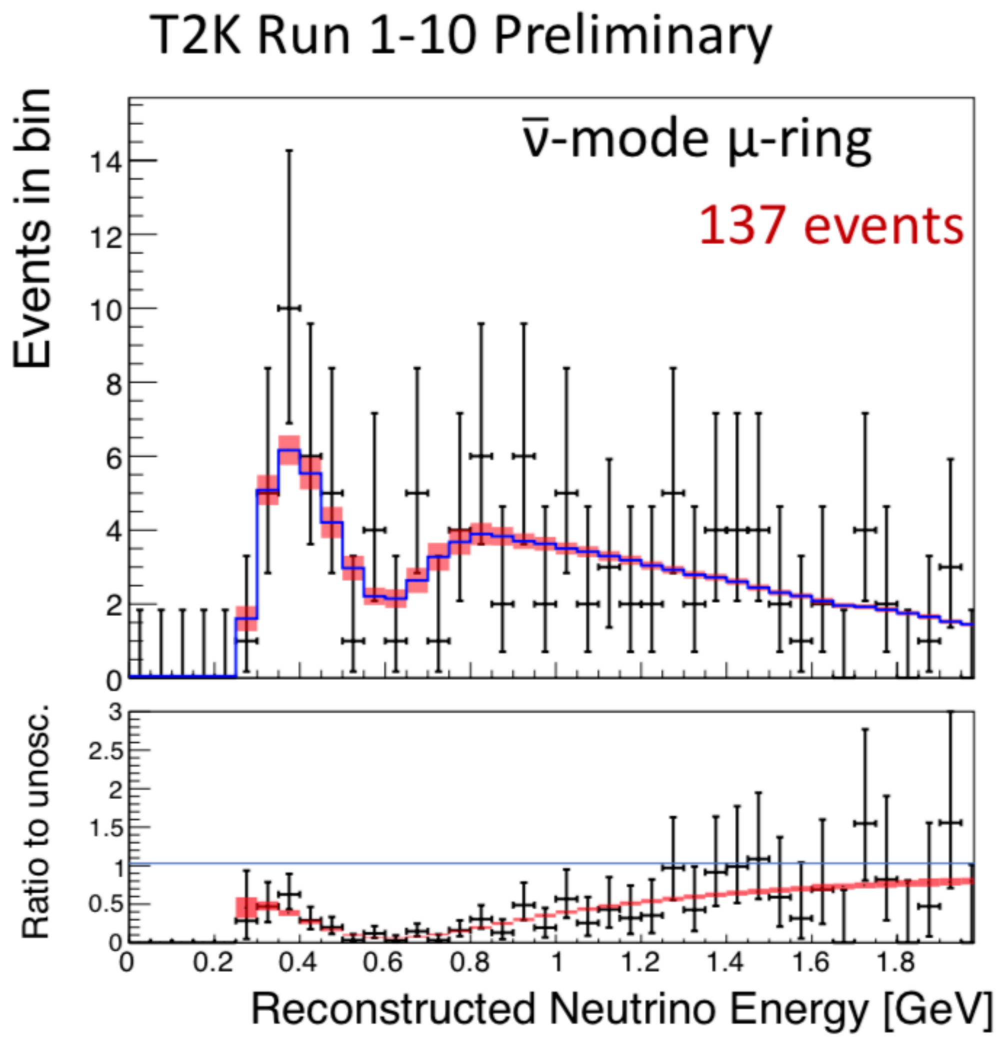
ν_μ CC0π: No π's in final state mostly CCQE



SK Event Spectra

- Predicted and observed spectra of samples with μ-like rings (left - ν mode, right - $\bar{\nu}$ mode) at SK detector. Clearly, a visible dip around 0.6 GeV in the ratio plot with un-oscillated spectra due to oscillations.
- Error band (1σ) is the post-SK fit systematic uncertainty (on rate, 3% - ν mode, 4% - $\bar{\nu}$ mode).



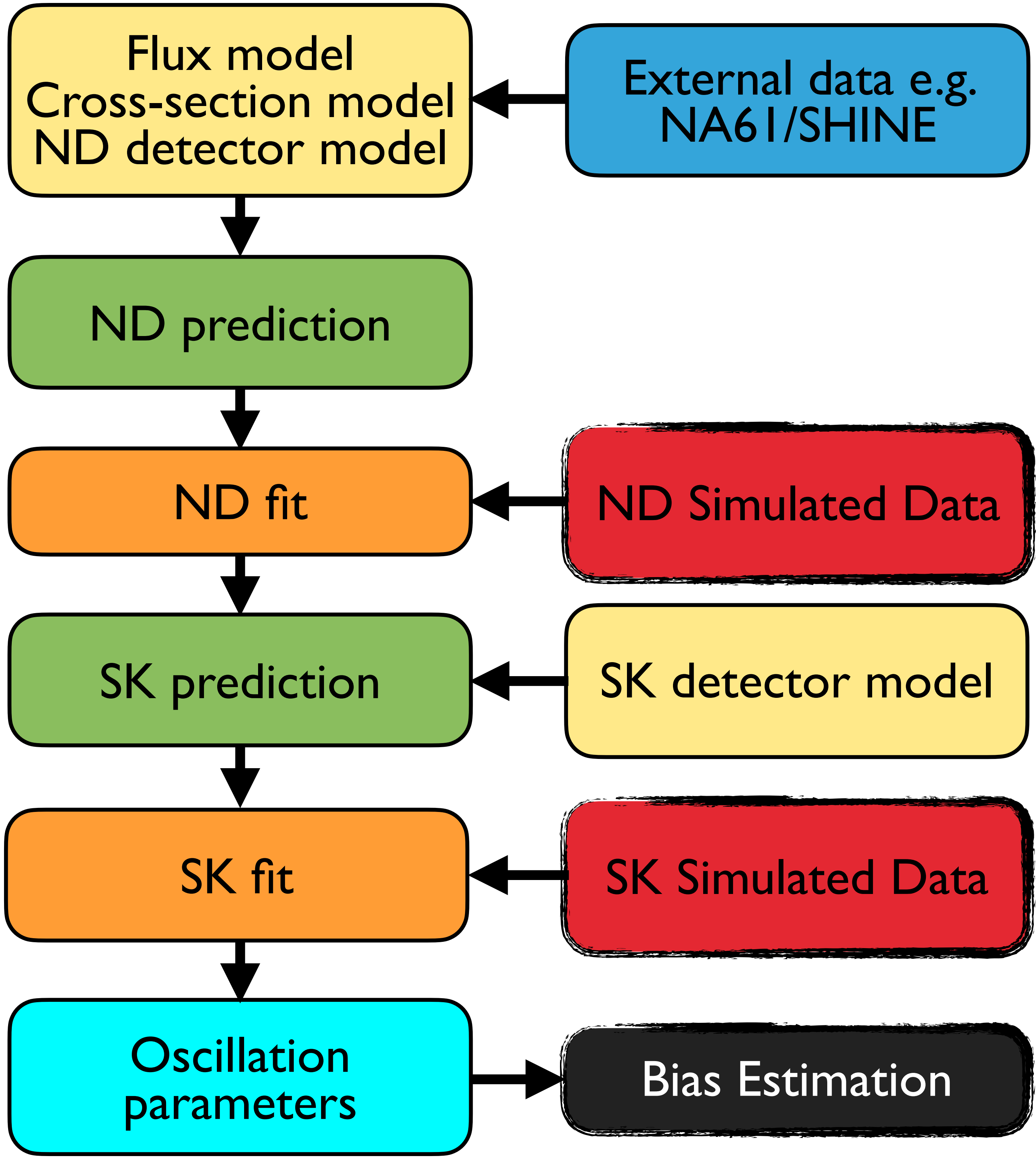


Simulated Data Robustness Studies

- There have been studies [JPhysG **44** 054001] shows that long-baseline experiments may be biased by the cross-section model choices.
- Simulated data studies are used to test the robustness of T2K analysis against model dependent assumptions.
- These studies are used to evaluate the bias in the oscillation parameters by varying the nominal cross-section models.
  - e.g. alternative 2p2h models, external data-driven tunes.
- Simulated data sets are created by applying weights to events in the nominal Monte Carlo sample both at ND280 and SK detector.
  - Weights are calculated as the ratio between altered interaction model and nominal cross-section model.

Simulated Data Robustness Studies

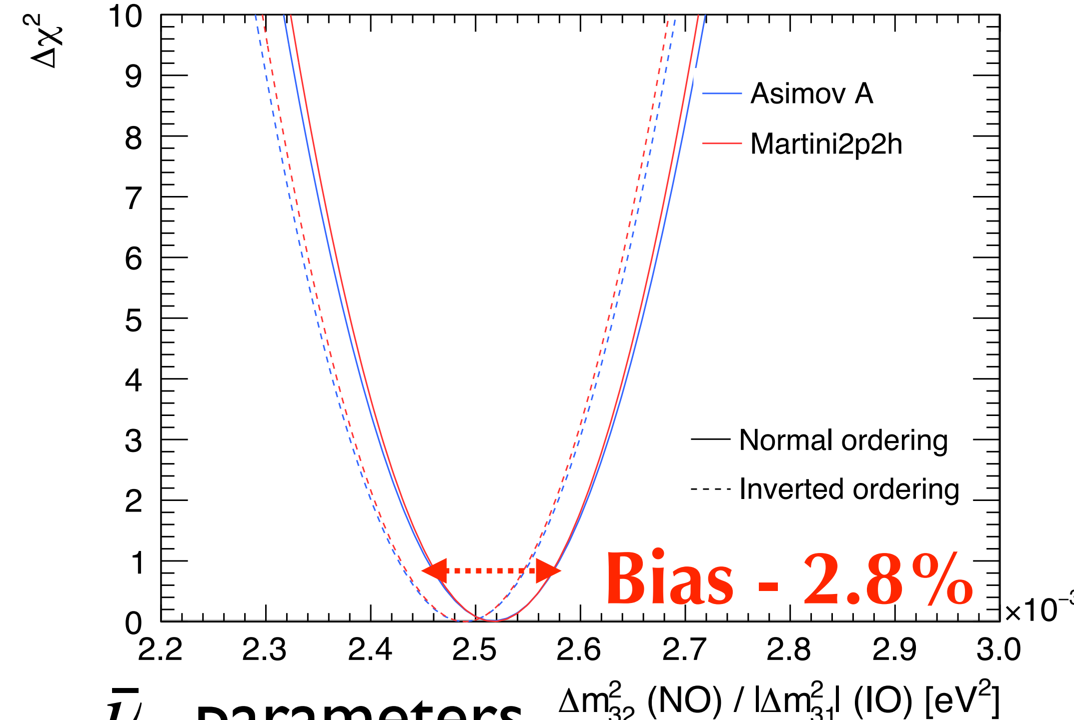
- Fits to simulated data sets are performed both at ND280 and SK detector, and produce the likelihood contours for oscillation parameters at SK.
- Likelihood contours from nominal MC and simulated data are then compared to estimate the bias.
  - Bias is an estimate of difference in the centers of 1σ intervals for Δm^2_{32} contours and divided by 1σ interval from nominal fit.



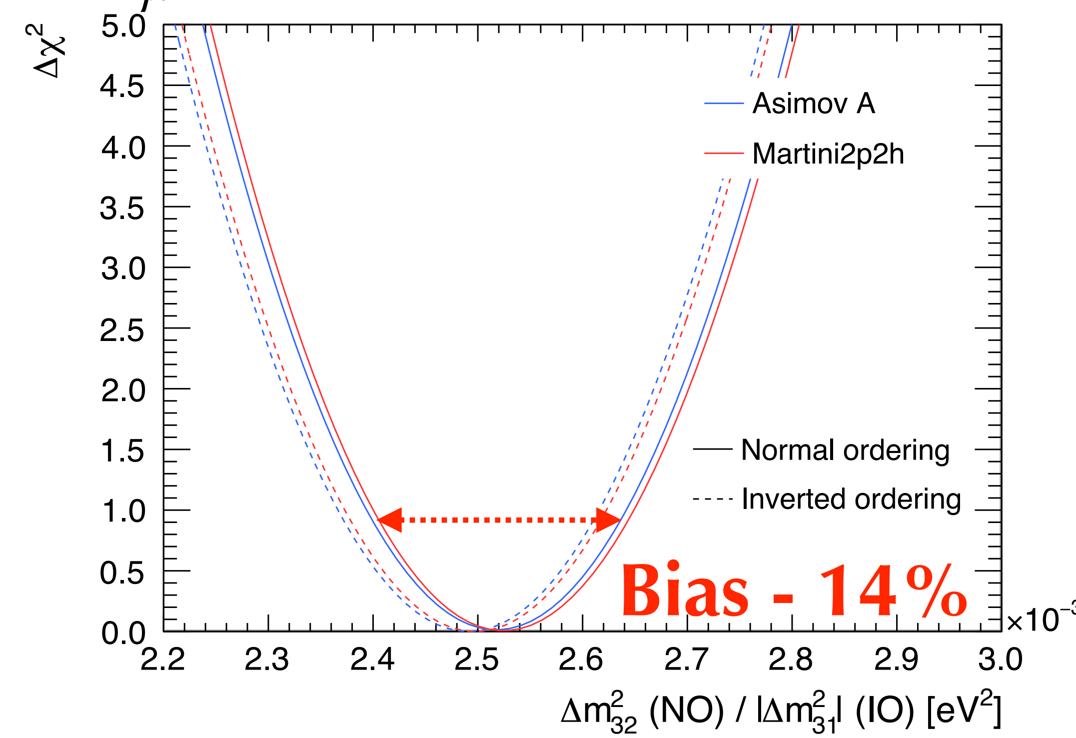
Simulated Data Robustness Studies

- An example of showing results from SK fits to alternative cross-section model for 2p2h events. A very different 2p2h neutrino vs anti-neutrino behavior of the two models.
  - Nominal - Nieves et.al
  - Altered - Martini et.al
- Fits to several other simulated data sets were performed as well.
- No significant biases seen on θ_{23} $(\bar{\theta}_{23})$ and Δm^2_{32} $(\Delta\bar{m}^2_{32})$ from any of the alternative models
  - Seen small bias on Δm^2_{32} $(\Delta\bar{m}^2_{32})$ which is accounted by adding an error of 0.57 (1.232) $\times 10^{-5}$ eV^2/c^4 in quadrature to the total post-fit uncertainty on Δm^2_{32} $(\Delta\bar{m}^2_{32})$

