Recent results from the MINOS Experiment

Mayly Sanchez
Argonne National Laboratory

Ayres Rocks! Symposium
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Overview of this talk

- Recent results from the MINOS experiment:
  - ✦ Results from the ν_μ disappearance analysis
  - ✦ Results of the test for ν_s using neutral currents
  - ✦ Upcoming results on ν_e appearance

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- Recent results from the MINOS experiment:
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  - ✦ Upcoming results on ν_e appearance

"We are in new territory. No one has ever done an experiment with a beam like this or a detector like this,"..."so there is a chance that our attempt to make precise measurements of neutrino oscillations will turn up something completely unexpected, and even more important than what we set out to study."

- Dave Ayres (2005)

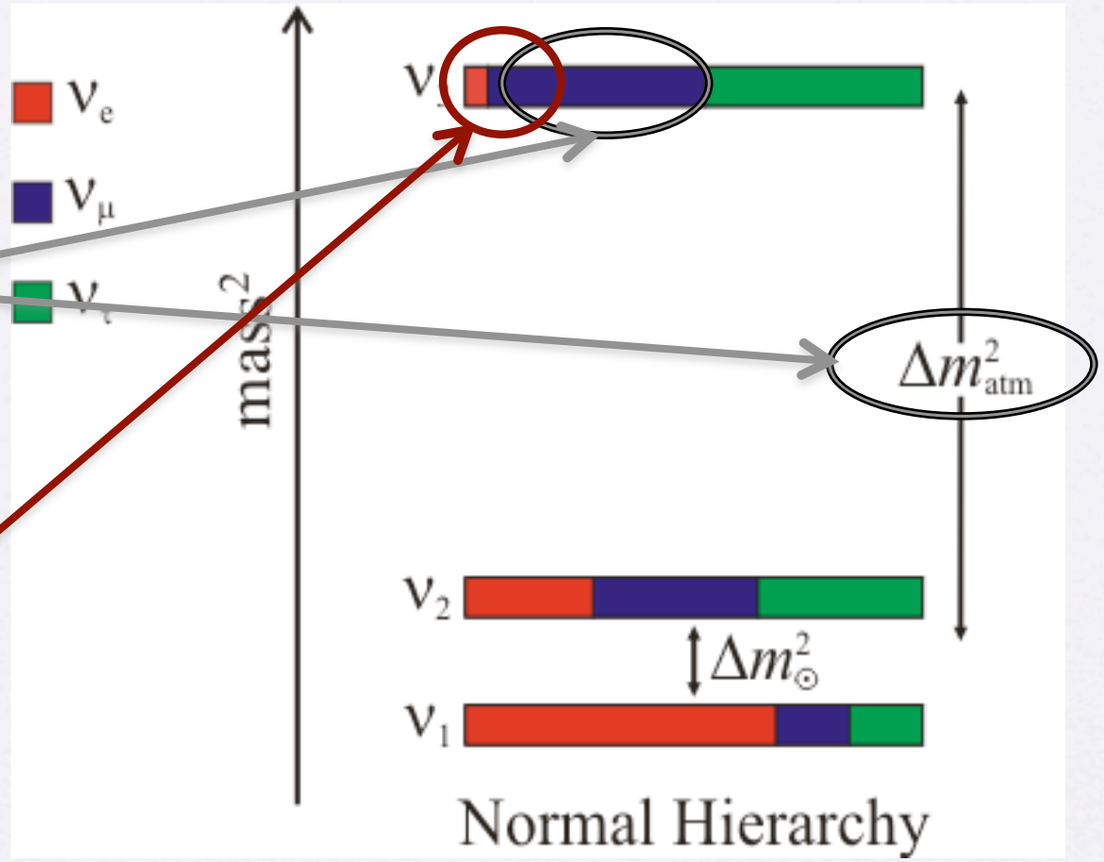
The MINOS experiment

... onto the era of precision!

MINOS Physics goals

study "atmospheric" neutrino oscillation parameters

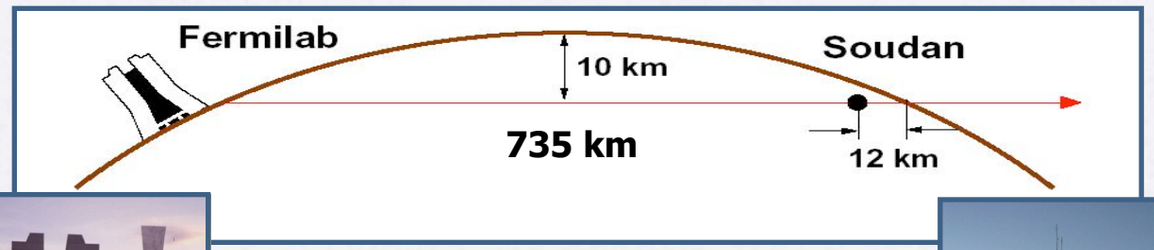
- ✦ Make precision measurements of Δm^2_{32} and $\sin^2(2\theta_{23})$.
- ✦ Confirm oscillations versus other exotic models: decay, decoherence.
- ✦ Search for subdominant oscillations.
- ✦ Mixing to sterile neutrinos.
- Use magnetized detectors for CPT tests.

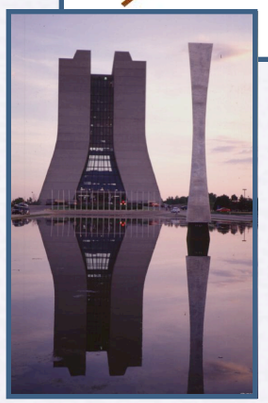


- Studies of cosmic rays and atmospheric neutrinos in the Far Detector.
- Neutrino interactions studies in the Near Detector.

MINOS in a nutshell

- Produce a high intensity beam of muon neutrinos at Fermilab, measure the energy spectrum at the Near Detector. Use it to predict the Far Detector spectrum.
- If neutrinos oscillate the dip of the oscillation in the energy spectra is observed at the Far Detector in Soudan, 735 km away.



