Search for ν_μ to ν_e oscillations in MINOS

URA thesis award talk

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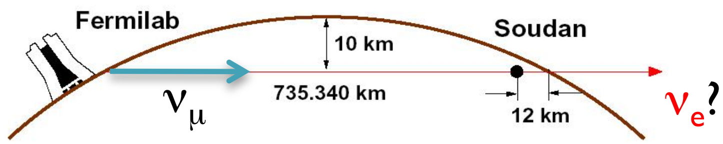
Neutrino Mixing

weak states mass states

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

- 3-flavor mixing: 2 independent mass^2 splittings
  - $\Delta m^2_{atm} \approx \Delta m^2_{32} \sim 2.4\times10^{-3}eV^2$
  - $\Delta m^2_{solar} \approx \Delta m^2_{21} \sim 8\times10^{-5}eV^2$
- 3 mixing angles
  - $\sin^2\theta_{12} \sim 1/3$, $\sin^2 2\theta_{23} \sim 1$
  - θ_{13}? topic of this talk
- CP violating phase δ_{CP}, Majorana phases

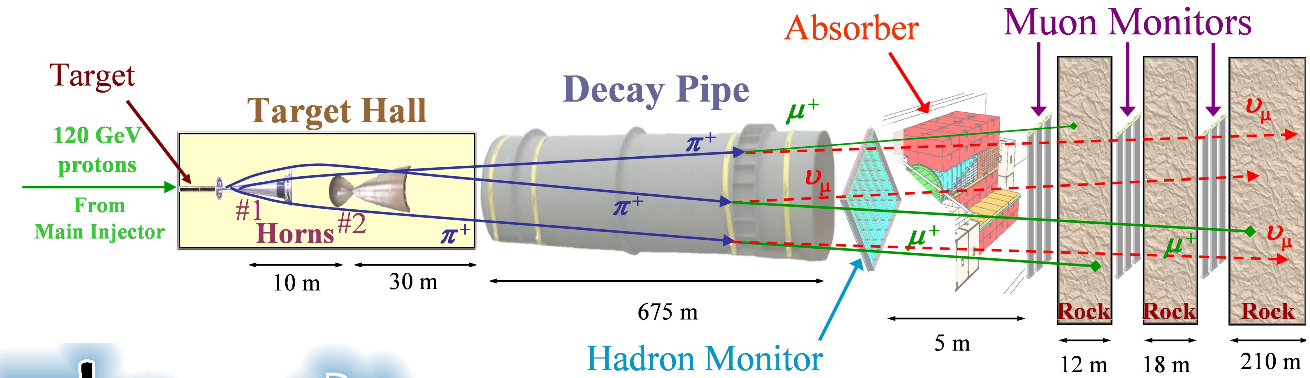
Measuring θ_{13} in MINOS



$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2\theta_{23} \boxed{\sin^2 2\theta_{13}} \sin^2\left(\Delta m^2_{32} L/4E\right)$$

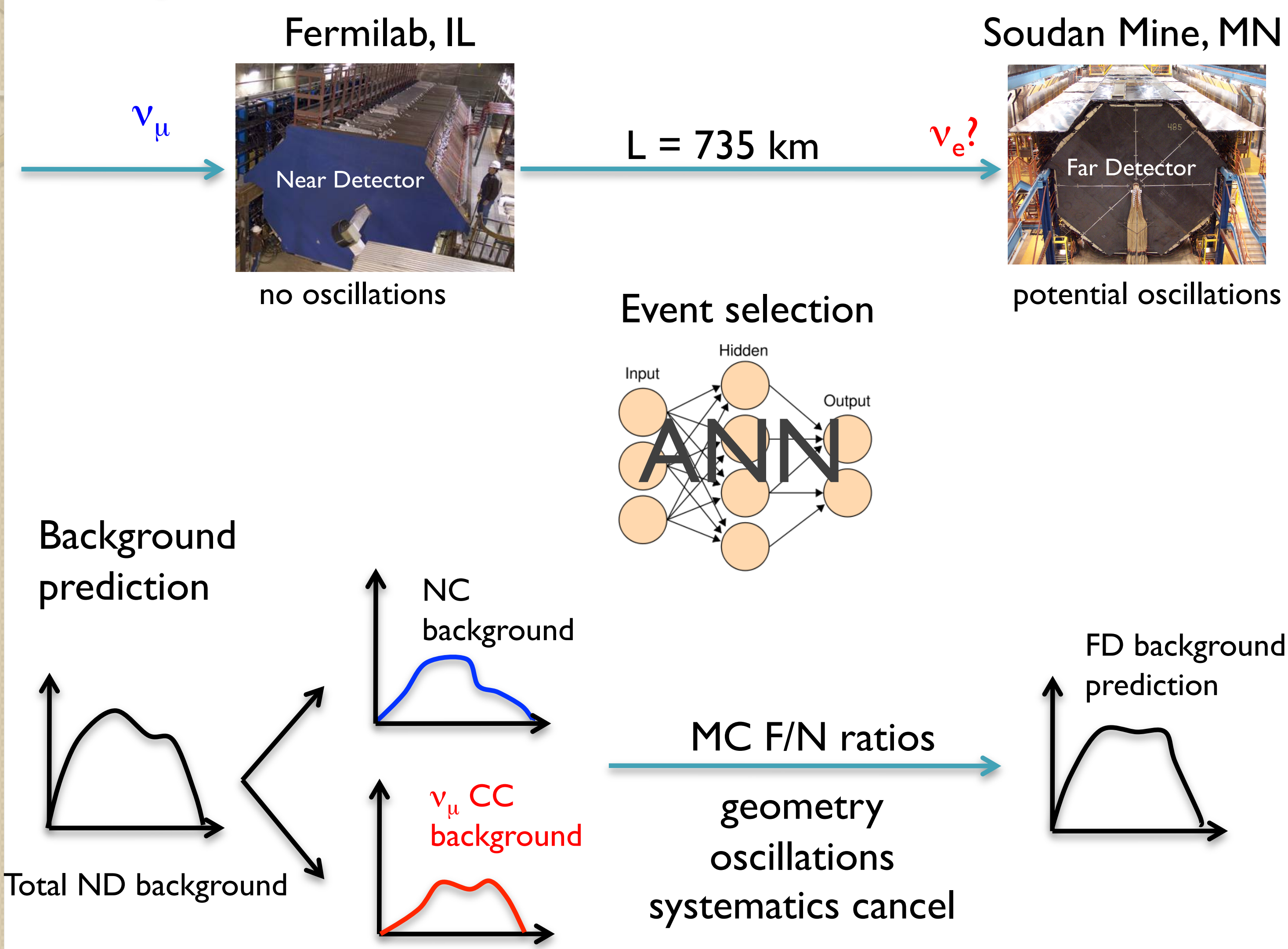
- MINOS can probe θ_{13} by searching for a ν_e signal in the ν_μ beam.
- The best limit on θ_{13} was set by the CHOOZ experiment.
  - $\sin^2 2\theta_{13} < 0.15$ at $\Delta m^2 = 2.4\times10^{-3} eV^2$ at 90% C.L.
- MINOS has the potential to improve the limit on θ_{13} or make the first measurement of its value.
- In this talk, I will mainly discuss the 1st MINOS ν_e analysis based on 3.14×10^{20} POTs, which is the topic of my thesis work and comment on the most recent analysis based on 7×10^{20} POTs in the end.

