



Anti-fiducial Muons in MINOS



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for the MINOS collaboration

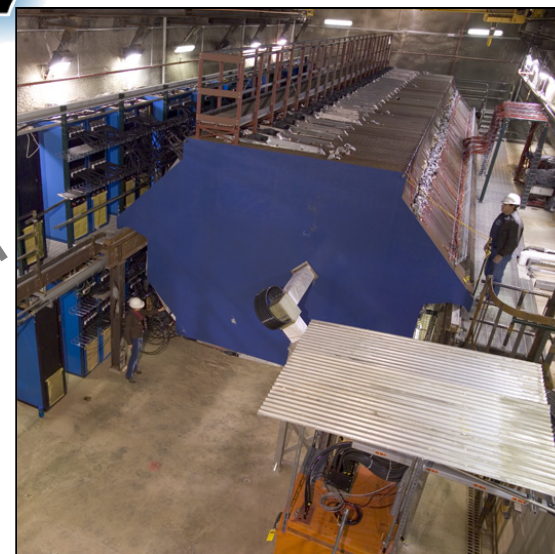
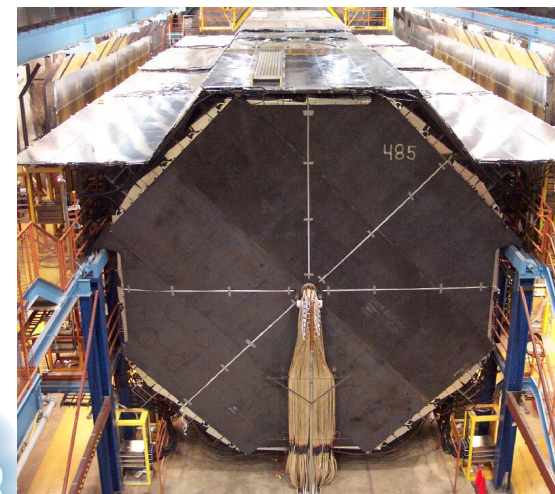
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The MINOS Experiment



- A long-baseline accelerator neutrino oscillation experiment
- ν_μ produced at Fermilab
- Two functionally identical magnetized detectors
 - 1 kt near detector at Fermilab; Measures initial composition/spectrum
 - 5.4 kt far detector in northern MN, 735 km away
 - Alternating planes of steel & solid scintillator
 - Scintillator alternates between perpendicular orientations

