First measurement of NuMI anti-neutrinos in MINOS

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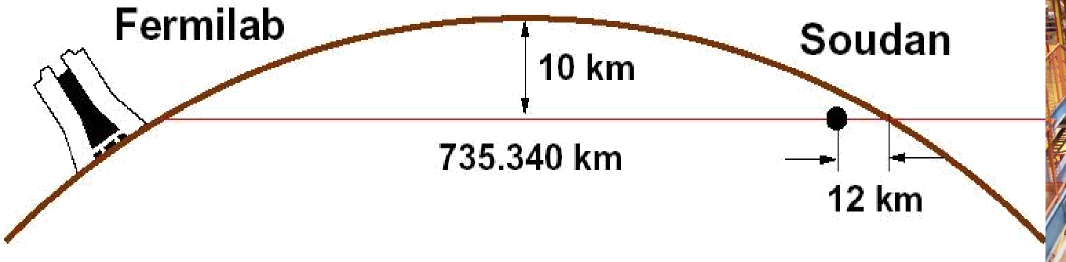
MINOS Overview

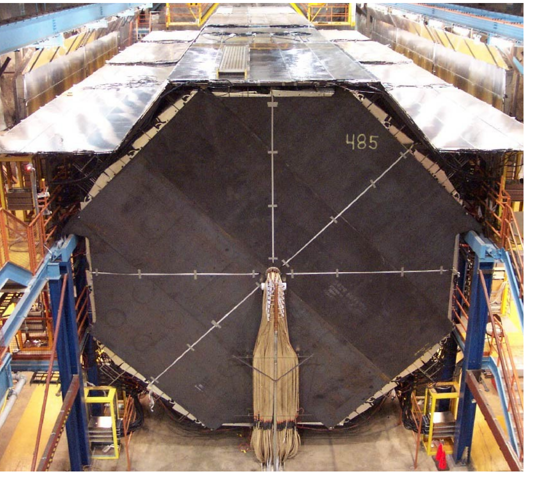
Main Injector Neutrino Oscillation Search

using high intensity neutrino beam created by the Main Injector at Fermilab

ν interactions are detected by two functionally identical magnetized tracking-calorimeter detectors to reduce systematics:

- Near detector measures ν -beam composition and energy spectra close to the source
- Far detector looks for differences after a ν's travel a long distance (735 km)





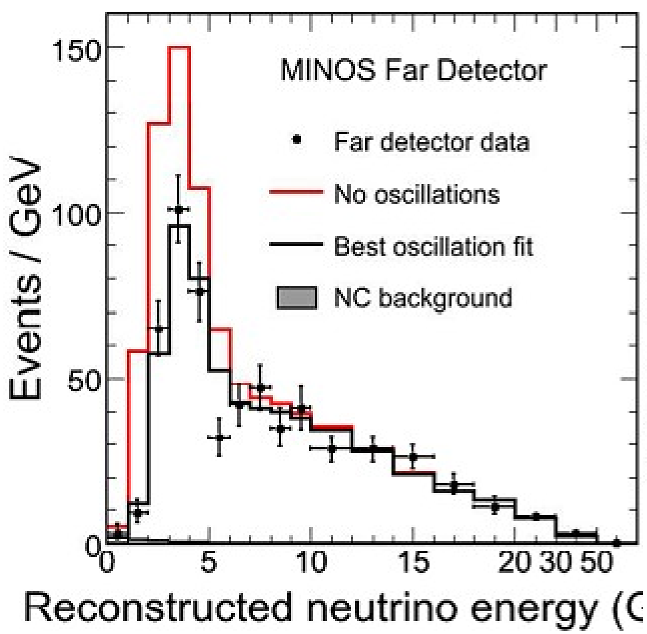
ν_μ oscillation result

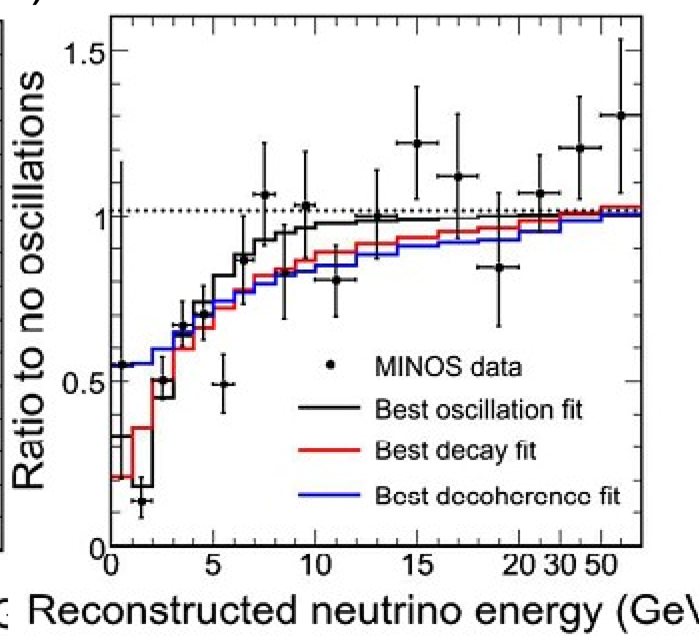
- Flagship measurement using the dominant ν_μ beam component (~92%)
- Far detector ν_μ deficit is interpreted as a result of $\nu_\mu \rightarrow \nu_\tau$ oscillation
- Disappearance probability as a function of energy gives oscillation parameters – best measurement of atmospheric mass splitting!

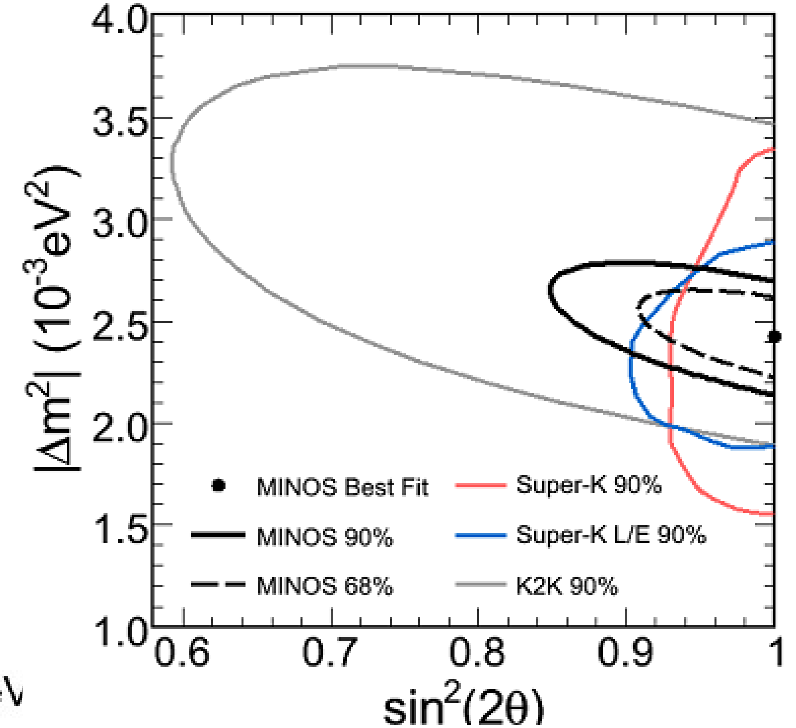
$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2(2\theta)\sin^2(1.27\Delta m^2 L/E)$$

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

PRL **101** 131802 (2008)





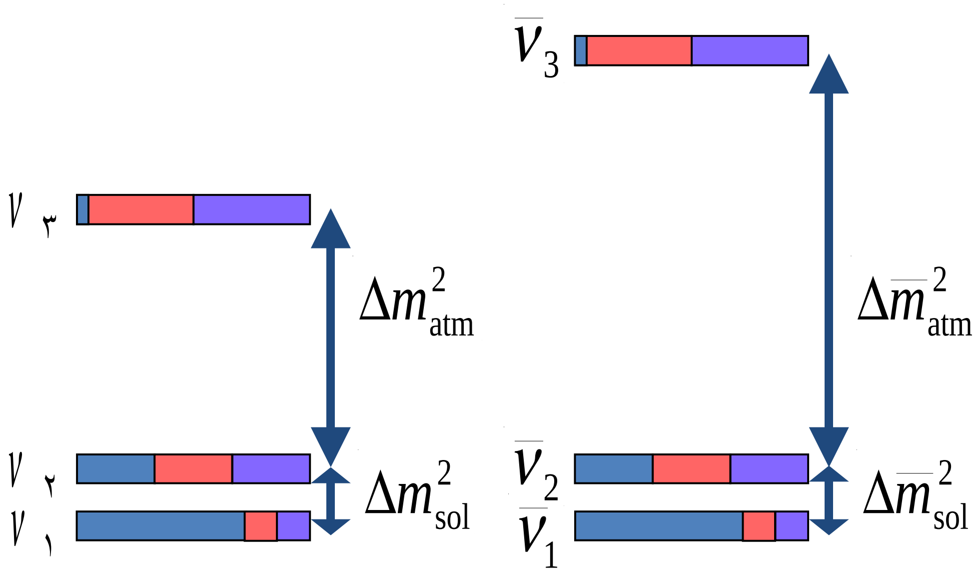


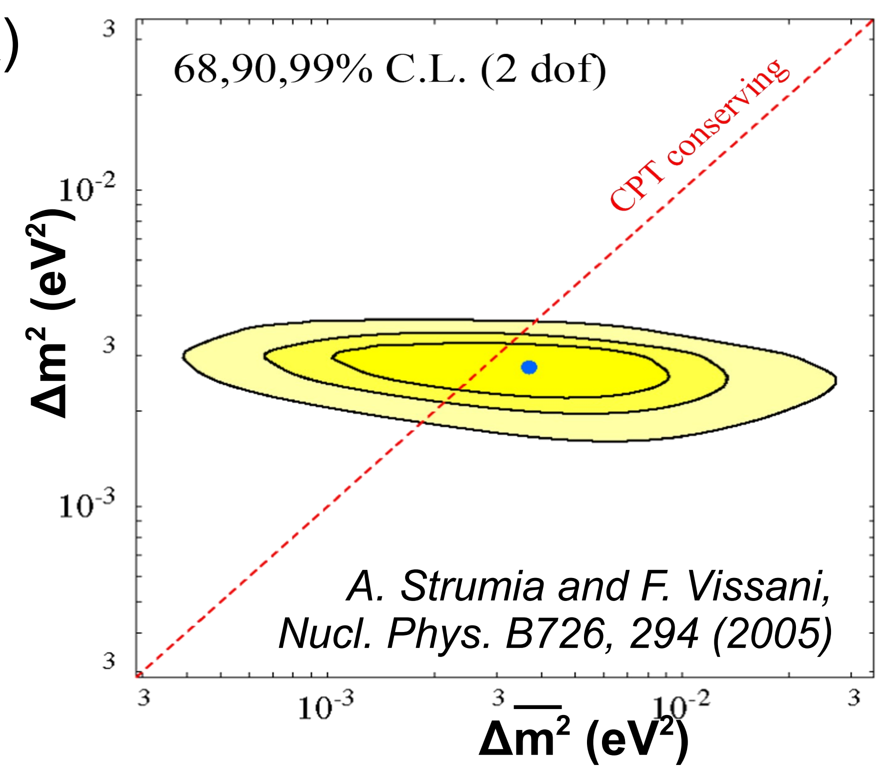
$\bar{\nu}_\mu$ physics motivation (1)

- Anti-neutrino oscillation would lead to $\bar{\nu}_\mu$ disappearance in the far det.
- Does $\bar{\nu}_\mu$ oscillate the same way as ν_μ?

