Muon Neutrino Disappearance Measurement at MINOS+

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New Perspectives 2016

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Overview

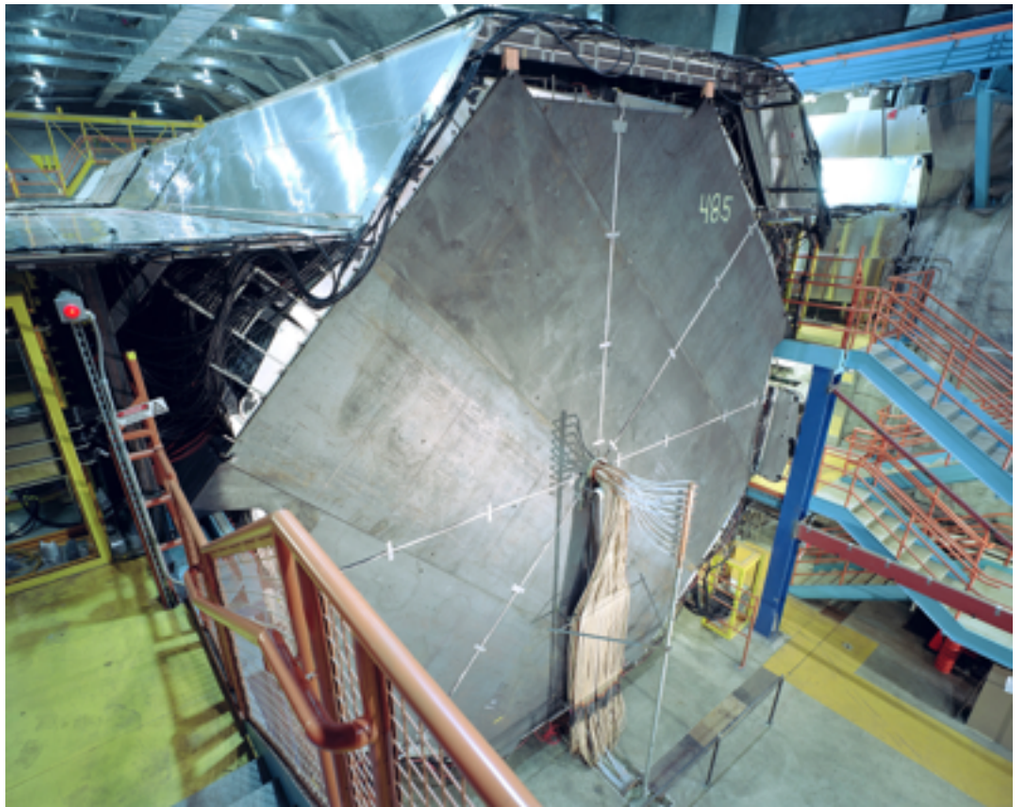
- ✦ Oscillations
  and the **M**ain **I**njector **N**eutrino **O**scillation **S**earch Detectors

  - The Medium Energy NuMI Beam

- ✦ Neutrino Disappearance at MINOS+

- ✦ Latest MINOS+ Results

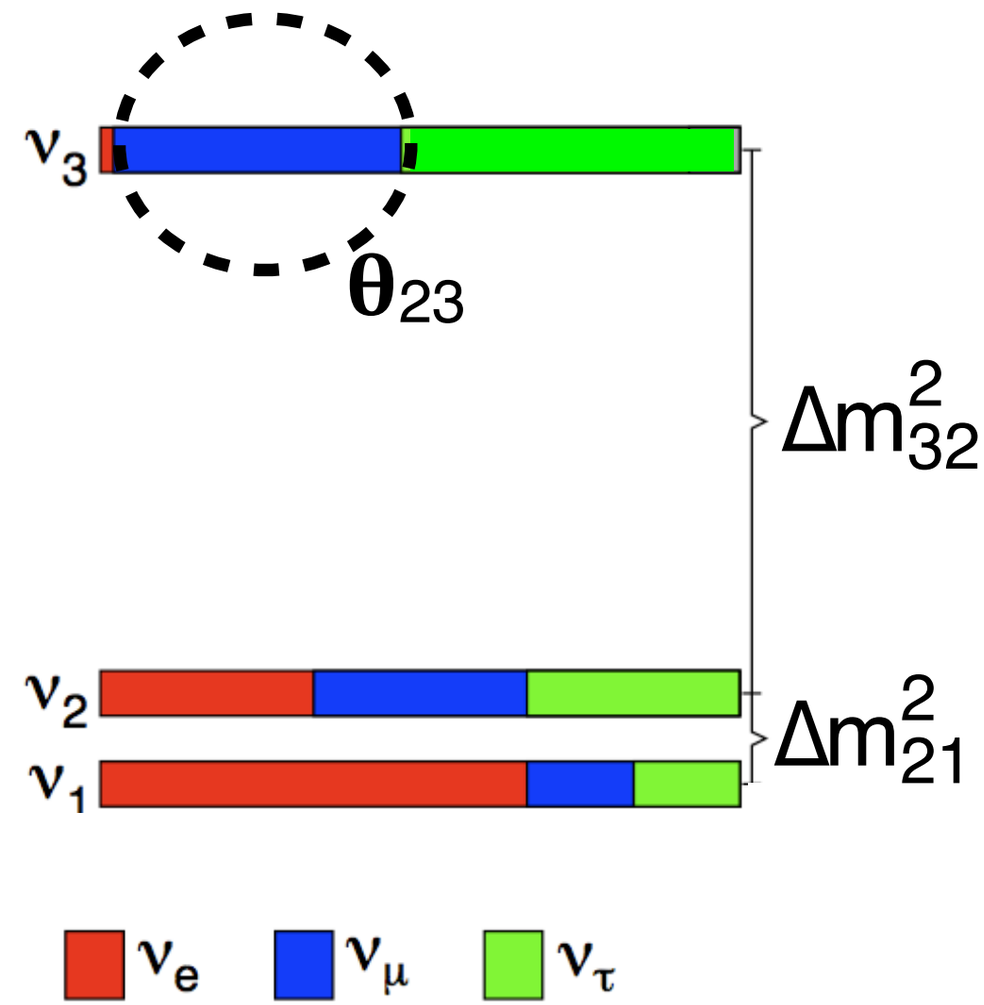
- ✦ MINOS+ and the Future



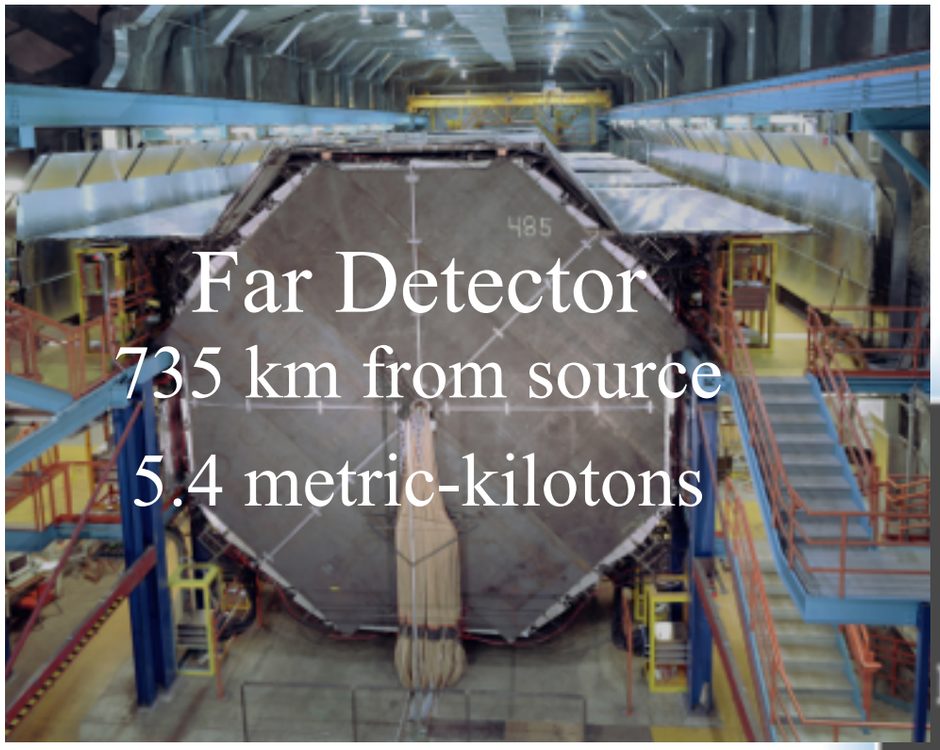
Neutrinos Oscillate

In the 3 flavor model:

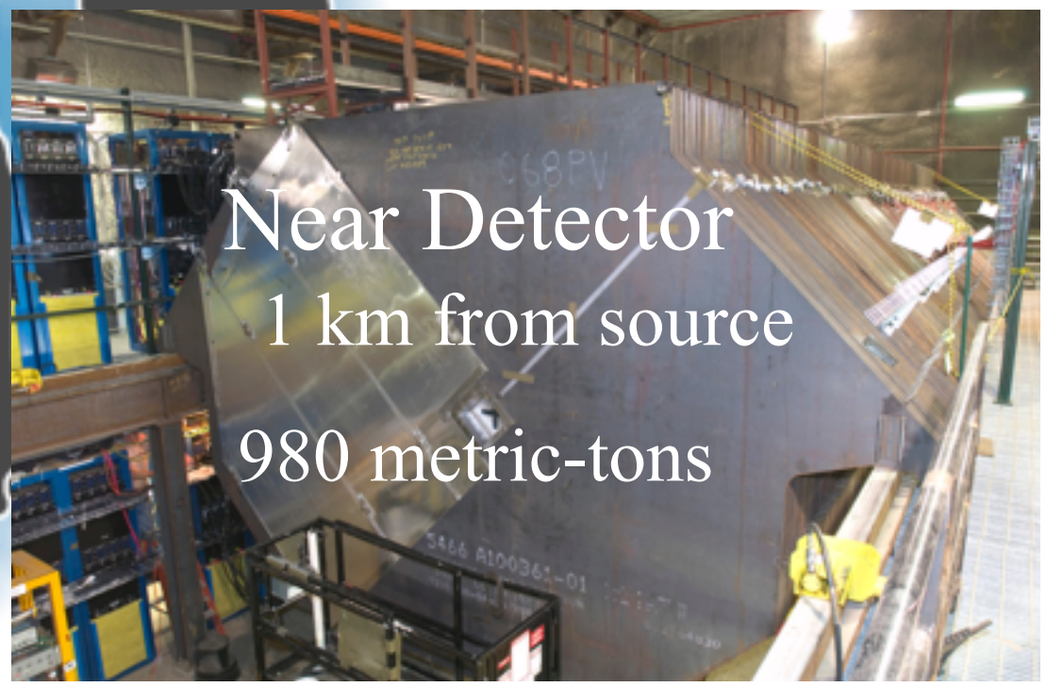
- Six paramaters describe oscillation probabilities
- 2 mass differences squared, 3 mixing angles and 1 phase
- Muon neutrino disappearance is sensitive to Δm^2_{32} and θ_{23}



