# MINOS unplugged

## *Not only the latest beam results…*

**OUTLINE**

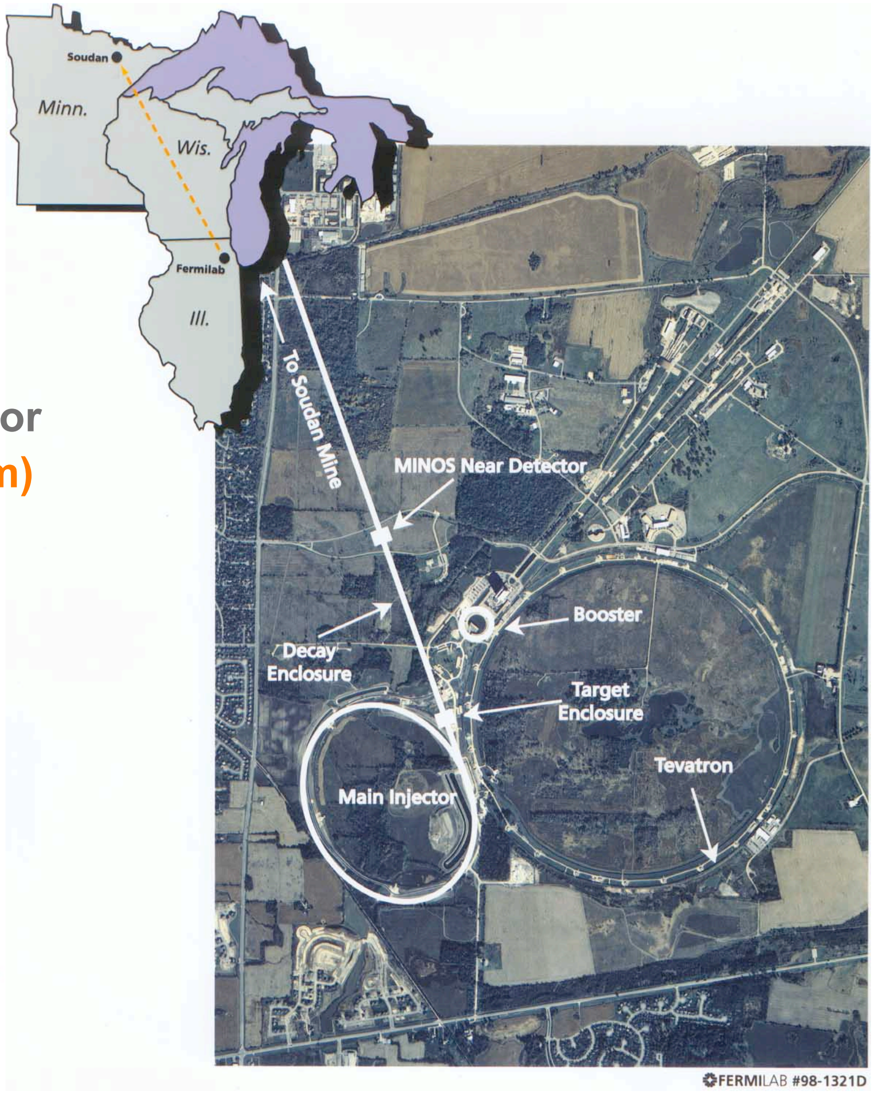
- The tools (beam, detectors, CR shield)
- Latest beam results
  - **New** results with anti-neutrinos
  - latest results with the Near Detector
- Old and new results with CR
  - Contained events and upward-going muons
  - Charge-separated muon rates and stratosphere
- Summary / outlook

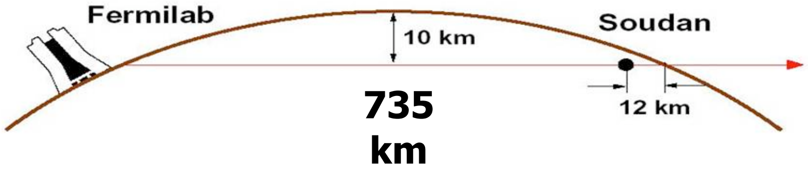
# MINOS

## **M**ain **I**njector **N**eutrino **O**scillation **S***tudies*

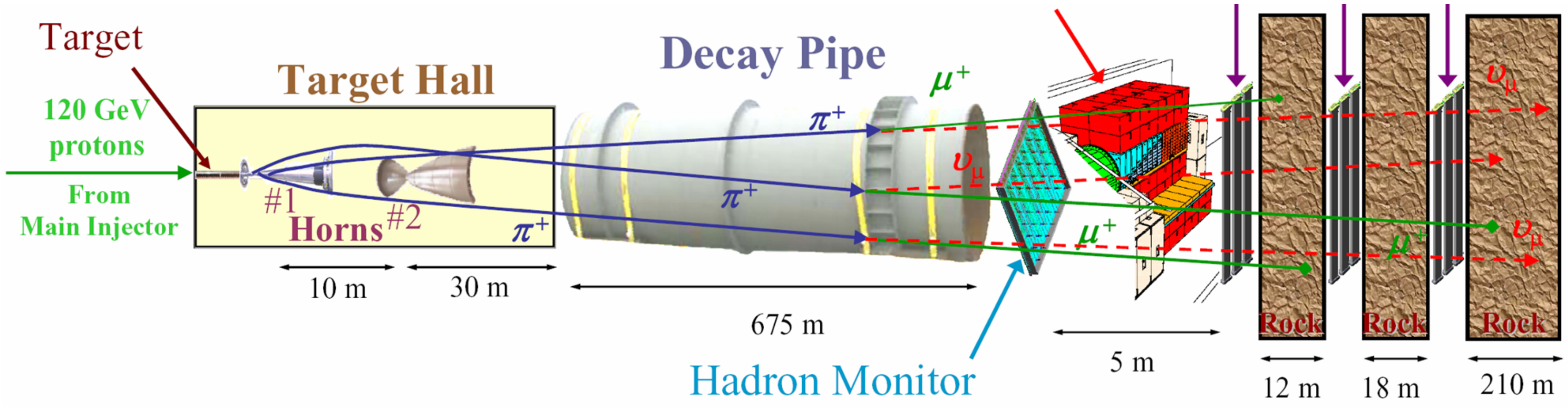
### Strategy for precision measurements:

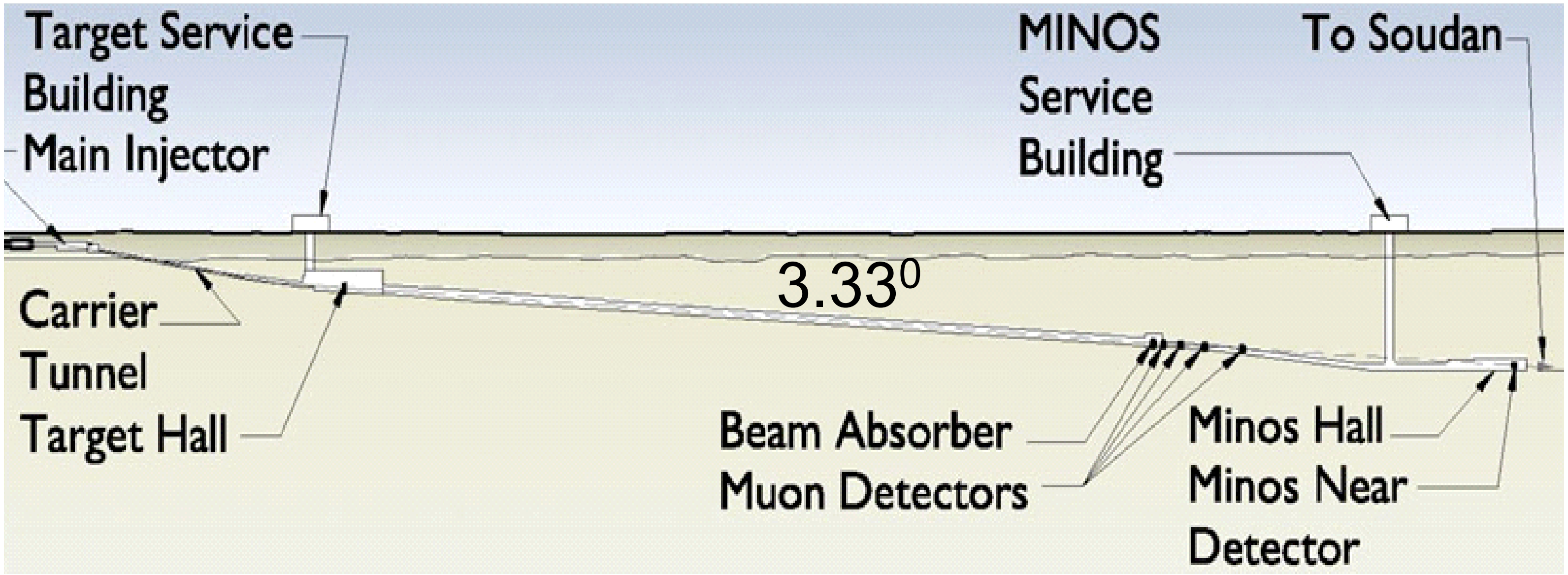
- Two-detector measurement
  - ⇨ long baseline (735km)
  - ⇨ underground (CR shielding + physics)
- High intensity beam from 120 GeV Main Injector
  - ⇨ (up to) $4x10^{13}$ protons/pulse (0.4 MW beam)
    (potential for ~$4x10^{20}$ protons/year)
  - ⇨ single turn extraction (8.67 μs)
- Flexible & well-controlled beam
  - ⇨ two parabolic magnetic horns
  - ⇨ movable target (→energy spectrum)





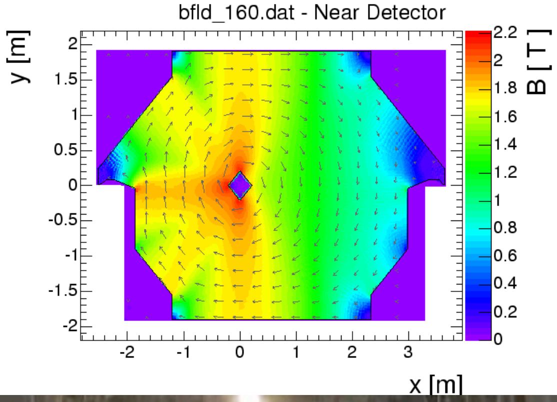
# Experimental setup: NuMI beam





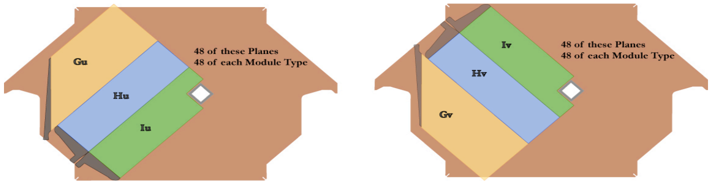
# Near Detector – 1,040 m from the target at Fermilab

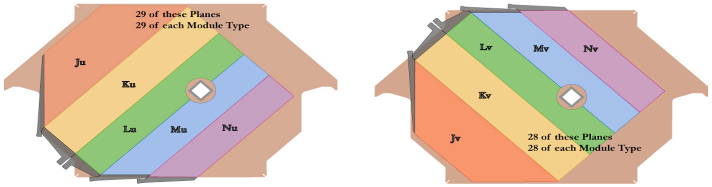
- ◆ veto - target - μ spectrometer
- ◆ mass = 1 kT
- ◆ 153 scintillator planes
- ◆ QIE-based front-end
- ◆ 3.8 x 4.8 “squeezed” octagon
- ◆ 12,300 scint.strips
- ◆ 1-end readout
- ◆ no-multiplexing
- ◆ 220 M64s
- ◆ 282 steel planes
- ◆ 65 km WLS fiber
- ◆ 51 km clear fiber



103 m underground

ν target region





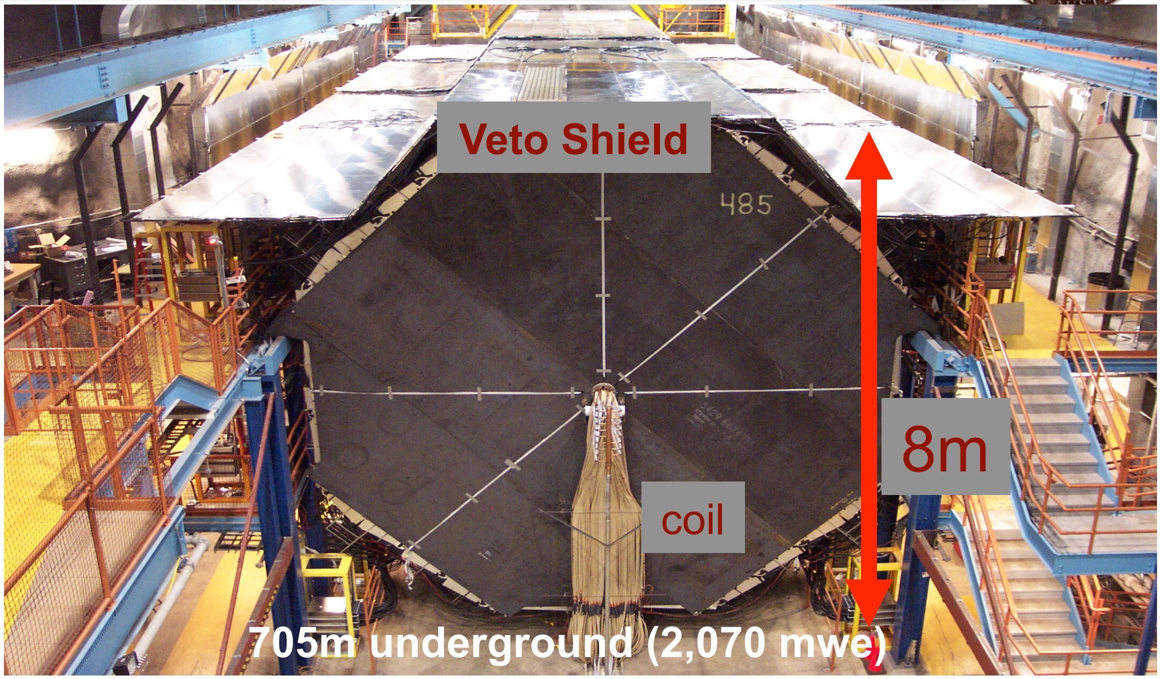
μ spectrometer region

View of the Near Detector Hall nearing end of detector construction

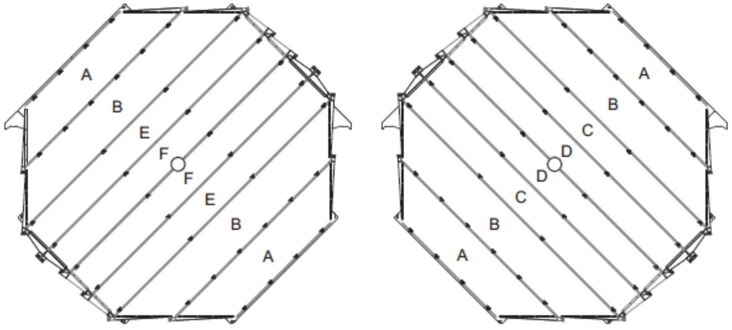
# Far Detector – 735.3 km away
(Soudan Mine, Mn)

## Running since July 2003

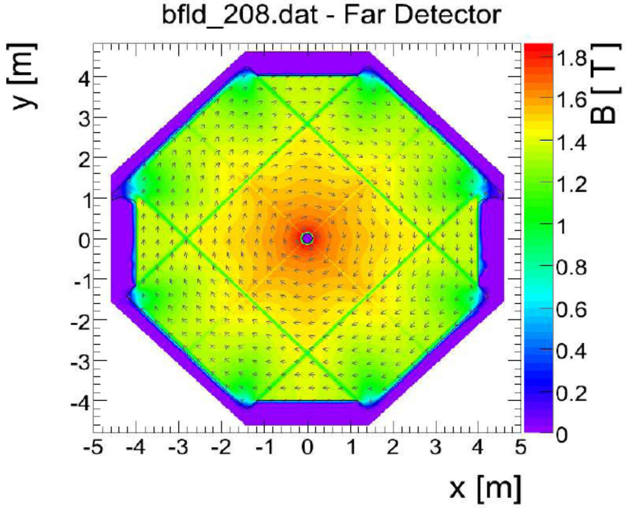
- 2 Supermodules
- 5.4 kT
- 484 scint. planes
- CR veto shield (2,070mwe)
- B ~ 1.5T (R=2m)
- 93,120 strips (4.1 x 1.0 cm)
- 8-fold MUXed 2-ended readout
- 1551 M16s
- 722 km of WLS fiber
- 794 km of clear fiber
- HAD = 56% / $E^{1/2}$
- EM = 23% / $E^{½}$



705m underground (2,070 mwe)



**Scintillator Plane**
**(8 modules, 192 strips)**



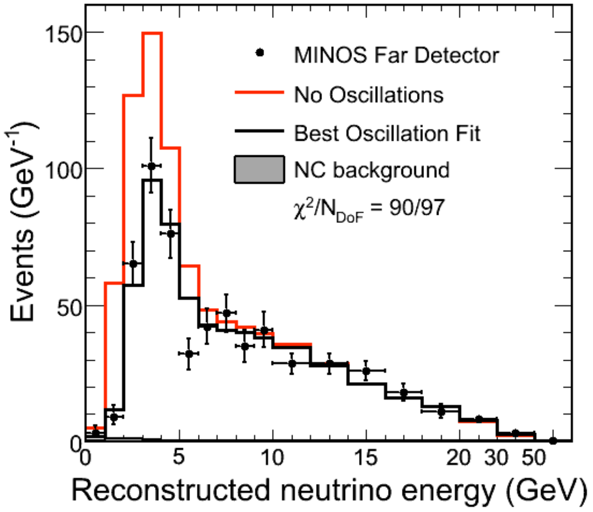
### Physics with the

# FAR DETECTOR

# MINOS disappearance highlights
# (based on 3.36x$10^{20}$ protons on target)

PRL **101,** 131802 (2008) PHYSICAL REVIEW LETTERS week ending 26 SEPTEMBER 2008

**Measurement of Neutrino Oscillations with the MINOS Detectors in the NuMI Beam**



Constrained ($\sin^2(2\theta)$=1.) fit

$|\Delta m|^2$ =(2.43±0.13) x $10^{-3}$ $eV^2$

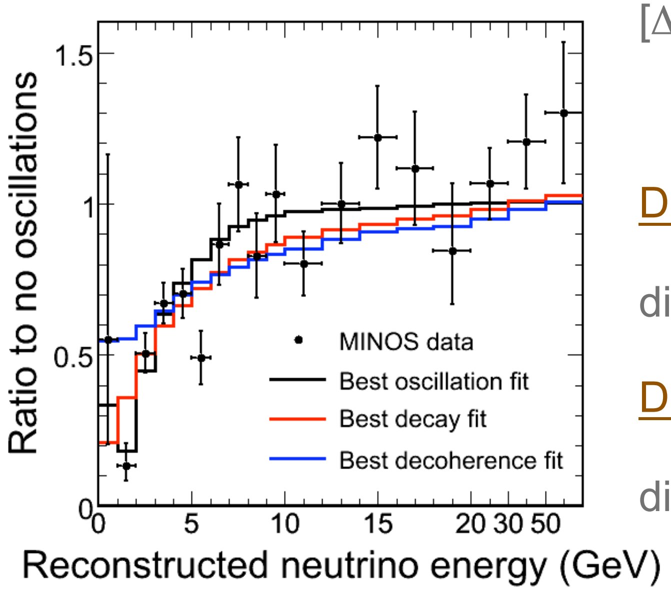
$\sin^2(2\theta)$ > 0.95 [ $\chi^2$/ndof = 90/97, 68% C.L.]

Unconstrained fit:

$|\Delta m|^2$ = 2.33 x $10^{-3}$ $eV^2$

$\sin^2(2\theta)$=1.07

[$\Delta\chi^2$=-0.6]



Decay

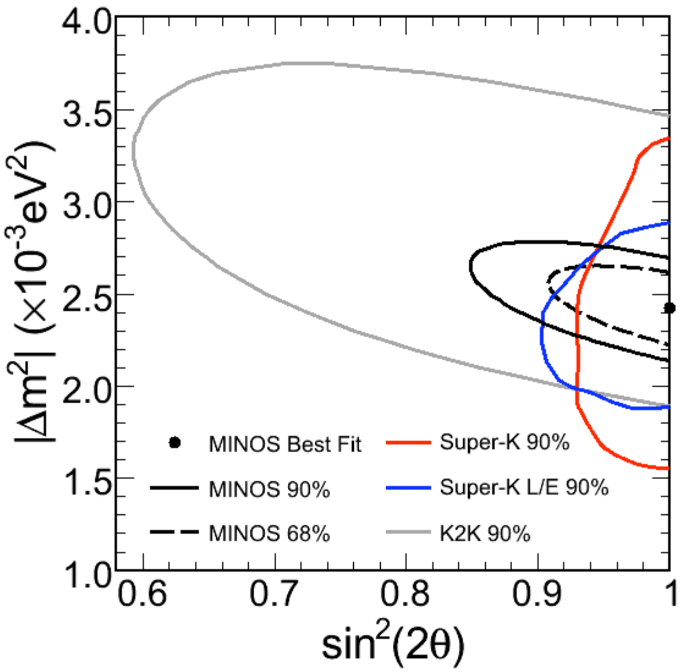
$\chi^2$ = 104/97

disfavored at 3.7σ

Decoherence

$\chi^2$ = 123/97

disfavored at 5.7σ



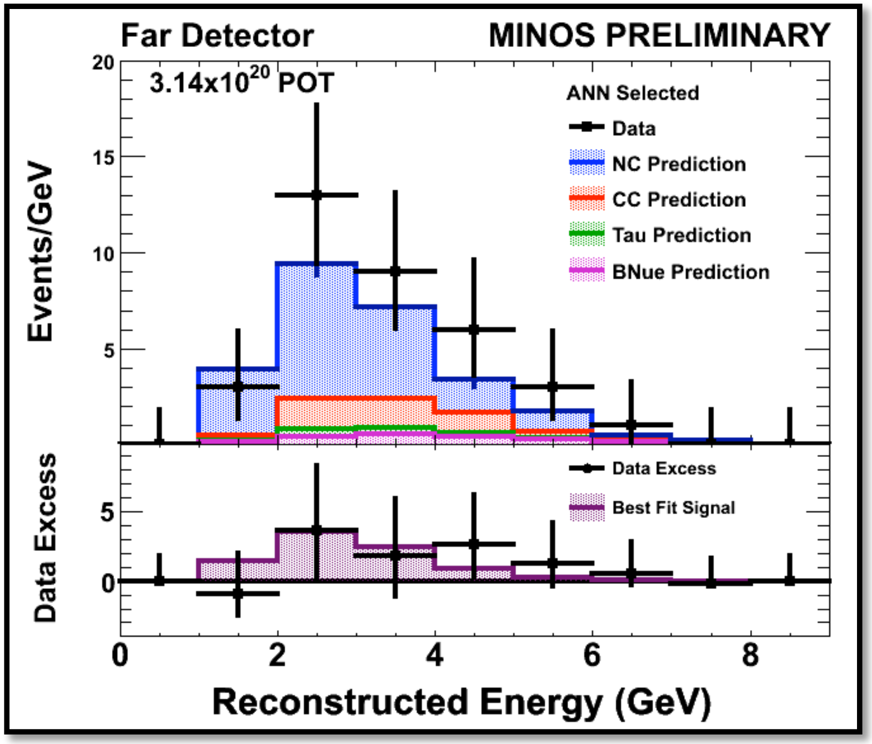
P. Adamson *et al*., Phys. Rev. Let. **101**,131802 (2008)

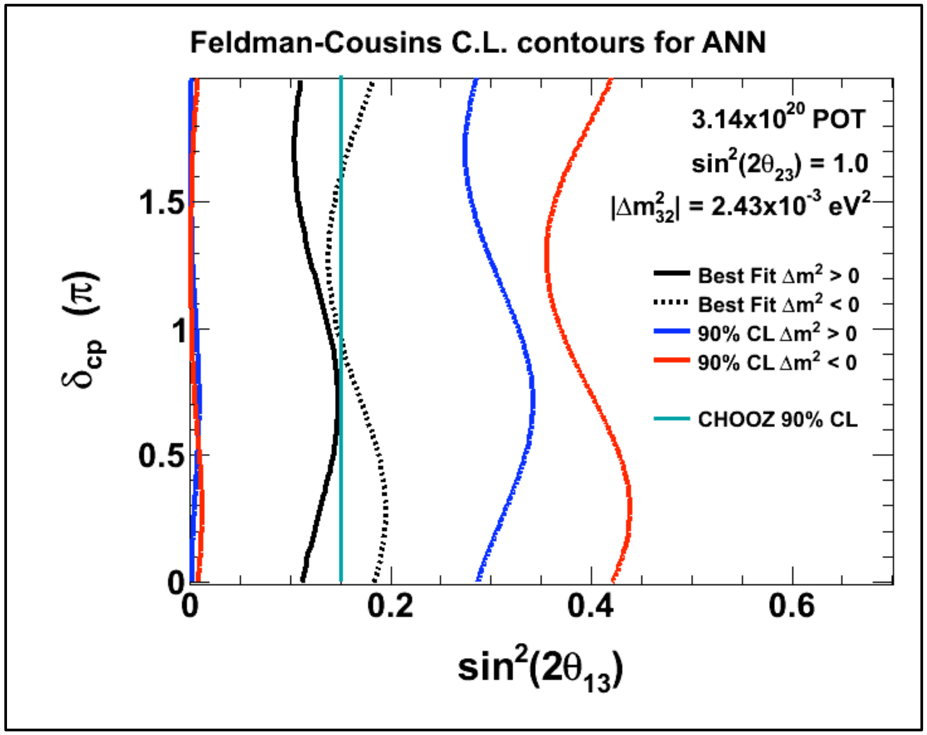
# $\nu_e$ appearance

(based on $3.36 \times 10^{20}$ protons on target)

- Expect: 27 ± 5(stat) ± 2(syst)
- Observed: 35 events
- Observed is 1.5σ higher than background expectation

- We do observe a similar sized excess of events in a (independent, signal-less) sideband region





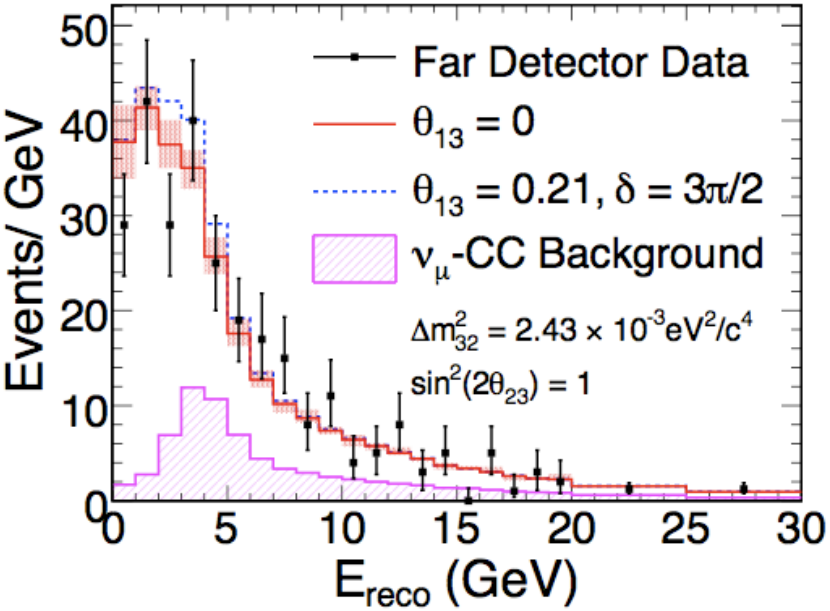
# A search for $\nu_\mu \rightarrow \nu_{sterile}$
## (based on $2.46\text{x}10^{20}$ protons on target)

PRL **101,** 221804 (2008) PHYSICAL REVIEW LETTERS week ending 28 NOVEMBER 2008

**Search for Active Neutrino Disappearance Using Neutral-Current Interactions in the MINOS Long-Baseline Experiment**

For $E_{vis} < 3$ GeV:
$f_s < 0.35$, 90% C.L.

