Neutrino Oscillation Search from the MINOS Experiment

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April. 20, 2010

Outline

- Neutrino Oscillation Physics
- The MINOS Experiment
- MuMI Flux Measurement
- MINOS θ_{13} Measurement

I will focus on my personal work in this talk.

3-Flavor Mixing

Weak state   Mass state

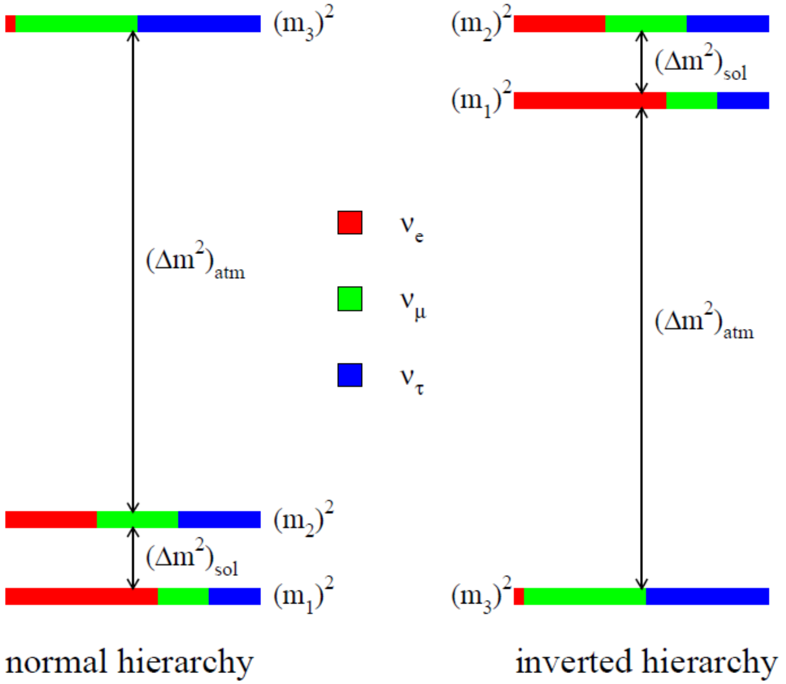
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$m_2^2 > m_1^2$$

$$m_2^2 - m_1^2 << \left| m_3^2 - m_{1,2}^2 \right|$$

$\Delta m_{31}^2 > 0$ Normal Mass Hierarchy

$\Delta m_{31}^2 < 0$ Inverted Mass Hierarchy



Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix relates the two bases, it can be expressed in 3 mixing angles, 1 CP phase and 2 Majorana phases:

$$\tan^2\theta_{12} \equiv \frac{|U_{e2}|^2}{|U_{e1}|^2}; \quad \tan^2\theta_{23} \equiv \frac{|U_{\mu 3}|^2}{|U_{\tau 3}|^2}; \quad U_{e3} \equiv \sin\theta_{13} e^{-i\delta}$$

PMNS Matrix Measurements

The neutrino mixing (PMNS) matrix can be factorized into 4 experimental regimes:

Atmospheric **Cross-mixing** **Solar** **Majorana**

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{-i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

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Solar ν (SNO)
KamLand
Future reactors

$\Delta m^2_{21} \sim 7.9\times10^{-5} eV^2$
$\theta_{12} \sim 34°$

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Atmospheric ν
K2K, SuperK
MINOS
Off-axis

$|\Delta m^2_{32}| \sim 2.4\times10^{-3} eV^2$
$\theta_{23} \sim 45°$

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Atmospheric	Cross-mixing	Solar
Atmospheric ν K2K, SuperK MINOS Off-axis	CHOOZ/Palo Verde K2K, MINOS Future reactors Off-axis NOvA, T2K	Solar ν (SNO) KamLand Future reactors
$|\Delta m^2_{32}| \sim 2.4\times10^{-3}\,eV^2$ $\theta_{23}\sim45^\circ$	$\theta_{13}<11^\circ$ at 90% C.L.	$\Delta m^2_{21}\sim7.9\times10^{-5}\,eV^2$ $\theta_{12}\sim34^\circ$

PMNS Matrix Measurements

The neutrino mixing (PMNS) matrix can be factorized into 4 experimental regimes:

Atmospheric | **Cross-mixing** | **Solar** | **Majorana**

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Neutrinoless
double beta
decay

2-Flavor Neutrino Oscillation

$$P_{osc} = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$

θ is the mixing angle

$\Delta m^2 = m_1^2 - m_2^2 (eV^2)$

L is the distance that neutrino travels (km)

E is neutrino energy (GeV)

Different oscillation experiments are generally sensitive to only **one mass scale** ($\Delta m^2 L/E = O(1)$) , 2-flavor approximation can be used.

If $\Delta m^2 L/E << 1$, $\sin^2(1.27\Delta m^2 L/E) \sim 0$; if $\Delta m^2 L/E >> 1$, $\sin^2(1.27\Delta m^2 L/E) \approx 1/2 \rightarrow$ average over E and L

Overview of the MINOS Experiment

- **MINOS (Main Injector Neutrino Oscillation Search)**
  – a long baseline neutrino oscillation experiment
  – sensitive to the atmospheric mass scale (L/E ~ 235[km/GeV])

ν_e **appearance**

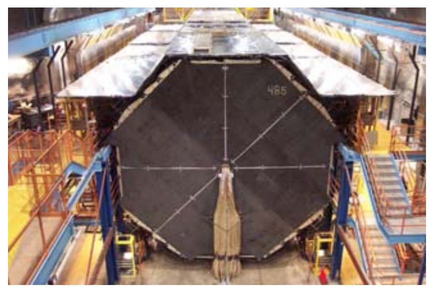
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

ν_μ **disappearance**

Two functional identical detectors.

- **Far Detector:**
  - **Mass: 5.4 kt**
  - **Distance : 735km**

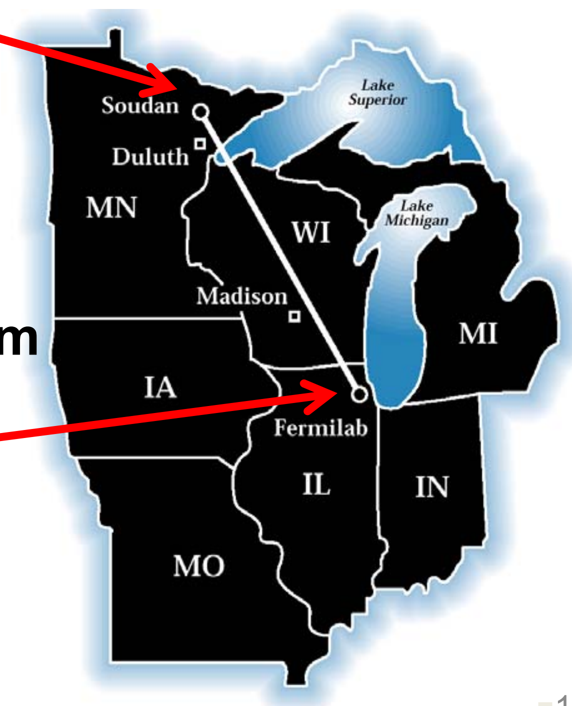
- **Near Detector:**
  - **Mass: 1kt**
  - **Distance : 1km**



Far Detector

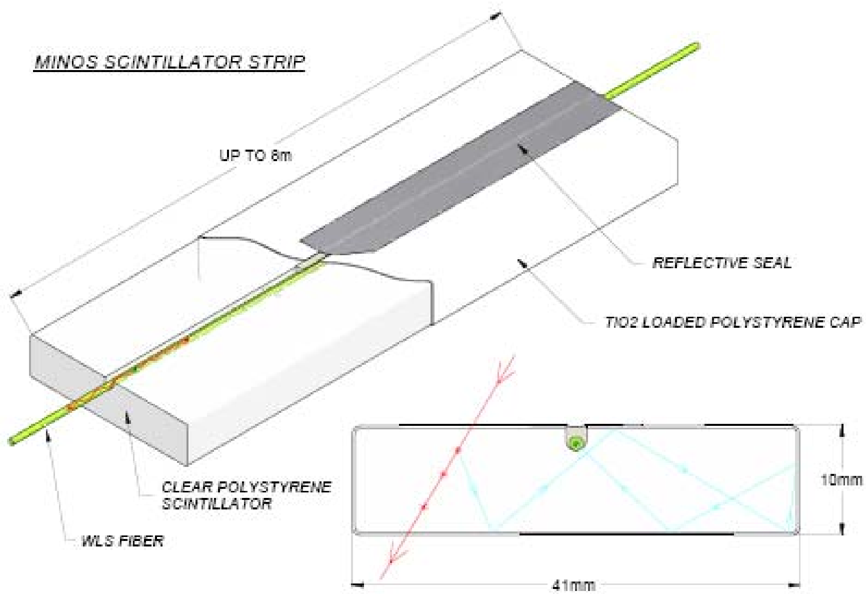
Near Detector

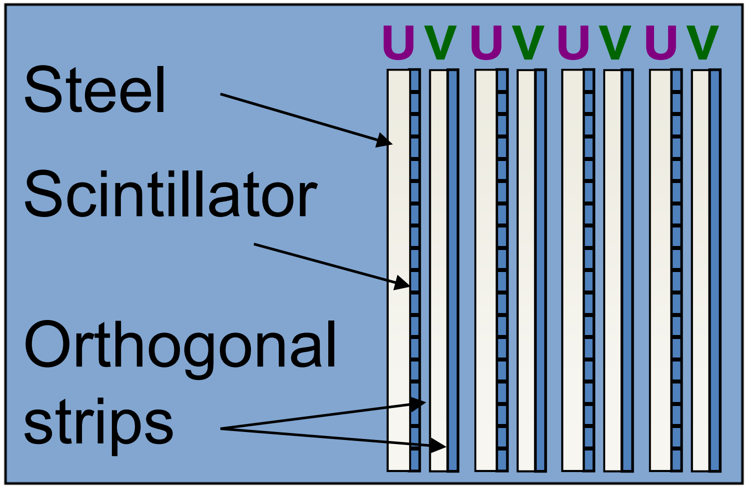
735km

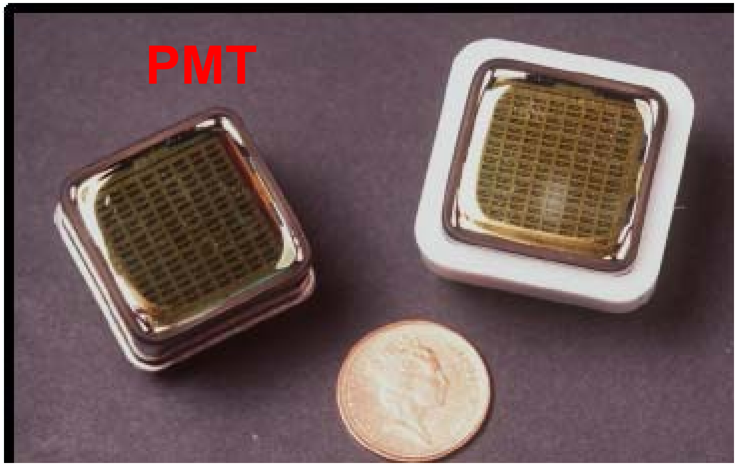


MINOS Detector Technology

Magnetized Iron/scintillator tracking calorimeter



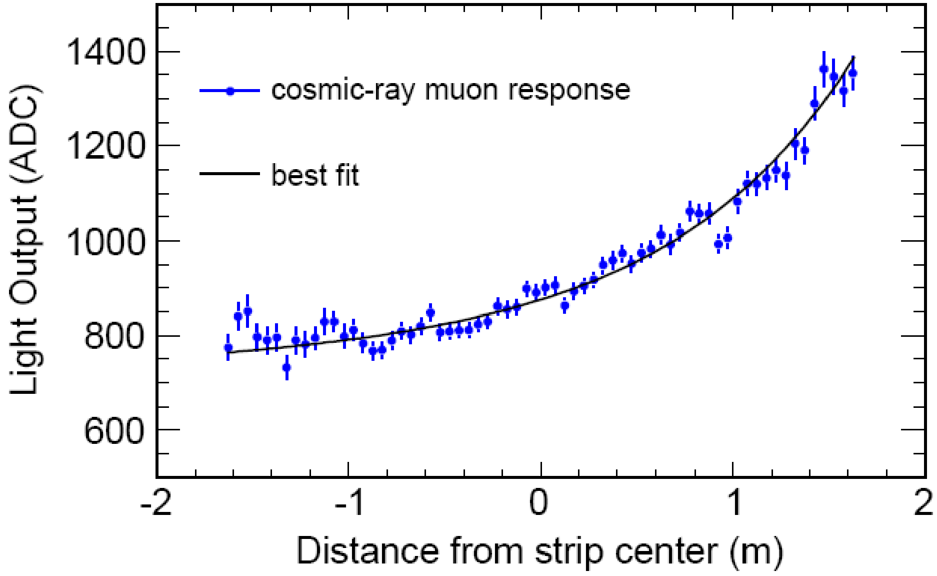


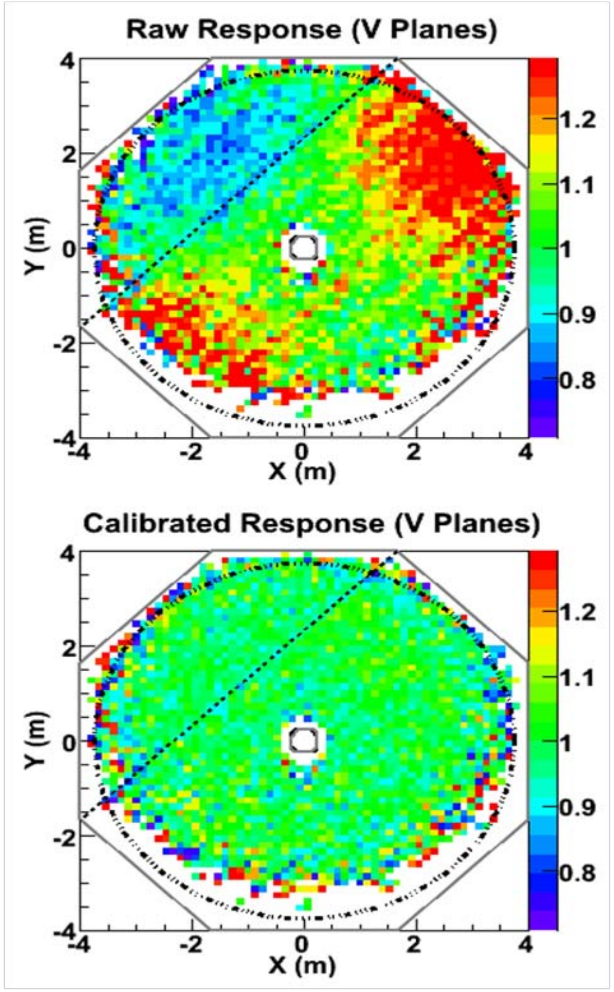


- Steel: 2.54cm thick
- Scintillator: 1cm thick, 4.1cm wide strips
- Alternate planes rotated by $\pm 90^o$ (U,V)
- Wavelength shifting fibers (WLS)
- Multi-anode Hamamatsu PMTs

Detector Calibration

- Measure & remove spatial and temporal variations (channel difference , attenuation , detectors)
- Attenuation Calibration
  - mapper data sample
  - cosmic-ray muon sample





Detector Calibration

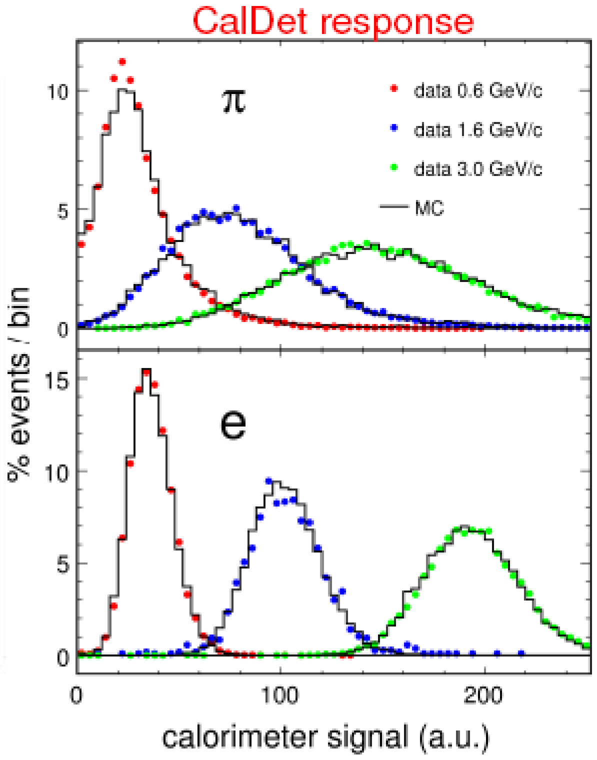
MINOS Calibration detector (CalDet):

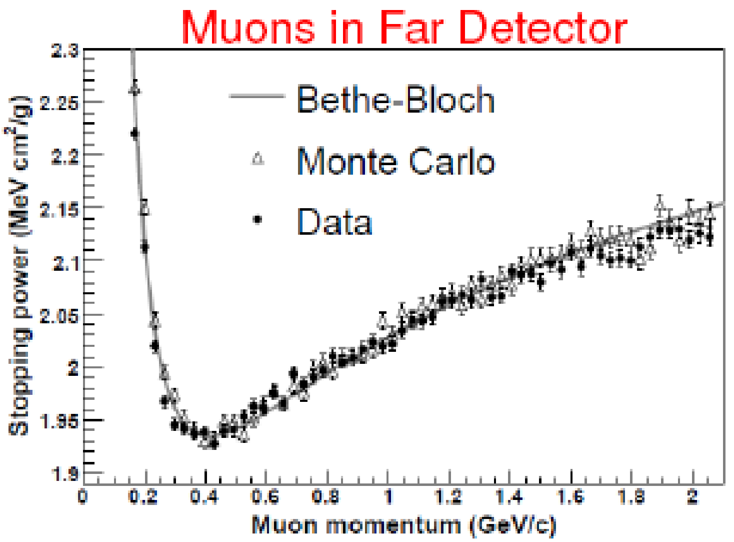
- Exposed to 0.2-10GeV p, e, μ, π at CERN

Energy resolution:

Hadrons: 56%/√E Electrons: 21%/√E

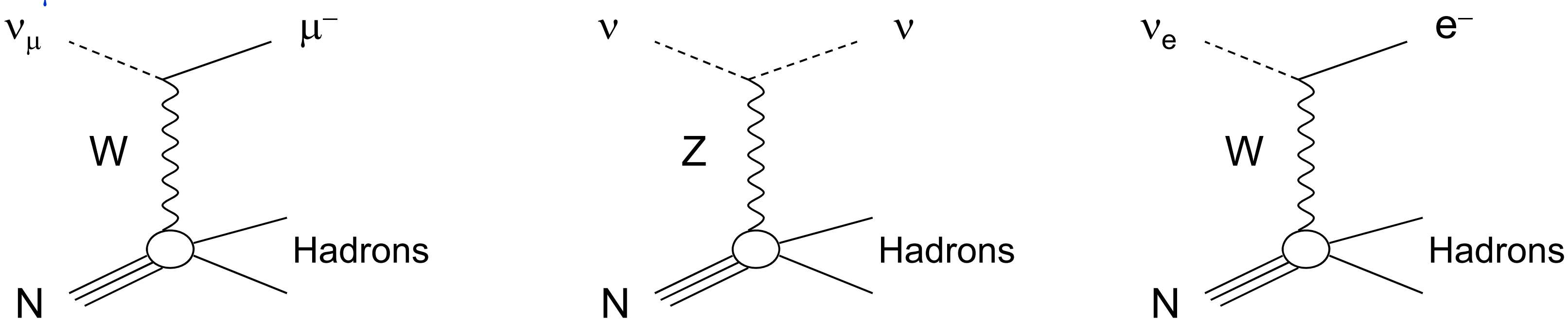
Energy Scale Uncertainty: ND-FD relative: 2% Absolute: 6%



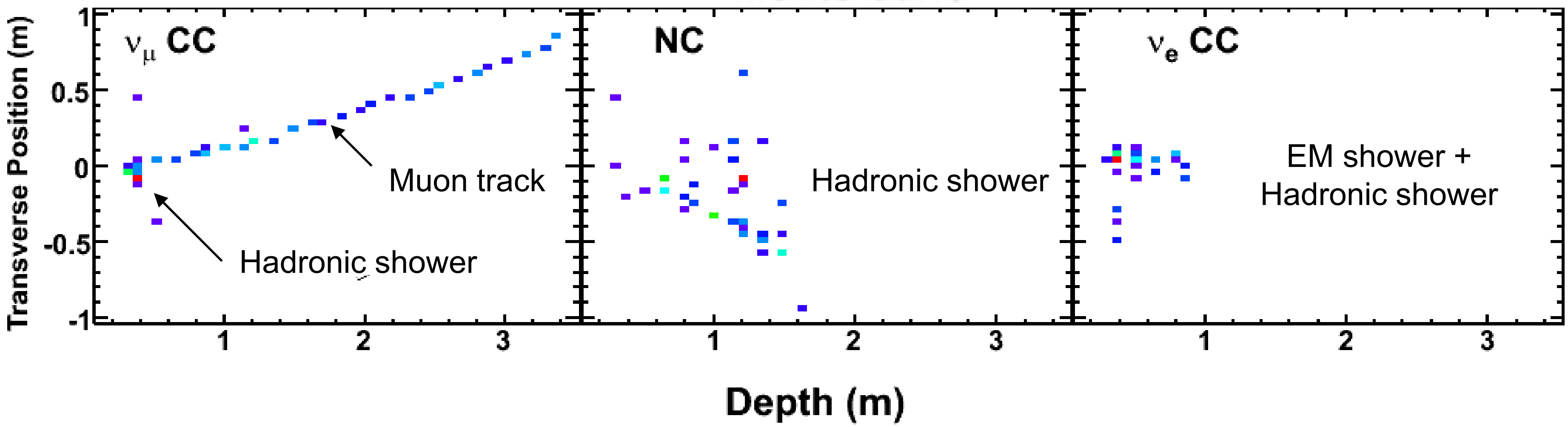


Event Reconstruction

ν_μ CC interaction $\quad$ ν_x NC interaction $\quad$ ν_e CC interaction



Monte Carlo



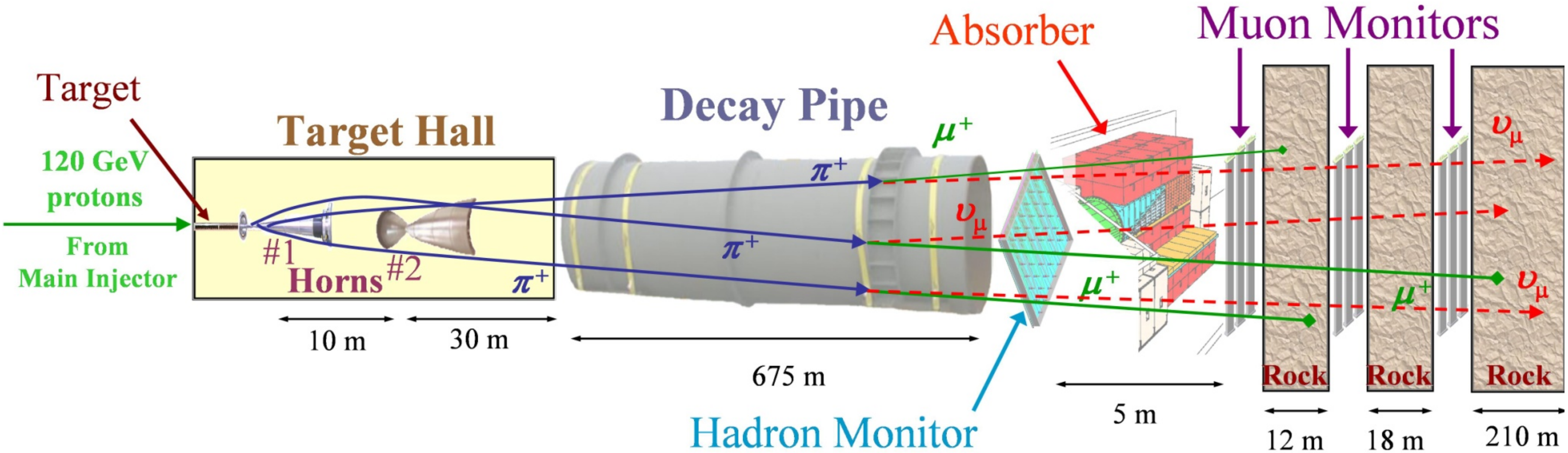
clean channel for ν_μ disappearance

background to ν_μCC and ν_e cc

search for ν_e appearance

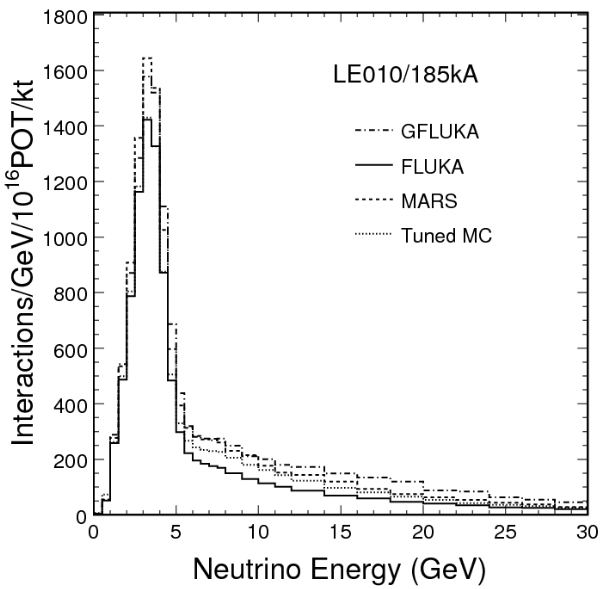
NuMI Flux Measurement

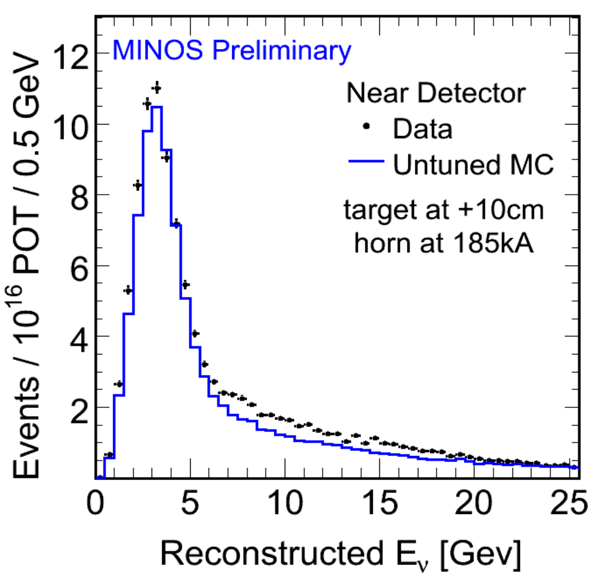
Neutrinos at Main Injector (NuMI)



- 120 GeV protons from Fermilab MI
- 1m segments of graphite target
- 2 focusing horns
- Mesons decay in the decay pipe to give a beam of neutrinos
- Various neutrino energy spectra by varying the relative positions of target and horns
- In the Low Energy configuration: 92.9% ν_μ, 5.8% $\overline{\nu}_\mu$, 1.3% $\nu_e+\overline{\nu}_e$

NuMI Flux Simulation





- Determining neutrino flux is quite hard:
  - Use FLUKA05 + GEANT3 MC simulation
  - Various cascade models indicate hardron production uncertainty 10-30%.
  - The neutrino + nucleon X-section uncertainty below 10GeV .
  - Beam-line simulation uncertainty.
  - Large uncertainty associated with MIPP measurement for the NuMI target .