The MINOS Experiment



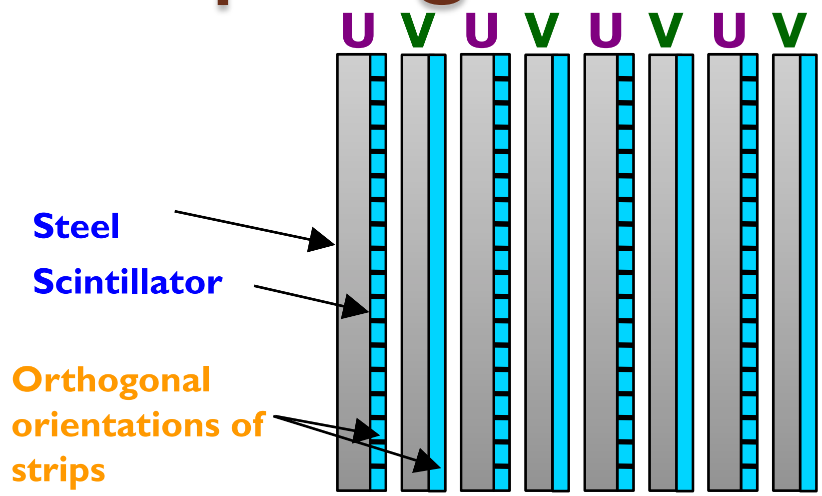
- Main Injector Neutrino Oscillation Search
- Long baseline accelerator neutrino experiment.
- Produce a high intensity beam of pure (>90%) muon neutrinos at Fermilab.
- Two functionally identical detectors
  - **Near Detector** at Fermilab to measure beam composition and energy spectrum
  - **Far Detector** at Soudan mine in MN to search for oscillation signals
  - Systematics largely reduced

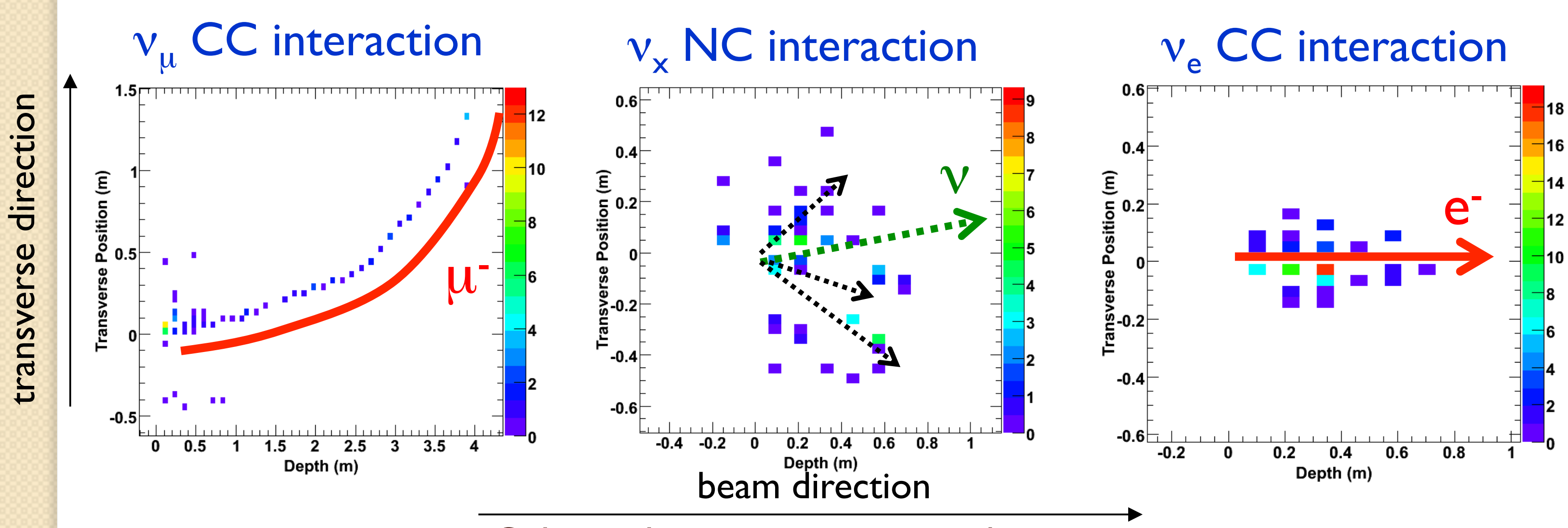
ν_e Appearance Analysis Overview



Neutrino Event Topologies

- steel/scintillator "sandwich" calorimeter
- Granularity
  - Longitudinal: steel plane 2.54 cm thick ~ 1.4 radiation lengths
  - Transverse: scintillator strip 4.1 cm width ~ 1.1 Molière radius
- Not optimized for ν_e search





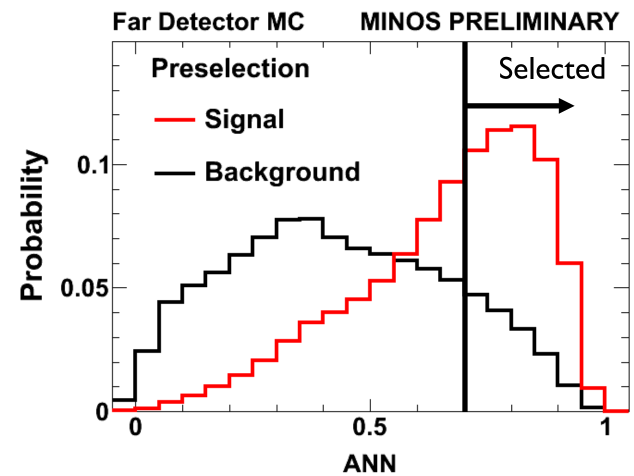
Color scale represents energy deposition

Selecting ν_e Events

- Select short condensed showers
  - No long track – reject ν_μ CC background
  - Reconstructed energy in the range of interest 1<E<8GeV
    - High energy cut to reject beam ν_e background
    - Low energy cut to reject NC background
- ANN with 11 variables
  - Longitudinal/transverse shower profiles
  - Energy density, etc.
- Overall background rejections
  - ν_μ CC: 99%, NC: 92%, beam ν_e: 87%
- Overall signal selection efficiency: 41%
- FD MC background composition after cuts
  - *69% NC, 19% CC, 8% beam ν_e, 4% ν_τ*

