Using Near Detector Data to Make Far Detector Predictions in an On-Axis Long-Baseline Experiment

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Intro

Why a near neutrino detector?

To observe oscillations, measure number of events in a detector and extract oscillation probability:

oscillations

measured

Exposure (mass x livetime)

$$N_F = \Phi(L_F) \times P_{osc} \times \sigma \times \epsilon \times M_F$$

Flux

Cross section

Detection efficiency

If you have an “identical” near neutrino detector, it's a relative measurement

$$\frac{N_F}{N_N} = \frac{\Phi(L_F) \times P_{osc}}{\Phi(L_N)} \frac{\sigma}{\sigma} \frac{\epsilon}{\epsilon} \frac{M_F}{M_N}$$

$\sim L_N^2 / L_F^2$

Flux and cross section uncertainties (which can be large) mostly cancel!

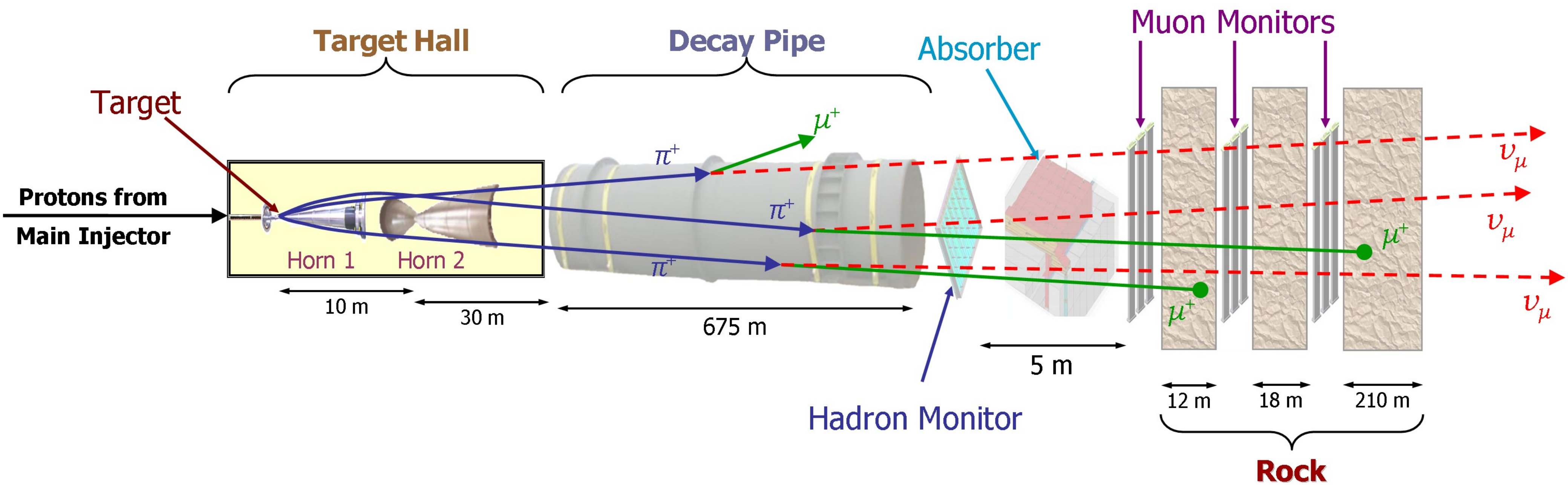
On-axis long-baseline experiments with a near detector:

K2K (1999-2004)

MINOS (2005-present)

LBNE (Future)

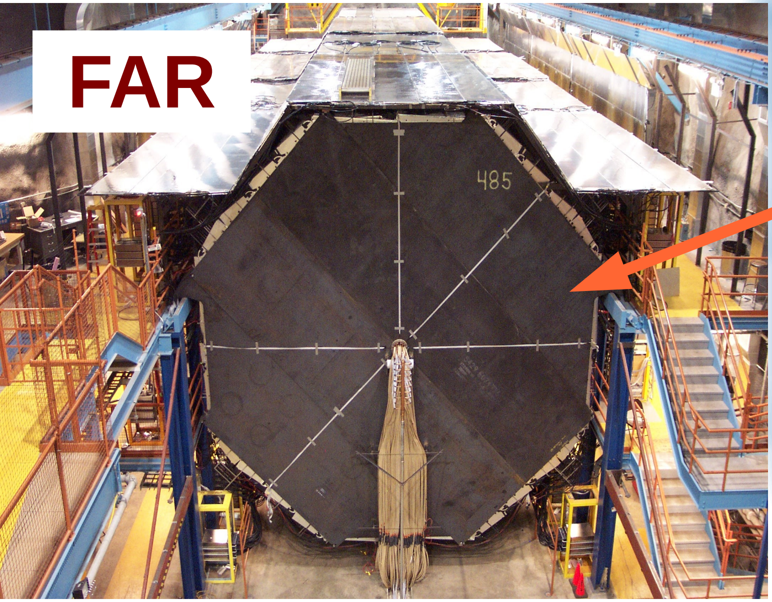
NuMI Beam



- protons from the Main Injector hit a carbon target, producing mostly π
- focus π^+, then $\pi^+ \rightarrow \mu^+ \nu_\mu$ (neutrino mode)
- OR focus π^-, then $\pi^- \rightarrow \mu^- \overline{\nu}_\mu$ (anti-neutrino mode)
- ν_e contamination from $\mu^{+(-)} \rightarrow e^{+(-)} \overline{\nu}_\mu \overset{(-)}{\nu}_e$
- Target position can be changed to tune the neutrino energy spectrum

MINOS detectors

Both detectors are made of alternating layers of steel plates and scintillator strips in a ~1.3 T toroidal magnetic field



735 km from the target
5.4 kilotons
8 m octagonal planes
486 planes (30 m)
700 m (2100 m.w.e.)
Few ν interactions/day

1 km from the target
1 kiloton
~4 m tall planes
282 planes (15 m)
100 m (280 m.w.e)
Few ν interactions/spill

How does MINOS use ND Data?