MINOS+



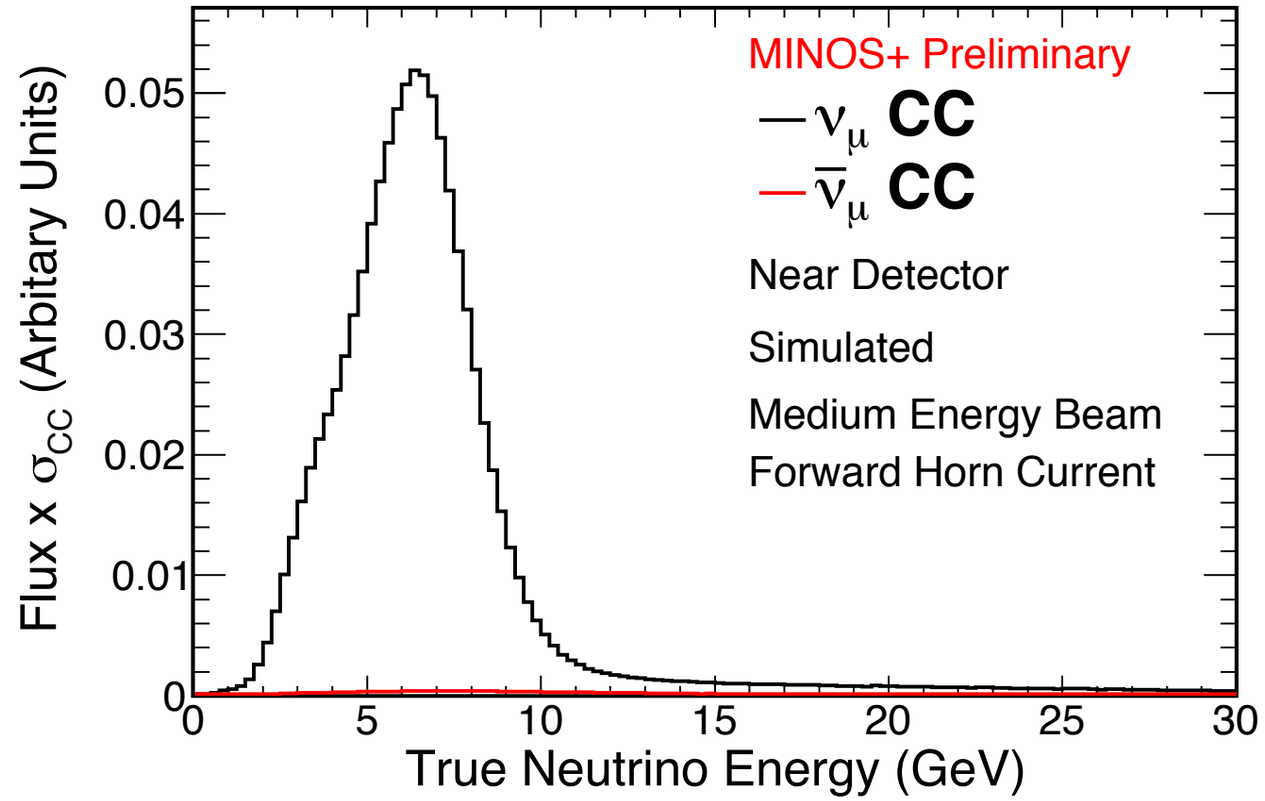
- Long-baseline neutrino oscillation experiment (on-axis)
- MINOS detectors in the medium energy NuMI beam
- Collecting data since September 2013



- Two functionally equivalent detectors
- Magnetized steel tracking sampling calorimeters

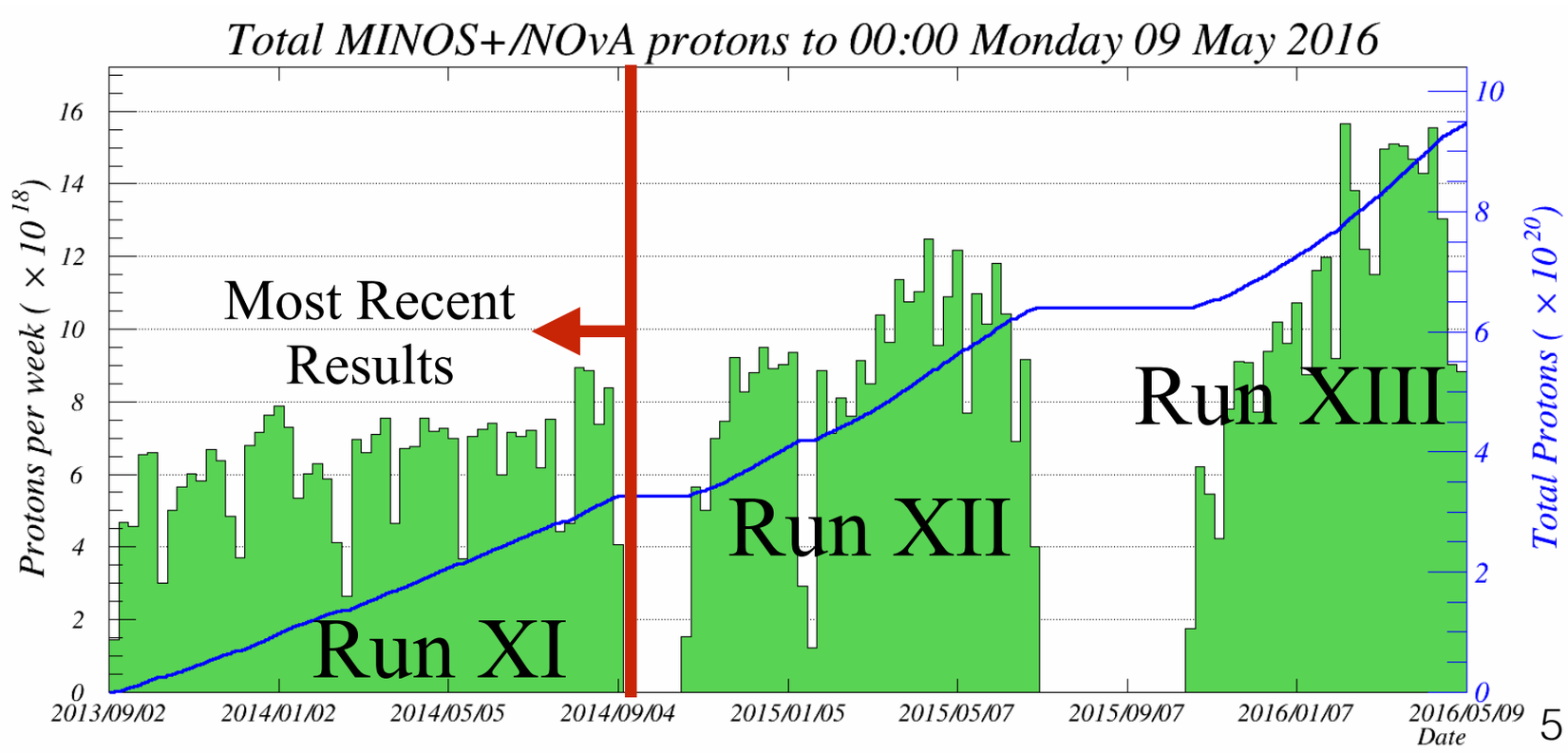
Medium Energy NuMI Beam

- ν_μ beam
- 120 GeV Protons on graphite
- Beam Power: 500+ kW
- 4.0×10^{13} protons per pulse
- Neutrino energy peaks around 6 GeV



