Refined measurement of $\sin^2\theta_{23}$ from the MINOS Experiment

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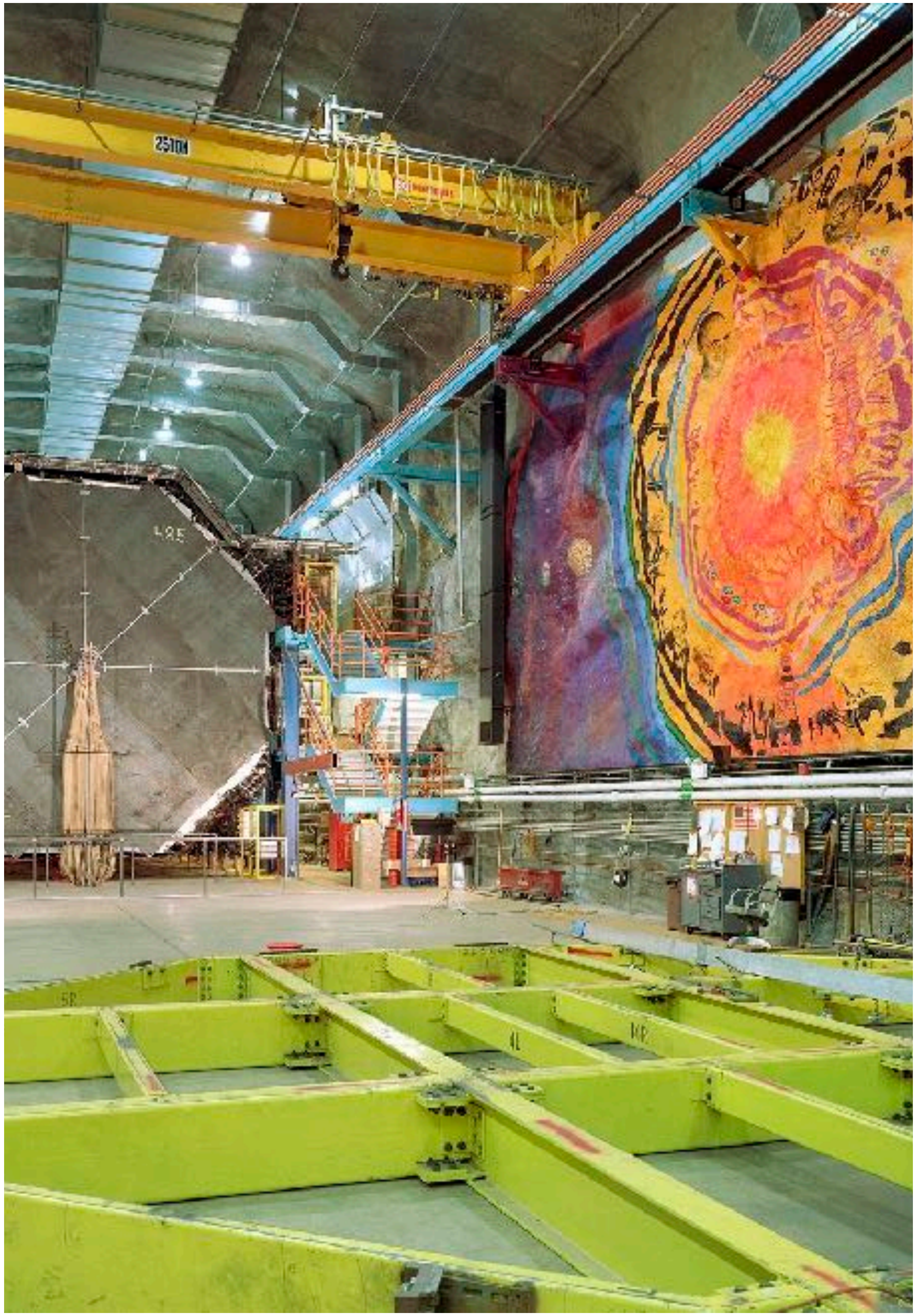
on behalf of

MINOS+ Collaboration

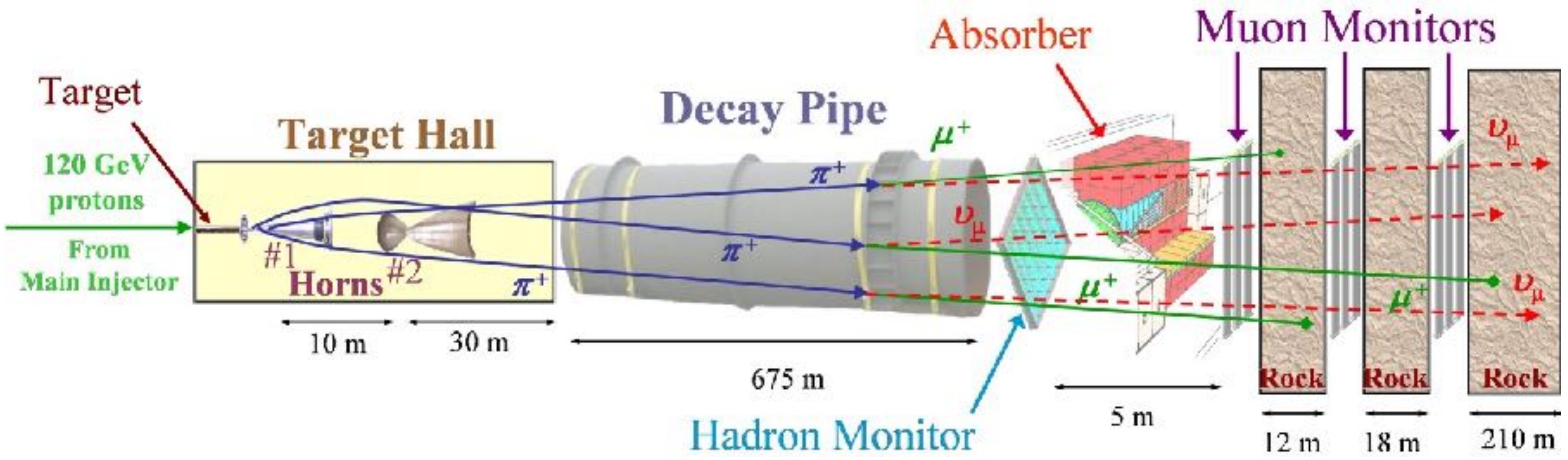
Neutrino 2026



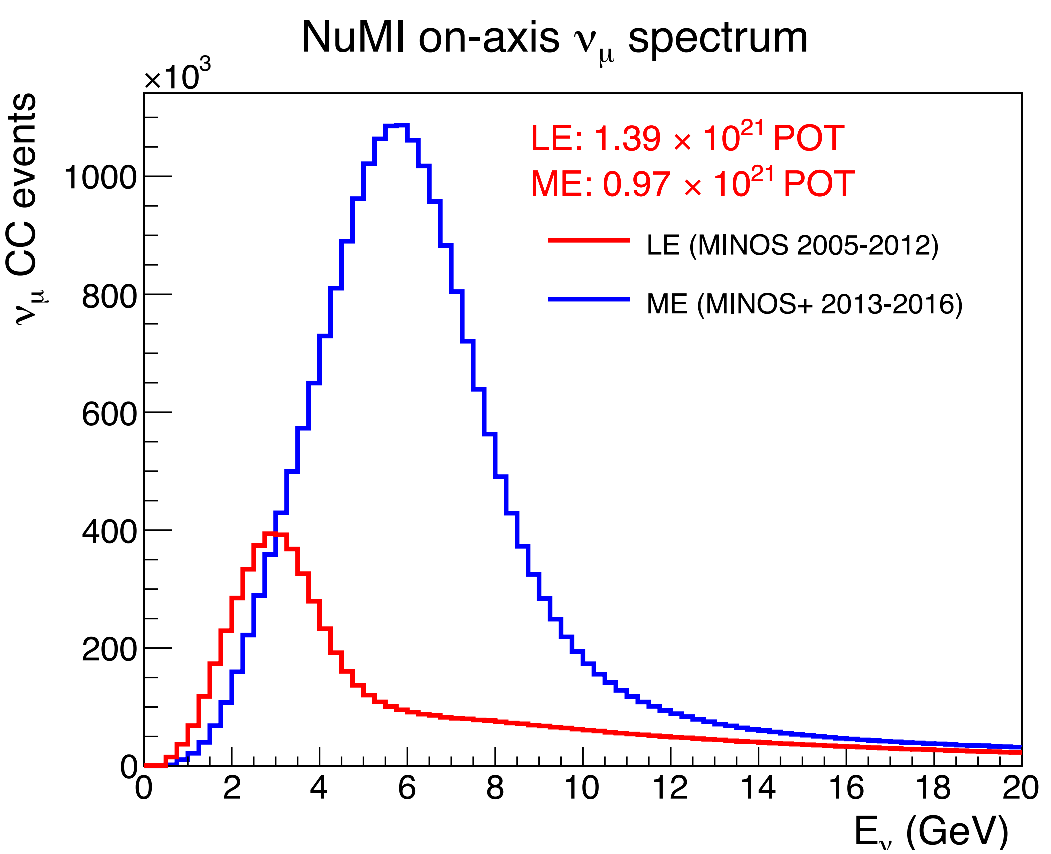
The Numbers

- 250 collaborators (at the peak)
- 10 years from proposal to beam (1995-2005)
- 11 years to collect data (2005-2016)
- 8 Targets (8 MINOS, 1 NOVA)
- 4 horns
- 4 FNAL Directors
- 5 Co-Spokespeople
- 43 papers (so far…) New Sun Shad
  arxiv.org/abs/2605.29306
- 43 students/postdocs went to academia
- $220,000,000 for 9770 events. (~$22.5K/event)

The NuMI Beam at FNAL



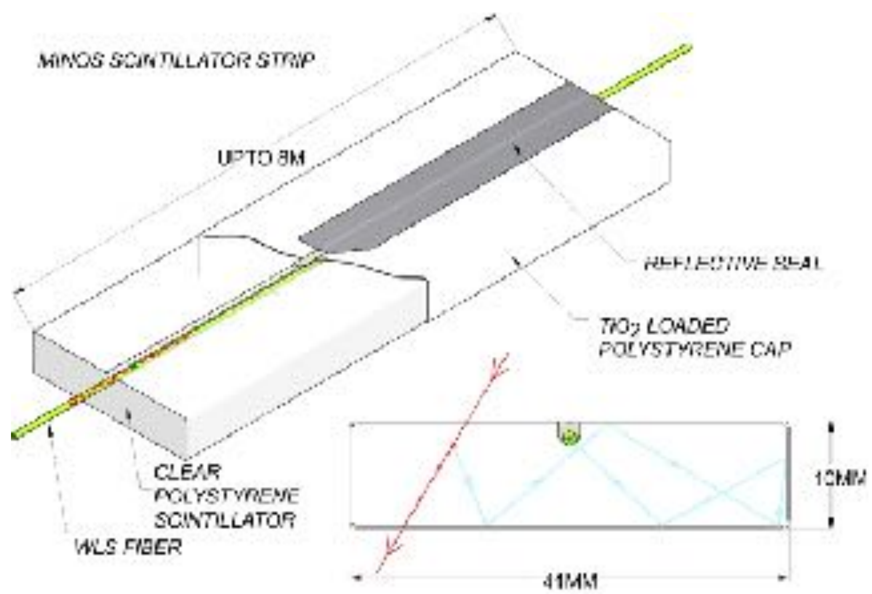
- Lowest energy possible was chosen as final LE setting (**just** low enough!)
  - Low Energy configuration, energy peak around 3 GeV (2005-2012)
  - Medium Energy configuration, energy peak at around 7 GeV (2013-2016), result of optimising off-axis flux at NOVA
- Hardware (slow) failings and component changes over time
- Forward Horn Current (FHC, ν) and Reverse Horn Current (RHC) ν-bar

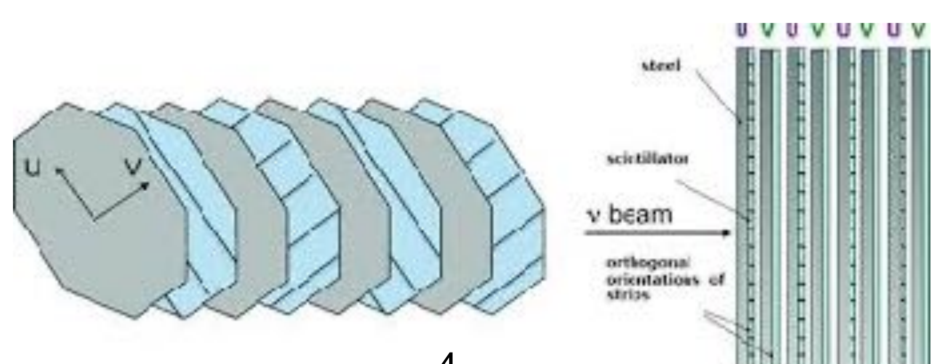


The MINOS Experiment

- MINOS detectors were two functionally identical, magnetised (1.4T), tracking, sampling calorimeter detectors.
- Oriented for beam νμ-charged current (CC) events (track orthogonal to planes), full event containment (muon and shower)

Far Detector
735 km from beam target
5.4 kton mass

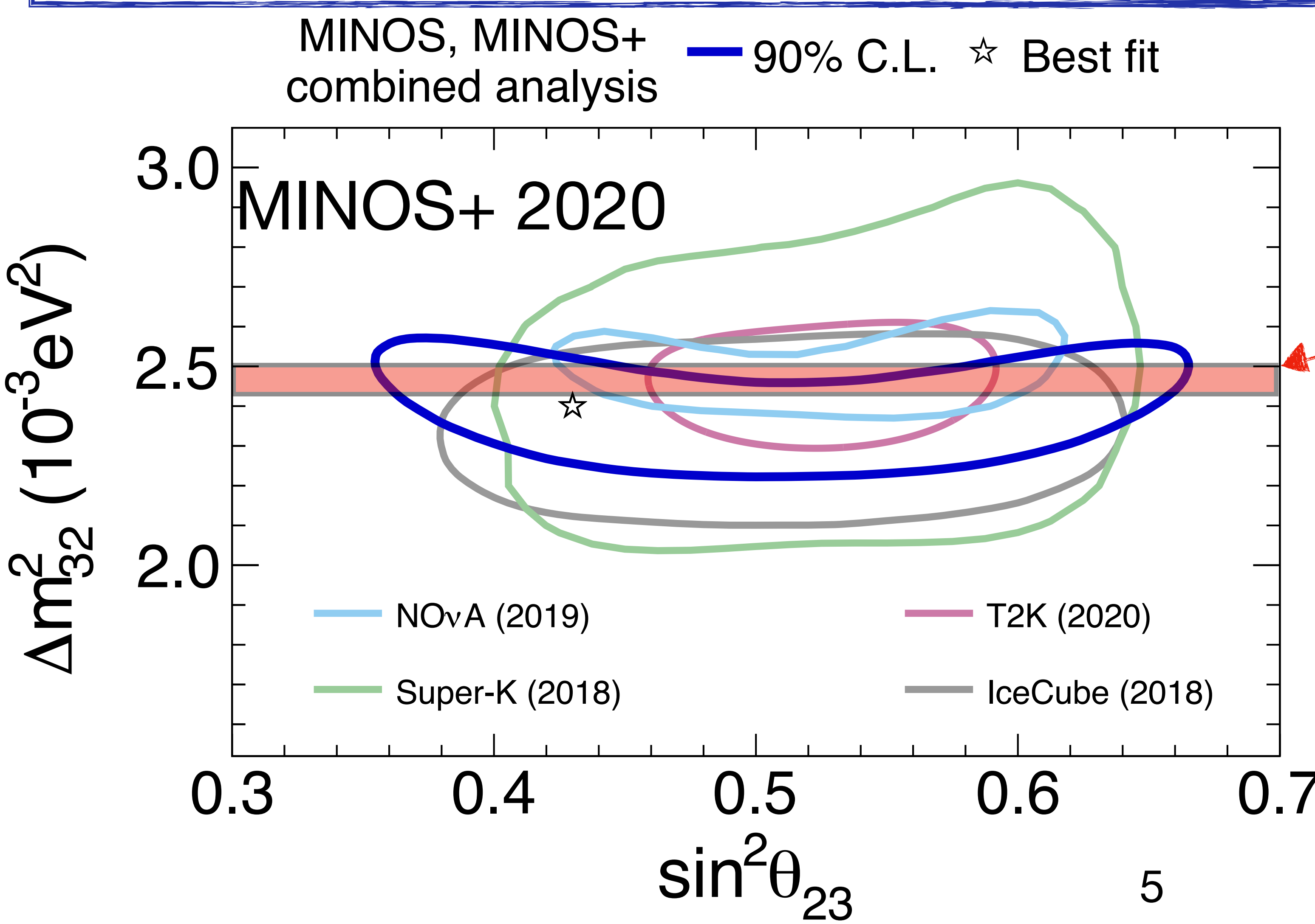




Near Detector
1 km from beam target
1 kton mass

Motivation

- Reactor experiments' precise measurement of Δm^2 independent of $\sin^2\theta_{23}$
- Increase precision on $\sin^2\theta_{23}$, the least well known of the mixing angles
- Focus on MINOS core strengths, use ν_μ wide band beam (WBB) data only
  - exploit **WBB beam ν_μ data** collected at and above oscillation max
  - exploit **detector's strength** of μ containment and total energy measurement
  - exploit **experiment's strength** of systematics cancellation between ND and FD



New Reactor Constraint (2025)

$\Delta m^2_{32} = 2.48 \pm 0.05 \times 10^{-3}$ eV^2 (NH)

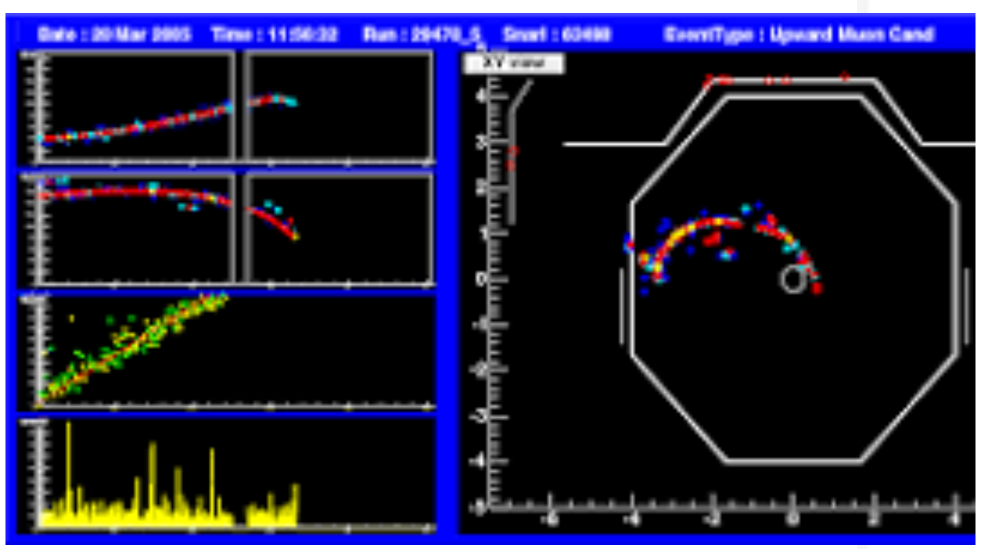
$\Delta m^2_{32} = -2.54 \pm 0.05 \times 10^{-3}$ eV^2 (IH)

DayaBay $\Delta m^2_{32} = 2.48\times10^{-3}eV^2 \pm 0.06\times10^{-3}$eV^2
(F. P. A. et al. (Daya Bay), Phys. Rev. Lett. 130, 161802913(2023))
RENO $\Delta m^2_{ee} = 2.57\times10^{-3}$eV^2 $^{+0.10}_{-0.11}$ $^{+0.05}_{-0.05}$ $\times10^{-3}$ eV^2
(S. Jeon et al. (RENO), Phys. Rev. D 111, 112006(2025))

P. A. et al. (MINOS+), Phys. Rev. Lett. 125, 131802874 (2020).

Analysis Revisited

- Beam flux simulation improvements
- Neutrino interaction modelling updates
- Hadronic Shower Energy Reconstruction
- ME resolution binning
- Re-evaluation of systematics



The NuMI Beam Simulation

- Extensive (~10^7 events) ND data used to inform the flux simulation
- Beam simulation : FLUGG package which is GEANT4 (geometry)+FLUKA (hadron production)
- Multi parameter fit to ND data
  - includes warping function for hadron production in FLUKA
  - Hardware changes tracked and modelled over time
  - RHC and FHC simultaneously fit
- Updated hadron production model between pT 0.1-0.5 GeV changes FLUKA prediction
- The combination of hadron production modelling and better geometry modelling has significantly improved the agreement between data and MC