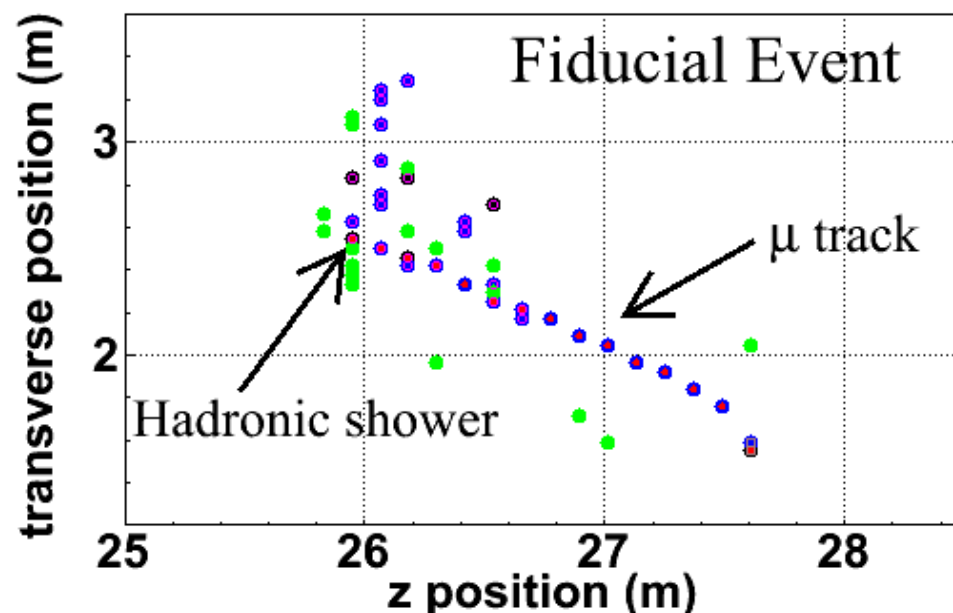




Analysis Introduction



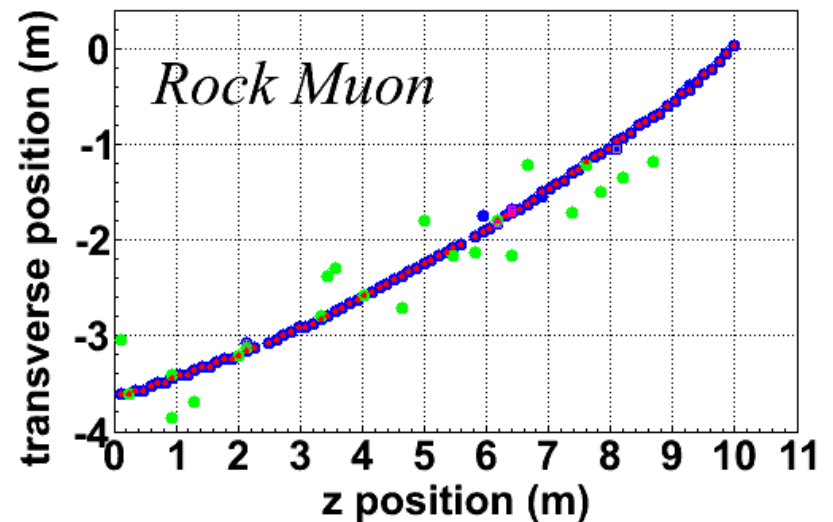
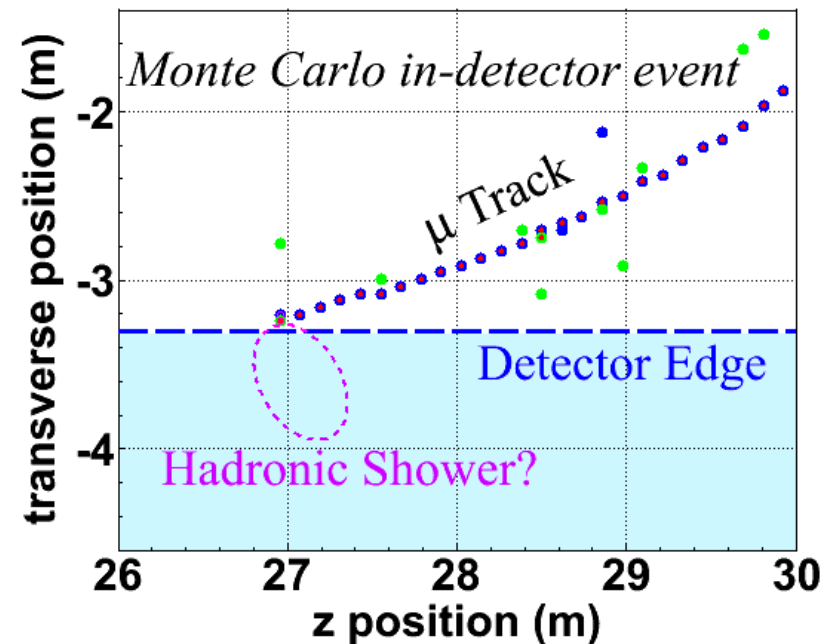
- MINOS's main analysis:
 - Charged current events identified by muon track in fiducial volume
 - Direct measurement of neutrino energy
 - $E_\nu = E_{\text{hadrons}} + E_\mu$
- This analysis:
 - In-detector events outside fiducial volume
 - Rock events
- Approximately same count of events as in main analysis
- These events provide a statistically independent oscillation measurement





Anti-fiducial Event Types

- In-detector events:
 - Well measured muon, poorly contained hadronic shower
 - $E_\nu \geq E_\mu$
- Rock events:
 - Have only muon's remaining energy
 - $E_\nu \geq E_\mu$; often $E_\nu \gg E_\mu$
 - Highly Monte Carlo-dependent, but rock is well characterized
 - Z/A sets normalization; known to 0.8%