$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\tau) = \sin^2(2\bar{\theta})\sin^2(1.27\Delta\bar{m}^2 L/E)$$

- If not that would indicate CPT violation or some new physics
- Loose constraint on $\bar{\nu}_\mu$ oscillation parameters from global fit (dominated by indirect measurements from Super-K)



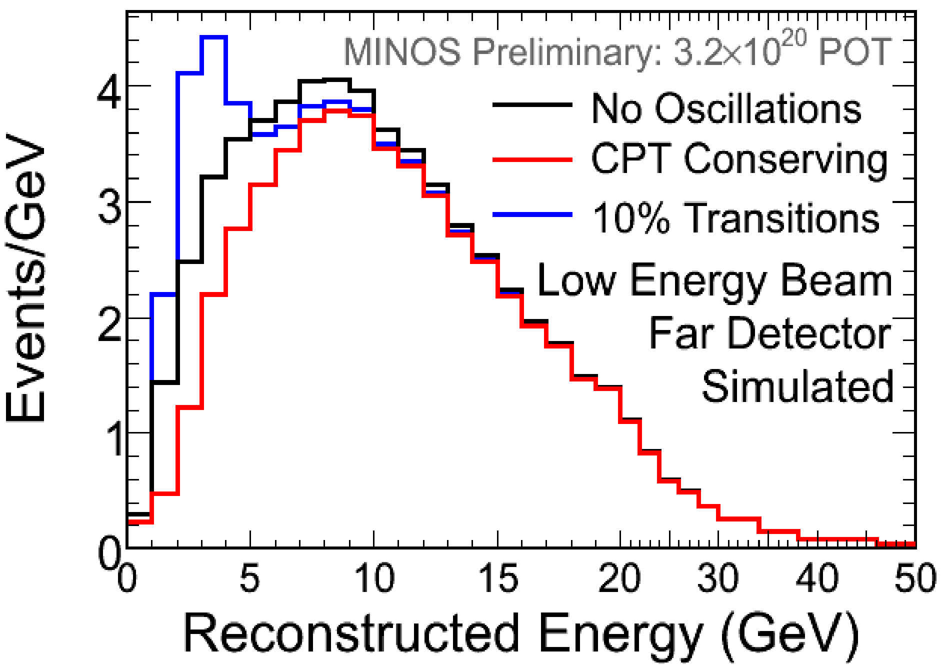


$\overline{\nu}_\mu$ physics motivation (2)

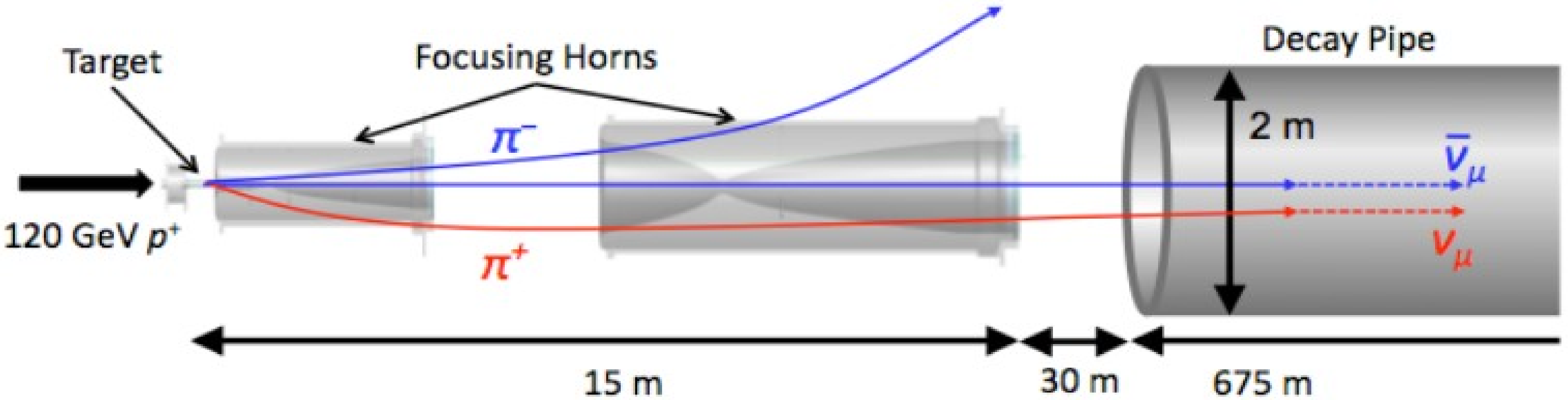
- It is plausible that the observed neutrino deficit in the far detector is caused by $\nu_\mu \to \overline{\nu}_\mu$ transition
- Then these missing ν_μ would show up as a $\overline{\nu}_\mu$ excess
- Transition probability for Majorana neutrinos is predicted to be very small in the Standard Model: $P(\nu_\mu \to \overline{\nu}_\mu) \sim (m/E)^2 \sim 10^{-18}$
- Transition is also allowed at low level in exotic models like large ν magnetic moment or ν decay *(Langacker & Wang, Phys. Rev. D 58, 093004)*
- Simple empirical parametrization:

$$P(\nu_\mu \to \overline{\nu}_\mu) = \alpha \sin^2(2\theta)\sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$

α is the fraction of ν_μ reappearing as $\overline{\nu}_\mu$



NuMI neutrino beam

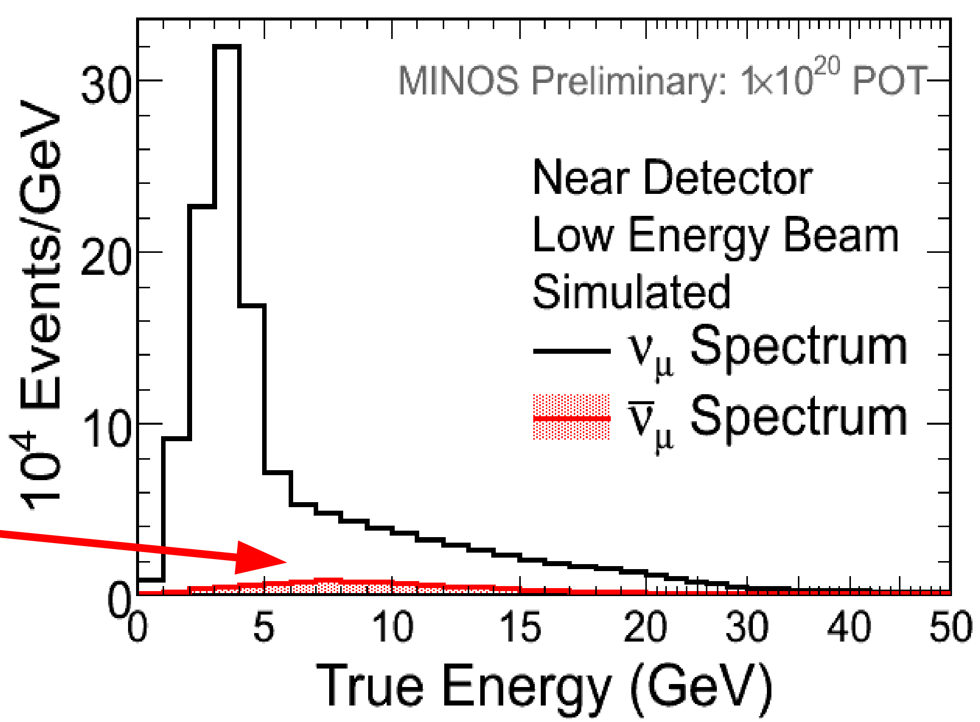


- Neutrinos are created by in-flight decay of secondary/tertiary particles (mainly pion, kaon, and also muons)
- Magnetic horns (de-)focus positive (negative) particles
- Only neck-to-neck π^-, K^- from the target will reach the decay region

Charge current interactions in near det.:

- ~91.7% ν_μ + ~7% $\bar{\nu}_\mu$

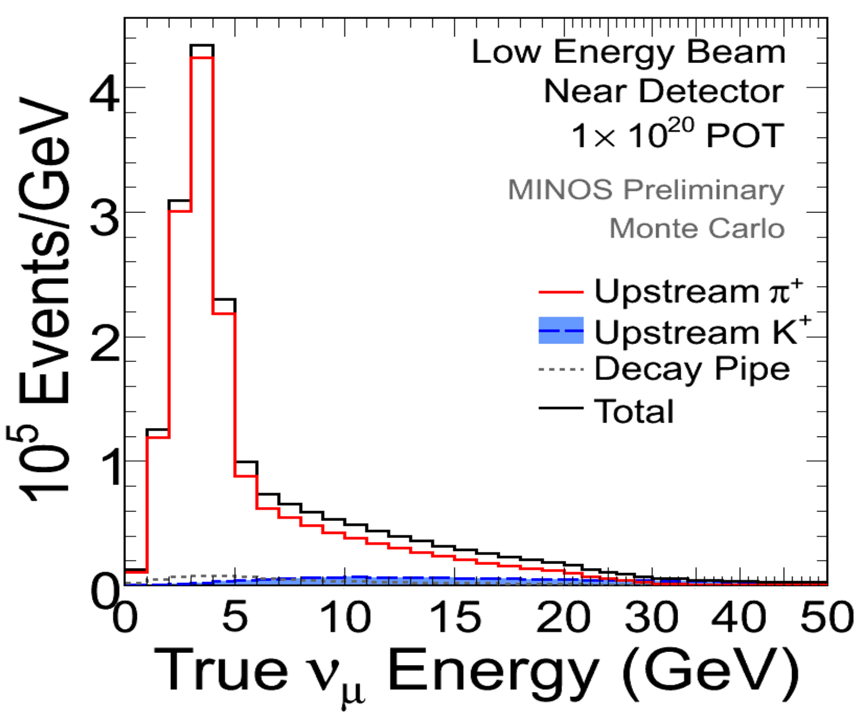
  ~1.3% ν_e + $\bar{\nu}_e$

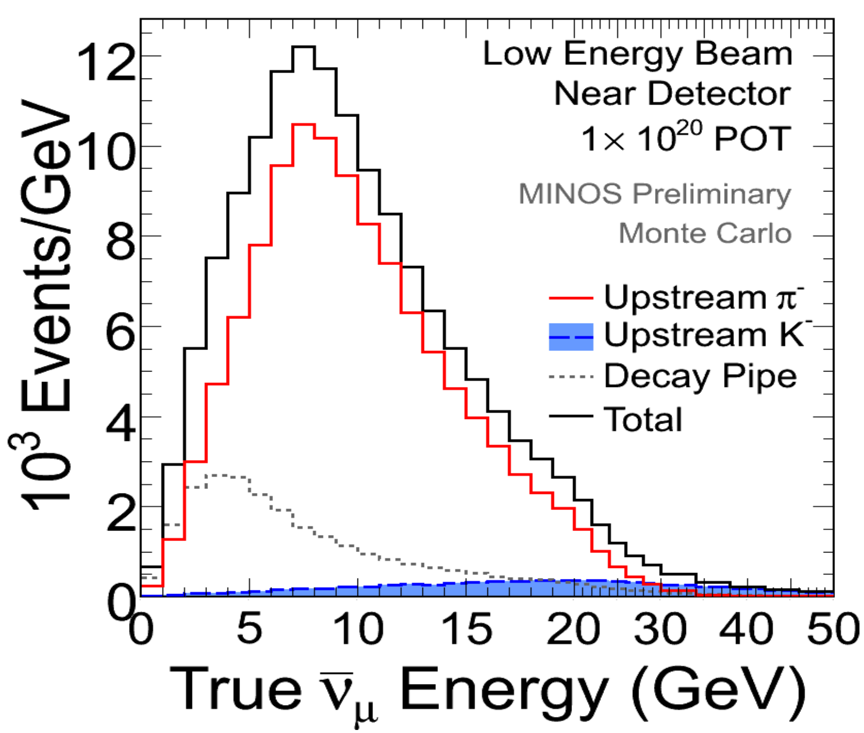


Difference in ν_μ and $\bar{\nu}_\mu$ spectra

- ν_μ spectrum peaks around ~3 GeV due to focusing effect on the parent particles (π^+, K^+)
- Close to oscillation maximum E_ν~2 GeV

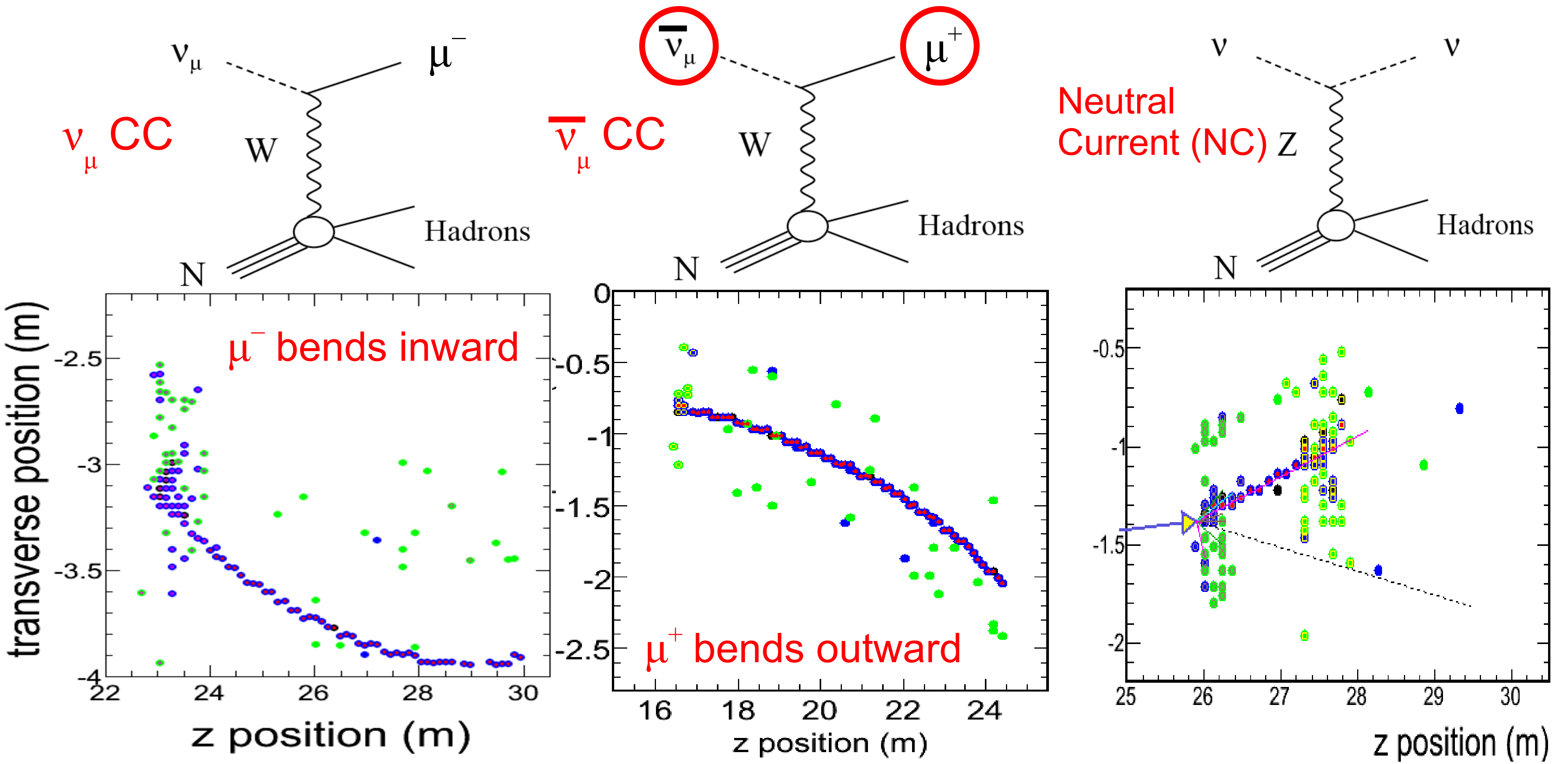
- $\bar{\nu}_\mu$ spectrum peaks ~8 GeV due to de-focusing on π^-
  - more sensitive to higher Δm^2
- Significant contribution from particles produced downstream in/around the decay pipe





