A Study of $\nu_\mu \rightarrow \nu_e$ Oscillations in MINOS

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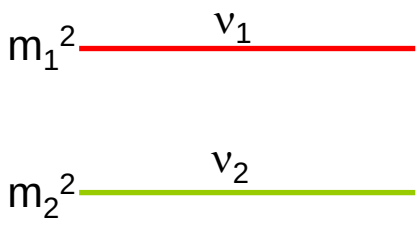
Outline

- A brief review of neutrino oscillation physics
- ν_e appearance analysis in MINOS
  - Brief description of beam and detectors
  - Event selection
  - Background estimation
  - Finally results
- Booster neutrinos in MINOS Near Detector

Neutrino Mixing – 2-flavor approximation

Weak state Mixing Matrix Mass state

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$



$$\left|\nu_\mu(0)\right\rangle = -\sin\theta\left|\nu_1\right\rangle + \cos\theta\left|\nu_2\right\rangle$$

θ is the mixing angle

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

$$P_{osc}(\nu_\mu \to \nu_e) = \left|\left\langle \nu_e \middle| \nu_\mu(t) \right\rangle\right|^2 = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$

L is the distance that neutrino travels (km)

E is neutrino energy (GeV)

3-flavor Neutrino Mixing

- The Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix

Weak state Mass state

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

3 mixing angles
1 CP phase
2 Majorana phases

Atmospheric Cross-mixing Solar Majorana

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

Atmospheric ν
K2K, MINOS

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

CHOOZ/Palo Verde
K2K, MINOS

$\theta_{13} < 11°$ at 90% C.L.

Solar ν (SNO)
KamLand

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

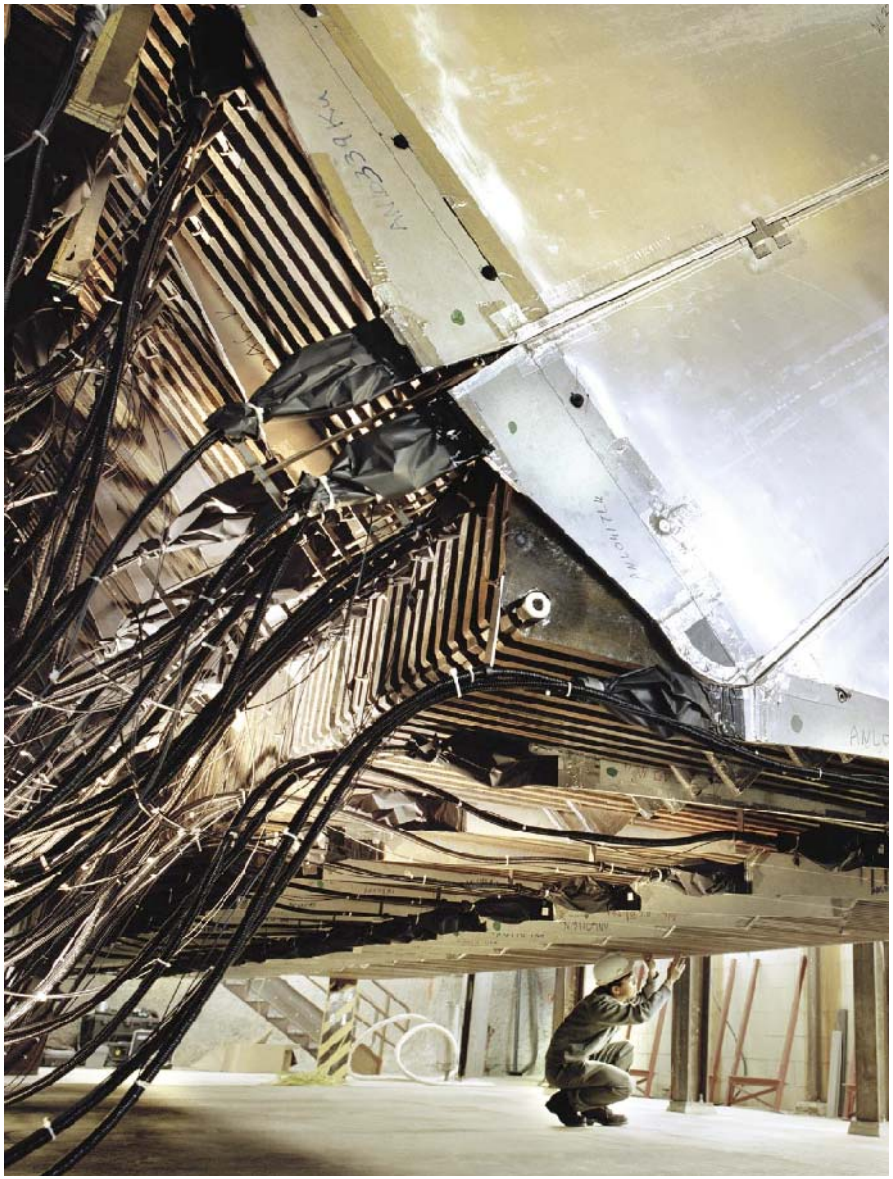
Neutrinoless double beta decay

EXO

MINOS

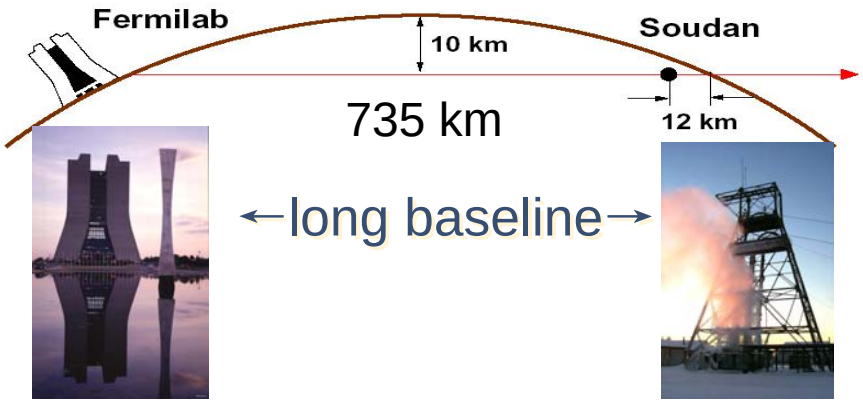
Main **I**njector **N**eutrino **O**scillation **S**earch

Long baseline accelerator ν experiment



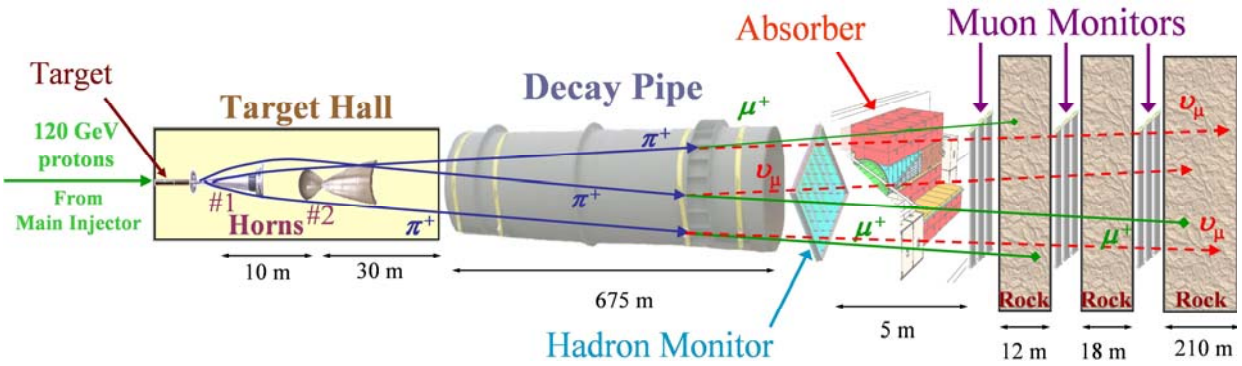
The MINOS Experiment

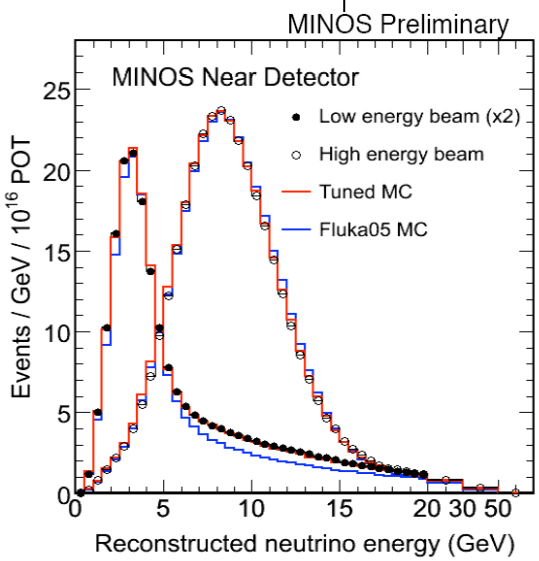
- Long baseline accelerator neutrino experiment.
- Produce a high intensity beam of muon neutrinos at Fermilab.
- A “Near Detector” at Fermilab to measure the beam composition and energy spectrum.
- A “Far Detector” in the Soudan Mine, Minnesota, to search for evidence of oscillations.



Main **I**njector **N**eutrino **O**scillation **S**earch

Neutrinos at Main Injector (NuMI)





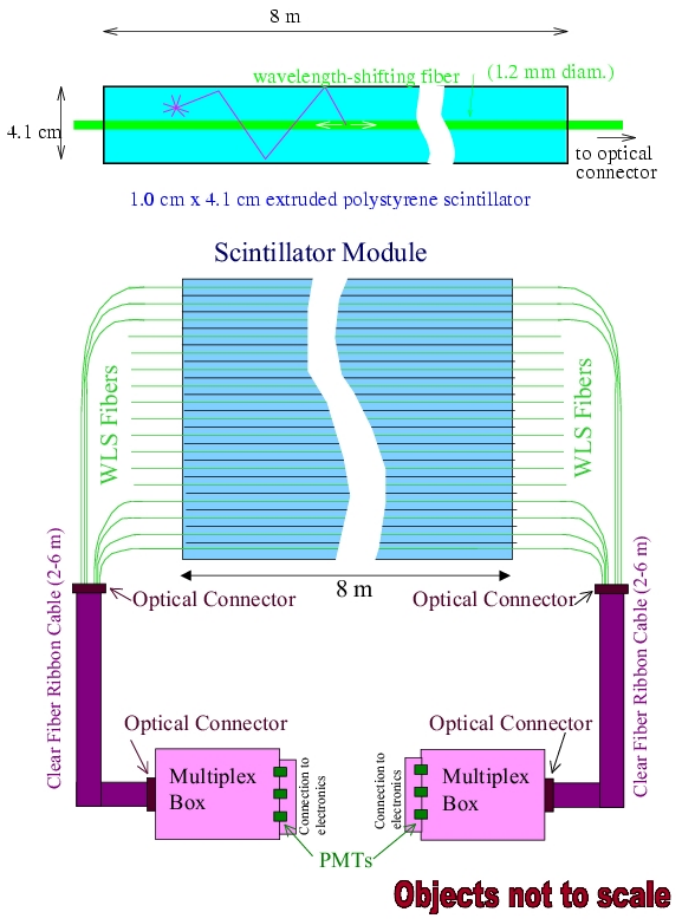
- 120 GeV protons from Fermilab Main Injector
- 1m graphite target
  - p+C→stream of mesons (π, K)
- 2 parabolic focusing horns optimized to focus π^+/K^+
- Mesons decay in the beam pipe to give a beam of neutrinos
- Various neutrino energy spectra by varying the relative positions of target and horns
- In the Low Energy configuration, interactions are 92.9% ν_μ, 5.8% $\bar{\nu}_\mu$, 1.3% $\nu_e+\bar{\nu}_e$

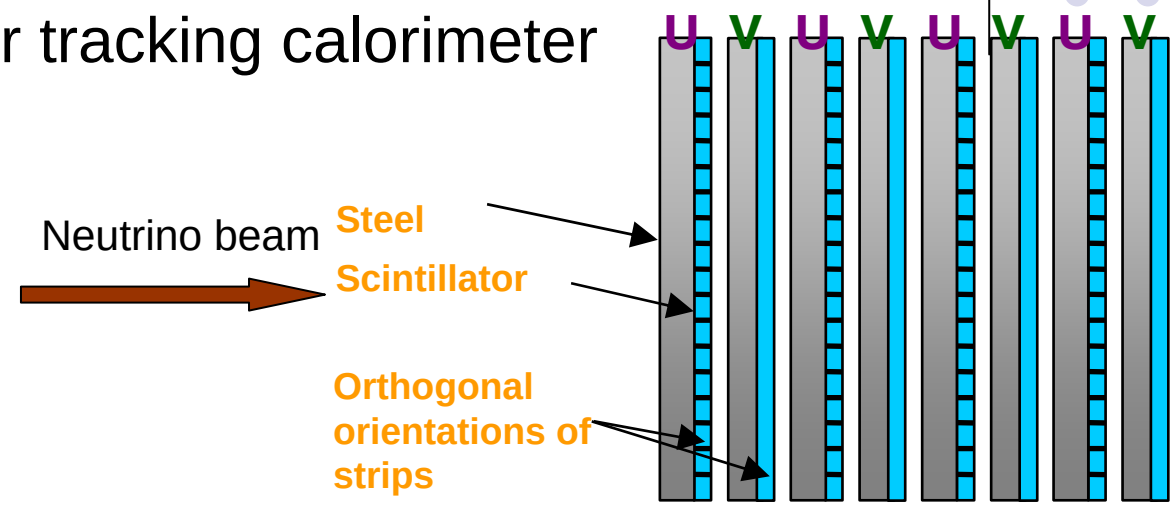
MINOS Detectors

- Massive, deep underground
  - 1 kt Near Detector (small fiducial volume), 100 m underground
  - 5.4 kt Far Detector, 714 m underground
- Functionally identical: steel/scintillator calorimeter
  - Steel planes
    - 2.54 cm thick
    - 1 GeV/c muon ~ 20 planes
    - 1.4 radiation lengths
  - Polystyrene scintillator strips
    - 1 cm thick
    - 4.1 cm wide
    - Molier radius ~ 3.7 cm
  - Magnetized (~1.3 T)

MINOS Detector Technology

Iron/scintillator tracking calorimeter





- Alternate planes rotated by ±90º (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.

MINOS Physics Goals

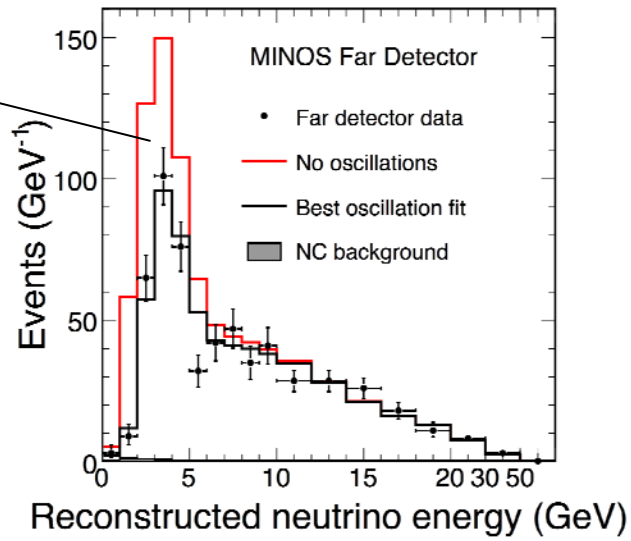
- The L/E configuration makes MINOS sensitive to the neutrino oscillations at atmospheric mass scale.
- Main physics goal: precision measurements of Δm^2_{32} and $\sin^2(2\theta_{23})$ through the disappearance of muon neutrinos in the Far Detector:
  - $|\Delta m^2_{32}| = 2.43 \pm 0.13 \times 10^{-3}$ eV^2 (68% CL)
  - $\sin^2 2\theta_{23} > 0.90$ (90% CL)

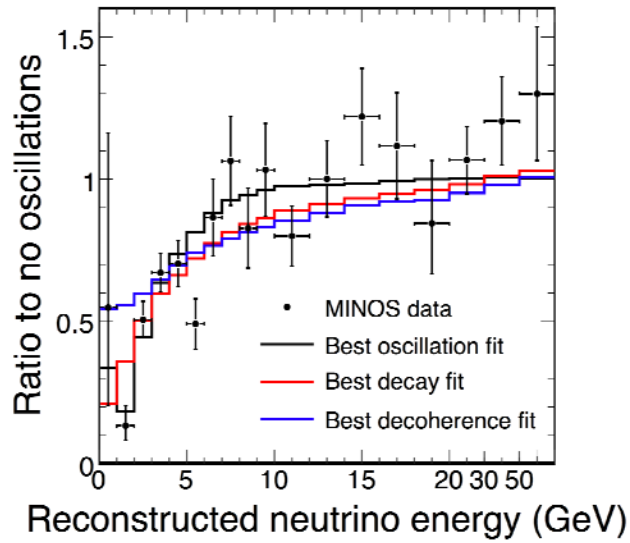
$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta \sin^2\left(\frac{1.27\,\Delta m^2 L}{E}\right)$$

disappearance of ν_μ

$\nu_\mu \rightarrow \nu_\tau$

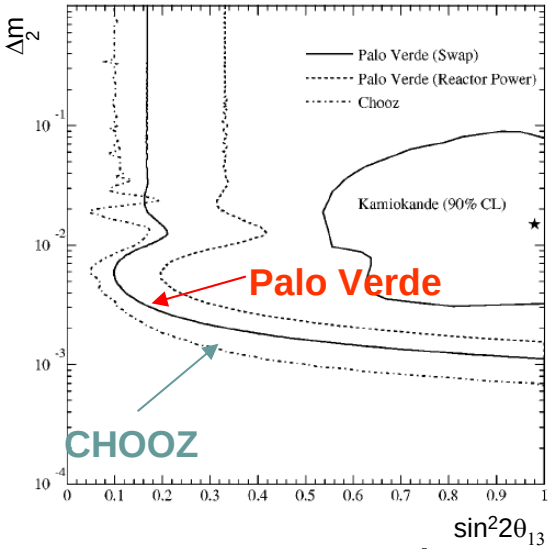
$\nu_\mu \rightarrow \nu_e$?





Measuring θ_{13} in MINOS

- θ_{13} is an unknown parameter in the neutrino mixing matrix
- Current best limit comes from reactor ν experiments



$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \approx 1 - \boxed{\sin^2(2\theta_{13})} \sin^2(1.27\Delta m^2 L/E)$$

Results from CHOOZ and Palo Verde:

- No evidence of oscillations in $\bar{\nu}_e$ **<u>disappearance</u>** mode
- $\sin^2(2\theta_{13}) < 0.15$ at 90% CL for $|\Delta m_{32}|^2 = 2.4\times10^{-3}\text{eV}^2$

- MINOS experiment has the potential to improve the limit on θ_{13} or make the first measurement of its value by searching for a ν_e **<u>appearance</u>** signal in the Far detector.
- First MINOS ν_e analysis based on 3.14×10^{20} POT

$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2\theta_{23} \boxed{\sin^2 2\theta_{13}} \sin^2\left(1.27\Delta m^2_{32} L/E\right)$$

Probability of $\nu_\mu \rightarrow \nu_e$ Appearance

$$P(\nu_\mu \rightarrow \nu_e) \approx \boxed{\sin^2 2\theta_{13}} \sin^2\theta_{23} \sin^2\Delta + \alpha^2\Delta^2 \cos^2\theta_{13} \cos^2\theta_{23} \sin^2 2\theta_{12}$$
$$+ \alpha\Delta \boxed{\sin 2\theta_{13}} \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin\Delta \cos(\Delta + \delta)$$
$$\equiv P_{atm} + P_{sol} + P_{int}$$

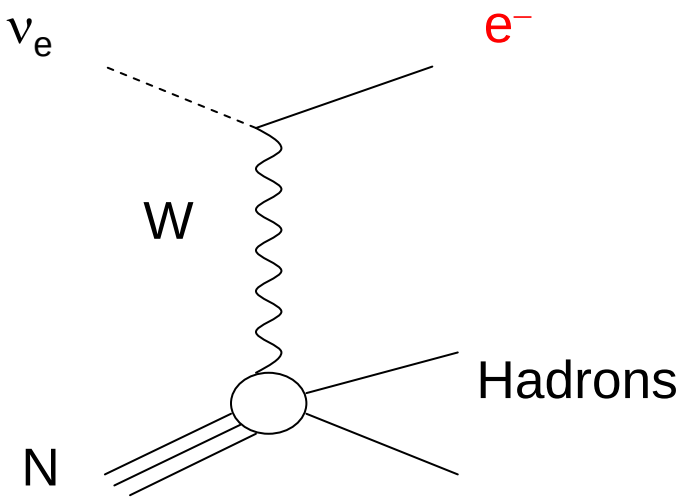
$|\alpha| \equiv \Delta m^2_{21} / |\Delta m^2_{31}| \approx 0.033 \qquad \Delta \equiv \Delta m^2_{31} L/(4E)$ $\qquad$ δ is CP violating phase.

- Leading term P_{atm} depends on $\sin^2 2\theta_{13}$
- Probability also depends on θ_{23} – different from reactor ν experiments
- P_{sol} is negligible
- Sub-leading term P_{int} is proportional to $\sin 2\theta_{13}$ and depends on CP-violating phase δ_{CP}
  - δ_{CP} can change transition probability by 25% if θ_{13} is at CHOOZ limit
- In earth, matter effects can suppress/enhance transition probability by 25% depending on mass hierarchy
  - Normal mass hierarchy: $\Delta m^2_{31} > 0$ – enhancement
  - Inverted mass hierarchy: $\Delta m^2_{31} < 0$ – suppression

Analysis Strategy

- Construct a selection algorithm to reject background and select ν_e
- Measure the background spectrum in the Near Detector
- Use Near Detector measurement to predict Far Detector background
- Compare Far Detector data with background prediction

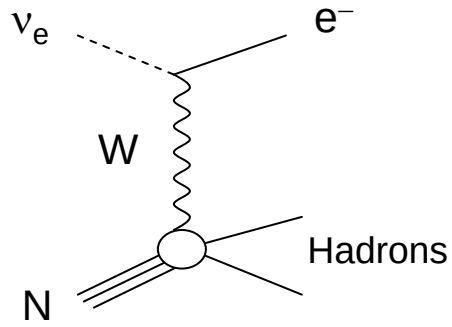
Electron Neutrino Selection



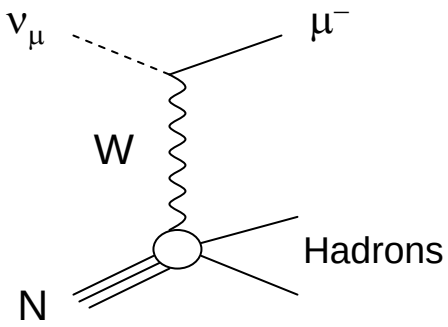
Neutrino Event Topologies

Monte Carlo

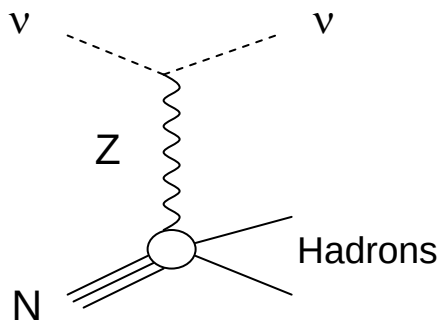
ν_e CC interaction



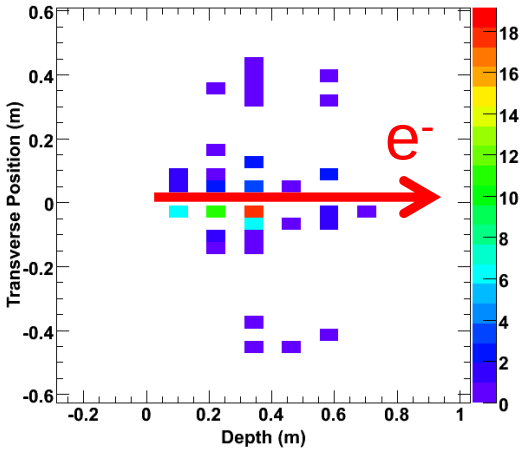
ν_μ CC interaction

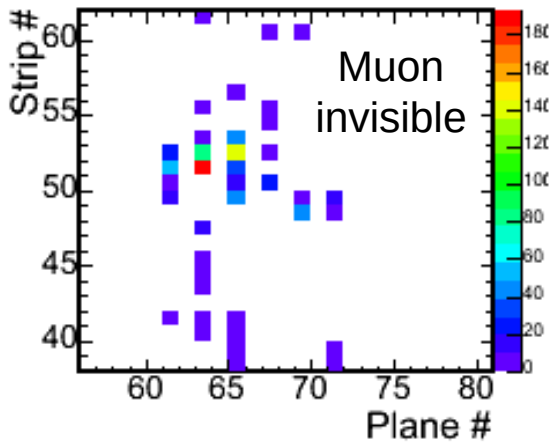


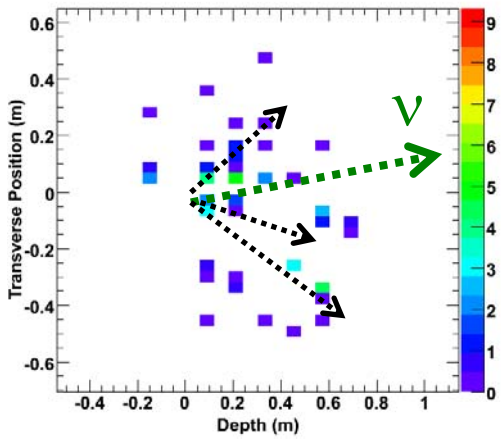
ν_x NC interaction



transverse direction







beam direction

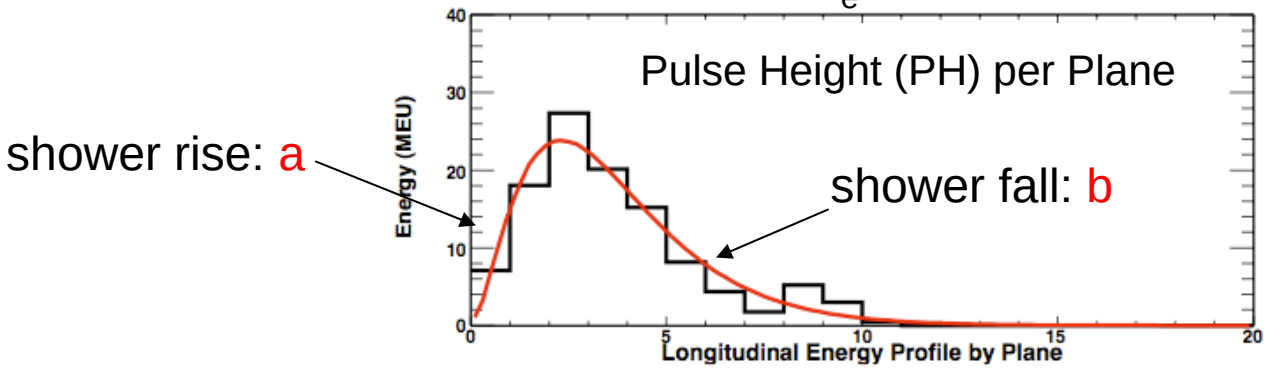
ν_e background: NC (π^0), high-y ν_μ CC (π^0), beam ν_e, ν_τ from oscillations in the Far Detector

Selecting ν_e Events

- Basic cuts:
  - Beam and detectors in good conditions
  - Interactions in the fiducial volumes
  - No long track – reject ν_μ CC background
  - Reconstructed energy is the range of interest 1<E<8GeV
    - Oscillations suppressed at high energies
    - Reject higher energy beam ν_e background and low energy NC background
- Artificial Neural Network (ANN)
  - Event topology
  - Longitudinal and transverse shower characteristics