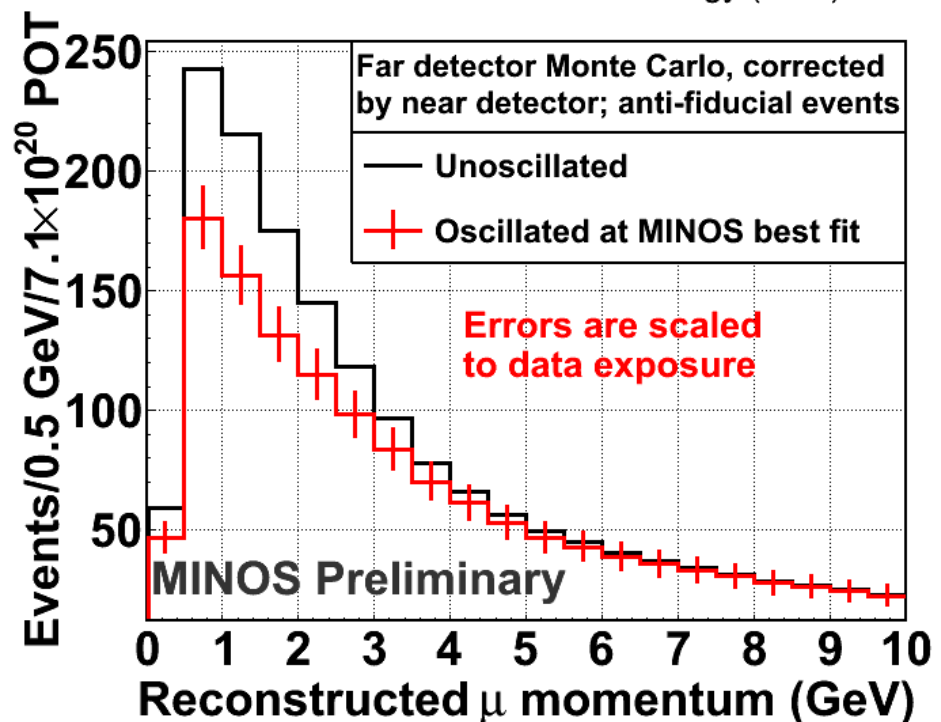
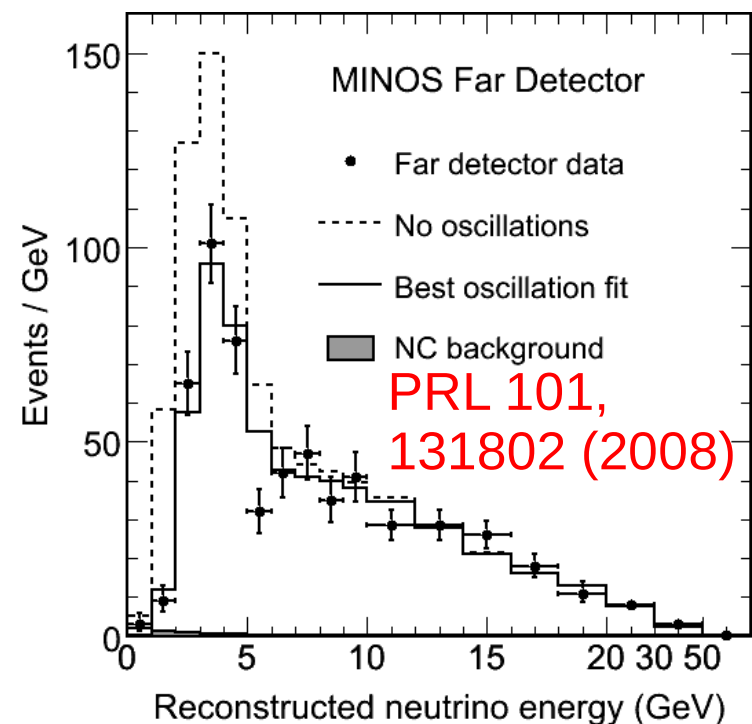




Oscillation



- Depth of oscillation deficit
 $\Rightarrow \sin^2 2\theta$
 - High E neutrinos reconstructed as low E muons form a **background**
- Location of deficit
 $\Rightarrow \Delta m^2$
 - Also partially masked by high energy feed-down
 - But total magnitude of deficit alone gives a strong constraint
 - Strength of this analysis
- Splitting events into several categories isolates the stronger parts of the signal



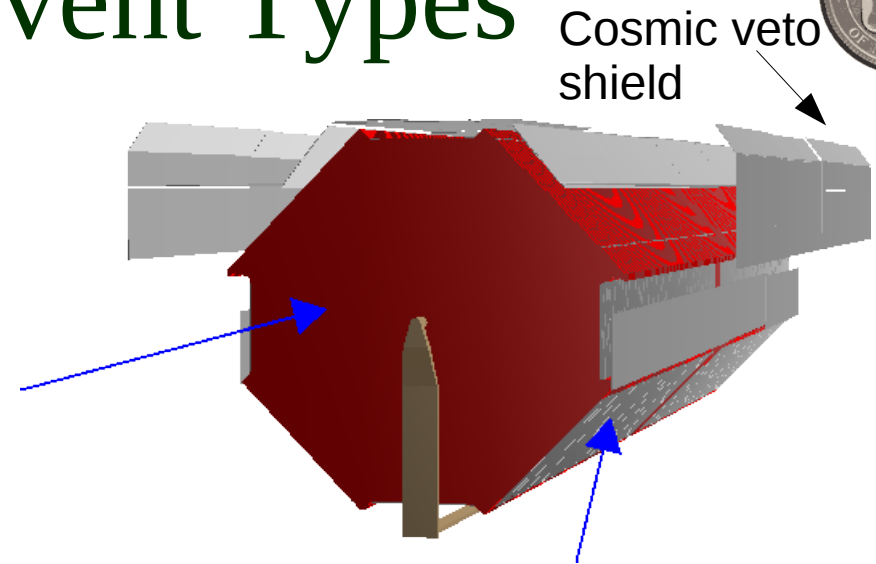


Anti-fiducial Event Types



Interactions in surrounding rock

- Muons enter the detector almost exclusively at the **front face** or around the **radial edge**