For oscillation studies:

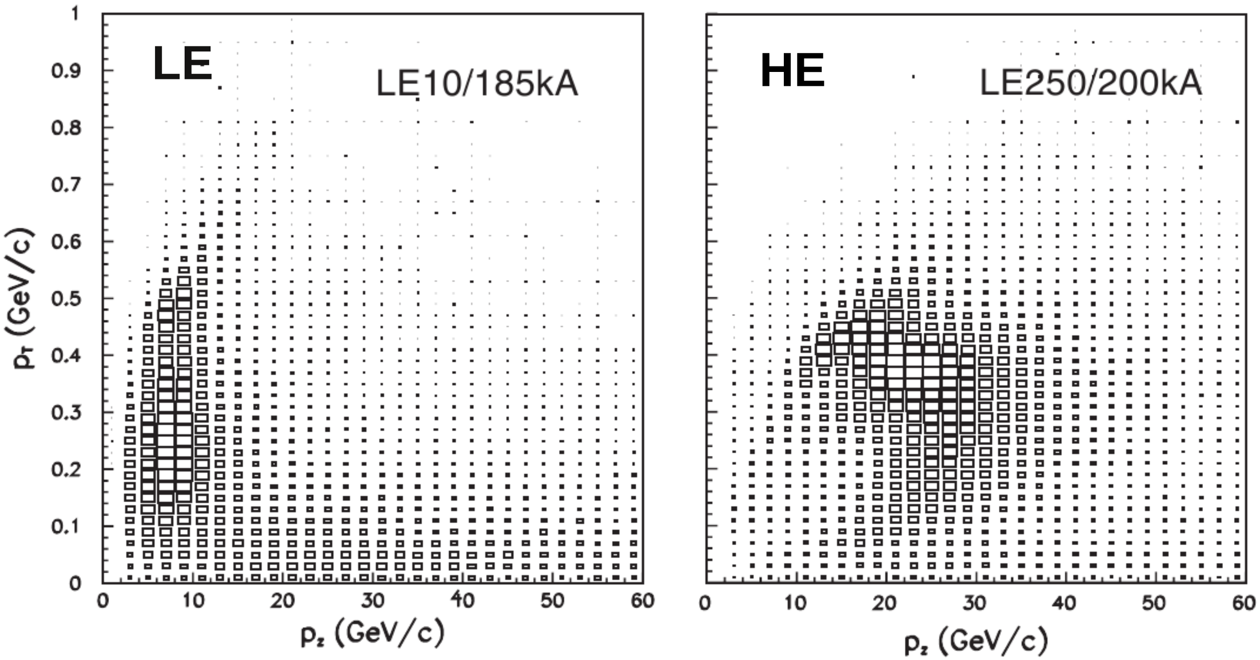
- Tuning of beam simulation
- Predicting the unoscillated ν_μ or $\bar{\nu}_\mu$ CC spectrum in the far detector
- Predicting the background to ν_e appearance in the far detector
- Predicting the NC spectrum in the far detector

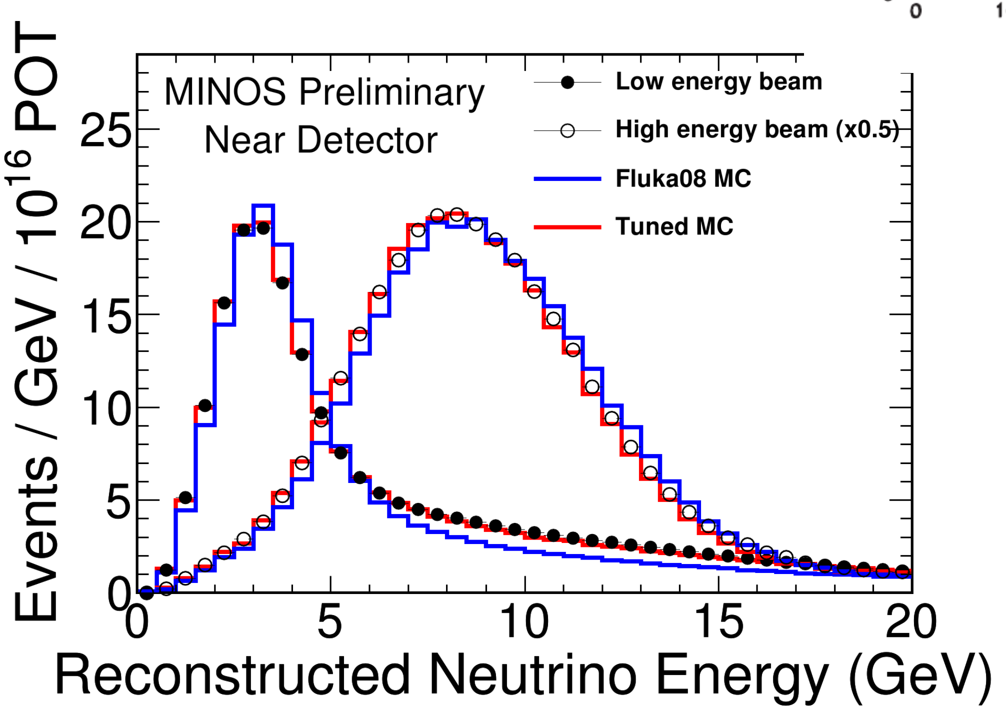
Other:

- neutrino cross section measurements
- observation of atmospheric muons

Beam Simulation Tuning

Data taken in several beam configurations is used to constrain the neutrino flux calculation

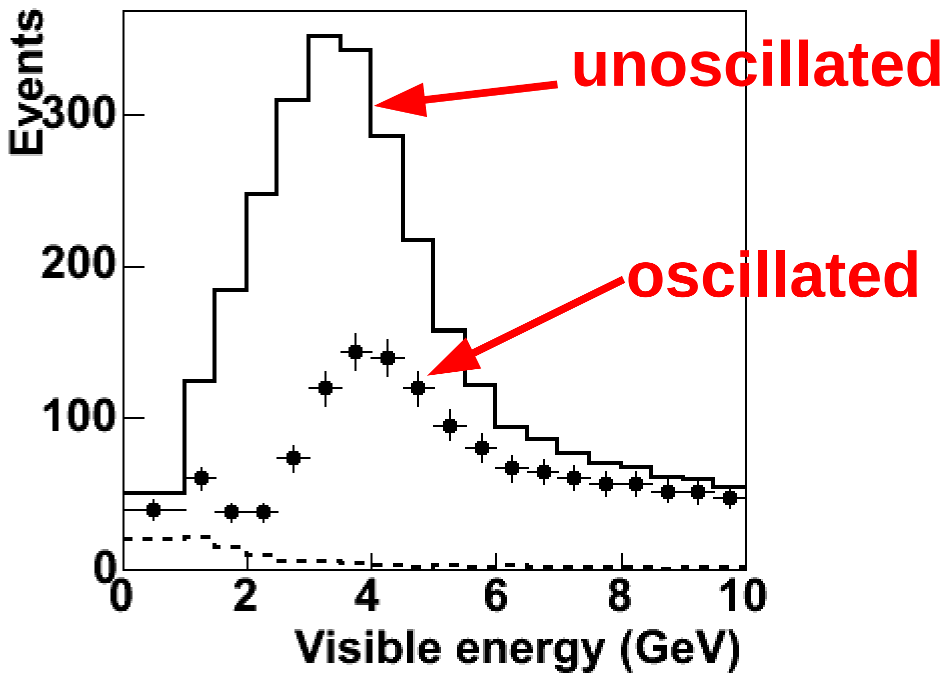




- Parametrize the production yield of π's off the target ($d^2N/dp_z dp_T$)
- Fit the data by tuning the production in the beam MC
- Data from different beam configurations sample different regions of the π's (p_z,p_T)