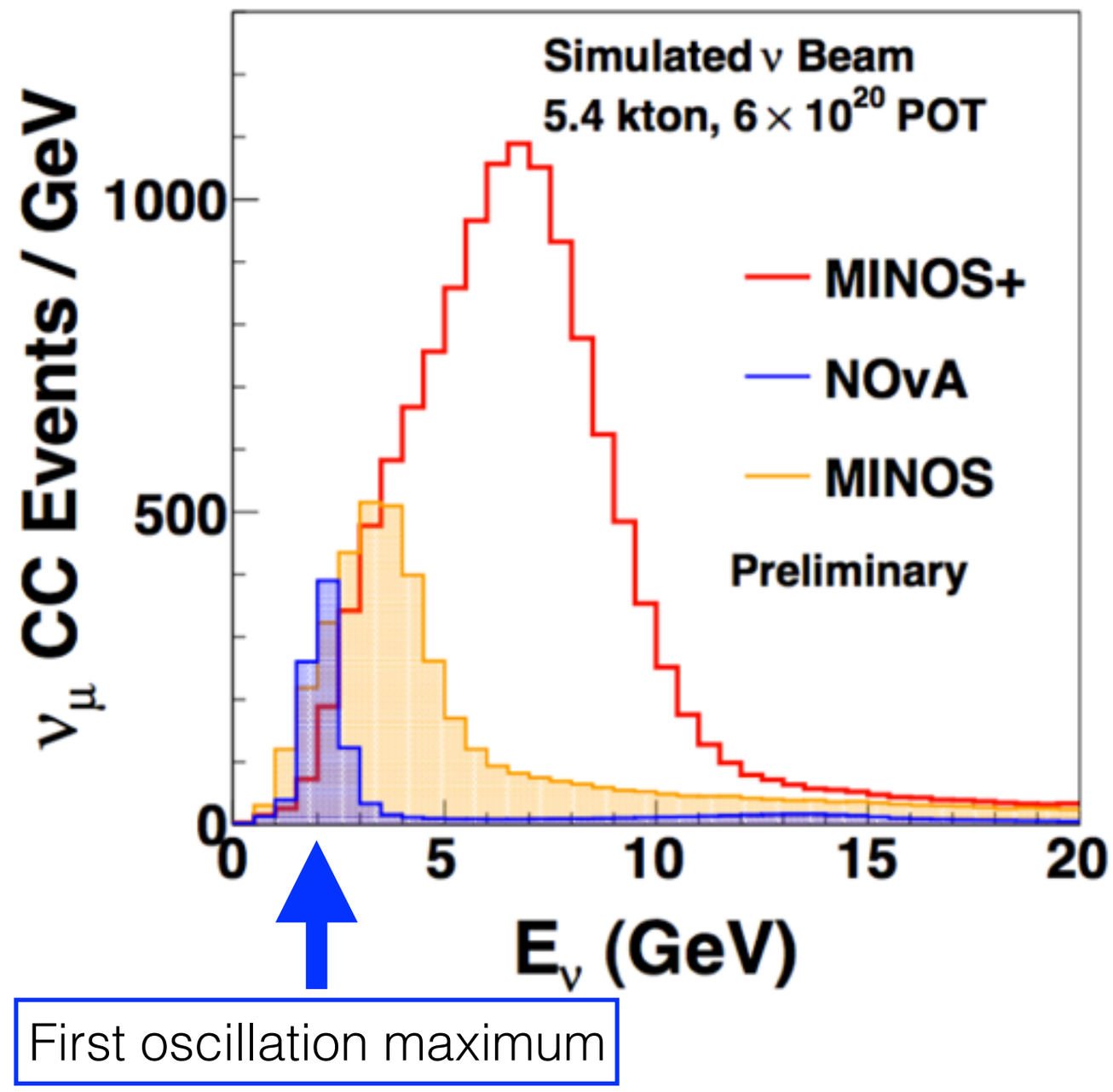
★ 9×10^{20} PoT and counting

★ Results from the first 3.0×10^{20} PoT



MINOS+ Motivation

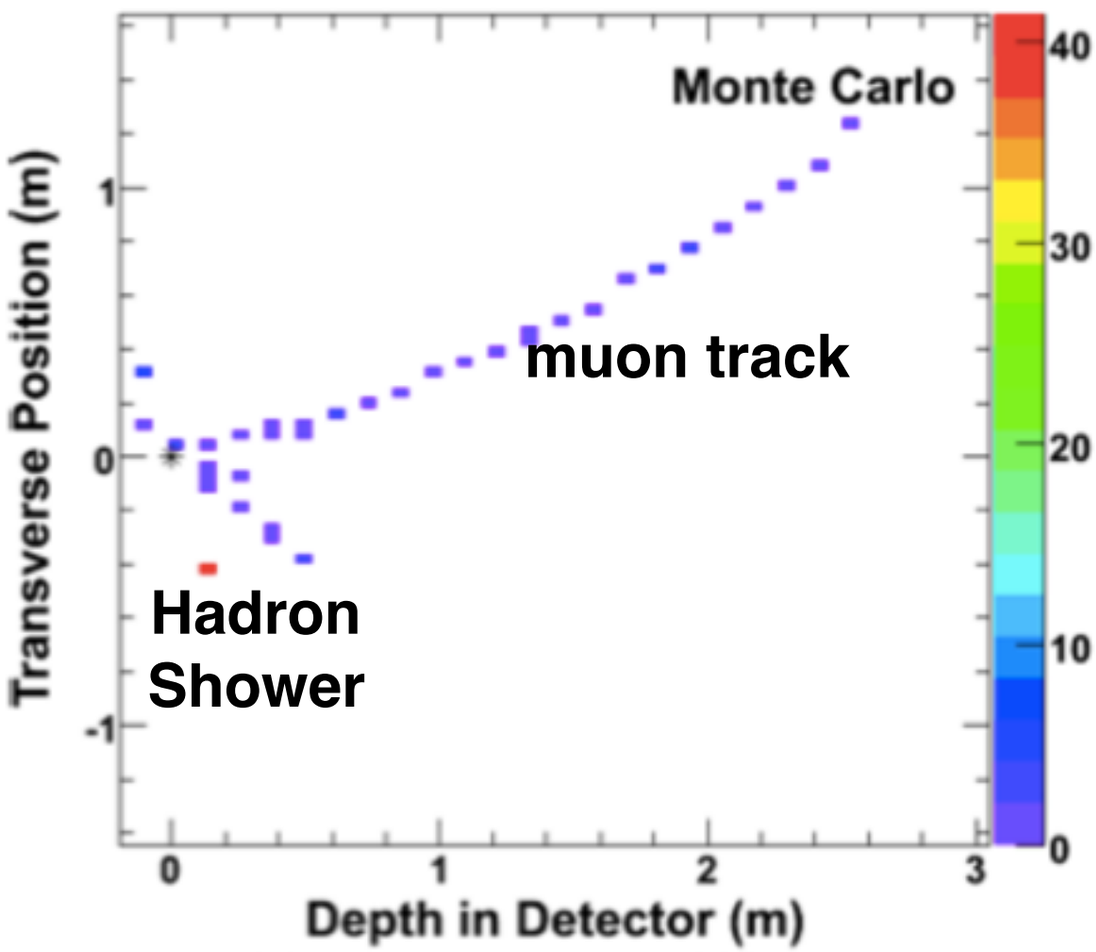
- Significantly increased event rate between 4-10 GeV
  - more than 5 times that of the low energy beam
- Can do sterile neutrino and extra dimension searches
- Opportunity to improve statistics above the first oscillation maximum covered by MINOS

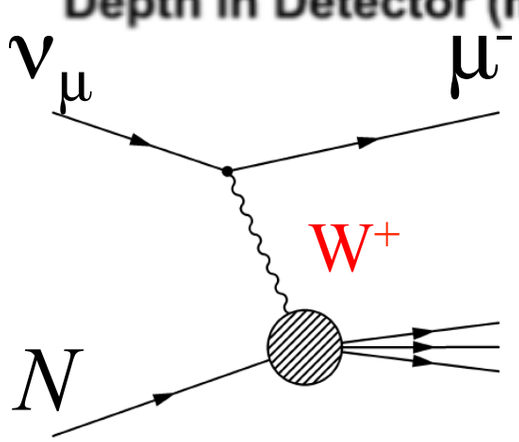


Events

Signal

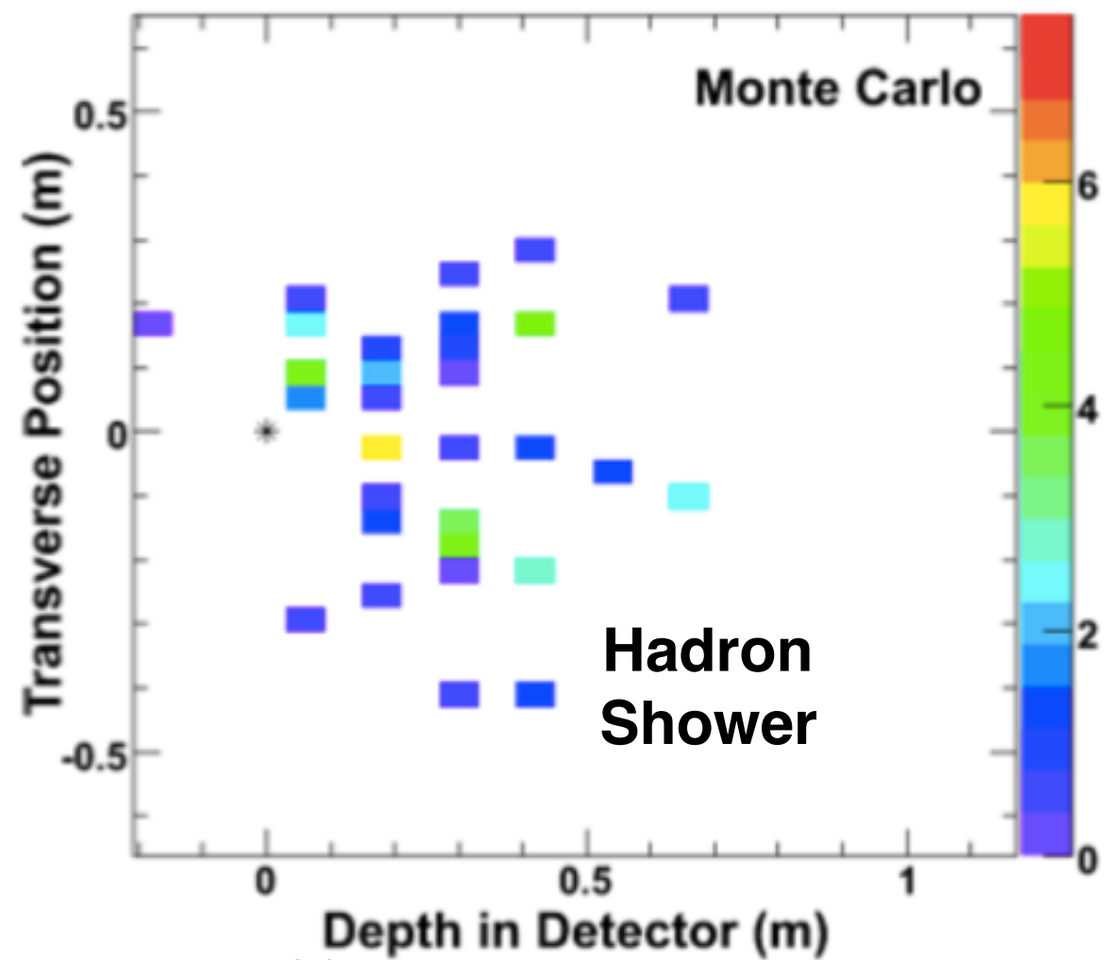
ν_μ Charged Current (CC)

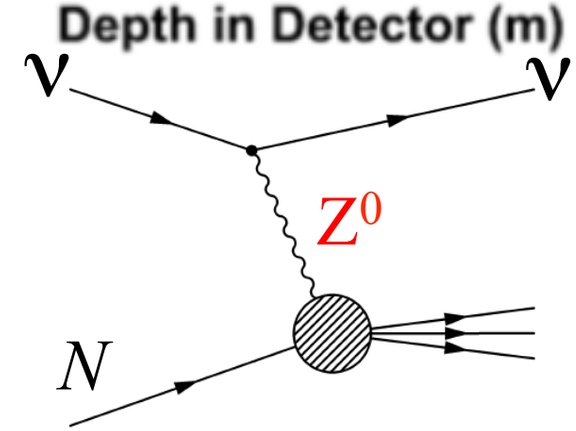




Background

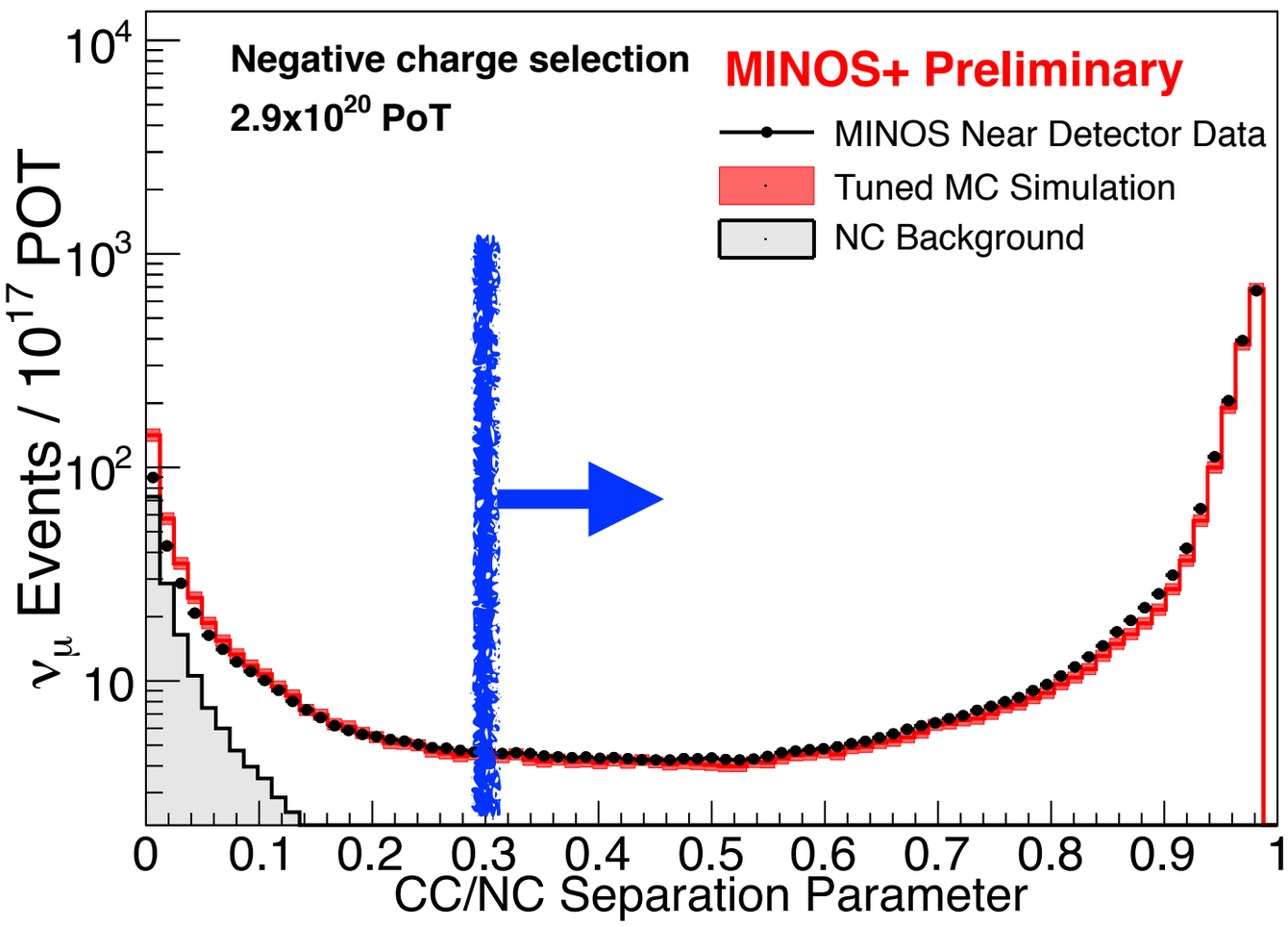
Neutral Current (NC)