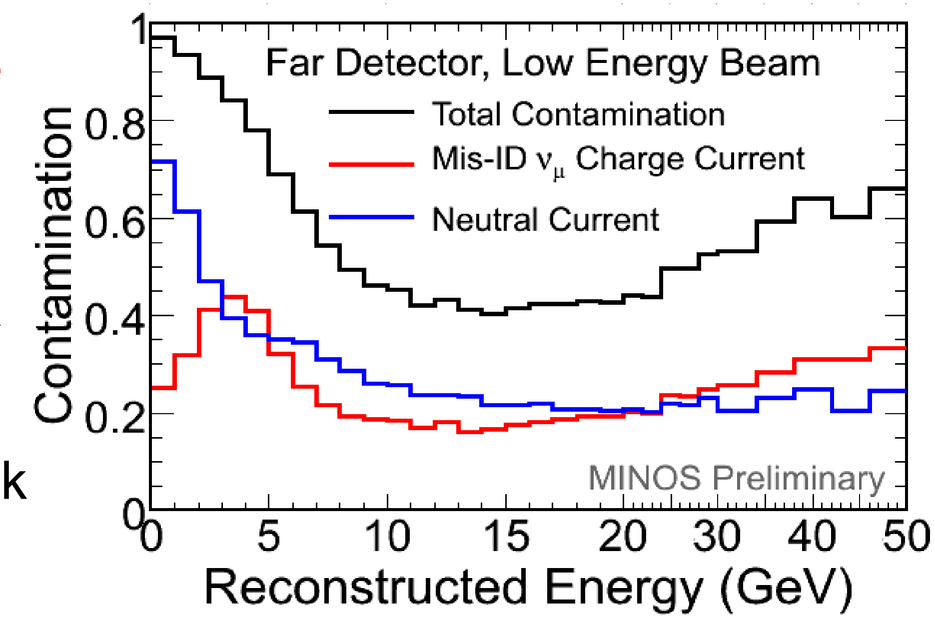
$\bar{\nu}_\mu$ in MINOS detector

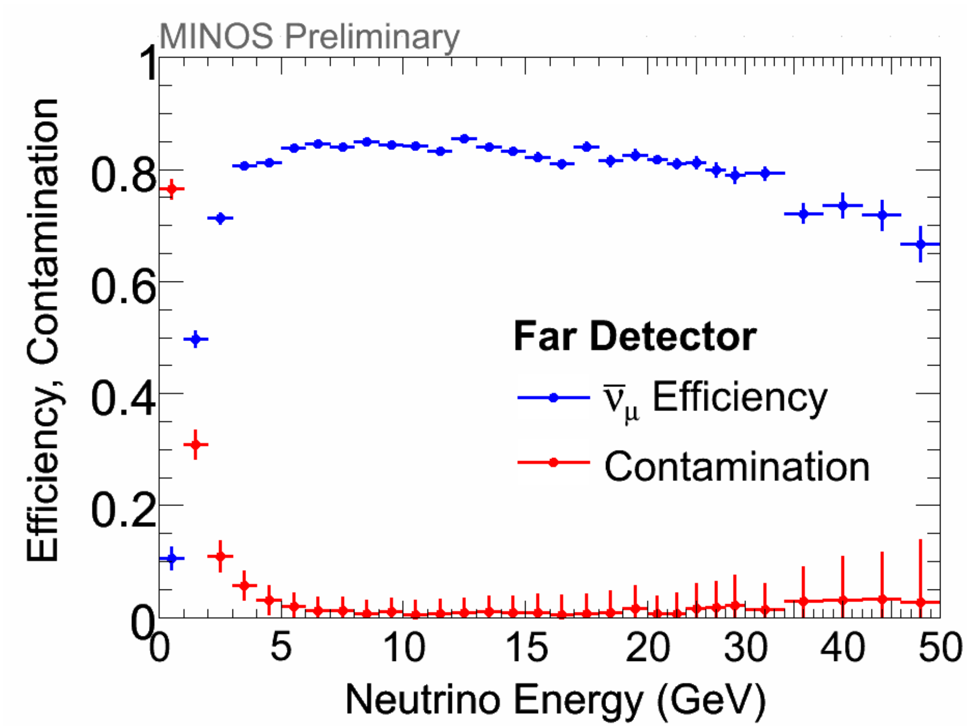
- Charged current (CC) ν_μ and $\bar{\nu}_\mu$ interactions produce a muon that typically leaves a long prominent track in the detector
- the $\bar{\nu}_\mu$ and ν_μ CC interactions can be separated event-by-event using the charge sign of the muon in the magnetic field of the detector



$\overline{\nu}_\mu$ selection

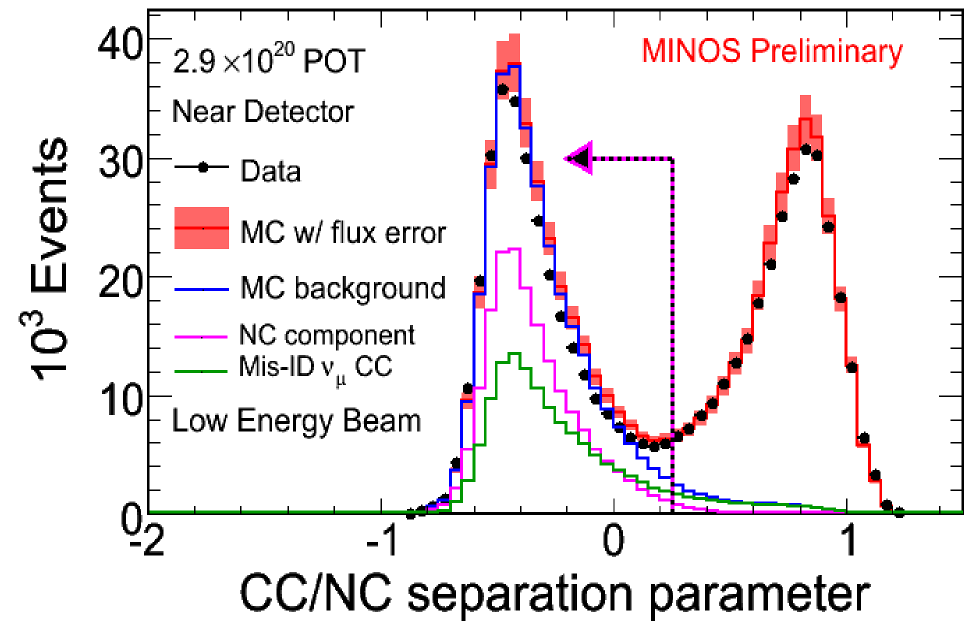
- Large contamination when only simple selection on charge-sign from fit applied (q/p>0)
  - ~8% of ν_μ-CC produce a positive track (mostly high inelasticity interactions)
  - 50% of NC events have a positive track
- Use three additional variables to improve $\overline{\nu}_\mu$ selection:
  - Significance of charge-sign determination: (q/p)/σ(q/p)
  - Relative angle of last track hit wrt projected hit w/o field
  - Likelihood variable for NC and CC event separation
- Selection is optimized for maximum sensitivity at CPT conserving osc.

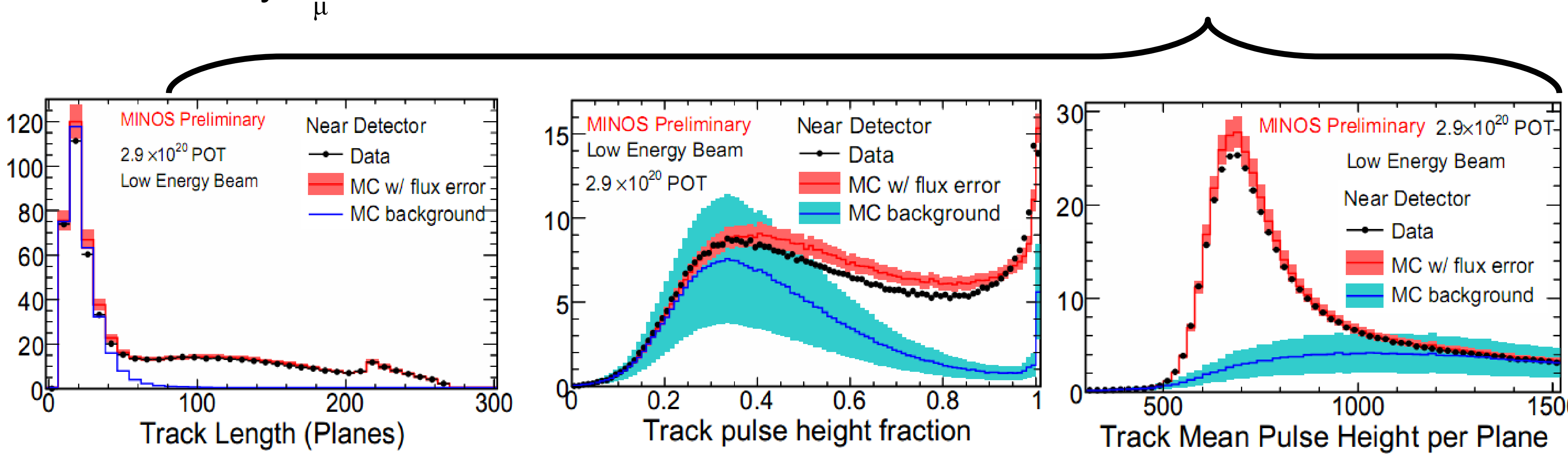




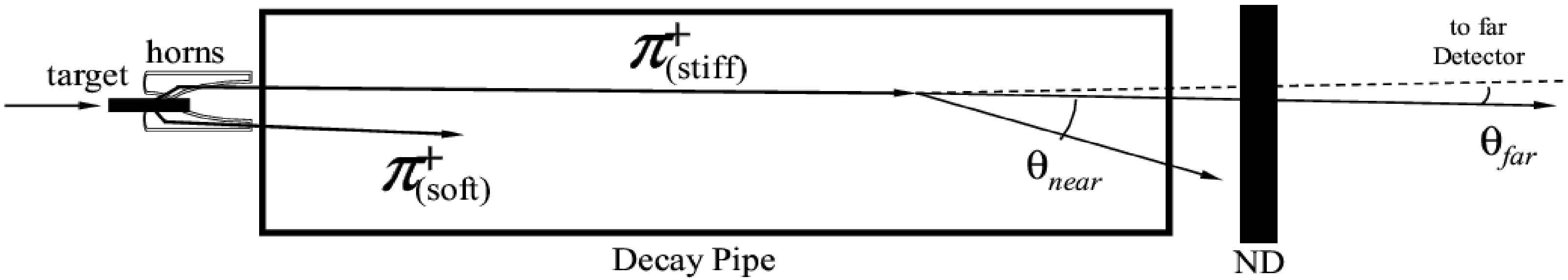
NC discriminator

- Combines three event topology variables:
  - Track length (muon energy)
  - Track pulse height fraction (inelasticity)
  - Average track pulse height per plane (dE/dx)
- It is also suppresses misidentified high-inelasticity ν_μ-CC events



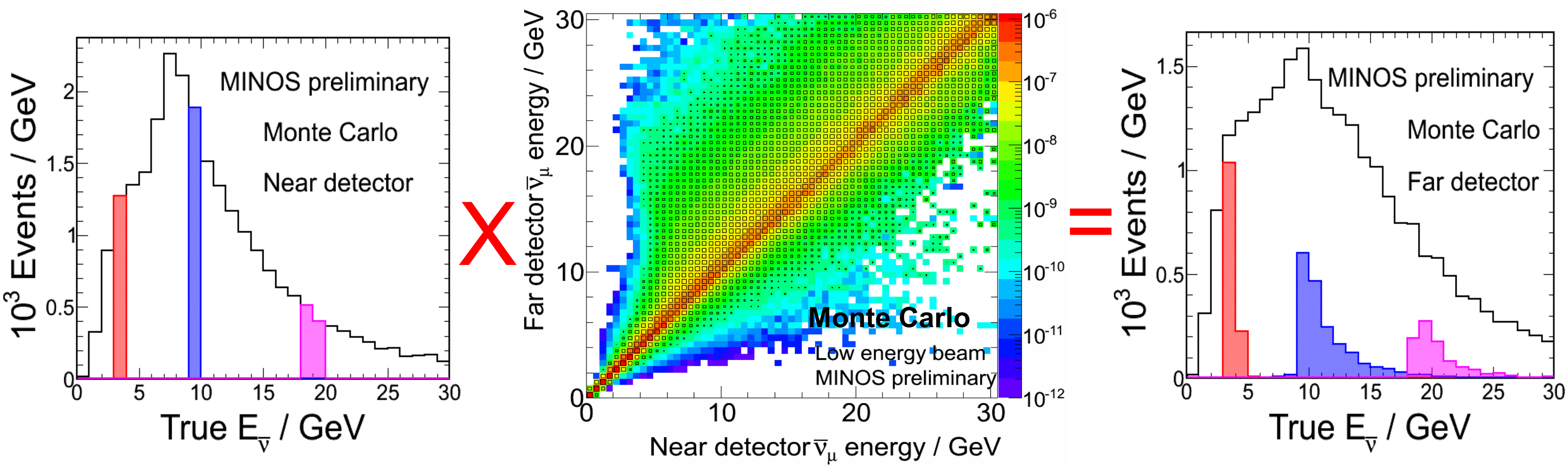


Far detector prediction



$$E_\nu = \frac{0.43 E_\pi}{1+\gamma^2\theta^2}$$

- Near and far detector spectra are not identical due to different solid angle and decay kinematics (neutrino energy depends on decay angle)
- Far detector spectrum is obtained from the near detector spectrum using a beam extrapolation matrix which encapsulates kinematics and beam-line geometry
- MC is used to correct for energy smearing and acceptance