$\Delta m^2=2.4\times10^{-3}eV^2$

Area normalized



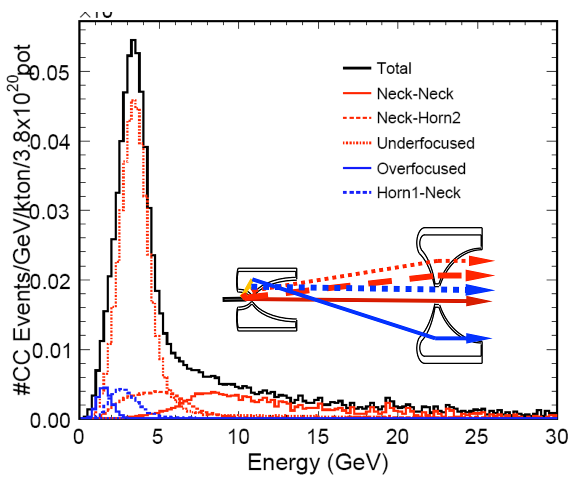
$\sin^2 2\theta_{13}=0.15$

Cuts	Sig/Bg
Fiducial Vol.	1:55
Basic cuts	1:12
ANN	1:3

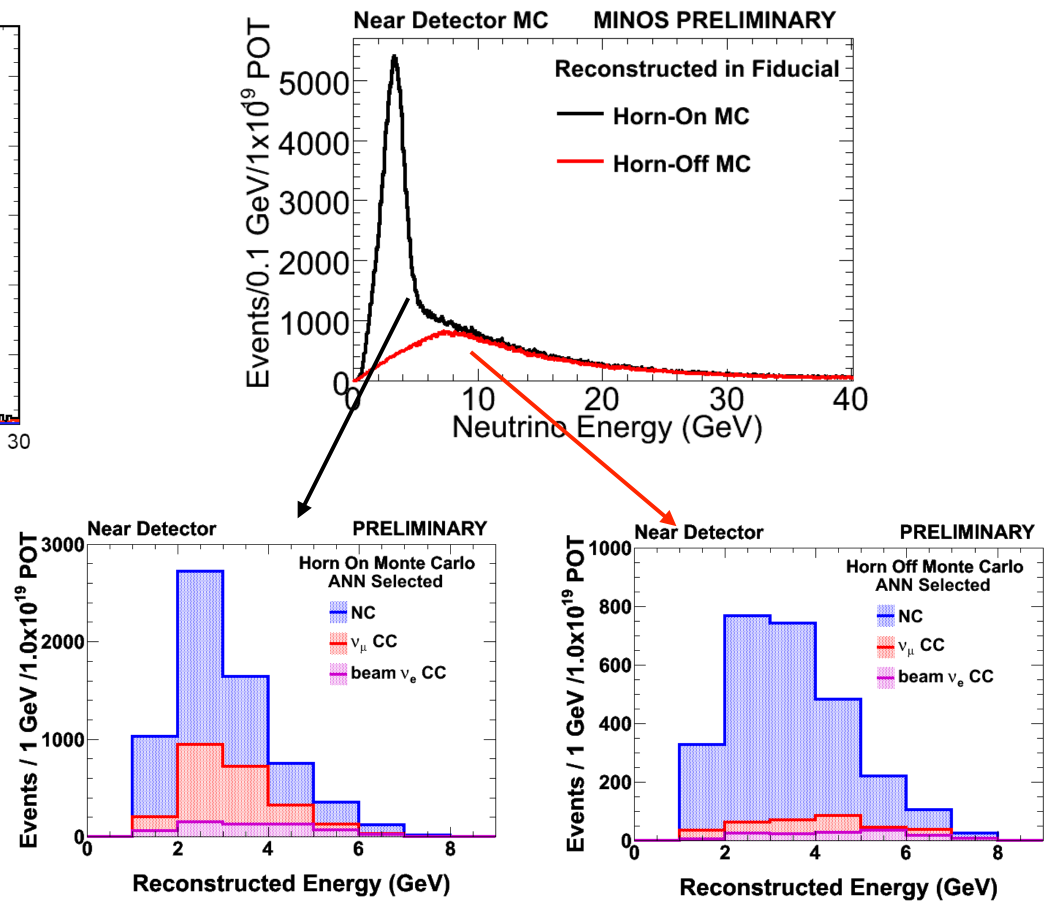
Predict FD Background

- Predict FD background rate through extrapolation
  - $FD^{predicted}=(FD/ND)^{MC}\times ND^{Data}$
- This is done for ν_μ CC and NC backgrounds
  - Beam ν_e and ν_τ components are taken from MC
- F/N ratio is very robust since a lot of systematics cancel
- Different background components extrapolate differently
  - ν_μ->ν_τ oscillations affect ν_μ CC background but not NC background
- Some knowledge about the relative contribution from NC and CC background components is necessary

CC/NC Separation (ND)



- Horn-on horn-off samples have different NC/CC ratios
- Data driven method to derive CC/NC components using MC **horn off/on ratios**
- Limited by horn-off data statistics



A secondary method based on muon removed CC showers gives very consistent result.

Background Systematics

$FD^{predicted} = (FD/ND)^{MC} \times ND^{Data}$

- ND background decomposition (horn on/off) – 3.6%
  - NC and CC background components are highly anti-correlated at ND
- Extrapolation (F/N ratios) – 6.5%

Cancel in F/N ratio

  - Flux – hadron production at target, beamline geometry
  - Cross section – QE, resonance, transition
  - **Hadronization**/Intranuke – hadrons produced in neutrino interactions

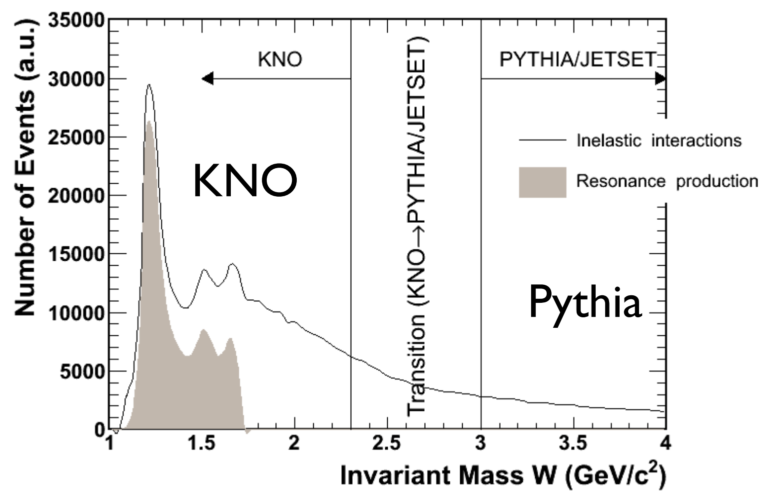
F/N differences

  - Normalization - POT counting, steel/scintillator thickness, fiducial masses
  - Calibration – light level, intra- inter- detector variations, PMT gains
  - **Crosstalk model** – improved crosstalk model
  - Intensity – different event rates at two detectors
- Beam ν_e and ν_τ systematics
- N^F_{bg}=27±5(stat.)±2(sys.) (3.14×10^{20}POT)
  - Sys. Error: 7%

Hadronization Model for MINOS

- Hadronization (or fragmentation) model – the model that determines the final state particles and 4-momenta in the ν-nucleon interactions.
- Affect shower topology – absolute background rate
- Combine Pythia with a low-E empirical model.
- KNO-based empirical model at low-W
- Pythia at high-W
- Smooth transition in between