ν_μ or $\bar{\nu}_\mu$ Disappearance

ν_μ spectrum



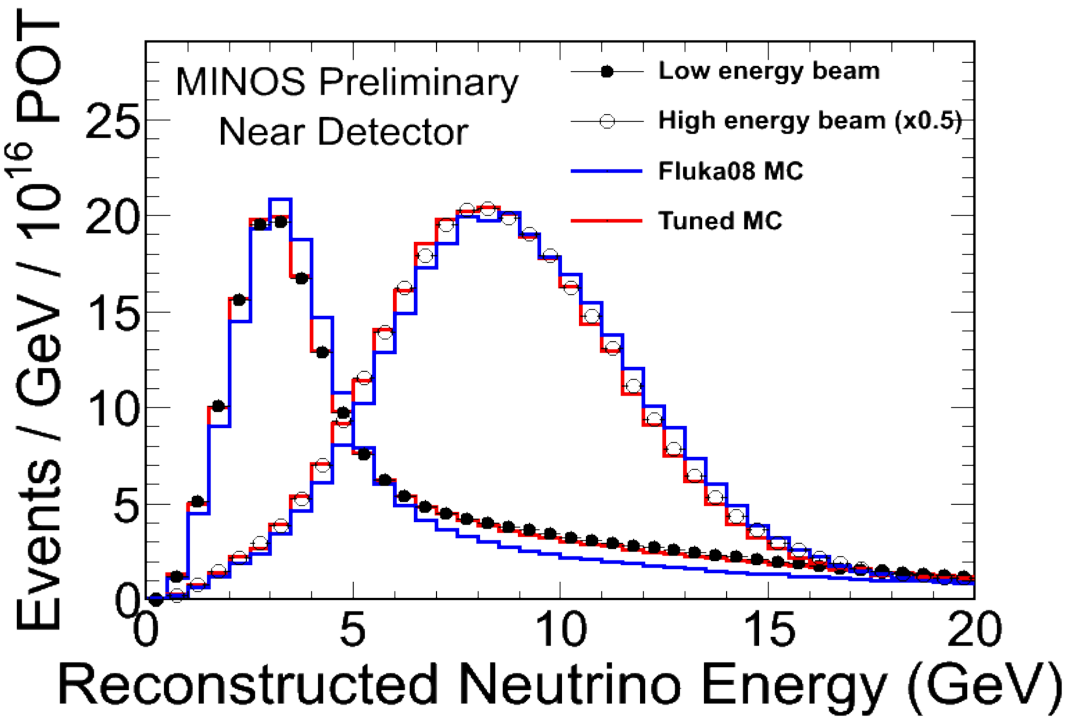
$$\sin^2(2\theta)=1.0$$
$$\Delta m^2=3.35\times10^{-3}\ eV^2$$

Use ND data to predict unoscillated spectrum

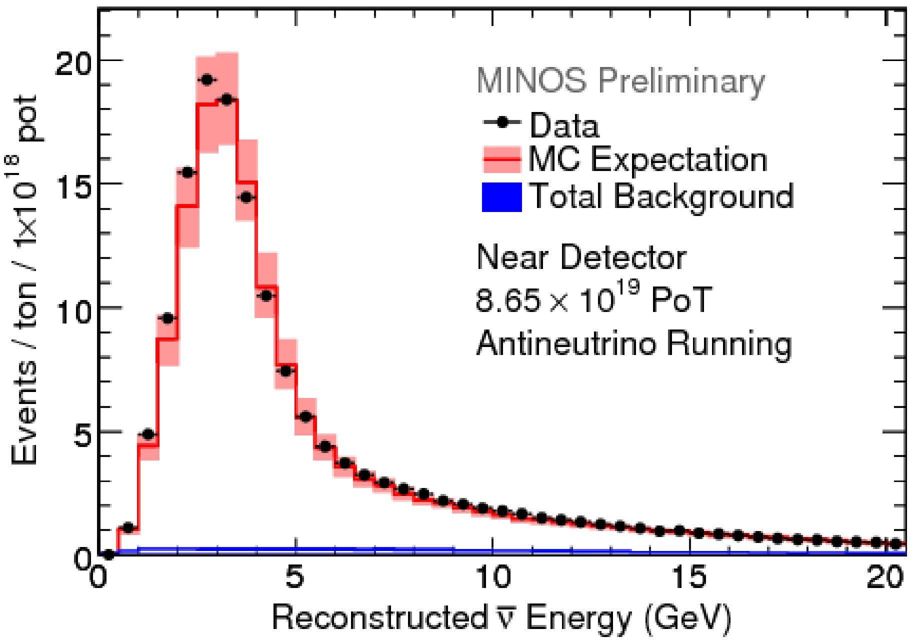
Look for deficit in FD data relative to prediction