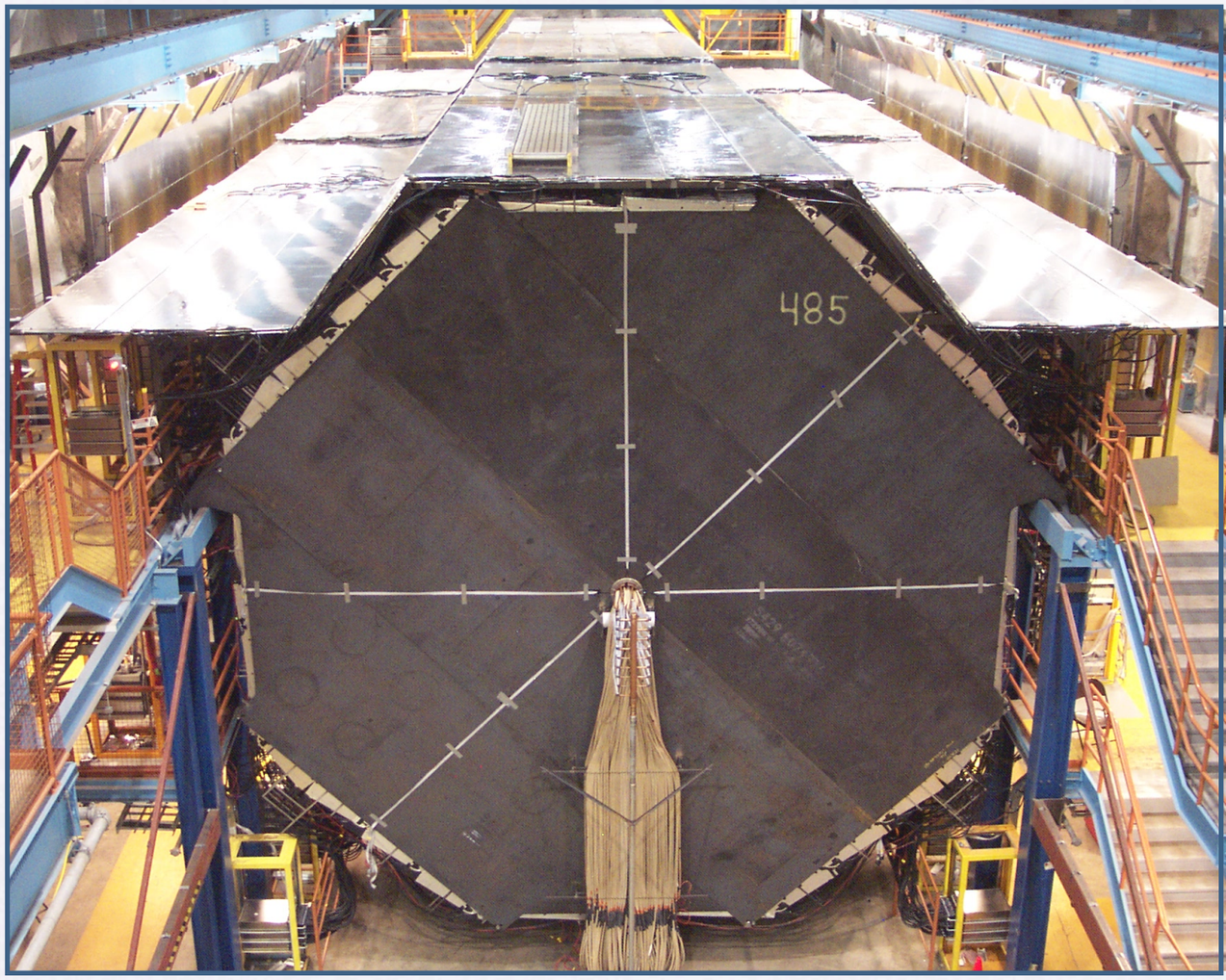


←long baseline→

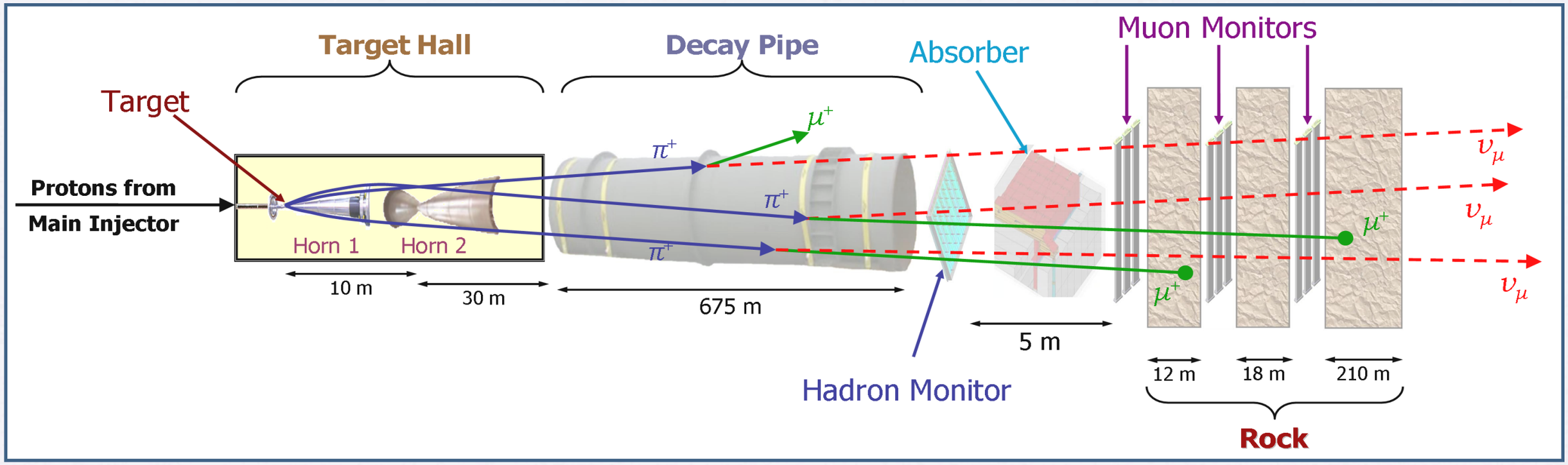
Main Injector Neutrino Oscillation Search

The MINOS detectors

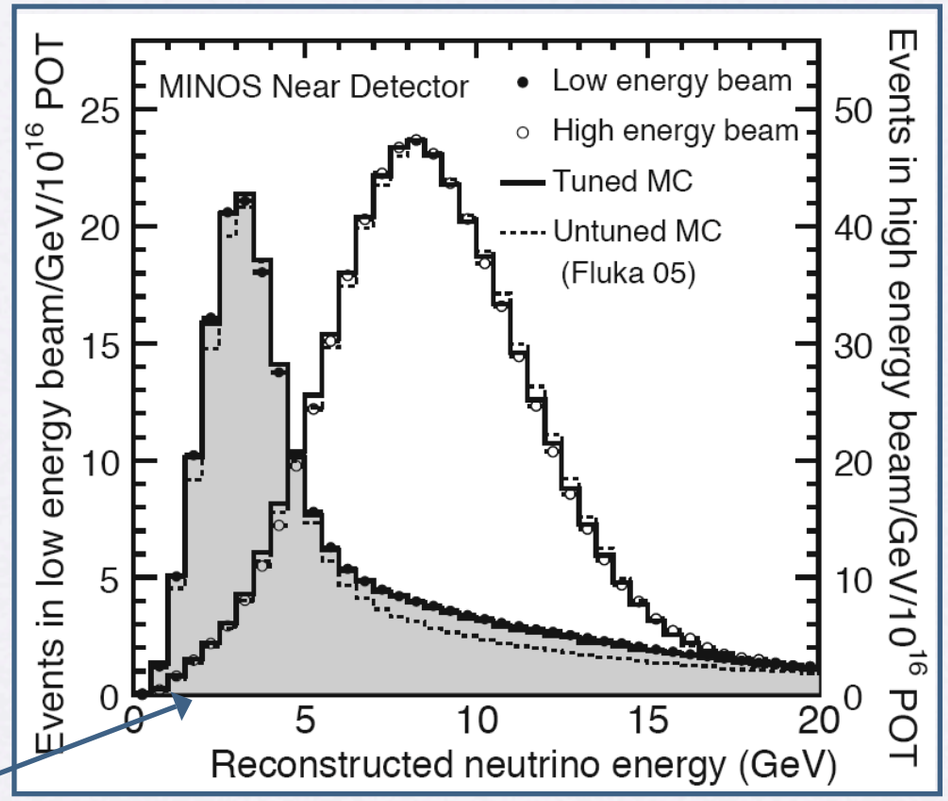
- To first order functionally identical: **Near and Far detectors**
- 1 inch thick octogonal steel planes, alternating with planes of 4.1cm x 1cm scintillator strips, up to 8m long.
  - **Near**: ~ 1kton, 283 steel squashed octagons. Partially instrumented. 153 scintillator planes. Requires faster readout.
  - **Far**: 5.4 kton, 486 (8m/octagon) fully instrumented planes.