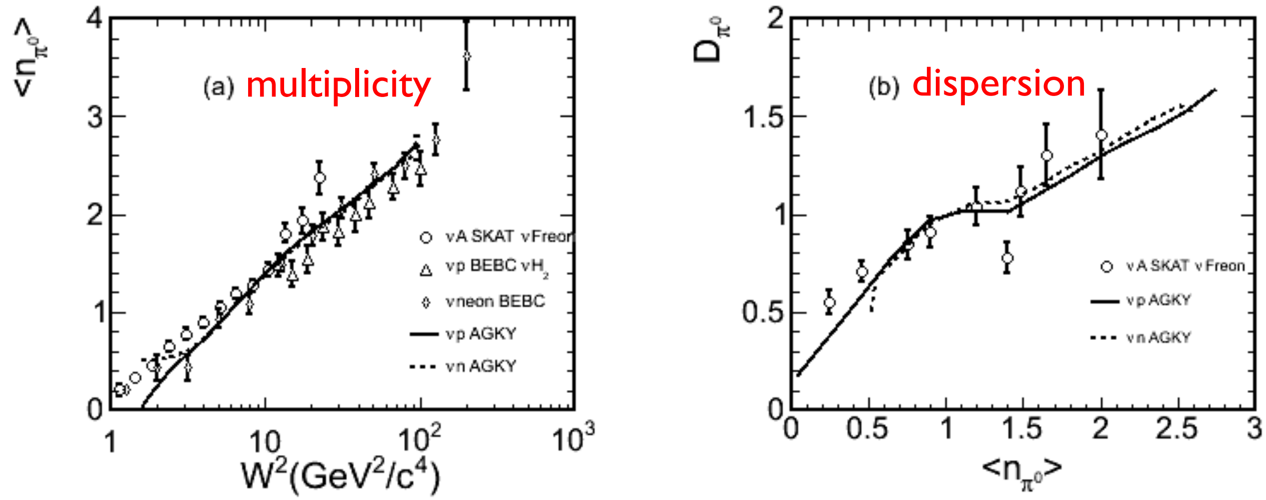
W distribution of inelastic events



Tuning Using External Data

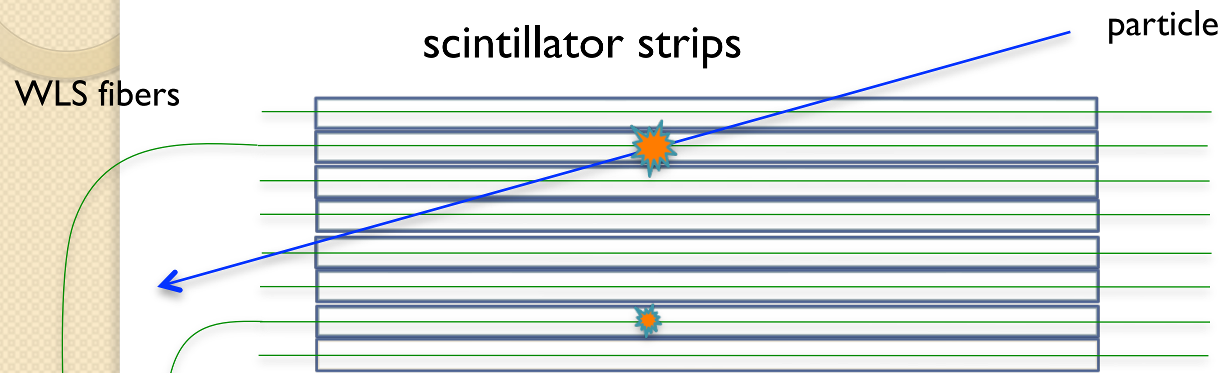
- We tuned our model with data from several bubble chamber experiments – 15ft-FNAL, BEBC, SKAT, etc

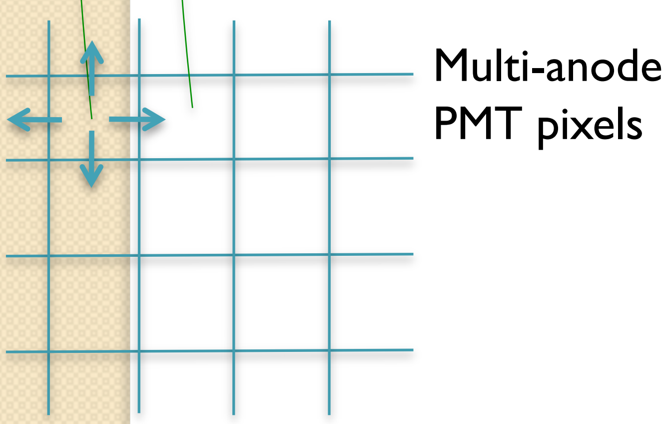
π^0 production

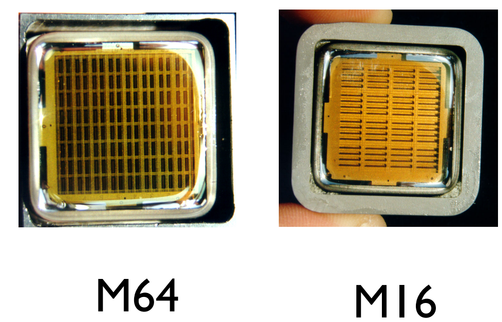


T.Yang, C.Andreopoulos, H.Gallagher, K.Hoffmann, P.Kehayias ***Eur.Phys.J.C63:1-10,2009***

PMT Crosstalk

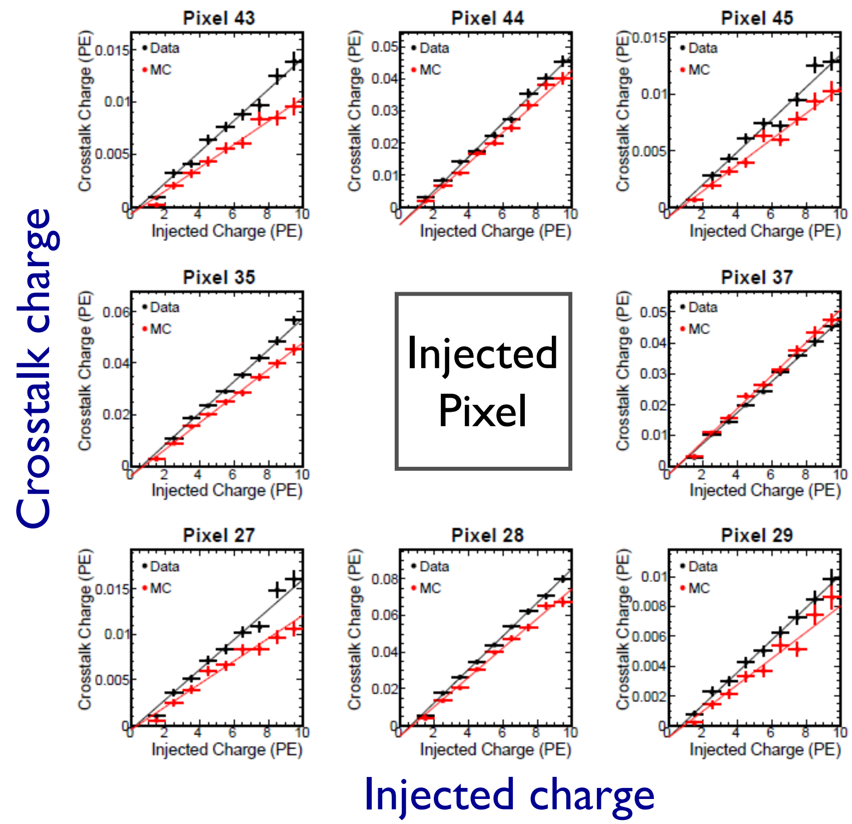






- Crosstalk phenomenon is an inherent property for multi-anode PMT
  - 7% of the signal from light on a given pixel appears in neighboring pixels
  - Crosstalk charge peaks at 1 PE
  - Affect energy calibration and event topology
- Crosstalk patterns are different at two detectors
  - Different PMTs are used: M64 vs M16
  - Potential Far/Near difference