ν_μ parameters

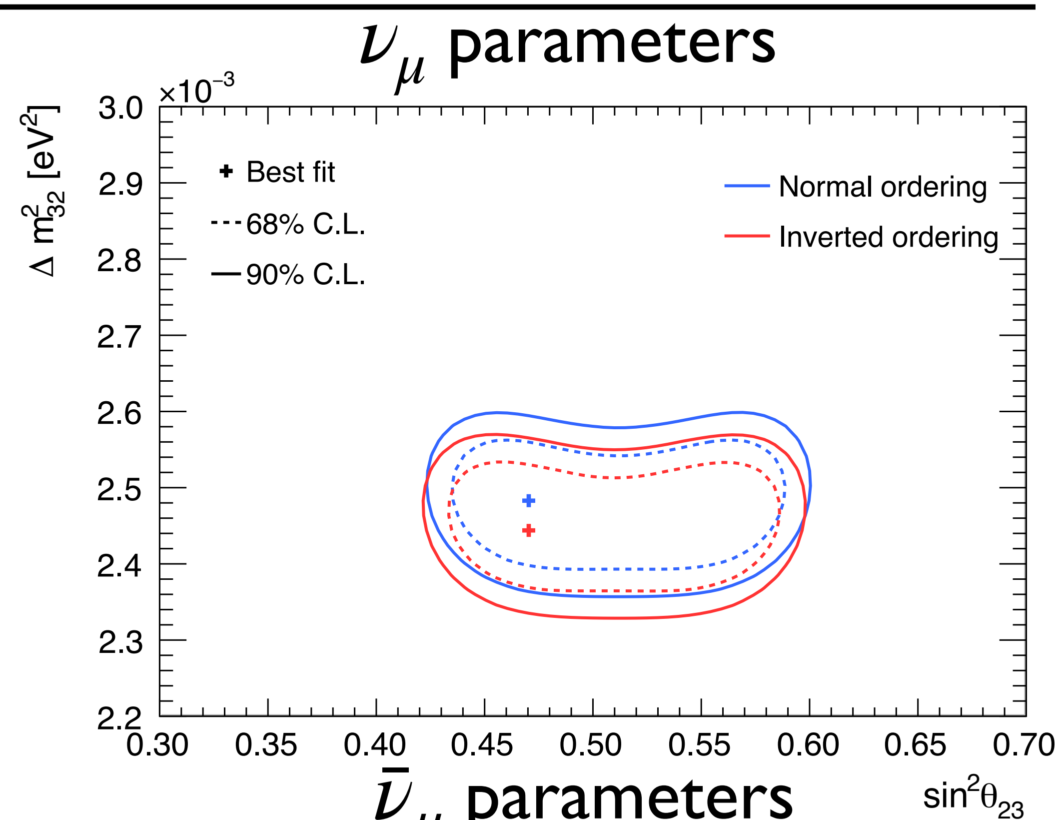


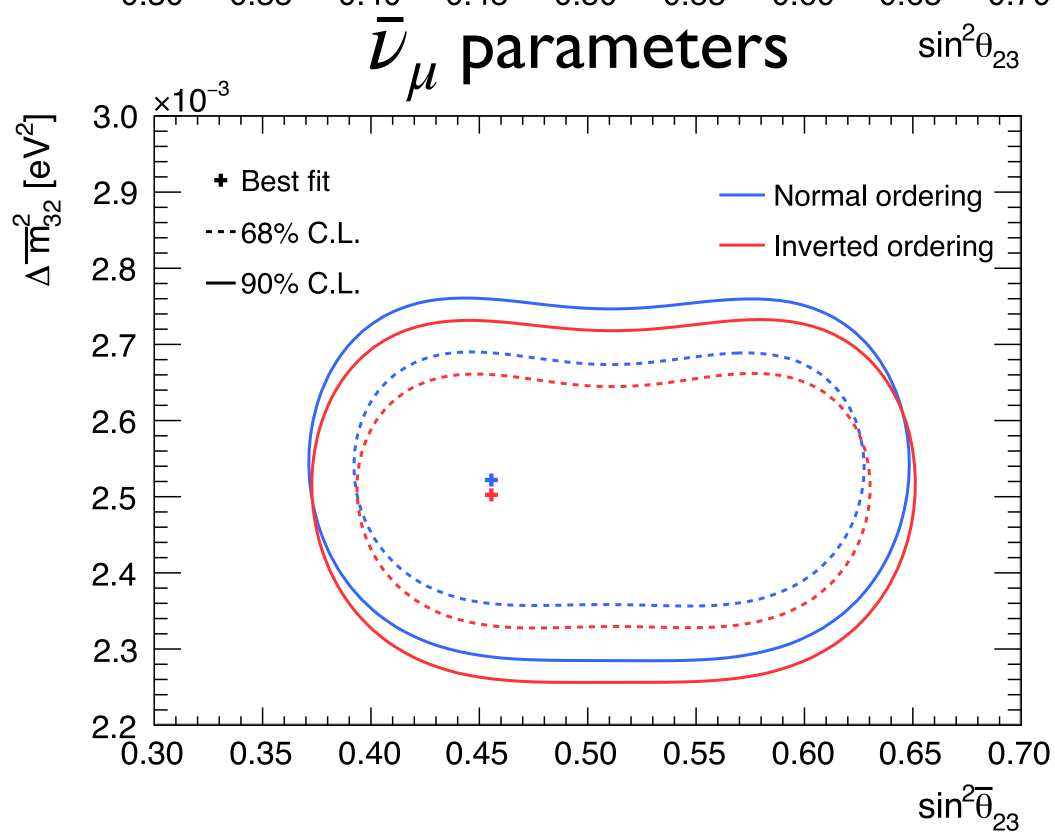
$\bar{\nu}_\mu$ parameters



Data Fit Results

- Fit to Δm^2_{32} and $\sin^2\theta_{23}$ while marginalizing over $\bar{\theta}_{23}$, $\Delta\bar{m}^2_{32}$ and other parameters and vice versa.
- Improved constraints from the previous analysis due to an additional POT in the neutrino mode and analysis improvements (e.g. improved cross-section models).
- Best-fit values
  - $(\sin^2\theta_{23}, \Delta m^2_{32}) = (0.47, 2.48 \times 10^{-5})$
  - $(\sin^2\bar{\theta}_{23}, \Delta\bar{m}^2_{32}) = (0.45, 2.52 \times 10^{-5})$





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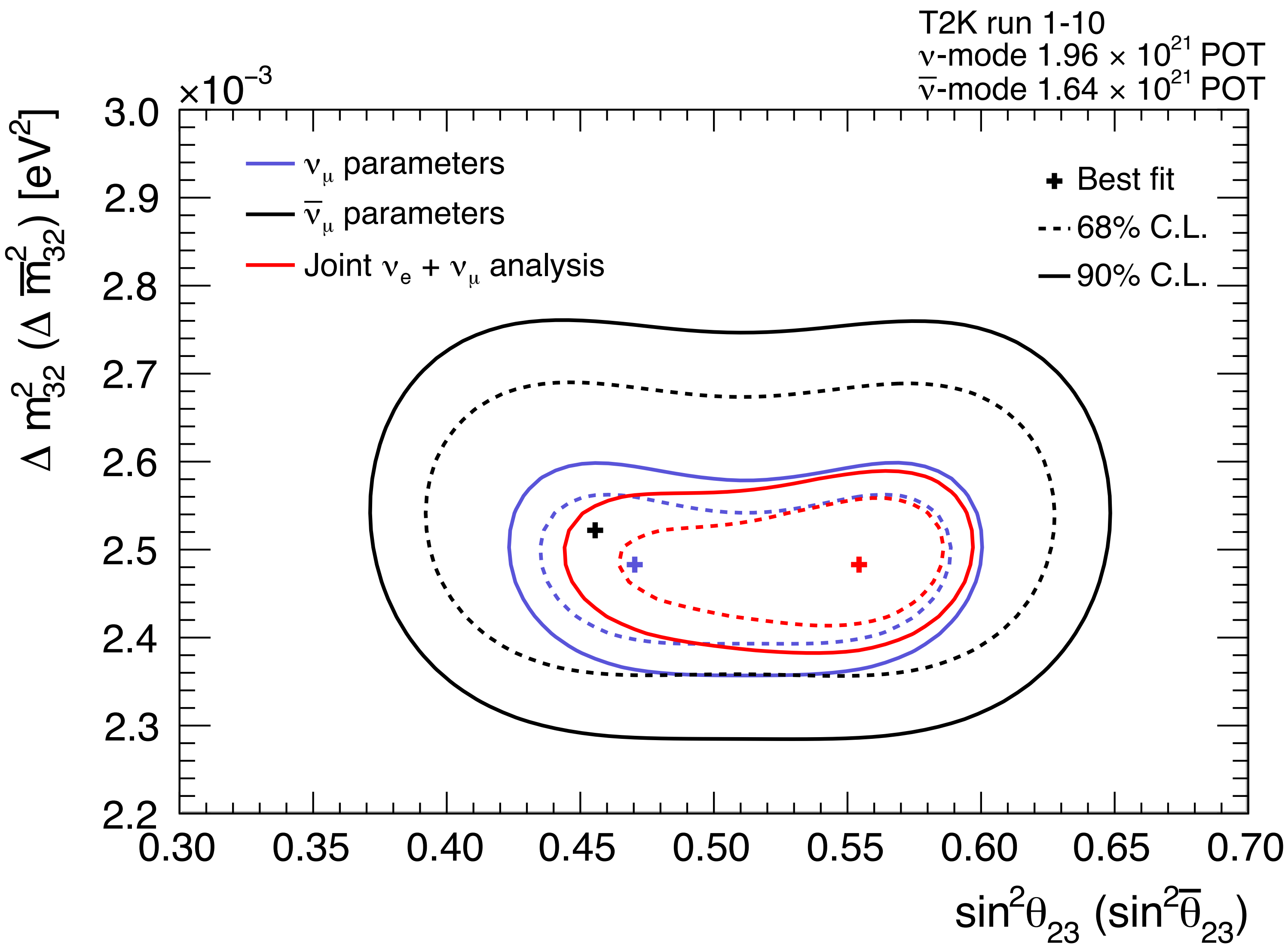