Low-ν Relative Flux Extrapolation

- D. Naple and S.R. Mishra introduced a low-ν relative flux extrapolation method.
- It relies on the independence of the neutrino(anti-neutrino) differential cross section dσ/dν with energy in the limit ν→0

$$\frac{d^2\sigma^{\nu(\bar{\nu})}}{dxdy} = \frac{G_F{}^2 ME}{\pi}\left[\left(1 - y - \frac{Mxy}{2E}\right)F_2^{\nu(\bar{\nu})} + \frac{y^2}{2}2xF_1^{\nu(\bar{\nu})} \pm y\left(1-\frac{y}{2}\right)xF_3^{\nu(\bar{\nu})}\right]$$

Using $\nu = E \times y$, and integrating the differential Xsec given above over x (from 0 to 1)

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

$$A = \frac{G_F^2 M}{\pi}\int F_2(x)dx$$

$$B = -\frac{G_F^2 M}{\pi}\int \left(F_2(x) \mp xF_3(x)\right)dx$$

$$C = B - \frac{G_F^2 M}{\pi}\int F_2(x)\left(\frac{1+2Mx/\nu}{1+R(x)} - \frac{Mx}{\nu} - 1\right)dx$$

As ν→0, the Xsection becomes independent of neutrino energy.

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Times flux on both sides and integrating the shower energy from 0 to 1

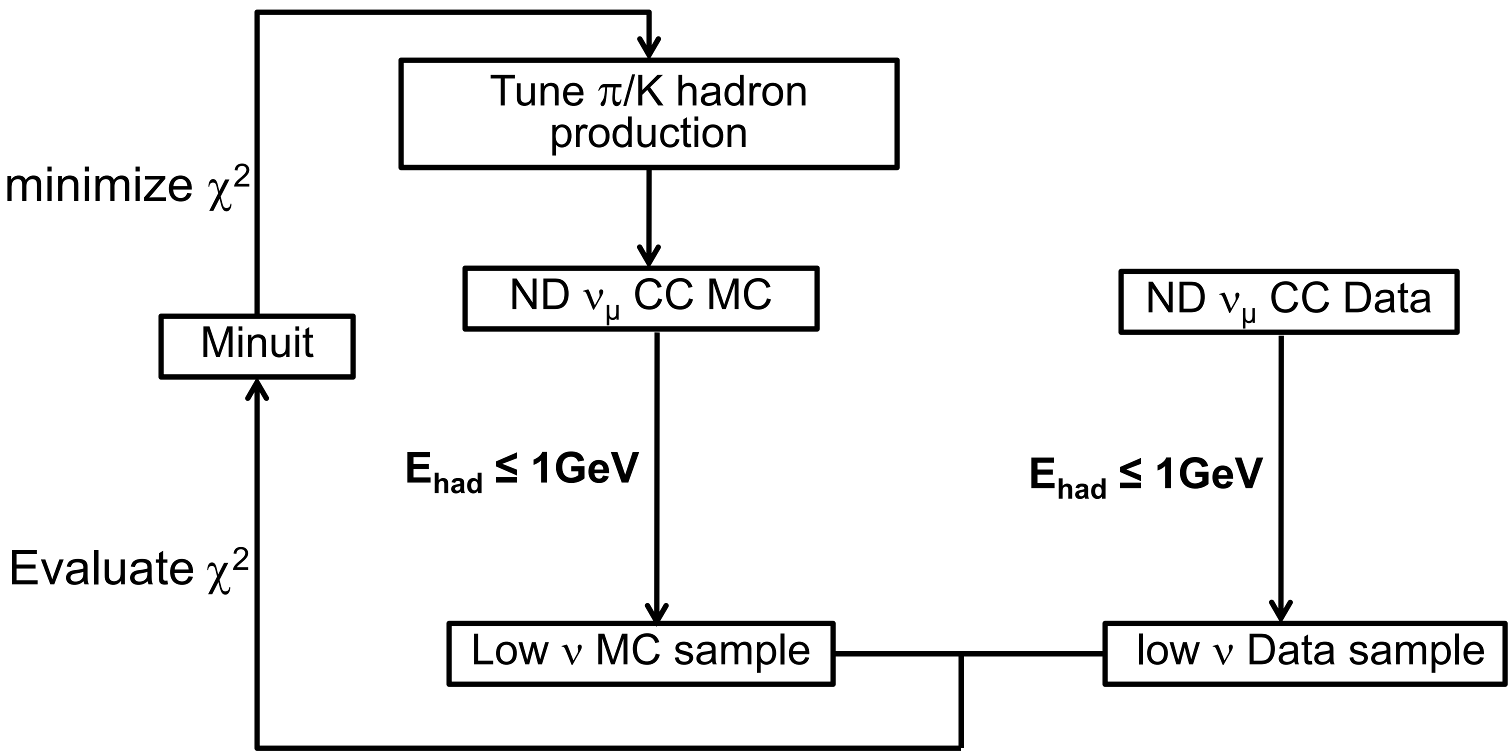
$$N(E)_{(\nu \le 1GeV)} = \Phi(E) \cdot A\int_0^1 \left(1 + \frac{B}{A}\frac{\nu}{E} - \frac{C}{A}\frac{\nu^2}{2E^2}\right)d\nu$$

the number of events in a given energy bin with hadronic energy less than 1GeV is proportional to the neutrino flux.

Physical Review D 81, 072002 (2010)

Empirical Parameterization (EP) Method

- In order to predict the neutrino flux in the Far Detector, we need to retune the π/K hadron production by using the low-nu flux sample.



Hadron Production Parameterization

Parameterize the π/K hadron production yield as a function of x_R (x_F) and p_T.

$$E \times \frac{d^3\sigma}{dp^3} = A(1 - x_R)^{\alpha}(1 + Bx_R)x_R^{-\beta} \times \left(1 + a'(x_R)p_T + b'(x_R)p_T^2\right)e^{-a'(x_R)p_T}$$

where $a'(x_R) = a / x_R^{\gamma}$ and $b'(x_R) = a^2 / 2x_R^{\delta}$

arxiv: hep-ph/0101163

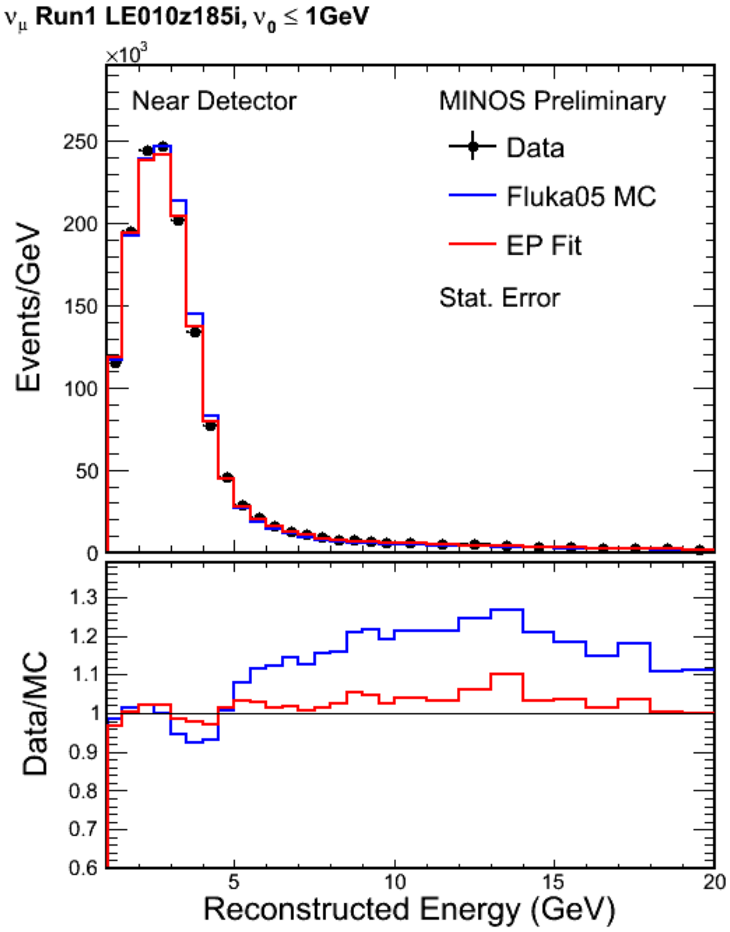
BMPT Function

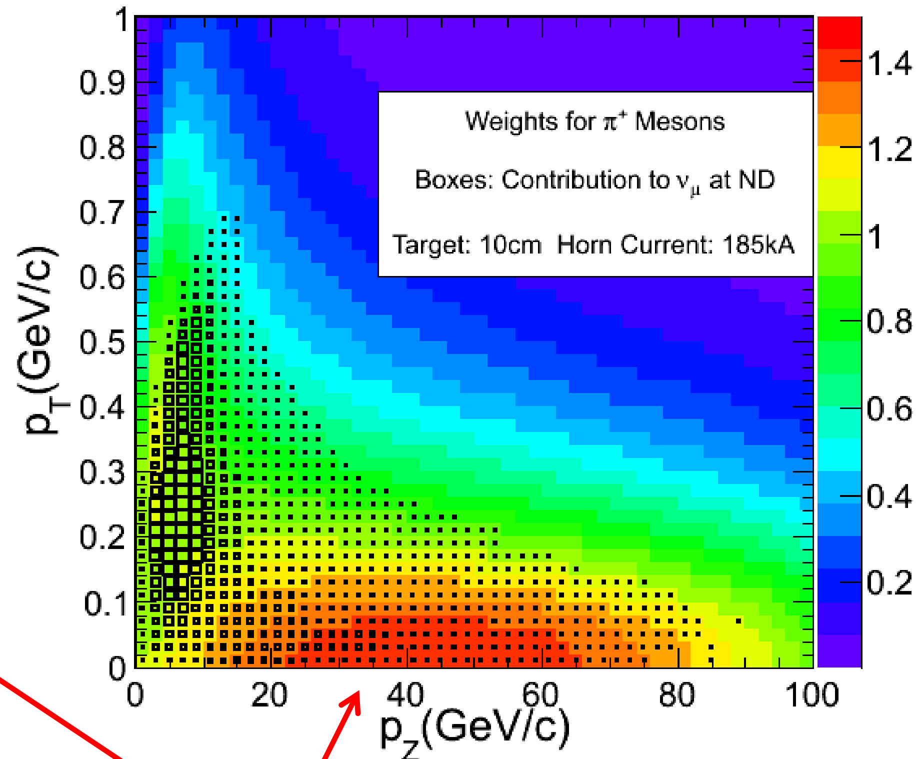
14 parameters are used: 7 for pion and 7 for Kaon.

- By varying these parameters, we can tune the neutrino flux shape.

$$Weight = \frac{BMPT(x_R, p_T, A', B', a', \ldots)}{BMPT(x_R, p_T, A, B, a, \ldots)}$$

Fit to Low-ν ND Data



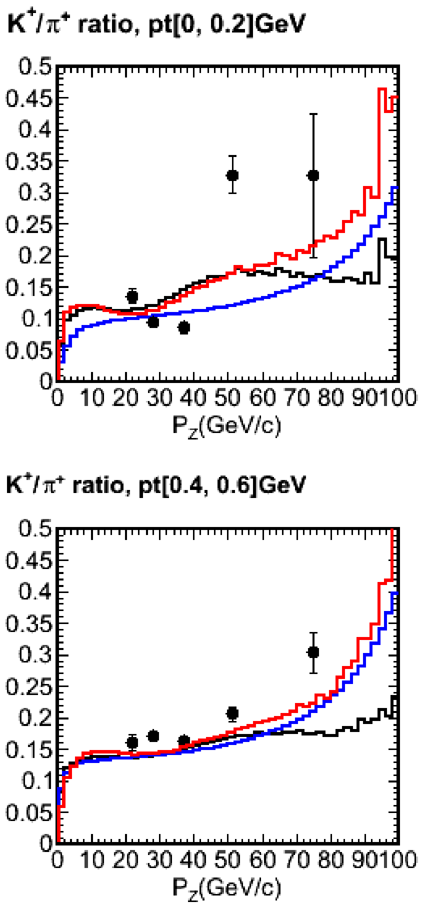


Correction for high energy tail

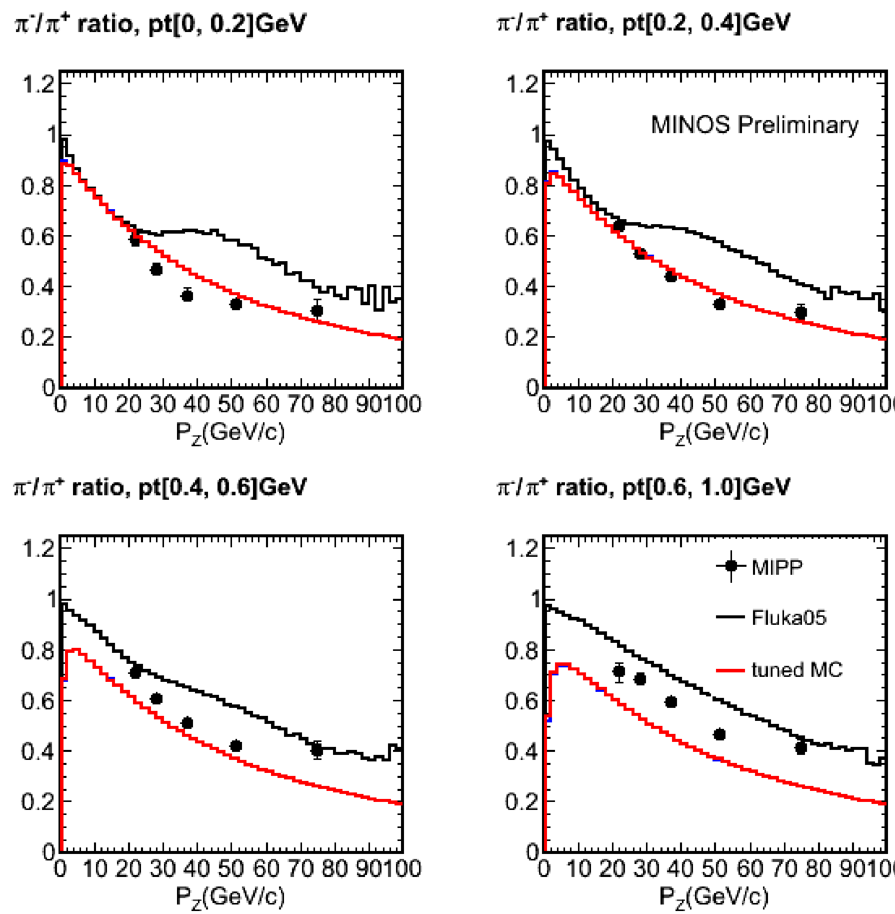
The EP retuned flux can fit the ND data within 10% level.

Hadron Ratios

K^+/π^+

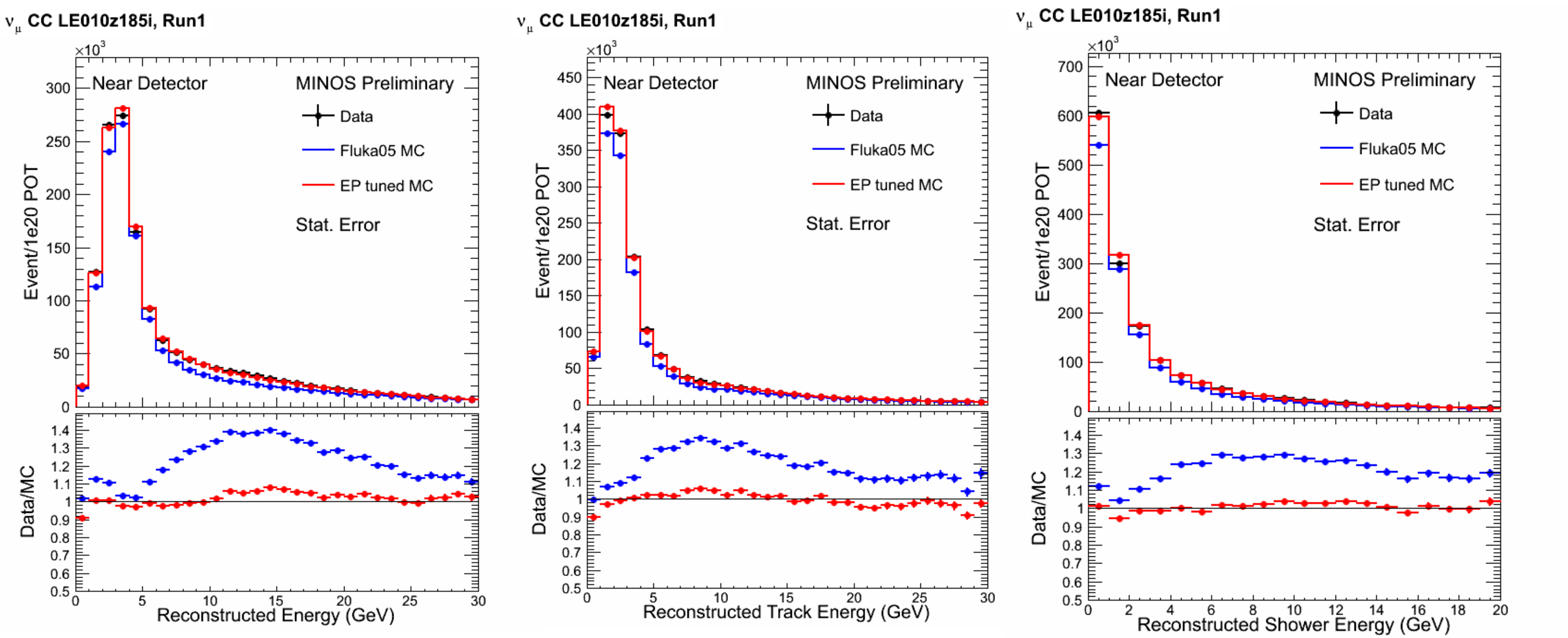


π^-/π^+



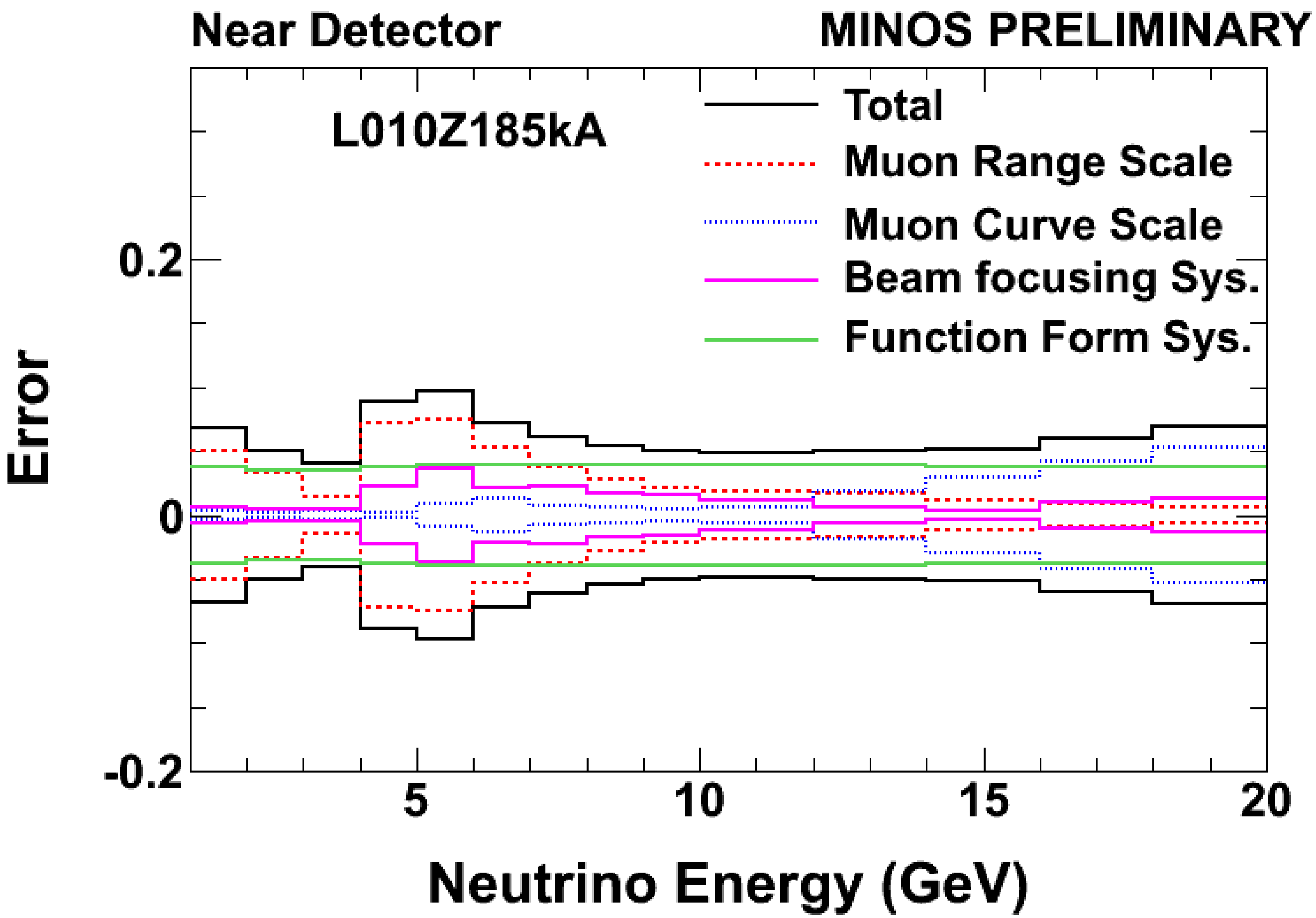
Fluka05	**BMPT**	**Tuned MC**	**MIPP**

Full Sample Data/MC Comparison



With the ND low-ν data constraint, EP retuned MC has a better agreement with ND data.

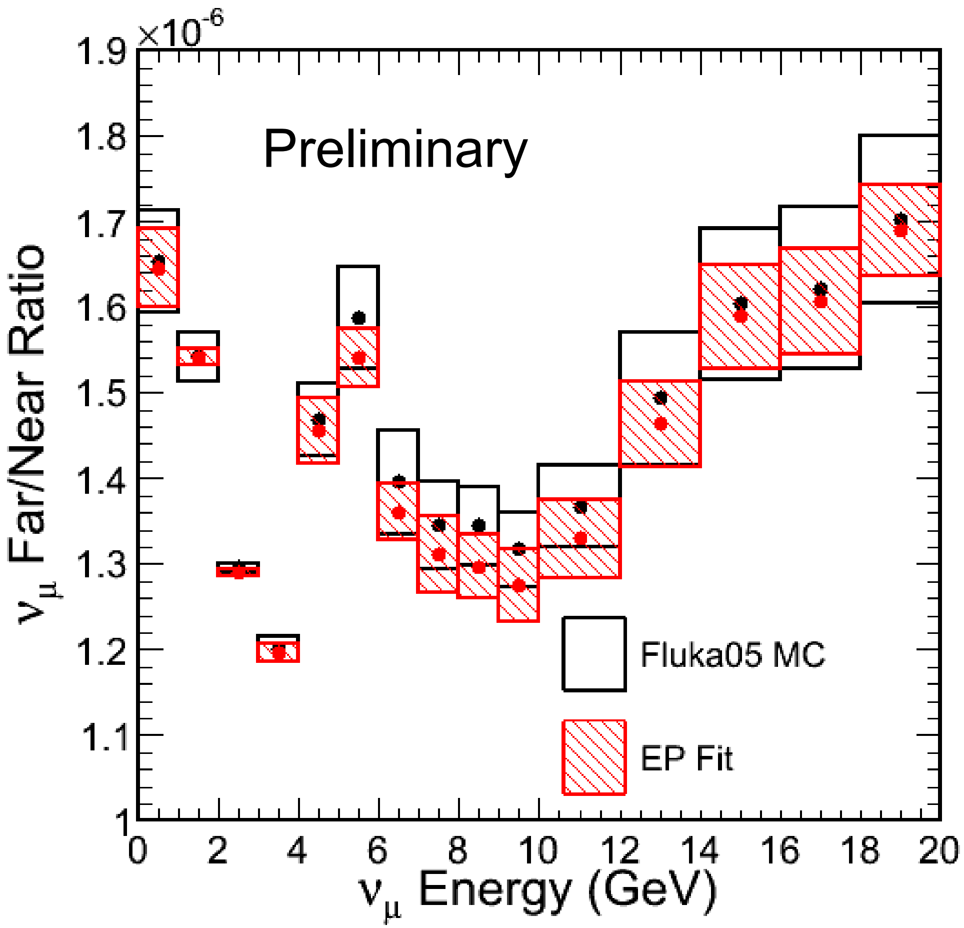
Systematic Uncertainty



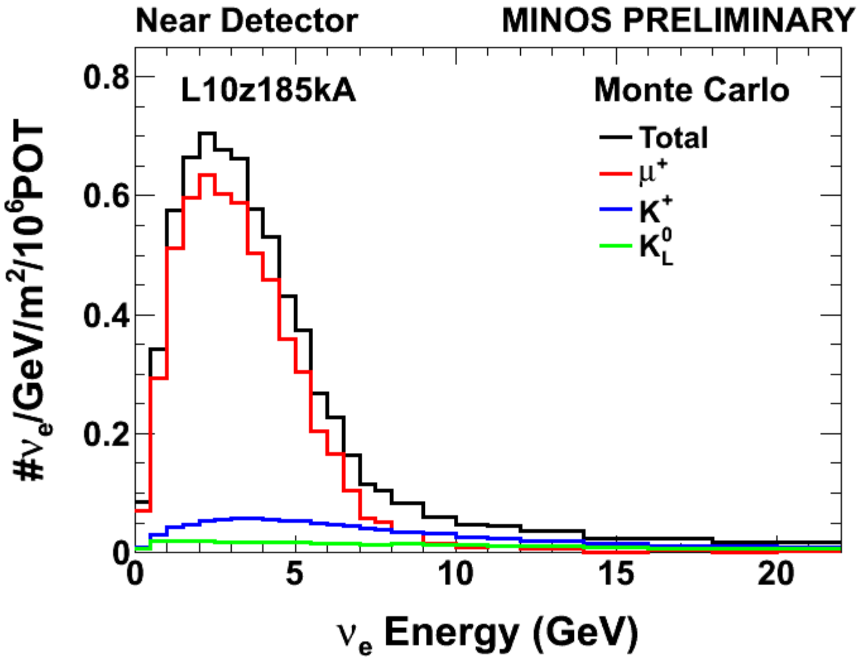
F/N Ratio Comparison

EP fit MC is able to reduce the systematic uncertainties on the F/N ratio.