Measuring Crosstalk with Cosmic Ray Muons

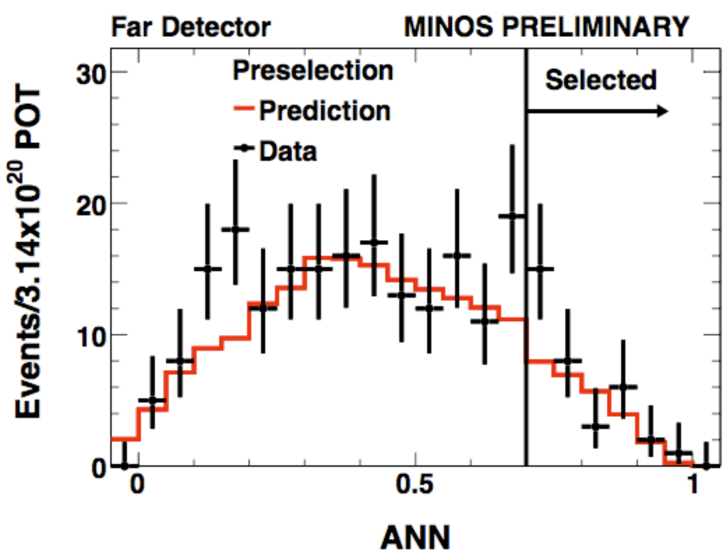


- We can measure the magnitude of crosstalk using cosmic ray muons.
- In the 1st ν_e analysis, we removed hits below 2 PEs, and used the improved crosstalk model to evaluate systematic uncertainty

ν_e Appearance Result

(3.14×10^{20}POT)

ν_e Selected Far Detector Data

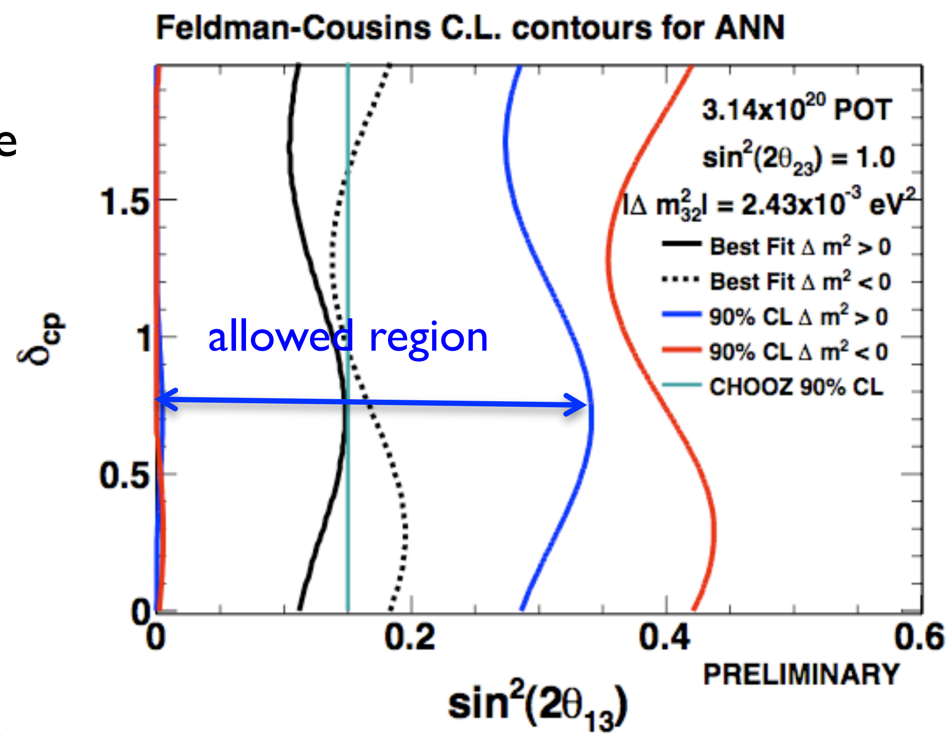


- We observed a total of 35 events after we opened the box.
- We expect 27±5(stat)±2(sys) background events.
- Results are 1.5σ above expected background.
- Number of expected signal events is 10±3(stat)±1(sys) at CHOOZ limit.

MINOS 90% CL in $\sin^2 2\theta_{13}$

- A Feldman-Cousins method was used.
- Fit simply to the number of events from 1-8 GeV, no shape or correlation information used.
- Best fit and 90% CL limits are shown:
  - as a function of δ_{CP}
  - for both mass hierarchies
  - at MINOS best fit value for Δm^2_{32} and $\sin^2 2\theta_{23}$
- Normal (Inverted) hierarchy (δ_{CP}=0) $\sin^2 2\theta_{13}$<0.29 (0.42) (90% CL)

3.14×10^{20}POT

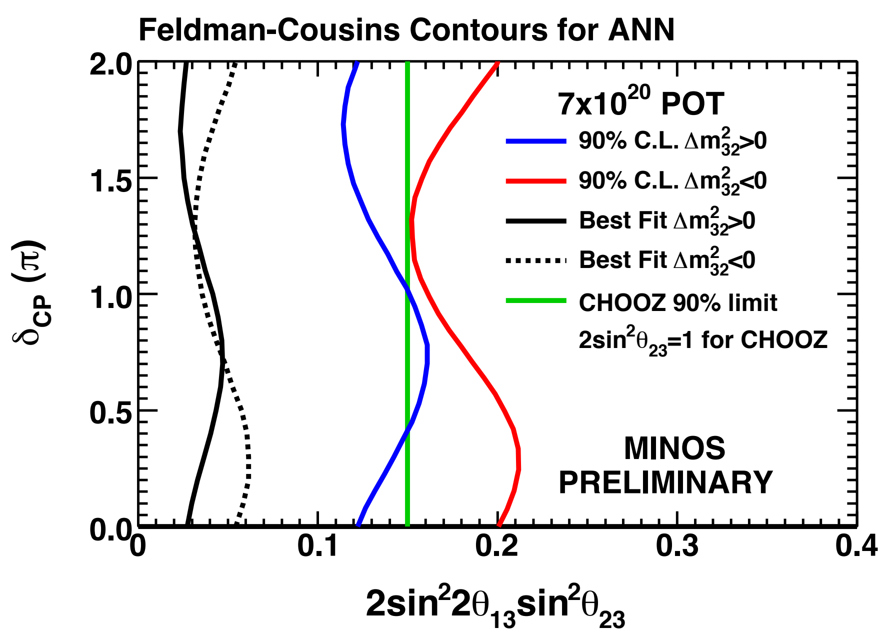


PRL 103:261802 (2009)

Updated results

- Highlights of the updated analysis
  - Doubled data statistics
  - MC with better nuclear effect modeling and PMT crosstalk modeling
  - Improved reconstruction after removing sub-PE hits
  - Retuned ANN with new MC
  - Add a third beam (HE) in the ND background decomposition
- Expected background
  - 49±7(stat)±3(sys)
- Observed: 54 (0.7σ)
- Normal (Inverted) hierarchy (δ_{CP}=0) $\sin^2 2\theta_{13}$<0.12 (0.20) (90% CL)

7.01×10^{20}POT



To be submitted soon

Future Improvements

- Add 20% more data
- A novel and promising event selection algorithm
  - LEM - Library Event Matching
  - Compare events to a large number of signal and background templates
- Fit to the PID distribution
- ~20% improvement in sensitivity

Summary

- MINOS is the first experiment to probe the unknown mixing angle θ_{13} with sensitivity below the CHOOZ limit
- Our current 90% CL upper limit is below the CHOOZ limit assuming normal hierarchy for almost all values of δ_{CP}

Acknowledgements

- I would like to thank Fermilab, URA and the committee members for this great honor.
- I also want to express my gratitude to my advisor Prof. Stanley Wojcicki for his exceptional guidance and to my MINOS colleagues for all the help, support and enjoyment during my PhD years.