➡ can mimic a CC event with a short track

Event Selection

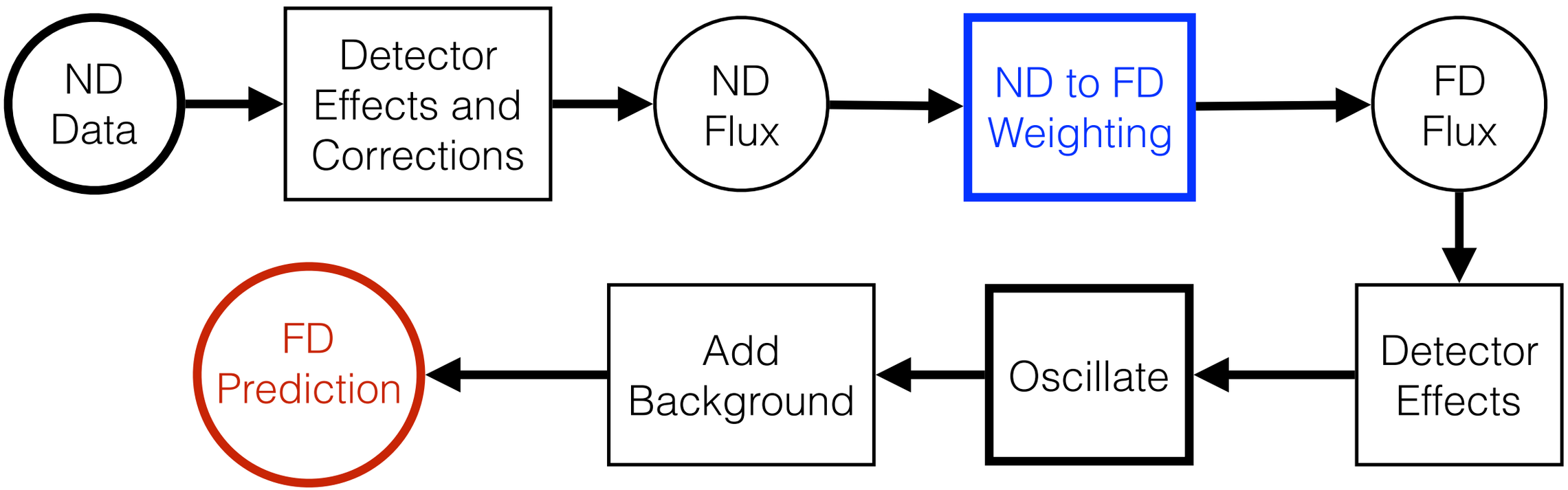


Select CC/NC >= 0.3

- Data quality cut
- Forward track coincident with the beam
- Fiducial volume cut
- Compare event to 80 similar MC events
  - Number of active planes
  - Energy profile
  - Average track pulse-height per plane
  - Track energy fluctuation

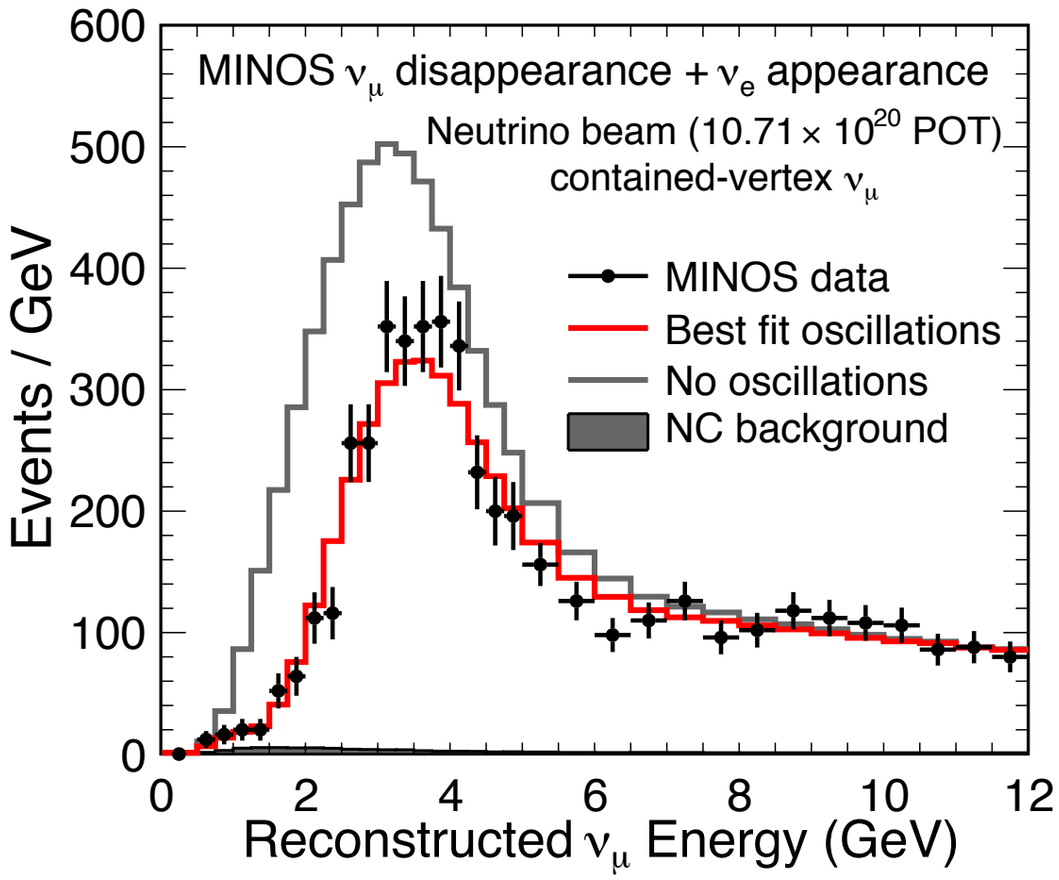
Data Driven Predictions

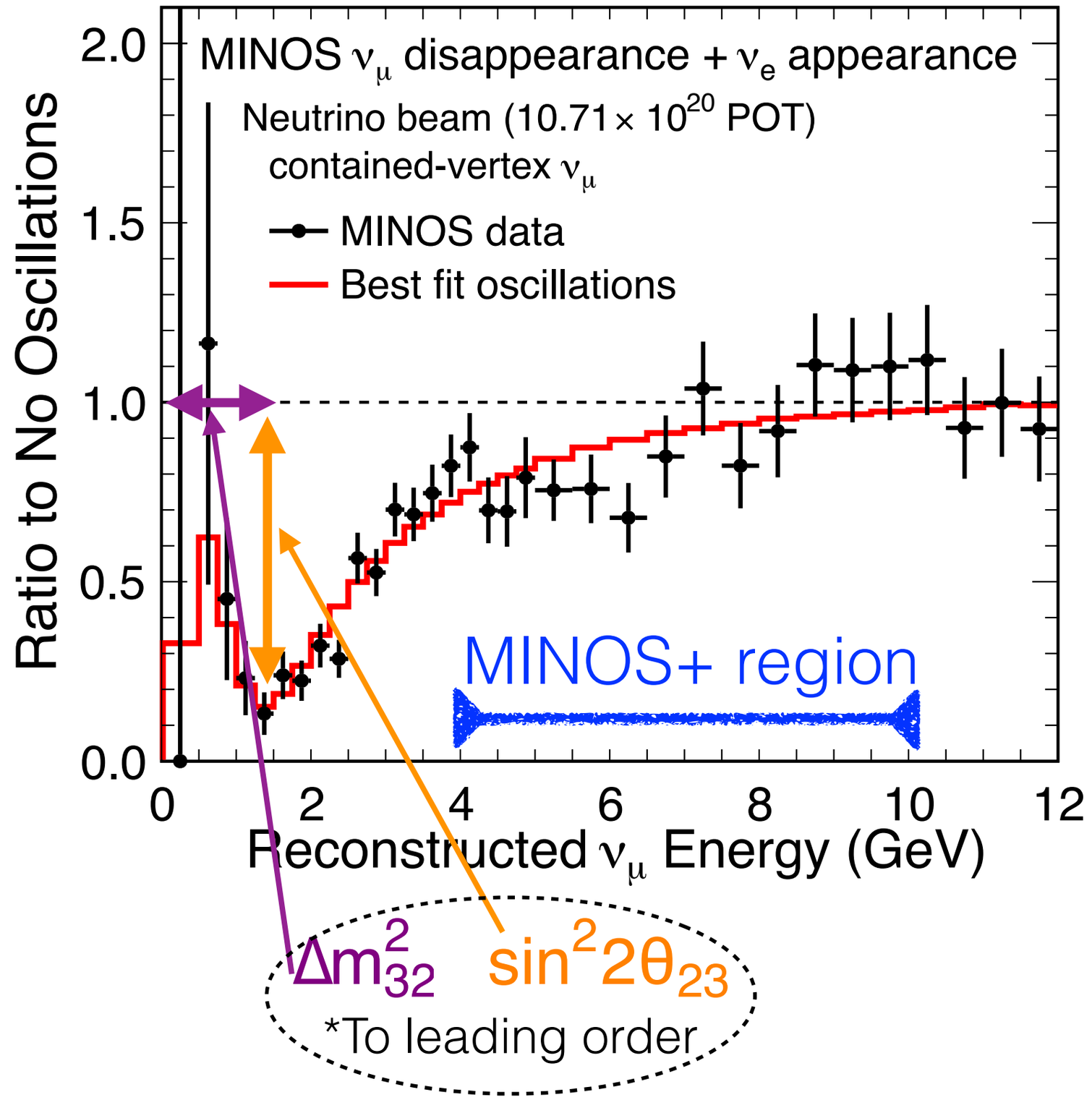
- Use Near Detector data to predict Far Detector spectrum



- Detector effects include mass, cross sections, efficiency
- Correct for background that is not removed by selection
- Weight Near Detector flux to get kinematically favored Far Detector flux