Producing Neutrinos



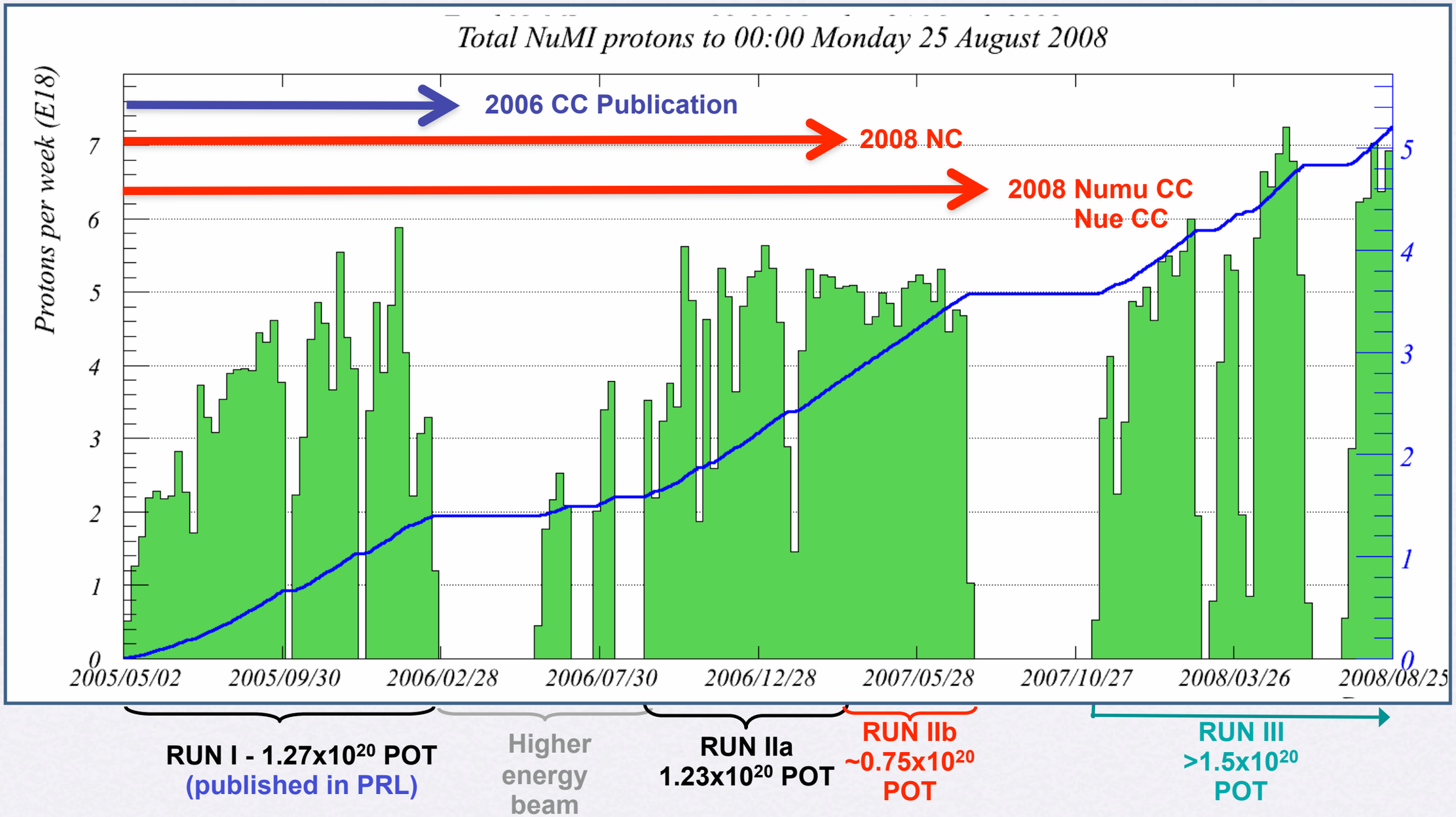
- Neutrinos from the Main Injector (NuMI)
- 10 μs spill of 120 GeV protons every 2.4 s
- 238 kW beam power (last week)
- 3 x 10^{13} protons per pulse (last week)
- ~10^{18} protons/day (last week)
- Neutrino spectrum changes with target position



Position of osc. minimum for Δm^2=0.0025 eV^2

The Beam: NuMI protons

Currently analyzing data through Run II



Results shown run I+II - 3.25 x 10^{20} POT

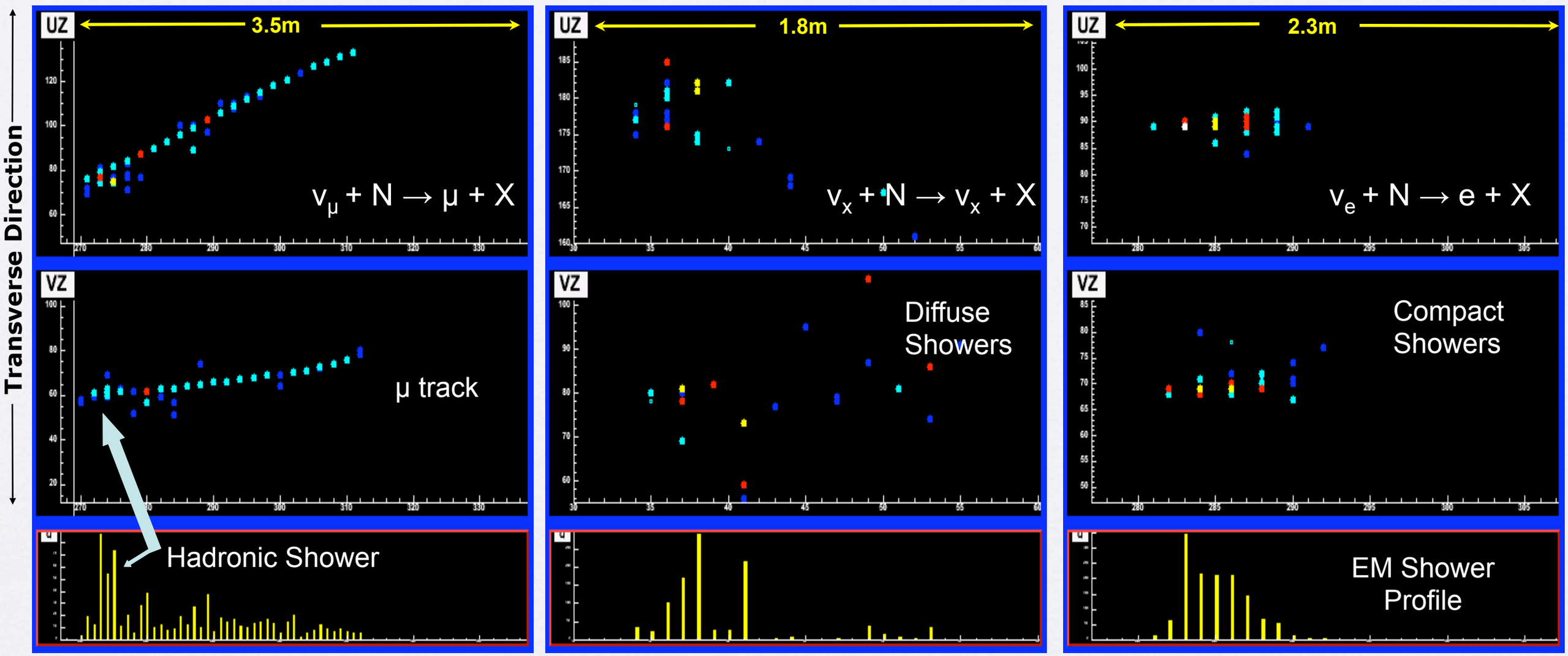
The ν_μ disappearance analysis:

- Result for full Run I+II
  (3.25×10^{20} POT)
- PRL accepted for publication

Neutrino Event Topologies

MINOS analyses use all of them!