Acknowledgements

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- We also gratefully acknowledge financial support from DOE, STFC(UK), NSF and thank the University of Minnesota and the Minnesota DNR for hosting us

The MINOS Collaboration

Thank you for your attention!

Backup slides

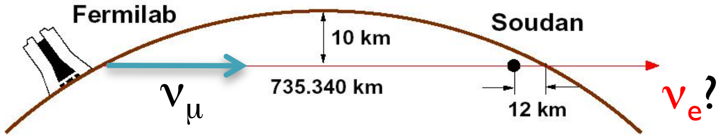
Measure θ_{13}

- Reactor neutrino experiments

$$P(\bar{\nu}_e \to \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2(\Delta m^2_{31} L/4E)$$

- Does not depend on θ_{23}, CP phase, matter effects
- Clean measurement of θ_{13}
- CHOOZ: $\sin^2 2\theta_{13} < 0.15$ at $\Delta m^2_{31} = 2.4\times10^{-3} eV^2$ at 90% C.L.
- Double-CHOOZ, Daya Bay, Reno

- Long baseline neutrino experiments



$$P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2(\Delta m^2_{32} L/4E)$$

+additional terms

- Depend on θ_{23}, CP phase, matter effects
- Possibilities to measure CP violation and ν mass hierarchy
- K2K, MINOS
- T2K, NOvA, LBNE

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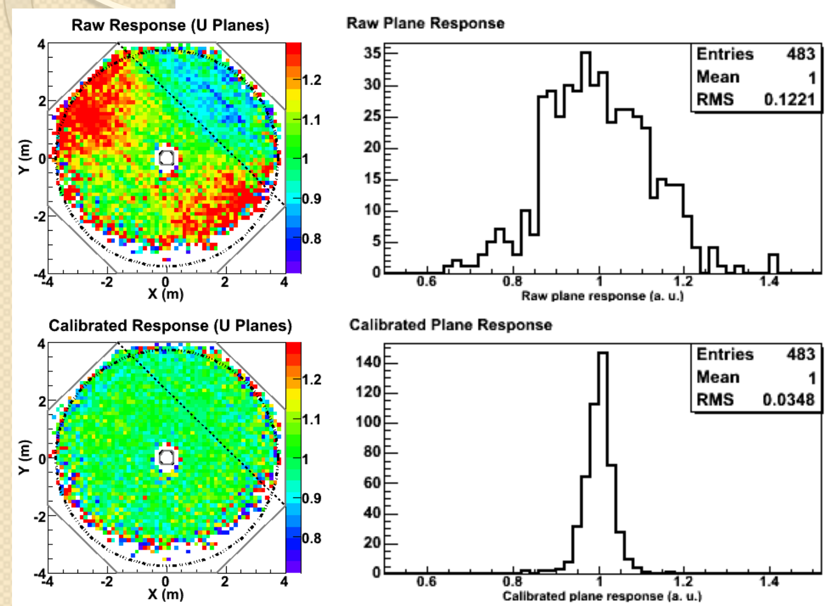
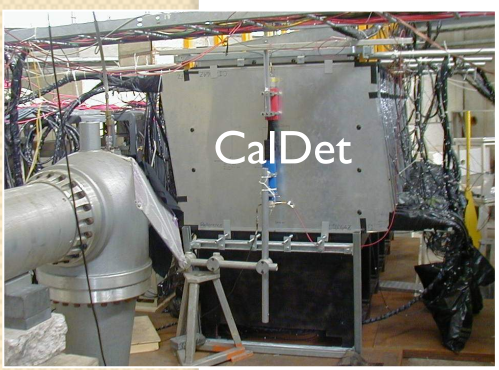
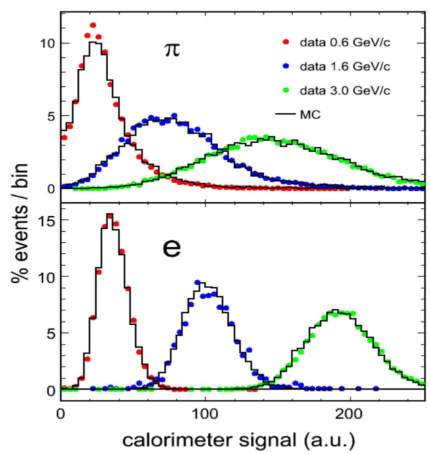
Detector Calibration