T2K latest results on joint $\nu_e + \nu_\mu$ analysis

See Joe Walsh Parallel talk

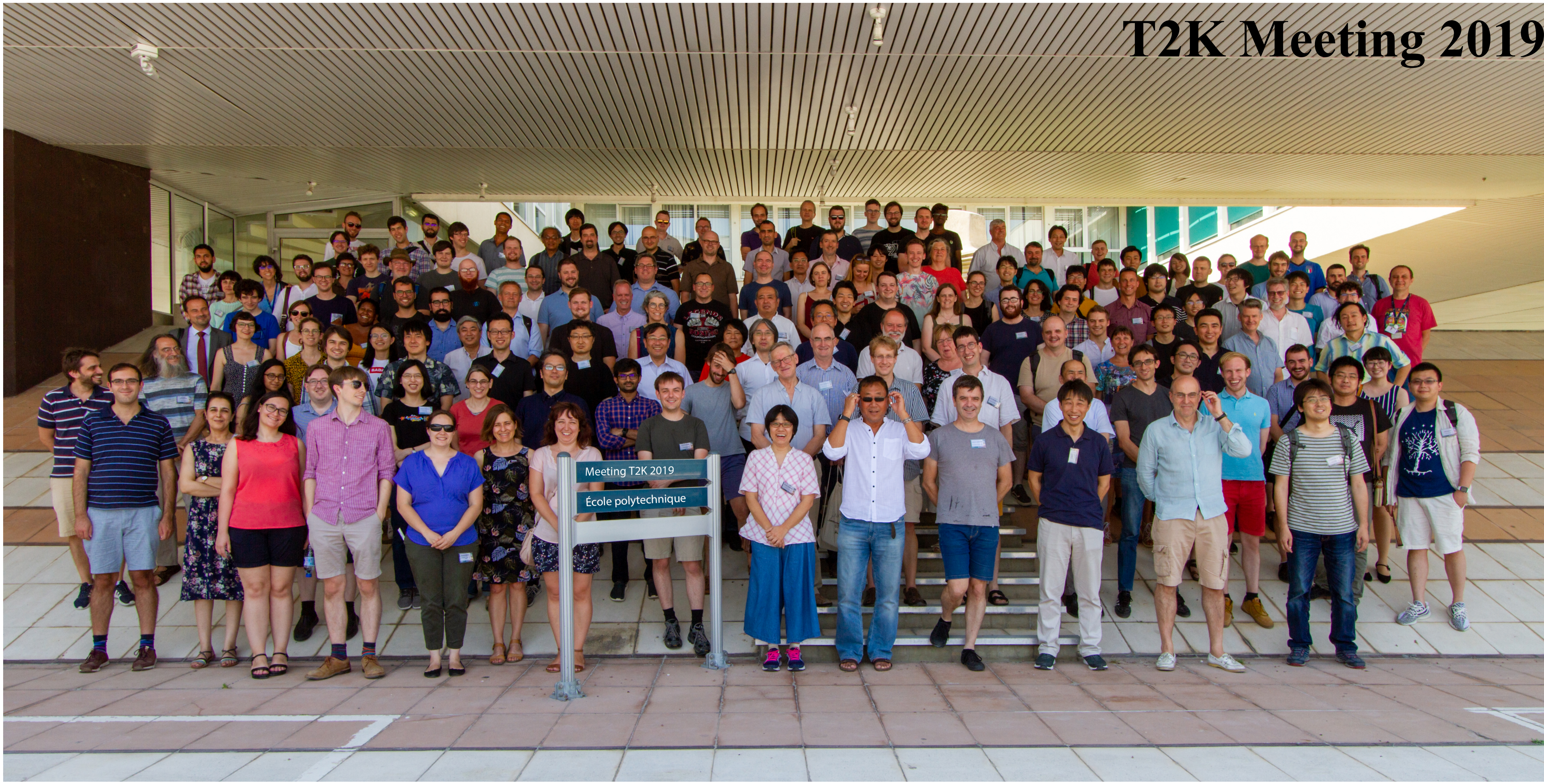
- Not sensitive to θ_{23} octant (leading order term ~ $\sin^2 2\theta_{23}$) as the lower octant and upper octant solutions have very similar likelihood in the joint fit with only μ-like samples.

Summary

- Improvements in this analysis
  - About twice the POT at Near Detector in both neutrino and anti-neutrino mode
  - 33% more data in the neutrino-mode at SK detector
  - Flux tuning with NA61/SHINE T2K replica target data
  - Significant improvement in the systematic uncertainties due to updated cross-section models
- Improved constraints on Δm^2_{32} and $\sin^2\theta_{23}$ from the previous analysis.
- Results in agreement with standard 3-flavor framework - no indication for new physics.
- Stay Tuned For More Exciting Results From T2K Experiment.

THANK YOU

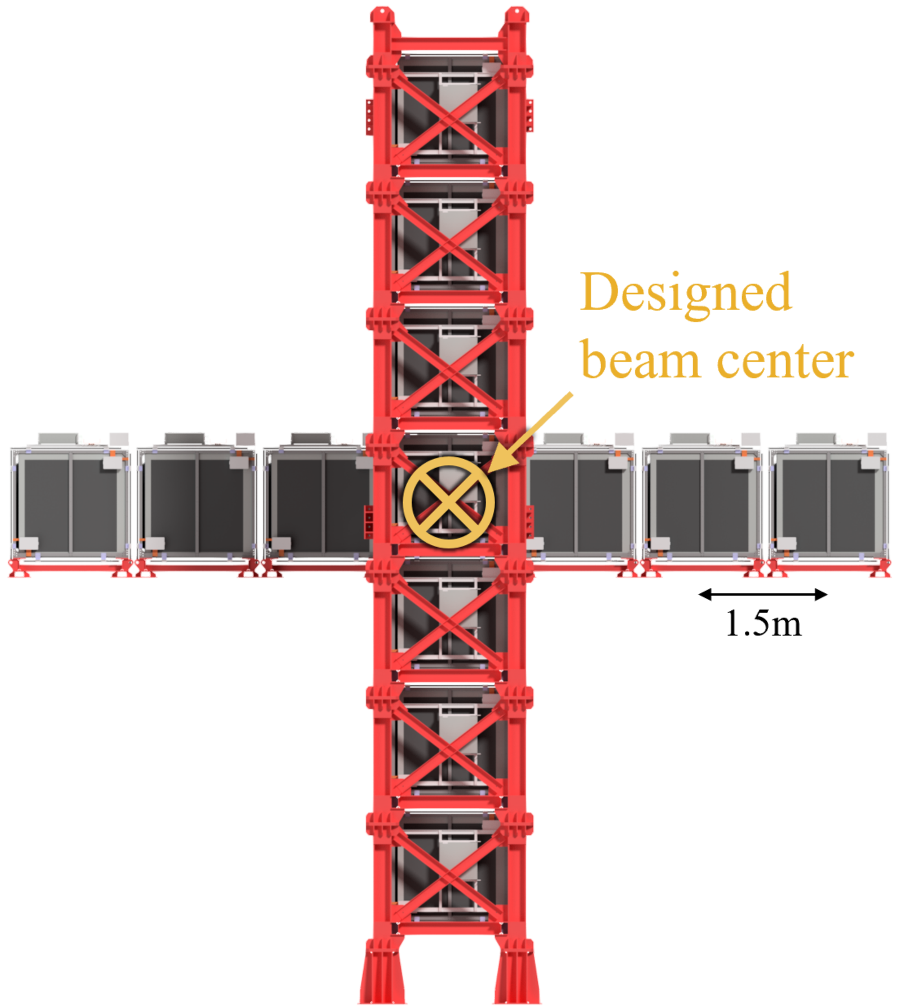
T2K Collaboration

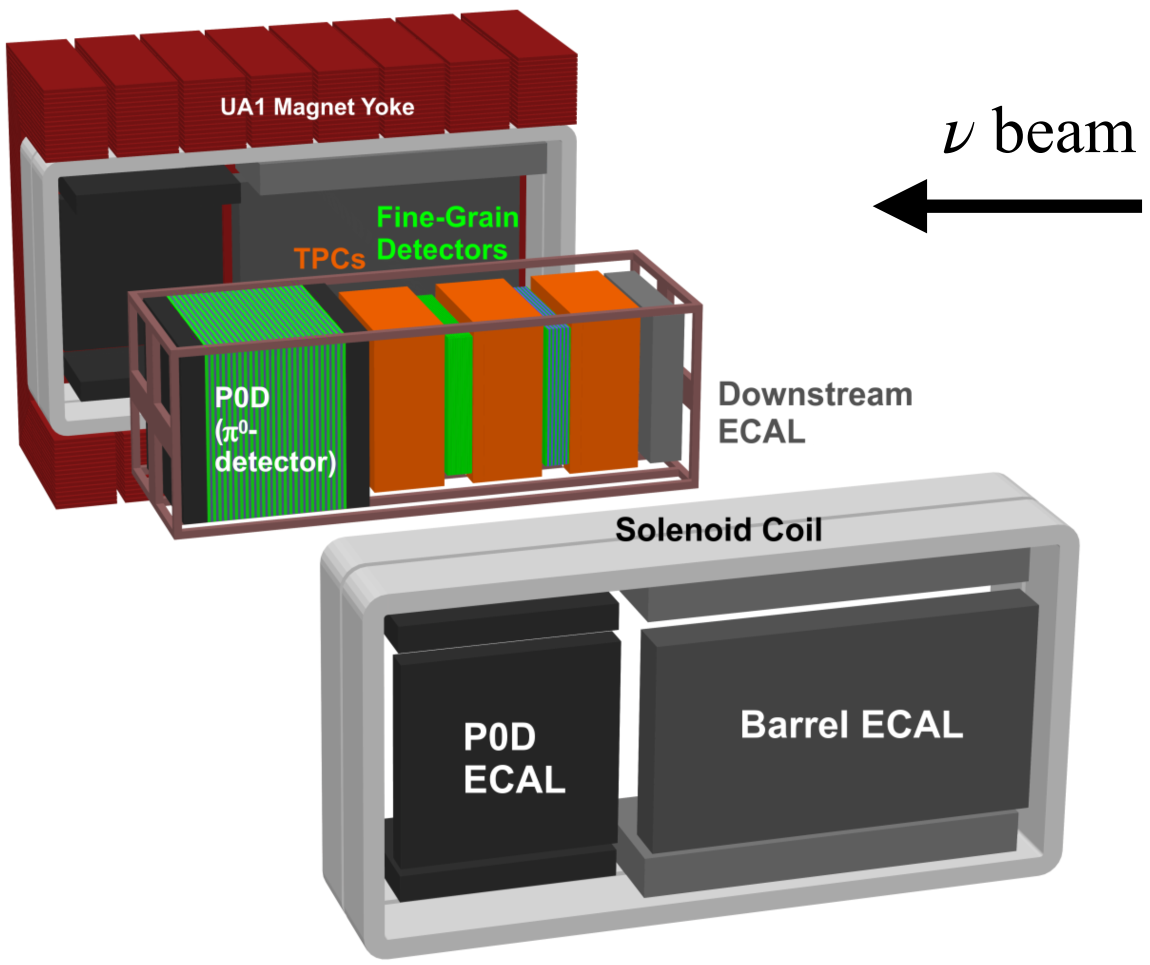


- About 500 members from Asia, Europe and USA.

BACK UP

Near Detectors





- On-axis detector
- Modular design with iron plates and scintillator trackers
- Precision of on-axis beam direction << 1 mrad

- Off-axis detector at 2.5^o
- Sub-detectors - Time Projection Chambers (TPC), Fine Grained Detectors (FGD), π^0 Detector
- Located inside UA1 magnet operated at 0.2 T.

Flux Prediction

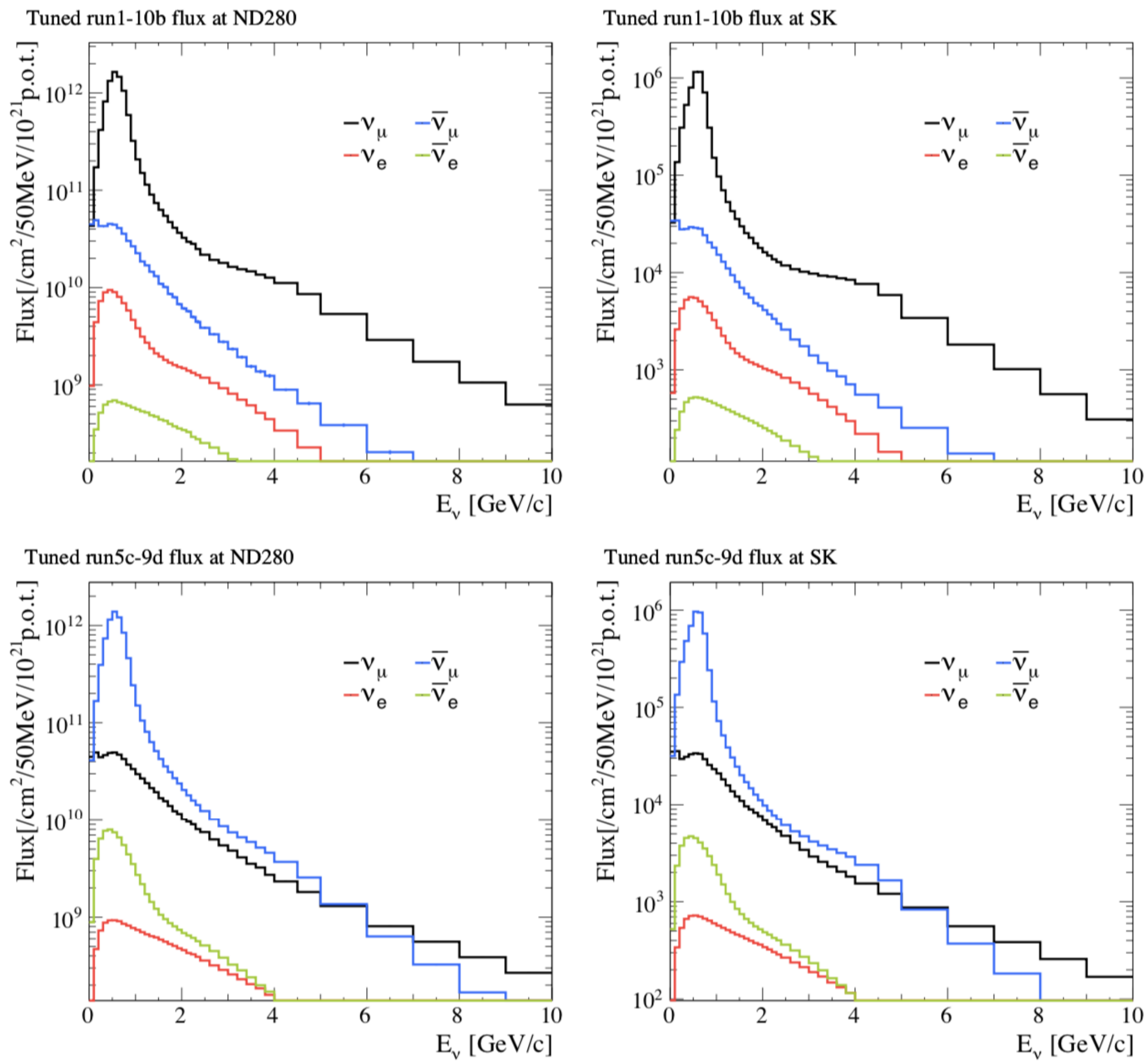


Figure 58: The tuned flux combined for Runs 1-10b (top) and 5c-9d (bottom), at ND280 (left) and at Super-Kamiokande (right). All species of neutrinos are shown. Only statistical error bars are shown.

