Cosmic Rays and Neutrinos at MINOS

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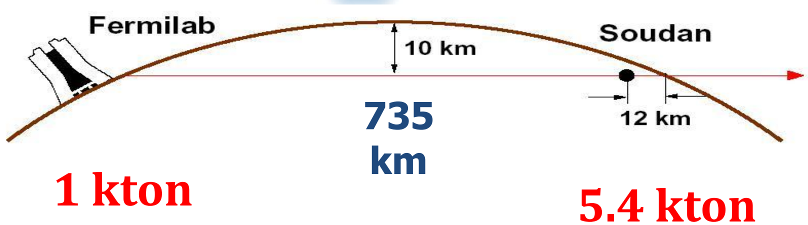
for the
MINOS Collaboration

The Reality of MINOS

- Intro
  - The MINOS Detector(s)
- Cosmic Ray Physics
  - Muon Charge Ratio at the surface
  - Seasonal Variations and Sudden Stratospheric Warmings
  - Atmospheric Neutrinos and Oscillations
- Neutrino Oscillations
  - Charged current oscillation parameters
  - Searching for sterile neutrinos
  - ν_e Appearance and θ_{13}

MINOS Overview

MINOS has two functionally identical detectors that measure the **NuMI** neutrino beam from Fermilab.



Oscillation Physics Goals:

- ❑ Precision measurements of $\sin^2 2\theta_{23}$ and Δm^2_{23}
- ❑ Mixing to sterile neutrinos
- ❑ Study subdominant oscillation mode ν_{μ}->ν_{e}, measure/limit θ_{13}

Other Studies:

- ❑ Cosmic ray physics and atmospheric neutrinos
- ❑ CPT tests
- ❑ Near Detector studies of neutrino interactions
- ❑ Lorentz violation

MINOS Collaboration

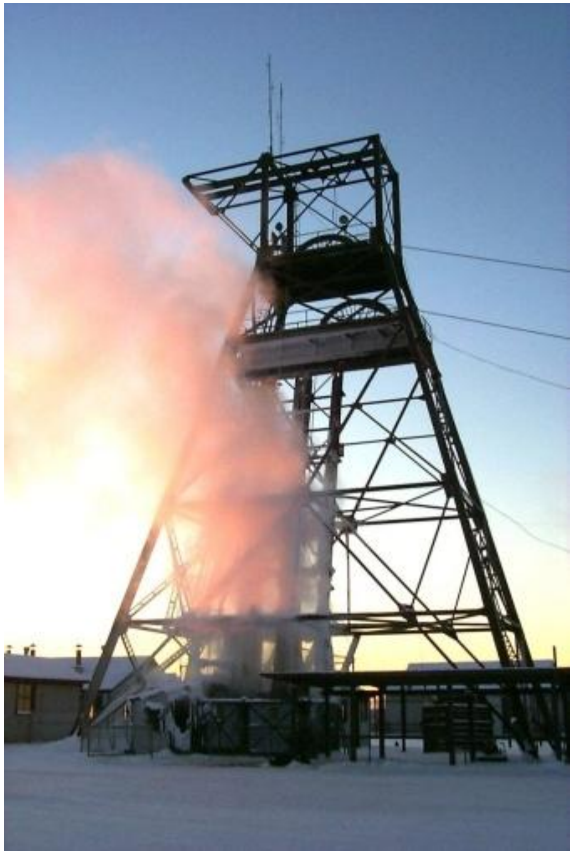
Argonne • Arkansas Tech • Athens • Benedictine • Brookhaven • Caltech • Cambridge • Campinas • Fermilab • Harvard • IIT • Indiana • Minnesota-Twin Cities • Minnesota-Duluth • Oxford • Pittsburgh • Rutherford • Sao Paulo • South Carolina • Stanford • Sussex • Texas A&M • Texas-Austin • Tufts • UCL • Warsaw • William & Mary

28 institutions, 175 scientists, funded by DOE, NSF, SFTC

MINOS Far Detector

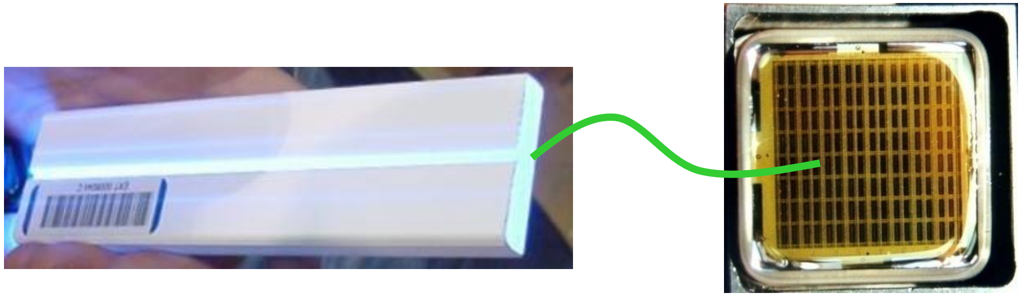
The far detector is located in northern Minnesota at the Soudan Underground Mine -- 2341 ft. below surface (2070 m.w.e.).

Construction on the far detector was completed in 2003.



Detector Technology

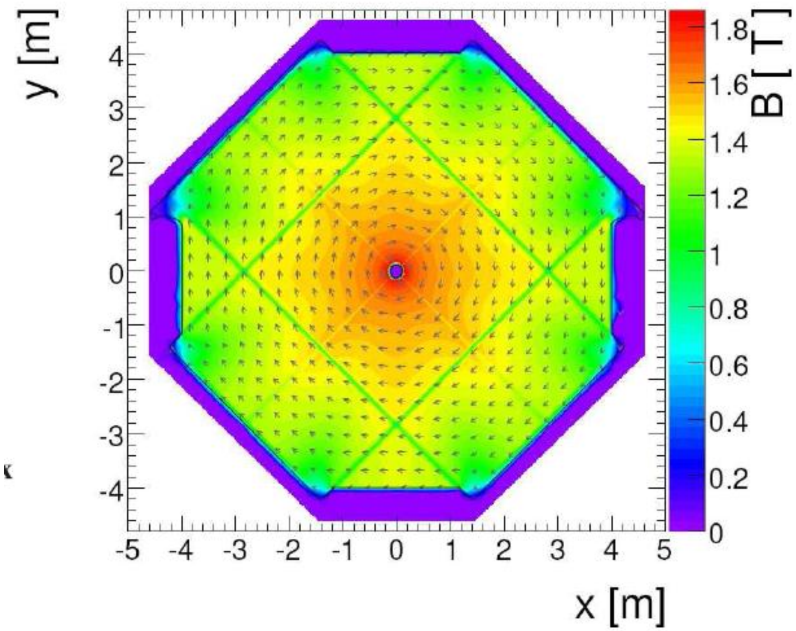
- 484 planes of steel mounted with scintillator strips totaling 5.4kT.
- Strips of scintillator 4.1cm wide and up to 8m long.
- Strips in successive planes rotated by 90°.
- Wavelength shifting fiber used to collect scintillator light.
- Double ended readout
- 8 strips are mapped to one PMT.

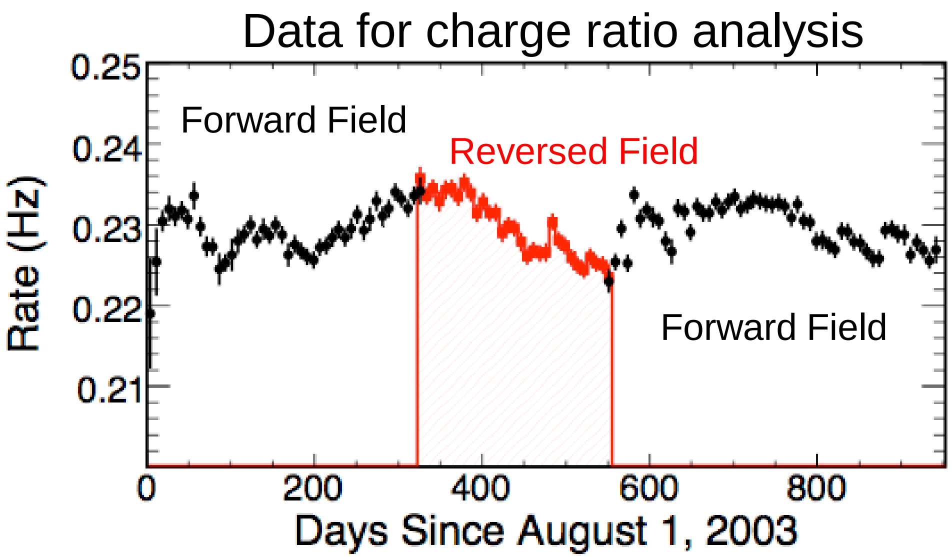


Magnetic Field

First large underground detector with a magnetic field.

Toroidal field with strength 1.3T. Separates μ+ and μ- up to 200GeV.