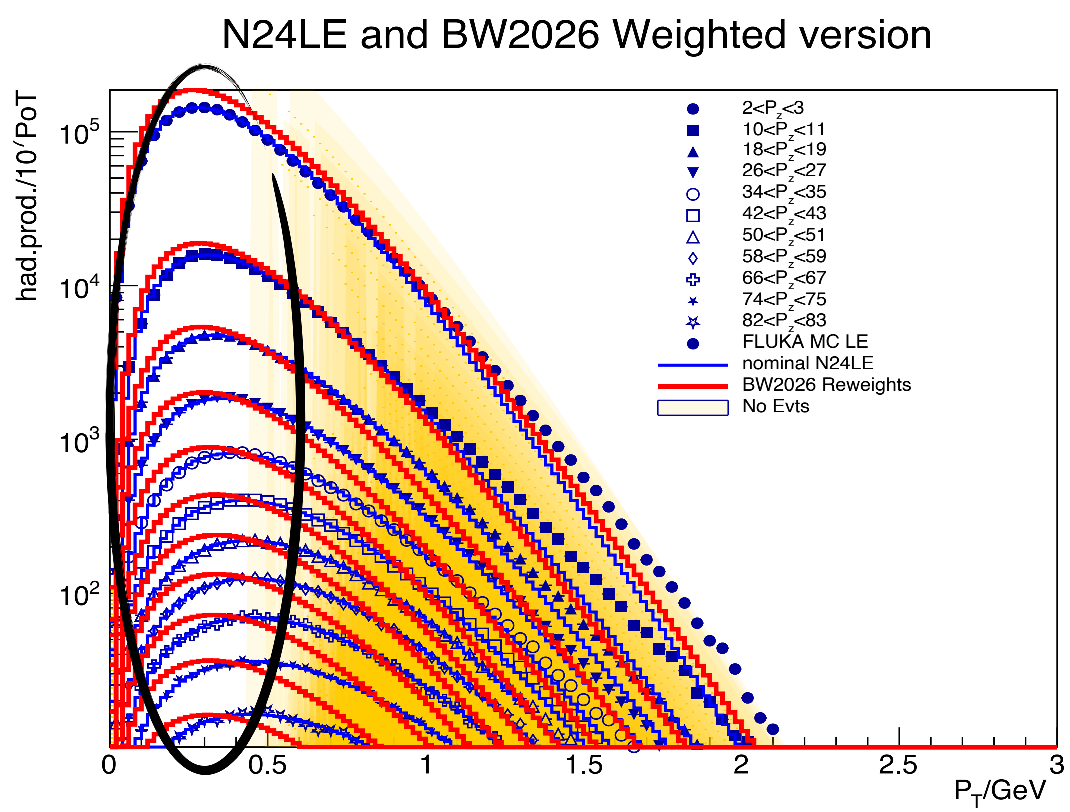
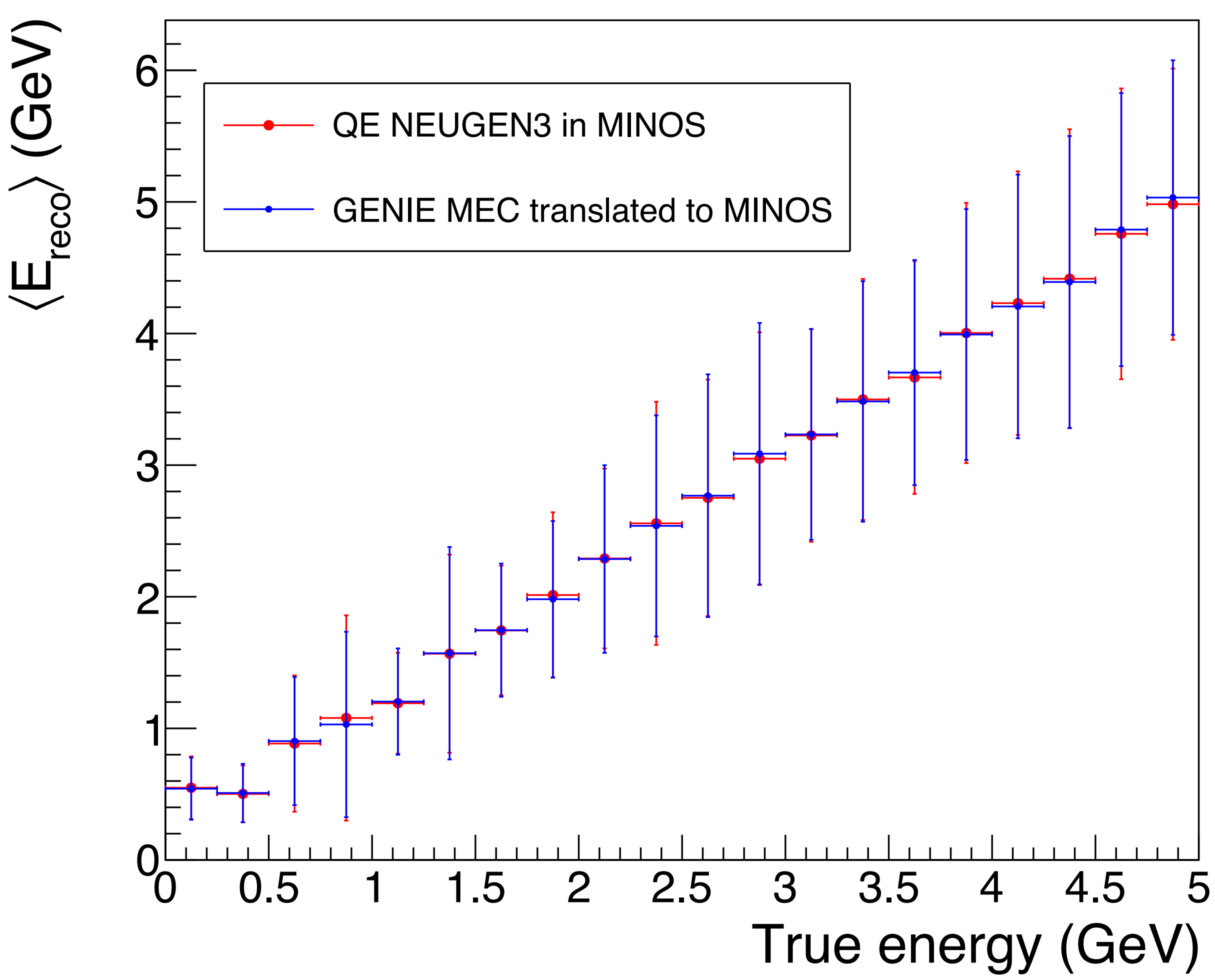


Figure 12: Original and improved warping functions compared to FLUKA predictions

$$\frac{d^2N}{dx_F d_{pT}} = [B(x_F)p_T + C(x_F)p_T^2]exp(-D(x_F)p_T^{E(x_F)})$$

Neutrino Interaction Modelling

- Since MINOS finished running, two pertinent developments in νμCC interactions
- new work has shone spotlight on 2p2h-Meson Exchange Current
- new phenomenological fits of resonant π production to bubble chamber data (W<1.7GeV)

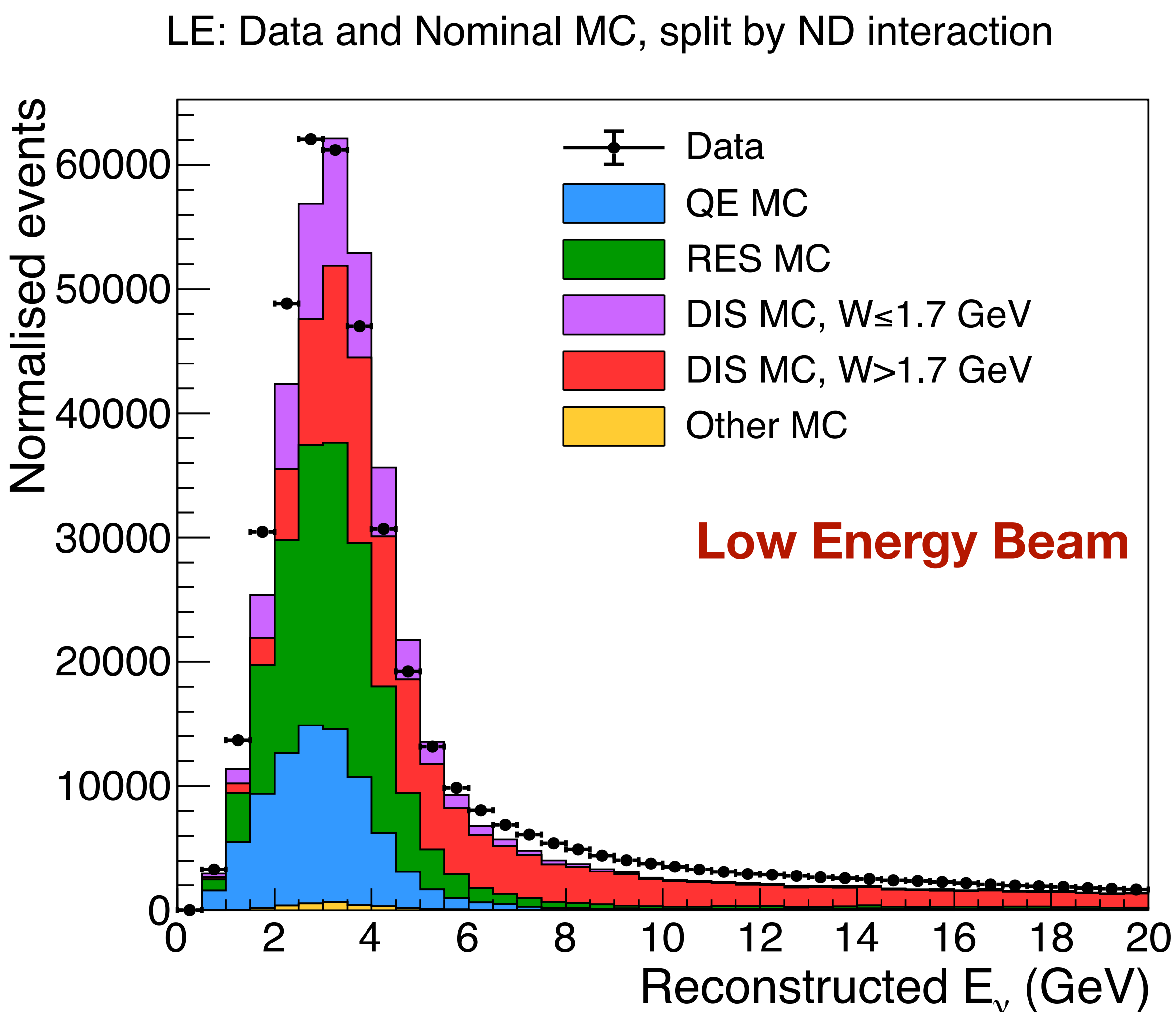


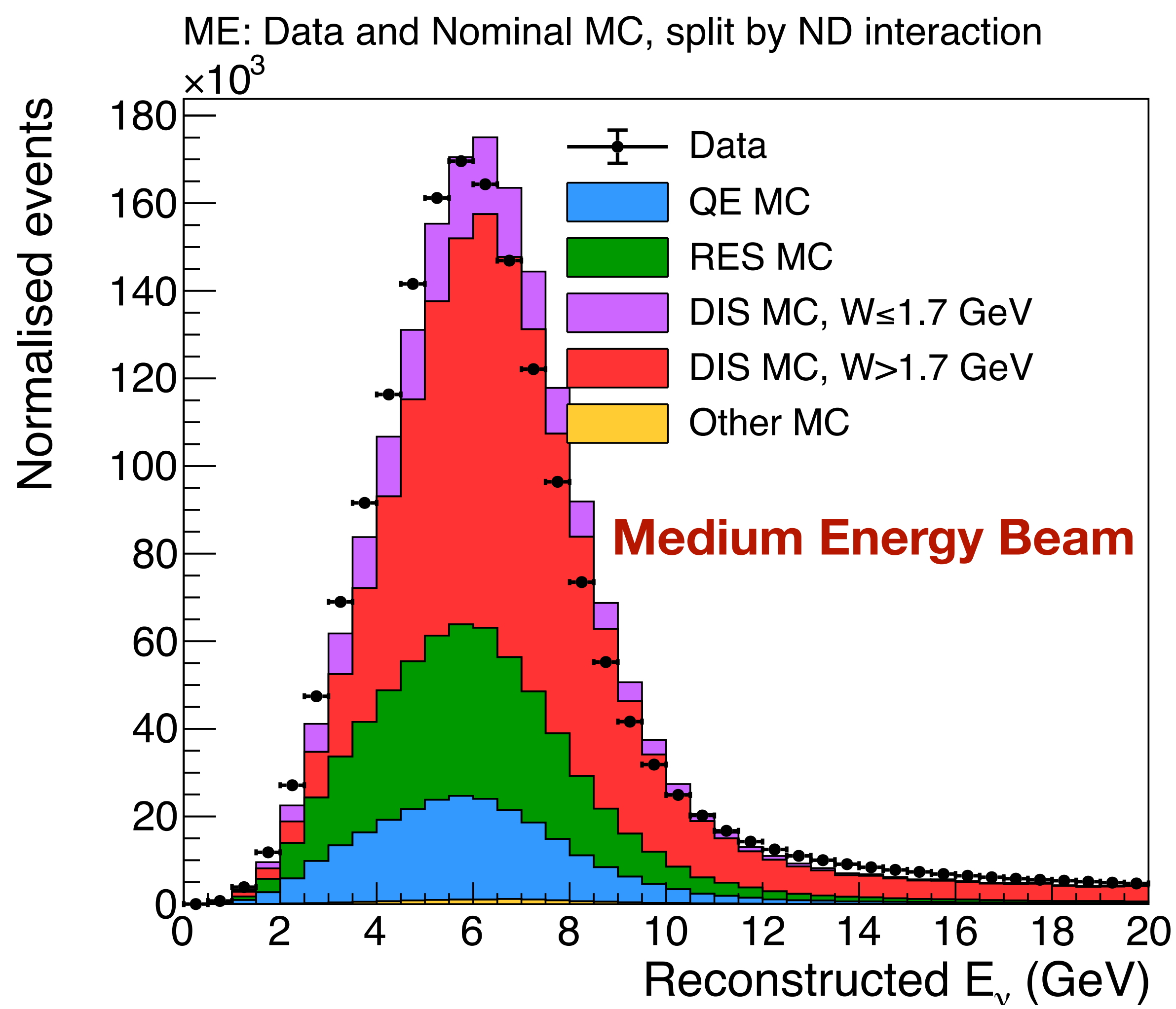
$$\nu_\mu + \mathcal{A}_{(nN+\mathcal{A}')} \rightarrow \mu^- + p + N + \mathcal{A}'$$

- MEC events produced in MINOS detector simulation via matching of NEUGEN3 truth #neutrons, Eμ and E_{had} using GENIE on Fe
- No discernable difference from QE events

*D. Ruterbories et al (MINERvA Collaboration) *Simultaneous measurement of proton and lepton kinematics in quasielastic-like ν_μ - hydrocarbon interactions from 2 to 20 GeV, Phys. Rev. Lett.* ***129***, *021803 (2022); arXiv:2203.08022.*

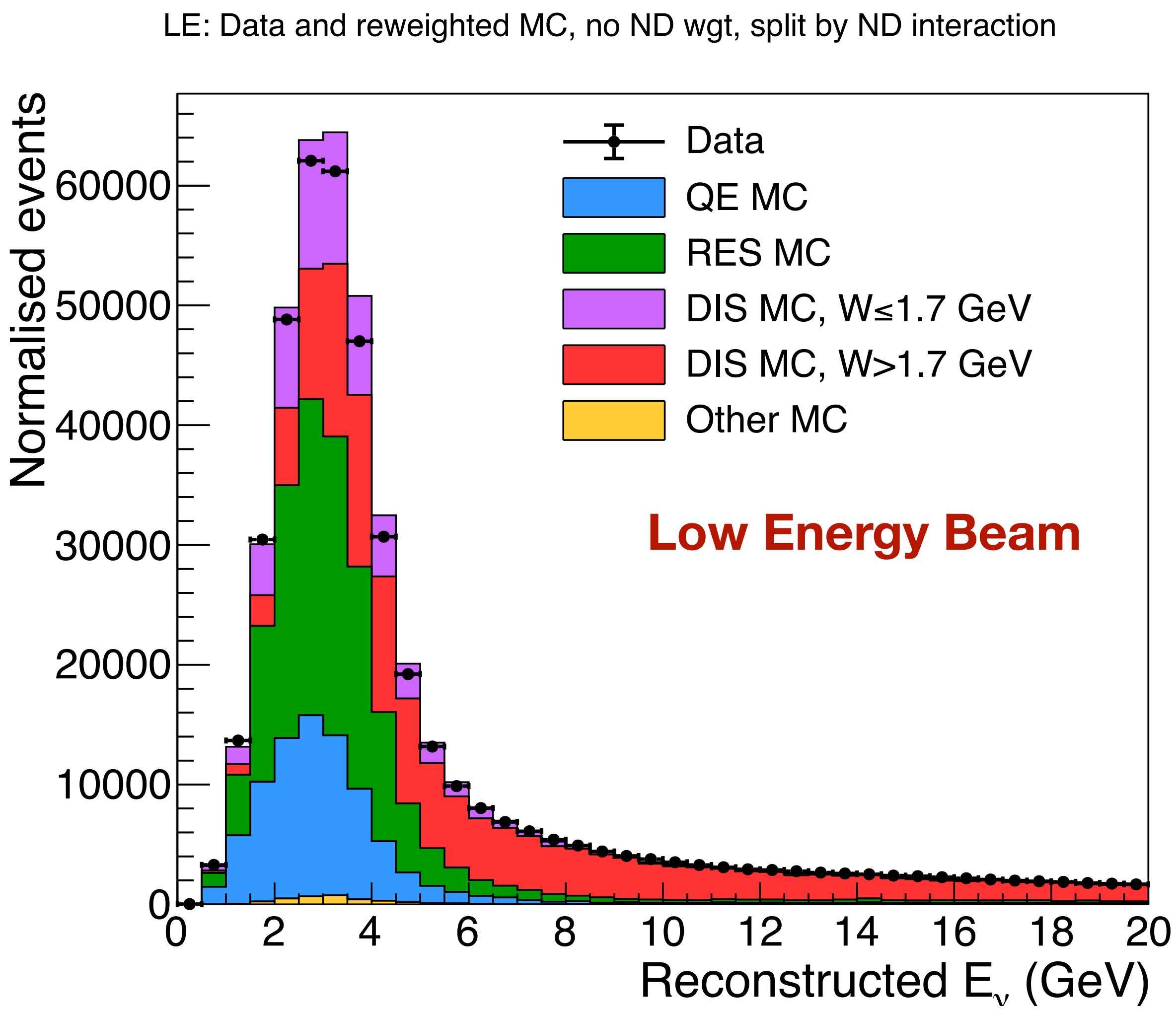
Beam Modelling Improvements

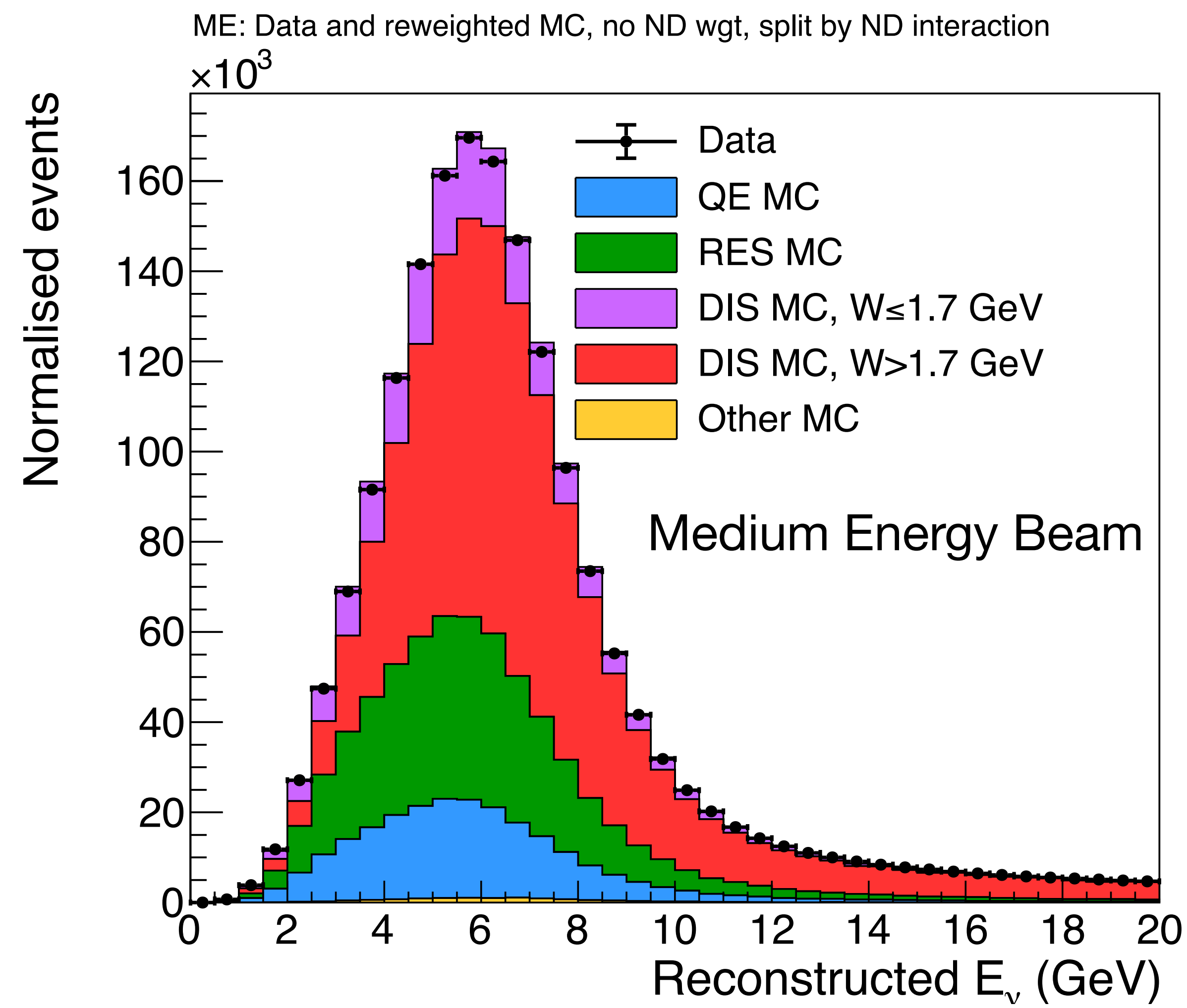




Original Neugen3 + out-of-the-box beam simulation (FLUGG)