CC Near Detector Data

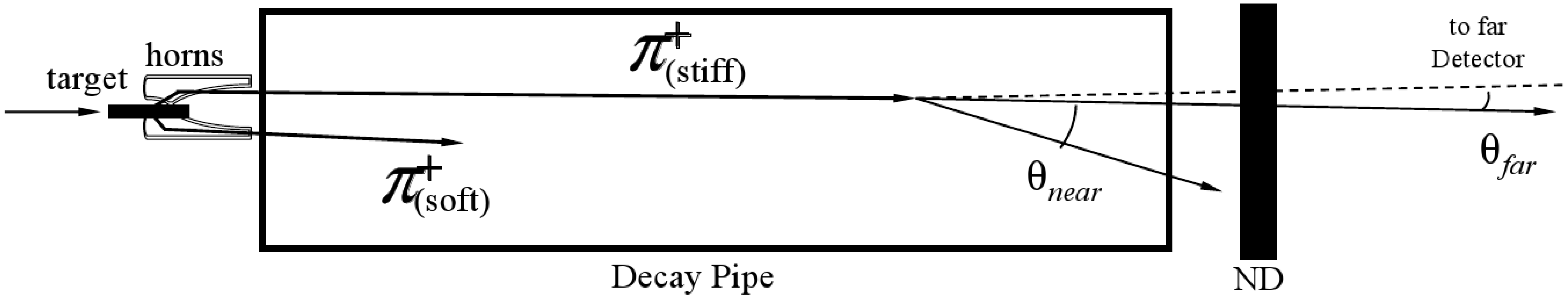
Neutrino data

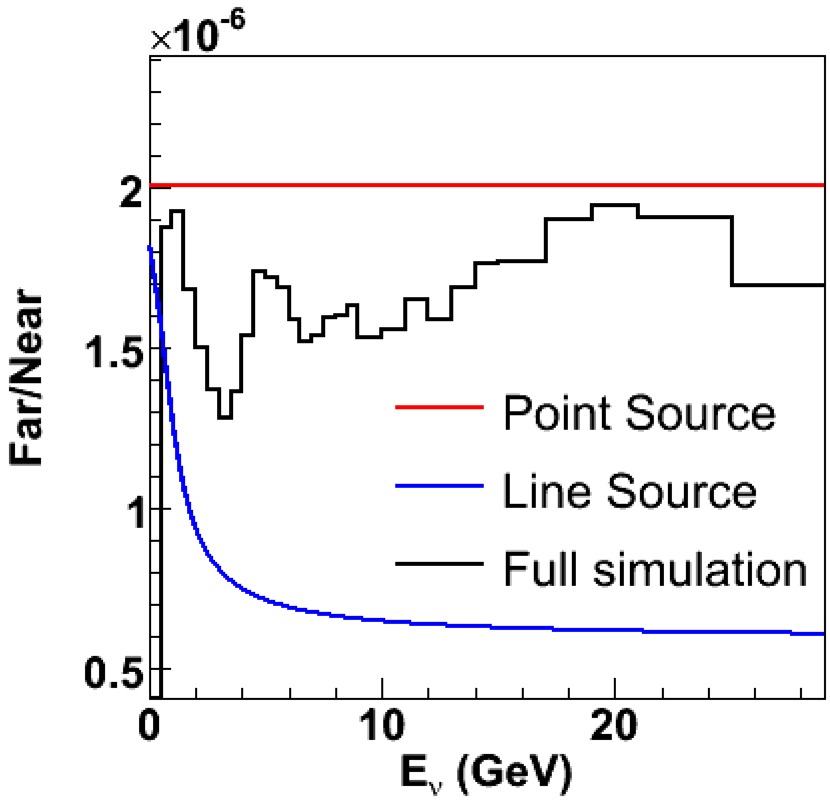


Anti-neutrino data



Far/Near Flux Ratio





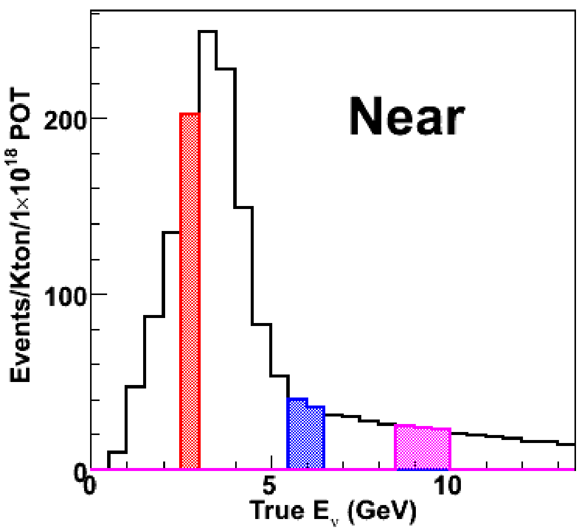
Flux Far/Near Ratio:

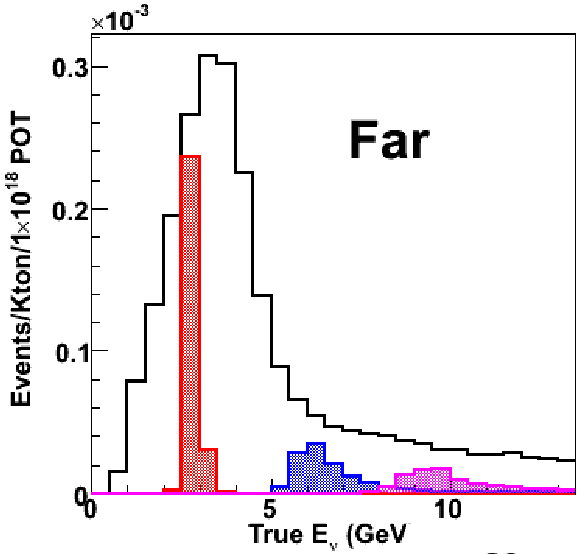
$1/R^2$ fall-off

Point source vs extended source

- solid angle acceptance
- decay kinematics
- focusing

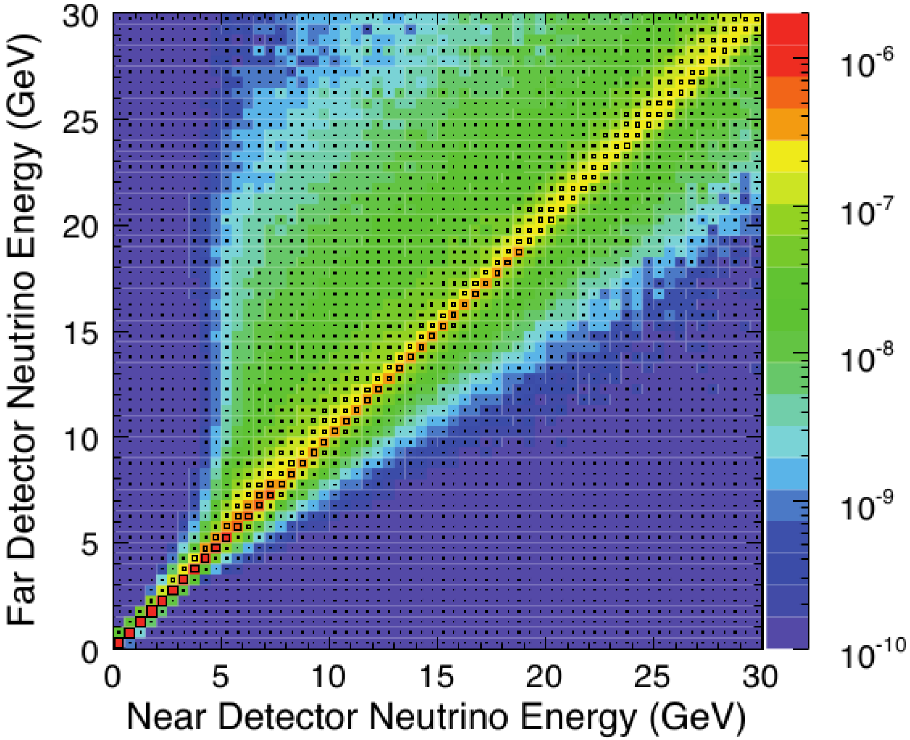
Near to Far Extrapolation





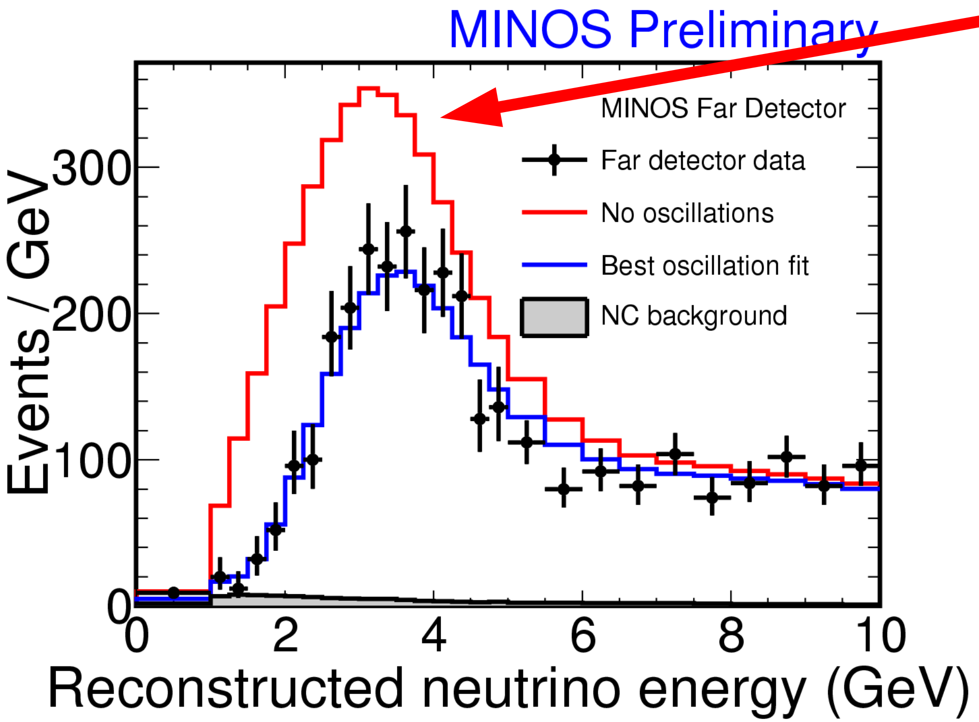
Far spectrum without oscillations is not identical to the near spectrum

