New results for muon neutrino to electron neutrino oscillations in the MINOS experiment

Anna Holin
University College London
12 April 2010, CERN

Outline

Outline

- Neutrinos and Physics Motivation
- The MINOS Experiment
- Electron Neutrino Appearance Analysis
- Results and Future Outlook

Neutrinos and Physics Motivation

- There are **3 generations of neutrino**: ν_e, ν_μ, ν_τ
- **neutrinos have mass and they oscillate**
- neutrino oscillations are governed by the PMNS matrix

PMNS mixing matrix (Pontecorvo-Maki-Nakagawa-Sakata):

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23}-c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23}-s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23}-c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23}-s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Weak Eigenstates

PMNS Matrix

Mass Eigenstates

where $s_{ij} = \sin\theta_{ij}$ and $c_{ij} = \cos\theta_{ij}$

ij=12 => solar terms
ij=23 => atmospheric terms
ij=13 => **unknown terms**
δ => **CP violating phase**

Neutrinos and Physics Motivation

- There are **3 generations of neutrino**: ν_e, ν_μ, ν_τ
- **neutrinos have mass and they oscillate**
- neutrino oscillations are governed by the PMNS matrix

PMNS mixing matrix (Pontecorvo-Maki-Nakagawa-Sakata):

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23}-c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23}-s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23}-c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23}-s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Weak Eigenstates

PMNS Matrix

Mass Eigenstates

where $s_{ij} = \sin\theta_{ij}$ and $c_{ij} = \cos\theta_{ij}$

θ_{13} and the CP-violating phase δ are linked –> if θ_{13}=0 then all terms containing δ vanish

Neutrinos and Physics Motivation

- neutrino oscillations are governed by 6 parameters:

  $\theta_{12}, \theta_{23}, \theta_{13}, \Delta m^2_{32}, \Delta m^2_{12}$ and δ.

- this includes **two independent mass scales:**
- **atmospheric mass scale** (ordering currently unknown – large mixing angle) $\boxed{\Delta m^2_{32} = \Delta m^2_{atm}}$
- **solar mass scale** (ordering known, non-maximal mixing angle) $\boxed{\Delta m^2_{12} = \Delta m^2_{sol}}$
- Values are:

  $$\Delta m^2_{sol} = (7.6 \pm 0.2)\, x\, 10^{-5}\, eV^2$$

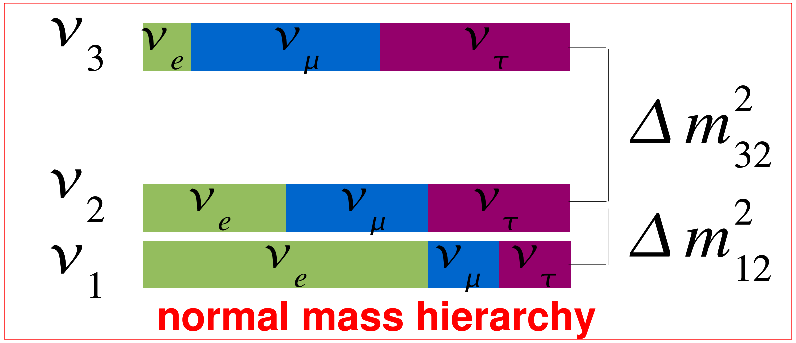
  $$\Delta m^2_{atm} = (2.43 \pm 0.13)\, x\, 10^{-3}\, eV^2$$

- Mixing angle values:

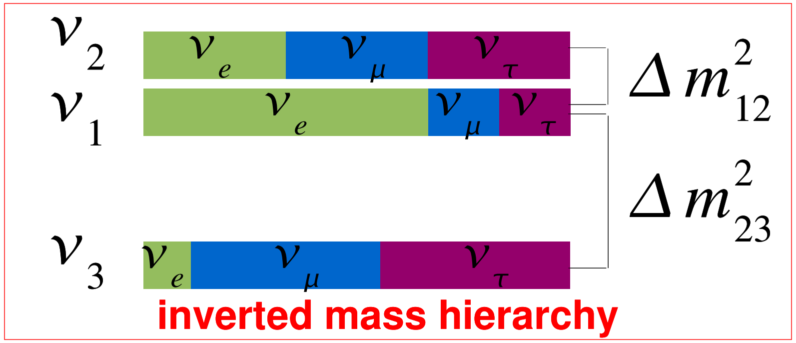
  $\theta_{12} = 34° \pm 3°$

  $\theta_{23} = 45° \pm 5°$

  $\theta_{13} < 11°$ (90% C.L.)



normal mass hierarchy



inverted mass hierarchy

Neutrinos and Physics Motivation

- neutrino oscillations are governed by 6 parameters:

$$\theta_{12}, \theta_{23}, \theta_{13}, \Delta m^2_{32}, \Delta m^2_{12} \text{ and } \delta .$$

- this includes **two independent mass scales:**
- **atmospheric mass scale** (ordering currently unknown – large mixing angle) $\boxed{\Delta m^2_{32} = \Delta m^2_{atm}}$
- **solar mass scale** (ordering known, non-maximal mixing angle) $\boxed{\Delta m^2_{12} = \Delta m^2_{sol}}$
- Values are:

$$\Delta m^2_{sol} = (7.6 \pm 0.2)\, x\, 10^{-5}\, eV^2$$

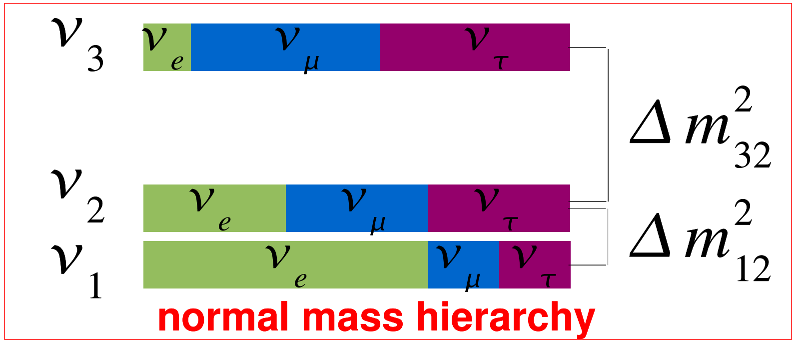
$$\Delta m^2_{atm} = (2.43 \pm 0.13)\, x\, 10^{-3}\, eV^2$$

- Mixing angle values:

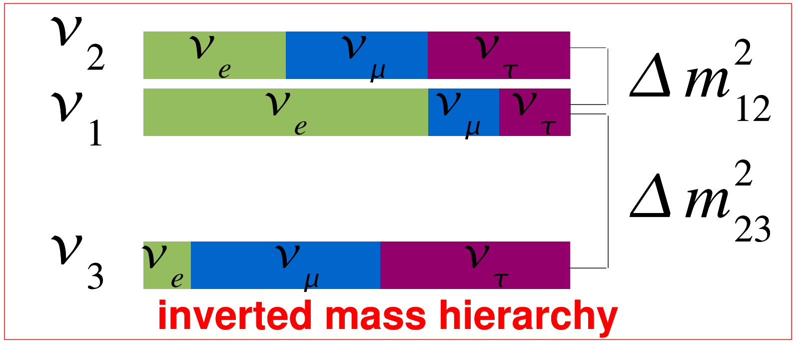
$\theta_{12} = 34° \pm 3°$

$\theta_{23} = 45° \pm 5°$

$\boldsymbol{\theta_{13} < 11°}$ (90% C.L.)



normal mass hierarchy



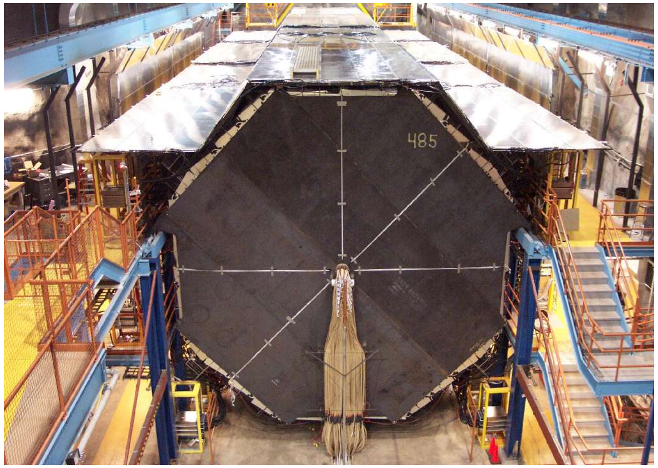
inverted mass hierarchy

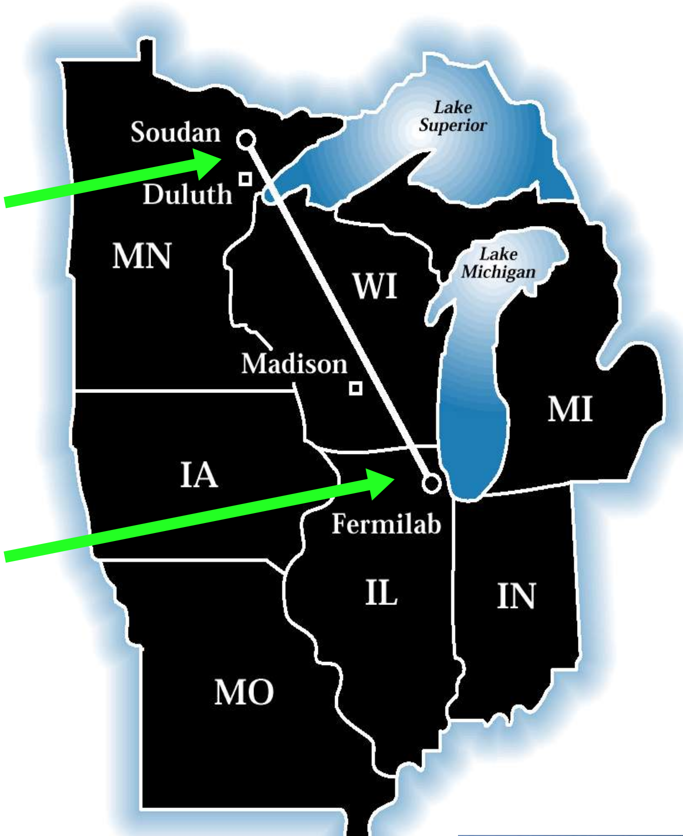
UNKNOWN:

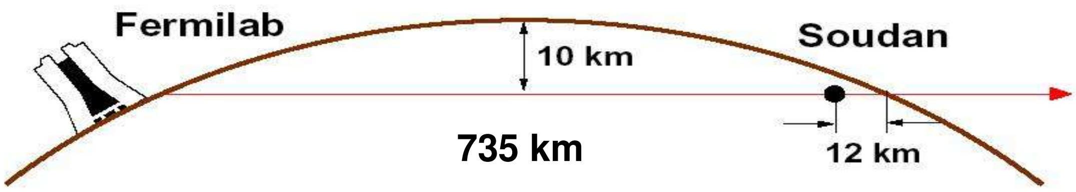
- **mixing angle θ_{13}**
- **CP-phase δ**

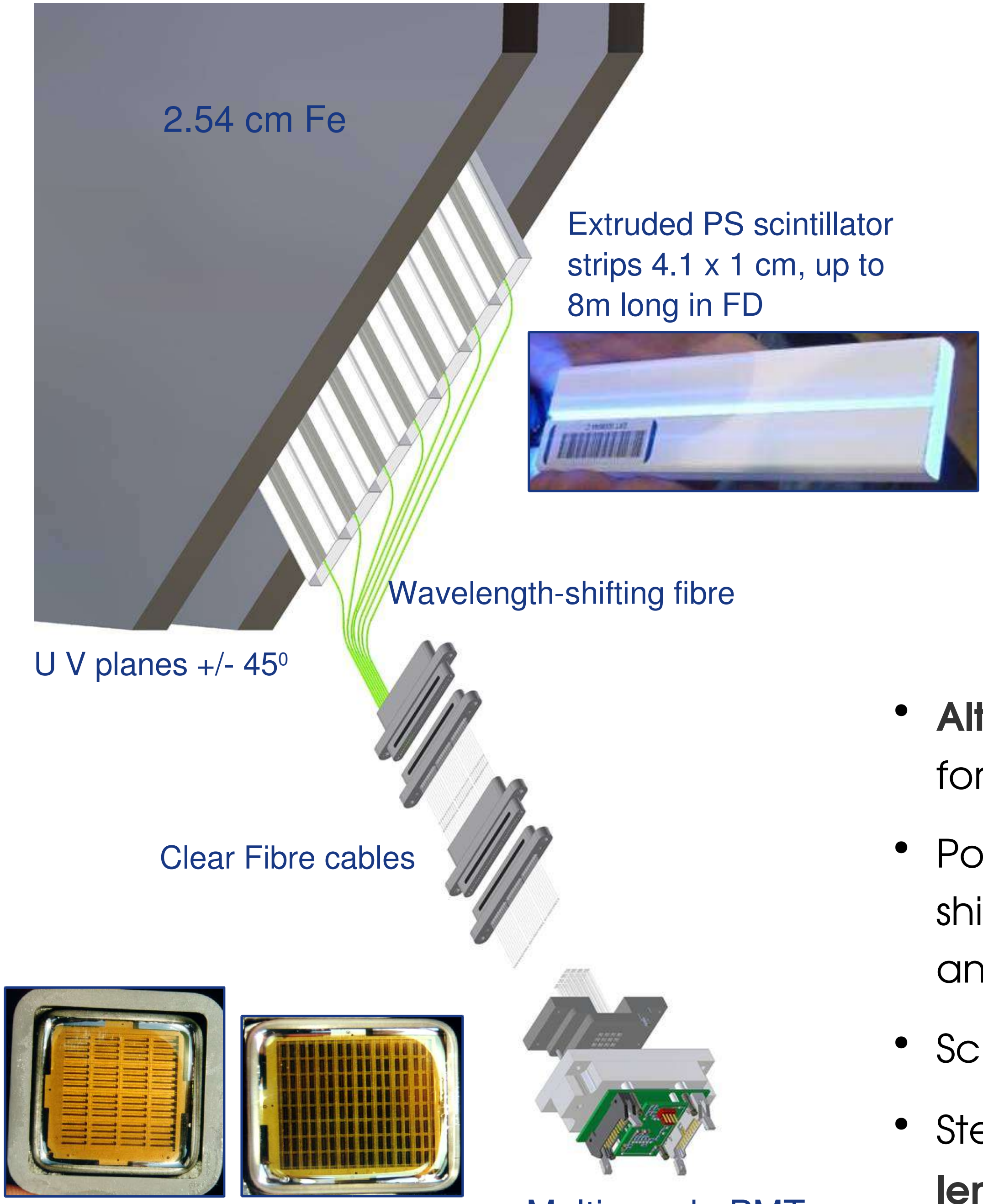
MINOS Experiment Overview

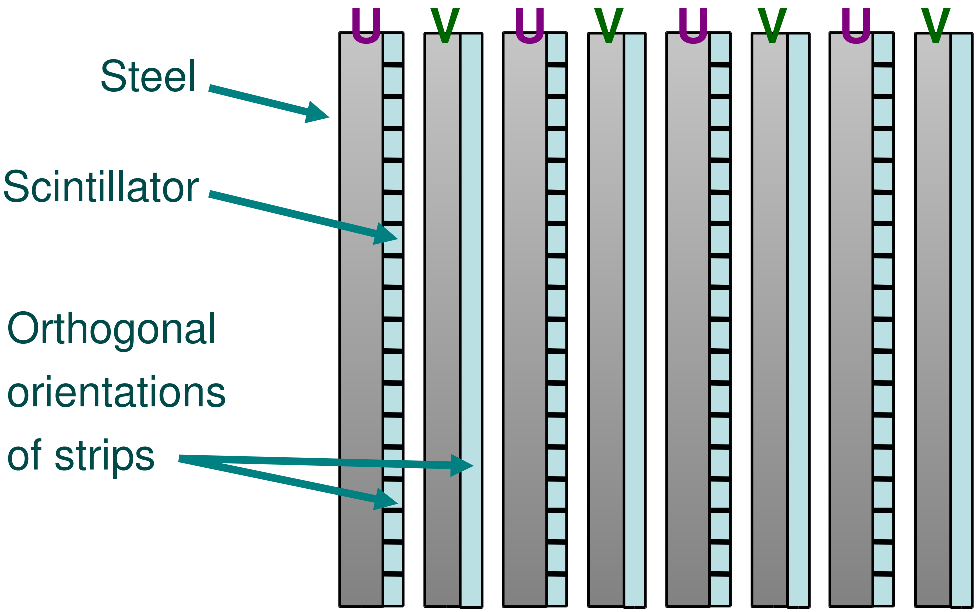
- Iron scintillator calorimeters, functionally identical
- **Far Detector:**
  - **Spectrum after oscillations**
  - 5.4 kT, 8m x 8m x 30m,
  - 484 steel/scintillator planes, veto shield
- **Near Detector**
  - **Spectrum before oscillations**
  - 1 kT, 3.8m x 4.8 m x 15m,
  - 282 steel planes, 153 steel/scintillator planes
- **Steel/scintillator planes:**
  - 1-inch thick steel planes alternating with planes of scintillator strips







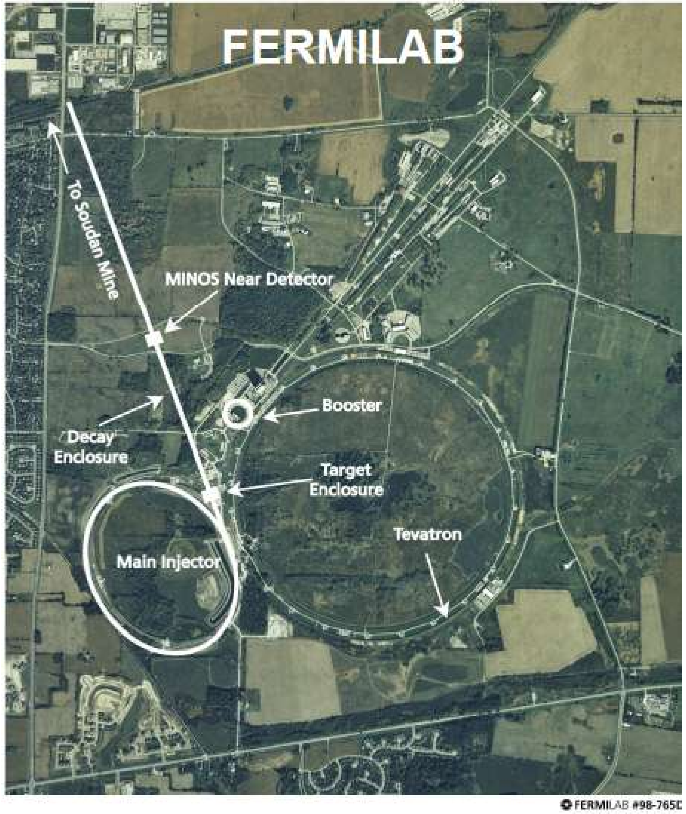


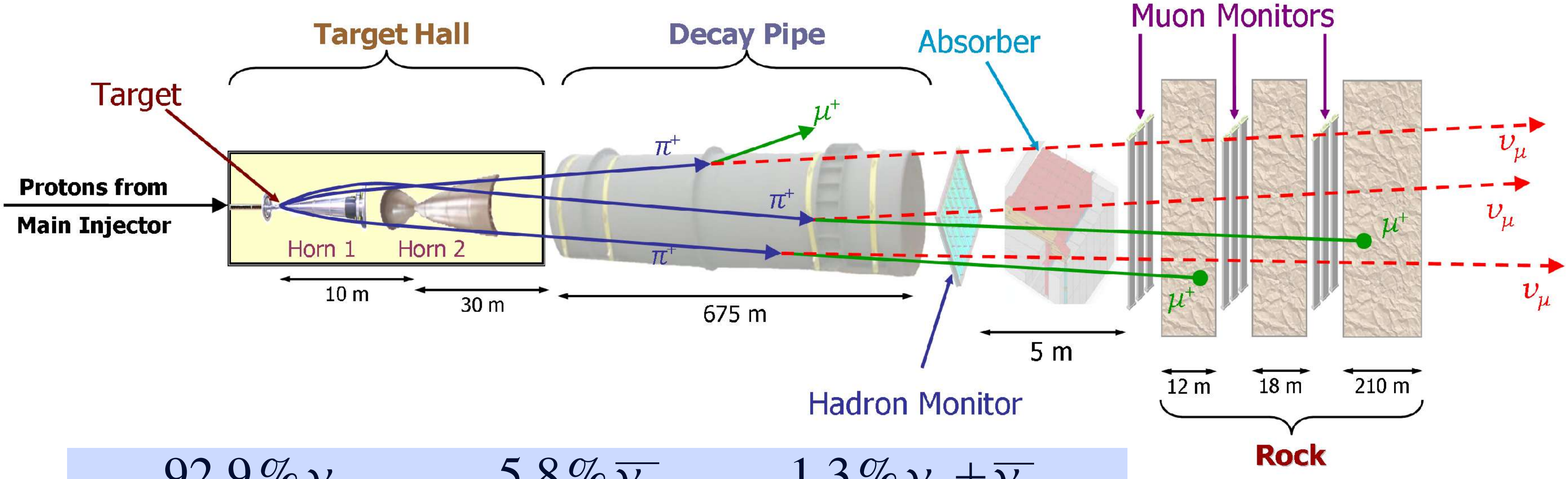


- **Alternative planes** are **orthogonal** to each other for 3-D reconstruction of events
- Polystyrene scintillator strips contain wavelength-shifting fibres which are then read out by multi-anode PMTs – M64 for ND, and M16 for FD
- Scintillator strip width of 4.1cm ≈ **1.1 Moliere radii**
- Steel plane thickness of 2.54cm ≈ **1.44 radiation lengths**

The NuMI Beam

- 120 GeV protons from Main Injector
- impact on graphite target
- ~10µs spill every ~2s, currently ~3.5x10^{13} protons on target/spill
- produced hadrons focused by 2 magnetic horns
- decay into neutrinos and other particles
- absorber/rock remove heavier particles, leave neutrinos
- **neutrino energy spectrum can be changed with target position**





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

Muon Neutrino Disappearance

$\nu_\mu \to \nu_\tau$ ➡ dominant oscillation mode

The probability that a muon neutrino will survive:

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

MINOS measures (exposure of 3.36x10^{20}POT):

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

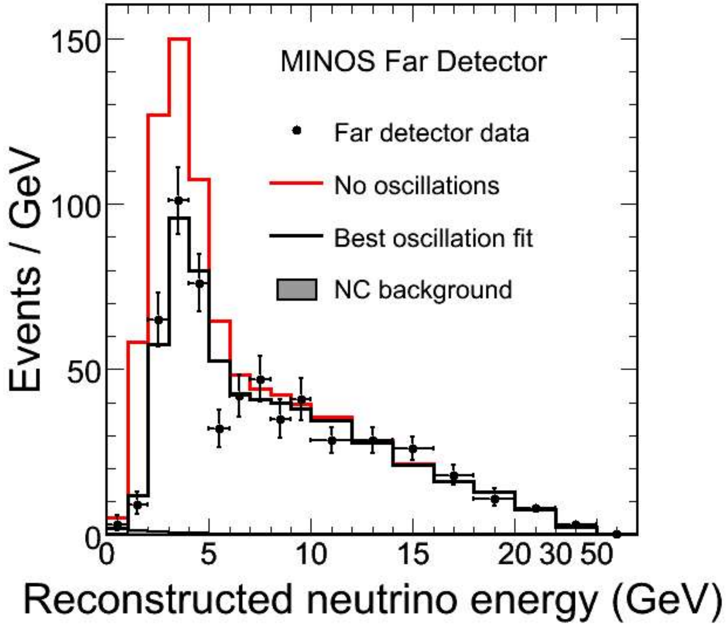
$\sin^2(2\theta_{23}) > 0.9$ at 90% C.L.