Cross-Section Models For 2p2h

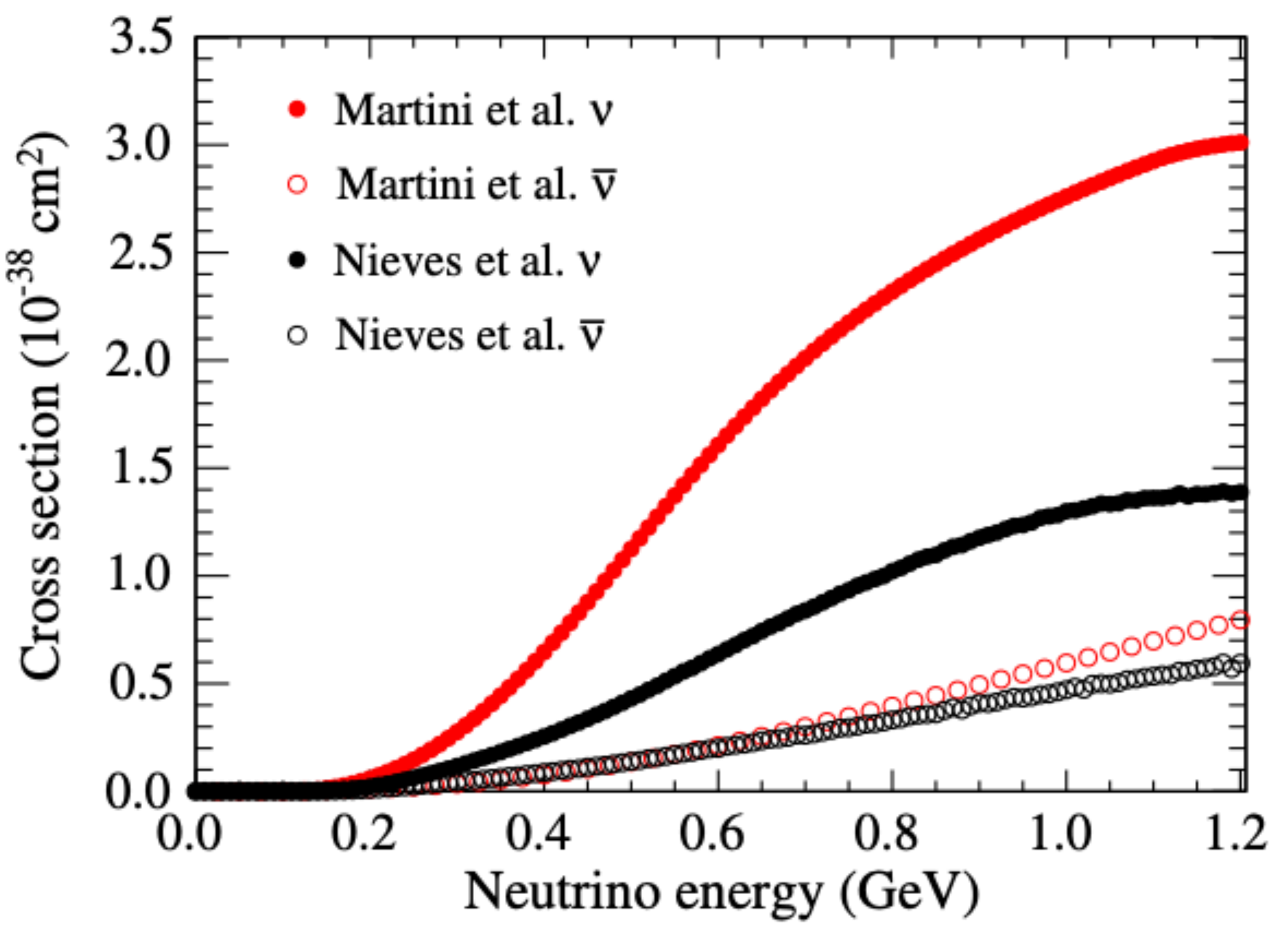
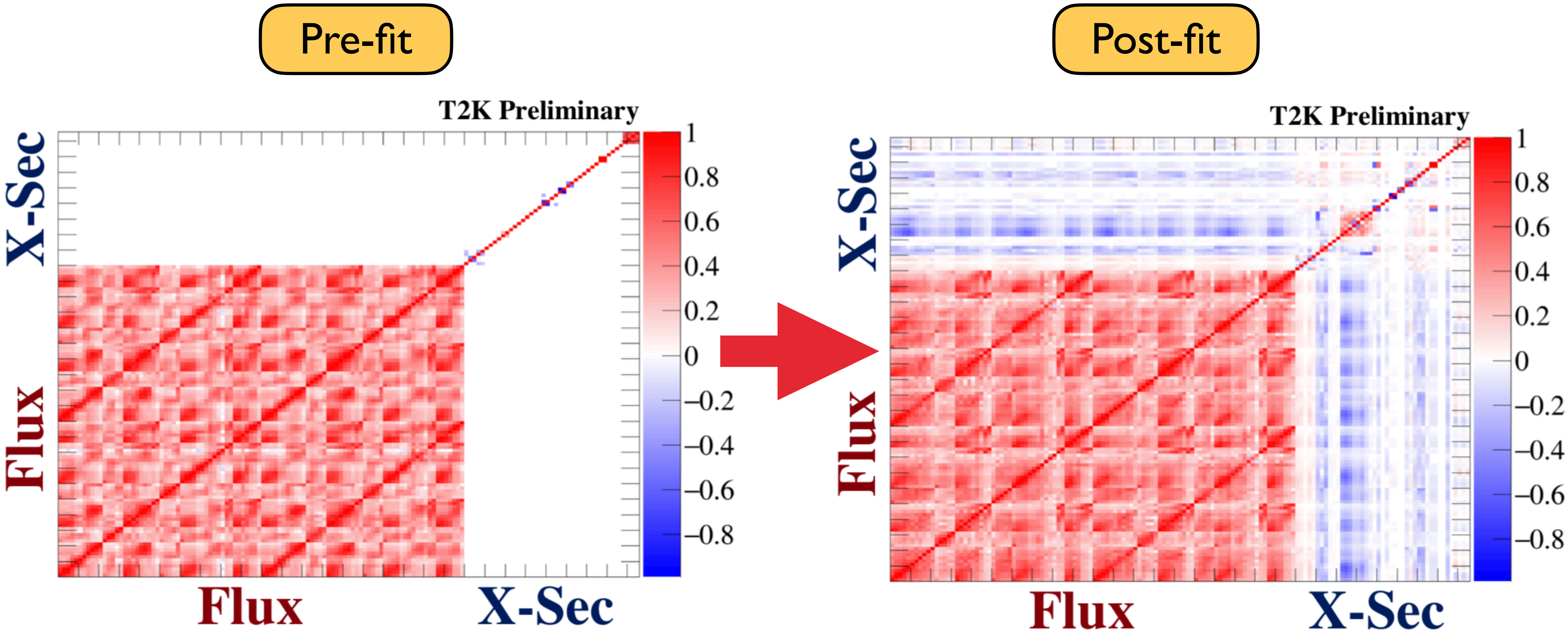


FIG. 4. Multinucleon interactions (2p2h) cross section on ^{12}C as a function of energy from the models of Nieves (reference model in the text) [40] and Martini (alternative model in the text) [70].

PhysRevD.96.092006

Near Detector Fit



- Near detector (ND280) fit to data constrains both flux and cross-section systematics uncertainties.
- No correlations before ND fit, but (anti) correlations after the ND fit between flux and cross-section systematic uncertainties.

Likelihood Estimation

- The marginal likelihood is given as

$$\mathcal{L}_{marg}(N_e^{obs.}, N_\mu^{obs.}, \boldsymbol{x}_e, \boldsymbol{x}_\mu, \boldsymbol{o}) = \int \mathcal{L}(N_e^{obs.}, N_\mu^{obs.}, \boldsymbol{x}_e, \boldsymbol{x}_\mu, \boldsymbol{o}, f)\,\mathrm{d}f.$$

$$\mathcal{L}(N_e^{obs.}, N_\mu^{obs.}, \boldsymbol{x}_e, \boldsymbol{x}_\mu, \boldsymbol{o}, f) = \mathcal{L}_e(N_e^{obs.}, \boldsymbol{x}_e, \boldsymbol{o}, f) \times \mathcal{L}_\mu(N_\mu^{obs.}, \boldsymbol{x}_\mu, \boldsymbol{o}, f) \times \mathcal{L}_{\text{syst.}}(f)$$

where
x - measurement variable like E_{rec}, p and θ,
o - oscillation parameters,
f - systematic parameters,
L_{syst} - likelihood term for systematic uncertainties

Covariance matrix from ND280 fit

$$\mathcal{L}_{\text{syst}} = \exp(-0.5 \sum_{i,j} v_i M_{ij} v_j)$$

- Use importance sampling for the numerical integration of marginal likelihood

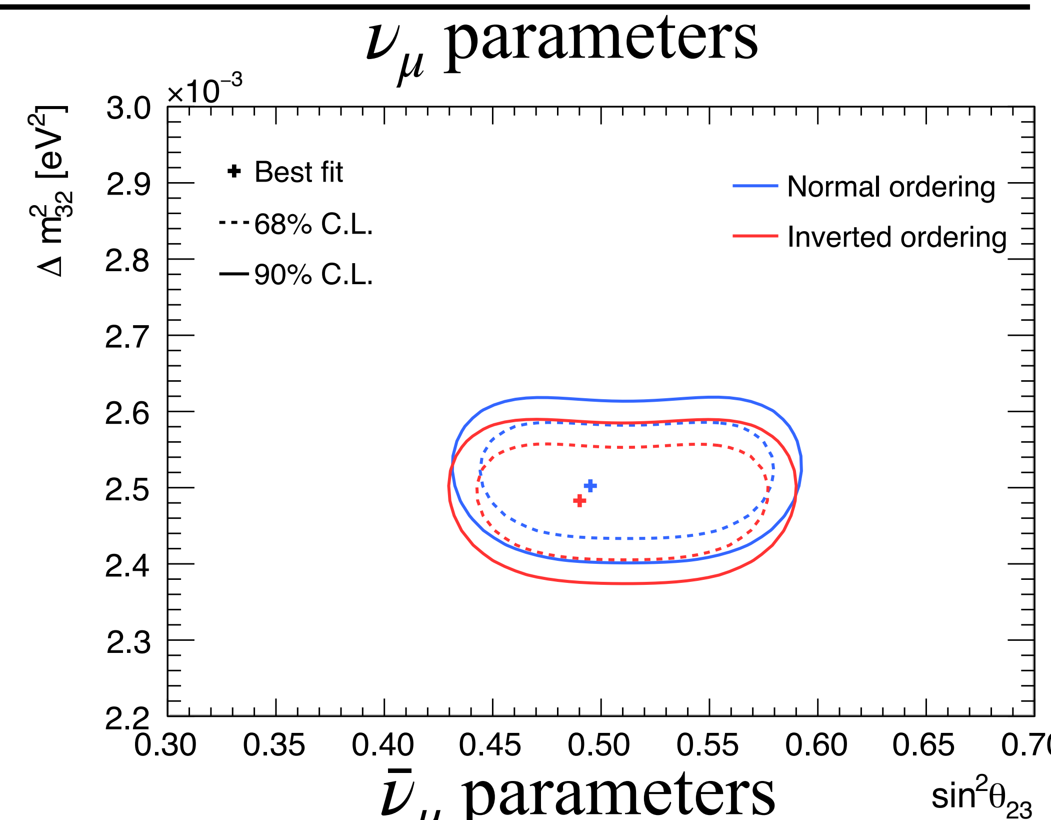
$$\mathcal{L}_{marg}(N_e^{obs.}, N_\mu^{obs.}, \boldsymbol{x}_e, \boldsymbol{x}_\mu, o) = \frac{1}{N} \sum_{i=1}^{N} \mathcal{L}_e(N_e^{obs.}, \boldsymbol{x}_e, o, f_i) \times \mathcal{L}_\mu(N_\mu^{obs.}, \boldsymbol{x}_\mu, o, f_i)$$

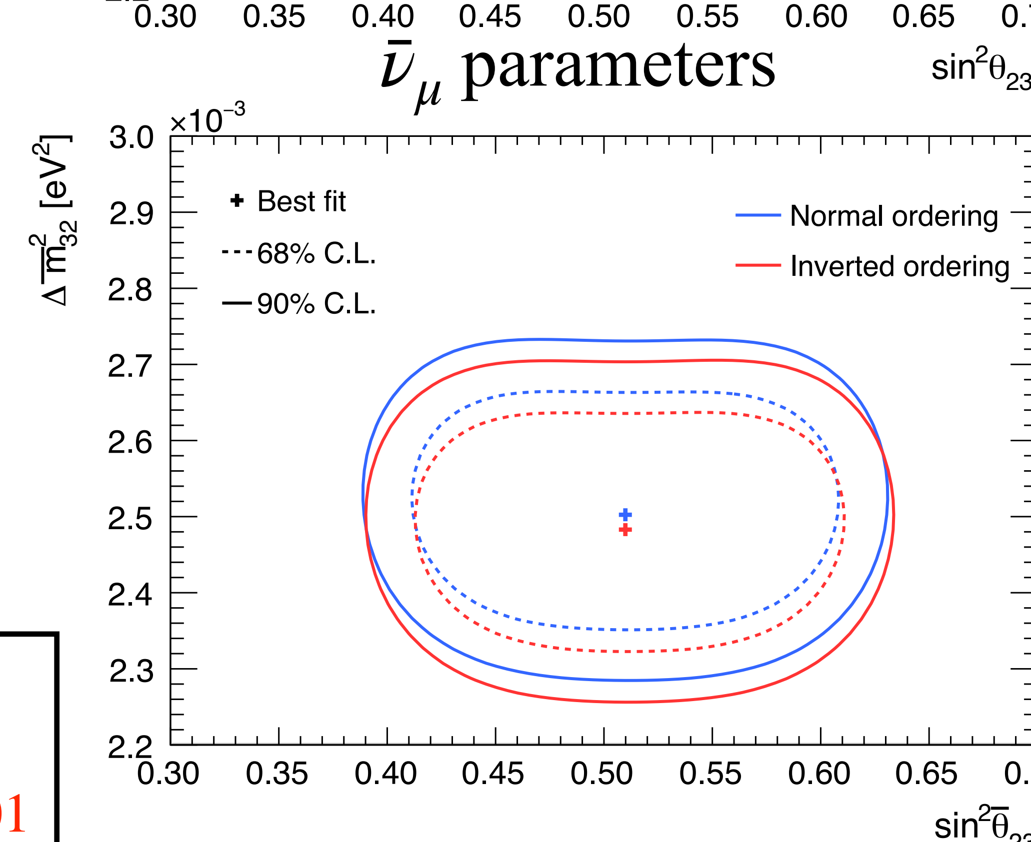
where N is the number of throws based on the prior distribution for systematic parameters, f.