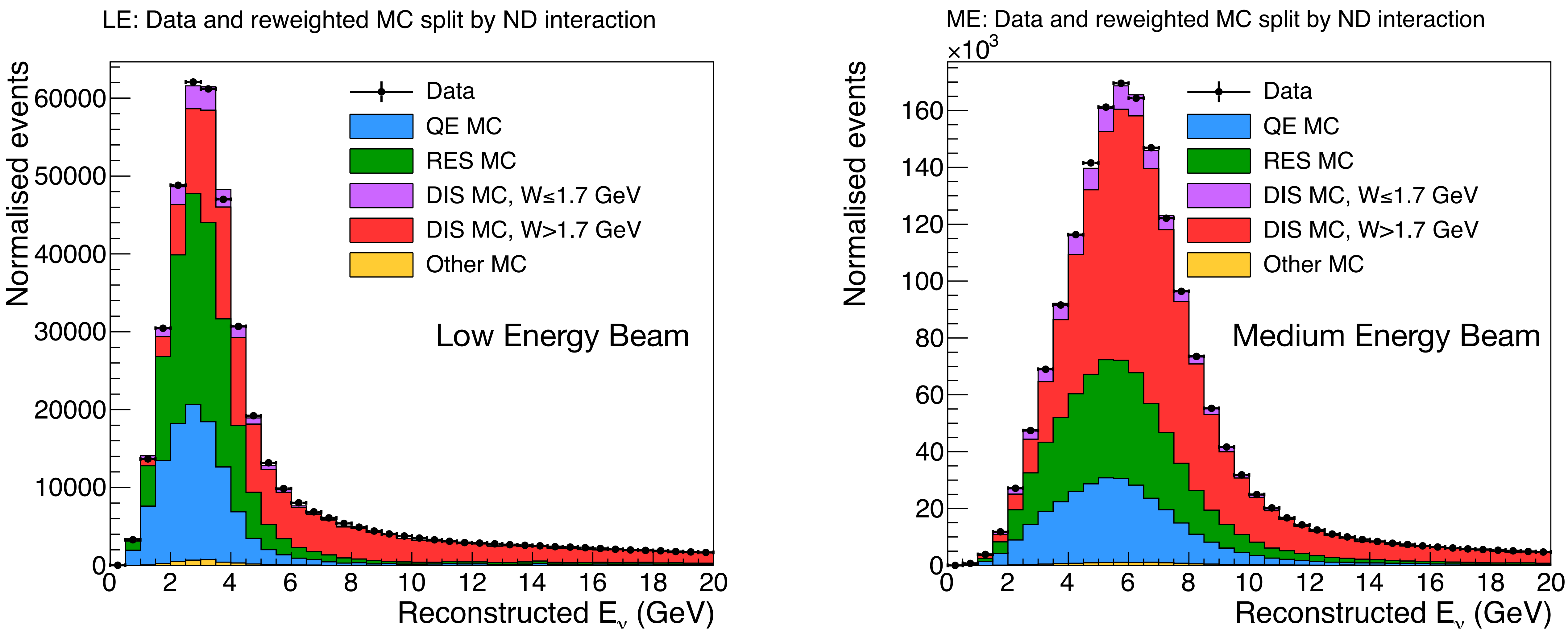
Beam Modelling Improvements





After FLUKA re-weighting of hadron production parameters

Modelling Improvements



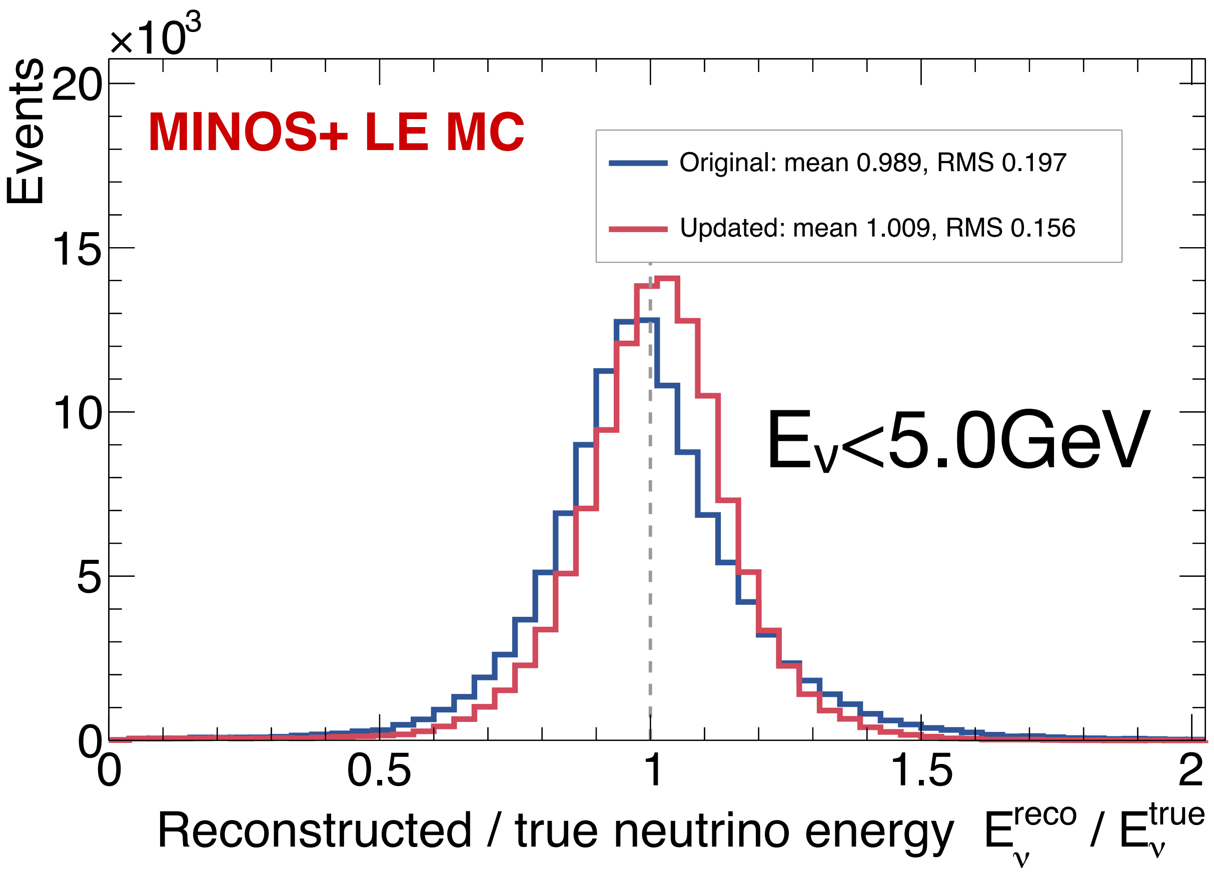
After QE and non-resonant pion production (W<1.7GeV) re-weighting

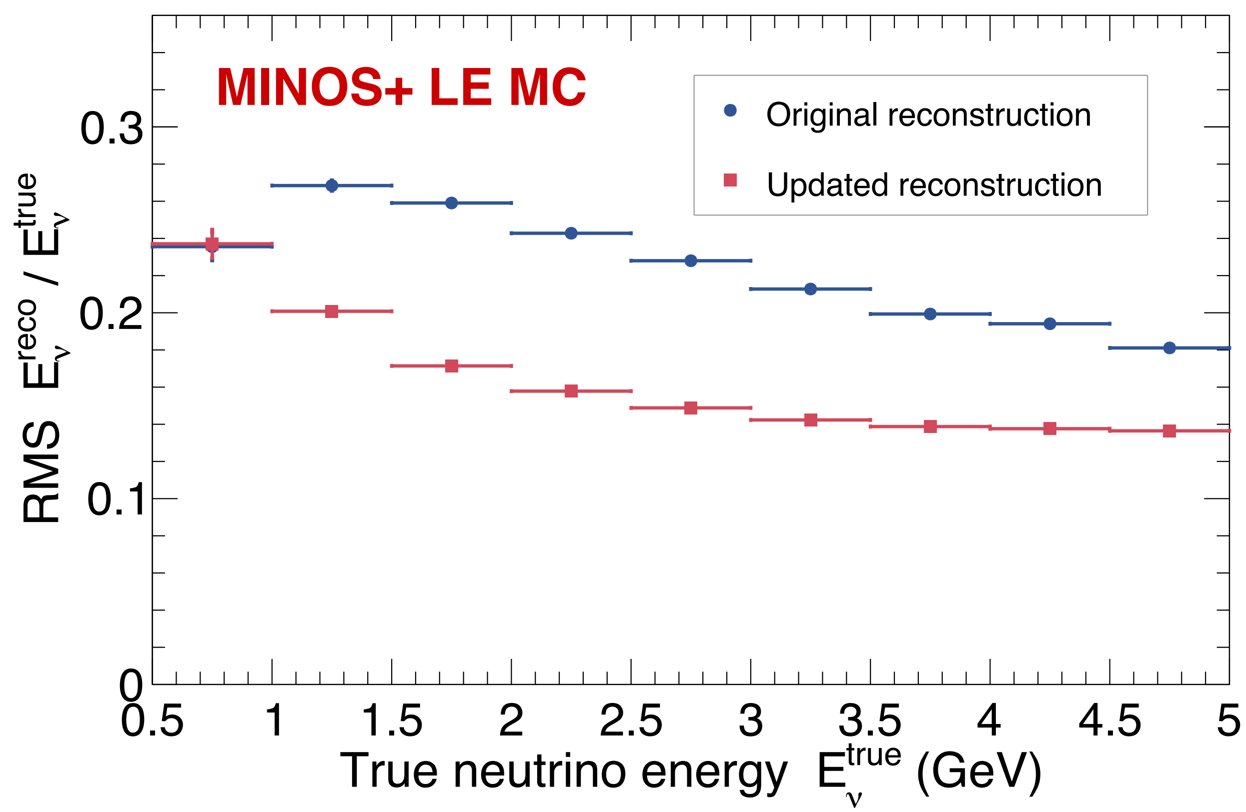
In line with eg: Minerva estimates (QE up 30%, W<1.7 down 60%)

Hadronic Shower Energy Estimator

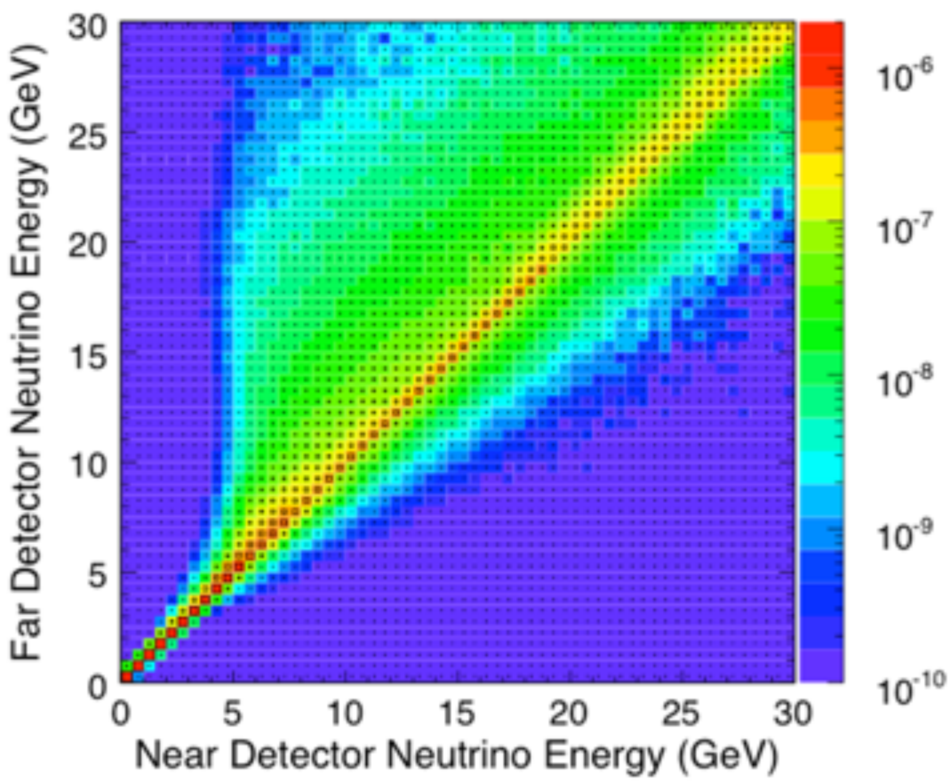
- k-Nearest Neighbours (kNN)
  - Shower PH, #planes in shower, PH around track
- reduced k from 400 to k=70, simplified calibration
- Improvement in region of interest in reconstructed energy

