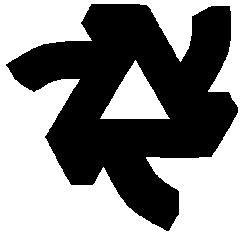
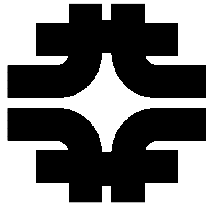




New Results from MINOS

Robert Zwaska, **Fermilab**

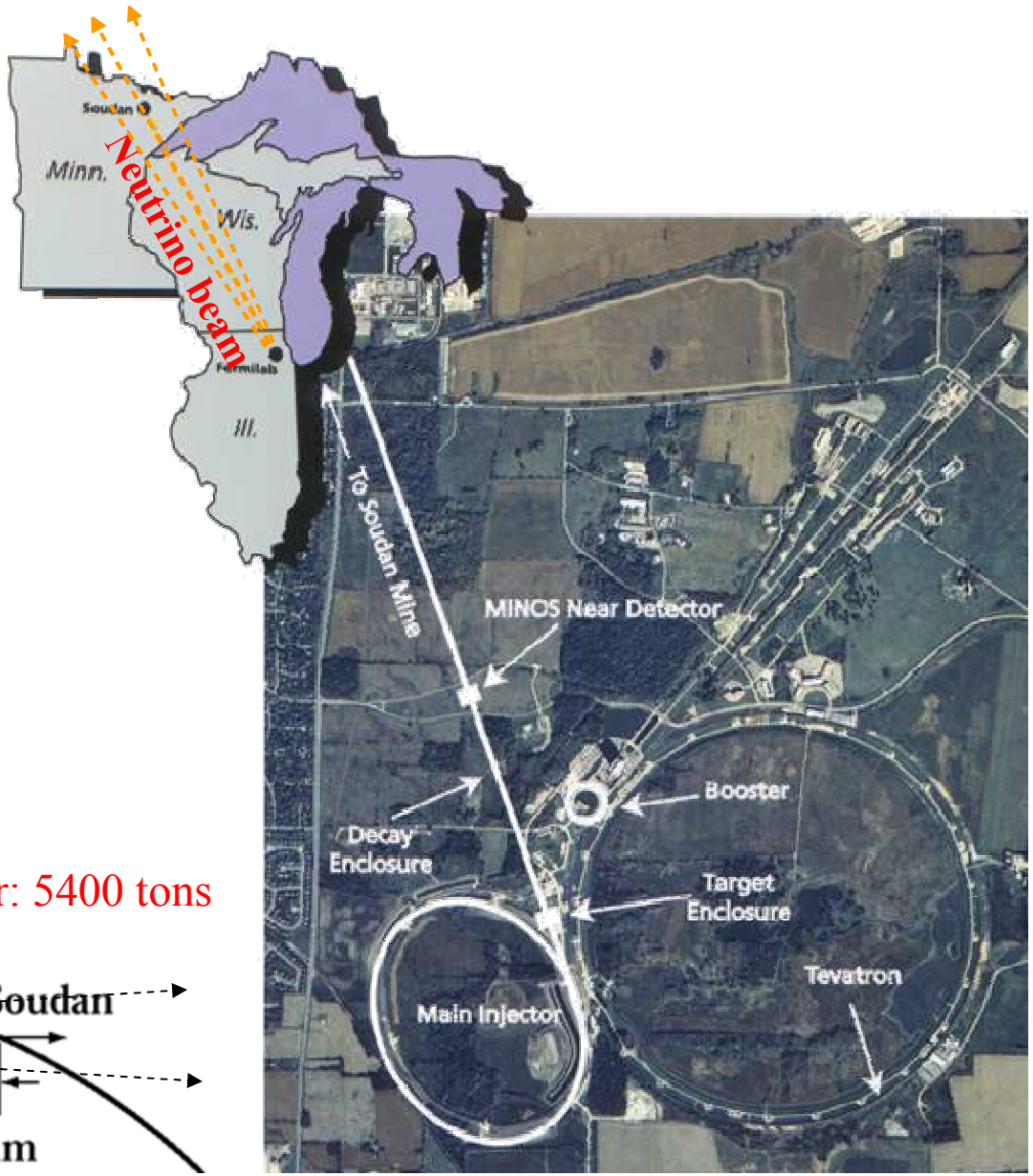
for the MINOS Collaboration

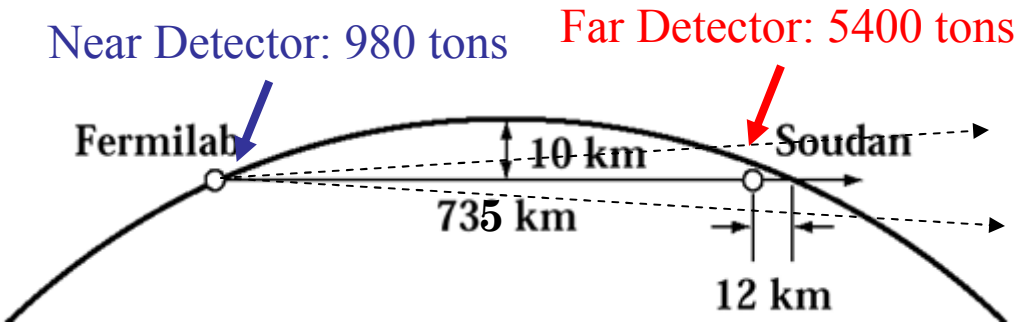
Pheno 2008 Symposium

April 28, 2008

The MINOS Experiment

- High-intensity neutrino beam for oscillation experiments
  - ➢ Predominantly ν_μ
- Neutrino beam travels to northern Minnesota
  - ➢ 735 km baseline
  - ➢ Intense source at Fermilab
  - ➢ Oscillated source in Minnesota
- Commissioned in 2004
- Operating since 2005