Expected: **1065±60** events

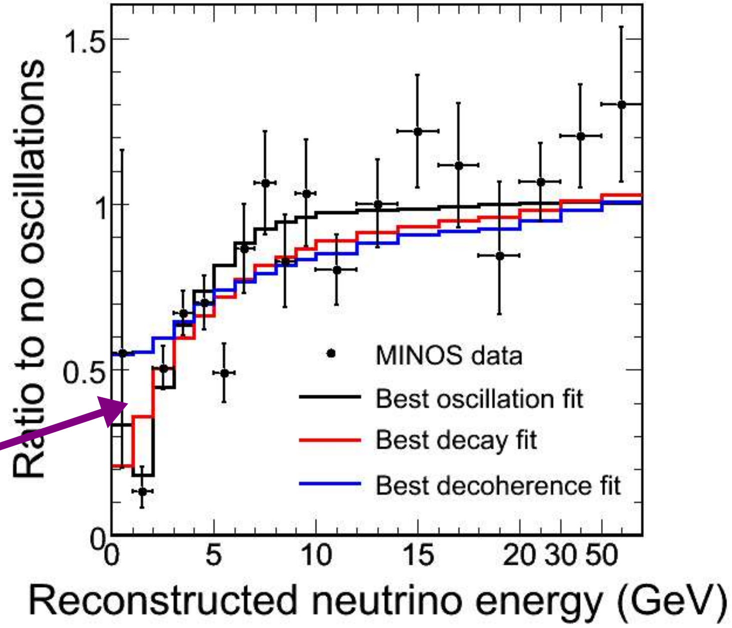
Observed: **848** events

PRL **101** 131802 (2008)

3.36 x10^{20} protons on target



Oscillations mostly between 2-6GeV



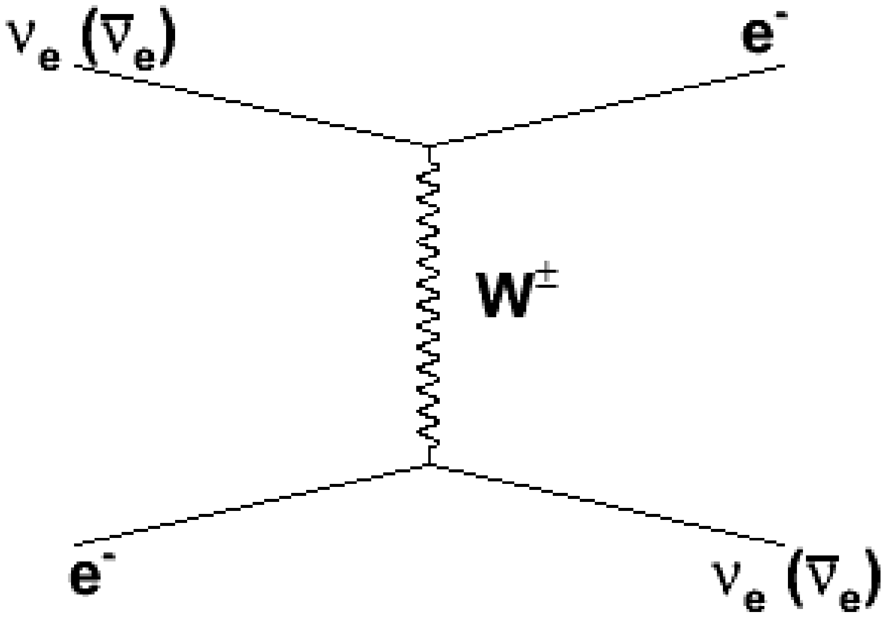
Electron Neutrino Appearance

$\nu_\mu \rightarrow \nu_e$ → sub-dominant oscillation mode

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

→ **Some ν_μ oscillate away into ν_e**

However, as electron neutrinos propagate through matter, they will be affected by **matter effects**:



Electron Neutrino Appearance

$\nu_\mu \rightarrow \nu_e$ → sub-dominant oscillation mode

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

→ **Some ν$_\mu$ oscillate away into ν$_e$**

However, as electron neutrinos propagate through matter, they will be affected by **matter effects**:

$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2\theta_{23} \sin^2 2\theta_{13} \frac{\sin^2(A-1)\Delta}{(A-1)^2}$$
$$-2\alpha \sin\theta_{13} \sin\delta\, \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \sin\Delta$$
$$+2\alpha \sin\theta_{13} \cos\delta\, \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \cos\Delta$$

$$A = \frac{G_f n_e L}{\sqrt{2}\Delta} \approx \frac{E}{11\,GeV}$$

$$\alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{31}} \approx 0.03$$

$$\Delta = \frac{\Delta m^2_{31} L}{4E}$$

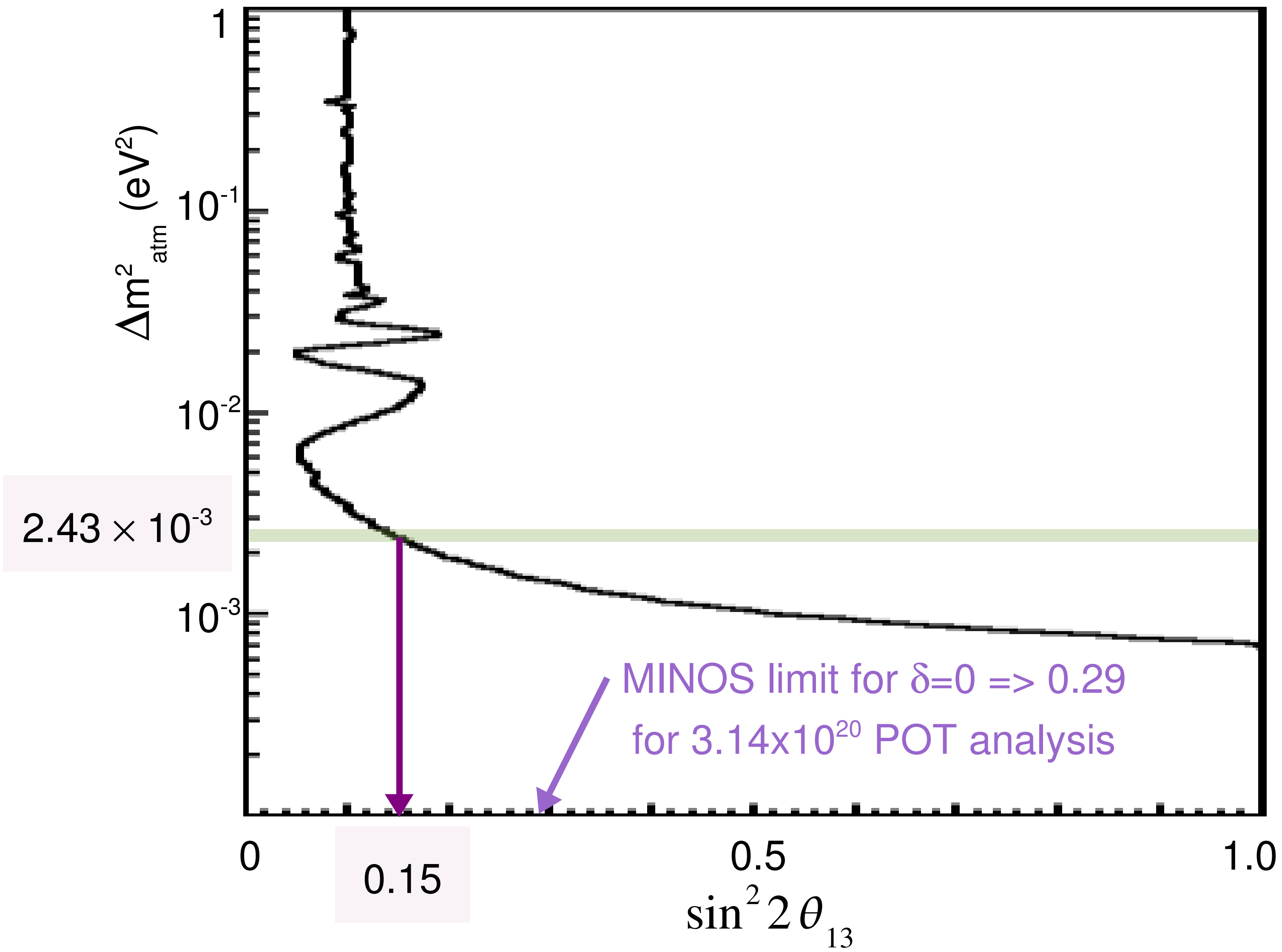
Oscillation probability sensitive to: θ$_{13}$, CP-phase δ, and the mass hierarchy

E. K. Akhmedov et al., J. High Energy Phys. 04 (2004) 078

Electron Neutrino Appearance Analysis

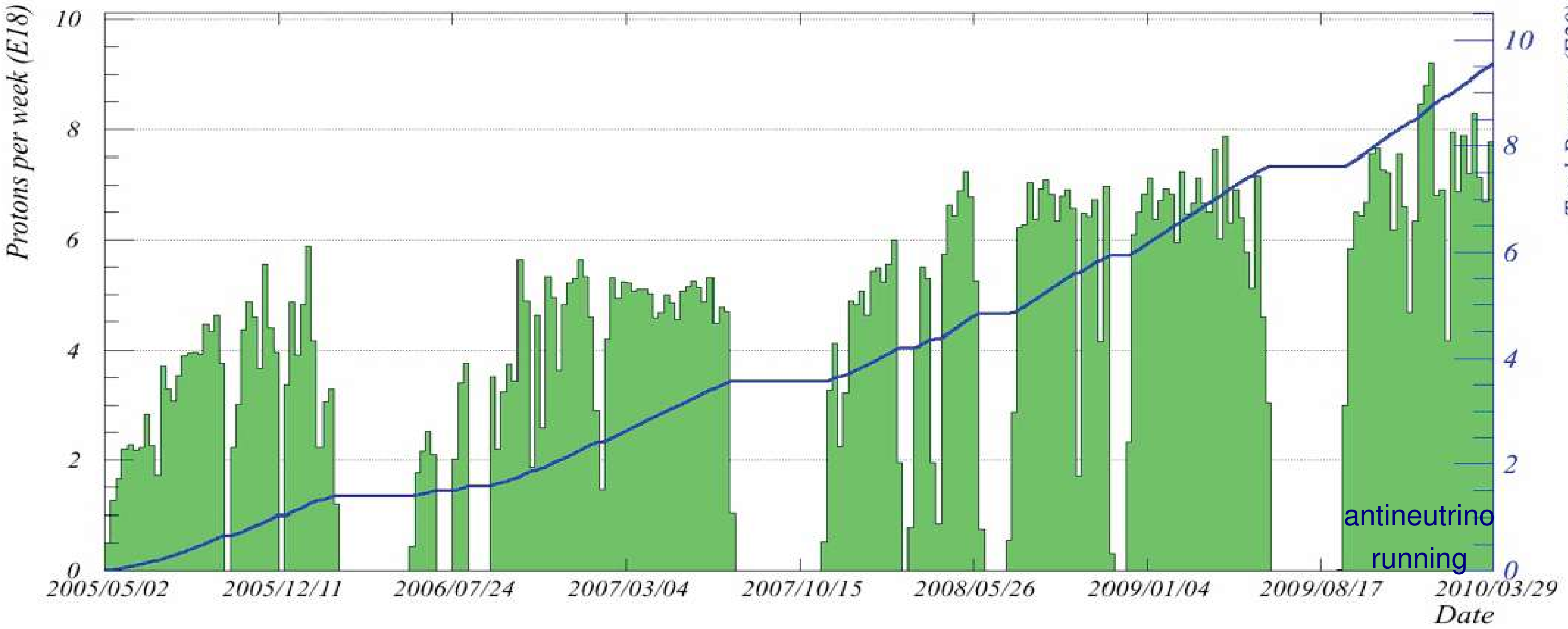
Anna Holin

Current best limit set by the CHOOZ experiment. At MINOS best-fit value for ν_μ disappearance:



CHOOZ different from MINOS as measures anti-neutrino disappearance, not neutrino appearance

New MINOS Results for an exposure of 7×10^{20} protons-on-target



3.14×10^{20} POT – previous MINOS result (PRL 103 261802, 2009)

7.01×10^{20} POT – new result

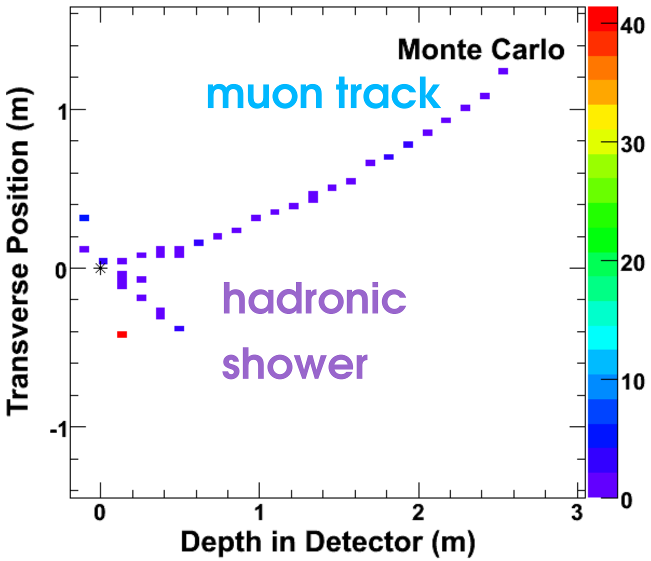
Analysis Procedure

- MINOS **selects CC-ν_e events** by shower topology
- MINOS measures backgrounds in **Near Detector before oscillations**, predicts **Far Detector** background **after oscillations**
- **ND** background after ν_e selection is **separated into its components** by using **different beam configurations**
- The number of ND background events is **extrapolated to the FD** (oscillations are taken into account)
- A **FD background prediction** is obtained

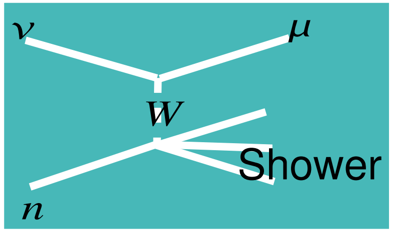
=> **look for an excess of ν_e events** in the FD data.

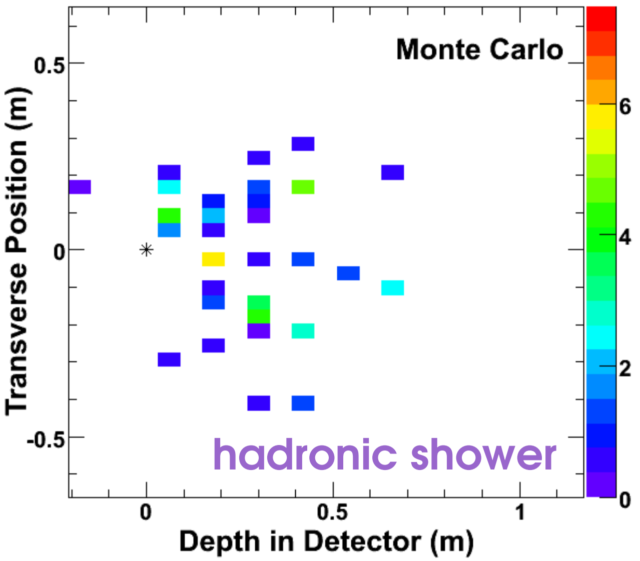
MINOS Event Topology

Basic MINOS interactions:

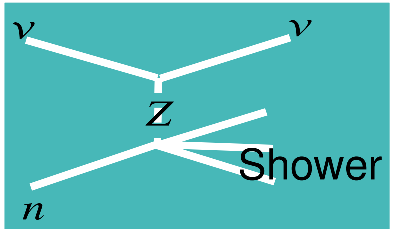


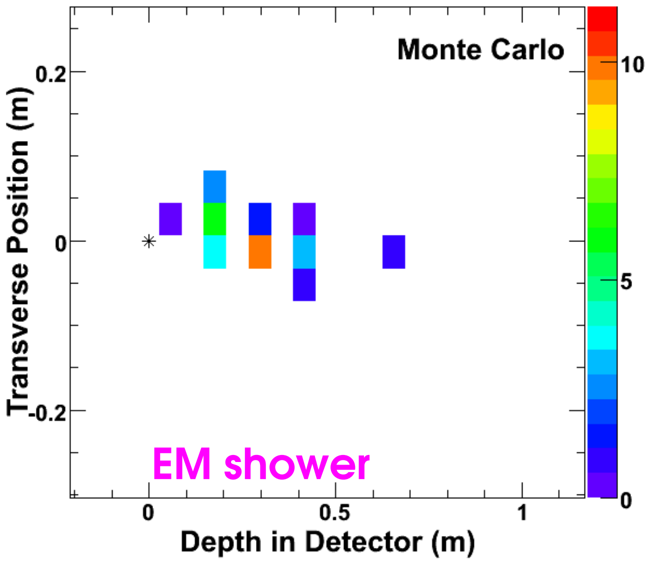
Charged Current
Muon Neutrino Event



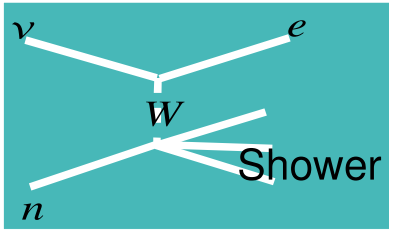


Neutral Current Event





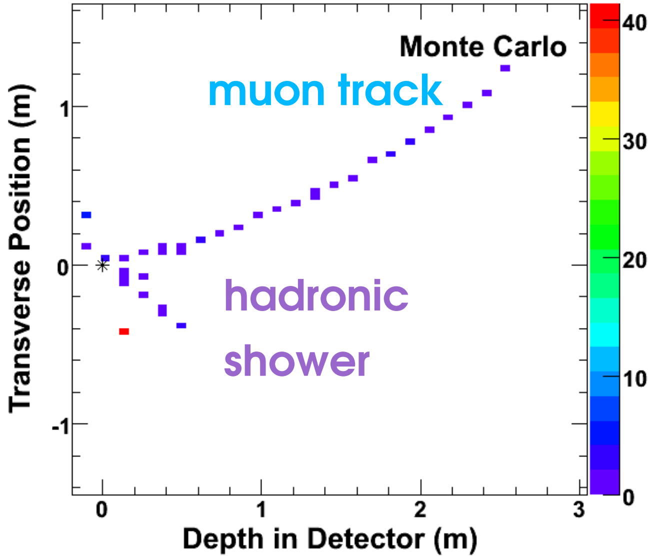
Charged Current
Electron Neutrino Event



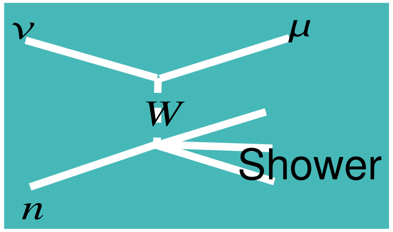
MINOS Event Topology

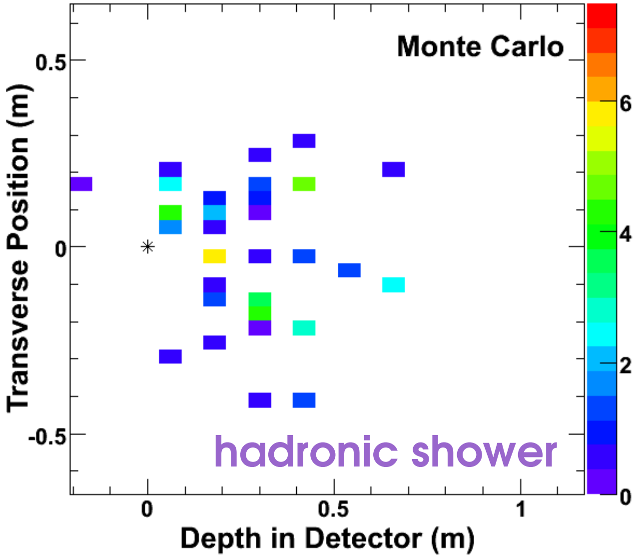
Basic MINOS interactions:

Signal and also
beam ν_e-CC background

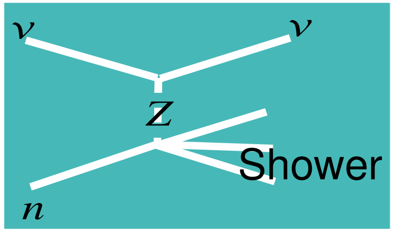


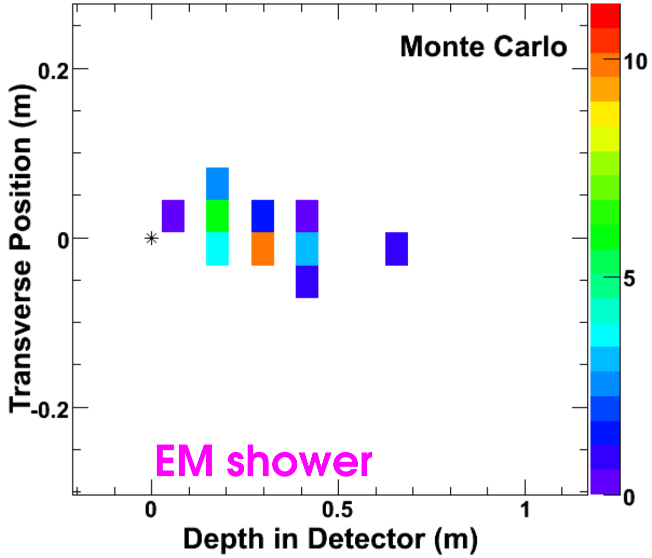
Charged Current
Muon Neutrino Event



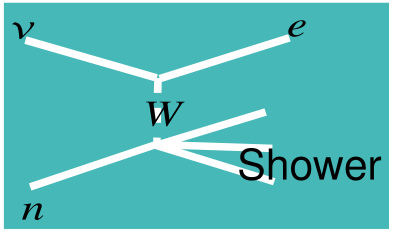


Neutral Current Event





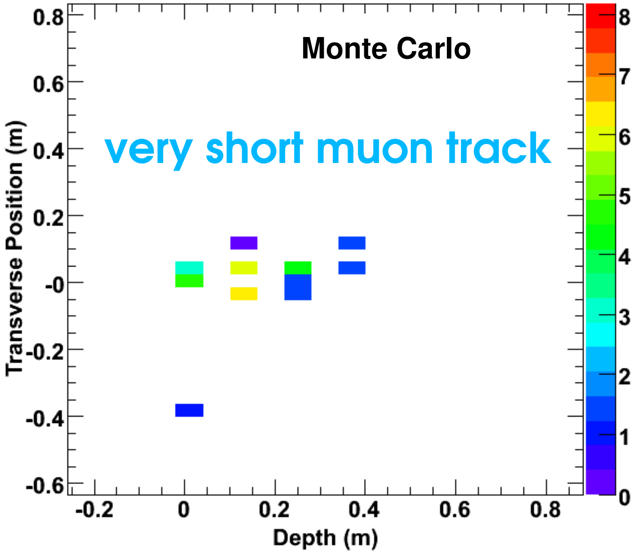
Charged Current
Electron Neutrino Event



MINOS Event Topology

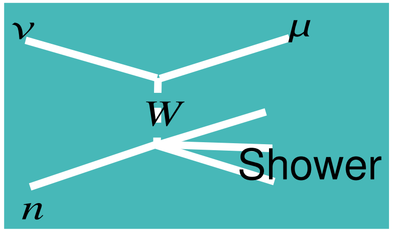
Backgrounds to ν_e appearance Analysis (in addition to beam ν_e-CC):