Data was taken in two configurations:

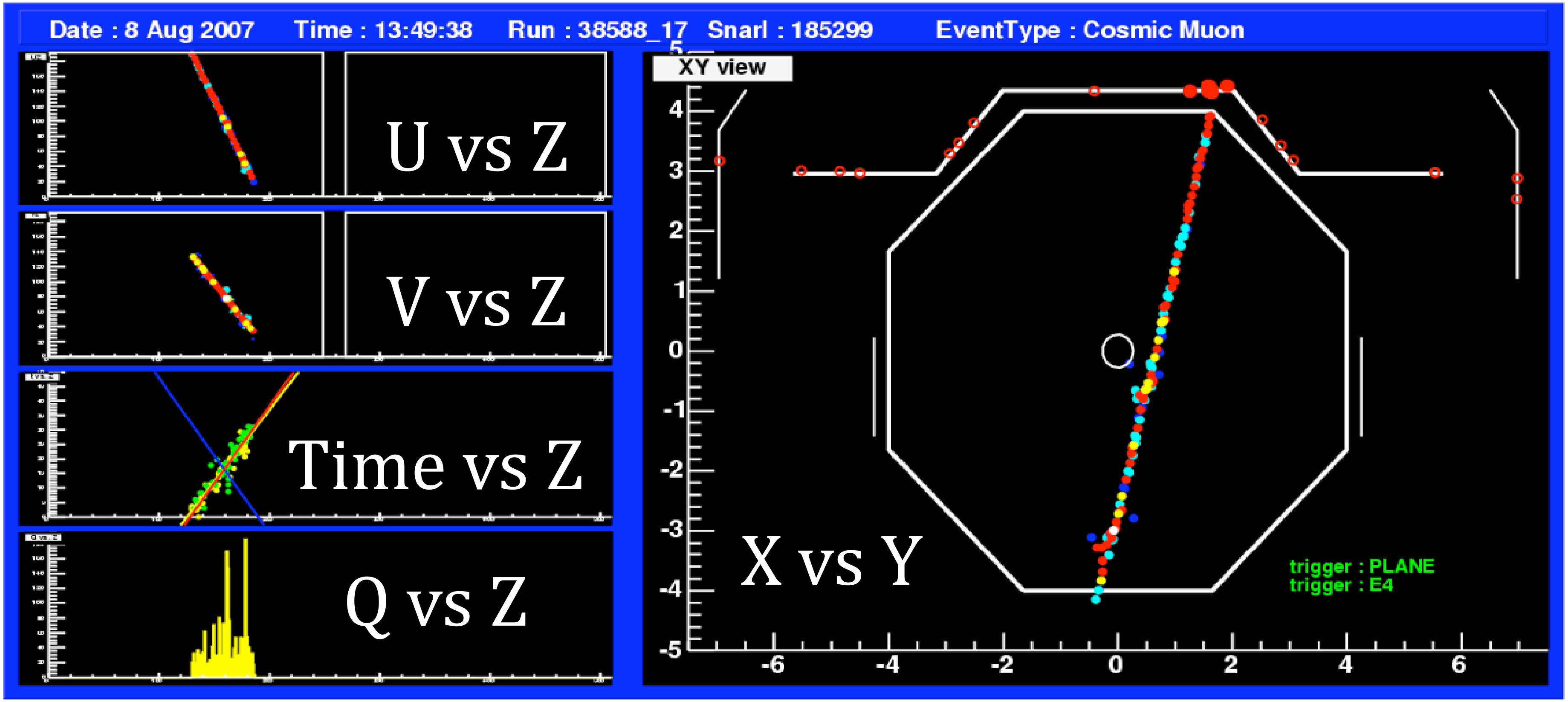
Forward Field – 609.82 live days

Reversed Field – 201.75 live days

Cosmic Ray Event

Event Display for a cosmic muon event.

Timing resolution is ~2.3ns.



Muon Charge Ratio

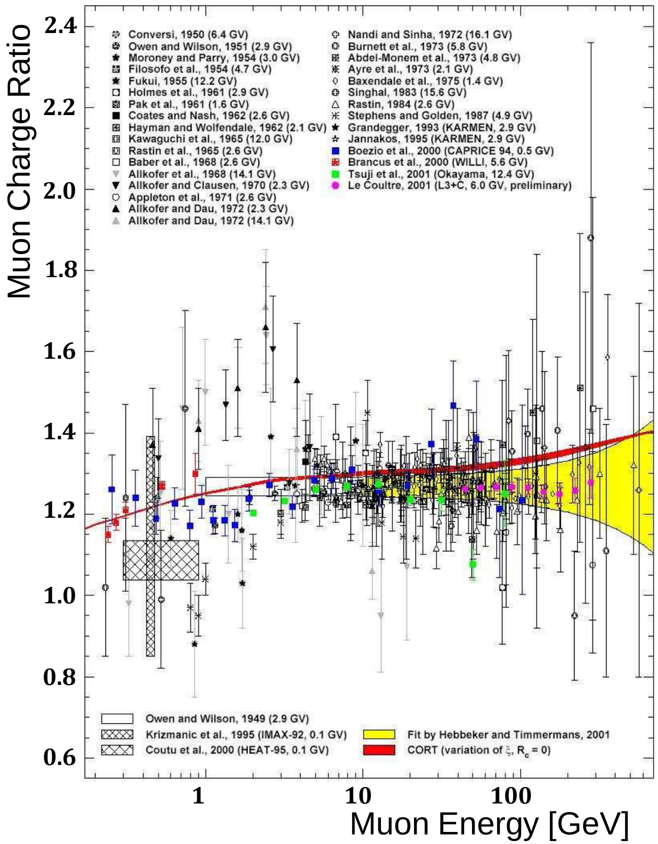
Muon Charge Ratio

Measure the ratio $R = \dfrac{\mu^+}{\mu^-}$

Charge Ratio changes at higher energies

- ❑ ***R*** can increase with energy – increased kaon importance.
- ❑ ***R*** can decrease with energy – effects from heavy elements.
- ❑ ***R*** can decrease with energy – increased charm production and semileptonic decays.

Charge ratio important for modeling cosmic ray interactions and doing accurate calculations of atmospheric fluxes. It is particularly important for measuring the ratio $\nu/\bar{\nu}$.



(Naumov, hep-ph/0201310)

MINOS has large statistics and can explore an energy range (1-7 TeV) where few measurements exist.

Event Selection

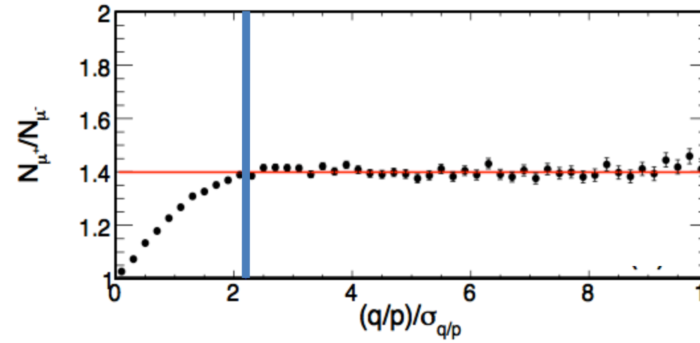
Use curvature of muon track to measure energy and charge.

Muons that have crossed more planes will have a more reliable charge determination.

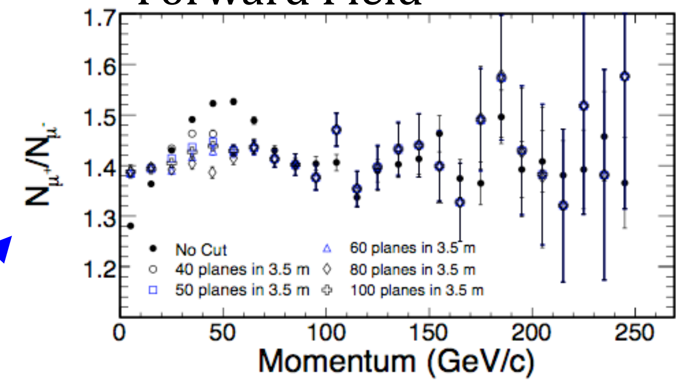
Important cuts

- ❑ Good Track Fit: $\mathbf{(q/p)/\sigma_{(q/p)}} > 2.2$
- ❑ Minimum Information Cut: Require N hits within 3.5m of coil hole.

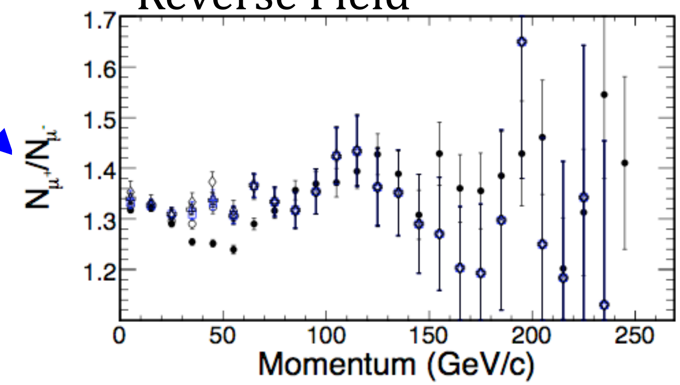
Hard cuts are required to minimize systematic effects ~95% of our data was removed.