For $E_{vis} < 120$ GeV:
$f_s < 0.17$, 90% C.L.



$$P_{\nu_\mu \rightarrow \nu_\mu} = 1 - \alpha_\mu \sin^2(1.27\Delta m^2 L / E)$$

$$P_{\nu_\mu \rightarrow \nu_e} = \alpha_e \sin^2(1.27\Delta m^2 L / E)$$

$$P_{\nu_\mu \rightarrow \nu_s} = \alpha_s \sin^2(1.27\Delta m^2 L / E)$$

$$P_{\nu_\mu \rightarrow \nu_\tau} = 1 - P_{\nu_\mu \rightarrow \nu_\mu} - P_{\nu_\mu \rightarrow \nu_e} - P_{\nu_\mu \rightarrow \nu_s}$$

$$f_s \equiv \frac{P_{\nu_\mu \rightarrow \nu_s}}{1 - P_{\nu_\mu \rightarrow \nu_\mu}}$$

| Energy Range (GeV) | Data | MC | Significance ($\sigma$) |
|---|---|---|---|
| 0-3 | 100 | 115.16 ± 7.67 | 1.15 |
| 0-5 | 165 | 175.92 ± 10.42 | 0.65 |
| 0-120 | 291 | 292.63 ± 15.02 | 0.10 |

PHYSICAL REVIEW D **76**, 072005 (2007)

# Measurement of neutrino velocity with the MINOS detectors and NuMI neutrino beam

- Previous measurements constrained muon and muon-neutrino interaction time difference $|v-c|/c < 4\times10^{-5}$ for E > 30 GeV over 500 m (FMMF collab. at FNAL)
- MINOS
  - Measure absolute times ND to FD
  - Distance of 734 km
  - we make the unique measurement of comparing the energies of neutrinos in charged-current (CC) interactions to the interaction times in the FD
- The measurement
  - The time of a neutrino interaction in the ND is taken as time of the earliest scintillator hit, $t_{ND}$
  - This time is compared to the time of extraction magnet signal, $t_0$ *and* corrected for known timing delays:

    $t_1 = t_{ND} - t_0 - d_{ND}$
  - for FD events, $t_2 = t_{FD} - t_0 - d_{FD}$
  - $\delta = (t_2 - t_1) - \tau$

$$P_2^n(t_2) = \int \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{(t_2 - t')^2}{2\sigma^2}\right) P_1^n(t')dt' \qquad (n = 5, 6).$$

$$\sigma = 150 \text{ ns}$$

$$L = \sum_i \ln P_2(t_2^i - \tau - \delta).$$

$$\delta = -126 \pm 32(\text{stat.}) \pm 64(\text{syst.}) \text{ ns} \qquad 68\%\text{C.L.}$$

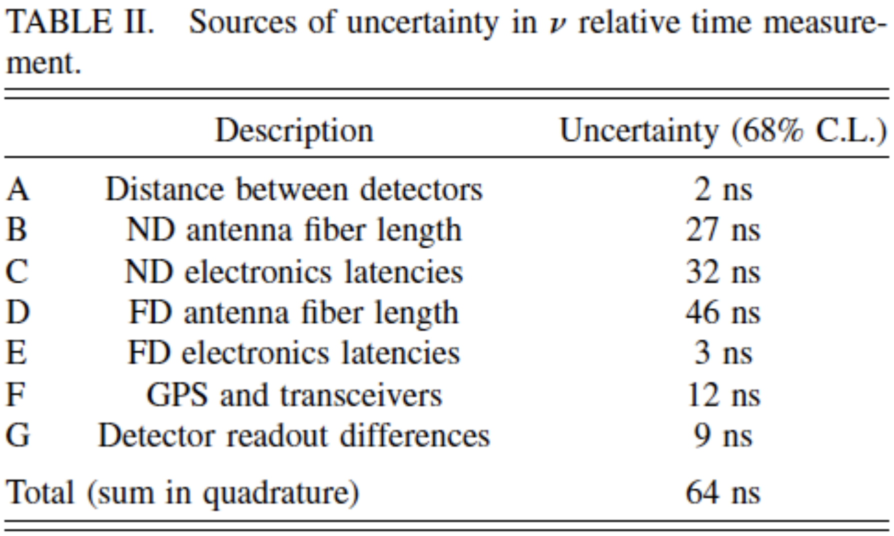
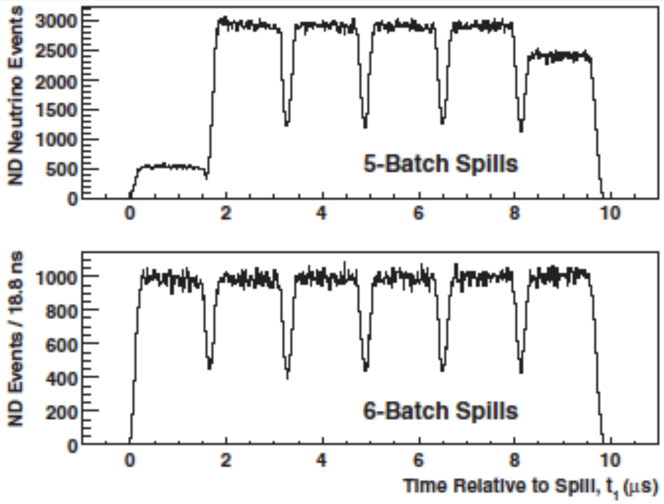


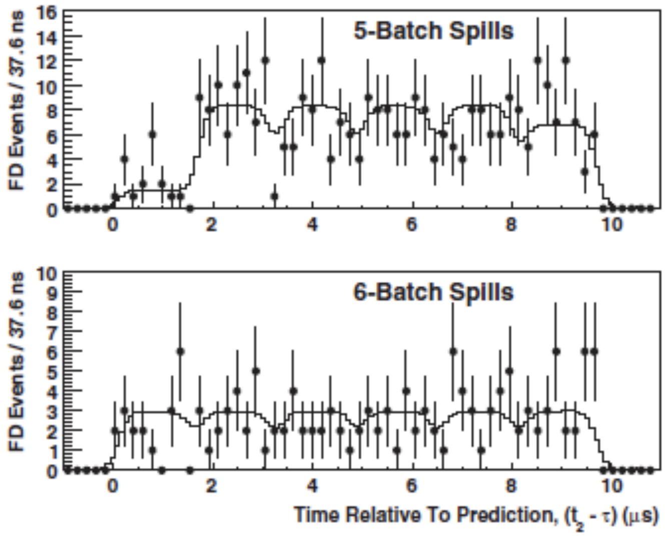
TABLE II. Sources of uncertainty in $\nu$ relative time measurement.

| | Description | Uncertainty (68% C.L.) |
|---|---|---|
| A | Distance between detectors | 2 ns |
| B | ND antenna fiber length | 27 ns |
| C | ND electronics latencies | 32 ns |
| D | FD antenna fiber length | 46 ns |
| E | FD electronics latencies | 3 ns |
| F | GPS and transceivers | 12 ns |
| G | Detector readout differences | 9 ns |
| Total (sum in quadrature) | | 64 ns |

PHYSICAL REVIEW D **76,** 072005 (2007)

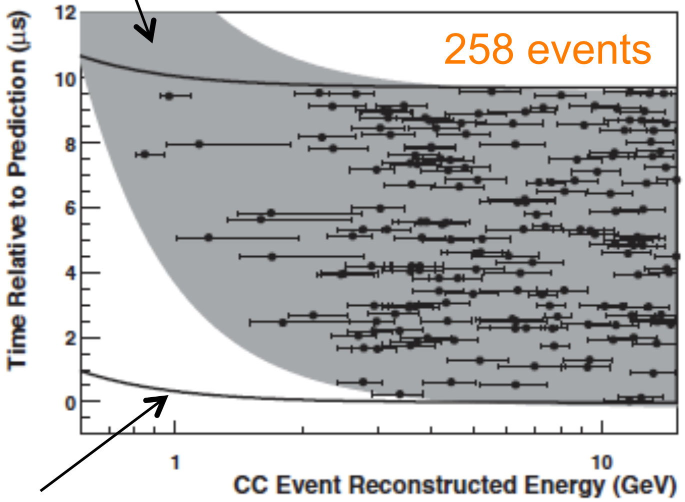
# Measurement of neutrino velocity with the MINOS detectors and NuMI neutrino beam





$m_\nu = 50\ MeV / c^2$

$$T_{m_\nu}(E_\nu) = \frac{\tau}{\sqrt{1-(\frac{m_\nu c^2}{E_\nu})^2}},$$



$m_\nu = 17\ MeV / c^2$

473 events

| | Baseline |
|---|---|
| Distance[a] ND to FD, $L$ | 734 298.6 ± 0.7 m [15] |
| Nominal time of flight, $\tau$ | 2 449 356 ± 2 ns |

$$\frac{(v-c)}{c} = \frac{-\delta}{\tau+\delta} = 5.1 \pm 2.9(\text{stat.}+\text{syst.}) \times 10^{-5} \quad 68\%\text{C.L.}$$

$$m_\nu = 17^{+13}_{-28}(\text{stat.})\ \text{MeV}/c^2 \qquad 68\%\ \text{C.L.}$$

$$m_\nu < 50\ \text{MeV}/c^2(\text{stat.} + \text{syst.}) \qquad 99\%\text{C.L.}$$

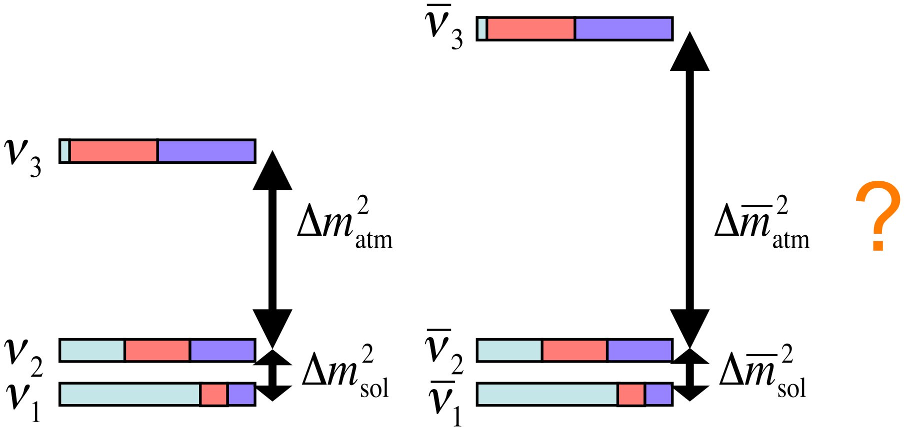
(New)

# ANTINEUTRINO OSCILLATIONS

# Antineutrino oscillations

- ◆ Do $\nu_\mu$ and $\bar{\nu}_\mu$ oscillate in the same way?

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



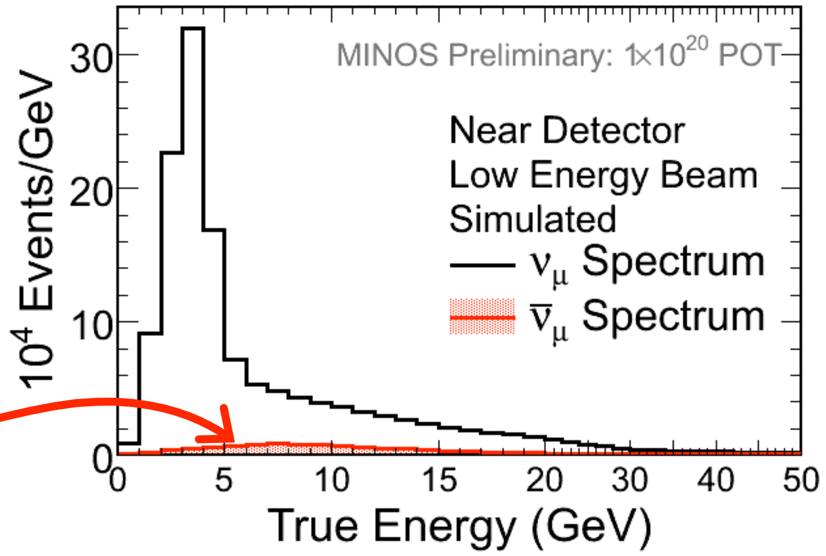
- ◆ If not, could be evidence for CPT violation or non-standard interactions
- ◆ $\bar{\nu}_\mu$ appearance predicted by the standard model at the $10^{-18}$ level if neutrinos are Majorana:

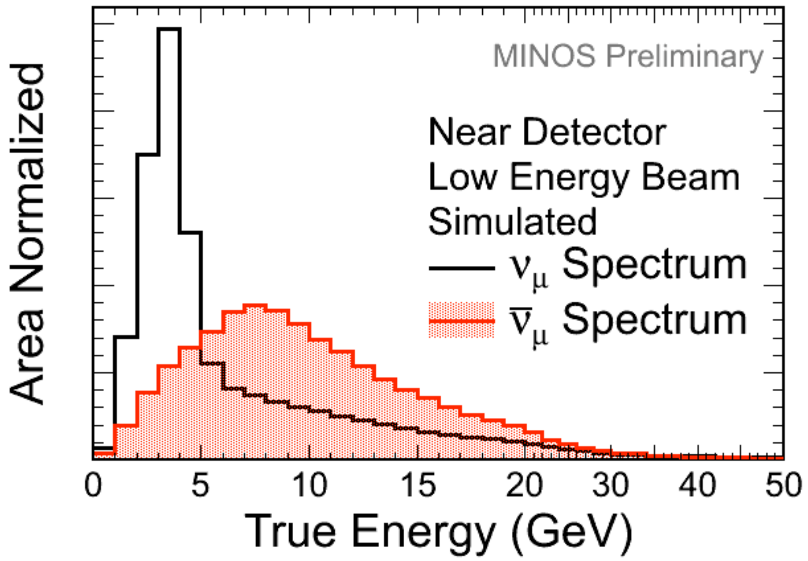
$$P(\nu_\mu \to \bar{\nu}_\mu) \sim (m_\nu / E_\nu)^2$$

- ◆ Also predicted at a very low level by models with a large neutrino magnetic moment, neutrino decay and other exotic processes (*Langacker and Wang, Phys. Rev. D 58:093004*)

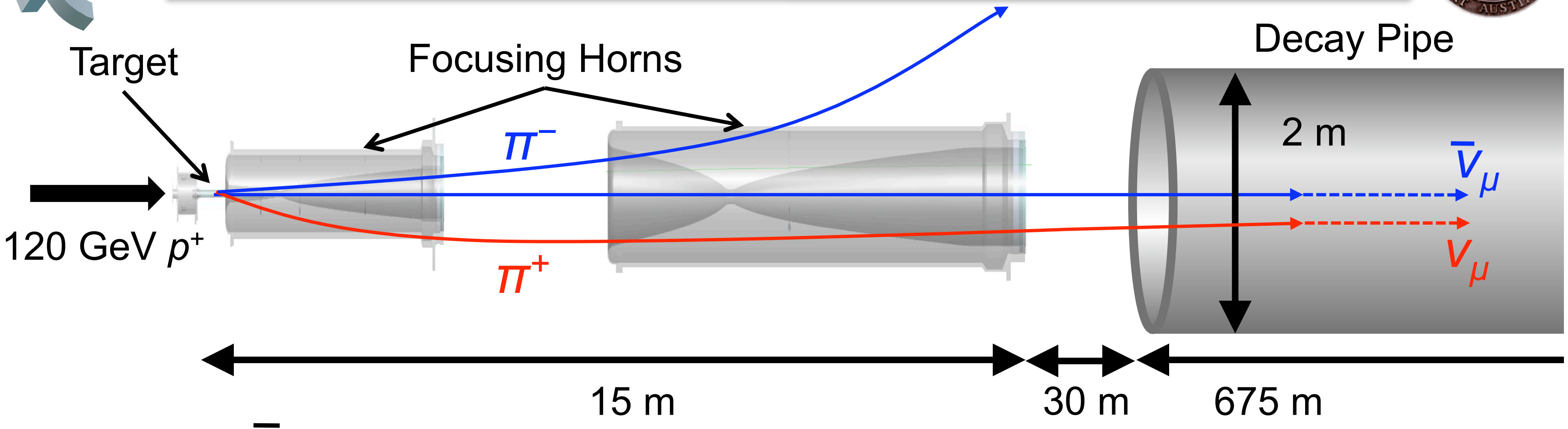
# Beam composition

- The charged current interactions in the Near detector comprise of:
    - 91.7% $\nu_\mu$
    - 7.0% $\bar{\nu}_\mu$
    - 1.3% $\nu_e$ and $\bar{\nu}_e$
- Significant difference in the energy spectrum:
    - $\nu_\mu$ peak at 3 GeV
    - $\bar{\nu}_\mu$ peak at 8 GeV

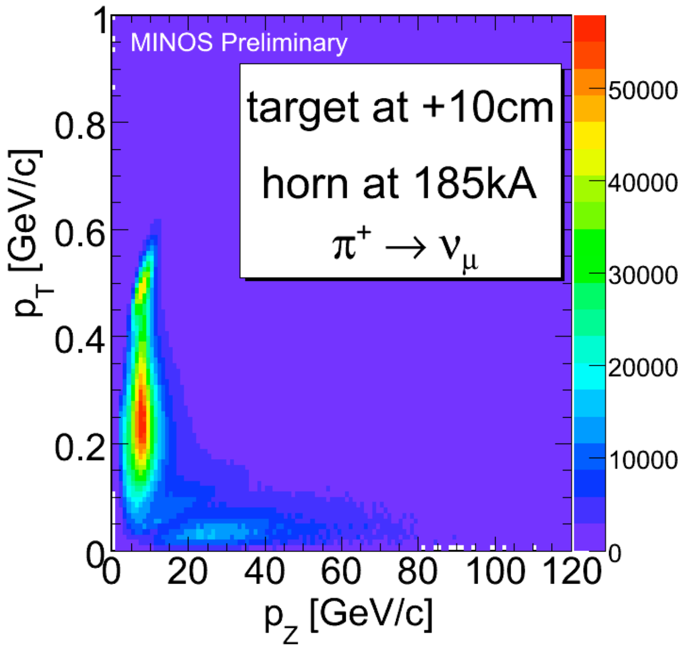


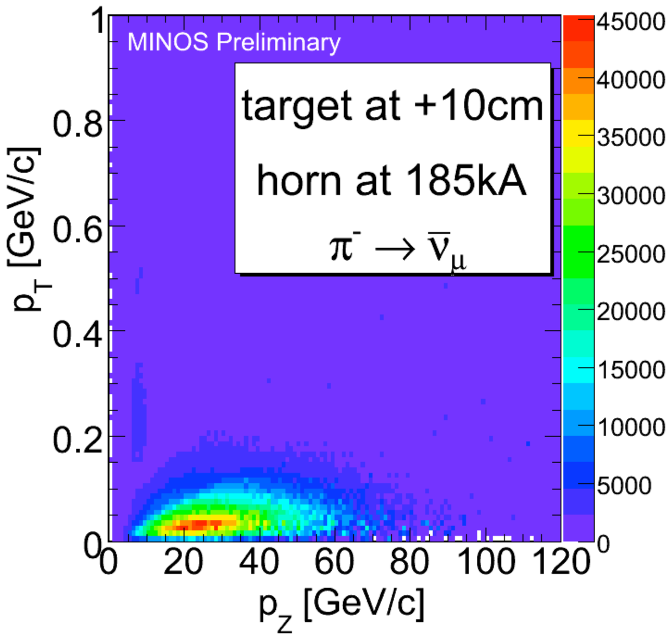


# Why are the spectra so different?



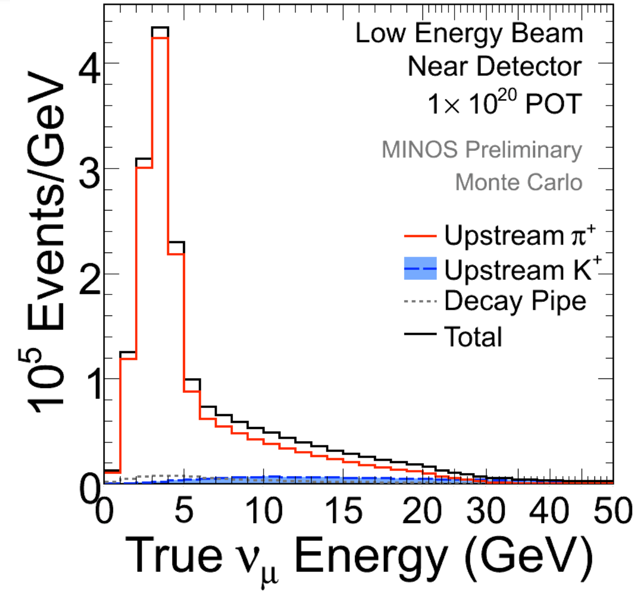
- Majority of $\bar{\nu}_\mu$ come from “neck-to-neck” low-$p_T$ $\pi^-$ that travel down the centre of the horns where there is zero magnetic field
- $\nu_\mu$ spectrum dominated by focused high-$p_T$ $\pi^+$



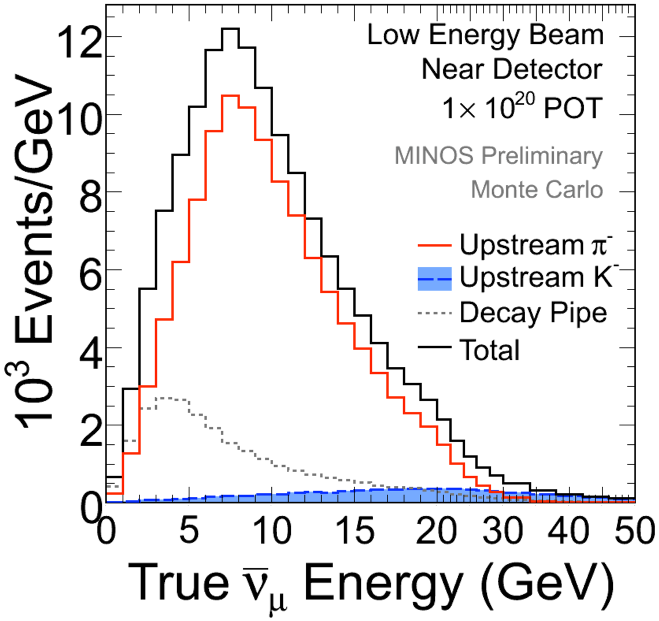


# Where do the $\nu_\mu$ and $\overline{\nu}_\mu$ originate?

- $\nu_\mu$ originate almost entirely from $\pi^+$ produced upstream of decay pipe



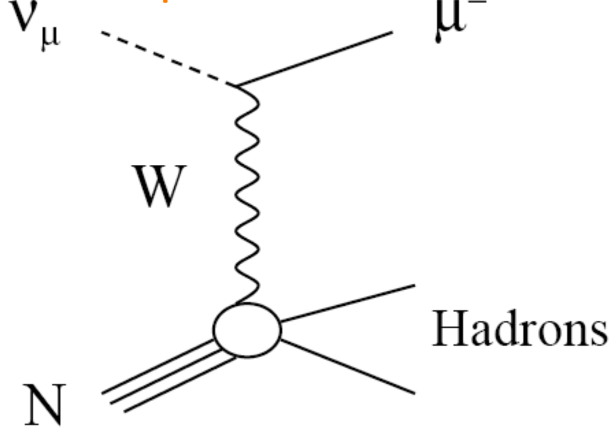
- $\overline{\nu}_\mu$ spectrum has significant components that originate from:
  - ⇨ Upstream produced $K^-$
    - constrained by external hadron production data
    - $K^0$ < 1% of total
  - ⇨ $\mu^+$ from $\pi^+$ (small and well constrained)
  - ⇨ Interaction of primary protons and secondary hadrons downstream
    - Decay pipe production in walls



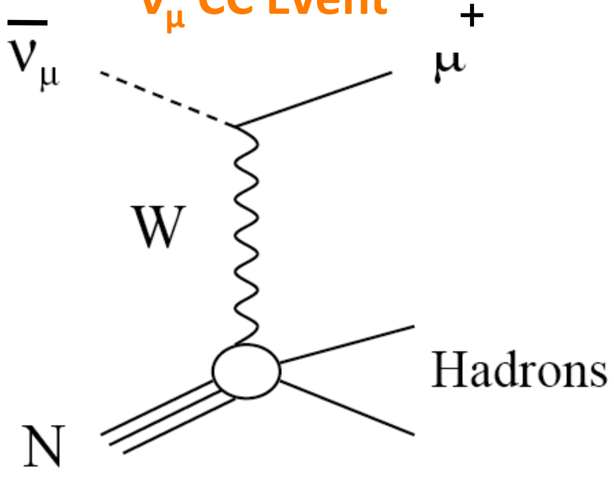
- Due to different solid angle acceptances for the two detectors, the upstream and downstream fractions are different at the two locations

# MINOS Event Topologies

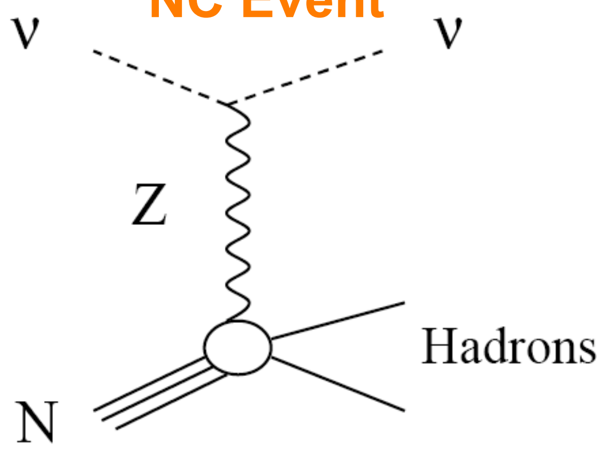
**$\nu_\mu$ CC Event**

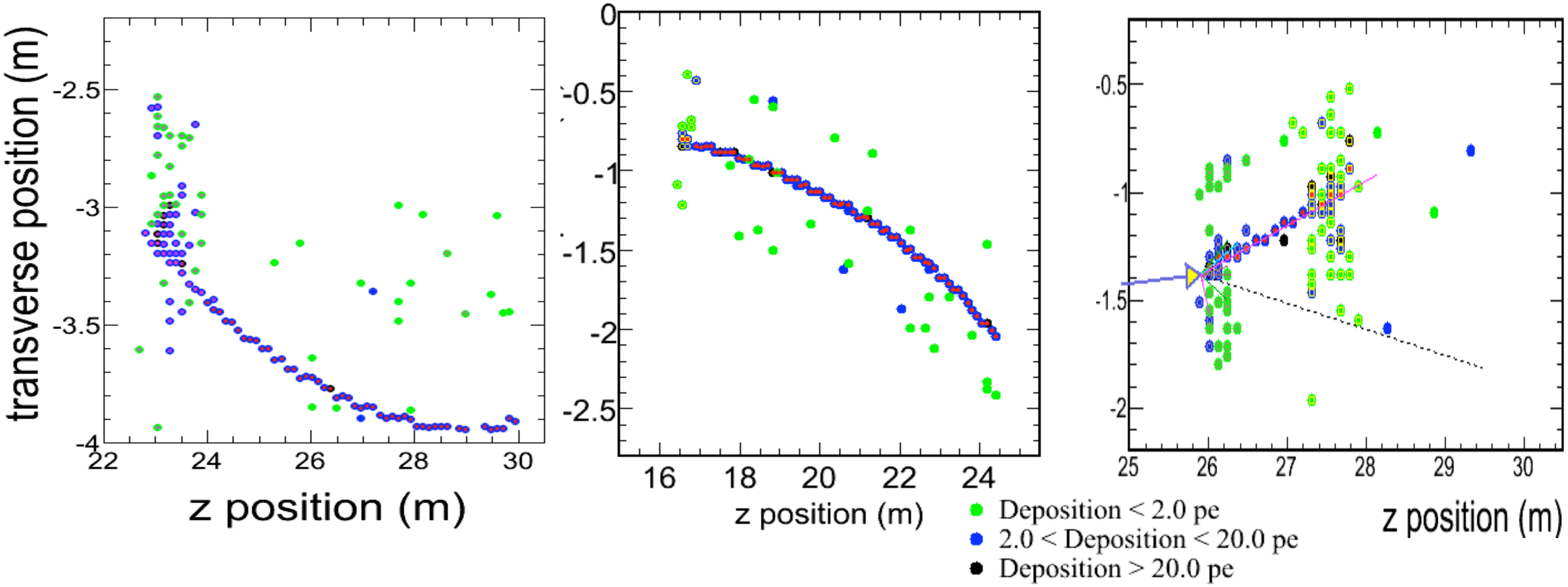


**$\bar{\nu}_\mu$ CC Event**



**NC Event**

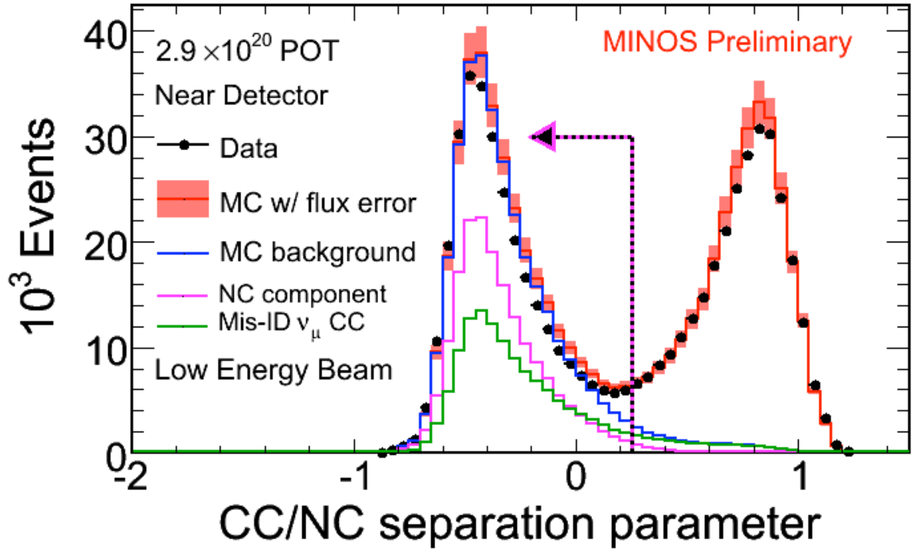


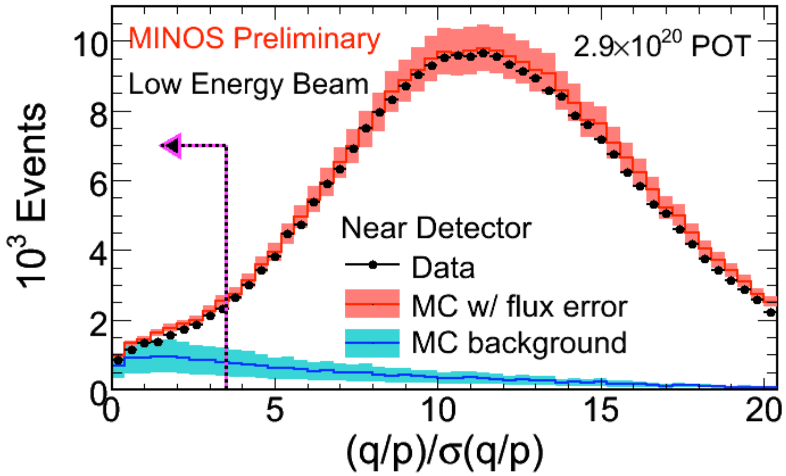


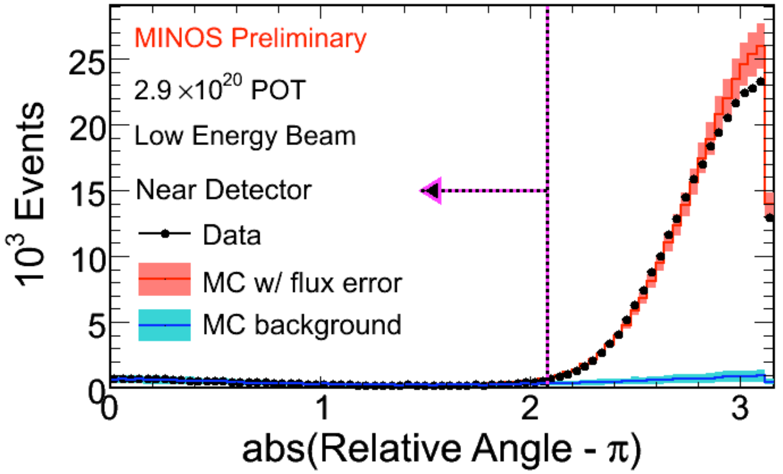
- 🟩 Deposition < 2.0 pe
- 🟦 2.0 < Deposition < 20.0 pe
- ● Deposition > 20.0 pe