background

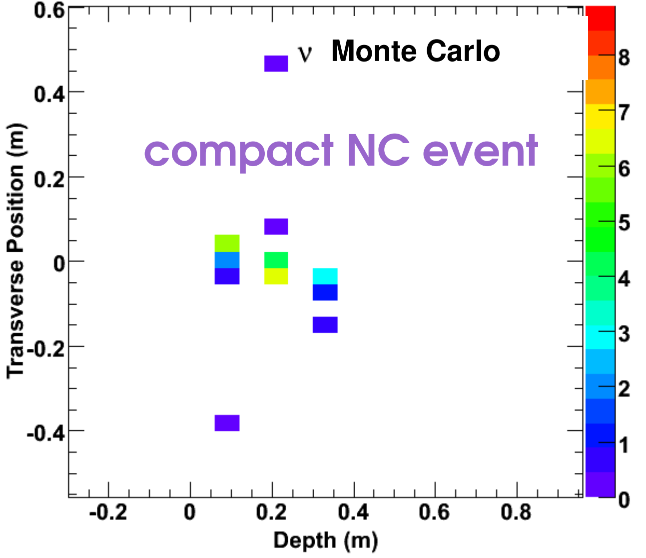


very short muon track

Charged Current
Muon Neutrino Event

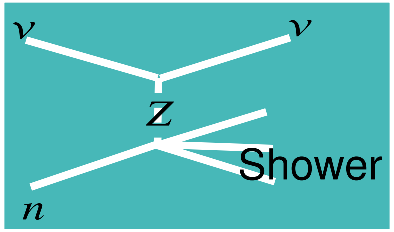


largest background

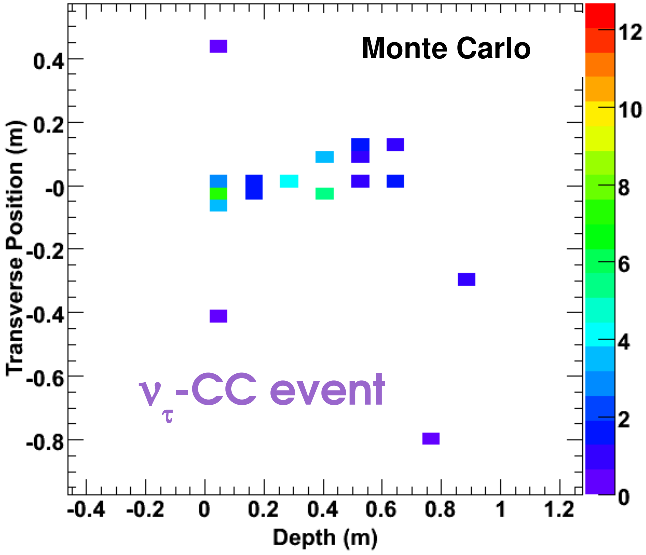


compact NC event

Neutral Current Event

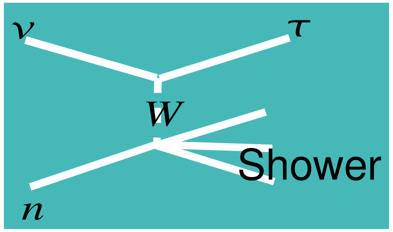


smallest background

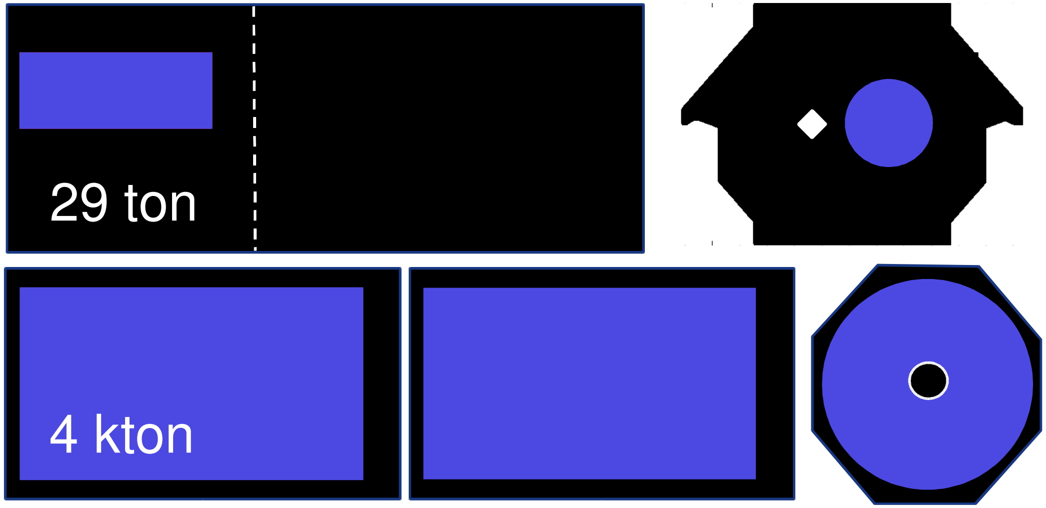


ν_τ-CC event

Charged Current
Tau Neutrino Event



FD only



Selecting ν_e events

First, **data quality cuts** are applied

- beam quality cuts
- detector quality cuts
- timing cuts
- cosmic rejection cuts (based on steepness)

Fiducial volume cuts

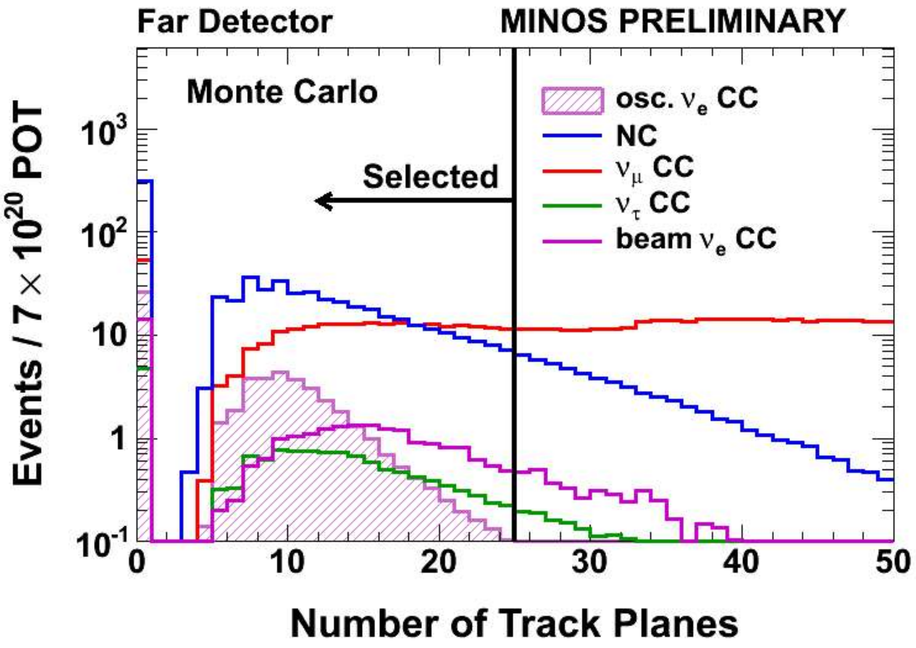
- Near Detector 1m < z < 5m, r < 0.8m
- Far Detector 0.5m < z < 14.3m, 16.3m < z < 28m, 0.5m < r < 3.7m

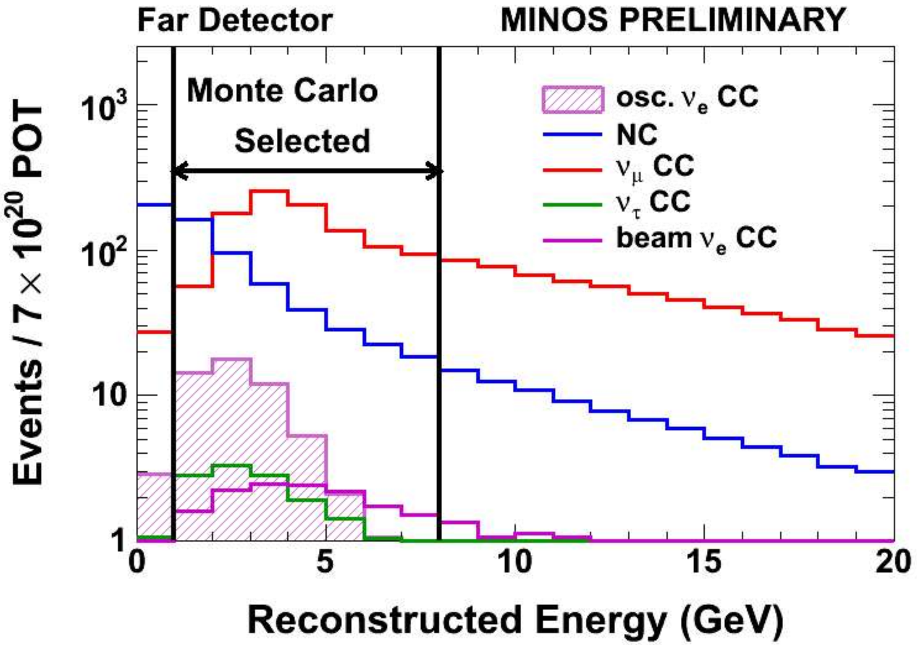
ν_e **preselection cuts** to reduce obvious backgrounds

ν_e **selection pid** based on shower topology

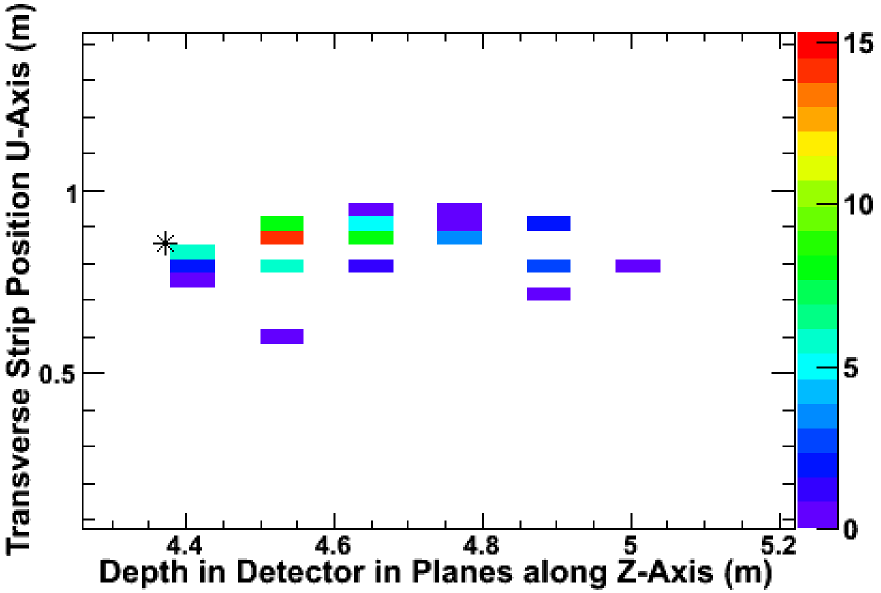
Preselection

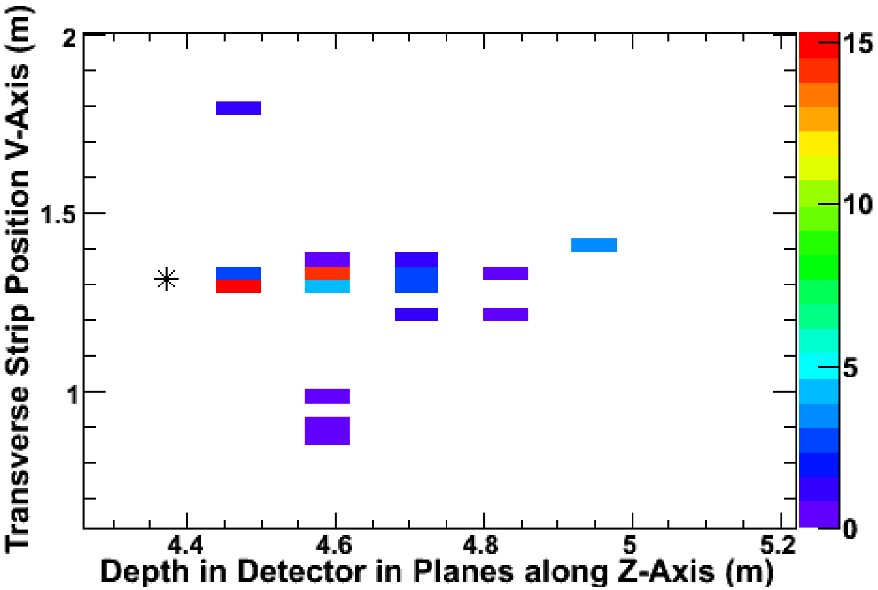
- track planes < 25 – remove obvious long track CC-ν_μ events
- track-like planes < 16 – remove events where track extends much outside shower
- number of showers > 0 – events have to have at least one reconstructed shower
- 1.0 GeV < reco. energy < 8.0 GeV – hones in on signal region
- at least 5 contiguous shower planes with minimum energy deposition of 1MeV each

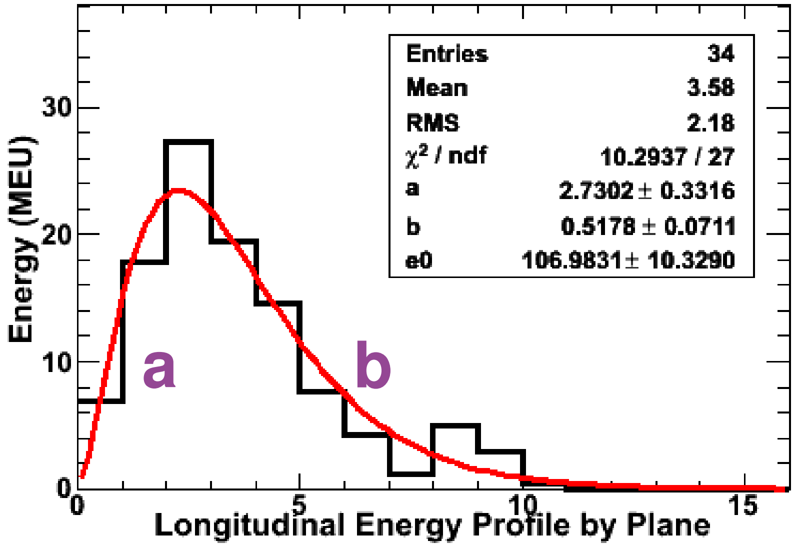




CC-ν_e Signal Selection





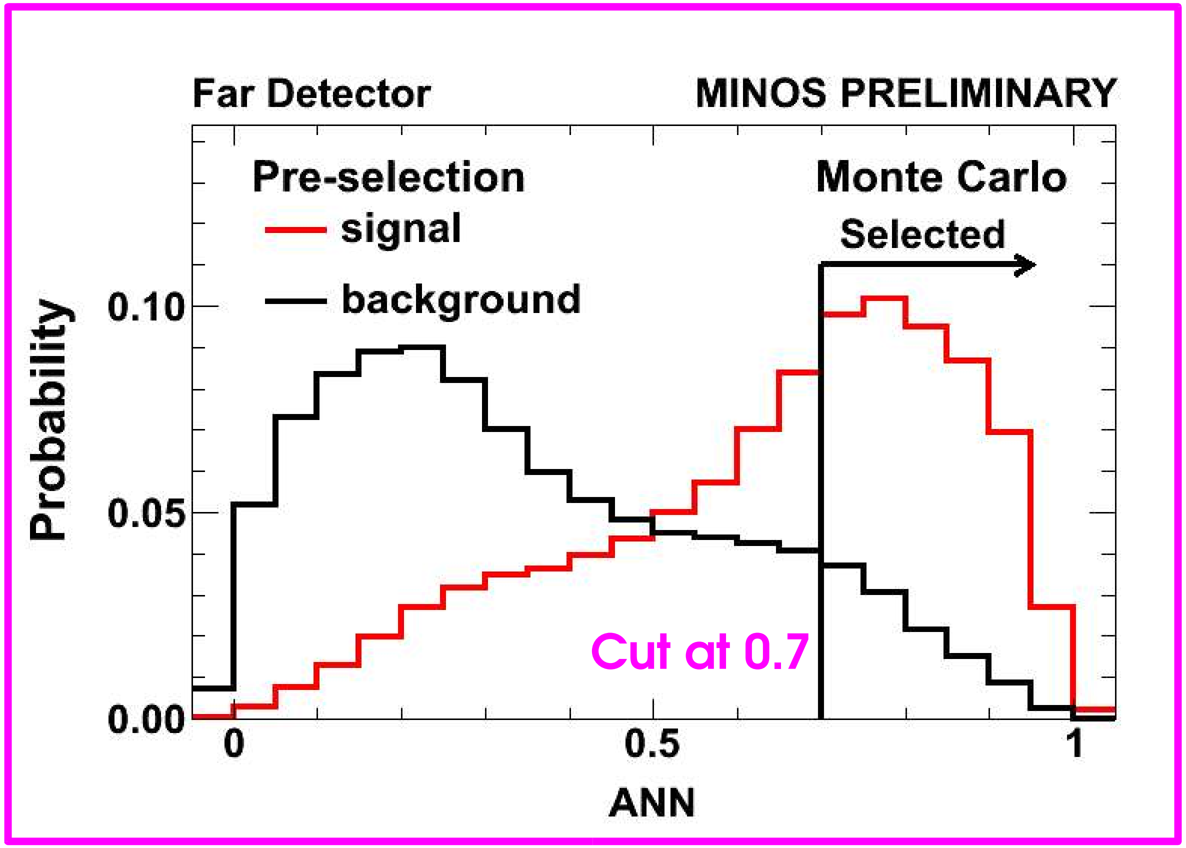


Typical Longitudinal EM – Shower Profile:

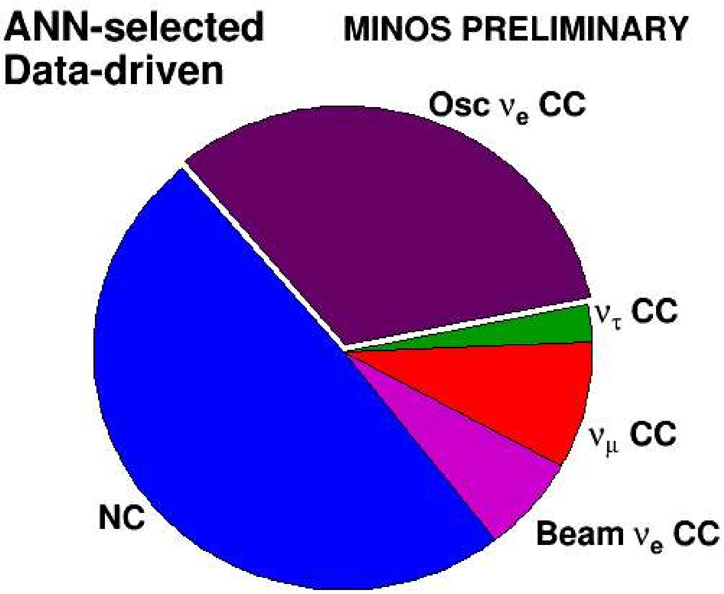
$$\frac{dE}{dt} = E_0 b \frac{(bt)^{a-1} e^{-bt}}{\Gamma(a)}$$

CC-ν_e Signal Selection

A neural network is constructed using 11 shower topological variables
=> those variables use longitudinal and transverse profiles of energy deposition



Final Signal/Background:



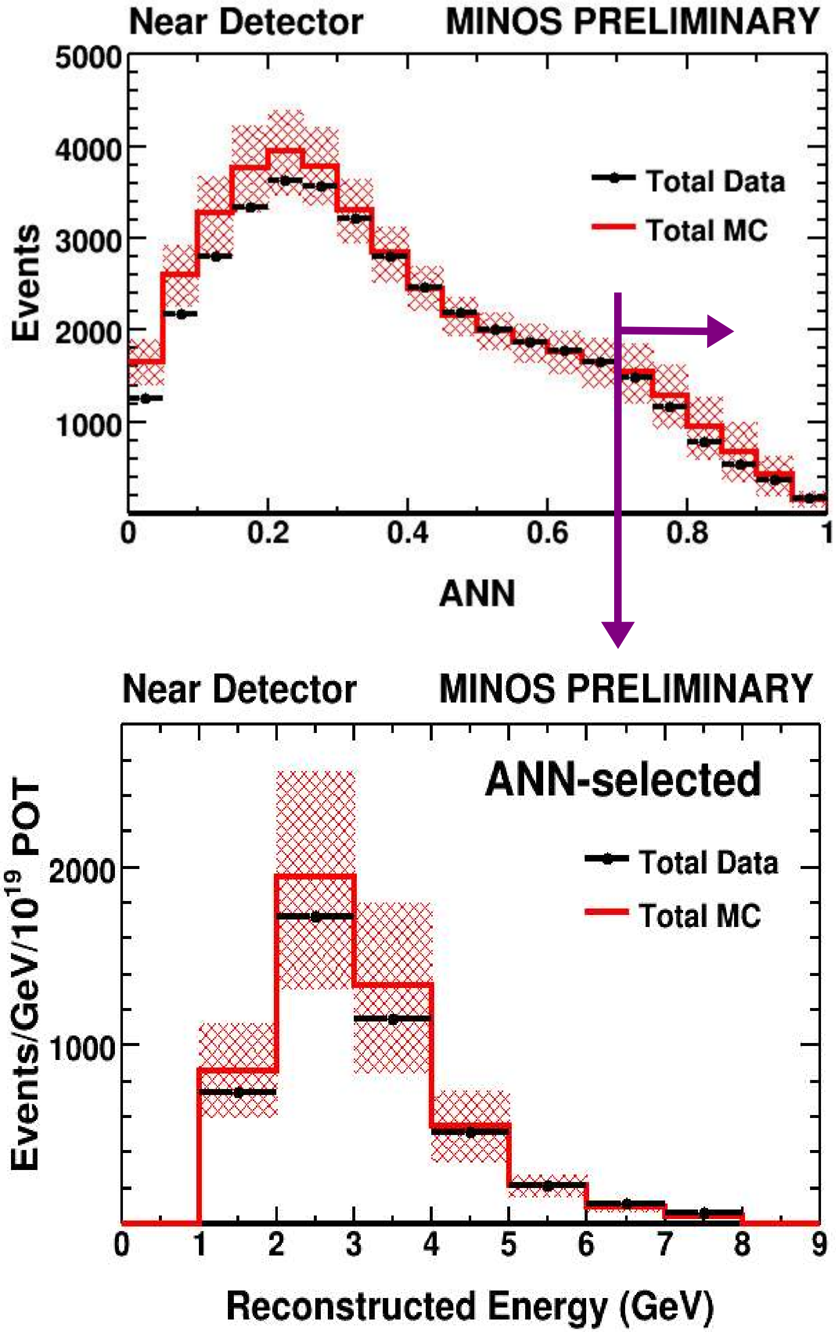
Signal:Background = 1:2

S:B before selection ~1:45

Two other selectors developed as cross-check, not shown here.