Far detector spectrum

- 42 events are observed in 3.1×10^{20} PoT

  First direct observation of nu-bar events in long-baseline accelerator experiment

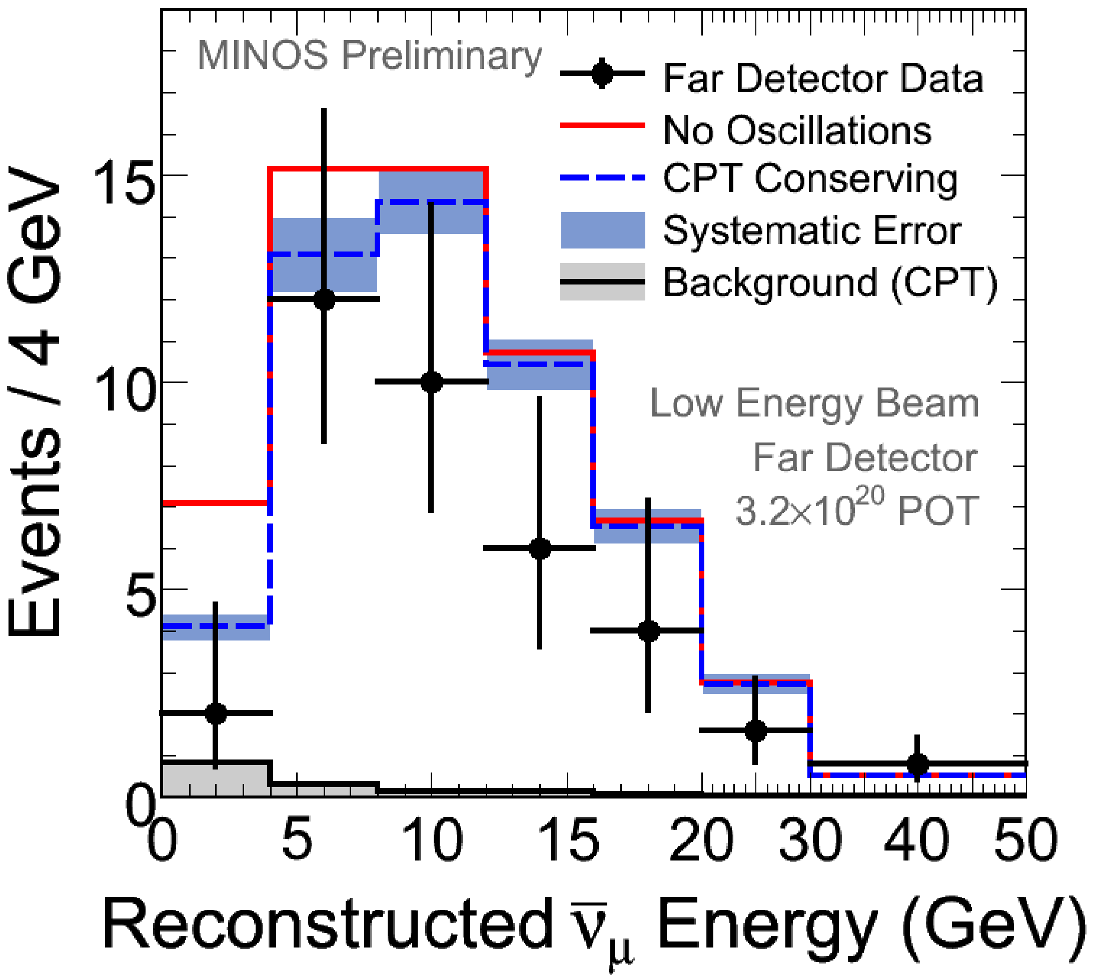
- Number of observed events is 1.9σ below prediction with CPT conserving oscillation:

  58.3 ± 7.6 (stat.) ± 3.6 (syst.)

  Predicted events with no oscillation:

  64.6 ± 8.0 (stat.) ± 3.9 (syst.)

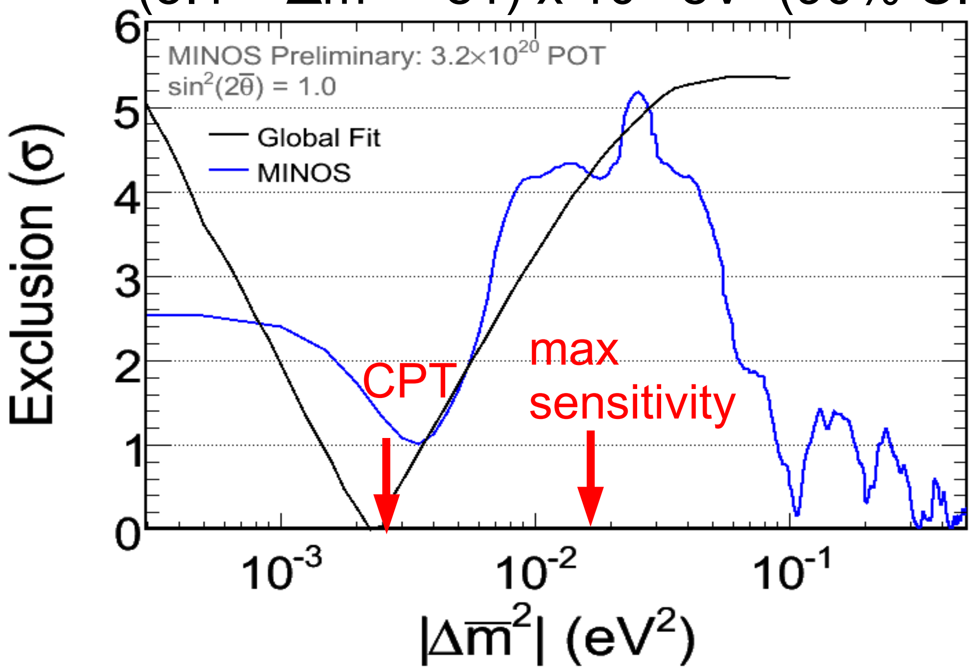
- Deficit seems to be statistical fluctuation (no sign of reconstruction or selection inefficiency)

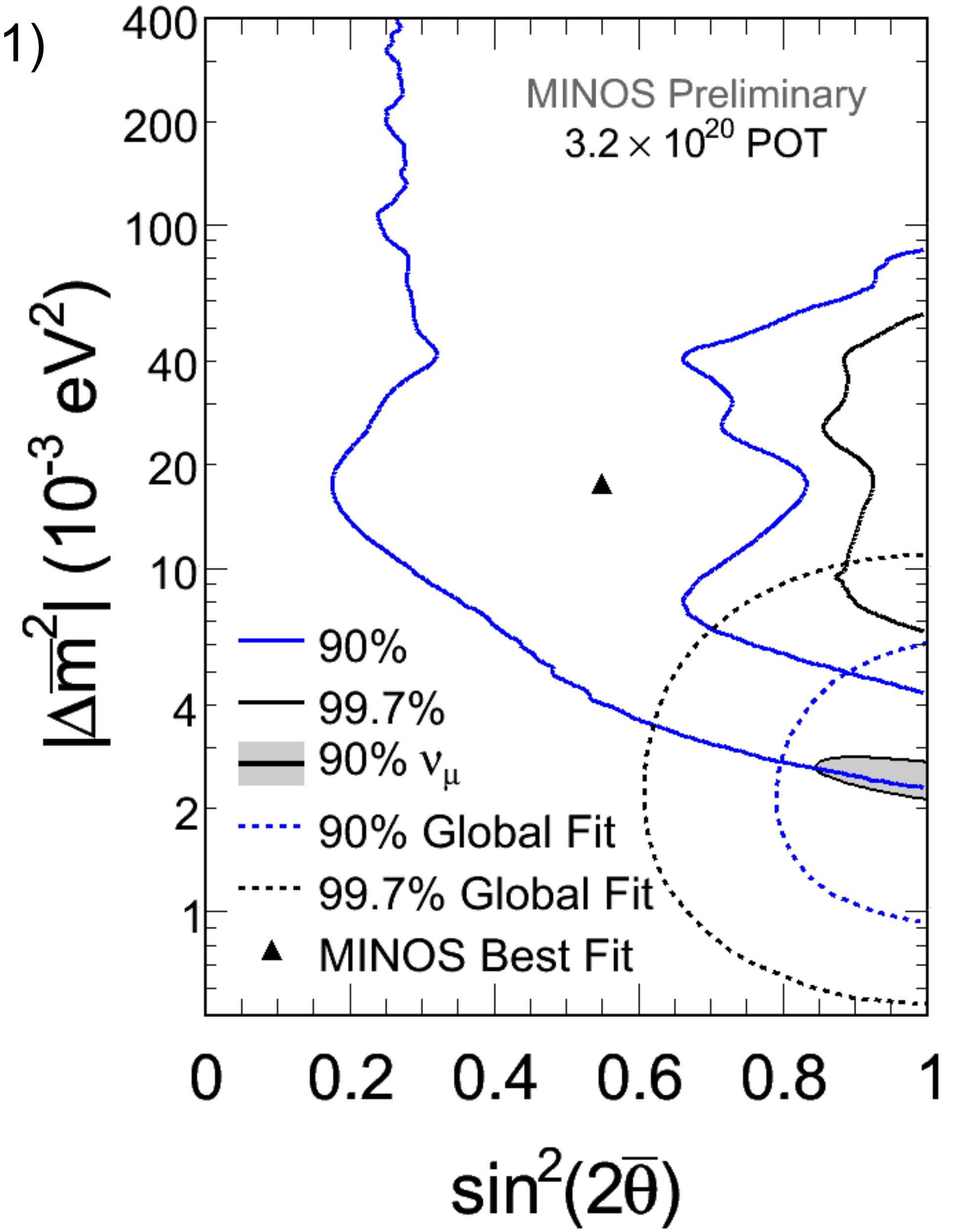


Oscillation result

- 2-parameter and 1-parameter (at $\sin^2(2\theta)=1$) binned maximum likelihood fit
- Best fit point at high Δm^2 due to overall deficit – Feldman-Cousin limits with systematic uncertainty incorporated
- No-oscillation scenario excluded at 99% , CPT invariance within 90%
- Excluded region at maximal mixing:

$(5.1 < \Delta m^2 < 81) \times 10^{-3}$ eV^2 (90% C.L.)





Global fit: M. C. Gonzales-Garcia and M. Maltoni, Phys. Rept. 460 (2008)

Transition result

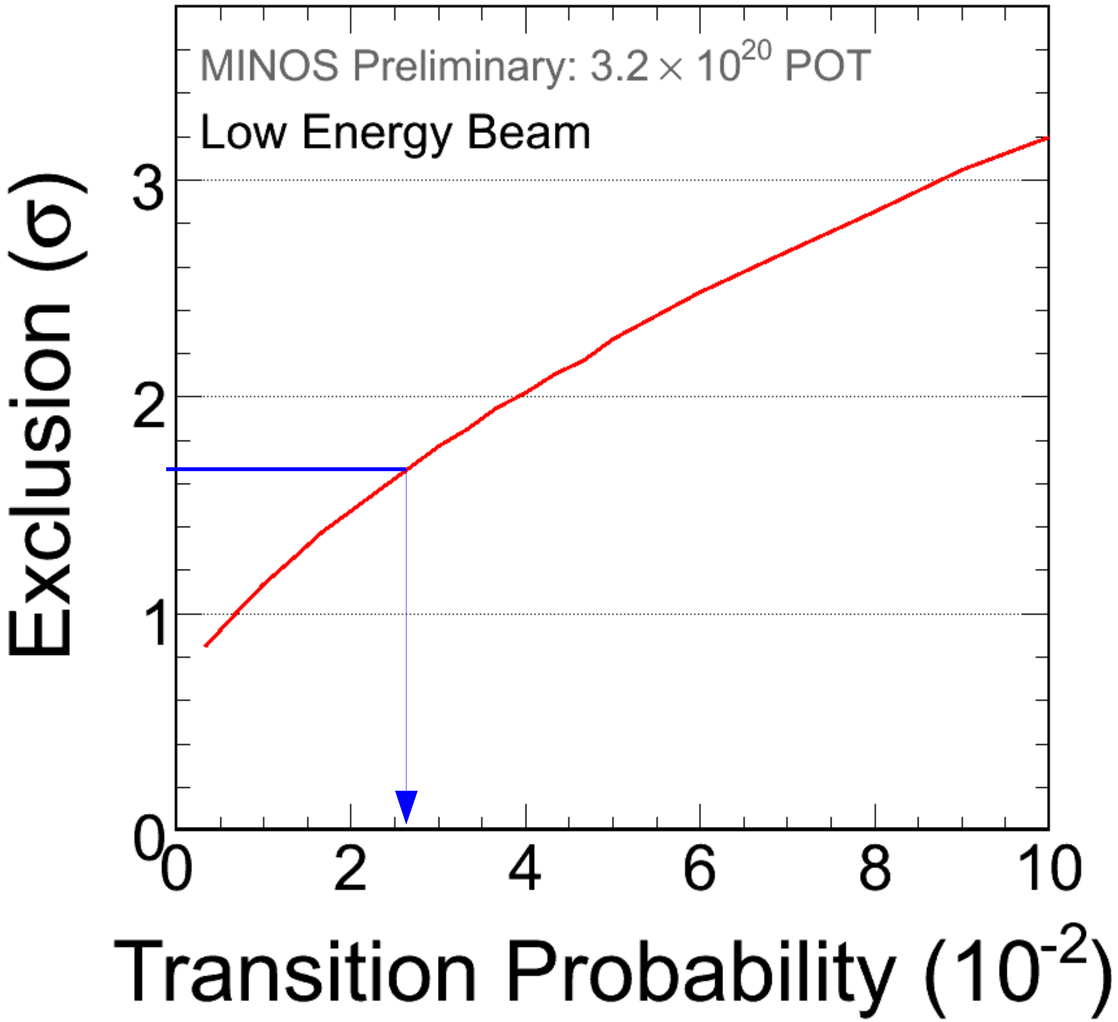
- No evidence for $\overline{\nu}_{\mu}$ appearance in the far detector
- 1-parameter fit for α using the parametrization

$$P(\nu_{\mu} \rightarrow \overline{\nu_{\mu}}) = \alpha \sin^2(2\theta)\sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$