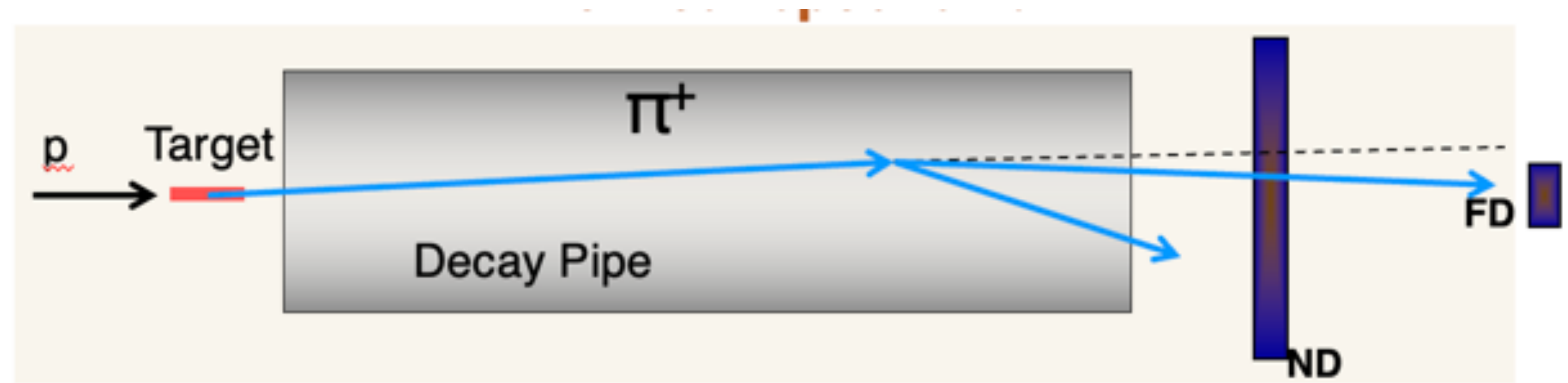
Far Detector Energy Reconstruction

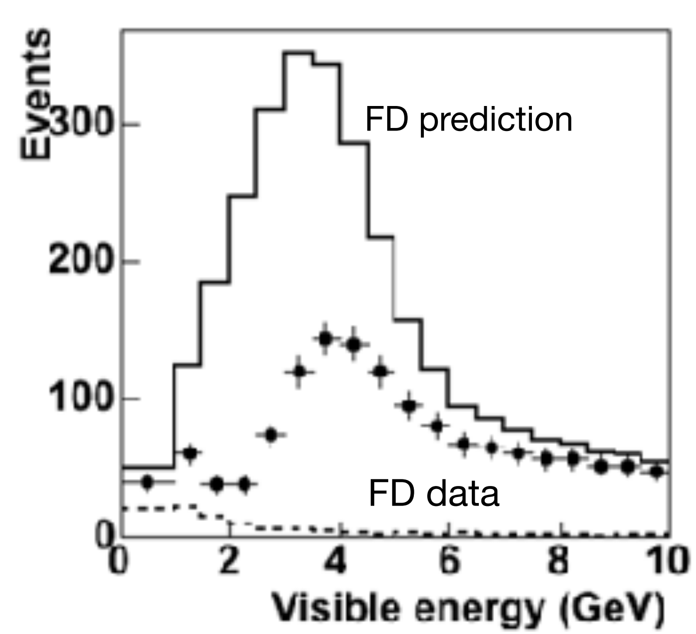


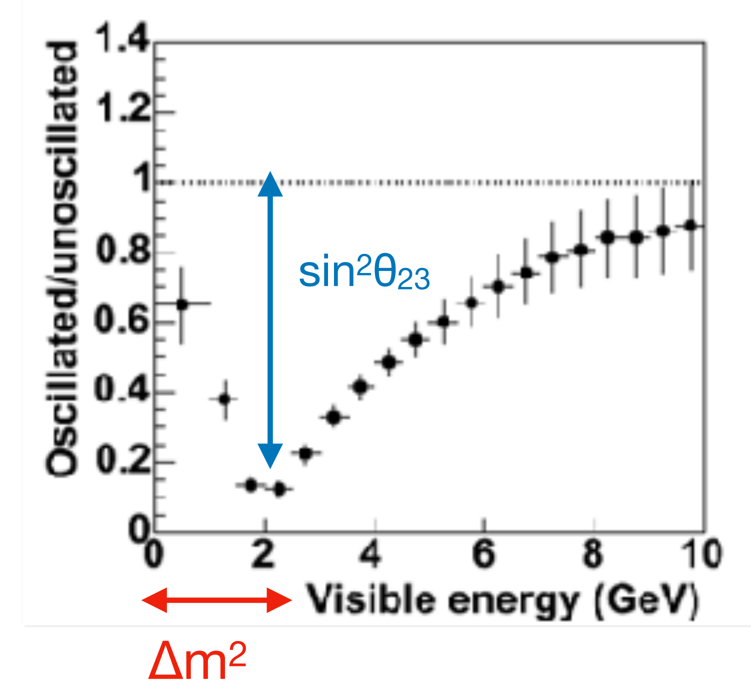


Basics of Oscillation Parameter Measurement





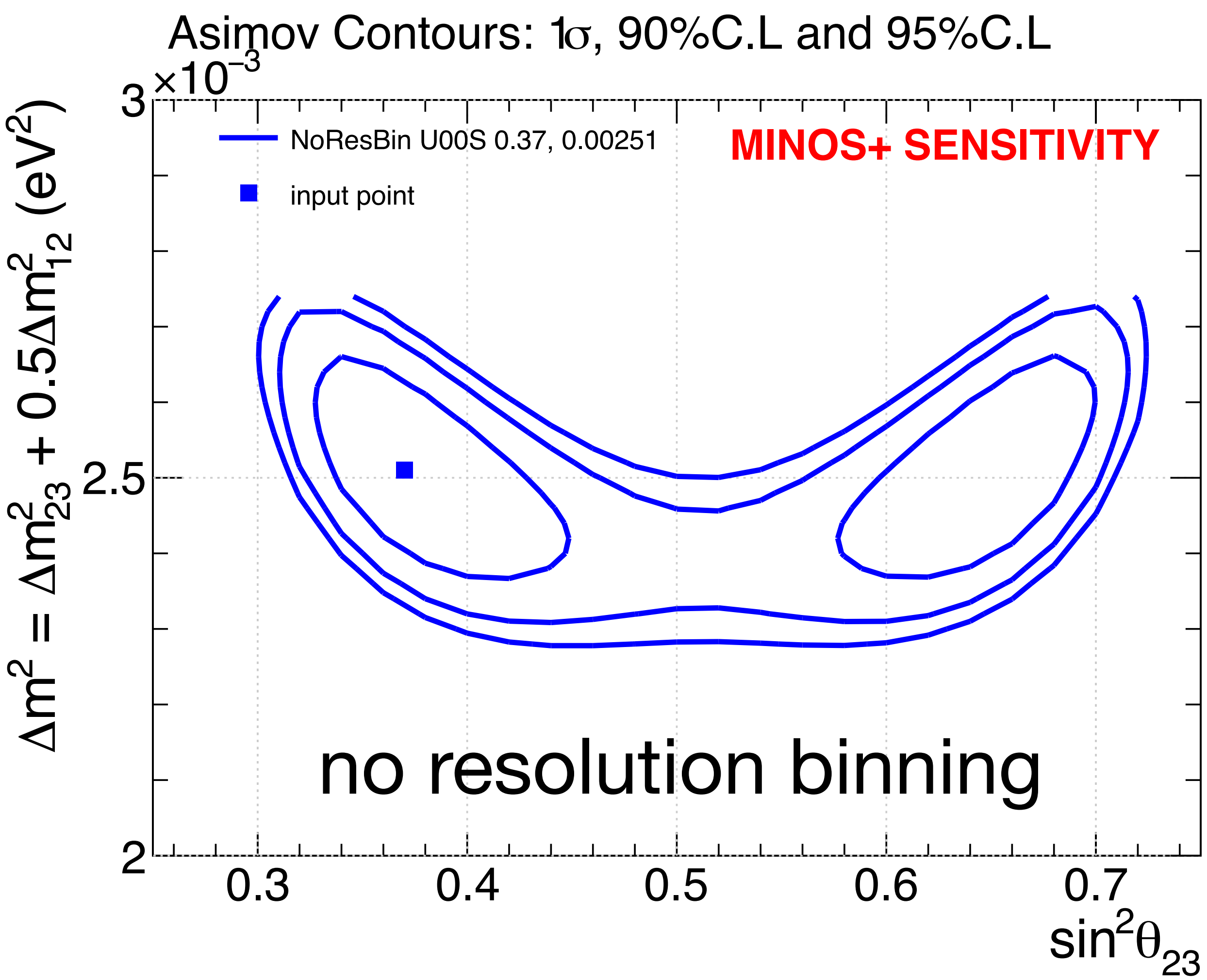


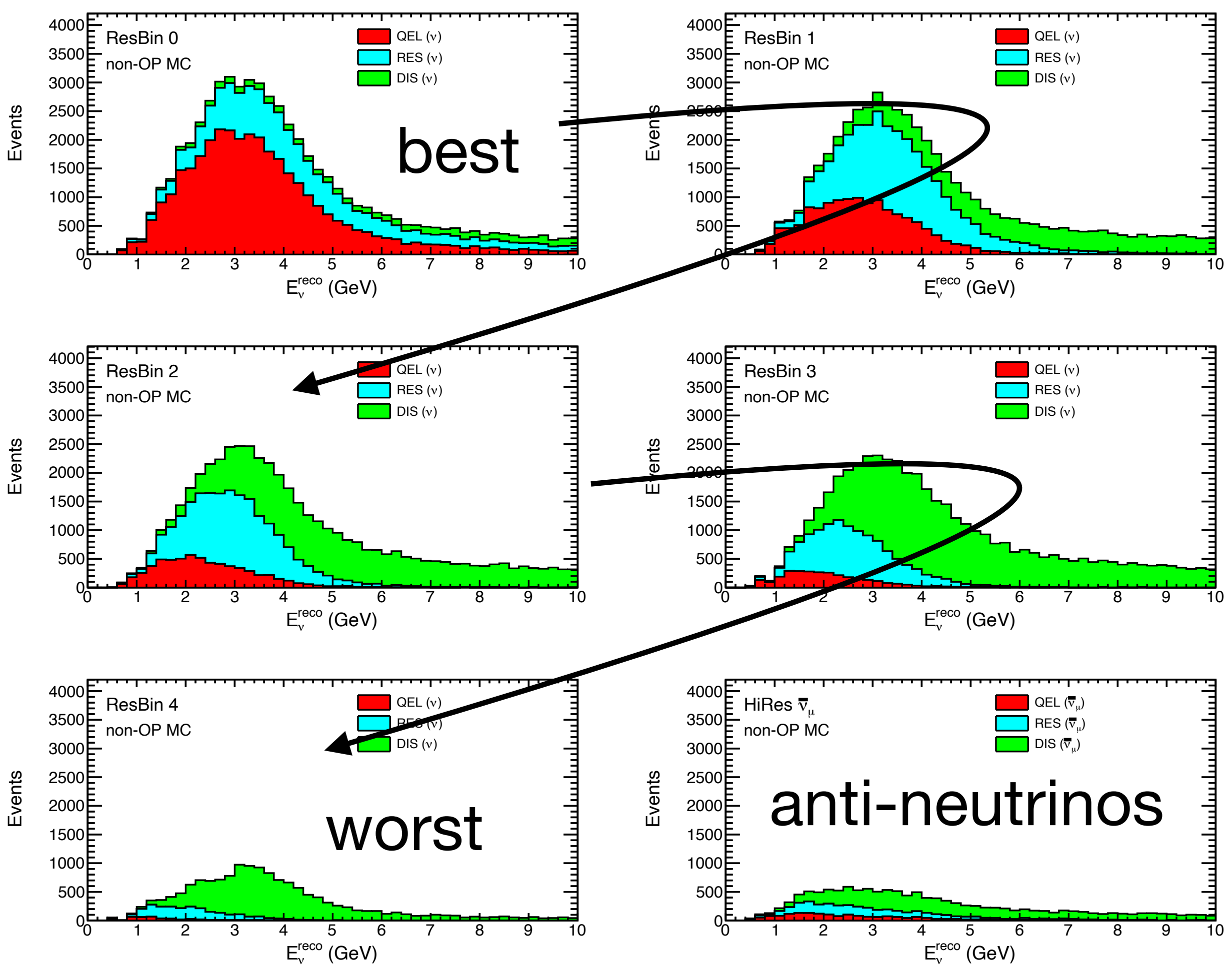


- Good model now of pions in the decay pipe, now add kinematics
- Push ND data through the ND->FD matrix
- FD prediction then compared to FD data

Resolution Binning

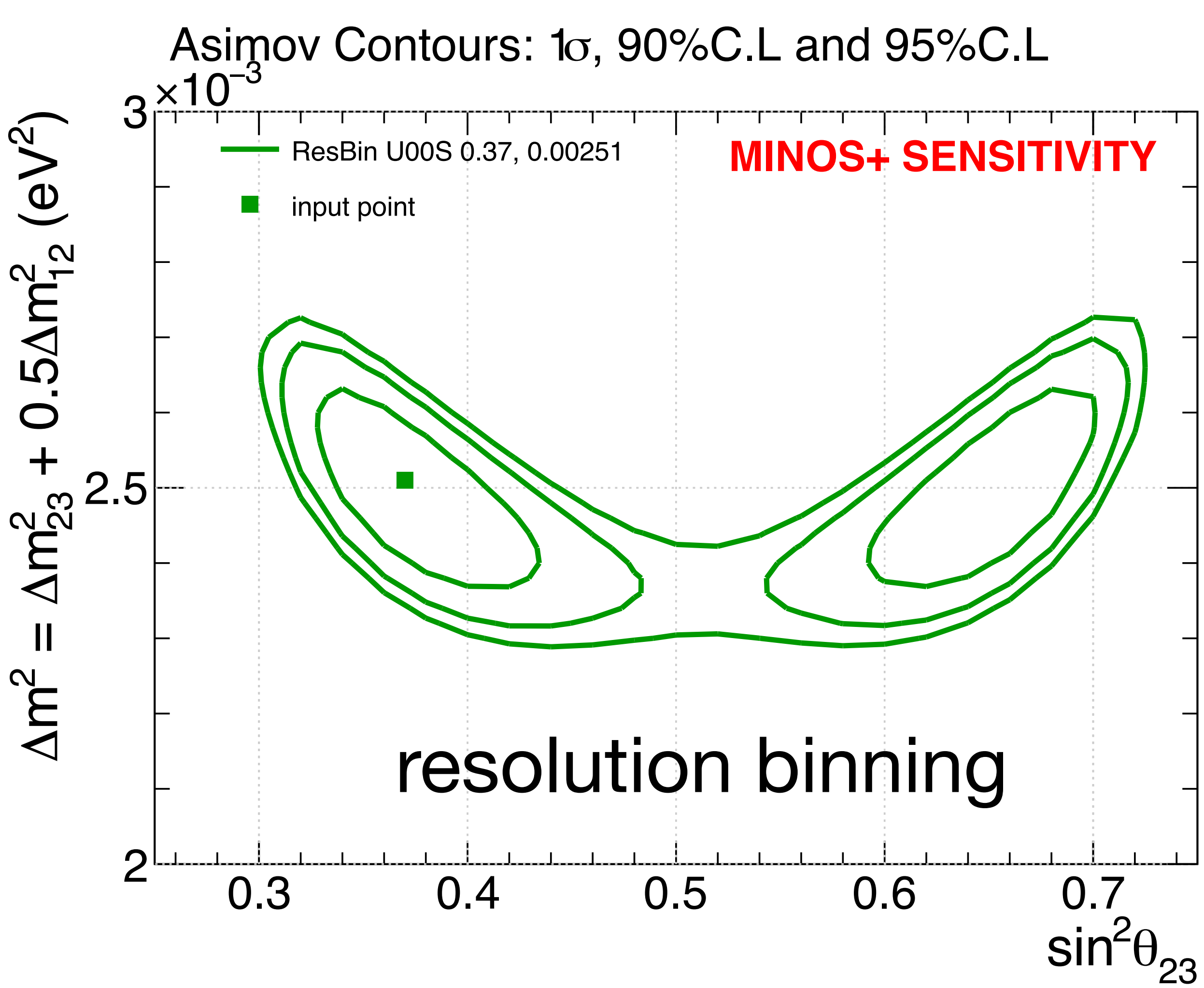
- The extrapolated ND spectrum is compared with the FD Data to find the best parameter fit values
- Resolution binning is used to group events together in the fit of similar resolution

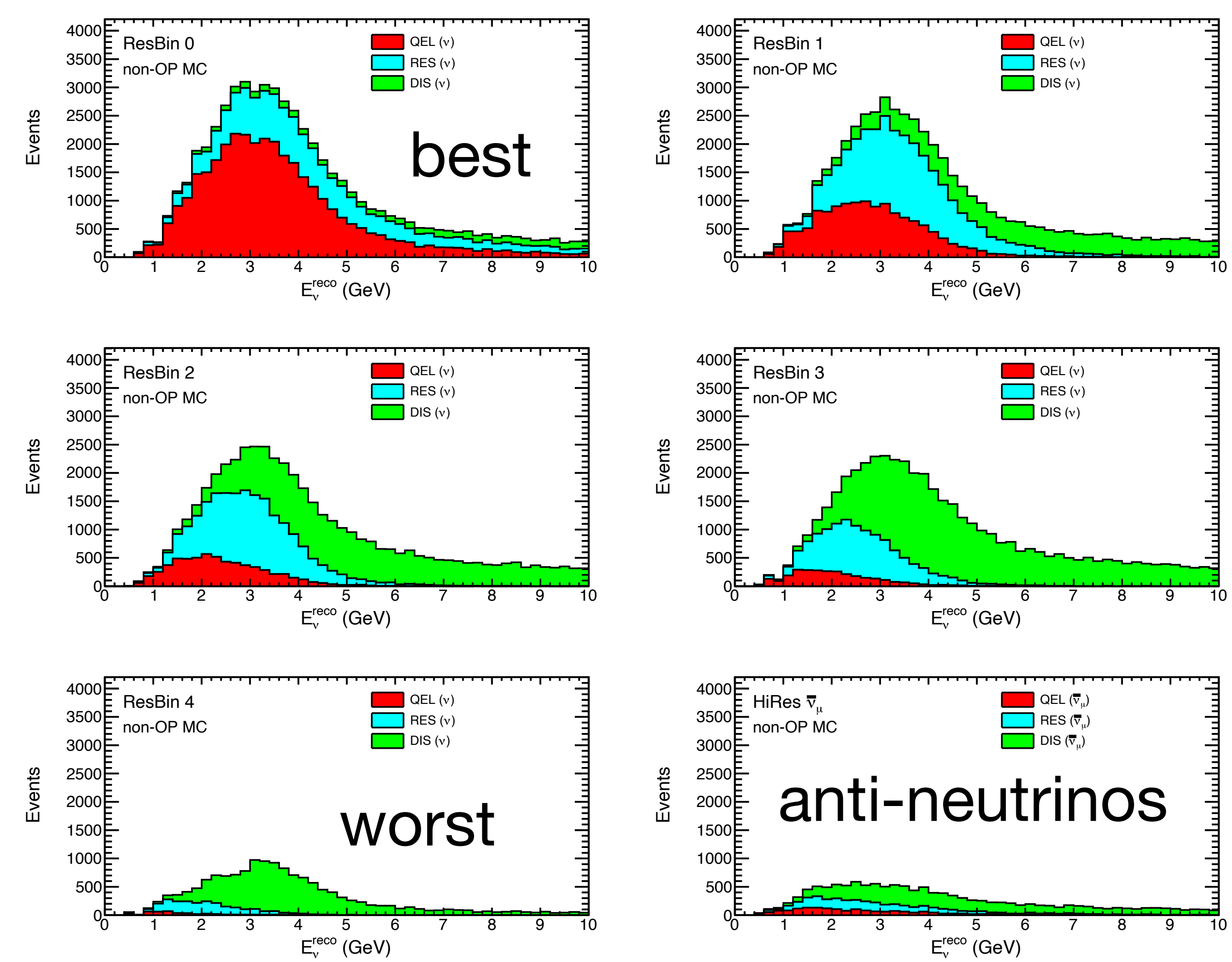




Resolution Binning

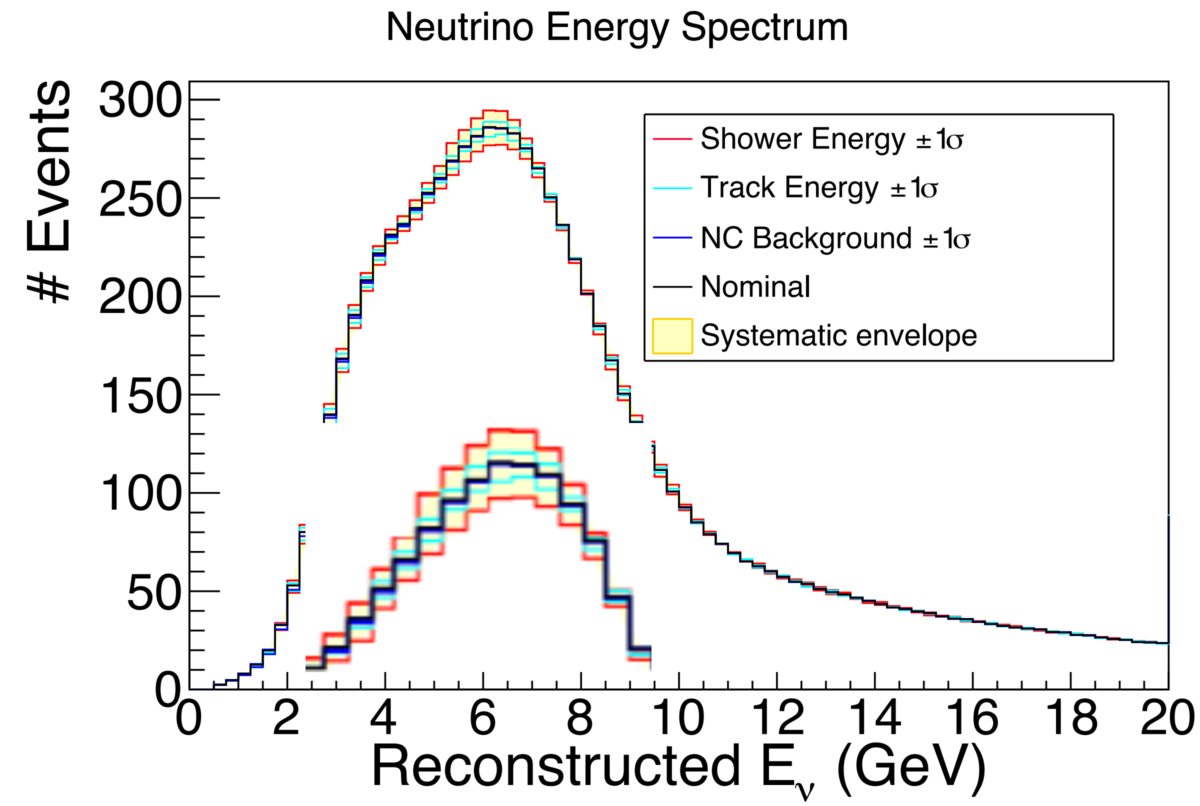
- The extrapolated ND spectrum is compared with the FD MC to find the best parameter fit values
- Resolution binning is used to group events together in the fit of similar resolution
- This improves sensitivity to Δm^2 and $\sin^2\theta_{23}$

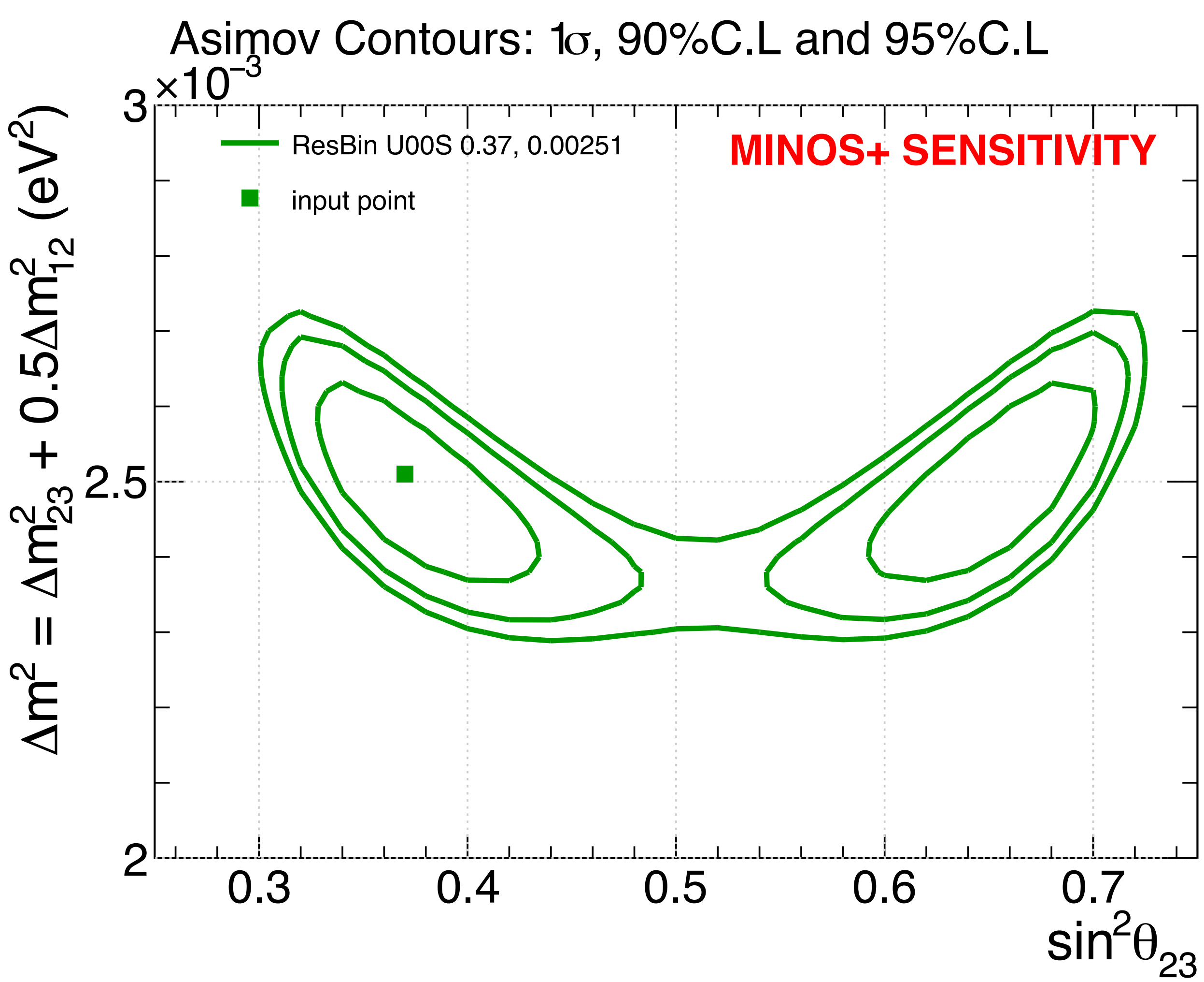


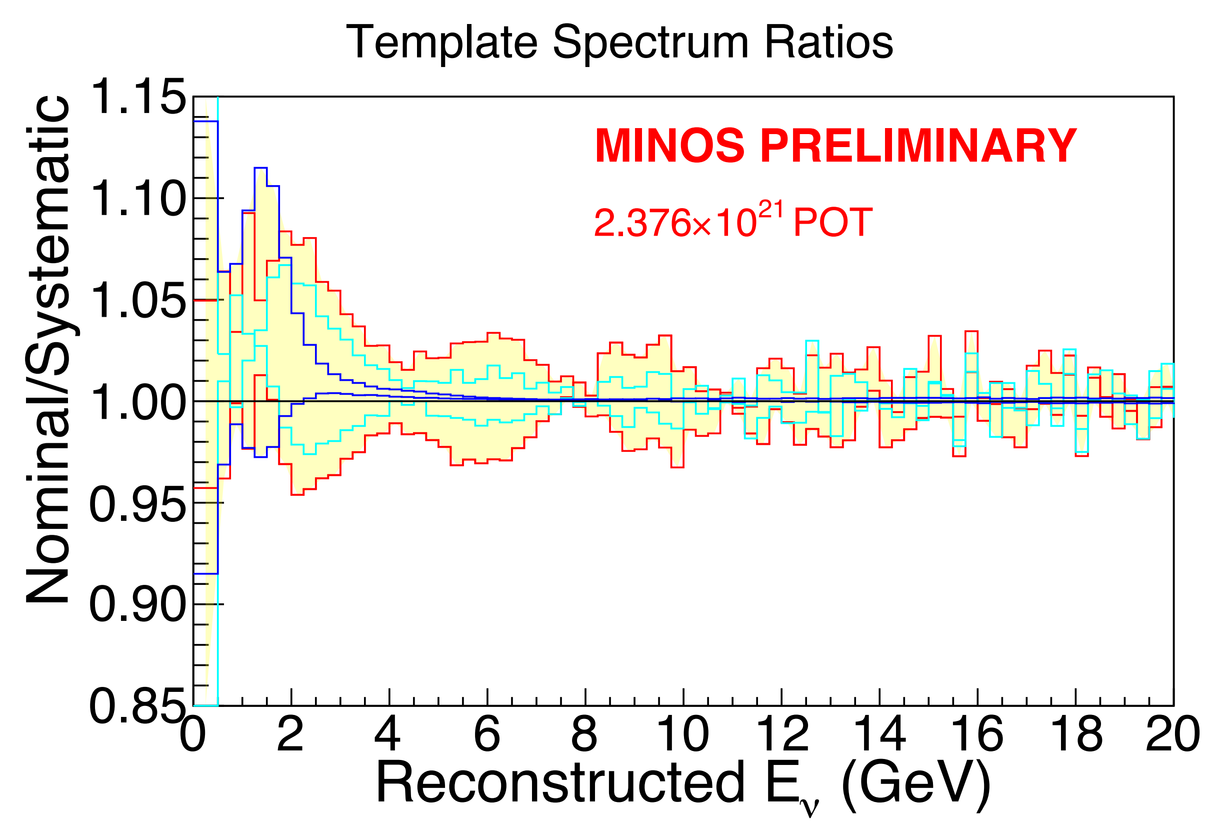


Systematic Studies Revisited

- Dominant systematics are Eshw, Etrk, NC Bkg and Normalisation
- The raw systematic envelope shows +/- 5-7% changes in region of interest for 1σ errors