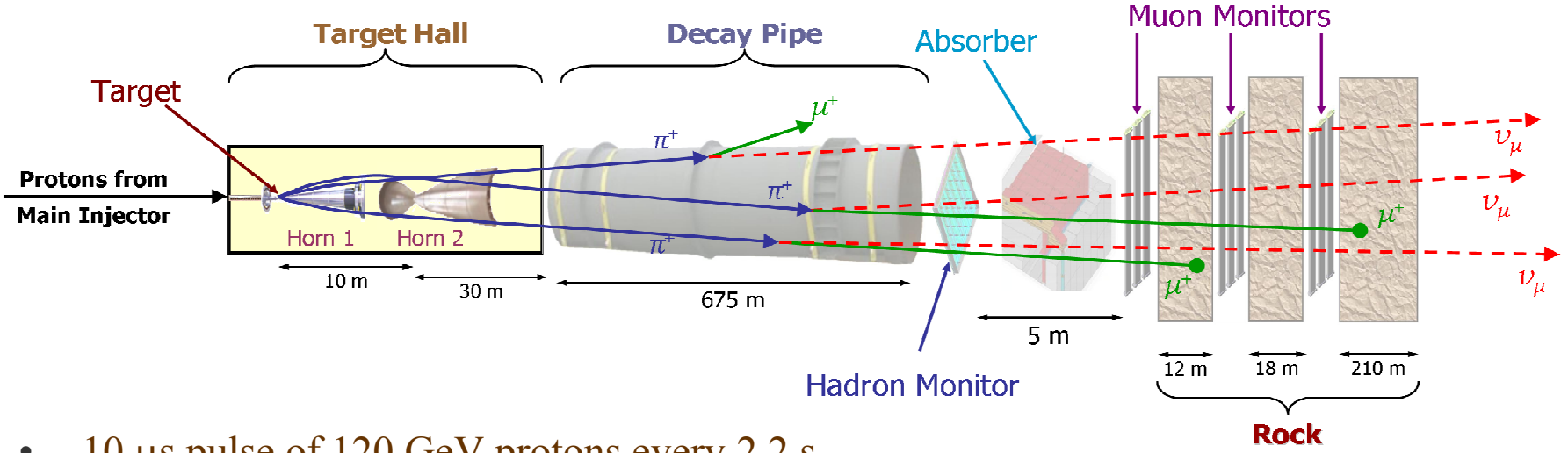


Overview

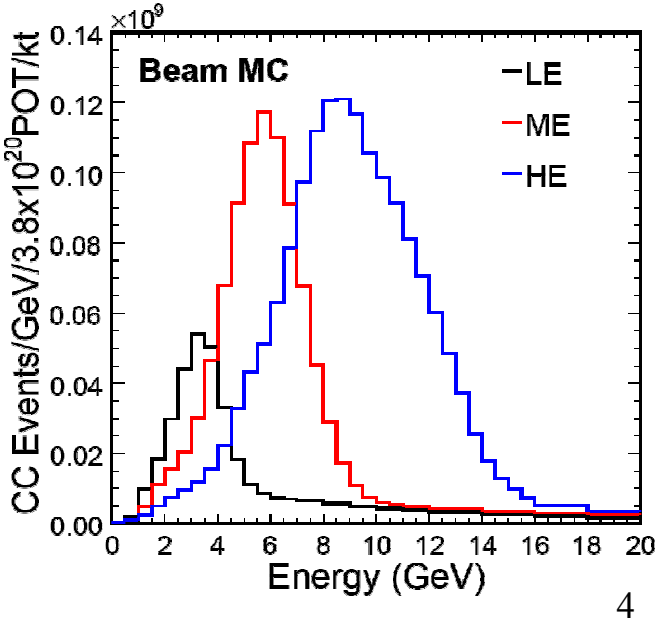
- Elements of the experiment: beam and detectors
- Neutrino interaction types and their measurement in the MINOS detectors
- Measurement of muon-neutrino disappearance and oscillation
  - Atmospheric Δm^2
- Search for active-neutrino disappearance
  - Sterile Neutrino search with Neutral Current interactions
- Sensitivity for electron-neutrino appearance
  - unmeasured $\sin^2(2\theta_{13})$
- Future Prospects & Summary

The Neutrino Beam

NuMI: Neutrinos at the Main Injector



- 10 μs pulse of 120 GeV protons every 2.2 s
  - 2.5 x 10^{13} protons per pulse
  - 200 kW typical beam power
- Pions produces by 2 interaction length target
  - Focuses by two magnetic horns
  - Decay in flight to ν_μ
- Energy spectrum is adjustable by moving the target with respect to horns
- 4.5 × 10^{20} total protons delivered

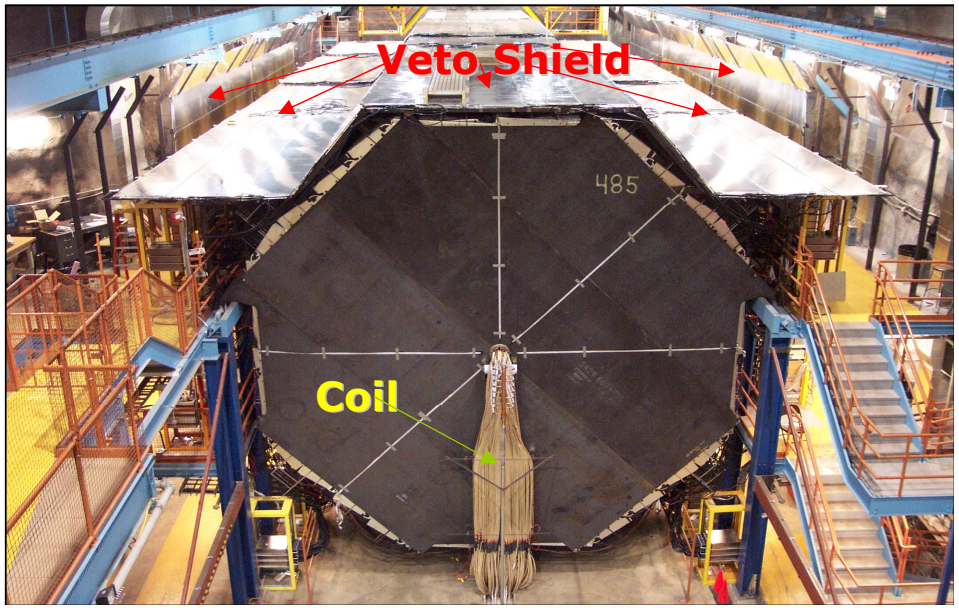


The MINOS Detectors

- Steel/Scintillator sandwiches
- Magnetized
- Tracking calorimeters
- Functionally identical
- 1 and 735 km from the neutrino production target
- 980 and 5400 tons