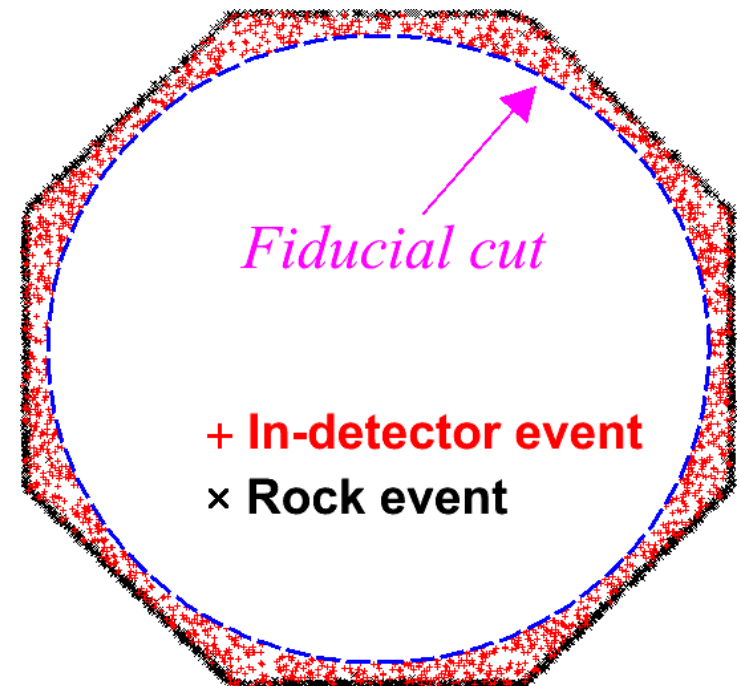


In-detector events

- Bulk of anti-fiducial detector mass is around the detector's **radial edge**
 - 0.8 kt (fiducial mass is 4.2 kt)

Separation of event types

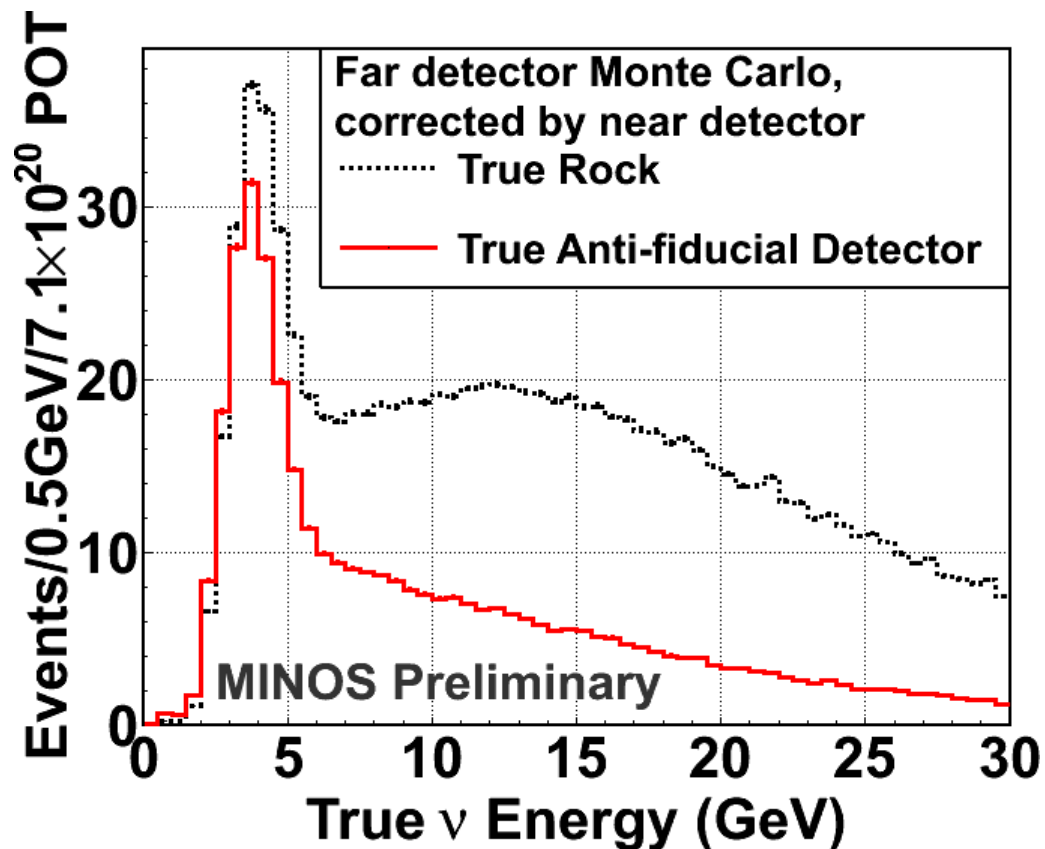
- $\geq 90\%$ of events are correctly labeled as rock-like or detector-like by muon track location