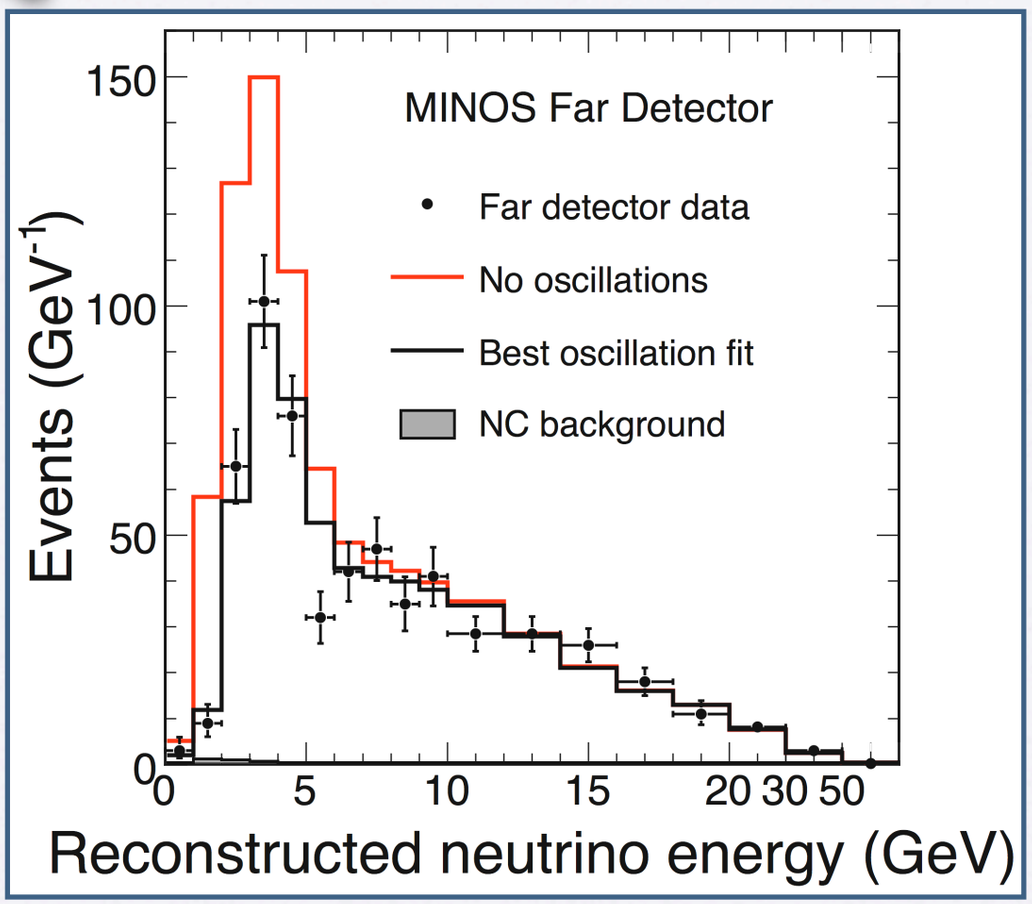
Monte Carlo events

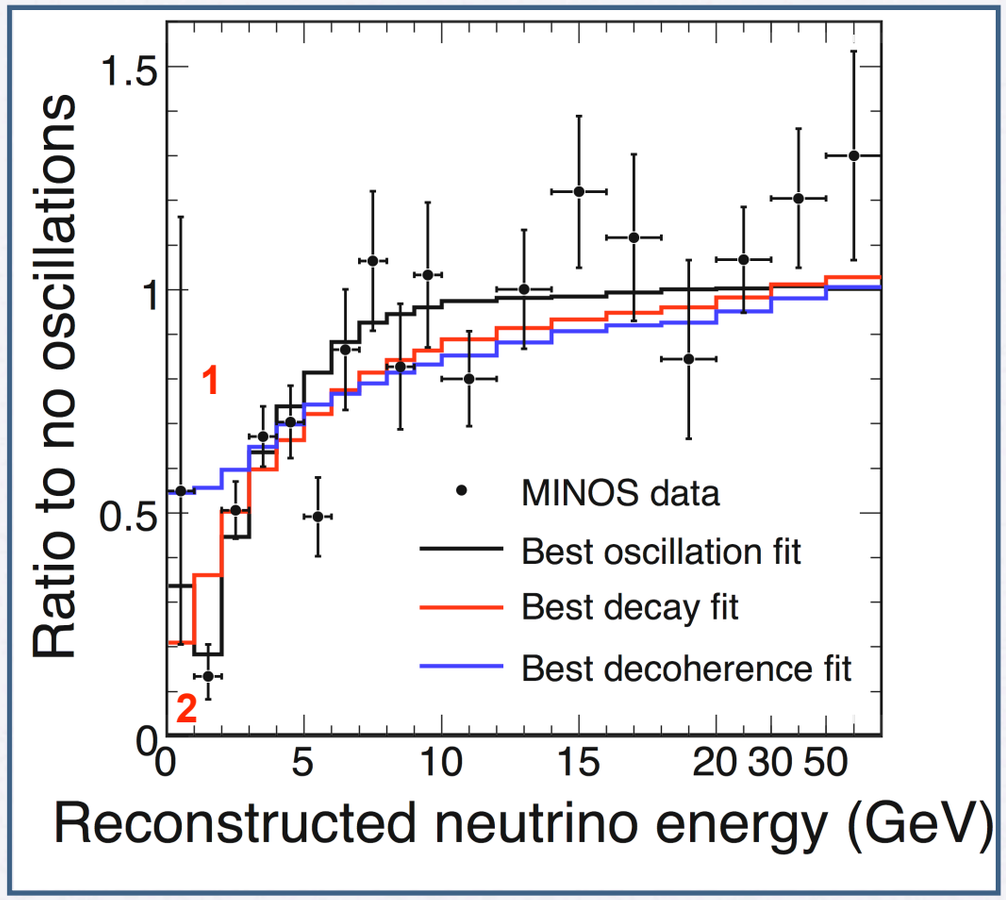


ν_μ CC event | NC event | ν_e CC event

This analysis focuses on finding tracks

ν_μ CC energy spectrum





$|\Delta m^2_{32}| = 2.43 \pm 0.13 \times 10^{-3}$ eV^2 (68% CL)

$\sin^2 2\theta_{23} > 0.90$ (90% CL)