Longitudinal Shower Profile

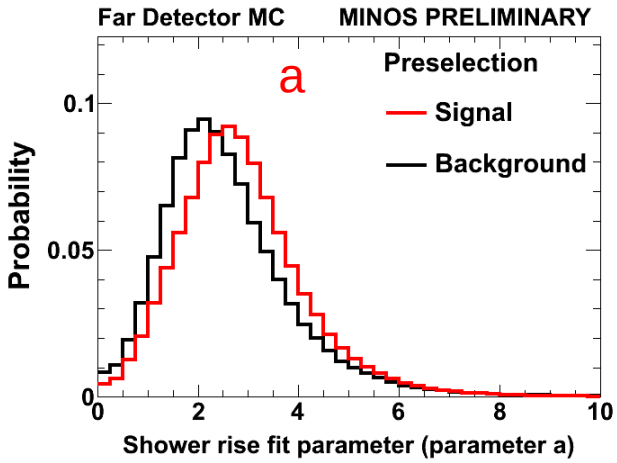
One candidate ν_e event in the FD

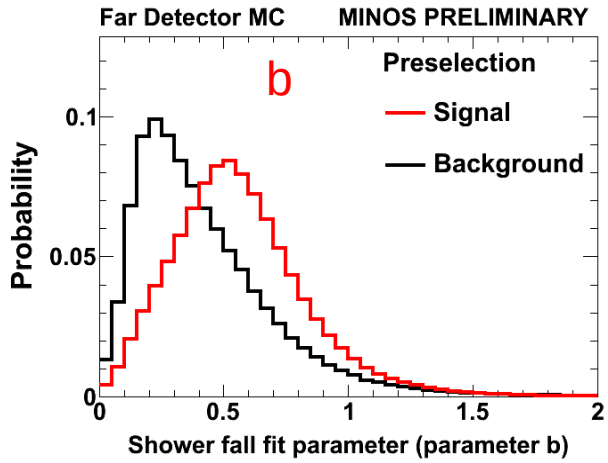


The average longitudinal profile of the energy deposition in an EM shower is reasonably well described by a gamma distribution:

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

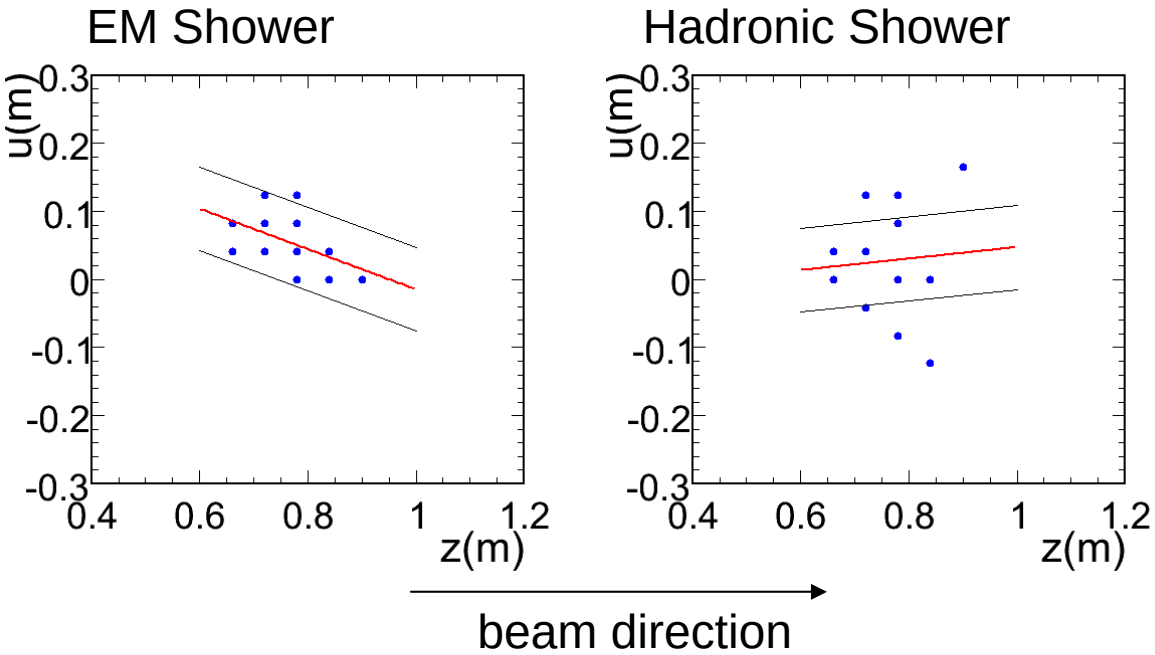
$t = x/X_0$ where X_0 is the radiation length

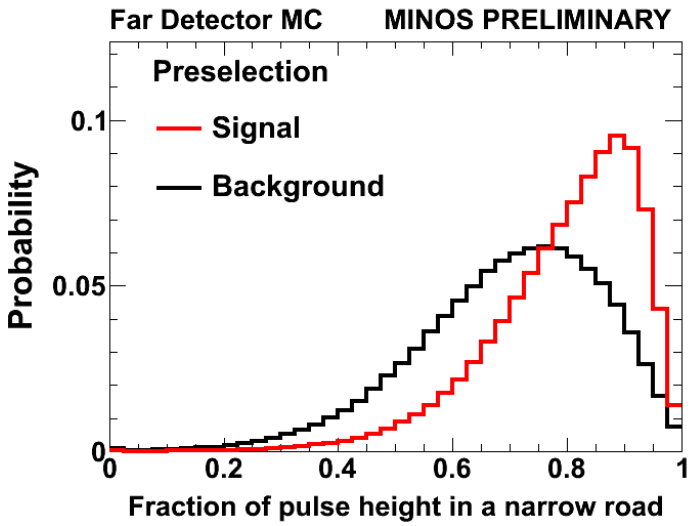




Other useful variables:
- fraction of energy deposited within 2,4,6 planes
- longitudinal energy projection

Transverse Shower Profile

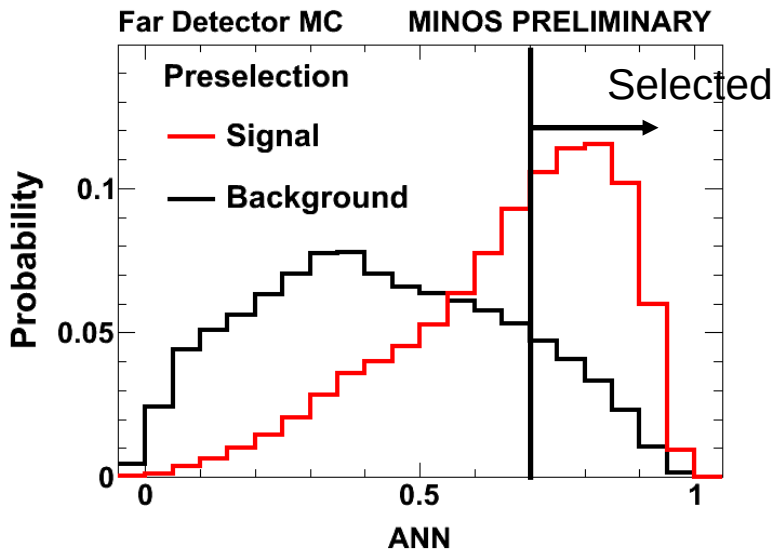




- Other useful transverse variables
  - lateral shower spread (RMS)
  - 90% containment radius
- EM showers are more compact than hadronic showers

Build an Artificial Neural Net – ANN

- 11 variables chosen describing shower length, width, and shape
- Build an ANN with those 11 variables to enhance the signal/background separation and take into account the correlations between input variables.



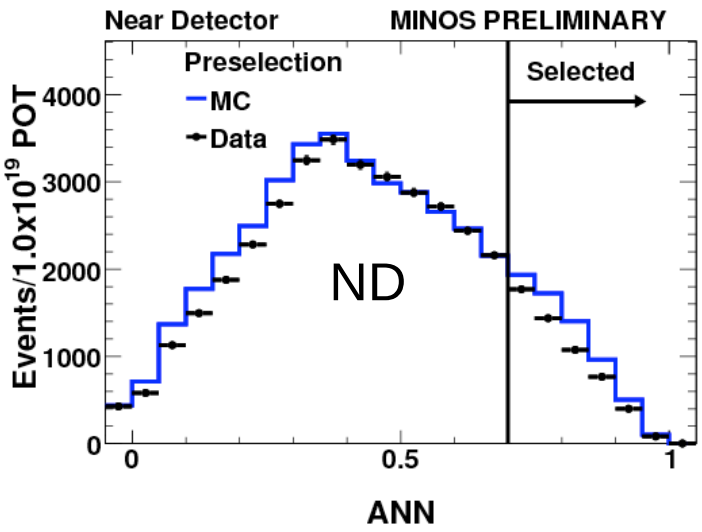
Signal efficiency: 41%
CC background rejection:99.4%
NC background rejection: 92.3%

Bg: 69% NC, 19% CC, 8% beam ν_e, 4% ν_τ

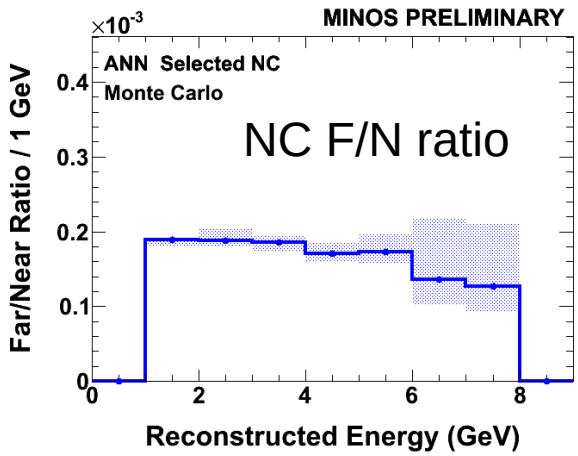
Area normalized, $|\Delta m^2_{31}|=2.4e^{-3}eV^2$, $\sin^2\theta_{23}=1$

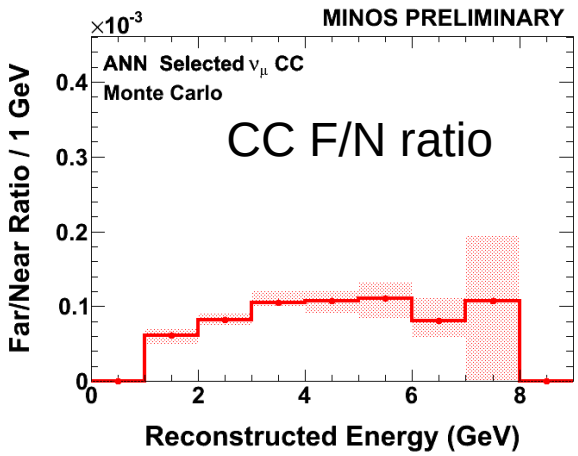
ND Background Decomposition

Predict FD Background



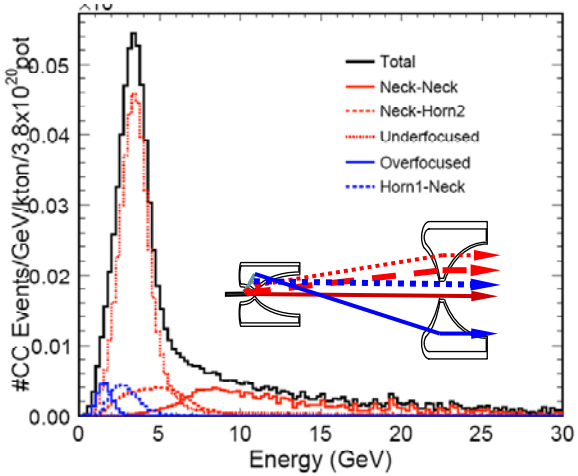
- Measure background rate at ND
- Predict FD background rate through extrapolation
  - $FD^{predicted}=(FD/ND)^{MC}\times ND^{Data}$
- MC does not model absolute background rate well, but F/N ratio is very robust
- A lot of uncertainties cancel in the F/N ratio

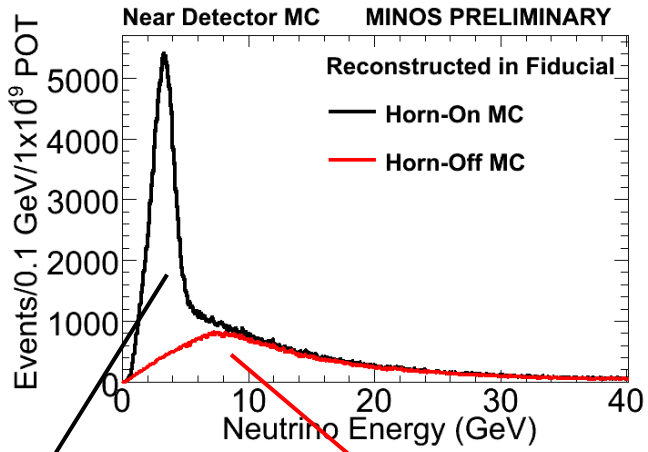




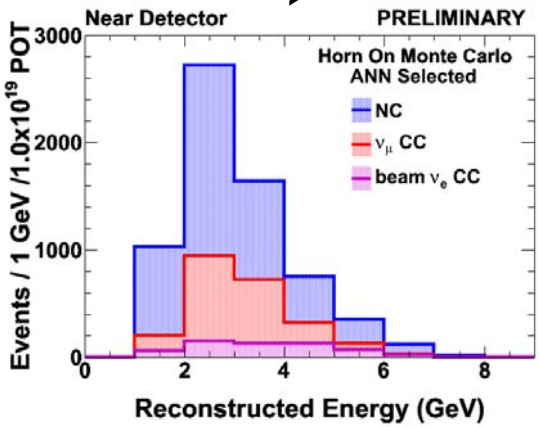
- Different background components extrapolate differently
- Some knowledge about the relative contribution from NC and CC background components is necessary.

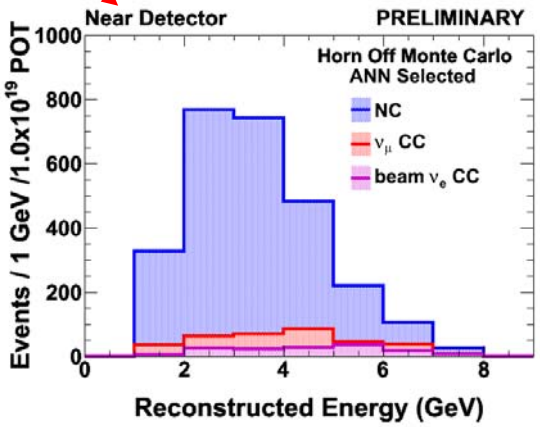
CC/NC Separation



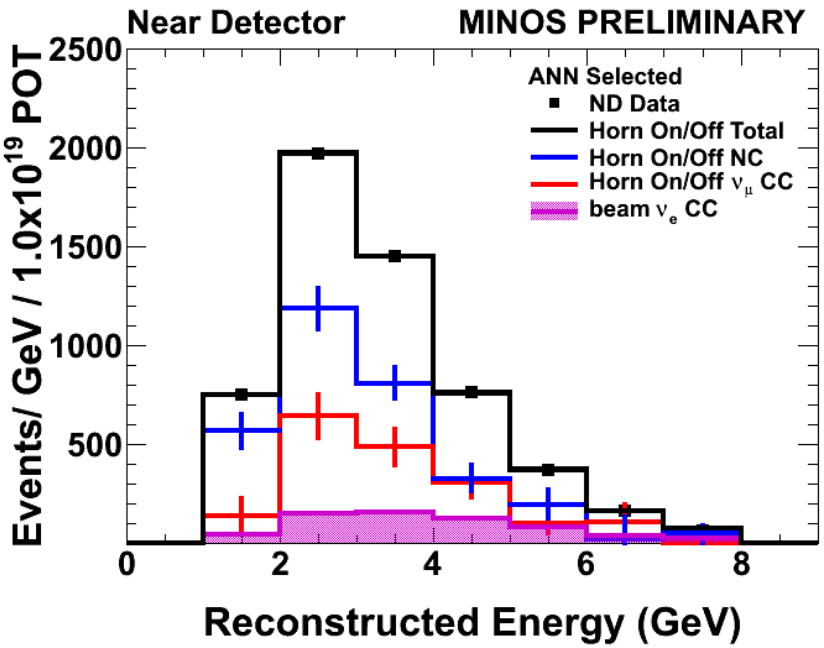


- Horn-on horn-off samples have different NC/CC ratios
- Data driven method to decompose CC/NC components using MC horn off/on ratios



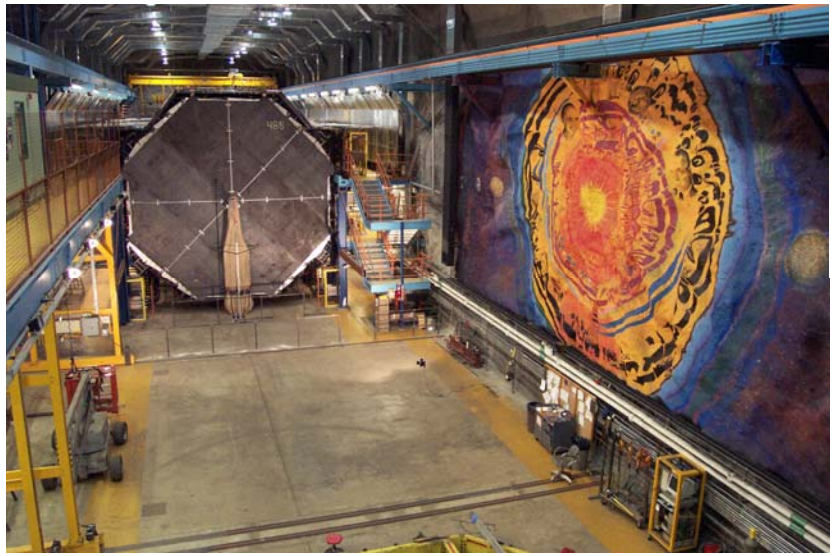


ND Background Decomposition



- Systematic errors mainly come from
  - Horn-off data statistics
  - Uncertainties associated with horn off/on ratios
- 9% sys. error on NC
  18% sys. error on CC
- Two background components are highly correlated
  - Total error is greatly reduced at FD

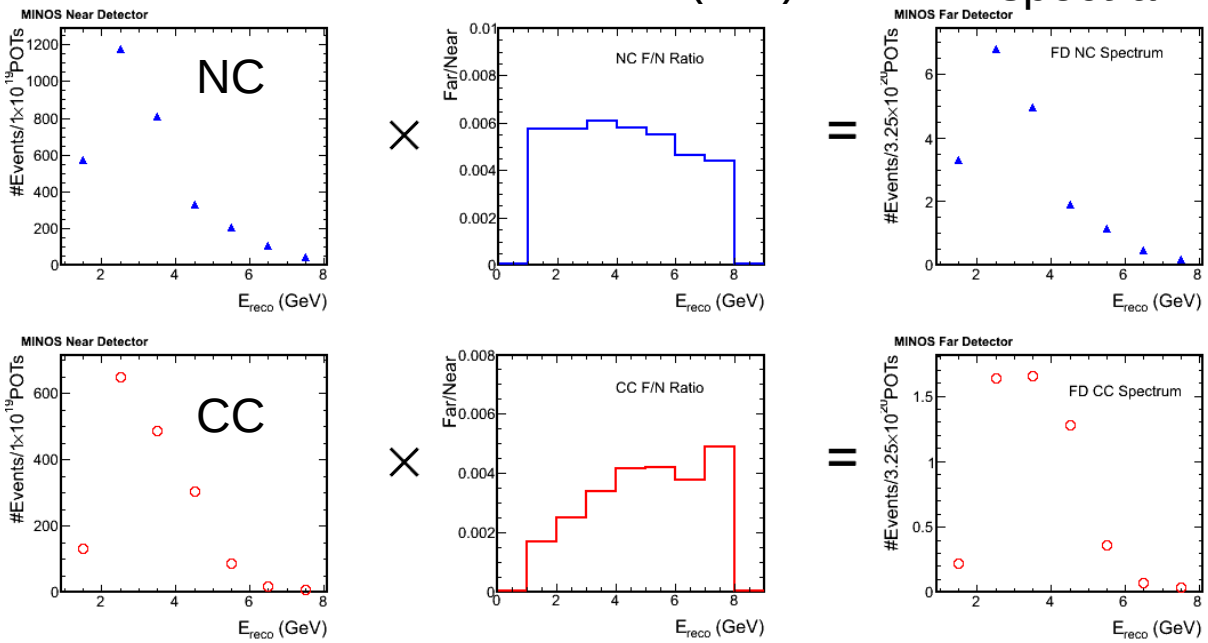
FD Background Prediction



FD Background Prediction

- FD background is composed of 4 categories of events: NC, CC, beam ν_e, and ν_τ:
  - $N^F = N^F_{NC} + N^F_{CC} + N^F_{b\nu e} + N^F_{\nu\tau}$
- Beam ν_e, and ν_τ are taken from MC
- NC and CC components are obtained from extrapolation

ND spectra | F/N Ratios (MC) | FD spectra



F/N Ratios:

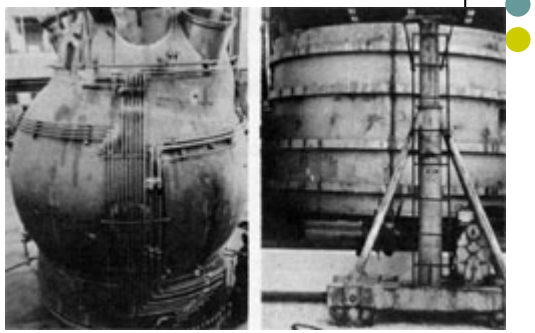
- Geometry ($1/r^2$)
- Oscillations

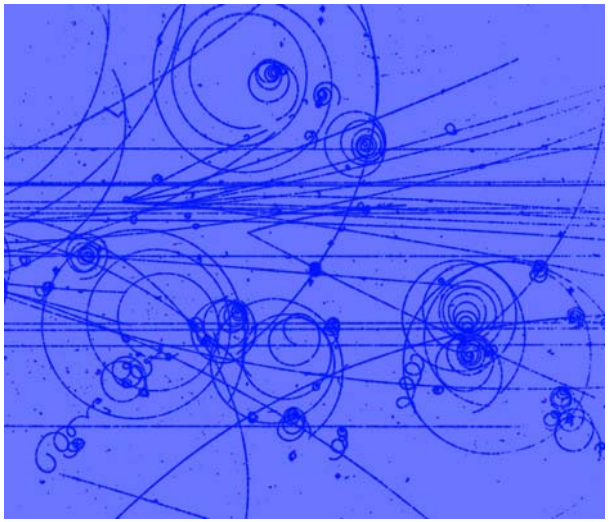
The FD background prediction at 3.14×10^{20} POT for ANN is:
27 ± 5(stat)±2(sys)

Background Systematics

- ND background decomposition – 3.6%
  - NC and CC background components are highly correlated at ND
- Extrapolation (F/N ratios) – 6.5%
  - Flux – hadron production at target, beamline geometry
  - Cross section – QE, resonance, transition
  - **Hadronization**/Intranuke – hadrons produced in neutrino interactions
  - Normalization - POT counting, steel/scintillator thickness, fiducial masses
  - Calibration – light level, intra- inter- detector variations, PMT
  - **Crosstalk model** – improved crosstalk model
  - Intensity – different event rates at two detectors
- Beam ν_e and ν_τ systematics

Hadronization Model Tuning

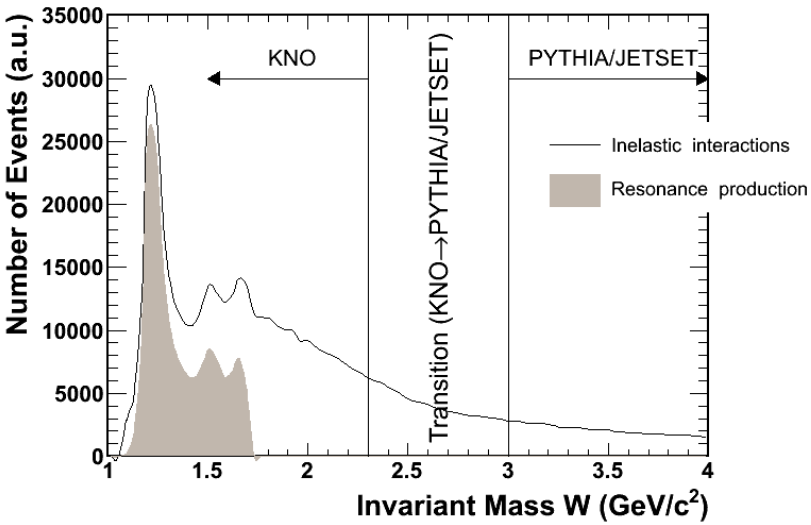




Hadronization Model for MINOS

- Hadronization (or fragmentation) model – the model that determines the final state particles and 4-momenta in the ν-nucleon interactions.
- KNO-based empirical model at low-W
- Pythia/JETSET at high-W
- Smooth transition in between

W distribution of inelastic events

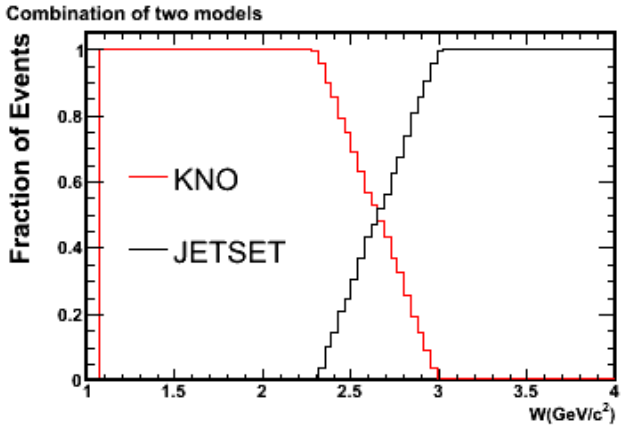


Low-W: KNO-based model

- Select particles
  - Decide hadron multiplicity based on W and KNO-distributions: $\langle n_{ch} \rangle = a + b \ln W^2$
- Determine 4-momenta for particles
  - Only one baryon in the final state, select baryon 4-momentum from proton PDF (x_F,p_T)
  - Decay remaining hadronic system and apply p_t reweighting
  - Rotate/boost hadronic system to lab frame

High-W: PYTHIA/JETSET

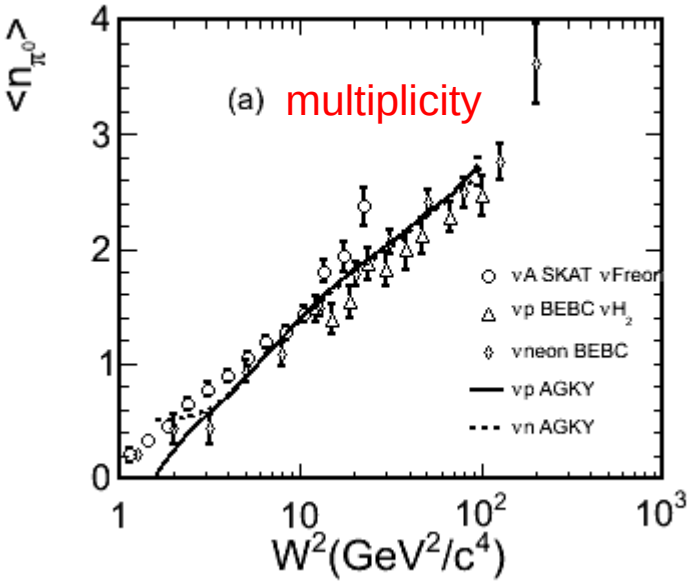
- Using PYTHIA/JETSET model for W>3GeV
- Including NUX's PYTHIA tuning (NOMAD exp. A.Rubbia's talk @ NuINT01)
- Smooth transition between KNO model and PYTHIA/JETSET from 2.3 GeV to 3 GeV