Rock/Detector Separation

- Distribution of ν energy differs for rock and in-detector events
- High E neutrinos have large rock mass available within μ range of detector
 - Above 10 GeV, essentially no oscillation information
 - Often cannot distinguish these events from low energy ones
- No such effect for in-detector spectrum
- \Rightarrow Separate these in fit

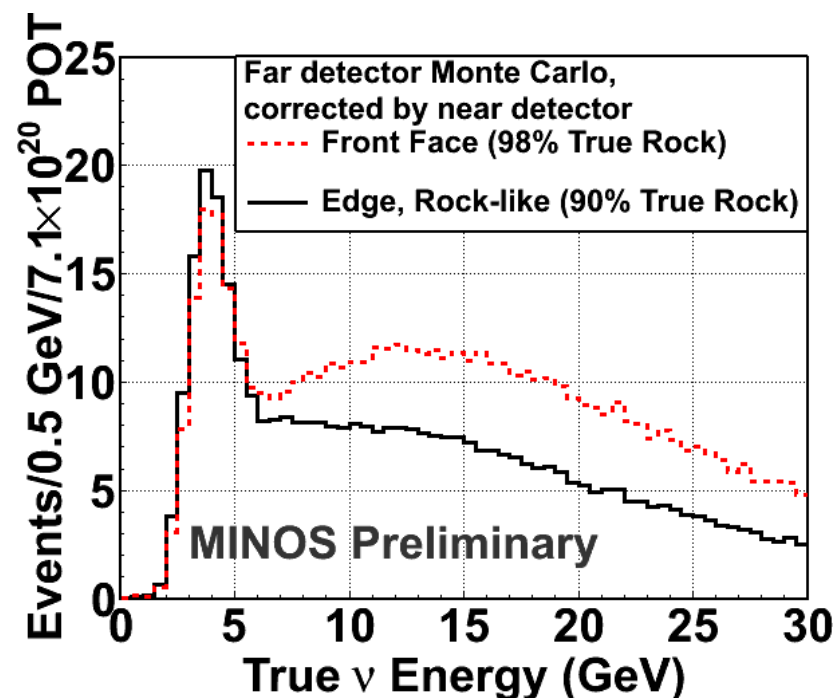
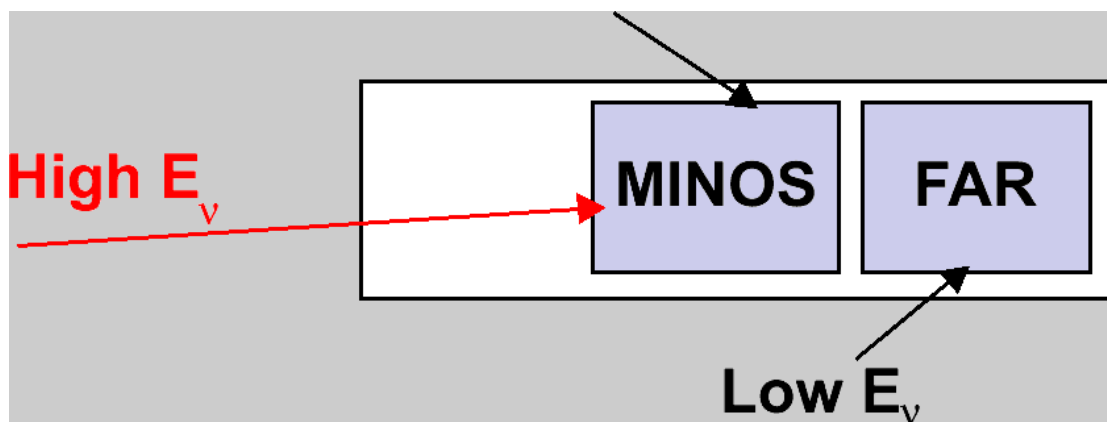




Rock/Rock Separation, Angles



- Rock events are not created equal:
 - A muon entering the **front face** is more likely from a high energy ν deep in rock
 - **Radial edge** accepts softer muons created closer to the detector
 - In either case, a *small* angle correlates with highly boosted, high E, event
 - \Rightarrow Separate by region+angle in fit