MINOS ν_μ Disappearance Measurement

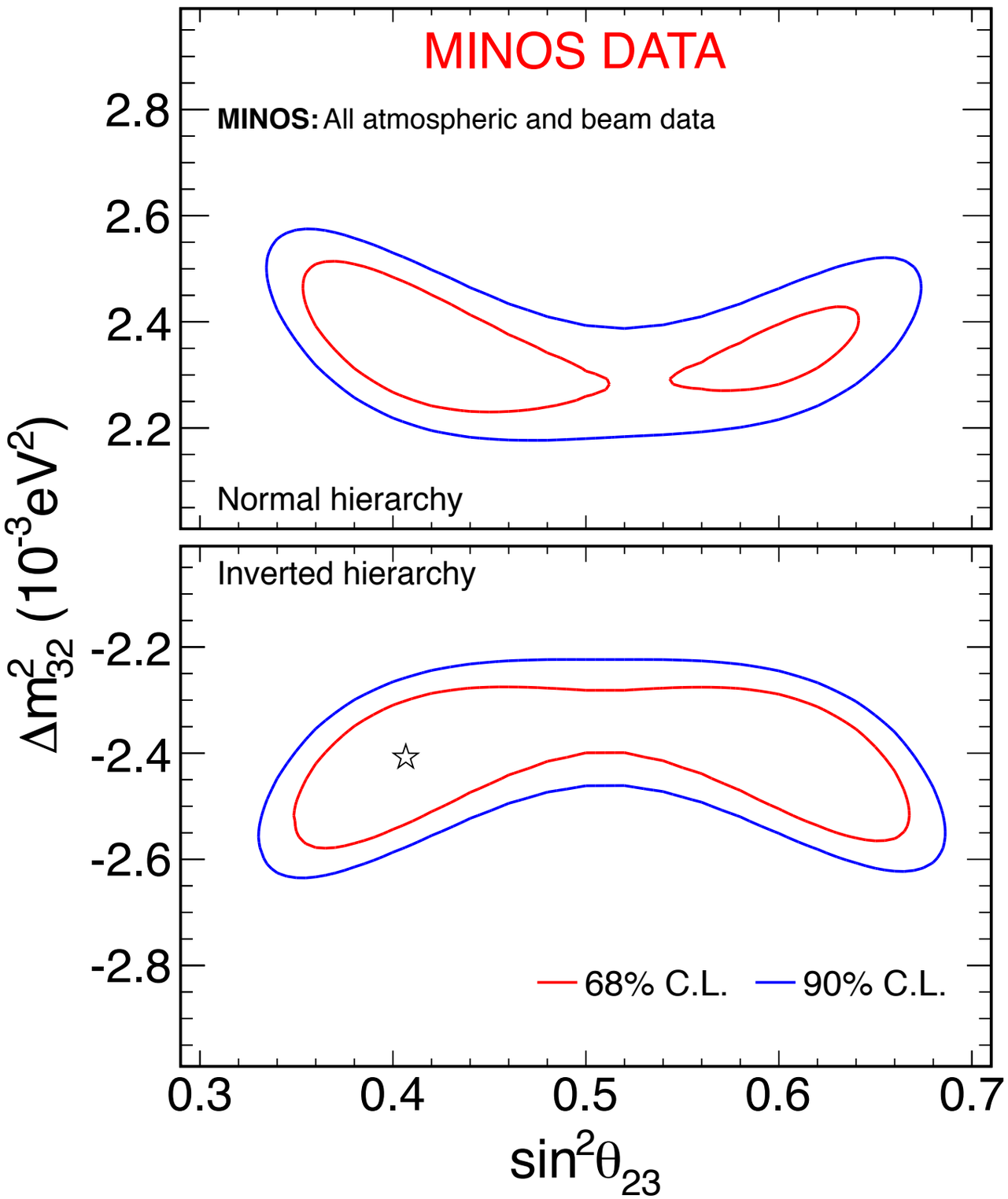




- Compare the far detector spectrum to the no oscillations case predicted using the near detector spectrum

➡Measure the ν_μ survival probability

MINOS Result



★PRL 112, 191801 (2014)

Normal Hierarchy:

$|\Delta m^2_{32}| = [2.28–2.46]\times10^{-3}$ eV^2 (68%CL)

$\sin^2\theta_{23} = [0.35 – 0.65]$ (90%CL)

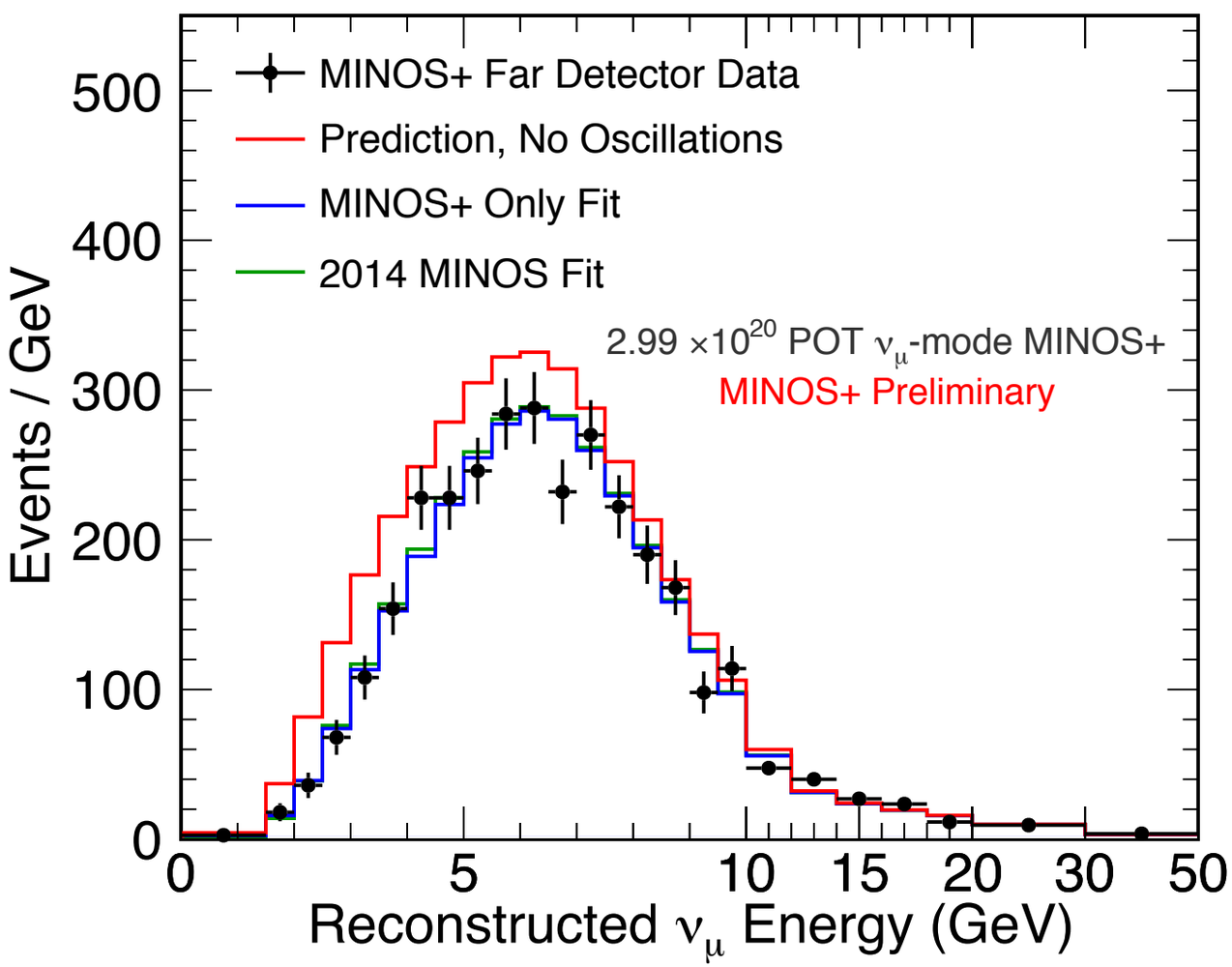
Inverted Hierarchy:

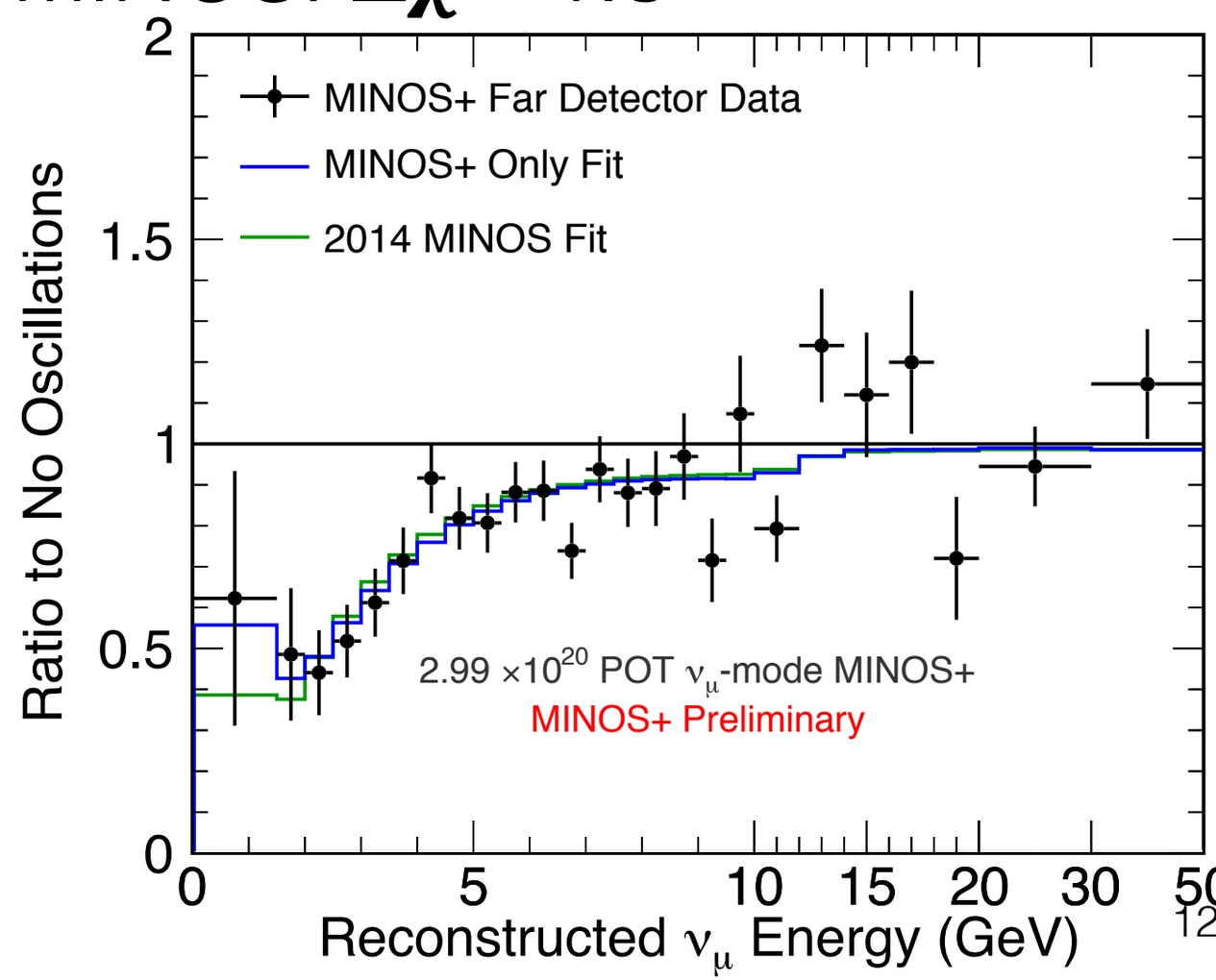
$|\Delta m^2_{32}| = [2.32–2.53]\times10^{-3}$ eV^2 (68%CL)

$\sin^2\theta_{23} = [0.34 – 0.67]$ (90%CL)

MINOS+: LATEST RESULTS!