Use beam simulation to create a matrix that transports the measured near spectrum to the far

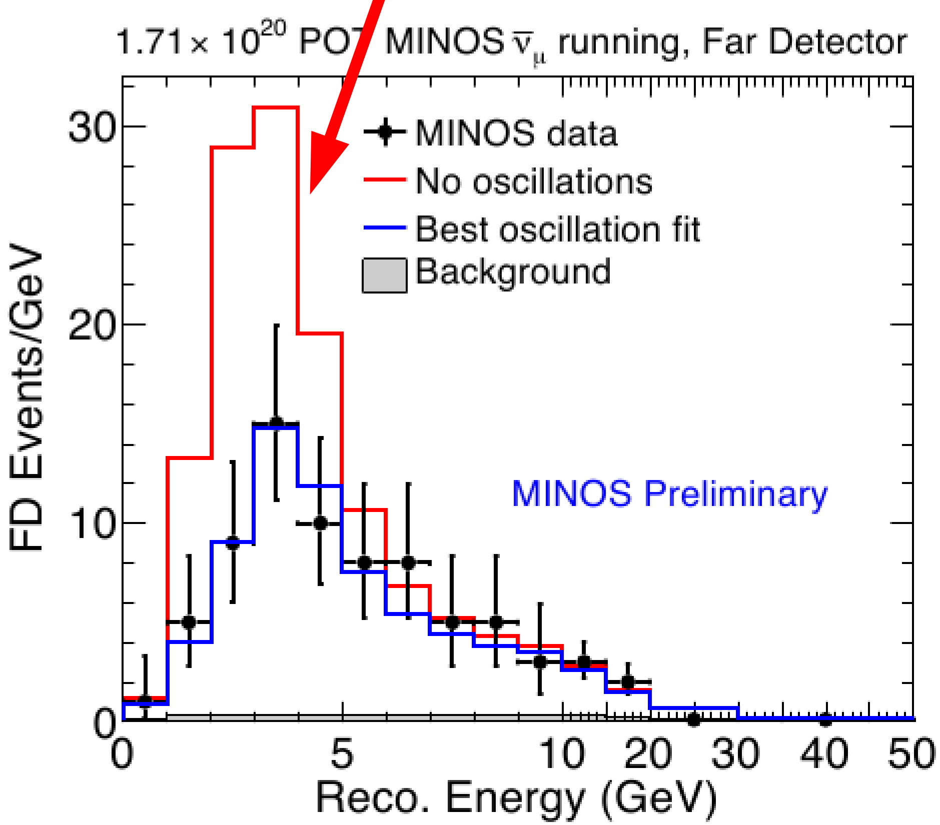


CC Far Detector Data

Neutrino data

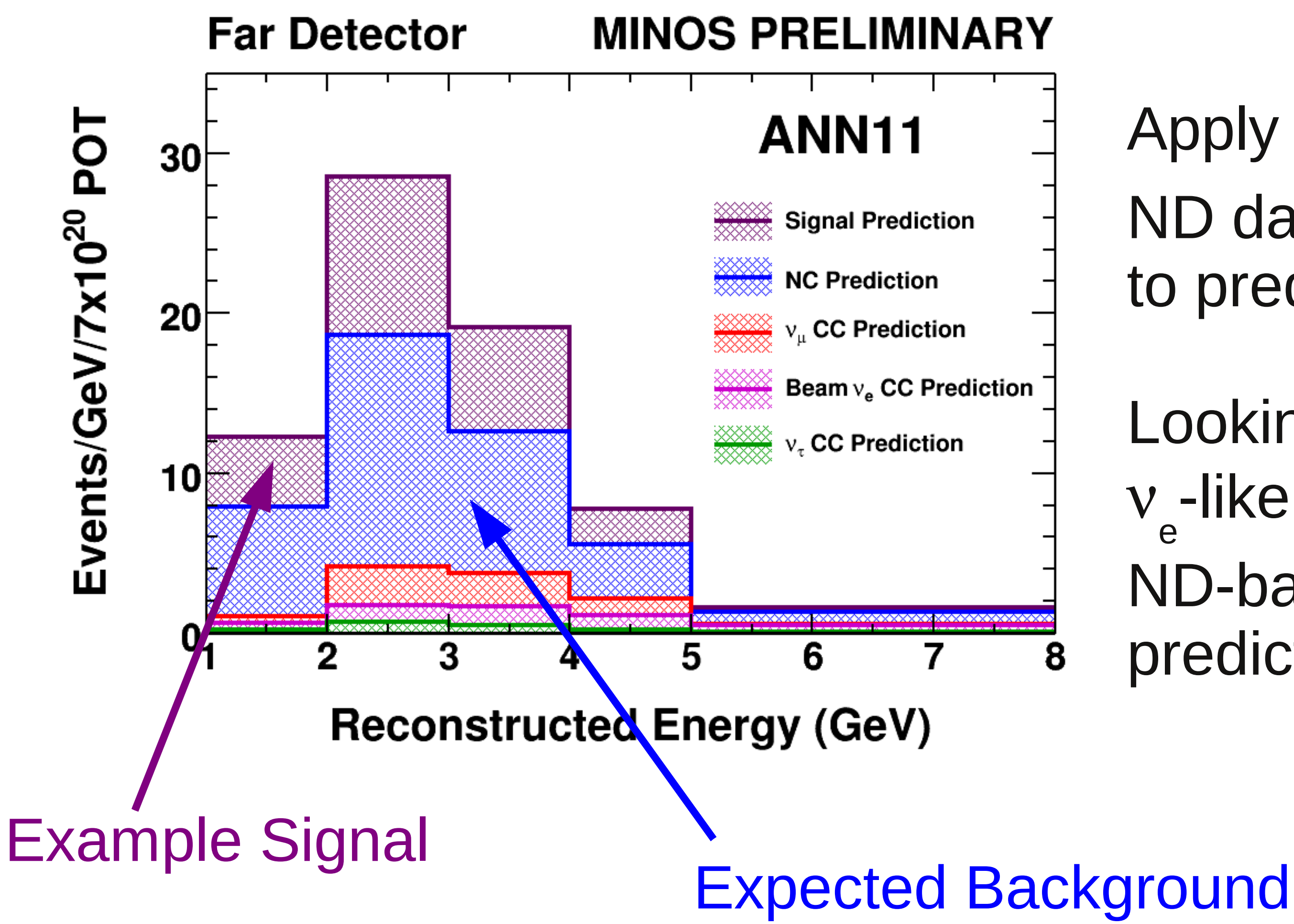


Prediction based on ND data



Anti-neutrino data

Electron Neutrino Appearance



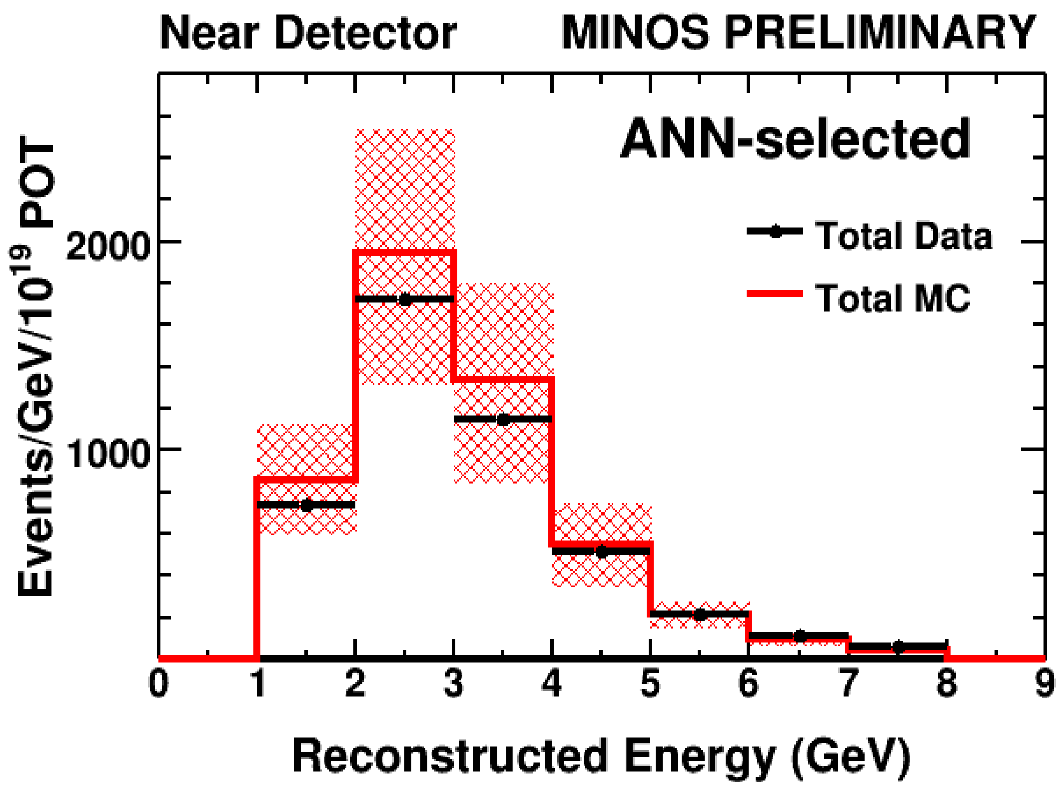
Apply ν_e selection criteria to ND data and use this sample to predict FD background

Looking for small excess of ν_e-like events in FD data over ND-based background prediction