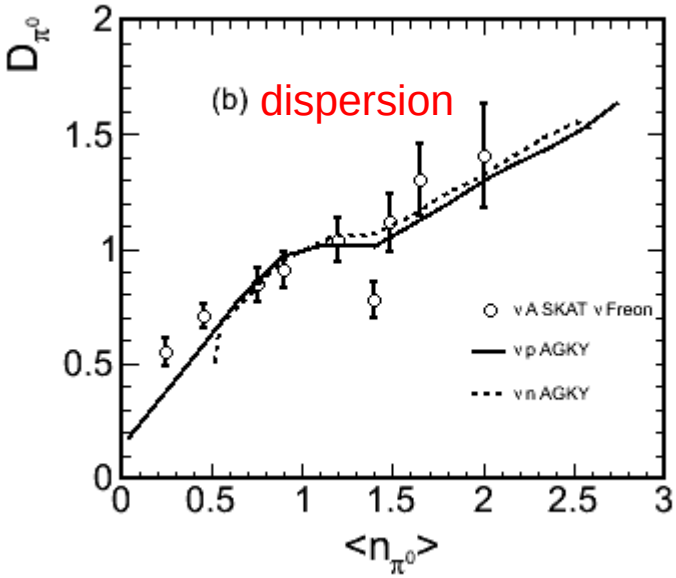


Compared with External Data

- We tuned our model with data from a lot of bubble chamber experiments – 15ft-FNAL, BEBC and SKAT.
- We focus on the following quantities:
  - Hadron multiplicity (n) – number of hadrons generated
  - Dispersion – sqrt($\langle n^2 \rangle - \langle n \rangle^2$)
  - π^0 production
  - $z=E_h/\nu$ – E_h is the hadron energy, ν is the shower energy
  - p_T – transverse momentum
- One difficulty: not many low energy data available (W<3GeV)
  - Model not well constrained in the region of interest

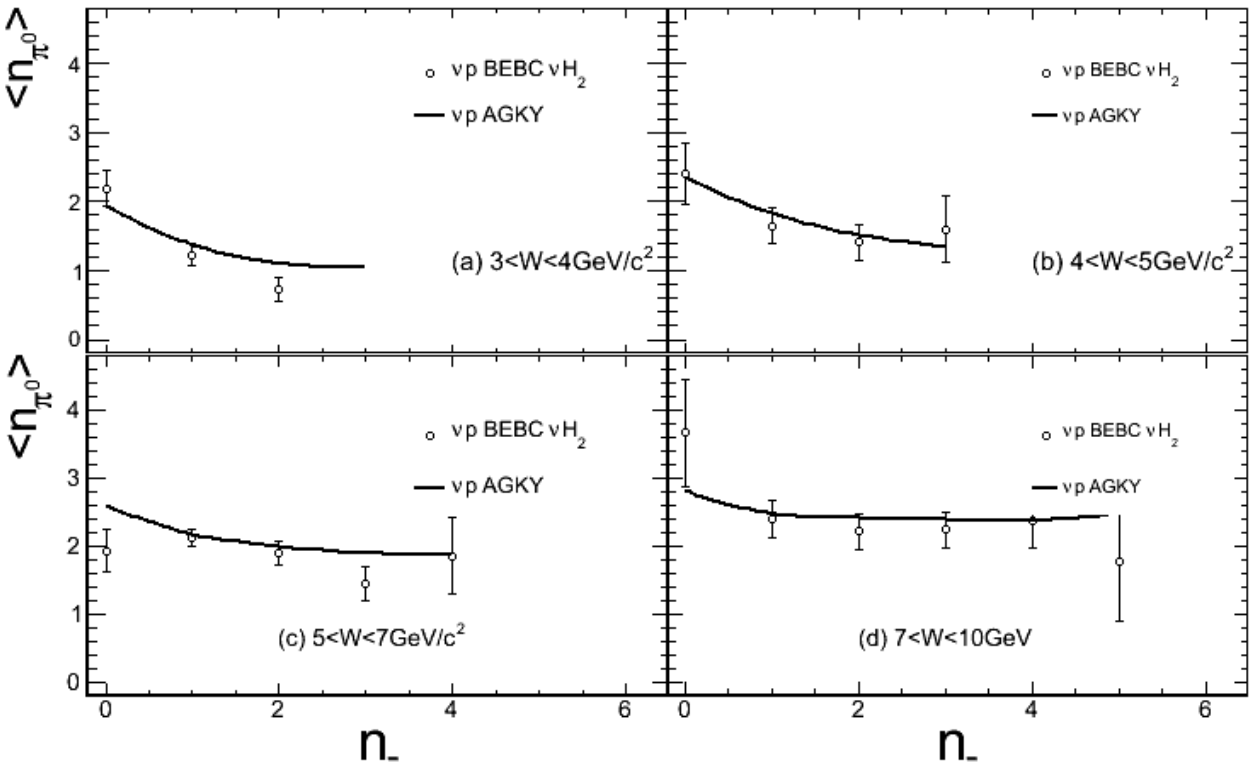
π^0 Multiplicity and Dispersion





- It was hard to make the π^0 measurements in the light target experiments. The interaction length was long so photons would escape the chamber easily.
- Heavy liquids such as Neon and Freon were often used. Studies showed rescattering of hadrons in the nucleus does not change distributions much.
- MC predictions agree with data quite well.

Correlation between Charged Pions and Neutral Pions

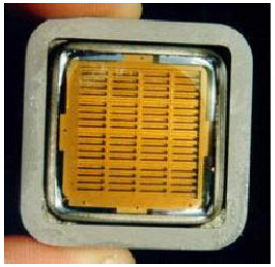


- At low W, $<n_{\pi^o}>$ decrease with n_- because of limited phase space.
- At high W, $<n_{\pi^o}>$ is rather independent of n_-.
- MC predictions agree with data quite well.

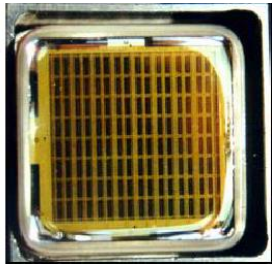
Summary of Hadronization Model

- The hadronization model has been tuned against bubble chamber data. MC predictions agree with external data quite well for most of the distributions.
- *A Hadronization Model for Few-GeV Neutrino Interactions,* T.Yang et.al accepted by Eur.Phys.J.C
- One difficulty in constraining the model is due to lack of data at low energies.
- New experiments dedicated to the measurements of neutrino interactions (*e.g.* ArgoNeuT, MINERvA) will help to address these issues.

PMT Crosstalk Modeling



M16



M64

PMT Crosstalk

- The scintillator strips of MINOS detectors are read out by Hamamatsu PMTs.
- Crosstalk phenomenon is an inherent property for multi-anode PMT.
  - 7% of the signal from light on a given pixel may appear in neighboring pixels
    - Spread of secondary electron flows over adjacent anodes
    - Charge induction through stray capacitances among anodes
- Crosstalk patterns are different at two detectors
  - Potential Far/Near difference

PMT Crosstalk Patterns

strip to pixel mapping

M64 PMT, ND

Pixel 0 23	Pixel 1 54	Pixel 2 41	Pixel 3 11	Pixel 4 35	Pixel 5 22	Pixel 6 53	Pixel 7 40
Pixel 8 43	Pixel 9 9	Pixel 10 37	Pixel 11 24	Pixel 12 55	Pixel 13 42	Pixel 14 10	Pixel 15 36
Pixel 16 39	Pixel 17 26	Pixel 18 57	Pixel 19 44	Pixel 20 8	Pixel 21 38	Pixel 22 25	Pixel 23 56
Pixel 24 59	Pixel 25 46	Pixel 26 6	Pixel 27 19	Pixel 28 27	Pixel 29 58	Pixel 30 45	Pixel 31 7
Pixel 32 4	Pixel 33 17	Pixel 34 29	Pixel 35 60	Pixel 36 47	Pixel 37 5	Pixel 38 18	Pixel 39 28
Pixel 40 31	Pixel 41 62	Pixel 42 49	Pixel 43 3	Pixel 44 16	Pixel 45 30	Pixel 46 61	Pixel 47 48
Pixel 48 51	Pixel 49 1	Pixel 50 14	Pixel 51 32	Pixel 52 63	Pixel 53 50	Pixel 54 2	Pixel 55 15
Pixel 56 12	Pixel 57 34	Pixel 58 21	Pixel 59 52	Pixel 60 0	Pixel 61 13	Pixel 62 33	Pixel 63 20

M16 PMT, FD

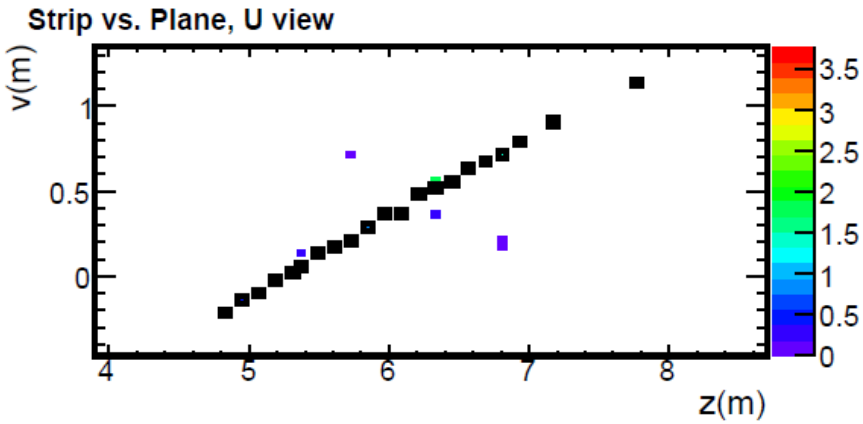
Pixel 0 50 4 166 27 96 73 189 143	Pixel 1 154 39 16 85 62 131 177 108	Pixel 2 190 167 51 97 5 74 120 28	Pixel 3 178 155 40 132 86 63 17 109
Pixel 4 156 87 41 133 18 64 110 179	Pixel 5 121 144 52 191 98 29 75 6	Pixel 6 157 65 134 180 42 111 88 19	Pixel 7 53 145 30 7 122 168 76 99
Pixel 8 8 146 31 54 100 77 123 169	Pixel 9 66 20 89 112 135 158 181 43	Pixel 10 101 55 32 78 9 147 124 170	Pixel 11 67 136 21 182 44 90 159 113
Pixel 12 22 91 137 68 160 45 114 183	Pixel 13 33 10 56 102 79 125 148 171	Pixel 14 46 115 69 184 138 23 92 161	Pixel 15 126 57 172 149 80 34 11 103

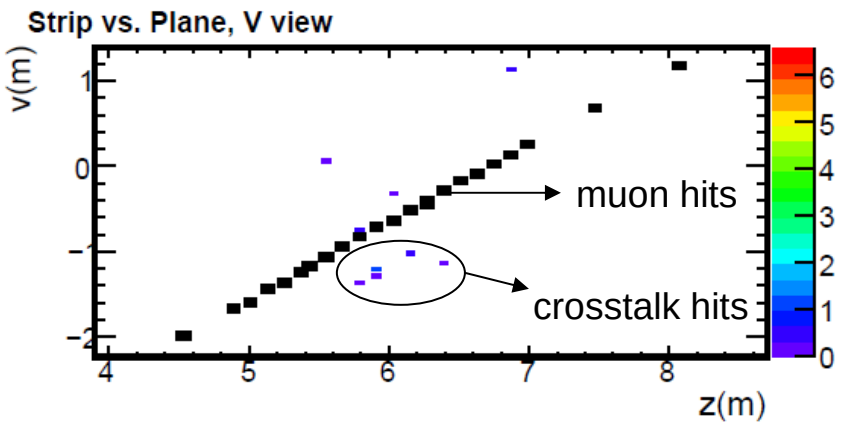
- Strips read out by adjacent pixels have certain patterns
  - ±13, ±20, *etc.*

- 8 strips are read out by one pixel at FD – multiplexing
- Unique crosstalk patterns
  - Adjacent pixels: ±9,10,11
  - Diagonal pixels: ±1,2,3

Two PMTs have different crosstalk patterns. Mis-modeling of crosstalk hits can affect the simulation of Far/Near ratios.

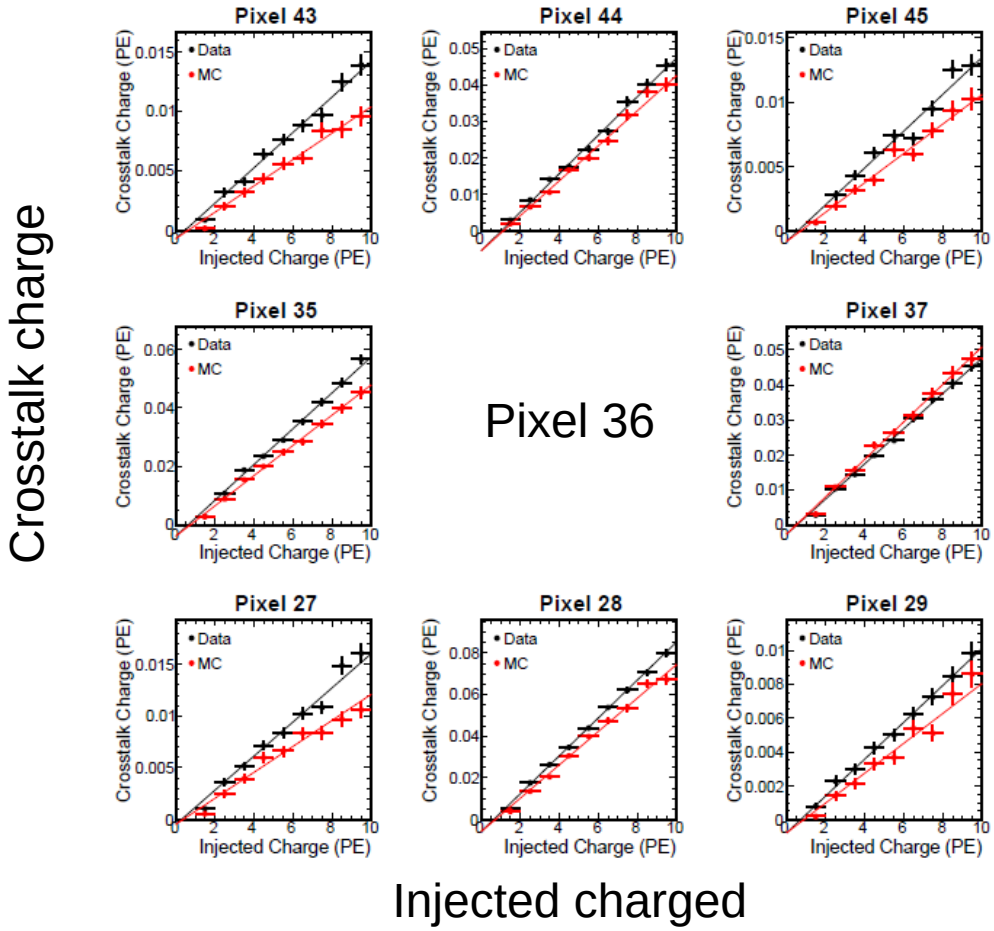
Measuring Crosstalk with Cosmic Data





- Cosmic ray muons are ideal for measuring the magnitude of crosstalk.
- It is easy to associate the crosstalk hits with the injected charge (muon hits).

Measuring Crosstalk with Cosmic Data



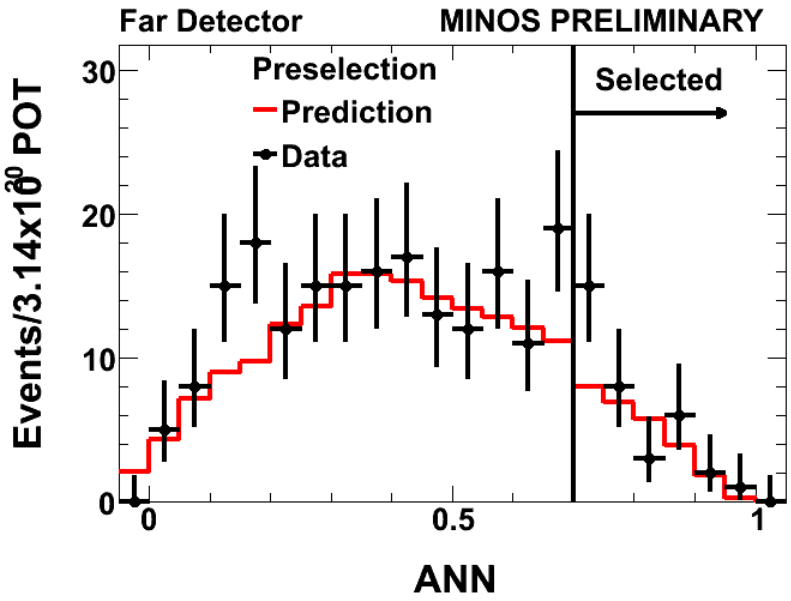
- We can measure the magnitude of crosstalk using cosmic ray muons.

Remove Crosstalk in Analysis

- In the first ν_e analysis, we still used the MC generated with old xtalk modeling.
- We tried to make the event selection more robust and make corrections based on better xtalk modeling.
  - To remove the dependence on crosstalk hits, we remove hits below 2 photo-electrons
  - Use improved crosstalk tables to evaluate systematic

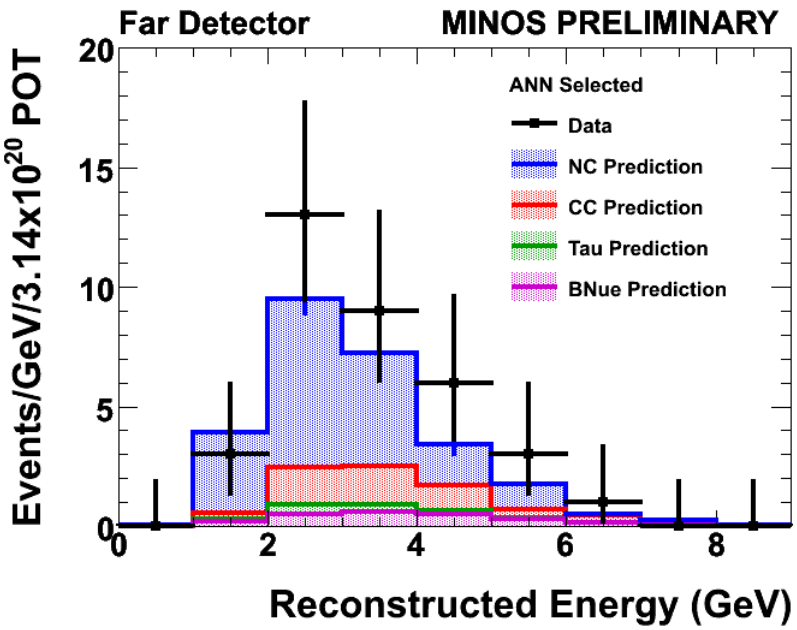
ν_e Appearance Result (3.14e20 POT)

ν_e Appearance Result

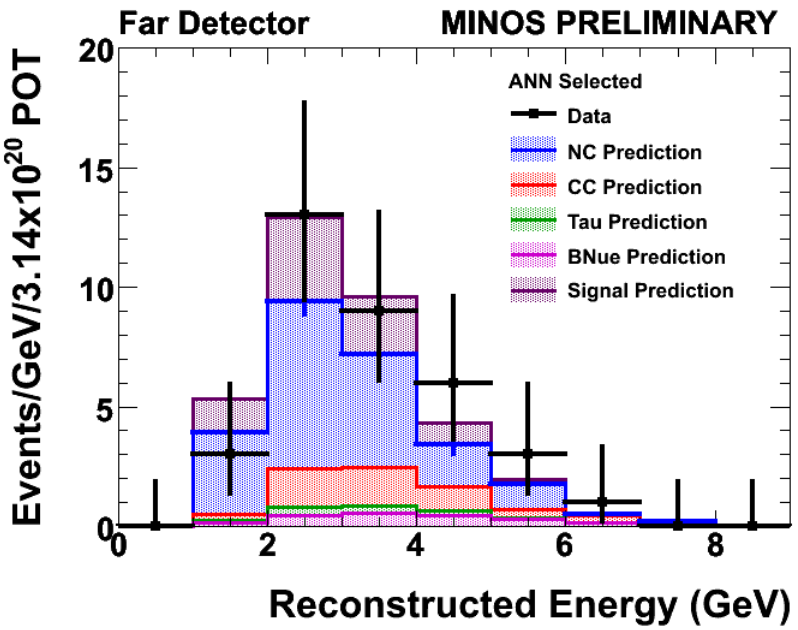


- We observe a total of 35 events.
- We expect 27±5(stat.)±2(sys.) background events.
- Results are 1.5σ above expected background.
- Number of potential signal events is 10±3(stat)±1(stat) at CHOOZ limit.

Energy Spectra of Select Events



Without signal prediction



With signal prediction

stack plots

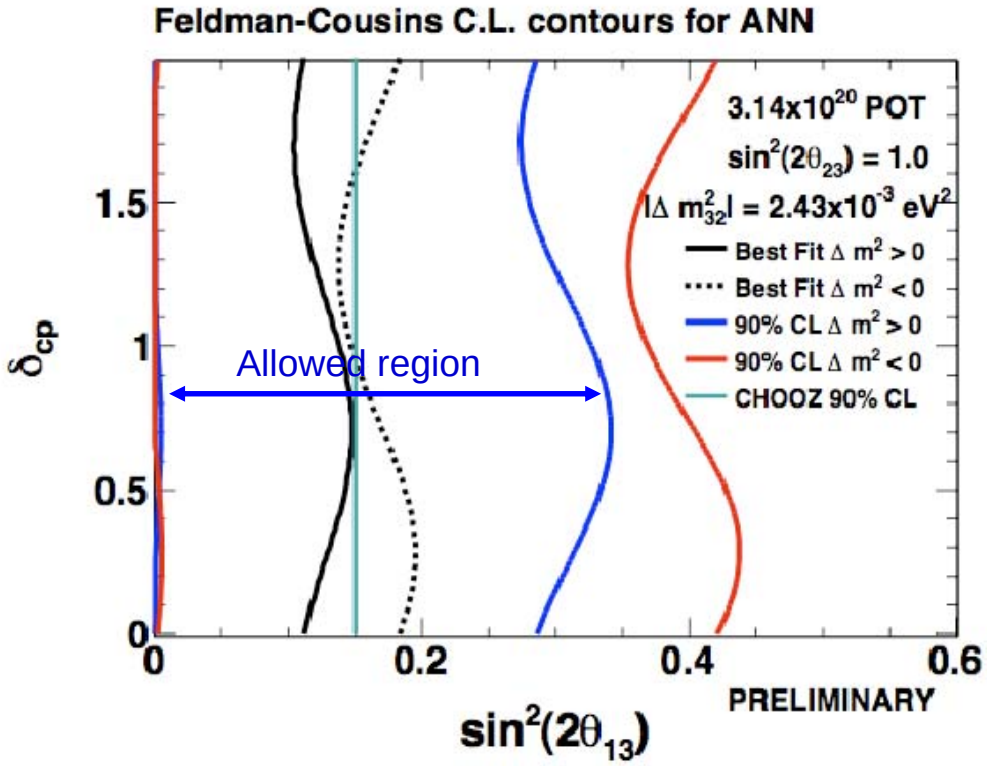
The excess is consistent with statistical fluctuation of background events or a ν_e signal.

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

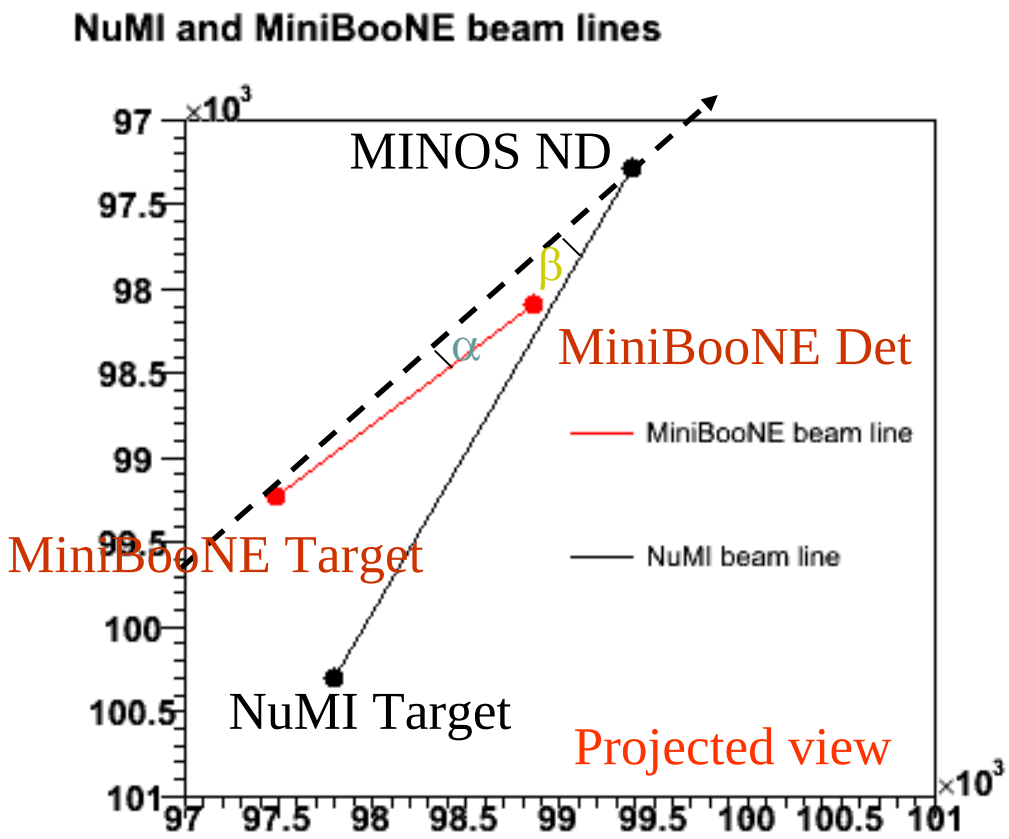
- A Feldman-Cousins method was used.
- Fit simply to the number of events from 1-8 GeV, no shape or correlation information used.
- Best fit and 90% C.L. limits are shown:
  - as a function of δ_{CP}
  - for both mass hierarchies
  - at MINOS best fit value for Δm^2_{32} and $\sin^2(2\theta_{23})$
-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

$$P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23} \boxed{\sin^2 2\theta_{13}} \sin^2\left(1.27\Delta m^2_{32} L/E\right)$$

Leading term



MiniBooNE neutrinos in MINOS Near Detector



α: off-axis angle to the MINOS detector = 9.13 deg

β: incident angle of MiniBooNE neutrinos on MINOS ND = 16.9 deg

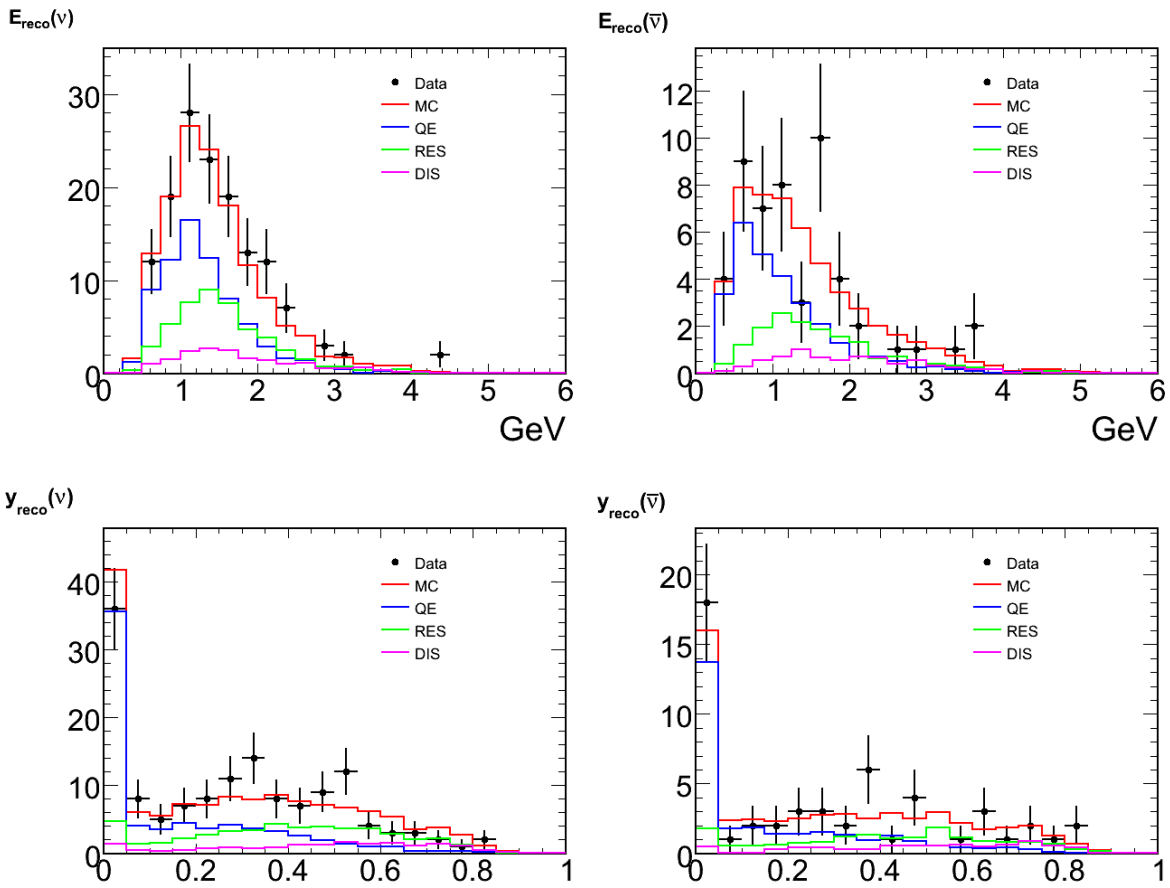
Incoming direction of MB neutrinos:
zenith: 83.5 deg

azimuth: 172.8 deg

Event Selection

- Vertex inside Fiducial Volume
- Track end containment
- Track direction cut
- Timing cut
- Background contamination ~2%

Clean neutrino sample



- Neutrino mode: 2005-03 to 2005-11: 1.9e20POT
- Anti-neutrino mode: 2006-01 to 2007-08: 1.3e20POT
- About 200 data events
- MC uses the MinibooNE flux
- Data and MC are in excellent agreement.