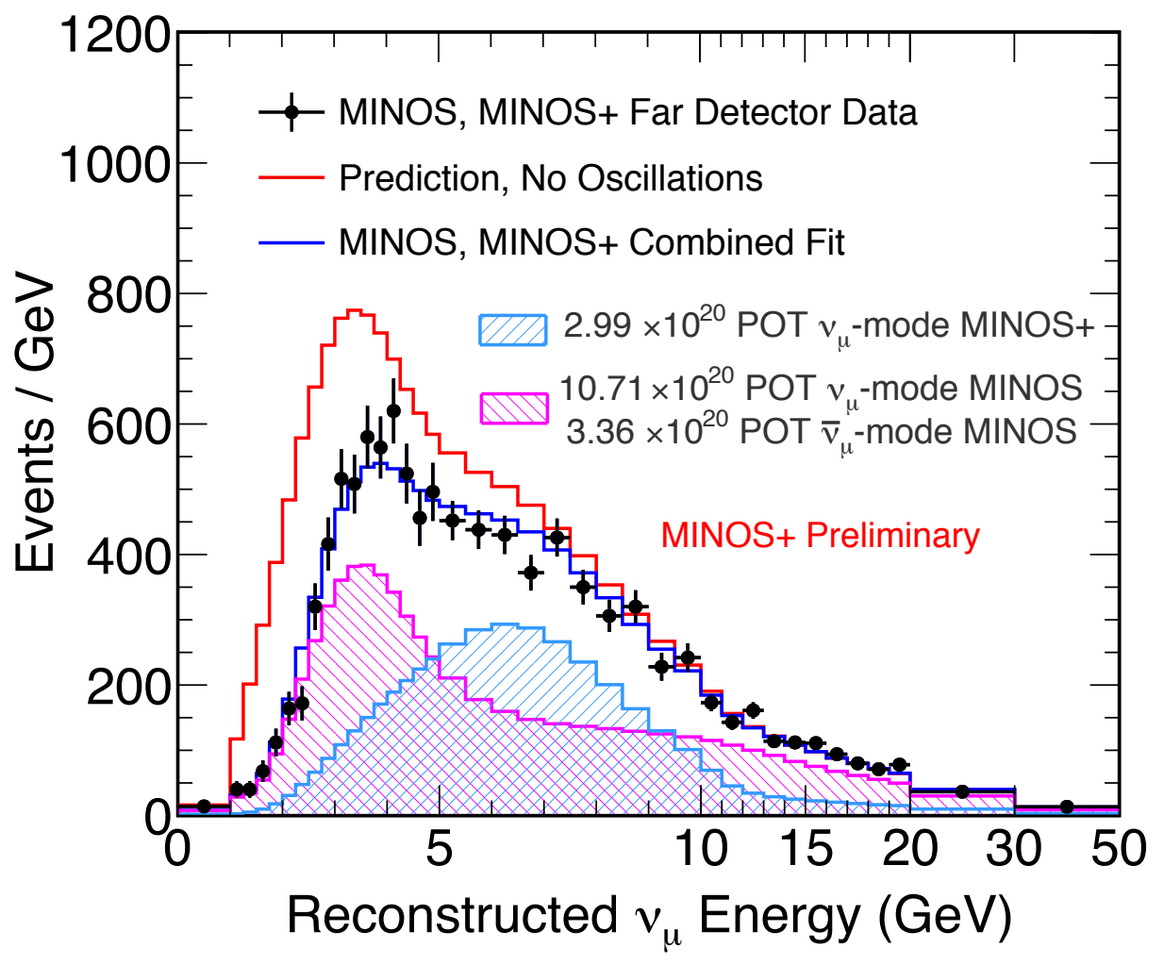
- Spectrum using first 3.0×10^{20} PoT of MINOS+
  - first year of beam data
- Significantly increased statistics beyond first oscillation maximum
- Opportunity to test for deviations from 3 flavor prediction
- MINOS+ fit consistent with MINOS: $\boldsymbol{\Delta\chi^2}=1.3$