(θ and Δm^2 set to best ν_{μ} oscillation parameter values)

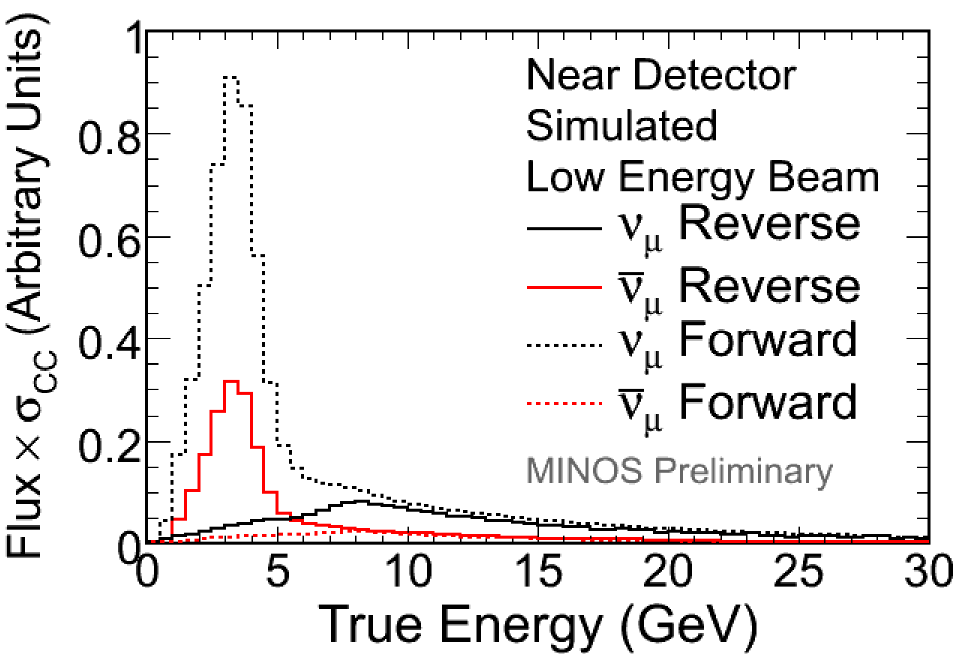
- FC limit on the fraction of nu that transition to nu-bar is

α < 2.6% (90% C.L.)

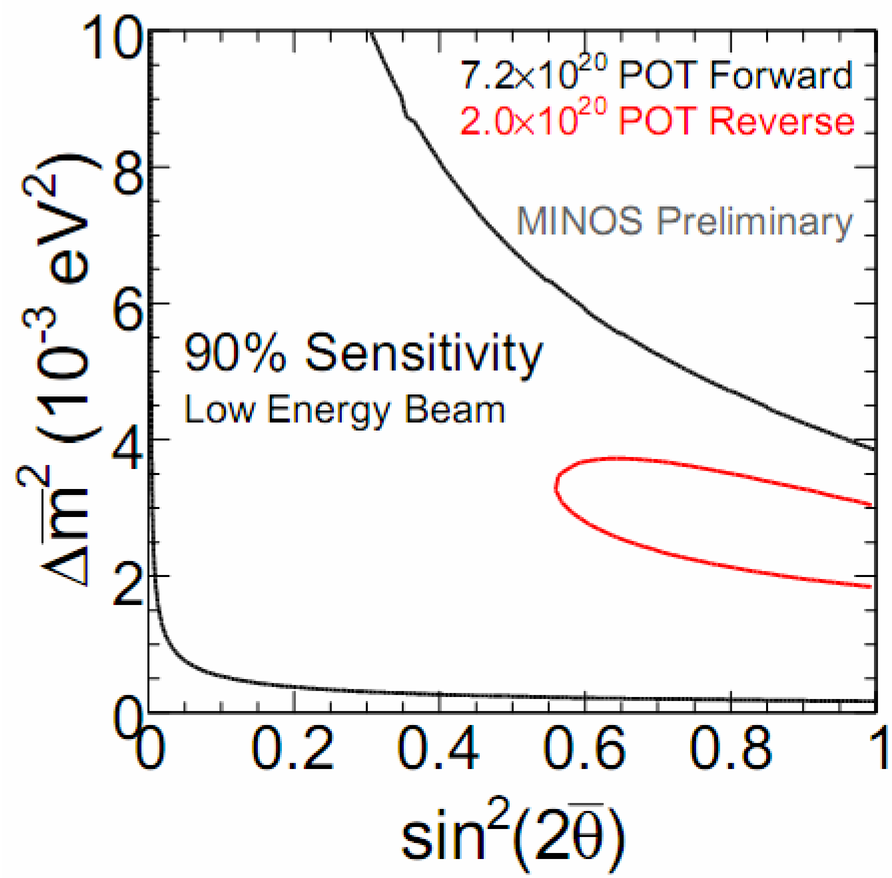


Future prospects

- Dedicated $\bar{\nu}_\mu$ running starts in September after reversing the current in the NuMI focusing horns
- Plan is to collect ~2x10^{20} PoT data in $\bar{\nu}_\mu$ mode



- Allow precision measurement of the oscillation parameters
- Improve limit on $|\Delta\bar{m}^2|$ by an order of magnitude
- 5δ observation of oscillation



Conclusion

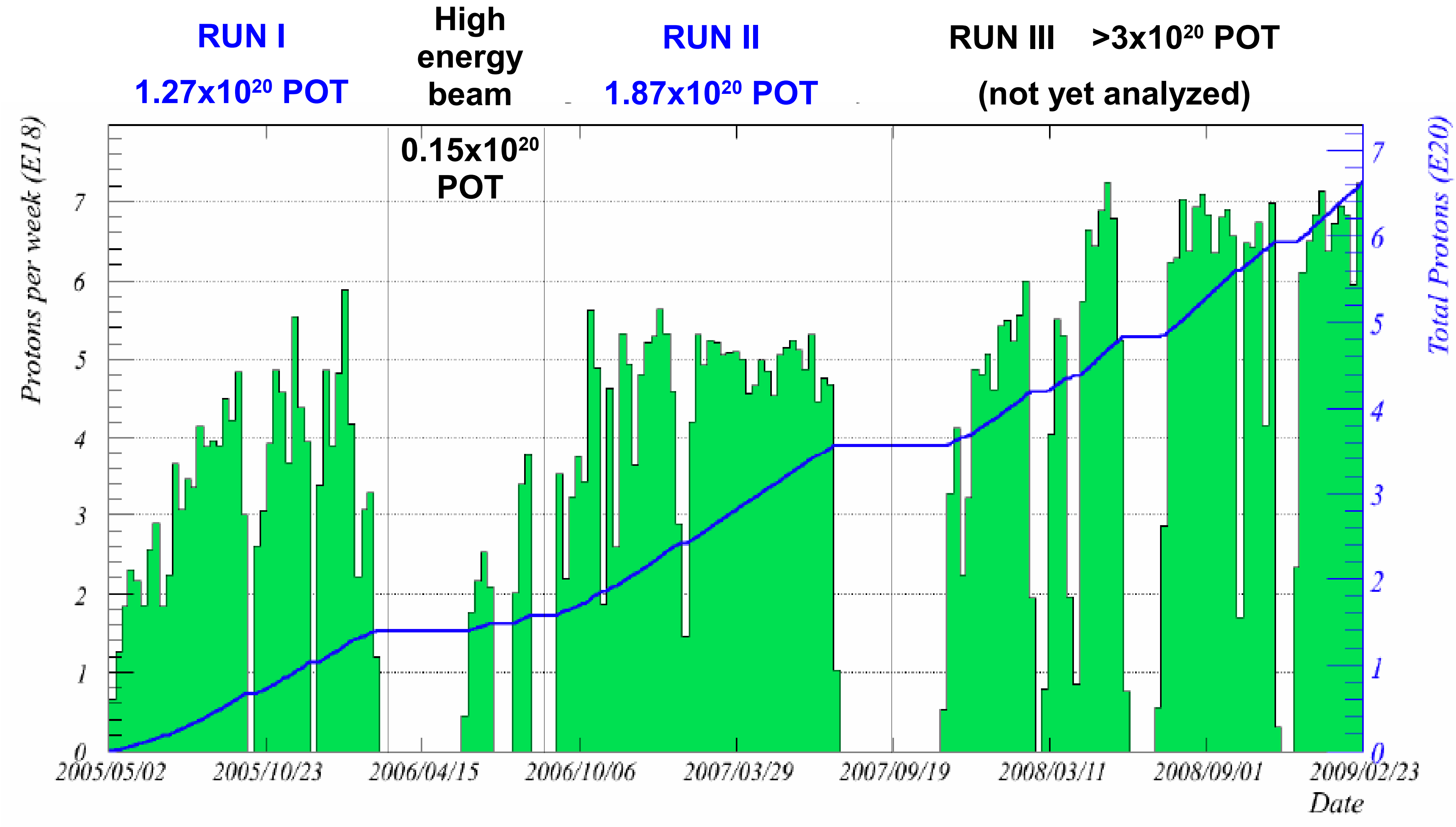
- First direct measurement of $\bar{\nu}_\mu$ in long-baseline accelerator experiment
  - separation achieved by using the magnetic field of the MINOS detectors
- CPT conserving oscillation parameters within 90% confidence limits
- Data excludes oscillation parameters at maximal mixing:

  $(5.1 < |\Delta\bar{m}^2| < 81)\mathrm{x}10^{-3}\ \mathrm{eV}^2$
- No $\bar{\nu}_\mu$ appearance observed

  Limit on the fraction of ν_μ transitioning to $\bar{\nu}_\mu$: $\alpha < 2.6\%$ (90% C.L.)
- Stay tuned for improved measurement with dedicated $\bar{\nu}_\mu$ beam in near future