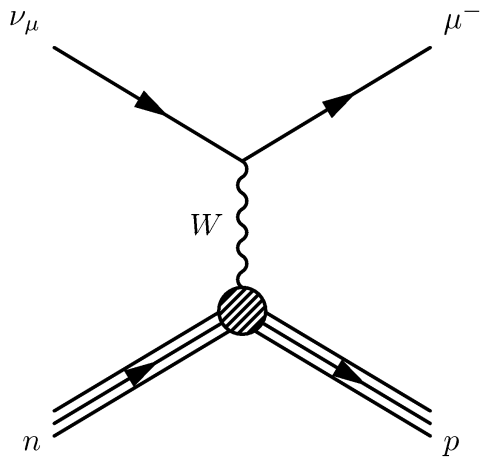
Near Detector

Far Detector

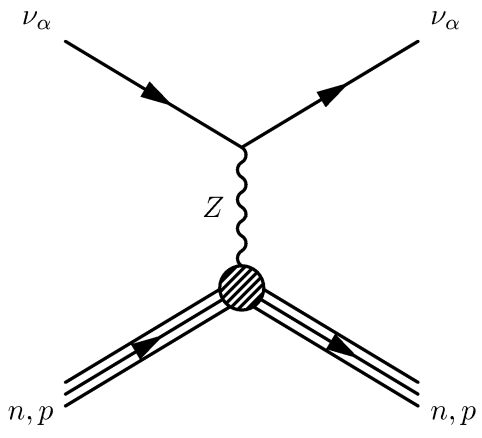


Interaction Types

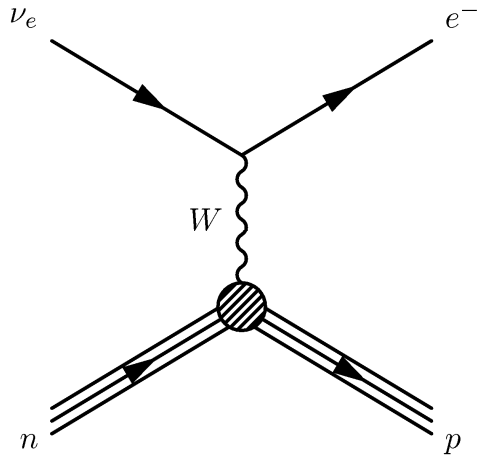
ν_μ CC Event



NC Event



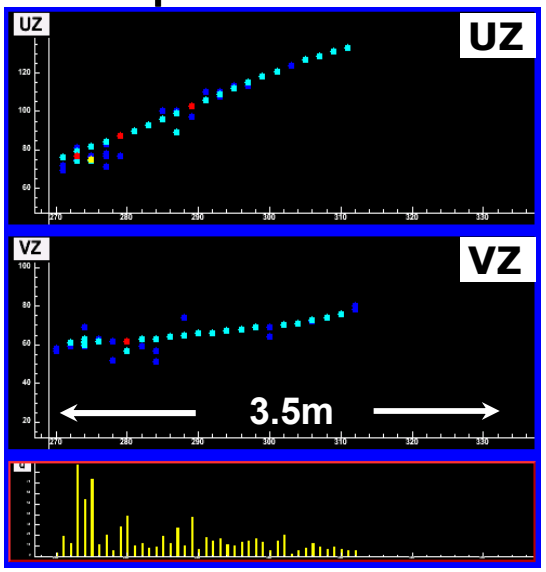
ν_e CC Event



Event Topologies

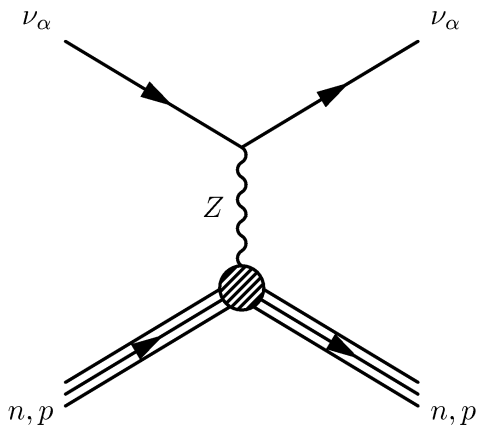
Monte Carlo

ν_μ CC Event

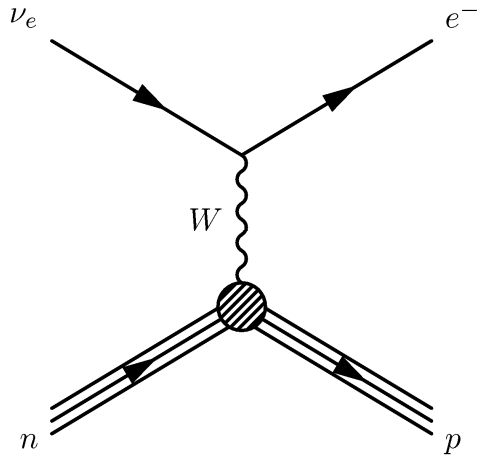


long μ track & hadronic activity at vertex

NC Event



ν_e CC Event



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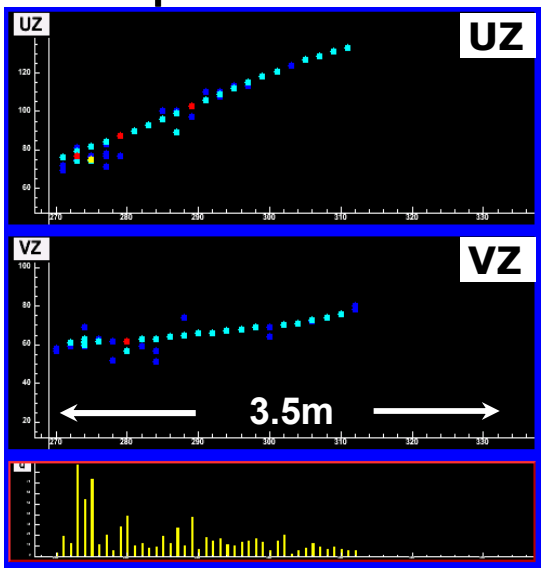
Monte Carlo

ν_μ CC Event



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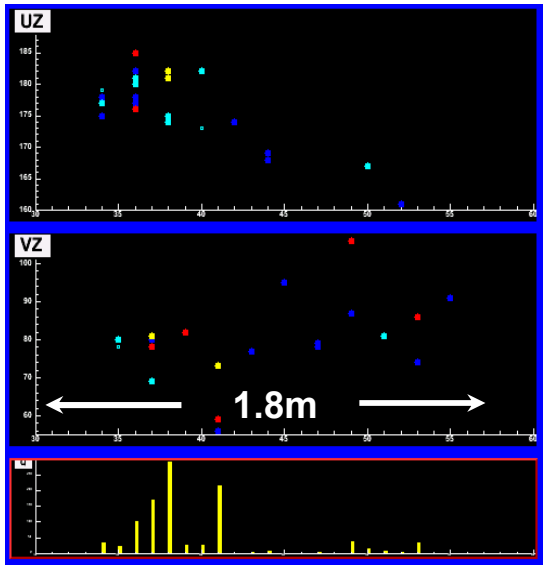
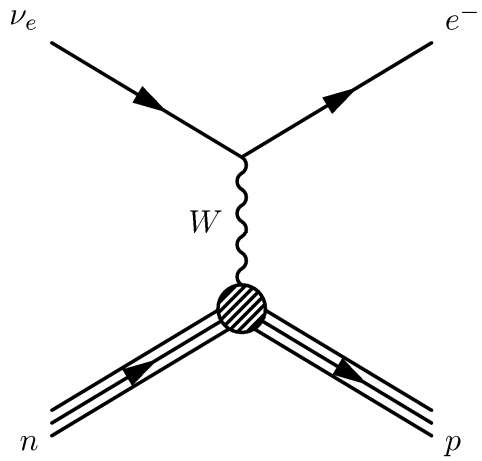


short event, often diffuse

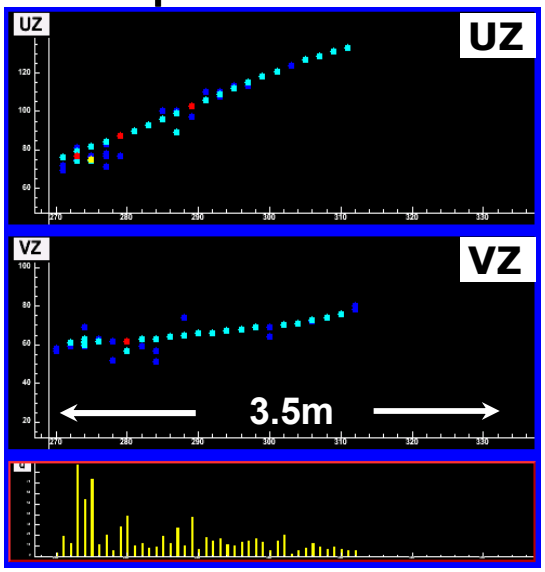
ν_e CC Event



Event Topologies

Monte Carlo

ν_μ CC Event



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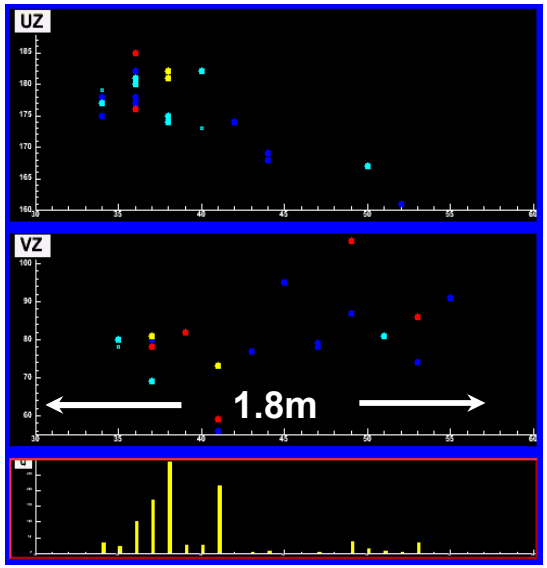