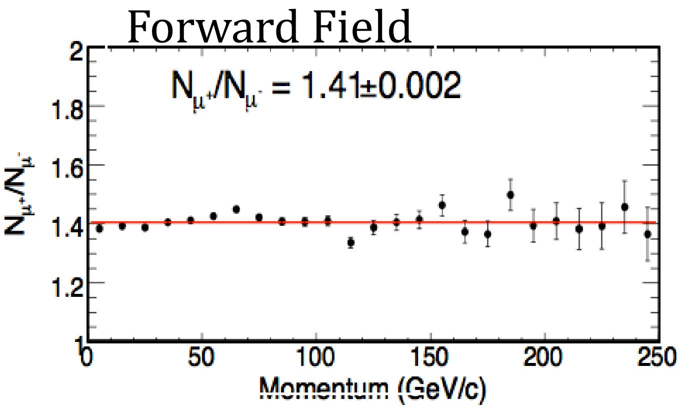
Forward Field

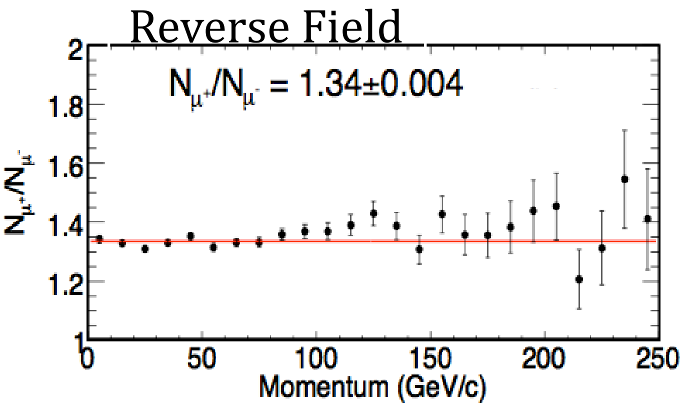


Reverse Field

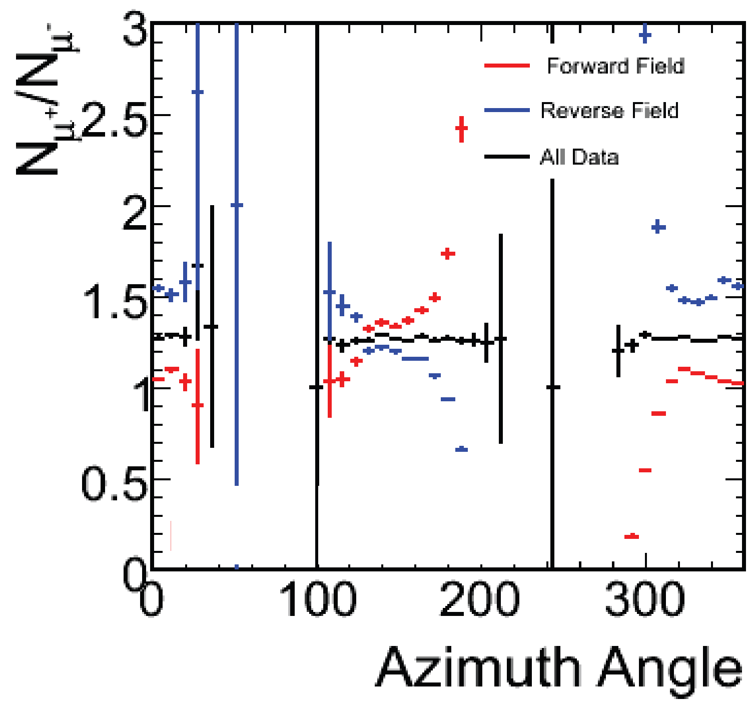


Systematic Errors





The forward and reverse field data sets found a different charge ratio. There still remains a systematic offset



Use geometric mean of forward and reverse data to cancel out geometric and alignment effects.

Charge Ratio Underground

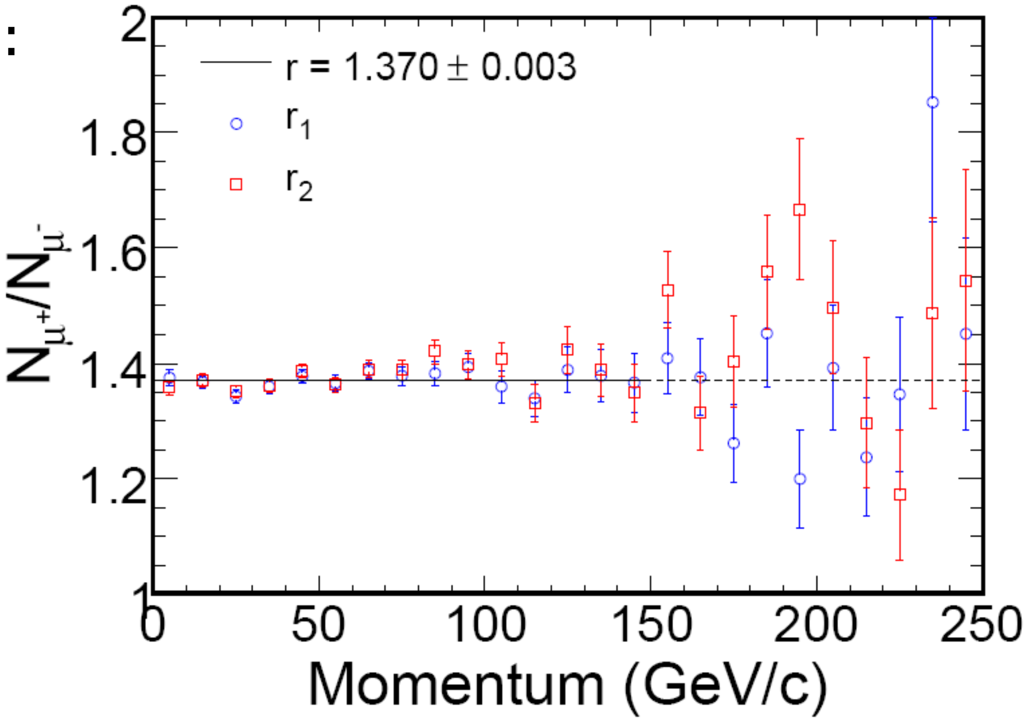
Create two indepent samples:

r1– geometric mean of

1st half reversed field+
forward field just before switch

r2– geometric mean of

2nd half of reversed field +
forward field just afield switch.



(Adamson *et. al*, PRD 76:052003)

$$R = 1.374 \pm 0.004(stat.)^{+0.010}_{-0.012}(syst.)$$

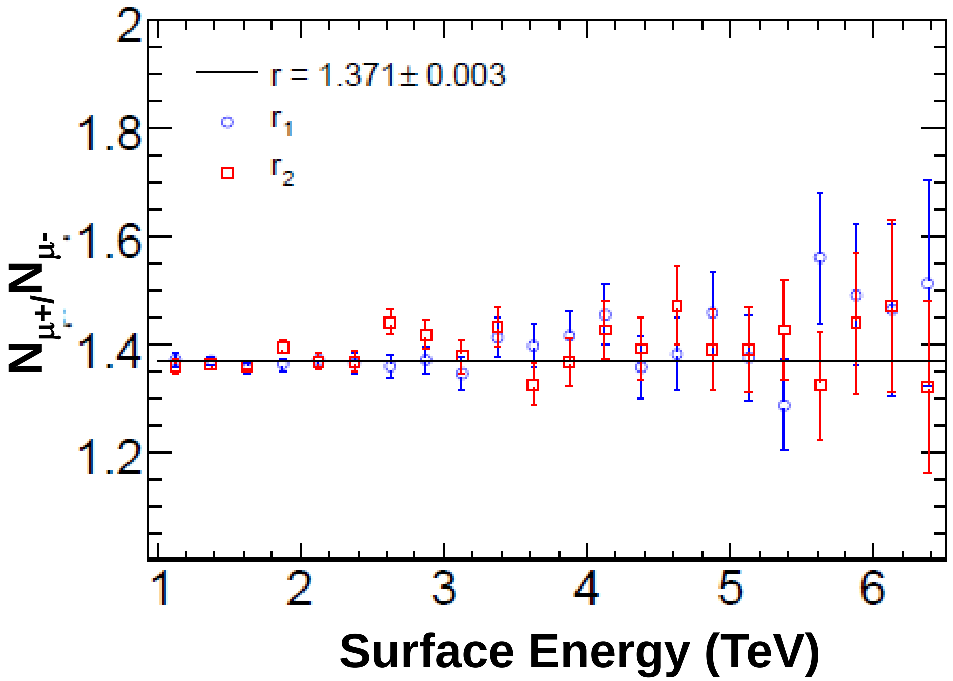
Project to the Surface

To find the energy at the surface:

$$E_{surface} = \left(E_{underground} + \frac{a}{b}\right) e^{bX} - \frac{a}{b}$$

a=ionization energy loss ***b***=radiative energy loss
X=slant depth

Project the energy of each muon to the surface using ***a*** and ***b*** for rock at Soudan.



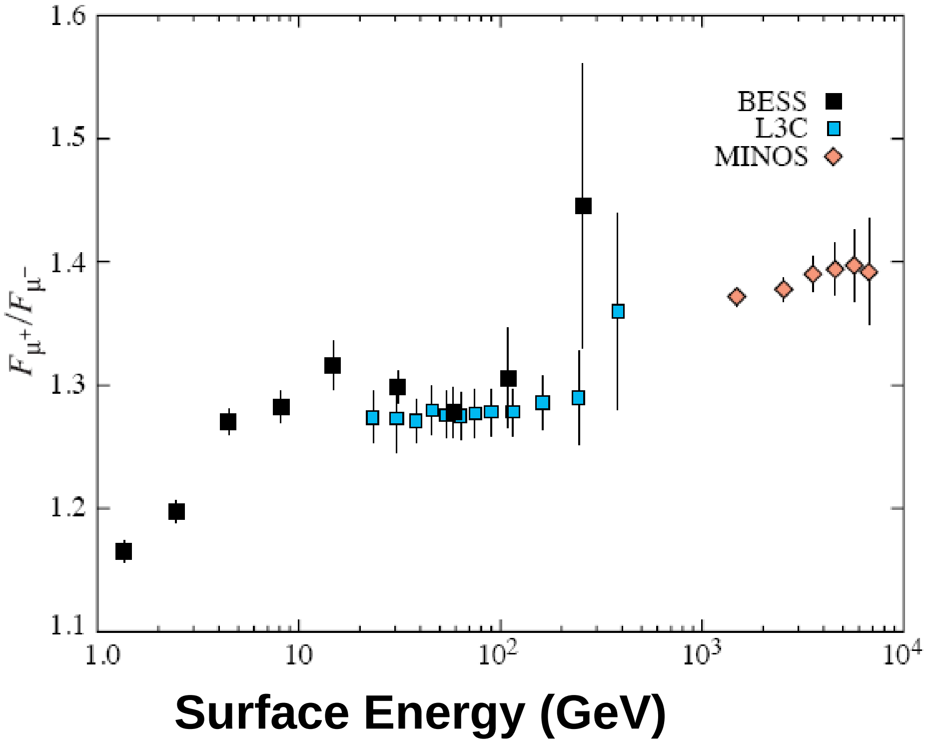
(Adamson *et. al*, PRD 76:052003)

Comparison with other Measurements

MINOS sees an increase in the charge in ratio comparison to other experiments.

Studies in the MINOS Near Detector are consistent with L3C showing the difference is not likely due to systematic errors.

C. Amsler et al. (Particle Data Group), Physics Letters B667, 1 (2008)



More details on the Near Detector results will be forthcoming.