The dominant errors come from muon energy scale and horn focusing.



Beam ν_e Determination



Source	0-8 GeV	8-20 GeV
μ^+	85%	21%
K^+	11%	52%
k^0_L	4%	27%

$\pi^+ \rightarrow \mu^+ + \nu_\mu$

$\hookrightarrow e^+ + \nu_e + \bar{\nu}_\mu$

ν_e from 1-8 GeV (region of interest by the ν_e oscillation analysis) is dominated by μ^+ decay and it is well constrained by the π^+ fit.

ν_e flux uncertainty is less than 10%.

Summary of EP Method

- Merit
  - Accurately predict ν_μ relative flux by using the ND low-ν data (independent of ν xsec).
  - Reduce the systematic uncertainty on F/N ratio.
  - ν_e flux can be constrained by the π/K fit.
  - Data/MC agreement improvement.
- Disadvantage
  - Level of agreement between the fit and low-ν data
  - Sensitive to the muon energy scale

MINOS θ_{13} Measurement

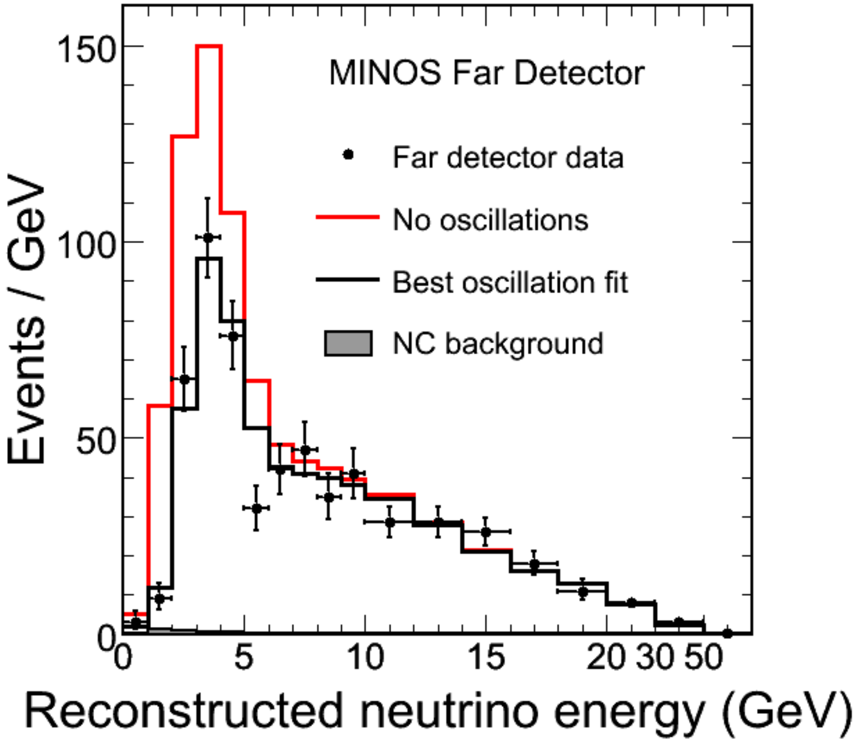
ν_μ CC Disappearance Results

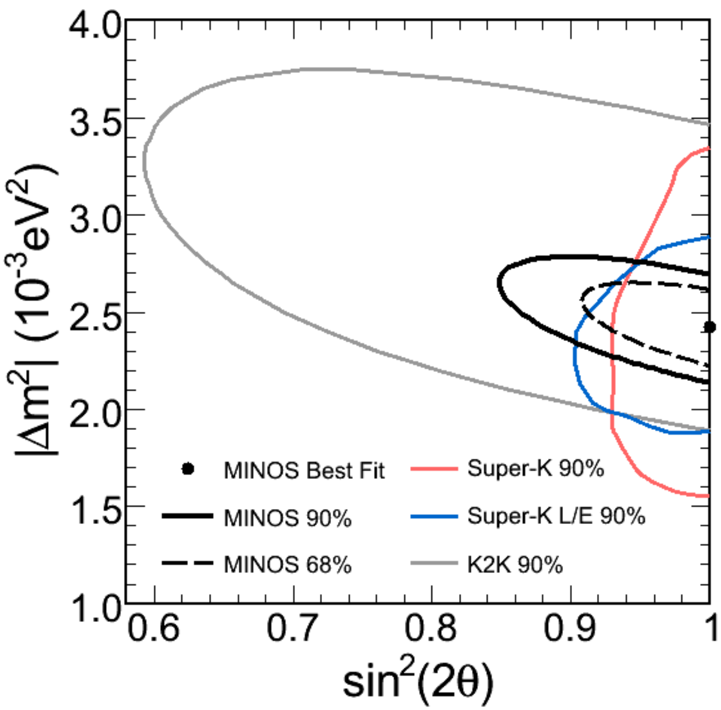
$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{1.27\Delta m^2_{32} L}{E}\right)$$

$|\Delta m^2_{32}| = 2.43 \pm 0.13 \times 10^{-3} eV^2$ (68% C.L.)

$\sin^2(2\theta_{23}) > 0.90$ (90% C.L.)

Most precise measurement of $|\Delta m^2_{32}|$





Phys. Rev. Lett. 101: 131802 (2008)

Expected: 1065±60 events
Observed: 848 events

ν_e Appearance

$$P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23} \boxed{\sin^2 2\theta_{13}} \sin^2\left(1.27\Delta m^2_{31} L / E\right)$$

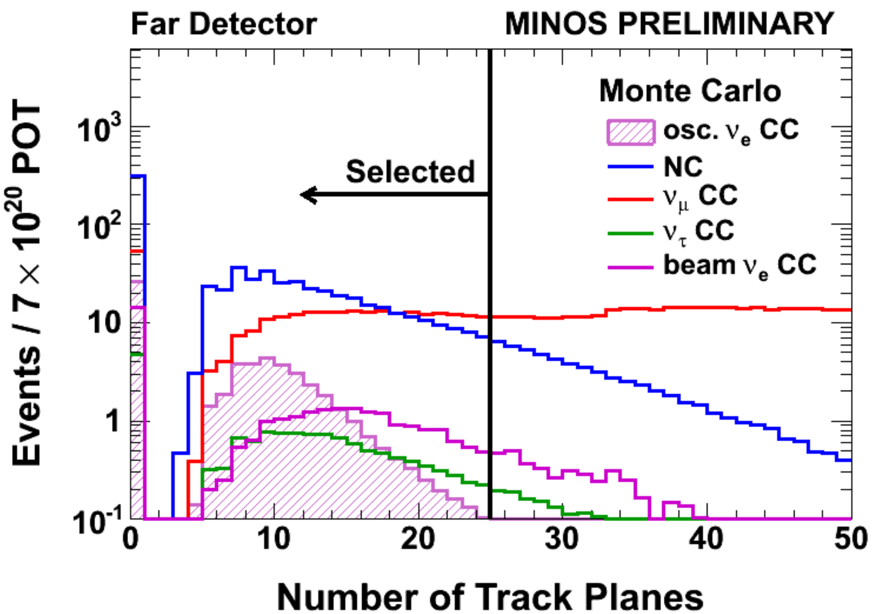
Leading order term

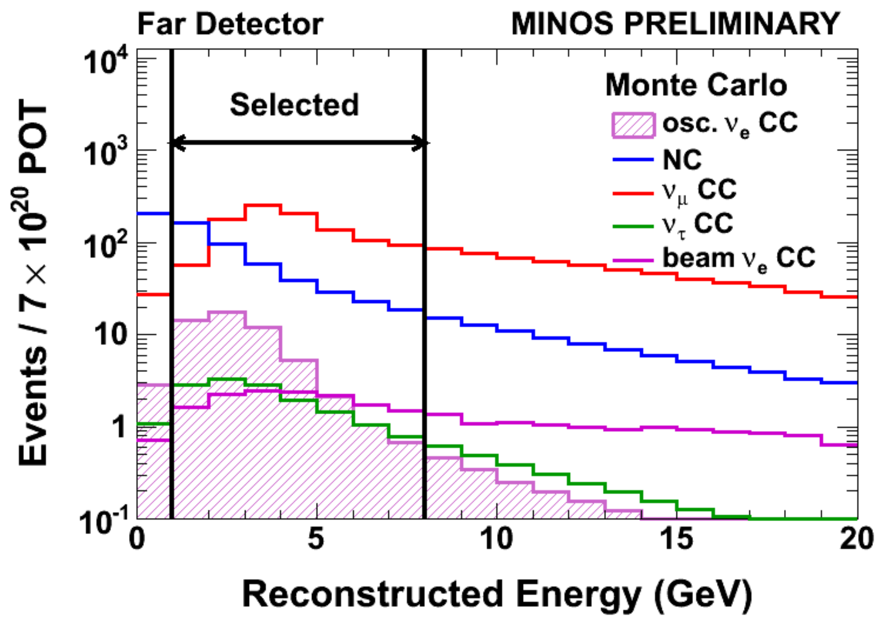
- **Analysis Approach**
  - *Determine the selection criteria for ν_e candidate events*
  - *Use ND data to decompose background components*
  - *Extrapolate ND background components to FD taking into account $\nu_\mu \to \nu_\tau$ oscillations*
  - *Measuring/constraining θ_{13} by looking for excess of ν_e-like events in the FD*

Challenge of MINOS ν_e Selection

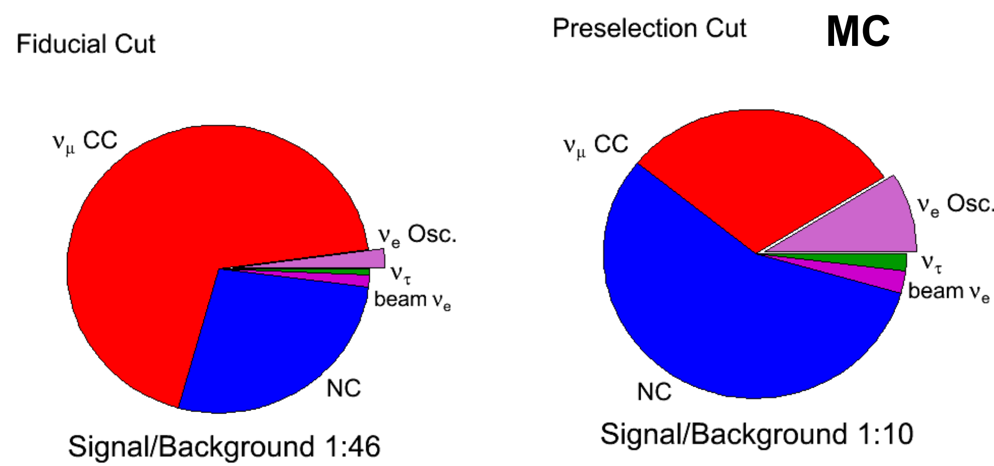
- Difficulties for the ν_e analysis
  - $\nu_\mu \rightarrow \nu_e$ oscillation is the sub-dominant oscillation mode in MINOS.
    - Only $\sim$ 3% FD events are ν_e CC events assuming $Sin^2(2\theta_{13})$= 0.15
  - Granularity of the MINOS Detectors
    - Steel thickness = 1.4 radiation length
    - Strip width = 1.2 Moliere radius
  - Various background components
    - NC Hadronic shower events: NC π^0
    - High y_{bj} CC events
    - Intrinsic beam ν_e components

ν_e Pre-selection Cuts





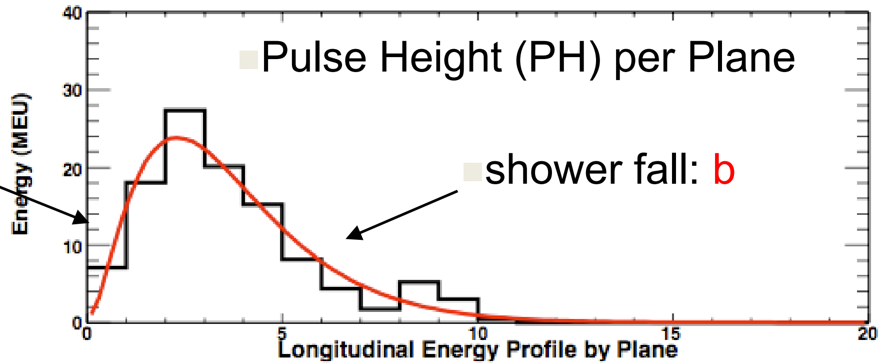
Assuming signal at CHOOZ limit



- Preselection requirements:
  - Track length < 25 planes.
  - Track like length < 16 planes.
  - Reconstructed energy 1-8 GeV.
  - At least one shower and 4 contiguous planes with > 0.5 M energy units.

Longitudinal Shower Profile

shower rise: a

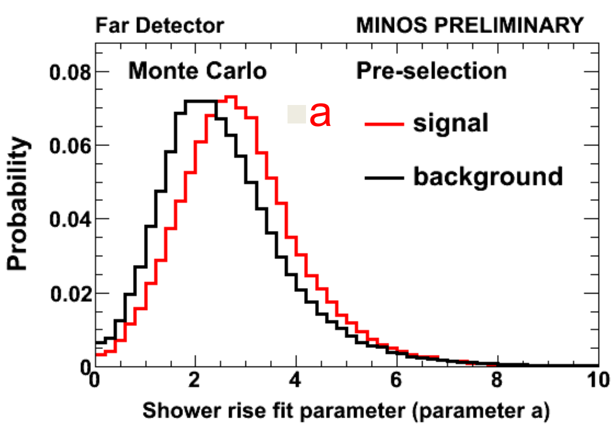


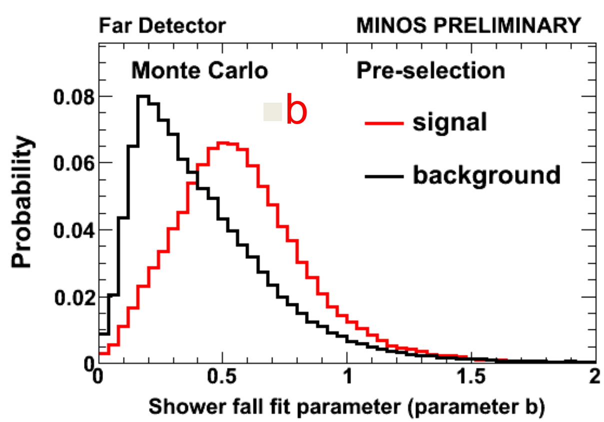
One candidate ν_e event in the FD

The average longitudinal profile of the energy deposition in an EM shower is reasonably well described by a gamma distribution:

$$\frac{dE}{dt} = E_0 b \frac{(bt)^{a-1} e^{-bt}}{\Gamma(a)}$$

$t = x/X_0$ where X_0 is the radiation length





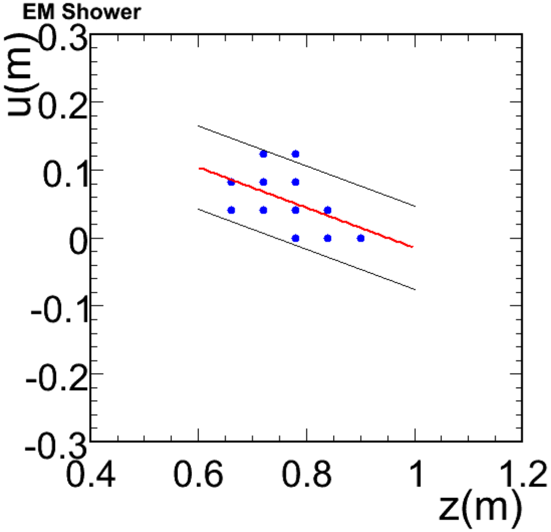
Other useful variables:

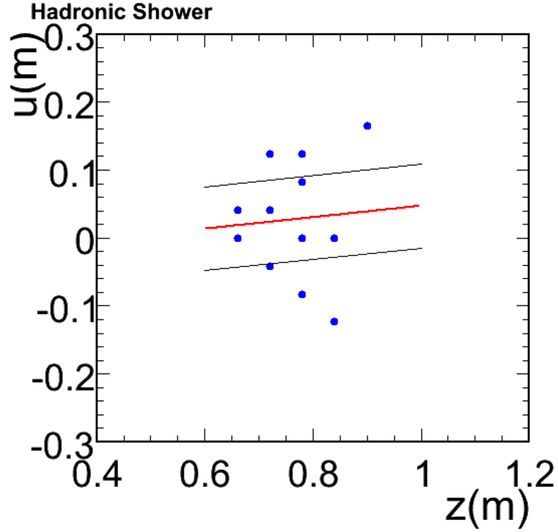
- fraction of energy deposited

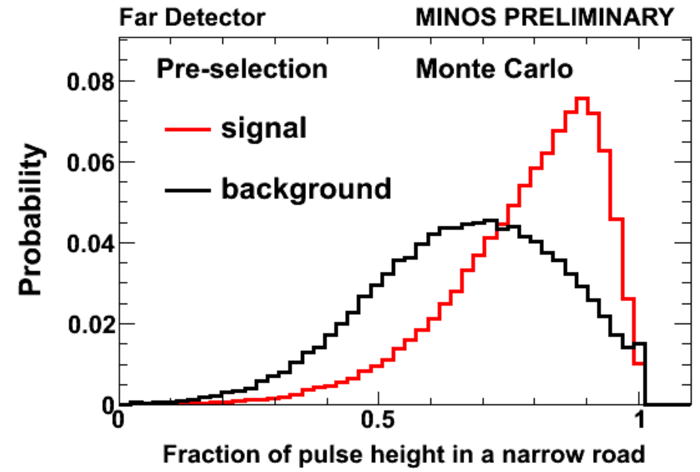
within 2,4,6 planes

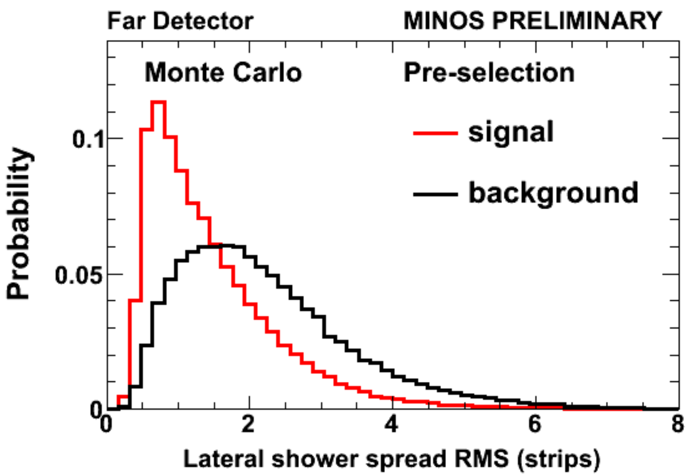
- longitudinal energy projection

Transverse Shower Profile



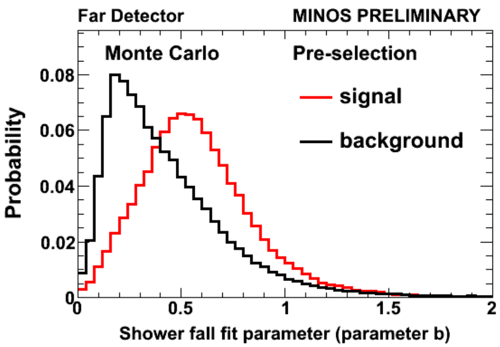


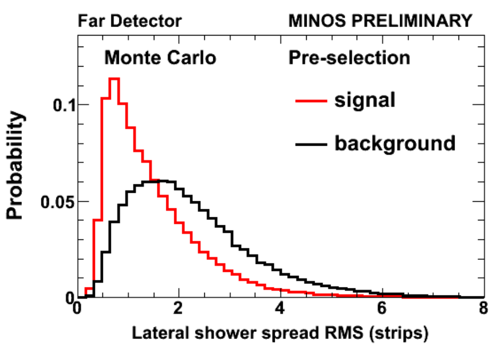


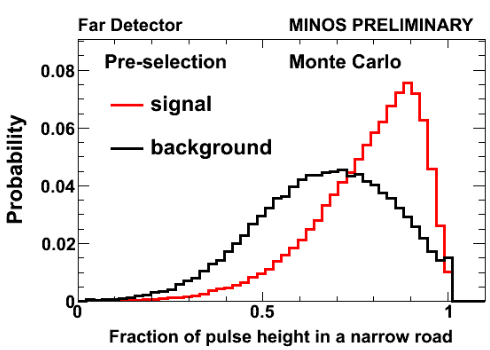


- EM showers are more compact than hadronic showers
- Other useful transverse variables
  - lateral shower spread (RMS)
  - 90% containment radius

Artificial Neural Network (ANN)

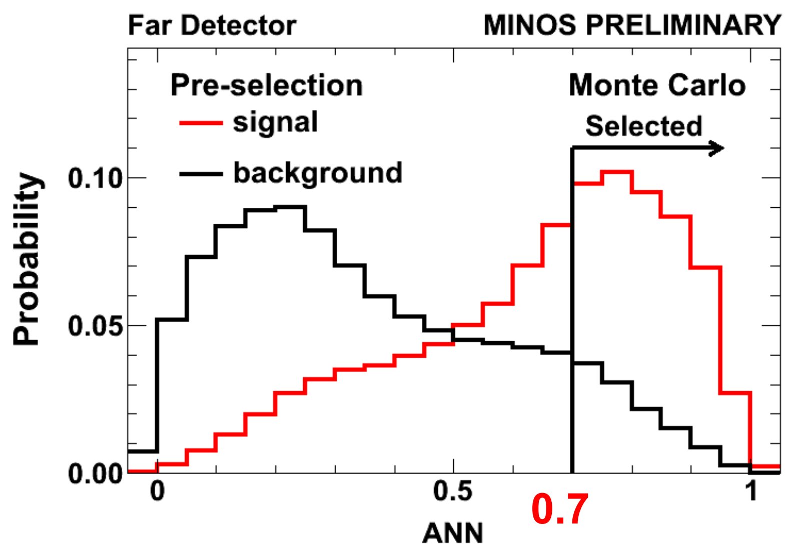






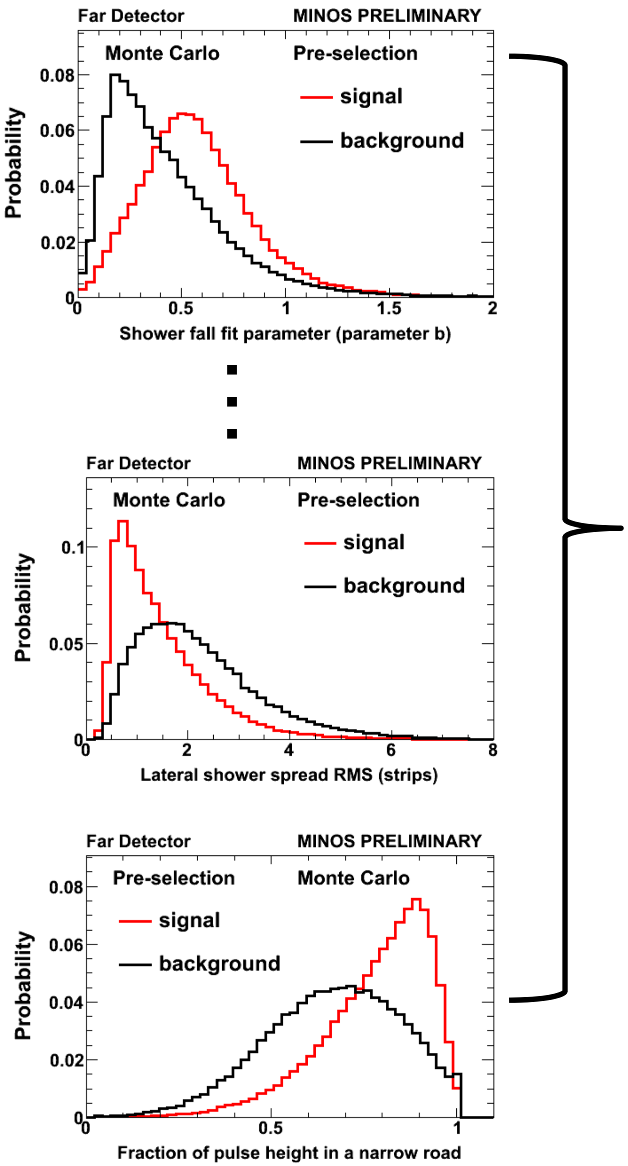
11 discriminating variables derived from the longitudinal and transverse profile of the energy deposition.

