Recent Results from MINOS

Bob Zwaska, Fermilab

for the MINOS Collaboration

2010 Fermilab Users Meeting

June 2, 2010

Tollestrup Award

Justin Evans – University College London

Measuring ν_μ and $\overline{\nu_\mu}$ oscillation parameters with MINOS

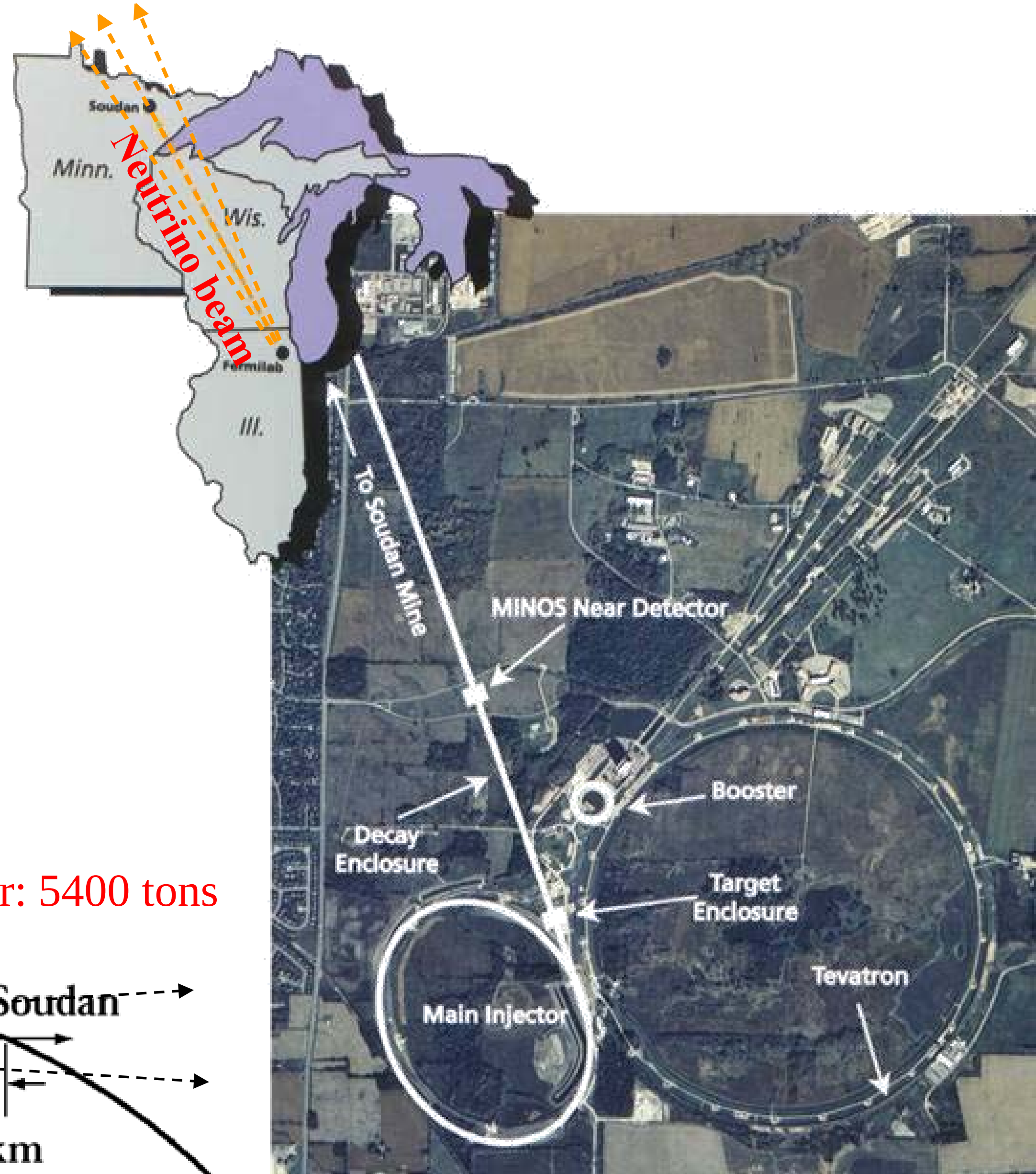
URA Thesis Prize

Tingjun Yang – Stanford University

Search for ν_μ to ν_e oscillations in MINOS

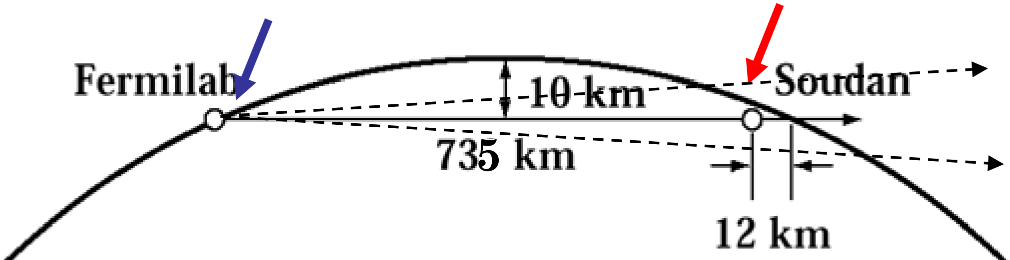
The MINOS Experiment

- High-intensity neutrino beam for oscillation experiments
  - ➢ Predominantly ν_μ beam
  - ➢ Explore and test the new standard model of neutrinos
- Operating since 2005
- Neutrino beam travels to northern Minnesota
  - ➢ 735 km baseline
  - ➢ Intense source at Fermilab
  - ➢ Oscillated source in Minnesota



Near Detector: 980 tons

Far Detector: 5400 tons



Overview

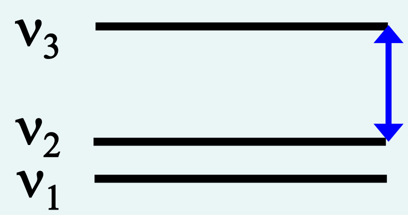
- Background of the experiment and its physics
- Description of the experiment
- Focus on the beam and our knowledge of it
- Selection of current results
- Much more from Justin and Tingjun

  - ➢ Note: a series of new results are in preparation and will be presented on June 14 at a special W&C and at the Neutrino 2010 conference

Physics Approach

1. Measure oscillation parameters at high precision
   - Muon-neutrino disappearance
2. Search for new, unobserved transitions and measure the associated parameters
   - Electron-neutrino appearance
   - Mass hierarchy & CP violation
3. Search for alternative transitions that come from other models and study standard neutrino interactions at high precision
   - Sterile neutrino searches
   - Anti-neutrino oscillation measurements
   - Lorentz violation
   - Neutrino cross-sections
   - Rare(r) interactions

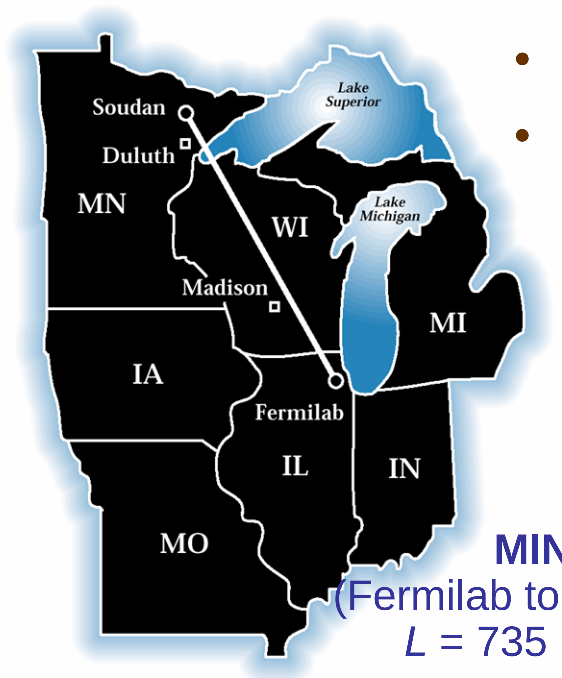
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

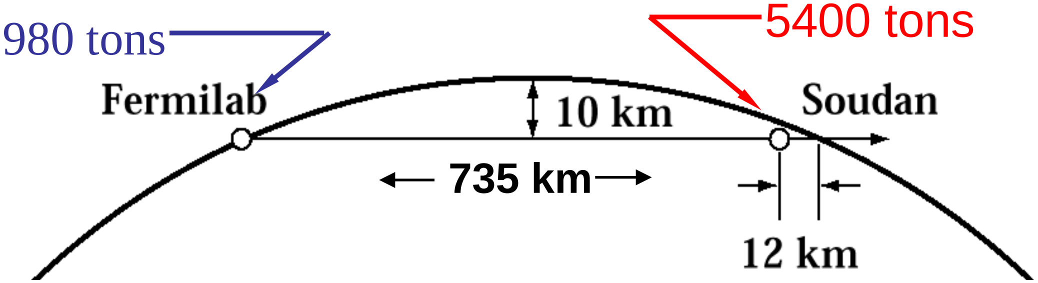


$$\Delta m^2_{32} = m_3^2 - m_2^2$$

Long Baseline ν Oscillation Exps.

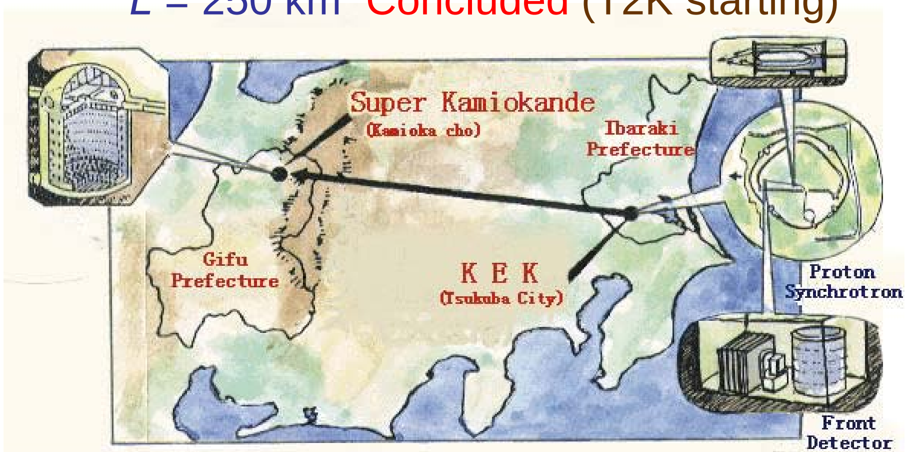
- Reproduce atmospheric ν effect using accelerator beams
- *L* ~ 100's kilometers to match oscillation frequency



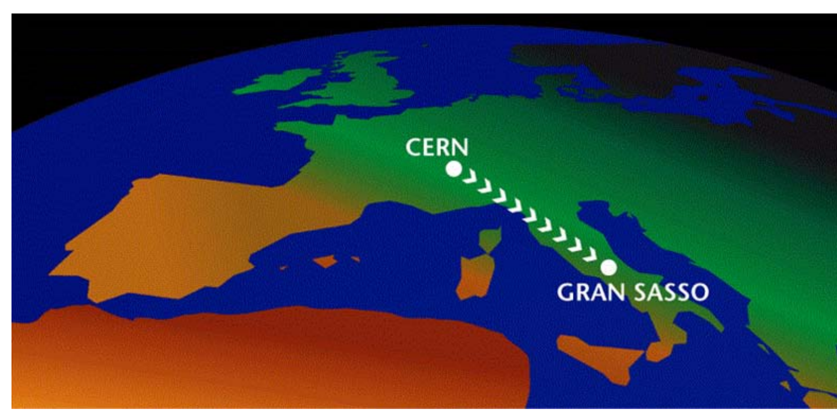


MINOS
(Fermilab to Minnesota)
L = 735 km 2005

K2K (KEK to SuperK)
L = 250 km Concluded (T2K starting)

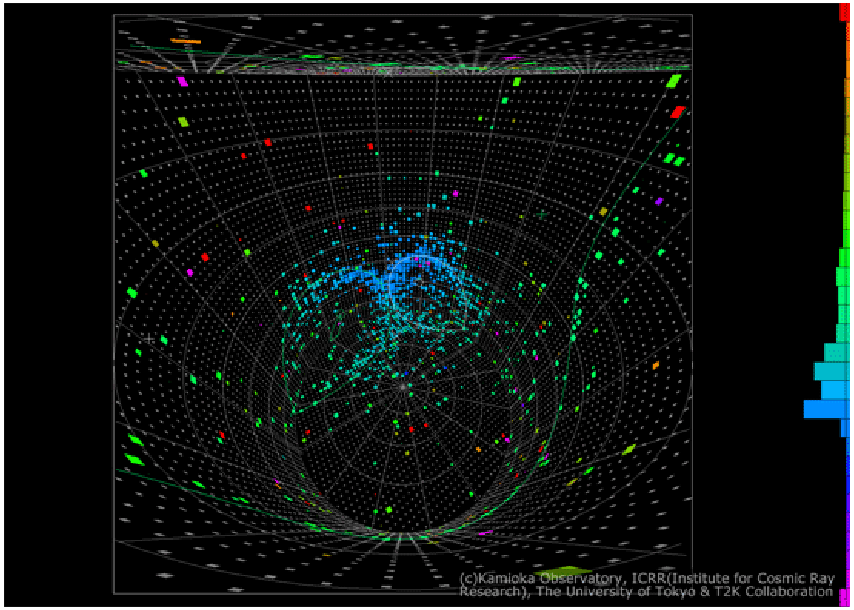


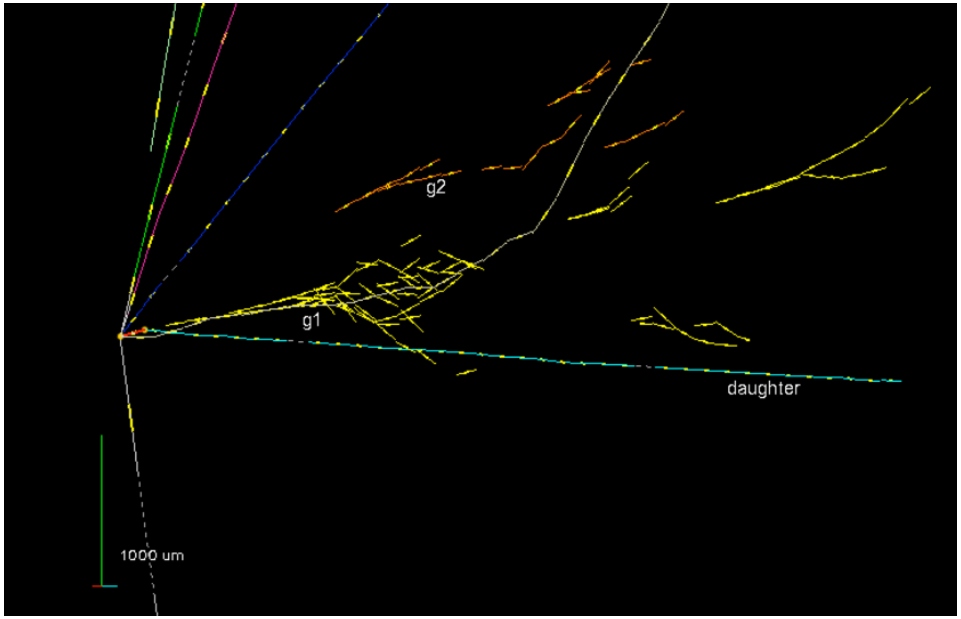
CNGS (CERN to Gran Sasso, Italy)
L = 750 km 2006