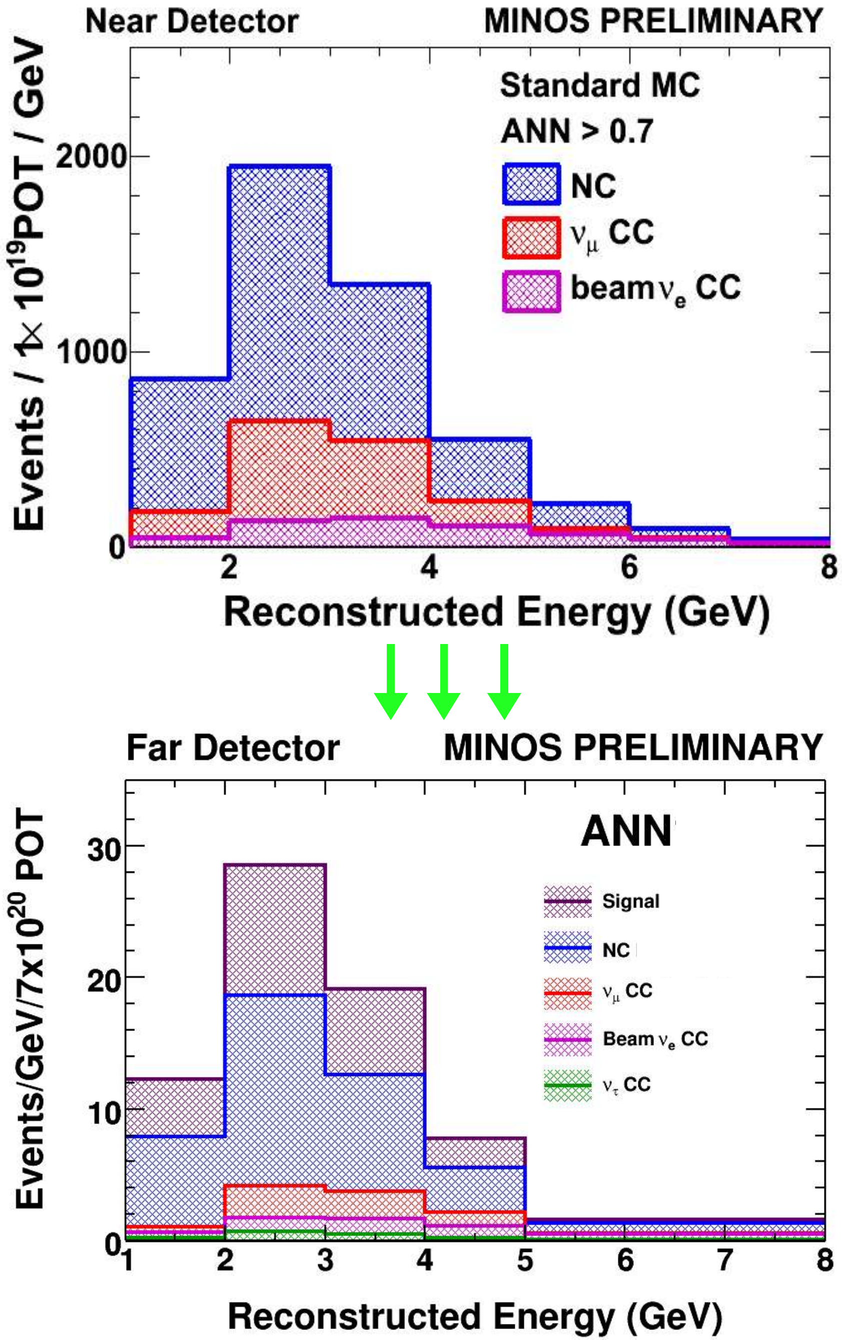
Near Detector Spectrum

- **ND provides high-statistics data sample** due to proximity to beam source and high event rate
- MINOS neutrino interactions occur in **kinematic region where little experimental data** available
- due to this particle **showers** in MINOS detectors **hard to model => data/MC differences**
- **discrepancy is within** the **uncertainties** of the MC model
- **Errors** are very similar in both detectors => they **cancel out**



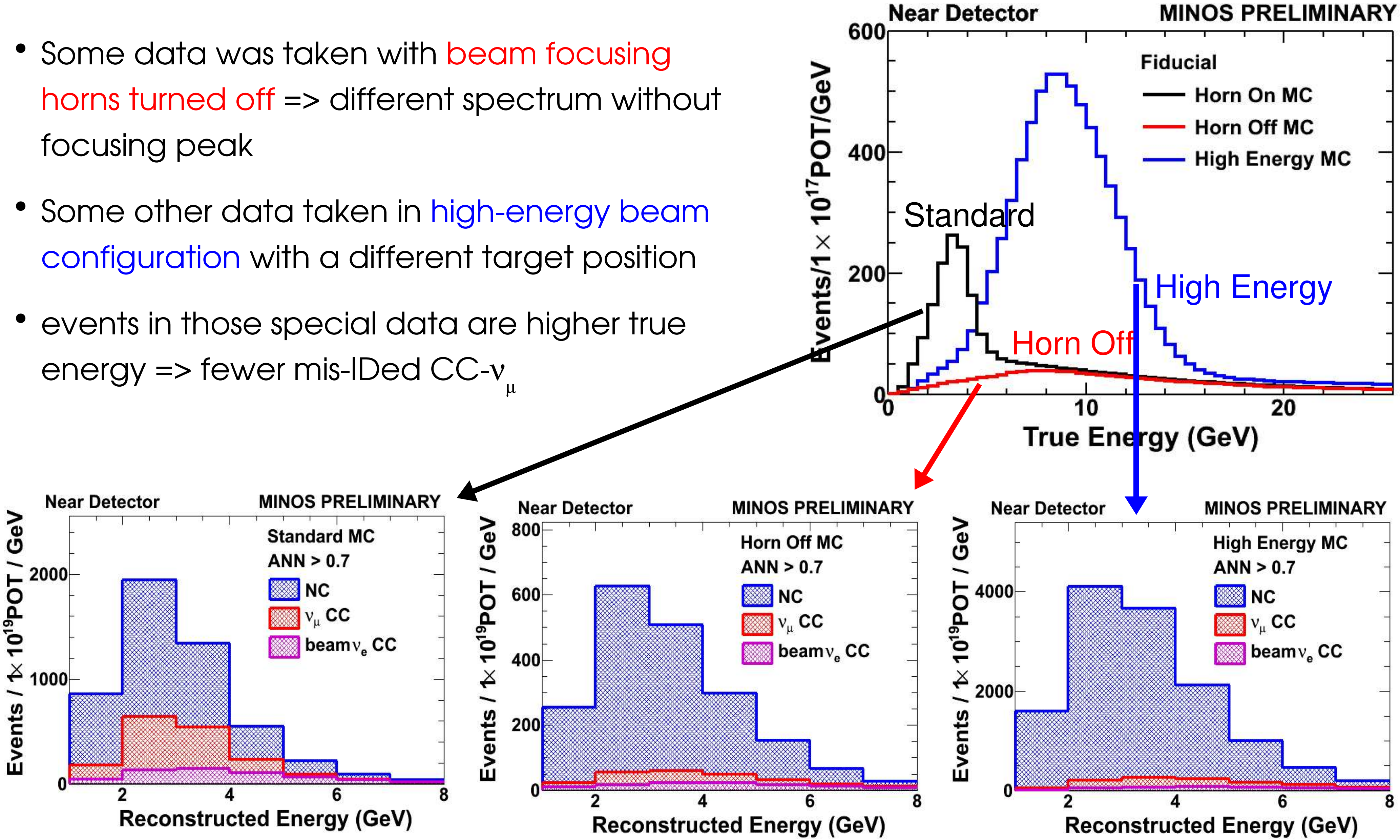
Near Detector Spectrum Decomposition

- **ND** background components **don't extrapolate the same way to FD** because of oscillations
- crucial to **separate ND data into its individual components** prior to extrapolating
- developed **2 data-driven methods** to decompose ND Data into background components
- first method is the **Multi-Beam method**
- second one is the **Muon Removed Charged Current method** – used as a cross-check



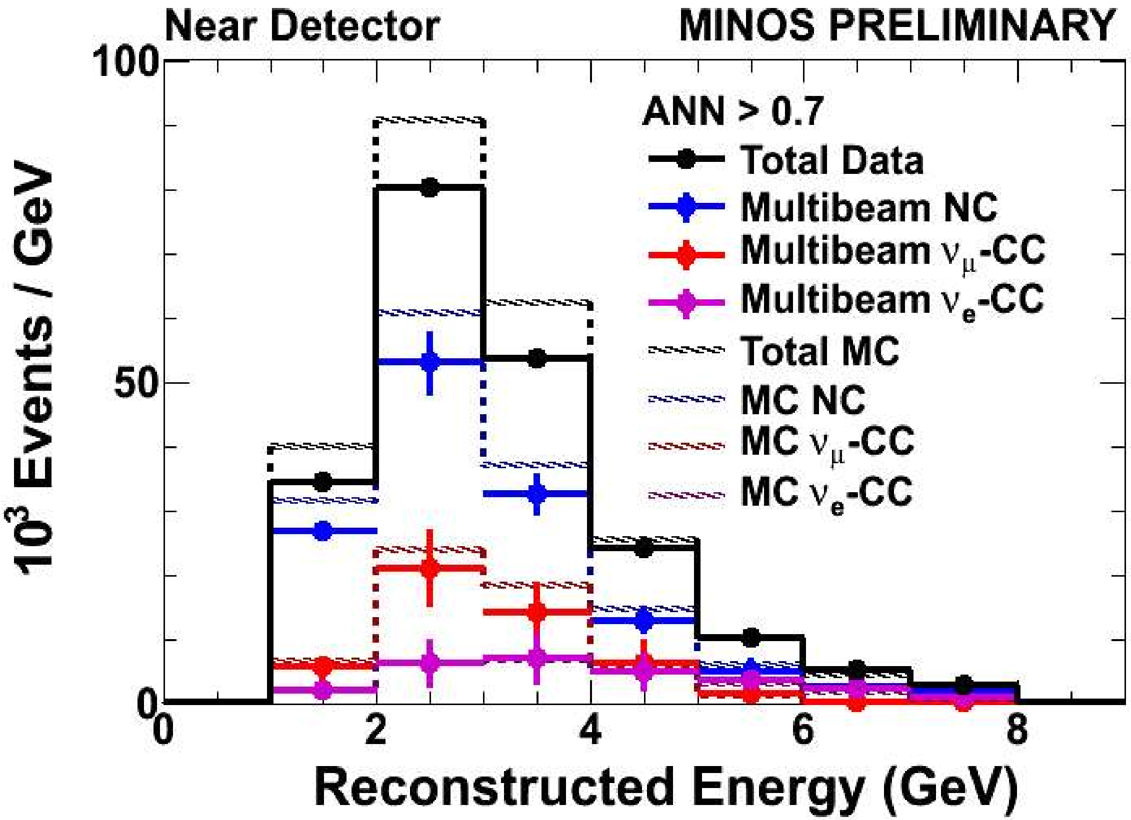
Decomposing the ND backgrounds - Multi-Beam Method

- Some data was taken with beam focusing horns turned off => different spectrum without focusing peak
- Some other data taken in high-energy beam configuration with a different target position
- events in those special data are higher true energy => fewer mis-IDed CC-ν_μ



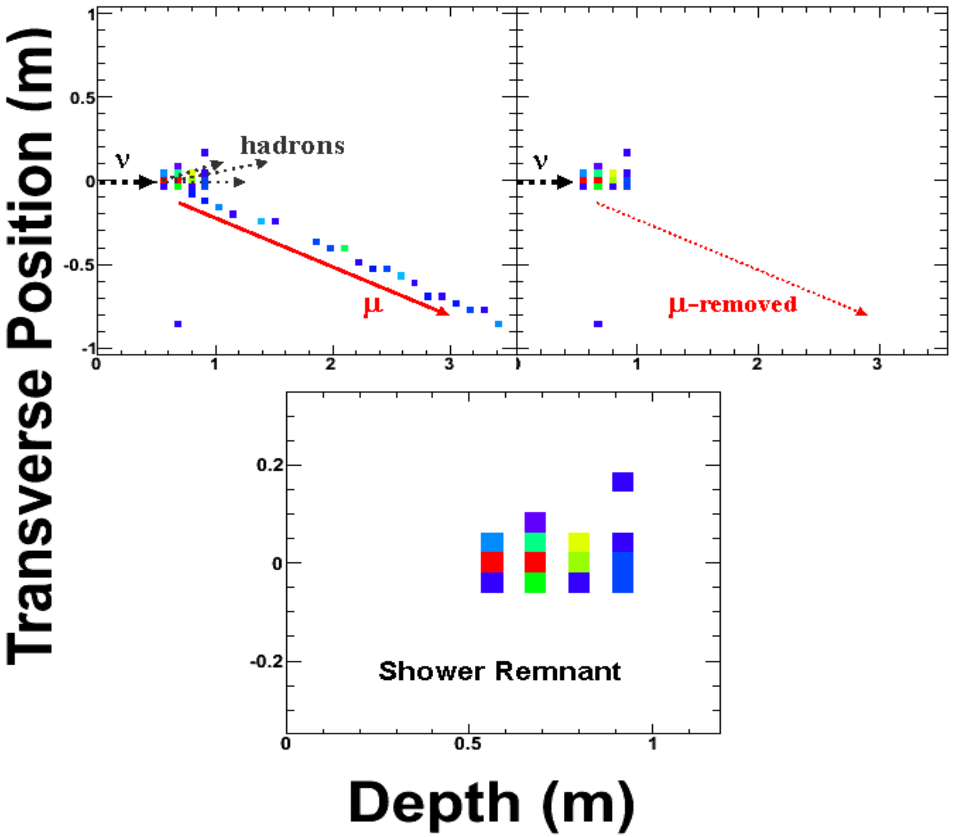
Decomposing the ND backgrounds - Multi-Beam Method

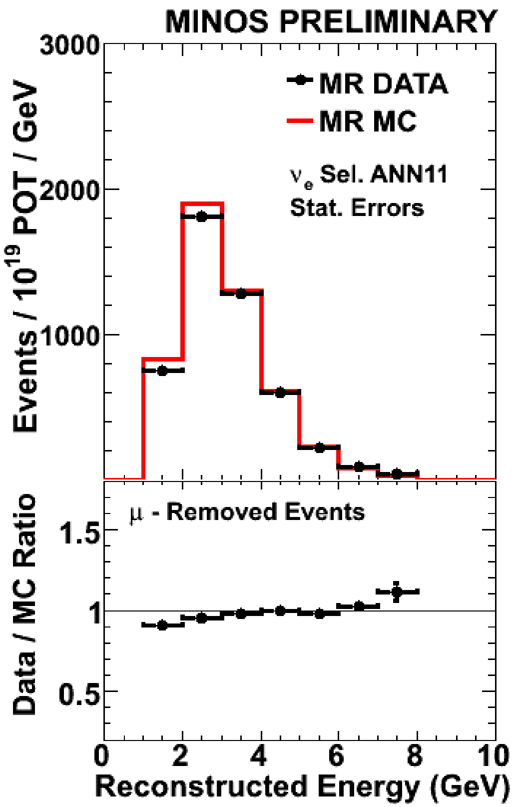
Separating the backgrounds essentially comes down to **solving a set of equations** with the three data spectra as inputs and the three ND background components as unknowns.



But we would like to **obtain a cross-check** for this ND data decomposition....

Decomposing the ND backgrounds - Muon Removal Method



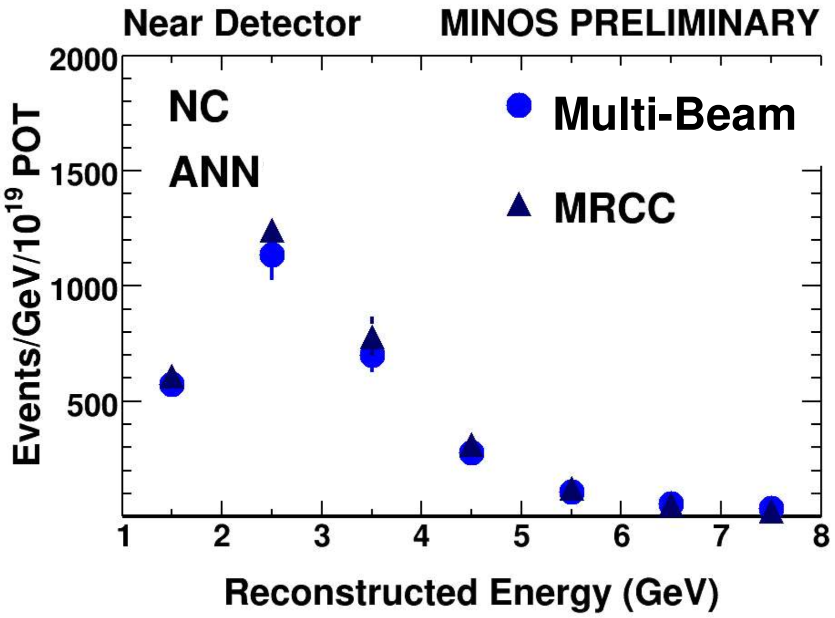


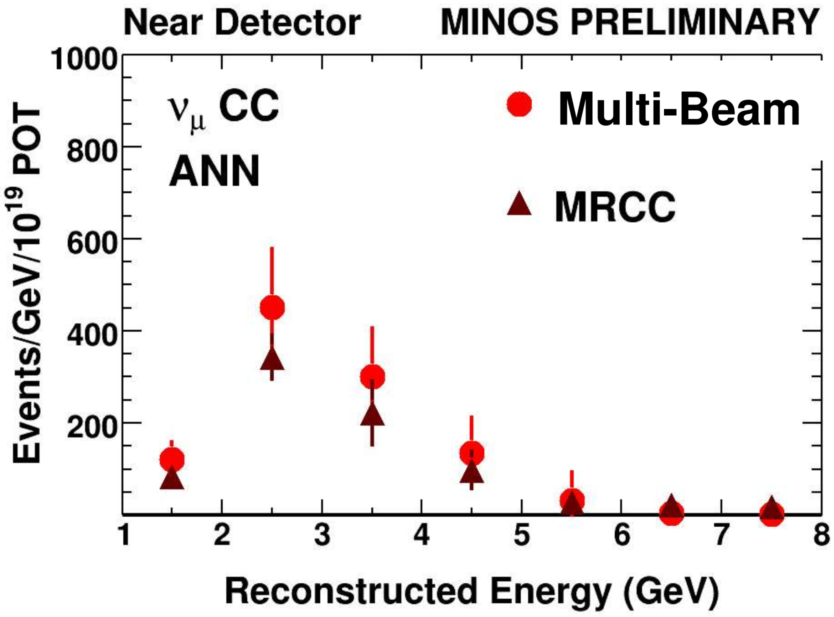
Muon-removed events are used to model the NC background and an ad-hoc correction of the ND MC using the MR Data/MC ratios on a bin-by-bin basis is carried out:

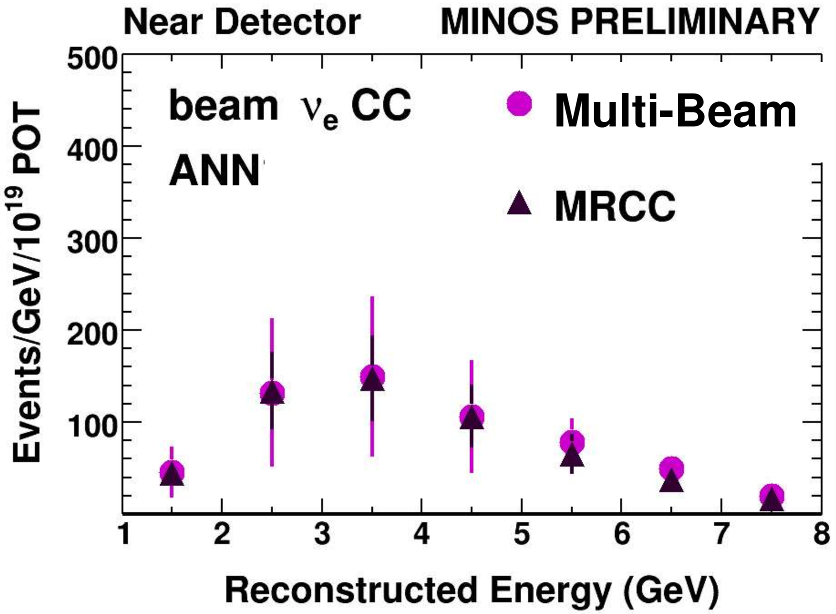
$$NC^{MRcorr.} = NC_{Std.MC}\left(DATA_{MR}/MC_{MR}\right)$$

$$CC\,\nu_{\mu}^{corr.} = Data - NC^{MRcorr.} - Beam\,\nu_{e}$$

Comparison of ND Data Decomposition Results







- The **two methods agree well** within errors
- The **ND spectra** are ready to be **extrapolated** to the Far Detector

Far Detector Extrapolation

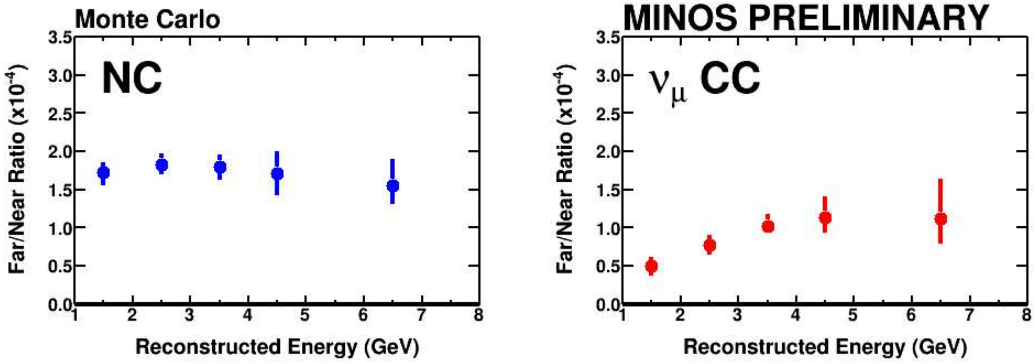
- A **Far/Near method** is used to extrapolate each ND background to the FD:

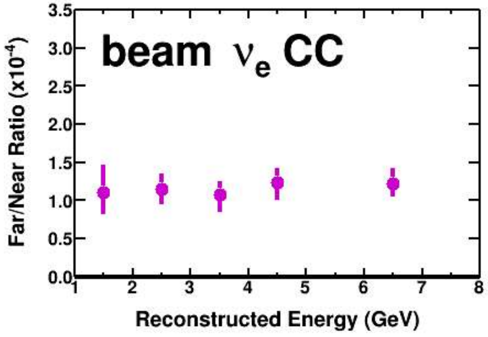
$$F_i^{pred,\alpha} = N_i^{\alpha} \, x \, \frac{f_i^{\alpha}}{n_i^{\alpha}}$$

- α = NC, CC-ν_μ, or beam CC-ν_e
- MC Far/Near ratios calculated in bins of energy *i*, ND decomposed data are input

- ND backgrounds multiplied by the relevant Far/Near MC ratios - Far MC is oscillated

- The **appearing CC-ν_τ** come from **oscillating the ν_μ**
- The Far/Near ratios account for:
  - Flux ($1/R^2$, geometry, focusing, acceptance, decay kinematics)
  - Energy smearing
  - ν_μ disappearance
  - Detector effects