$$\sin^2(2\theta_{13}) = 0.15$$
$$\sin^2(2\theta_{23}) = 1.0$$
$$\Delta m^2 = 2.43 \times 10^{-3} \ eV^2$$

Near Detector ν_e-like Data

Background composed of
NC, **ν_μ CC**, **Beam ν_e CC**



FD prediction must account for:
- flux (~1/R^2)
- fiducial volume
- beam geometry
- oscillations
- detector effects

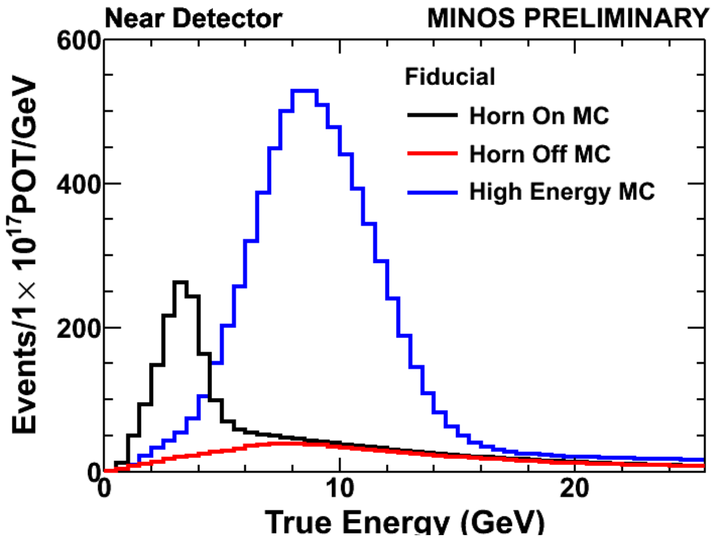
Some factors affect each background component differently

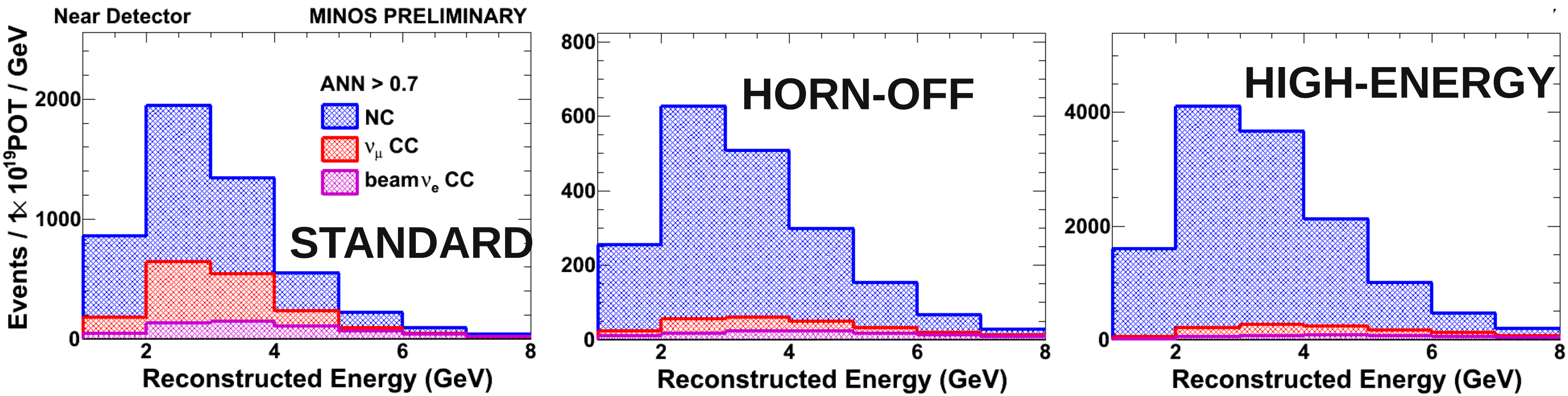
Need to separate the background into different components for extrapolation!