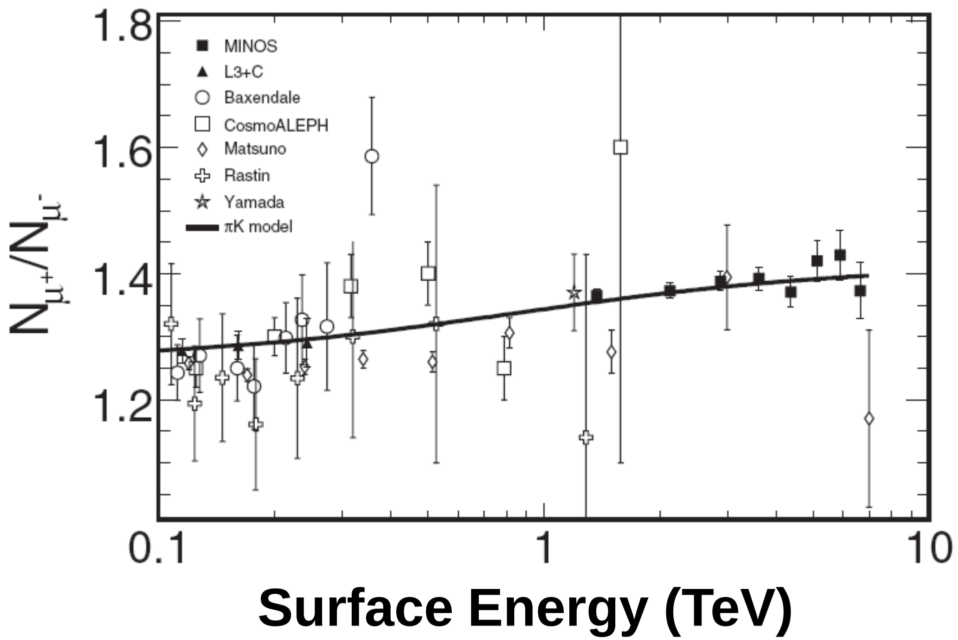
What is the physics behind this rise in the charge ratio?

πK Model

Qualitative Model:

(Gaiser, 1990)

$$\frac{N_{\mu^+}}{N_{\mu^-}} = \frac{\left[\dfrac{f_{\pi^+}}{1+\dfrac{1.1E_\mu\cos\theta}{115\text{GeV}}} + \dfrac{0.054 f_{K^+}}{1+\dfrac{1.1E_\mu\cos\theta}{850\text{GeV}}}\right]}{\left[\dfrac{(1-f_{\pi^+})}{1+\dfrac{1.1E_\mu\cos\theta}{115\text{GeV}}} + \dfrac{0.054(1-f_{K^+})}{1+\dfrac{1.1E_\mu\cos\theta}{850\text{GeV}}}\right]}$$



(Adamson *et. al,* PRD 76:052003)

$f_{\pi+}$/ f_{K+} = fraction of pions/kaons giving μ^+

$(1-f_{\pi+})$/ $(1-f_{K+})$ = fraction of pions/kaons giving a μ^-

$f_{\pi+}$, f_{K+} independent of energy

best fit values:

$f_{\pi+}$ = 0.55 f_{K+}=0.67

Seasonal Variations

Seasonal Variations

Previous experiments (Barrett, MACRO, AMANDA) have seen the muon rate change for different seasons of the year.

As the temperature increases:

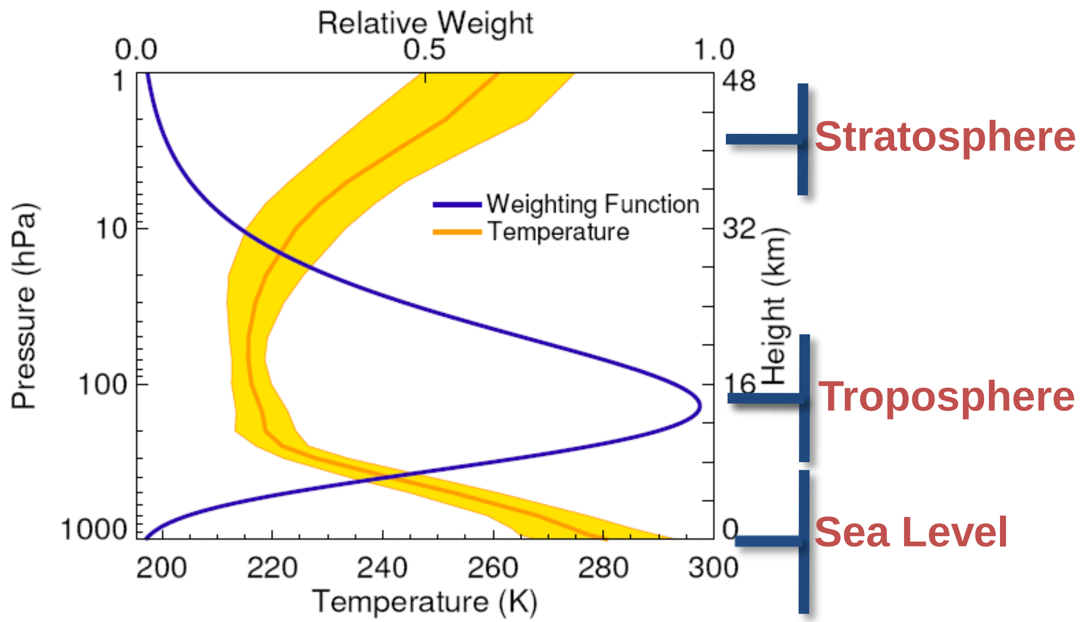
- The atmosphere expands and correspondingly decreases the density causing a higher muon flux reducing the chances for interaction.
- For low energy muons the change in the production height can be cause the muon to decay before it reaches the earth.

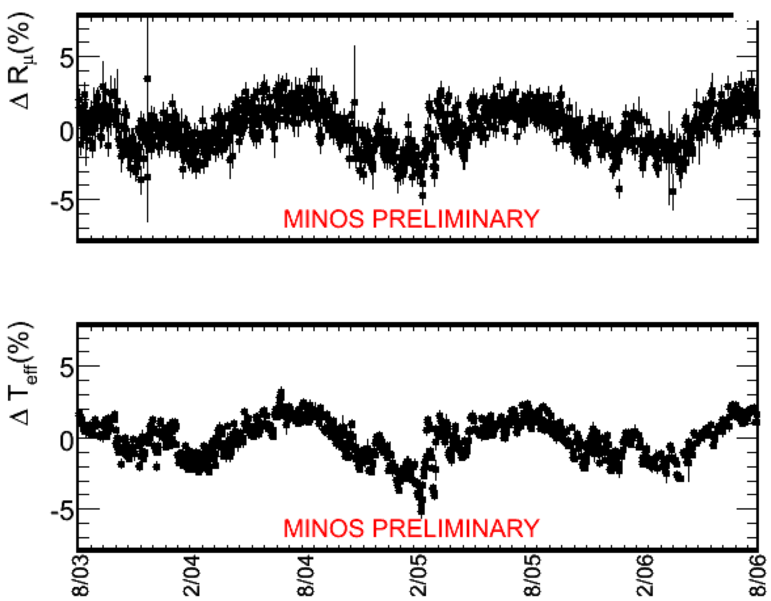
Measure the correlation between muon flux underground and the temperature

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

Correlations

Temperature data taken from European Centre for Medium-Range Weather Forecasts (ECMWF). Effective temperature taken by weighting according to where muons detected in MINOS originate.





Three years of data shows a high correlation between muon flux and effective temperature. From a straight line fit:

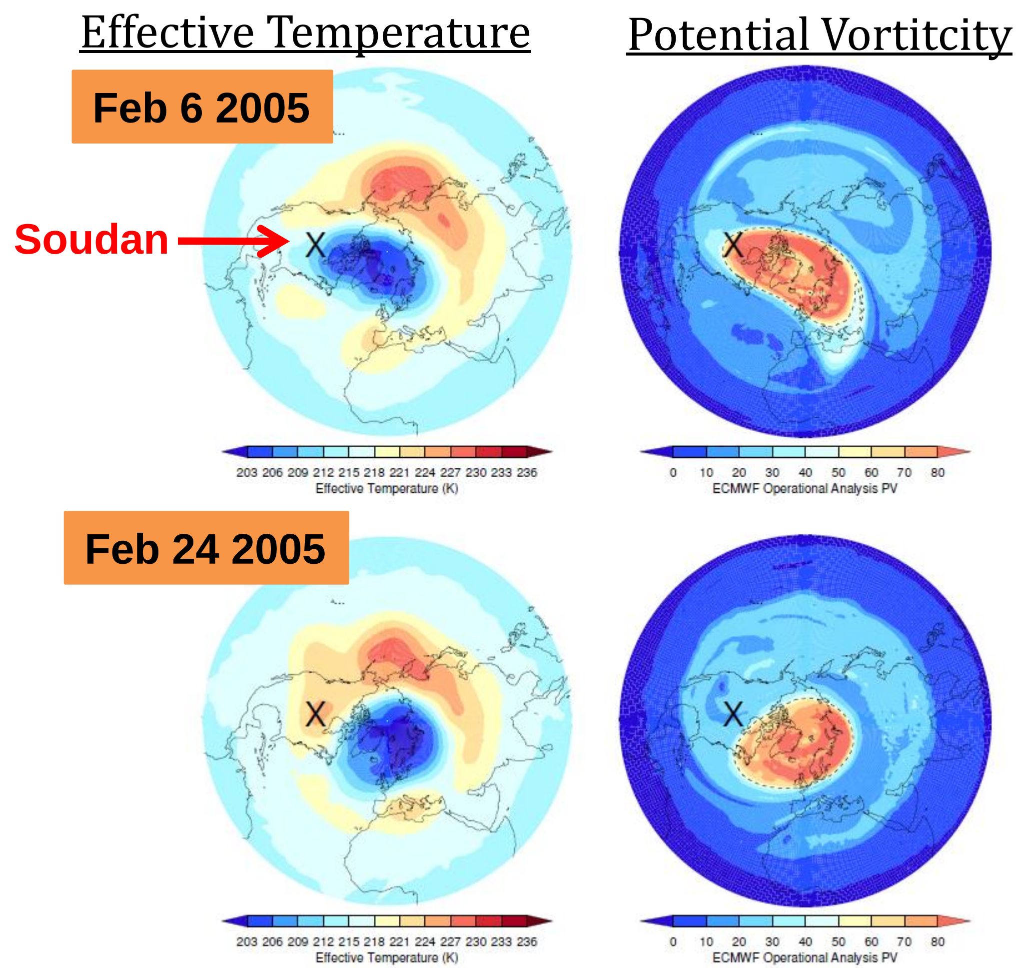
$$\alpha_T = 0.87 \pm 0.03$$

A brief look at SSWs

Previous experiments have seen correlations averaged over seasons.