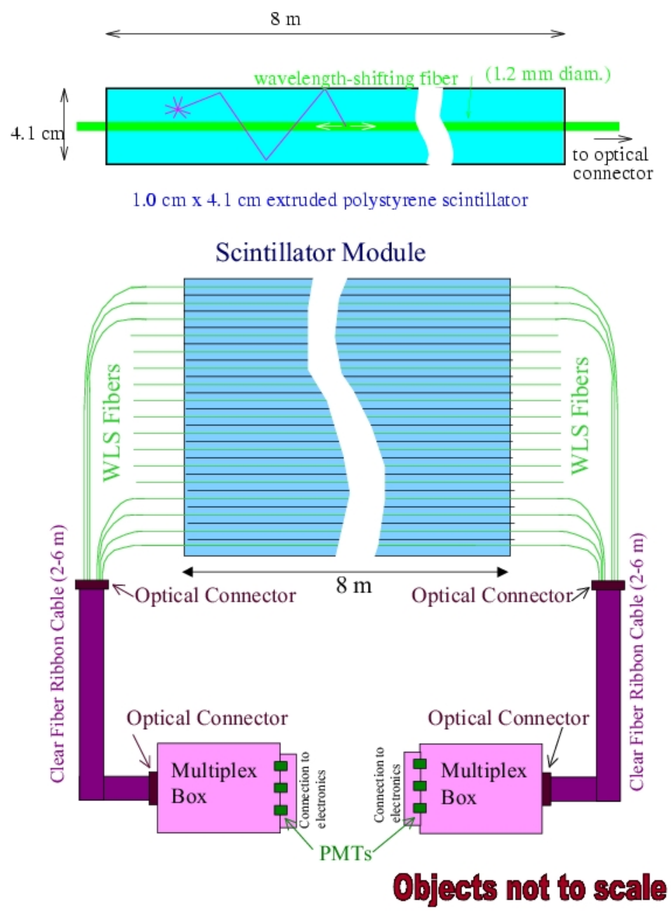


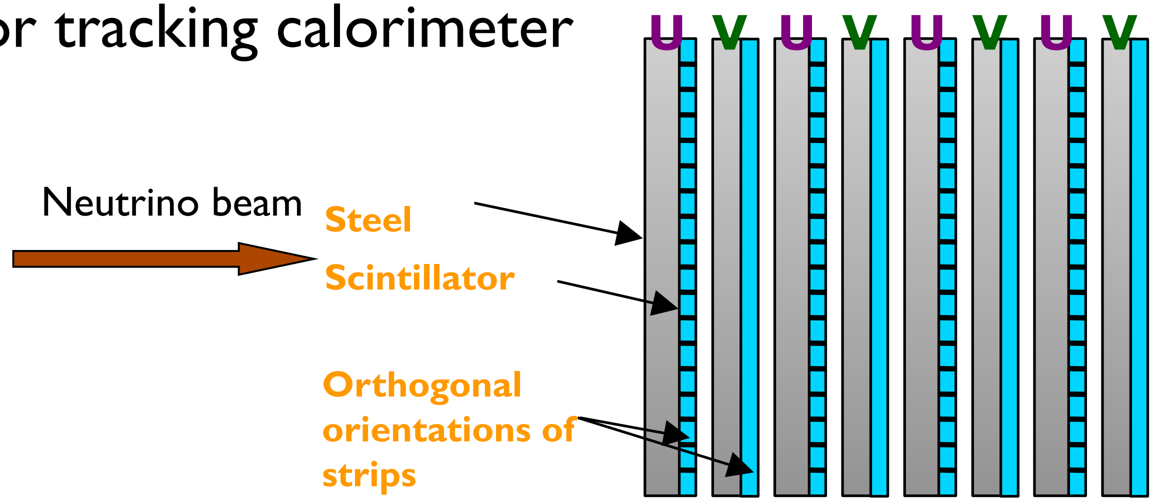


- Charge Injection System
  - Electronics calibration
- Light injection System
  - PMT non-linearity, gains
- Cosmic ray muons
  - Scintillator aging
  - Variations along and between strips
  - Detector to detector calibration
- Calibration Detector
  - Detector response to e/μ/π/p
- Energy resolution: (E in GeV)
  - Hadrons: $56\%/\sqrt{E} \oplus 2\%$
  - Electrons: $21\%/\sqrt{E} \oplus 4\%/E$