Data-Driven Background Separation

Take ND data with 3 different beam configurations

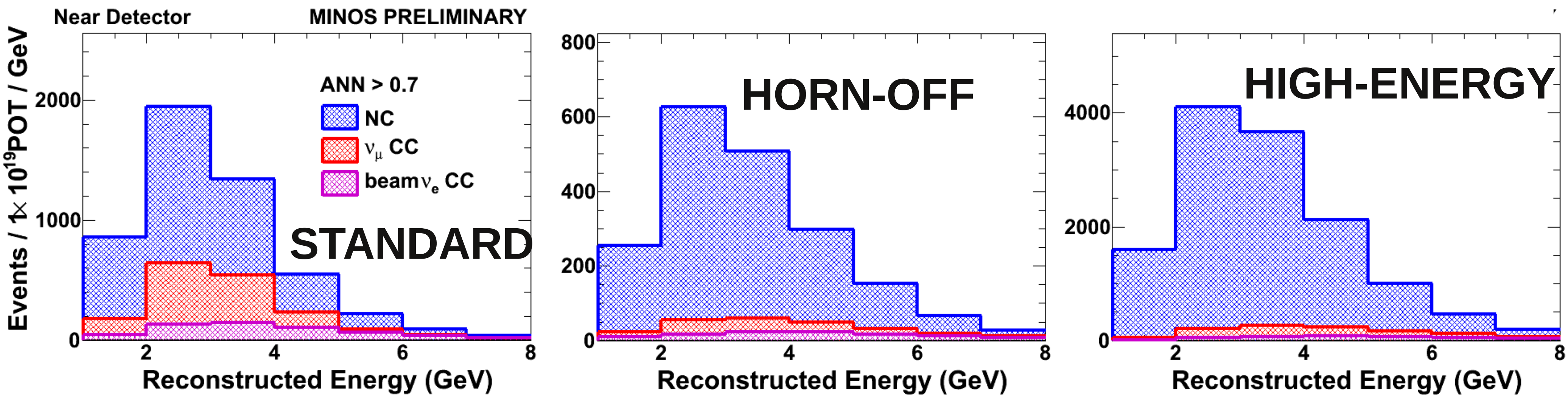
Select ν_e-like events in each data set





Use these 3 data sets to measure the 3 background components in the standard sample...

Data-Driven Background Separation



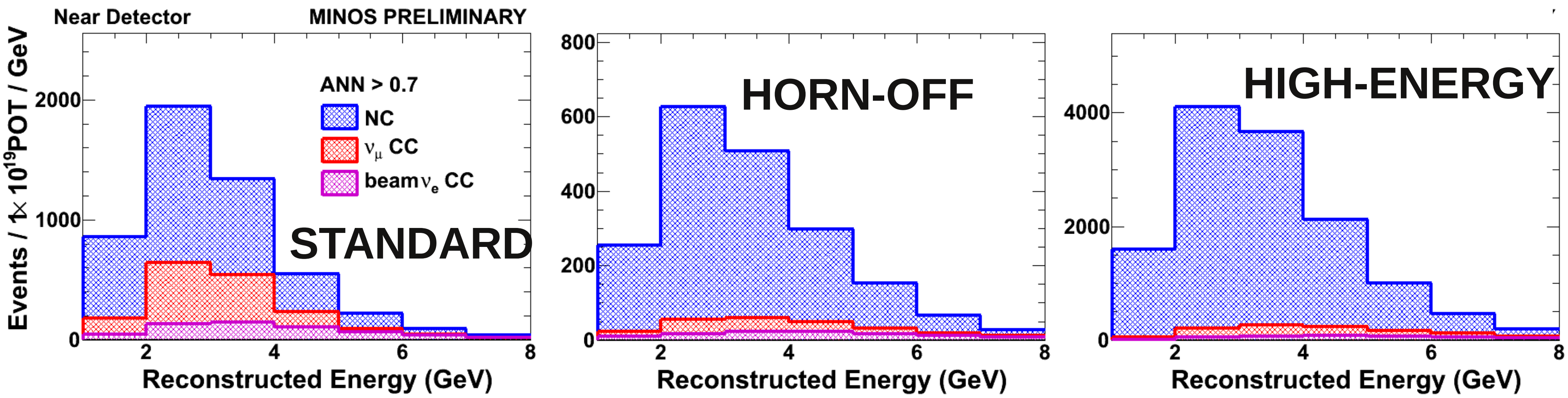
MC doesn't model the absolute event rate well
BUT the MC does model the relative event rate well

For example -
The relative rate of NC interactions between the standard configuration and the horn off configuration.

$$R_{NC}^{Off/Std}$$

Similarly: $R_{NC}^{HE/Std}, R_{\nu_\mu CC}^{Off/Std}, R_{\nu_\mu CC}^{HE/Std}, R_{\nu_e CC}^{Off/Std}, R_{\nu_e CC}^{HE/Std}$

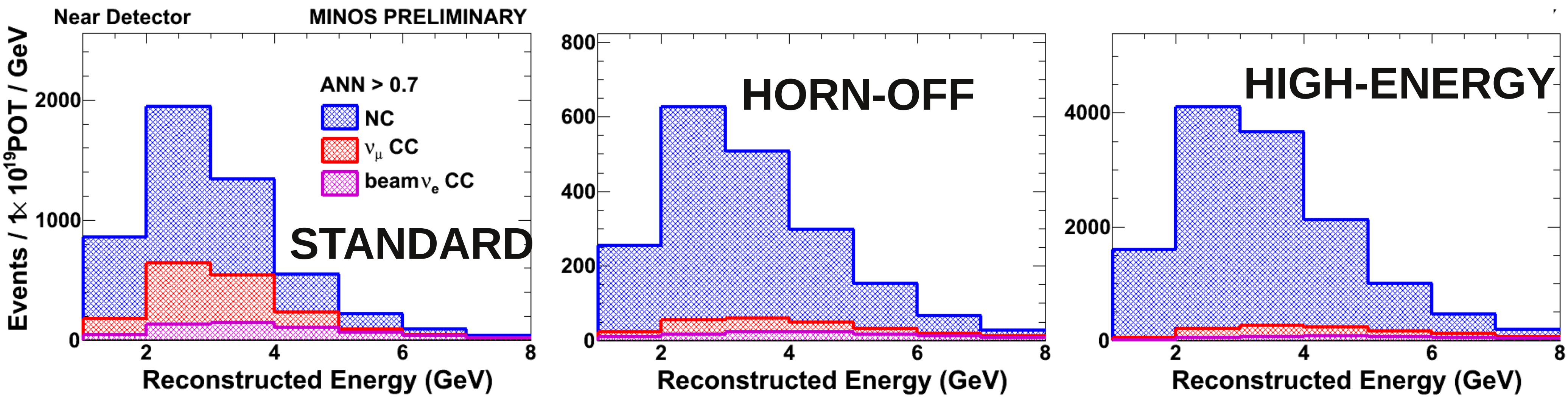
Data-Driven Background Separation



Using:
- Total measured rate in each beam configuration
- Relative interaction rates for each background component from the MC simulation