Conclusion

- We have completed an initial search for ν_e appearance in the MINOS data.
- My contribution to the first MINOS ν_e analysis includes:
  - ANN based event selection
  - Horn on/off background estimation method
  - Hadronization model
  - Crosstalk simulation
- We observed a 1.5σ excess in the ν_e appearance channel.
- We have already doubled the data. The future analysis is very promising.

Thank you for your attention!

The MINOS Collaboration

Brazil • Greece
Poland • UK • USA

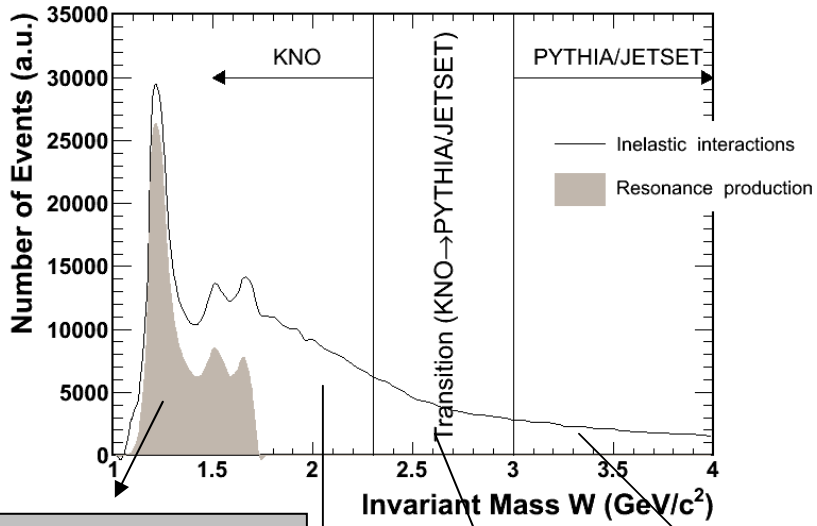
28 institutions

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

Hadronization Model for MINOS

- Hadronization (or fragmentation) model – the model that determines the final state particles and 4-momenta in the ν-nucleon interactions.

W distribution of inelastic events



Resonance interactions: Rein-Sehgal model

Low-W DIS interactions: KNO based model

High-W DIS interactions: PYTHIA/JETSET model

Smooth transition between KNO model and PYTHIA/JETSET

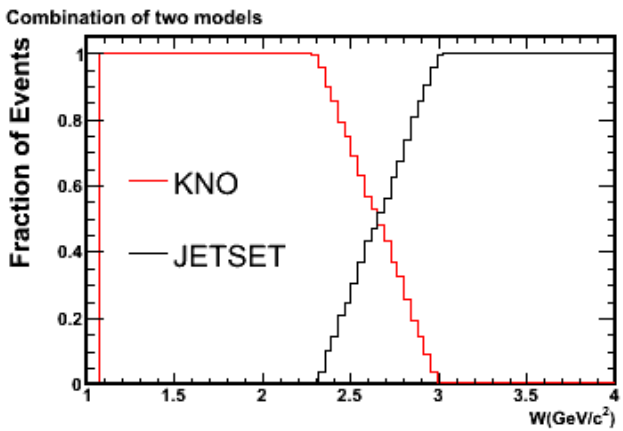
- The modeling of DIS events is very important for ν_e analysis.
- For DIS events, we combine a low energy hadronization model with a standard "high-energy" package (JETSET) – AGKY model
- At low invariant mass (W<2.3GeV), we use our empirical model (modified KNO-based model).
- At high invariant mass (W>3GeV), we use the tuned JETSET model
- Smooth transition between KNO model and JETSET in between.

Low-W: KNO-based model

- Select particles
  - Decide hadron multiplicity based on W and KNO-distributions: $\langle n_{ch} \rangle = a + b \ln W^2$
- Determine 4-momenta for particles
  - Only one baryon in the final state, select baryon 4-momentum from proton PDF (x_F,p_T)
  - Decay remaining hadronic system and apply p_t reweighting
  - Rotate/boost hadronic system to lab frame

High-W: PYTHIA/JETSET

- Using PYTHIA/JETSET model for W>3GeV
- Including NUX's PYTHIA tuning (NOMAD exp. A.Rubbia's talk @ NuINT01)
- Smooth transition between KNO model and PYTHIA/JETSET from 2.3 GeV to 3 GeV

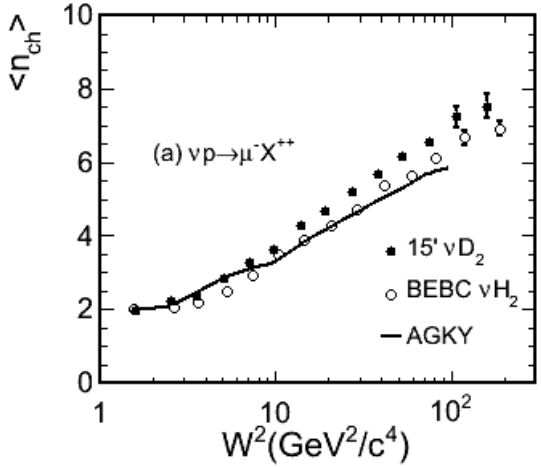


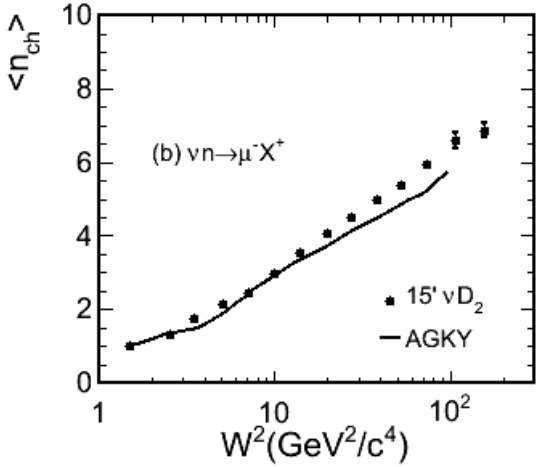
Compared with External Data

- We tuned our model with data from a lot of bubble chamber experiments – 15ft-FNAL, BEBC and SKAT.
- We focus on the following quantities:
  - Hadron multiplicity (n) – number of hadrons generated
  - Dispersion – sqrt($\langle n^2 \rangle - \langle n \rangle^2$)
  - π^0 production
  - $z=E_h/\nu$ – E_h is the hadron energy, ν is the shower energy
  - p_T – transverse momentum
- One difficulty: not many low energy data available (W<3GeV)
  - Model not well constrained in the region of interest

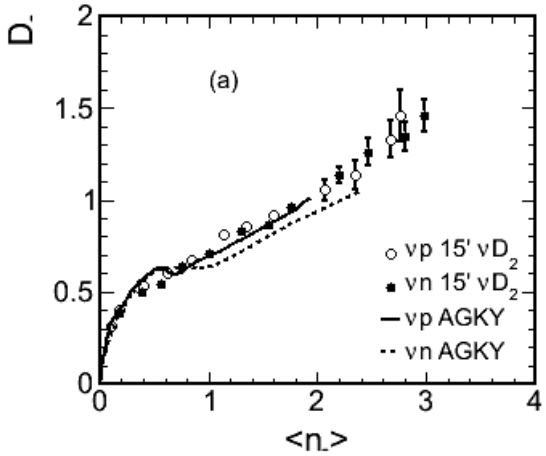
Charged Hadron Multiplicity and Dispersion

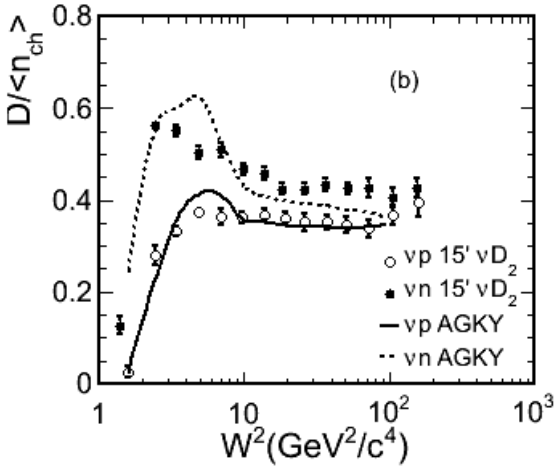
Multiplicity



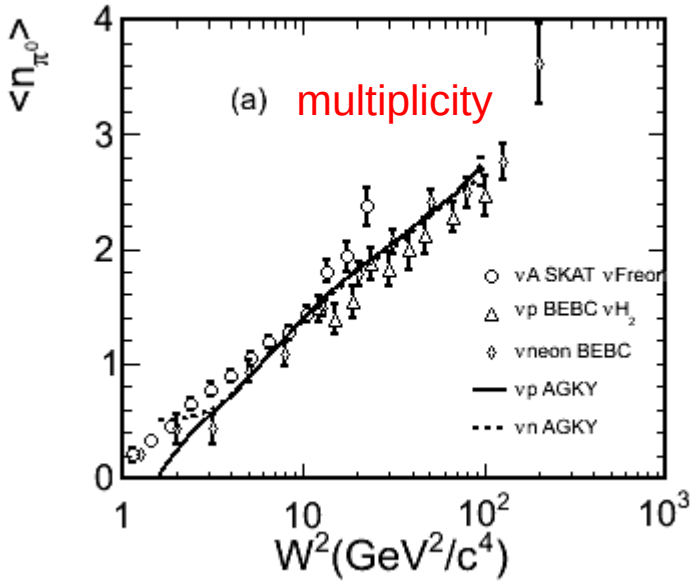


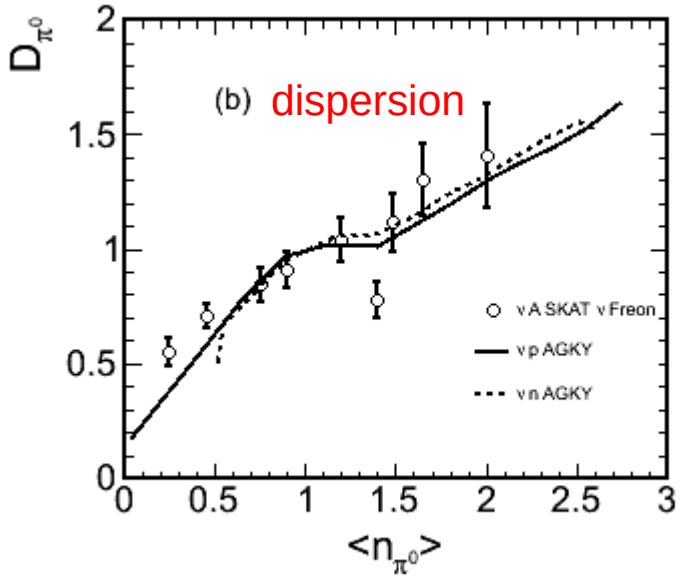
Dispersion





π^0 Multiplicity and Dispersion





- It was hard to make the π^0 measurements in the light target experiments. The interaction length was long so photons would escape the chamber easily.
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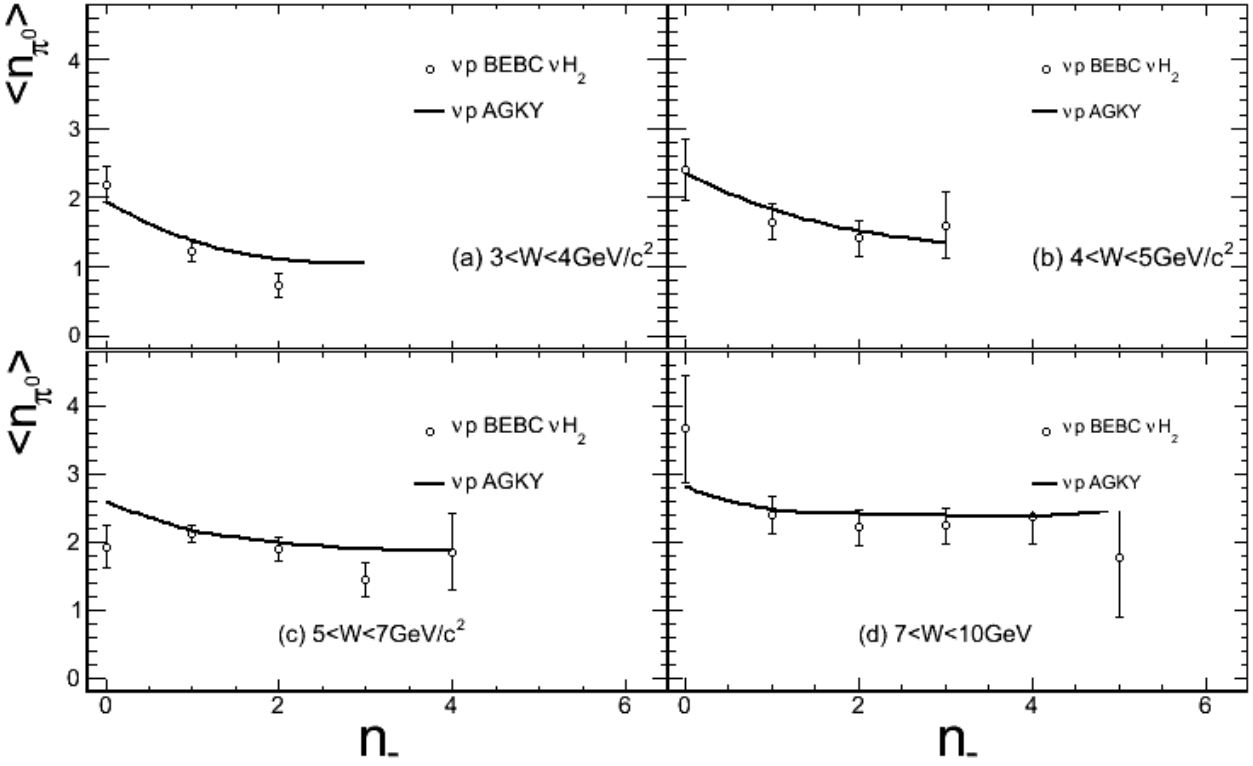
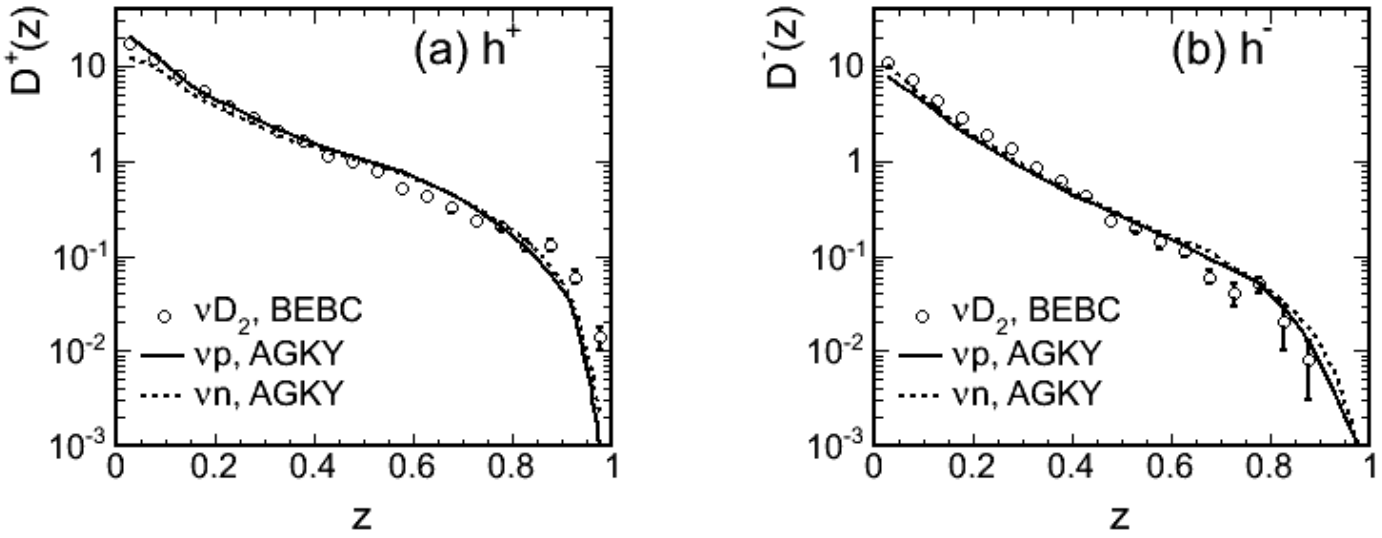
Correlation between Charged Pions and Neutral Pions



- At low W, $<n_{\pi^o}>$ decrease with n_- because of limited phase space.
- At high W, $<n_{\pi^o}>$ is rather independent of n_-.
- MC predictions agree with data quite well.

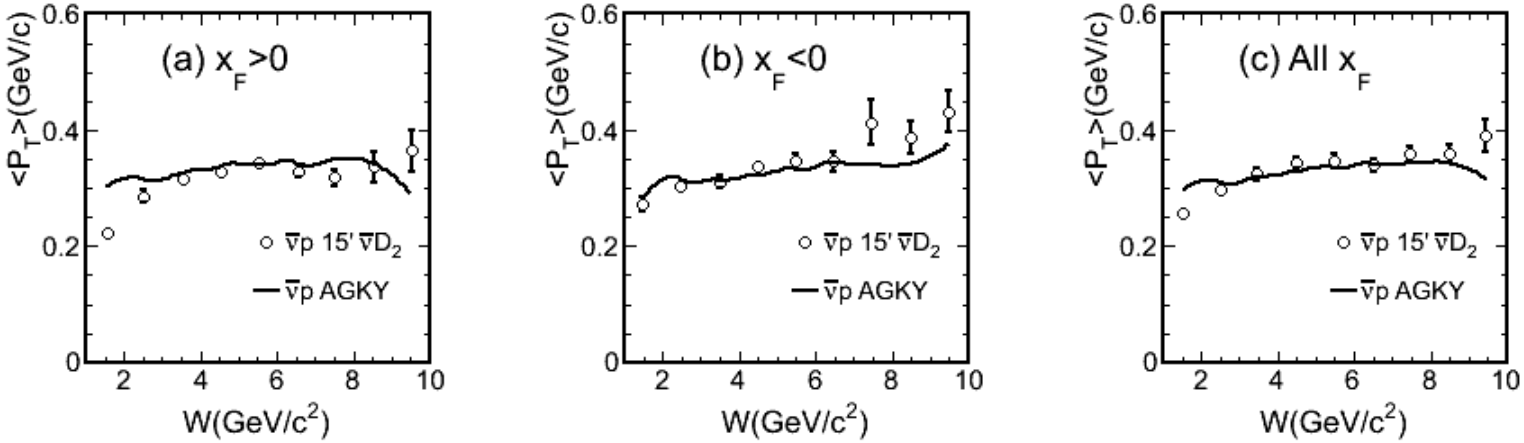
Fragmentation Function

W^2>5GeV, Q^2>1GeV

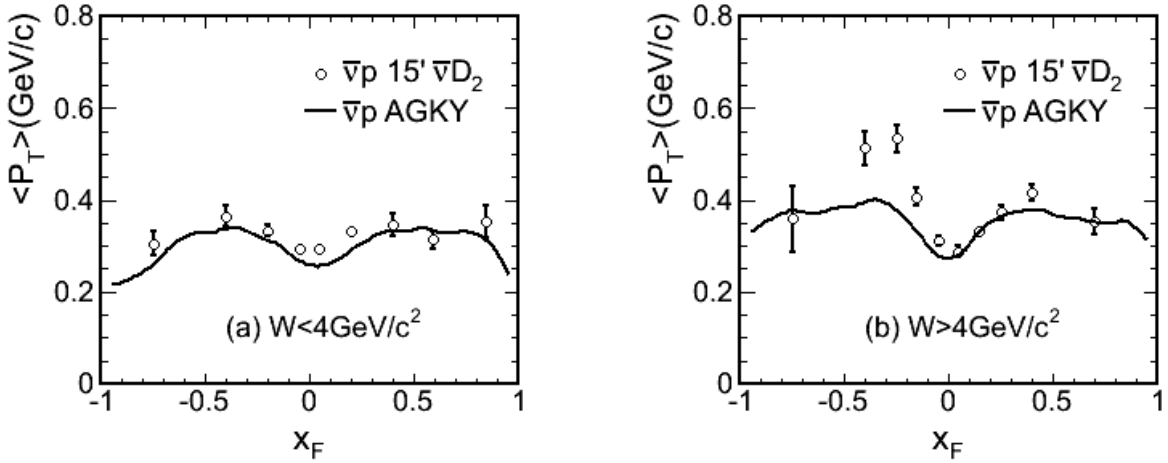


- $z=E/\nu$ is the fraction of the total energy transfer carried by each final hadron in the lab frame
- Fragmentation function: $D(z)=(1/N_{evt})dN/dz$
- MC predictions agree with data quite well.

Transverse Momentum



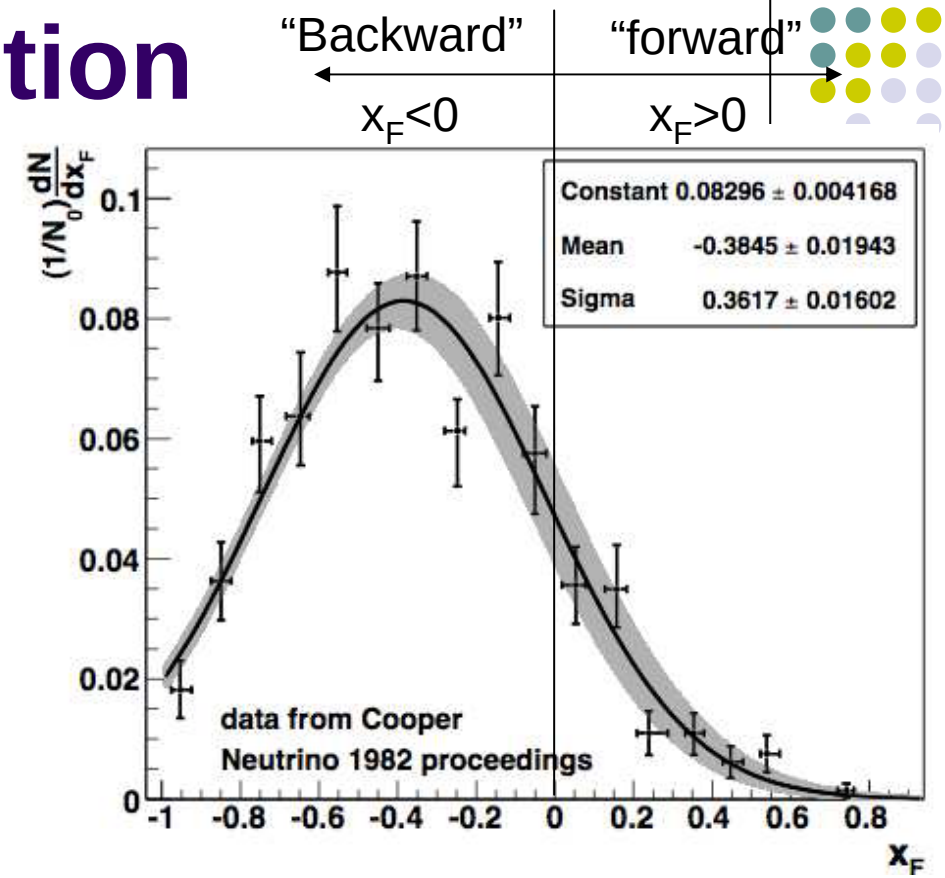
Seagull effect



- MC predictions agree with data quite well.