New Players

- Neutrino physics is getting busy
- T2K: first event in far detector
- OPERA: first tau-neutrino observed
  - ➢ Seminar on Friday
- Online in the next few years: Double-CHOOZ, Daya Bay, RENO, NOvA



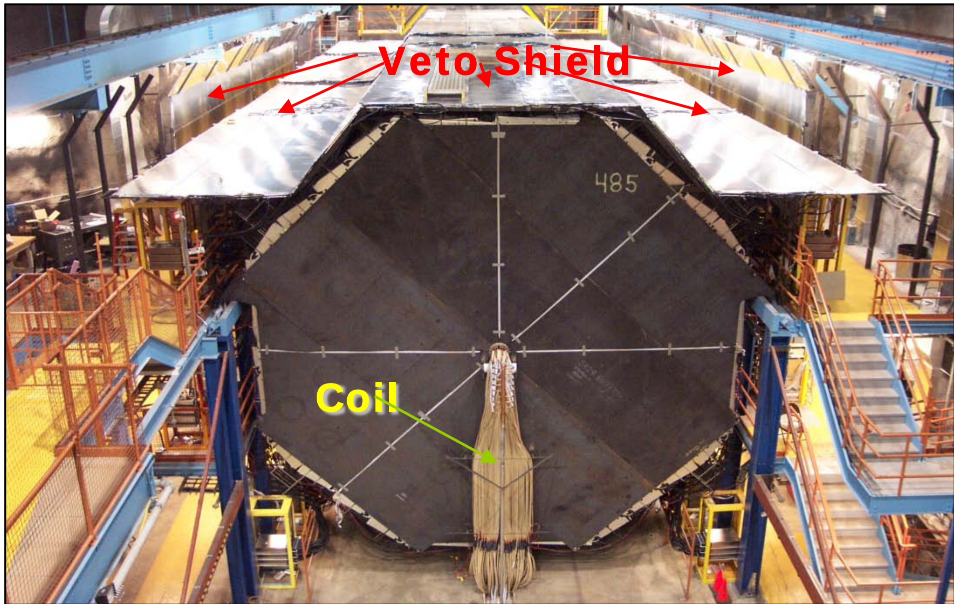


The MINOS Detectors

- Steel / Scintillator sandwiches
- Magnetized steel
- Tracking calorimeters
  - Alternating planes of scintillator strips
  - PMT readout
- Functionally identical
- 1 and 735 km from the neutrino production target
- 980 and 5400 tons