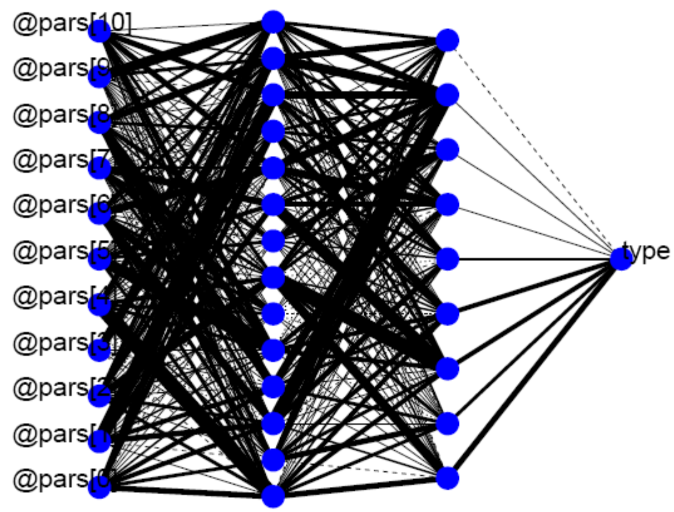
ANN



Build an neural net (ANN11) to enhance the signal/background separation and take into account the correlations between input variables.

ANN11 Retuning





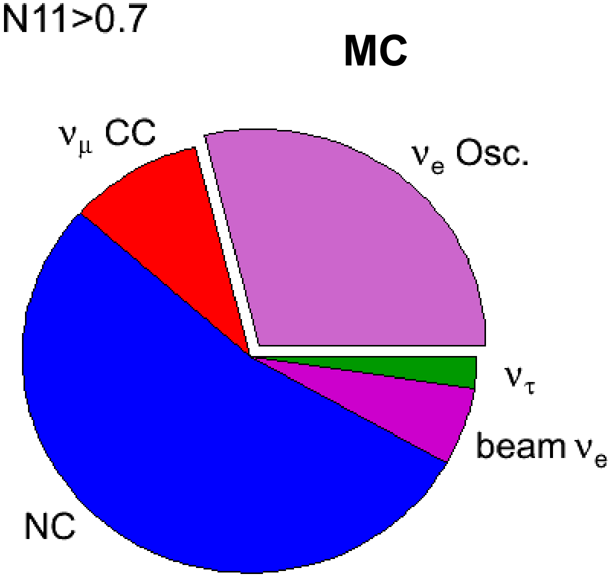
- The architecture of neural net are optimized with more hidden nodes (11:14:9:1)
- The size of training sample are increased by a factor of ten.
- All the input variables are normalized before processing.

Cut Value Determination

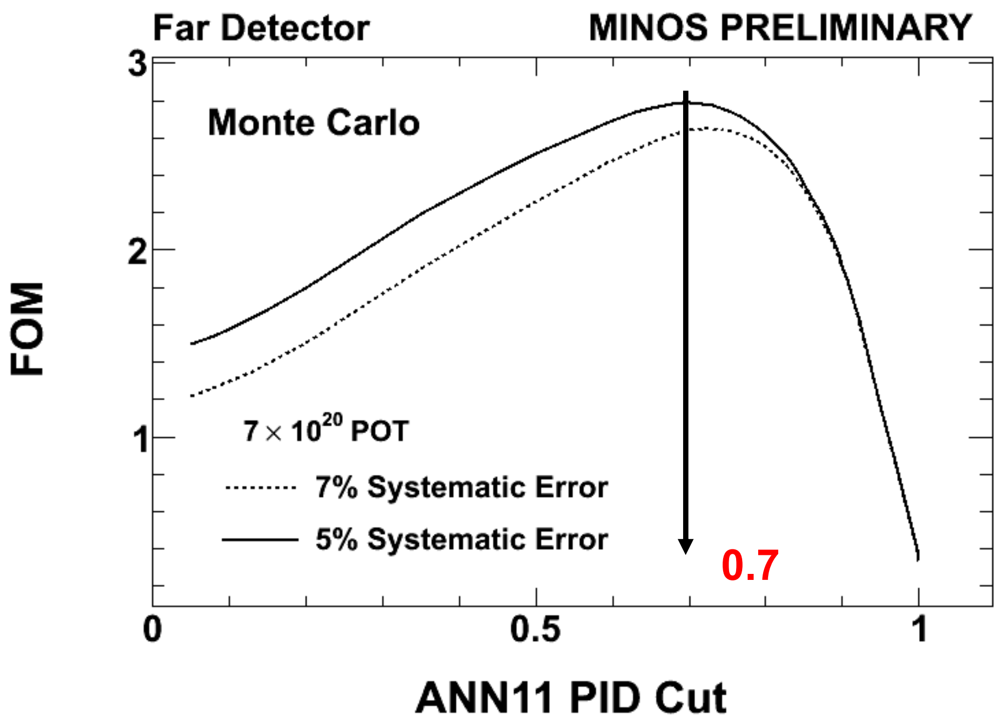
$$FOM = \frac{N_{sig}}{\sqrt{N_{bg} + (\sigma_{sys}^{bg})^2 N_{bg}^2}}$$

$$\sigma_{sys}^{bg} = (5/7)\%$$

ANN11>0.7



Signal/Background 1:2.5



- The cut value is determined by maximizing sensitivity to observe signal events.

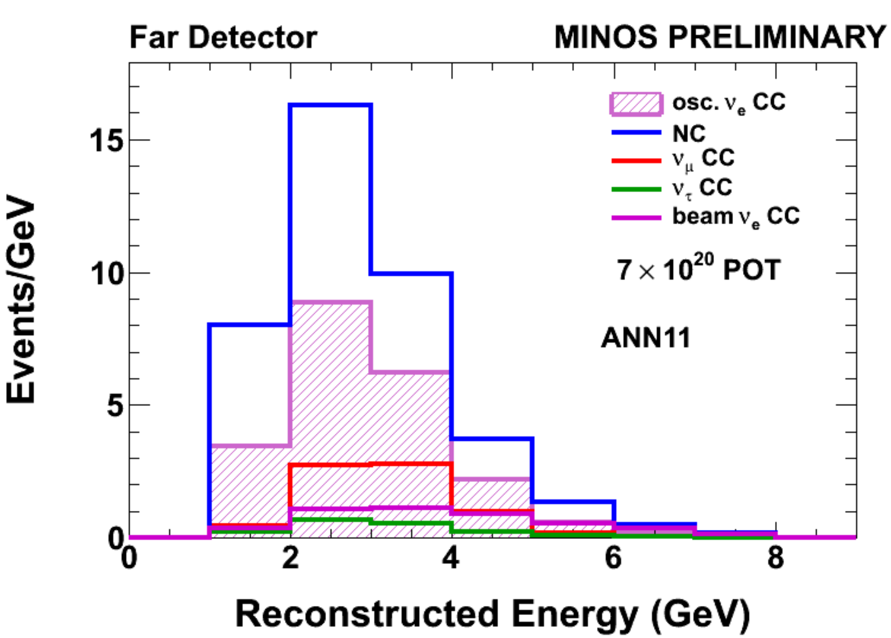
$\sin^2(2\theta_{13})=0.15$ (CHOOZ limit),

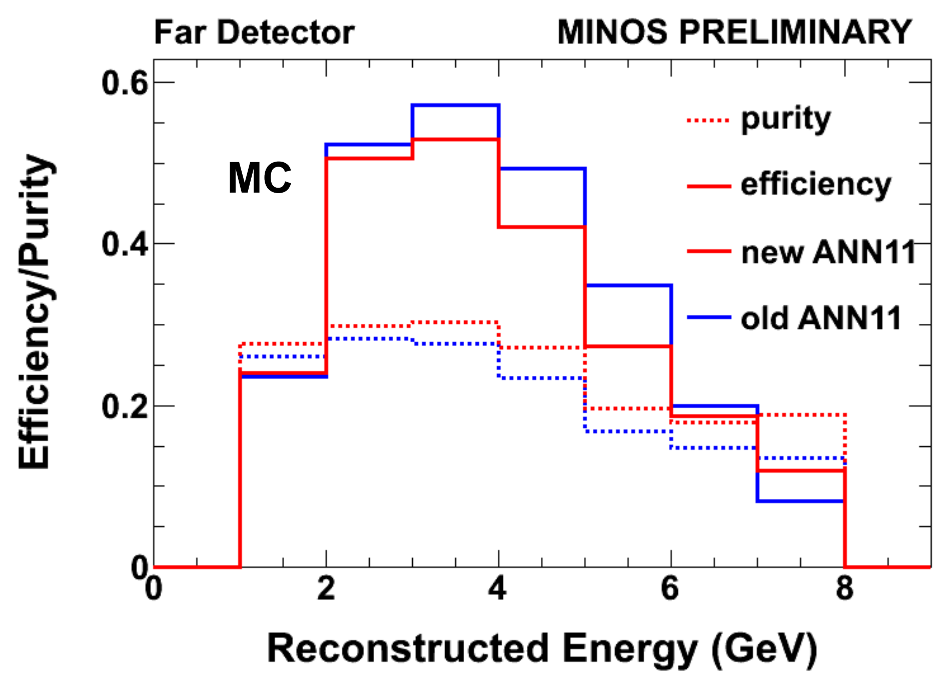
$|\Delta m^2_{31}|=2.43e\text{-}3eV^2$, $\sin^2(2\theta_{23})=1$.

POT = 7E20 (4-year exposure).

Signal Efficiency and Background Rejection

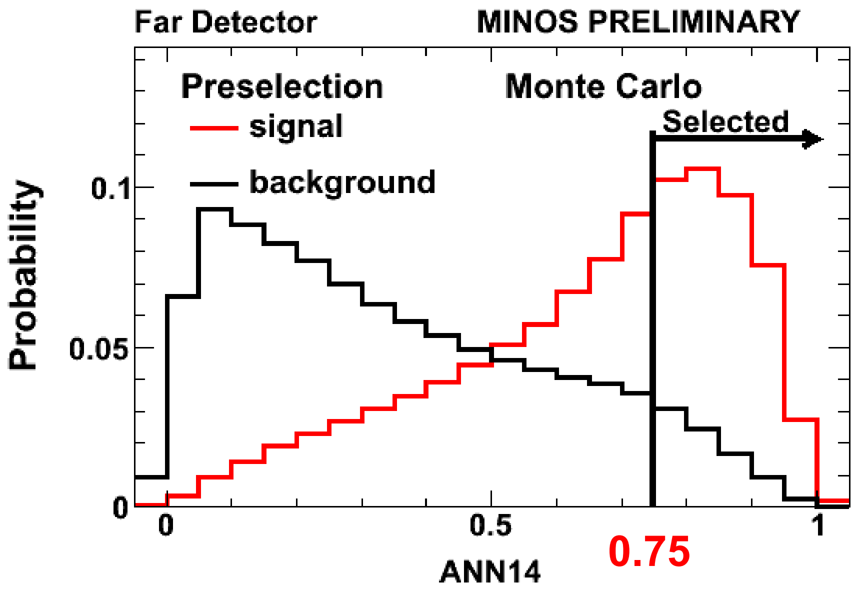
PID	signal	background	FOM (MC only)
ANN11(new)	37.6%	97.9%	2.77σ
ANN11(old)	39.8%	97.6%	2.66σ

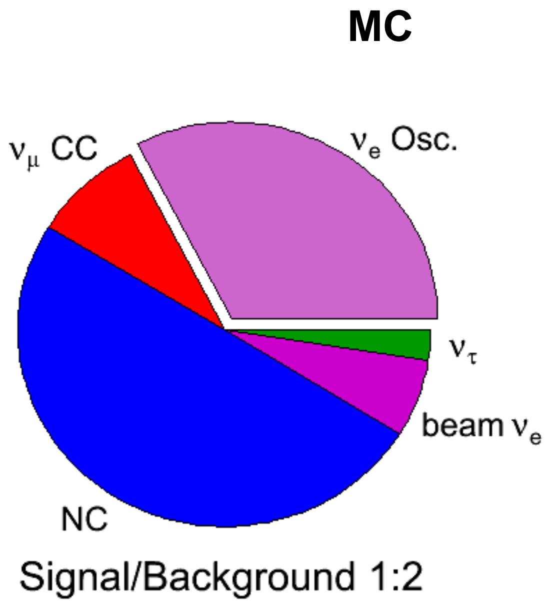




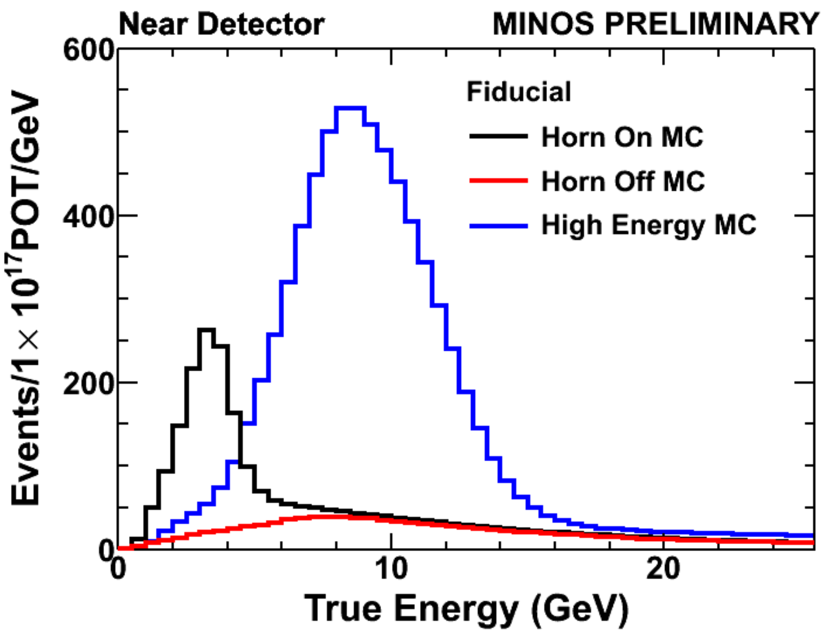
Further Improvement Attempt

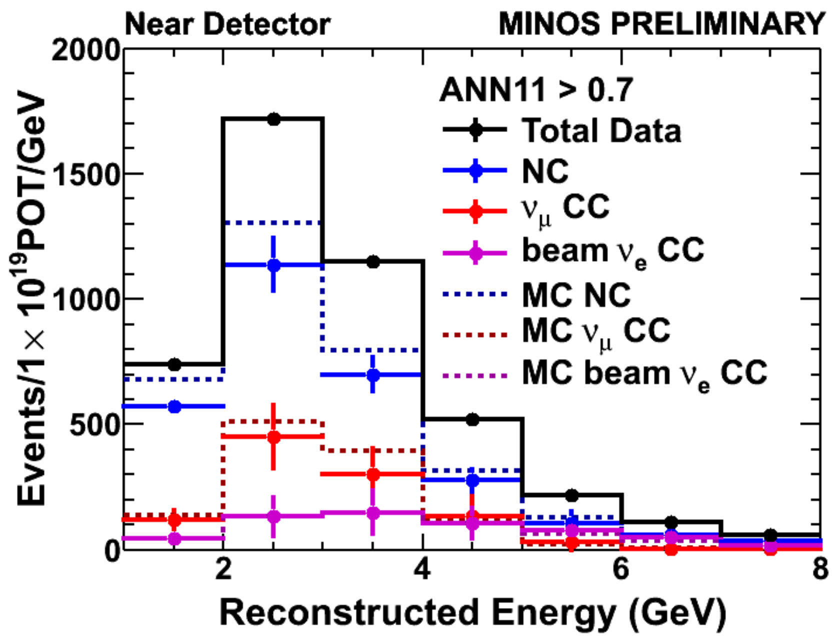
- 20 more new variables are added into a large neural net
- Systematically removing each variable to evaluate the weight of the variable.
- 14 most powerful variables are selected for the another PID: ANN14.
- A better signal/background discrimination power.
- Relatively large systematic uncertainties (7%).
- The FOM of ANN14 is effectively the same as ANN11 PID.





Decomposition & Extrapolation





Monte Carlo can't be relied on to determine the background components due to large uncertainties in the hadronization model. We can use ND data with different beam configurations to do the ND background decomposition

FD prediction for component α in energy bin i

$$F_i^{predicted,\alpha} = N_i^{\alpha} \times \left(\frac{f_i^{\alpha}}{n_i^{\alpha}} \right)$$

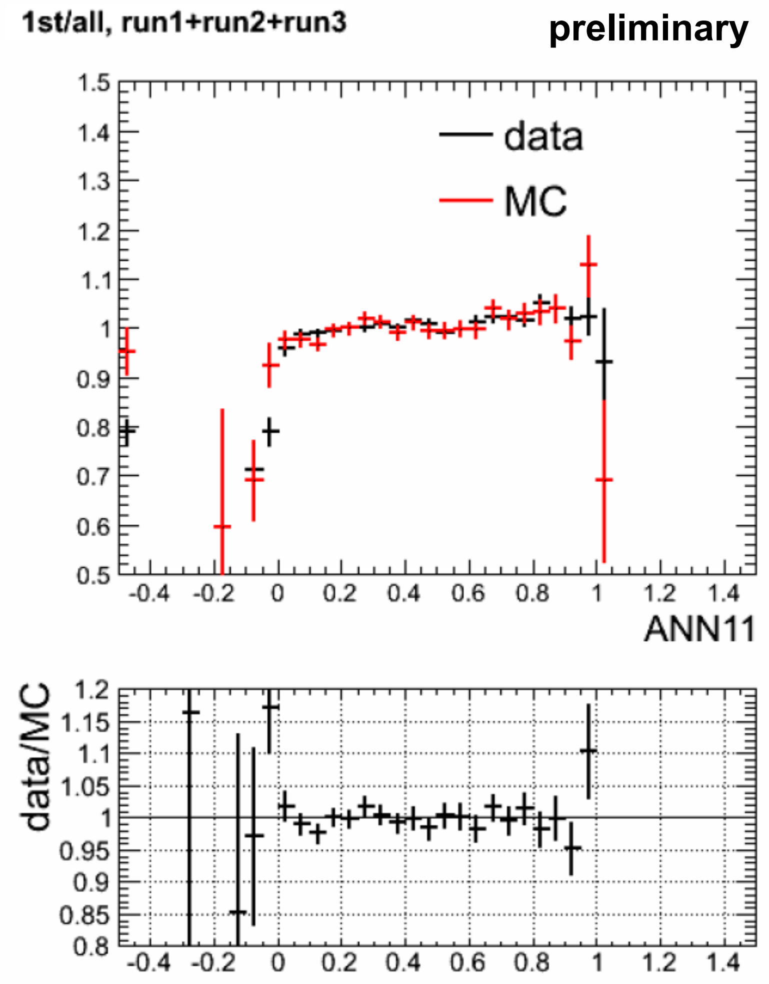
ND data (under N_i^{α})

F/N ratio of MC selected events from component α in energy bin i

Beam Intensity Uncertainties

- ND and FD have different beam intensity, and due to the high intensity beam in the ND, there are some late activities and noise.
- We analyze the first event .vs. all the events PID selection efficiency to estimate the intensity systematic error.
- The results shows the intensity effect is modeled quite well.

	ANN11		
All Runs	data	mc	data/mc
1^{st} event	0.117±0.001	0.121±0.001	
all events	0.114±0.001	0.118±0.000	
1st/all ratio	1.027±0.007	1.025±0.009	1.002±0.011

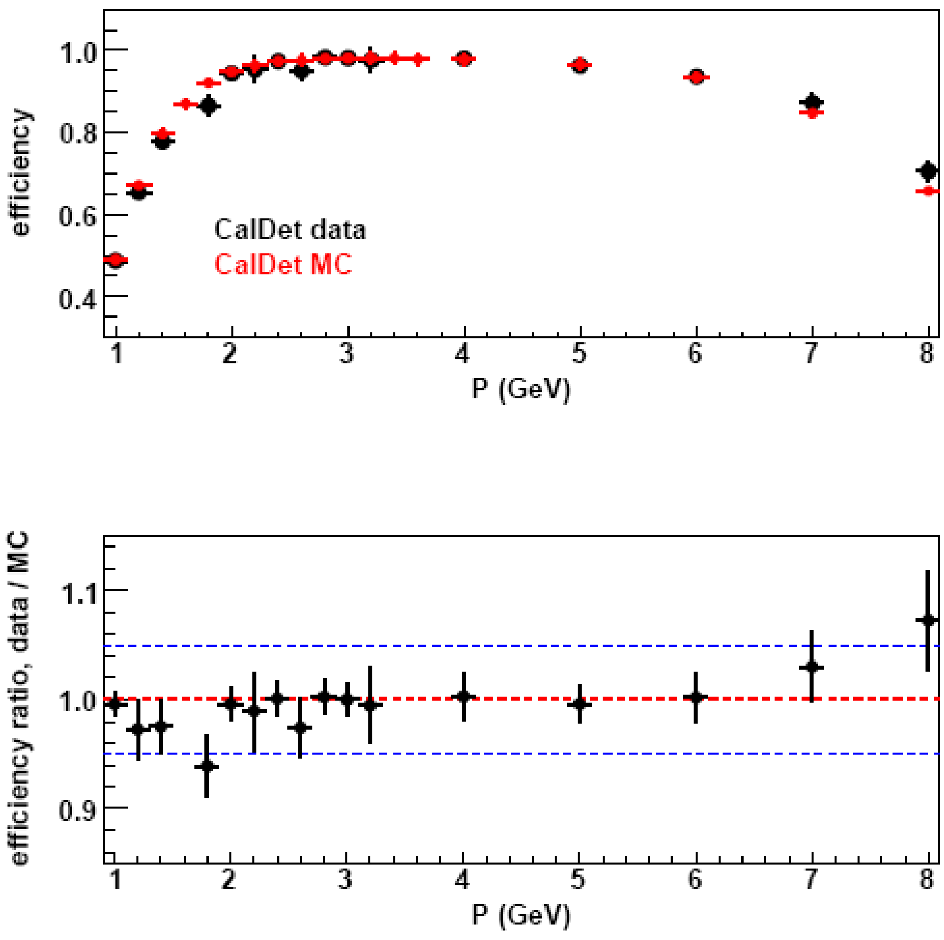


Background Systematic Uncertainty

Source of Uncertainty	Effect on Background Prediction
ND Decomposition	$\pm 2.8\%$
Calibration	$+2.8\%, -2.3\%$
Far/Near Normalization	$\pm 2.4\%$
Hadronization Model	$\pm 2.3\%$
ν_τ CC component	$\pm 1.7\%$
Intranuclear Model	$+0.9\%, -1.0\%$
Beam Model	$\pm 0.5\%$
Crosstalk	$\pm 0.4\%$
Cross Section	$\pm 0.1\%$
Total Background Systematic	$\mathbf{+5.6\%, -5.3\%}$

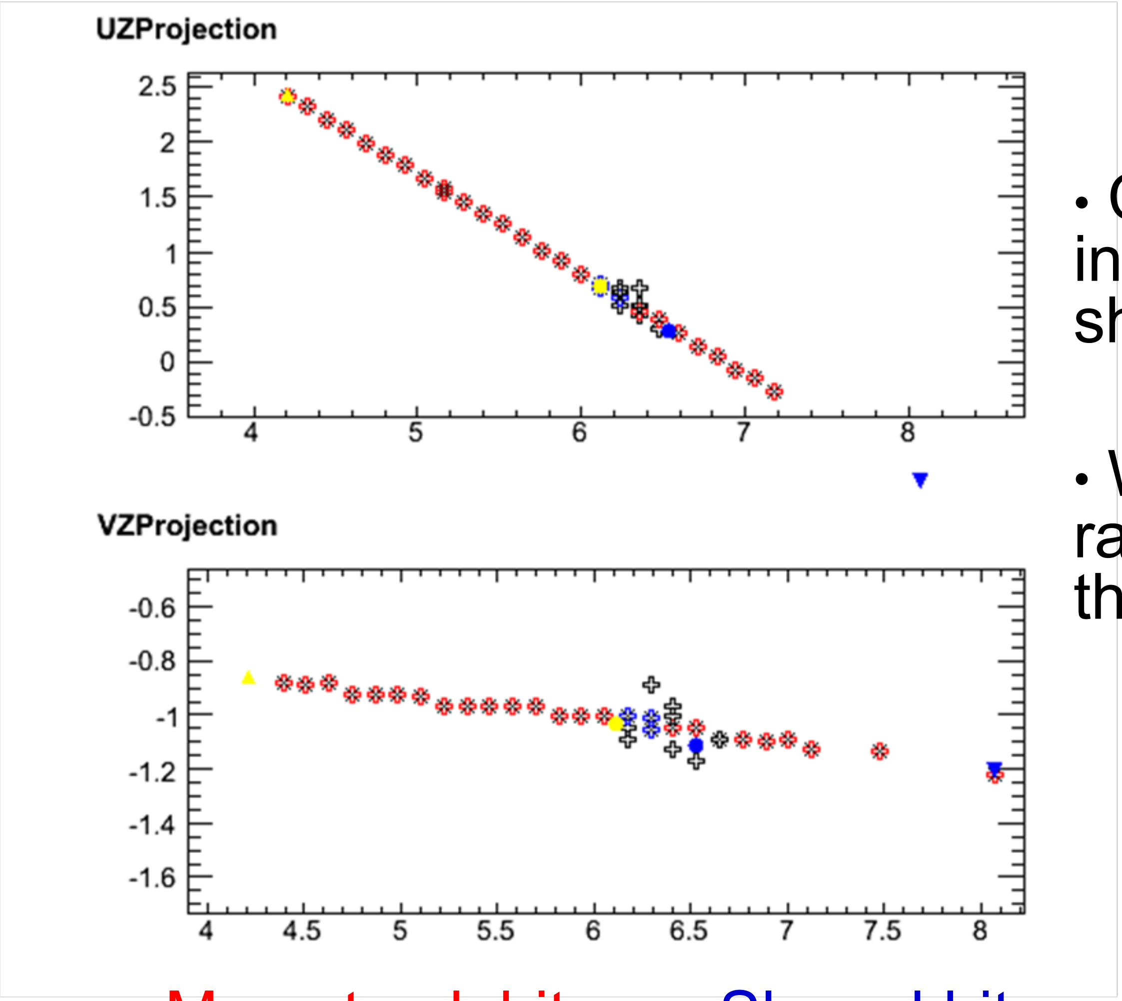
Expected Statistical Uncertainty ~14%

EM Shower Modeling Check: CalDet Data Sample



Single electrons are well modeled in the MINOS detector and the selection efficiency agrees with the simulation within 1.6%.