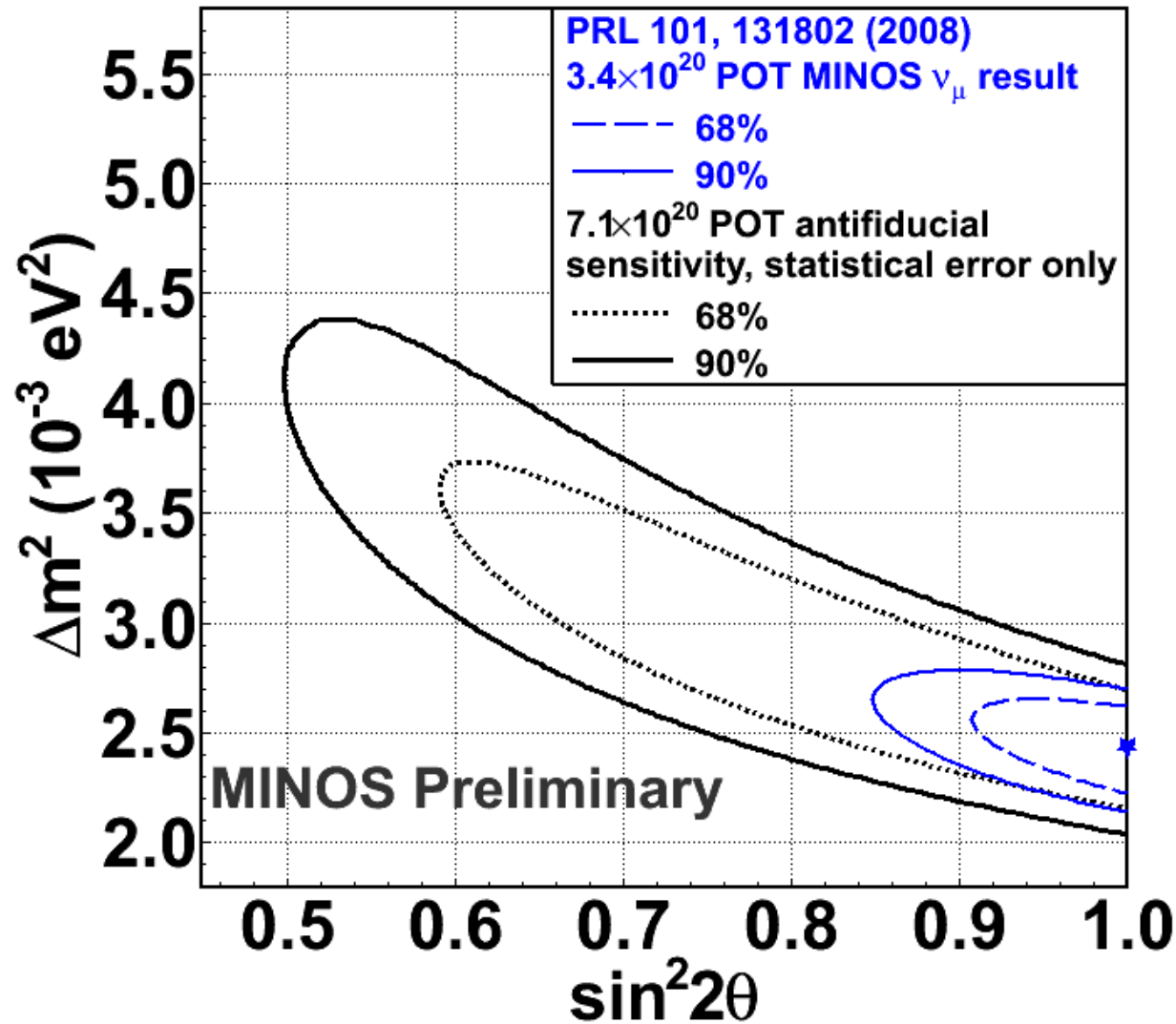
- **In-detector events:**
 - *Large* muon angle correlates with high E hadronic shower
 - \Rightarrow Also bin these by angle



Sensitivity and Conclusions



- Shown is:
 - 2008 fiducial **data** (PRL)
 - 2010 antifiducial **sensitivity**
- At maximal mixing, sensitivity to Δm^2 is $\pm 0.18 \times 10^{-3} \text{ eV}^2$
 - Combined with fiducial analysis, total MINOS sensitivity improved 15%
- Proportionally much less sensitivity to $\sin^2 2\theta$
 - Still provides a statistically independent measurement