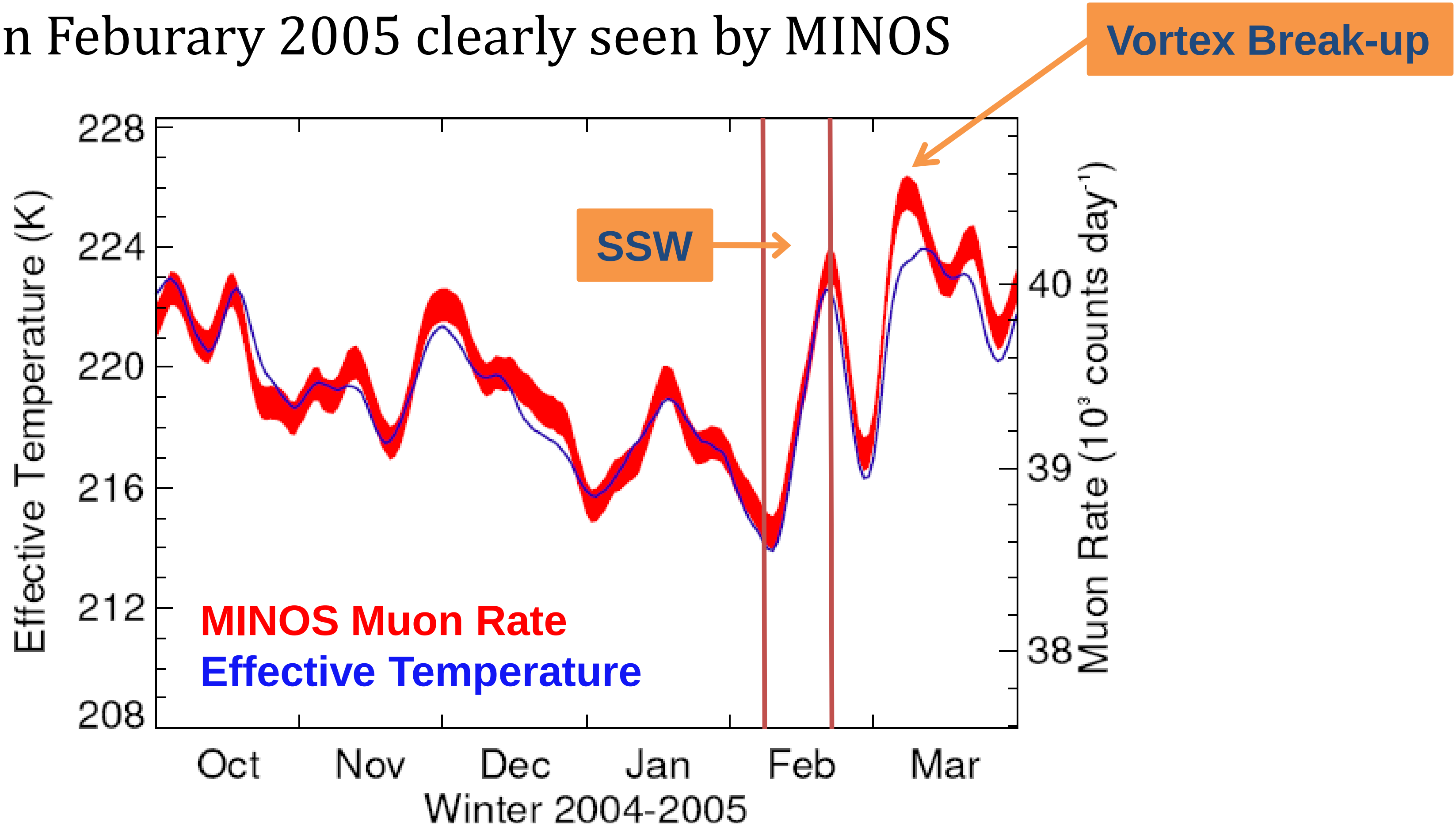
Sudden Stratospheric Warmings (SSW) cause large temperature changes over a few days. First seen in 1950 they occur ~4/decade.

Can MINOS see correlations on shorter timescales?



MINOS observes a SSW

SSW in Feburary 2005 clearly seen by MINOS



First correlation between underground muons and meteorological phenomena in the stratosphere. Can data be used such data for future meteorological applications?

Atmospheric Neutrinos

Atmospheric Neutrinos

Contained vertex events **(Adamson *et. al*, PRD 73:072002)**

August 2003 to February 2005

Live time – 418 days

Upward-going muon events **(Adamson *et. al*, PRD 75:092003)**

August 2003 to April 2006

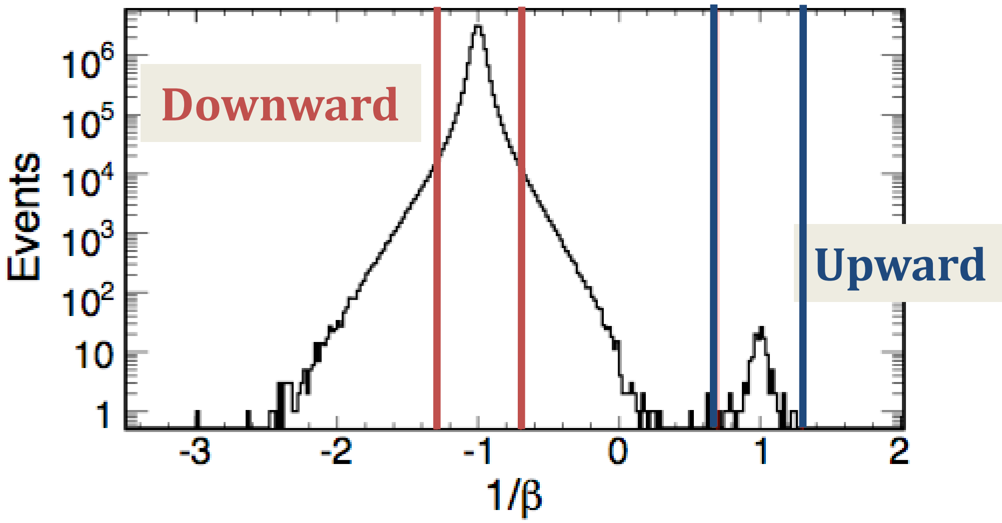
Live time – 854.1 days

Total Live Time up to Date: ~1200 days

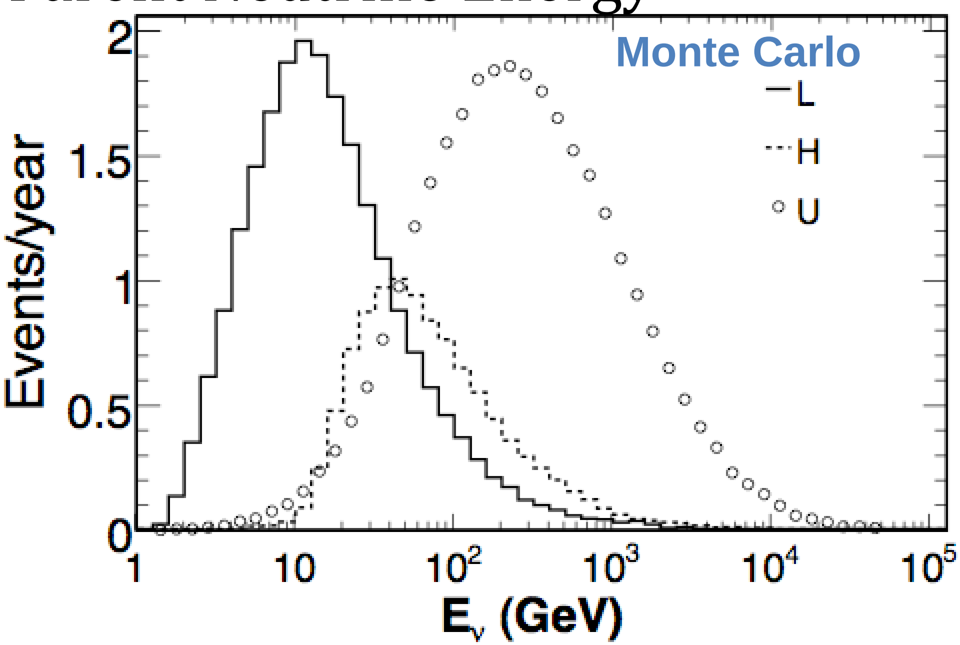
Selecting Neutrino Induced Muons

Upward muons come from neutrinos not cosmic rays.