EM Shower Modeling Check: Cosmic-ray Muon Shower Sample

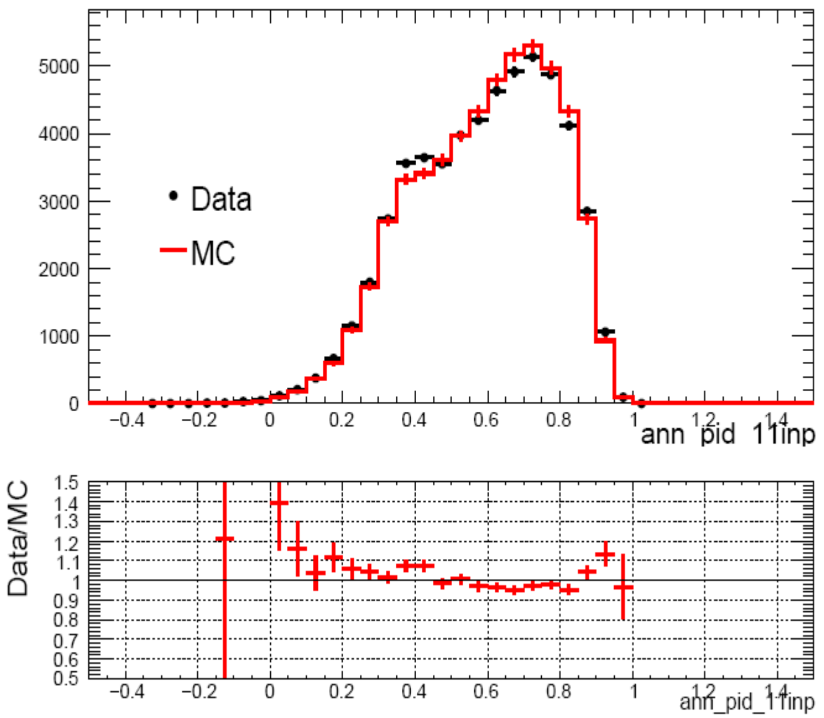


- Cosmic-ray muon induced bremsstrahlung showers are EM showers.
- We can use the cosmic ray showers sample to do the cross check.

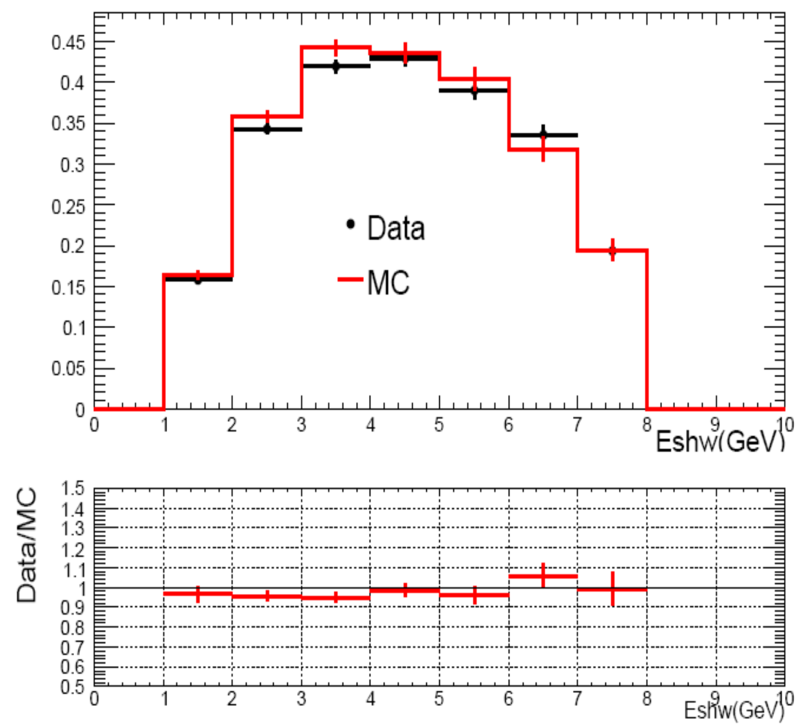
* Muon track hits   * Shared hits   ╬ Retained hits

EM Shower Modeling Check: Cosmic-ray Muon Shower Sample

ANN11 PID

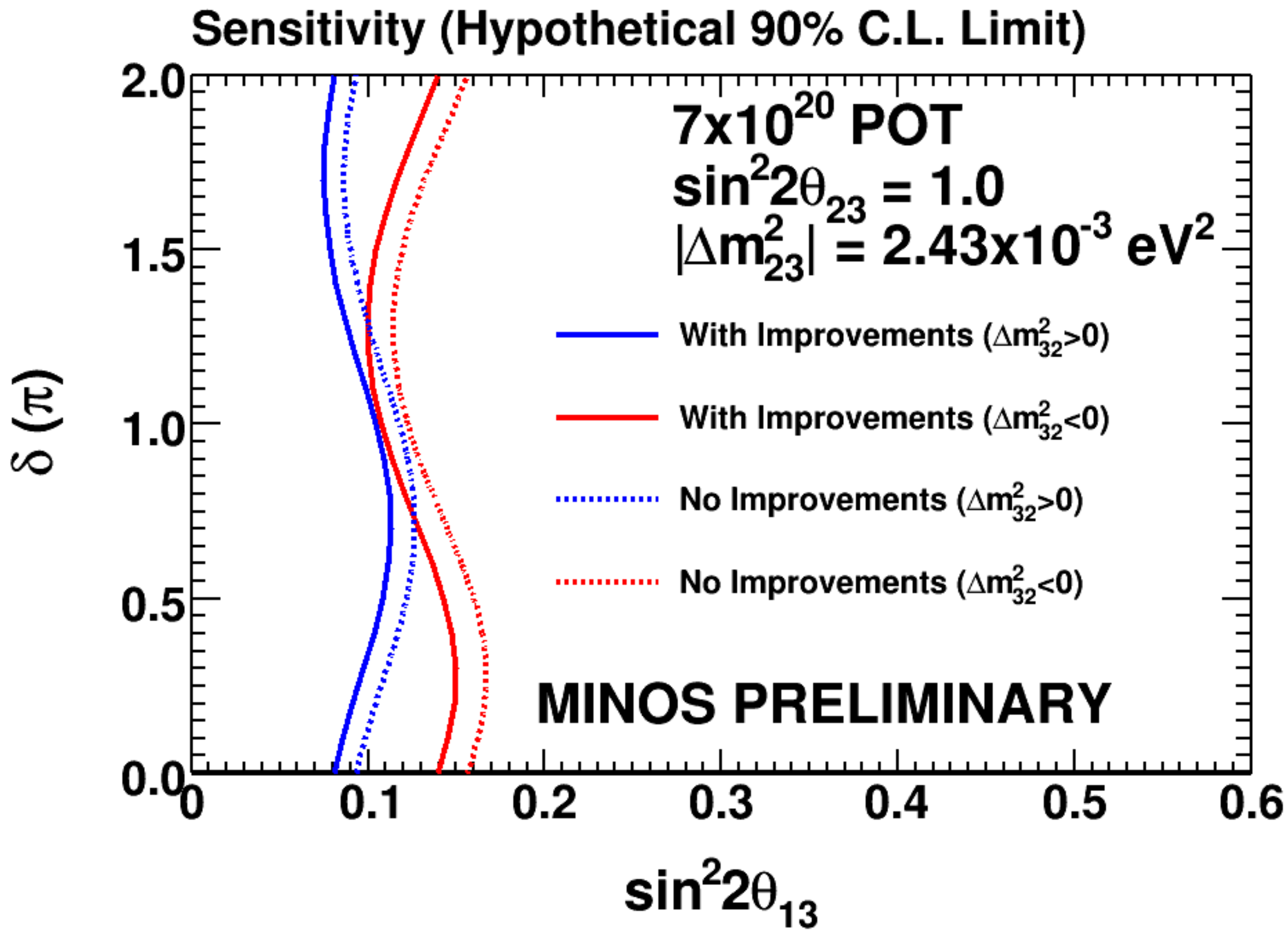


EM Shower Selection Efficiency



EM shower selection efficiencies of data and MC agree within 5%.

θ_{13} Sensitivity



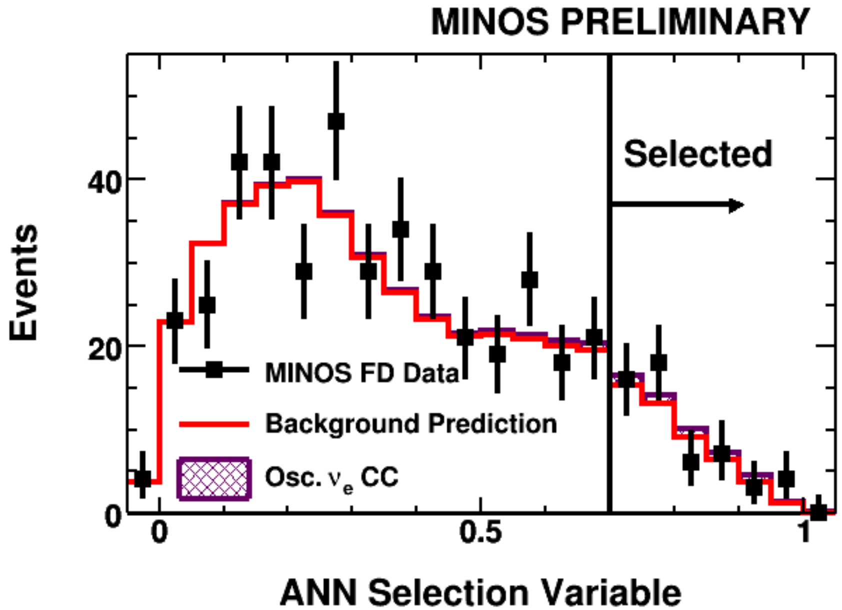
- Retuned ANN with better background rejection
- Improved background decomposition
- Reduced systematic uncertainty (7.3% → 5.6%) with improve MC simulation and event reconstruction

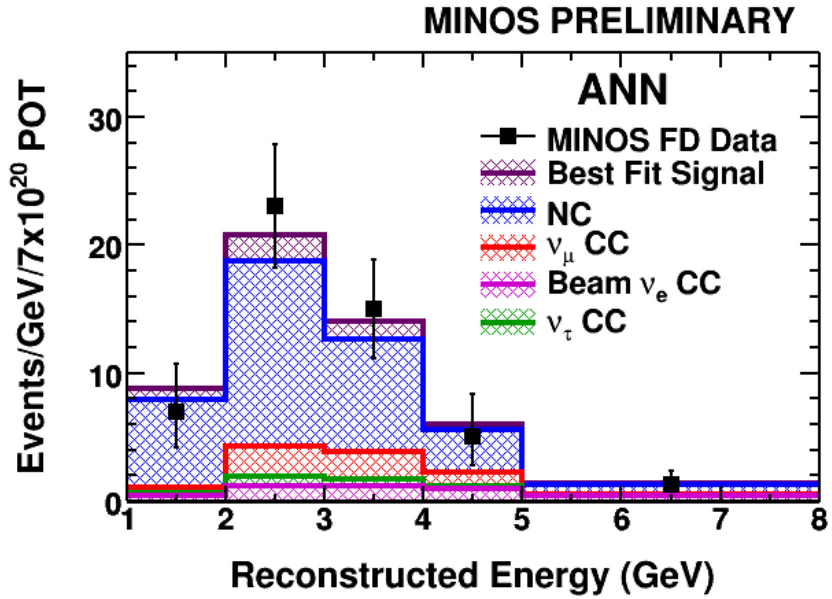
ν_e appearance Results

Expected background: 49.1 ± 7.0 (stat) ± 2.7 (syst)

Observation: 54 events, 0.7σ more than expectation

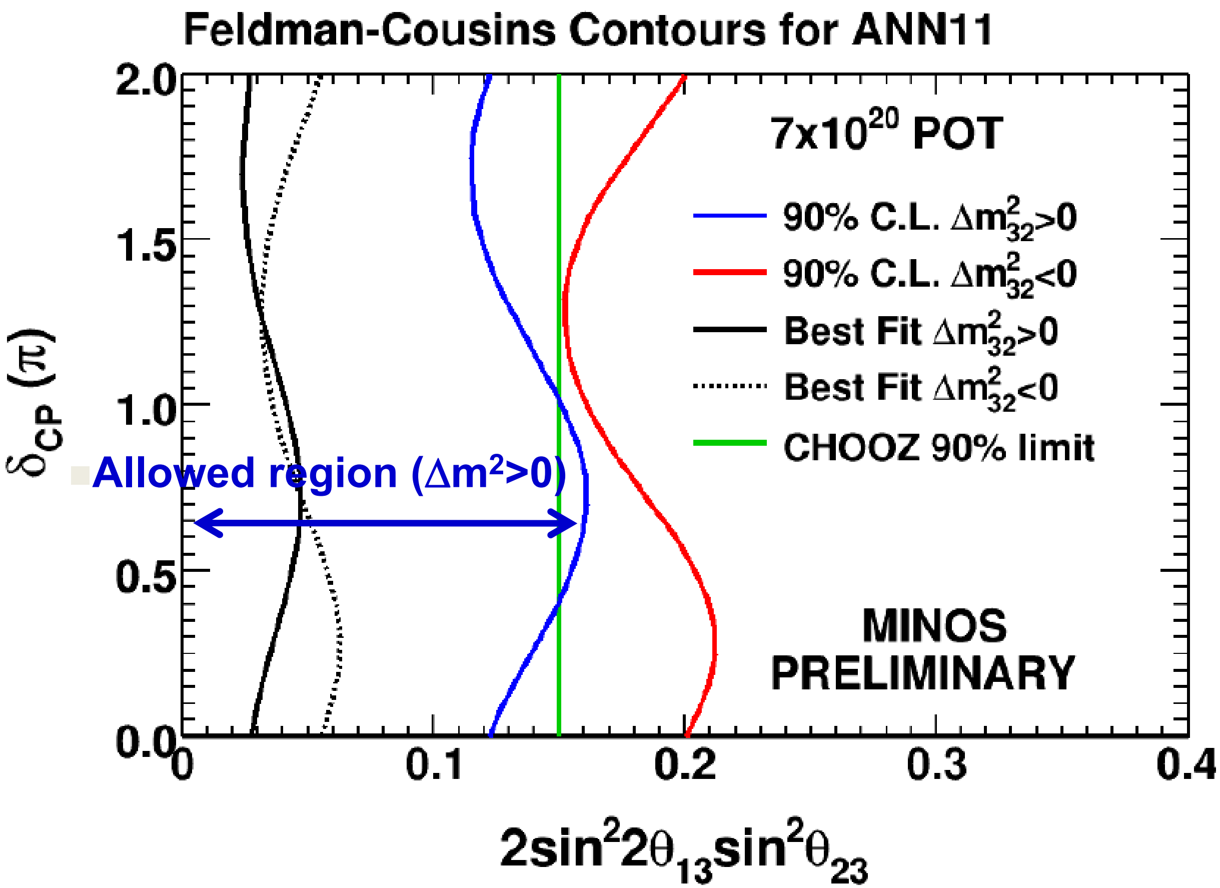
If θ_{13} is at the CHOOZ limit, we expect 23.7 signal events





- Assuming best fit value of θ_{13} at δ=0, normal hierarchy

90% Upper Limit for θ_{13}



At δ=0,

$\sin^2(2\theta_{13}) < 0.12$
(normal mass hierarchy)

$\sin^2(2\theta_{13}) < 0.20$
(Inverted mass hierarchy)

Best Fit:

$\sin^2(2\theta_{13}) = 0.027$
(normal mass hierarchy)

$\sin^2(2\theta_{13}) = 0.055$
(Inverted mass hierarchy)

Our 90% C.L. upper limit is beyond the CHOOZ limit assuming normal hierarchy for almost all values of δ

Summary

- MINOS data require $\sin^2(2\theta_{13})<0.12(0.20)$ at $\delta_{cp}=0$ for normal and inverted hierarchy.

- Remaining questions :
  - Is ν_3 mostly ν_μ or ν_τ? ($\theta_{23}>\pi/4$, $\theta_{23}<\pi/4$, or $\theta_{23}=\pi/4$?)
  - What is the ν_e component of ν_3? ($\theta_{13}\neq 0$?)
  - Is CP-invariance violated in neutrino oscillations? ($\delta_{cp}\neq 0,\pi$?)
  - What is the neutrino mass hierarchy?
  - ……..

backup

Other selection methods

All consistent

Official selector (ANN11):

Observed: **54**
BG expected: **49 ± 7(stat.) ± 3(syst.)**
Difference: **0.67σ**

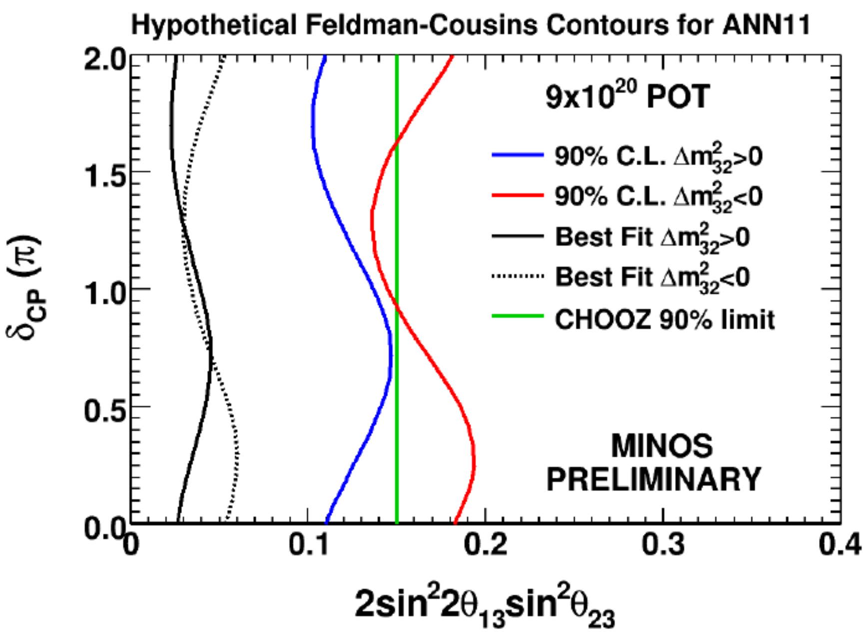
Alternate selector (ANN14):

Observed: **36**
BG expected: **34 ± 6(stat.) ± 2(syst.)**
Difference: **0.35σ**

Alternate selector (PAR):

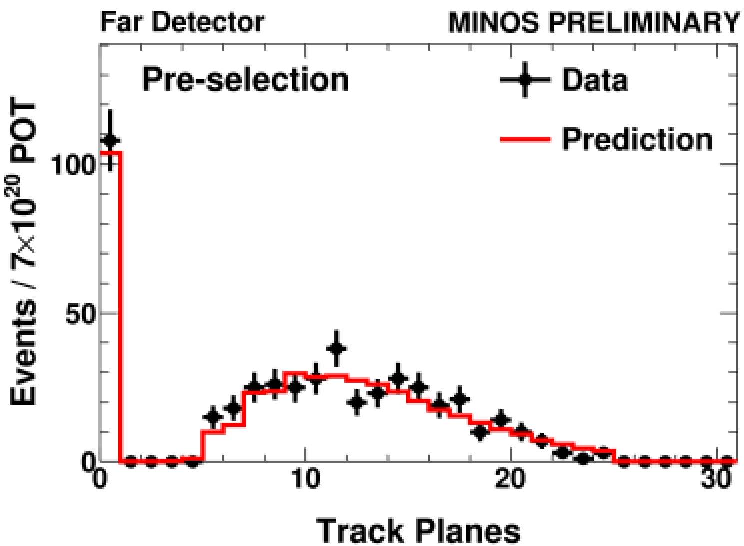
Observed: **59**
BG expected: **54 ± 7(stat.) ± 3(syst.)**
Difference: **0.64σ**

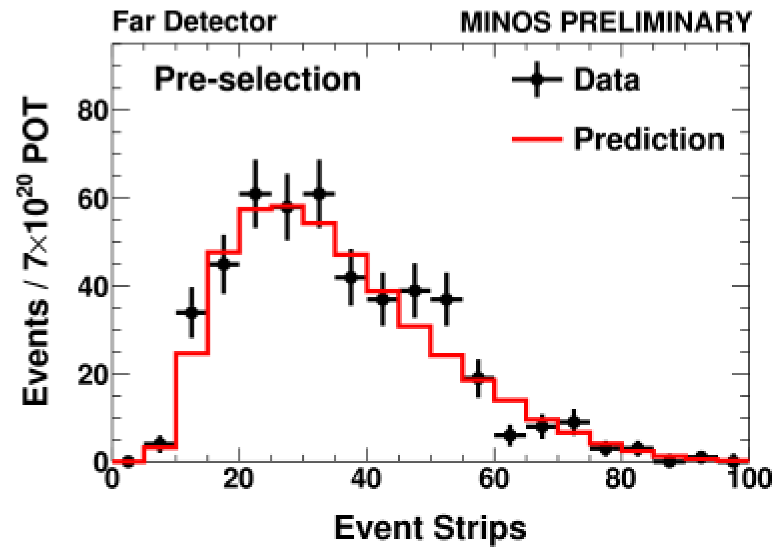
Future

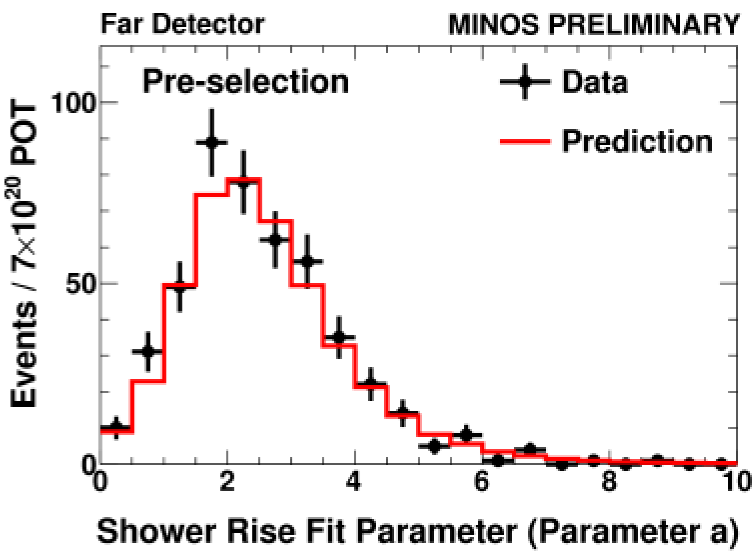


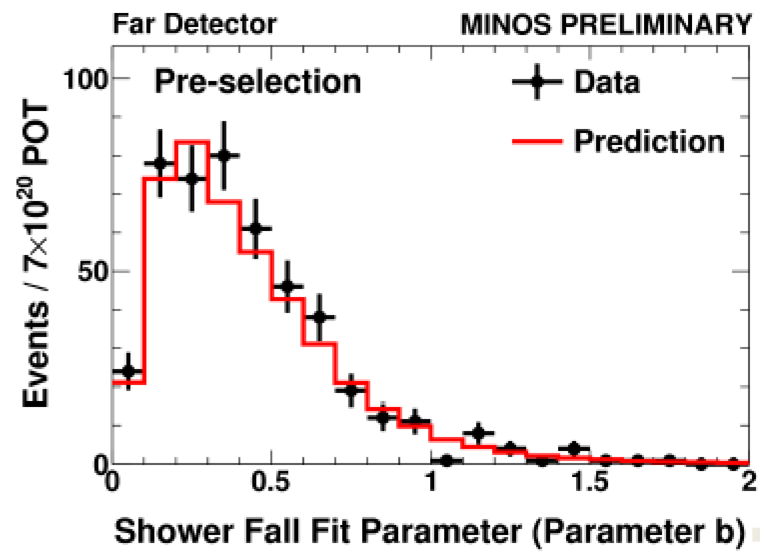
Expected results with 9×10^{20} POT assuming the data excess persists

Event Shape in the Far Detector

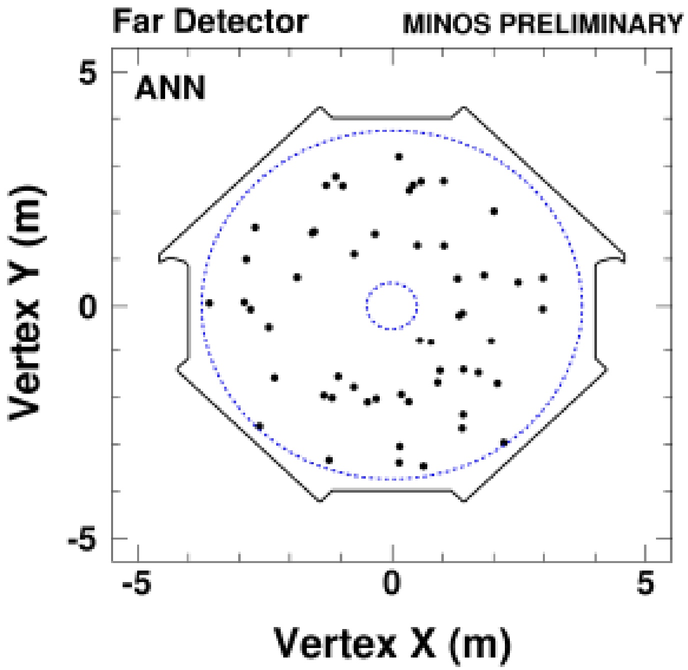


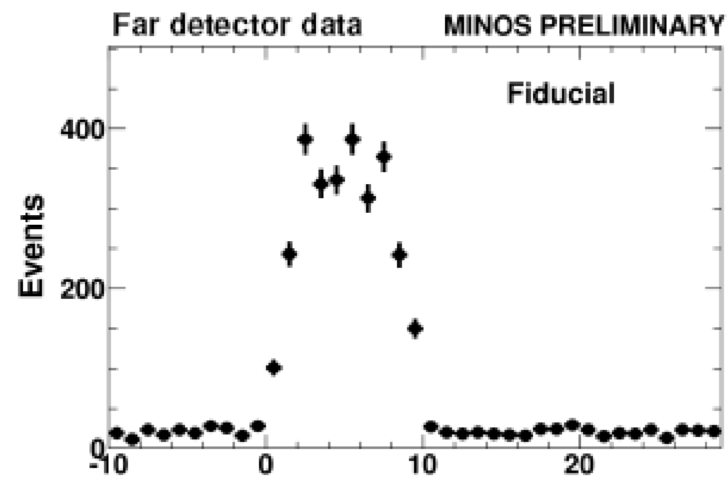


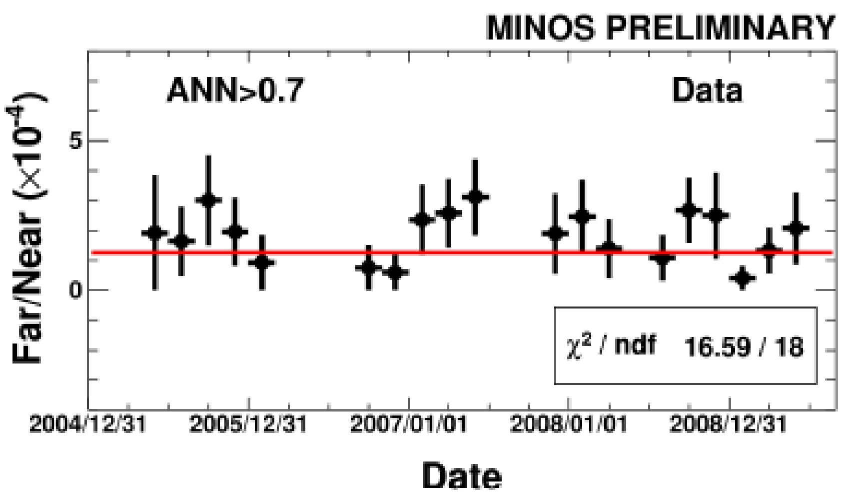


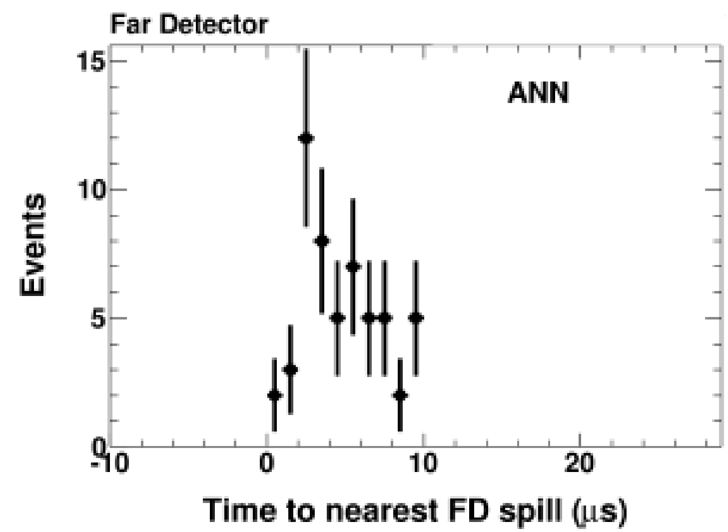


Position and times









ANN variables

Fraction of pulseheight in a n-plane window (n=2,4,6): the fraction of energy deposited in sliding window of n planes divided by the event energy.