Baryon x_F Selection

- Select baryon x_F based on measurement
- Baryon tends to go backwards (xF<0) in the hadronic cms: expected from Quark Parton Model (QPM)
- When boosted to the lab frame, baryon tends to have low energy. Consequently pions would carry more energy.
- However, the plot is for identified protons only. In bubble chamber, it is only possible to reliably identify low energy protons (P<1GeV/c).
- It is possible we may underestimate the baryon momentum in the lab frame.
  - Biggest uncertainty in hadronization model
  - Shower events may be overestimated in MC: more ν_e-like events in MC



$x_F = 2P_L^*/ W$

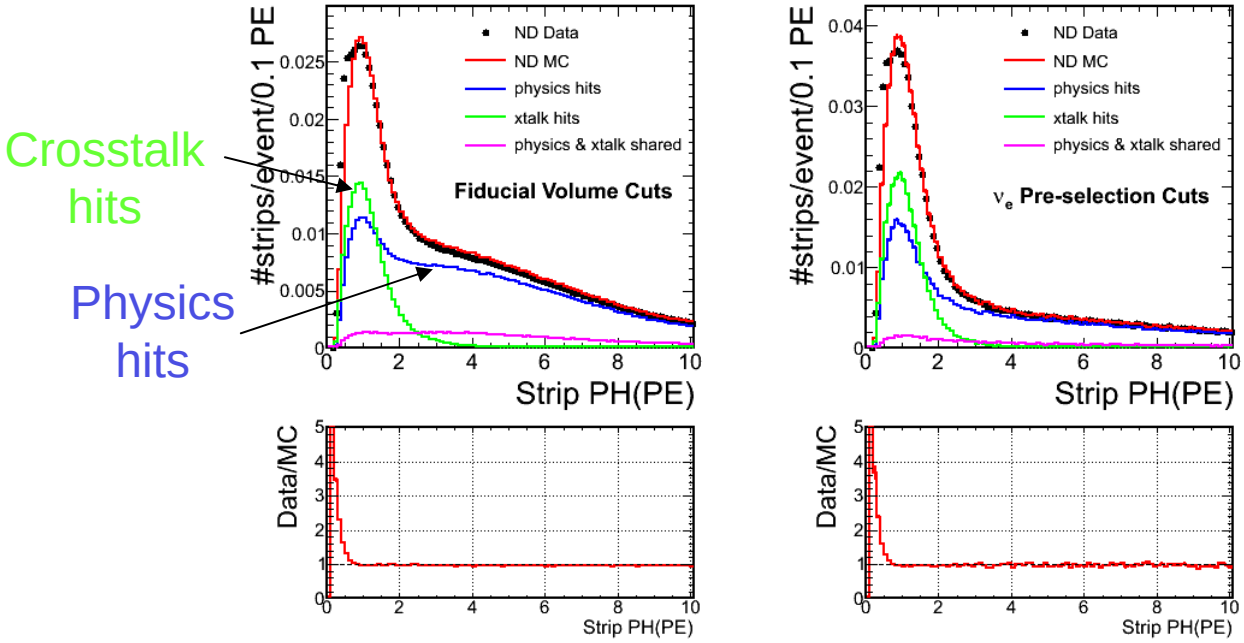
P_L^* longitudinal momentum in hadronic cms

Summary of Hadronization Model

- The hadronization model has been tuned against bubble chamber data. MC predictions agree with external data quite well for most of the distributions.
- The biggest uncertainty in our model is the selection of baryon x_F.
- One difficulty in constraining the model is due to lack of data at low energies.
- New experiments dedicated to the measurements of neutrino interactions (ArgoNeuT, MINERvA) will help to address these issues.

Low Pulse Height Excess

ND data/MC comparisons (strip PH)

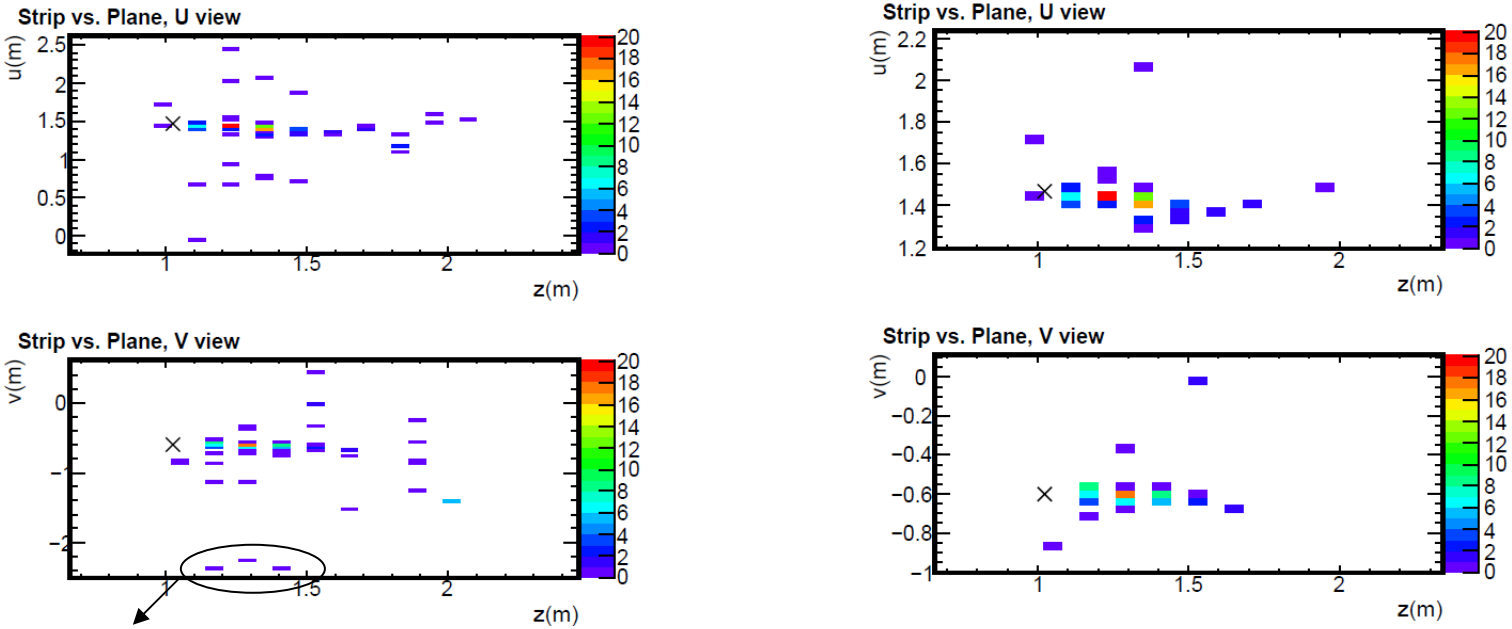


- Low pulse height hits are poorly modeled
  - Crosstalk mismodeling
- Impact of low pulse height hits on the ν_e analysis
- Understand the sources and make improvements
- Make ν_e selection less sensitive to the low pulse height hits

Impact on ν_e analysis

Original Event

Remove hits below 2PE



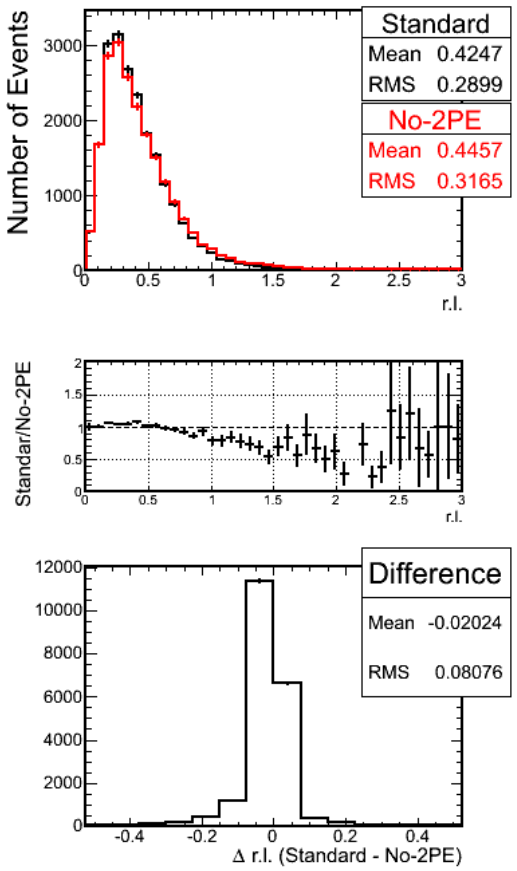
Crosstalk hits

One ND MC event

- Removing low pulse-height hits changes the event topology.
  - Event looks more condensed without the peripheral hits

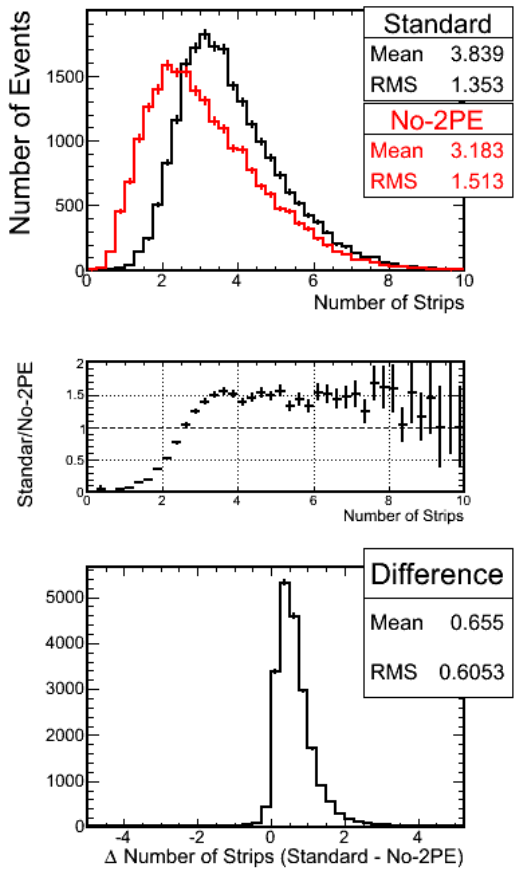
Impact on ν_e Variables

Par b from shw fit



Longitudinal variable

Shw lateral spread



Transverse variable

- Remove hits below 2PE during the reconstruction and compare distributions between the standard sample and No-2PE sample
- Low pulse height hits can change event topology (transverse feature) drastically
  - Mismodeling of those hits could pose a problem
  - Need to understand the sources and make selection less sensitive to those hits

PMT Crosstalk

- The scintillator strips of MINOS detectors are read out by Hamamatsu PMTs.
- Crosstalk phenomenon is an inherent property for multi-anode PMT.
  - 7% of the signal from light on a given pixel may appear in neighboring pixels
    - Spread of secondary electron flows over adjacent anodes
    - Charge induction through stray capacitances among anodes
  - Crosstalk is most likely to occur in the neighboring pixels of the injected pixel.
  - Two components
    - Optical crosstalk: single PE peak
    - Electrical crosstalk: shifted pedestal, below 1 PE
  - To help identify crosstalk hits, adjacent strips are read out by non-adjacent pixels.

PMT Crosstalk Patterns

strip to pixel mapping

M64 PMT, ND

Pixel 0 23	Pixel 1 54	Pixel 2 41	Pixel 3 11	Pixel 4 35	Pixel 5 22	Pixel 6 53	Pixel 7 40
Pixel 8 43	Pixel 9 9	Pixel 10 37	Pixel 11 24	Pixel 12 55	Pixel 13 42	Pixel 14 10	Pixel 15 36
Pixel 16 39	Pixel 17 26	Pixel 18 57	Pixel 19 44	Pixel 20 8	Pixel 21 38	Pixel 22 25	Pixel 23 56
Pixel 24 59	Pixel 25 46	Pixel 26 6	Pixel 27 19	Pixel 28 27	Pixel 29 58	Pixel 30 45	Pixel 31 7
Pixel 32 4	Pixel 33 17	Pixel 34 29	Pixel 35 60	Pixel 36 47	Pixel 37 5	Pixel 38 18	Pixel 39 28
Pixel 40 31	Pixel 41 62	Pixel 42 49	Pixel 43 3	Pixel 44 16	Pixel 45 30	Pixel 46 61	Pixel 47 48
Pixel 48 51	Pixel 49 1	Pixel 50 14	Pixel 51 32	Pixel 52 63	Pixel 53 50	Pixel 54 2	Pixel 55 15
Pixel 56 12	Pixel 57 34	Pixel 58 21	Pixel 59 52	Pixel 60 0	Pixel 61 13	Pixel 62 33	Pixel 63 20

M16 PMT, FD

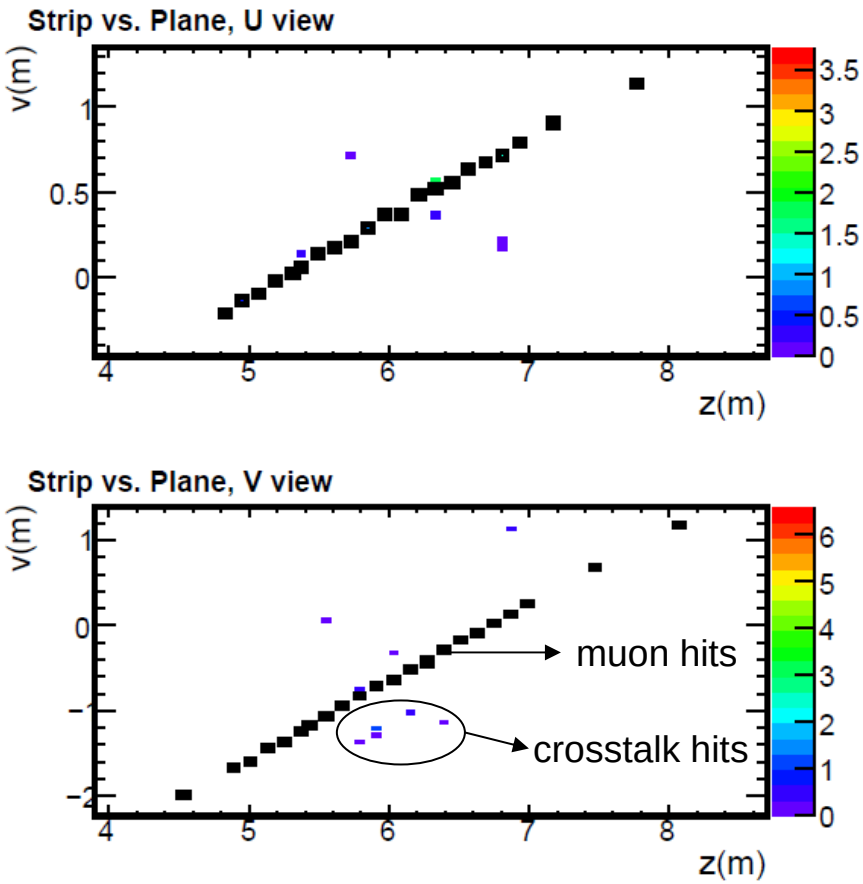
Pixel 0 50 4 166 27 96 73 189 143	Pixel 1 154 39 16 85 62 131 177 108	Pixel 2 190 167 51 97 5 74 120 28	Pixel 3 178 155 40 132 86 63 17 109
Pixel 4 156 87 41 133 18 64 110 179	Pixel 5 121 144 52 191 98 29 75 6	Pixel 6 157 65 134 180 42 111 88 19	Pixel 7 53 145 30 7 122 168 76 99
Pixel 8 8 146 31 54 100 77 123 169	Pixel 9 66 20 89 112 135 158 181 43	Pixel 10 101 55 32 78 9 147 124 170	Pixel 11 67 136 21 182 44 90 159 113
Pixel 12 22 91 137 68 160 45 114 183	Pixel 13 33 10 56 102 79 125 148 171	Pixel 14 46 115 69 184 138 23 92 161	Pixel 15 126 57 172 149 80 34 11 103

- Strips read out by adjacent pixels have certain patterns
  - ±13, ±20, *etc.*

- 8 strips are read out by one pixel at FD – multiplexing
- Unique crosstalk patterns
  - Adjacent pixels: ±9,10,11
  - Diagonal pixels: ±1,2,3

Two PMTs have different crosstalk patterns. Mis-modeling of crosstalk hits can affect the simulation of Far/Near ratios.

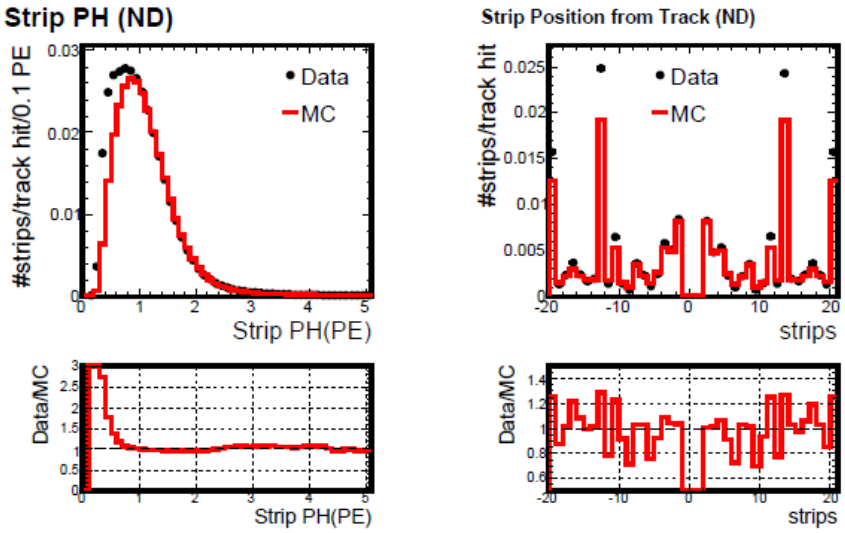
Measuring Crosstalk with Cosmic Data



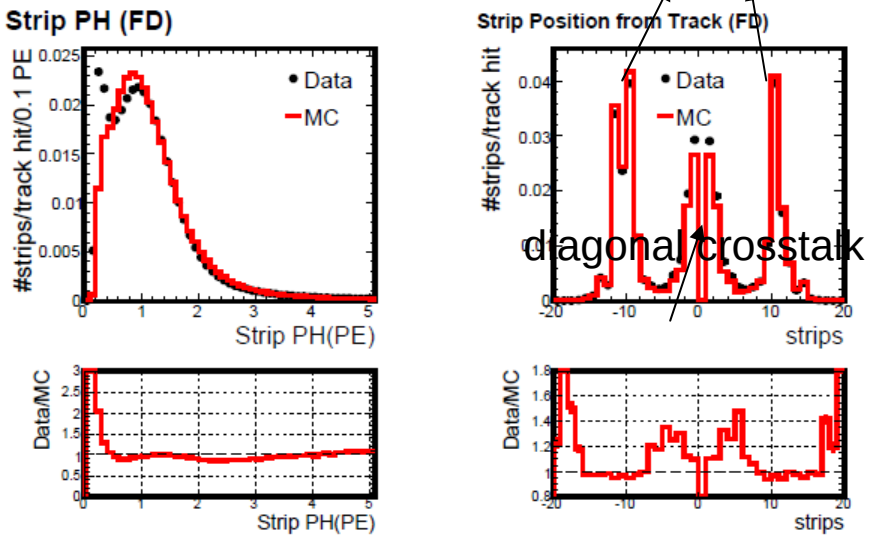
- Cosmic ray muons are ideal for measuring the magnitude of crosstalk.
- It is easy to associate the crosstalk hits with the injected charge (muon hits).
- Select clean muon tracks:
  - cut on azimuth and zenith angles to remove steep tracks
  - only one track per event
  - no reconstructed shower
  - through-going muons only
  - one track hit per plane
- Focus on two quantities of crosstalk hits:
  - Charge
  - Distance from the muon hit

Distributions of Crosstalk Hits

ND



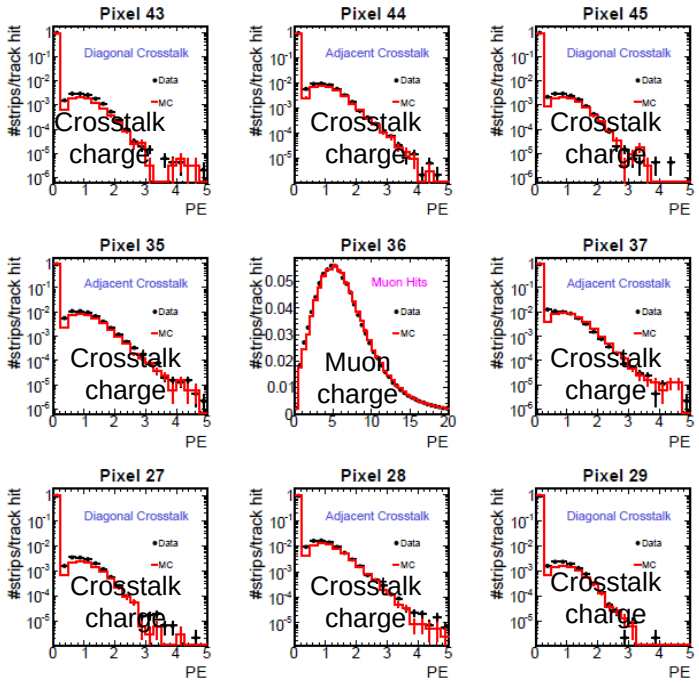
FD

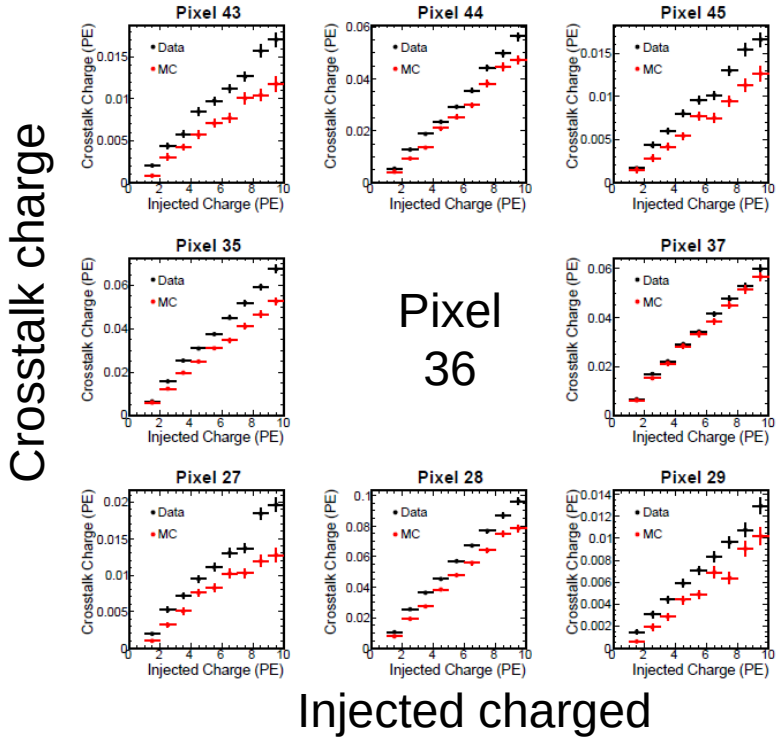


- Crosstalk not well modeled
  - An excess of data hits below 1 PE
  - An excess of data hits at ±13, ±20: underestimate crosstalk in MC

- Two peaks in the data PH distribution:
  - Optical crosstalk: single PE
  - Electrical crosstalk: shifted pedestal
- Two groups of crosstalk hits:
  - Adjacent crosstalk: slightly overestimated in MC
  - Diagonal crosstalk: underestimated in MC

Injected Charge and Crosstalk Charge (ND)

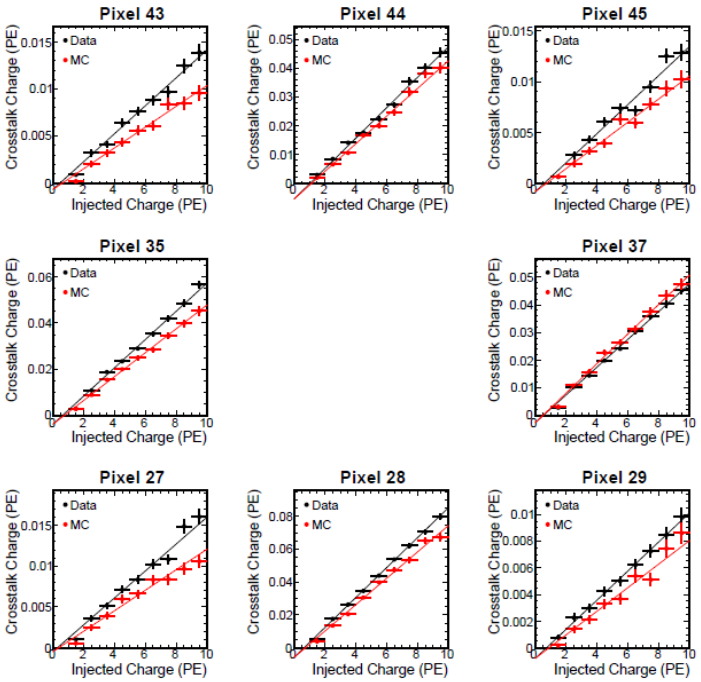




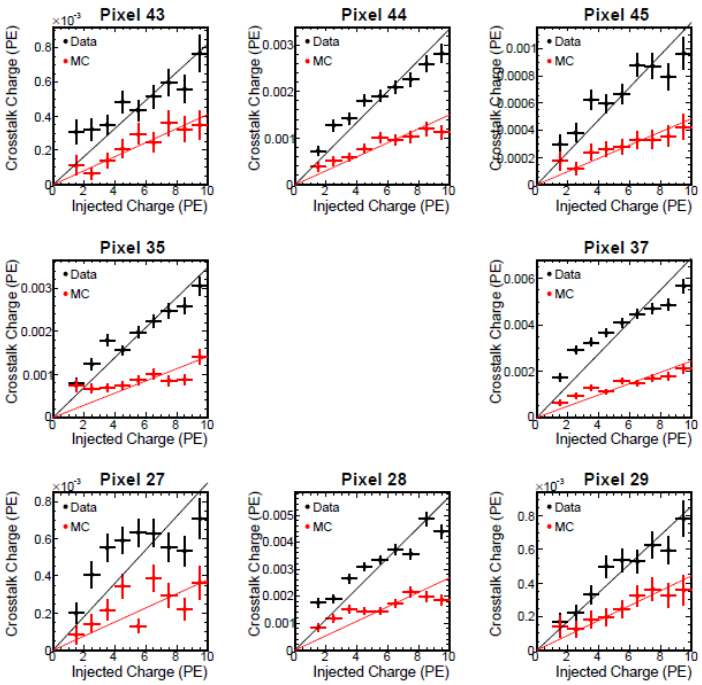
- MC simulation uses the measured crosstalk magnitude at test stand.
- The slope of crosstalk charge vs injected charge represents the fraction of crosstalk in a particular pixel.
- The standard MC underestimates the crosstalk fractions.