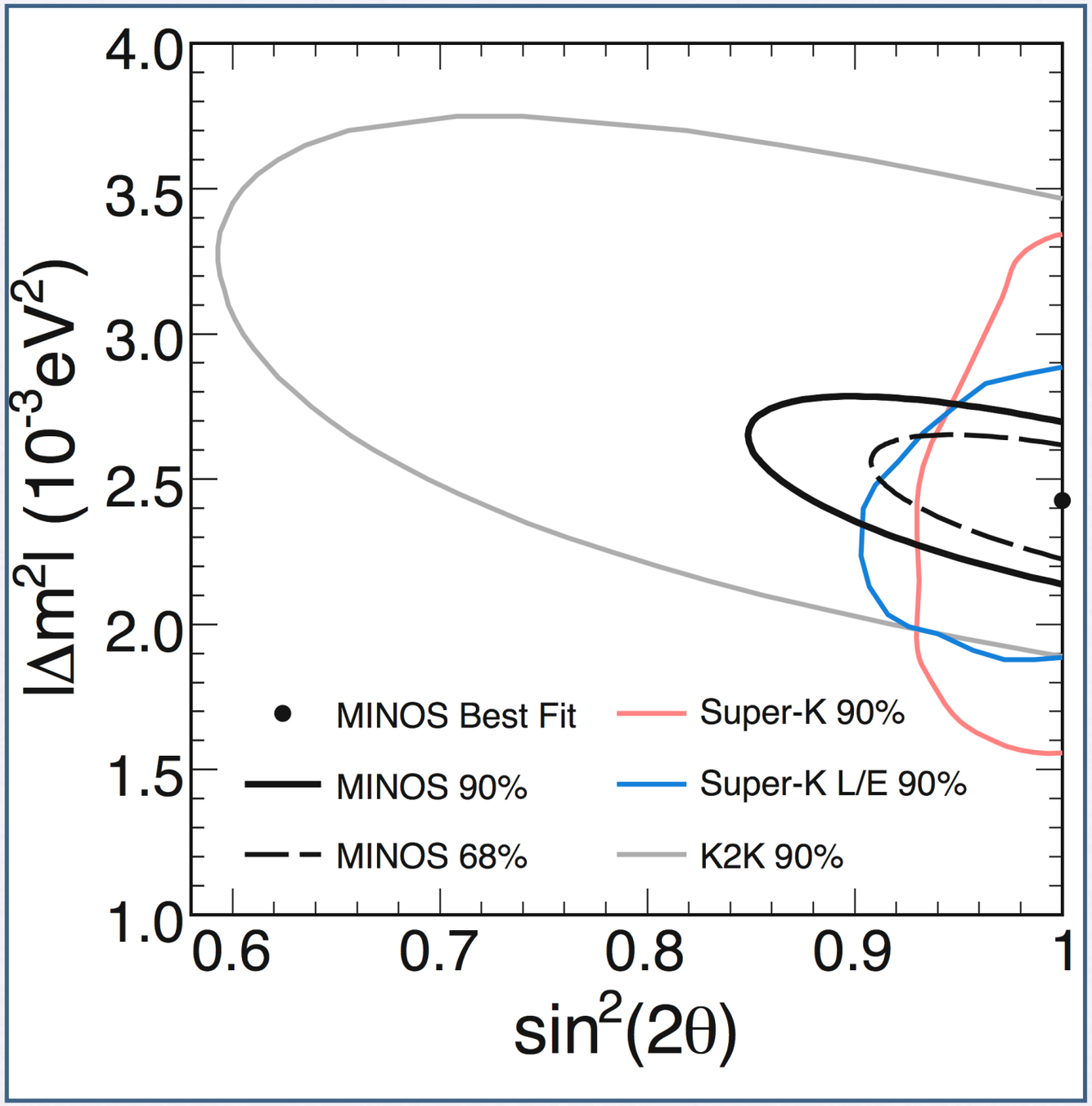
χ^2/ndf=90/97

Decay: disfavored at 3.7 σ

Decoherence: disfavored at 5.7 σ

$$P(\nu_\mu \rightarrow \nu_\tau) = \underbrace{\boxed{\sin^2(2\theta)}}_{1} \sin^2\left(\frac{1.27\underbrace{\boxed{\Delta m_{23}{}^2}}_{2} L}{E_\nu}\right)$$

Allowed region



- Fit includes penalty terms for dominant systematics:
  - Far/Near normalization,
  - hadronic energy scale, and
  - NC contamination
- Fit is constrained to physical region: $\sin^2(2\theta_{23}) \leq 1$
- **Best world measurement of $|\Delta m^2_{32}|$**

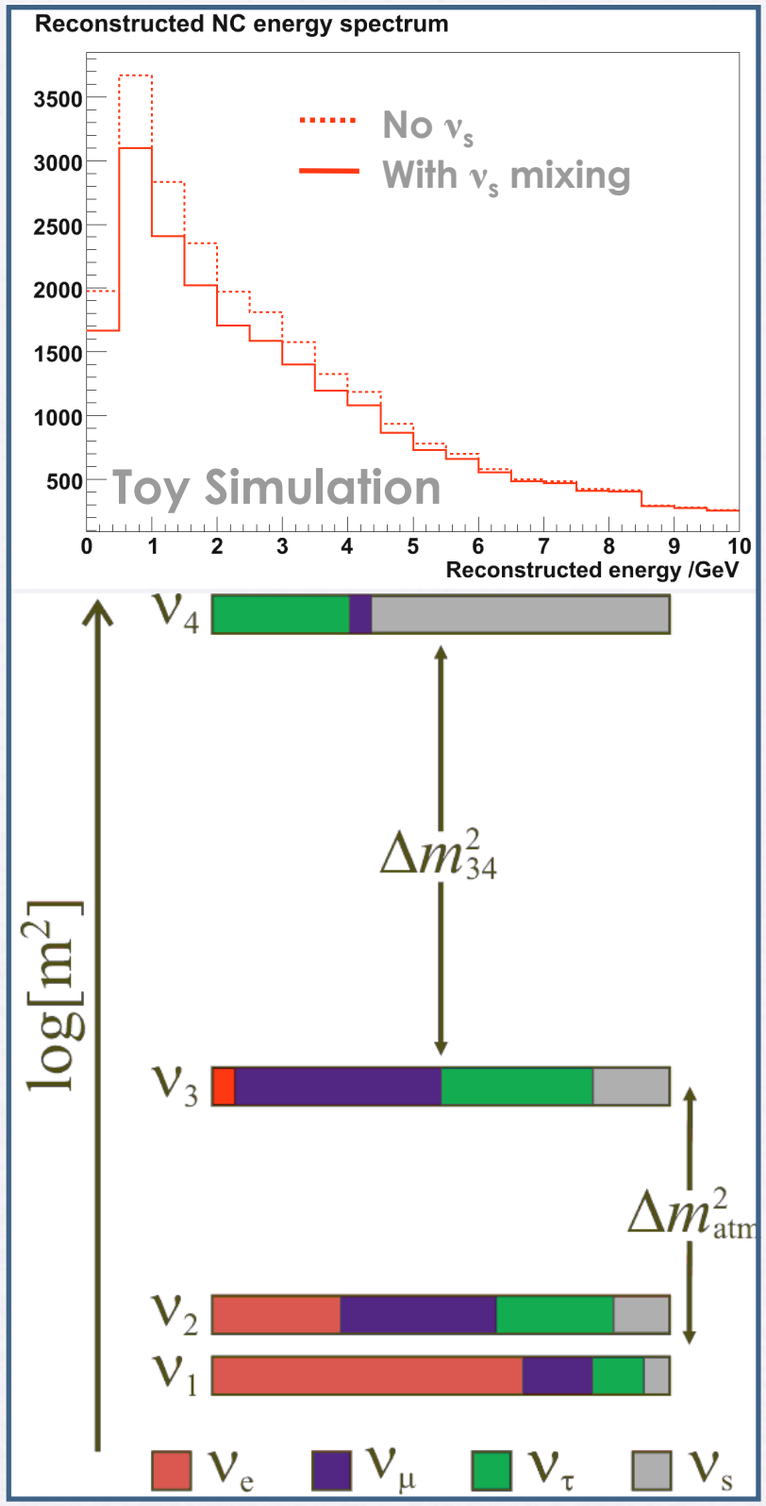
Test for ν_s using the NC energy spectrum:

- Run I+IIa (2.5×10^{20} POT) shown here
- Paper submitted for Run I+IIa

MINOS ν_s Physics

- Total neutrino NC event rate should stay constant if oscillations among active neutrinos only.
- Deficit could indicate presence of sterile neutrinos.
- The presence of sterile neutrinos could indicate a 4th mass eigenstate:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$