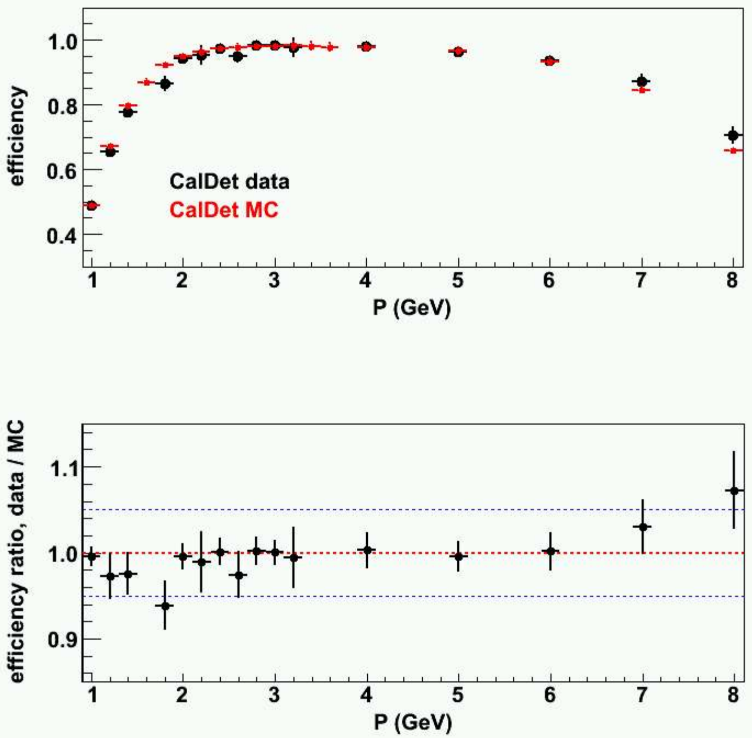




Far/Near ratios as a function of energy – the data between 5-8GeV are one bin

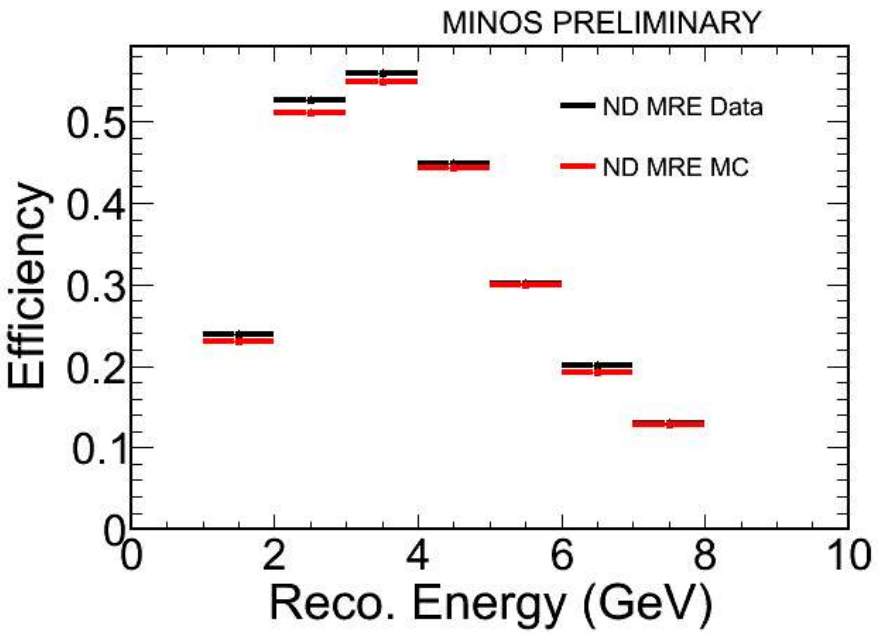
FD Extrapolation – Data-Driven Signal Prediction

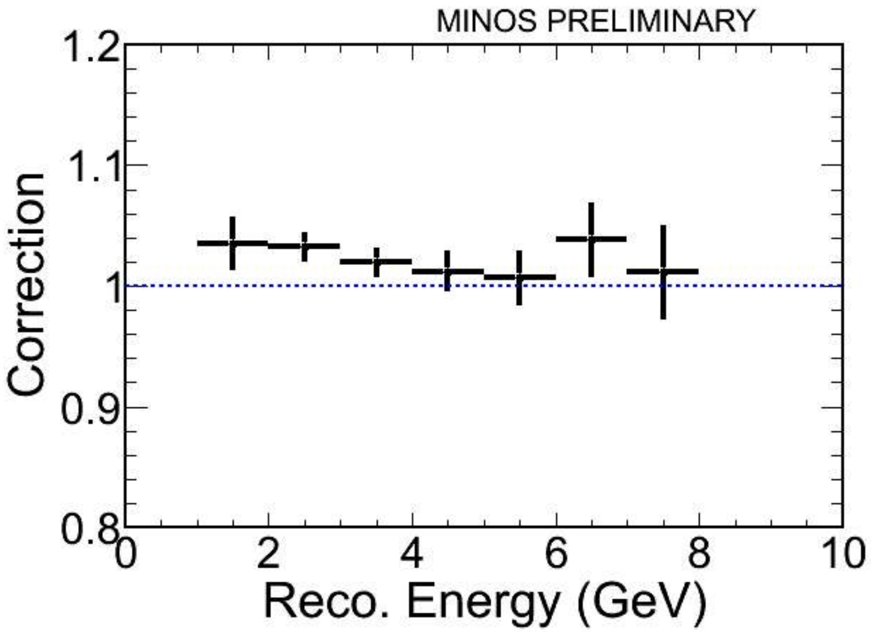
- The **signal CC-ν_e** need to be predicted **as a function of θ_{13}**
- The **track-like CC spectrum extrapolated to FD** and oscillated to obtain data-driven prediction of track-like spectrum at the FD
- The **oscillation probabilities are applied to obtain a signal prediction**
- **The prediction is corrected by the signal selection efficiency**
- To this end, MINOS uses **MRE – Muon Removed Electron Added** - samples
    - take **MR event and add a MC electron** in place of removed muon, with same momentum
    - we know that our **MC models electrons well** from the MINOS calibration detector in a test beam at CERN



FD Extrapolation – Data-Driven Signal Prediction

- The MRE process is applied to both data and MC and CC-ν_e selection efficiencies are calculated – their ratio is used to correct the signal efficiency

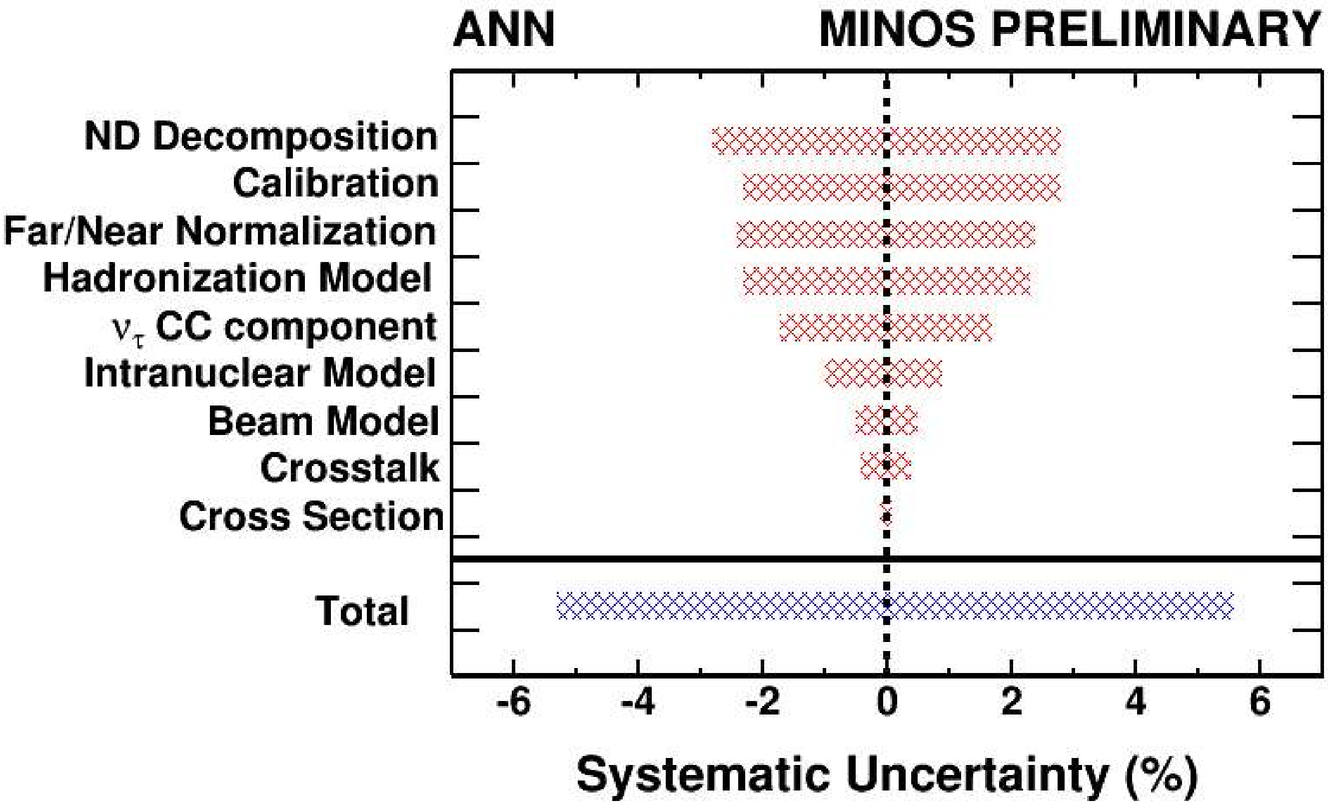




Selection Efficiency: 41.6±1.0 %

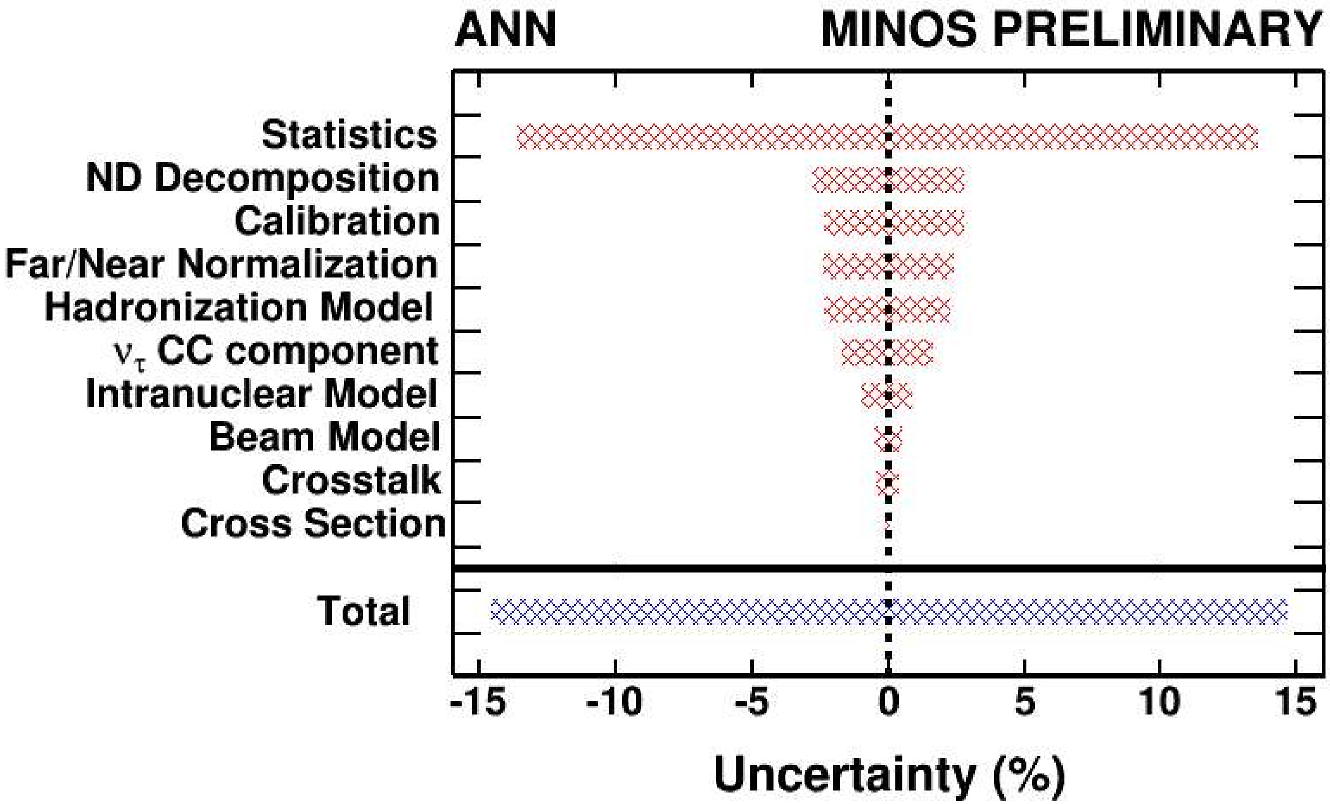
Systematic Errors

- most systematics are evaluated by **generating special MC with modified parameters in both the Near and Far detectors.** This modified MC is used to extrapolate and calculate the difference with the standard results
- **many errors cancel out** in the Far/Near extrapolation

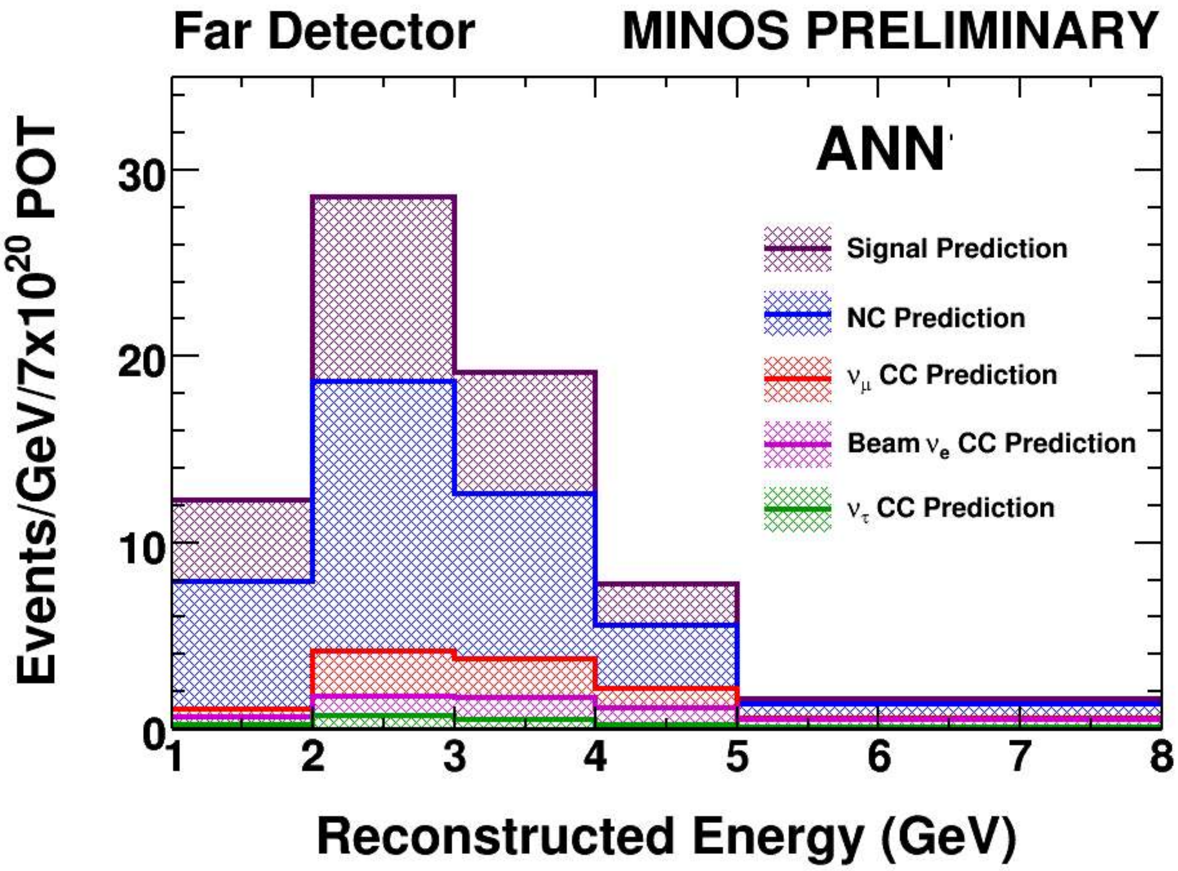


Systematic Errors

- most systematics are evaluated by **generating special MC with modified parameters in both the Near and Far detectors.** This modified MC is used to extrapolate and calculate the difference with the standard results
- **many errors cancel out** in the Far/Near extrapolation
- **the statistical uncertainty dominates at over 14%**



Final Far Detector Prediction



	Total	Stat. Err.	Syst. Err.	NC	CCNuMu	Beam NuE	CcNuTau
ANN	49.1	7.0	2.7	35.8	6.3	5.0	2.0

Expected signal at **Chooz limit**: **24 events** => **3.2σ signal** at this limit

Far/Near Differences

It is **crucial** that we **understand our Far/Near differences** well for this analysis.

Most of them will be taken care of by the MC, however, we want to see if there are **unexpected Far/Near differences** not taken into account.

*=> It was decided to look at **sidebands prior to unblinding** the main analysis box.*

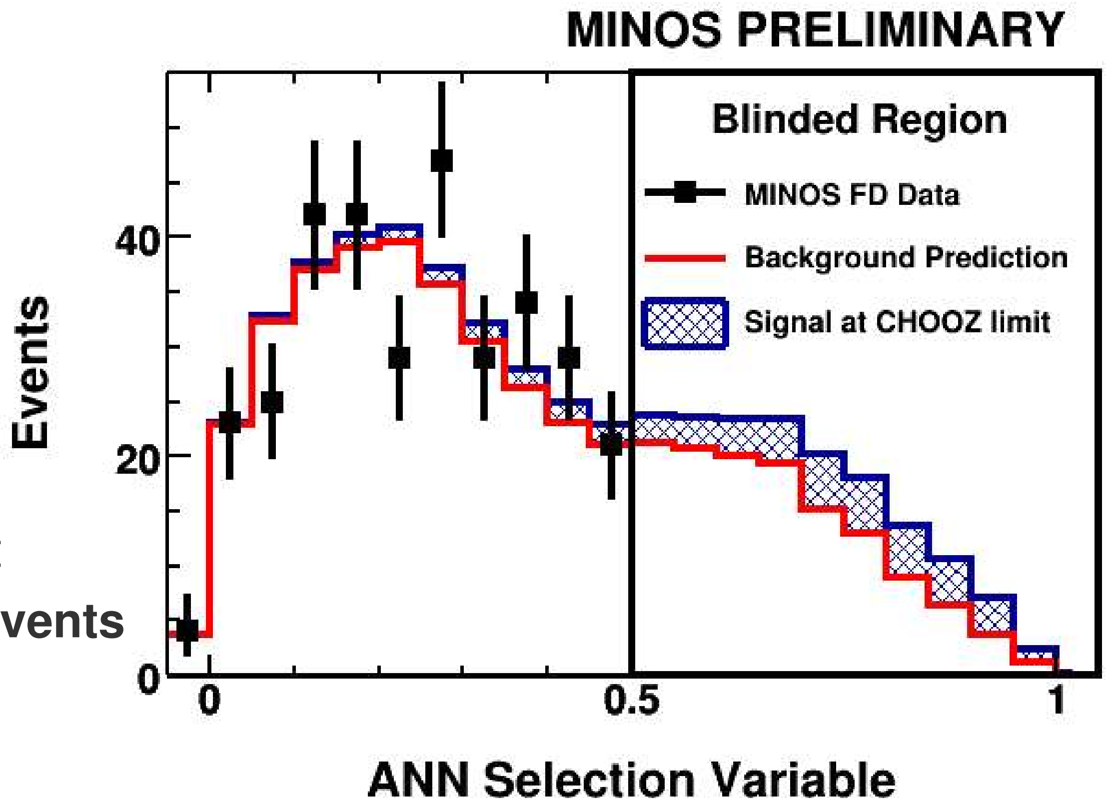
Looked at:

- **Anti-PID sideband**
- **Muon Removed sideband**

Far/Near Differences – Anti-PID Sideband

ANN < 0.5

Predicted **314** +- 18(stat.), observed **327** events, **0.75σ** excess



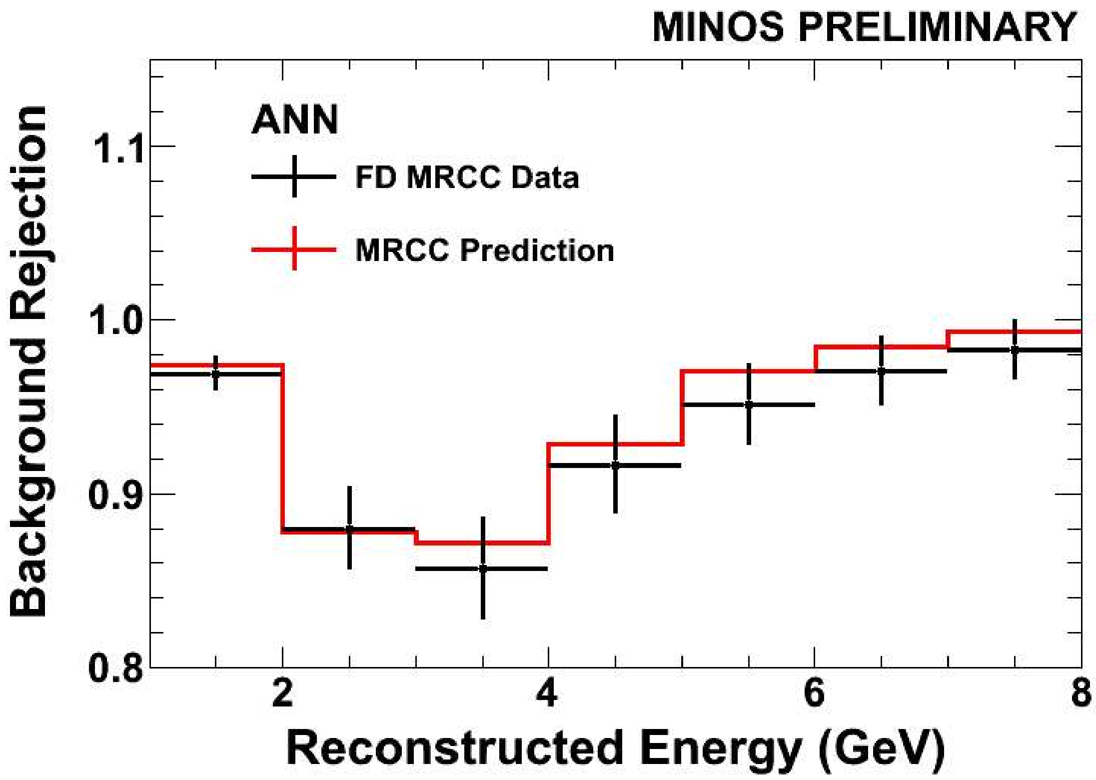
Signal expected at CHOOZ limit: **13 events**

Good agreement (region chosen not to be sensitive to signal).

Tested the whole FD extrapolation chain + agreement between prediction and data

Far/Near Differences – Muon Removed Sideband

Use **muon removed data events in FD** and measure selection efficiency for these showers
=> compare with prediction derived from FD MR MC and ND MR data and MC



Average rejection rates
(stat. errors only):

data: **92.8 ± 0.9 %**
pred: **93.58 ± 0.05 %**

agreement within **0.86σ**

This sideband is important to test the background shower selection.
Agreement is reasonable, within statistical errors.