Near Detector

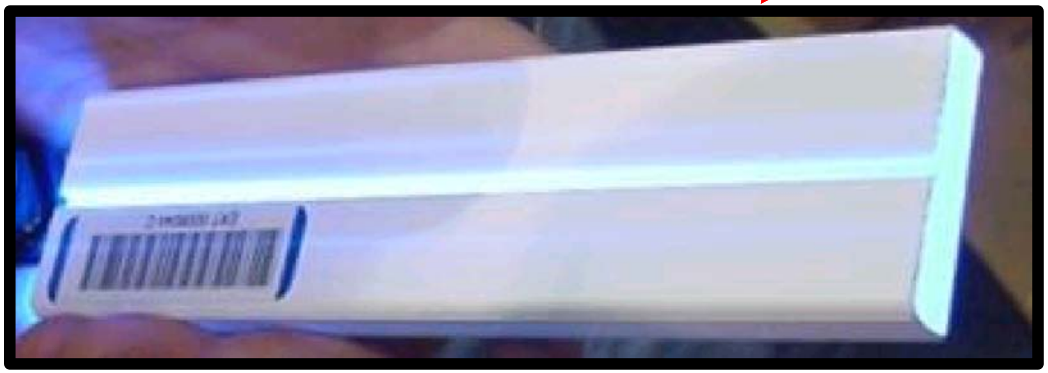
Far Detector



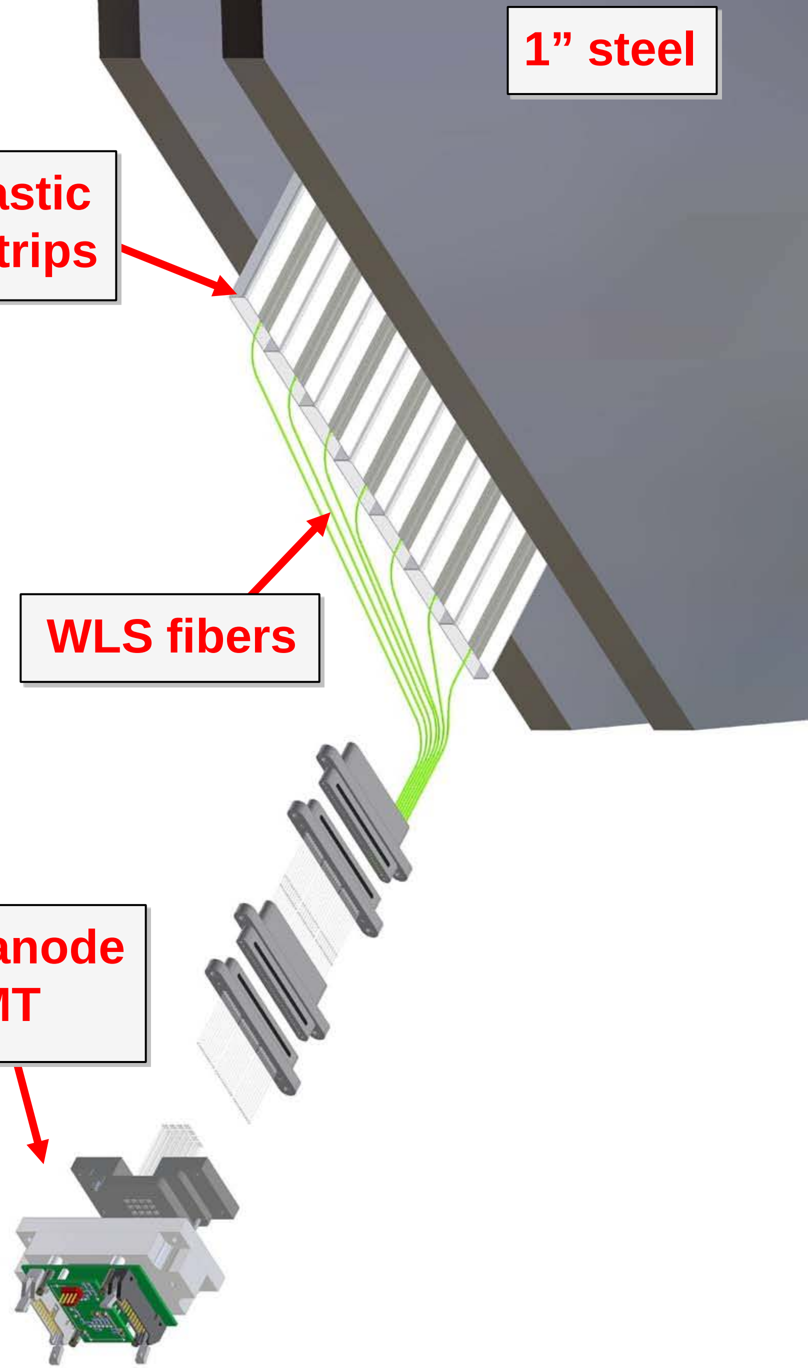
MINOS Detectors

1” steel

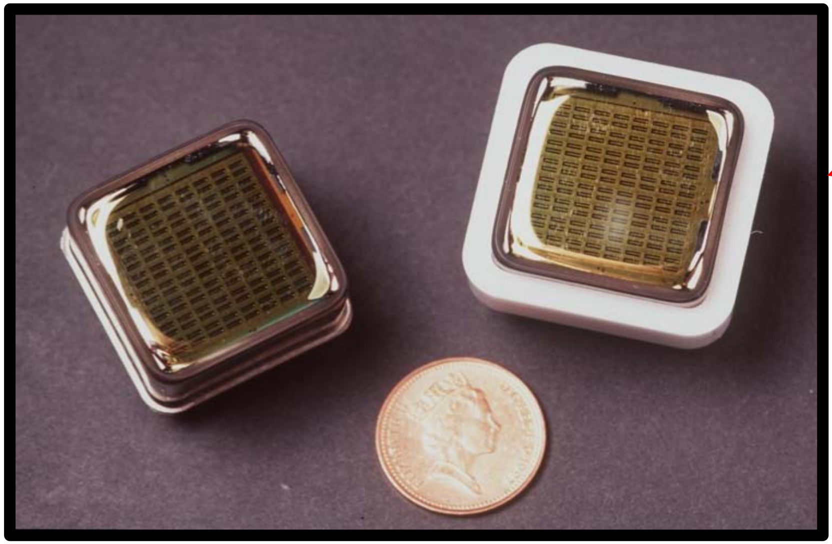
Extruded plastic scintillator strips



WLS fibers

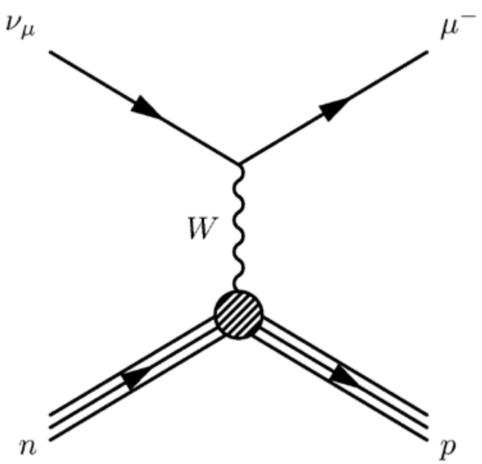


Multi-anode PMT

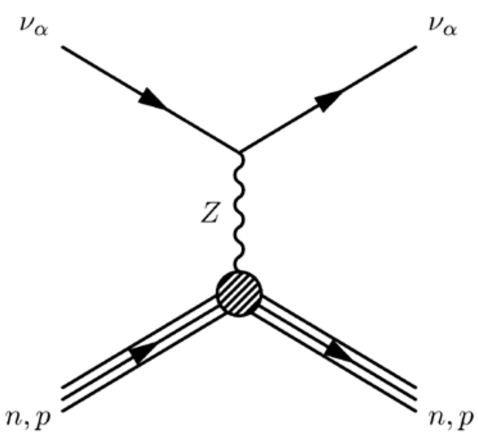


Interaction Types

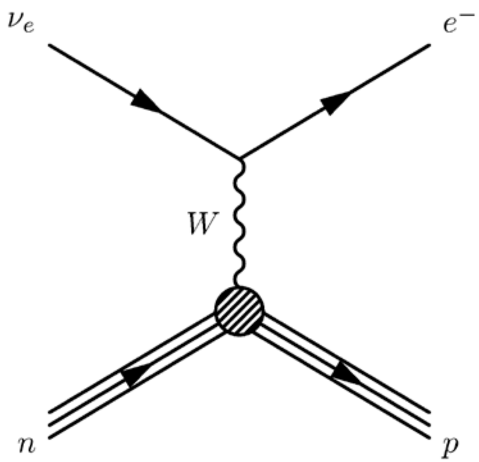
ν_μ CC Event



NC Event



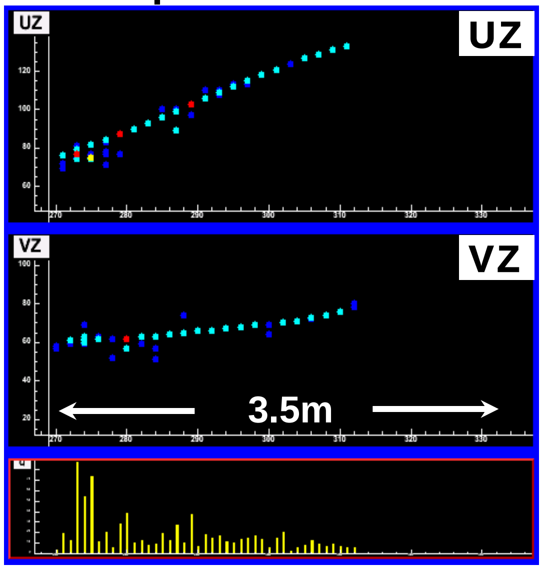
ν_e CC Event



Event Topologies

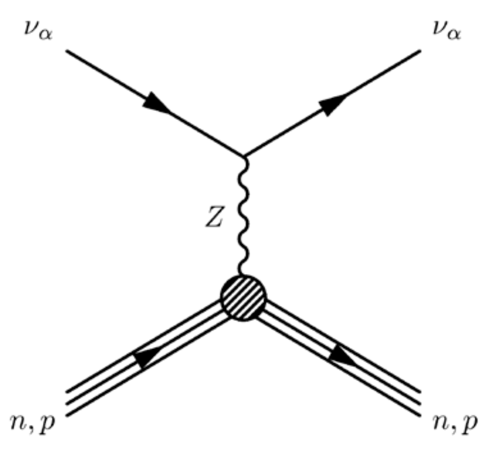
Monte Carlo

ν_μ CC Event

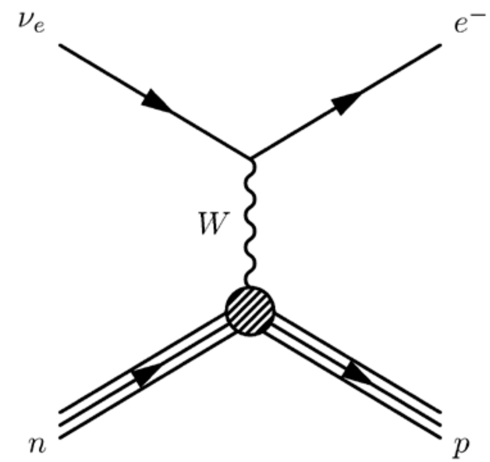


long μ track & hadronic activity at vertex

NC Event



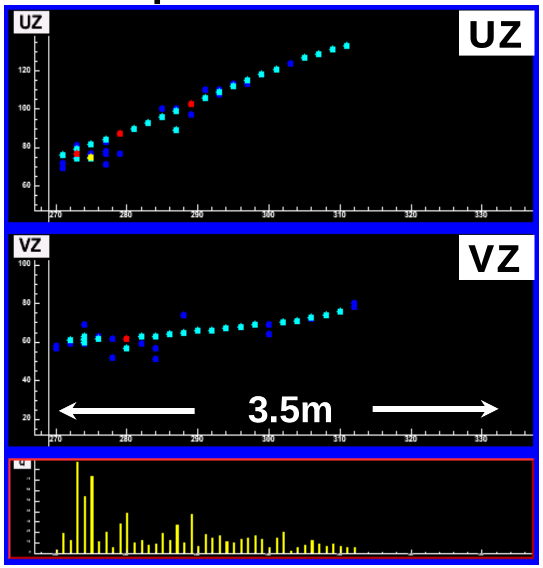
ν_e CC Event



Event Topologies

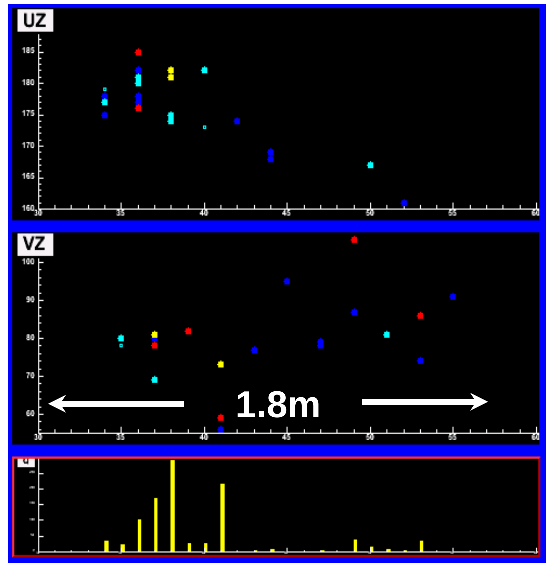
Monte Carlo

ν_μ CC Event



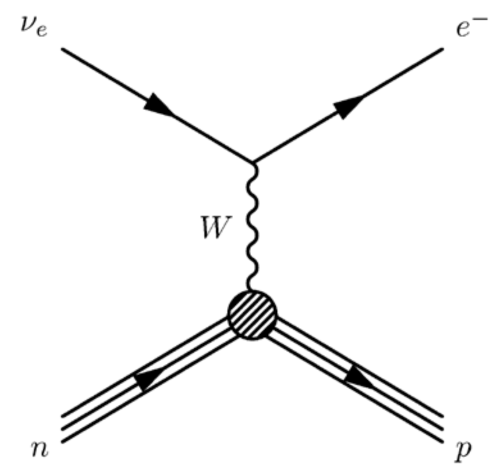
long μ track & hadronic activity at vertex

NC Event



short event, often diffuse

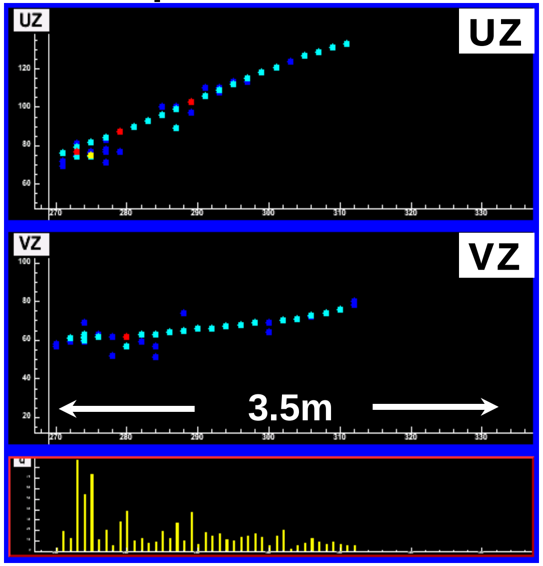
ν_e CC Event



Event Topologies

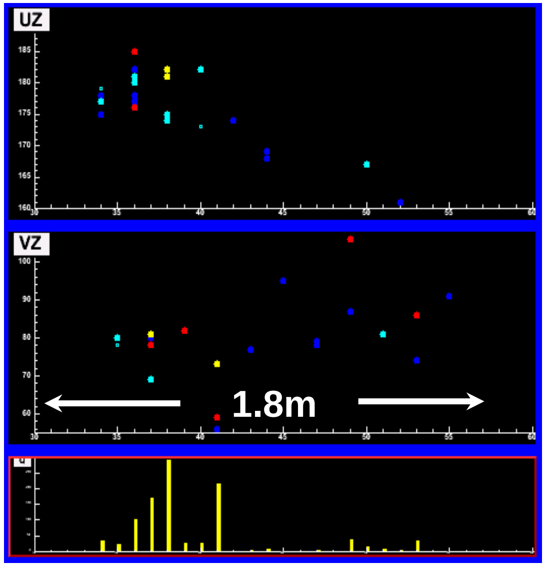
Monte Carlo

ν_μ CC Event



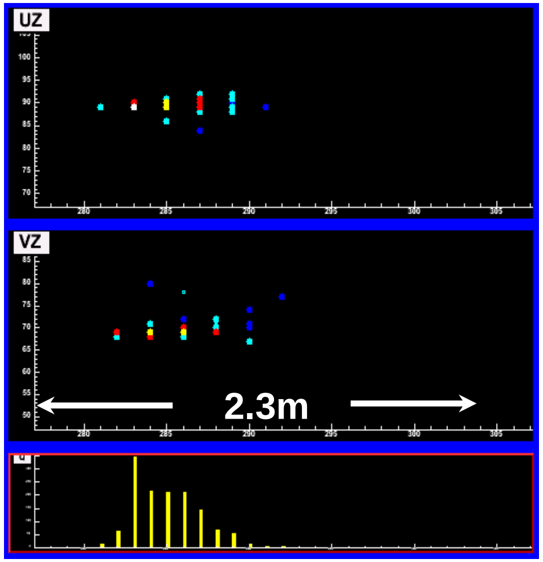
long μ track & hadronic activity at vertex

NC Event



short event, often diffuse

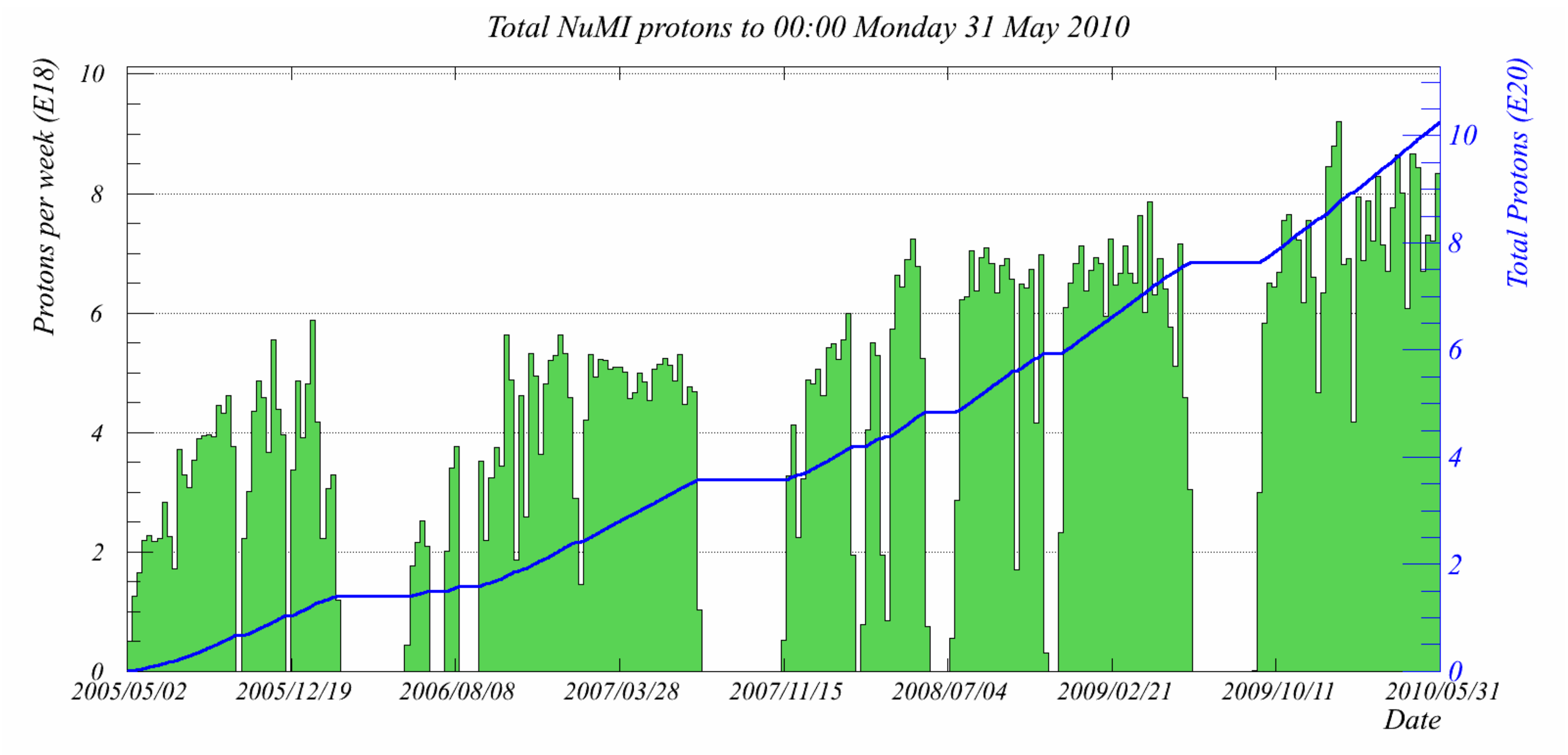
ν_e CC Event



short, with typical EM shower profile

Protons as Raw Material

- High-power 120 GeV beam from the Main Injector feeds the neutrino beam
- Typical beam power is 310 kW
  - Occasional running at 400 kW
  - 10e20 total protons passed on May 5
- Weekly delivery of protons has continually improved
  - Thanks to the Accelerator Division



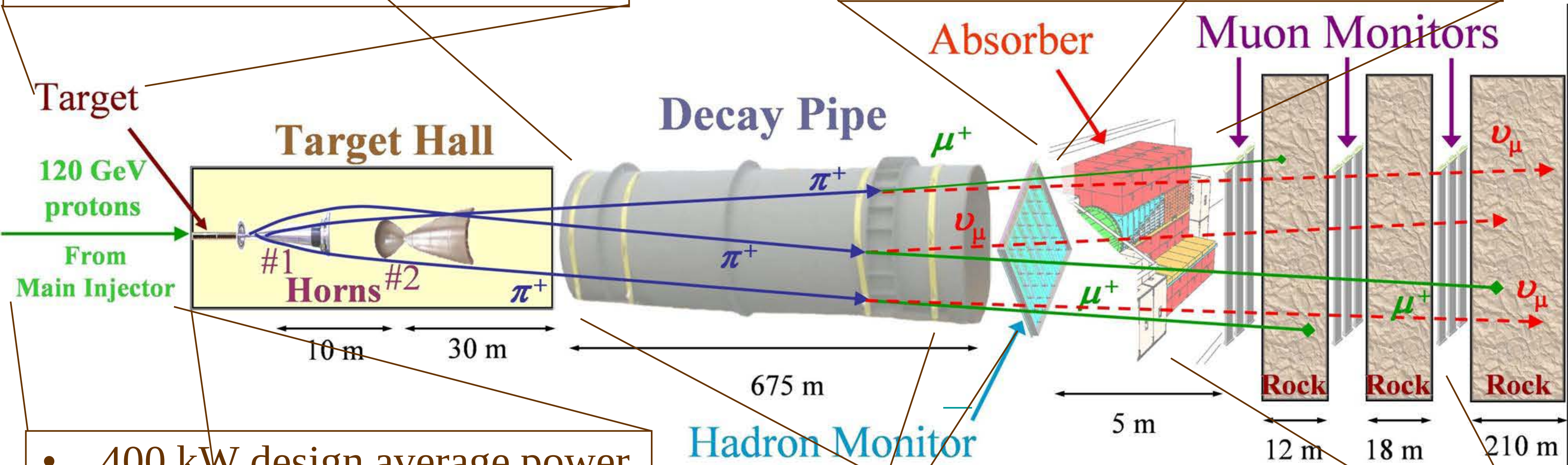
The NuMI Beam

“Neutrinos at the Main Injector”