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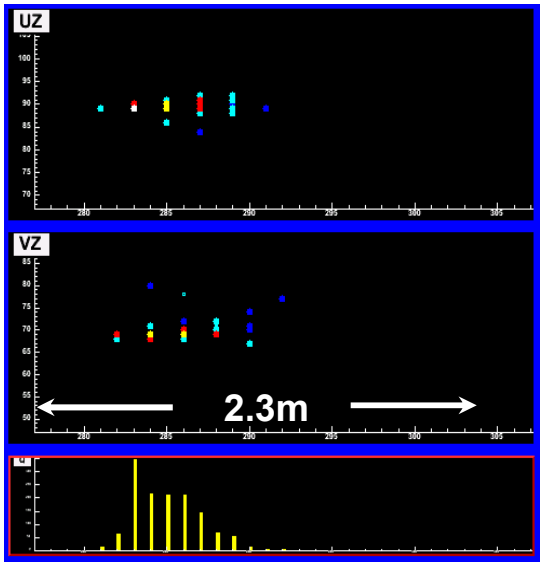
ν_e CC Event



short, with typical EM shower profile

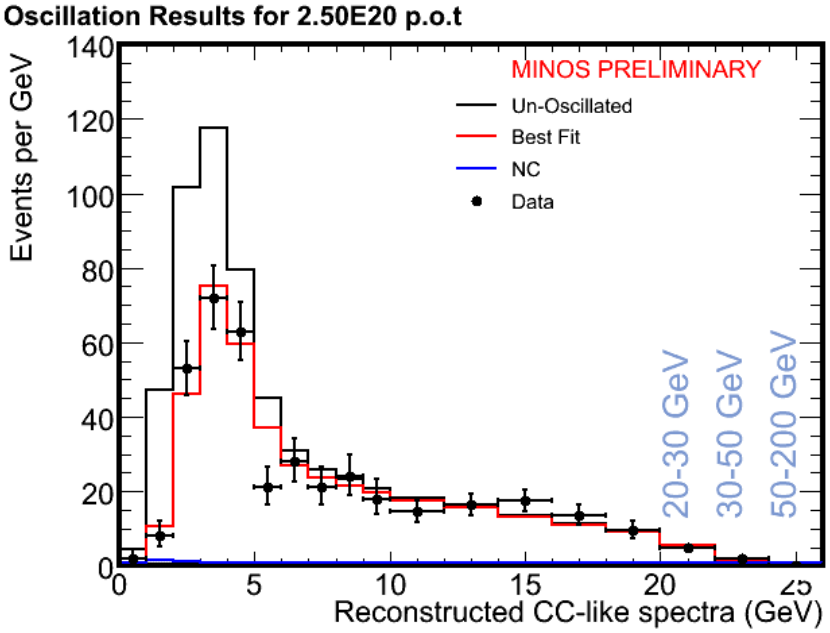
The ν_μ disappearance analysis:

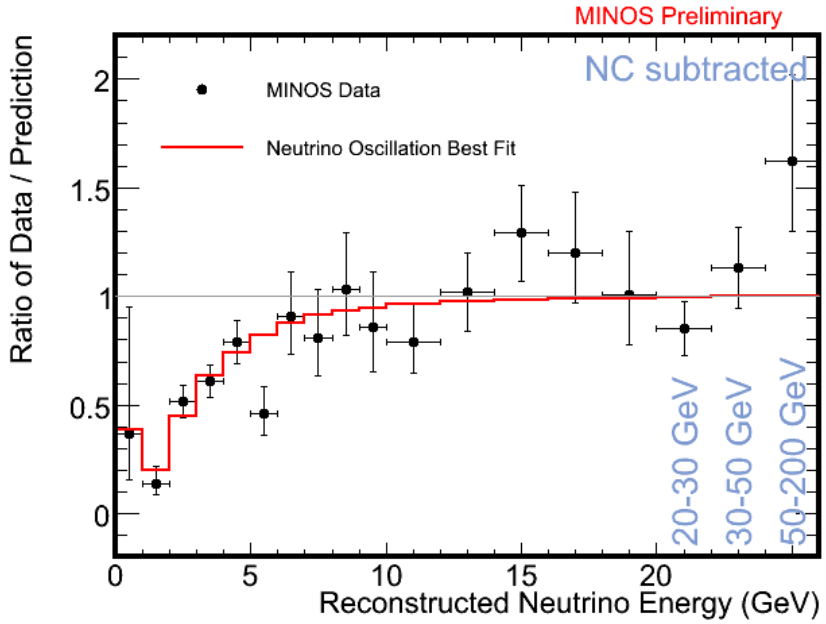
- Run I+IIa (2.5×10^{20} POT) shown here

- Paper in draft form for full Run I+II

(3.25×10^{20} POT)

ν_μ Charged Current Energy Spectrum





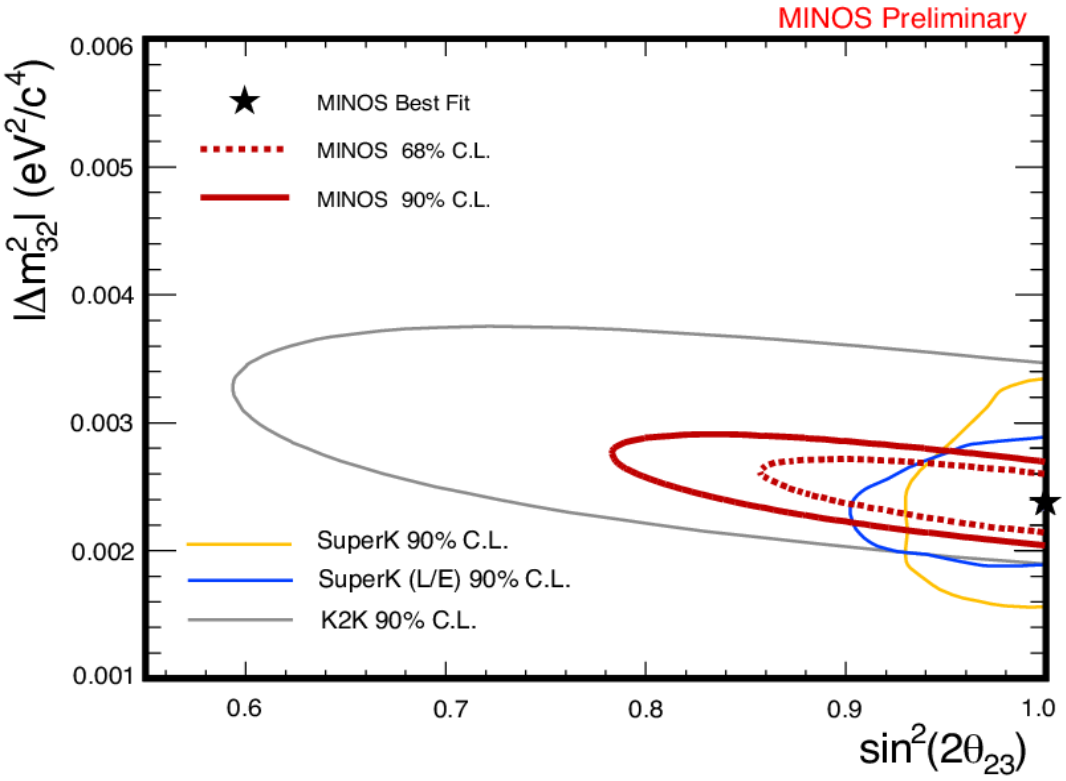
$$|\Delta m^2_{32}| = 2.38\ ^{+0.20}_{-0.16}\ (\text{stat + syst}) \times 10^{-3}\ \text{eV}^2$$

$$\sin^2 2\theta_{23} = 1.00\ ^{}_{-0.08}\ (\text{stat + syst})$$

χ^2/ndf=41.2/34 (18 bins x 2 spectra (Run I, Run IIa) – 2) ndf

Measurement errors are 1σ, 1 DOF

Allowed Parameter Space



- Results expected shortly with 3.25 x 10^{20} POT:
  - More data
  - New track-based PID
  - Improved systematic errors
- Plans for future analyses:
  - Looser cuts as systematics are better understood
  - Add anti-neutrinos
  - Add rock muons
  - Search for or rule out exotic scenarios