Final Box Opening

Result of Blind Analysis for an Exposure of $7.0\text{x}10^{20}$ protons on target

Result of Blind Analysis for an Exposure of 7.0×10^{20} protons on target

We obtained:

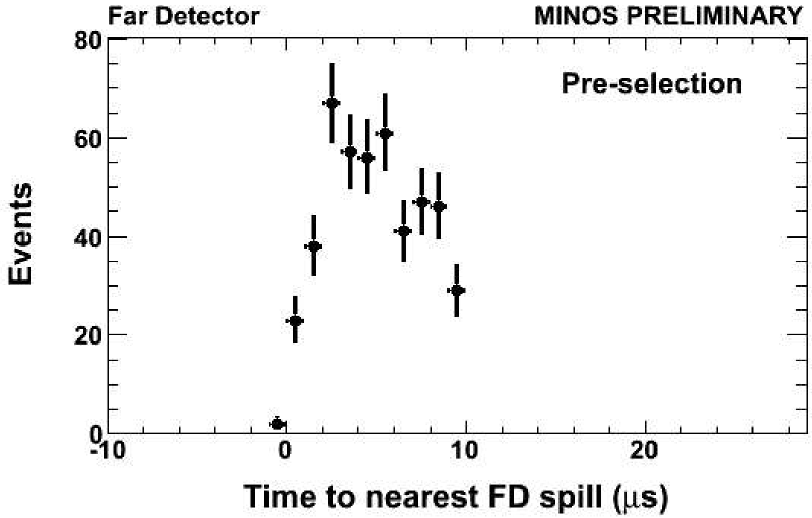
- **Data-driven Near Detector background decompositions**
- **=> Data-driven Far Detector background predictions**
- **Data-driven Far Detector signal prediction**

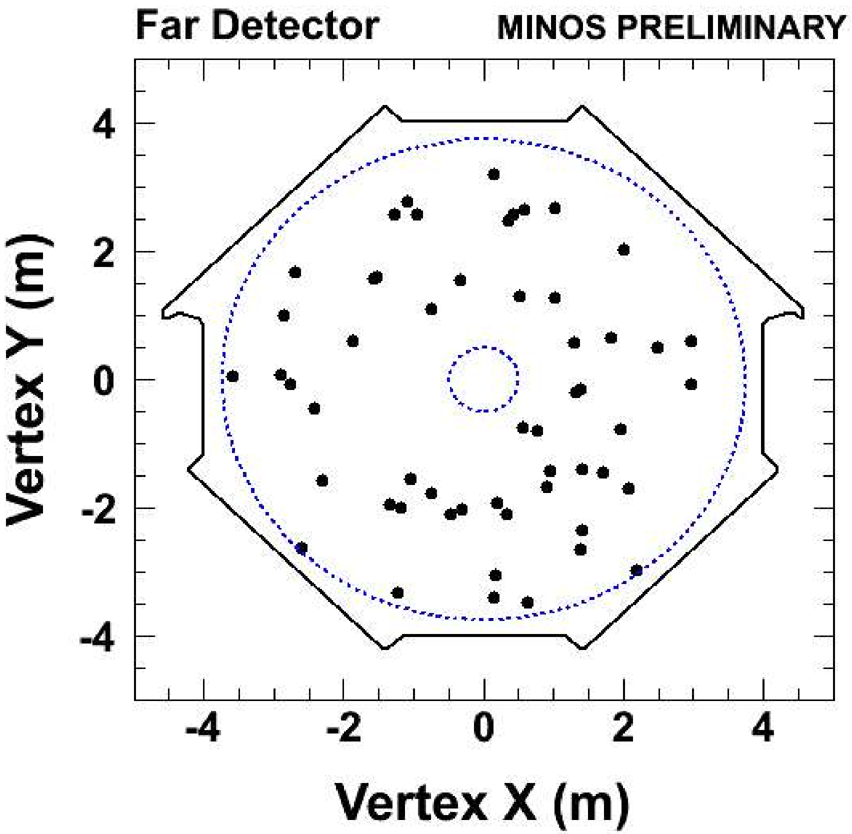
Opened two sidebands to check if there are any unexpected Far/Near differences => agreement ok

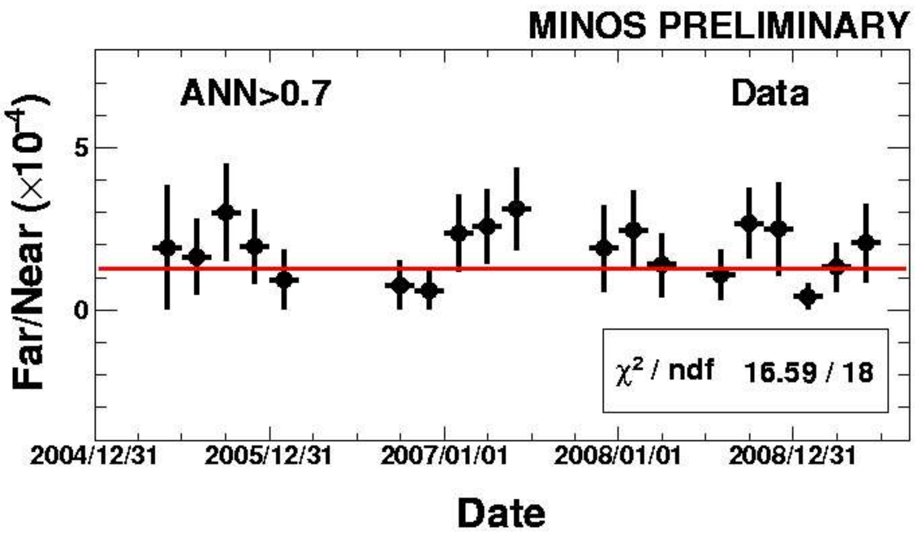
=> Next step: look at FD distributions and unblind the box!

FD Box Opening

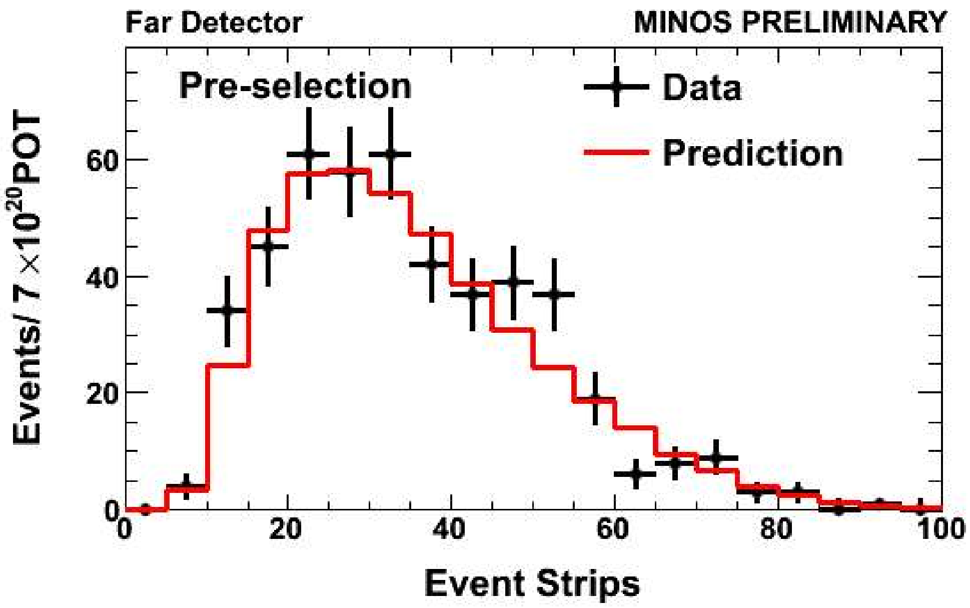
FD data distributions look reasonable

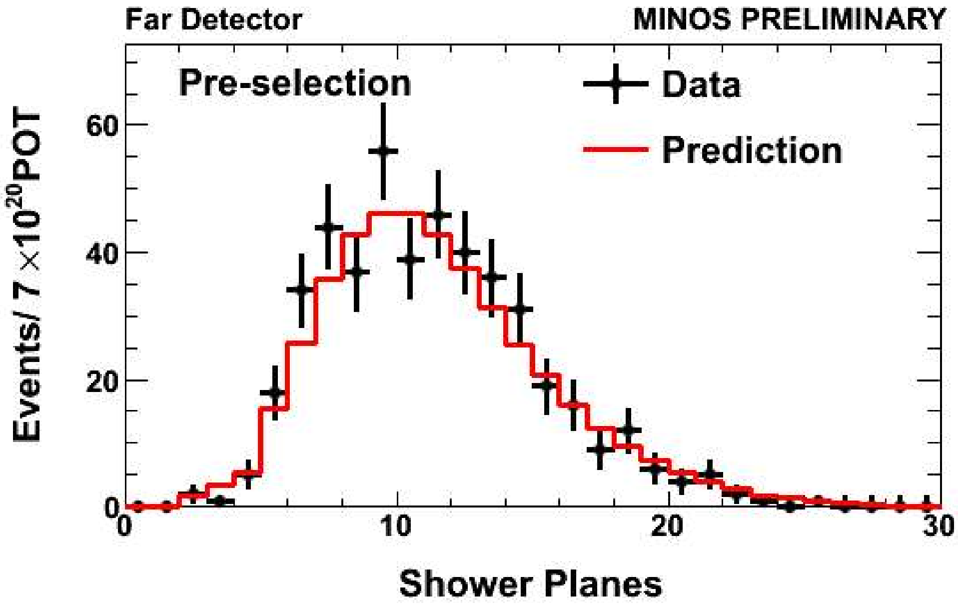


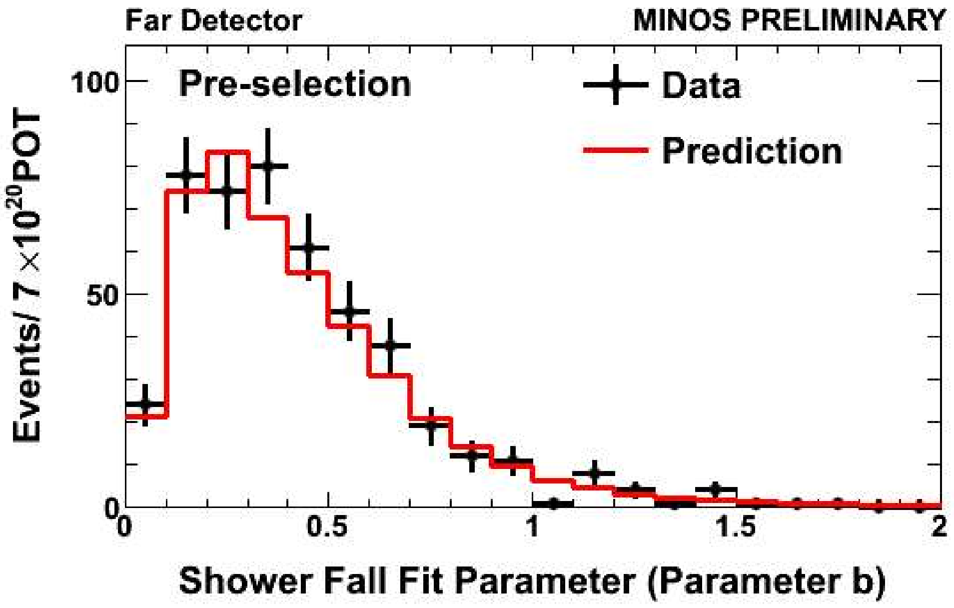


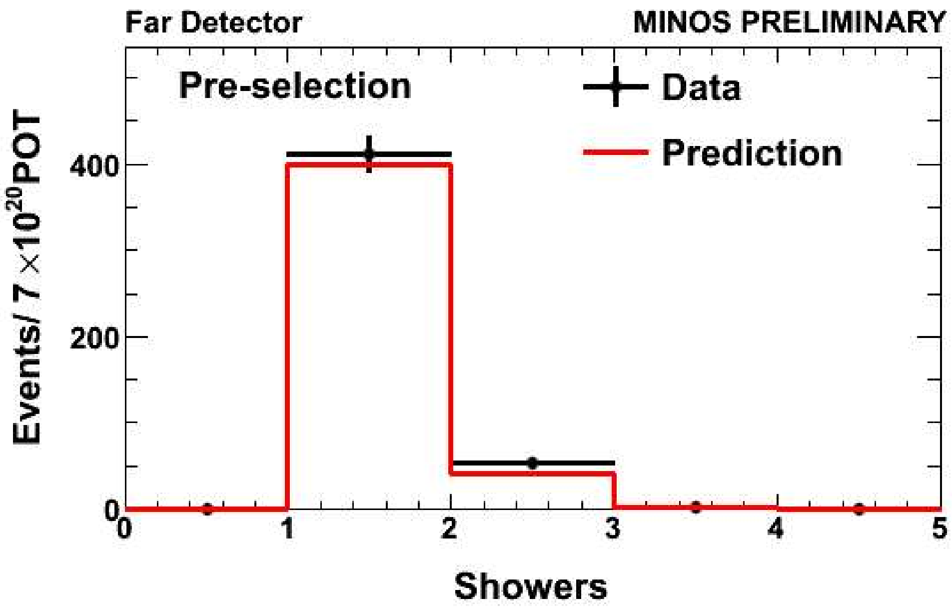


FD Box Opening

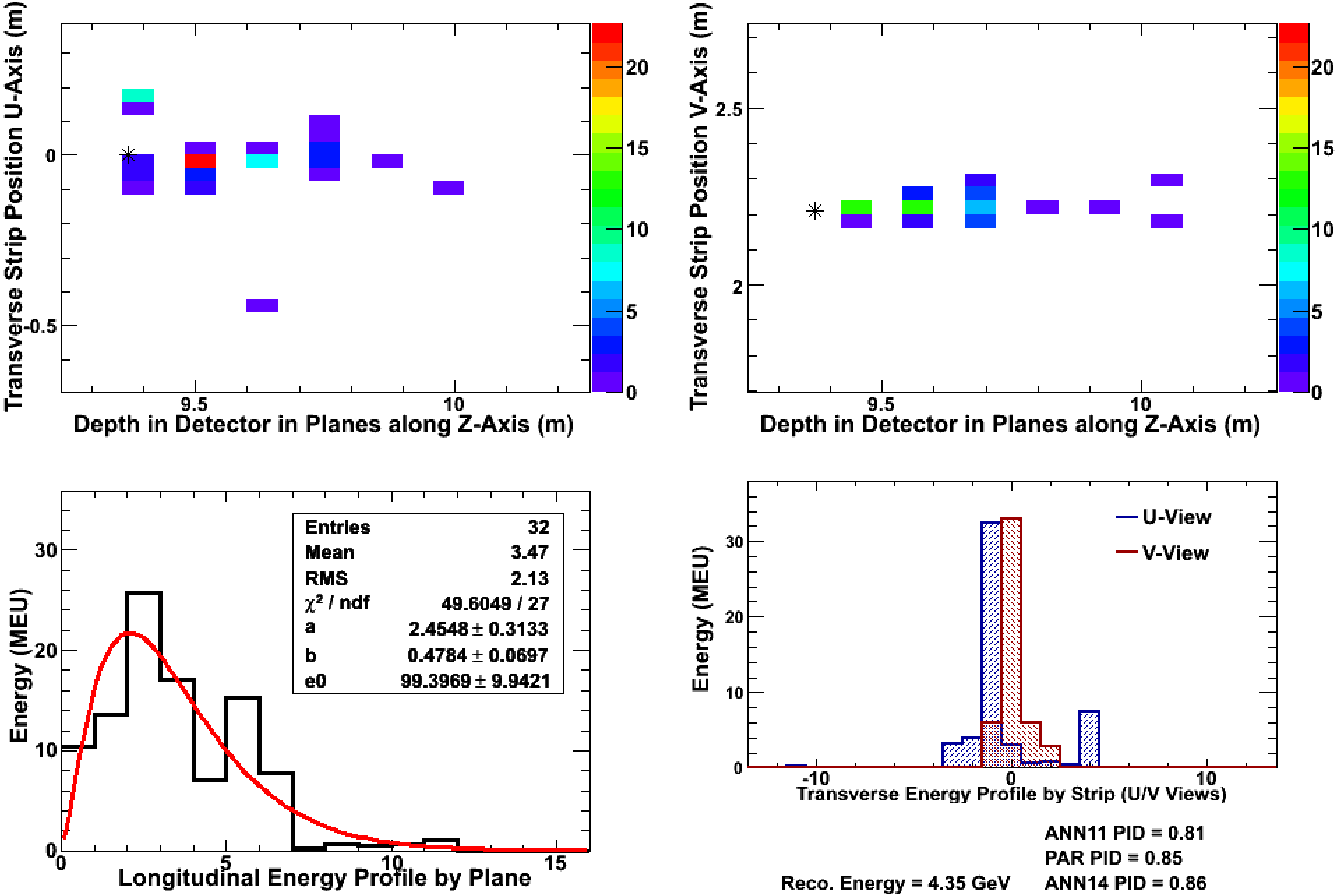








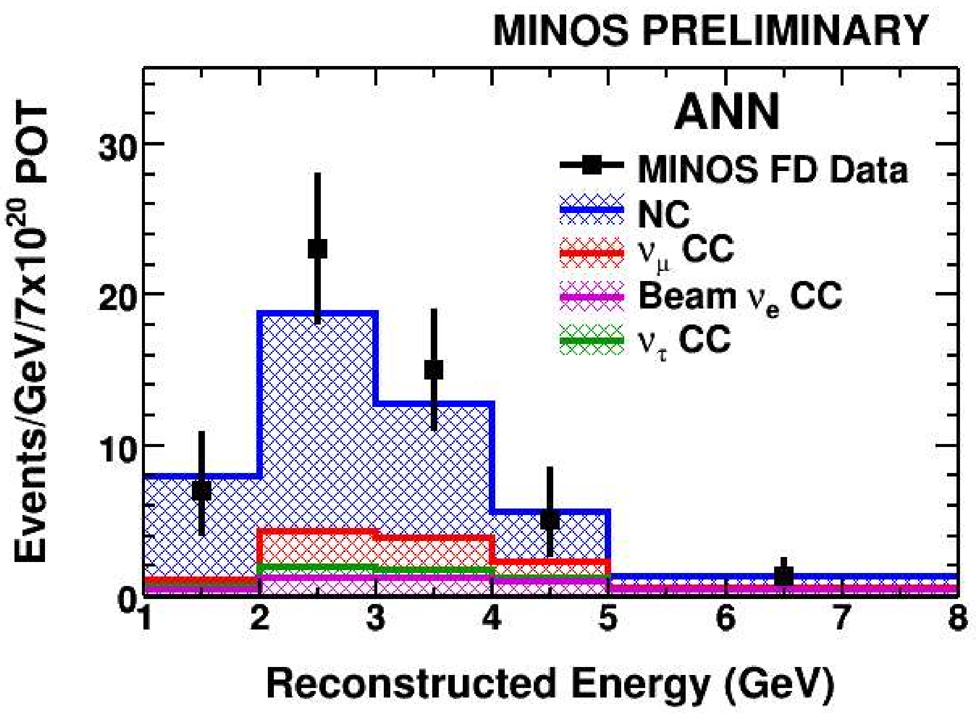
Far Detector Selected Events

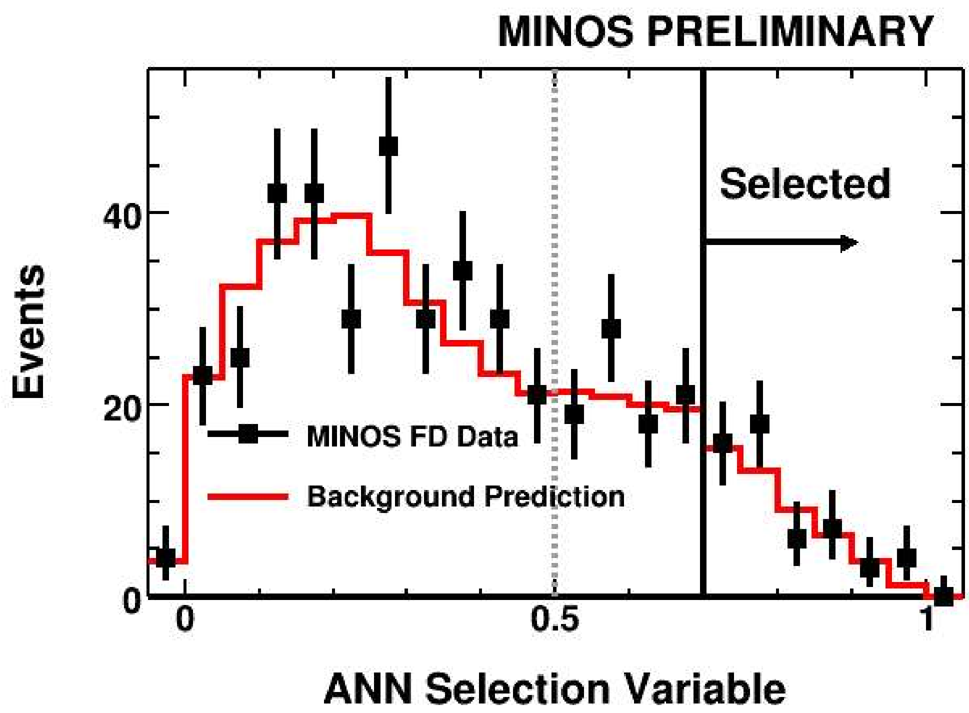


ANN11 PID = 0.81
PAR PID = 0.85
Reco. Energy = 4.35 GeV
ANN14 PID = 0.86

FD Box Opening

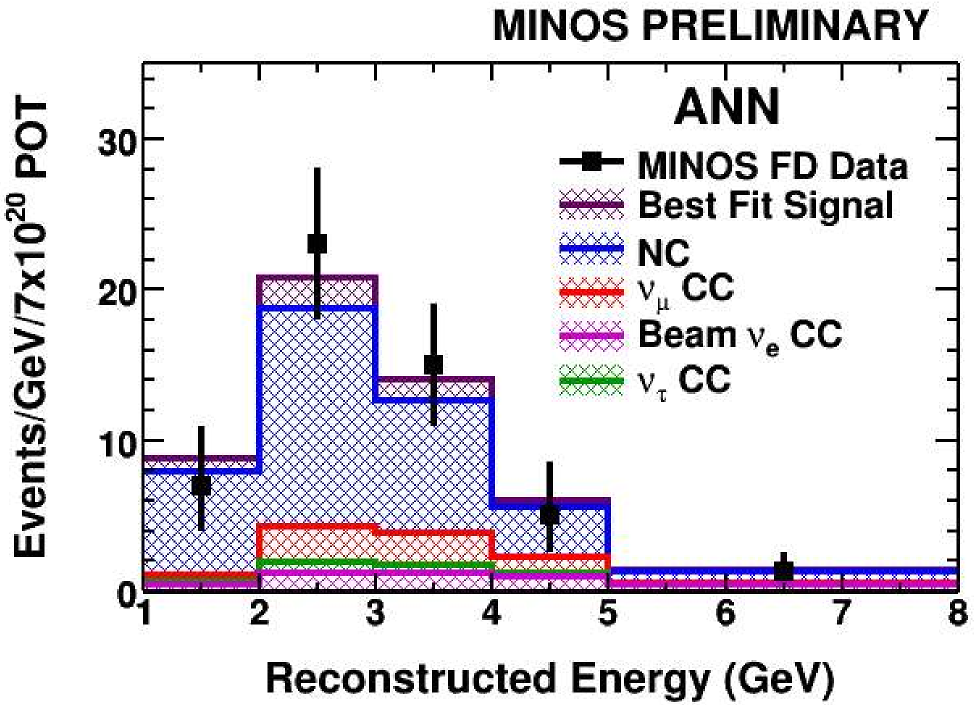
	Total	Stat. Err.	Syst. Err.	DATA	Excess	Sigma
ANN	49.1	7.0	2.7	54	4.9	0.7

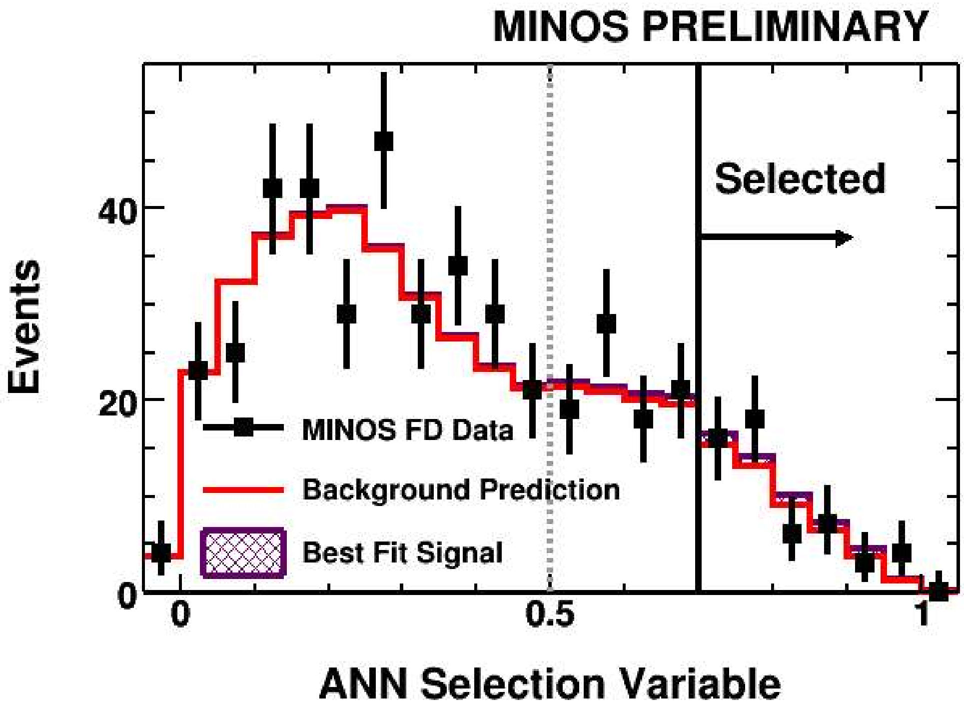




FD Box Opening

	Total	Stat. Err.	Syst. Err.	DATA	Excess	Sigma
ANN	49.1	7.0	2.7	**54**	**4.9**	**0.7**