- 2 interaction length, C target
- Produces π, K mesons

- 2 m diameter
- Roughly decay length for 10 GeV π^+
- Evacuated or He-filled & cooled

- Absorbs 160 kW of protons and other hadrons
- Allows high-energy muons to penetrate



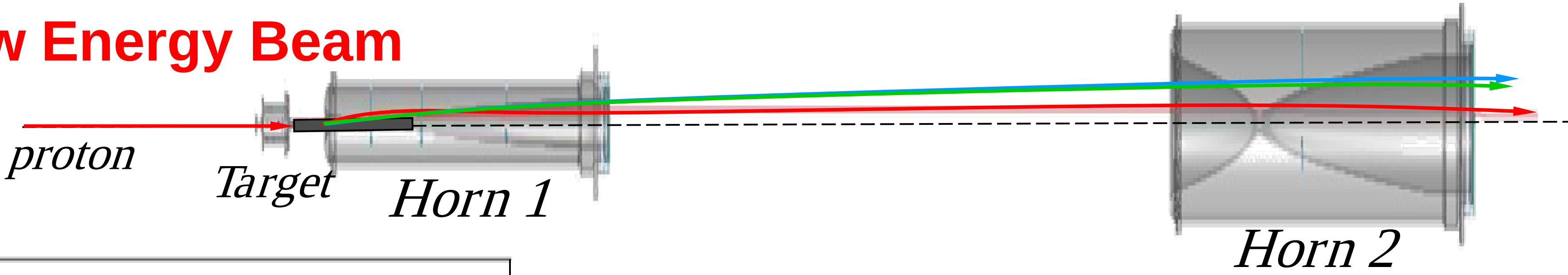
- 400 kW design average power
- σ ~ 1 mm

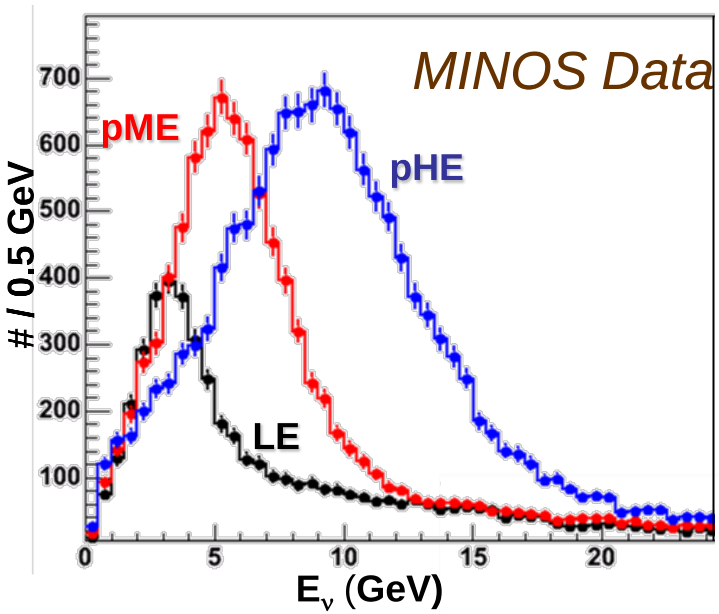
- Pulsed focusing horns
- Toroidal magnetic field
- Parabolic inner conductor profile
- Focuses meson momentum band

- Measure hadron & muon fluxes
- Arrays measure distributions

Neutrino Beam Design

Low Energy Beam





Pions with

p_T=300 MeV/*c* and

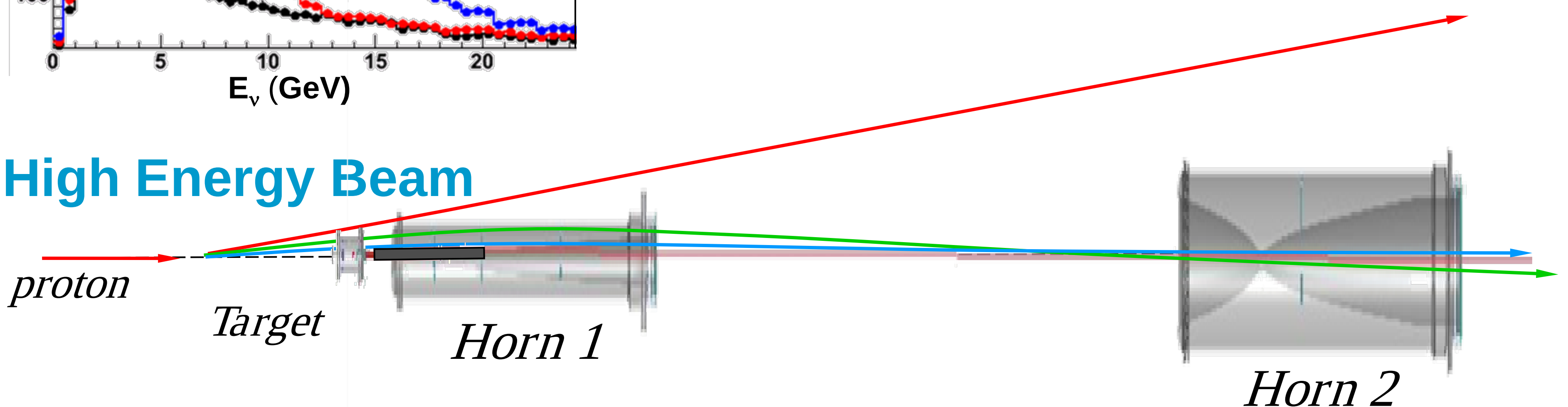
p=5 GeV/*c*

p=10 GeV/*c*

p=20 GeV/*c*

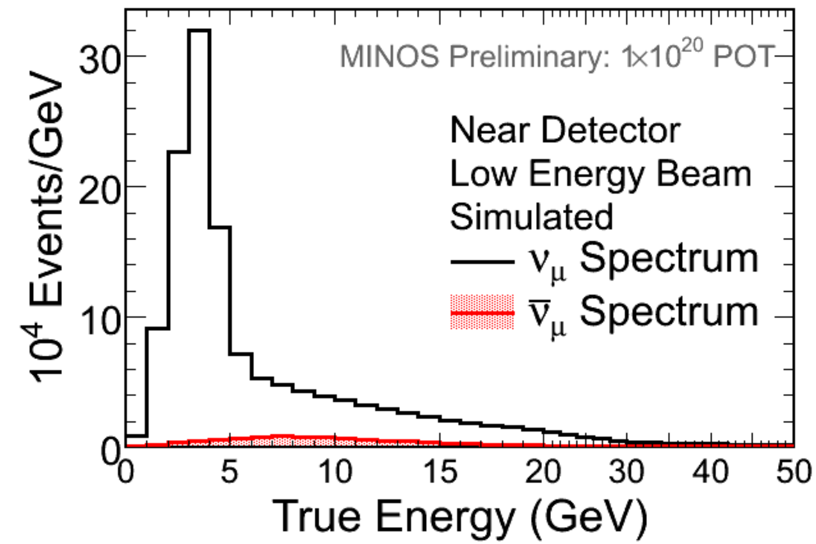
Vary ν beam energy by sliding the target in/out of the 1st horn

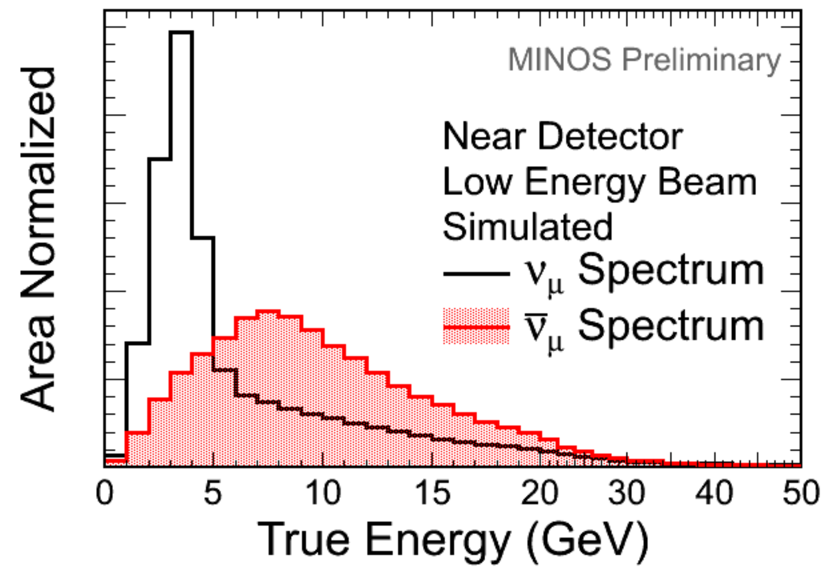
High Energy Beam



Neutrino Energy Spectrum

- Optimal beam configuration for $|\Delta m^2_{32}|$ “Low Energy”
  - Focusing positive mesons
- Beam composition in the Near Detector
  - 91.7 % of ν_μ
  - 7.0 % of $\bar{\nu}_\mu$
  - 1.3 % of ν_e and $\bar{\nu}_e$
- Significant difference in energy spectra:
  - ν_μ peaks at 3 GeV
  - $\bar{\nu}_\mu$ peaks at 8 GeV





Precision Neutrino Beam

- Why is precision needed?
  - 1000s of events in Far Detector, but 100s of millions in Near Detector
  - Errors must be held to < 2% for oscillation analyses
    - Short-baseline measurements could do with much better

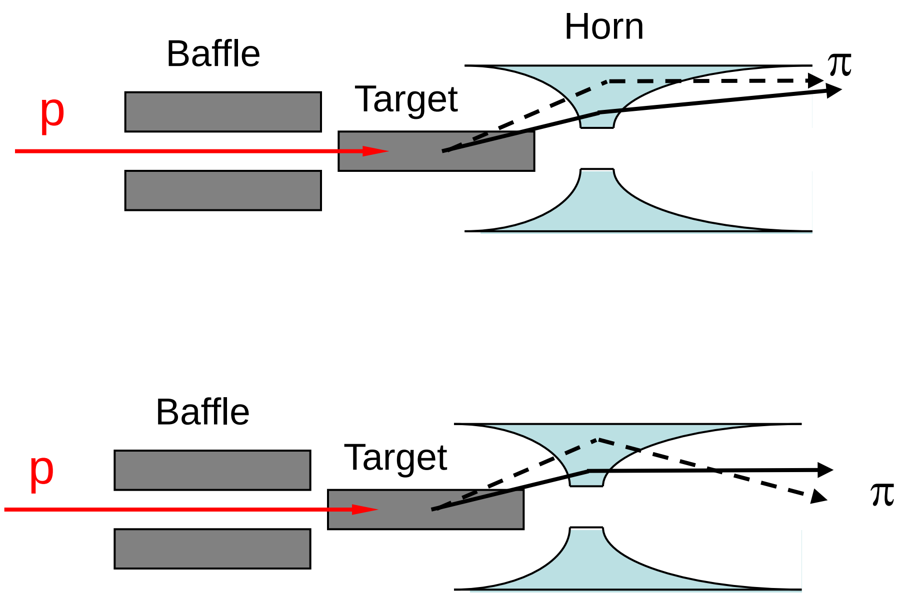
- Why is precision hard?
  - Meson production cross sections not well known
  - Neutrino interaction cross sections not well known
    - Both aggravated by nuclear effects
  - Beam is produced over a large volume and mesons have numerous opportunities to reinteract
  - High-power beam can damage components
    - Heating can also cause components to change position

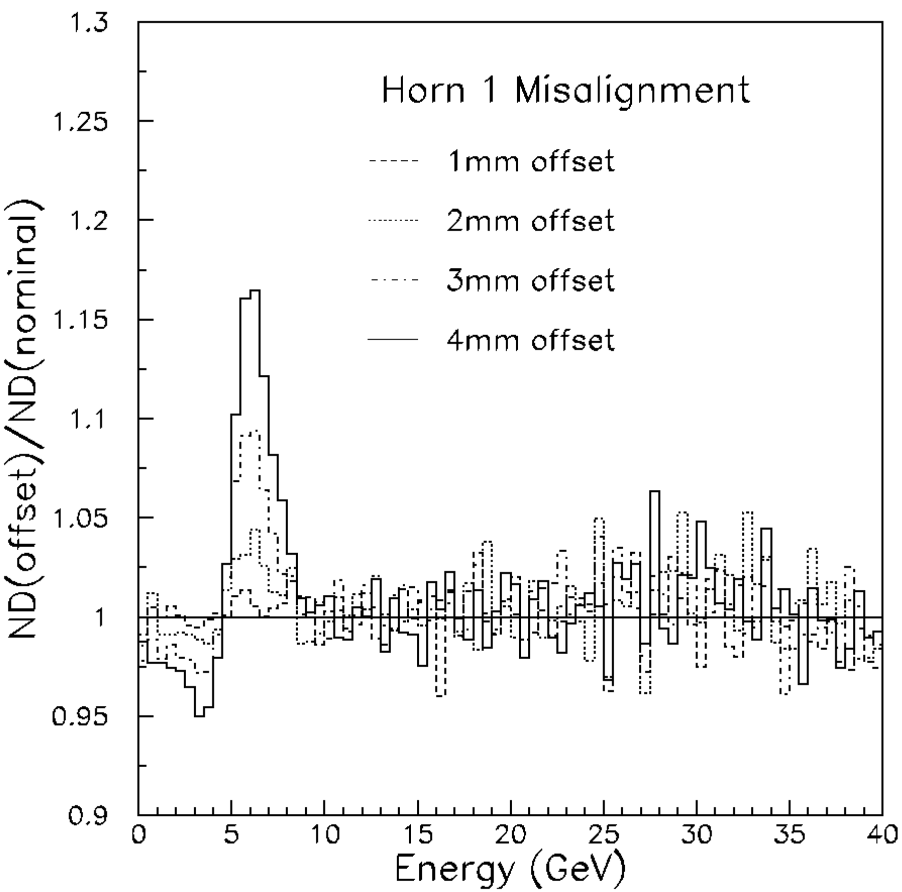
- How do we achieve precision?
  - Build everything to tight tolerances
    - Verify those tolerances
  - Spend a lot of effort on simulation
  - Incorporate external data
  - Monitor the beam
  - Use the enormous amount of Near Detector data with different beam tunes to constrain production