Correct Crosstalk Fractions (ND)

Optical crosstalk

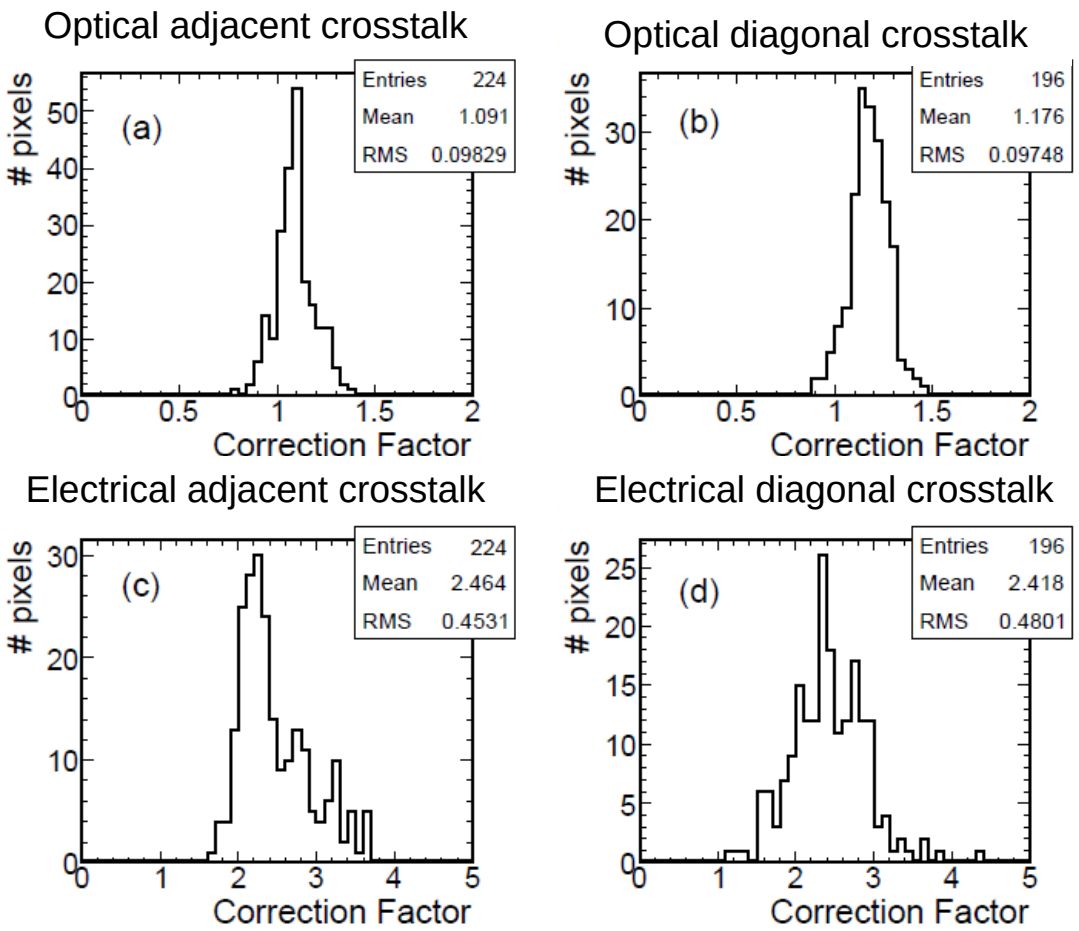


Electrical crosstalk



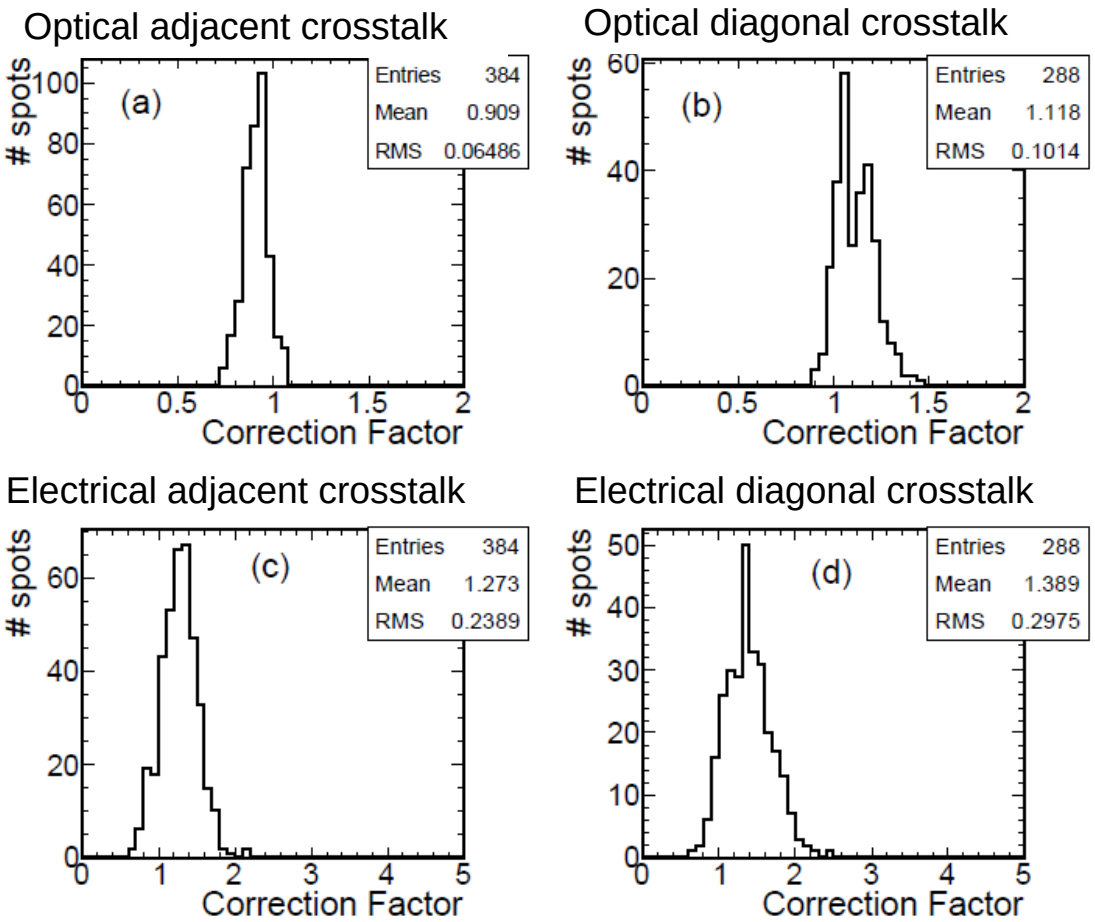
- We can measure the crosstalk fraction by fit a straight line to the crosstalk charge vs injected charge distribution.
- We separate optical crosstalk and electrical crosstalk by PH: PH>0.8PE – optical crosstalk; PH<0.5PE – electrical crosstalk
- We perform the fit to both data and MC distributions. The ratio of the two slopes are taken as the correction factor applied to the MC crosstalk simulation.

Correction Factors (ND)



- Corrections are applied on a pixel by pixel basis
- Optical crosstalk
  - Adjacent pixels: increase by 9%
  - Diagonal pixels: increase by 18%
- Electrical crosstalk
  - Increase by a factor of 2.4

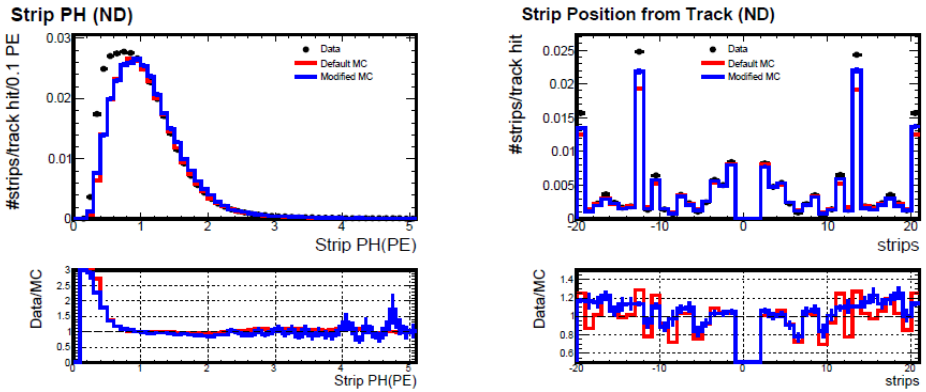
Correction Factors (FD)



- Optical crosstalk
  - Adjacent pixels: decrease by 9%
  - Diagonal pixels: increase by 12%
- Electrical crosstalk
  - Adjacent pixels: increase by 27%
  - Diagonal pixels: increase by 38%

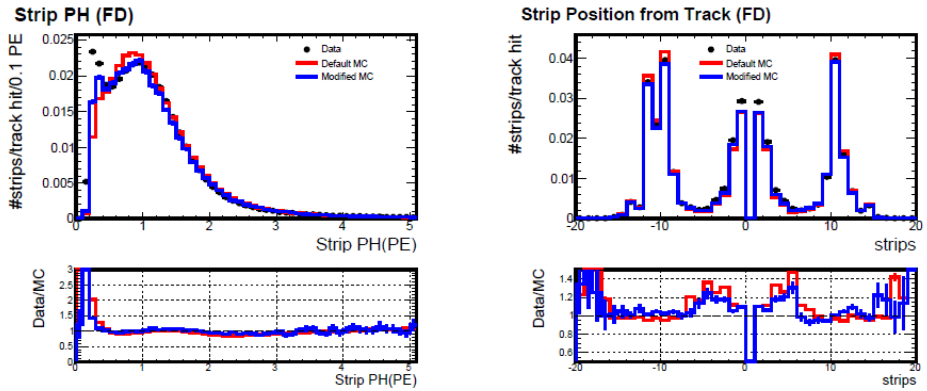
Updated Crosstalk Model

Default MC Updated MC



- ND
  - Strip PH: not changed
  - Strip position: improved

Default MC Updated MC



- FD
  - Strip PH: improved
  - Strip position: improved

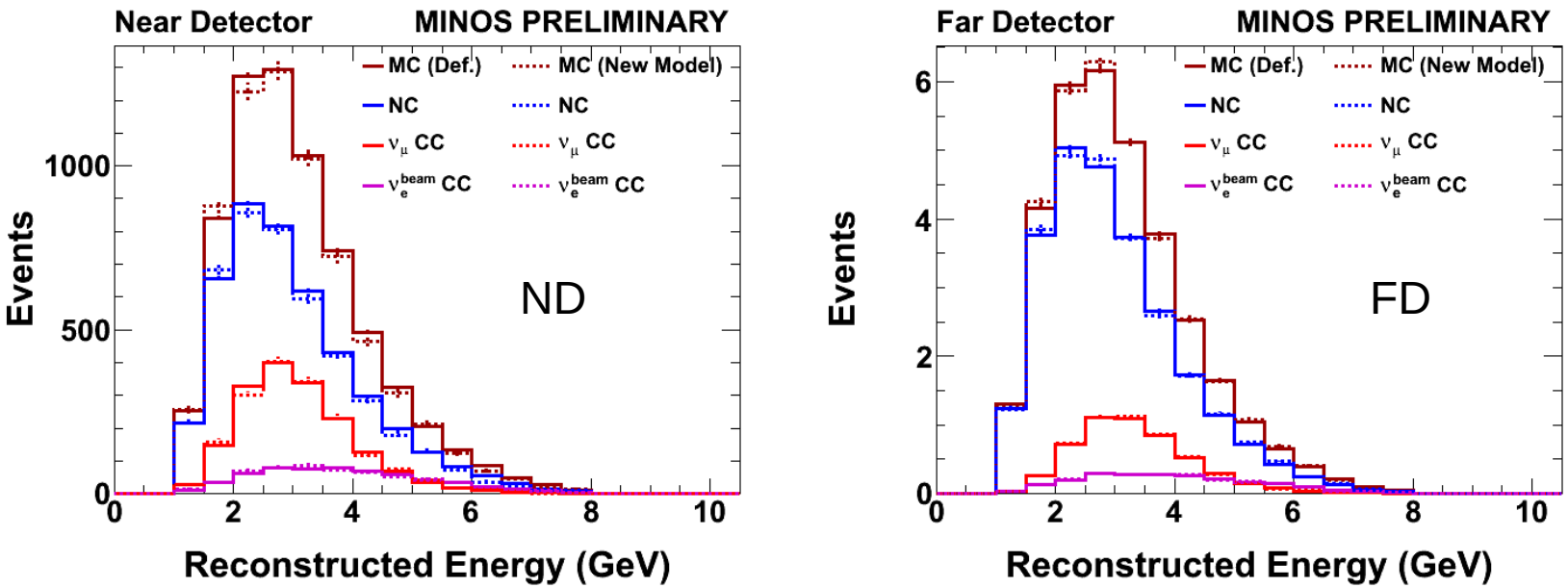
- Agreements are greatly improved with the update crosstalk model.
- There may be other effects that account for the mis-modeling of low pulse-height hits. We do not want to overtune crosstalk to compensate for other effects.
- We can make the ν_e selection less sensitive to the low pulse-height hits.

Changes to ν_e Selection Algorithm

- Because of the time constraints and the fact that the improved crosstalk model does not fix all the problems, we decided to use the MC with the older crosstalk model and make the following changes:
  - Compute variables with hits whose pulse height is larger than 2PE (keep the reconstruction unchanged)
  - Refine some PID variables:
    - Ignoring hits that are more than 9 strips away from the event vertex transversely
    - Weighting each strip by pulse-height squared
- Generate a small sample of MC using the improved crosstalk simulation to evaluate the systematics and make corrections to the background prediction.

Energy Spectra of ANN Selected Events

Solid: MC with older crosstalk model
Dashed: MC with updated crosstalk model

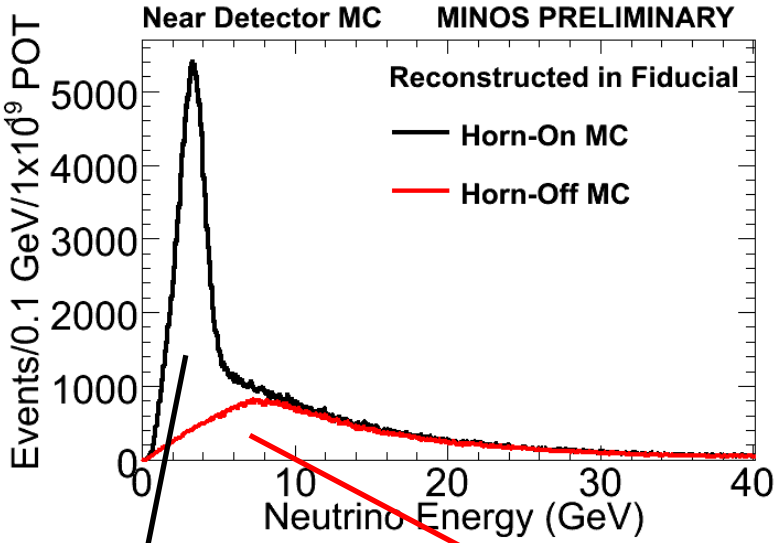


- After the changes, the ANN PID is not sensitive to the detailed modeling of crosstalk hits.
- With the updated crosstalk model, the ND background rate decreases by 1.9%±1.0% while the FD background rate increases by 0.3% ± 0.7% - Far/Near ratio increases by 2.2% ±1.3%.
- We will increase the FD background prediction by 2.2% and take 1.3% as systematic associated with crosstalk modeling.

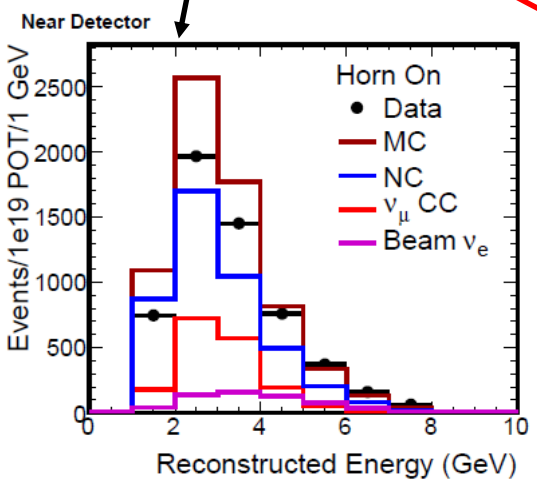
Background Decomposition

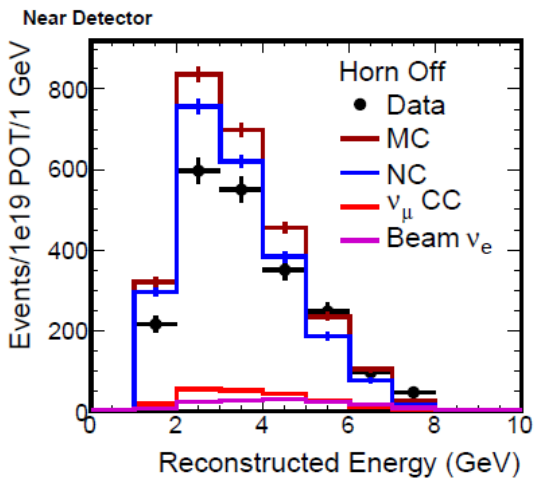
- FD background prediction is done through extrapolation from ND:
  - $FD^{predicted}=(FD/ND)^{MC}\times ND^{Data}$
- Different background sources extrapolate differently:
  - CC background is suppressed in the FD because of $\nu_\mu \rightarrow \nu_\tau$ oscillations while NC background is unaffected by the oscillations.
- Some knowledge about the relative contribution from different background sources is necessary.
- We have developed a method that can be used to obtain relative CC and NC background contributions in the ND by comparing horn on and horn off spectra.

Horn-on/Horn-off Spectra (ND)



- When focusing horns are turned off, the pions do not get focused, resulting in the disappearance of the low energy peak in the neutrino energy spectrum.
- The consequence is a spectrum dominated by NC arising from the long tail in true neutrino energy that gets measured in our region of interest in visible energy.





- Apply the ANN cut to both samples
- Very different CC/NC ratios
- MC does not model the absolute background rate well
- Simulated Horn-off/Horn-on ratios are more robust, *e.g.*
  - $r^{NC}=(NC)^{off}/(NC)^{on}$

Estimating background using horn-on/off data

- The two main background components can be estimated using the number of data events in the horn on and horn off configurations: $\mathbf{N^{on}}$ and $\mathbf{N^{off}}$.
- $\mathbf{N^{on}} = \mathbf{N_{NC}} + \mathbf{N_{CC}} + N_e$ (1)
  $\mathbf{N^{off}} = r_{NC} \times \mathbf{N_{NC}} + r_{CC} \times \mathbf{N_{CC}} + r_e \times N_e$ (2)

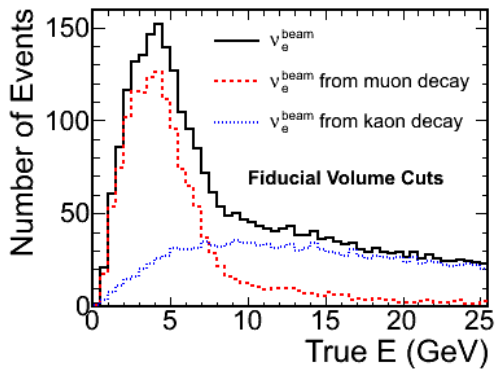
  from MC:

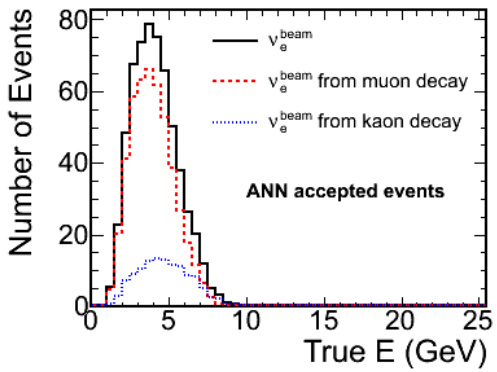
  $r_{NC(CC,e)} = N_{NC(CC,e)}^{off} / N_{NC(CC,e)}$, N_e

- The **beam ν_e flux** is obtained from the ν_μ CC flux which is constrained by data in the different beam configurations.
- Take N_e and three horn-off/on ratios from MC and solve the equations to produce **data-driven predictions** for NC and ν_μ CC background for the horn on configuration.

Systematic Errors on Background Estimation

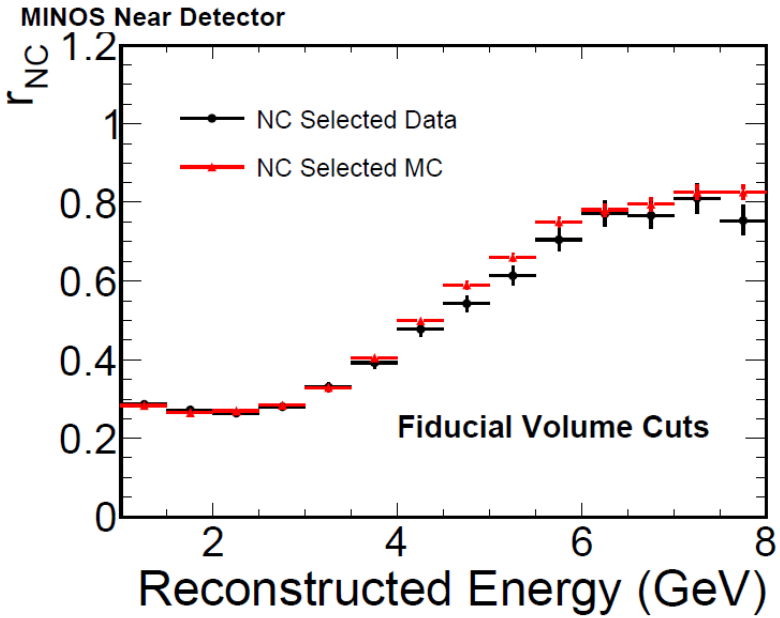
- The uncertainties associated with the horn-on/off methods:
  - Data statistics: horn-on – 4.55e19POT; horn-off – 5.52e18POT
  - Beam ν_e background

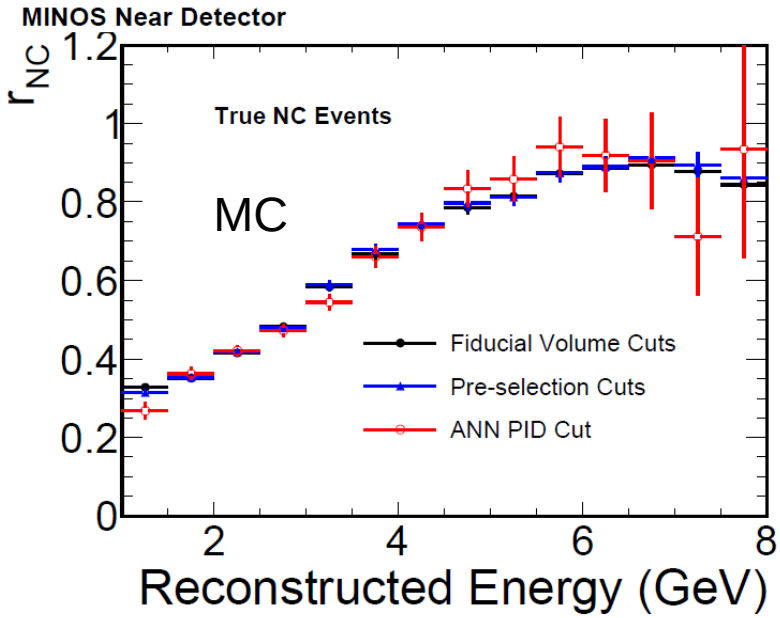




    - Mostly from μ^+ decay, μ^+ is the decay product of the π+ decay
    - π^+ production is well constrained by the ν_μ CC data
    - We assign a 15% error to the number of beam ν_e background events
  - Horn off/on ratios: quite robust since systematics cancel in the ratios

Robustness of r_{NC} $=(NC)^{off}/(NC)^{on}$





- r_{NC} is well modeled in the fiducial volume sample.
- r_{NC} is almost the same in the fiducial volume, pre-selection, and ν_e-selected samples.
- We conclude that r_{NC} is also well modeled ν_e-selected sample.
- The same argument applies to r_{CC} and r_e

Uncertainties on the Horn-off/on Ratios

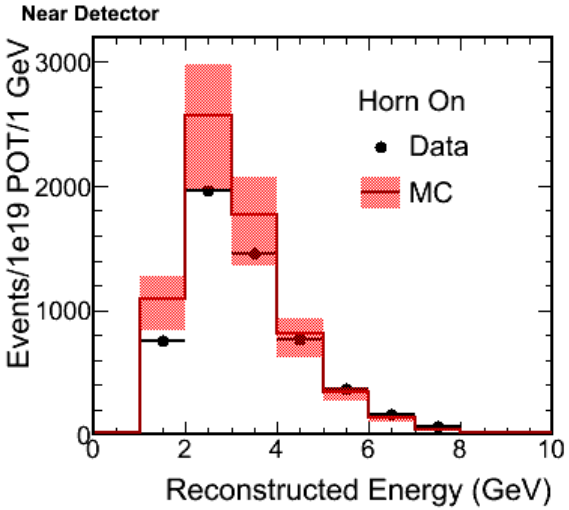
- Flux uncertainties
  - Hadron production at the target, target position, horn current, baffle scraping, *etc.*
- Cross section uncertainties
  - Quasi-elastic, resonance production, transition region between DIS and resonant production
- Hadronization model uncertainties
  - Baryon x_F selection, π^0 production, charged-neutral pion correlation, x_F vs p_T correlation, $\langle p_T \rangle$, two-body decays, charged hadron multiplicity
- Intranuke uncertainties
  - Rescattering of final-state hadrons within nucleus
- Crosstalk model
  - Use the update crosstalk model to evaluate the systematic

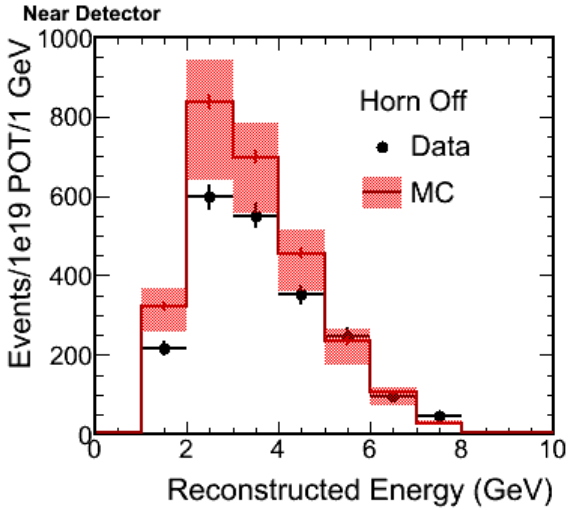
Percentage Systematic Errors on r_{NC} in Reconstructed Energy Bins

E_{reco}(GeV)	1 to 2	2 to 3	3 to 4	4 to 5	5 to 6	6 to 7	7 to 8
Flux	0.5/0.4	1.1/1.0	1.6/1.4	1.2/1.1	0.6/0.6	0.3/0.2	0.2/0.2
Crosssection	1.0/0.9	0.6/0.6	0.3/0.4	0.1/0.1	0.2/0.3	0.1/0.3	0.2/0.4
Hadronization	4.8/4.0	6.1/5.1	6.8/5.9	3.2/2.3	2.2/2.5	5.5/4.3	18.0/13.8
Intranuke	6.6/0.0	0.0/3.2	0.0/1.7	3.9/0.0	5.2/0.0	0.0/8.9	11.1/0.0
Crosstalk	0.0/0.7	1.5/0.0	0.0/0.5	1.3/0.0	3.1/0.0	35.8/0.0	27.8/0.0
Total	**8.2/4.2**	**6.4/6.2**	**7.0/6.3**	**5.4/2.6**	**6.5/2.6**	**36.2/9.9**	**34.9/13.8**

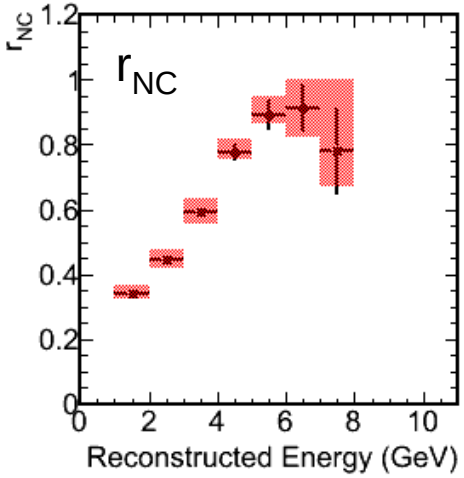
The systematic errors on r_{NC} are below 10% in the region where most data sit.