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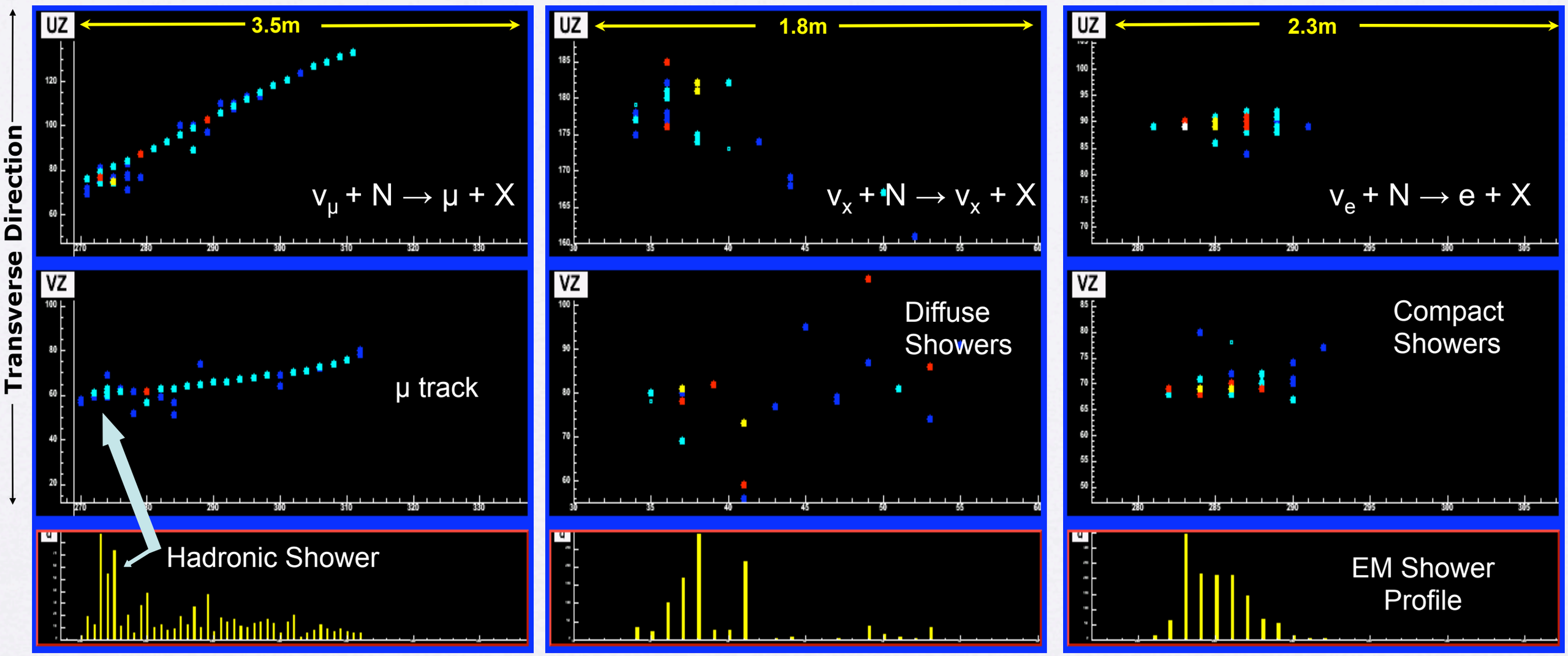
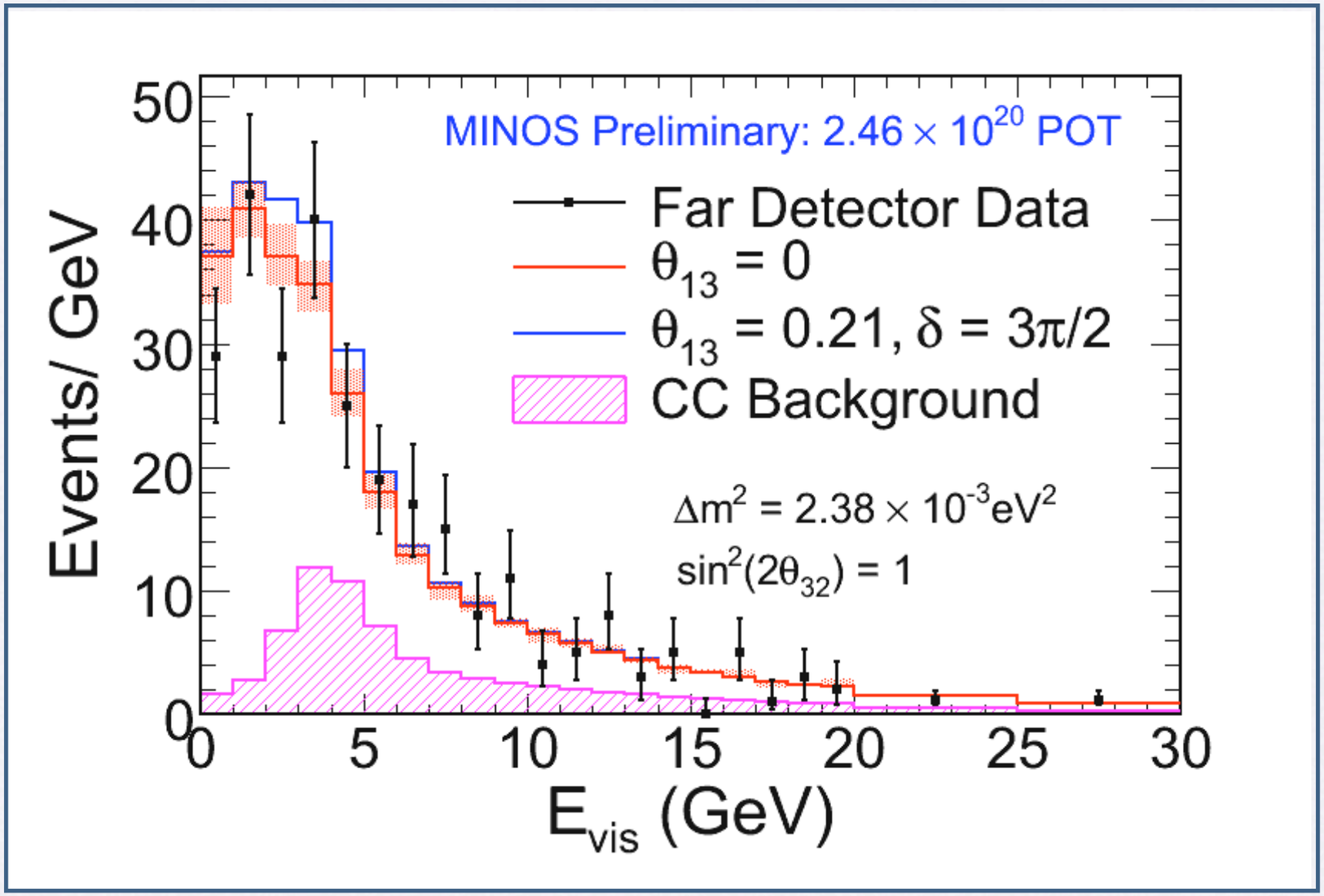


ν_μ CC event | NC event | ν_e CC event

This analysis focuses on finding anything that is not a track

3-flavor analysis

- Test NC energy spectrum data for consistency with the standard 3-flavor oscillation physics.
- For given oscillation parameter values from the MINOS CC measurement and KamLAND+SNO.



3-flavor analysis

Energy Range (GeV)	Data	MC $\Theta_{13} = 0$	Sig. (σ) $\Theta_{13} = 0$	MC $\Theta_{13} = 0.21$ $\delta = 3\pi/2$	Sig. (σ) $\Theta_{13} = 0.21$ $\delta = 3\pi/2$
0-3	100	115.16 ± 7.67	1.15	122.09 ± 8.42	1.56
0-5	165	175.92 ± 10.42	0.65	191.26 ± 11.88	1.42
0-120	291	292.63 ± 15.02	0.10	311.54 ± 16.28	0.89

- **Data and Monte Carlo agree within 1-2σ.**
- ν_e CC identified as NC-like with near 100% efficiency, thus comparisons made with and without ν_e appearance.
- Systematic uncertainties are shown.

Search for ν_e appearance:

- Expect results soon using Run I+II (3.25×10^{20} POT)

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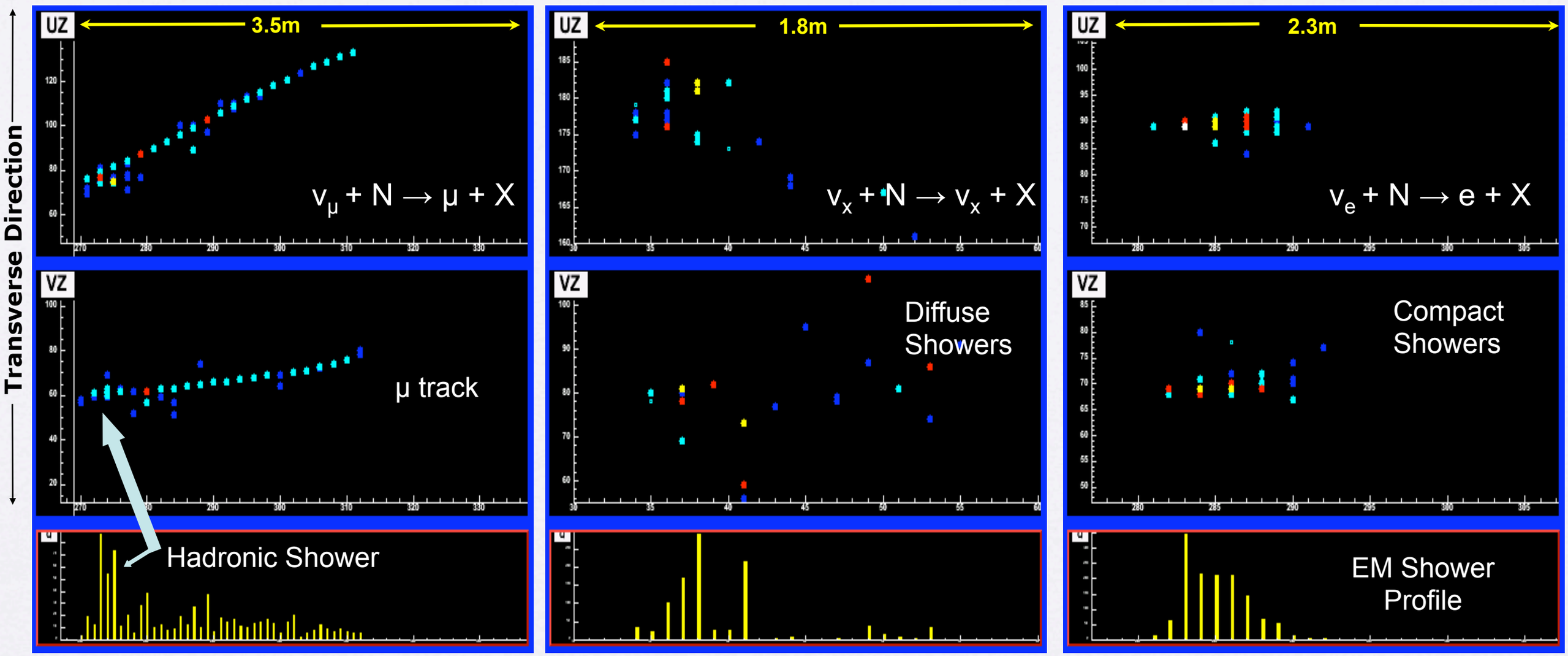
Monte Carlo events