# Antineutrino event classification

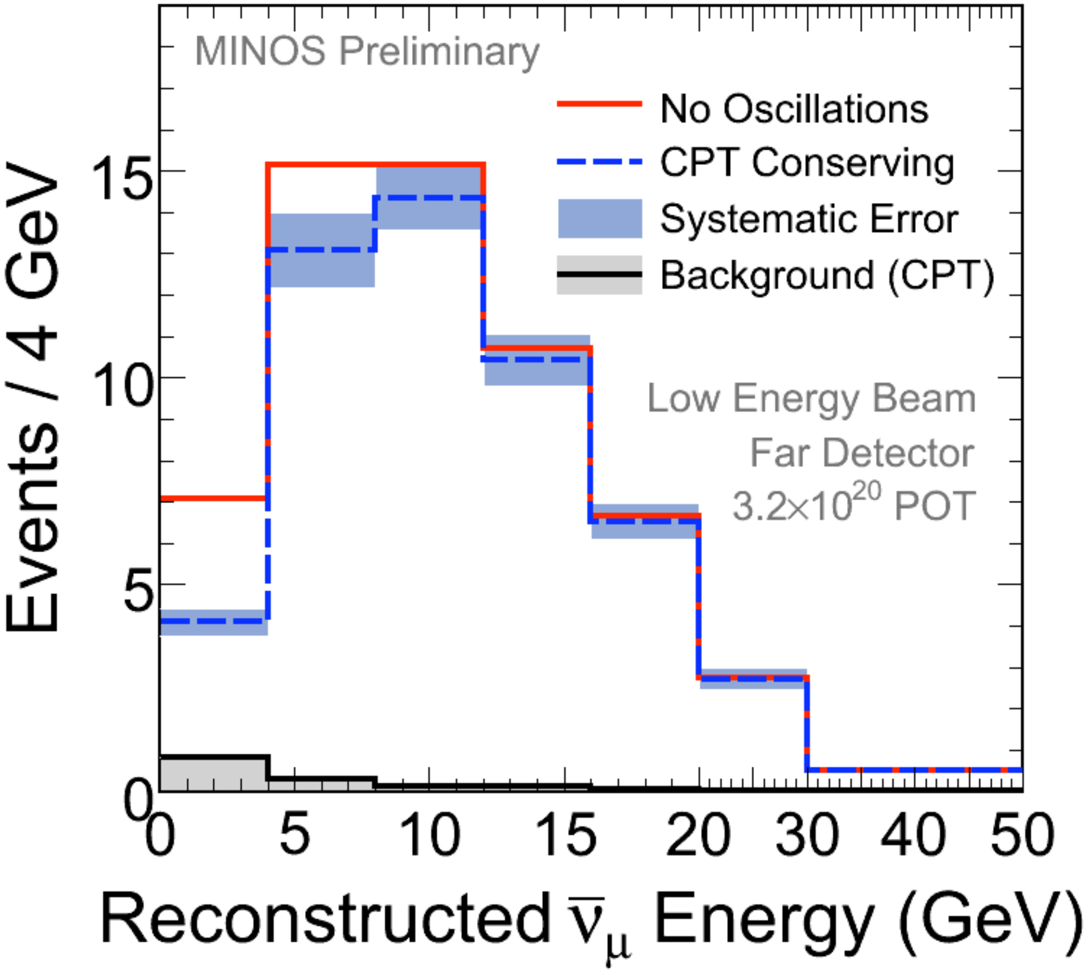
- **Likelihood-based with 3 Probability Density Functions:**
  - ❒ **Track length**
  - ❒ **Pulse height fraction in track**
  - ❒ **Pulse height per plane**
  - ❒ **+ two more variables**







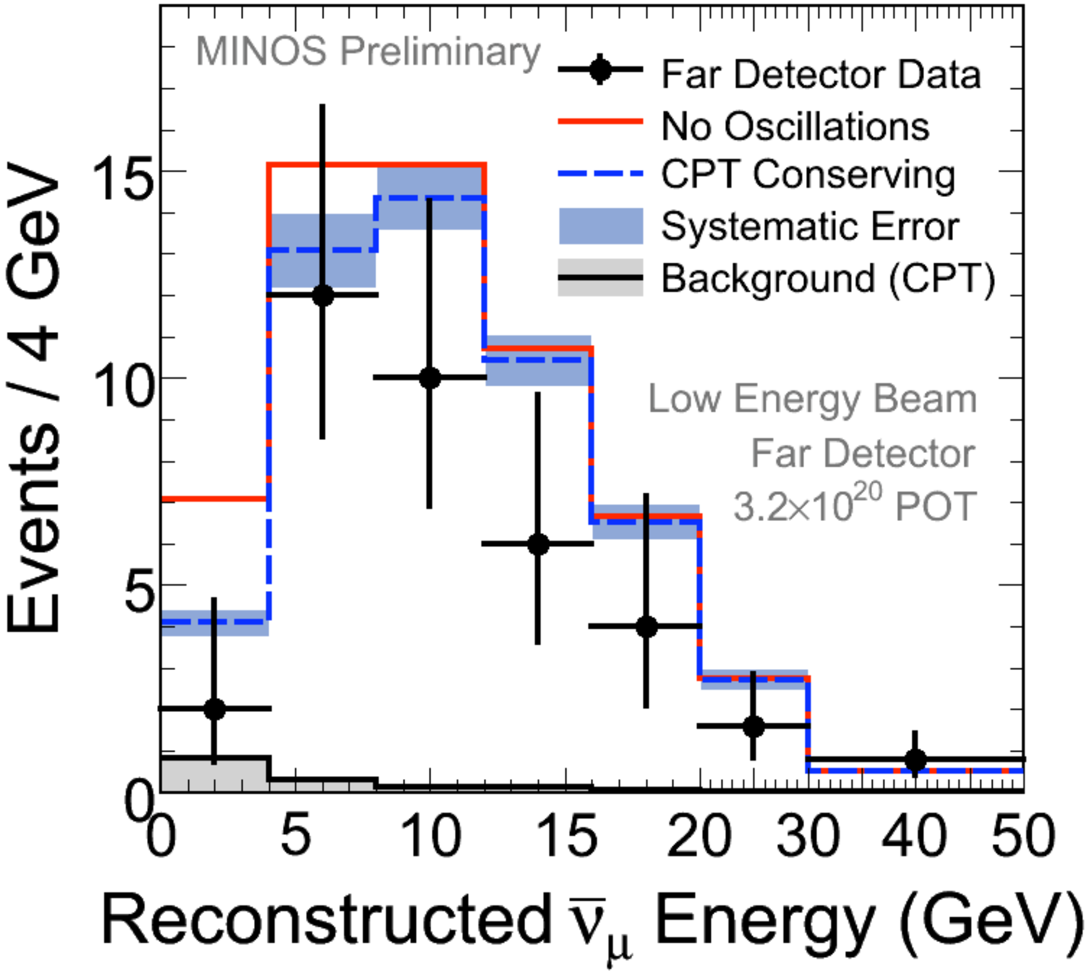
# **Predicted** Far Detector Spectrum



- **Predicted events with CPT conserving oscillations:**
  - ⇨ **58.3 ± 7.6 (stat.) ± 3.6 (syst.)**
- **Predicted events with null oscillations:**
  - ⇨ **64.6 ± 8.0 (stat.) ± 3.9 (syst.)**

# Far Detector Spectrum

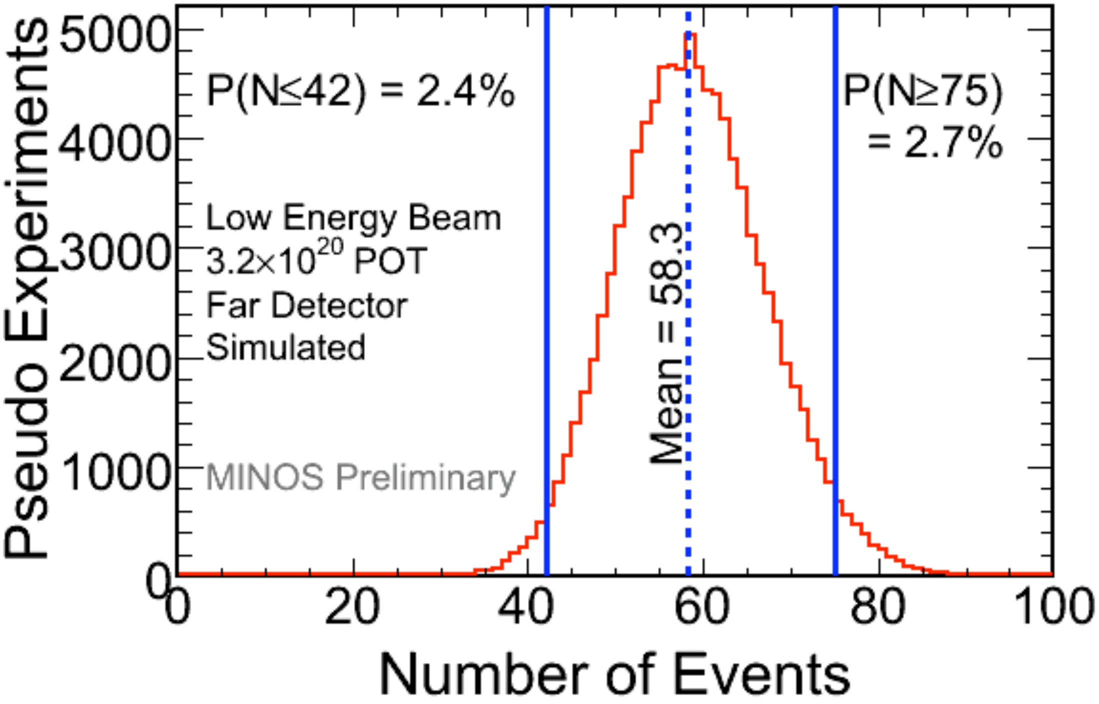
- Observe **42 events** in the Far detector
- **First direct observation of $\bar{\nu}_\mu$ in an accelerator long-baseline experiment**



- Predicted events with CPT conserving oscillations:
  - ⇨ 58.3 ± 7.6 (stat.) ± 3.6 (syst.)
- Predicted events with null oscillations:
  - ⇨ 64.6 ± 8.0 (stat.) ± 3.9 (syst.)

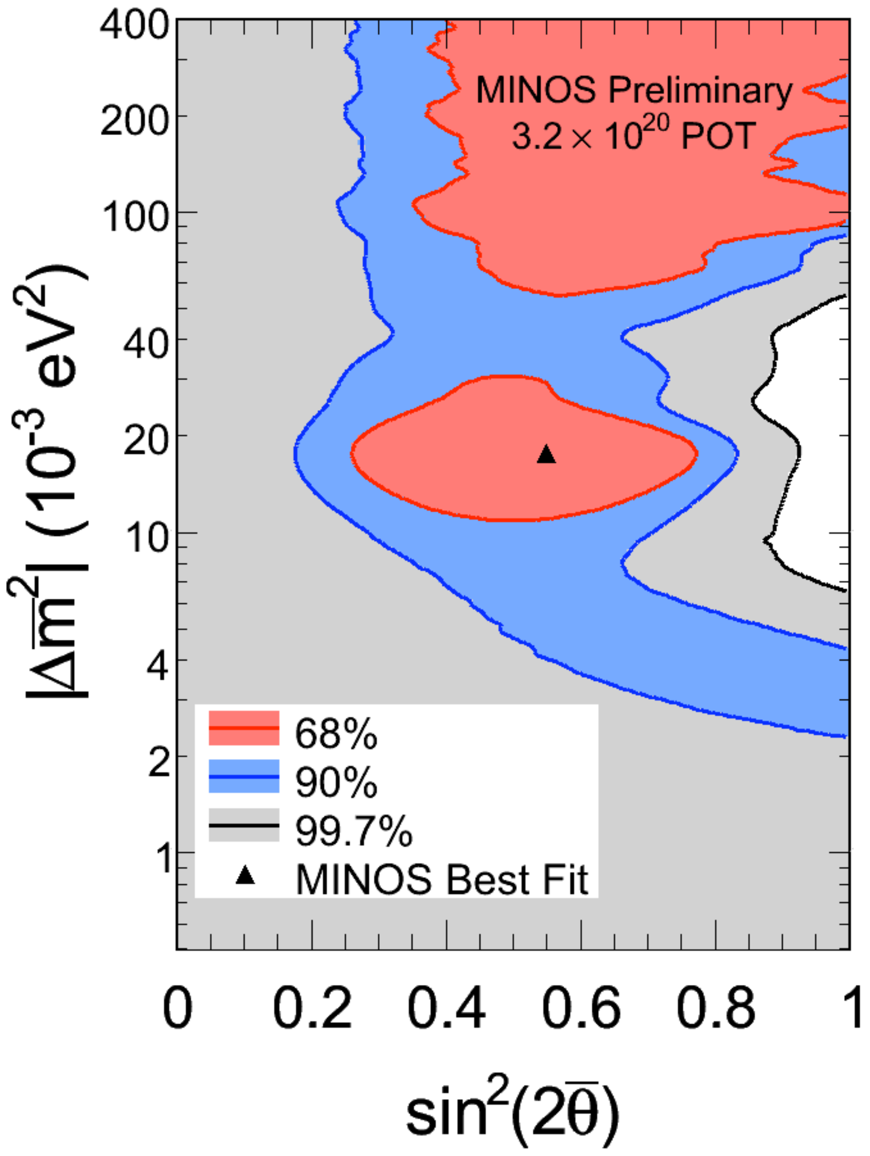
# Statistical Context

- Compared to the CPT -conserving oscillation hypothesis we have a deficit of **16.3 events**
- Using **normalisation information alone** this is a 1.9 sigma effect
- A study using 100,000 fake experiments including systematics gave the probabilities in accordance with expectations



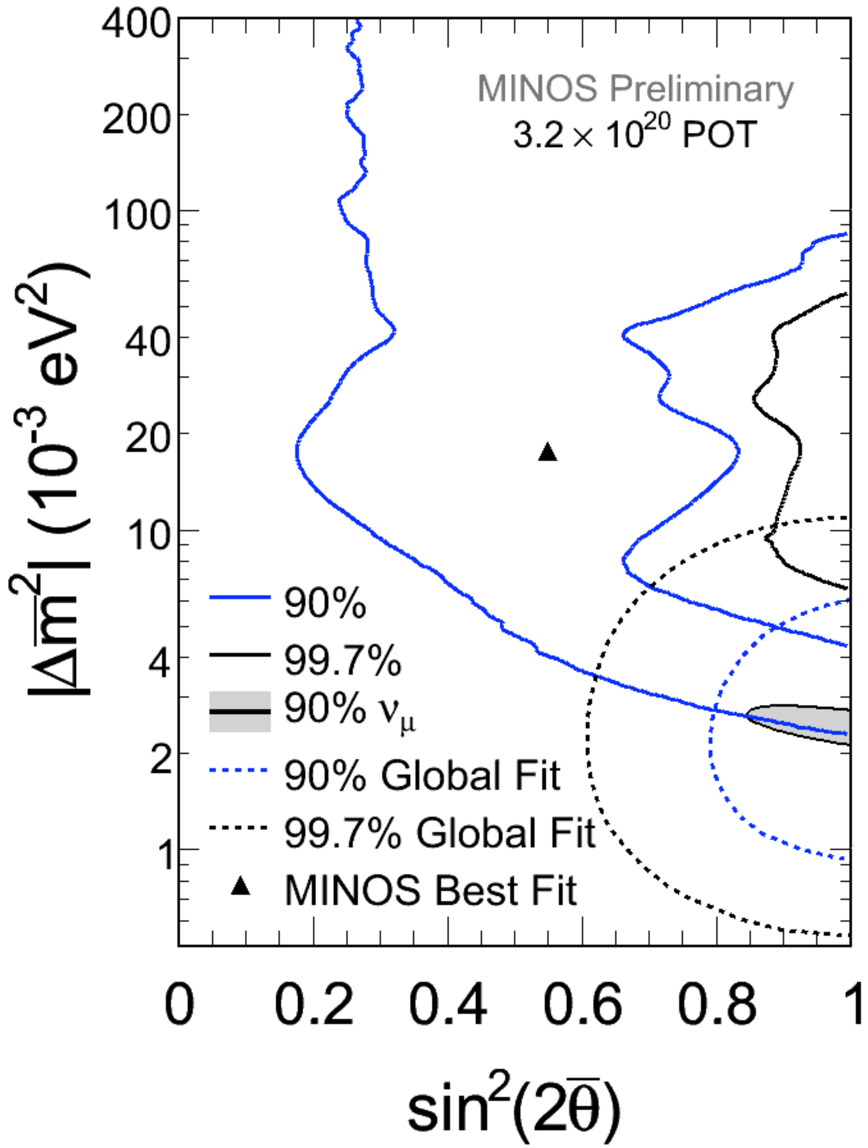
# Allowed Region

- Contours obtained using Feldman-Cousins technique, including systematics
- Null oscillation hypothesis excluded at 99%
- CPT conserving point from the MINOS neutrino analysis is within 90% contour
- $\overline{\nu}_{\mu}$ best fit is at high value, due to deficit at high energy
- Unshaded region around maximal mixing is excluded at 99.7% C.L.



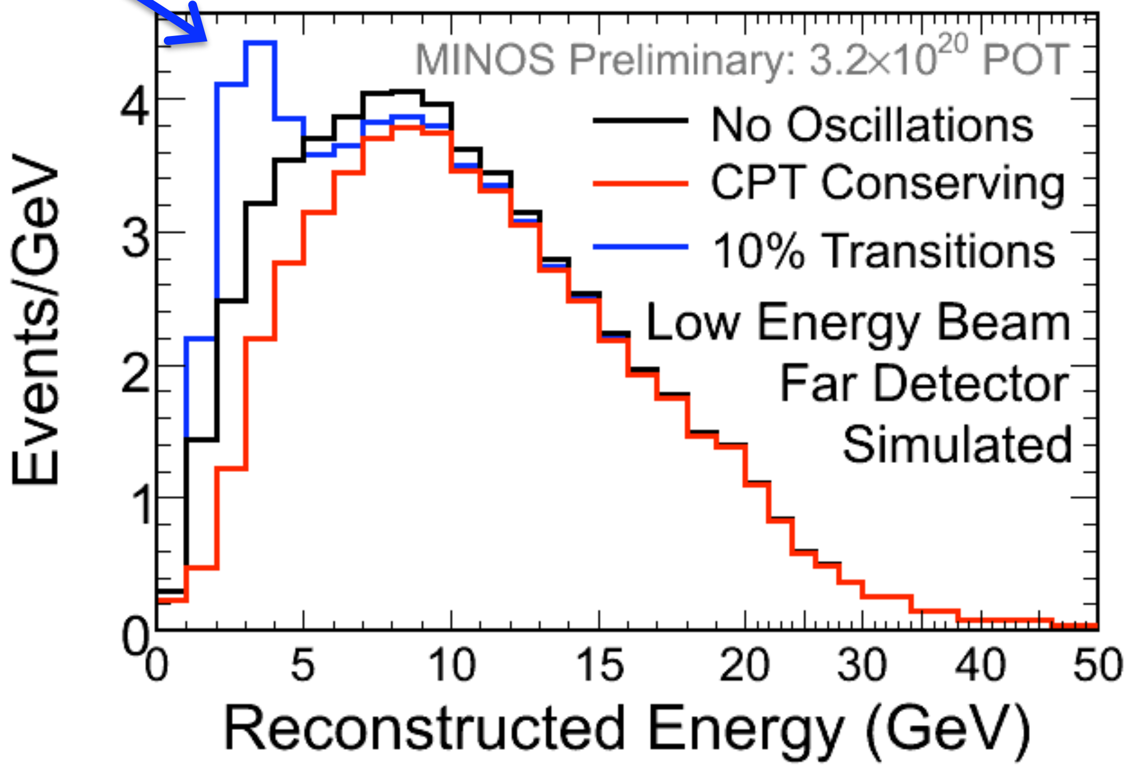
# Comparison to Global Fit

- Global fit to previous data
  - Super-Kamiokande dominates
  - Includes SK-I and SK-II data
  - M. C. Gonzalez-Garcia & Michele Maltoni, Phys. Rept. 460 (2008)
- MINOS data excludes previously allowed CPT violating regions of parameter space, particularly near maximal mixing



# Predicted Far Detector Spectrum with 10% $\bar{\nu}_\mu$ Appearance

- ◆ **If 10% of $\nu_\mu$ transitioned to $\bar{\nu}_\mu$ we would see this experimental signature**
- ◆ **The intrinsic $\bar{\nu}_\mu$ in the NuMI beam are effectively the background to a search for $\bar{\nu}_\mu$ appearance**



# Results of Search for $\bar{\nu}_\mu$ Appearance

- MINOS observes no appearance of $\bar{\nu}_\mu$ in the NuMI beam

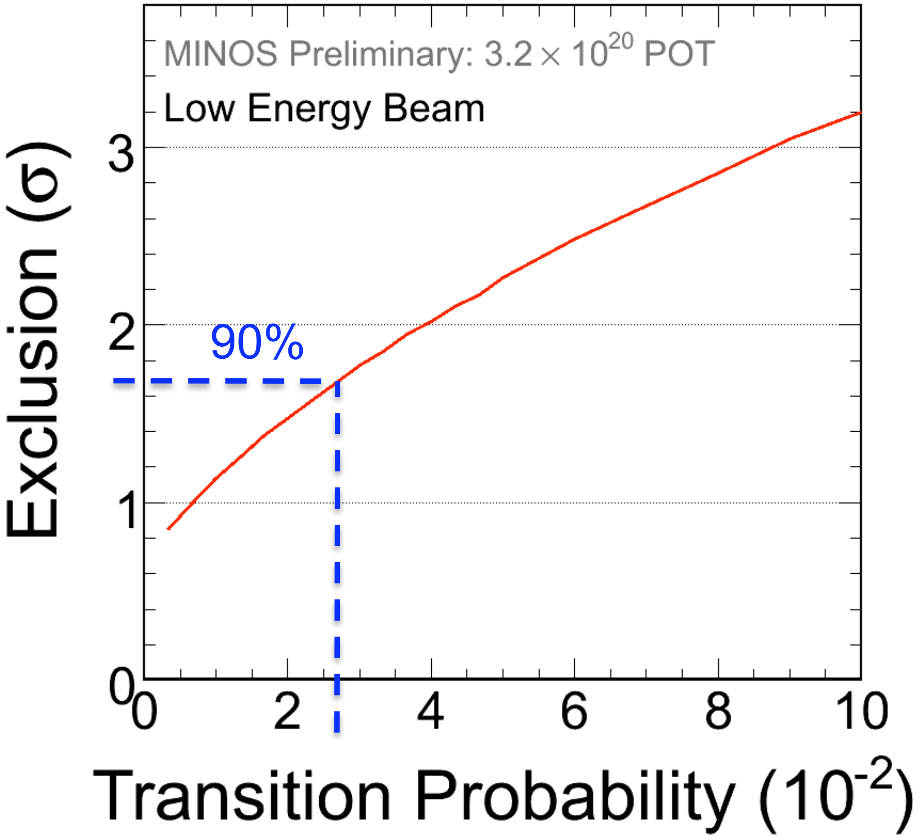
- 1-parameter fit for *α* using simple parameterization

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

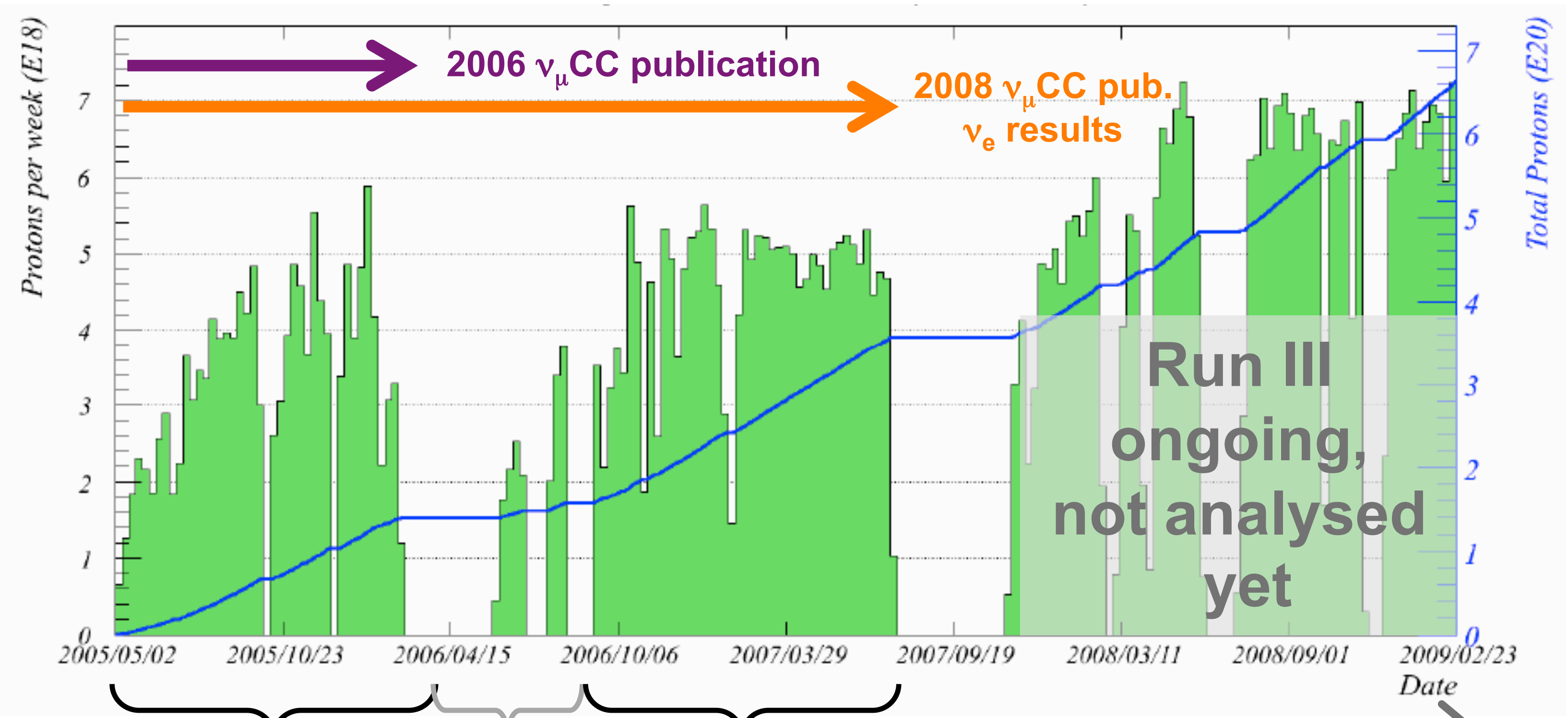
(θ and *Δm*$^2$ set to CPT conserving case)

- Uncertainty from $\bar{\nu}_\mu/\nu_\mu$ cross section ratio

- Result: limit fraction, α, of events transitioning from $\nu_\mu$ to $\bar{\nu}_\mu$:
  - α < 0.026 (90% C.L.)



# Accumulated Beam Data



**RUN I**

**$1.27 \times 10^{20}$ POT**

**Higher energy beam**

**$0.15 \times 10^{20}$ POT**

**RUN II**

**$1.87 \times 10^{20}$ POT**

**RUN III**

**$>3 \times 10^{20}$ POT**

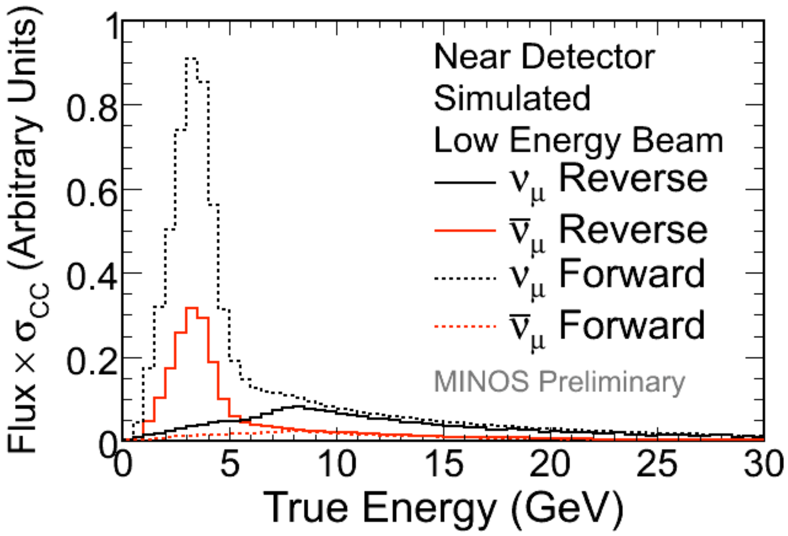
**The muon anti-neutrino analysis presented today uses Run I + Run II**

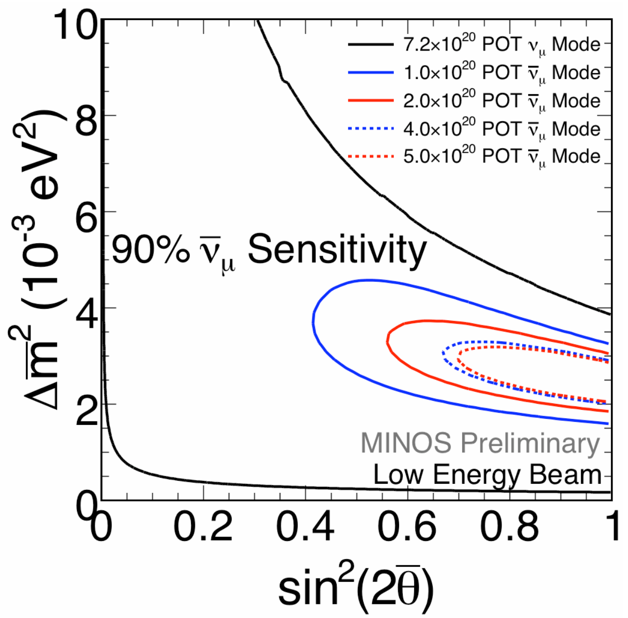
# Dedicated $\bar{\nu}_\mu$ running

- Plan to reverse current in NuMI magnetic horns to focus $\pi^-$ from September (create a $\bar{\nu}_\mu$ beam)

- MINOS can directly observe $\bar{\nu}_\mu$ disappearance at 7σ with $5 \times 10^{20}$ POT

- rapidly reduce the uncertainty on $\Delta\overline{m}^2_{32}$





Physics with the

# NEAR DETECTOR

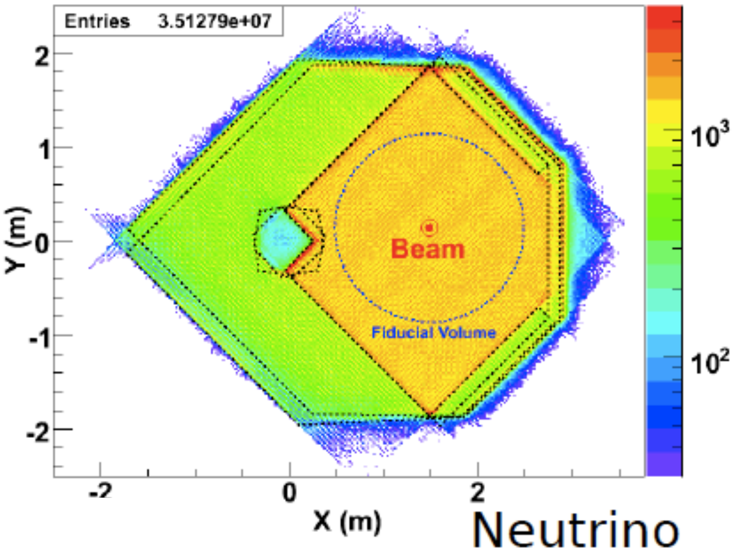
# Neutrino and anti-neutrino cross-section (PRD in the works)

- Based on $2.45 \times 10^{20}$ POT (LE beam)
  [ June 2005 – April 2007 ]
- Based on $1.94 \times 10^{6}$ (3-50 GeV) neutrinos
  and $1.59 \times 10^{5}$ (5-50 GeV) anti-neu.
- use

$$\frac{d\sigma}{d\nu} = A\left[1 + \frac{B}{A}\frac{\nu}{E} - \frac{C}{2A}\frac{\nu^2}{E^2}\right]$$

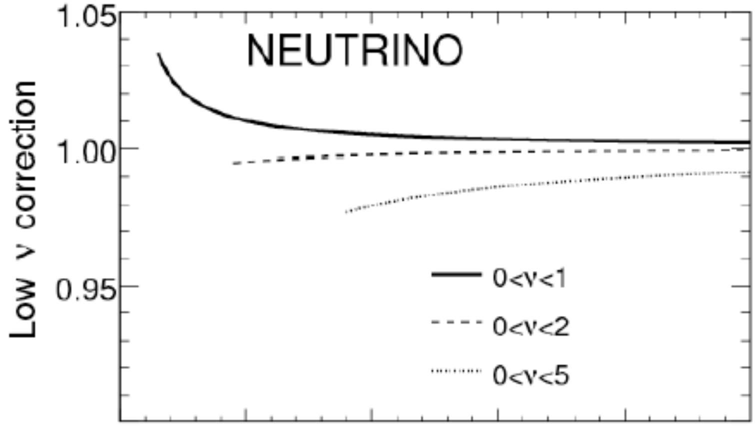
$d\sigma/d\nu \to$ constant

as $\nu/E \to 0$

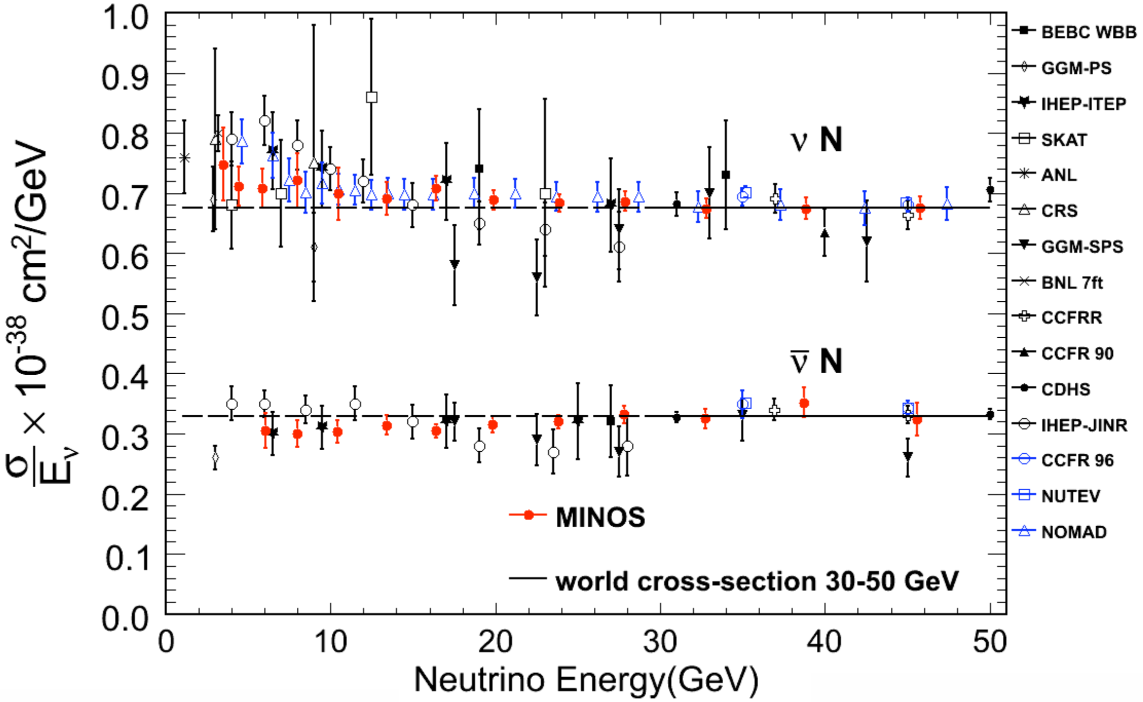


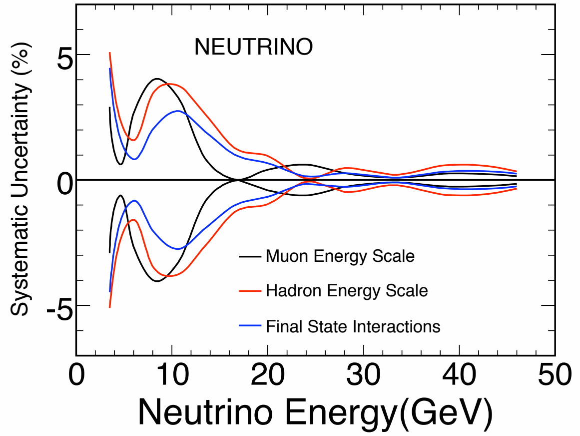
Neutrino Tomography!