Fraction of pulseheight in a narrow road: fraction of total visible energy deposited in a 3 strip window along the shower axis.

Lateral shower spread (RMS): the RMS of the transverse energy deposition profile, where the RMS is computed over a 9 strip window around the pulseheight weighted center of the event.

Radius of 90% energy containment (strips): the number of strips away from the peak of the transverse energy distribution to contain 90% of the energy deposited in a 9 strip window around the pulseheight weighted center of the event.

Shower fit raise and fall parameters (a and b): parameters from the fit to the longitudinal profile of the energy deposition of an event.

Longitudinal energy projection: the energy weighted sum of the distance to each strip projected along the detector z axis.

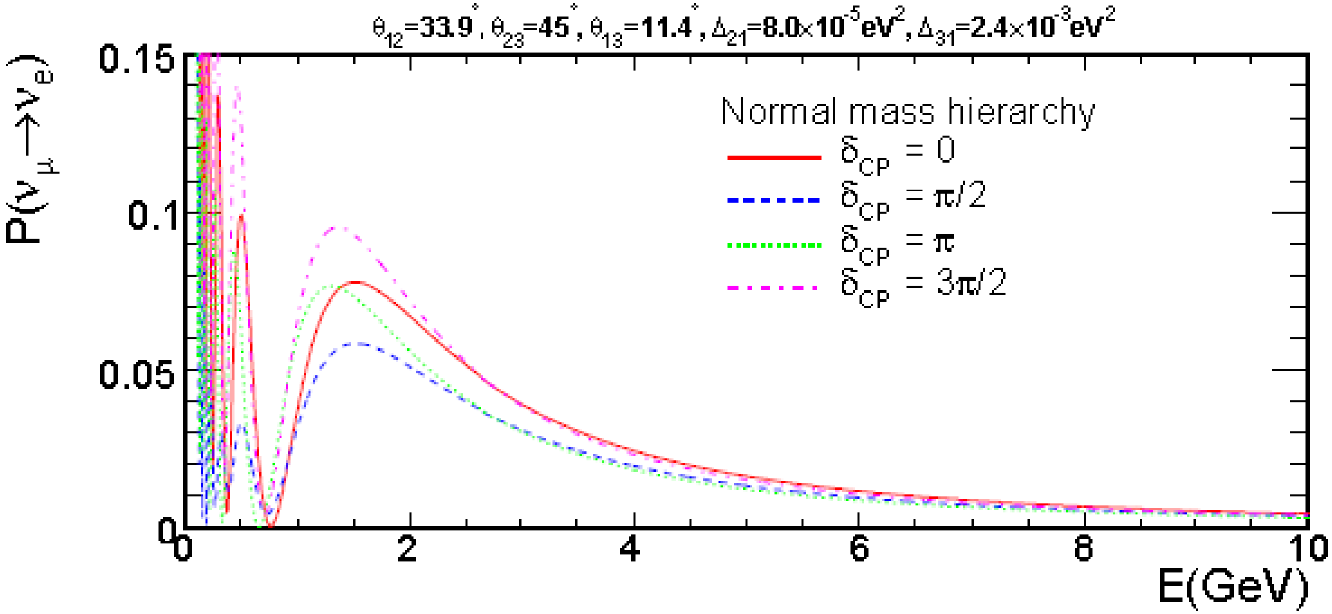
Minimal spanning tree summed weight: the sum of the minimum distances that join the hits of larger than average pulseheight hits in an event.

Fraction of pulseheight in 8 highest PH strips: the fraction of pulseheight in the highest 8 strips divided by the event energy.

3-flavor oscillation

$$\begin{aligned} P(\nu_\mu \to \nu_e) &= \left|e^{-i(\Delta_{32}+\delta)} \sin 2\theta_{13} \sin\theta_{23} \sin\Delta_{31} + \sin 2\theta_{12} \cos\theta_{23} \cos\theta_{13} \sin\Delta_{21}\right|^2 \\ &= \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2\Delta_{31} + \cos^2\theta_{13} \cos^2\theta_{23} \sin^2 2\theta_{12} \sin^2\Delta_{21} \\ &\quad + J_r \sin\Delta_{21} \sin\Delta_{31} \cos(\Delta_{32}+\delta) \\ &= P_{atm} + P_{sol} + P_{int} \end{aligned} \qquad (2.7)$$

$$J_r \equiv \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \cos\theta_{13}$$



Neutrino Mixing

- The Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix can be factorized into 4 experimental regimes:

Atmospheric

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{-i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

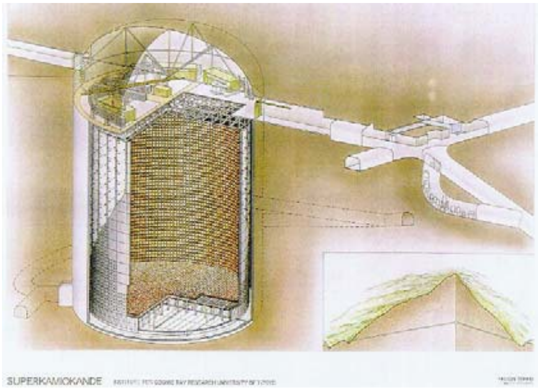
- (23) Sector identified with atmospheric mixing

✓ driven by larger $|\Delta m^2_{32}| \sim 2.4\times10^{-3}\,\mathrm{eV}^2$

✓ $\theta_{23} \sim 45^\circ$ (Is it maximal?)

✓ experiments with L/E ~ 500 km/GeV

[SuperK, K2K, MINOS]



SuperK

Neutrino Mixing

- The Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix can be factorized into 4 experimental regimes:

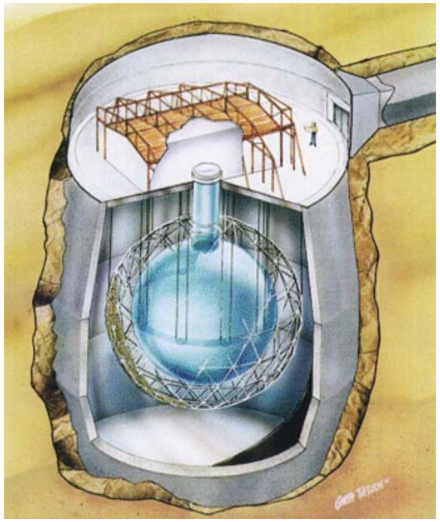
Solar

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{-i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- (12) Sector identified with solar mixing

✓ driven by small $\Delta m^2_{21} \sim 7.6\times10^{-5}\,\mathrm{eV}^2$ and moderately large $\theta_{12} \sim 34°$

✓ Reactor + Solar experiments at L/E ~ 15,000 km/GeV [SNO/Kamland]



SNO

Neutrino Mixing

- The Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix can be factorized into 4 experimental regimes:

Cross-mixing

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \boxed{\begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{-i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix}} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- (13) Sector mixing not yet observed

✓ θ_{13} is small (θ_{13}<10° at 90% C.L.)

✓Reactor experiment (CHOOZ/Palo Verde) + accelerator experiments L/E ~ 500km/GeV (K2K/MINOS)

✓ Is θ_{13} zero? (Double CHOOZ / Daya bay)

✓ Is there CP violation in the lepton sector?

(next generation experiments: T2K/Nova/LBNE)

Daya bay

Neutrino Mixing

- The Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix can be factorized into 4 experimental regimes:

Majorana

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{-i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- Majorana phases

✓ two majorana phases are not observable in the oscillation experiments.

✓ They can only be measured by Neutrinoless double beta decay experiments.

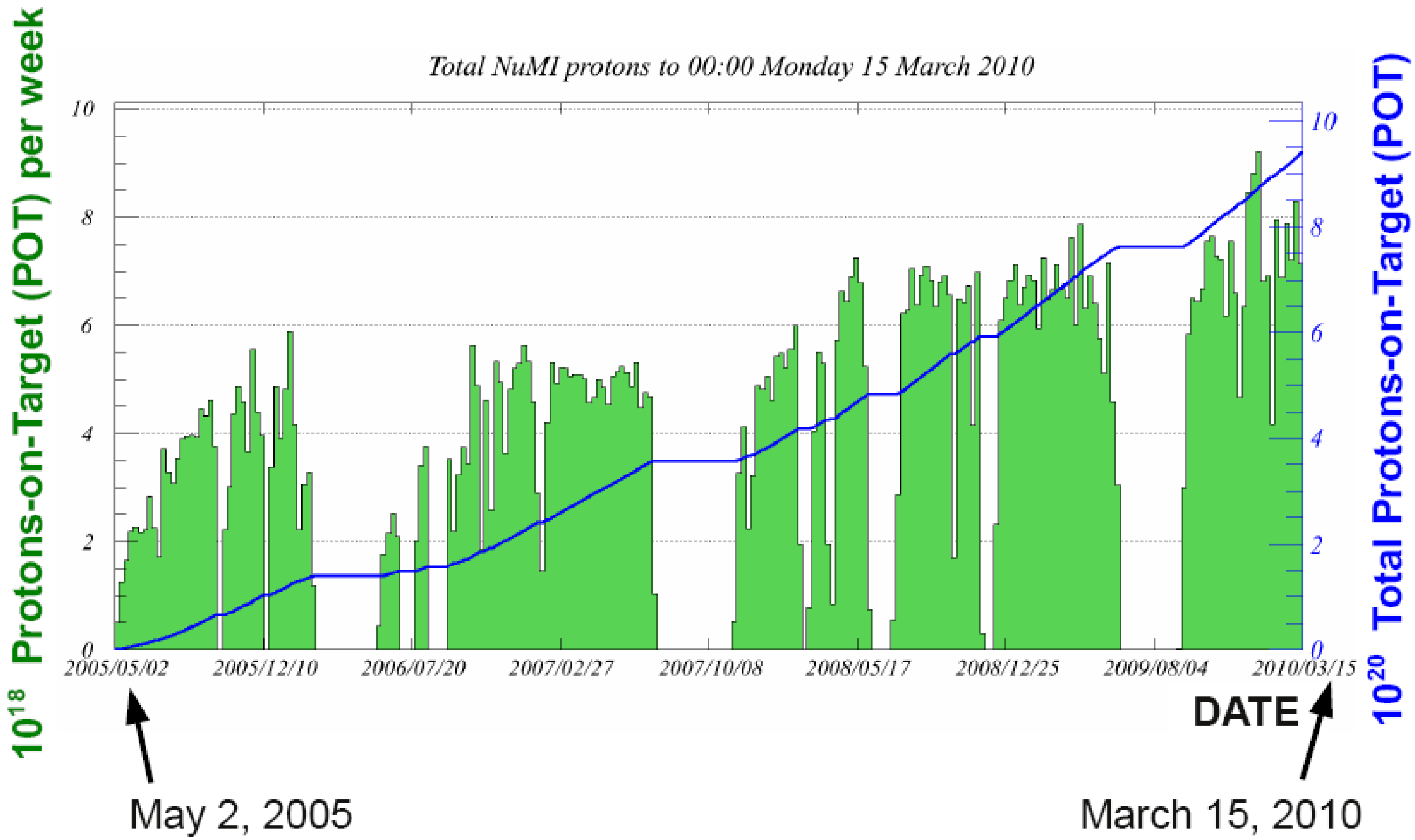
✓ Remaining questions: Dirac neutrino or Majorana neutrino?

Some Remaining Physics Questions

- Is ν_3 mostly ν_μ or ν_τ? ($\theta_{23}>\pi/4$, $\theta_{23}<\pi/4$, or $\theta_{23}=\pi/4$?)
- What is the ν_e component of ν_3? ($\theta_{13} \neq 0$?)
- Is CP-invariance violated in neutrino oscillations? ($\delta_{cp} \neq 0,\pi$?)
- What is the neutrino mass hierarchy?

➢ All of these can be address in neutrino oscillation experiments if we get lucky, that is θ_{13} is large enough.

➢ Mass-driven neutrino oscillations lead to a new picture of lepton sector of the standard model.

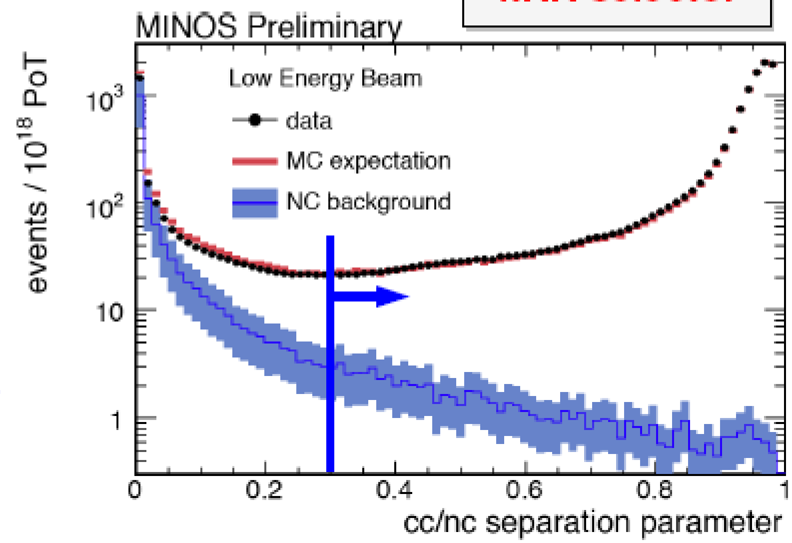


Total NuMI protons to 00:00 Monday 15 March 2010
10^{18} Protons-on-Target (POT) per week
10^{20} Total Protons-on-Target (POT)
0
2
4
6
8
10
2005/05/02
2005/12/10
2006/07/20
2007/02/27
2007/10/08
2008/05/17
2008/12/25
2009/08/04
2010/03/15
DATE
May 2, 2005
March 15, 2010

Muon neutrino disappearance

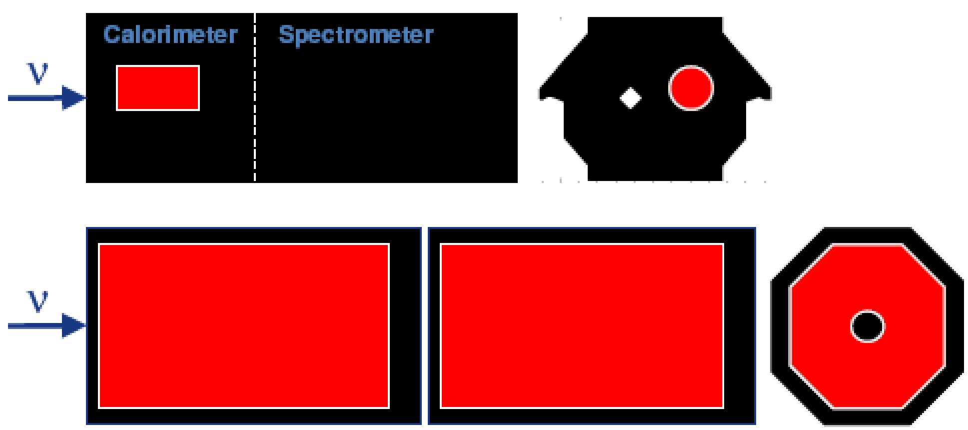
- Start by measuring ν_μ charged current rate in **near detector**
- *Selection:*
  - **Fiducial volume** (below)
  - Beam **timing**, **cosmic** removal
  - How "**track-like**" is the event? – a ***k*-nearest-neighbors** algorithm using:
    - *track length*
    - *mean pulse height in each place*
    - *fluctuation in pulse heights*
    - *transverse track profile*

***k*NN selector**



Near det.

Far det.

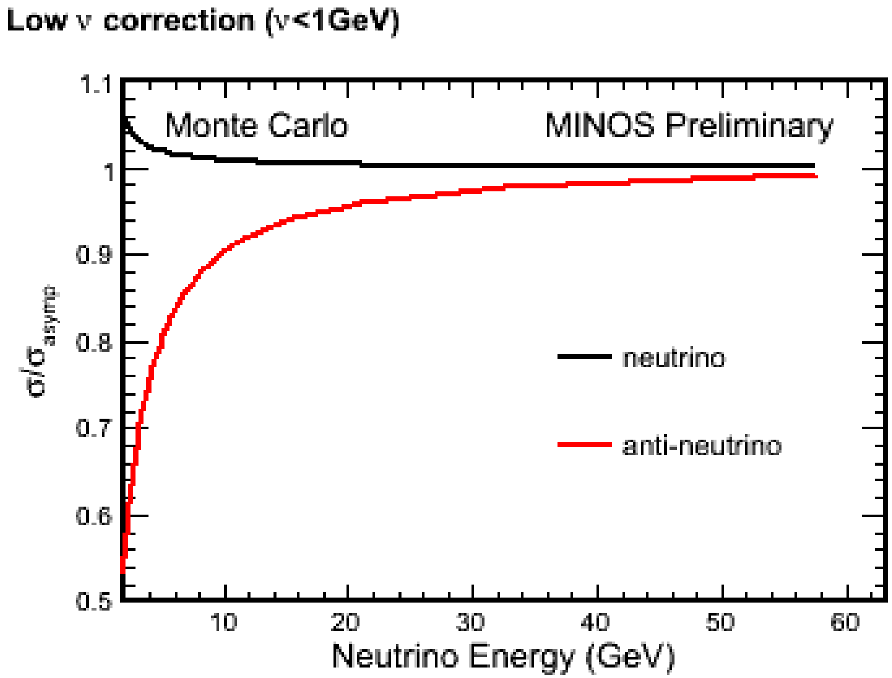


Fiducial regions (in red)

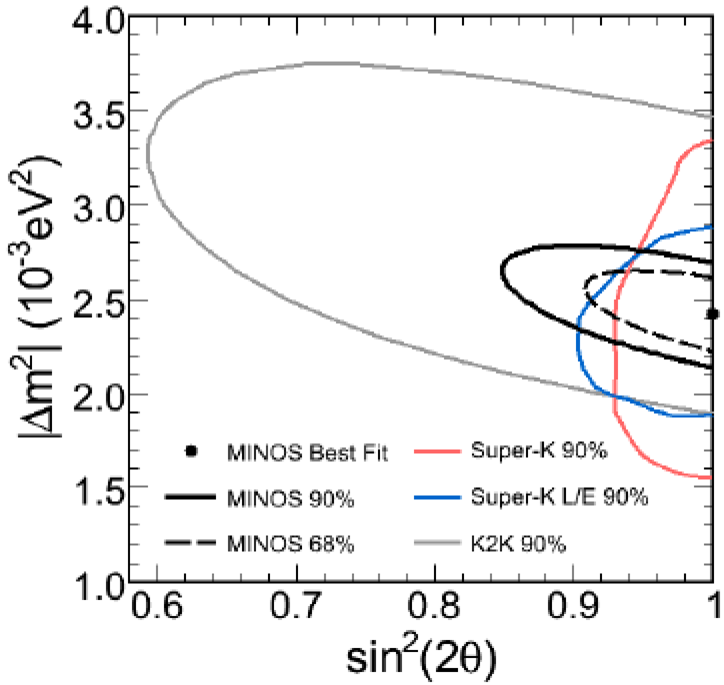
ν_0 Correction

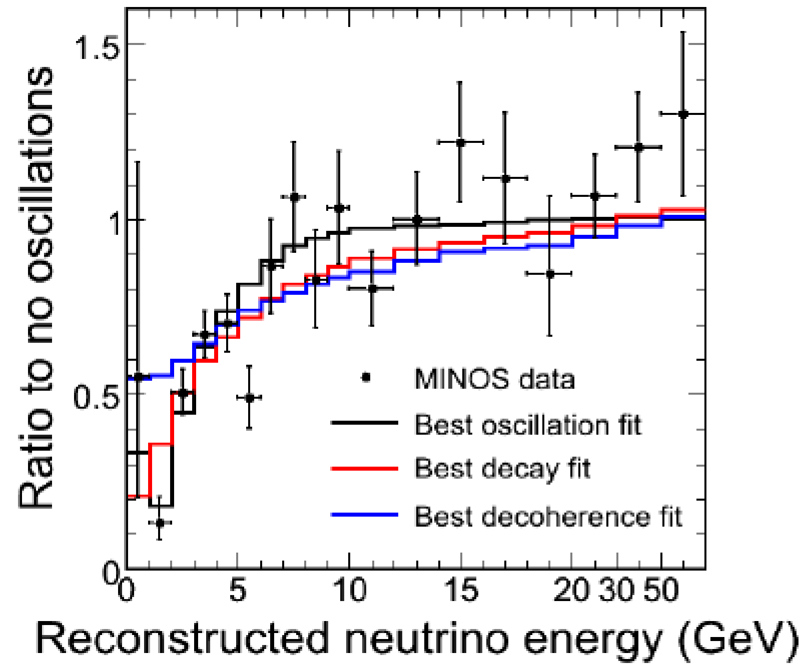
$$\Phi \propto \frac{N(E)_{(\nu \le \nu_0)}}{\int_0^{\nu_0}\left(1+\frac{B}{A}\frac{\nu}{E}-\frac{C}{A}\frac{\nu^2}{2E^2}\right)d\nu}$$

With small but finite ν_0, we need to take the low-ν correction, which is calculated with the *NEUGEN* xsection model.



- Advantage:
  - Only dependent on the neutrino interaction cross-section which can be derived without invoking the nucleon structure and type of interactions: scaling(DIS) or non-scaling (QE/RES) process.
- Disadvantage:
  - Sensitive to the muon momentum scale





Oscillation interpretation:

- Parameter space shown above.
- Most precise Δm_{atm}^2 measurement:

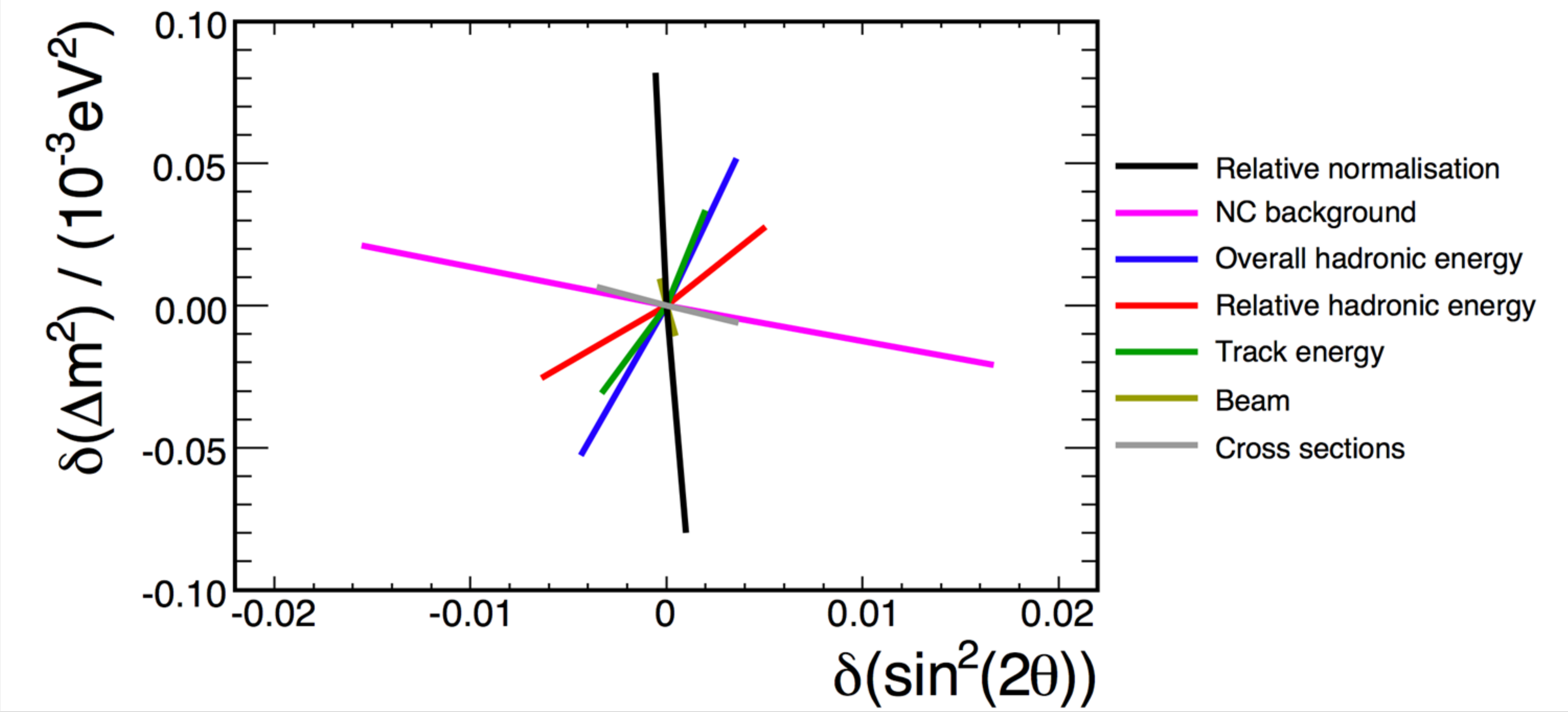
$$\Delta m_{atm}^2 = (2.43 \pm 0.13) \times 10^{-3} \text{ eV}$$

(Uses 3.36 protons-on-target. More than twice this has been collected.)