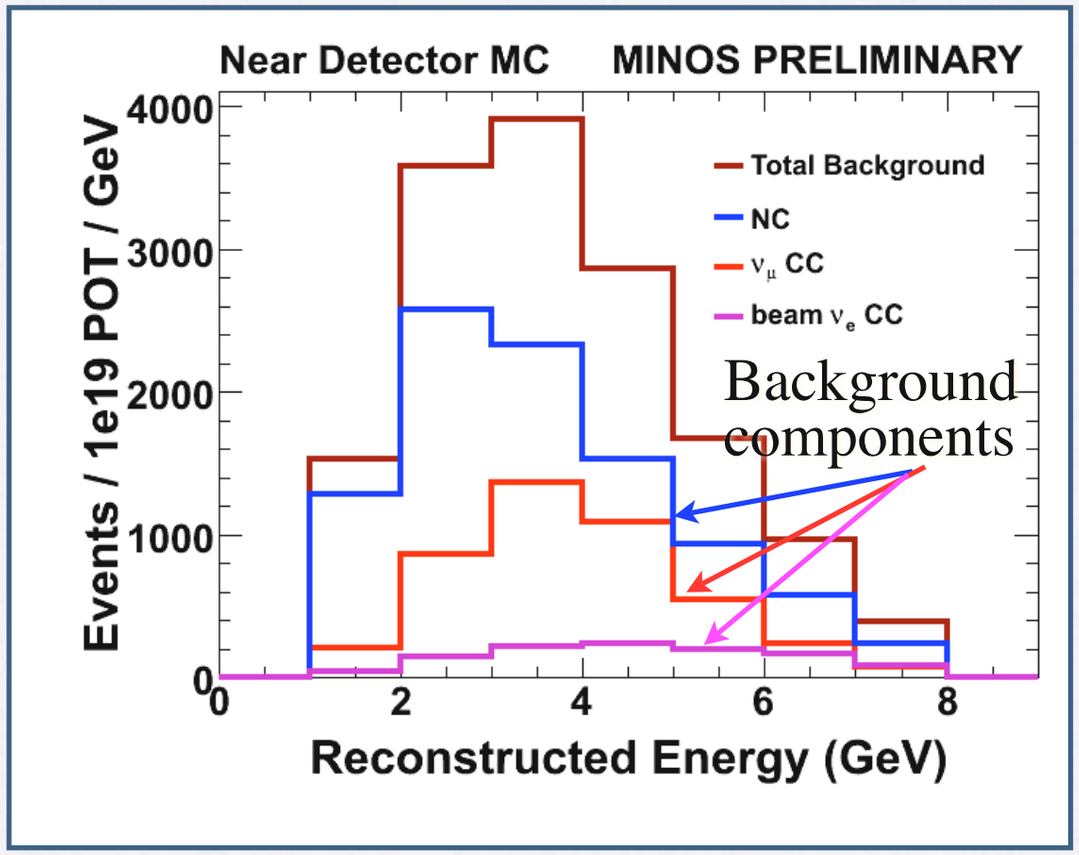


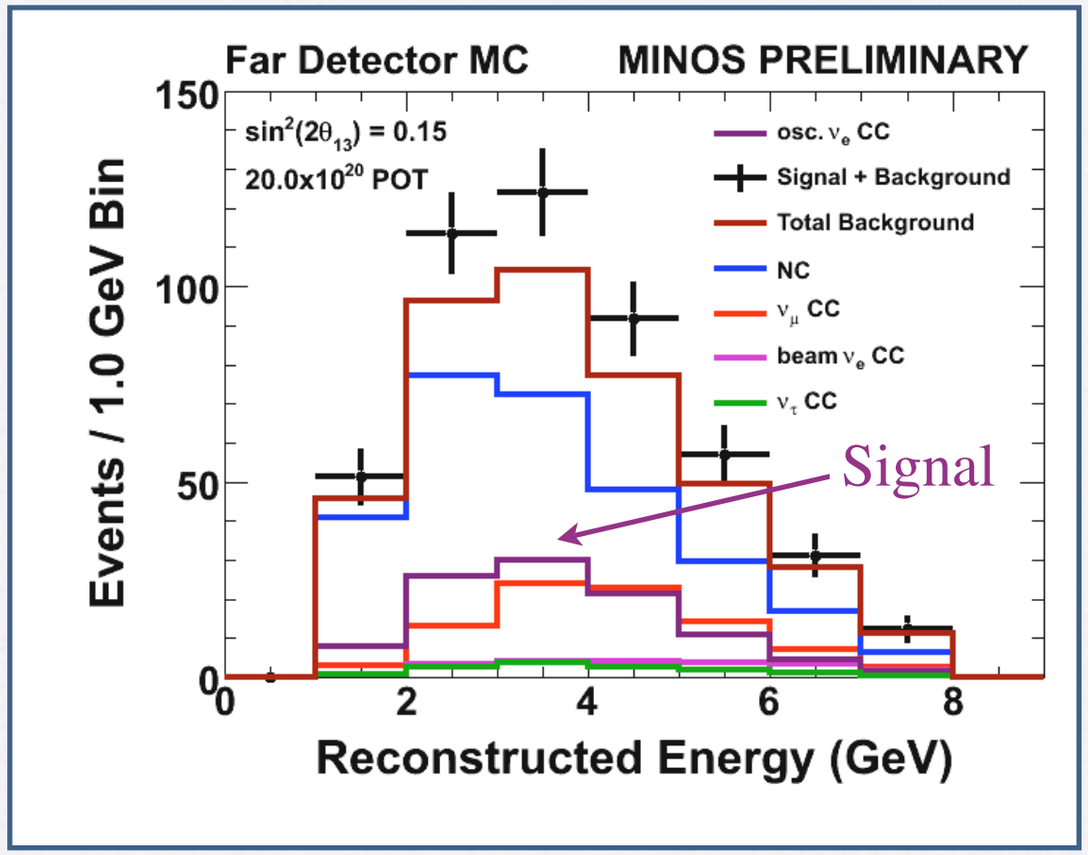
ν_μ CC event | NC event | ν_e CC event

This analysis focuses on finding compact showers

ν_e appearance in MINOS

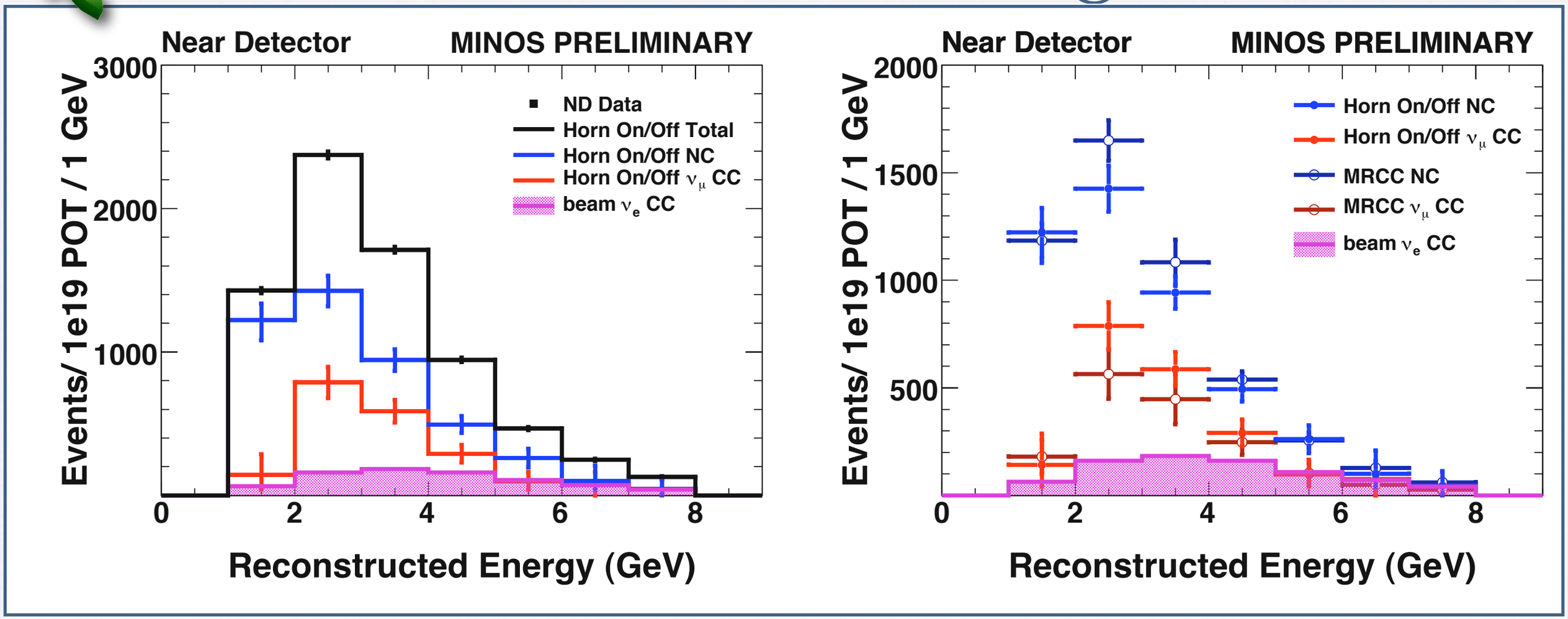
Understanding of the background is the key!





- We measure the **main background components NC, ν_μ CC and beam ν_e CC** events, in the Near Detector. We then extrapolate each of those to the Far Detector, oscillate the ν_μ CC component and obtain the ν_τ CC.
- The signal is proportional to $\sin^2 2\theta_{13}$, expect 12 signal events for $\sin^2 2\theta_{13}=0.15$ (CHOOZ).

ND data-driven background



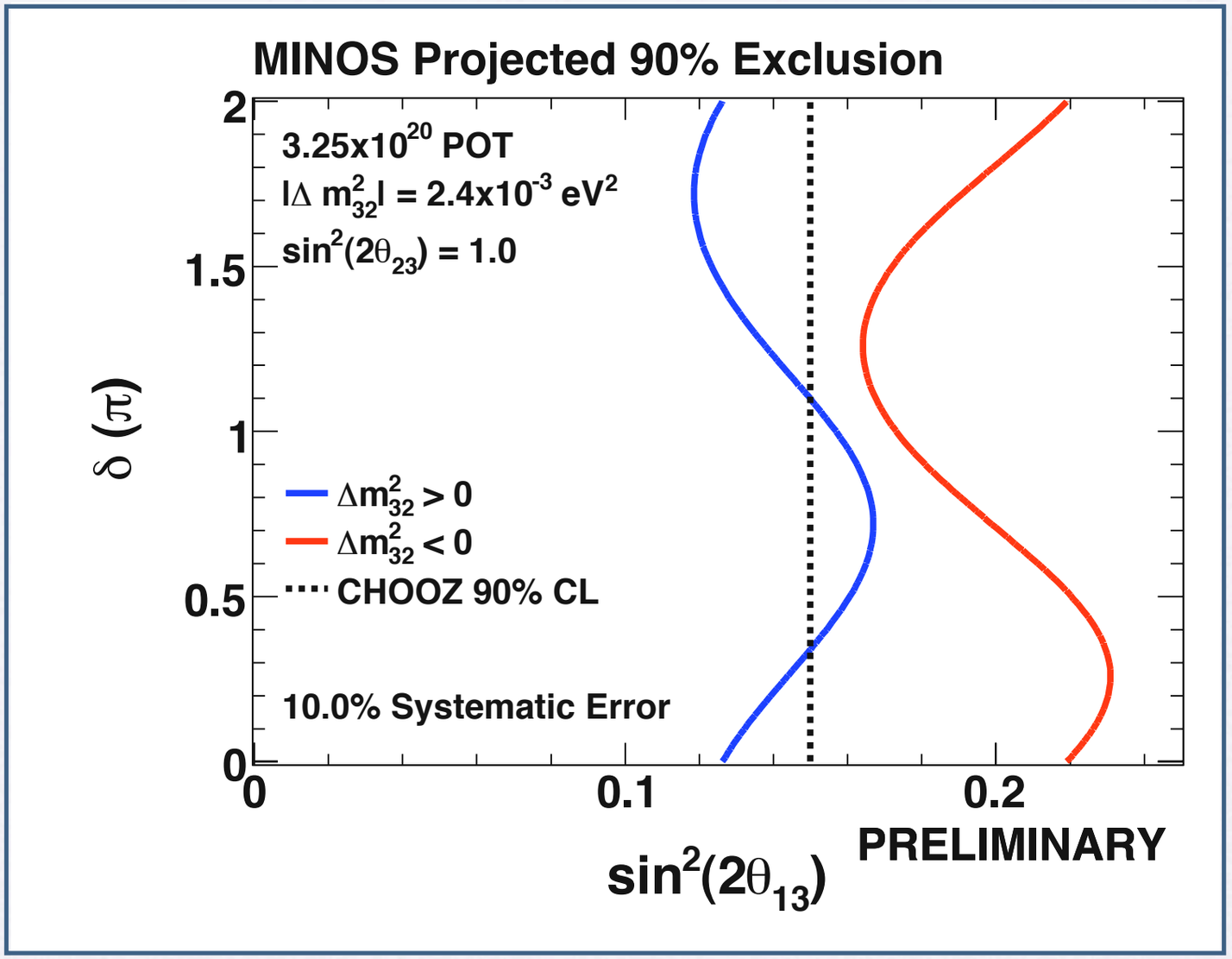
- The ν_μ CC component is obtained from subtracting the NC corrected and the beam ν_e components from the data resulting in a perfect match between the data and MC.
- The **two data-driven methods**, MRCC and Horn on/off, are in good agreement in the Near Detector NC and ν_μ CC background for the ν_e analysis.

Physics reach of MINOS

Data-driven ν_e sensitivity

- Our preliminary expectation from the two methods is 42-43 background events in the Far Detector for run I+II.

- **We have a chance at making the first measurement of θ_{13}.**
  - Matter effects can significantly change ν_e yield.
  - Reach comparable to the CHOOZ limit.



Results coming soon!

Summary

- MINOS continues to improve the precision of the measurement of oscillation parameters from muon neutrino disappearance.
- First results of a test for sterile neutrinos with MINOS. Currently consistent with no sterile neutrinos.
- Search for electron neutrino appearance in progress, results later this year.

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Dave we are working on it! We might get lucky!
Thanks for all the hard work!