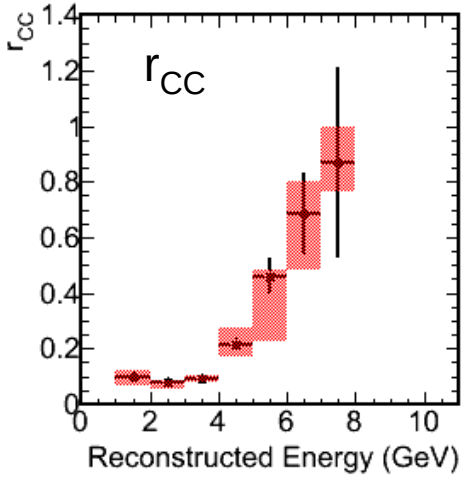
Systematic Errors on the Spectra and Ratios

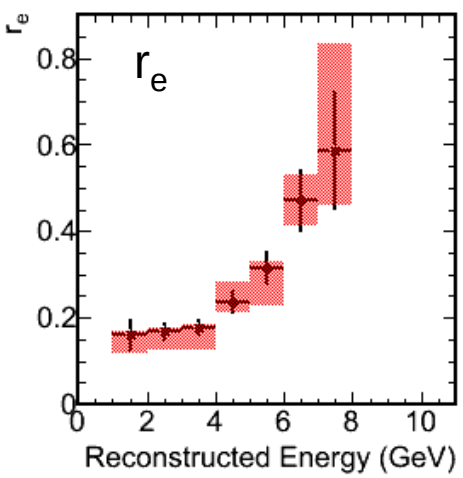




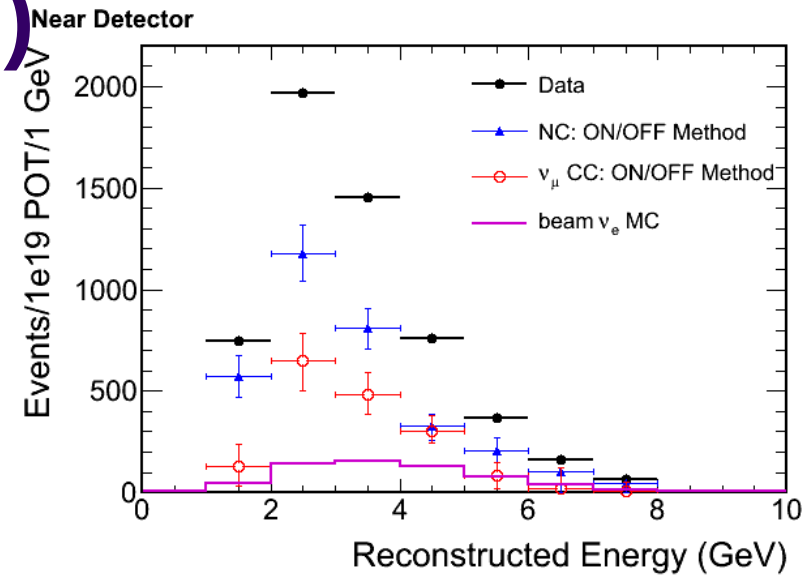
- Errors are big on the spectra but are a lot smaller on the ratios.







ND Background Decomposition (horn-on)



	Total	NC	CC	Beam ν_e
Data Driven	5524±35	3246_{-291}^{+275}	1685_{-281}^{+297}	594±89
Monte Carlo	6765 ±21	4426 ±17	1744 ±10	594 ±6
|MC-Data|/MC	18%	27%	3%	-

9% systematic error on NC background and 18% systematic error on CC background

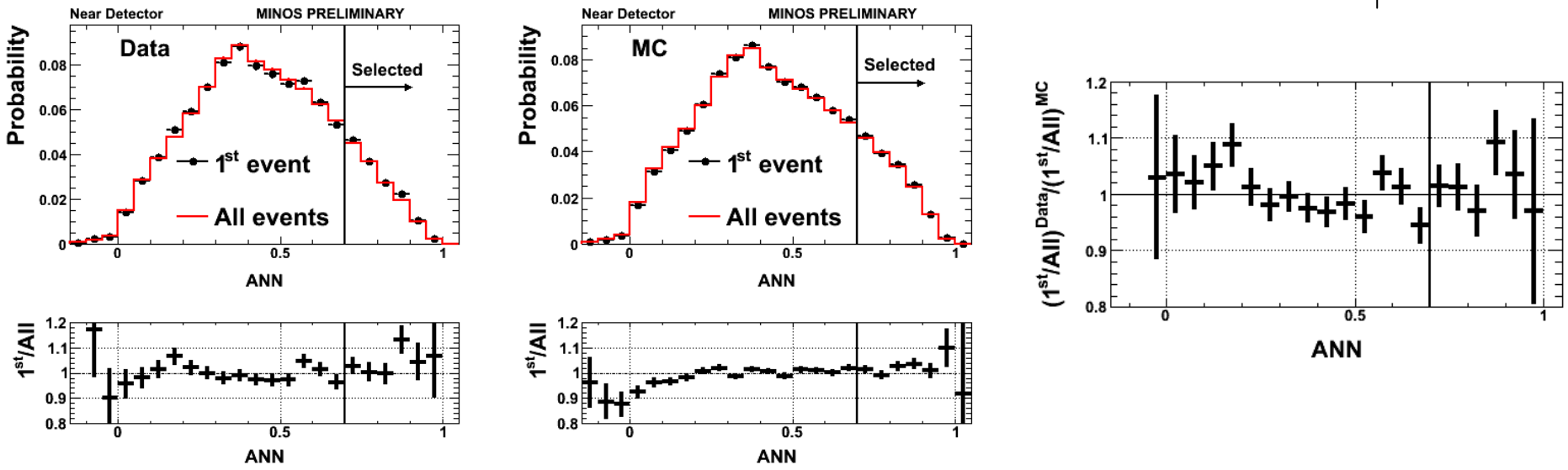
Background Systematic Errors

- Predicted NC and CC background events are obtained from extrapolation. Two sources of systematic errors:
  - ND data decomposition method (horn on/off)
    - 9% on NC component and 18% on CC component
    - Total error is highly reduced at FD since the two components are highly correlated at ND: NC+CC=ND^{Data}-beam ν_e
    - Systematic error from horn on/off method is 3.6%
  - Extrapolation (Far/Near ratios)
- Predicted beam ν_e and ν_τ background events are obtained from Monte Carlo
  - Their contributions are relatively small, and beam ν_e component is well modeled.
  - Systematic errors are the full uncertainties on the MC Simulation
  - $N^F_{b\nu e}$ = 2.2±1.5(stat.)±0.4(sys.) 18% systematic error
  - $N^F_{\nu\tau}$ = 1.1±1.1(stat.)±0.6(sys.) 50% systematic error

Systematic Errors from Extrapolation

- Flux uncertainties
- Cross section uncertainties
- Hadronization model uncertainties
- Intranuke uncertainties
- Crosstalk model
- Normalization
  - POT counting, steel/scintillator thickness, fiducial masses
- Absolute energy scale
  - Scale MC light level of both detectors simultaneously according to the calibration errors
- Relative energy scale
  - Scale MC light level of one detector while the other one unchanged
- Other calibration uncertainties
  - PMT Gains, PMT linearity, intra-detector variation, variation along scintillator strip
- Intensity effects
  - Different event rates at two detectors
- For most systematic errors, we generated special MC with the modified parameter in Near and Far. Used this modified MC for extrapolation and calculated the difference with the standard results.

Intensity systematic



- Different rates at two detectors: ~8 events in 10μs spill window in ND fiducial volume and ~1 event per day in FD.
- First event in each ND spill is unaffected by late activities of other events. We compare the 1st event to all other events to understand potential systematic effects.
- Difference in relative efficiencies between data and MC is 1.6%±1.9%. We will increase the FD NC+CC background prediction by 1.6% and take 1.9% as the systematic error.

Percentage Systematic Errors on NC+CC from Extrapolation

Systematic	NC	CC	**NC+CC**
Flux	0.7%	1.0%	**0.8%**
Cross section	0.2%	0.2%	**0.1%**
Hadronization	3.5%	4.1%	**2.0%**
Intranuke	0.7%	0.4%	**0.7%**
Normalization	2.4%	2.4%	**2.4%**
Absolute E scale	1.7%	2.5%	**1.5%**
Relative E scale	3.1%	4.8%	**3.5%**
Hadron energy	1.1%	1.6%	**0.7%**
Calibration	1.4%	9.0%	**2.8%**
Preselection	1.0%	1.0%	**1.0%**
Crosstalk	1.4%	2.4%	**1.3%**
Low pulse-height	1.1%	4.2%	**1.7%**
Intensity effects	1.9%	1.9%	**1.9%**
Total	6.5%	12.7%	**6.5%**

FD Background Systematic Error

- Total systematic error on NC+CC background:
  - 3.6%(ND horn-on/off)$\oplus$6.5%(extrapolation)=7.3%
- Increase the prediction number of NC+CC background events by:
  - 2.2%(crosstalk)+1.6%(intensity)=3.8%
- Add contributions from beam ν_e and ν_τ
  - N^F_{bg}=27.3±5.2(stat.)±1.8(sys.) for 3.14e20 POT
  - Total background systematic error is 6.7%

Signal Systematics

- The predicted number of potential signal events is well modeled by MC:
  - Neutrino flux is well constrained by ND ν_μ CC data
  - Efficiency of ν_e selection is well modeled, evaluated using a data driven method:
    - Remove tracks from identified ν_μ CC events
    - A electron with the momentum of the removed track is simulated and added to the remnant of the original ν_μ CC event
    - Uncertainty on the efficiency of ν_e selection: 2.5%
- At CHOOZ limit ($\sin^2 2\theta_{13}$=0.15), without matter effects:
  - N^F_{sig}=10.3±3.2(stat.)±0.8(sys.)
  - Total signal systematic error is 7.3%

Define χ^2

- Define χ^2

$$\chi_0^2 = 2(N_{exp} - N_{obs} + N_{obs} \ln \frac{N_{obs}}{N_{exp}})$$

N_{exp}: expected number of events

N_{obs}: observed number of events

- Take into account systematic errors by rescaling χ^2

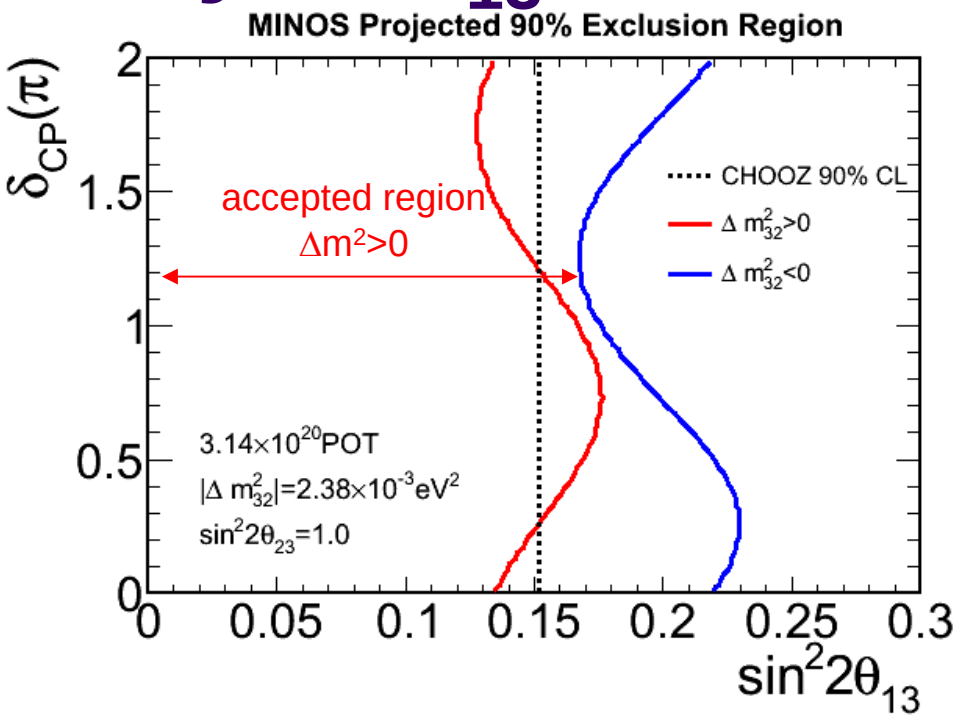
$$\chi^2 = \chi_0^2 \times \frac{N_{exp}}{\sigma_{bg}^2 + \sigma_{sig}^2 + N_{exp}}$$

σ^2_{bg}: systematic error on background

σ^2_{sig}: systematic error on signal

- Minimize χ^2 to find the best fit point oscillation values.
- $\Delta\chi^2$=2.71 defines the 90% limit.
- Present the result as a function of δ_{cp} (NDF=1).

Sensitivity to θ_{13}

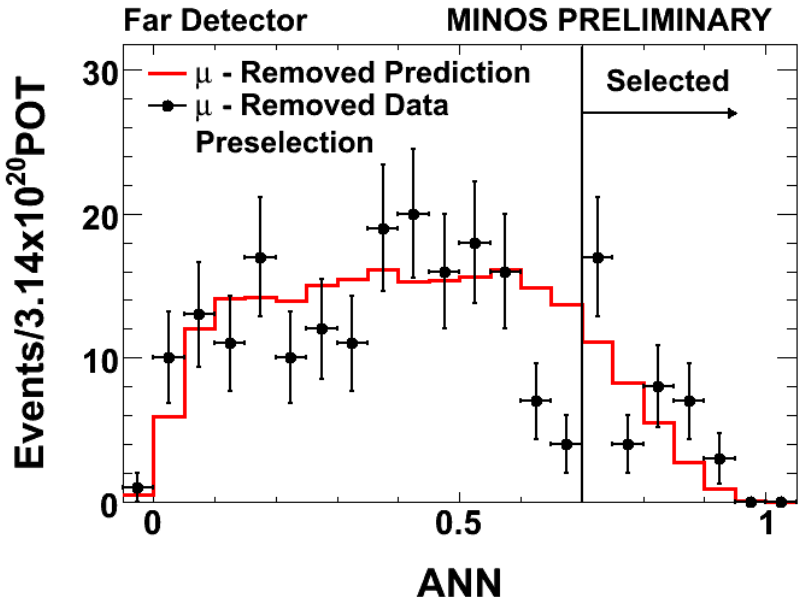


- The limits we can set if we do not observe an excess.
- The probability of ν_e appearance is enhanced (suppressed) for the normal (inverted) mass hierarchy.
- The MINOS experiment has the potential to explore the region not excluded by the CHOOZ experiment.

Blind Analysis

- We have performed a **blind analysis.**
- Before using any Far Detector data in the signal region all background and signal predictions were finalized.
  - Including systematic errors
- We also studied 3 sidebands available:
  - Far Detector Muon Removed events.
  - ANN PID < 0.55
  - 0.55 < ANN PID < 0.7

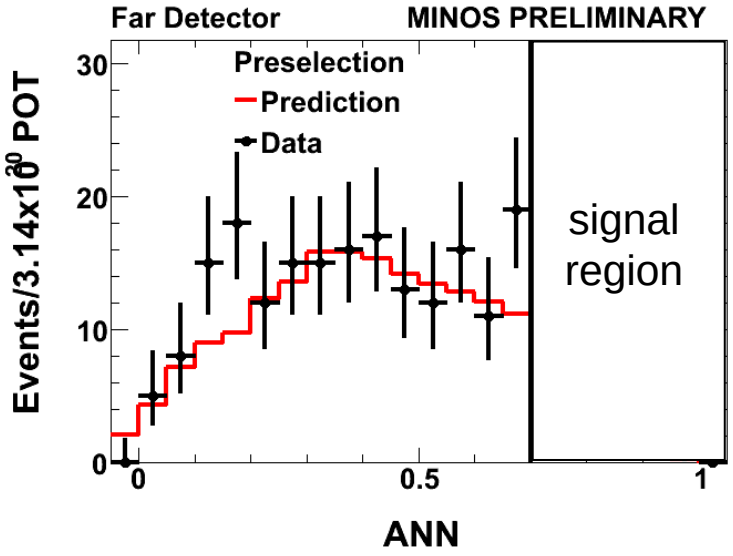
Muon Removed Showers from CC



- Remove the muon tracks from ν_μ CC events.
- Use the remnant hadronic showers to study the background
- Complete check of analysis by looking at FD events without looking at signal.

- We observe a total of 39 events.
- We expect $29 \pm 5(\text{stat}) \pm 2(\text{sys})$ events.
- We see a 1.8σ excess.
- It is possible this is a statistical fluctuation or it might suggest an unexplained Far/Near difference.

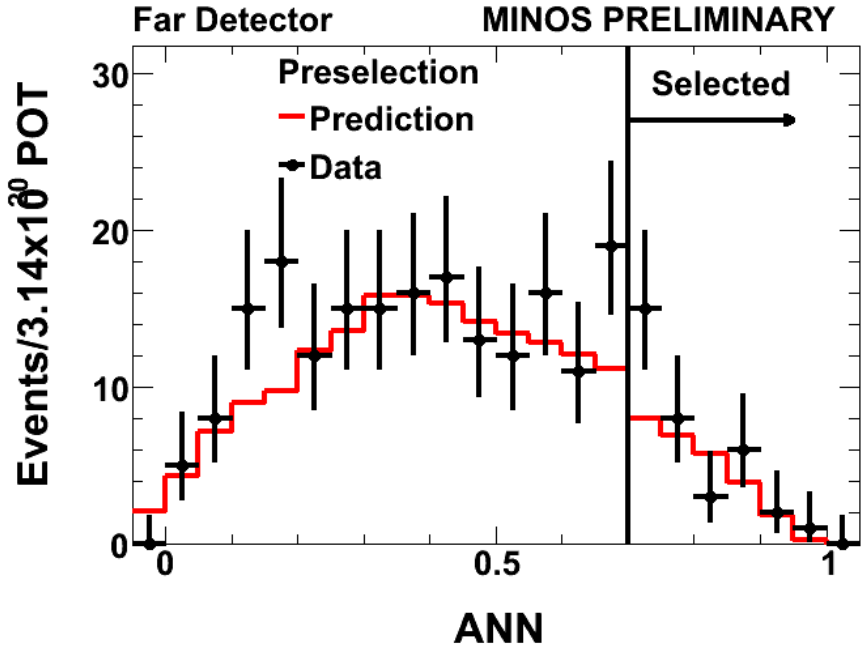
Low PID Regions



Cuts	Data	Bg prediction	Potential signal
ANN<0.55	147	131.8±11.5(stat)±8.4(sys)	4.9
0.55<ANN<0.7	46	37.6±6.2(stat)±2.5(sys)	4.9

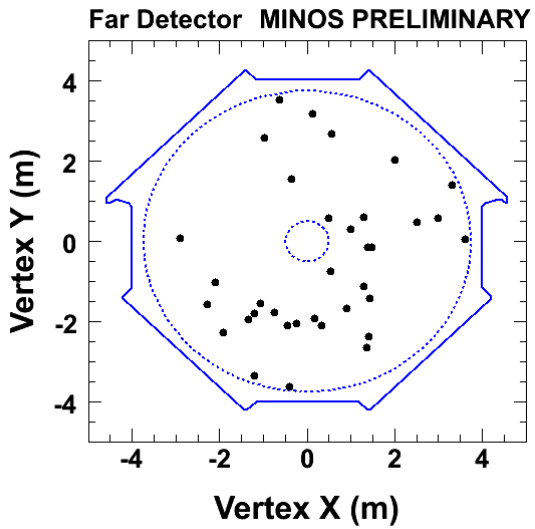
- σ differences are 1.1 and 1.3 with assumption of no signal
- σ differences are 0.7 and 0.5 assuming signal at CHOOZ limit

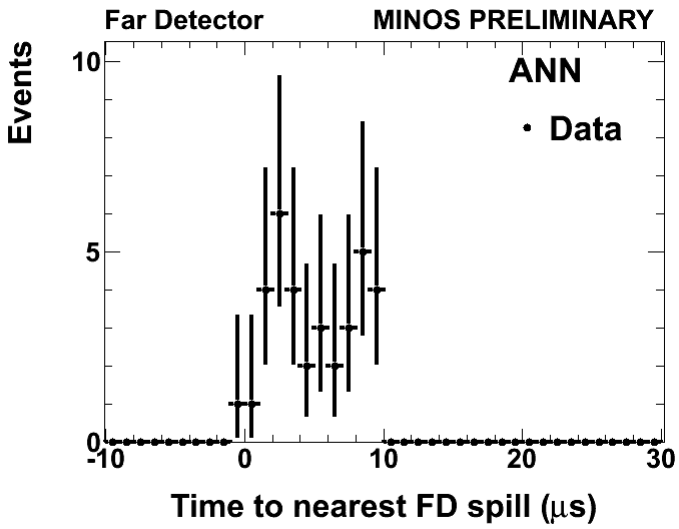
ν_e Appearance Result

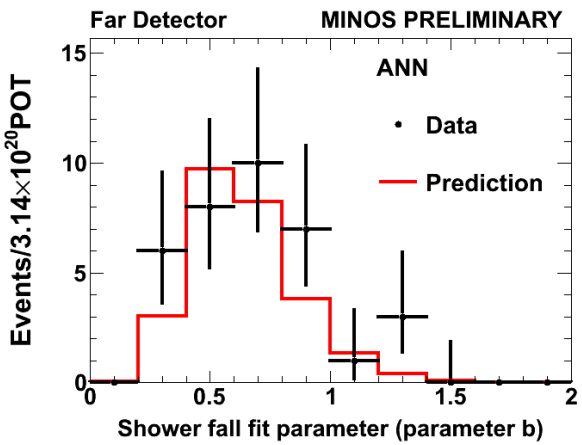


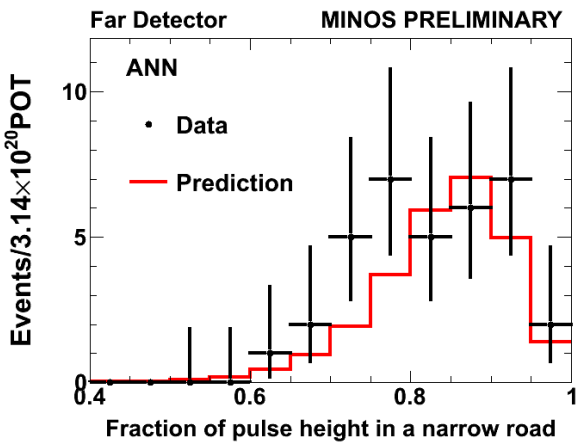
- We observe a total of 35 events.
- We expect 27.3±5.2(stat.)±1.8(sys.) background events.
- Results are 1.4σ above expected background.
- Number of potential signal events is 10.3±3.2(stat)±0.8(stat) at CHOOZ limit.

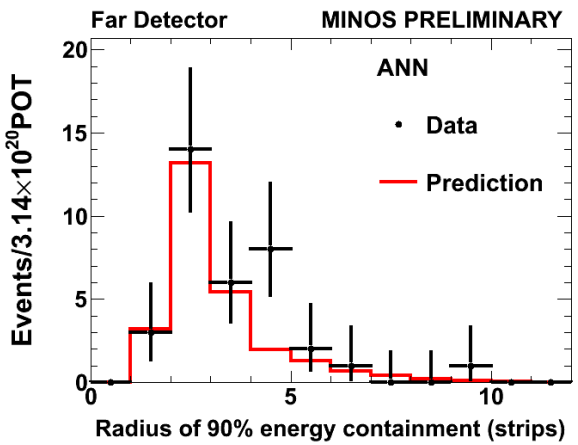
FD Data ν_e Selected Distributions



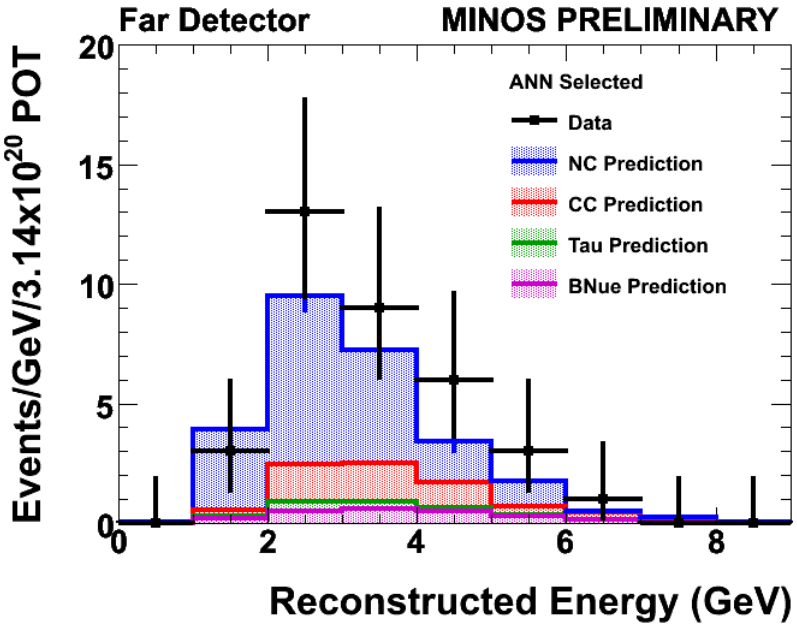




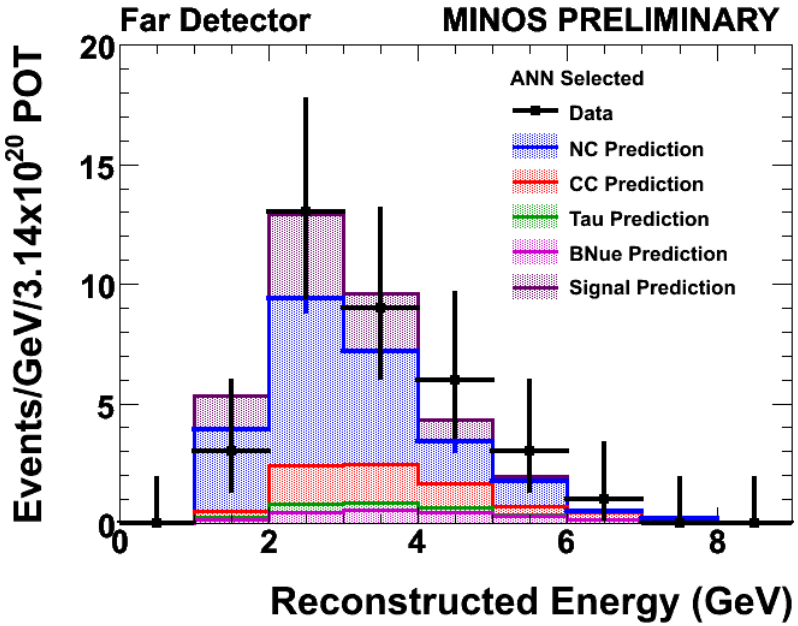




Energy Spectra of Select Events



Without signal prediction



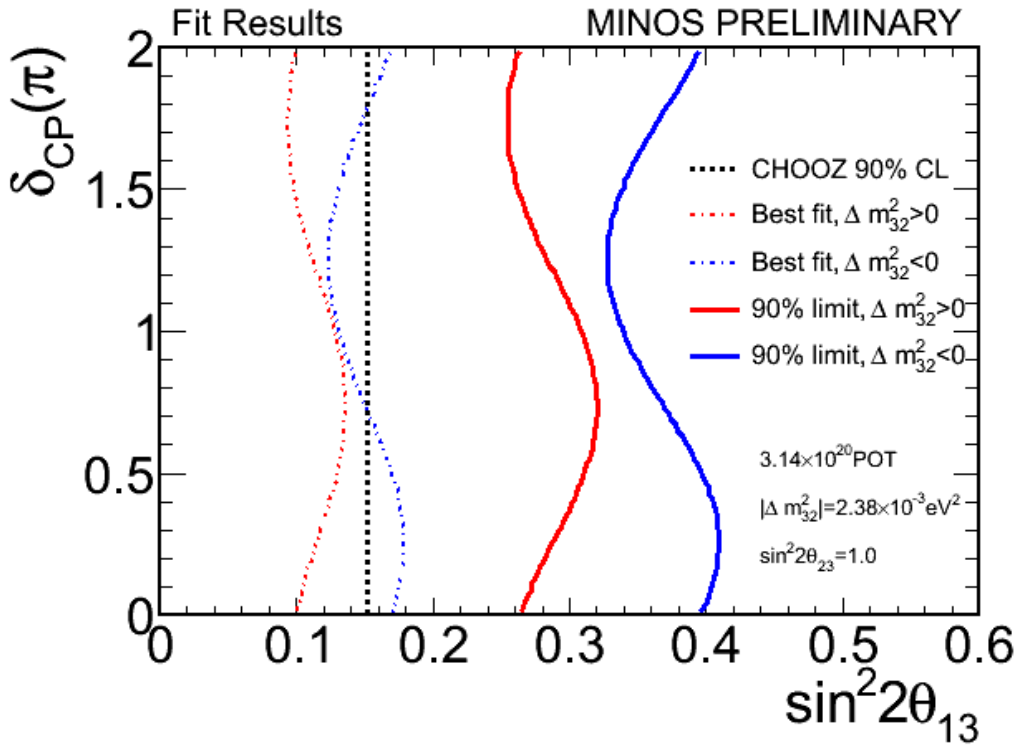
With signal prediction

stack plots

The excess is consistent with statistical fluctuation of background events or an observation of ν_e signal.