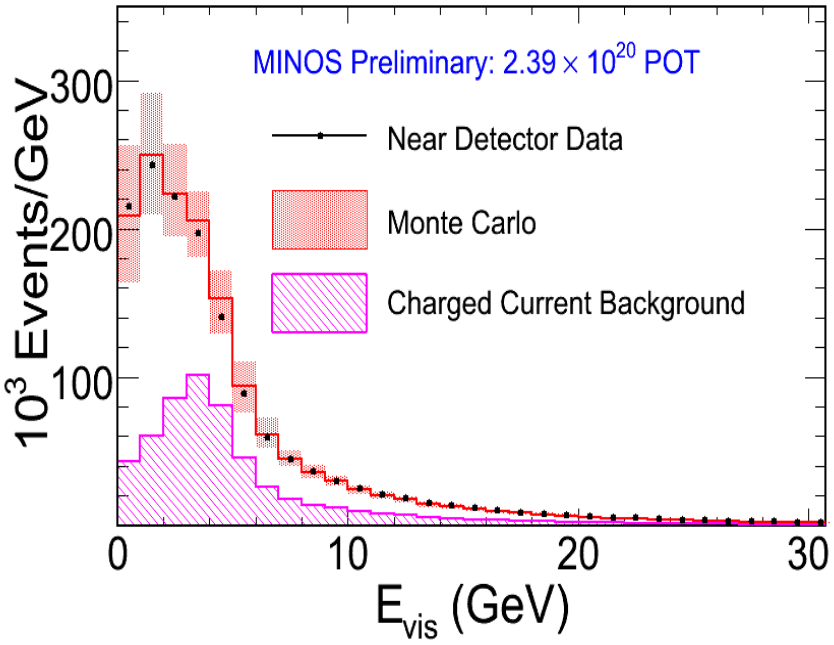
Results from Run I+IIa presented at Lepton-Photon 2007.
2.5×10^{20} Protons on Target

Search for active-neutrino disappearance:

- Directly test for ν_s using Neutral Current Interactions

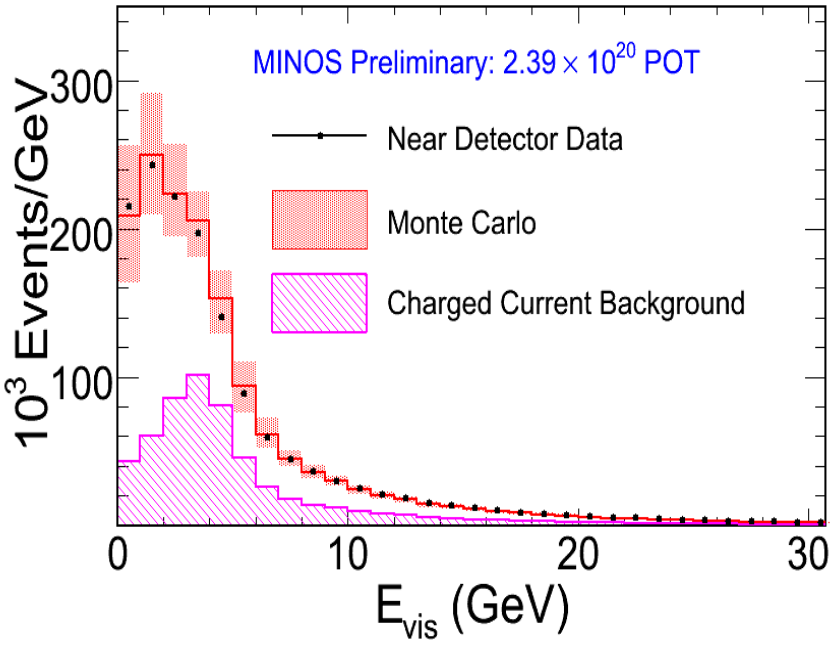
with Run I+IIa (2.46×10^{20} POT)

Neutral Current Energy Spectra



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

Neutral Current Energy Spectra



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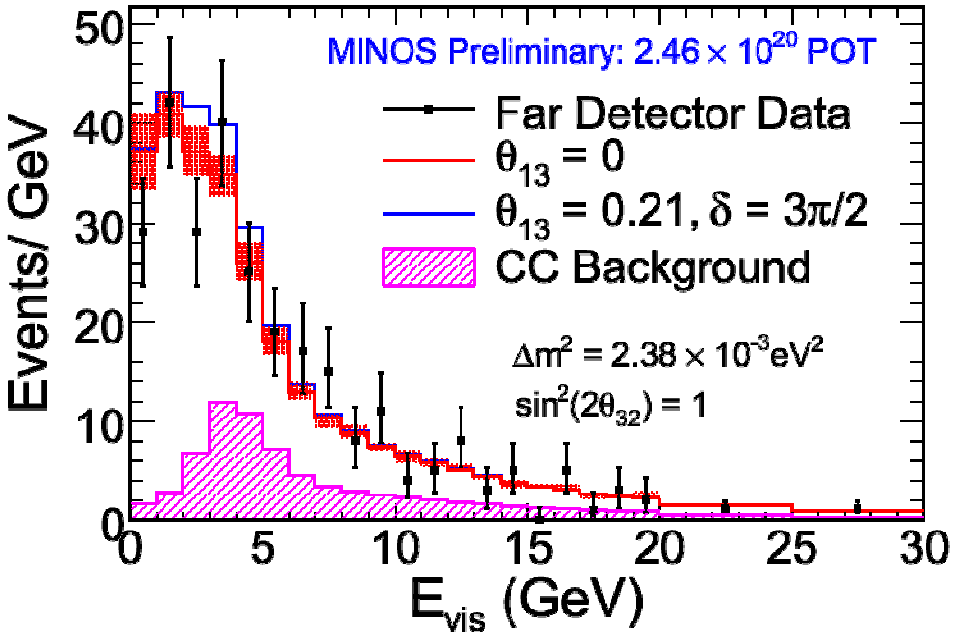


- Far Detector reconstructed energy spectra for NC-like events
- Oscillation parameters are fixed. MC predictions with Θ_{13}=0 and Θ_{13} at the CHOOZ limit are shown
  - ➢ ν_e charged current interactions selected as NC in this analysis
- The expected total number of events is given by

$$MC = NC\,(1 - f) + CC\,\nu_\mu + CC\,\nu_e + CC\,\nu_\tau$$

where f is the fraction of total neutral current events that disappear

- ➢ For $E_{vis} < 3$ GeV $\Rightarrow$ $f < 0.35$, 90% C.L.

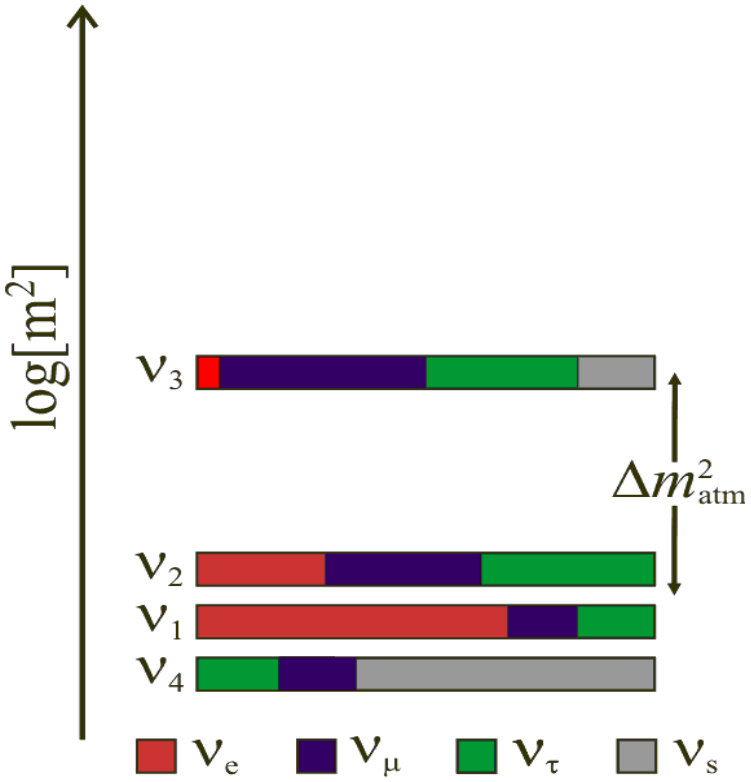
Simplified 4-Flavor Model : 3+1

- Assumes $\Delta m^2_{41} = 0$
  - Oscillation at single mass scale
  - Oscillation probabilities simplify to:

$$
\begin{aligned}
P_{\nu_\mu \to \nu_\mu} &= 1 - 4\left|U_{\mu 3}\right|^2 \left(1 - \left|U_{\mu 3}\right|^2\right) \Delta^2_{31} \\
P_{\nu_\mu \to \nu_e} &= 4\left|U_{\mu 3}\right|^2 \left|U_{e 3}\right|^2 \Delta^2_{31} \\
P_{\nu_\mu \to \nu_s} &= 4\left|U_{\mu 3}\right|^2 \left|U_{s 3}\right|^2 \Delta^2_{31} \\
P_{\nu_\mu \to \nu_\tau} &= 1 - P_{\nu_\mu \to \nu_\mu} - P_{\nu_\mu \to \nu_e} - P_{\nu_\mu \to \nu_s}
\end{aligned}
$$