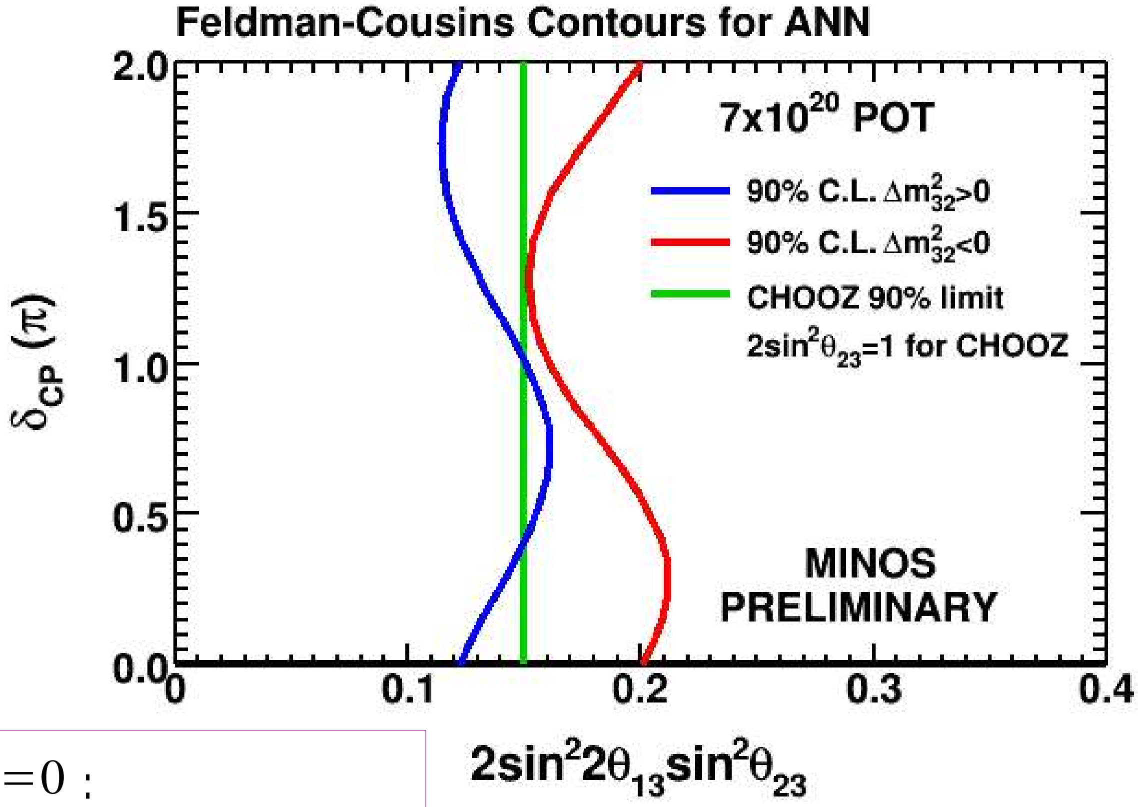


For **normal mass hierarchy**, with **δ=0**, the signal is obtained using the **best-fit parameters**

Final Contours

Final contours calculated using a Feldman Cousins method

Results given for normal and inverted mass hierarchies (calculated for MINOS best fit value of $\Delta m^2_{32} = 2.43 \times 10^{-3} eV^2$)



The obtained limits are in the case of $\delta = 0$:

$\sin^2(2\theta_{13}) < 0.12$ at 90% C.L., for normal mass hierarchy

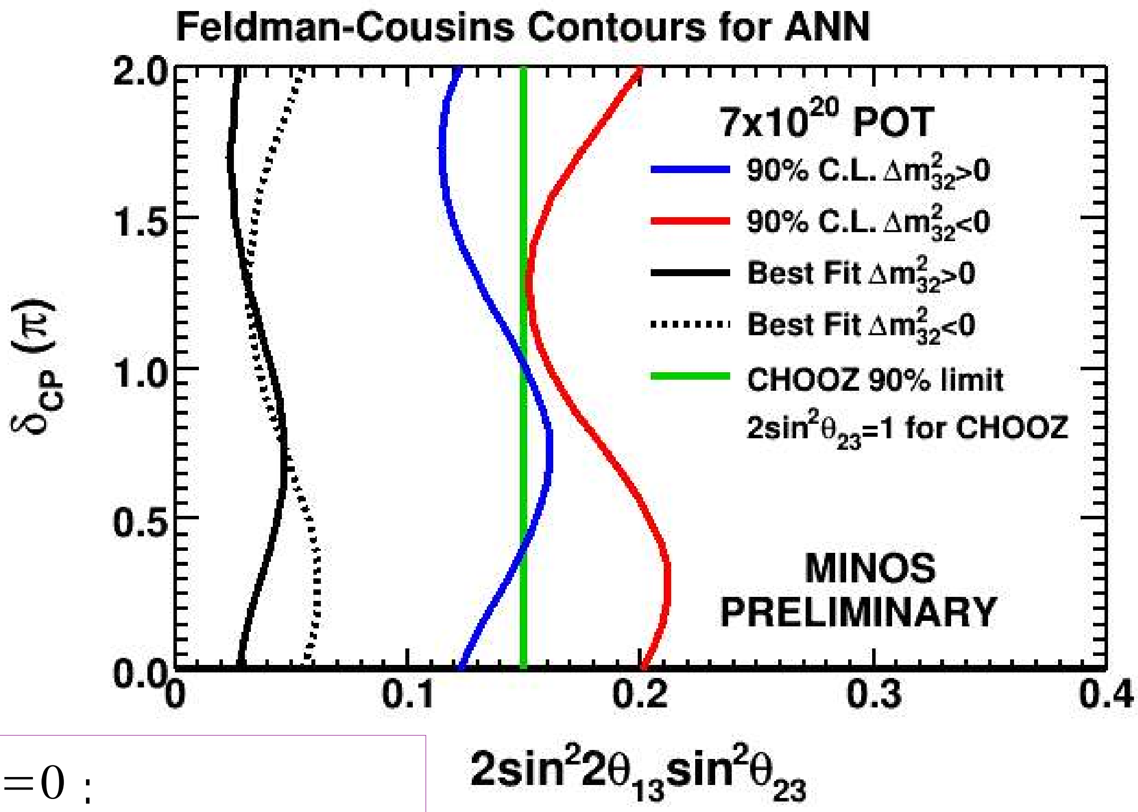
$\sin^2(2\theta_{13}) < 0.20$ at 90% C.L. for inverted mass hierarchy

Obtained consistent results with two other selectors that were used as a cross-check

Final Contours

Final contours calculated using a Feldman Cousins method

Results given for normal and inverted mass hierarchies (calculated for MINOS best fit value of $\Delta m^2_{32} = 2.43\times 10^{-3} eV^2$)



The obtained limits are in the case of $\delta = 0$:

$\sin^2(2\theta_{13}) < 0.12$ at 90% C.L., for normal mass hierarchy

$\sin^2(2\theta_{13}) < 0.20$ at 90% C.L. for inverted mass hierarchy

The obtained best fits are in the case of $\delta = 0$:

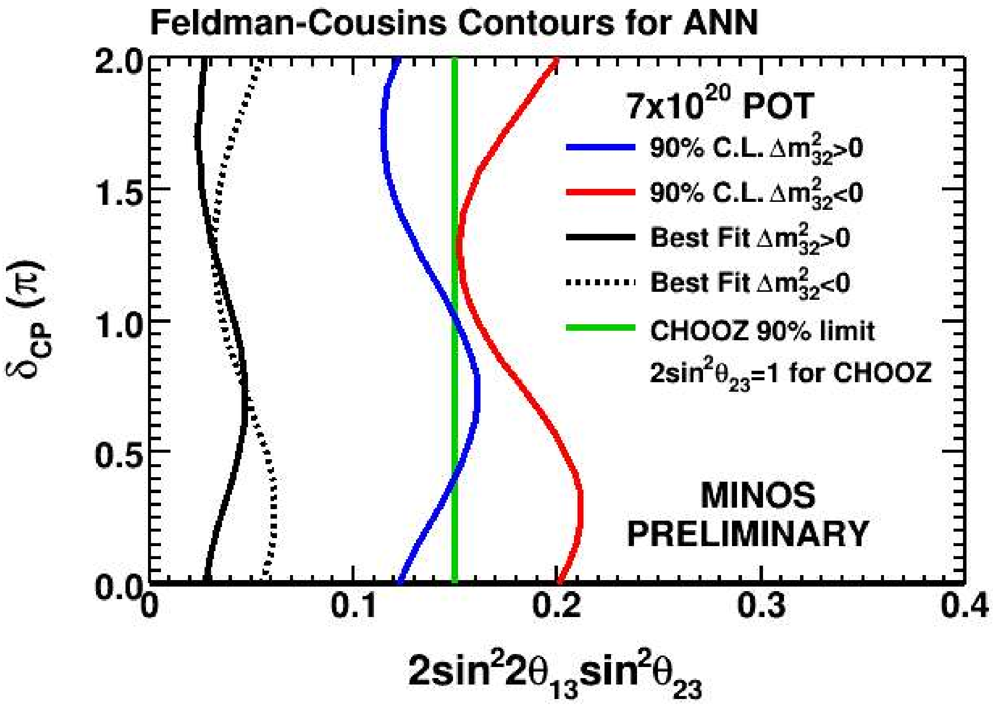
$\sin^2(2\theta_{13}) = 0.027$ for normal mass hierarchy

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

Obtained consistent results with two other selectors that were used as a cross-check

Future Analysis and Summary

- MINOS observed **54 events** with a predicted background of **49.1+ 7.0 (stat.) + 2.7 (syst.)**. This small 4.9 event excess yields a limit of **$\sin^2(2\theta_{13}) < 0.12$** at $\delta=0$ for the normal mass hierarchy.
- The MINOS experiment is the **first experiment** to have been able **to probe the θ_{13} angle with sensitivity beyond the CHOOZ limit**



- MINOS will take **at least 2x10^{20} POT more neutrino data** this year, and has already **accumulated ~2x10^{20} POT anti-neutrino data**
- **Analysis improvements**, combined with the additional data, could yield a **substantial increase in sensitivity** for an improved analysis next year

Acknowledgements

The MINOS Collaboration would like to thank the many Fermilab groups who provided technical expertise and support in the design, construction, installation and operation of the MINOS experiment.

Thank you to the Accelerator Division for the neutrinos!

We also acknowledge the financial support from DOE; NSF; STFC(UK); the University of Athens, Greece; Brazil's FAPESP, CNPq, and CAPES.

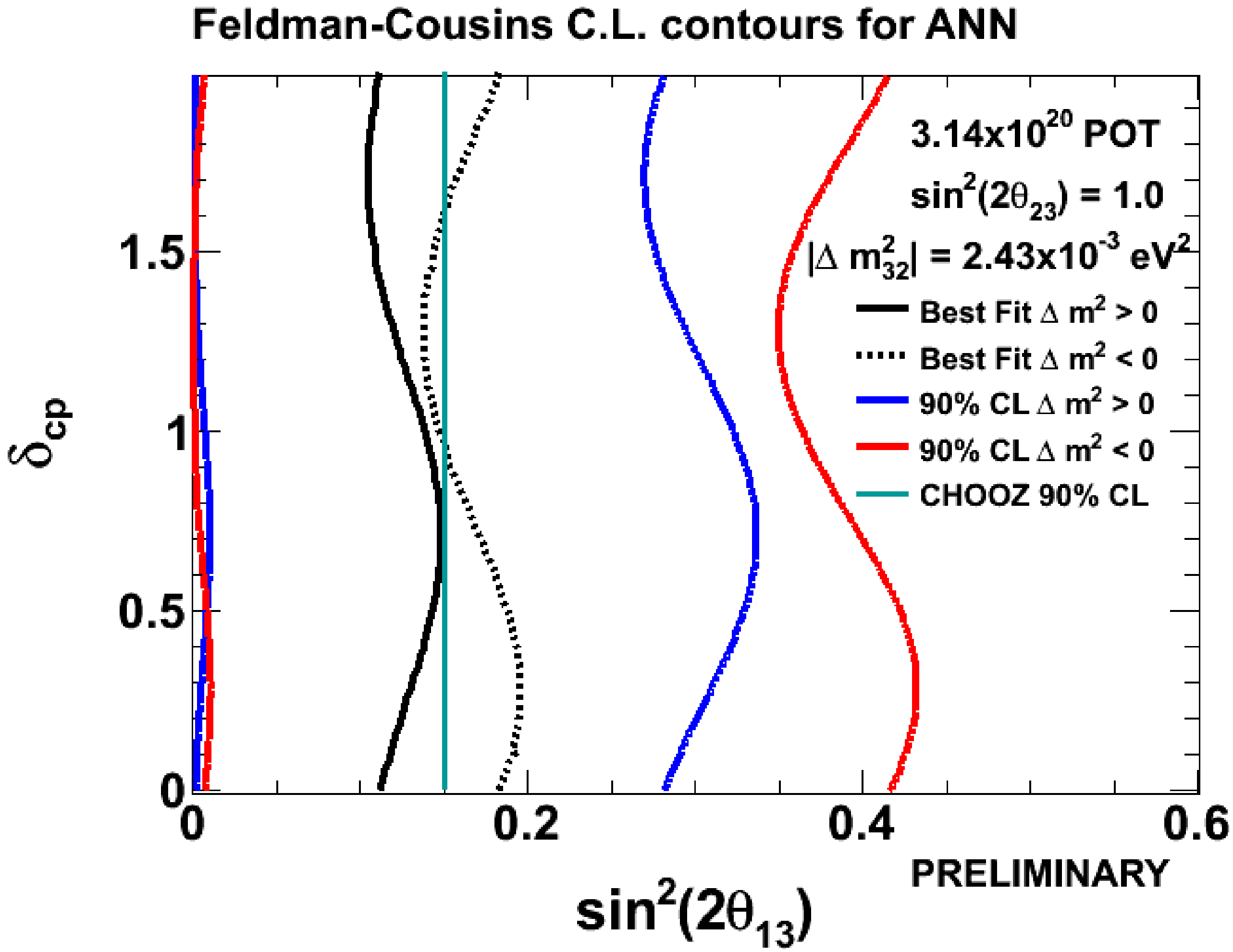
We are grateful to the University of Minnesota and the Minnesota Department of Natural Resources for hosting us.

Additional Slides

Anna Holin

Additional Slides

Previous MINOS Result for 3.14x10^{20} POT exposure PRL **103** 261802 (2009):



Expected: **27** ± 5(stat.) ± 2(syst.)

Observed: **35** events

Difference: **1.5** σ

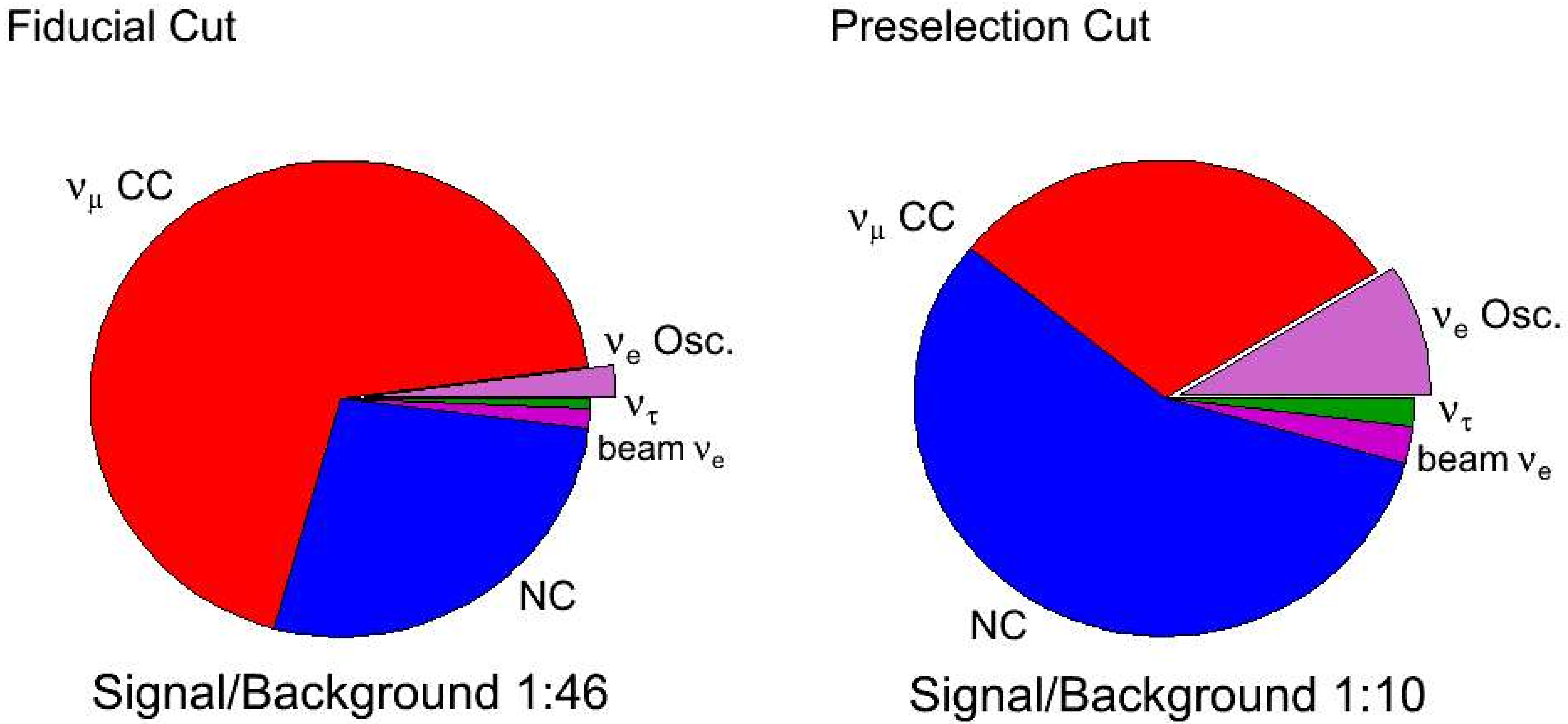
The obtained limits are in the case of CP-Violating phase $\delta = 0$:

$\sin^2(2\theta_{13}) < 0.29$ at 90% C.L., for normal mass hierarchy

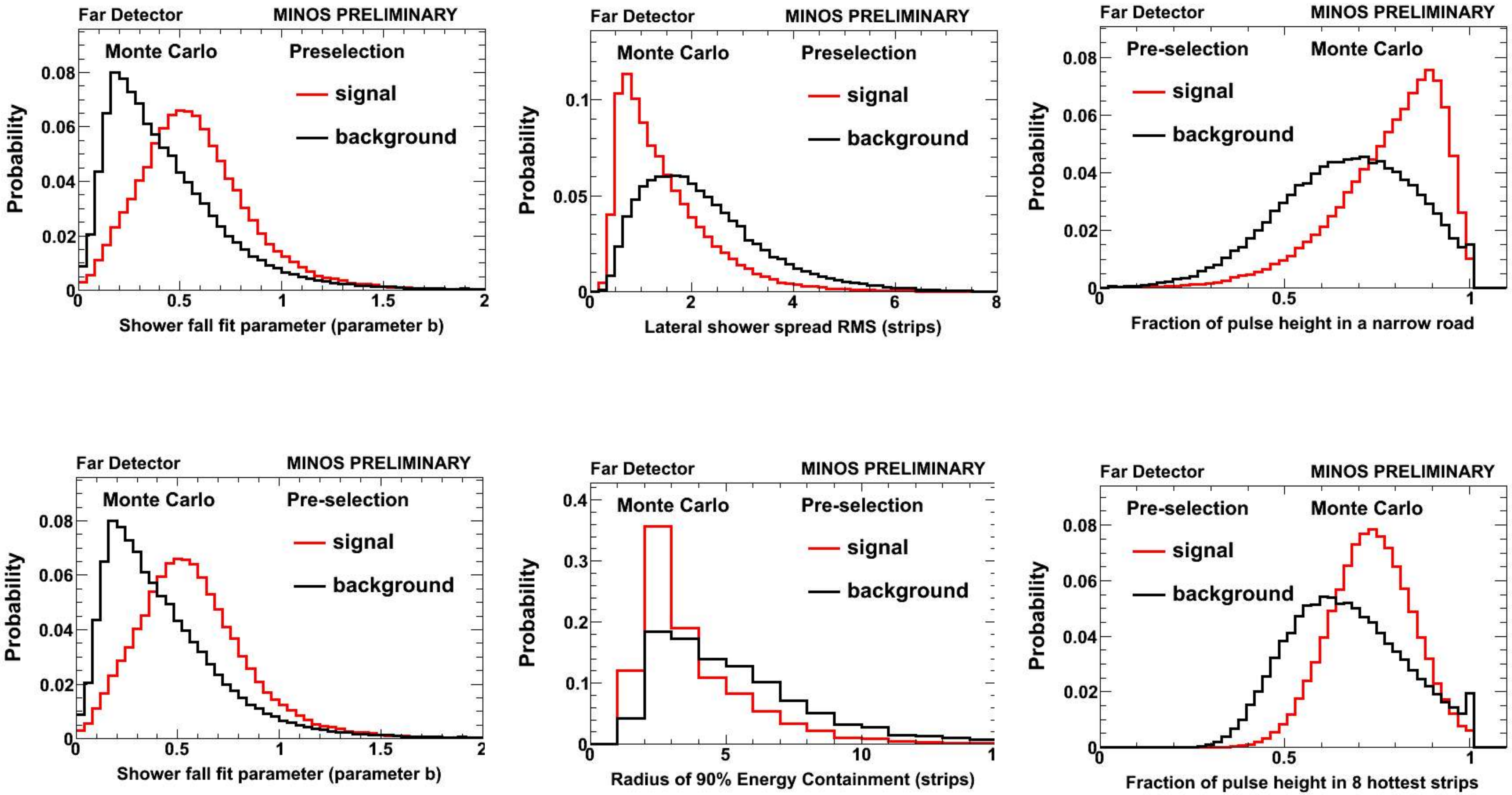
$\sin^2(2\theta_{13}) < 0.42$ at 90% C.L. for inverted mass hierarchy

Signal/Background after Preselection

The preselection improves the signal/background ratio from 1:46 to 1:10 (Monte Carlo numbers)