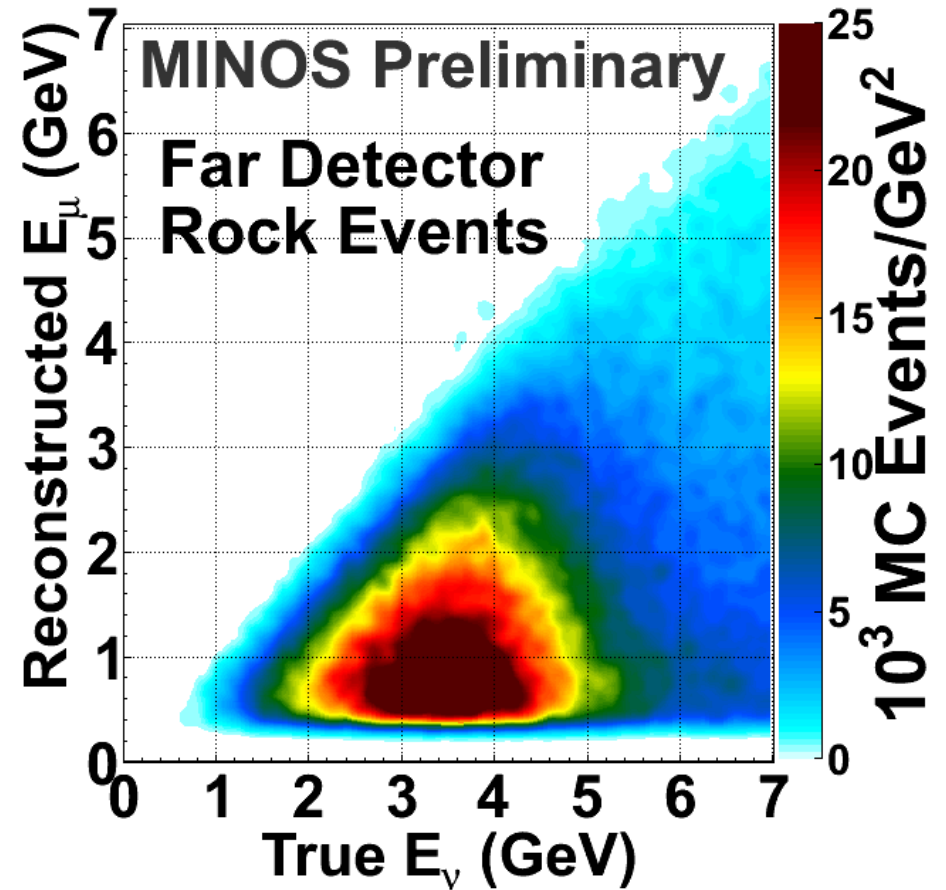
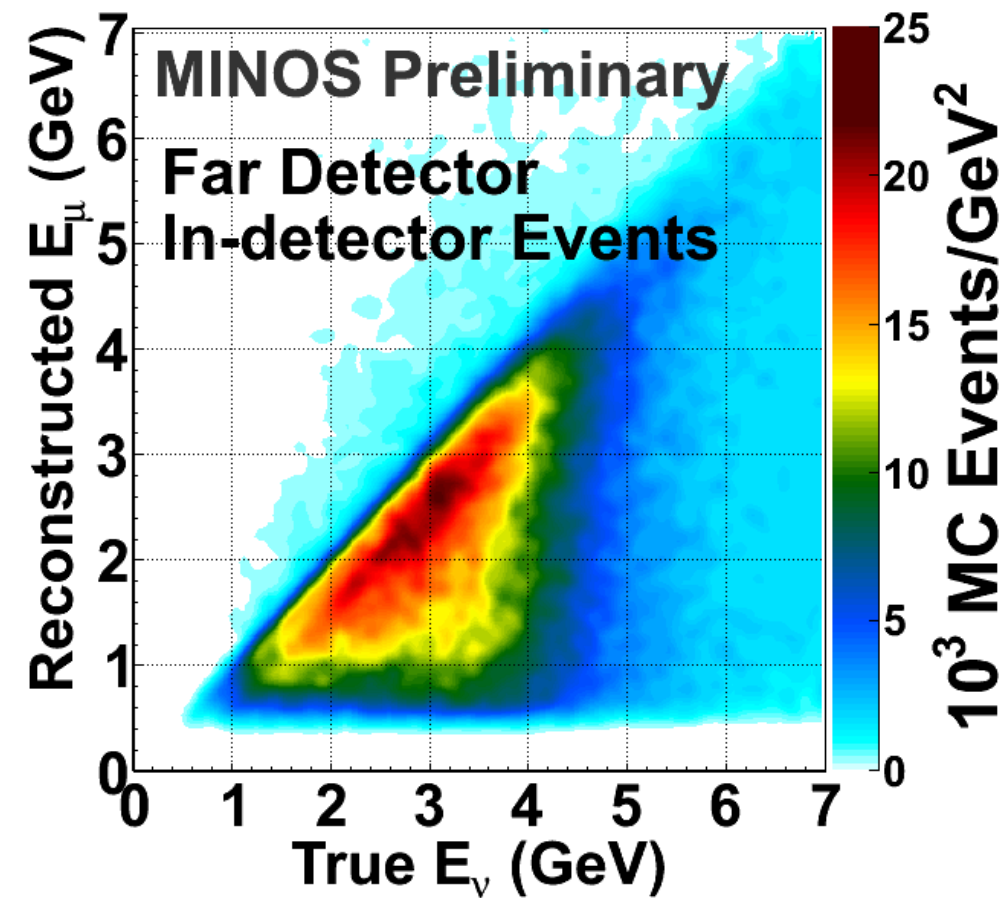