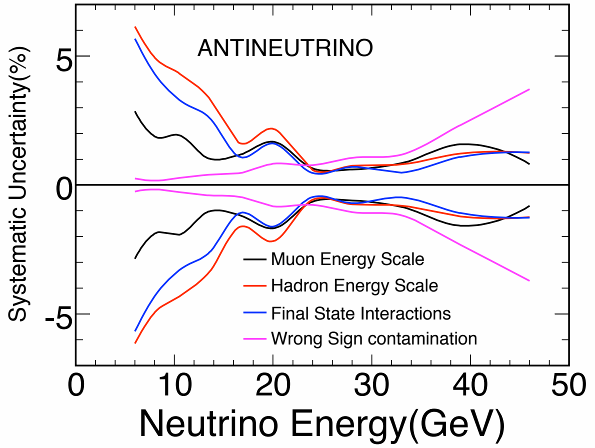
- Constrain data 30-50 GeV
  to the world average
- Use NEUGEN Monte Carlo for
  - ⇨ acceptance
  - ⇨ finite ν/E, QEL, RES part



# Final results







# Charge Current Quasi-elastic (CC QEL) interactions ($\nu_\mu + N^* \rightarrow \mu^- + N'$)

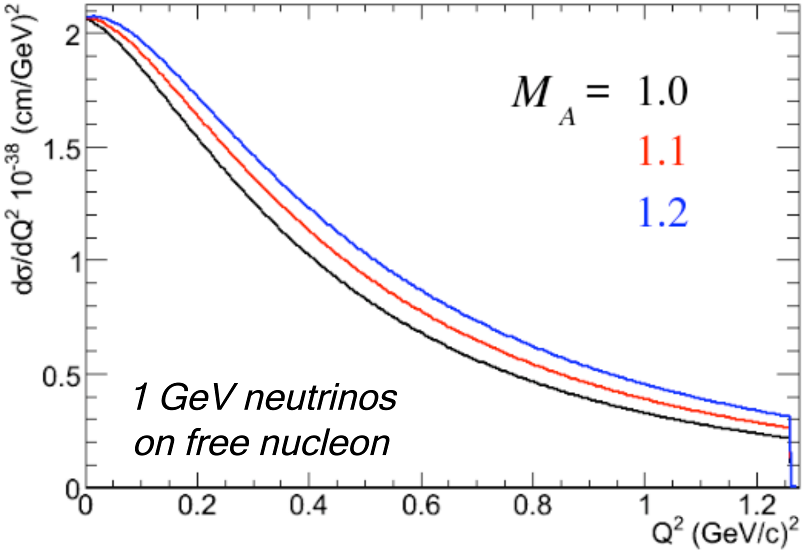
- The uncertainty in the QE cross section is dominated by the uncertainty in the axial-vector form factor. $F_A$ is written using a dipole form as:

$$F_A(q^2) = \frac{F_A(0)}{\underbrace{(1 - \frac{q^2}{M_A^2})^2}_{\text{'Dipole Form'}}}$$

Known from neutron beta-decay experiments.

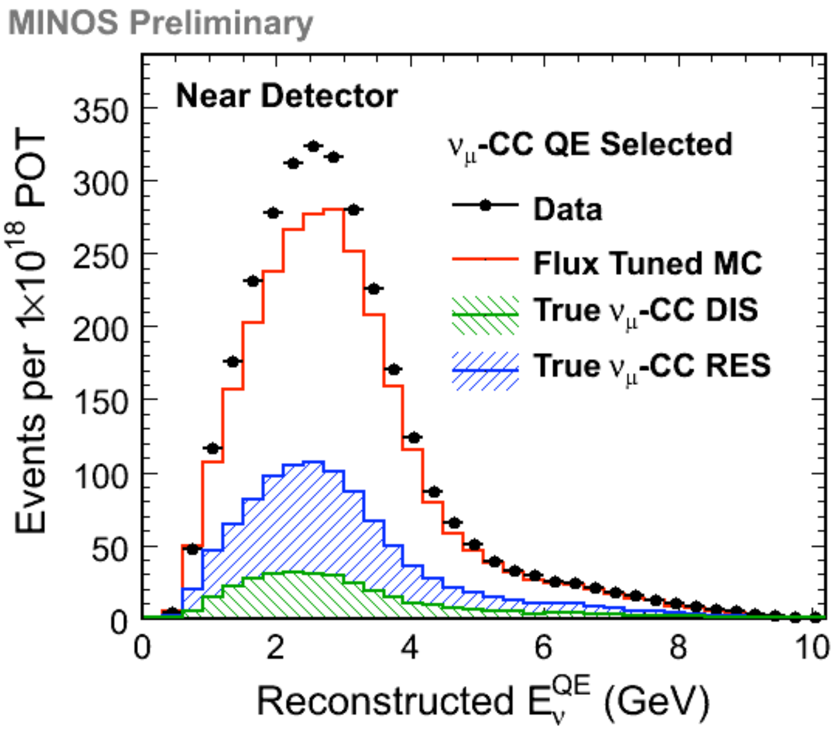
The quasi-elastic axial-vector mass.

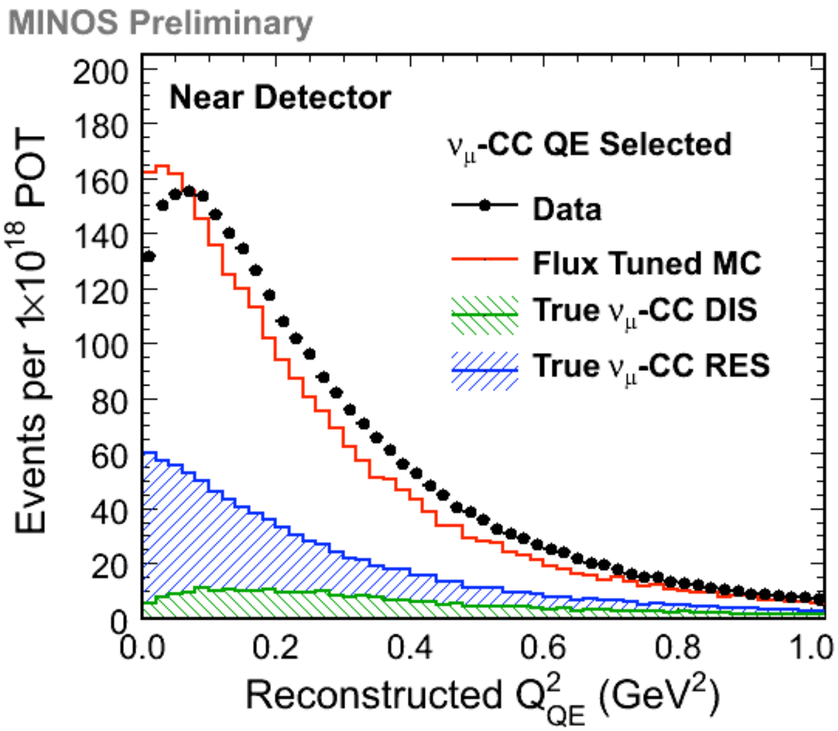
- Can measure $M_A^{QE}$ by looking at the $Q^2$ distribution for a QE-like event sample. Both the shape and rate of the distributions are affected by changes to $M_A^{QE}$:



# CC QE Near Detector

## (based on 1.26x$10^{20}$ protons on target)



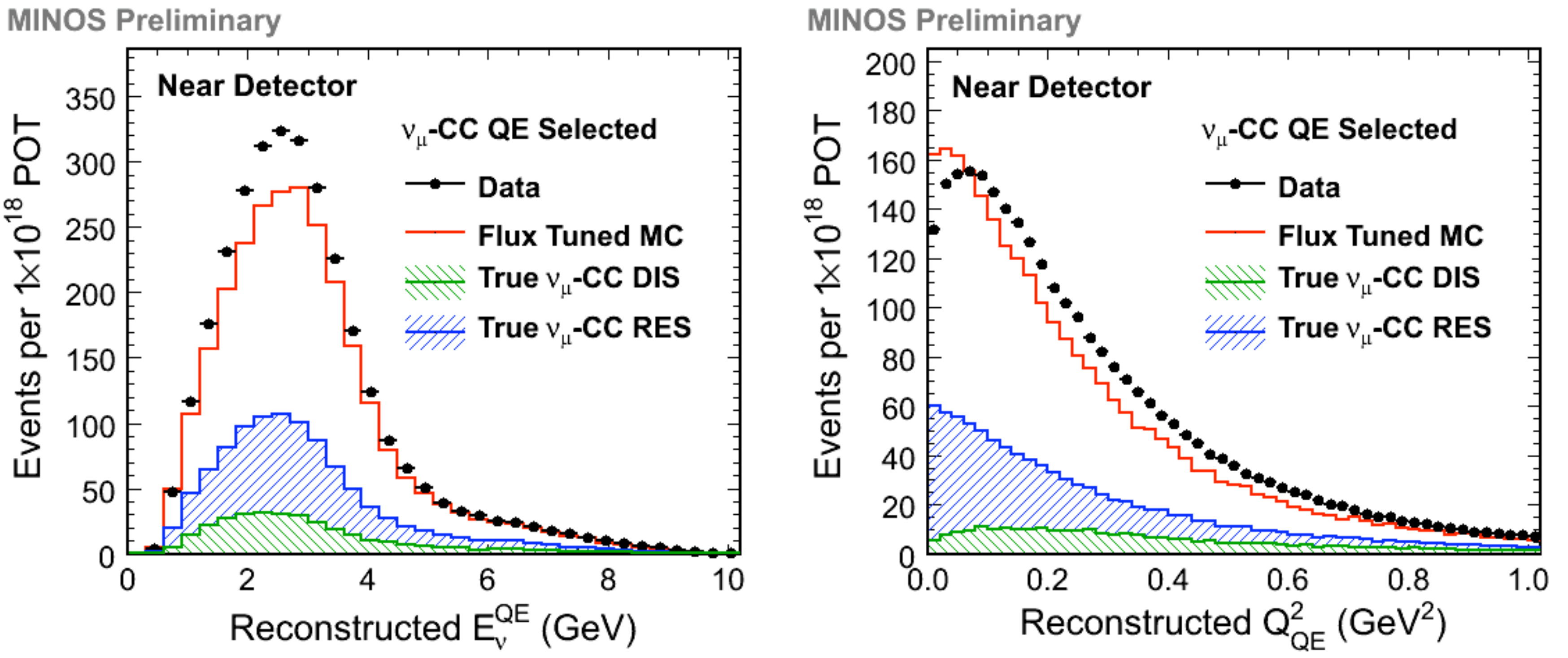


$$E_\nu^{QE} = \frac{(m_N + \varepsilon_B)E_\mu - 2(m_N\varepsilon_B + \varepsilon_B^2 + m_\mu^2/2)}{m_N + \varepsilon_B - E_\mu + p_\mu \cos(\theta_\mu)}$$

$$Q^2_{QE} = -2E_\nu^{QE}[E_\mu - p_\mu \cos(\theta_\mu)] + m_\mu^2$$

# CC QE Near Detector

(based on 1.26x$10^{20}$ protons on target)



Total # of events selected:

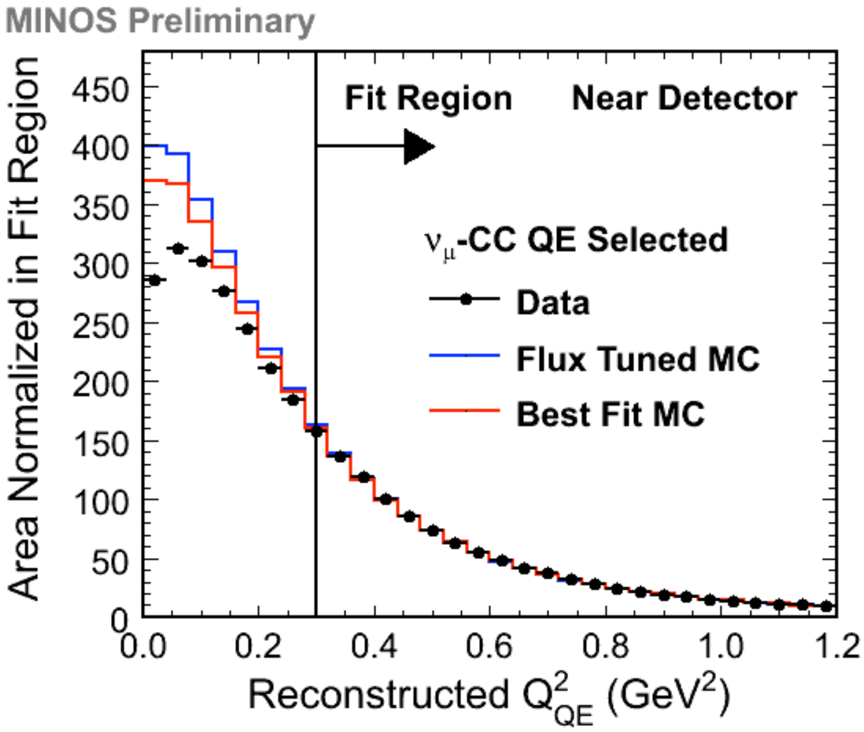
Data: 344,736

MC: 292,501

Data wants more low $Q^2$ suppression and a flatter spectrum at higher $Q^2$.

# Preliminary results

## (based on 1.26x10$^{20}$ protons on target)



$Q^2 > 0.3$

| Systematic Source | Positive Shift (GeV) | Negative Shift (GeV) |
|---|---|---|
| QE Selection Cut | 0.018 | 0.033 |
| Hadronic Energy Offset | 0.045 | 0.047 |
| Final State Interactions | 0.042 | 0.042 |
| DIS Cross Section | 0.033 | 0.035 |
| Flux Tuning | 0.025 | 0.025 |
| QE Nuclear Effects | 0.000 | 0.077 |
| RES Nuclear Effects | 0.000 | 0.021 |
| Quadrature Sum | 0.076 | 0.115 |

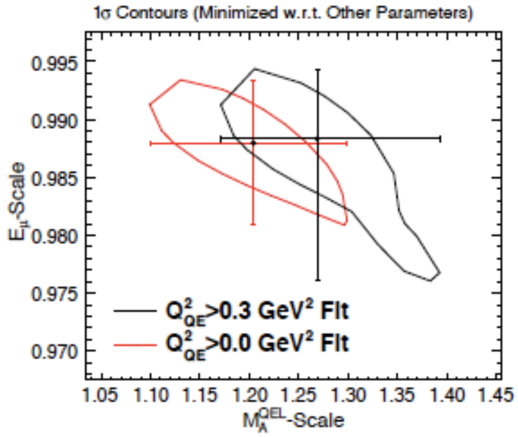
MINOS Preliminary

$Q^2 > 0.3$

Effective $M_A^{QE} = 1.26\ ^{+0.12}_{-0.10}$ (fit) $^{+0.08}_{-0.12}$ (syst) GeV

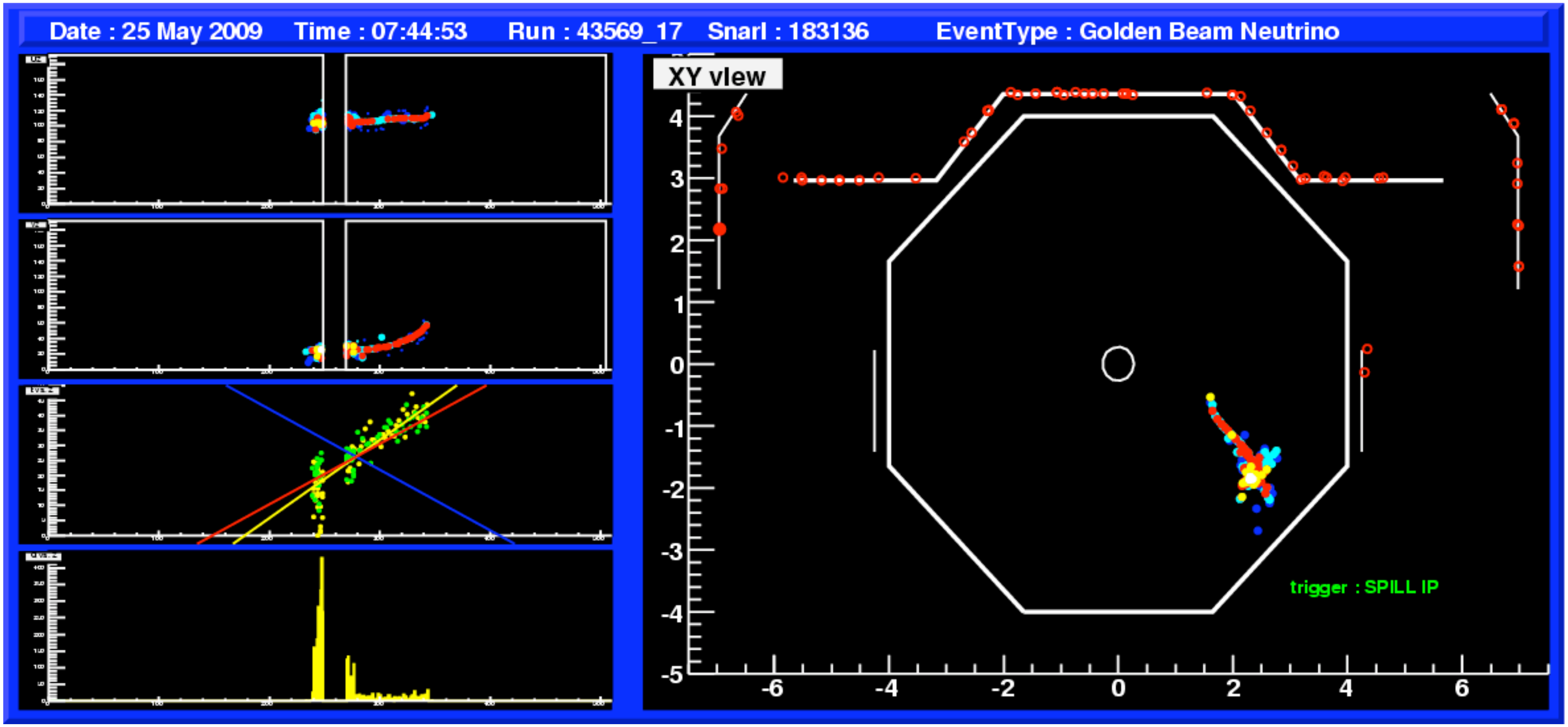
$Q^2 > 0.0$

Effective $M_A^{QE} = 1.19\ ^{+0.09}_{-0.10}$ (fit) $^{+0.12}_{-0.14}$ (syst) GeV



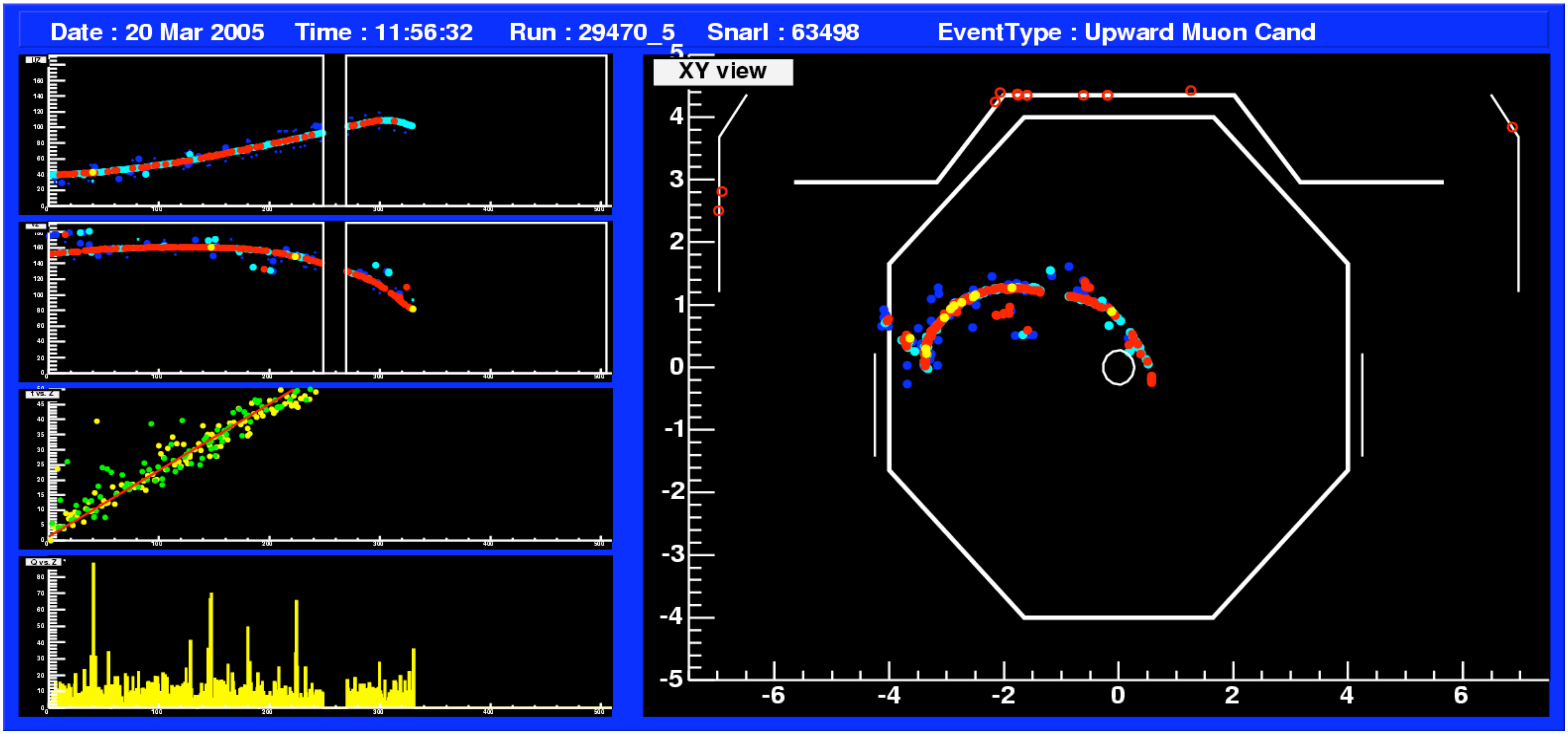
# MINOS OBSERVATORY

# NuMI beam event



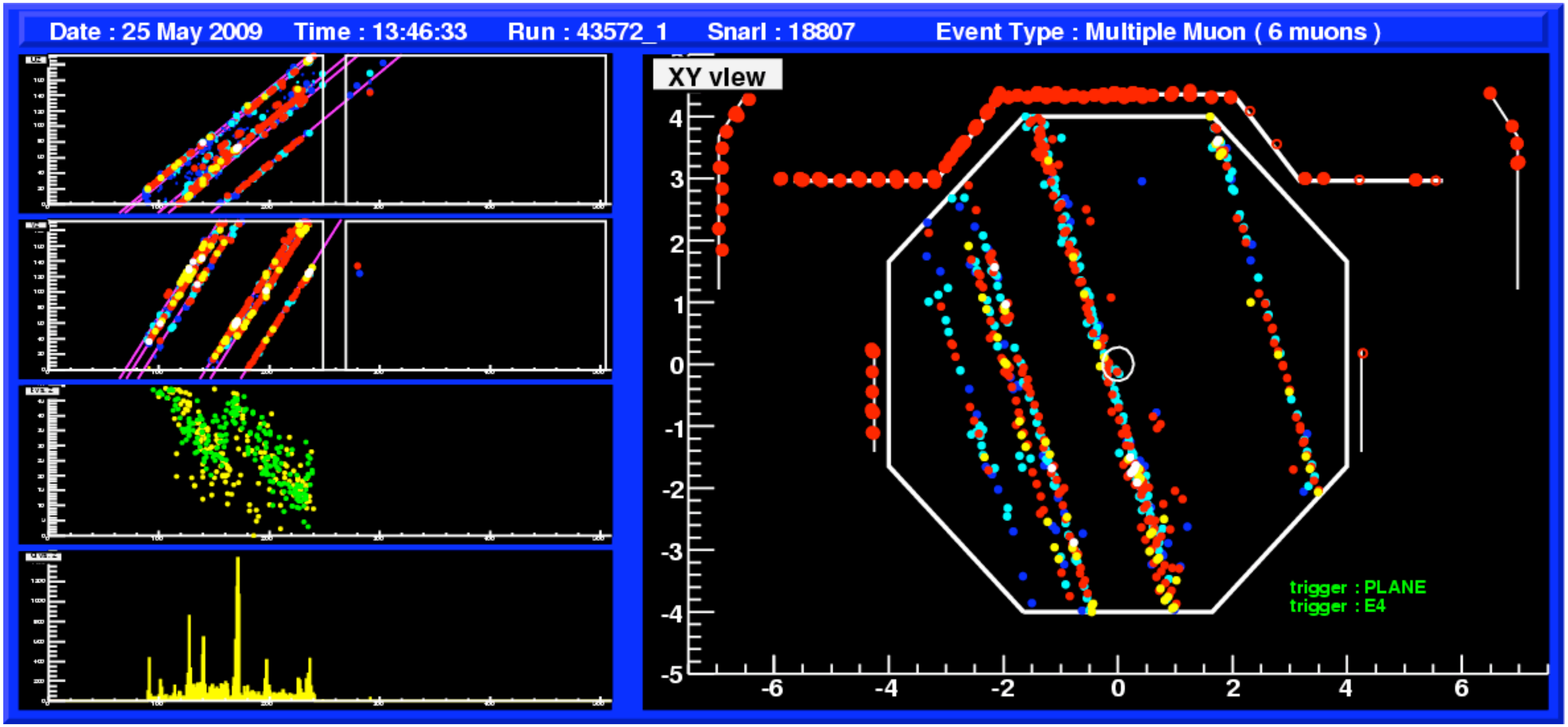
Date : 25 May 2009 Time : 07:44:53 Run : 43569_17 Snarl : 183136 EventType : Golden Beam Neutrino