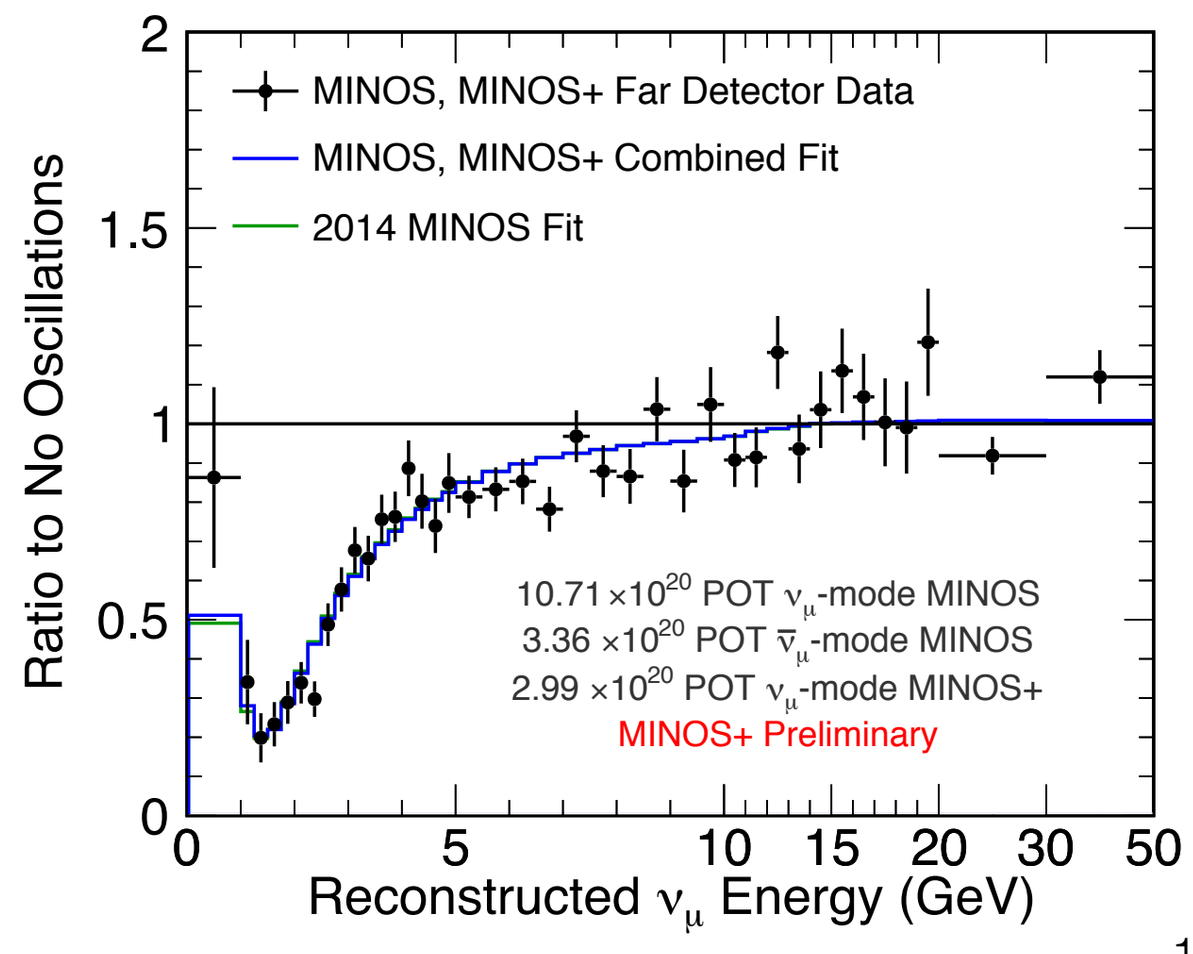




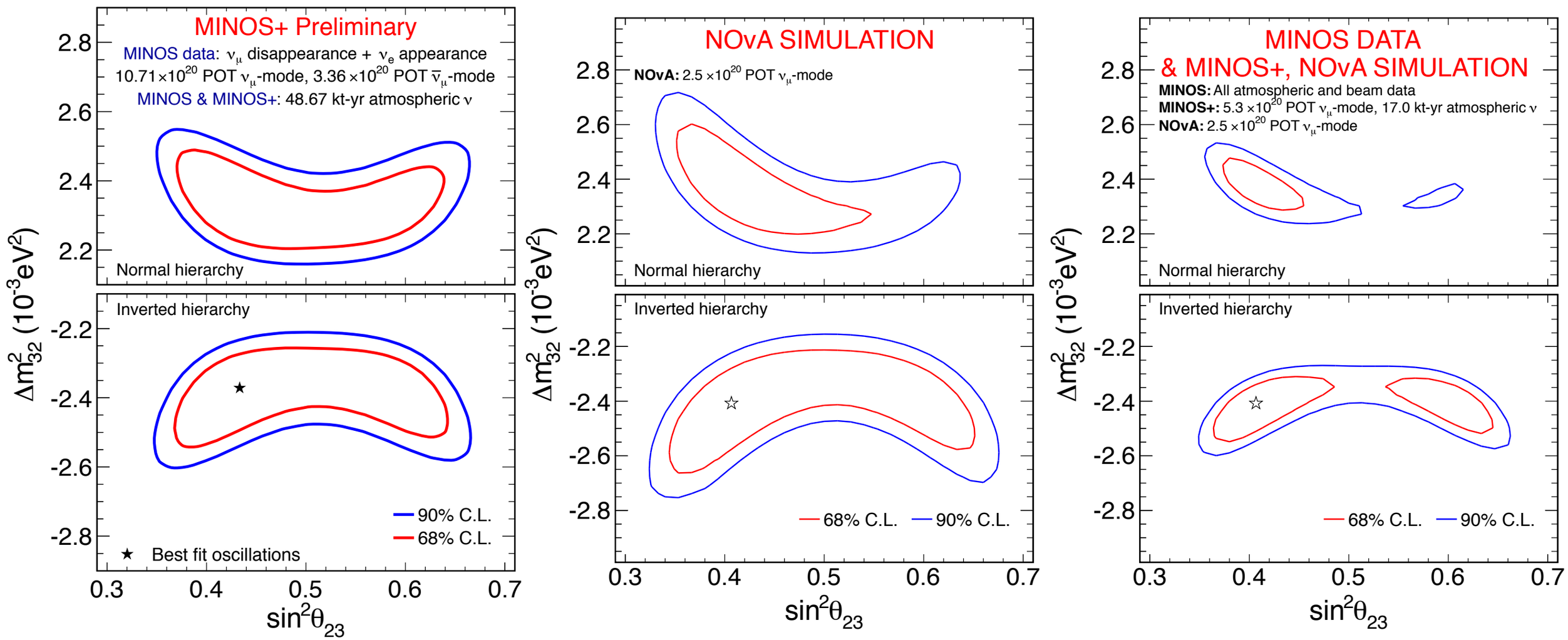
MINOS and MINOS+

Robust combination using both MINOS and MINOS+ disappearance samples





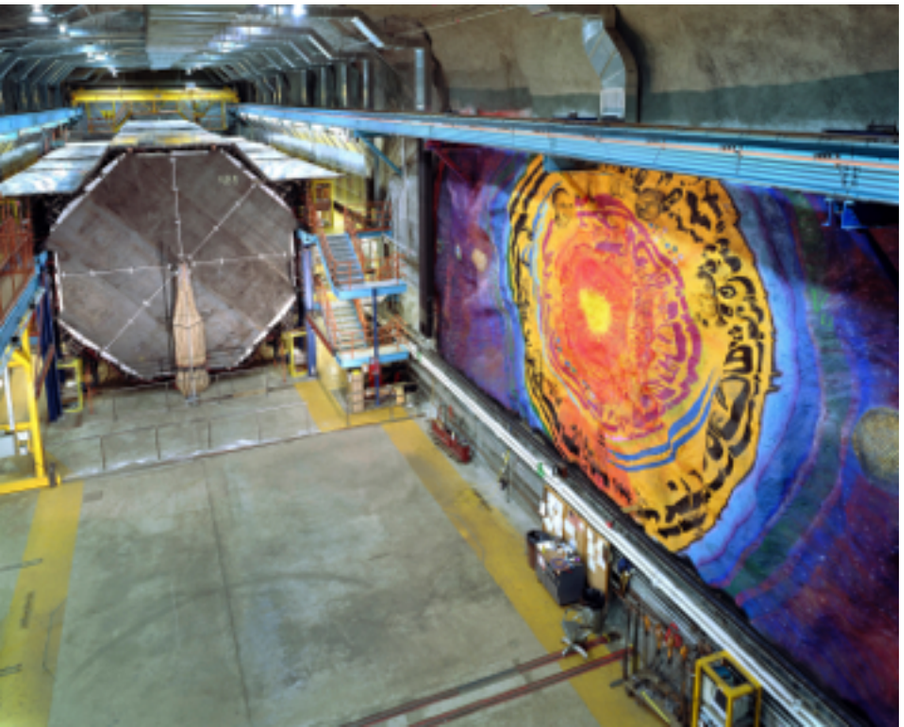
The Future

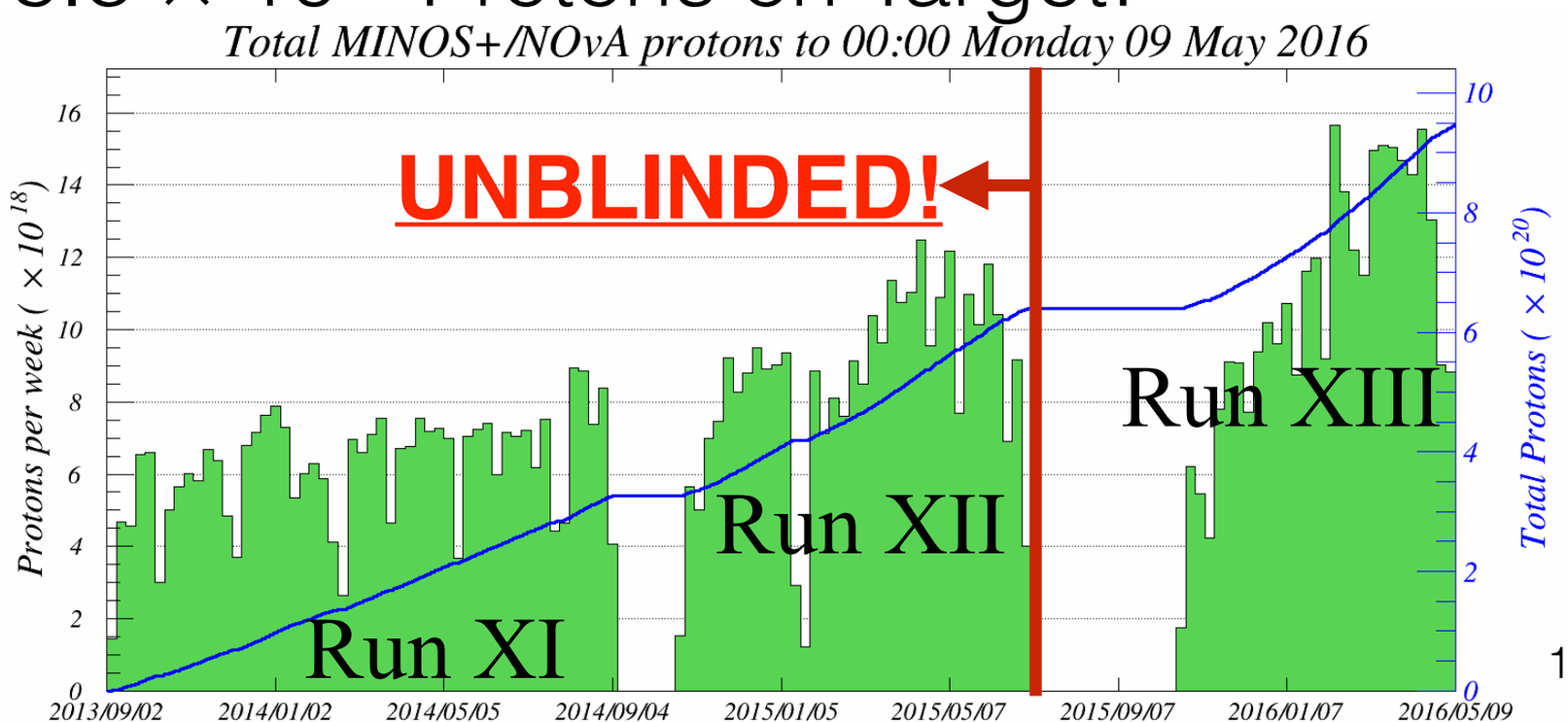


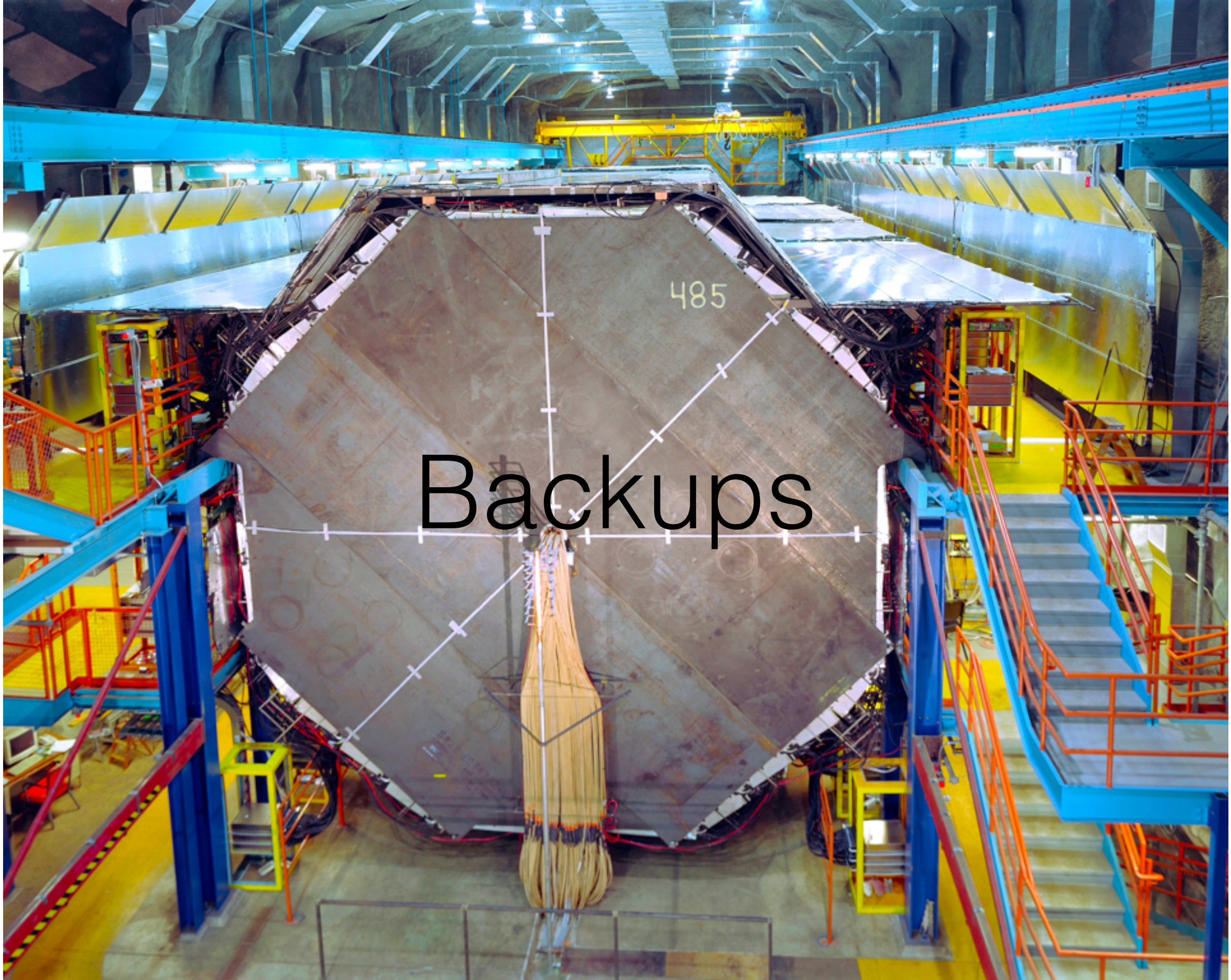
- No published beam oscillation result yet with MINOS+
- MINOS+ results important for the next few years as NOvA strives to resolve mass $\boldsymbol{\theta}_{23}$ quadrant and mass hierarchy

Conclusion

- MINOS+ is testing the 3 flavor paradigm
- We have the data for valuable combinations with reactor and other long-baseline experiments
- Look for latest 3 flavor oscillations results at Neutrino 2016
  - MINOS and MINOS+ Runs XI and XII
  - An additional 5.8×10^{20} Protons on Target!