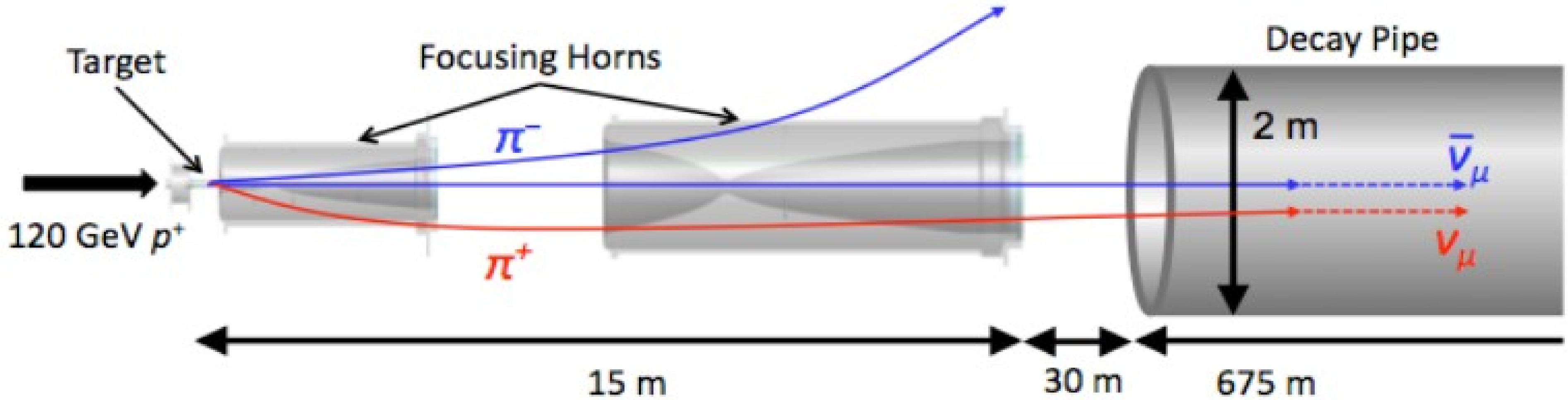
Extra slides

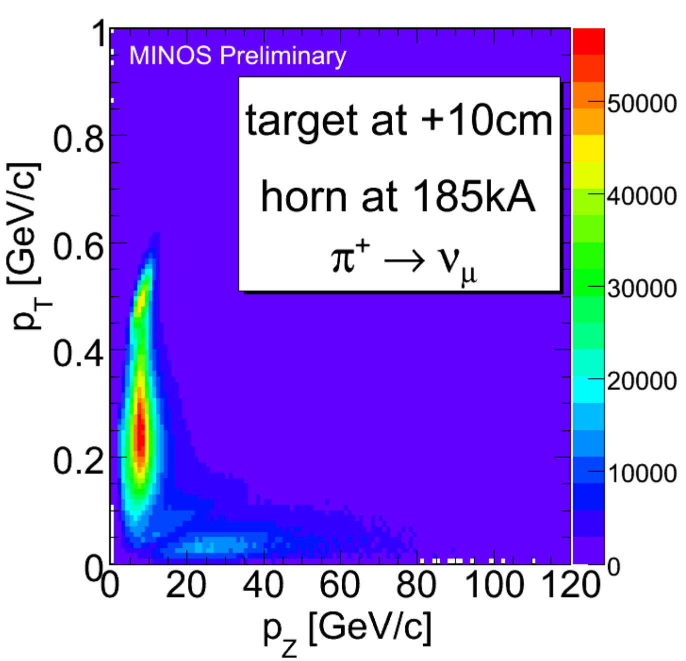
MINOS data

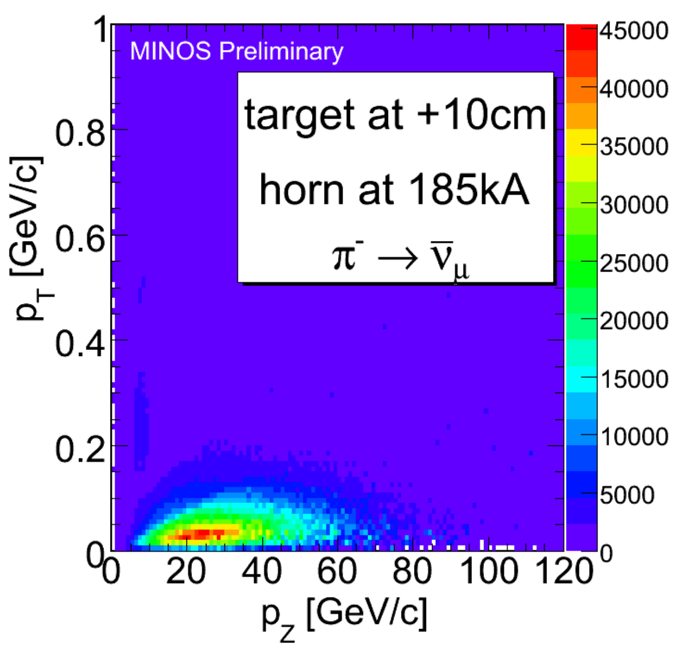


- $\overline{\nu}_\mu$ analysis used Run I + II data: 3.1×10^{20} PoT total

Why are the spectra so different?



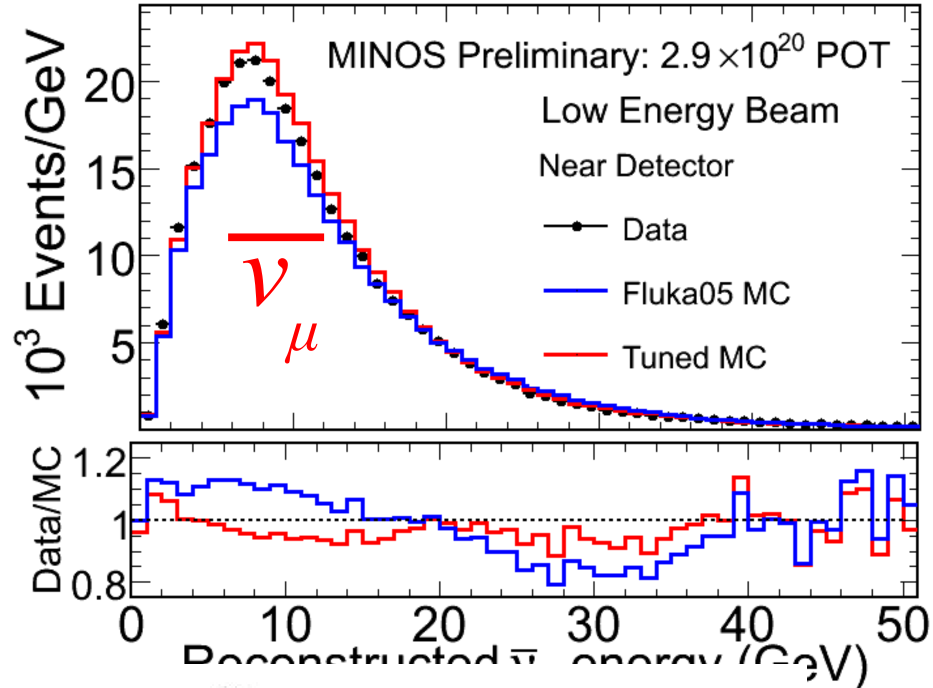




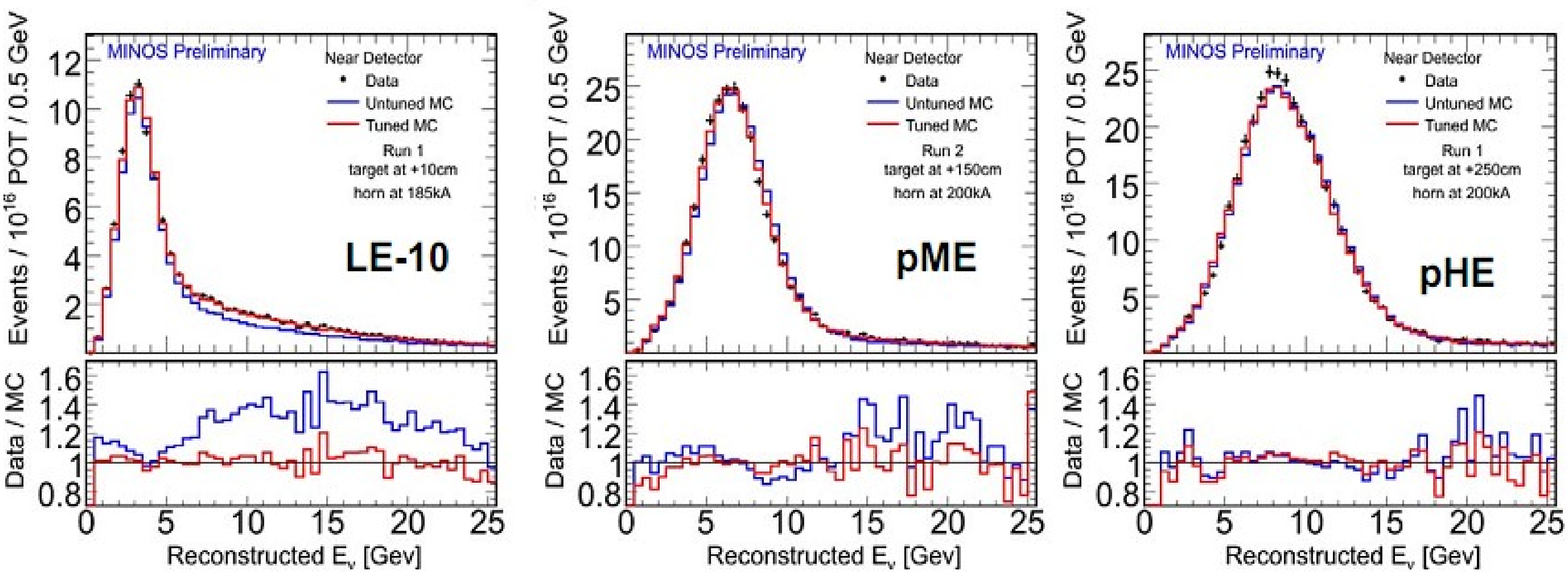
- Majority of nu-bar comes from neck-to-neck pi- parents traveling down the center of the horns
- Nu-bar spectrum dominated by low-p_t parents

Tunning the hadron production

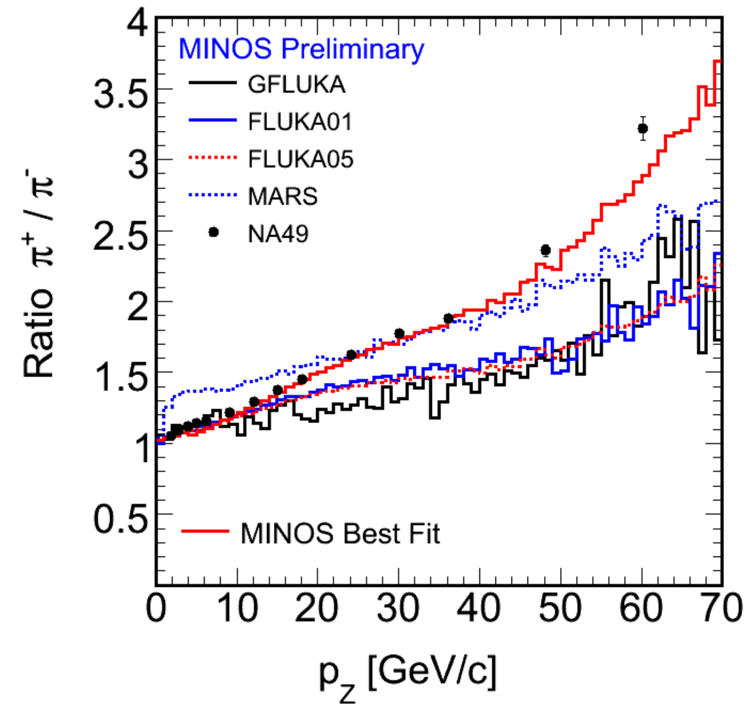
- Hadron production from target is parametrized as a function of p_t and p_z and fit to near detector data at different beam energies
- Constrains π^+ production well but not π^-
  - $\bar{\nu}_\mu$ spectrum remains the same within 10% in all beam config.



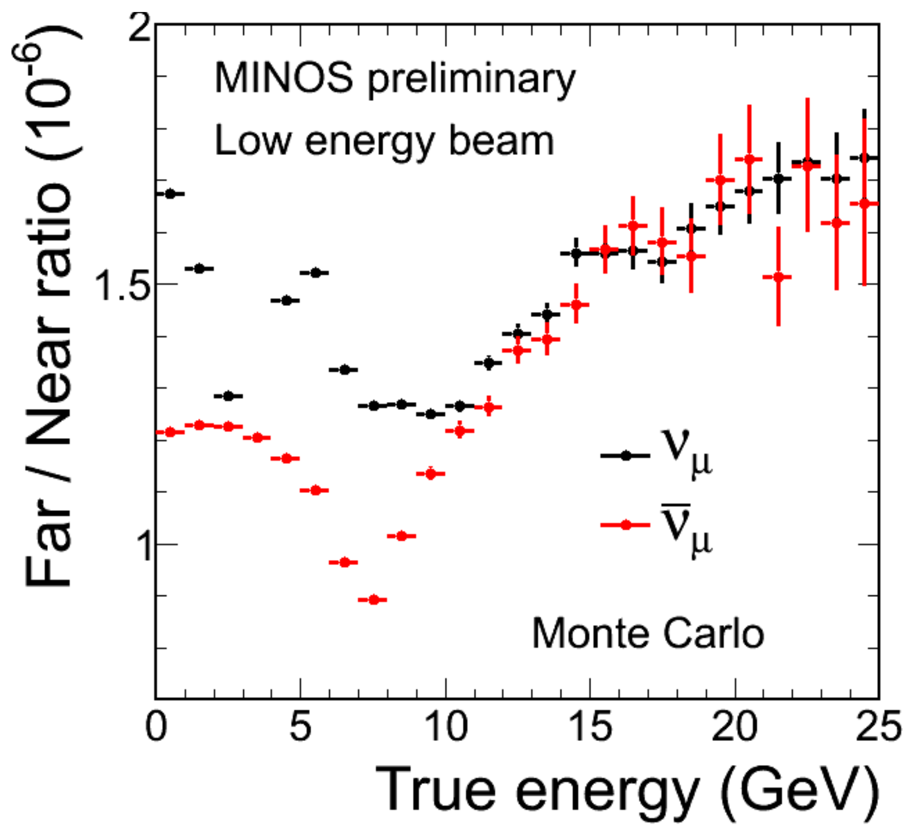
ν_μ



- Ratio of π^+/π^- production after tuning agrees well with recent NA49 data (Eur. Phys. J. C49 (2007) 897)