# First NuMI beam event (in the rock)



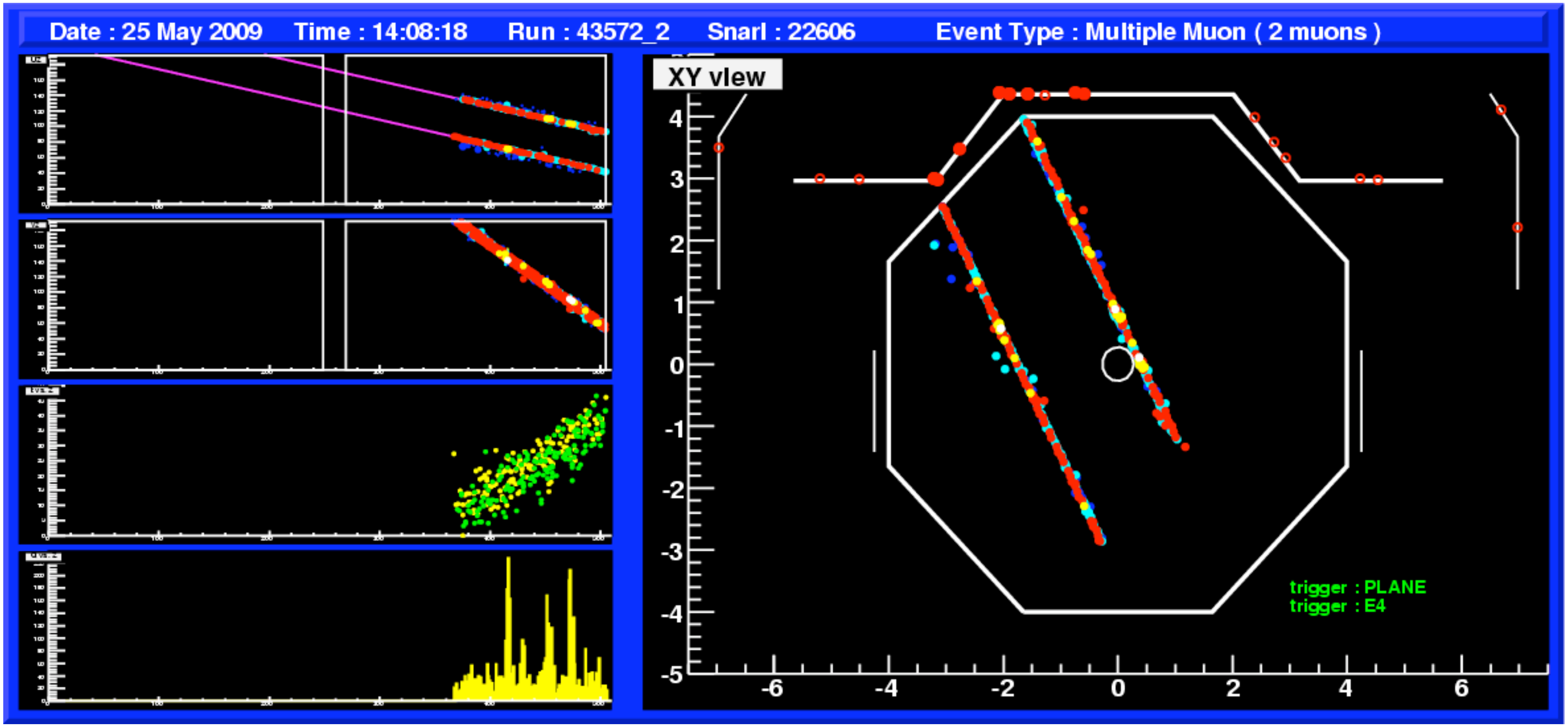
Date : 20 Mar 2005 Time : 11:56:32 Run : 29470_5 Snarl : 63498 EventType : Upward Muon Cand

# High multiplicity



Date : 25 May 2009 Time : 13:46:33 Run : 43572_1 Snarl : 18807 Event Type : Multiple Muon ( 6 muons )

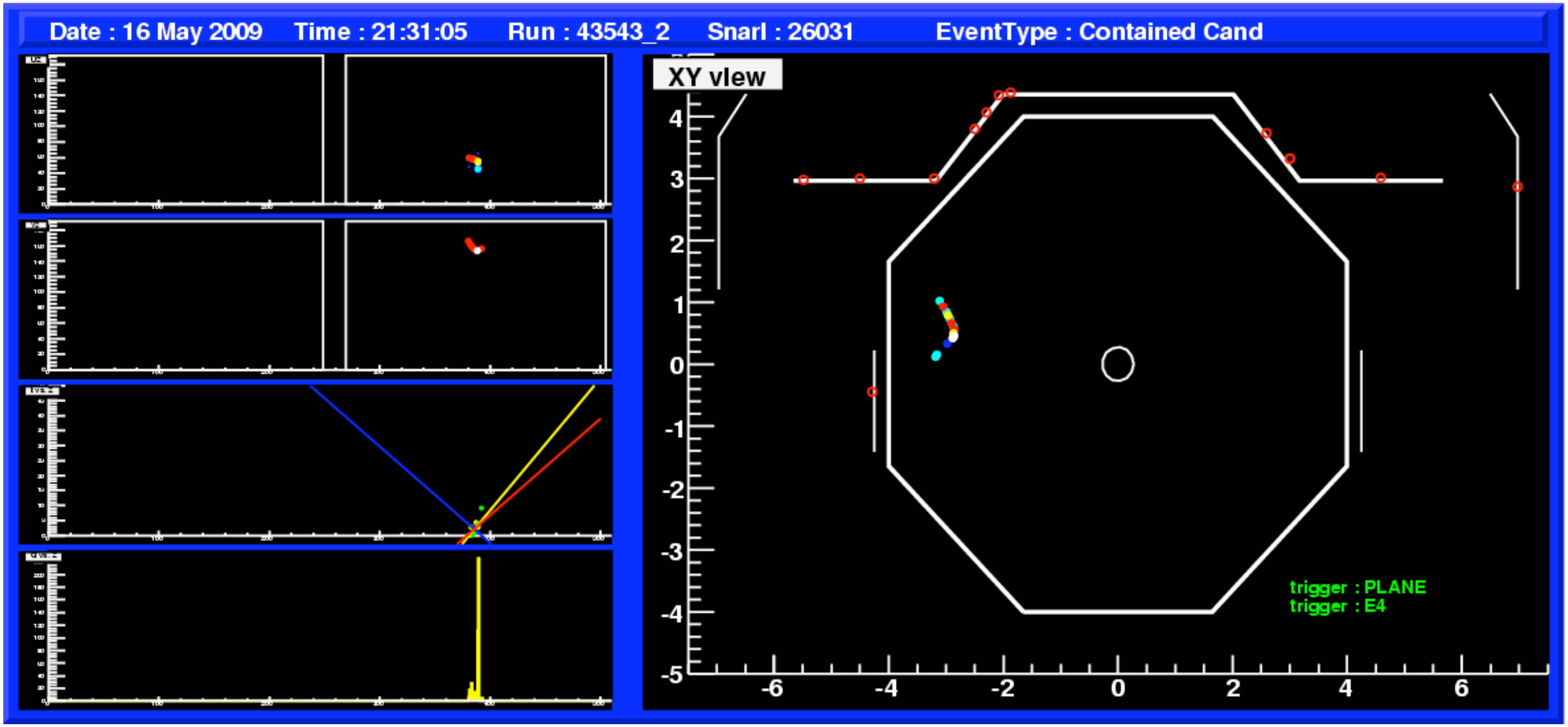
# Multiple muon



Date : 25 May 2009 Time : 14:08:18 Run : 43572_2 Snarl : 22606 Event Type : Multiple Muon ( 2 muons )

trigger : PLANE
trigger : E4

# Contained event candidate

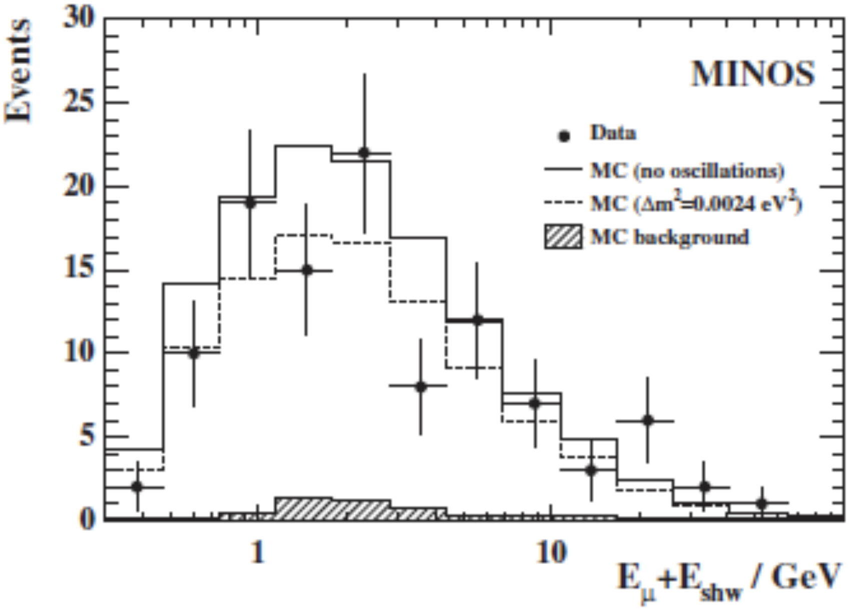


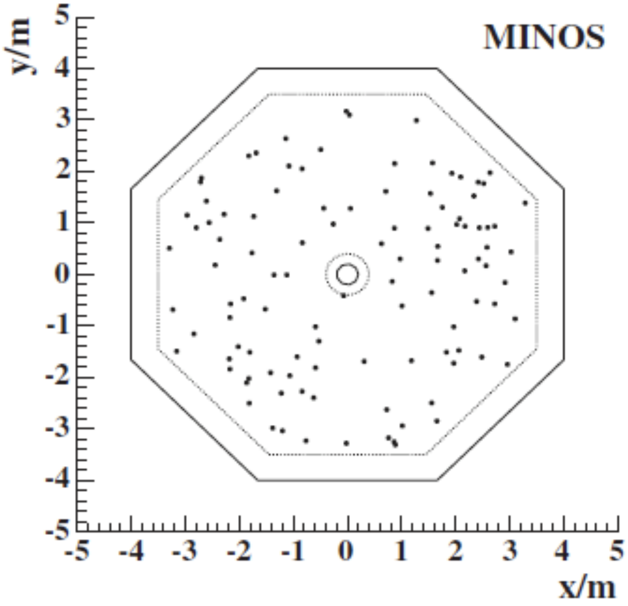
Date : 16 May 2009 Time : 21:31:05 Run : 43543_2 Snarl : 26031 EventType : Contained Cand

PHYSICAL REVIEW D 73, 072002 (2006)

# First observations of separated atmospheric $\nu_\mu$ and $\bar{\nu}_\mu$ events in the MINOS detector

First MINOS physics paper
107 events





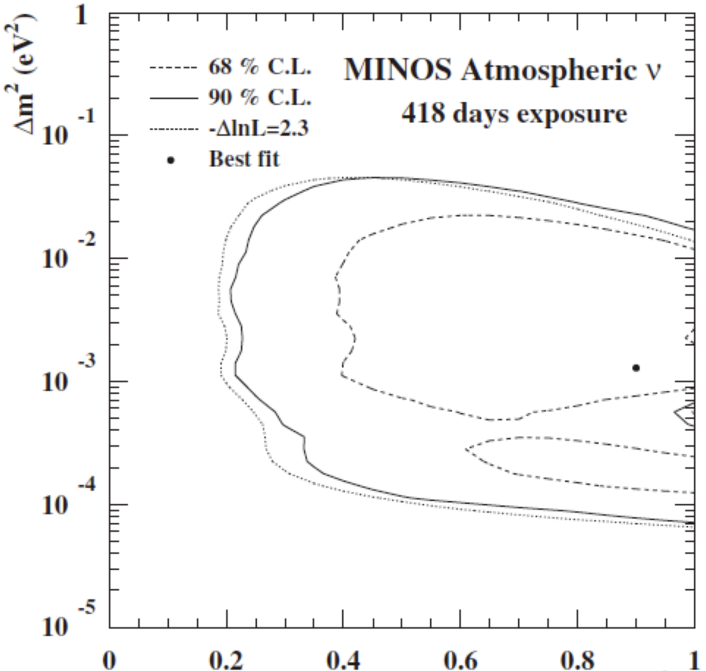
| Selection | Data | Expected no oscillations | Expected $\Delta m^2_{23} = 0.0024$ eV$^2$ |
|---|---|---|---|
| Good timing | 77 | $90 \pm 9$ | $68 \pm 7$ |
| Low res. | 30 | $37 \pm 4$ | $28 \pm 3$ |
| All events | 107 | $127 \pm 13$ | $96 \pm 10$ |

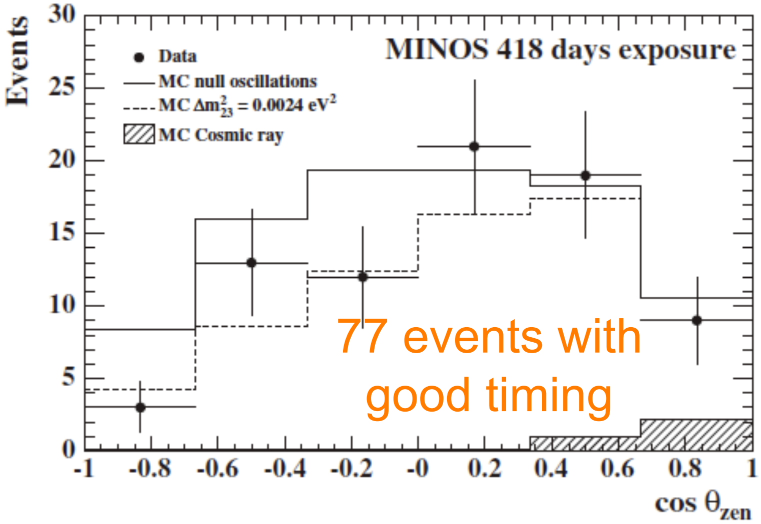
PHYSICAL REVIEW D 73, 072002 (2006)

# First observations of separated atmospheric $\nu_\mu$ and $\bar{\nu}_\mu$ events in the MINOS detector

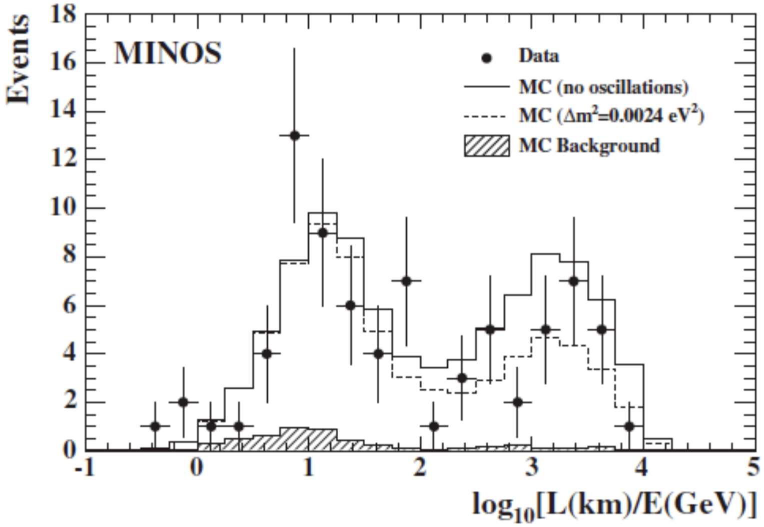
- 77 events with good timing
- 49 are downward-going ($cos\theta_{zenith} > 0$)
- 28 are downward-going ($cos\theta_{zenith} < 0$)

$$\frac{R^{data}_{\frac{up}{down}}}{R^{MC}_{\frac{up}{down}}} = 0.62^{+0.19}_{-0.14}(stat) \pm 0.02(syst)$$





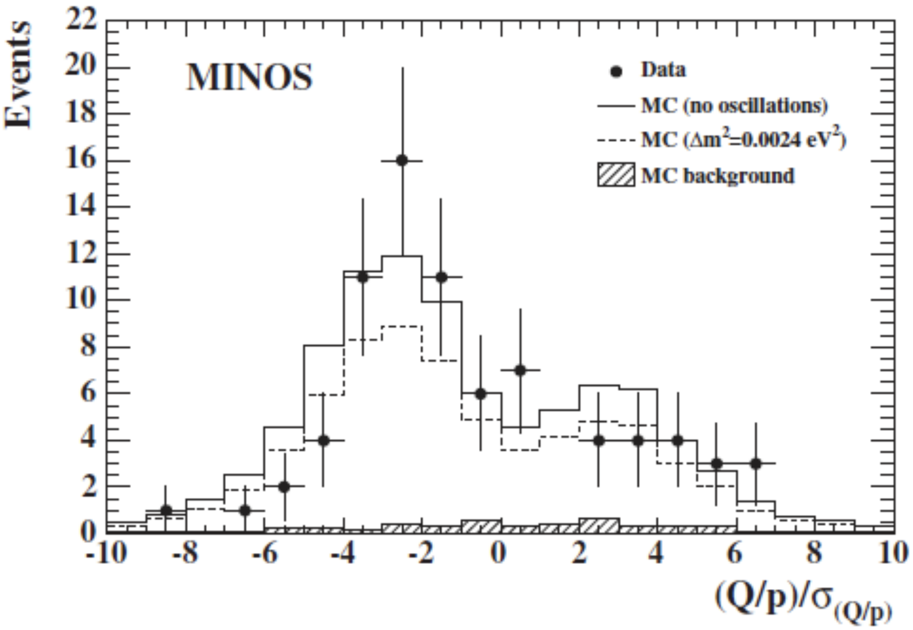
77 events with good timing

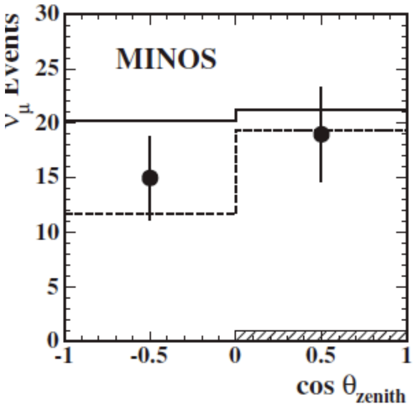


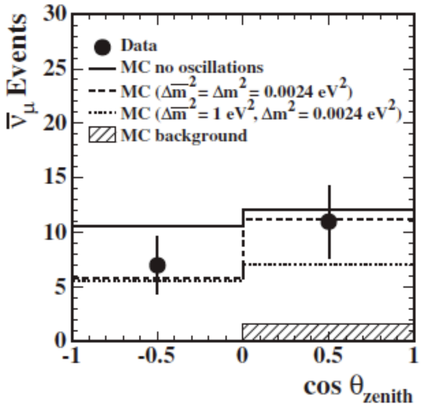
# Atmospheric separate neutrino and anti-neutrino (first observation)

- 18 events are cleanly identified as neutrinos (Q/p)/σ < - 2
- 34 events are anti-neutrinos (Q/p)/σ > + 2

$$\frac{R^{data}_{\frac{\bar{\nu}_\mu}{\nu_\mu}}}{R^{MC}_{\frac{\bar{\nu}_\mu}{\nu_\mu}}} = 0.96^{+0.38}_{-0.27}(stat) \pm 0.15(syst)$$

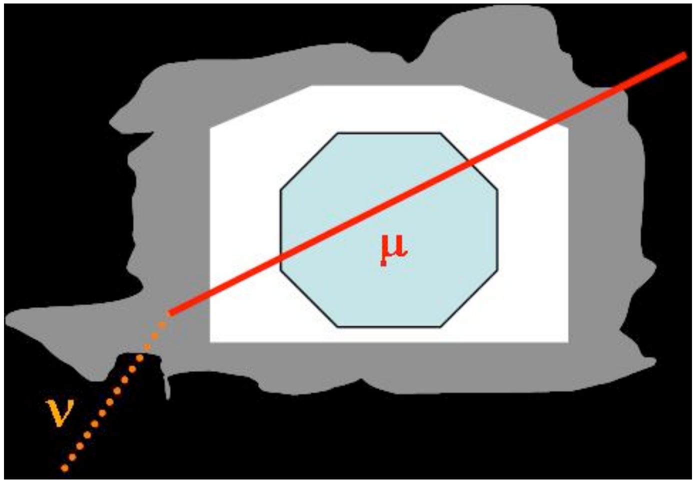


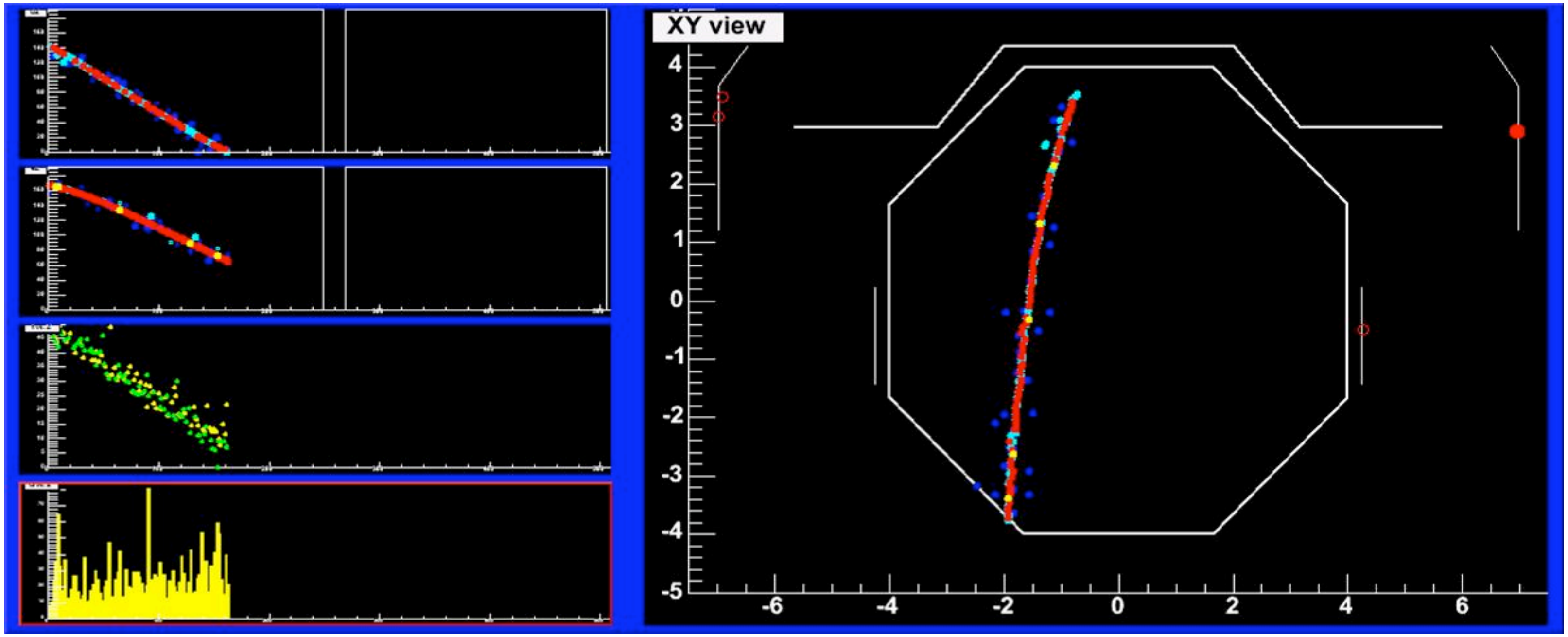




| Selection | Data | Expected no oscillations | Expected $\Delta m^2_{23} = 0.0024$ eV$^2$ |
|---|---|---|---|
| Low res. | 30 | 37 ± 4 | 28 ± 3 |
| Ambig. $\nu_\mu/\bar{\nu}_\mu$ | 25 | 26 ± 3 | 20 ± 2 |
| $\nu_\mu$ | 34 | 42 ± 4 | 31 ± 3 |
| $\bar{\nu}_\mu$ | 18 | 23 ± 2 | 17 ± 2 |

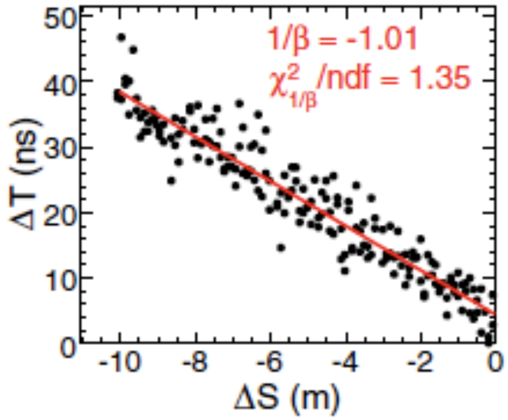
# MINOS Observatory: upward-going muons



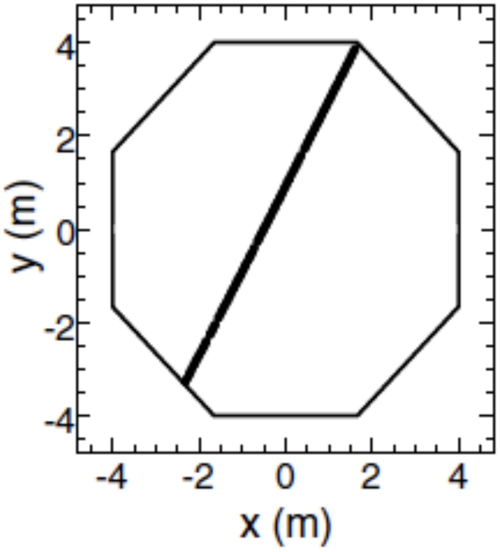


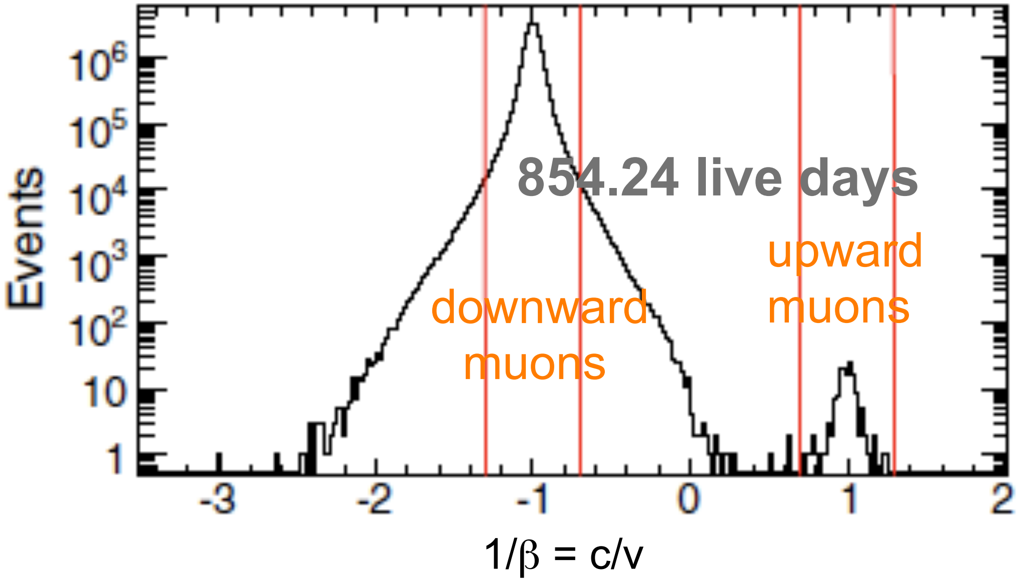
PHYSICAL REVIEW D **75**, 092003 (2007)

# Charge-separated atmospheric neutrino-induced muons in the MINOS far detector



| Muon type | Events | Background | |
|---|---|---|---|
| | | Contained | Cosmic $\mu$ |
| Upward-going | 130 | 4.2 | 0.0 |
| Horizontal | 10 | 0.1 | 0.3 |



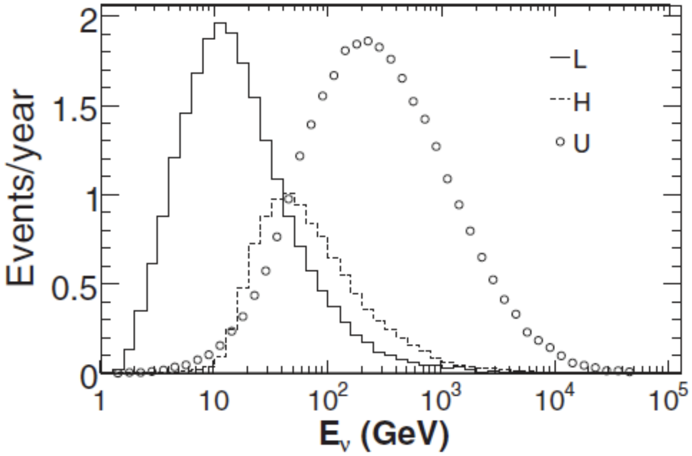


854.24 live days

downward muons

upward muons

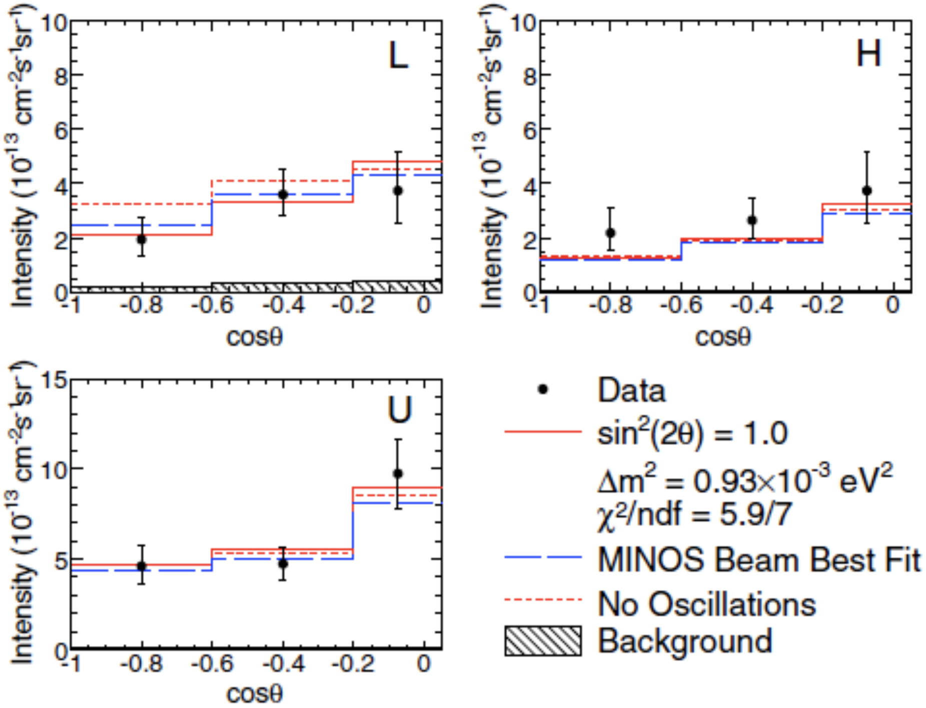
# Upward-going muons

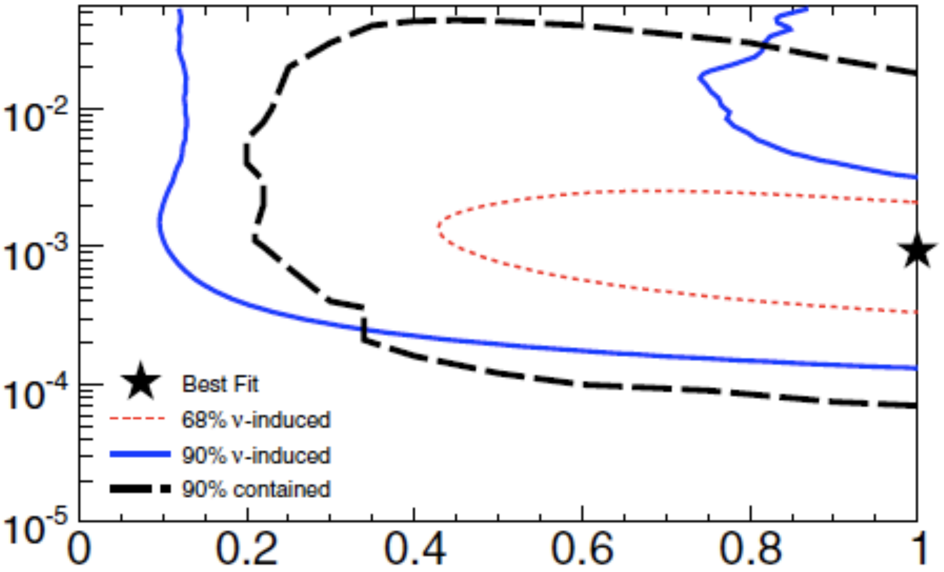


**Charge-separated, low-to-high momentum event ratio**

$$\tilde{\mathcal{R}}_{CPT} = \mathcal{R}_{-}/\mathcal{R}_{+} = 0.89^{+0.54}_{-0.33}(\text{stat}) \pm 0.03(\text{syst}).$$