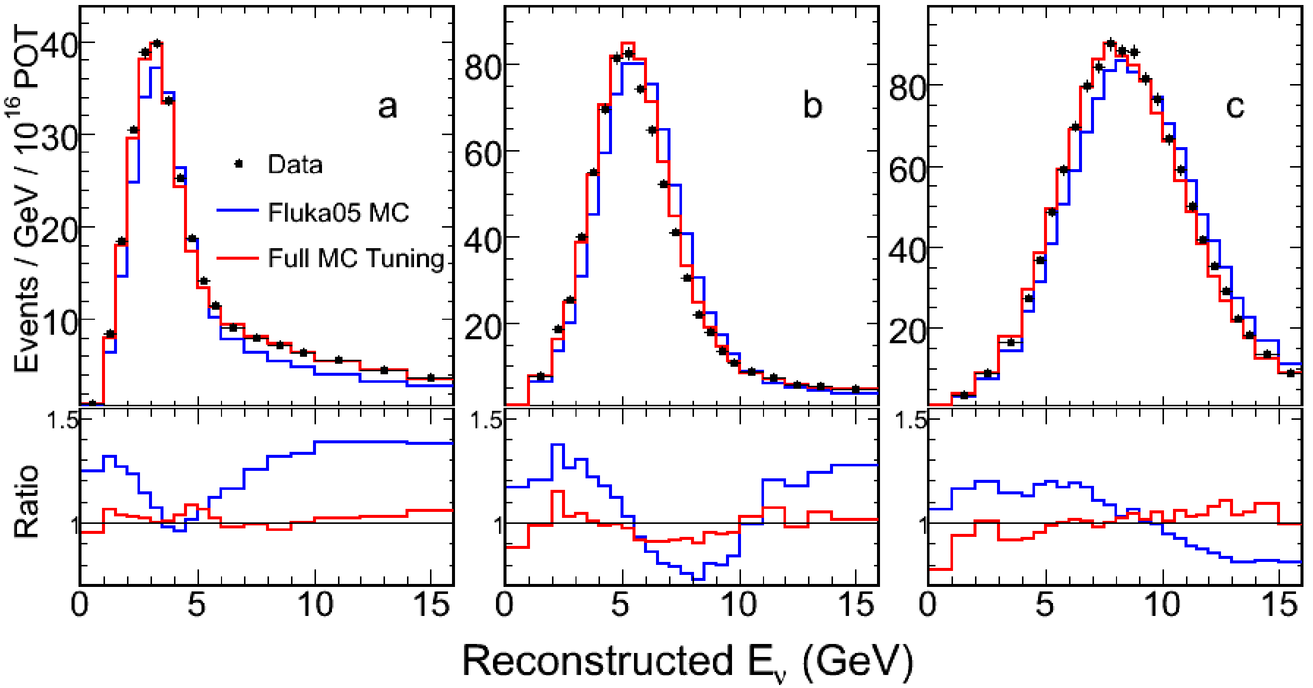
Strongly disfavored alternative interpretations:

- Neutrino decay: 3.7σ
  (5.4σ with NC sample)
- Decoherence: 5.7σ

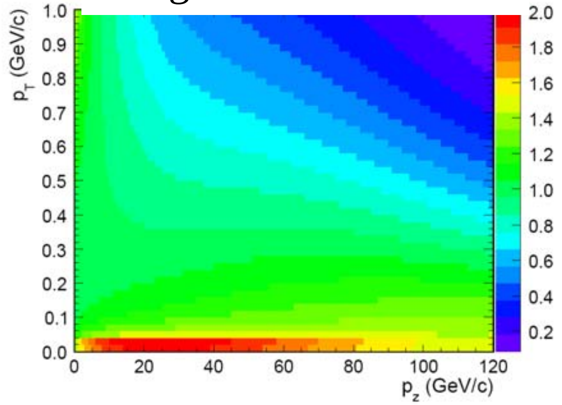
CC Systematic Uncertainties

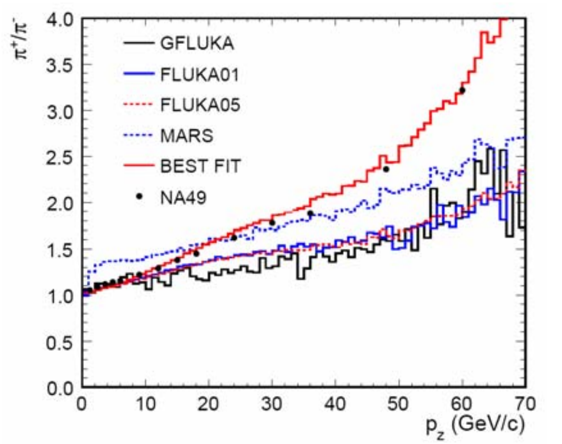


Standard Hadron Production Tuning



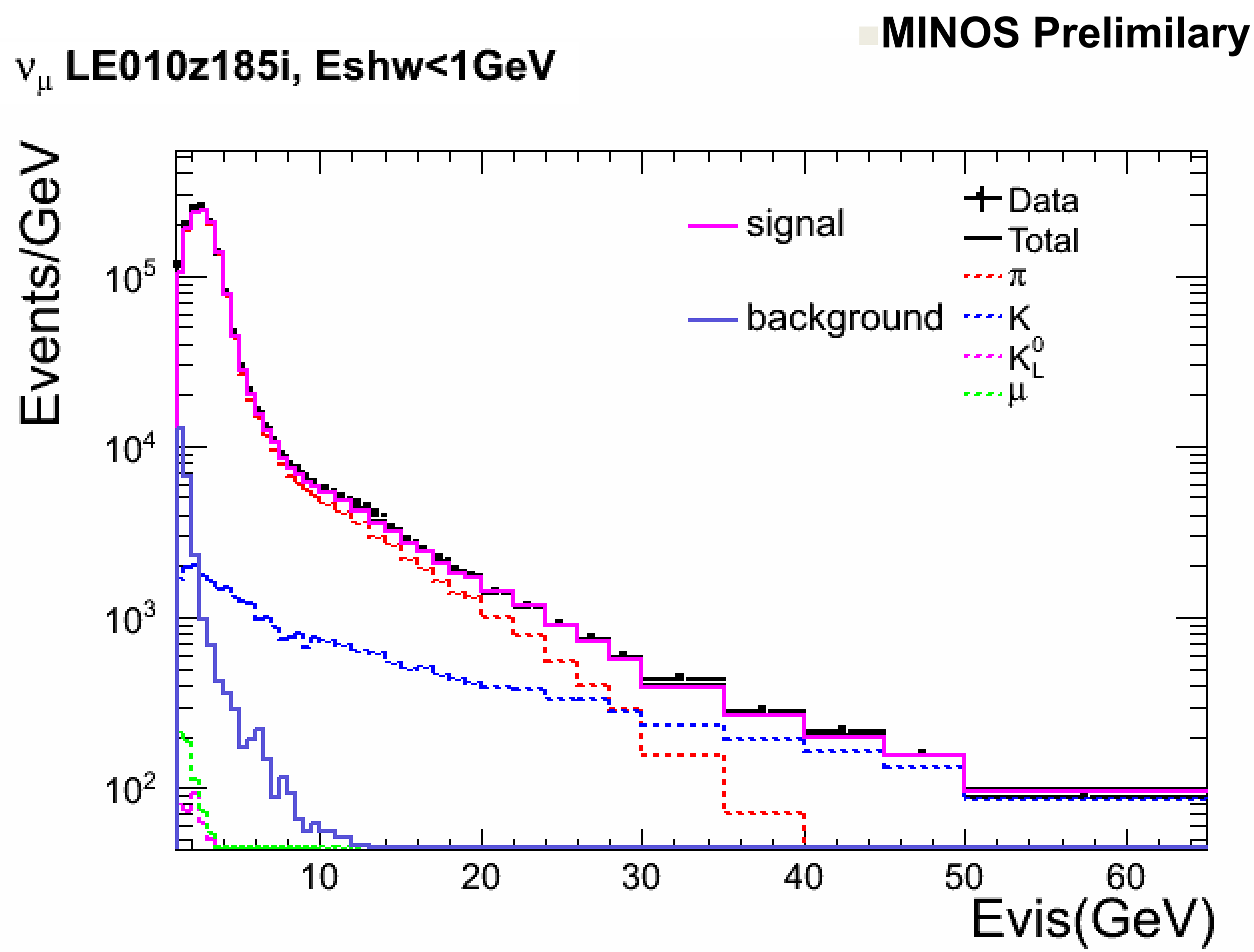
Weights for Fluka05 π^+





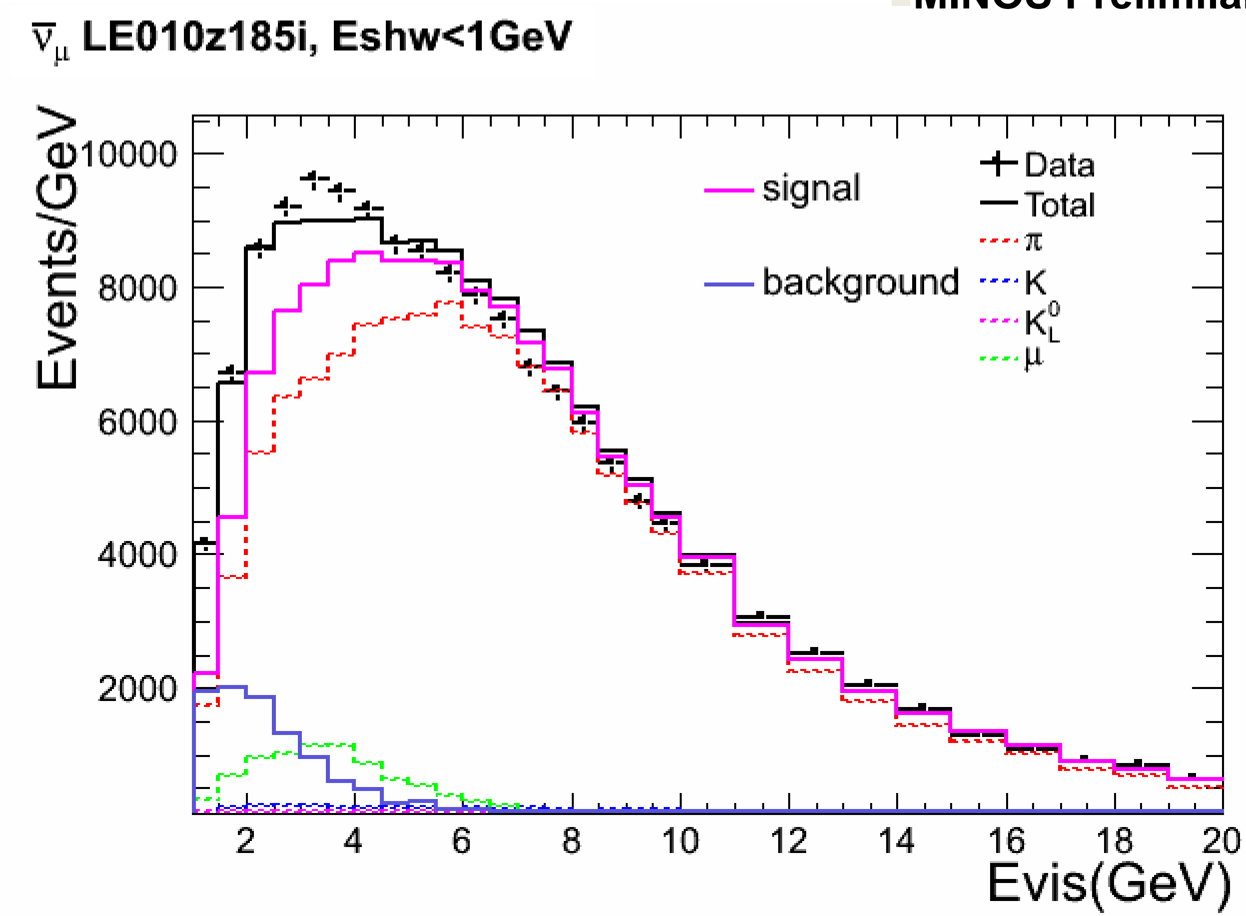
- 3 different beam configurations
- Same hadron production, different focusing
- Default hadron simulation: Fluka05
- Tune hadron production to improve data/MC agreement

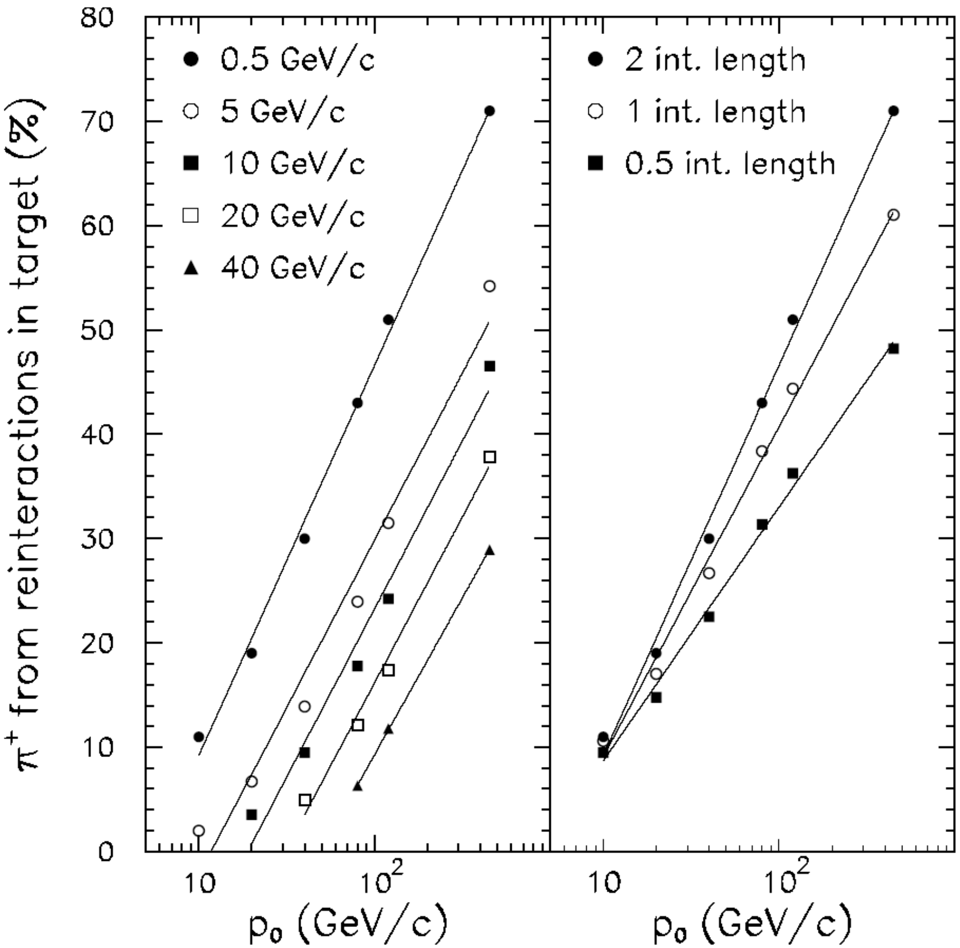
ν_μ low-nu data sample composition



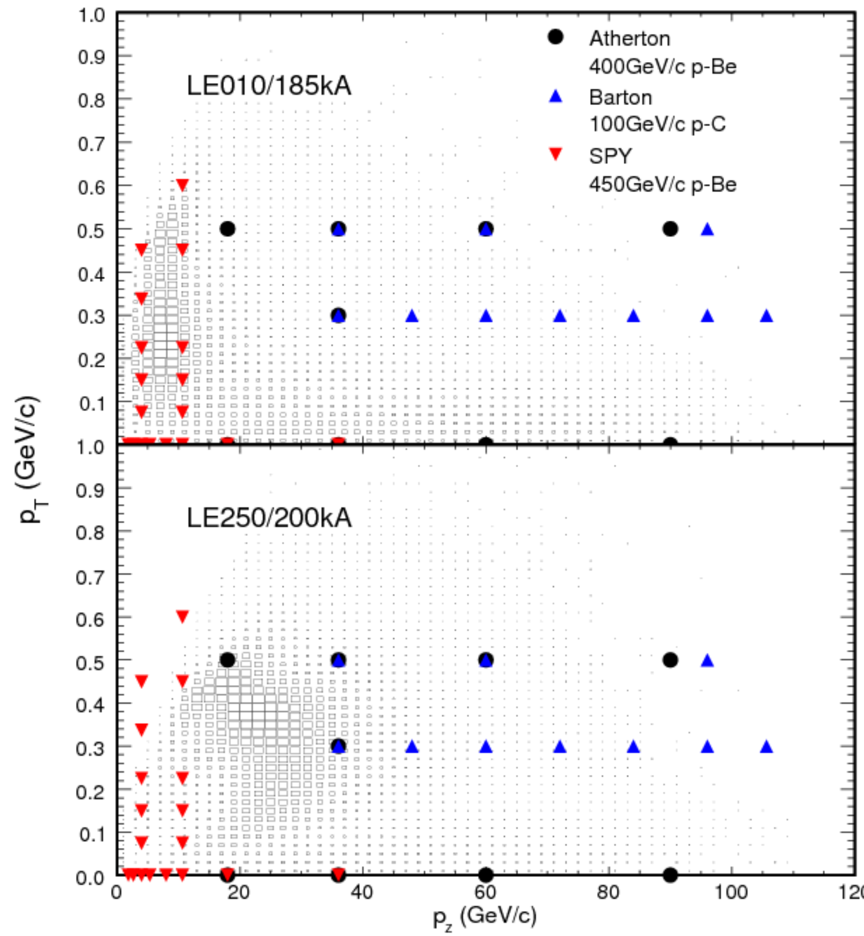
Anti-ν_μ low-nu data sample composition

MINOS Prelimilary

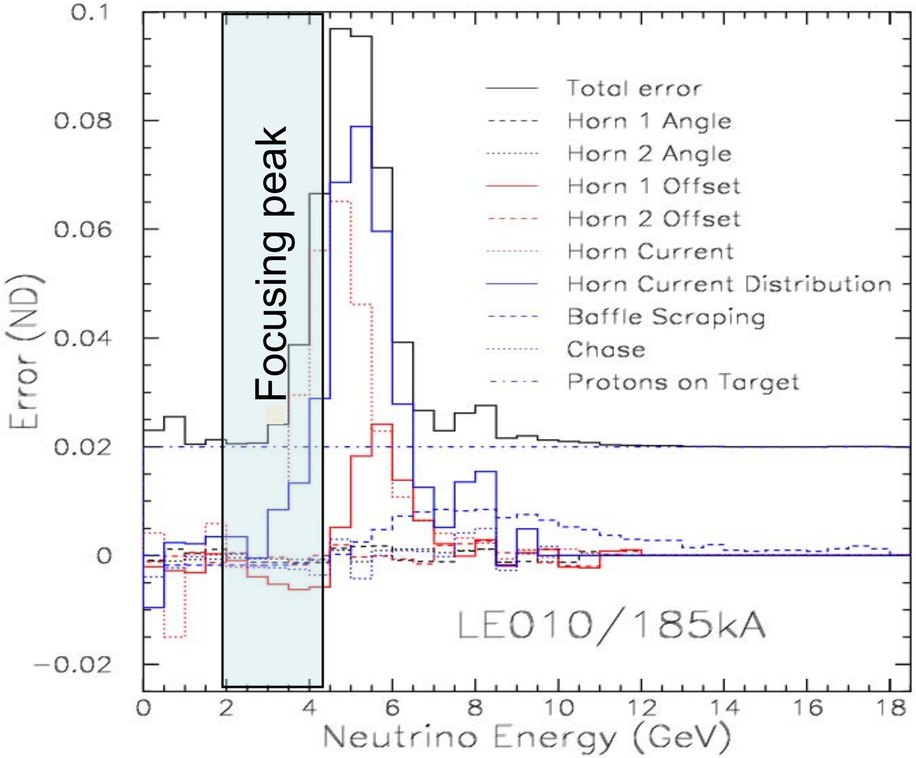




0.5 GeV/c
5 GeV/c
10 GeV/c
20 GeV/c
40 GeV/c
2 int. length
1 int. length
0.5 int. length
π+ from reinteractions in target (%)
p0 (GeV/c)
p0 (GeV/c)



LE010/185kA
LE250/200kA
Atherton
400GeV/c p-Be
Barton
100GeV/c p-C
SPY
450GeV/c p-Be
pT (GeV/c)
pz (GeV/c)

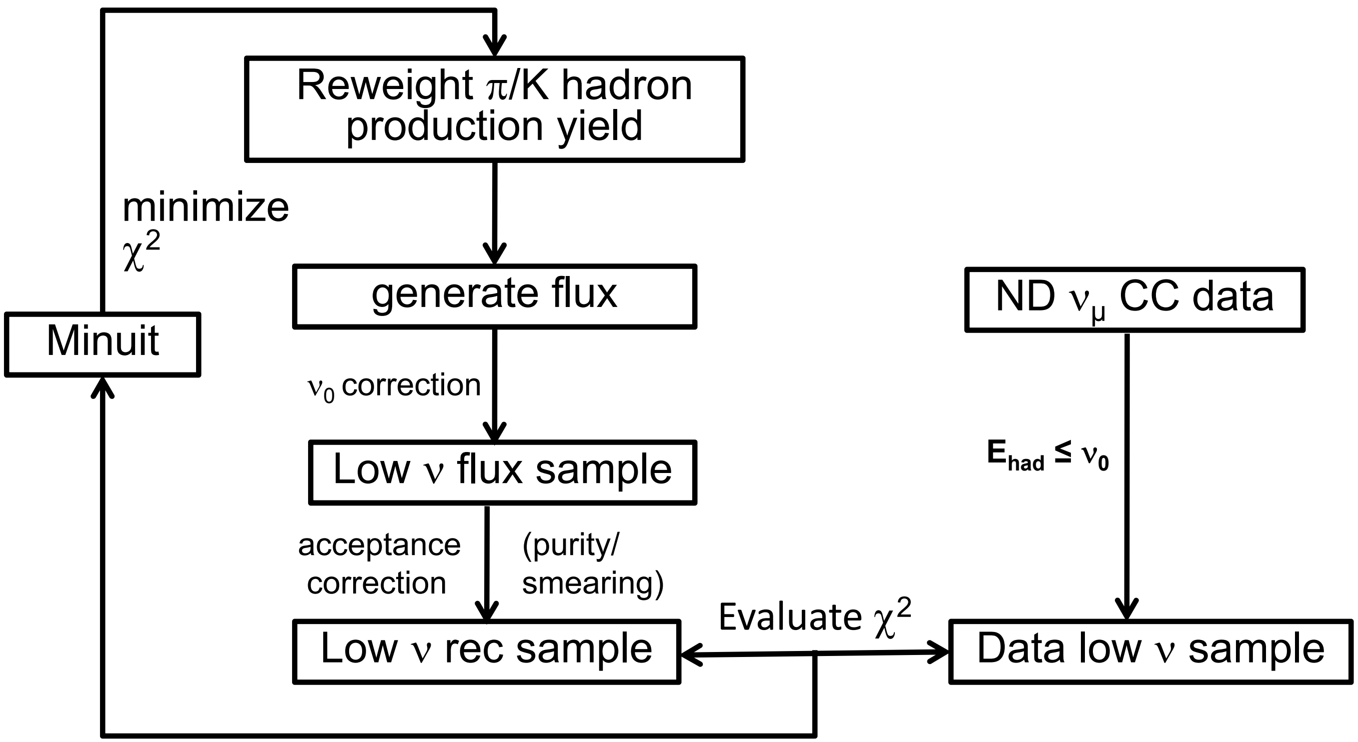


Focusing peak
Total error
Horn 1 Angle
Horn 2 Angle
Horn 1 Offset
Horn 2 Offset
Horn Current
Horn Current Distribution
Baffle Scraping
Chase
Protons on Target
LE010/185kA
Error (ND)
Neutrino Energy (GeV)

Empirical Parameterization (EP) Method

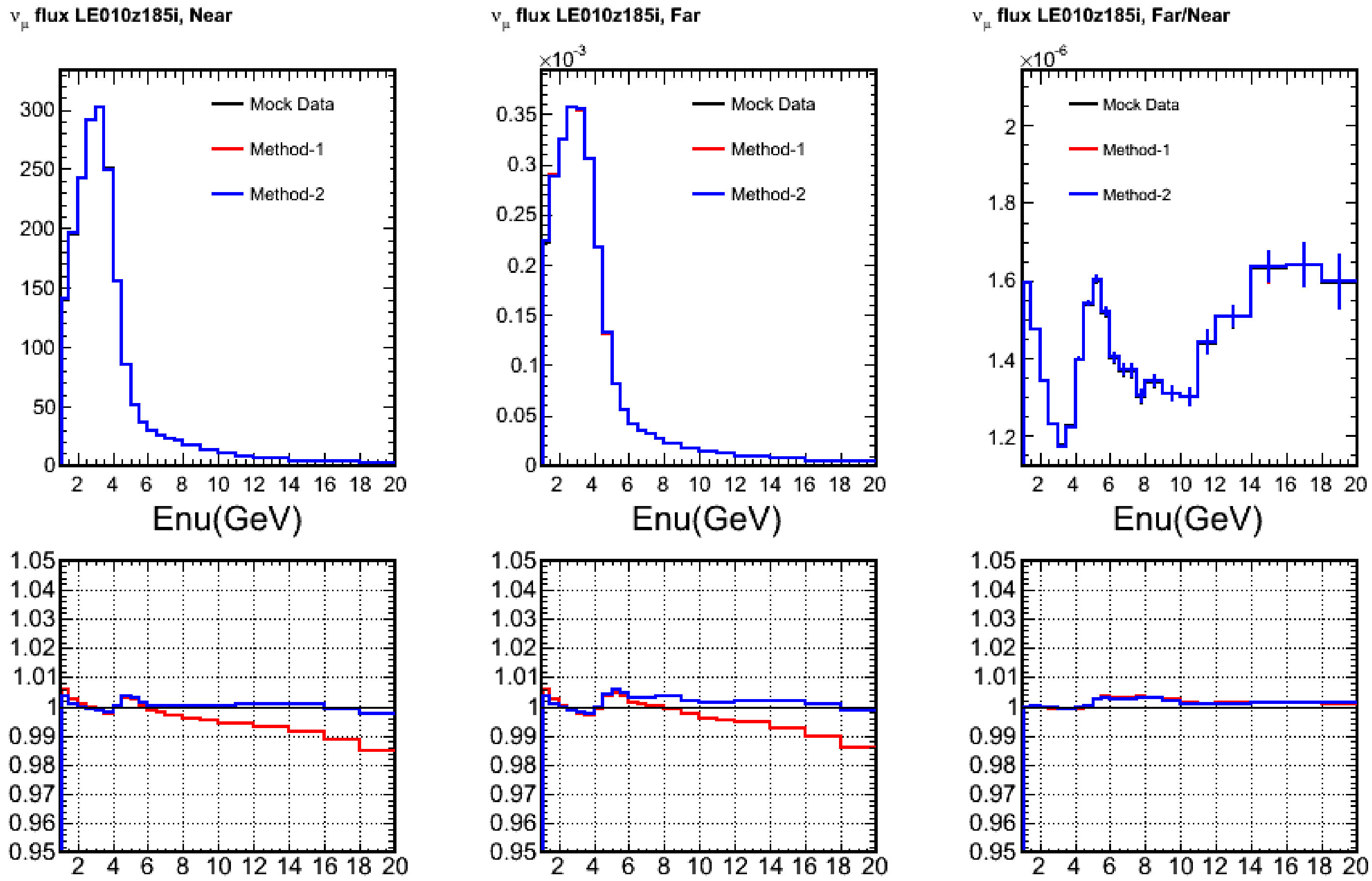
- In order to predict the neutrino flux in the Far Detector and estimate the FD/ND flux ratio, we need to parameterize the π/K mesons by using the low-nu flux sample.