- Fit for Δm^2_{31}, $|U_{\mu 3}|^2$ and $|U_{s3}|^2$
- Joint fit of NC and CC spectra
- Fix $|U_{e3}|^2 = 0$ and 0.04 (CHOOZ limit)

$$
\begin{aligned}
\sin^2 2\theta_{23} &\leftrightarrow 4\left|U_{\mu 3}\right|^2 \left(1 - \left|U_{\mu 3}\right|^2\right) \\
\Delta^2_{31} &= \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)
\end{aligned}
$$



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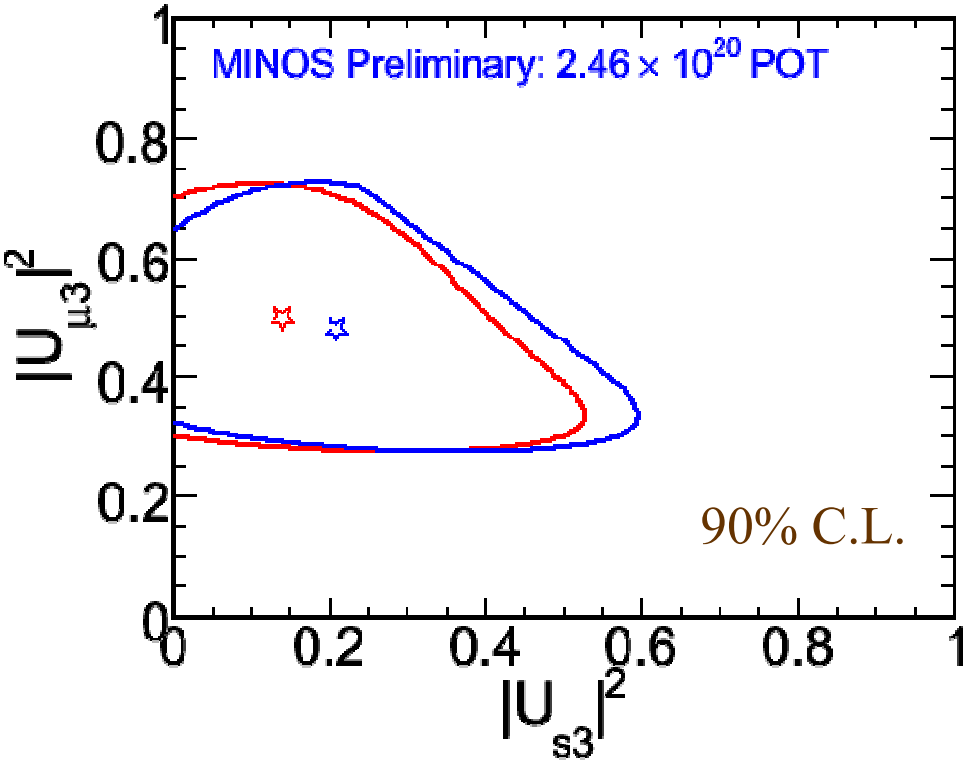
$$



$|U_{e3}|^2 = 0$ $\quad$ $|U_{e3}|^2 = 0.04$

$|U_{\mu 3}|^2 = 0.50^{+0.16}_{-0.15}$ $\quad$ $|U_{\mu 3}|^2 = 0.48^{+0.18}_{-0.12}$

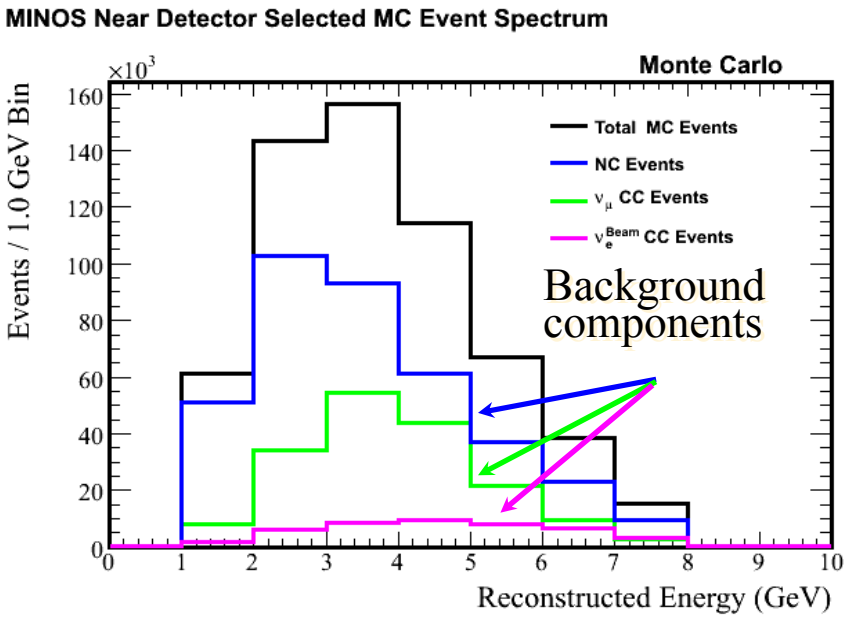
$|U_{s3}|^2 = 0.14^{+0.18}_{-0.13}$ $\quad$ $|U_{s3}|^2 = 0.21^{+0.20}_{-0.12}$

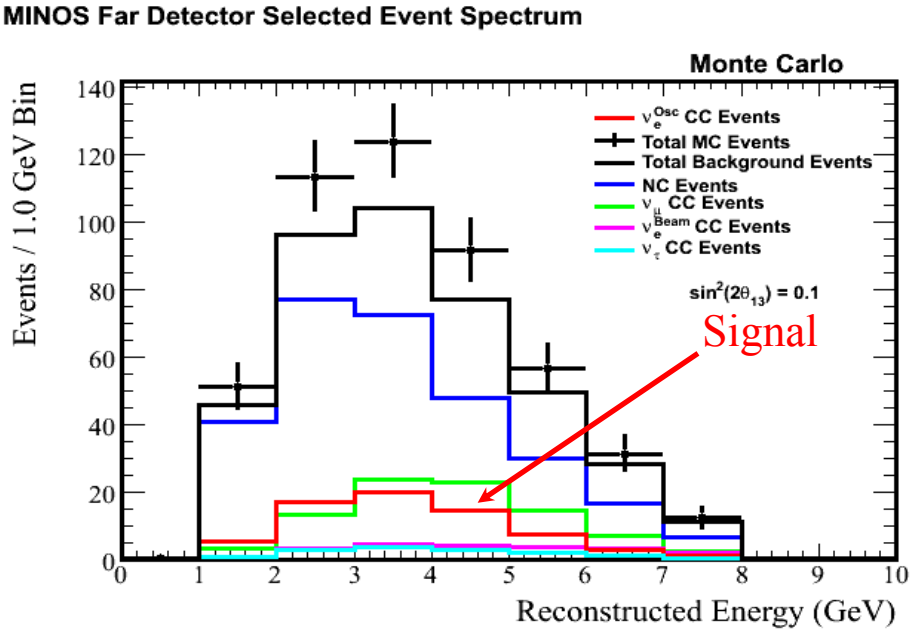
Sensitivity for ν_e appearance

using data-driven methods

with Run I+II (3.25×10^{20} POT)