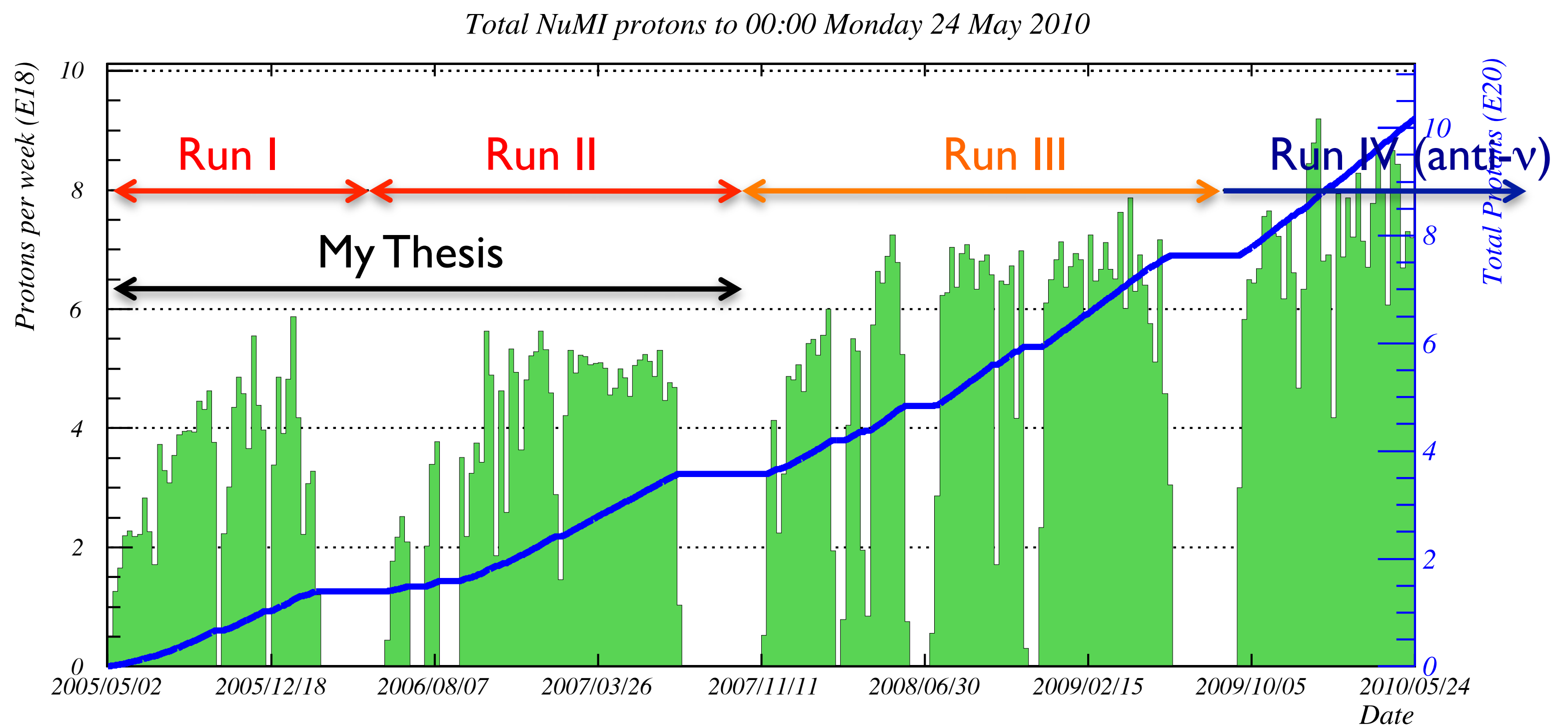
MINOS Detector Technology

Iron/scintillator tracking calorimeter



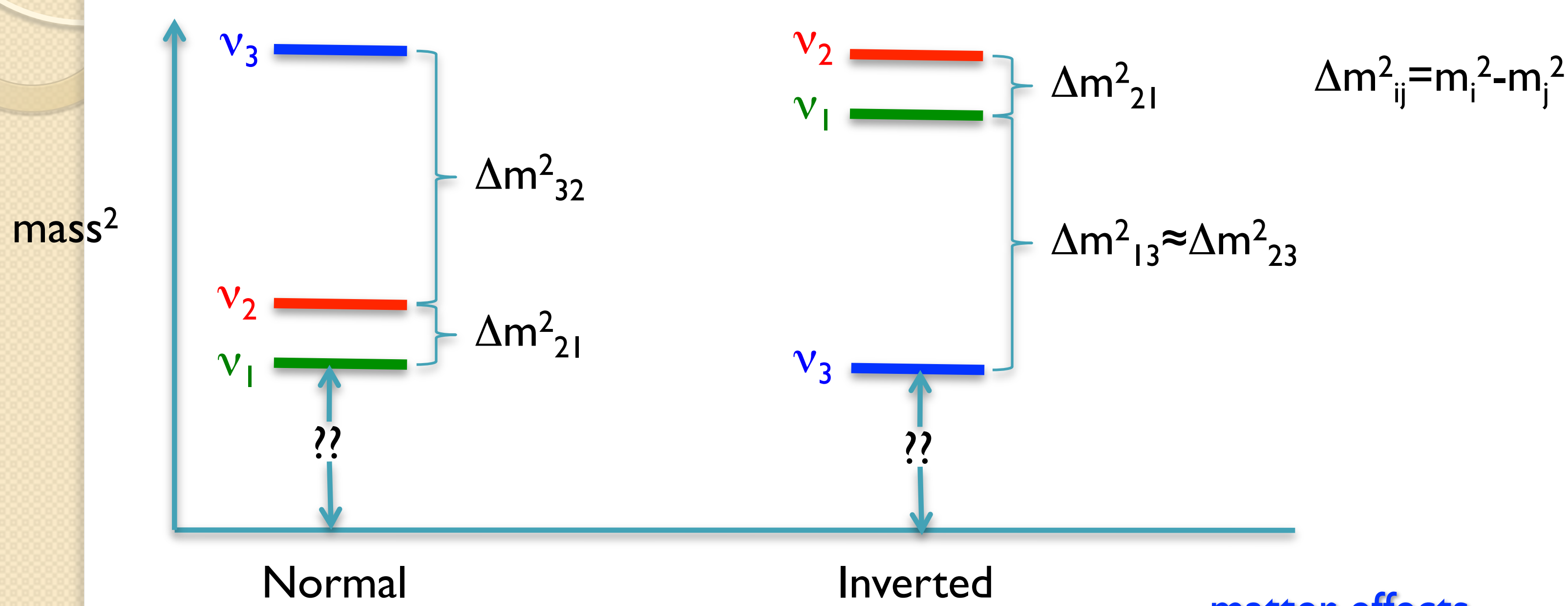


- Alternate planes rotated by ±90° (U,V) for 3D tracking
- Light transported through wavelength shifting fiber and clear fiber
- Signal read out by multi-anode Hamamatsu PMTs
- To reduce the instrumentation cost, 8 strips at FD are readout by one PMT pixel – multiplexing
- ND uses high-speed, dead-timeless front-end electronics because of the high event rate in ND.

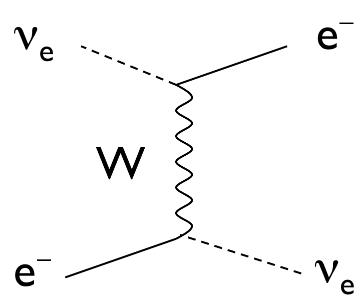


Total NuMI protons to 00:00 Monday 24 May 2010
Protons per week (E18)
Total Protons (E20)
Run I
Run II
Run III
Run IV (anti-ν)
My Thesis
2005/05/02
2005/12/18
2006/08/07
2007/03/26
2007/11/11
2008/06/30
2009/02/15
2009/10/05
2010/05/24
Date

Mass Hierarchy



Mass hierarchy can be resolved using matter effects if $\theta_{13} \neq 0$



matter effects

Coherent forward scattering on electron induces an effective potential for ν_e that changes the ν propagation in matter.

Probability of ν_e Appearance

$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \Delta_{31}$$

P_{atm}: leading term

$$+\cos^2 \theta_{13} \cos^2 \theta_{23} \sin^2 2\theta_{12} \sin^2 \Delta_{21}$$

P_{solar}: solar term - negligible

$$+\sin 2\theta_{13} \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin\Delta_{21} \sin\Delta_{31} \cos(\Delta_{32} + \delta)$$

$P_{interference}$

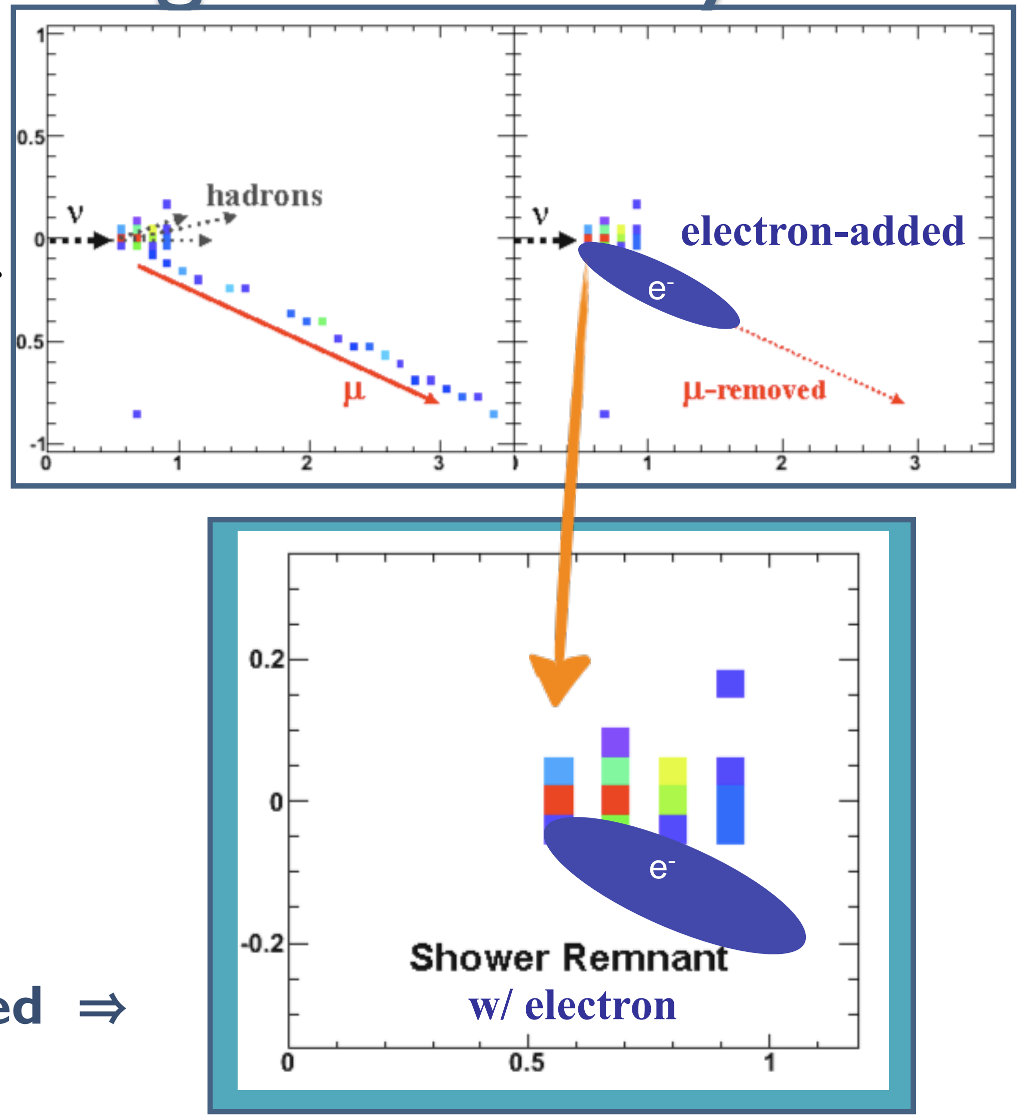
$$\Delta_{ij} \equiv \Delta m_{ij}^2 L/(4E)$$

δ is CP violating phase.

- The leading term depends on $\sin^2 2\theta_{13}$
- P_{solar} is negligible (if θ_{13} at CHOOZ limit)
- δ can change oscillation probability by a maximal 25% (if θ_{13} at CHOOZ limit)
- Matter effects can enhance/suppress oscillation probability by a maximal 25% depending on the sign of Δm^2_{31} – mass hierarchy
- Final results presented as a function of δ and for normal/inverted mass hierarchies separately

Estimating the signal efficiency

- After removing the muon track in selected ν_μ CC events, we replace the lepton with a MC electron.
- This simulates a DIS signal event using the hadronic shower from the data.
- Simulation of electrons benchmarked against test beam data.
  - Agreed better than 3%.



Muon Removed w/ electron added ⇒ MRE events