Sensitivity To ν_μ And $\bar{\nu}_\mu$ Disappearance

- Fit to Δm^2_{32} and $\sin^2\theta_{23}$ while marginalizing $\bar{\theta}_{23}$, $\Delta\bar{m}^2_{32}$ and other parameters.
- Fit to $\Delta\bar{m}^2_{32}$ and $\sin^2\bar{\theta}_{23}$ while marginalizing θ_{23}, Δm^2_{32} and other parameters.
- Not sensitive to θ_{23} octant due to lack of electron-like samples.
- Improved sensitivities from the previous analysis due to an additional POT in the neutrino mode (33% more) and analysis improvements (e.g. new cross-section models).

$\Delta m^2_{21} = 7.53 \times 10^{-5}$ eV^2,
$\Delta m^2_{32} = 2.509 \times 10^{-3}$ eV^2, $\sin^2\theta_{23} = 0.528$,
$\sin^2\theta_{12} = 0.307$, $\sin^2\theta_{13} = 0.0218$, $\delta_{cp} = -1.601$

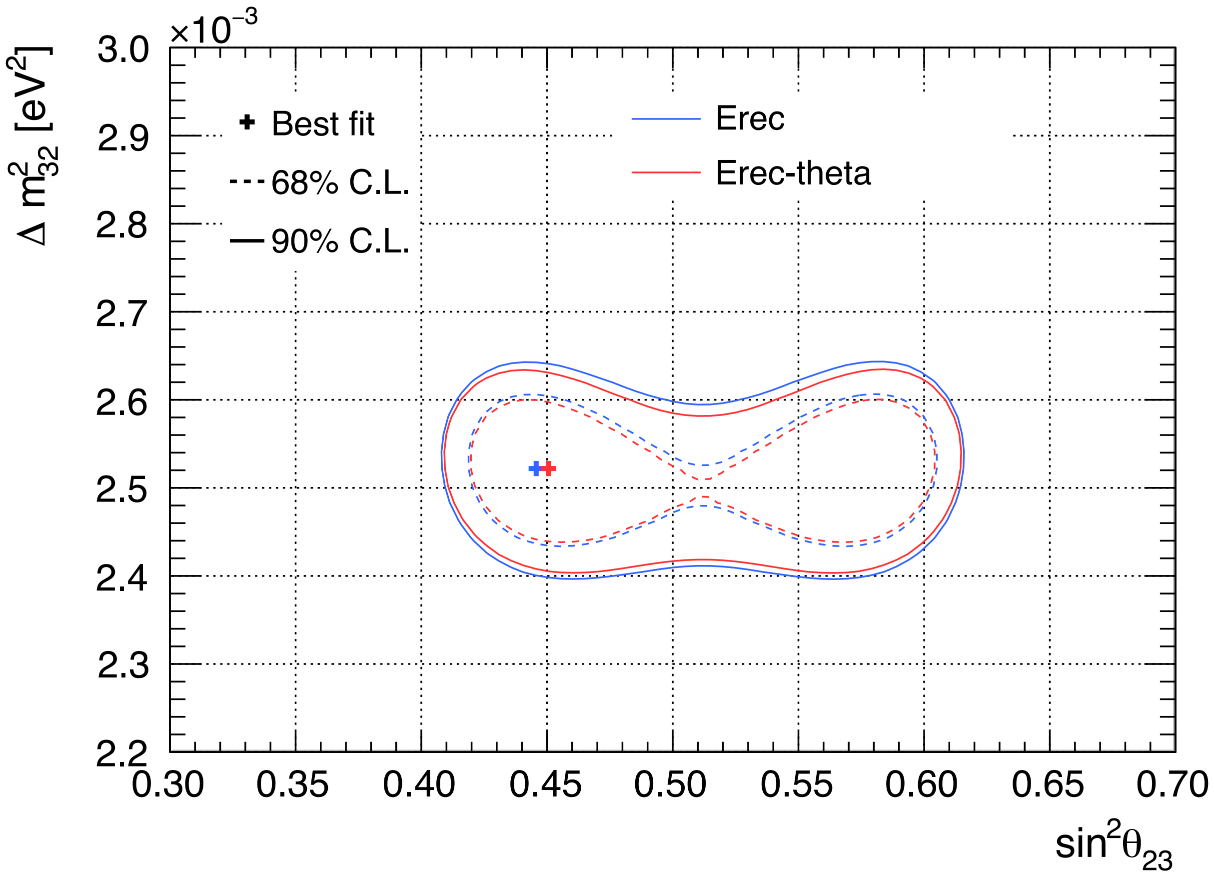




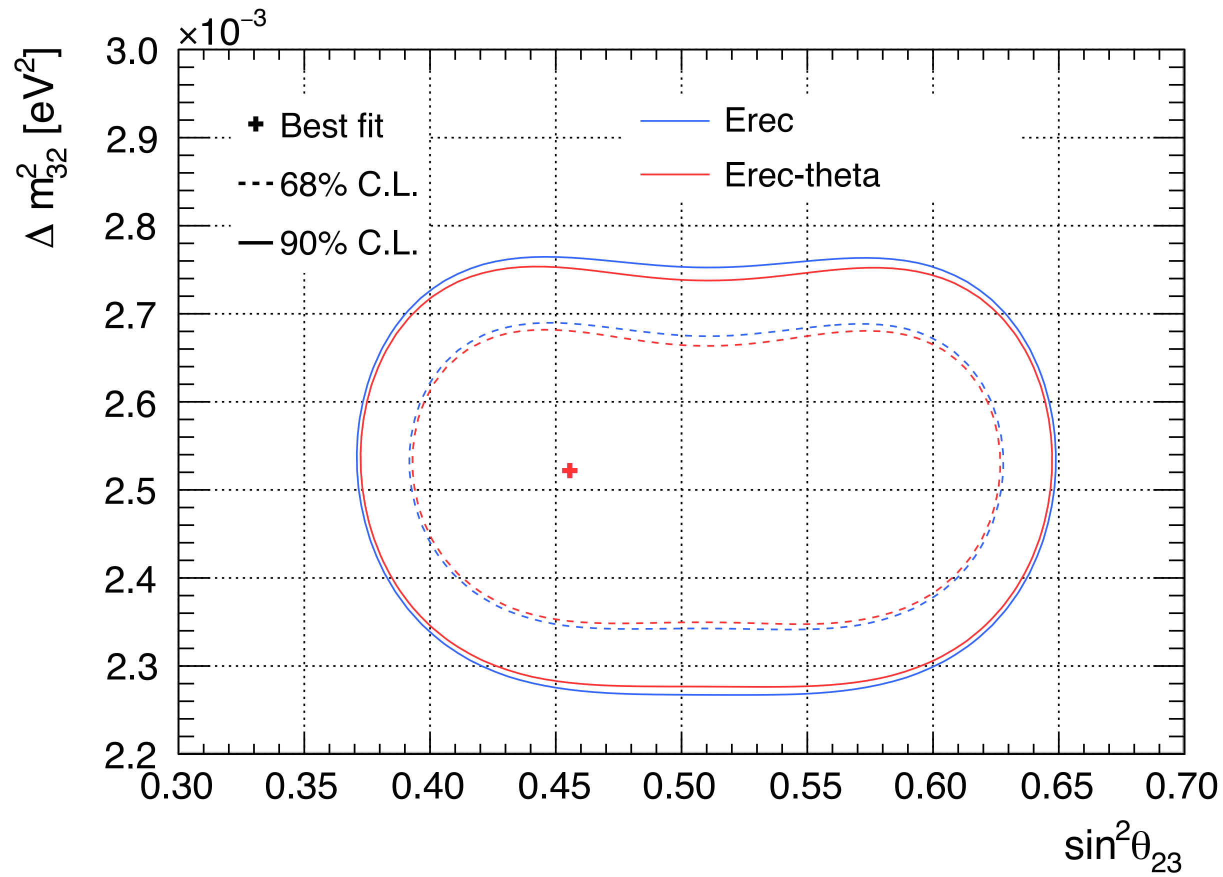
Sensitivity

$\Delta m^2_{21} = 7.53 \times 10^{-5}$ eV^2,
$\Delta m^2_{32} = 2.509 \times 10^{-3}$ eV^2, $\sin^2\theta_{23} = 0.45$,
$\sin^2\theta_{12} = 0.307$, $\sin^2\theta_{13} = 0.0218$, $\delta_{cp} = 0$

- Showing $(\sin^2\theta_{23}, \Delta m^2_{32})$ sensitivity on left and $(\sin^2\bar{\theta}_{23}, \Delta\bar{m}^2_{32})$ on right with **Run 1-10** POT.