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

- Plot shows 90% limits on $\sin^2 2\theta_{13}$ as a function of δ_{CP}
- shown at the MINOS best fit value for Δm^2_{32} and $\sin^2 2\theta_{23}$.
- Best fit values are consistent with CHOOZ limit
- Our result is consistent with θ_{13}=0 at 90% CL
- What we really measure is $2\sin^2\theta_{23}\sin^2 2\theta_{13}$, which is different from reactor experiments.



Summary

- We have completed an initial search for ν_e appearance in the MINOS data.
- We developed an ANN based ν_e selections that have a rejection of >92% for NC and >99% for ν_μ CC, the main background components for this analysis.
- We tried to improve two aspects of Monte Carlo simulation: hadronization model and crosstalk simulation.
- We studied FD sidebands
  - Muon removed CC sideband showed a 1.8σ.
  - Observed excess could be a statistical fluctuation or a hint of a Far/Near difference.
  - More data will clarify these issues.

Summary

- We observe a total of **35 events** and expect **27±5(stat)±2(sys)** background events for 3.14×10^{20} POT.
- If fitted to a oscillation hypothesis we obtain the limits at the MINOS best fit for Δm^2_{32} and $\sin^2(2\theta_{23})$:
  - Best fit values are consistent with CHOOZ limit
  - normal hierarchy, $\delta_{CP} = 0$: **$\sin^2(2\theta_{13}) < 0.26$ (90% CL)**
  - inverted hierarchy, $\delta_{CP} = 0$: **$\sin^2(2\theta_{13}) < 0.38$ (90% CL)**
- We are close to doubling these data in current running!
- Expect next result with > 7×10^{20} POT

A brief history of neutrinos

- 1930 – Postulates of neutrino by Pauli
- 1932 – Name *neutrino* was coined by Fermi
- 1956 – Observation of neutrino by Cowan and Reines
- 1958 – Neutrinos were found to be left-handed by physicists at BNL
- 1957-62 – Theorists speculate that neutrinos oscillate (Pontecorvo and Sakata)
- 1962 – Muon-neutrino was identified at BNL
- 60's, 70's, 80's – The first indications of the "solar neutrino problem" and the "atmospheric neutrino anomaly"
- 90's until today – Solid experimental evidence for neutrino oscillations.
- Other neutrino related discoveries/measurements: weak neutral current interaction (1973), supernova SN1987A, measurement of the width of the Z resonance (1989), etc.

Neutrinos in Standard Model

- According to the SM, fermions acquire mass as they interact with the Higgs boson:

  $L = -fv\bar{e}_R e_L + h.c.$ - Higgs Mechanism

- Neutrinos are found to be *left-handed* (BNL, 1958).
- In SM, neutrinos have to be massless.

Massive Neutrinos

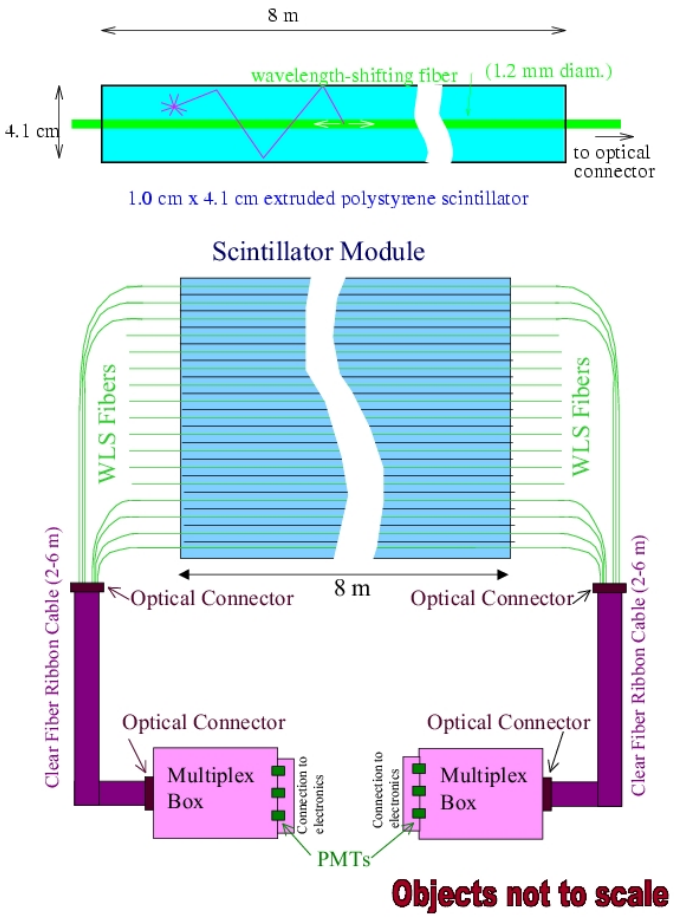
- Neutrino oscillation experiments have provided compelling evidence that neutrinos do have mass.
- The SM has to be extended to accommodate neutrino mass.
- Seesaw mechanism: the neutrino masses are inversely proportional to the GUT scale (~10^{15}GeV).

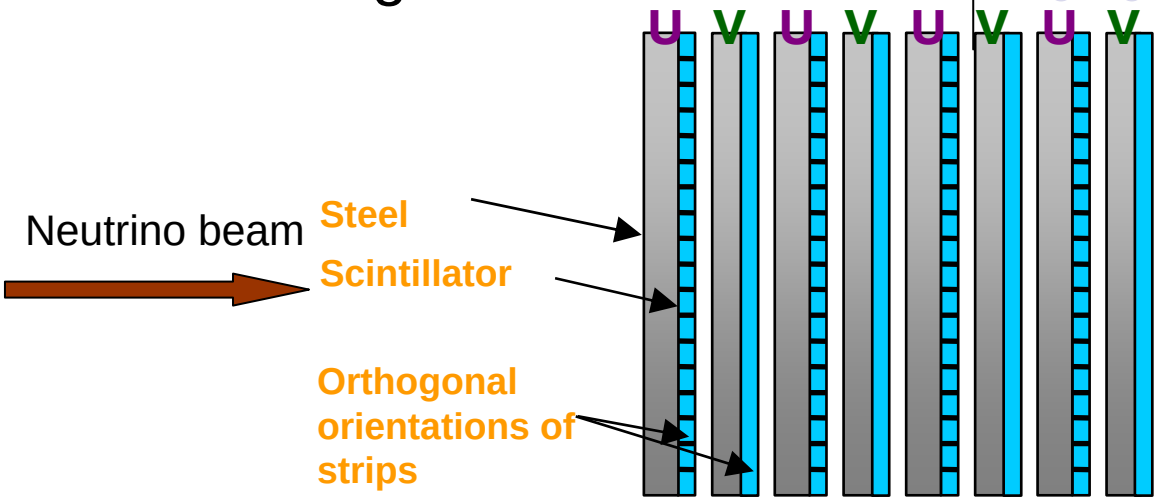
The MINOS Detectors

- Functionally identical: **Near and Far detectors**
- 1 inch thick octogonal steel planes, alternating with planes of 4.1cm x 1cm scintillator strips, up to 8m long. Magnetized.
  - **Near**: ~ 1kton, 282 steel squashed octagons. Partially instrumented.
  - **Far**: 5.4 kton, 486 (8m/octagon) fully instrumented planes.

MINOS Detector Technology

Iron/scintillator tracking calorimeter





- 2.54cm thick magnetized steel planes <B> = 1.2T
- 1cm thick scintillator planes segmented into 4.1cm wide strips
- Alternate planes rotated by ±90º (U,V) for 3D tracking
- 1GeV/c muon will go through ~20 planes
- Sampling frequency: 1.4 radiation length
- Light is transported through wavelength shifting fibers (WLS) and clear fibers
- Signal read out by multi-anode Hamamatsu PMTs

Probability of ν_e Appearance – in Vacuum

$$P(\nu_\mu \to \nu_e) \approx \sin^2 2\theta_{13} \sin^2\theta_{23} \sin^2\Delta + \alpha^2\Delta^2 \cos^2\theta_{13} \cos^2\theta_{23} \sin^2 2\theta_{12}$$

$$+ \alpha\Delta \sin 2\theta_{13} \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin\Delta \cos(\Delta + \delta)$$

$$\equiv P_{atm} + P_{sol} + P_{int}$$

$|\alpha| \equiv \Delta m_{21}^2 / |\Delta m_{31}^2| \approx 0.033 \qquad \Delta \equiv \Delta m_{31}^2 L/(4E)$ $\qquad$ δ is CP violating phase.

At the first oscillation maximum of the atmospheric Δm^2 scale, $|\Delta|=\pi/2$

$\theta_{12} = 34^o$, $\theta_{23} = 45^o$

$$P_{atm} \approx 0.5 \sin^2 2\theta_{13}$$

$$P_{sol} \approx 0.001$$

$$P_{int} \approx -0.05 \sin 2\theta_{13} \sin\delta$$

- The contribution of solar term is negligible if $\sin^2 2\theta_{13} >> 0.002$
- P_{int} is proportional to $\sin 2\theta_{13}$ while the leading term is proportional to $\sin^2 2\theta_{13}$
  - The sub-leading term becomes more important as θ_{13} get smaller
  - At $|\Delta|=\pi/2$, δ can give a maximal 25% enhancement or suppression in the transition probability if θ_{13} is at CHOOZ limit.

Matter Effects

- ν_e transition probability in matter is modified by coherent forward ν_e-electron scattering via the W-exchange.
- Matter-induced effective potential for ν_e:
  - $V = \sqrt{2} G_F n_e$, G_F is the Fermi coupling constant, n_e is the number density of electrons.

$$P(\nu_\mu \to \nu_e) \approx \boxed{\sin^2 2\theta_{13}} \sin^2\theta_{23} \frac{\sin^2[(1-A)\Delta]}{(1-A)^2} + \alpha^2 \cos^2\theta_{13} \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(A\Delta)}{A^2}$$

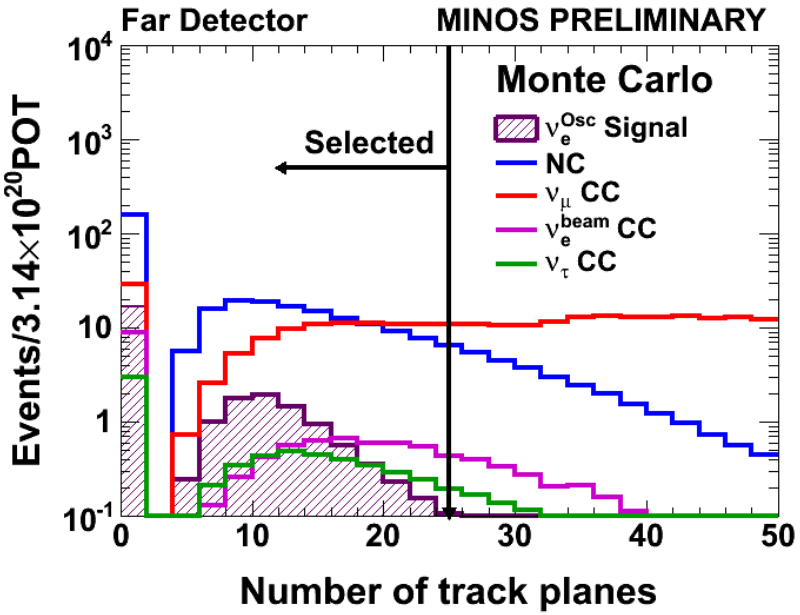
$$+ \alpha \boxed{\sin 2\theta_{13}} \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \cos(\Delta + \delta) \frac{\sin(A\Delta)}{A} \frac{\sin[(1-A)\Delta]}{1-A} \quad A = \frac{2EV}{\Delta m_{31}^2} \approx \frac{E}{11(GeV)}$$

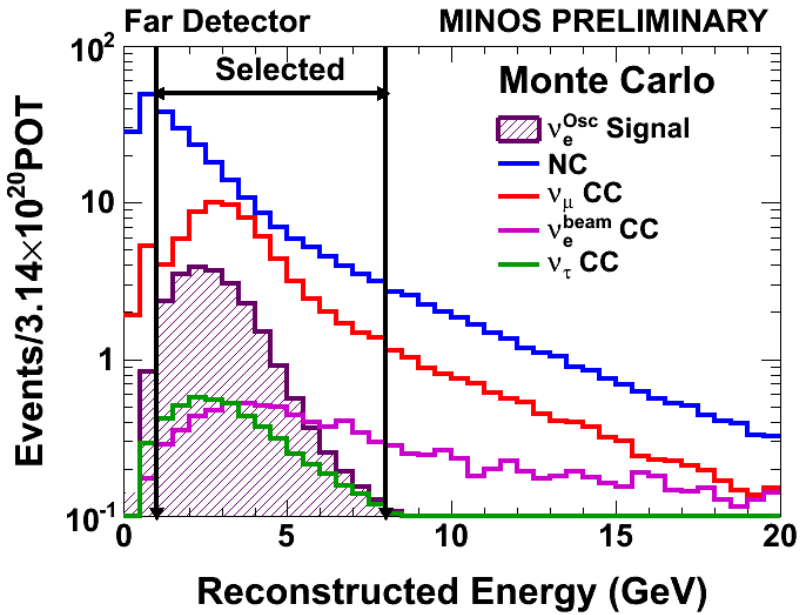
- Matter effects depend on the sign of Δm^2_{31}
  - Normal mass hierarchy $\Delta m^2_{31}>0$, enhance neutrino transition probability
  - Inverted mass hierarchy $\Delta m^2_{31}<0$, suppress neutrino transition probability
- Matter effects give a 25% enhancement or suppression in the ν_e appearance probability at $\Delta=\pi/2$.

ν_e appearance in MINOS

- Construct a selection algorithm to reject background and select ν_e.
- Measure the background from events passing ν_e selection in the Near Detector.
- Use Near Detector measurement to Predict Far Detector background.
- Minimize dependence on Monte Carlo.
- Look for an excess of ν_e events in the Far Detector data.

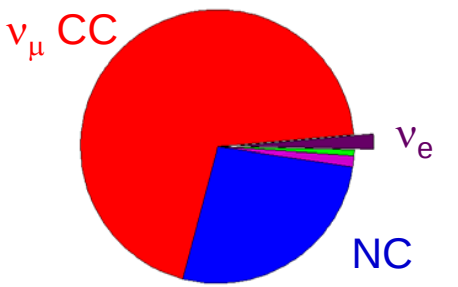
ν_e Preselection Cuts





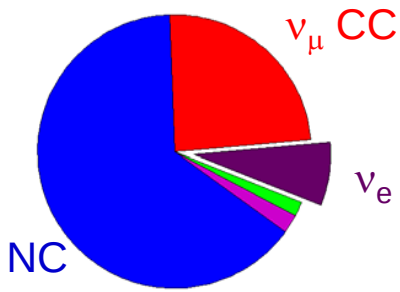
signal at CHOOZ limit

- 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 MIP energy units.



Signal/Background 1:55

Before

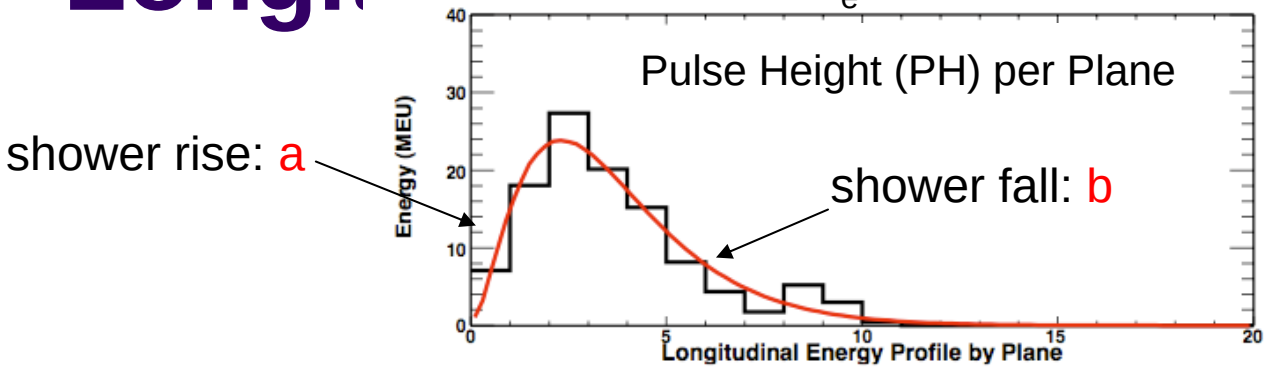


Signal/Background 1:12

After

Longitudinal Shower Profile

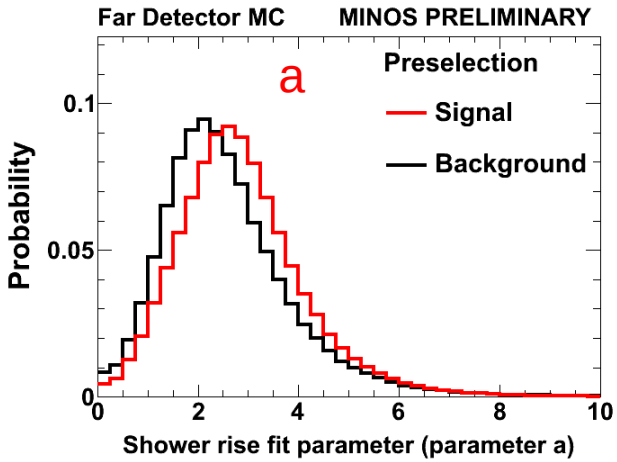
One candidate ν_e event in the FD

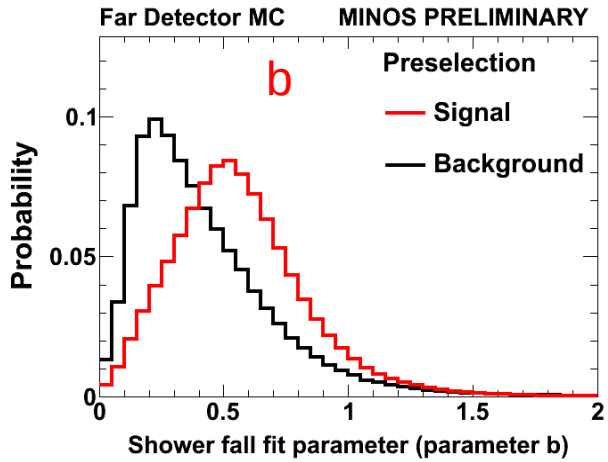


The average longitudinal profile of the energy deposition in an EM shower is reasonably well described by a gamma distribution:

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

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

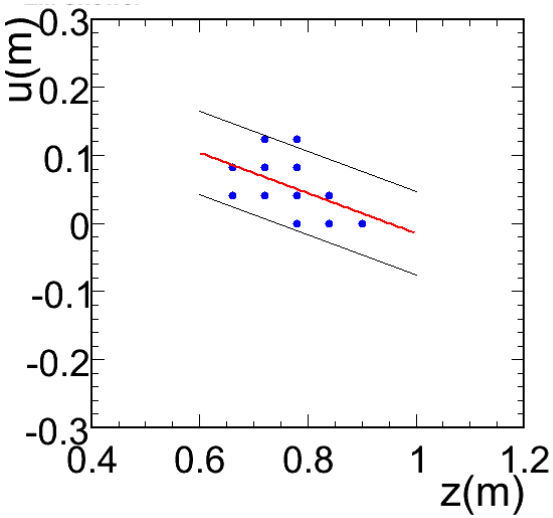




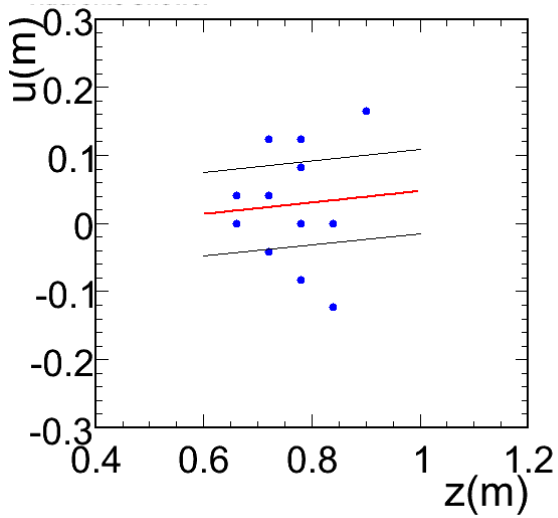
Other useful variables:
- fraction of energy deposited within 2,4,6 planes
- longitudinal energy projection

Showers Shower Profile

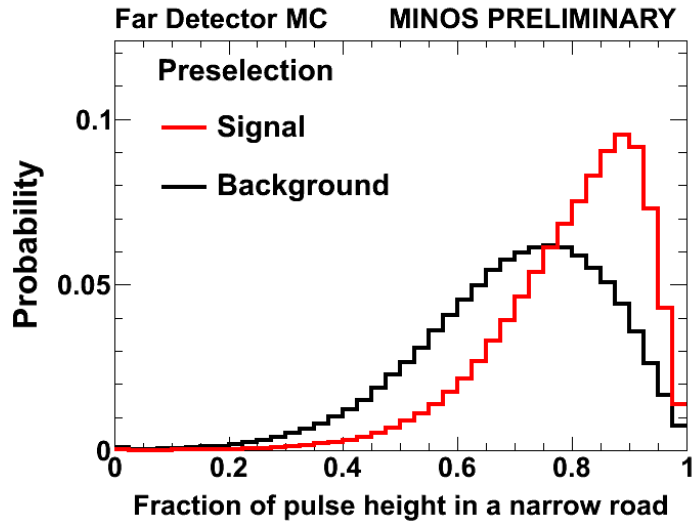
EM Shower

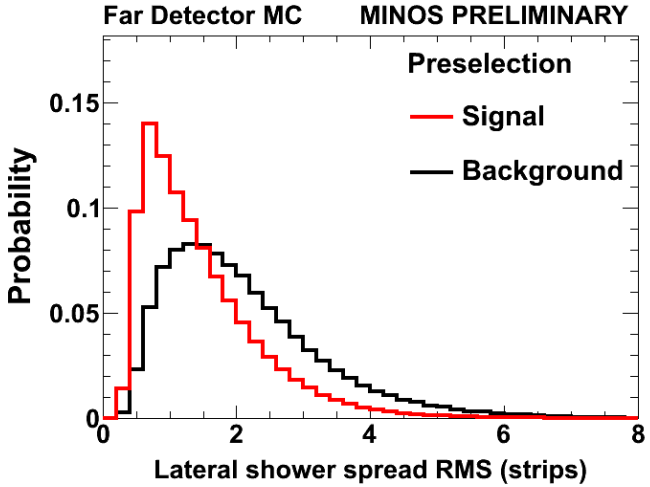


Hadronic Shower



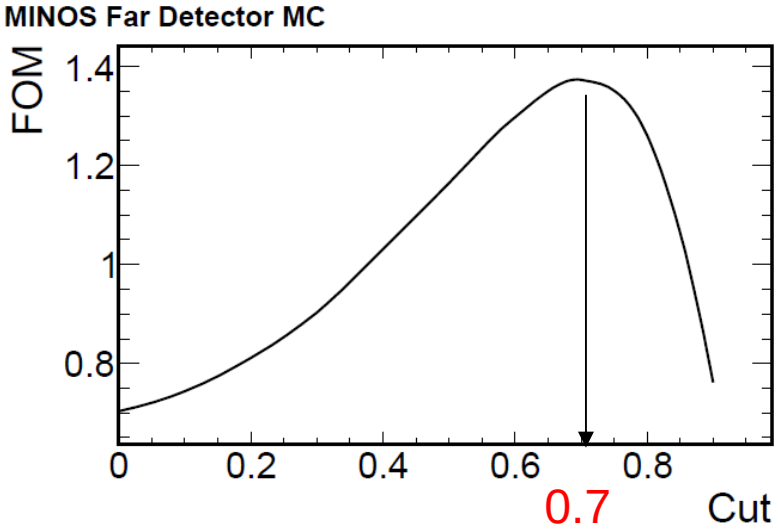
beam direction





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

Determine the Cut



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

$$\sigma_{stat}^{bg} = \sqrt{N_{bg}}$$

$$\sigma_{sys}^{bg} = 10\% \times N_{bg}$$

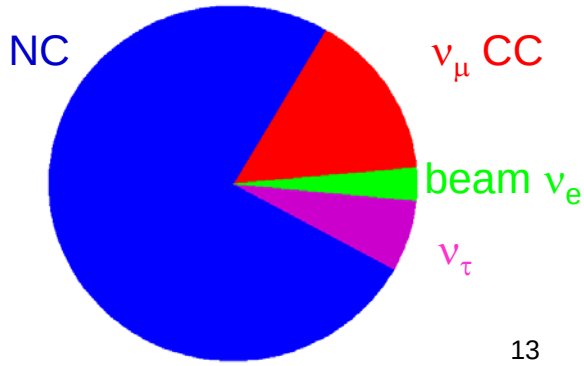
Assume a 10% systematic error on the background estimation

$\sin^2(2\theta_{13})=0.15$ (CHOOZ limit), $|\Delta m^2_{31}|=2.4e\text{-}3eV^2$, $\sin^2(2\theta_{23})=1$, POT=3.25e20

- ANN algorithm achieves:
  - signal efficiency 41%
  - NC rejection > 92.3%
  - CC rejection > 99.4%
  - signal/background 1:4

After cut on ANN pid

Background composition



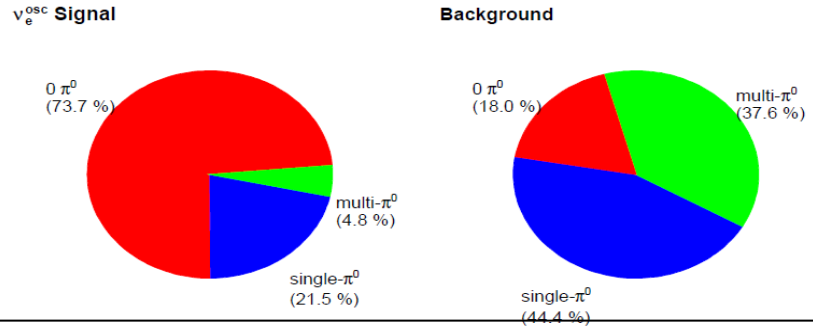
Breakdown of Accepted Events – Monte Carlo

Signal Background

0 π^0

single-π^0

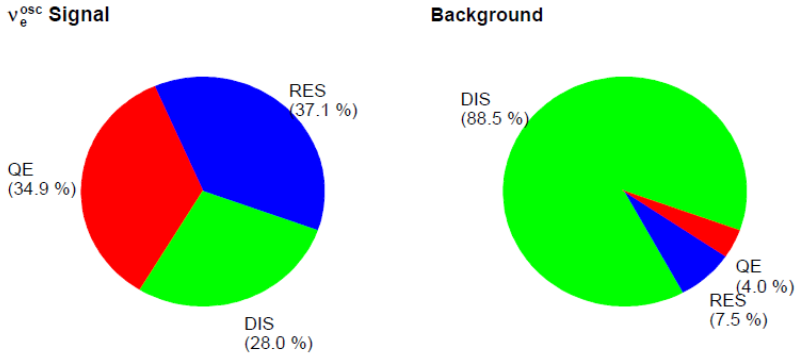
multi-π^0



Quasi-elastic

Resonance

Deep-inelastic



- One important aspect of MC simulation for ν_e analysis:
  - π^0 production in the deep-inelastic interactions