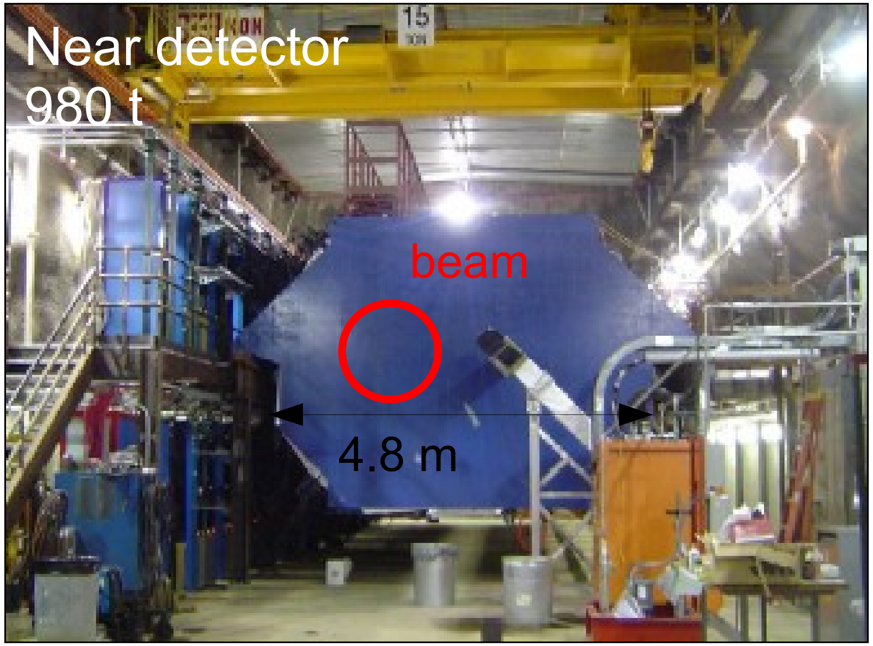


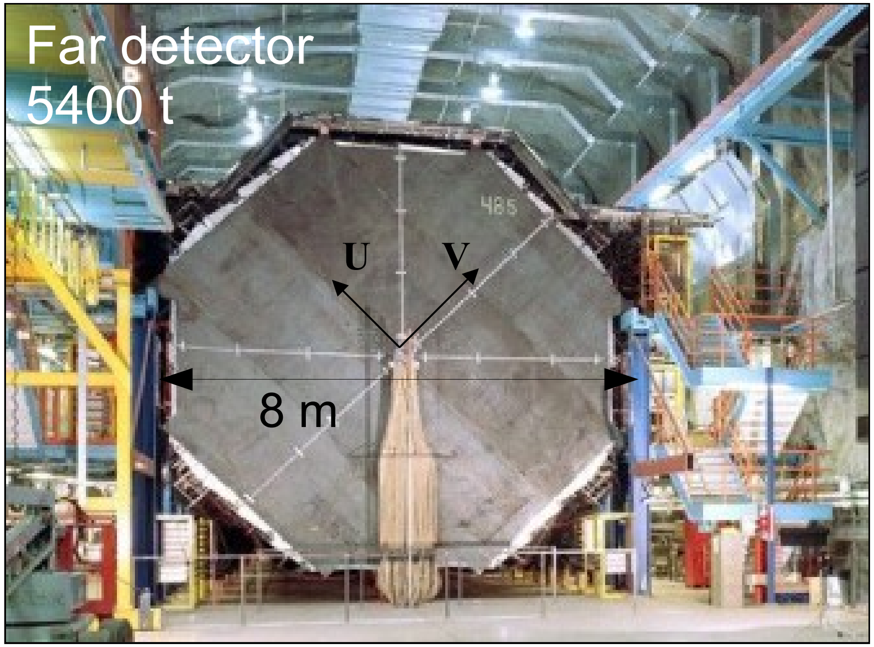
- Data driven hadron production cross check
- ν_μ and $\bar{\nu}_\mu$ far/near ratio is almost identical above 10 GeV
- $\bar{\nu}_\mu$ high energy tail in data agrees well with prediction
- constrains ν_μ prediction within 10% above 10 GeV

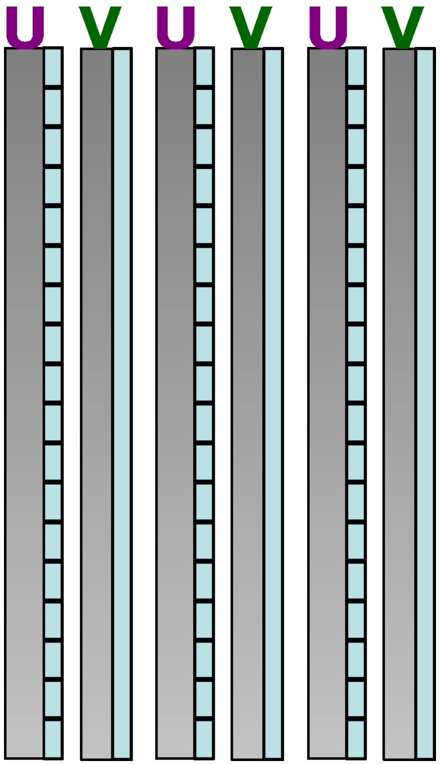


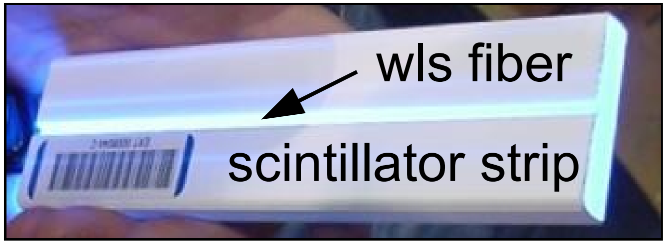
MINOS detectors

- 1 inch thick iron planes
- Extruded scintillator strips in orthogonal (u and v) orientation in alternating planes
- Light transmitted by optical fiber to multi-anode PMTs
- Toroidal magnetic field









Magnetic field

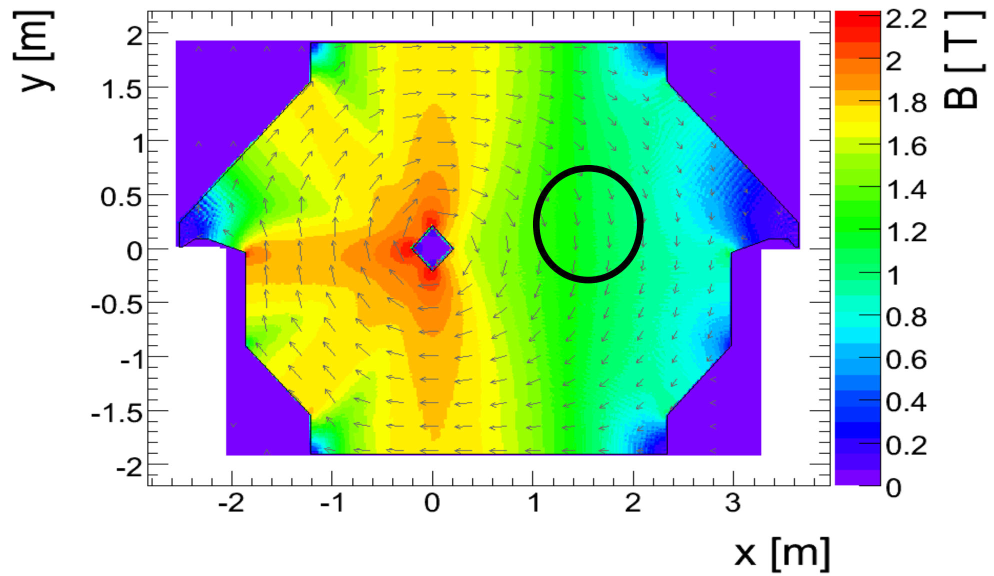
- Coils running at the center along the detector length produce toroidal field
- Average field strength in fiducial volume:

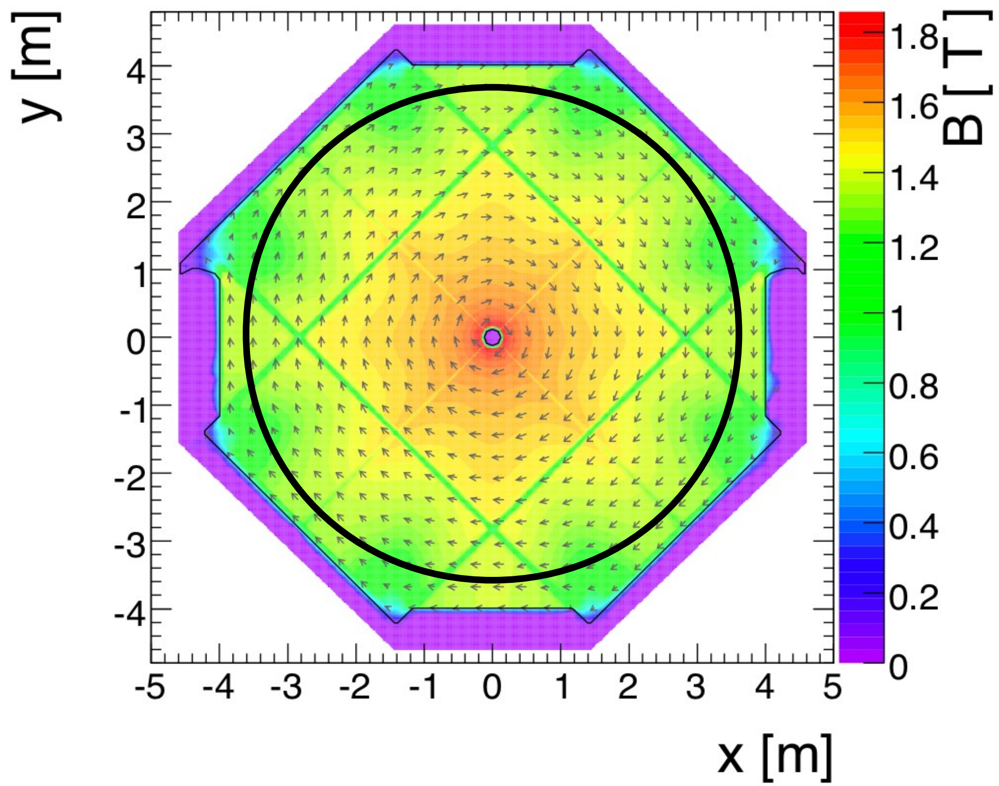
  ND: <B> ~1.3 T

  FD: <B> ~1.4 T

- Existing data is taken in forward coil current:

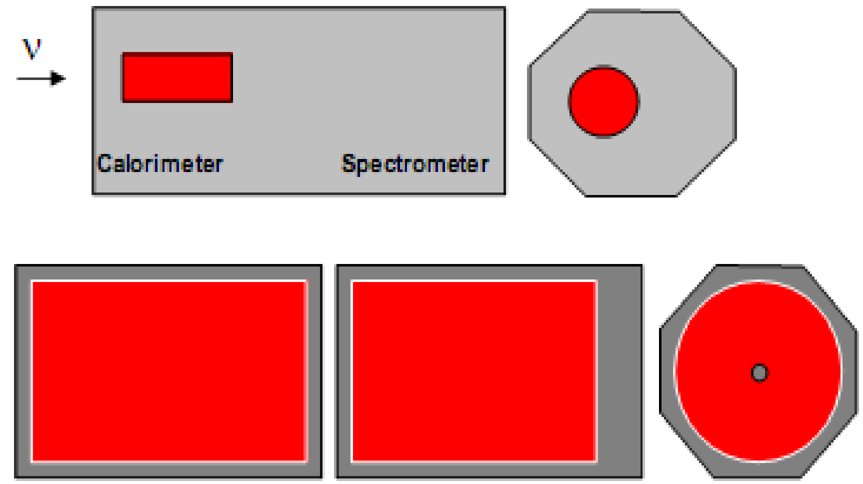
  μ^- (μ^+) are (de-)focused towards (away) from the coil

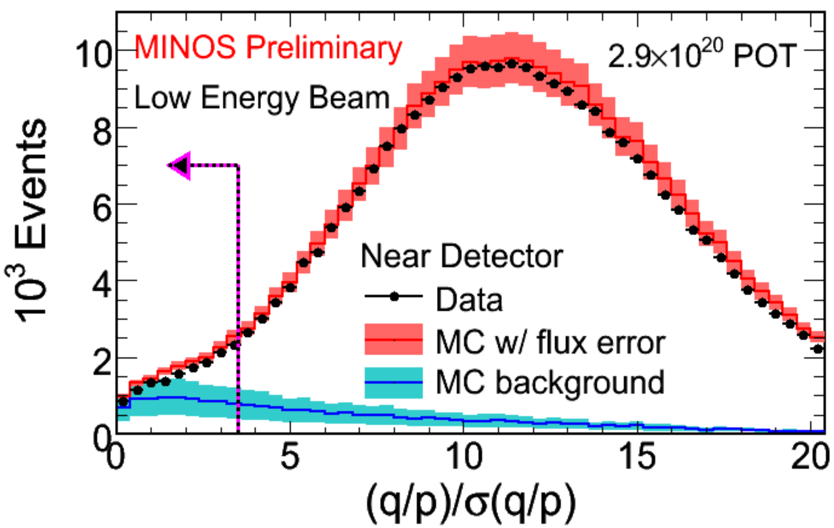


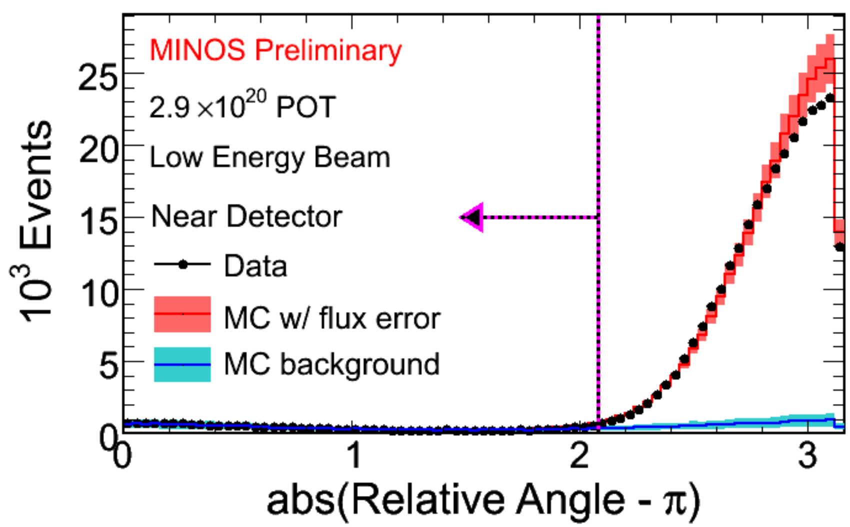


Additional nu-bar selection

- At least one reconstructed track
  - Longest track identified as muon candidate
- Vertex inside fiducial volume (for hadronic shower containment and cosmic muon rejection)
- Further cosmic muon suppression in far detector by muon angle (cosθ>0.6) and event timing (within 14μs of beam spill) requirement
- Charge sign selection