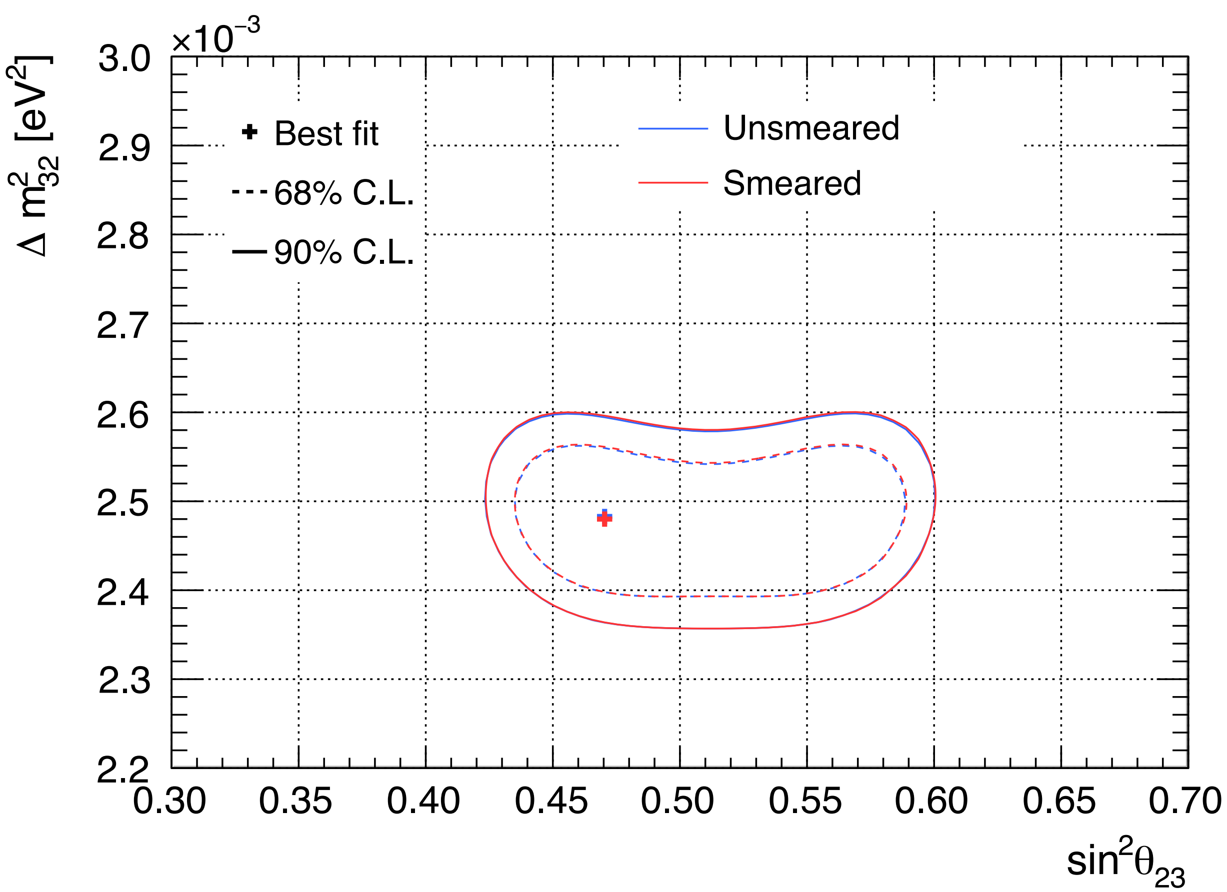
ν_μ parameters



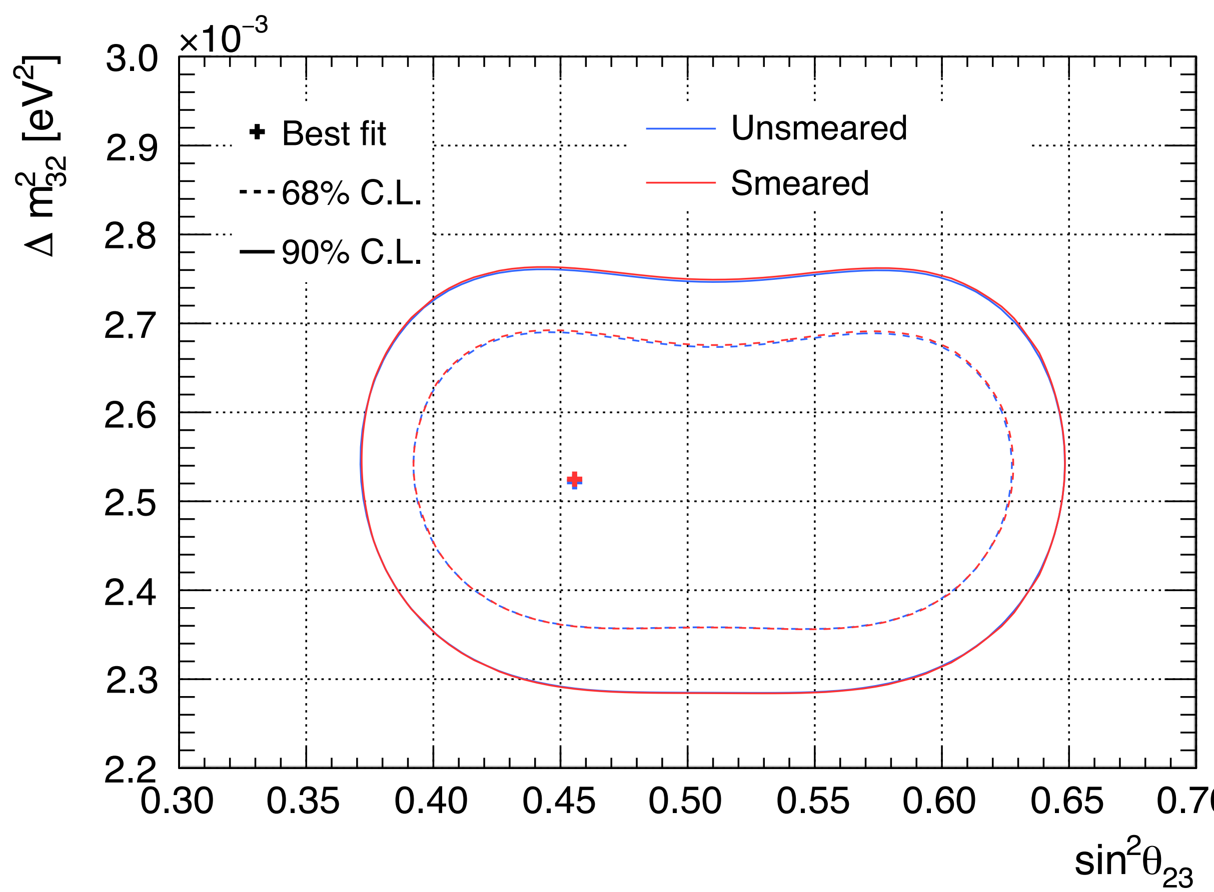
$\bar{\nu}_\mu$ parameters

Smearing For Data Fit

- Showing $(\sin^2\theta_{23}, \Delta m^2_{32})$ sensitivity on left and $(\sin^2\bar{\theta}_{23}, \Delta\bar{m}^2_{32})$ on right for **Run 1-10** data with smearing applied.
- Smearing has negligible effect on contours and the best-fit.



ν_μ parameters



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

Predicted Event Rates

Event Type	$\nu_\mu \to \nu_\mu$	$\nu_e \to \nu_e$	$\bar{\nu}_\mu \to \bar{\nu}_\mu$	$\bar{\nu}_e \to \bar{\nu}_e$	$\nu_\mu \to \nu_e$	$\bar{\nu}_\mu \to \bar{\nu}_e$	Total
CC_QE	224.4	0.00433	13.95	0.0003419	0.0352	0.0002102	238.4
CC_MEC	39.01	0.001806	2.095	3.315e-05	0.01311	4.345e-05	41.12
CC_1PI	42.53	0.003503	3.678	0.0001257	0.04575	4.578e-05	46.26
CC_COH	0.3088	0	0.07071	2.593e-05	0	1.28e-05	0.3796
CC_DIS	0.83	0	0.04415	0	0	0	0.8741
CC_MPI	7.629	0.001044	0.4421	4.111e-05	0.00218	0	8.075
CC_MISC	1.211	0	0.07409	0	0	0	1.285
NC_1PI0	0.5152	0.01595	0.01909	0.001519	0	0	0.5517
NC_1PIC	5.324	0.1152	0.1971	0.01098	0	0	5.647
NC_COH	0	0.0004912	0	0	0	0	0.0004912
NC_GAM	0.0092	0	0	0	0	0	0.0092
NC_OTHER	2.402	0.09885	0.1345	0.01007	0	0	2.646
Subtotal	324.2	0.2412	20.71	0.02313	0.09624	0.0003122	345.3

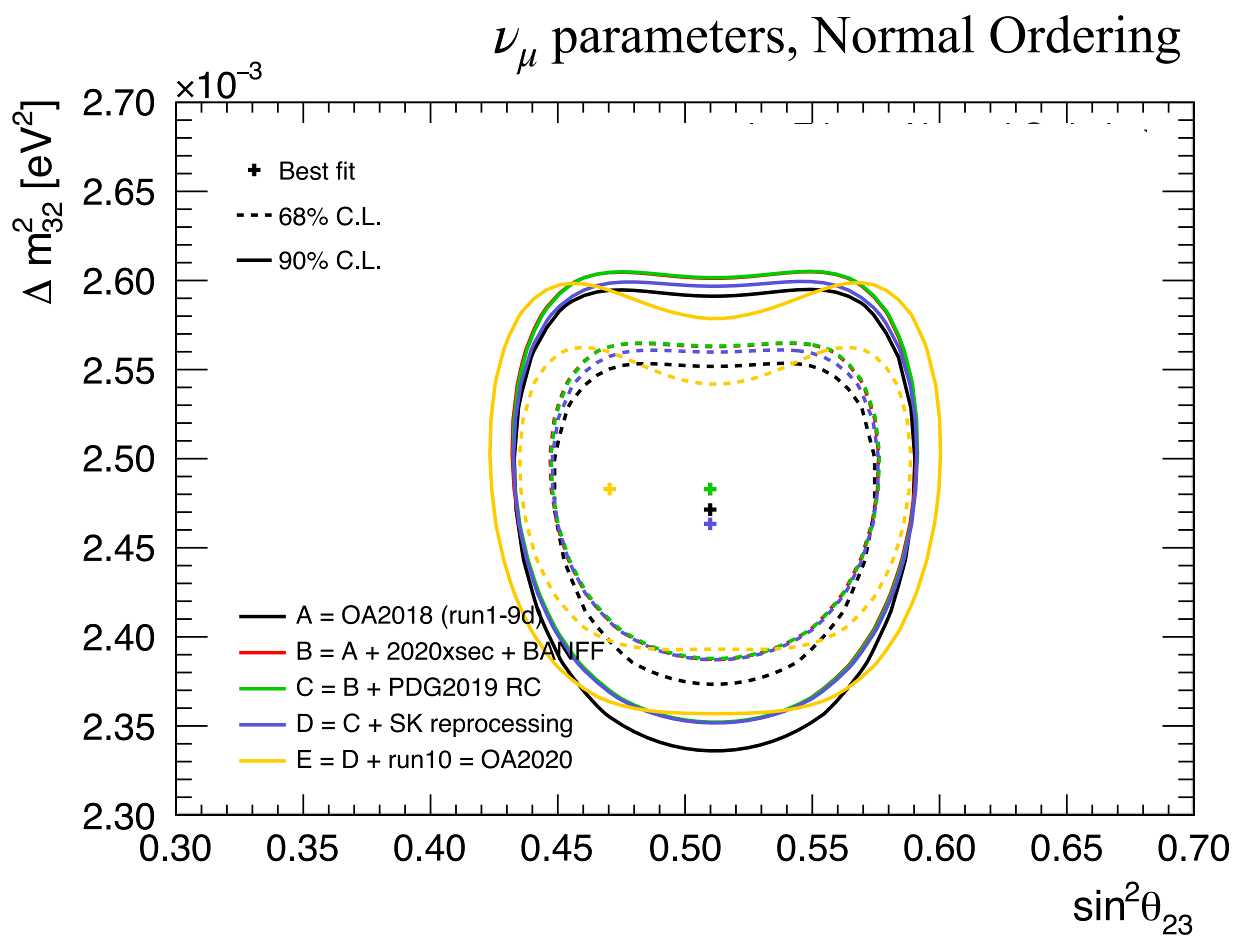
ν_μ

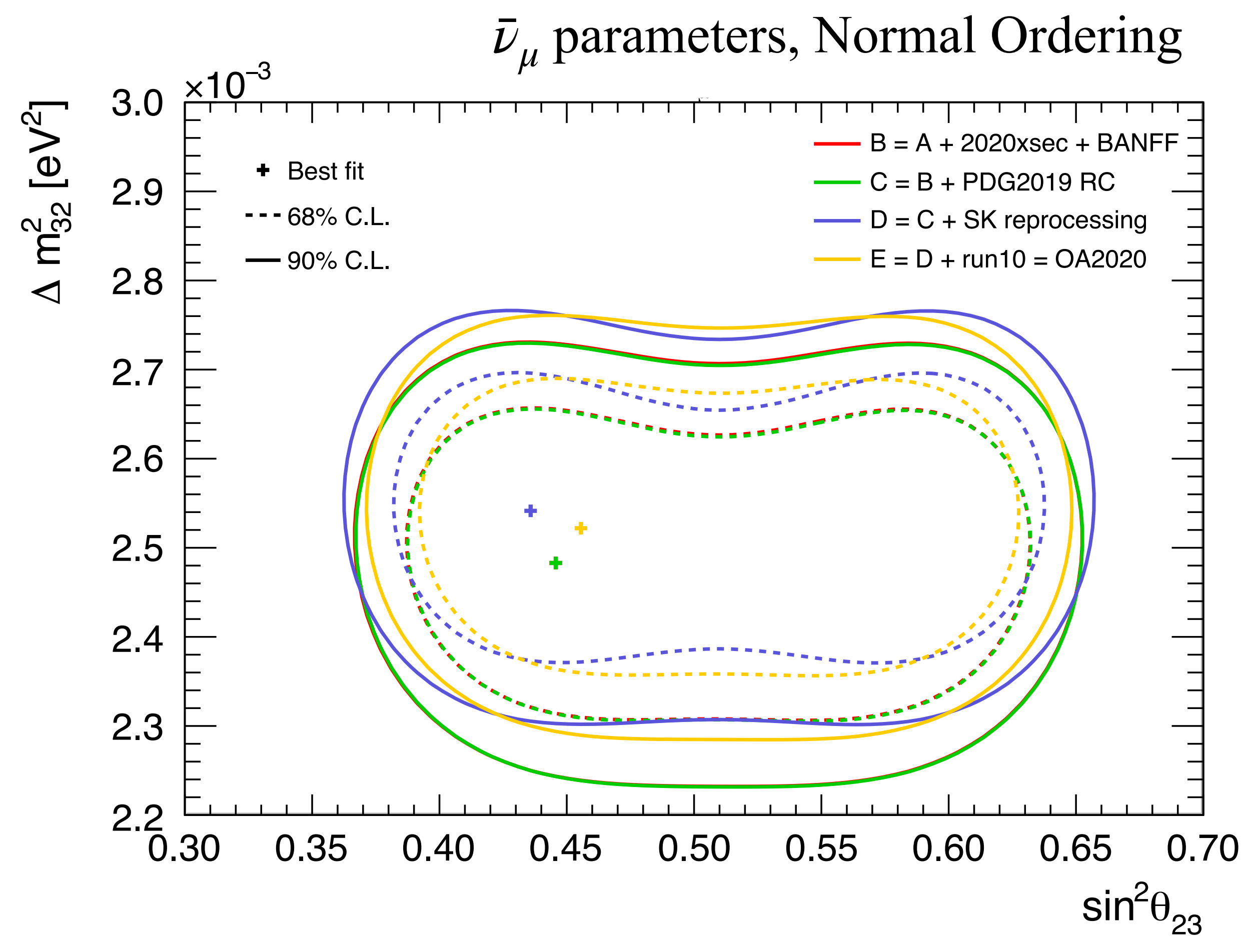
Event Type	$\nu_\mu \to \nu_\mu$	$\nu_e \to \nu_e$	$\bar{\nu}_\mu \to \bar{\nu}_\mu$	$\bar{\nu}_e \to \bar{\nu}_e$	$\nu_\mu \to \nu_e$	$\bar{\nu}_\mu \to \bar{\nu}_e$	Total
CC_QE	34.03	0.001462	59.32	0.001888	0.0003753	0.003054	93.36
CC_MEC	7.751	0.0004212	7.075	0.0002513	0.0006926	0.0003011	14.83
CC_1PI	9.999	0.0004752	10.03	0.0003229	0.0007675	0.000186	20.03
CC_COH	0.06299	0	0.2153	0	0	0.0001855	0.2784
CC_DIS	0.1364	0	0.1121	0	0	0	0.2486
CC_MPI	1.994	0.0001368	1.043	7.814e-05	6.994e-05	0.0001705	3.037
CC_MISC	0.3569	0	0.1713	0.0001327	0	0	0.5284
NC_1PI0	0.07759	0.00348	0.07529	0.001473	0	0	0.1578
NC_1PIC	0.6823	0.02619	0.9445	0.02219	0	0	1.675
NC_COH	0.0006056	0	0	0	0	0	0.0006056
NC_GAM	0	0	0	0	0	0	0
NC_OTHER	0.625	0.02542	0.3478	0.01391	0	0	1.012
Subtotal	55.72	0.05759	79.33	0.04025	0.001905	0.003897	135.2

$\bar{\nu}_\mu$

- Predicted number of events at SK with the ND post-fit constraints broken down by interaction mode and oscillation channel.