Distinguish upward from downward muons by
$\Delta T/\Delta S \rightarrow 1/\beta = c/v$



Parent Neutrino Energy

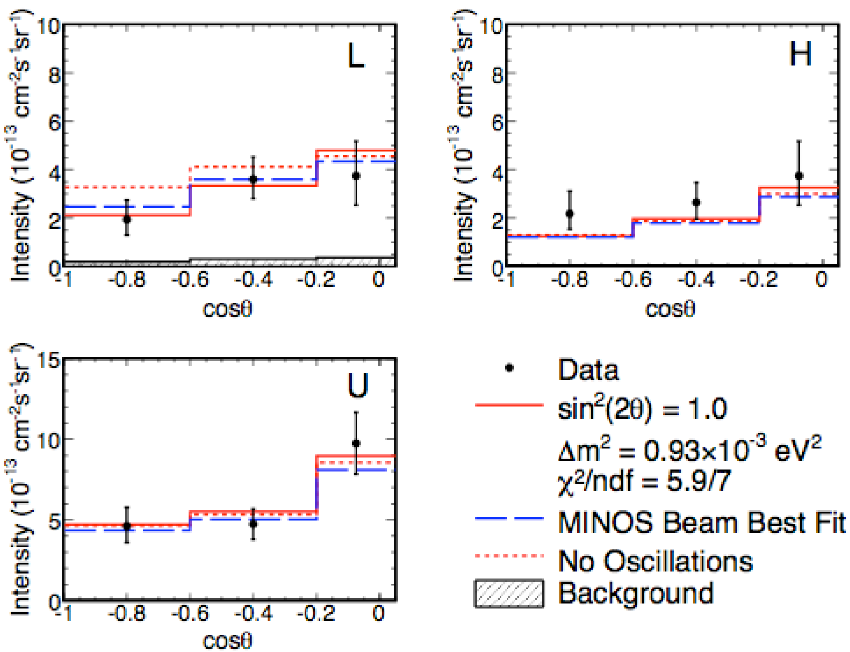


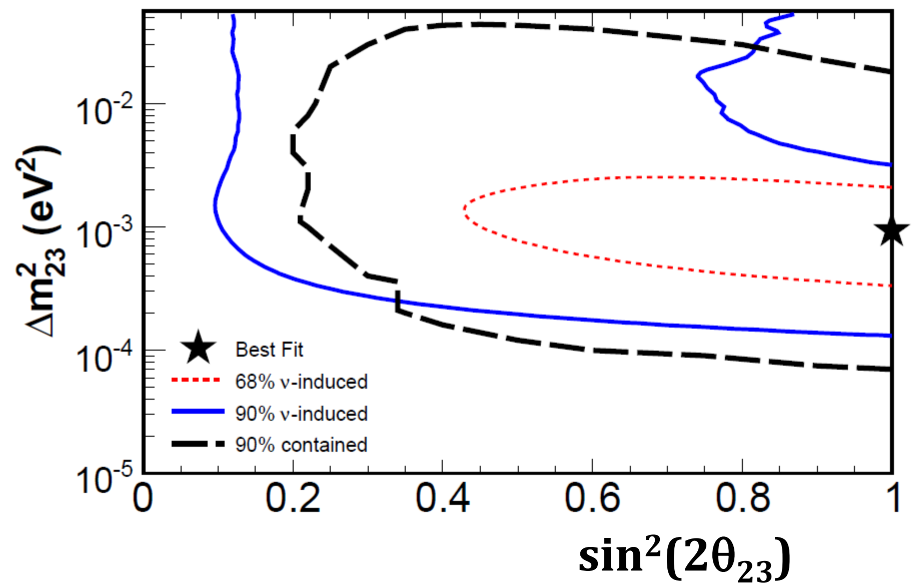
Divide into low (**L**), high (**H**) and undefined (**U**) energy.

L : 1GeV < Energy < 10 GeV
H: 10 GeV< Energy < 100 GeV
U: ???

Atmospheric Oscillation Results

Oscillations most prominent for low energy.





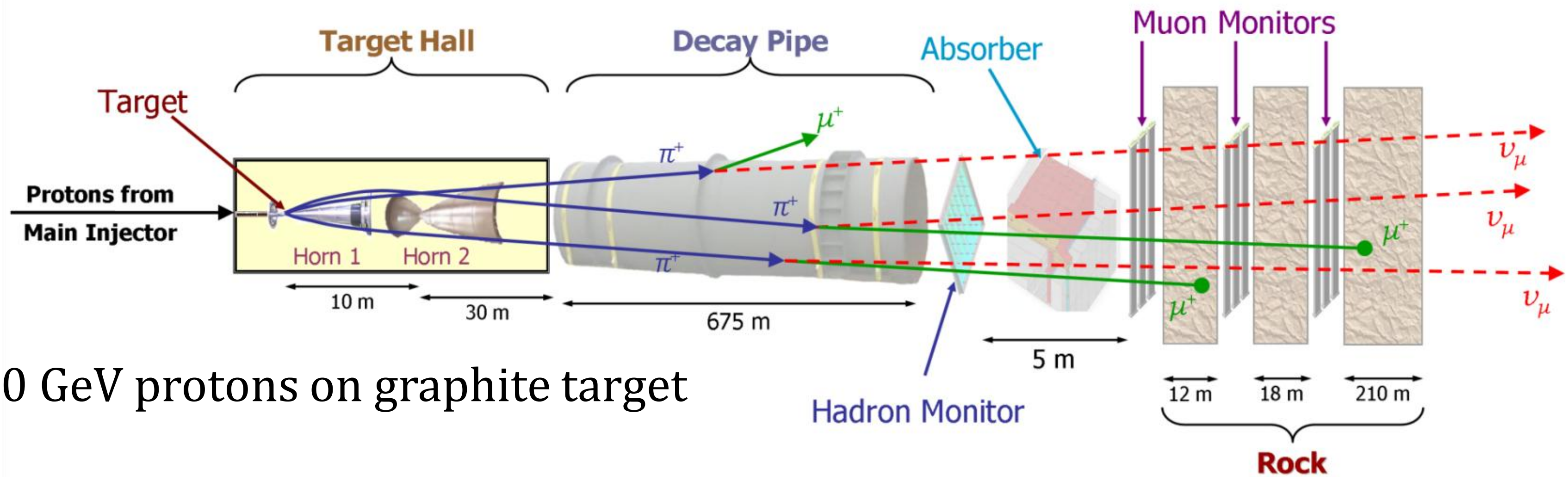
A better way to do this measurement is . . .

Neutrino Oscillations in MINOS

CHANGE
WE CAN BELIEVE IN

The NuMI Beam

Neu**t**rinos at the **M**ain **I**njector



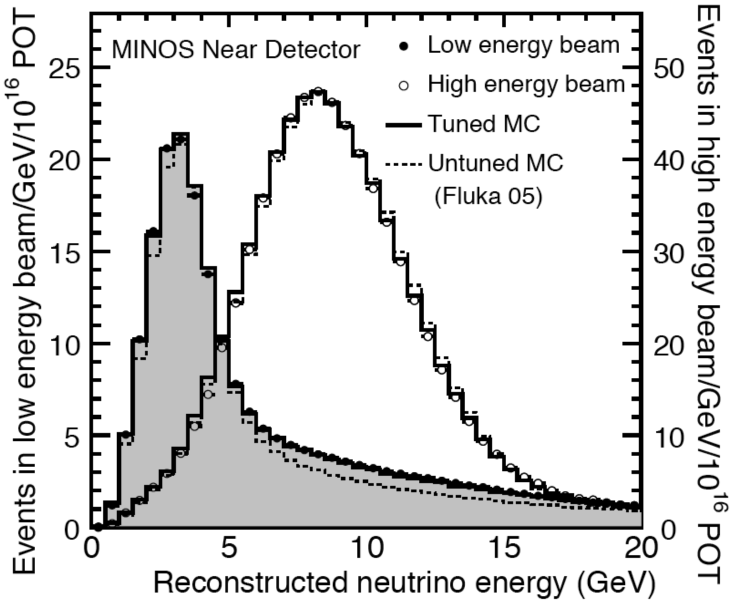
120 GeV protons on graphite target

Secondary hadrons are focused by magnetic horns

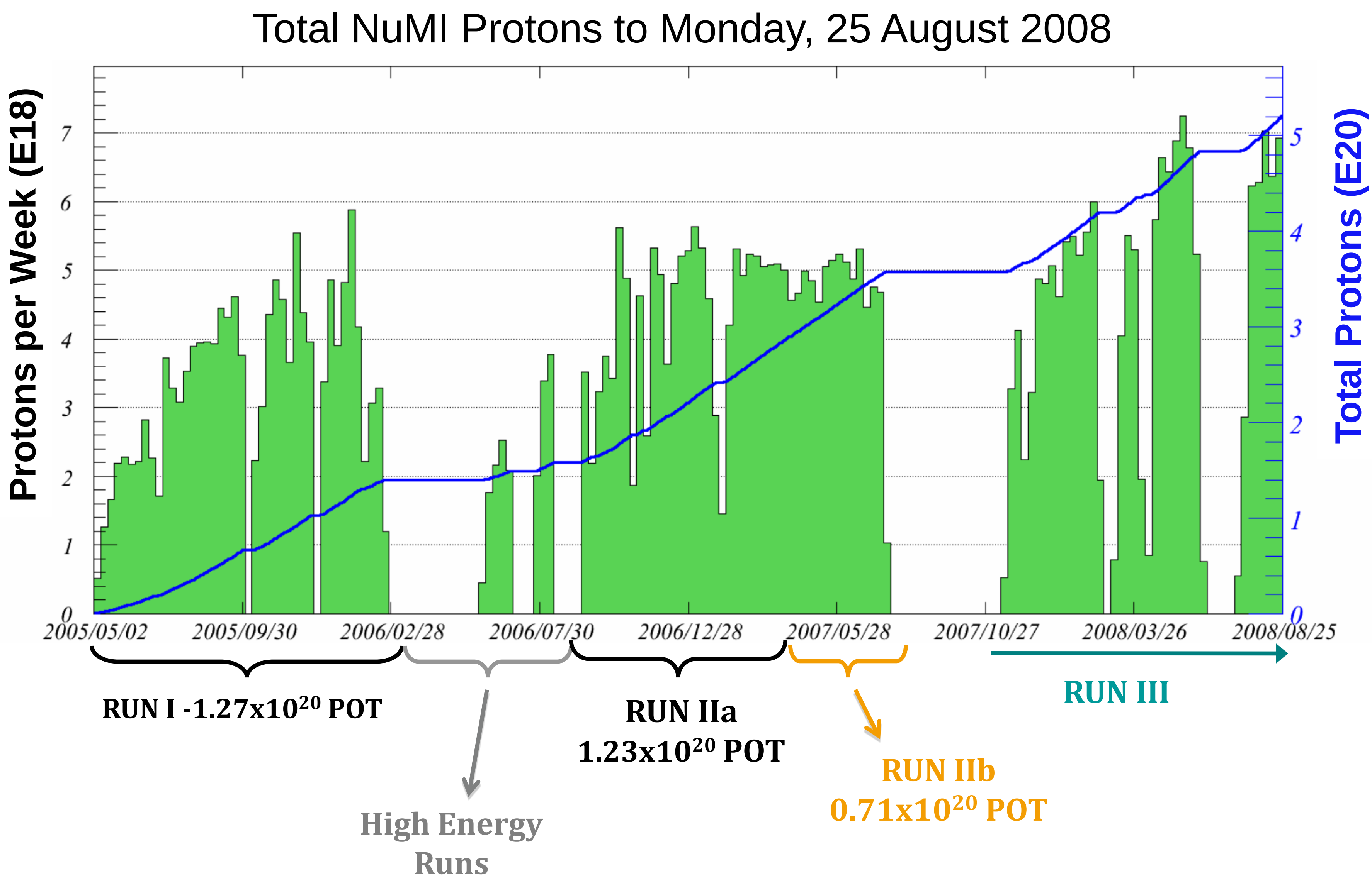
Tunable energy beam by changing relative positions of horns and target