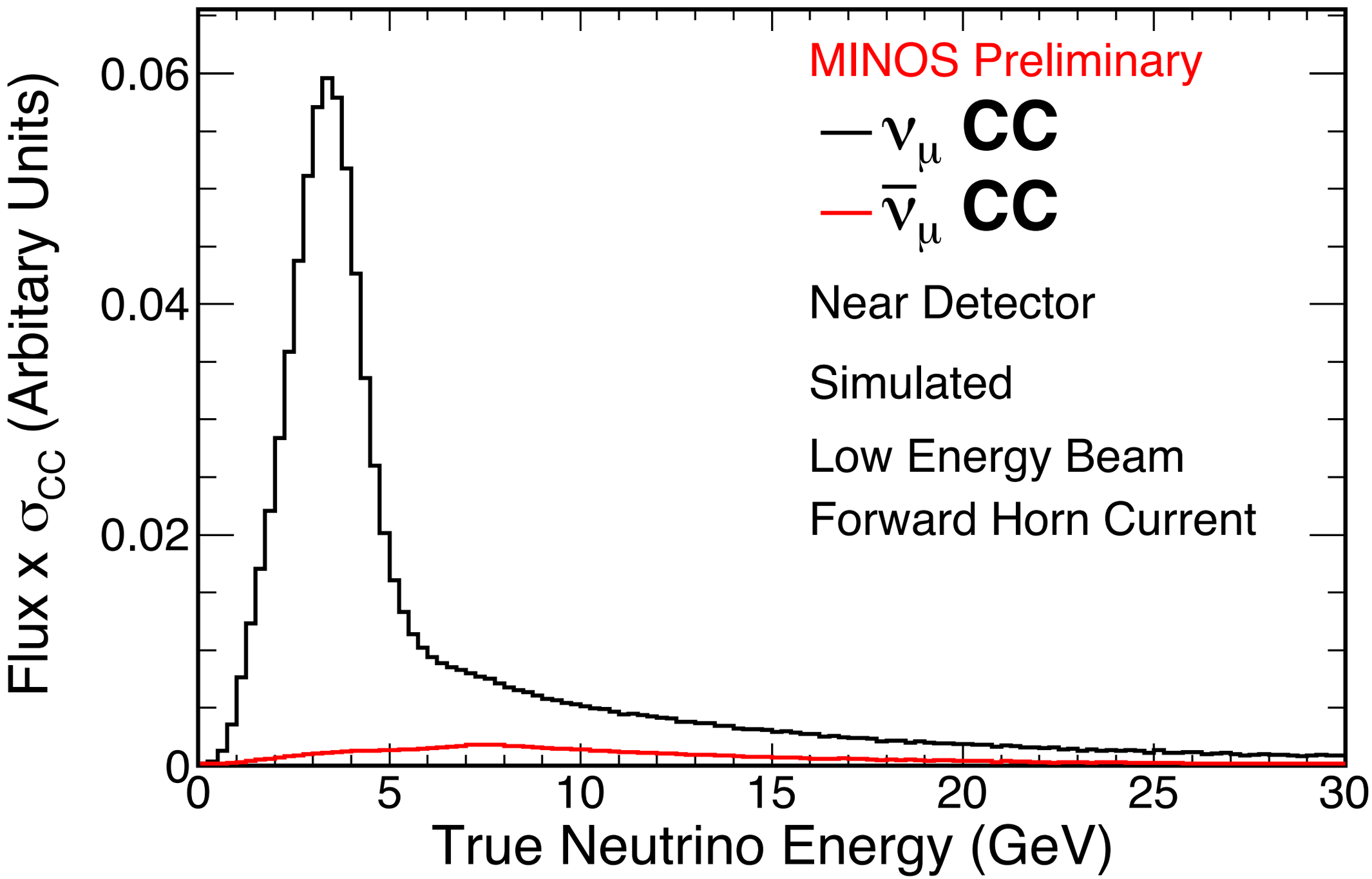




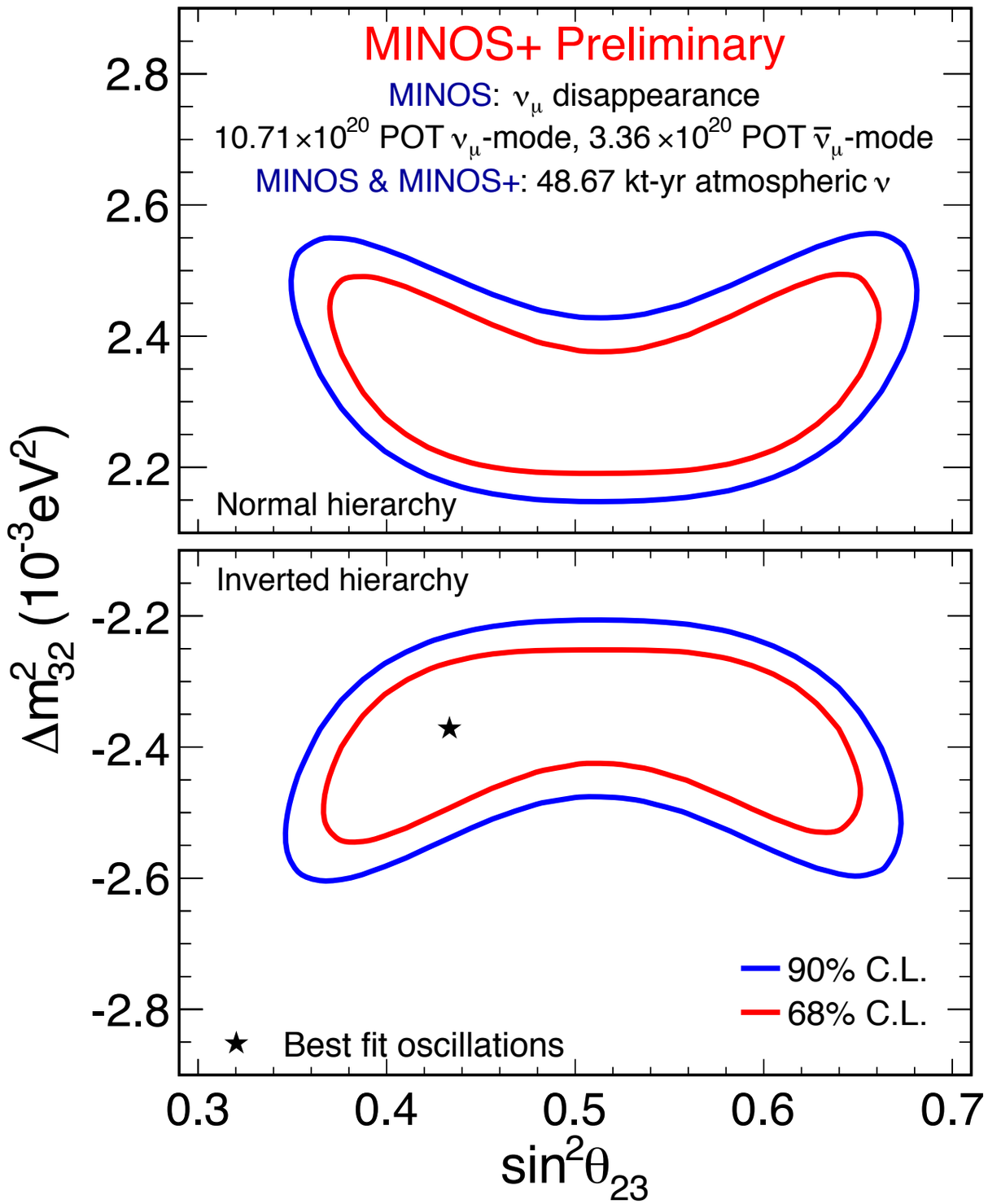


Backups

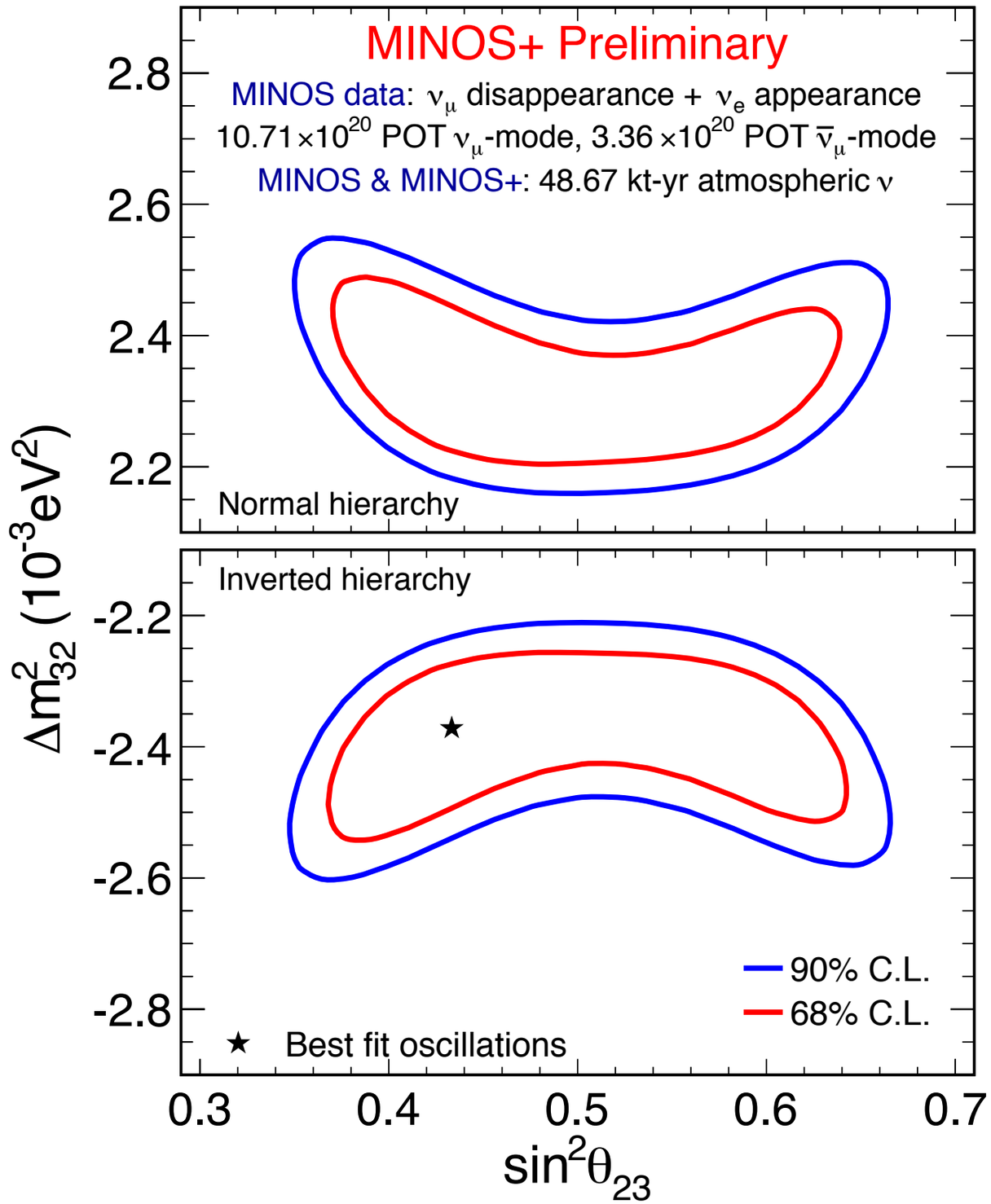
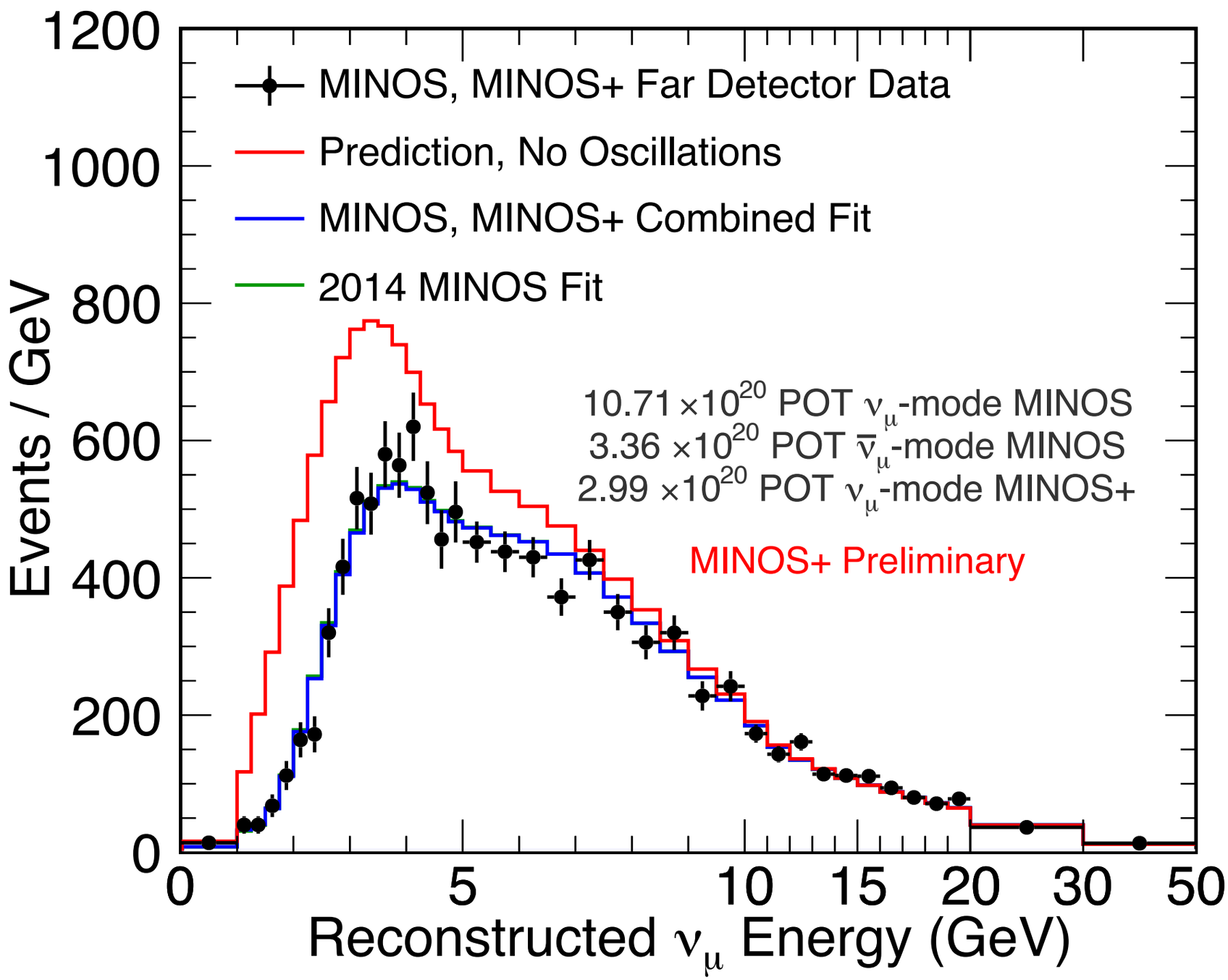
Flux from Low Energy Beam



ν_μ Disappearance Only



ν_μ Disappearance + ν_e Appearance



MINOS and Run XI Spectrum