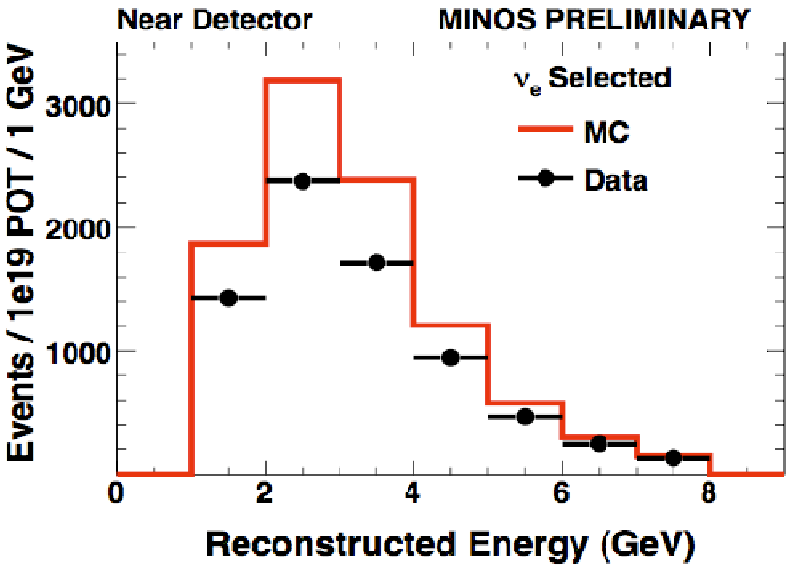
Background is key for ν_e Appearance Measurement

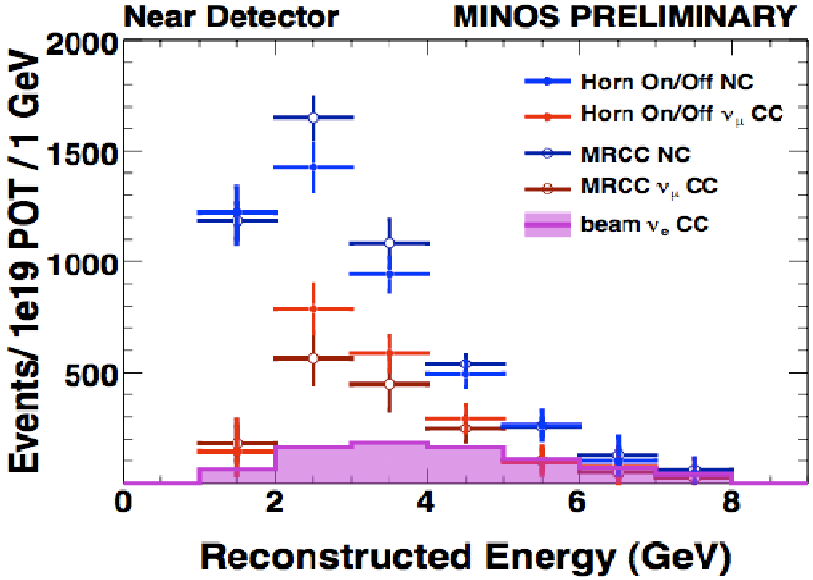




- Measure the main background components in Near Detector
  - NC, ν_μ CC, and beam ν_e CC interactions
- Extrapolate each to the Far Detector,
  - oscillate the ν_μ CC component to obtain the ν_τ CC

Near Detector ν_e Events





- ν_e selection algorithm based on characteristics of electromagnetic showers
- MC tuned to bubble chamber experiments for hadronization models
- However, the available literature is for higher energy than our region of interest
- Not surprisingly, the data/MC shows disagreement with the model

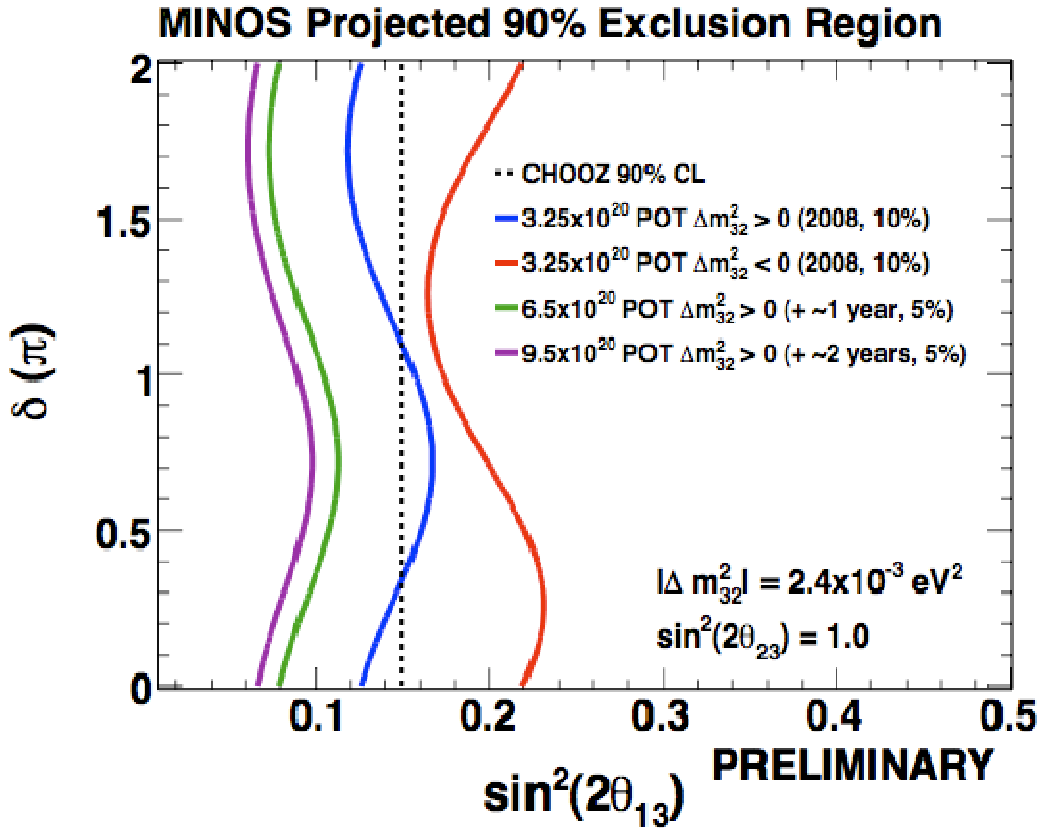
Thus, we have developed two **data-driven methods** to correct the model to match the data

- The two data-driven methods, are in good agreement in the Near Detector NC and ν_μ CC background for the ν_e analysis

- Each background in the Horn on/off method is extrapolated to the Far Detector and data-driven sensitivity limits are obtained

Future Data-Driven ν_e Sensitivity

- Projected limits shown for expected MINOS exposures using normal hierarchy
  - Inverted hierarchy shown only for lowest exposure for simplicity
- Data-driven systematics at 5% is a reasonable expectation as our understanding of the data improves



It is possible with MINOS to achieve half the current CHOOZ limit!