Beam Composition:

$$92.9\%\ \nu_\mu,\ 5.8\%\ \bar{\nu}_\mu,\ 1.3\%\ \nu_e + \bar{\nu}_e$$



Beam Performance



ν_μ Disappearance

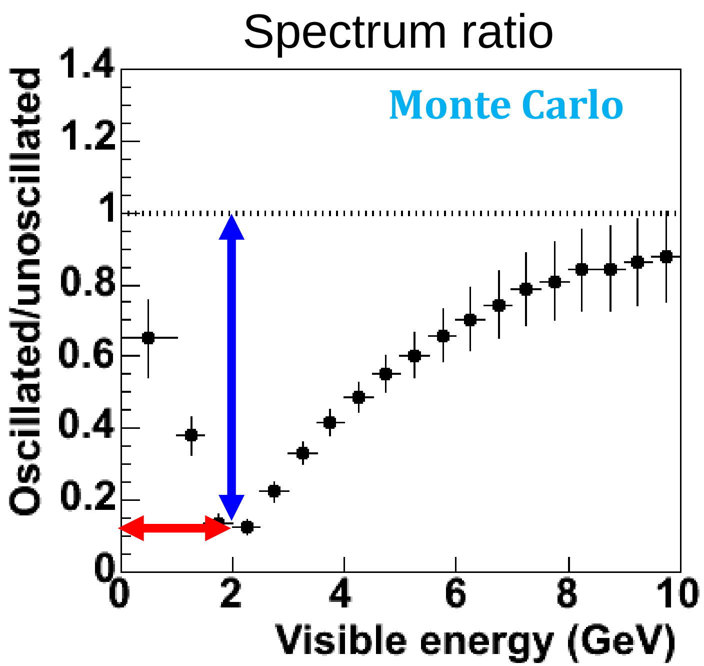
Measure ν_μ spectrum at the near detector and extrapolate to the far detector. If neutrinos oscillate you expect an energy-dependent reduction at the far detector.

Survival Probability:

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta \sin^2\left(1.27\frac{\Delta m^2[\mathrm{eV}^2]L[\mathrm{km}]}{E[\mathrm{GeV}]}\right)$$

Why?

- Needed for reactor θ_{13} experiments
- Is θ_{23}=45°? New symmetry?
- Demonstrate that it can be done.



ν_μ Disappearance Results

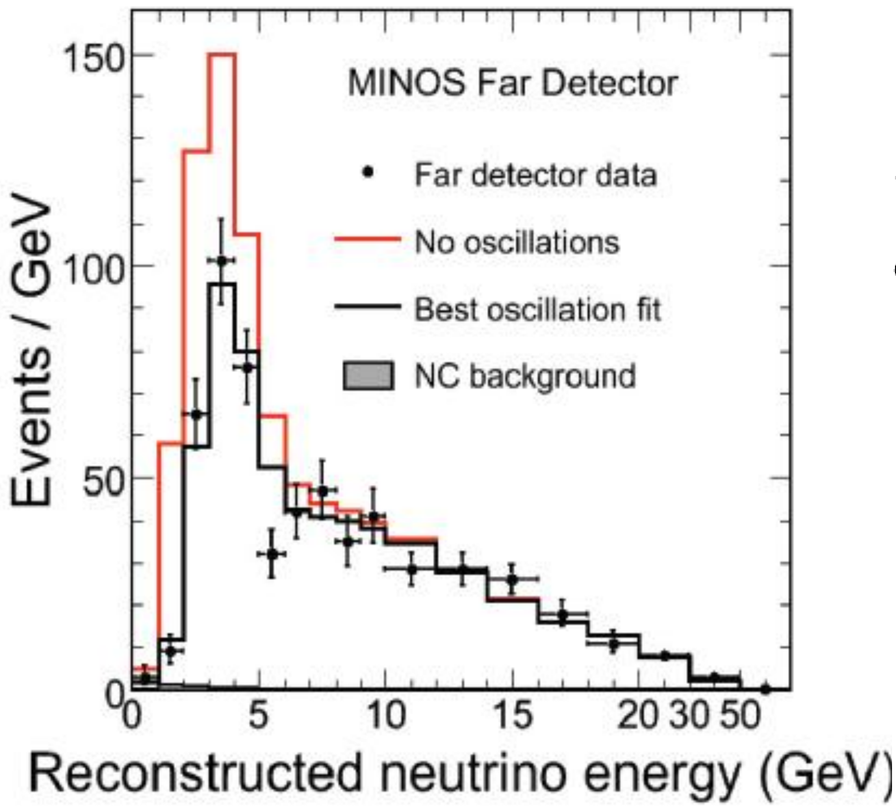
Consistent with 2 flavor oscillations and maximal mixing.

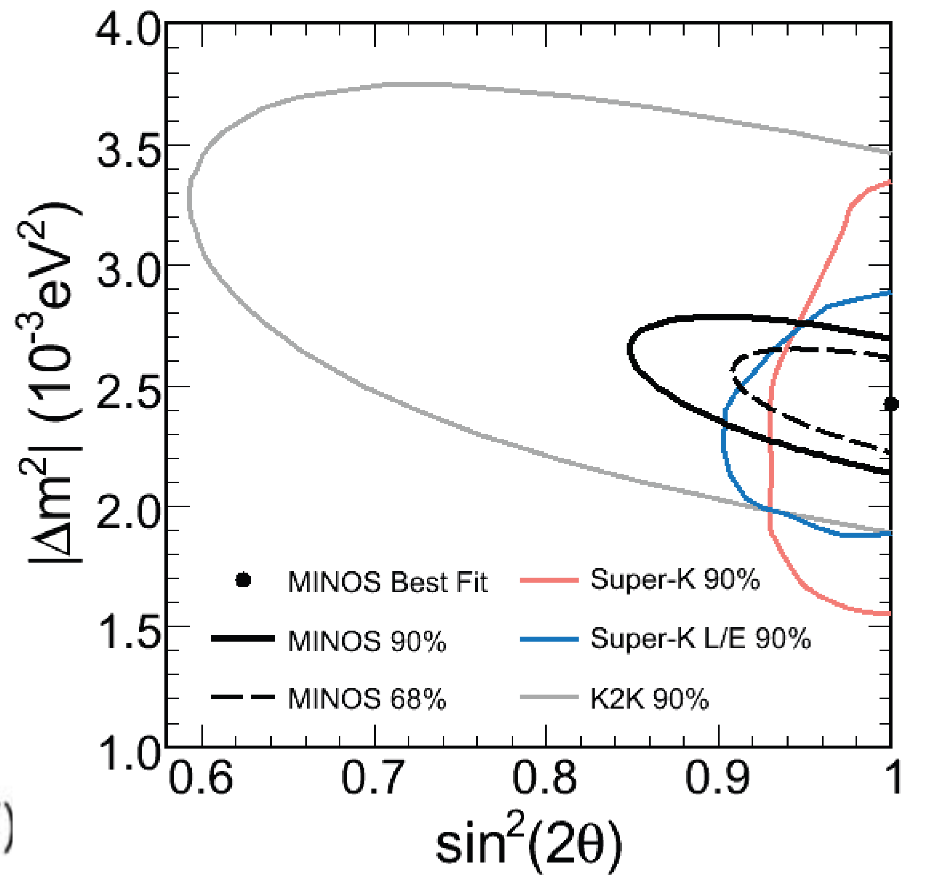
(hep-ex/0806.2237 , accepted by PRL)

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

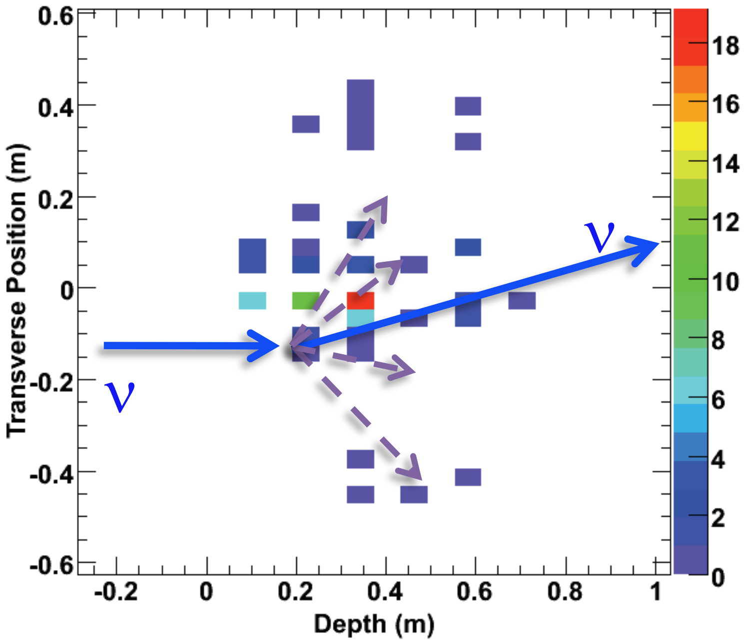
$\sin^2(2\theta) > 0.9$ (90% C.L.)