Method 1:



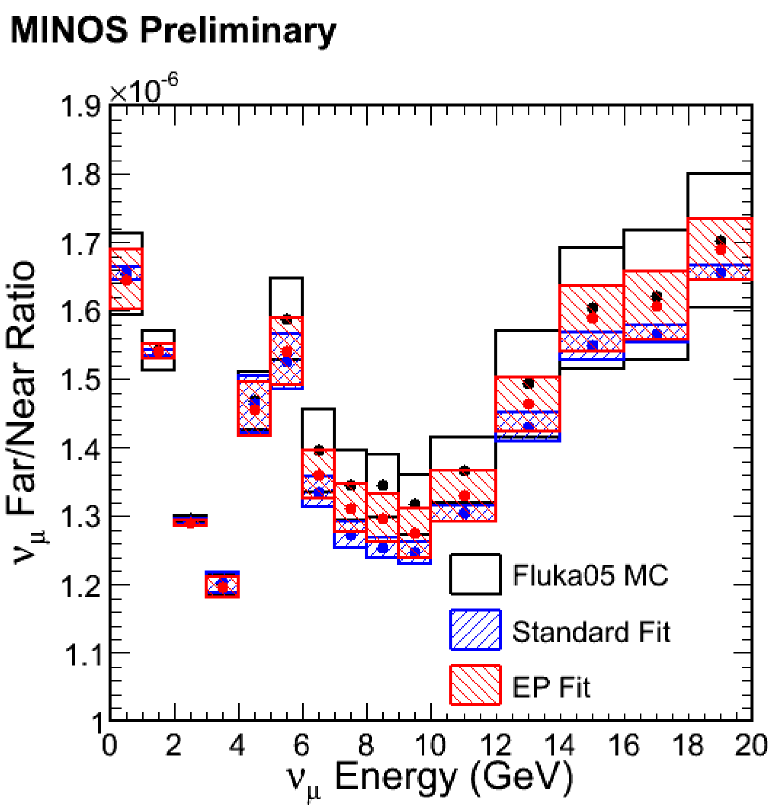
It is time consuming

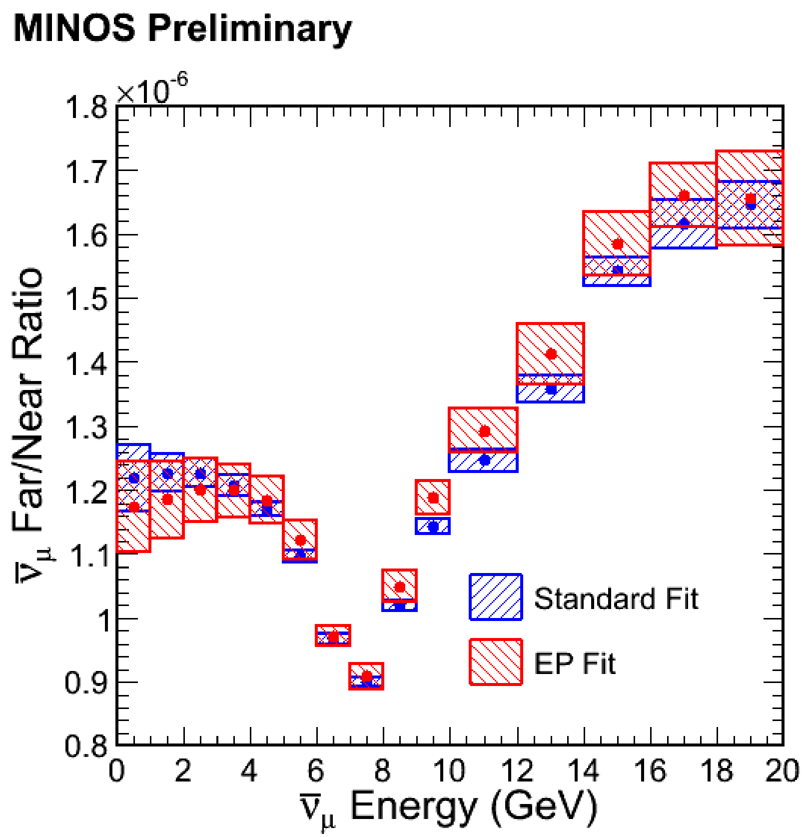
Mock Data Study



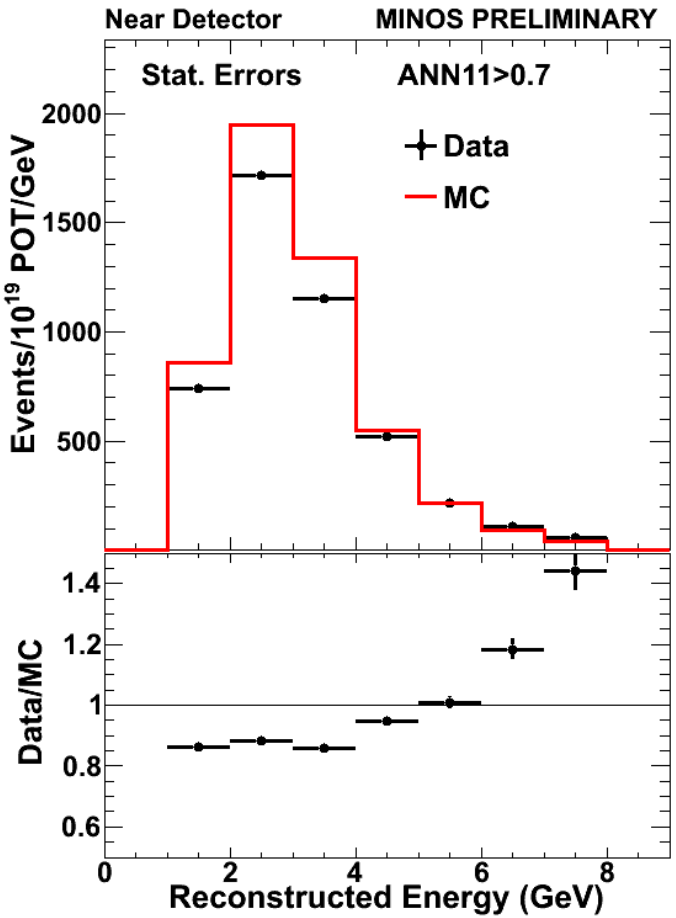
- Method 1 and Method 2 are equivalent.

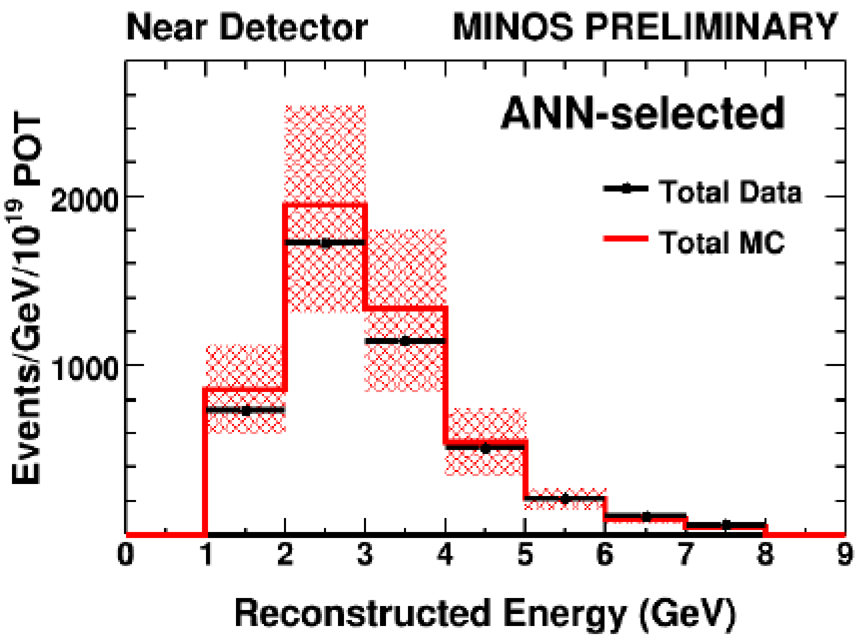
Far/Near Ratio





Background of ND data





ND Decomposition

- There are large uncertainties in our hadronization model. Monte Carlo can't be trusted to determine the background components.
- We can use 3 different beam configurations to do the ND background decomposition. They have different NC/CC/beam ν_e composition.

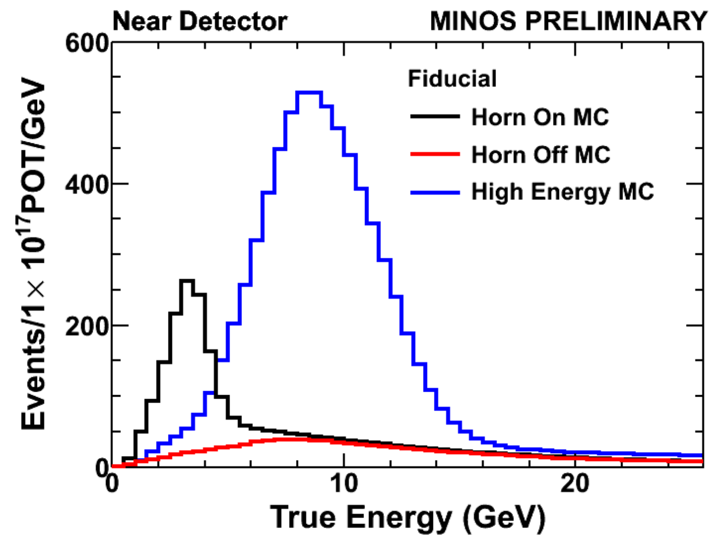
$$N_{NC} + N_{CC} + N_{\nu_e} = N_{data}^{ON}$$

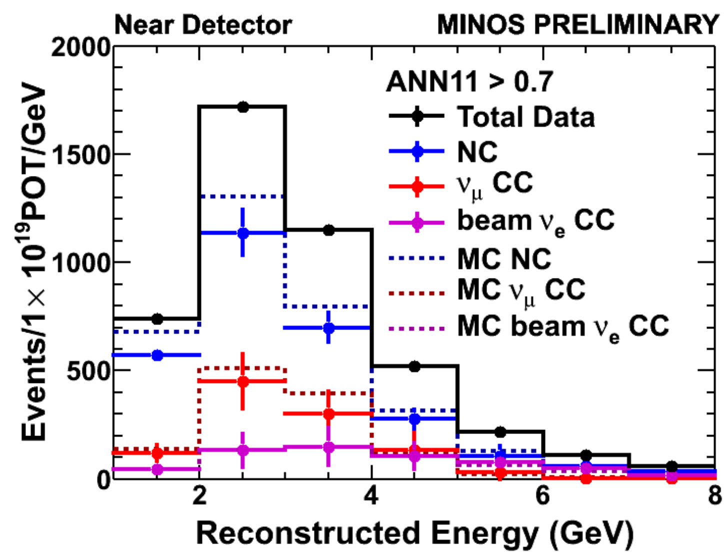
$$\frac{N_{NC}^{OFF\ MC}}{N_{NC}^{ON\ MC}} N_{NC} + \frac{N_{CC}^{OFF\ MC}}{N_{CC}^{ON\ MC}} N_{CC} + \frac{N_{\nu e}^{OFF\ MC}}{N_{\nu e}^{ON\ MC}} N_{\nu_e} = N_{data}^{OFF}$$

$$\frac{N_{NC}^{HE\ MC}}{N_{NC}^{ON\ MC}} N_{NC} + \frac{N_{CC}^{HE\ MC}}{N_{CC}^{ON\ MC}} N_{CC} + \frac{N_{\nu e}^{HE\ MC}}{N_{\nu e}^{ON\ MC}} N_{\nu_e} = N_{data}^{HE}$$

Monte Carlo	
NC	$(65\pm23)\%$
ν_μ-CC	$(24\pm8)\%$
ν_e-CC	$(11\pm2)\%$

Data Driven	
NC	$(64\pm5)\%$
ν_μ-CC	$(23\pm5)\%$
ν_e-CC	$(13\pm3)\%$





F/N Extrapolation

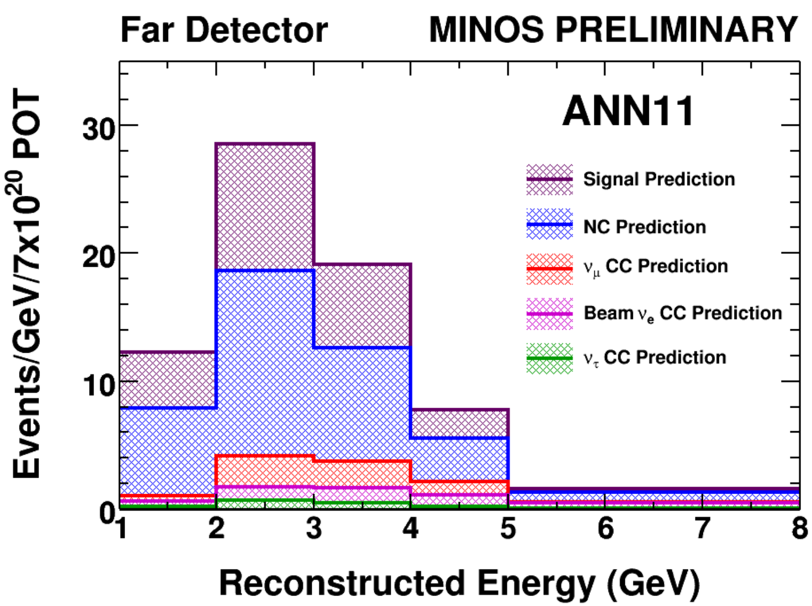
- Use ND measurement of NC, ν_μ CC and beam ν_e CC backgrounds to predict FD background:

FD prediction for component α in energy bin i

$$F_i^{predicted,\alpha} = N_i^{\alpha} \times \left(\frac{f_i^{\alpha}}{n_i^{\alpha}} \right)$$

ND data (N_i^{α})

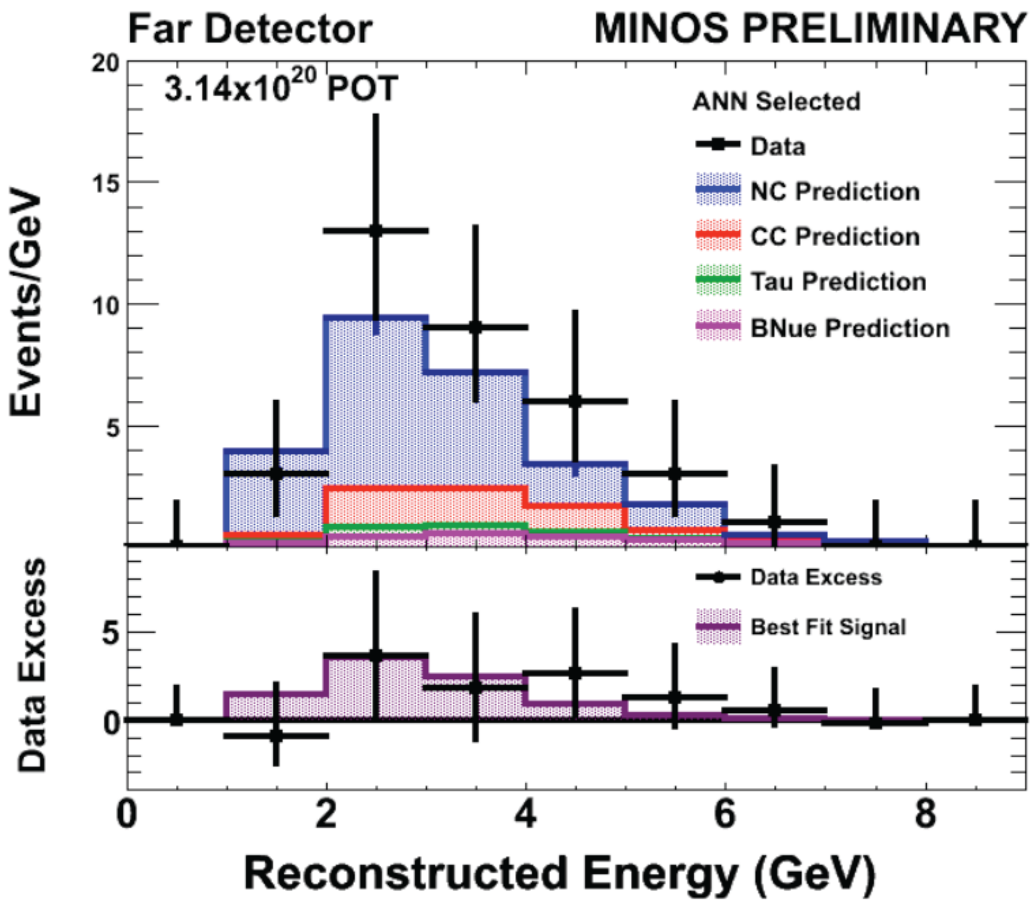
F/N ratio of MC selected events from component α in energy bin i ($f_i^{\alpha}/n_i^{\alpha}$)

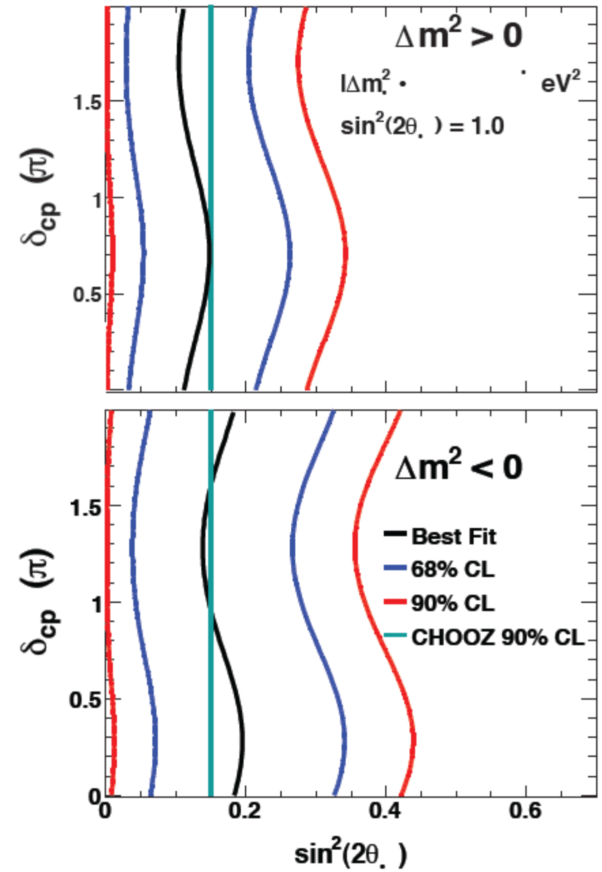


Component	#Event
NC	35.8
ν_μ CC	6.3
Beam ν_e CC	5.0
ν_τ CC	2.0
Total Background	49.1
ν_e CC signal	23.9

$\sin^2(2\theta_{13})=0.15$ (CHOOZ limit), $|\Delta m^2_{31}|=2.43\text{e-}3\text{eV}^2$, $\sin^2(2\theta_{23})=1$.

ν_e 3×10^{20} POT Results





* We observe 35 events, and expect 27 ± 5 (stat) ± 2 (syst) events.
* Results are 1.5 σ high: $\sin^2(2\theta_{13})=0$ is included at the 92% level.

ν_μ CC Disappearance

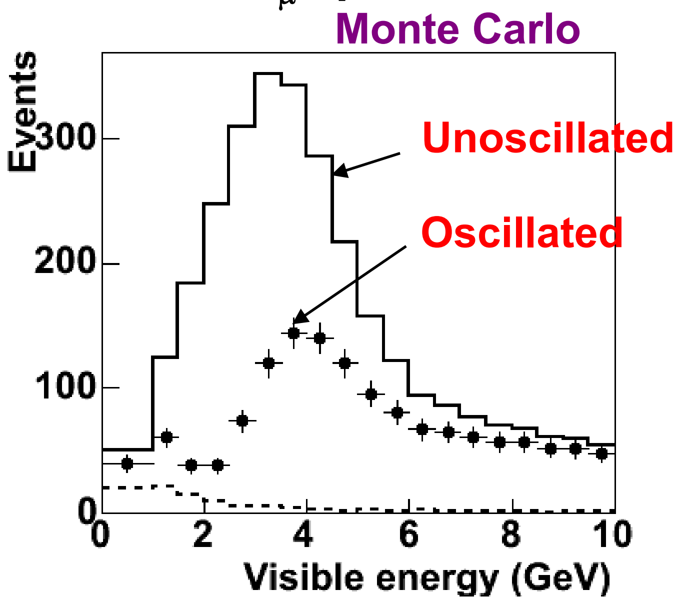
- Precision measurements of atmospheric Δm^2 and $\sin^2(2\theta)$.
- Test the neutrino oscillation hypothesis.

Look for a deficit of ν_μ events in the Far Detector .

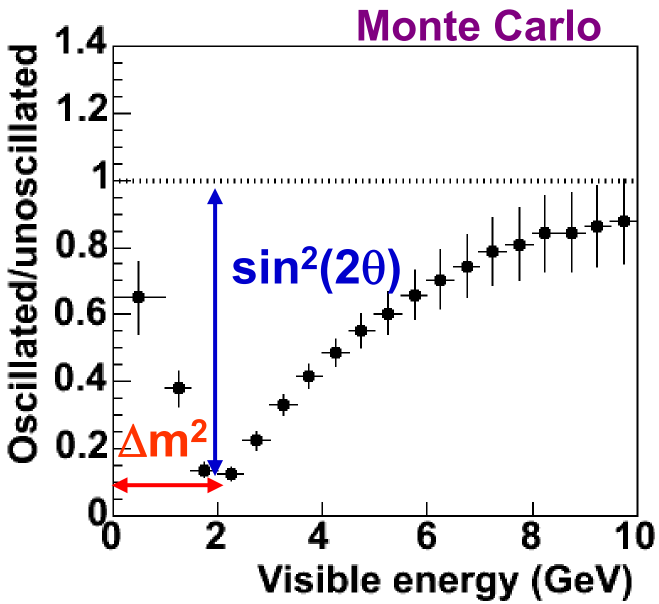
$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta \sin^2\left(\frac{1.27 \Delta m^2 L}{E}\right)$$

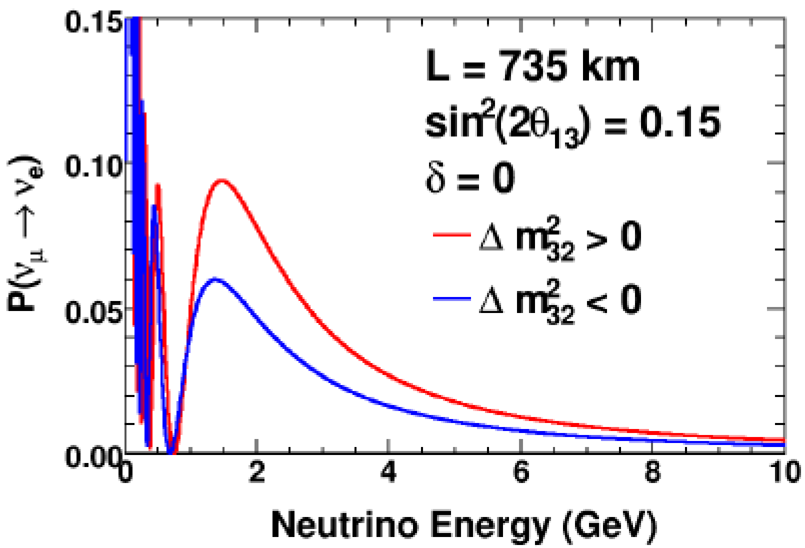
L=735 km

ν_μ spectrum



spectrum ratio




L = 735 km
sin²(2θ13) = 0.15
δ = 0
Δ m²32 > 0
Δ m²32 < 0
P(νμ → νe)
Neutrino Energy (GeV)
0.15
0.10
0.05
0.00
0
2
4
6
8
10