Backup



Neutrino \rightarrow Muon Relationships

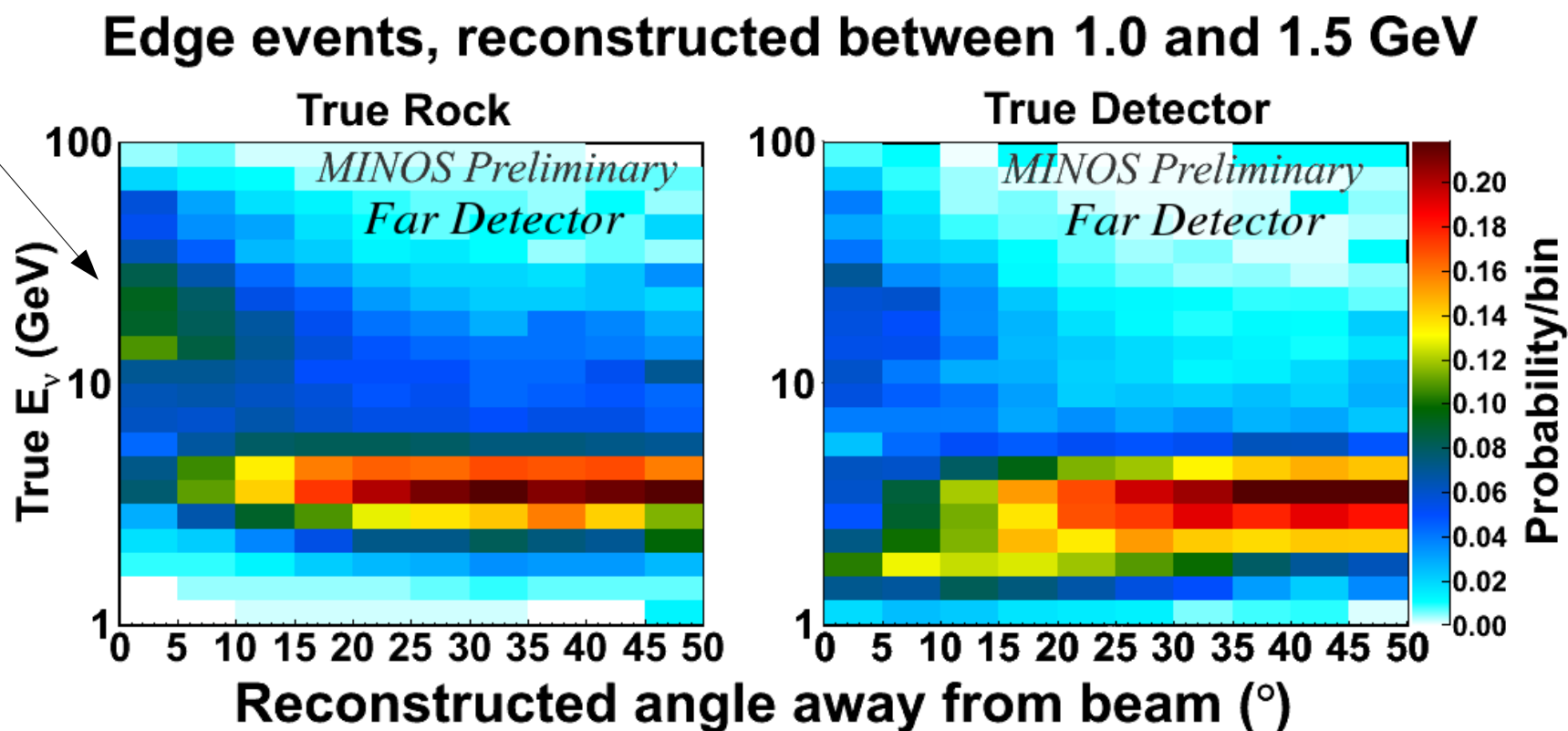




Energy/Angle Relationships



High E tail
separated
by angle





Edge Types