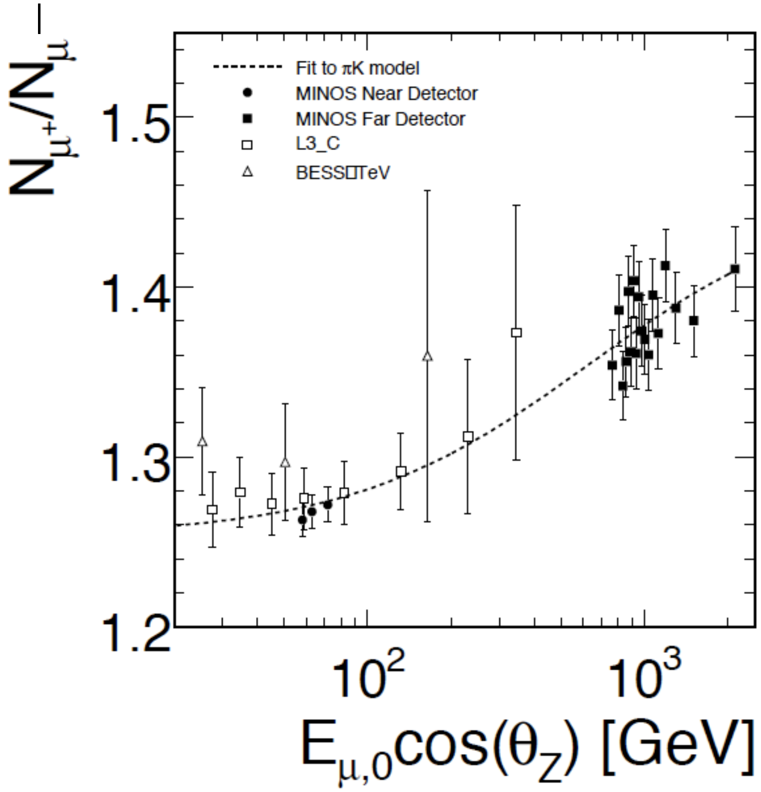
$$\mathcal{R} = \frac{R^{\text{data}}_{L/H+U}}{R^{\text{MC}}_{L/H+U}} = 0.65^{+0.15}_{-0.12}(\text{stat}) \pm 0.09(\text{syst})$$





# $\mu+/\mu-$
# Need to include kaon interactions

- Start with $$\frac{dN_\mu}{dE_\mu} \approx \frac{0.14 \cdot E_\mu^{-2.7}}{cm^2 sr GeV} \times \left( \frac{1.0}{1 + \frac{1.1 \cdot E_\mu cos(\theta)}{\epsilon_\pi}} + \frac{0.054}{1 + \frac{1.1 E_\mu cos(\theta)}{\epsilon_K}} \right)$$



⇨ Critical energies above which the pions and kaons "prefer" to interact more often than decay

$$\varepsilon_\pi = 115\ GeV \qquad \varepsilon_K = 850\ GeV$$

⇨ 0.054 is related to π/K ratio in showers and the Br to a muon

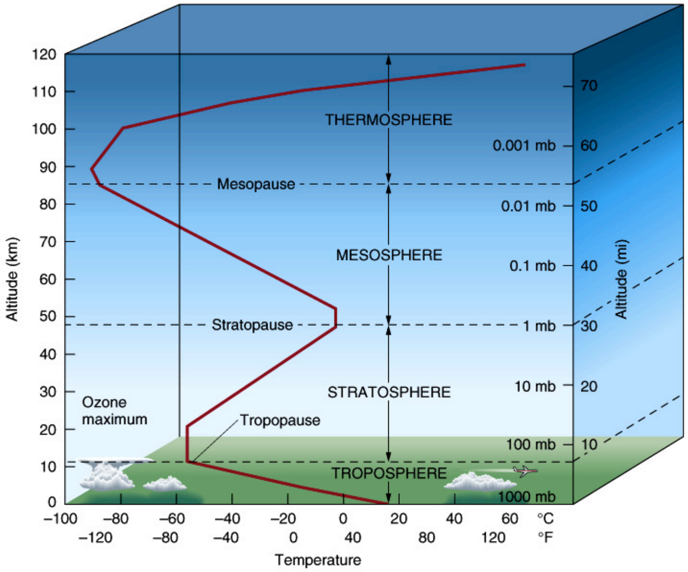
⇨ 1st term reflects the muon contribution from pions

⇨ 2nd term from kaons

⇨ $f_{\pi+}$ and and $f_{K+}$ are fractions of all decaying pions and kaons with a detected $\mu+$

$$\frac{N_{\mu+}}{N_{\mu-}} = \frac{\left( \frac{f_{\pi+}}{1 + \frac{1.1 E_{\mu+} cos(\theta)}{\epsilon_\pi}} + \frac{0.054 f_{K+}}{1 + \frac{1.1 E_{\mu+} cos(\theta)}{\epsilon_K}} \right)}{\left( \frac{(1 - f_{\pi+})}{1 + \frac{1.1 E_{\mu-} cos(\theta)}{\epsilon_\pi}} + \frac{0.054 (1 - f_{K+})}{1 + \frac{1.1 E_{\mu-} cos(\theta)}{\epsilon_K}} \right)}$$

# Seasonal variations – muon rate correlation with stratospheric temperatures



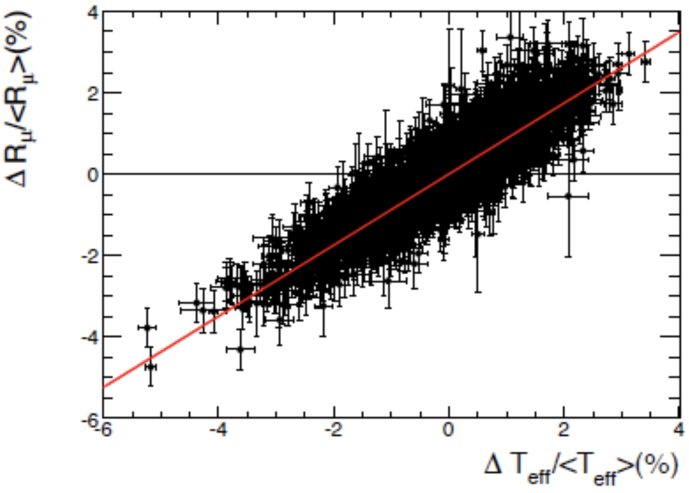


**FIG. 5:** A plot of the time series analysis, $\Delta R_\mu / \langle R_\mu \rangle$ vs. $\Delta T_{\rm eff} / \langle T_{\rm eff} \rangle$ for single muons. The fit has a $\chi^2/ndf = 1905/1797$, and the slope is $\alpha_T = 0.874 \pm 0.009$.

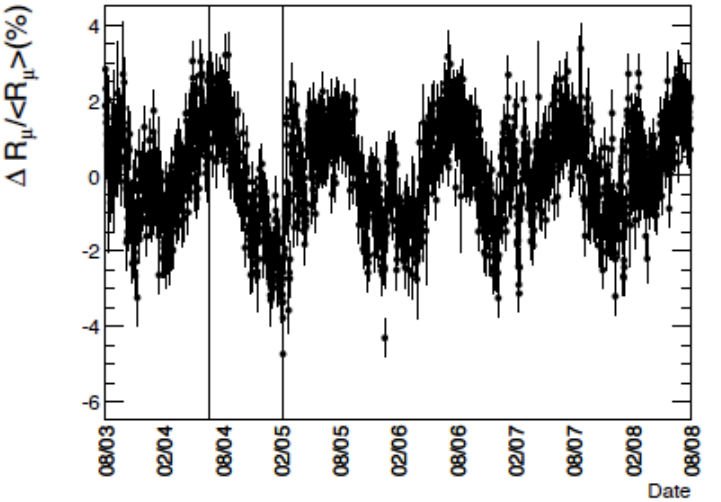


**FIG. 3:** The daily deviation from the mean rate of cosmic ray muon arrivals from 8/03-8/08, shown here with statistical error bars. The periodic fluctuations have the expected maxima in August, minima in February. The vertical bars indicate the period of time when the detector ran in nominal reverse field mode.

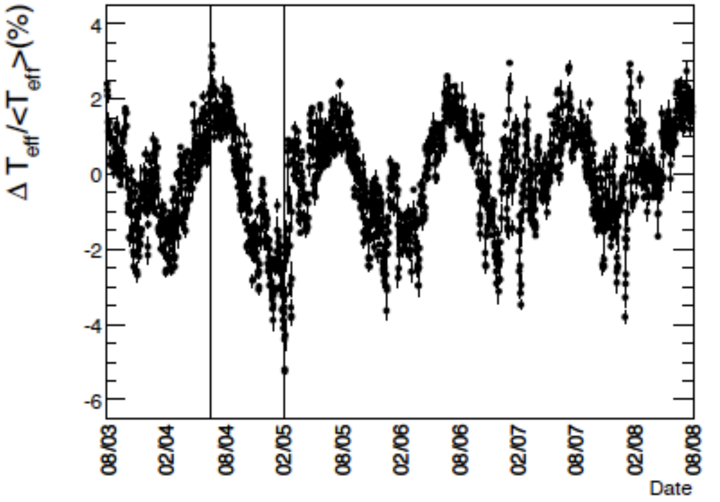


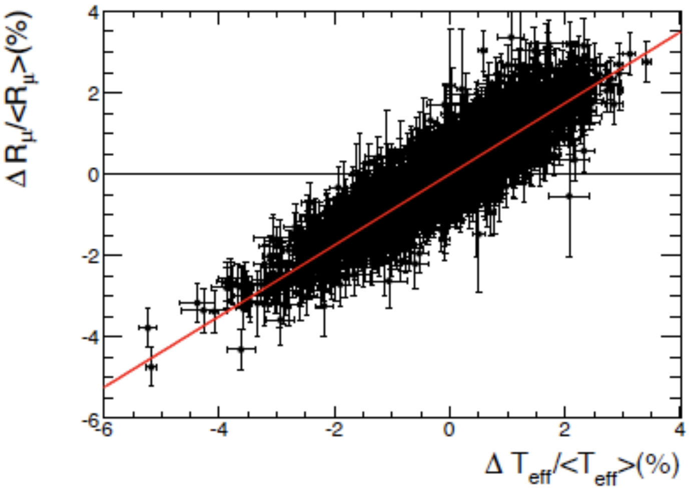
**FIG. 4:** The daily deviation from $\langle T_{\rm eff} \rangle$ over a period of five years, beginning when the Far Detector was complete, 08/03-08/08. The vertical bars indicate the period of time when the detector ran in nominal reverse field mode.

# Seasonal variations – muon rate correlation with stratospheric temperatures

- 67 mln muons

$$\alpha_T \frac{\Delta T_{\text{eff}}}{\langle T_{\text{eff}} \rangle} = \frac{\Delta R_\mu}{\langle R_\mu \rangle}$$

$$\alpha_T = 0.874 \pm 0.009.$$



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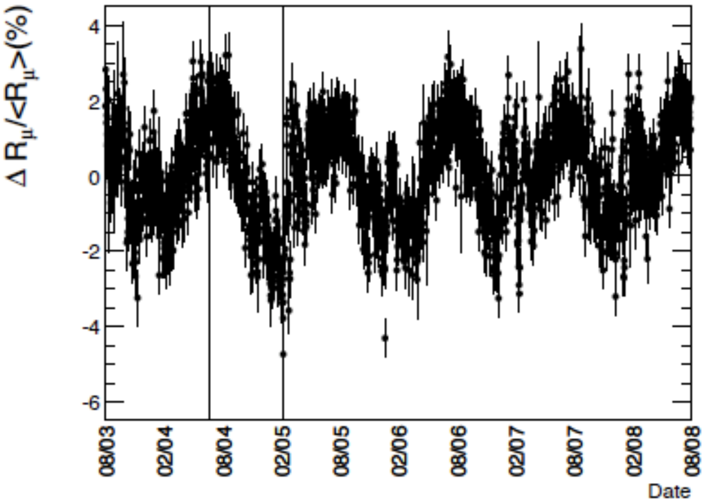


FIG. 3: The daily deviation from the mean rate of cosmic ray muon arrivals from 8/03-8/08, shown here with statistical error bars. The periodic fluctuations have the expected maxima in August, minima in February. The vertical bars indicate the period of time when the detector ran in nominal reverse field mode.

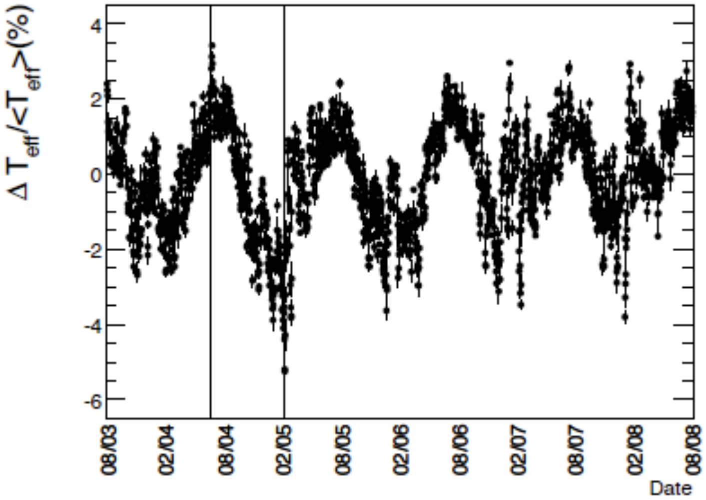


FIG. 4: The daily deviation from $\langle T_{\text{eff}} \rangle$ over a period of five years, beginning when the Far Detector was complete, 08/03-08/08. The vertical bars indicate the period of time when the detector ran in nominal reverse field mode.

# Charge separated

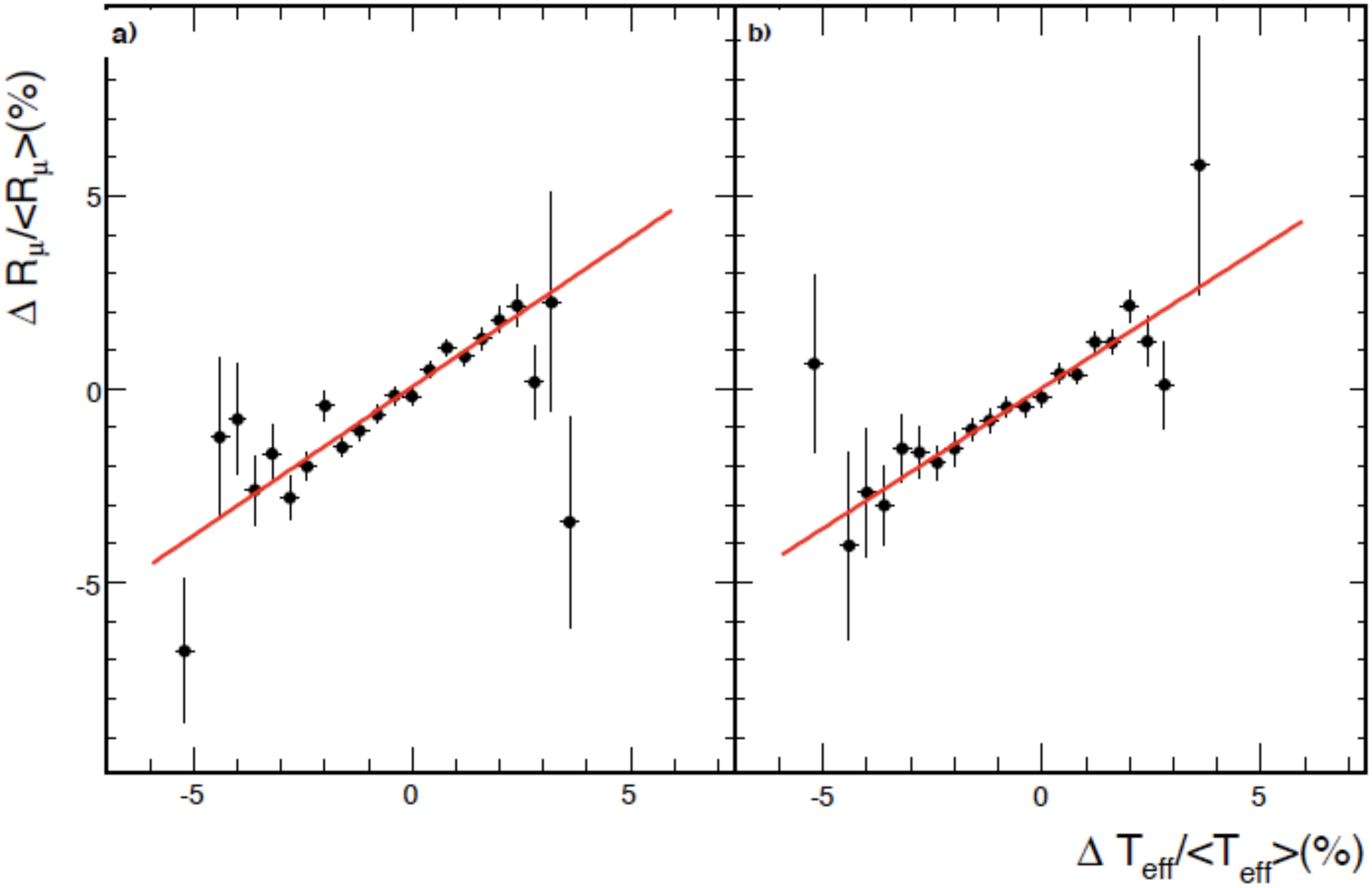


**FIG. 7:** A histogram of $\Delta R_\mu / \langle R_\mu \rangle$ vs. $\Delta T_{\rm eff} / \langle T_{\rm eff} \rangle$ in bins of $0.4\,\%$ width for $\mu^+$(a) and $\mu^-$(b). The fit results are $\alpha_T = 0.769 \pm 0.051, \chi^2/ndf = 36.3/20$ for $\mu^+$, $\alpha_T = 0.727 \pm 0.061, \chi^2/ndf = 17.2/19$ for $\mu^-$.

# Need kaon (again)

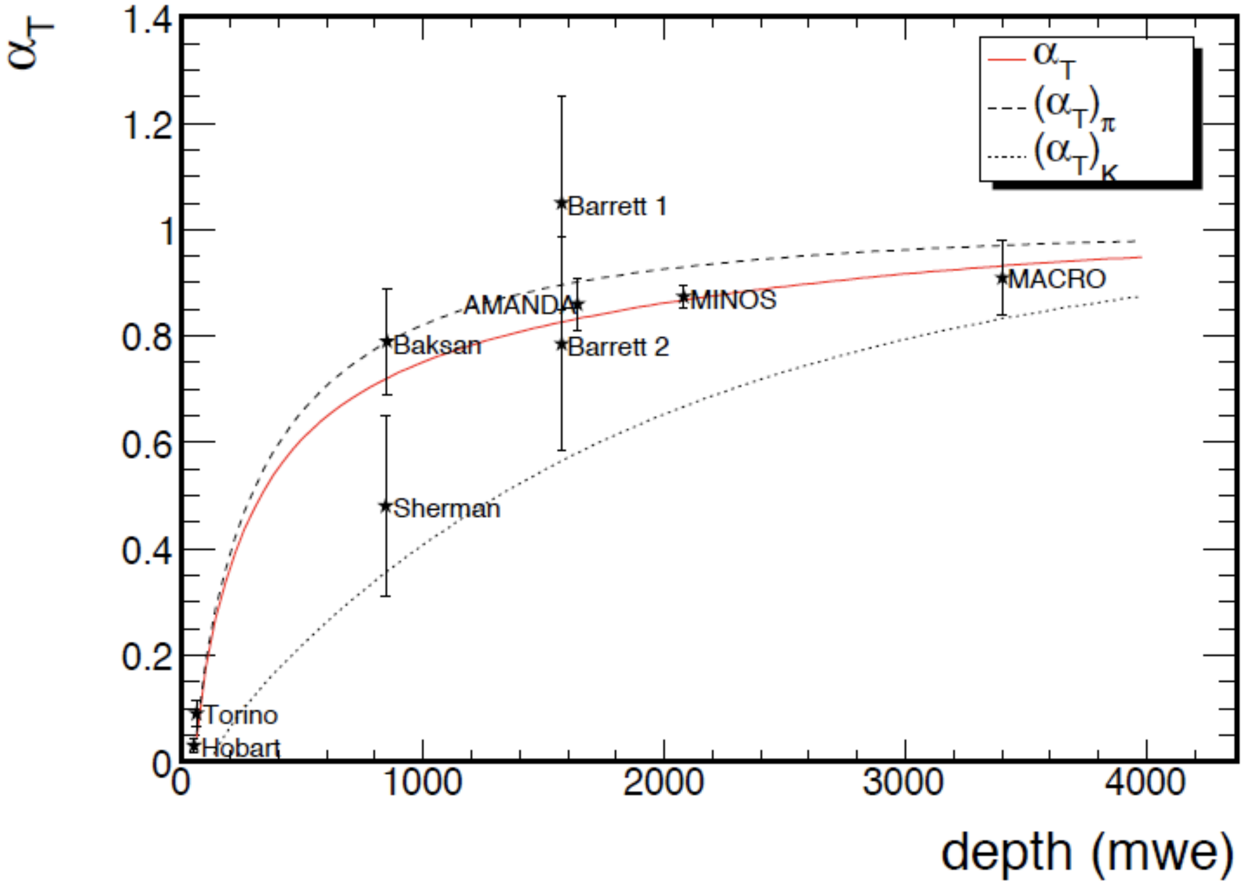
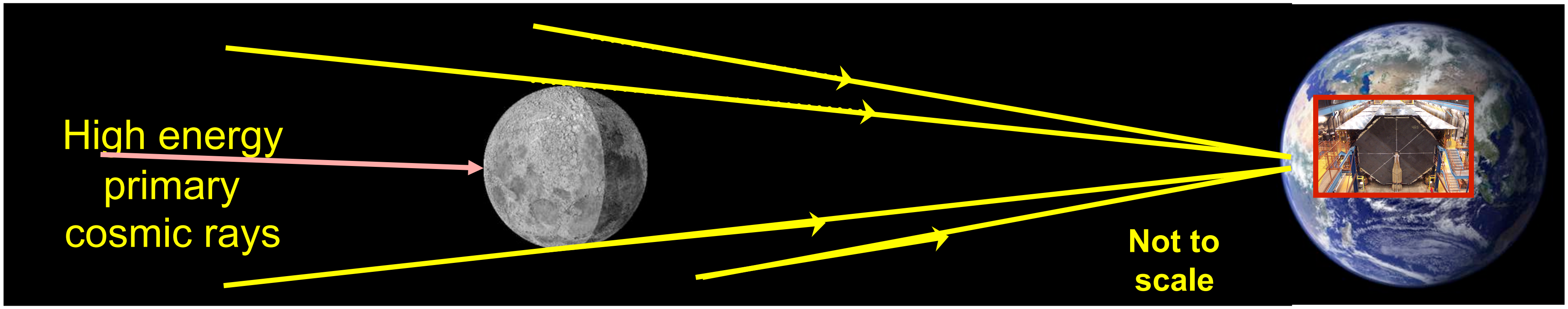
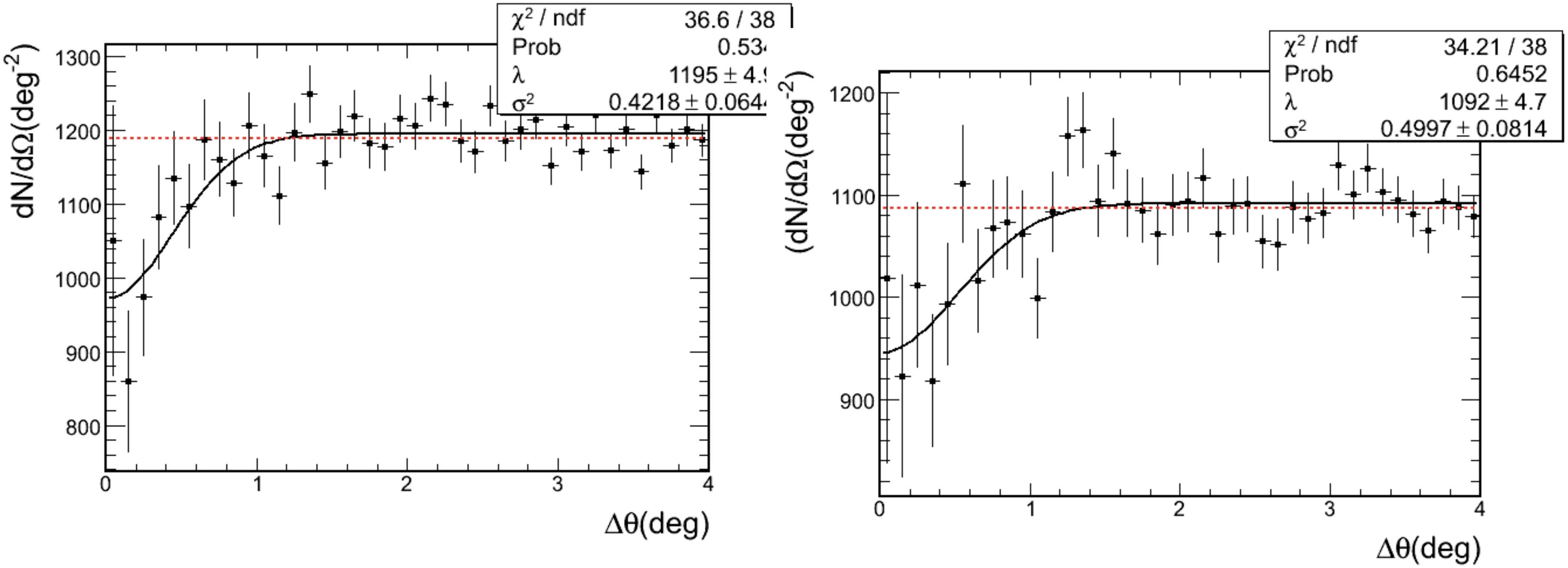


**FIG. 8:** The theoretical prediction for $\alpha_T$ as a function of detector depth. The solid (top) curve is the prediction using the pion-only model (of MACRO) and the dotted (bottom) curve is the prediction using a kaon-only model. The solid red (middle) curve is the new prediction including both $K$ and $\pi$. The data from other experiments are shown for comparison only, and are from Barrett 1, 2 [1], AMANDA [3], MACRO [14], Torino [15], Poatina [16], Utah [17] , Sherman [18], Hobart [19] and Baksan [20].