Achieving a Precision ν Spectrum

- Component placement affects the ν beam
  - Beam monitors detect changes in muon & hadron beams
  - Variation measured spill-to-spill
- Beam based alignment for all major components

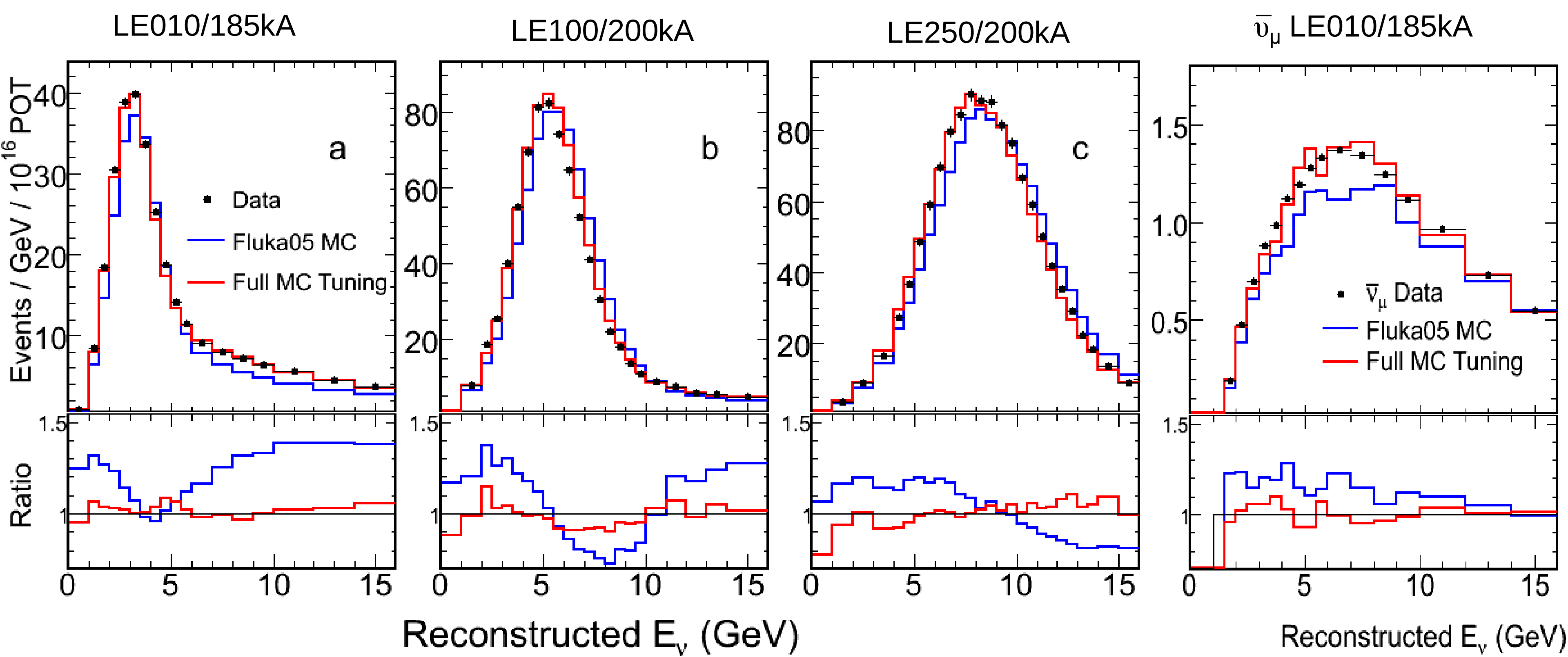
- Horn 1 displacements affect pion focusing





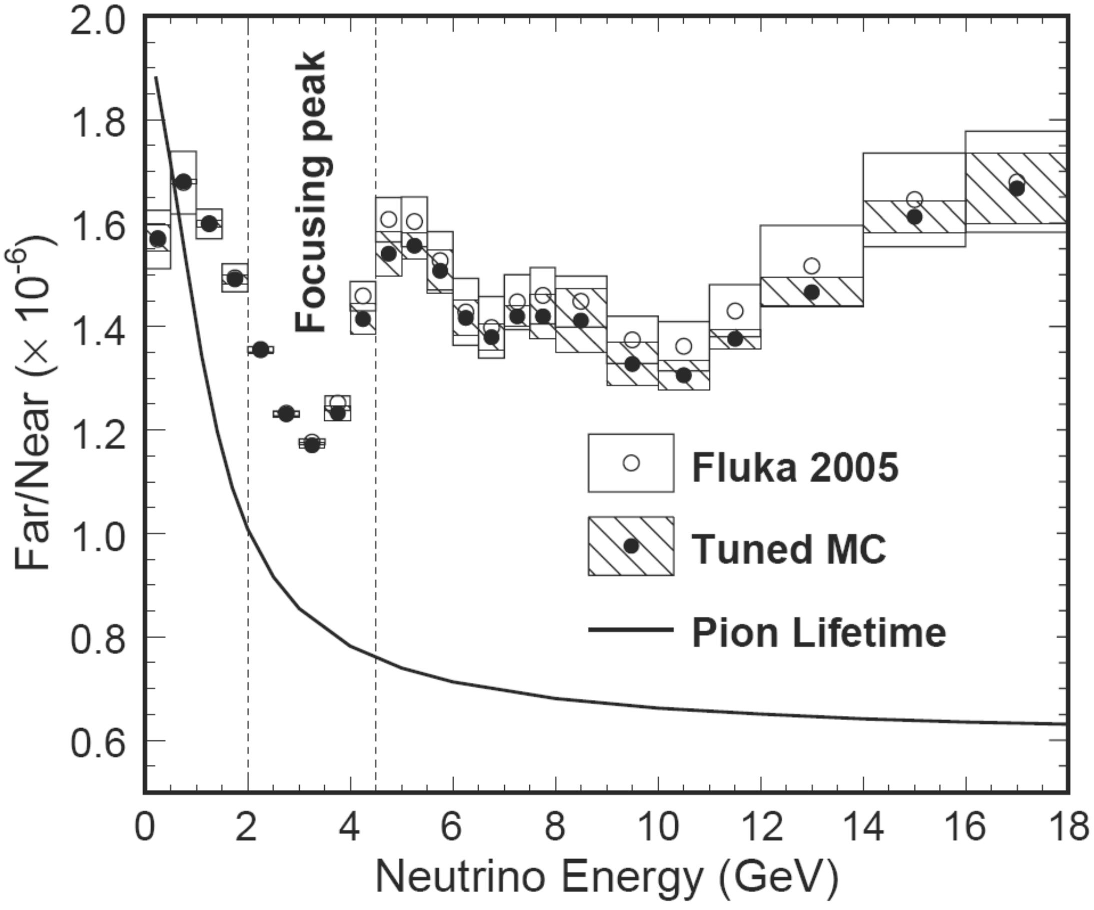
Tuning MC

- Fit ND data from all beam configurations
  - Warp underlying hadron production to match neutrino data
- Simultaneously fit ν_μ and $\overline{\nu}_\mu$ spectra



Far/Near Ratio

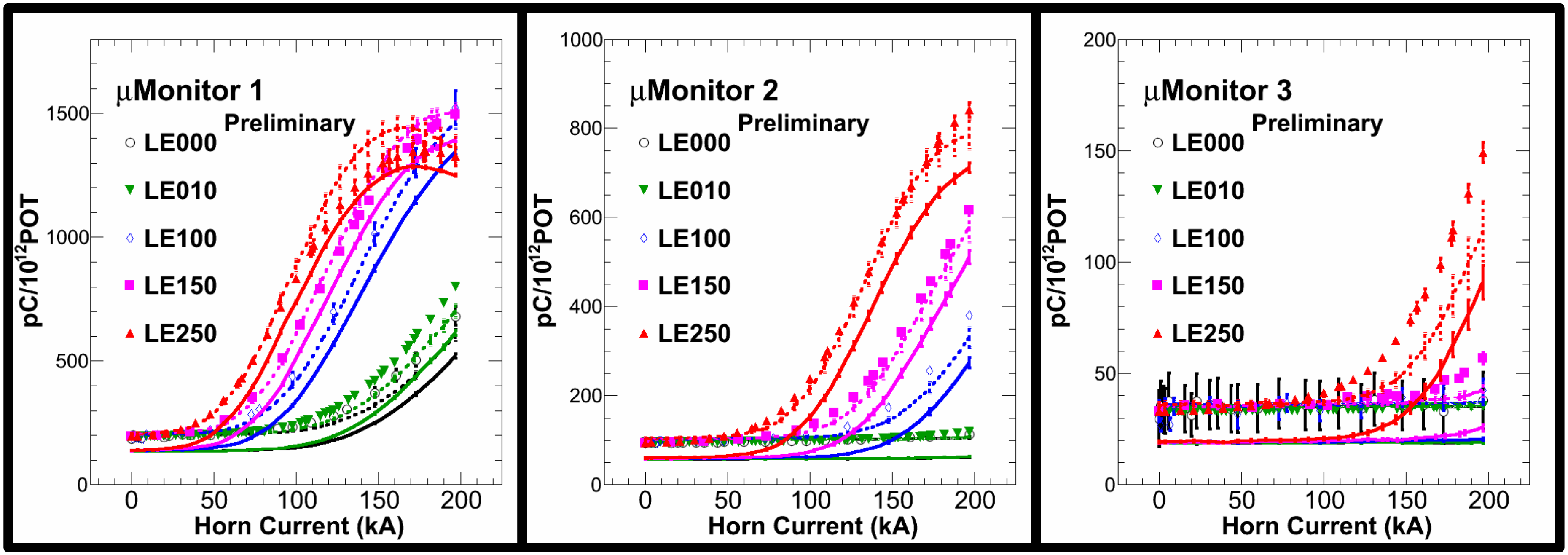
- Point source -> both detectors same flux
- Due to finite pion lifetime higher energy pions decay closer to ND
- Full simulation includes acceptance effects



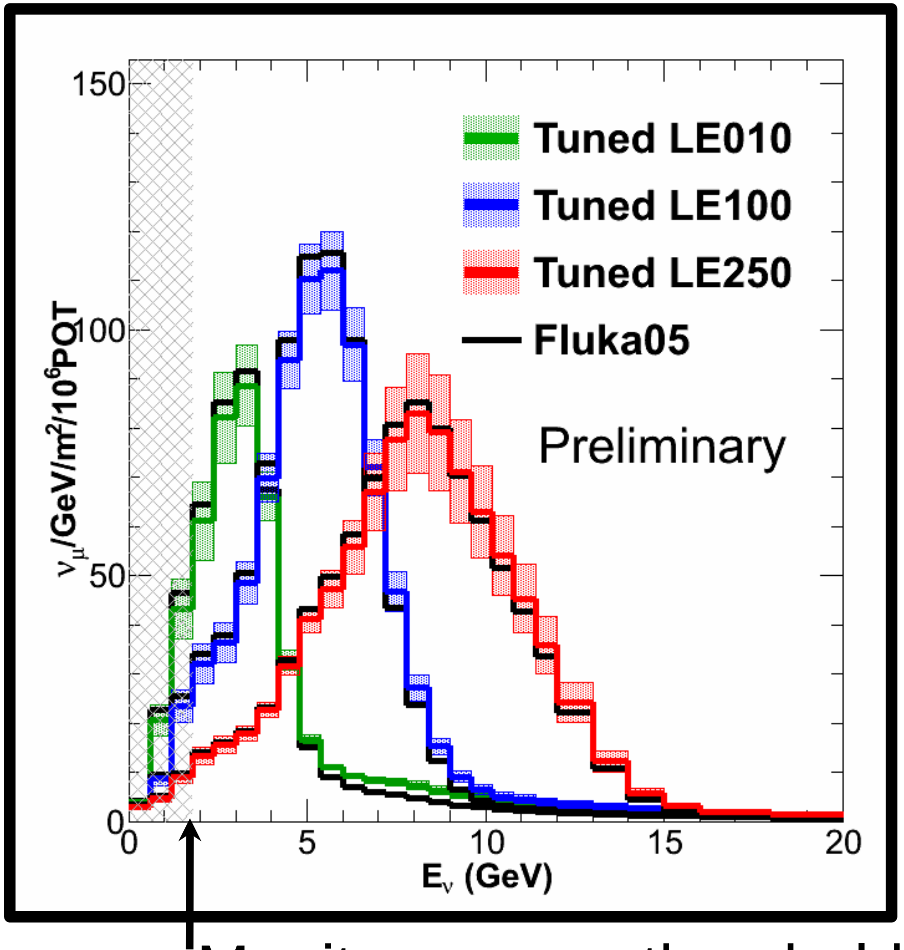
Muon Monitor Tuning

- Measure muon fluxes in numerous beam configurations
  - Vary target position and horn current
- Parameterization for hadron production, $f(p_T, p_z)$.
- Warp p_T and p_z to tune default MC to Muon Monitor data.