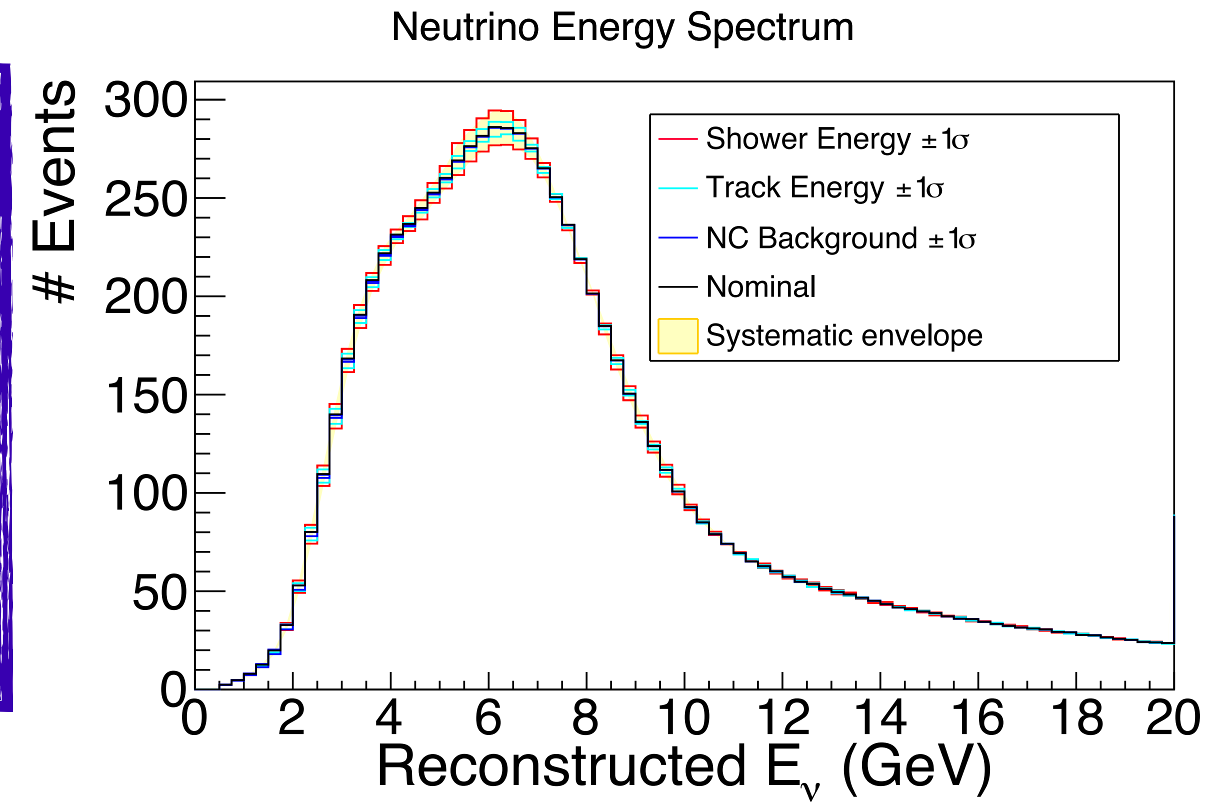


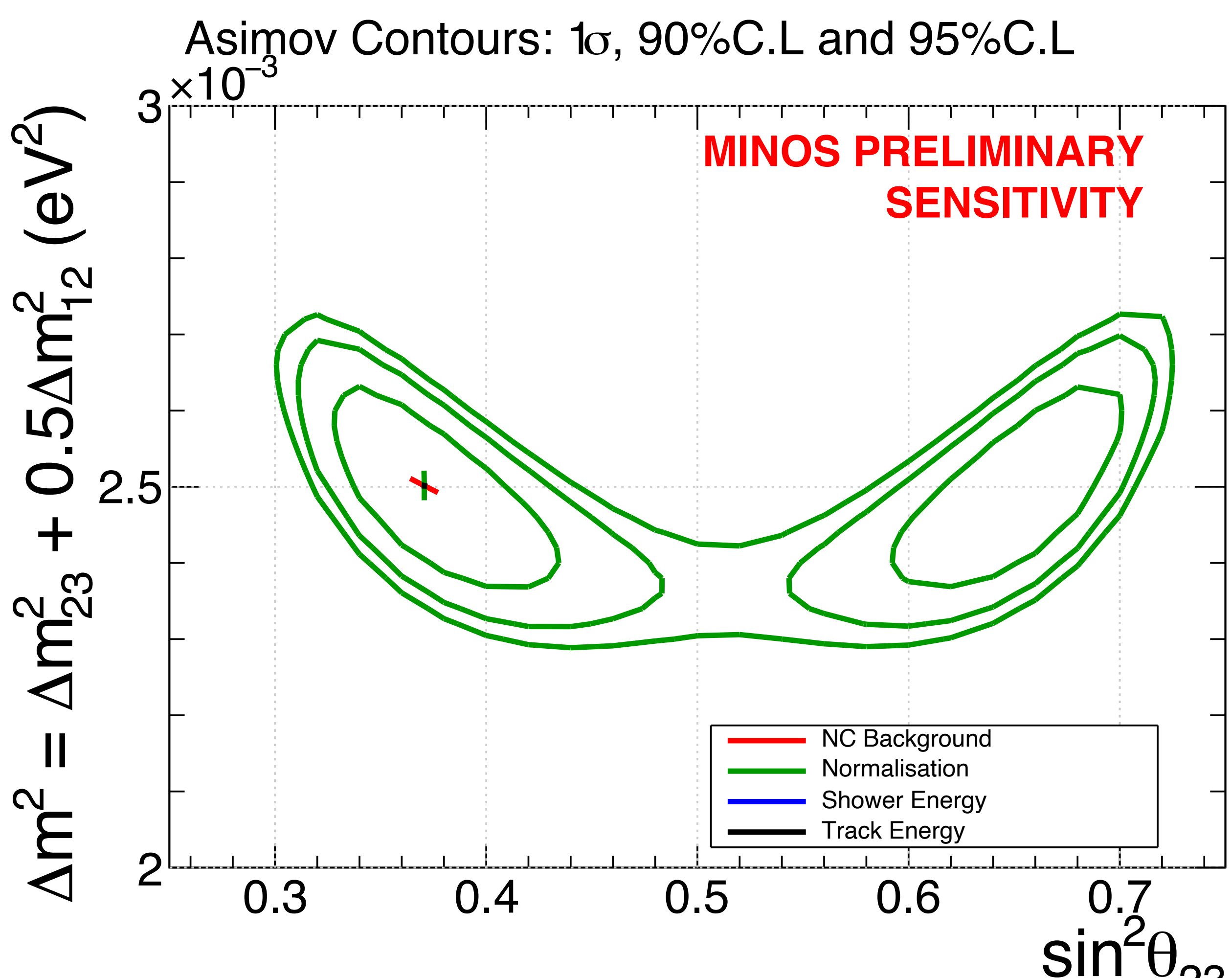


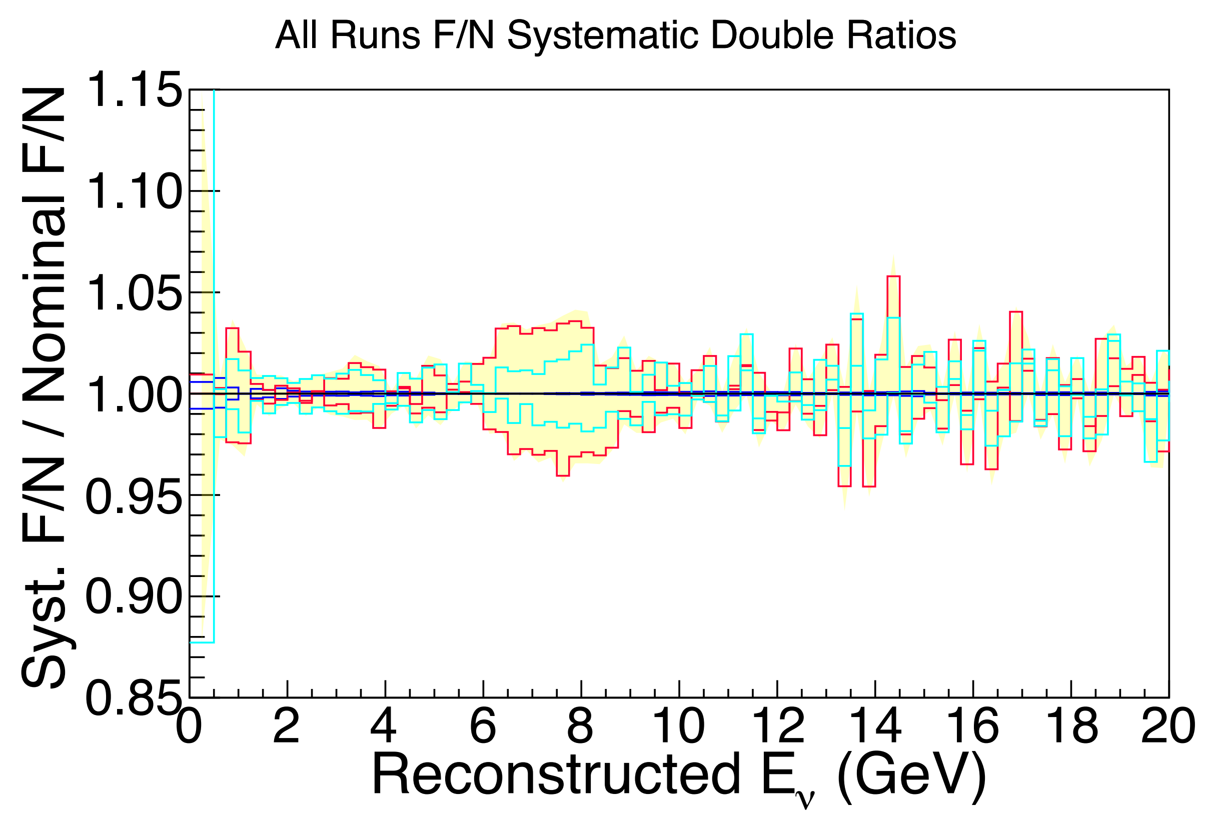


Systematic Studies Revisited

- Dominant systematics are Eshw, Etrk, NC Bkg and Normalisation
- F/N shows ~2% errors in region of interest
- Impact of systematics very small compared to statistics after fitting for systematics







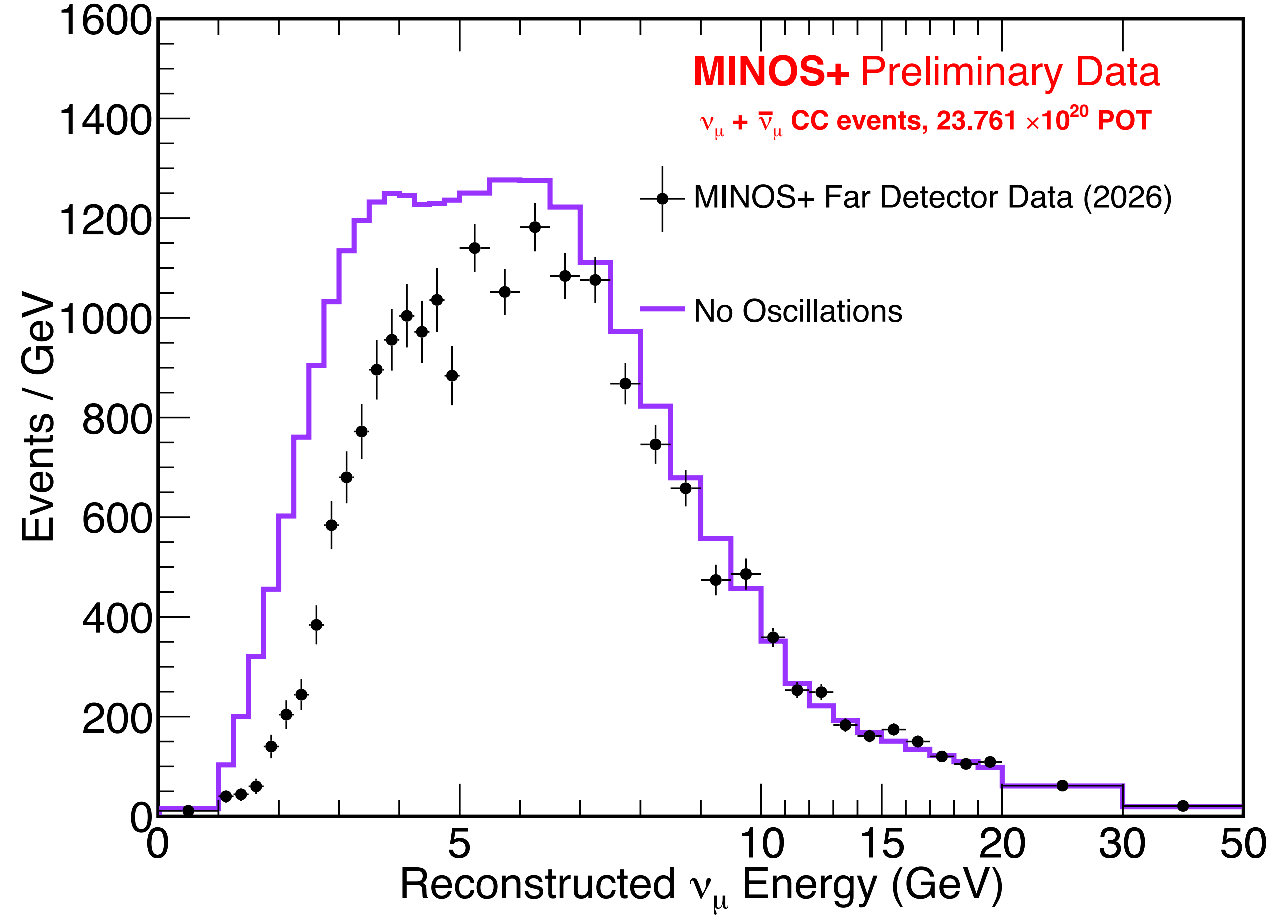
Results

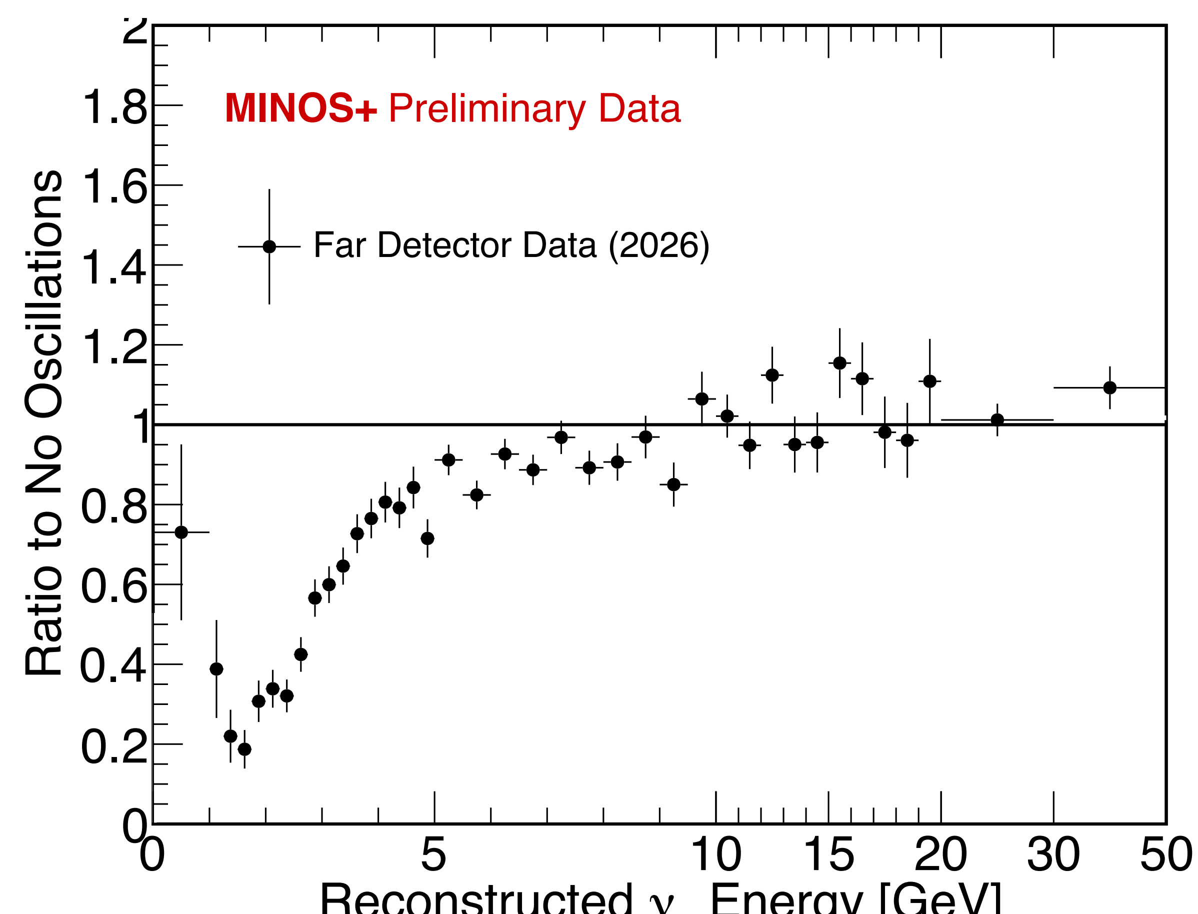
MINOS Results

"Whatever it is, it's very, very little."