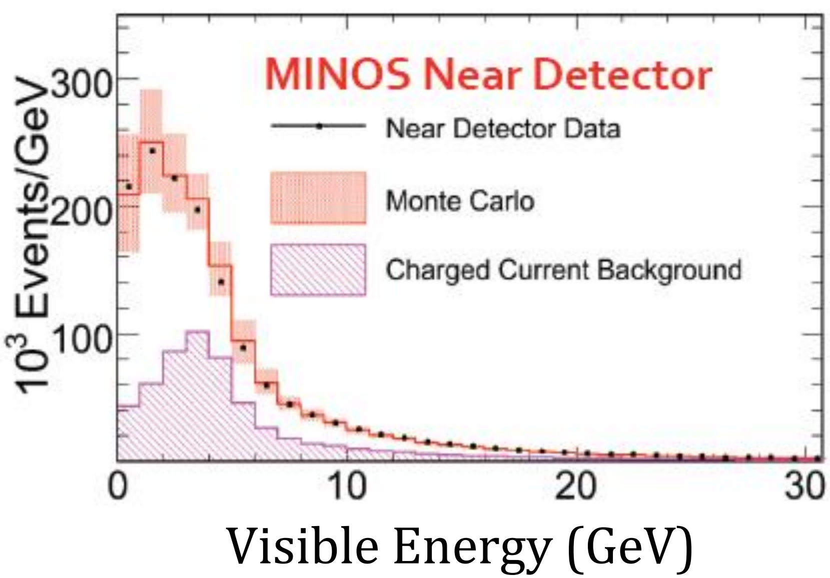
3.36×10^{20} protons on target





Searching for Sterile Neutrinos





Neutral current (NC) events appear as shower-like events without a track.

All active flavors participate in NC interactions. Their yield should be similar between the Near and Far Detectors.

Any deficit of NC events at the far detector could indicate mixing from ν_μ to sterile neutrinos.

Must take into account ν_e appearance since they are hard to distinguish in our detector.

Sterile Neutrino Results

Use oscillation results from MINOS and Kamland+SNO. Look at both θ_{13}=0 and θ_{13} at the CHOOZ limit.

Rate based: $R = \frac{N_{Data} - N_{CC\ Bkg}}{N_{MC}}$

R=0.99±0.09±0.07 (θ_{13}=0)
R=0.9±0.09±0.07 (max θ_{13})

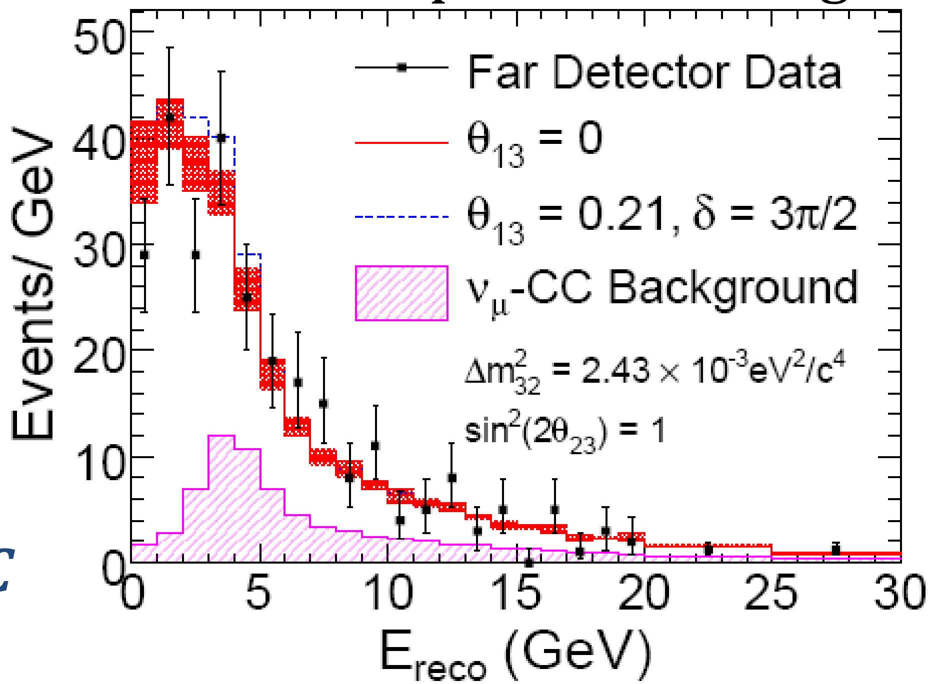
Spectrum Fit: $f_s = \frac{P_{\nu_\mu \to \nu_s}}{1 - P_{\nu_\mu \to \nu_\mu}}$

f_s < 0.68 (90% C.L.) (θ_{13}=0)
f_s < 0.80 (90% C.L.) (max θ_{13})

Consistent with no deficit of NC events.

(hep-ex/0807.2424 , submitted to PRL)

2.46×10^{20} protons on target

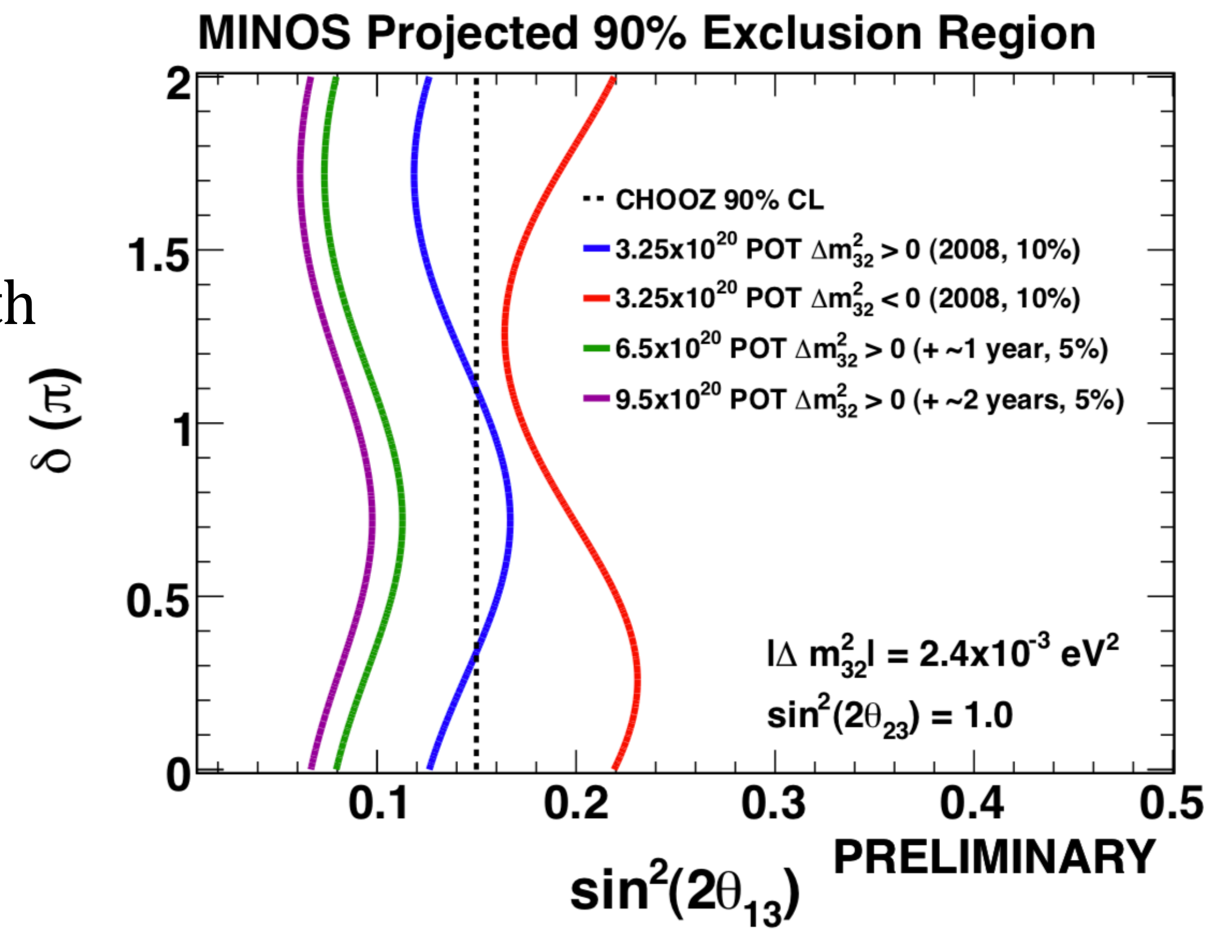


ν_e Sensitivity and θ_{13}

At the CHOOZ limit we expect ~12 ν_e signal events and ~42 background events with 3.25×10^{20} protons.

Matter effects and δ affect the sensitivity.

Results should be out by next year!



Summary and Future

- Cosmic Ray Physics
  - The muon charge ratio was measured to be for surface energies from 1-7 TeV. This significantly higher than previous experiments
  - Correlations between the muon flux and temperature were seen.
  - Atmospheric muons have some sensitivity to oscillation parameters.
  - ❑ Work on neutrino point source searches and coincidences with gamma ray bursts is making its way through the collaboration.

- Neutrino Physics
  - Precise measurements of $\sin^2 2\theta_{23}$ and Δm^2_{23}.
  - No evidence for sterile neutrinos was seen.
  - ❑ Results for θ_{13} will be released soon.

The End