● Data ▬ Monte-Carlo ▪▪▪▪ Tuned Monte-Carlo



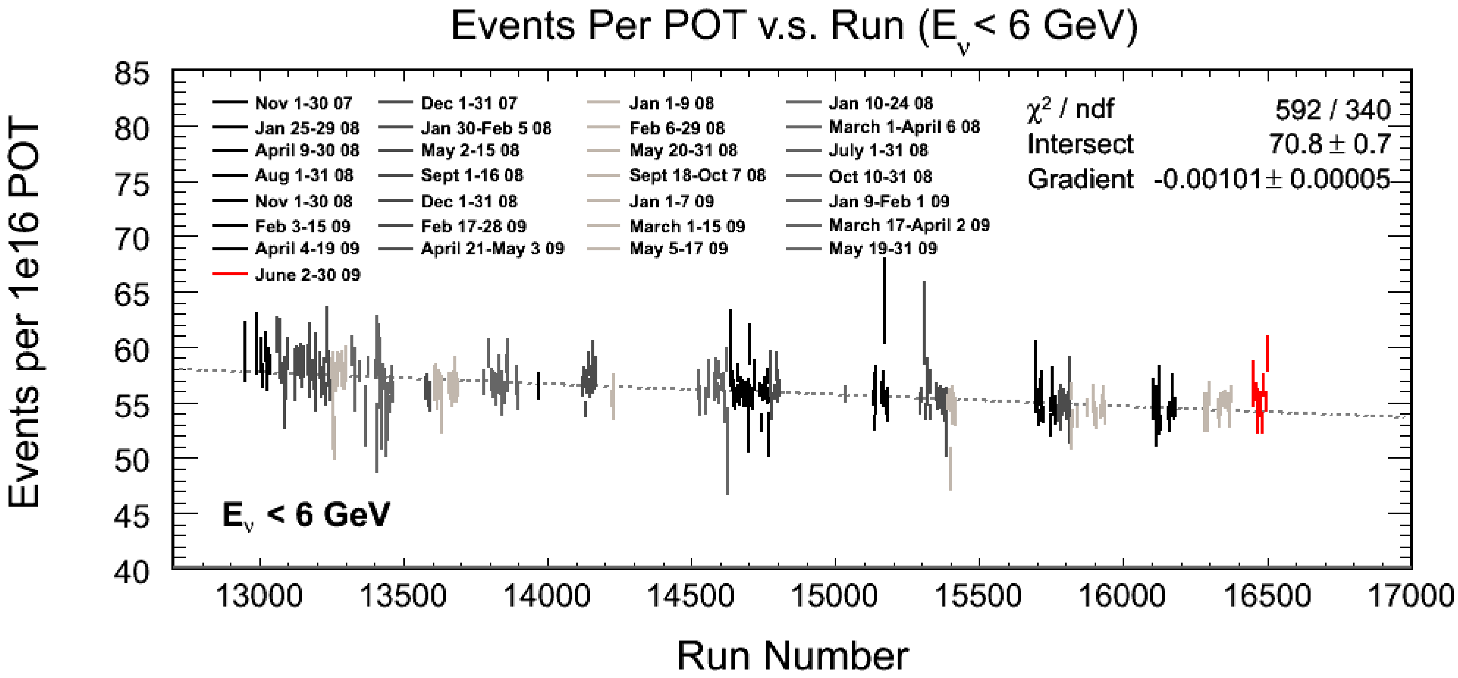
Muon Monitor Flux



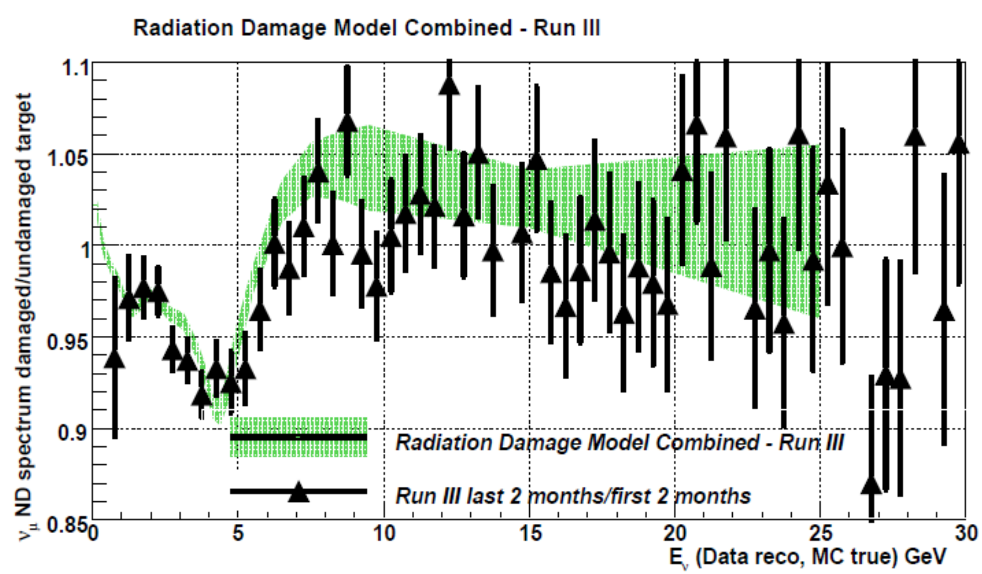
μ Monitor energy threshold.

- Shape only measurement
  - Large uncertainty in Ionization Scale flux requires normalization to MINOS data for $E_\nu >$ 26GeV.
- Error bars come from...
  - π+/π- ratio, K/π ratio
  - Non-linearity
  - Backgrounds
- In situ measurement; accounts for real beamline conditions
- Independent of neutrino data

NuMI Target Degradation



- Neutrino yield from the NuMI target degraded by ~5% over an exposure of ~ 6e20 protons
  - Spectral shape also changes
- Analyses must allow for a changing beam
- This experience will guide the considerations for targets in future experiments



The ν_μ disappearance analysis:

- Run I+II (3.36×10^{20} POT)

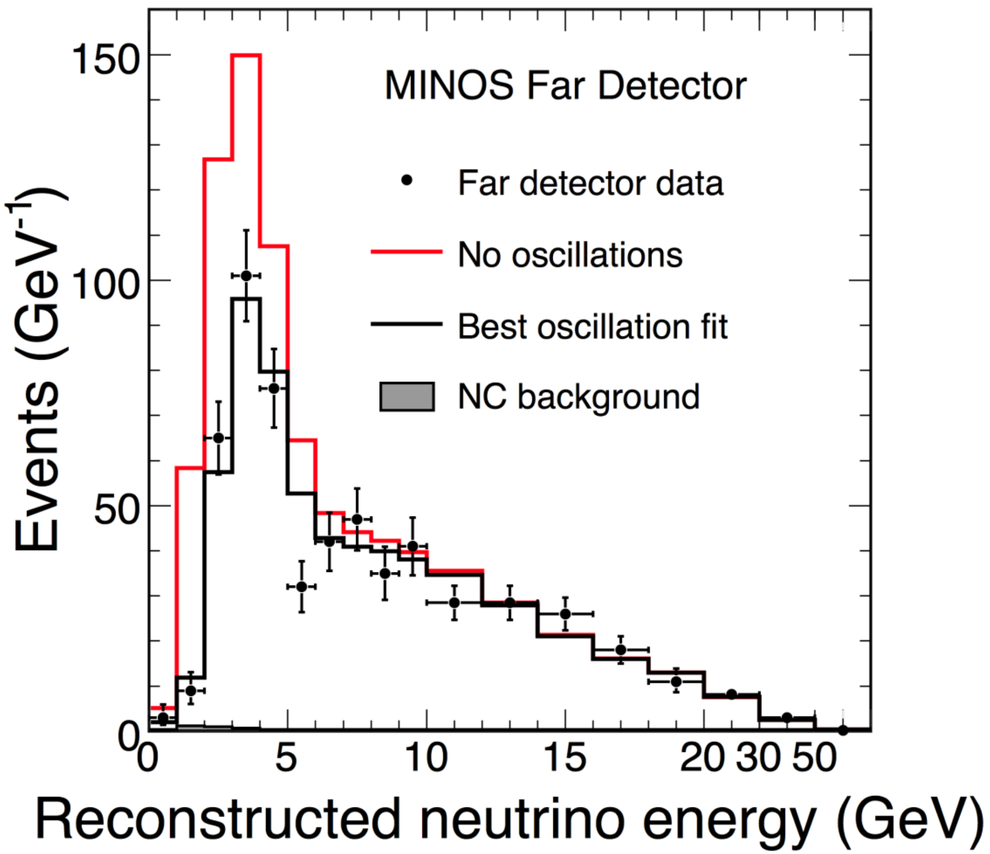
Phys.Rev.Lett.101:131802,2008

-New analysis in preparation

- See Evans talk for more detail

ν_μ disappearance

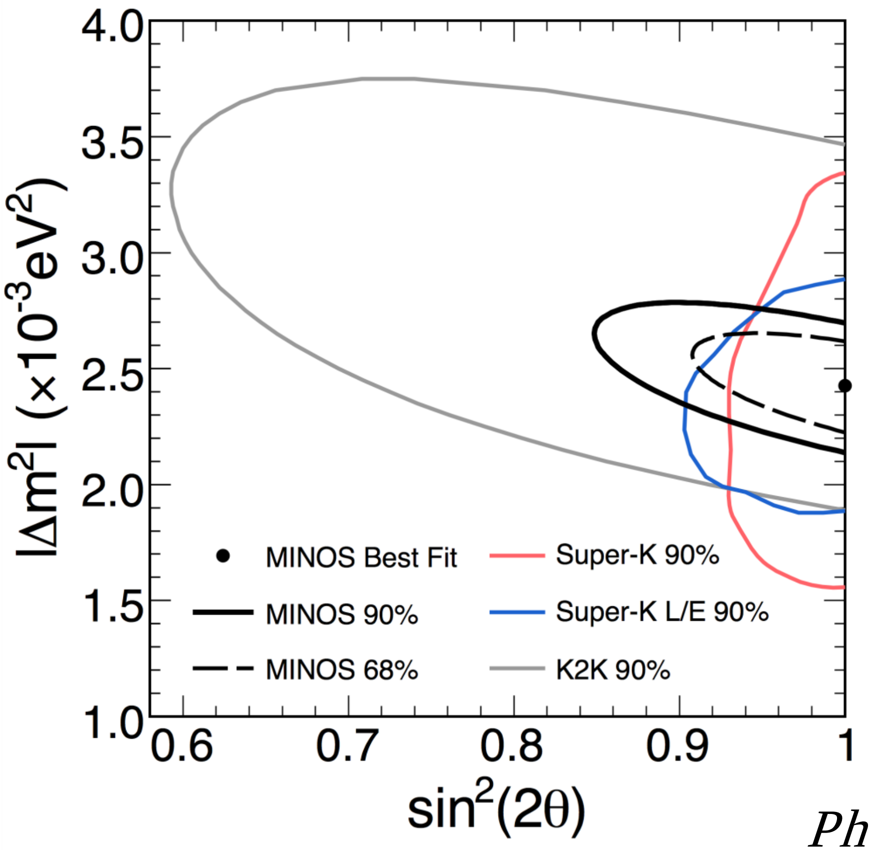
- Use both low and high energy beam
  - Blind analysis
  - Expected 1065 ± 60 with no osc.
  - Observed 848 events.
- Energy spectrum fit with the oscillation hypothesis



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

$$P(\nu_\mu \to \nu_\mu) = 1 - P(\nu_\mu \to \nu_x)$$

Allowed Parameter Space



- Analysis of 7e20 is nearing completion
- Improvements:
  - Looser cuts as systematics are better understood
  - Combine anti-neutrinos
  - Add rock muons and the edges of detector

Phys. Rev. Lett. ***101****, 131802 (2008)*

Best fit (3.1e20 protons)

- $|\Delta m_{32}^2| = (2.43 \pm 0.13) \times 10^{-3}$ eV^2 (68% C.L.)
- $\sin^2(2\theta_{23}) > 0.95$ (68% C.L.), 0.90 (90% C.L.)