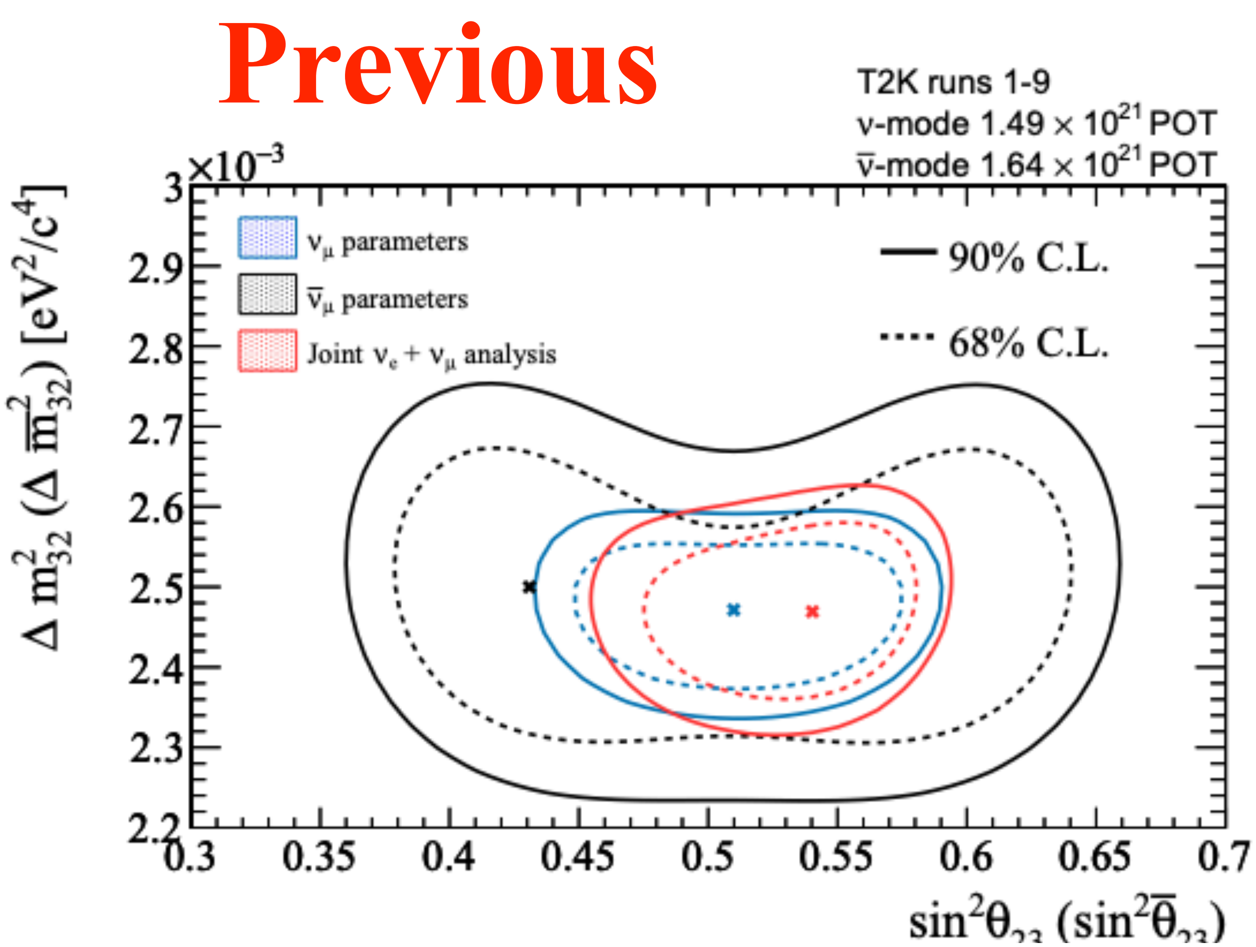
Evolution Of Constraints

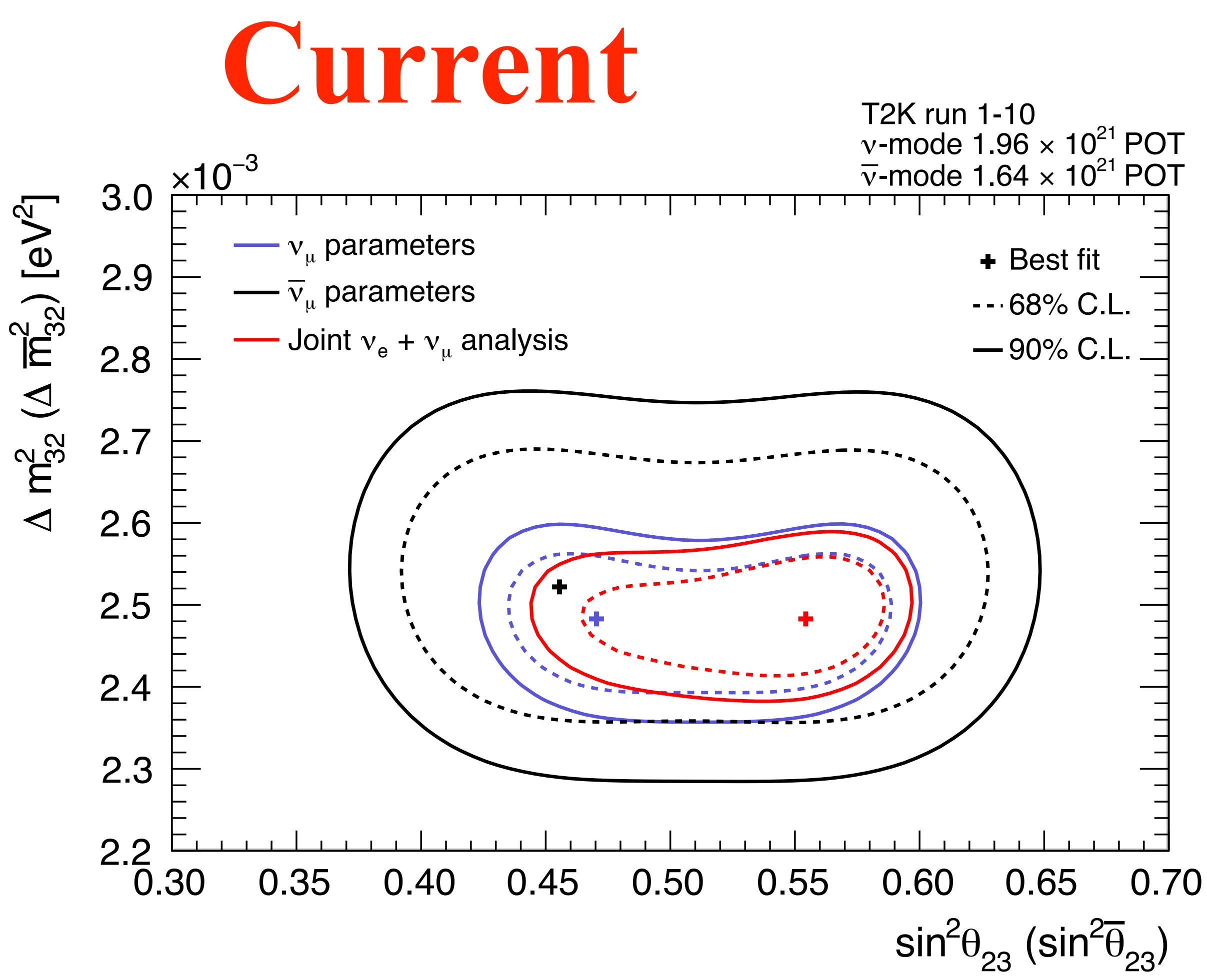




- A - 2019 analysis result with run 1-9d
- B - 2020 analysis. Used 2020 BANFF constraints, but used PDG 2018 reactor constraint, and run 1-9d POT
- C - Same as B, but used PDG 2019 reactor constraint
- D - Same as C, but using SK reprocessed data
- E - Same as C, but used run 10 POT.