# Moon and Sun shadow





# Summary / outlook

- MINOS is exploiting it’s potential
  - Beam
    - Antineutrinos
    - Near Detector
  - Observatory
    - Expect updates atm. oscillations results
    - Charge ratios (neutrinos and CR)

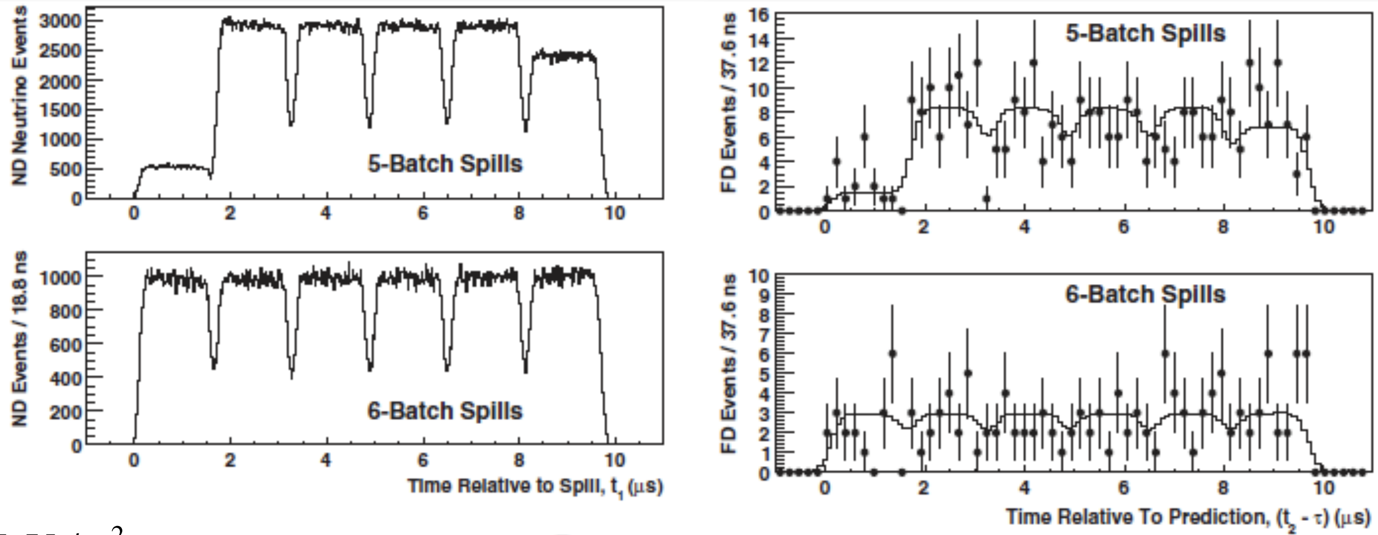
- May be the last two weeks with neutrinos
  - After the 2000 summer shutdown will likely run focusing “-”
  - Will have collected > 7x 1020 POT

- Expect improved results on most topics

# THE END

PHYSICAL REVIEW D 76, 072005 (2007)

# Measurement of neutrino velocity with the MINOS detectors and NuMI neutrino beam

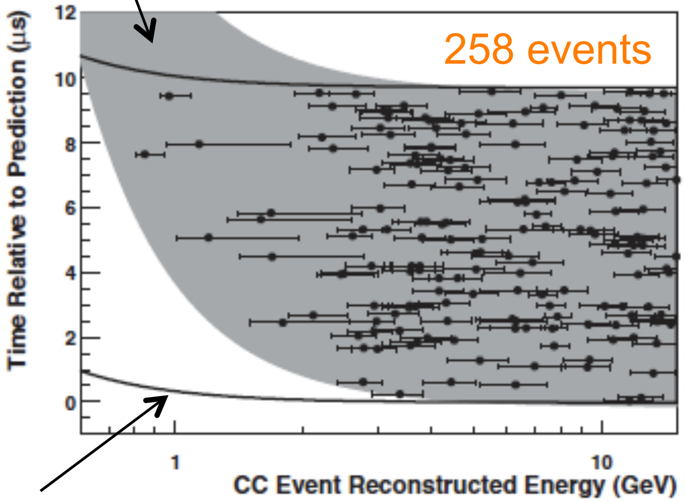


$$T_{m_\nu}(E_\nu) = \frac{\tau}{\sqrt{1 - (\frac{m_\nu c^2}{E_\nu})^2}},$$

GPS precision: +/- 200 ns

473 events

$m_\nu = 50\ MeV / c^2$



258 events

$m_\nu = 17\ MeV / c^2$

| Baseline | |
|---|---|
| Distance[a] ND to FD, $L$ | 734 298.6 ± 0.7 m [15] |
| Nominal time of flight, $\tau$ | 2 449 356 ± 2 ns |

$$\boxed{\delta = -126 \pm 32(\text{stat.}) \pm 64(\text{syst.})\ \text{ns} \qquad 68\%\text{C.L.}}$$

$$\boxed{\frac{(v-c)}{c} = \frac{-\delta}{\tau + \delta} = 5.1 \pm 2.9(\text{stat.} + \text{syst.}) \times 10^{-5} \qquad 68\%\text{C.L.}}$$

$$m_\nu = 17^{+13}_{-28}(\text{stat.})\ \text{MeV}/c^2 \qquad 68\%\ \text{C.L.}$$

$$\boxed{m_\nu < 50\ \text{MeV}/c^2(\text{stat.} + \text{syst.}) \qquad 99\%\text{C.L.}}$$

PRL **101,** 151601 (2008) PHYSICAL REVIEW LETTERS week ending 10 OCTOBER 2008

# Testing Lorentz Invariance and CPT Conservation with NuMI Neutrinos in the MINOS Near Detector

$$P_{\nu_\mu\to\nu_x} \simeq L^2[(\mathcal{C})_{\mu x} + (\mathcal{A}_c)_{\mu x}\cos(\omega_\oplus T_\oplus) + (\mathcal{A}_s)_{\mu x}\sin(\omega_\oplus T_\oplus) + (\mathcal{B}_c)_{\mu x}\cos(2\omega_\oplus T_\oplus) + (\mathcal{B}_s)_{\mu x}\sin(2\omega_\oplus T_\oplus)]^2, \quad (1)$$

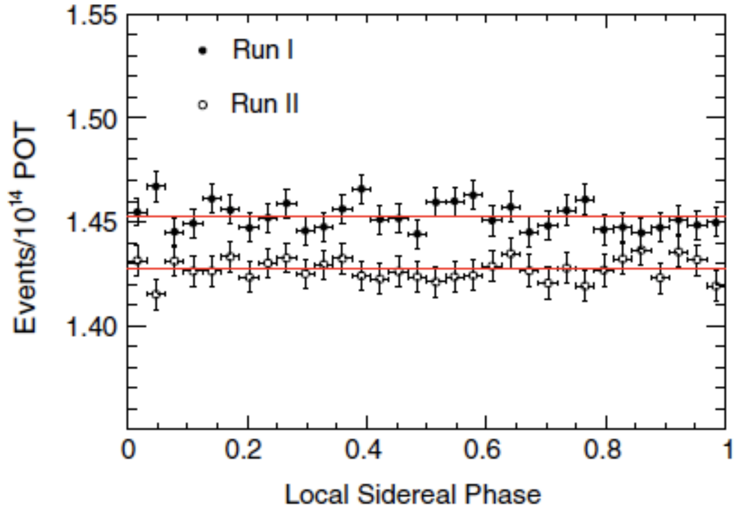


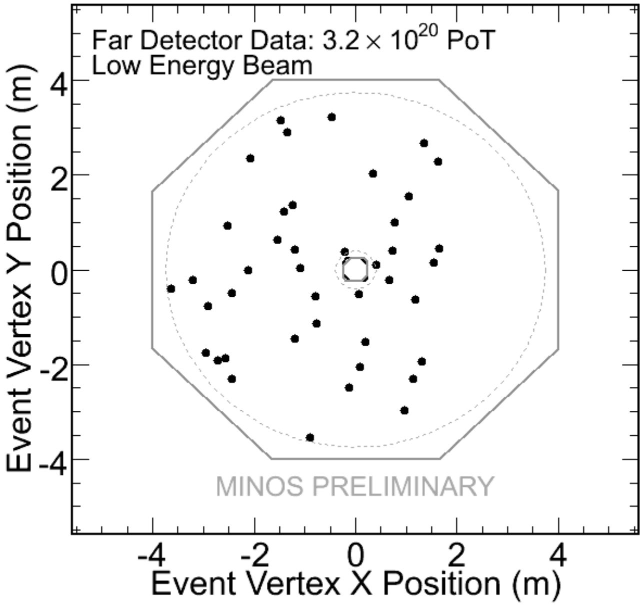
FIG. 1 (color online). The local sidereal phase histograms for run I and run II. Superposed are fits to a constant sidereal rate.

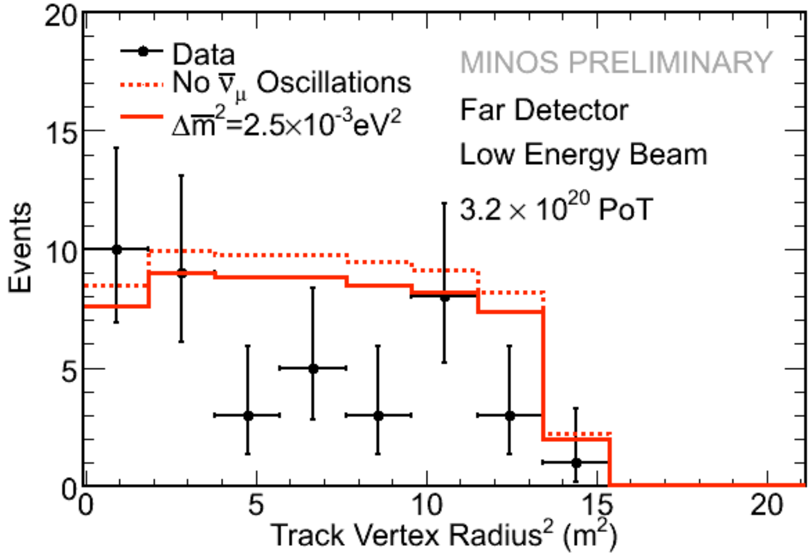
TABLE III. Limits to the magnitudes of the SME coefficients for $\nu_\mu \to \nu_x$ in terms of the suppression factor $m_W/m_P \sim 10^{-17}$; $a_L$ have units of (GeV) and $c_L$ are unitless.

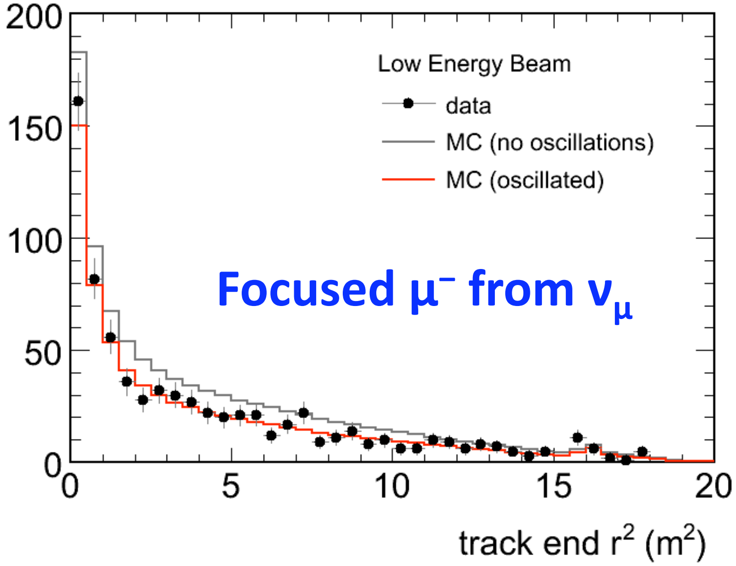
| | $\times 10^{-17}$ | | $\times 10^{-17}$ |
|---|---|---|---|
| $a_L^X$ | $3.0 \times 10^{-3}$ | $a_L^Y$ | $3.0 \times 10^{-3}$ |
| $c_L^{TX}$ | $0.9 \times 10^{-5}$ | $c_L^{TY}$ | $0.9 \times 10^{-5}$ |
| $c_L^{XX}$ | $5.6 \times 10^{-4}$ | $c_L^{YY}$ | $5.5 \times 10^{-4}$ |
| $c_L^{XY}$ | $2.7 \times 10^{-4}$ | $c_L^{YZ}$ | $1.2 \times 10^{-4}$ |
| $c_L^{XZ}$ | $1.3 \times 10^{-4}$ | ... | ... |

At experimentally accessible energies, signals for Lorentz and CPT violation can be described by a theory based on the standard model and general relativity, referred to as the standard-model extension (SME) [1,2]. The SME was developed following the suggestion in string theory that extended quantum strings introduce non-locality that could break Lorentz invariance [3]. It is an observer independent theoretical framework that contains all the Lorentz-violating (LV) terms involving particle fields in the standard model of particle physics and gravitational fields in general relativity (GR). SME is an effective field theory with quantum field action applying to quantum fields and elementary particles and classical action applying to gravitational fields. Since the standard model is thought to be the low-energy limit of a more fundamental theory that unifies quantum physics and gravity at the Planck scale, mP ’ 1019 GeV, it has been suggested [2] that the violations of Lorentz and CPT symmetries introduced by SME provide a link to Planck scale physics. Although the magnitude of LV signatures in the accessible energy limit are suppressed by a factor of order the electroweak scale divided by the Planck scale, mW=mP 1017 [4], these low-energy probes of new physics can and have been explored in many ways with current experimental technologies [5].

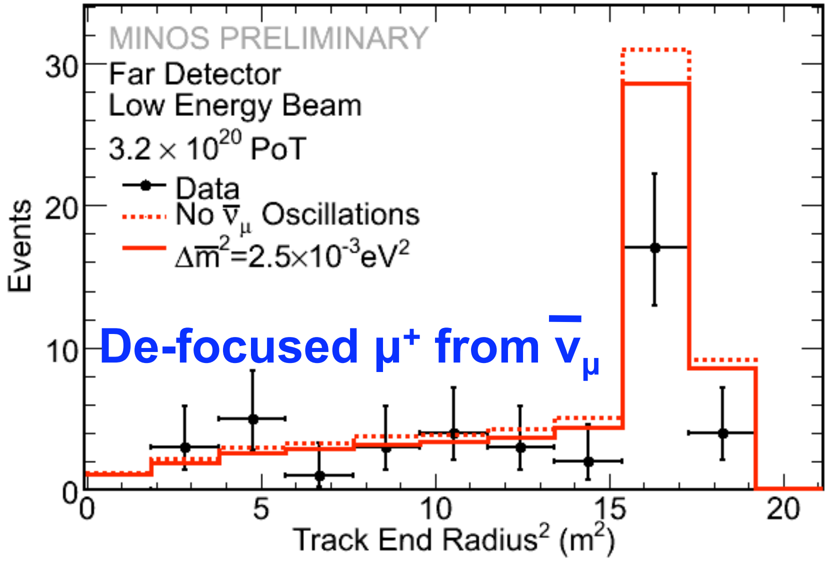
# Far Detector Distributions







**Focused $\mu^-$ from $\nu_\mu$**



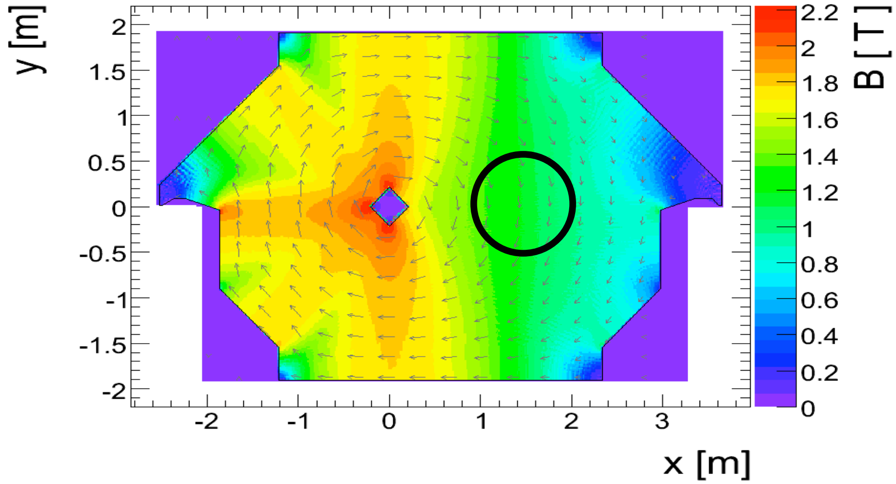
**De-focused $\mu^+$ from $\overline{\nu}_\mu$**

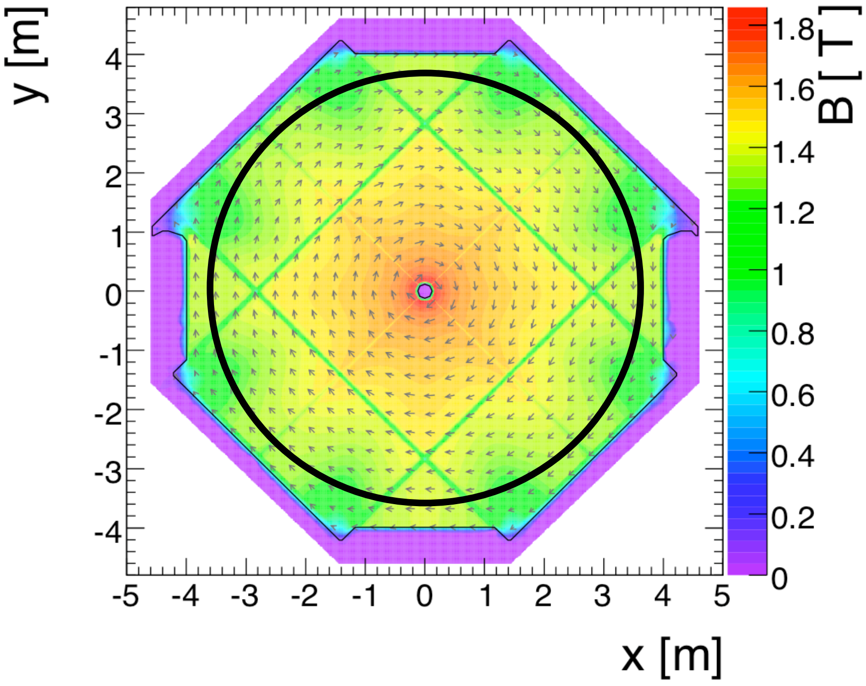
# Magnetic field in MINOS

- Magnetic coil runs down the detector centre and back along the bottom
  - ⇨ Produces a “toroidal” field
  - ⇨ Fiducial volume has <B> = 1.3 T

- Magnetic field separates $\mu^-$ from $\mu^+$
  - ⇨ Focused μ’s typically follow an “S” shaped path: bending towards, then crossing the coil
  - ⇨ De-focused μ’s are bent outwards to the detector edges, typically exiting

- Coil current polarity is “forward” to focus $\mu^-$ from $\nu_\mu$ towards the coil





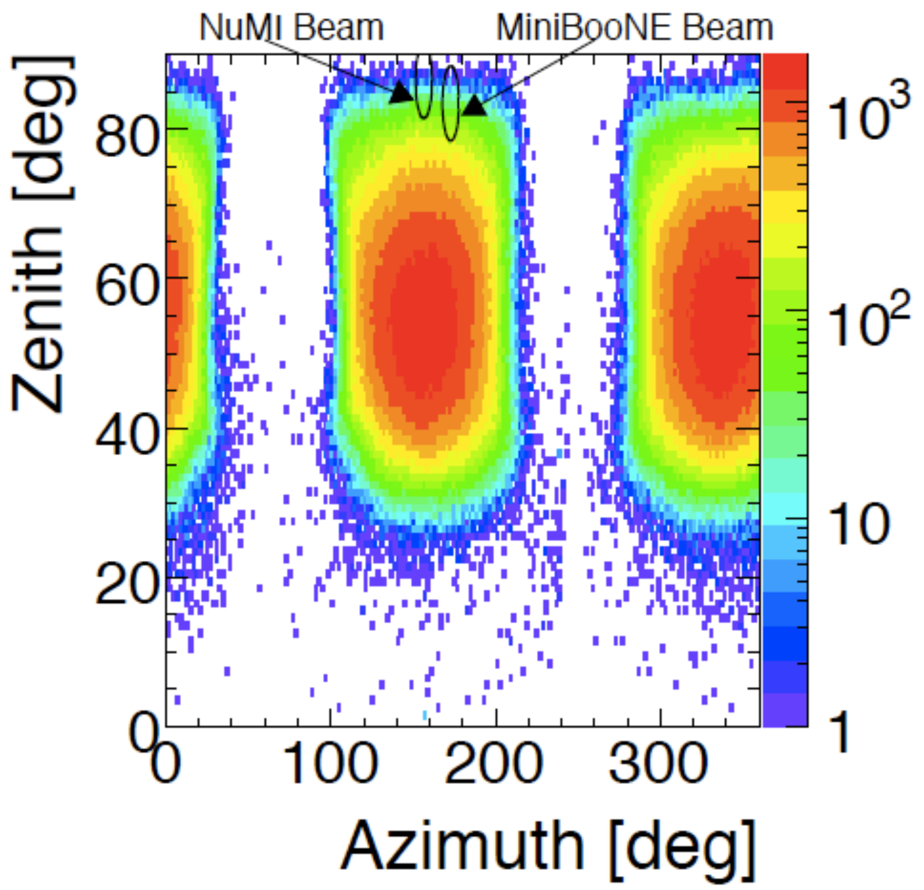
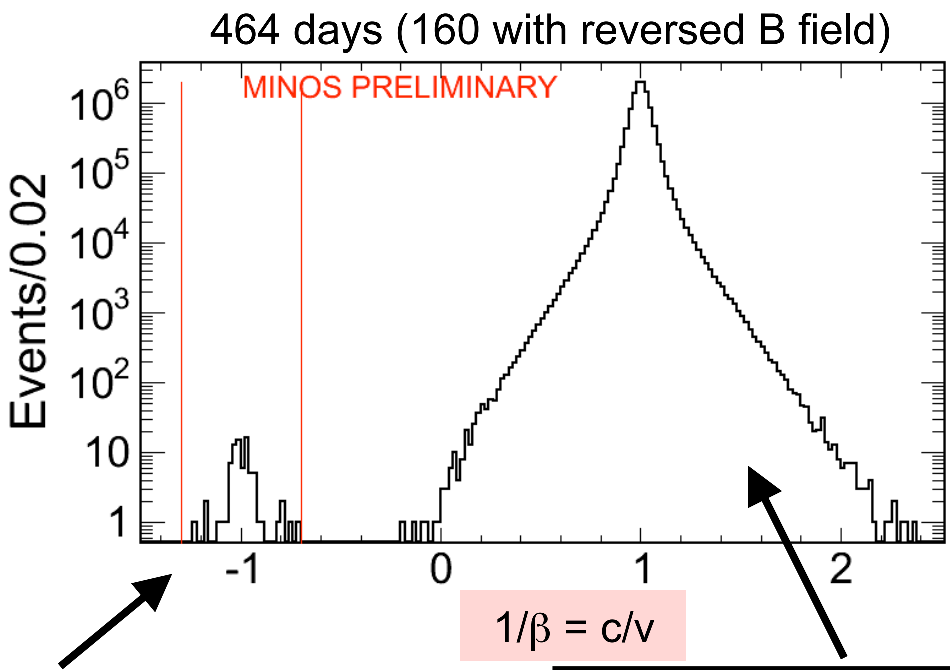


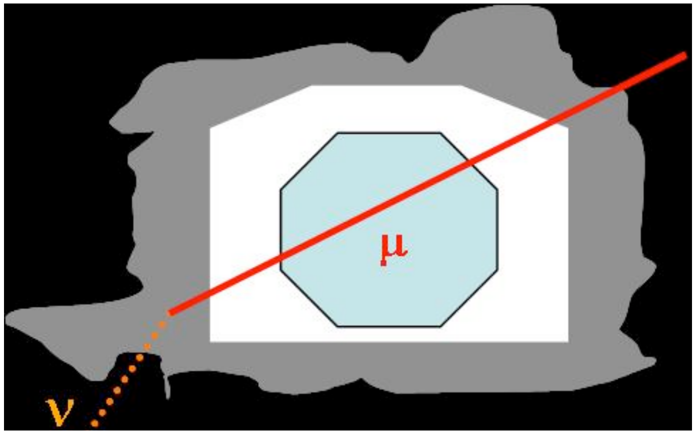
Figure 27: The directionality of all cosmic muons passing our selection criteria. Note that there is no statistical excess in the regions where we might expect neutrinos from numi and mini-boone.

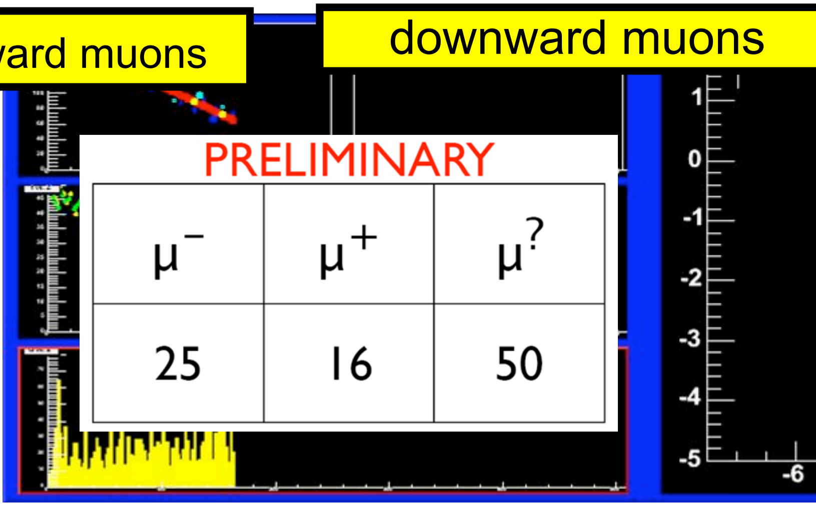
# MINOS Observatory: upward-going muons



$91\ \nu$ upward muons

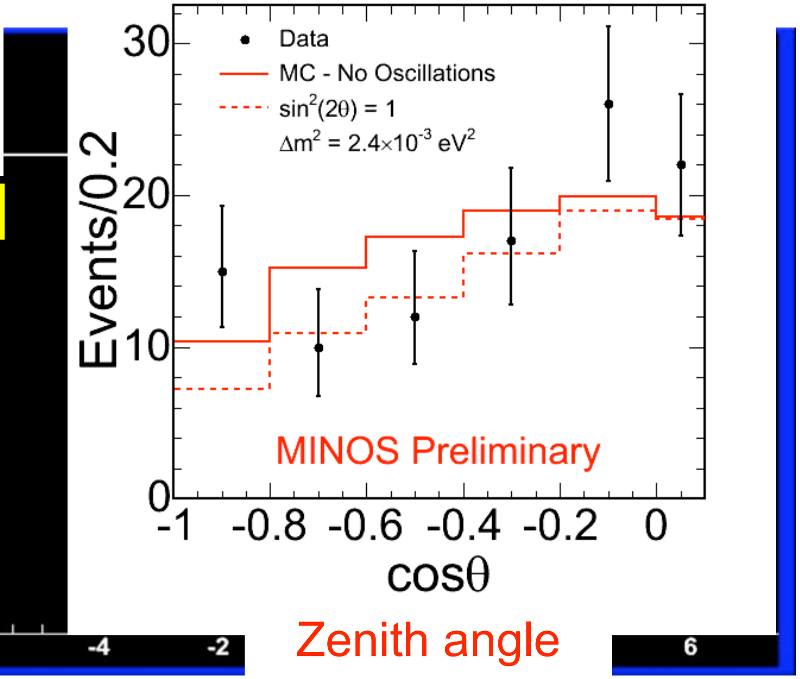
downward muons





PRELIMINARY

| $\mu^-$ | $\mu^+$ | $\mu^?$ |
|---|---|---|
| 25 | 16 | 50 |



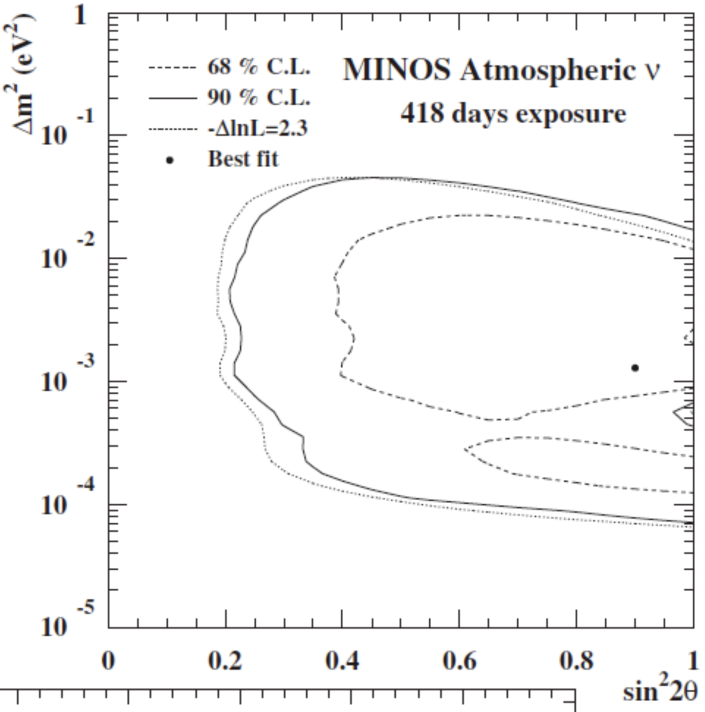
Zenith angle

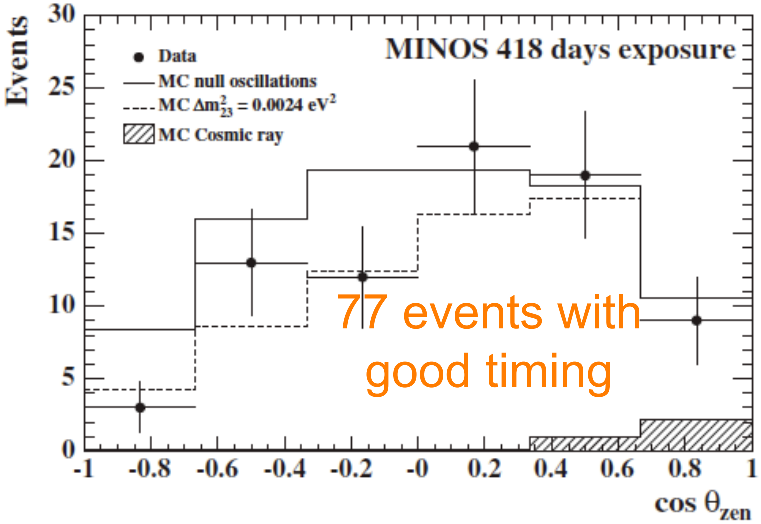
PHYSICAL REVIEW D 73, 072002 (2006)

# First observations of separated atmospheric $\nu_\mu$ and $\bar{\nu}_\mu$ events in the MINOS detector

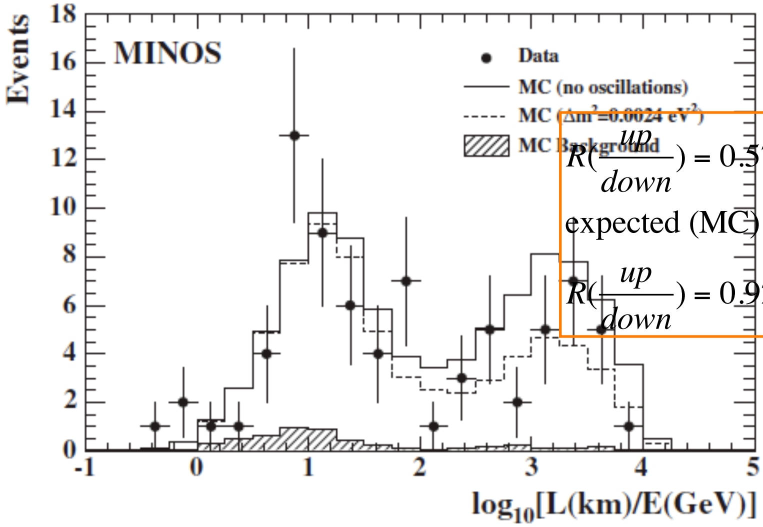
- 77 events with good timing
- 49 are downward-going ($cos\theta_{zenith} > 0$)
- 28 are downward-going ($cos\theta_{zenith} < 0$)

$$\frac{R^{data}_{\frac{up}{down}}}{R^{MC}_{\frac{up}{down}}} = 0.62^{+0.19}_{-0.14}(stat) \pm 0.02(syst)$$