Conclusion

- MINOS sees a large disappearance of muon-neutrinos from the NuMI neutrino beam
  - Significance in low-energy region is 6.5 σ
  - Disappearance is consistent with our expectations of neutrino oscillations

    $|\Delta m^2_{32}| = 0.00238^{+0.00020}_{-0.00016}\ \mathrm{eV}^2/\mathrm{c}^4 \qquad \sin^2(2\theta_{23}) = 1.00_{-0.08}$
  - New result forthcoming for Neutrino 2008
- Neutral Current interactions have been studied for evidence of sterile neutrinos
  - From 3-flavor analysis:

    for E < 3 GeV $\Rightarrow$ $f < 0.35$ to 90% C.L.
    - Results consistent with no sterile neutrino admixture
  - 4-flavor analysis best fit values:

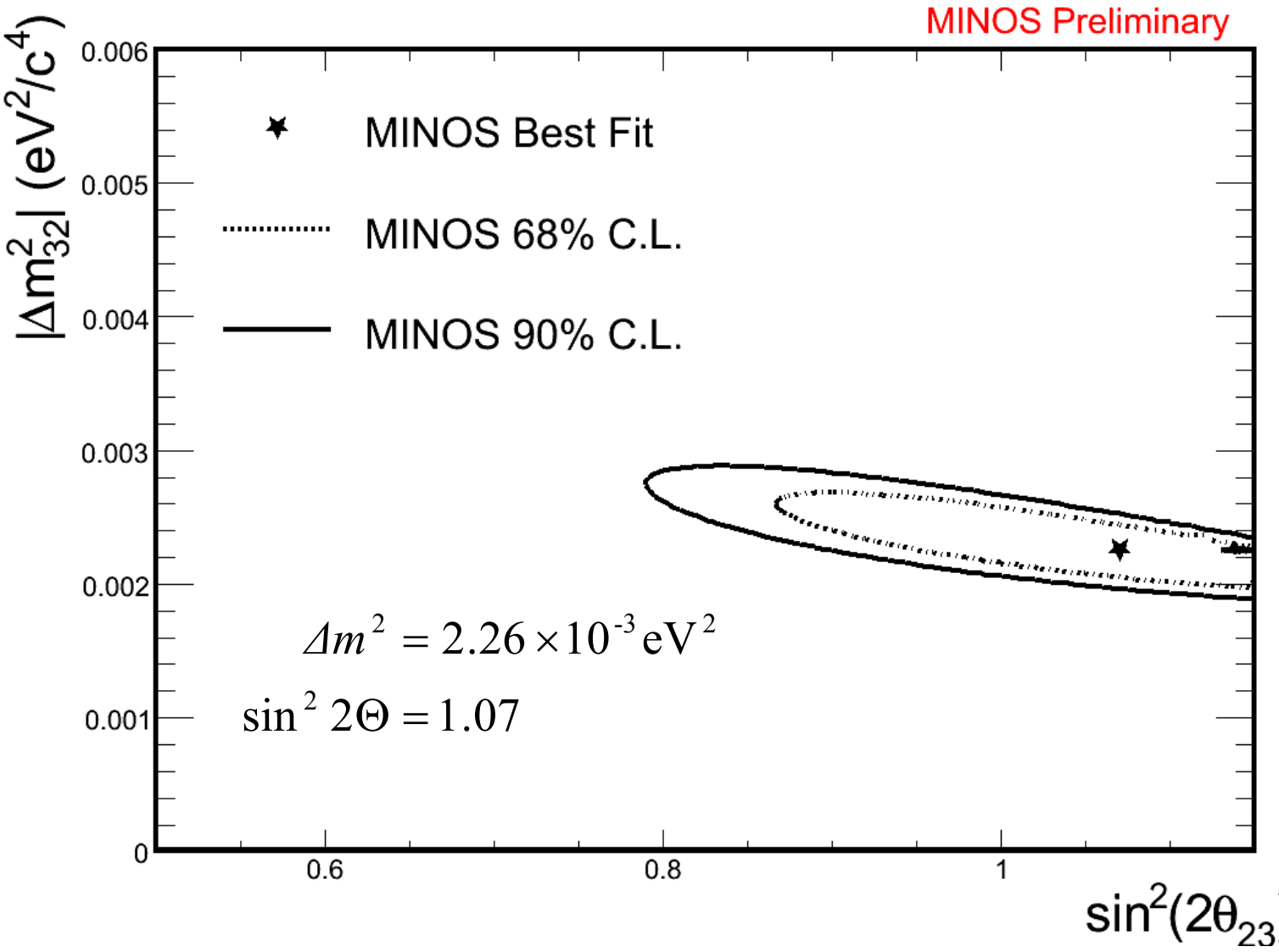
    $|U_{s3}|^2 = 0.14^{+0.18}_{-0.13}$, for $|U_{e3}|^2 = 0$ (no ν_e admixture)

    $|U_{s3}|^2 = 0.21^{+0.20}_{-0.12}$, for $|U_{e3}|^2 = 0.04$ (ν_e admixture)
- Electron-neutrino appearance will be studied using a data-driven background estimation
  - Sensitivity will be close to the CHOOZ limit this year
  - With 2-3 years more running, may halve the CHOOZ limit

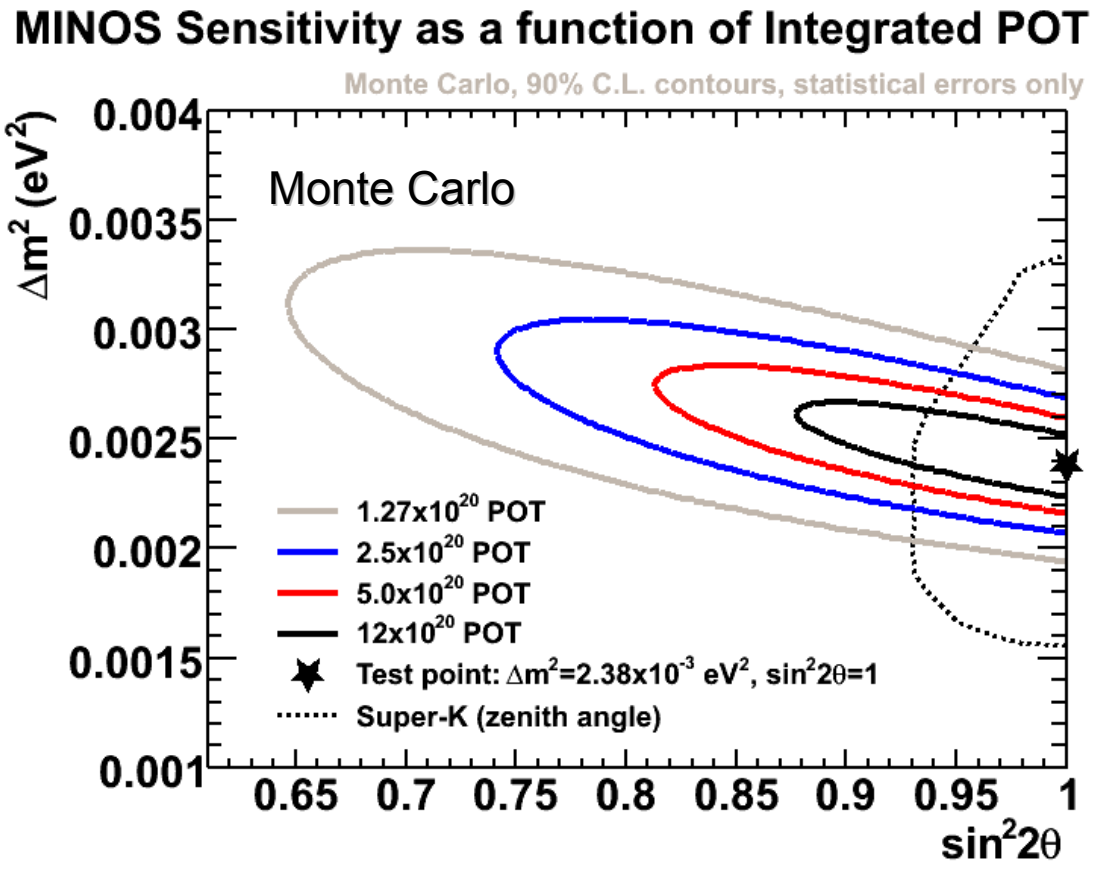
The MINOS Collaboration

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

Unconstrained Fit



Future MINOS ν_μ sensitivity



90% CL sensitivity for future MINOS exposures.
Statistical errors only