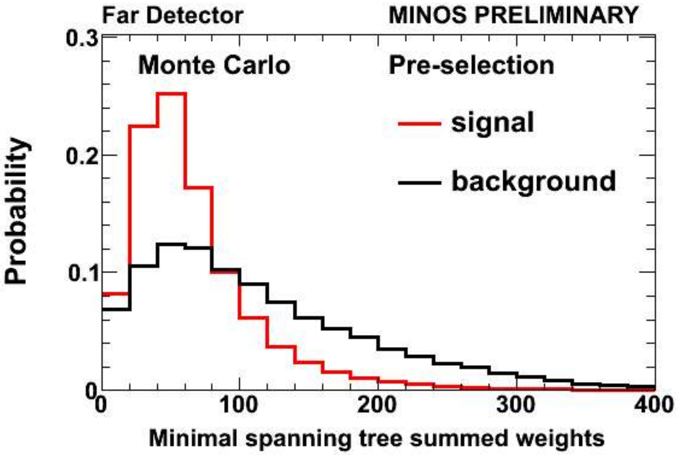


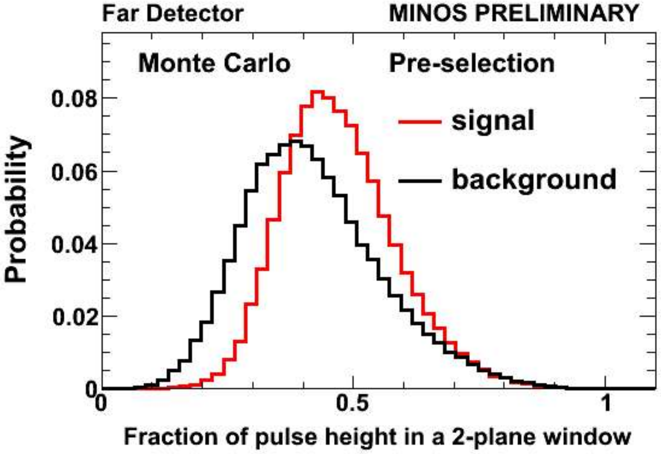
Signal Selection

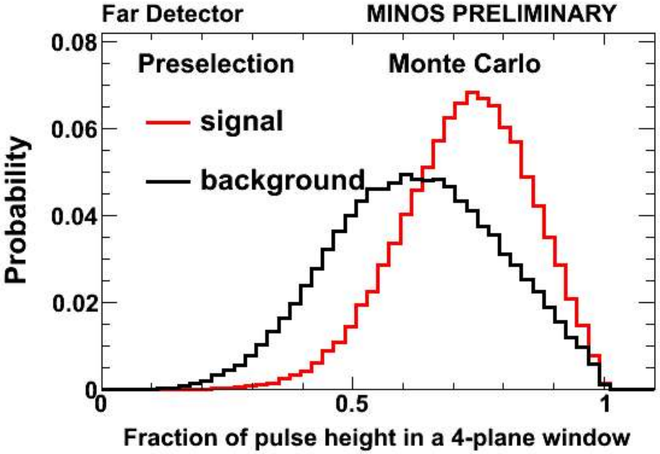


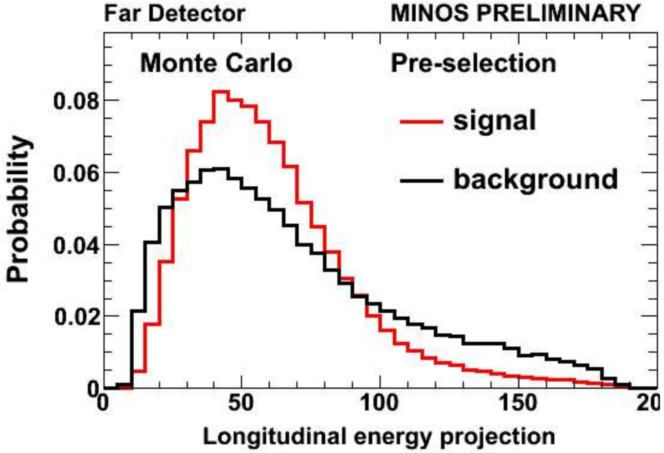
A neural network is constructed using 11 shower topological variables

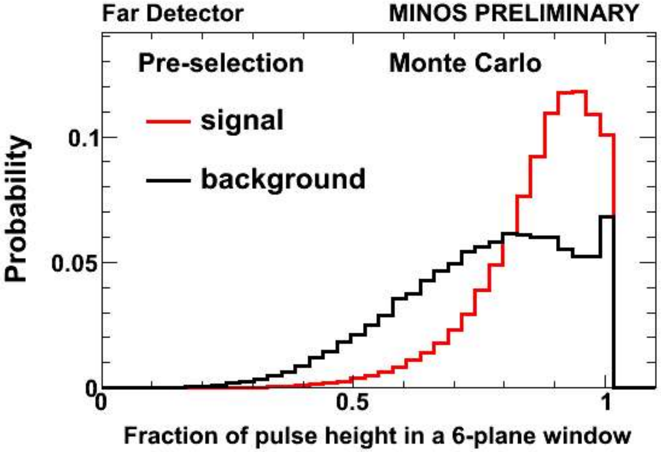
Signal Selection







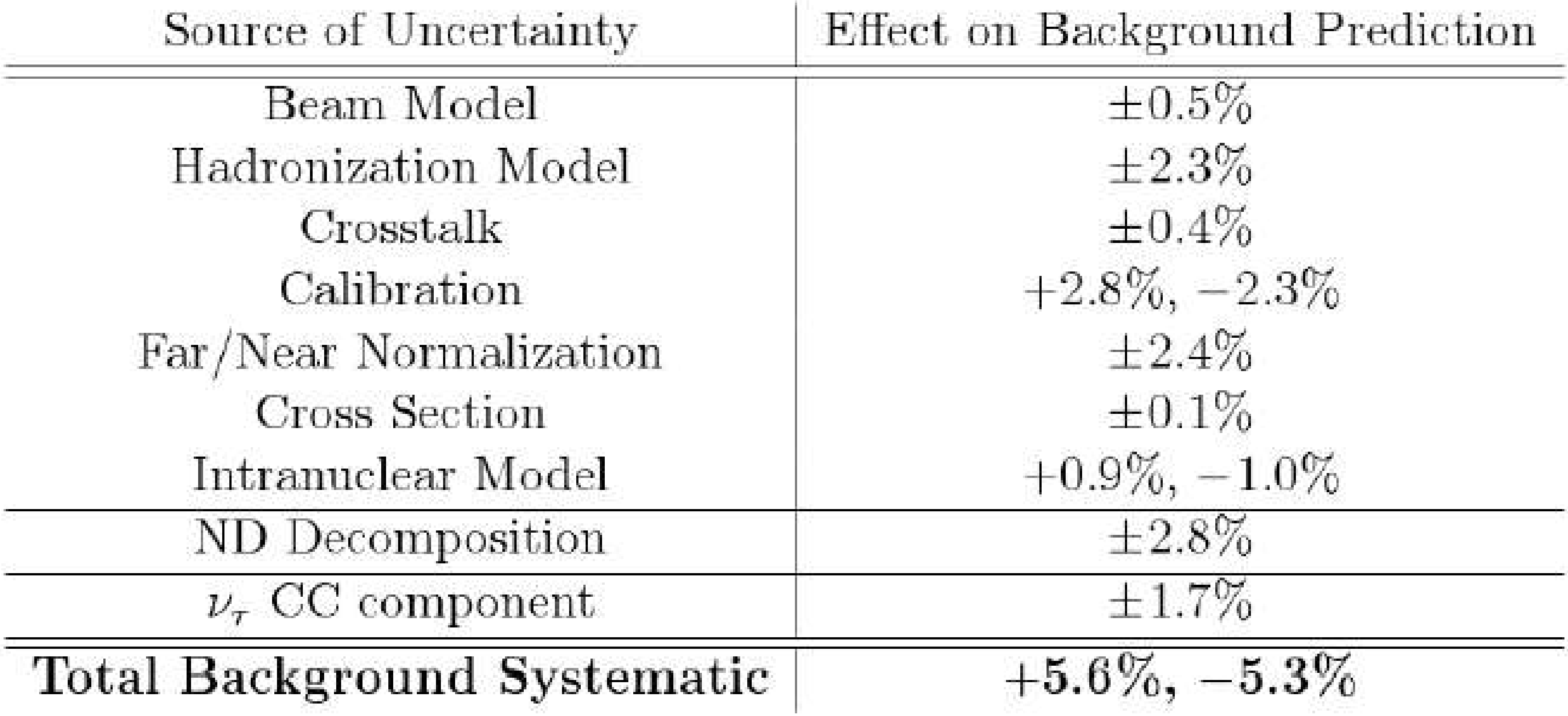




A neural network is constructed using 11 shower topological variables

Systematic Errors

- Most systematics are evaluated by generating special MC with modified parameters in both the Near and Far detectors. This modified MC is used to extrapolate and calculate the difference with the standard results
- The statistical uncertainty dominates at **14.4%**



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

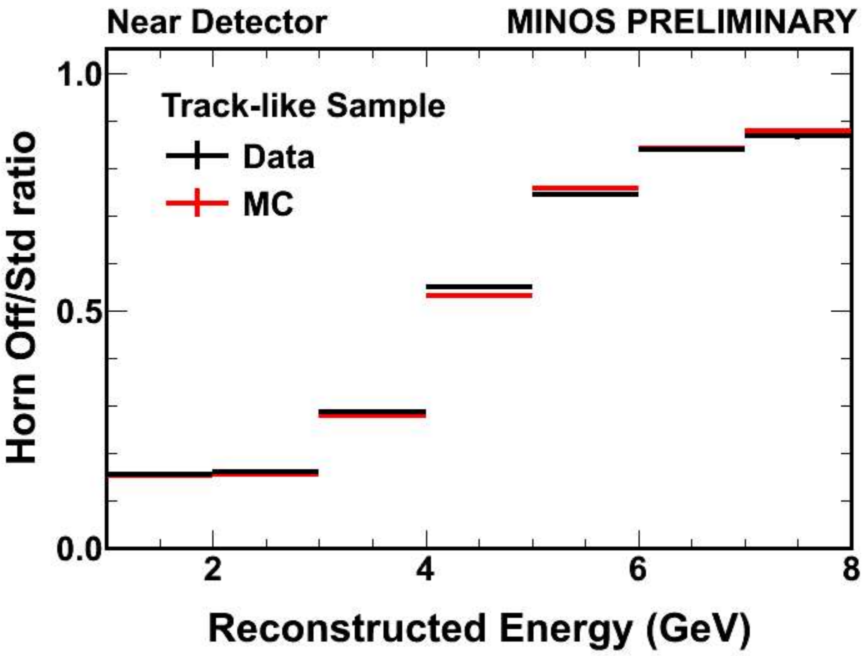
Decomposing the ND backgrounds - The Multi-Beam Method

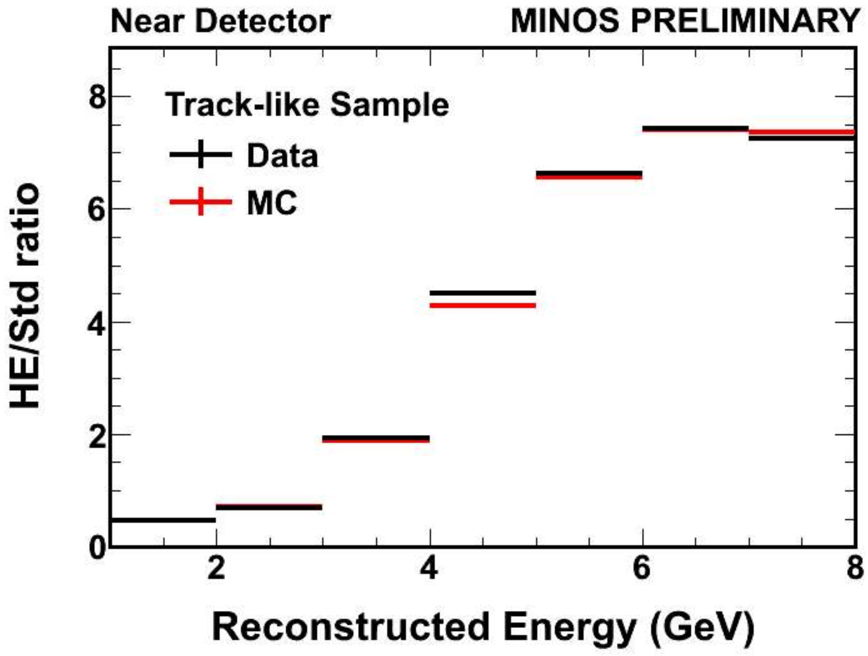
- Separating the backgrounds essentially comes down to solving a set of equations with the data spectra as inputs and the background components as unknowns

- MC ratios need to be used to complete the equations – ratios similar for data and MC

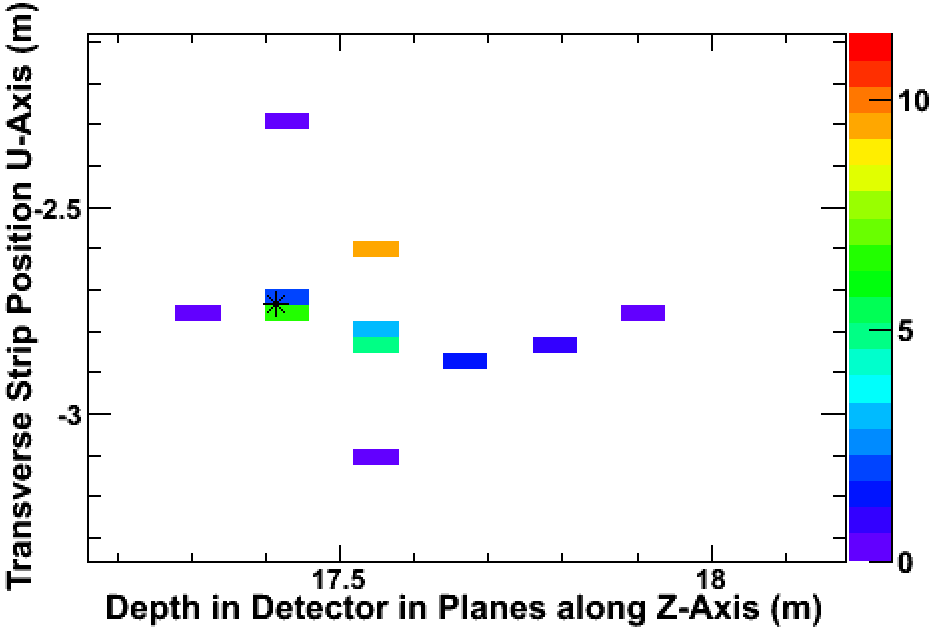
$$\begin{aligned}
N^{LE} &= \mathbf{N_{NC}^{LE}} + \mathbf{N_{CC}^{LE}} + \mathbf{N_{\nu e}^{LE}} \\
N^{Off} &= N_{NC}^{Off} + N_{CC}^{Off} + N_{\nu e}^{Off} \\
N^{HE} &= N_{NC}^{HE} + N_{CC}^{HE} + N_{\nu e}^{HE}
\end{aligned}$$

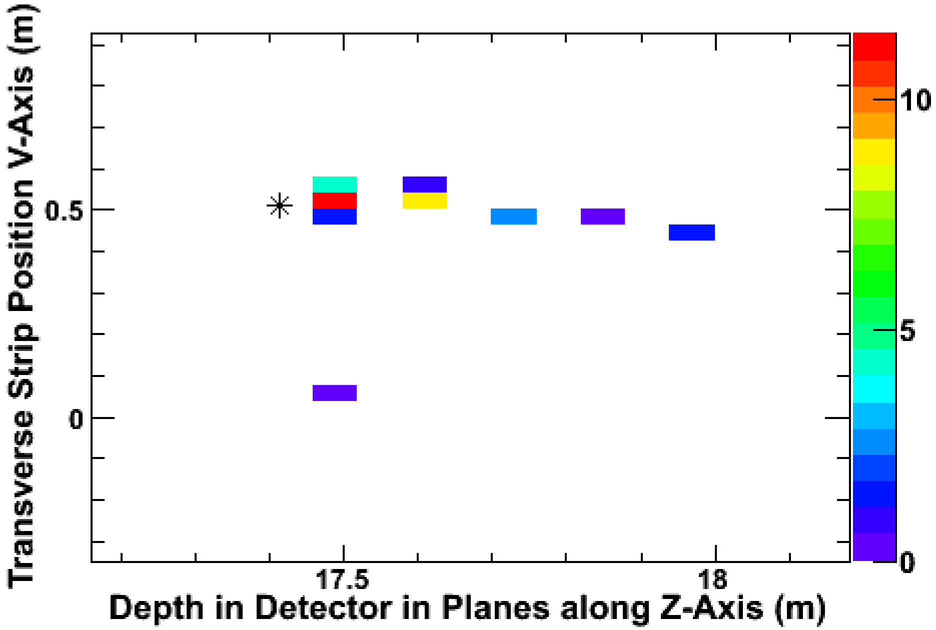
$$\begin{aligned}
N^{LE} &= N_{NC}^{LE} + N_{CC}^{LE} + N_{\nu e}^{LE} \\
N^{Off} &= (r_{NC}^{Off})N_{NC}^{LE} + (r_{CC}^{Off})N_{CC}^{LE} + (r_{\nu e}^{Off})N_{\nu e}^{LE} \\
N^{HE} &= (r_{NC}^{HE})N_{NC}^{LE} + (r_{CC}^{HE})N_{CC}^{LE} + (r_{\nu e}^{HE})N_{\nu e}^{LE}
\end{aligned}$$

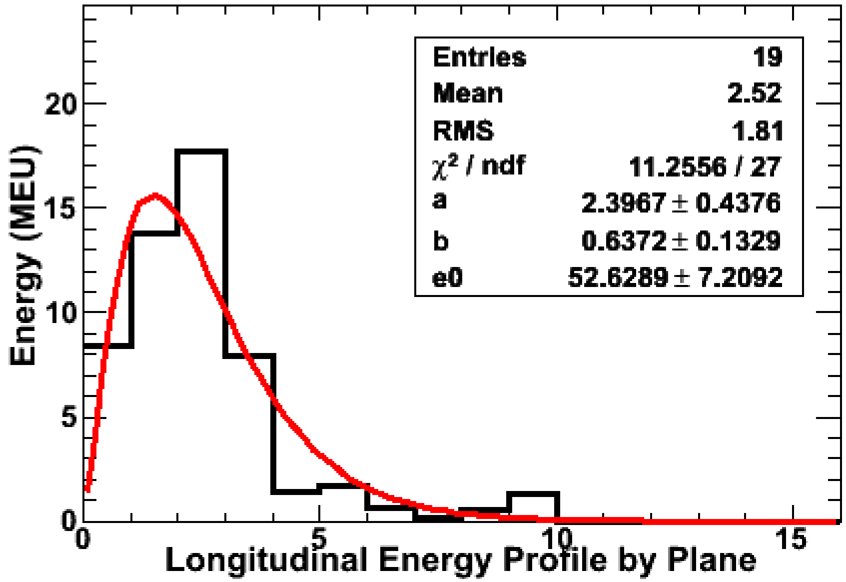


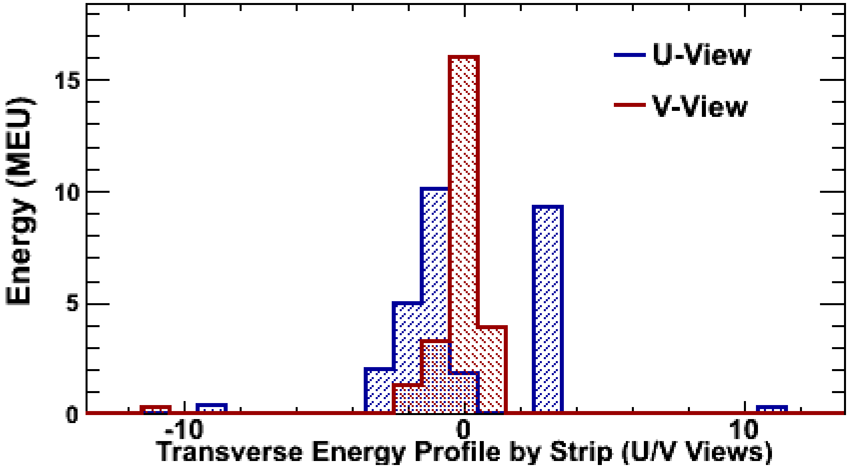


Far Detector Selected Events



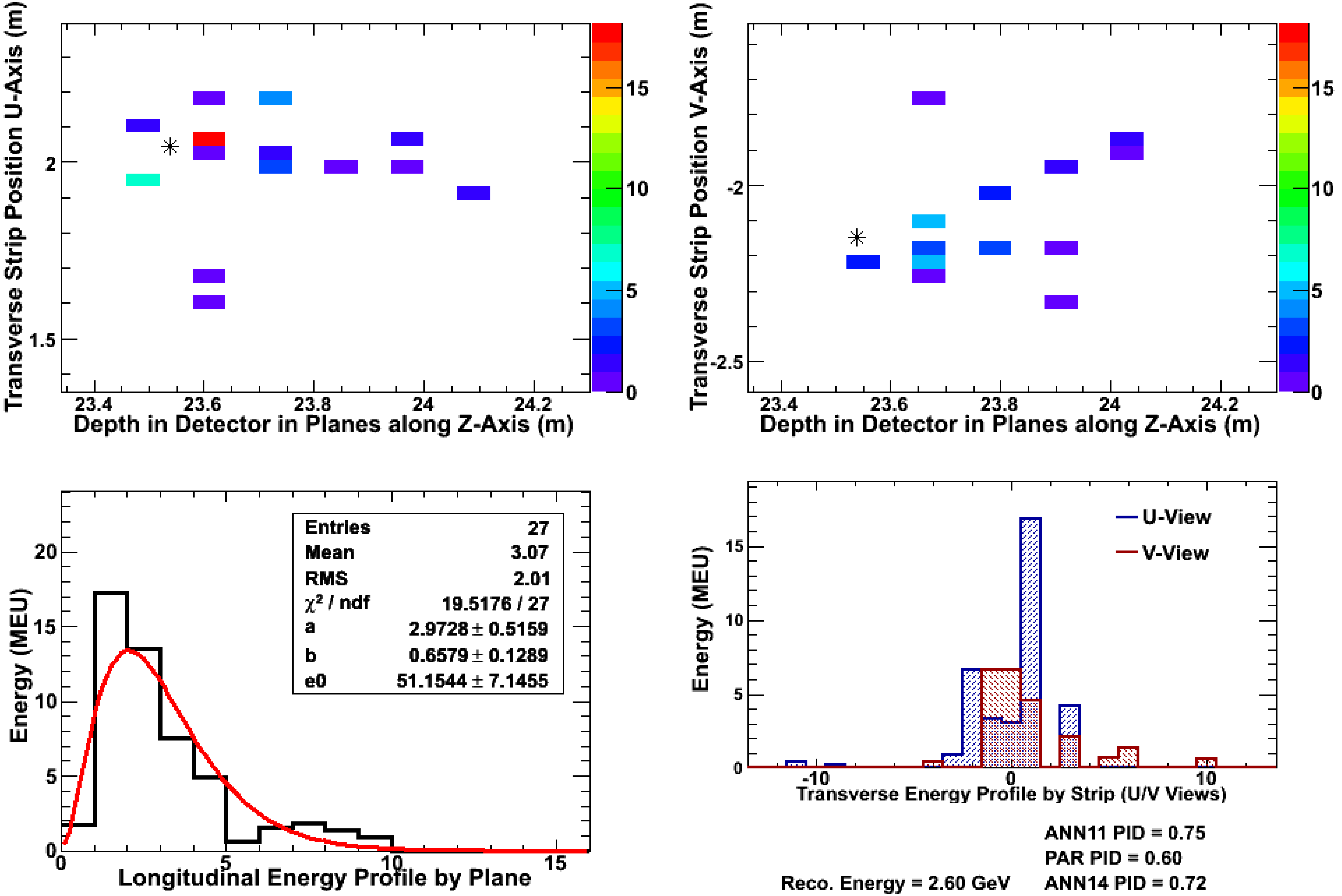






ANN11 PID = 0.78
PAR PID = 0.73
Reco. Energy = 2.38 GeV ANN14 PID = 0.72

Far Detector Selected Events



Entries	27
Mean	3.07
RMS	2.01
χ^2 / ndf	19.5176 / 27
a	2.9728 ± 0.5159
b	0.6579 ± 0.1289
e0	51.1544 ± 7.1455

ANN11 PID = 0.75
PAR PID = 0.60
Reco. Energy = 2.60 GeV
ANN14 PID = 0.72