77 events with good timing



$$R(\frac{up}{down}) = 0.57^{+0.17}_{-0.13}(stat)$$

expected (MC) for no oscillations

$$R(\frac{up}{down}) = 0.92 \pm 0.03$$

# Beam: a how to

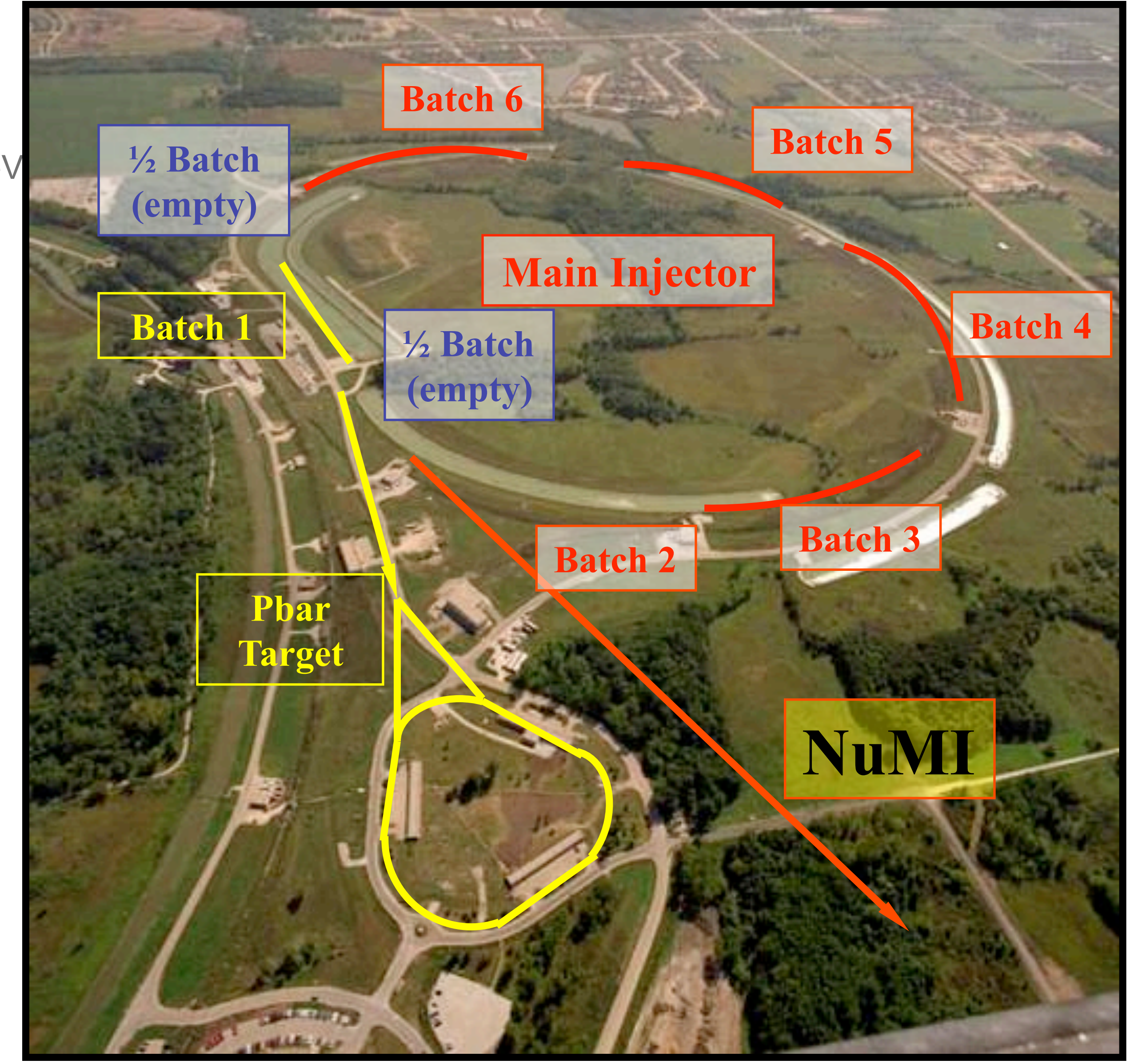
(Main Injector = MI)

❑ MI is fed 1.56 μs batches from 8 GeV Booster
(MI ramp time ~1.5sec)

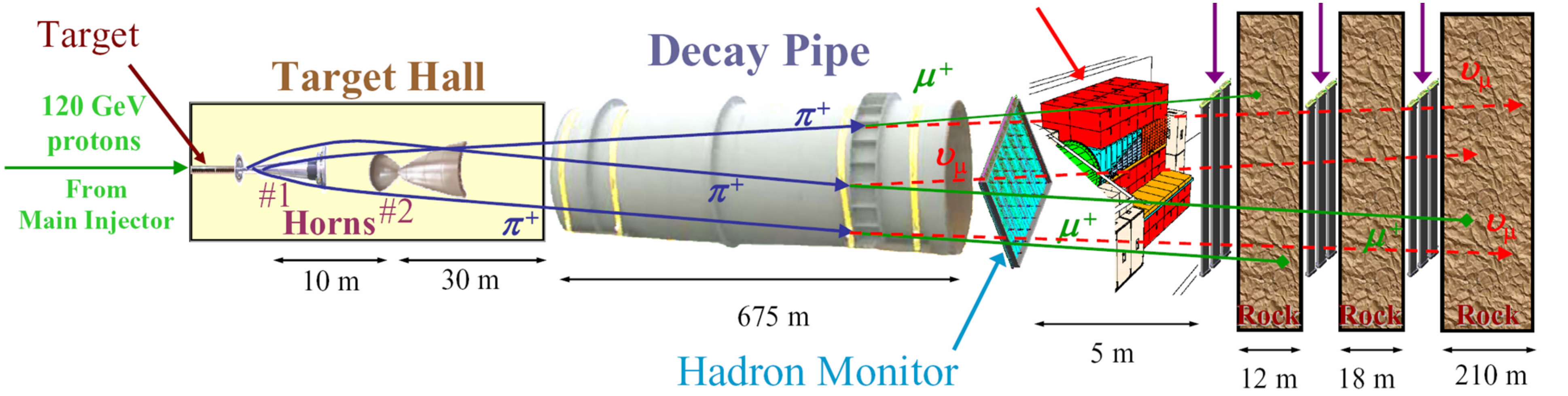
❑ NuMI designed for
  - ➔ 8.67 μsec single turn extraction
  - ➔ 4 × $10^{13}$ppp @ 120 GeV
  - ➔ 1.9 second cycle time
  - ➔ beam power ~400kW

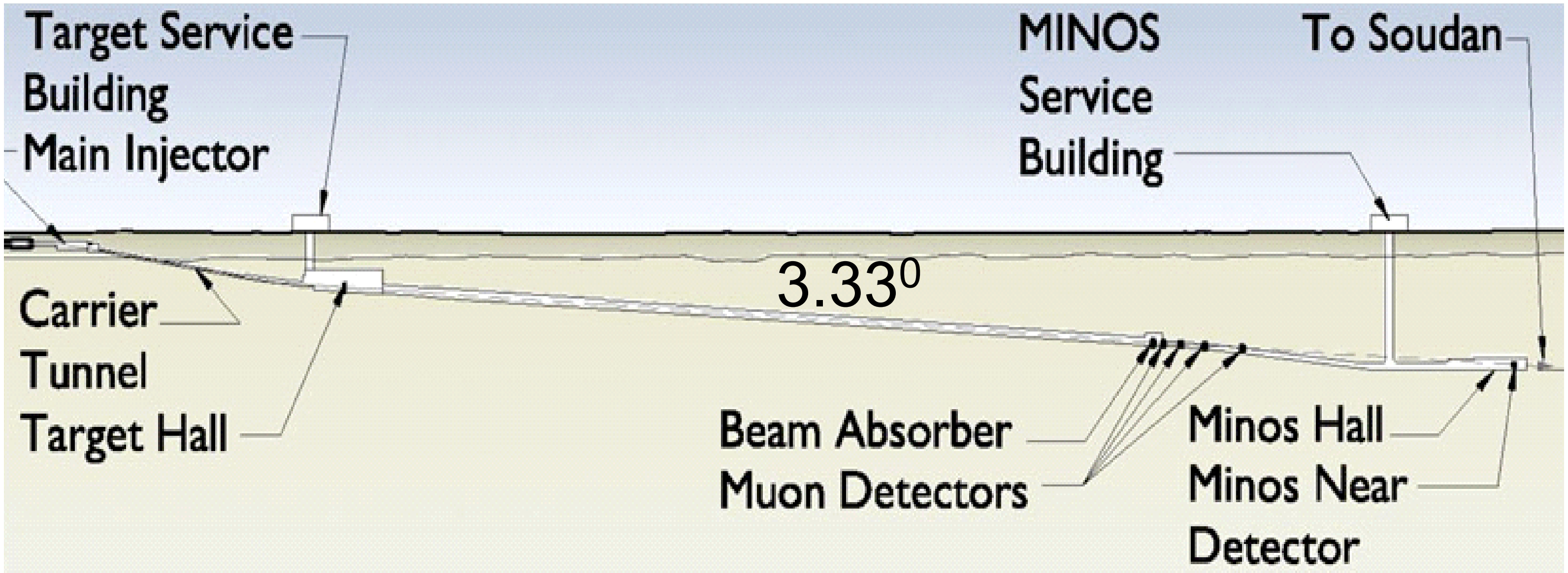
❑ Typical performance to date:
  - ➔ 3.2 × $10^{13}$ ppp @ 120 GeV
  - ➔ 2.2 second cycle time

❑ Achieved records:
  - ➔ 3.7 ×$10^{13}$ ppp @ 120 GeV
  - ➔ 2.0 second cycle time
  - ➔ 320 kW

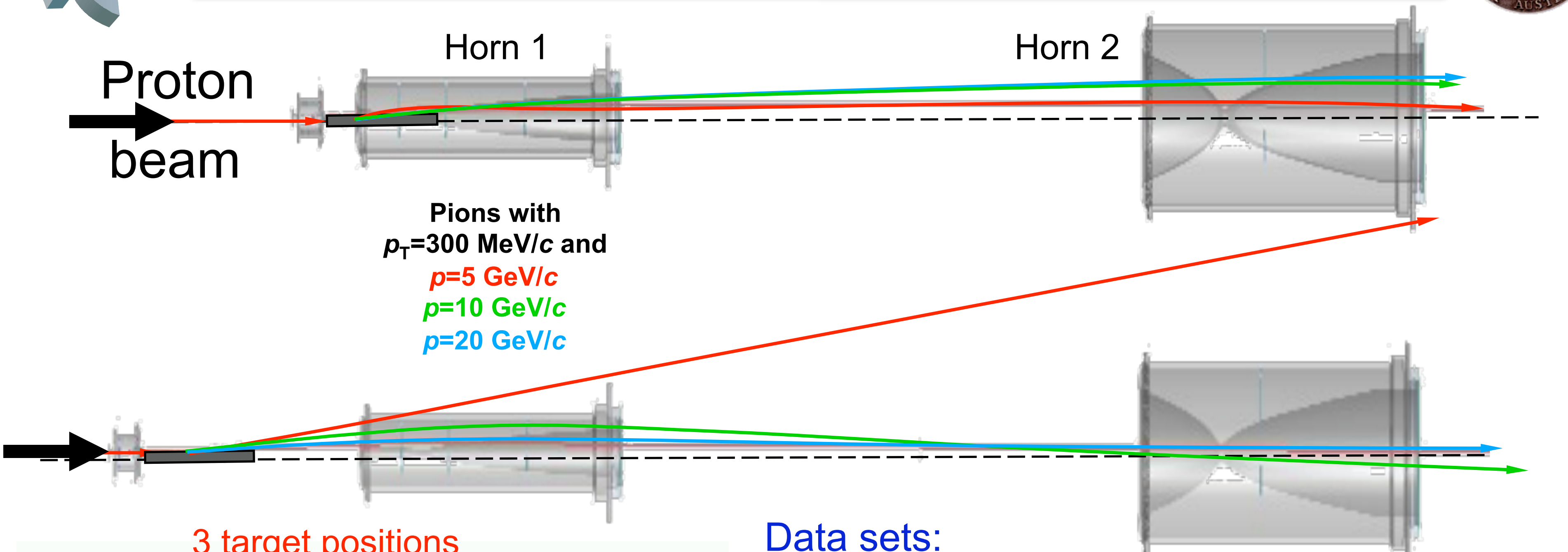


# Experimental setup: NuMI beam



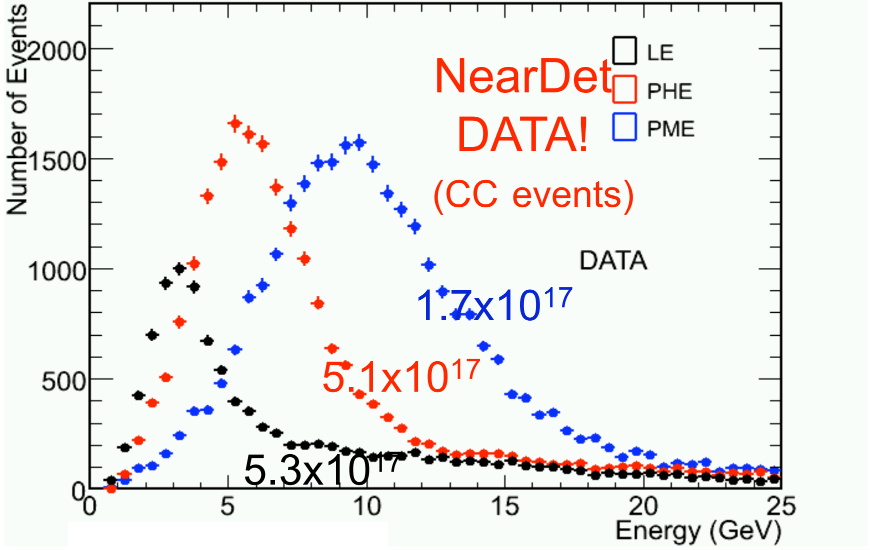


# NuMI – multi-beam



**Pions with**
**$p_T$=300 MeV/$c$ and**
**$p$=5 GeV/$c$**
**$p$=10 GeV/$c$**
**$p$=20 GeV/$c$**

3 target positions



## Data sets:

| Beam | Target z position (cm) | FD Events per $1 \times 10^{20}$ pot | Horn Current (kA) |
|---|---|---|---|
| LE-10 | -10 | 390 | 0,170, 185 ,200 |
| pME | -100 | 970 | 200 |
| pHE | -250 | 1340 | 200 |

95% data

LE-10: Far Det: 1 event / ~4hrs

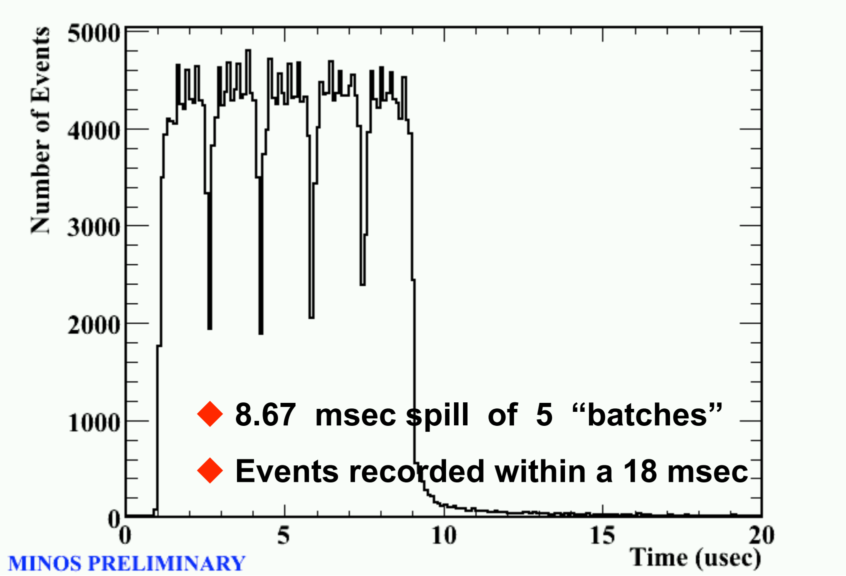
**Flavor composition:** **92.9% $\nu_\mu$**

**5.8% anti- $\nu_\mu$,**

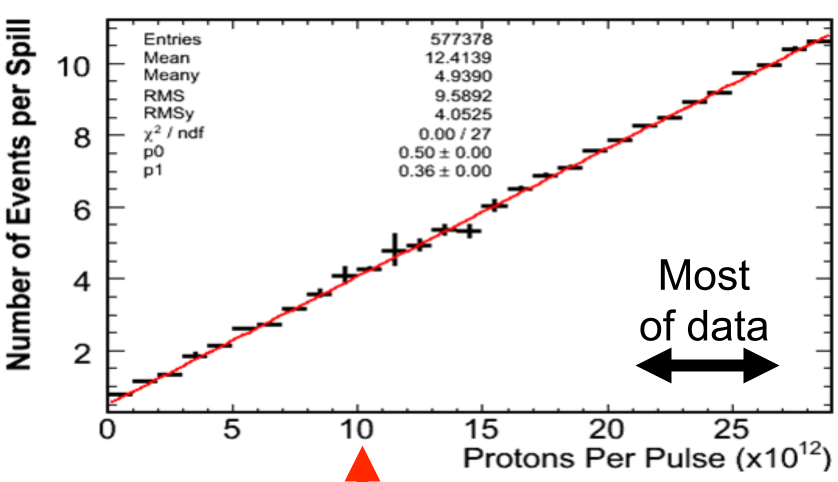
**1.2% $\nu_e$, 0.1%anti- $\nu_e$**

# New experimental challenges in neutrino physics - intensity

## Near Detector spill

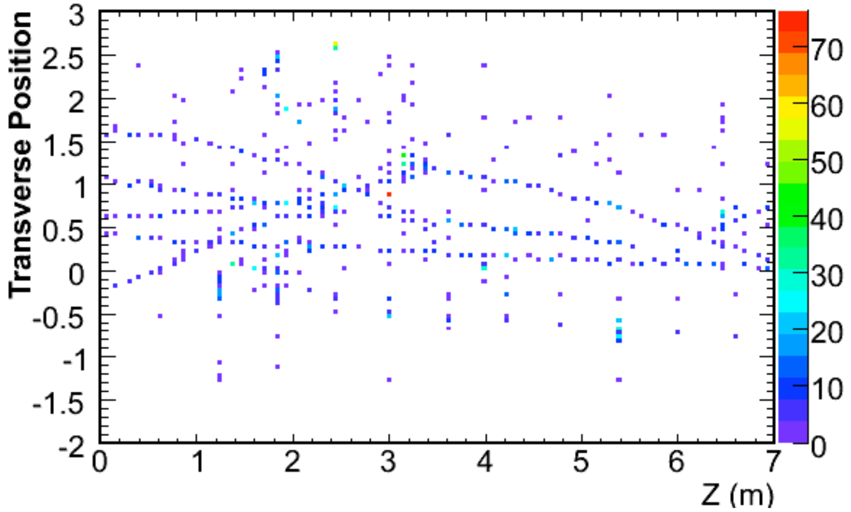


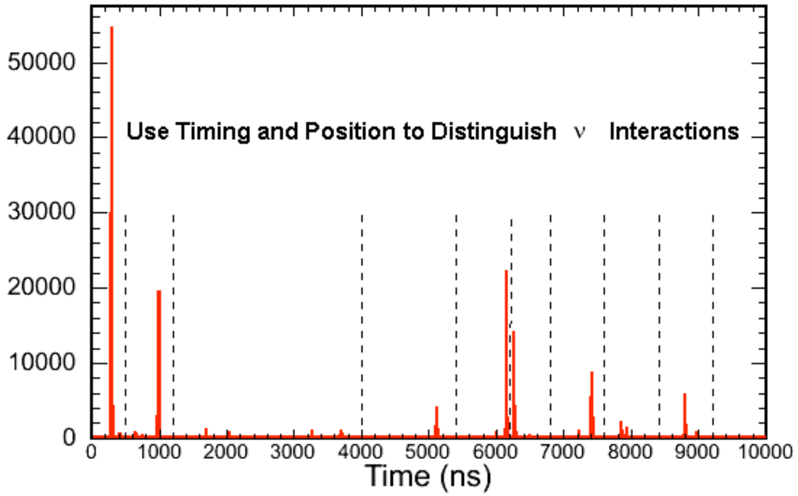
- 8.67 msec spill of 5 "batches"
- Events recorded within a 18 msec



Most of data

$10^{13}$ protons per pulse



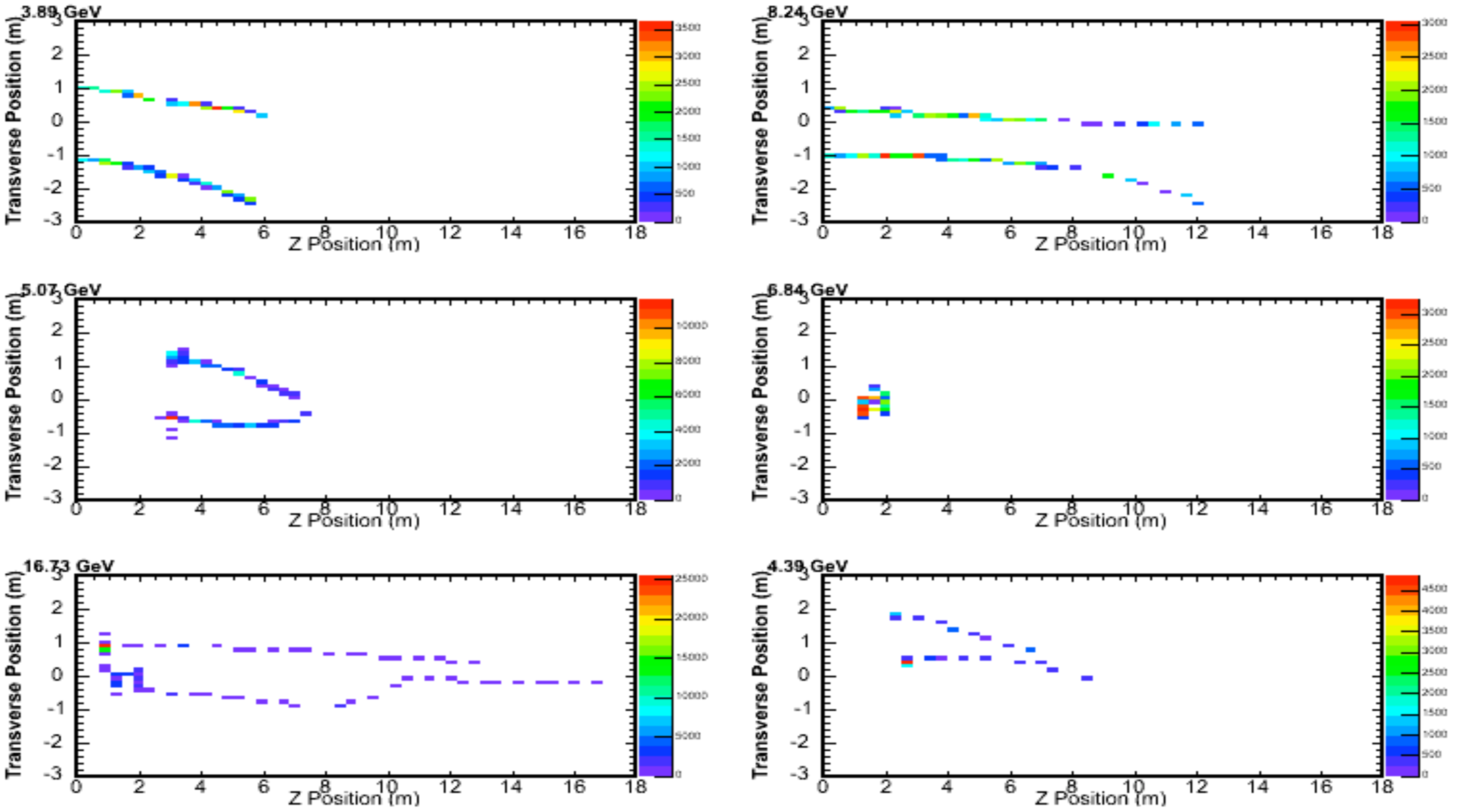


Use Timing and Position to Distinguish ν Interactions

# New experimental challenges in neutrino physics - intensity

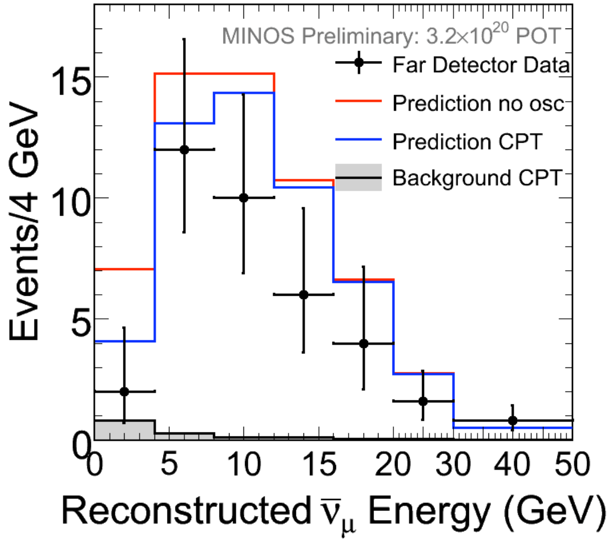
## Near Detector spill

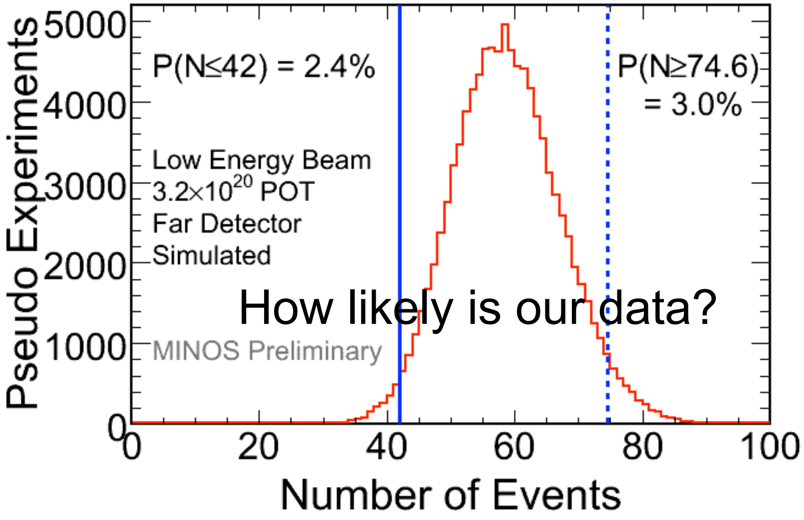
## 1 spill lasts ~10 $\mu$s



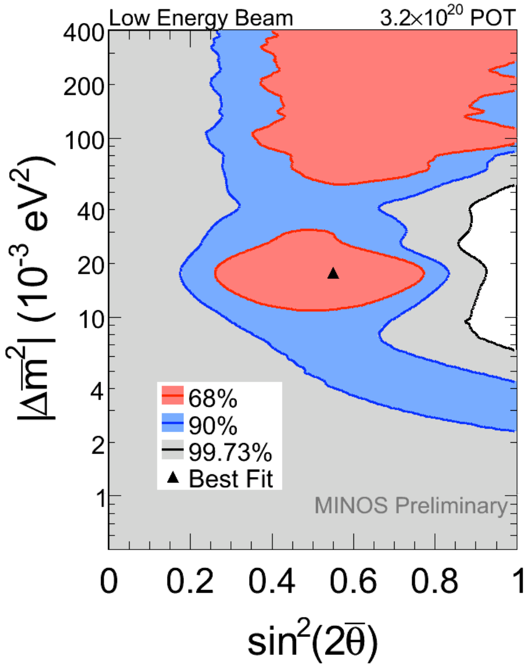
# Anti-neutrino disappearance (NEW !!!)

- Observe **42 events** in the Far detector
- Predicted events with CPT conserving oscillations:
  - ⇨ 58.3 ± 7.6 (stat.) ± 3.6 (syst.)
- Predicted events with null oscillations:
  - ⇨ 64.6 ± 8.0 (stat.) ± 3.9 (syst.)
- CPT conserving point from the MINOS neutrino analysis is within the 90% contour





How likely is our data?



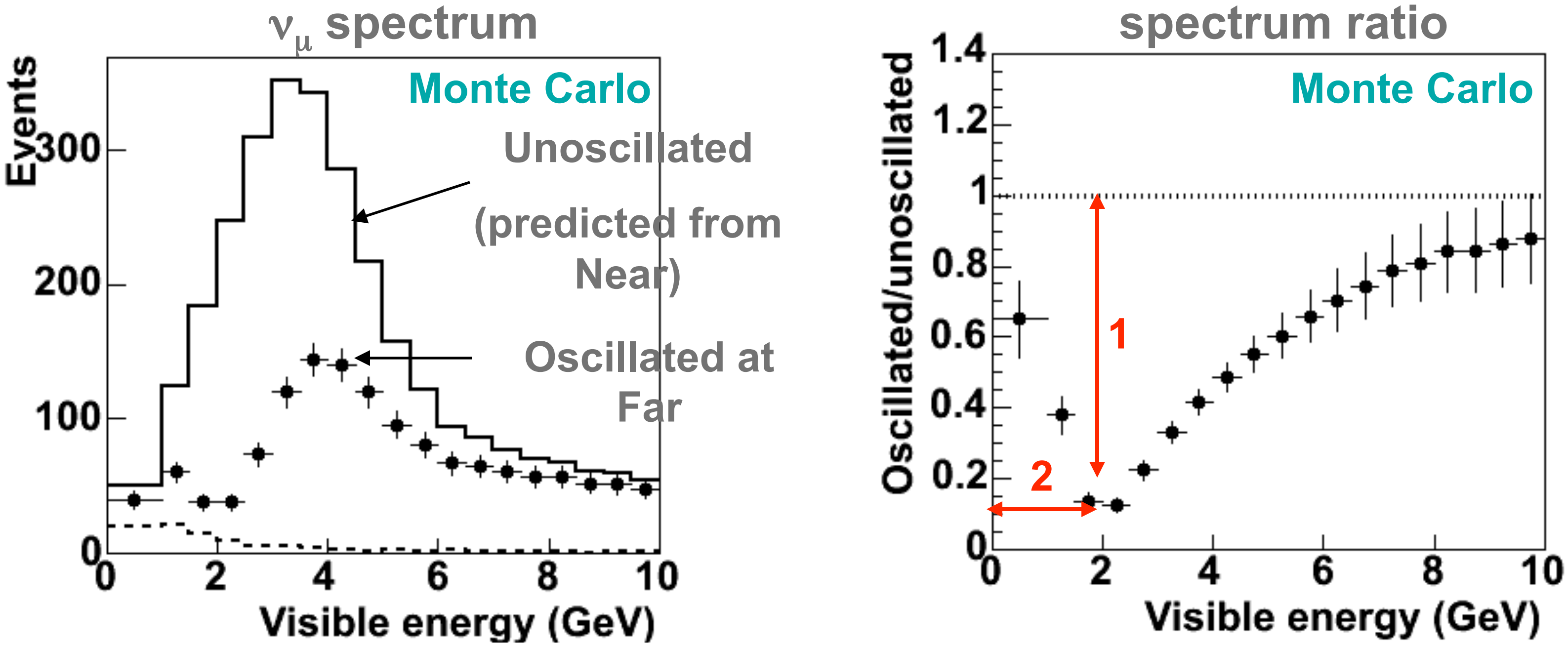
# MINOS Physics Program

**Main goals:**

- ❑ Decisive low-systematics observation of disappearannce ($\nu_\mu \to \nu_x$)
- ❑ Determine $|\Delta m_{32}^2|$ and $\sin^2 2\theta_{23}$ with < 10% accuracy
- ❑ Measure (or improve limits) on $\nu_\mu \to \nu_e$ / $\nu_\mu \to \nu_{sterile}$ / “exotic” transitions
- ❑ Test **CPT** in atmospheric $CC_\mu$ charge-separated interactions

**The method:**

$$\boxed{P(\nu_\mu \to \nu_\mu) = 1 - \underset{1}{\sin^2 2\theta} \bullet \sin^2(1.267 \underset{2}{\Delta m^2} L / E)}$$



$\nu_\mu$ spectrum

Unoscillated (predicted from Near)

Oscillated at Far

spectrum ratio

Monte Carlo plots for $\Delta m^2 = 0.003\ eV^2$ and $7.4x10^{20}$ pot