Alternative models

Two alternative disappearance models are disfavored:

[1] Decay without oscillations:

χ^2/ndof = 104/97

$\Delta\chi^2 = 14$

disfavored at 3.7σ

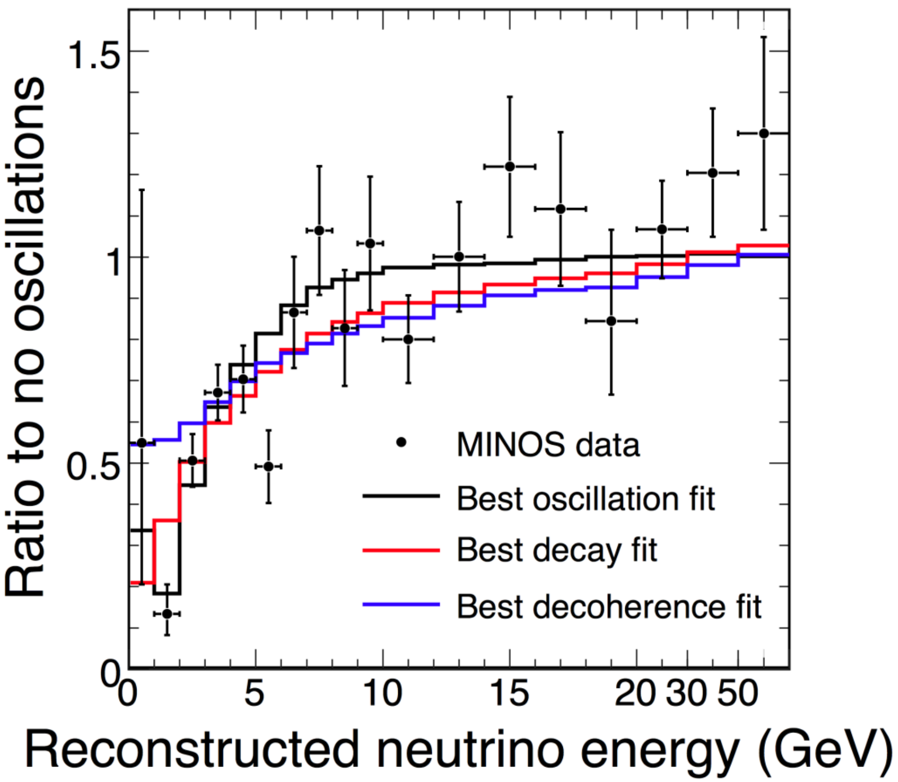
(*5.4σ* if combine CC & NC)

[2] Decoherence:

χ^2/ndof = 123/97

$\Delta\chi^2 = 33$

disfavored at 5.7σ



[1] V. Barger *et al.*, PRL **82**, 2640 (1999)

[2] G.L. Fogli *et al.*, PRD **67**, 093006 (2003)

Search for active-neutrino disappearance:

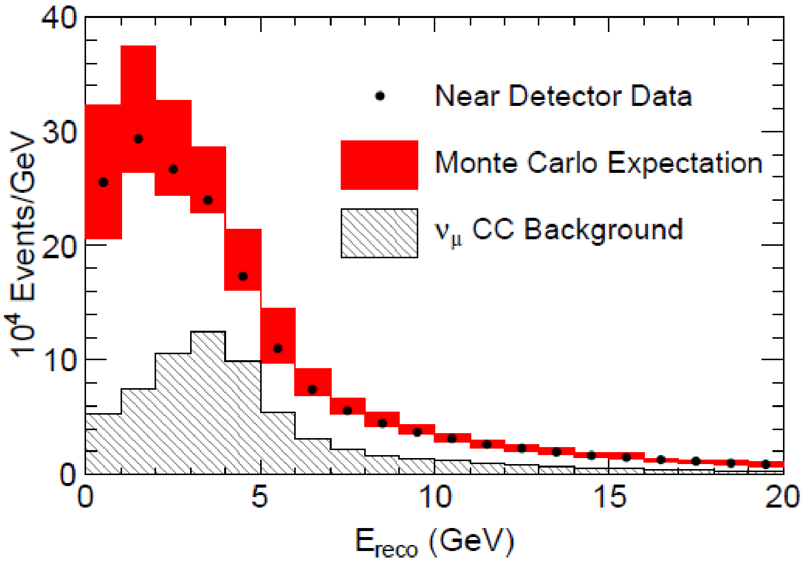
- Directly test for ν_s using Neutral Current Interactions

with Run I+II: 3.18×10^{20} protons

Phys.Rev.D81:052004,2010

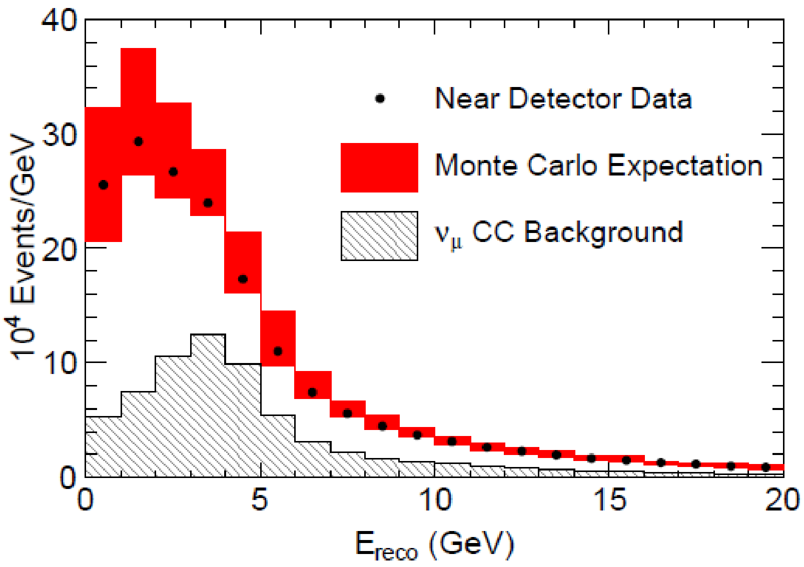
New analysis in preparation

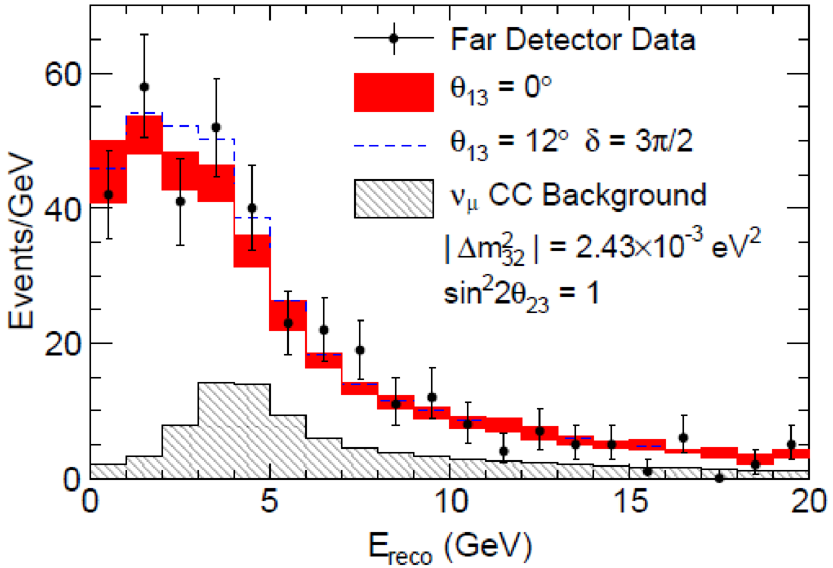
Neutral Current Energy Spectra



- NC selected Data and MC energy spectra for Near Detector
- Good agreement between Data and Monte Carlo
- Discrepancies smaller than systematic uncertainties
- NC events are selected with 90% efficiency and 60% purity

Neutral Current Energy Spectra





- NC selected Data and MC energy spectra for Near Detector
- Good agreement between Data and Monte Carlo
- Discrepancies smaller than systematic uncertainties
- NC events are selected with 90% efficiency and 60% purity

- Far Detector reconstructed energy spectra for NC-like events
- Oscillation parameters are fixed. MC predictions with θ_{13}=0 and θ_{13} at the CHOOZ limit are shown
  - ν_e charged current interactions selected as NC in this analysis
- Expect 377 ± 19.4(stat) ± 18.5(syst)
  - Observe 388 events

Search for ν_e appearance:

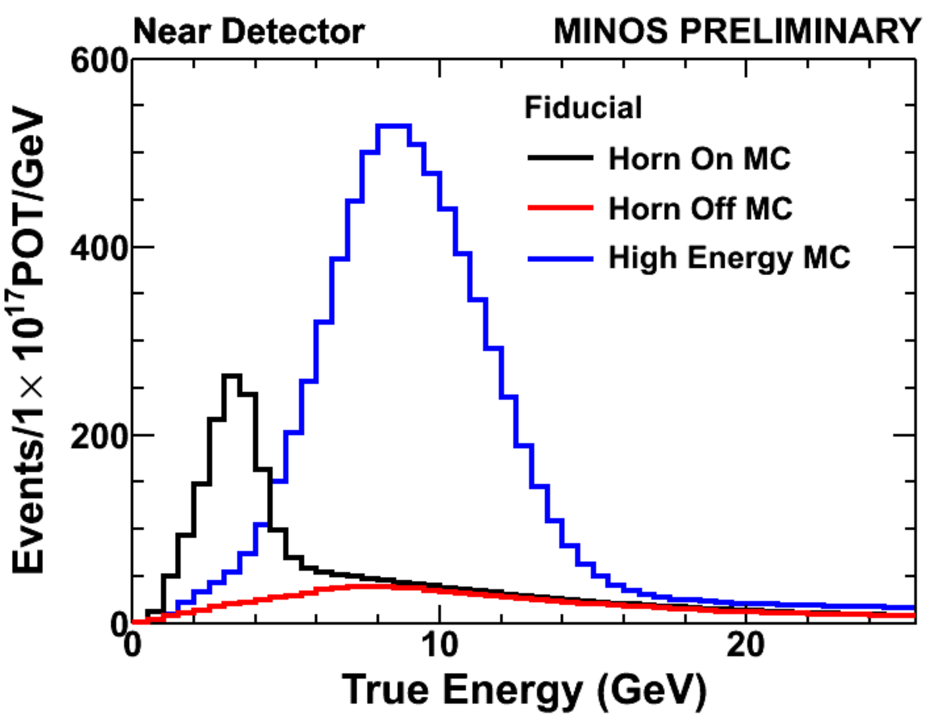
with Run I+II+III (7 x 10^{20} POT)

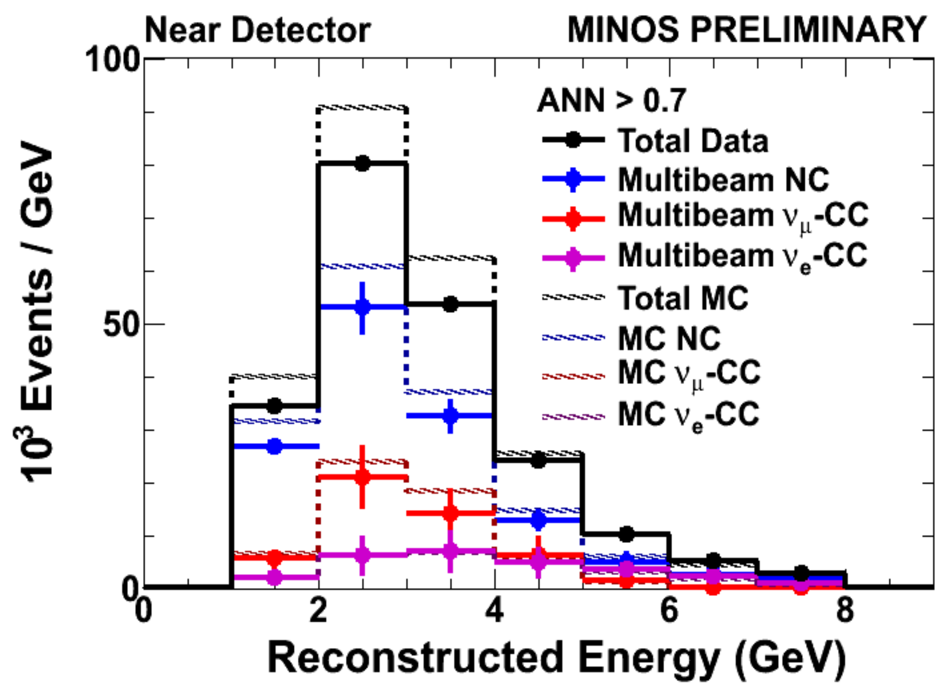
Phys.Rev.Lett.103:261802,2009

- See Yang talk for more detail

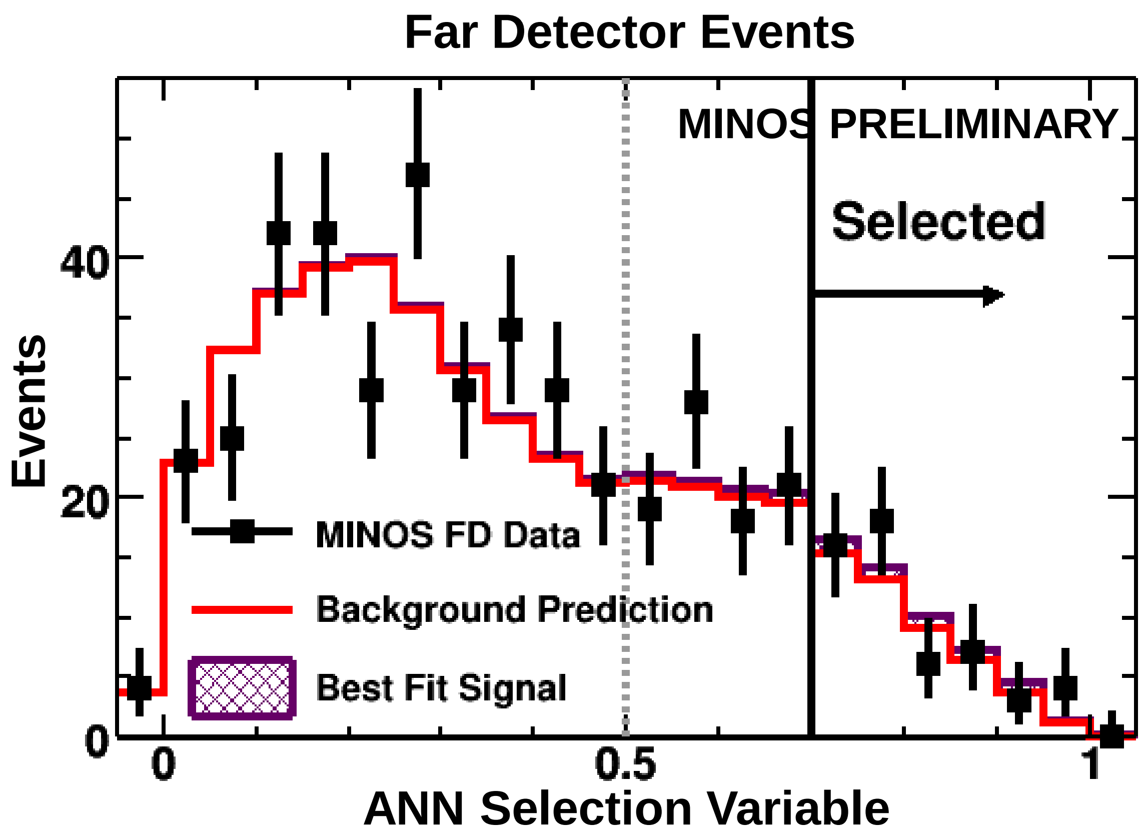
Background - Near Detector Decomposition