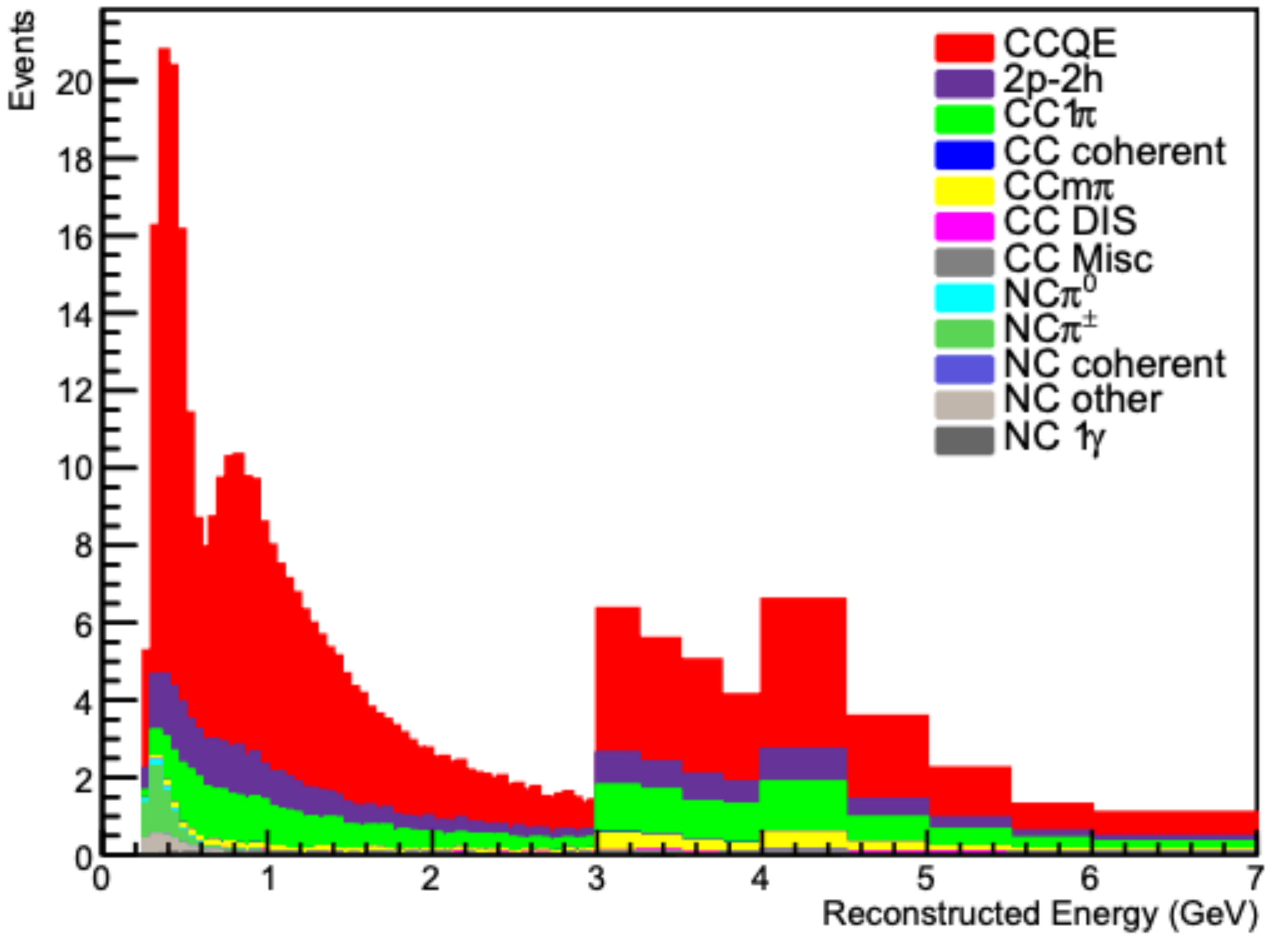
Data Fit Results

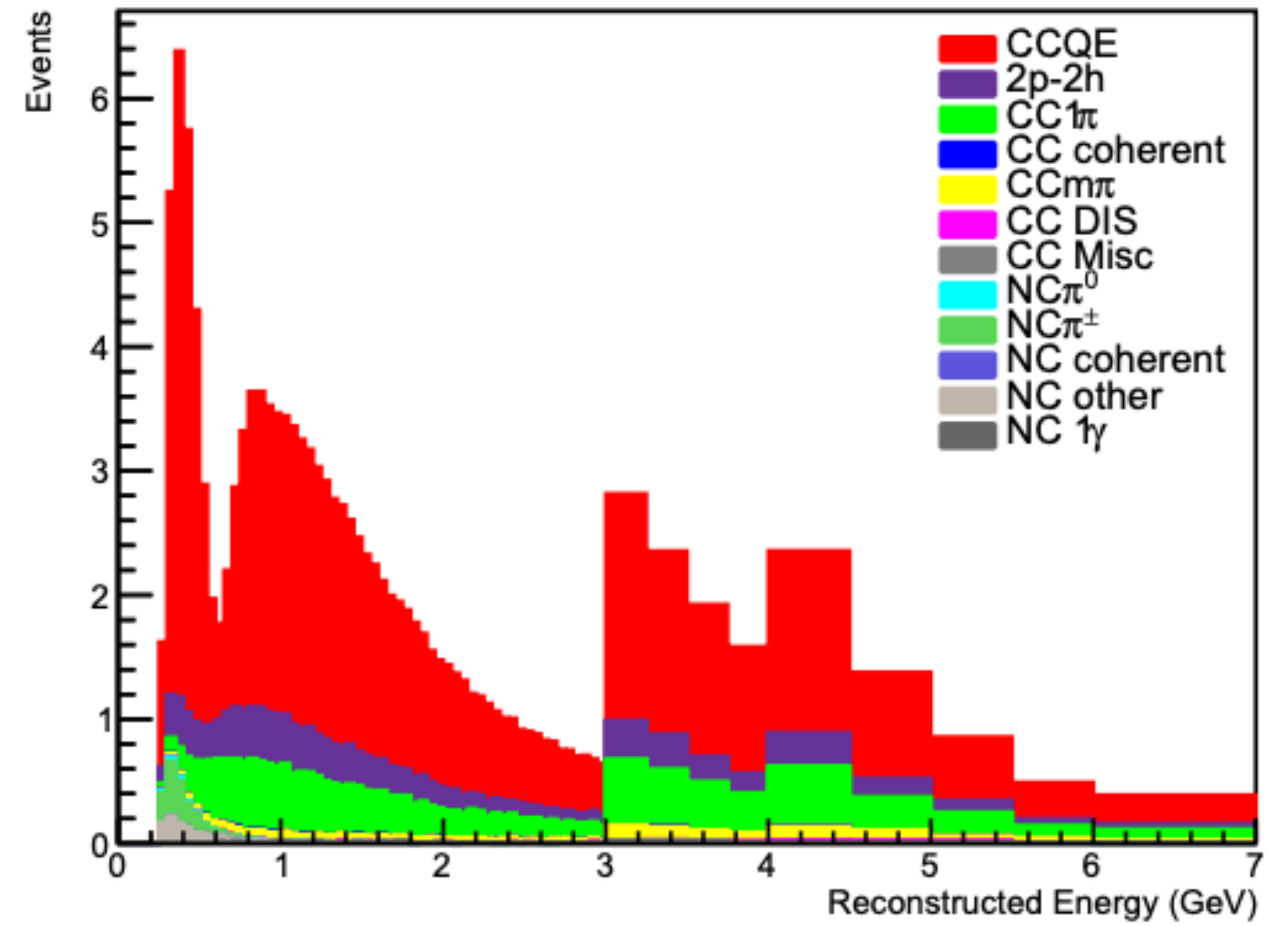




- Comparison of constraints between the previous analysis and the current analysis.

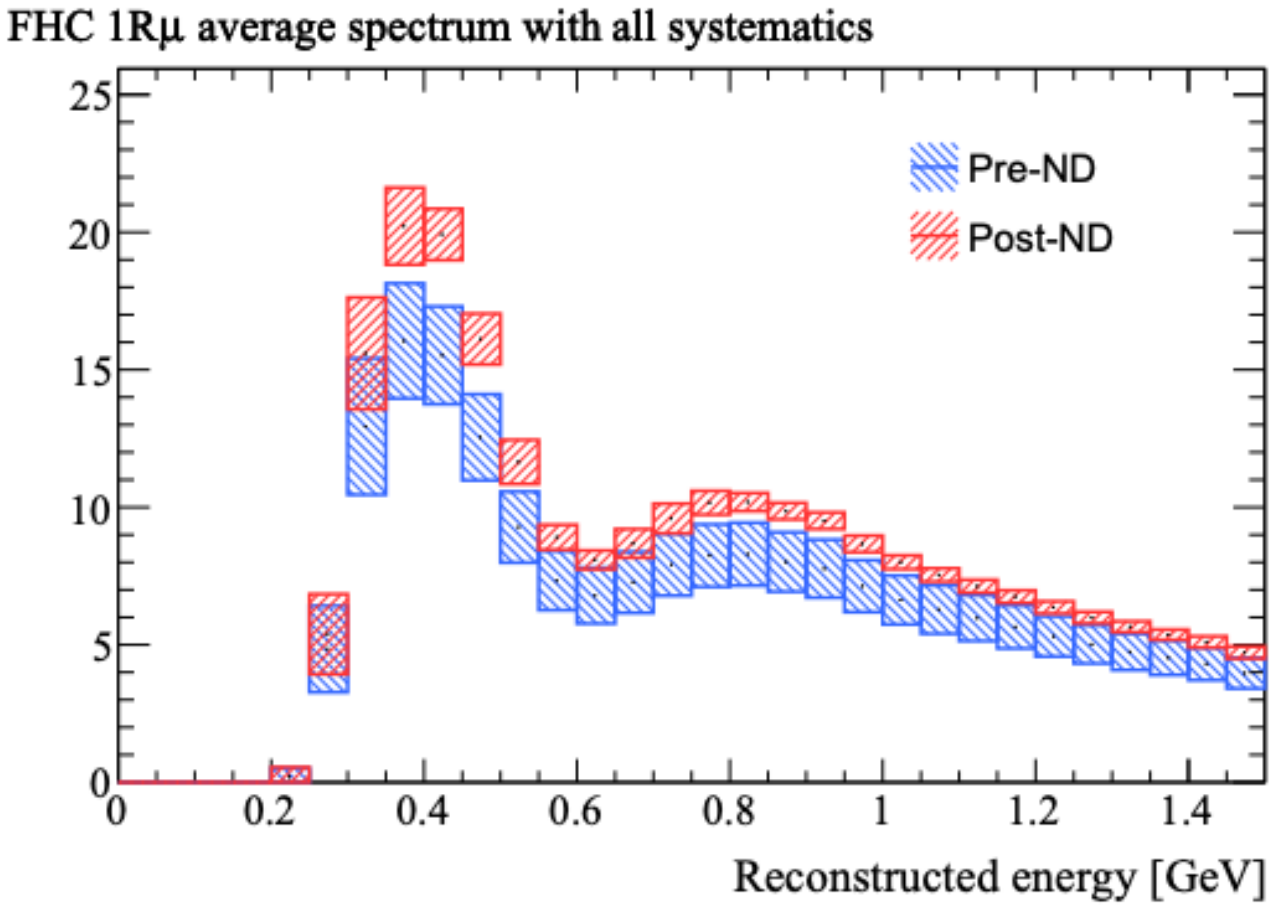
Oscillated Event Spectra At SK

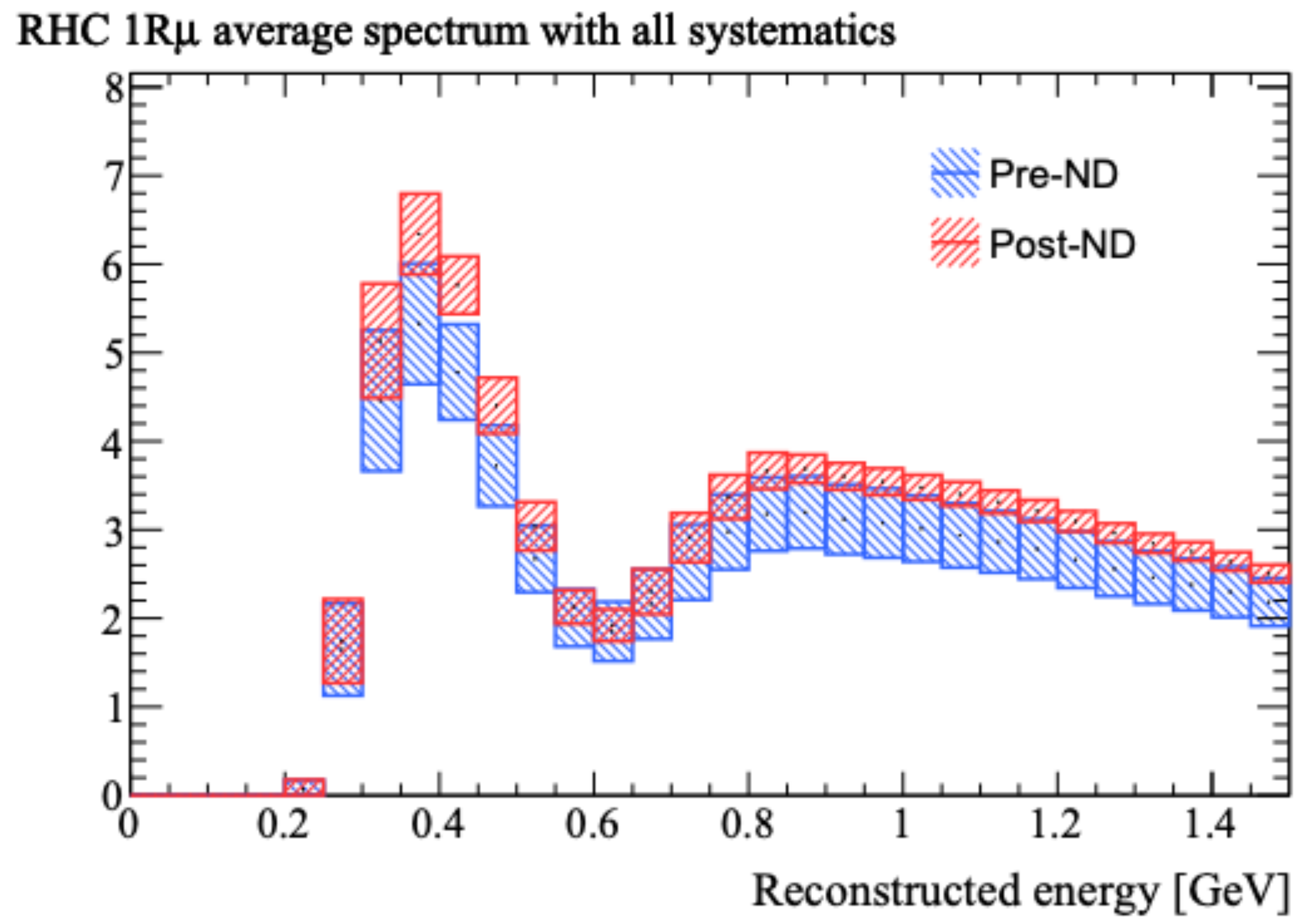




- Oscillated event rate spectra in reconstructed energy for different true interaction modes.
- Parameter values:
  - $\Delta m^2_{21} = 7.53 \times 10^{-5}$ eV^2, $\Delta m^2_{32} = 2.509 \times 10^{-3}$ eV^2, $\sin^2\theta_{23} = 0.528$, $\sin^2\theta_{12} = 0.307$, $\sin^2\theta_{13} = 0.0218$, $\delta_{cp} = -1.601$

Effect Of Systematics On Event Spectra At SK





- Oscillated event rate spectra in reconstructed energy before and after applying ND constraints.
- Parameter values:
  - $\Delta m^2_{21} = 7.53 \times 10^{-5}$ eV^2, $\Delta m^2_{32} = 2.509 \times 10^{-3}$ eV^2, $\sin^2\theta_{23} = 0.528$, $\sin^2\theta_{12} = 0.307$, $\sin^2\theta_{13} = 0.0218$, $\delta_{cp} = -1.601$

SYSTEMATIC SUMMARY

Pre-fit

Error source (units: %)	1Rμ FHC	1Rμ RHC
Flux	5.1	4.7
Cross-section (all)	10.1	10.1
SK+SI+PN	2.9	2.5
Total	11.1	11.3

Post-fit

Error source (units: %)	1Rμ FHC	1Rμ RHC
Flux	2.9	2.8
Xsec (ND constr)	3.1	3.0
Flux+Xsec (ND constr)	2.1	2.3
2p2h Edep	0.4	0.4
BG_A^{RES} low-p_π	0.4	2.5
$\sigma(\nu_e)$, $\sigma(\bar{\nu}_e)$	0.0	0.0
NC γ	0.0	0.0
NC Other	0.2	0.2
SK+SI+PN	2.1	1.9
Total	3.0	4.0

- Uncertainty on number of events at SK after the ND fit. Significant reduction in the uncertainty after the ND fit.