MINOS+ Results

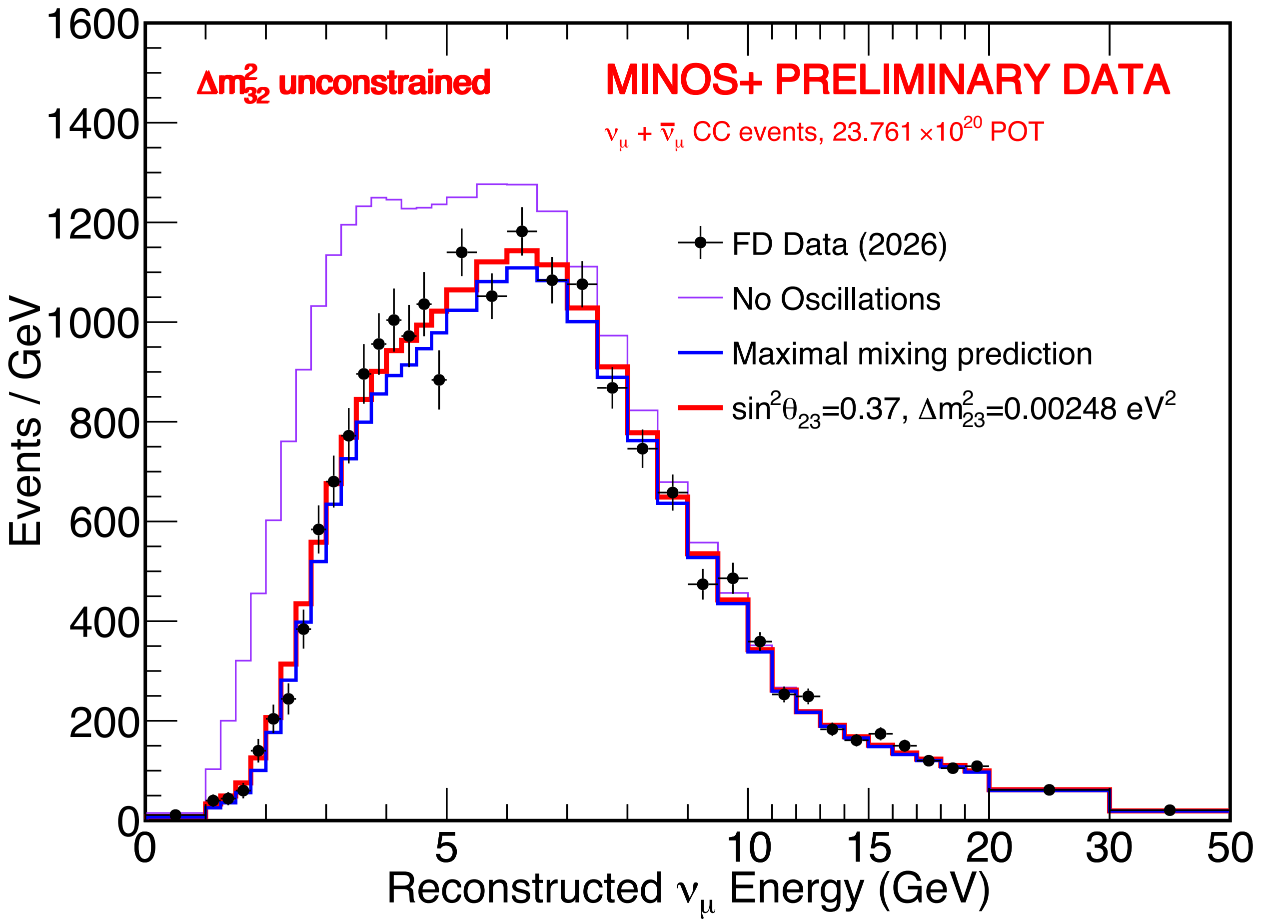
- Standard (three-flavour) fit to Δm^2 and $\sin^2\theta_{23}$
- Disappearance only, no νe appearance: no δCP, no octant information

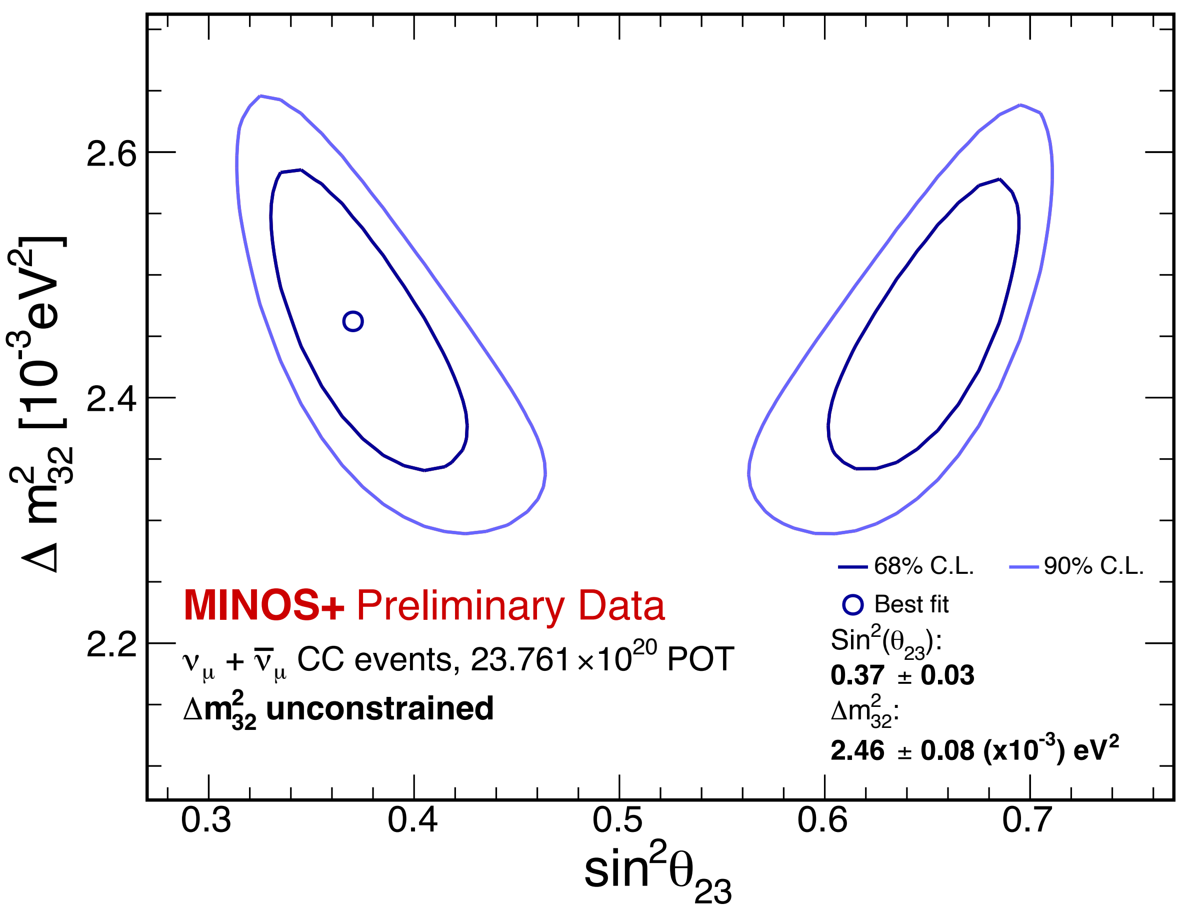


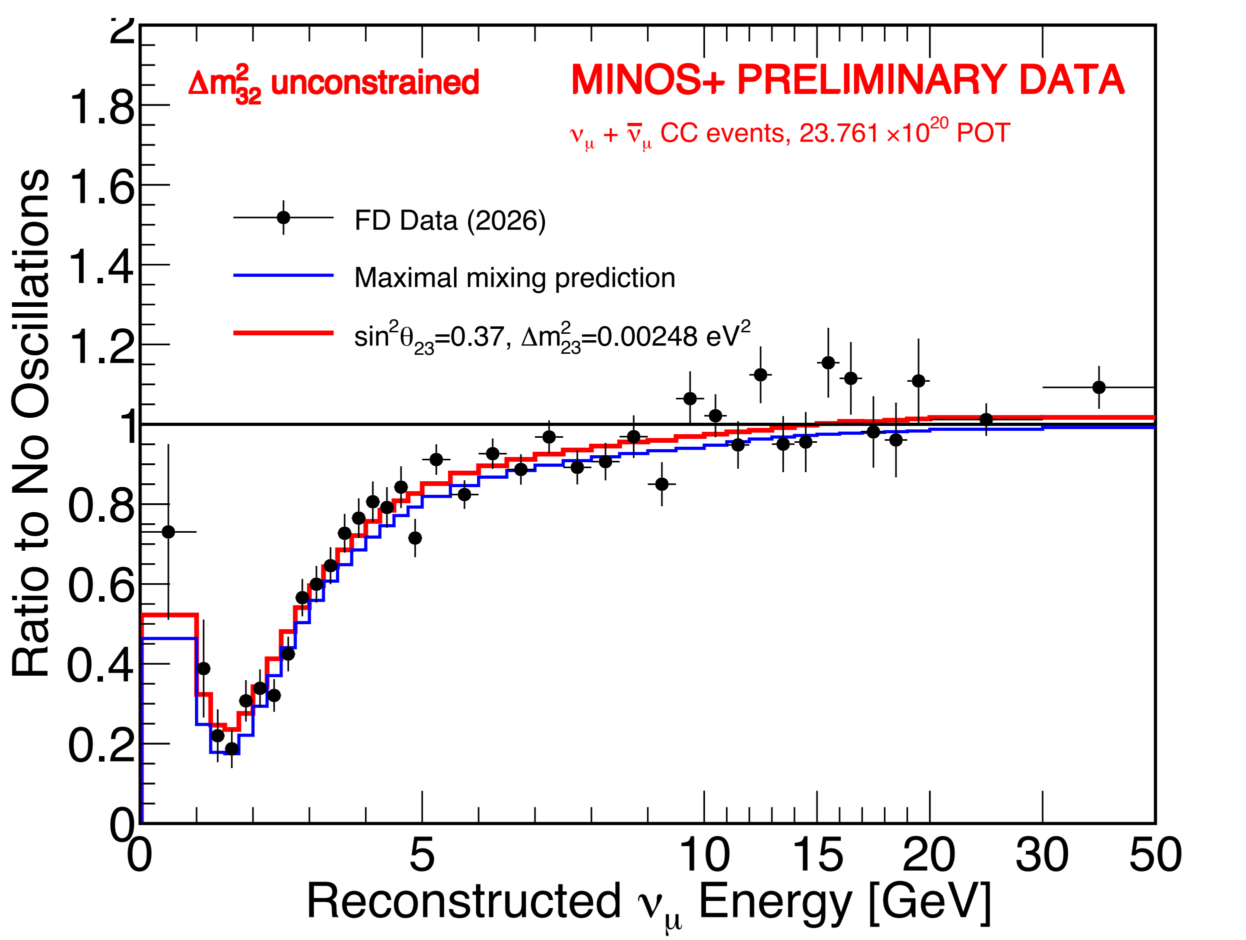


MINOS+ Results

- 3 flavour fit produces symmetrical contour (only disappearance)
- Unconstrained fit with both parameters excludes maximal mixing solution at 90% C.L.