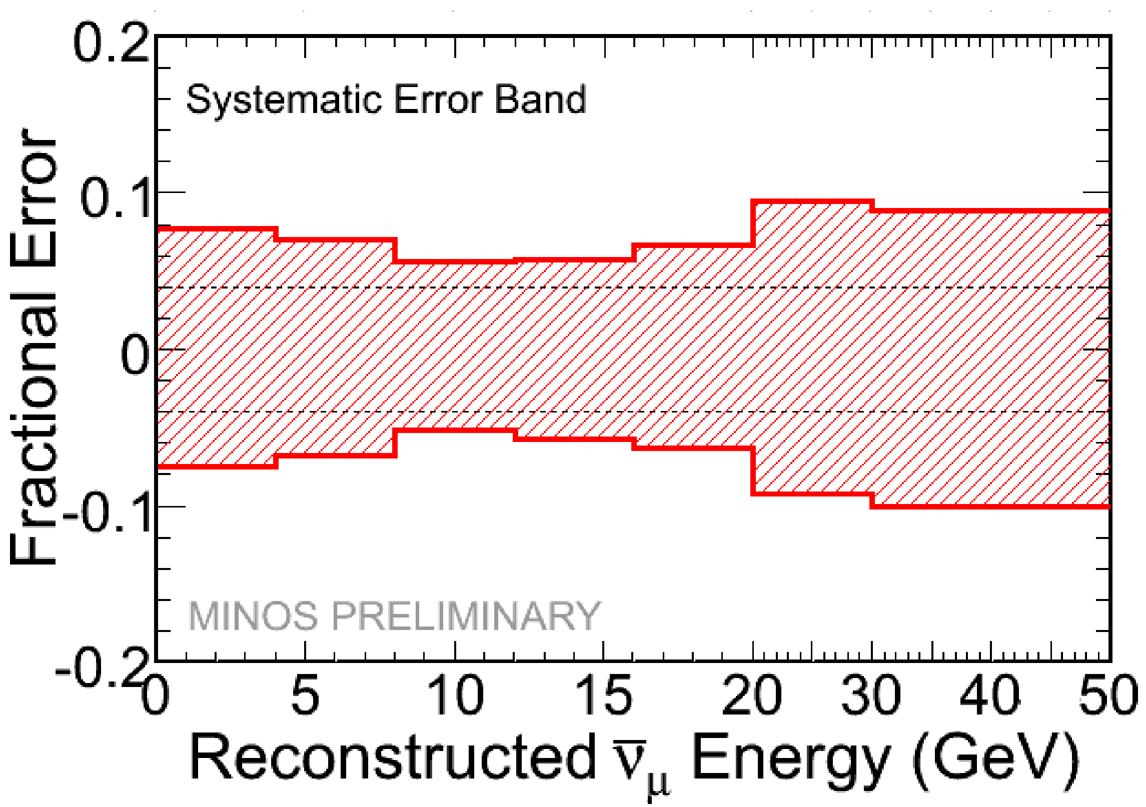






Systematic uncertainties

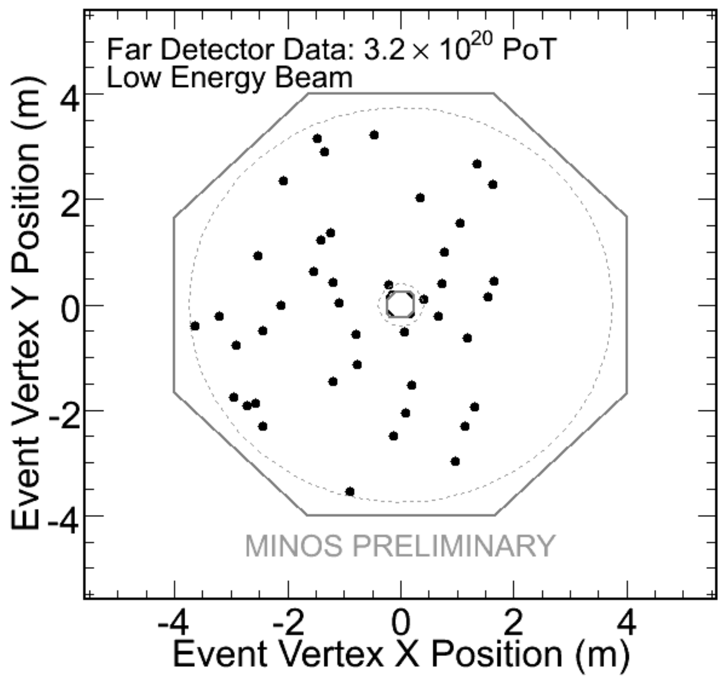
- Uncertainties common with ν_μ analysis:
  - Normalization: 4% (relative reconstruction eff., detector live time and mass)
  - Muon energy from range (curvature): 2% (4% , slightly higher due to more exiting tracks)
  - Relative (absolute) shower energy: 3% (10%)
  - Beam extrapolation
- ν_μ uncertainties:
  - Downstream (decay pipe) production: 40%
  - Background: 50%
- Total systematic uncertainty is < 10% over all energies

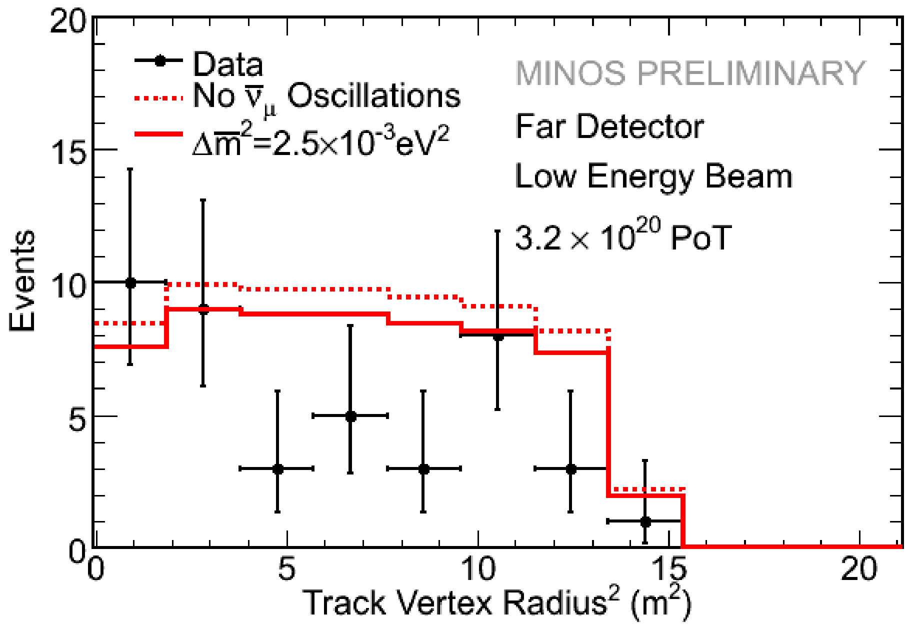


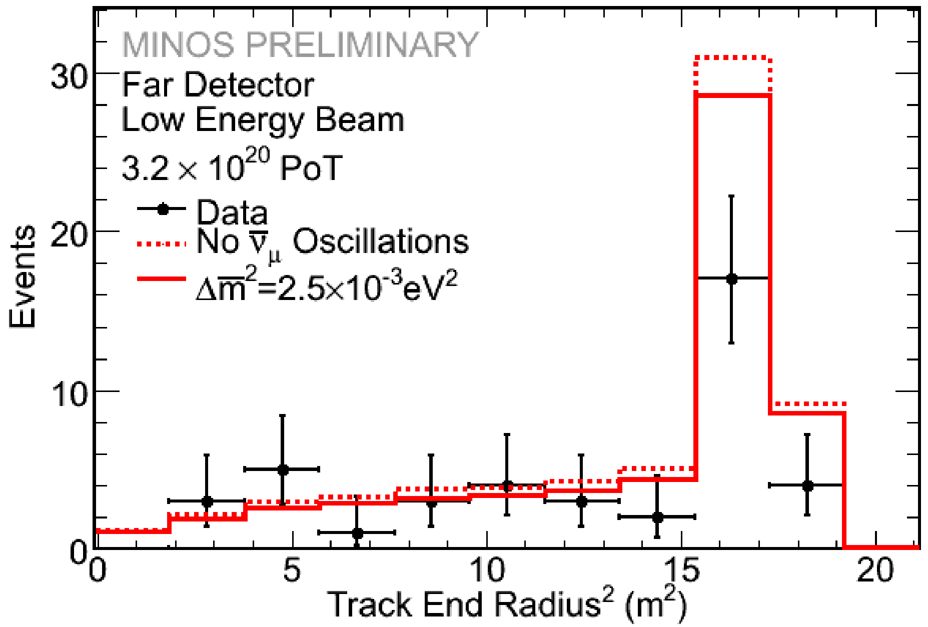
Extensive cross checks

- Analysis performed with an independent event selection
- Used two independent extrapolation methods
- Checked muon charge sign assignment with independent track fitter
- Hand scan of all far detector events with positive track; events with negative track ending at the detector edge; and events with no reconstructed track
- Checked track finding efficiency, in particular exciting track, using stopped and through going cosmic muon samples

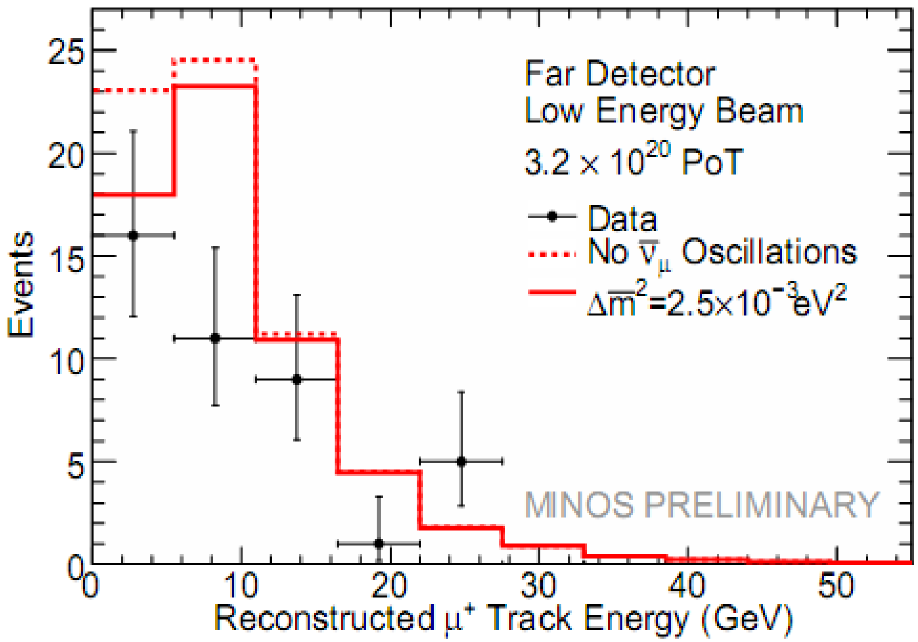
Far detector events

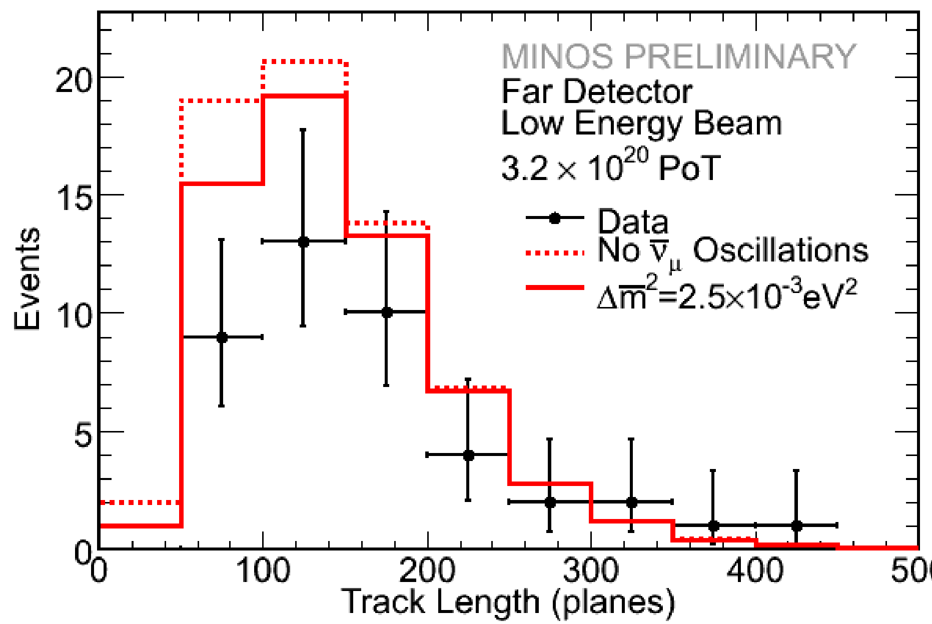






- Typical "missing" events have ~10 GeV muon that travel ~100 planes
  - Hard to miss or misidentify





Selection variables (far detector)

Background agrees with MC prediction

- No sign of excess