- Use large Near Detector samples to measure backgrounds
  - ➢ 3 different beams allow decomposition into background type
- Different backgrounds extrapolate differently to far detector





ν_e Selected Far Detector Data



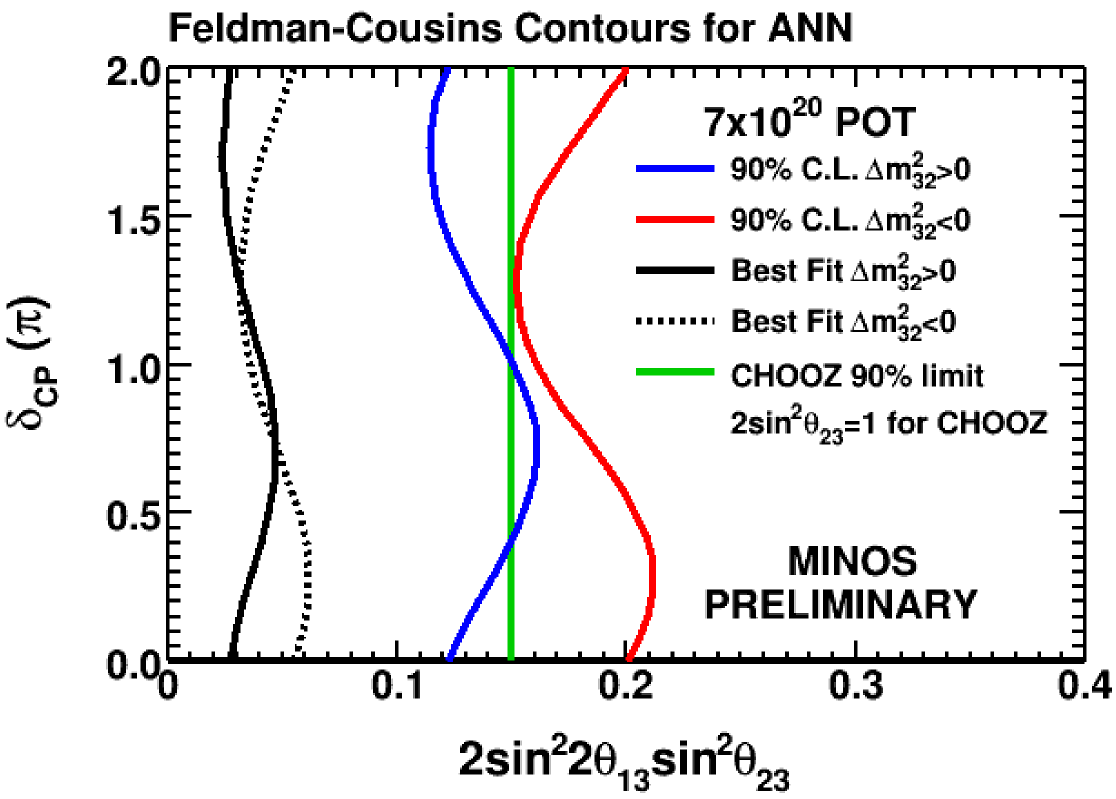
Background Prediction: 49.1   7.0 (stat)   2.7 (sys)

Observed Data: 54

0.7 sigma excess above background

Limits

- Set limits based on total selected events



MINOS sets the tightest limits on θ_{13} assuming a normal mass hierarchy

Antineutrino Disappearance in a Neutrino Beam

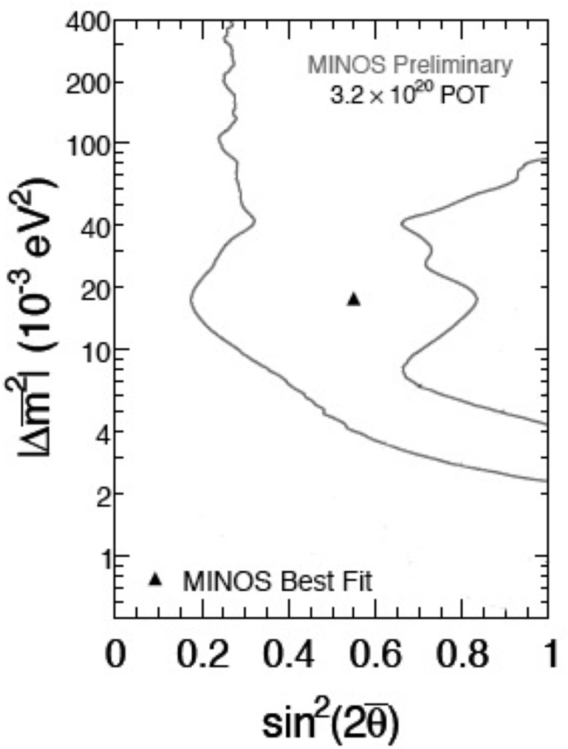
with Run I+II (3.2×10^{20} POT)

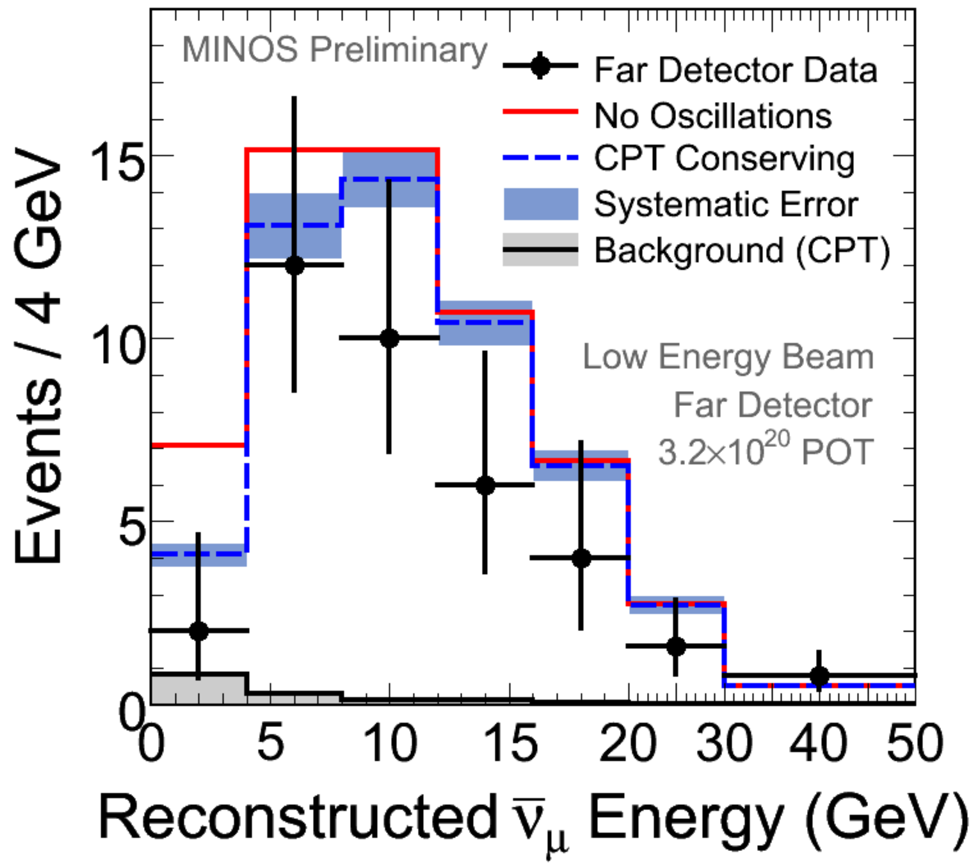
New analysis in preparation

- See Evans talk for more detail

Antineutrinos at the Far Detector

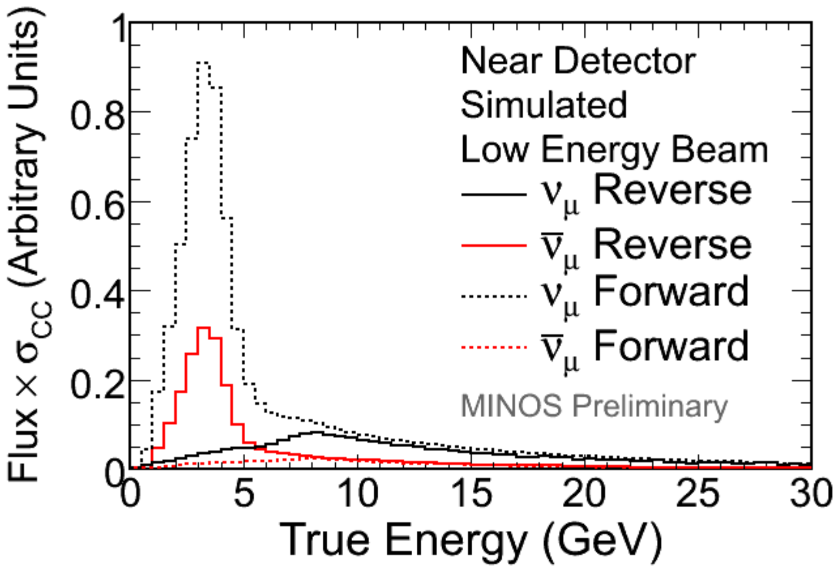
- ***Predict:***
  - Null oscillations:
    64.6 ± 8.0 (stat.) ± 3.9 (syst.)
  - CPT conserving oscillations:
    58.3 ± 7.6 (stat.) ± 3.6 (syst.)
- ***Observe:***
  42 events





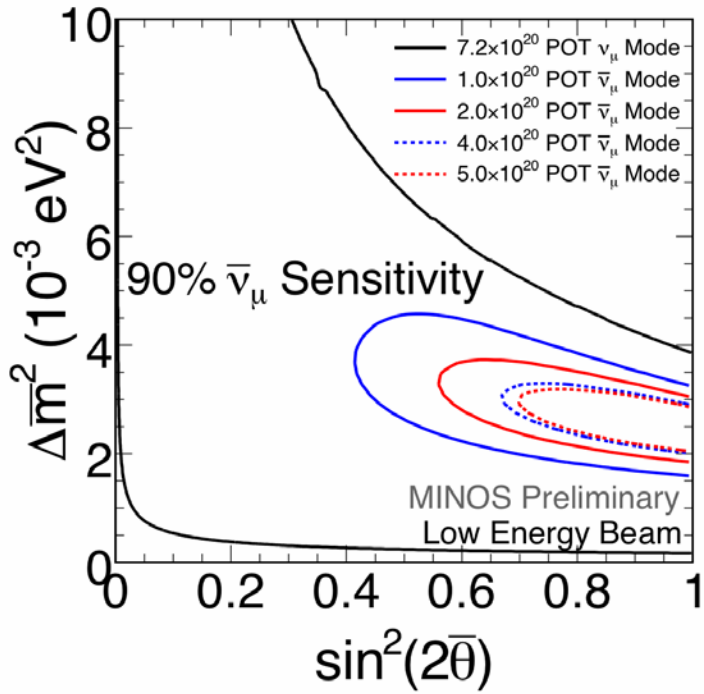
- Examine 7% antinuetrino component
- Detector magnetic field allows charge discrimination

Dedicated Antineutrino running



- Reverse current in the NuMI focusing horns.
- Obtain a greatly enhanced antineutrino sample below 5 GeV (incl. the oscillation maximum).
- Have accumulated 1.76e20 in this mode

- Will enable a more precise measurement of the antineutrino oscillation parameters than possible with forward horn current
- Analysis is nearing completion



Selection of Additional Measurements

- Atmospheric neutrinos
  - **Phys.Rev.D75:092003,2007**
  - New analysis in preparation
- Lorentz Invariance
  - **Phys.Rev.Lett.101:151601,2008**
  - New analysis in preparation
- Neutrino cross sections
  - Inclusive charged current: **Phys.Rev.D81:072002,2010**
  - Several others under preparation
- Sudden Stratospheric Warming (Climate Physics with cosmic rays)
  - **Geophys.Res.Lett.36:L05809,2009**
- Cosmic ray variation with season
  - **Phys.Rev.D81:012001,2010**
- Cosmic ray charge ratio
  - **Phys.Rev.D76:052003,2007**

Conclusion

- MINOS is a mature experiment
- Significant effort has resulted in a precisely understood beam
- Several of the major goals have been achieved
  - ➢Muon-neutrino disappearance verified as an oscillation phenomenon
    - Parameters precisely measured, alternatives rules out
  - ➢The neutrinos change into a type that interacts via the Neutral Current
    - Predominantly not ν_e – so we presume ν_τ
  - ➢Limits on electron-neutrino appearance have been improved
- Improvement still to be made
  - ➢Better measurements / limits (evidence?)
  - ➢Exploration of anti-neutrinos
- Wide range of additional measurements
  - ➢Neutrino fluxes / cross sections / interaction types
  - ➢Cosmic ray physics (and applied to atmospheric physics)
- Enjoy the next few talks, and come to the W&C on June 14

Recent MINOS Theses

- **Bob Armstrong** – Indiana university
  - Muon neutrino disappearance at MINOS
- **Pedro Ochoa** – California Institute of Technology
  - A search for muon neutrino to electron neutrino oscillations in the MINOS experiment
- **Steve Cavanaugh** – Harvard University
  - A Measurement of Electron Neutrino Appearance in the MINOS Experiment After Four Years of Data
- **Anna Holin** – University College London
  - Electron neutrino appearance event selection optimization in the MINIS far detector
- **David Auty** – University of Sussex
  - Analysis of numubar from the NuMI beam
- **Laura Loiacano** – University of Texas at Austin
  - Measurement of the Muon Neutrino Charged Current Inclusive Cross Section on Iron
- **Masaki Watabe** – Texas A&M University
  - Using Quasi Elastic Events to Measure Neutrino Oscillation with the MINOS detectors in the NuMI Neutrino Beam