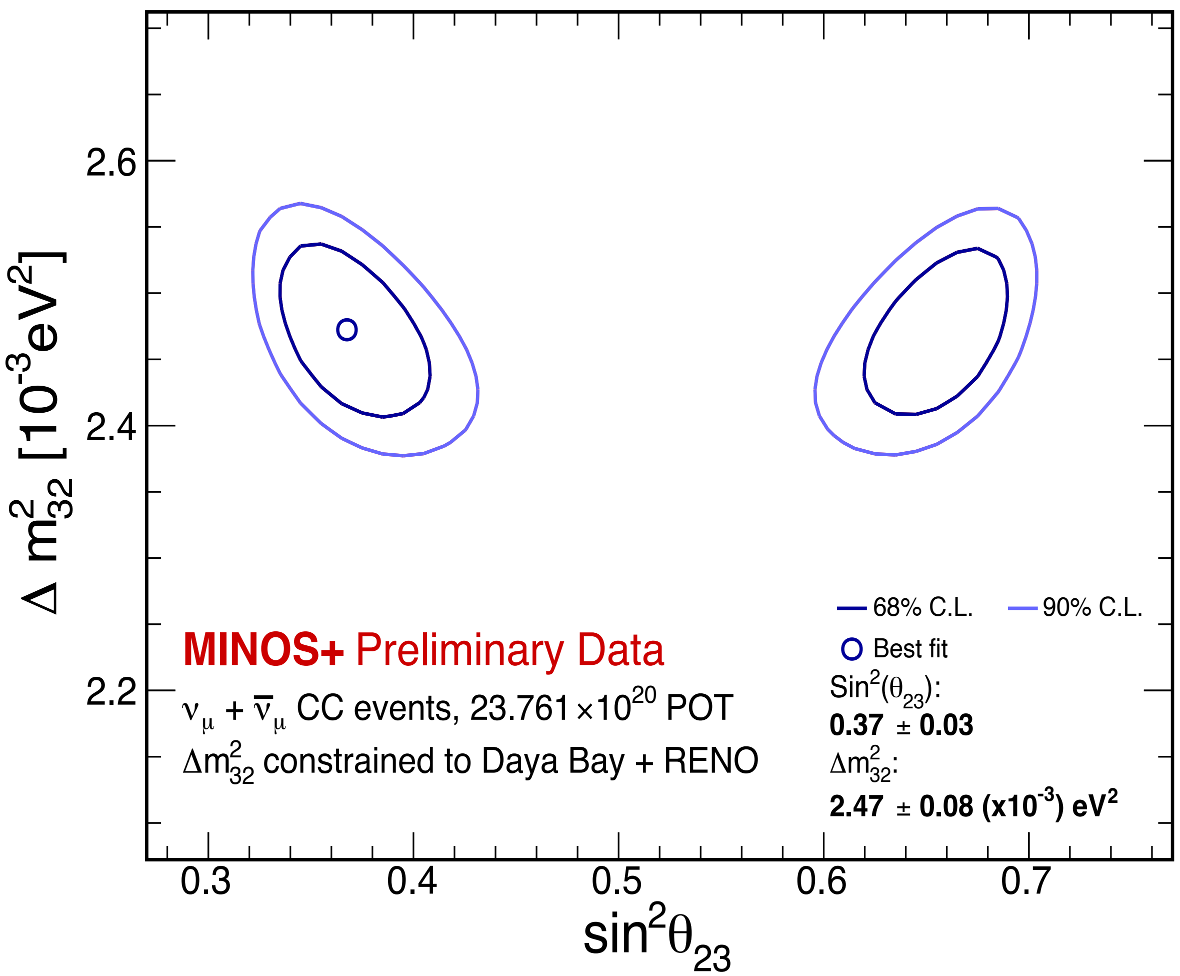


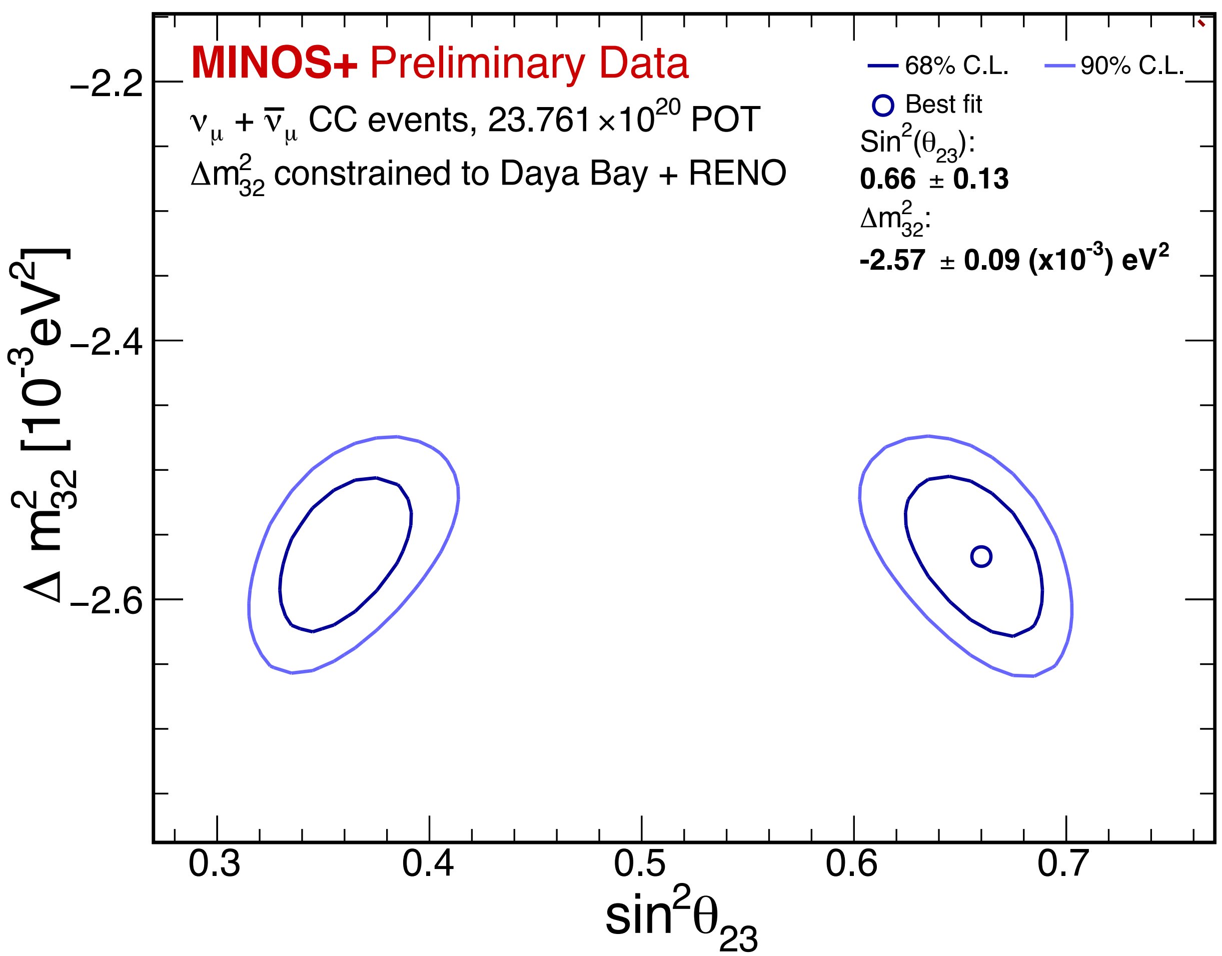




MINOS Results

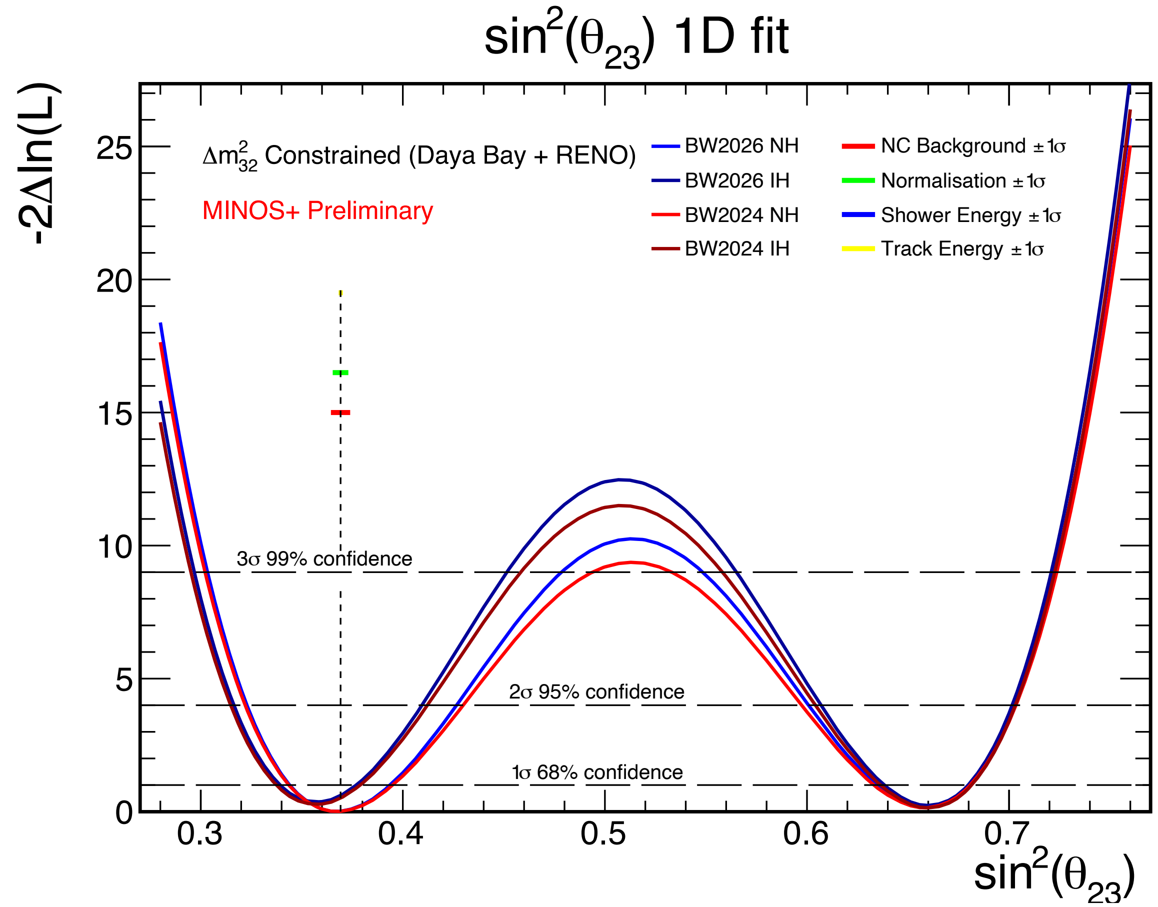
- **Constrain Δm^2** with Reactor value

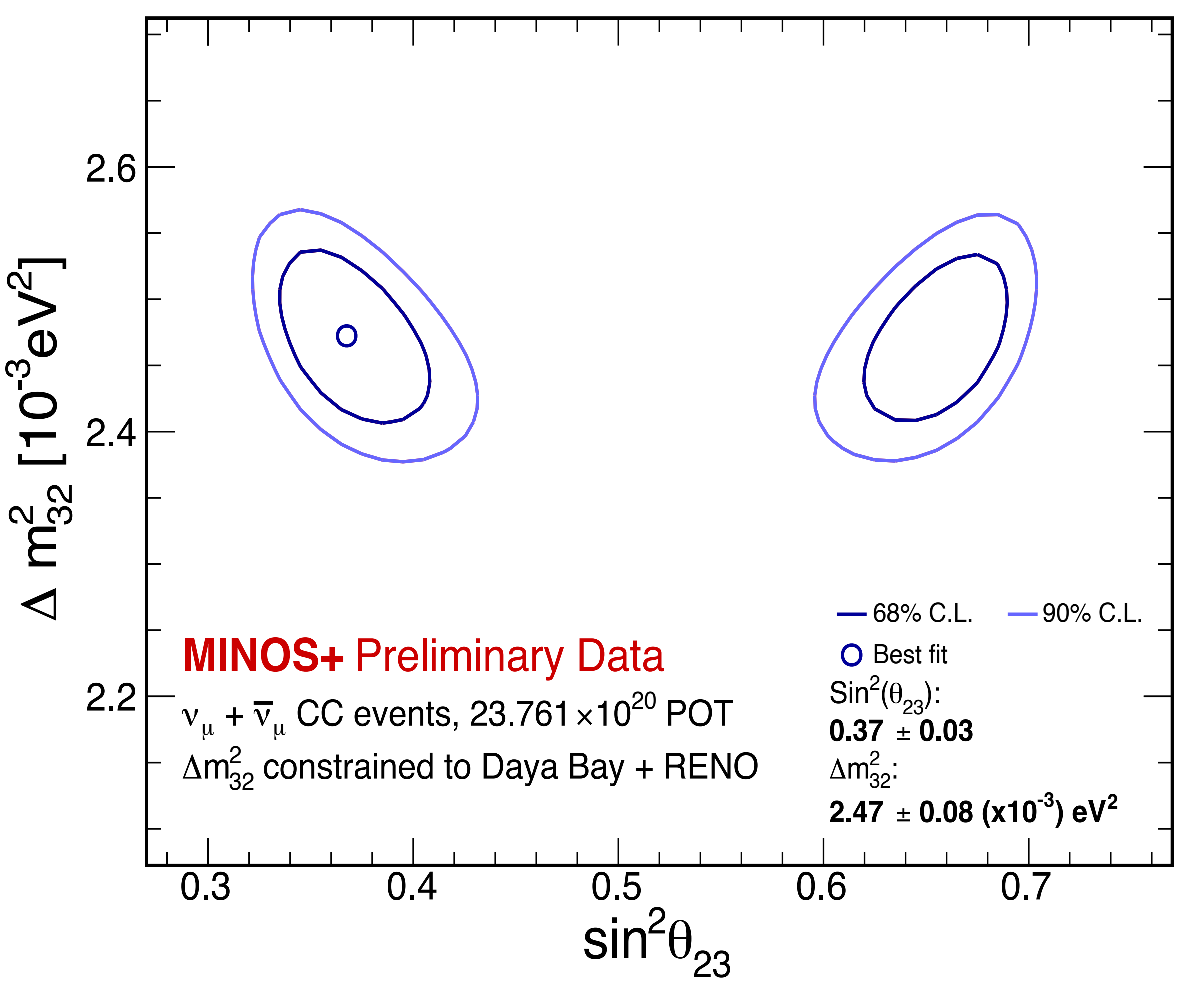


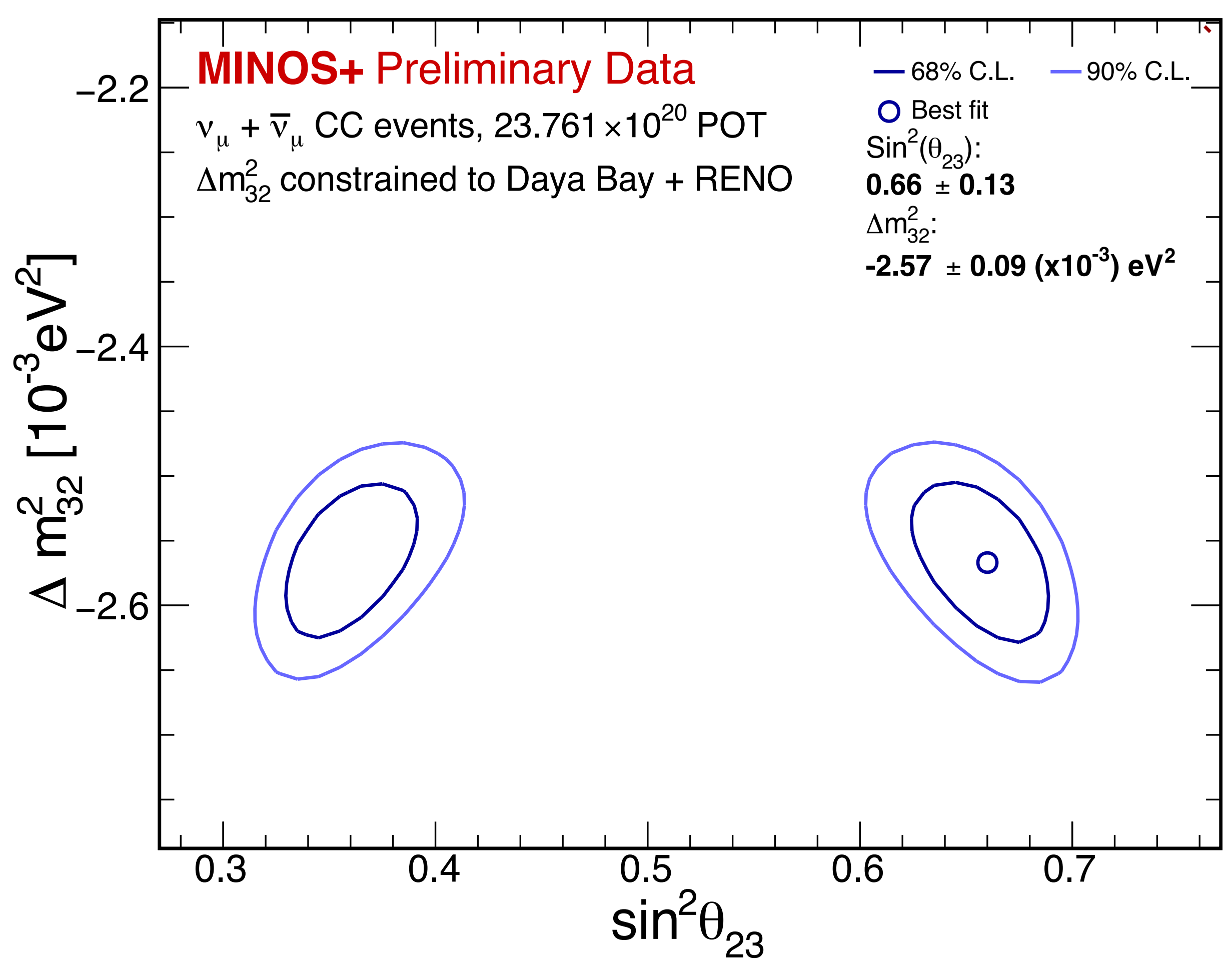


MINOS Results

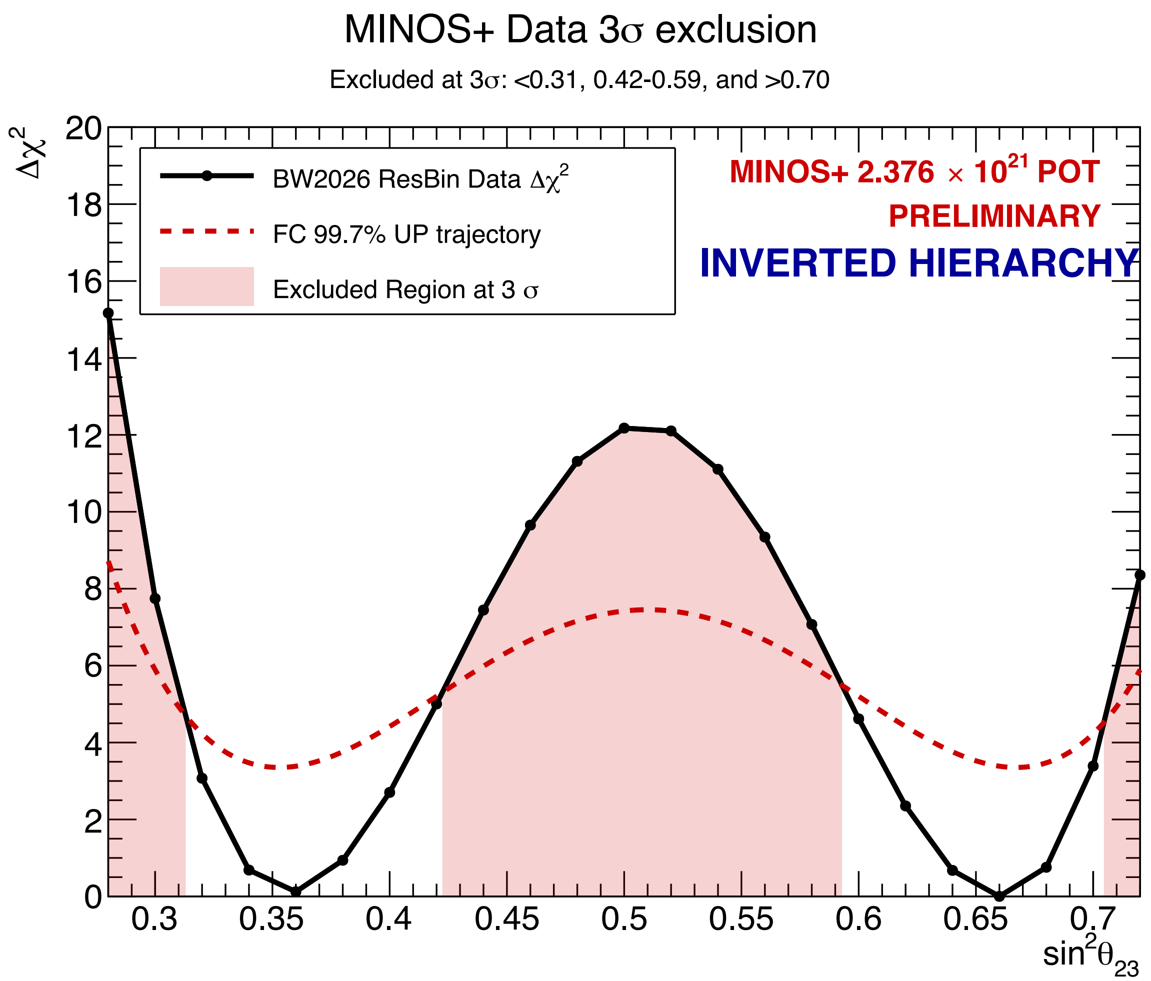
- **Constrained Δm^2** with Reactor Constraint excludes maximal mixing at 3σ
- FC Corrections important with a constrained fit

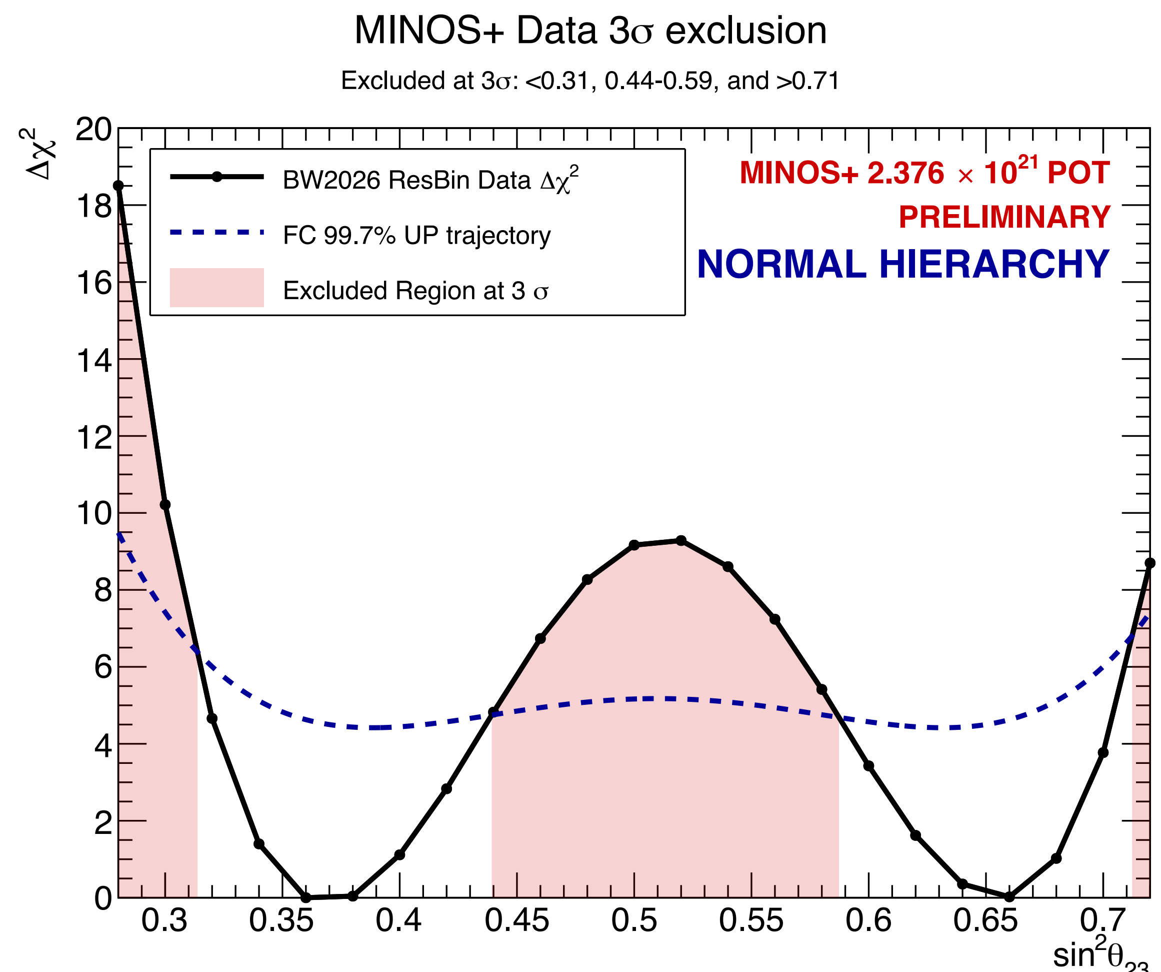




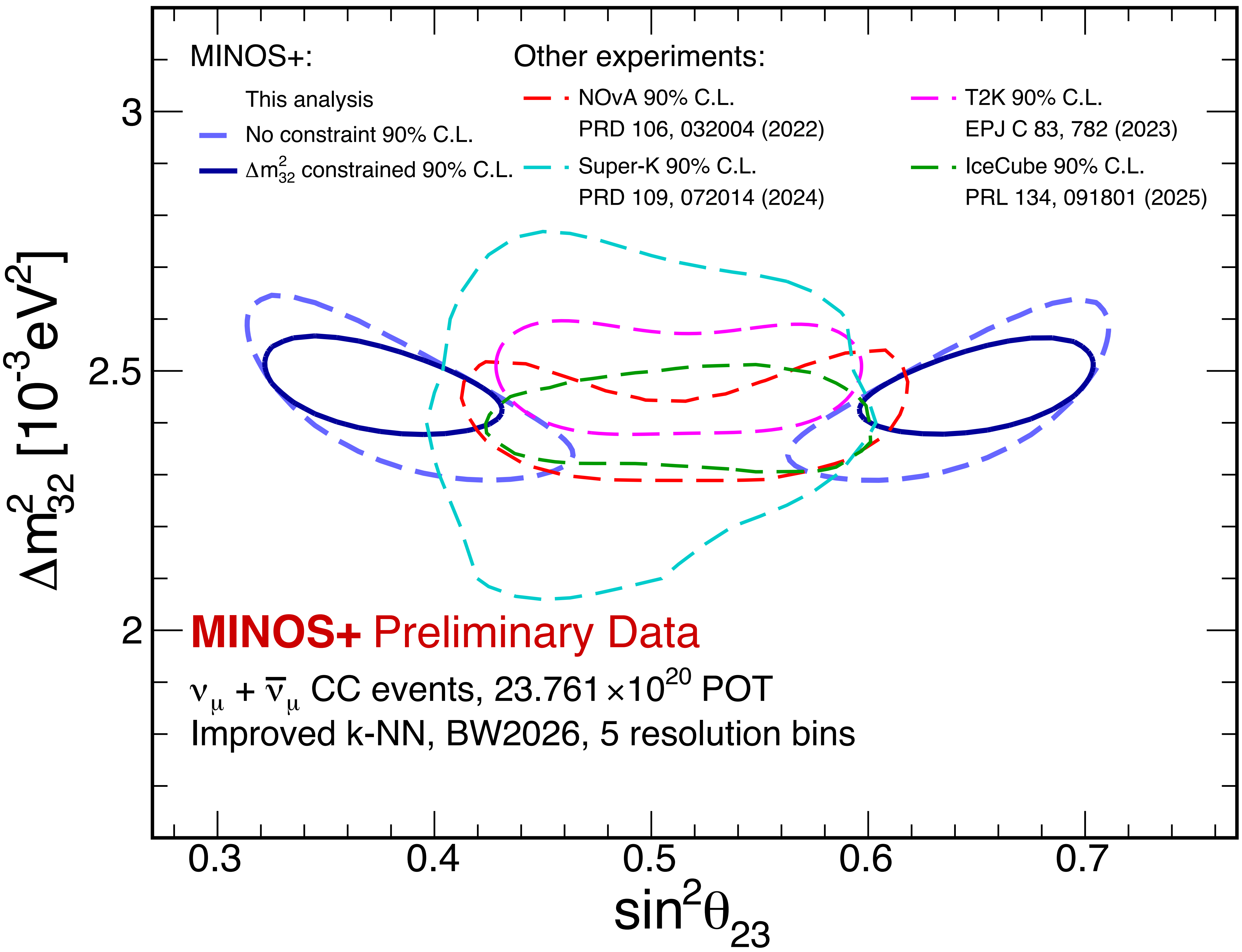


MINOS Results (Feldman Cousins Corrected)





- MINOS data with **reactor constrained Δm^2** excludes maximal mixing at 3σ
- IH : 0.42-0.59 excluded at 3σ
- NH : 0.44-0.59 excluded at 3σ


MINOS+:
This analysis
No constraint 90% C.L.
Δm^2_{32} constrained 90% C.L.
Other experiments:
NOvA 90% C.L.
PRD 106, 032004 (2022)
Super-K 90% C.L.
PRD 109, 072014 (2024)
T2K 90% C.L.
EPJ C 83, 782 (2023)
IceCube 90% C.L.
PRL 134, 091801 (2025)
MINOS+ Preliminary Data
$\nu_\mu + \bar{\nu}_\mu$ CC events, 23.761×10^{20} POT
Improved k-NN, BW2026, 5 resolution bins
Δm^2_{32} [10^{-3}eV^2]
3
2.5
2
0.3
0.4
0.5
0.6
0.7
$\sin^2\theta_{23}$

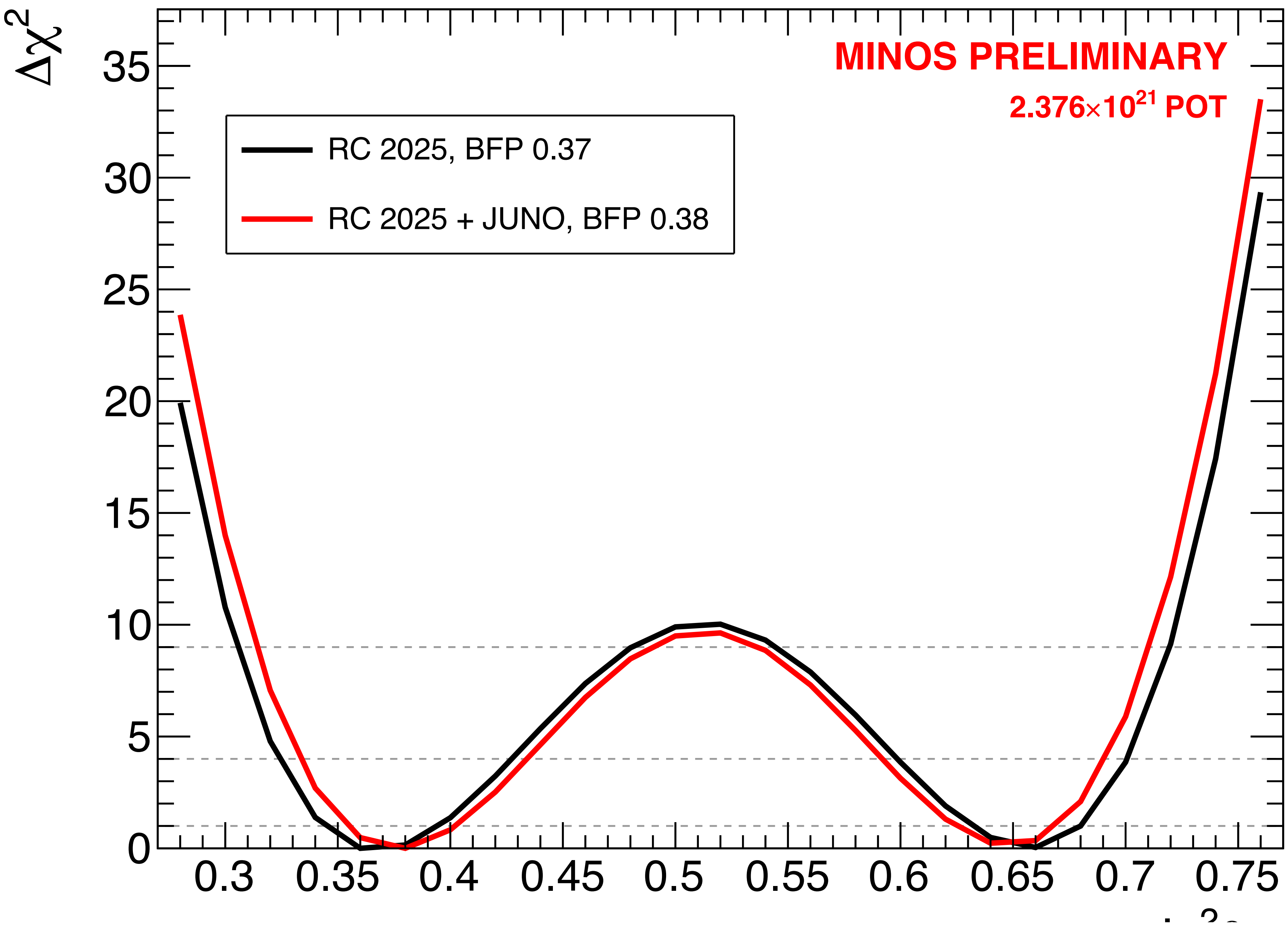
Looking to the future

- MINOS on-axis data set will be curated
  - Keep it in a raw form that can be used easily with ML : this will become an industry
  - Keep current in light of new modelling developments $$$$$ - curate the MC too!
- Conference rush means there are always things left on the table
  - Come back to them!
- New experiments coming soon (when?) but existing data will be a spring board to get quickly to the remaining unknowns

Conclusion

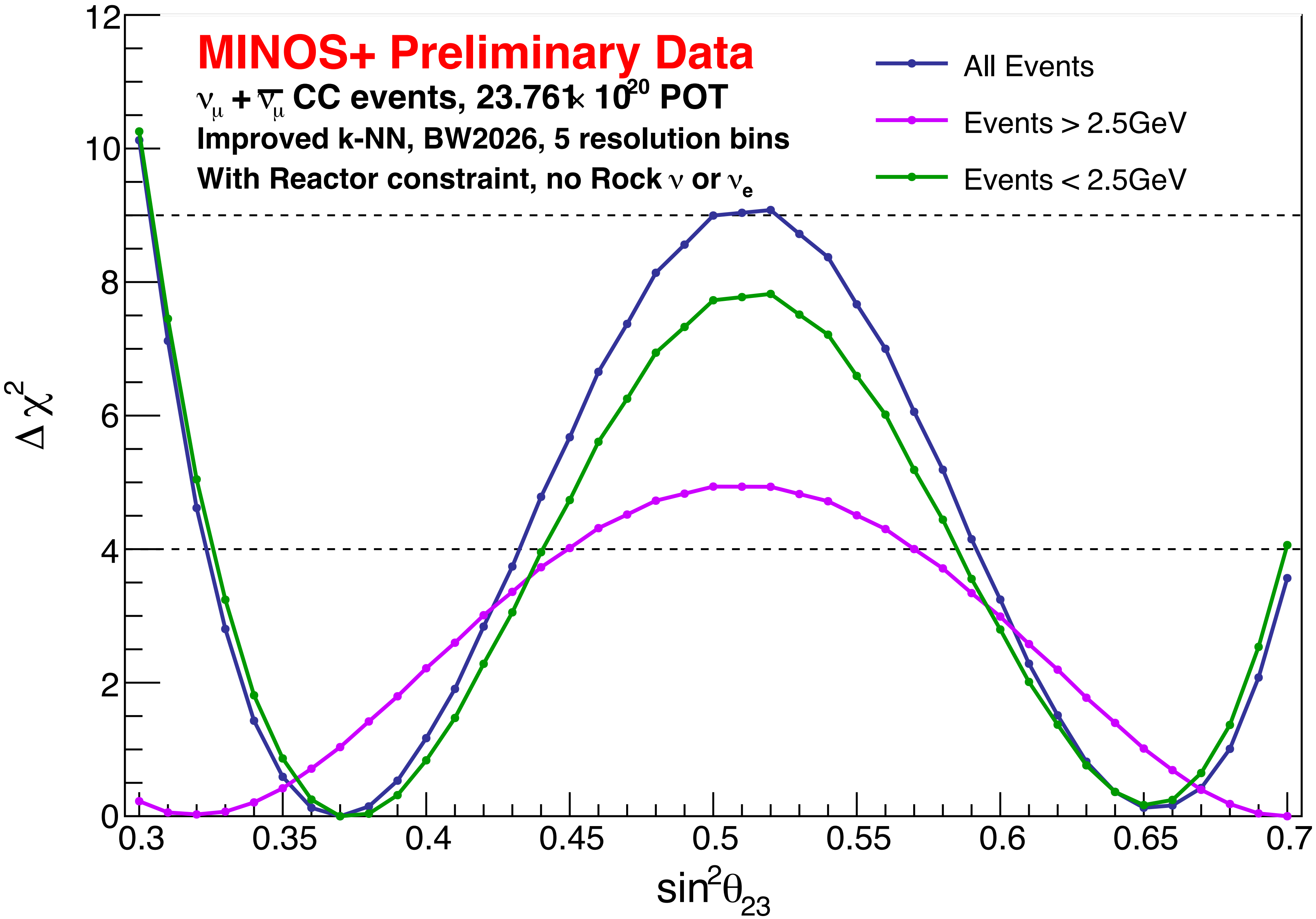
- The MINOS analysis has been renovated and polished
- MINOS rules out maximal mixing at the 3σ level with reactor constraint
- Excluded region extends from 0.44 to 0.59 in $\sin^2\theta_{23}$
- Potentially important tension with off-axis LBL experiments must be understood
- Until DUNE, MINOS is still the only 2-detector on axis experiment in town!

MINOS+ Results (JUNO + RC constraint)



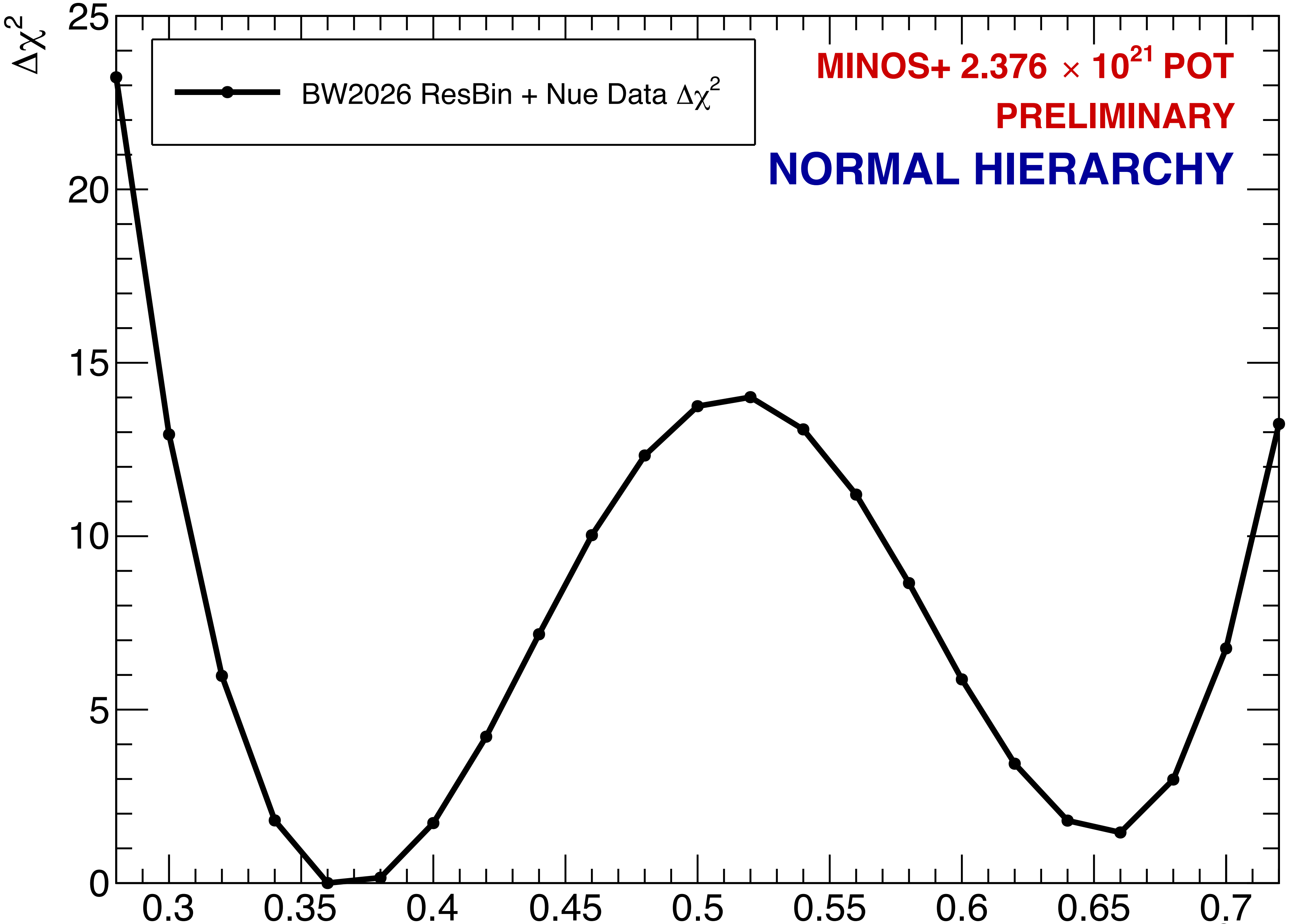
MINOS+ Results (Cross checks)

- Sanity check at below and above 2.5 GeV renders similar trend



MINOS+ Results (Cross checks)

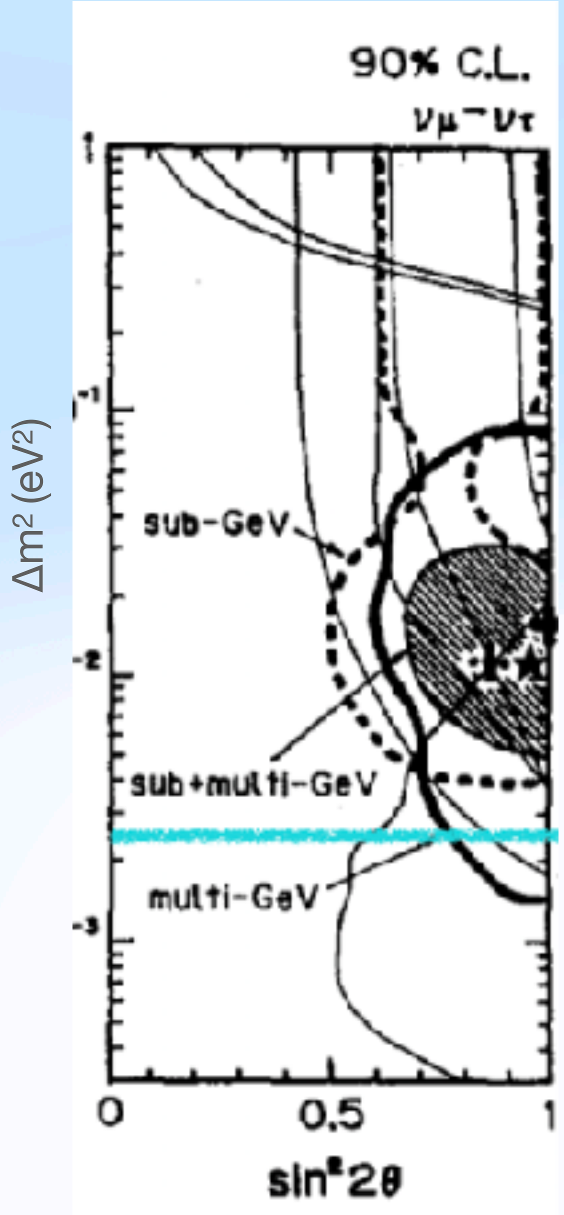
- Including nue chi



The conventional wisdom at the time

The Kamiokande Experiment

- In 1991 Kamiokande had shown that if neutrino oscillations were the cause of the missing atmospheric neutrinos in their water Cherenkov detector, then the Δm^2 (difference in mass squared of the two types of neutrinos) was ~10^{-2} eV^2



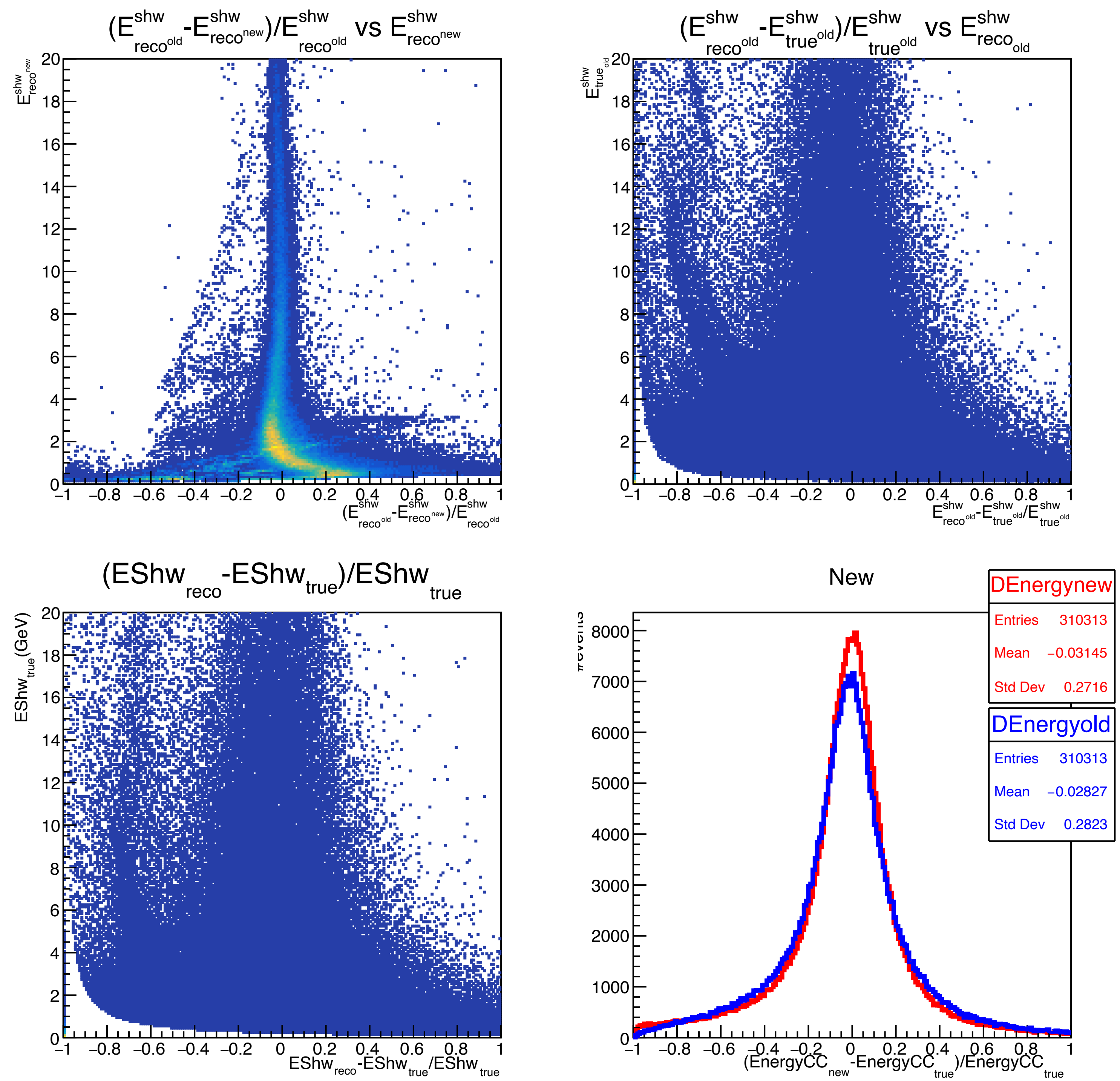
- The Japanese funding agency took it seriously….

"The Super-Kamiokande project was approved by the Japanese Ministry of Education, Science, Sports and Culture in 1991 for total funding of approximately $100 million."

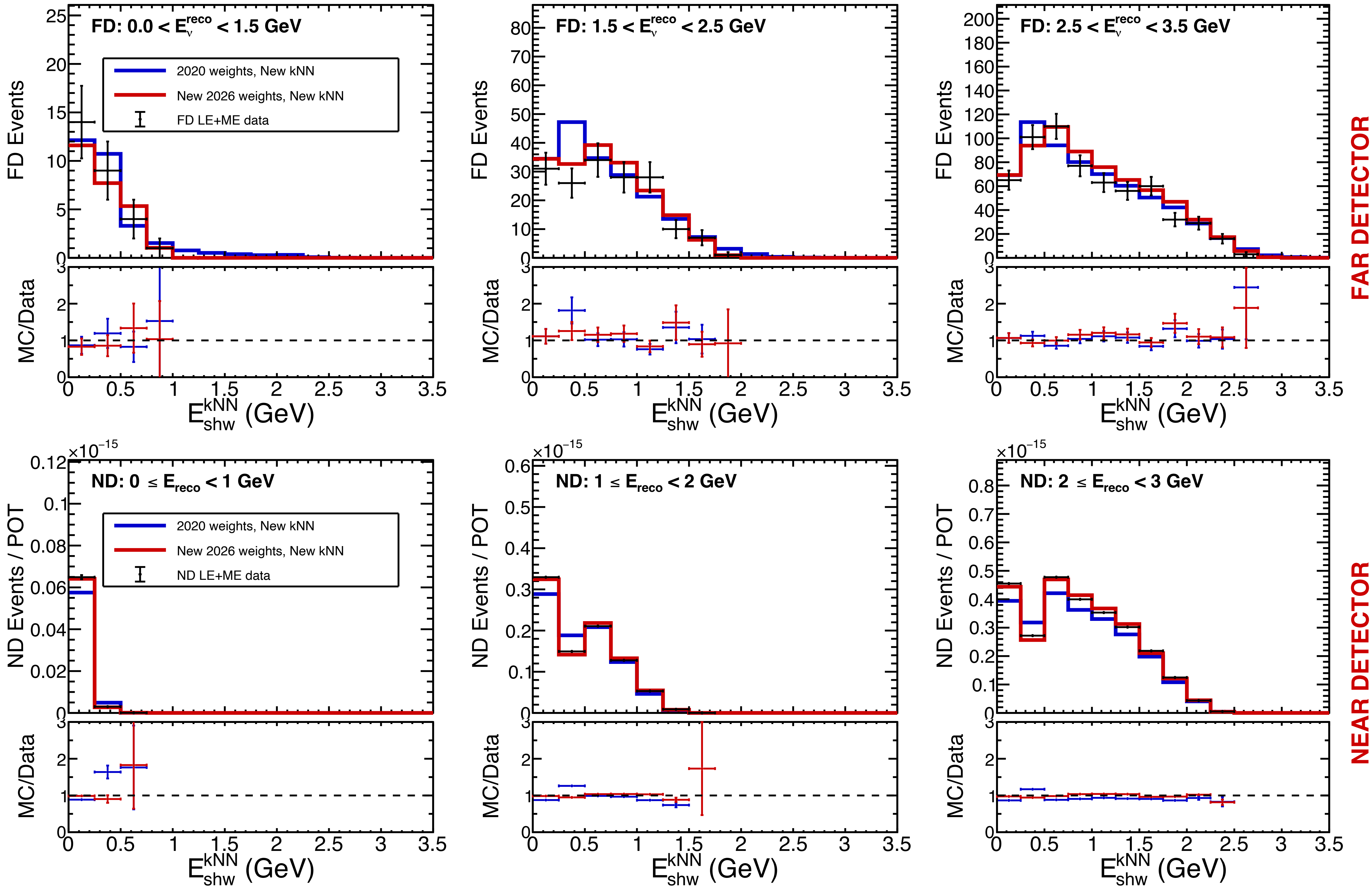
$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta \sin^2(1.267 \Delta m^2 L / E)$$

Shower Energy Estimator

- The shower energy estimator uses three variables
  - raw PH in shower
  - PH along identified track
  - #planes in shower
- Previous calibration step was removed
- Movement in energy between new and old approaches is shown
- Overall, total fractional reconstructed energy distribution marginally improved



Hadronic Shower Energy MC/Data



Hadronic energy in bins of total reconstructed neutrino energy : LE+ME

The extrapolation procedure