Can fit for the background components in the standard sample (in bins of energy)

Data-Driven Background Separation



$$N^{Std} = N_{NC} + N_{\nu_\mu CC} + N_{\nu_e CC}$$

Determined by fit

$$N^{Off} = R^{Off/Std}_{NC} N_{NC} + R^{Off/Std}_{\nu_\mu CC} N_{\nu_\mu CC} + R^{Off/Std}_{\nu_e CC} N_{\nu_e CC}$$

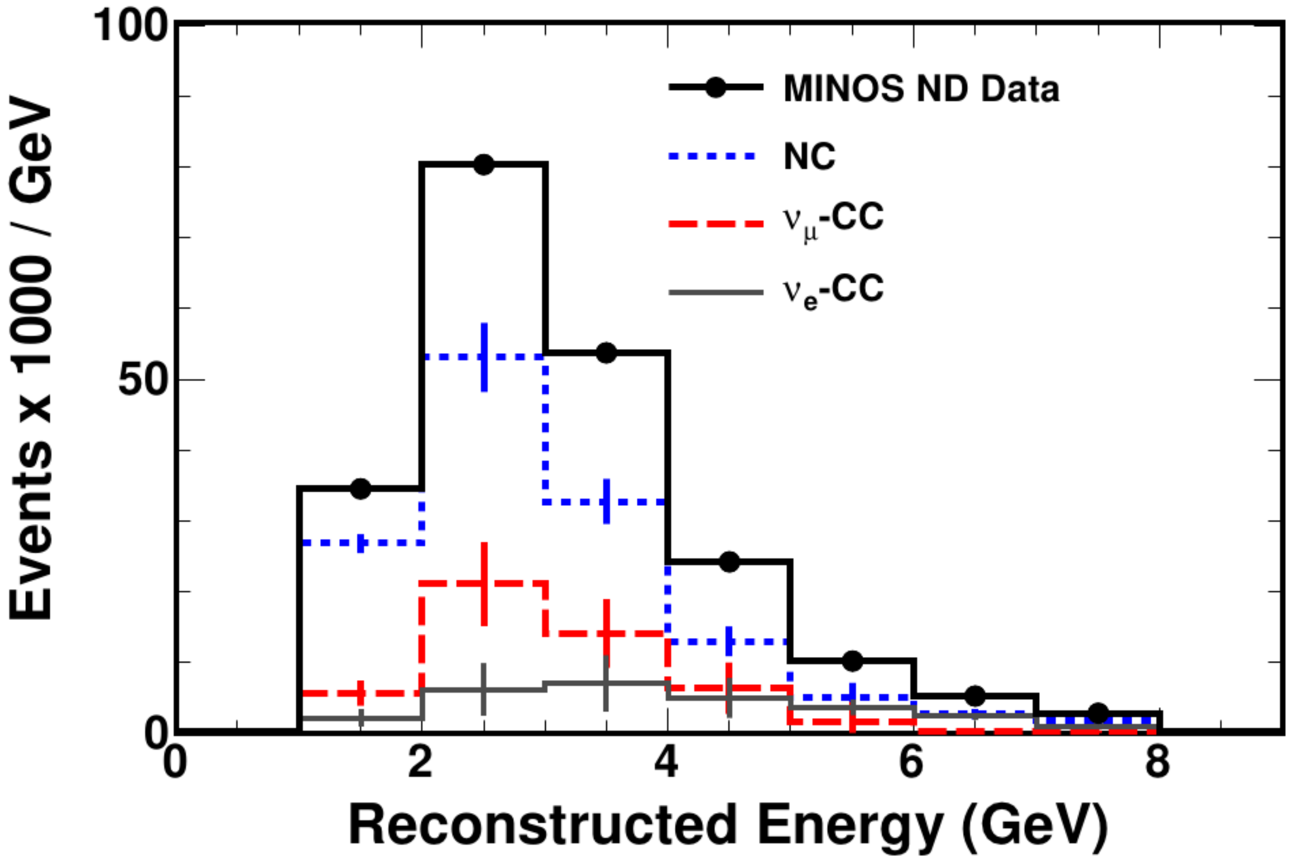
$$N^{HE} = R^{HE/Std}_{NC} N_{NC} + R^{HE/Std}_{\nu_\mu CC} N_{\nu_\mu CC} + R^{HE/Std}_{\nu_e CC} N_{\nu_e CC}$$

Measured

MC ratios

Data-Driven Background Separation

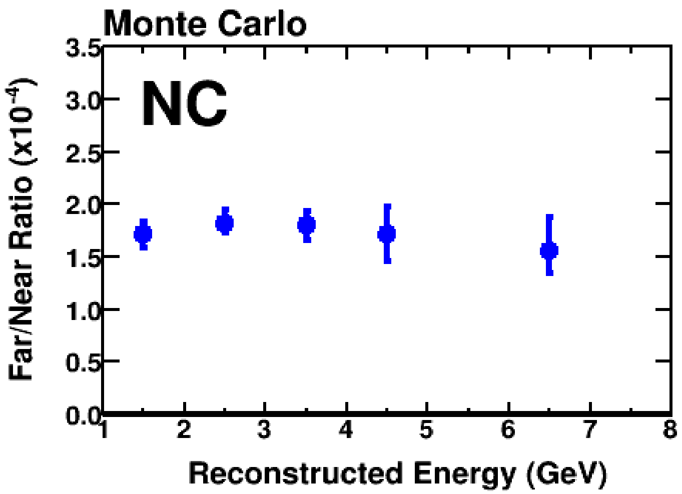
Results of the Fit

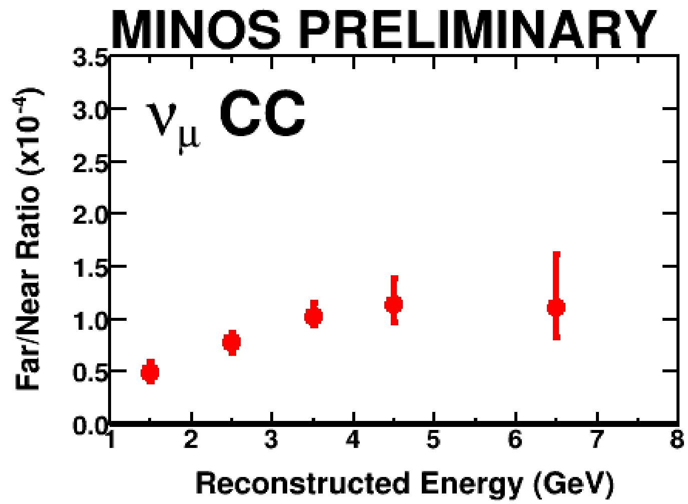


Near Detector ν_e Background sample is:

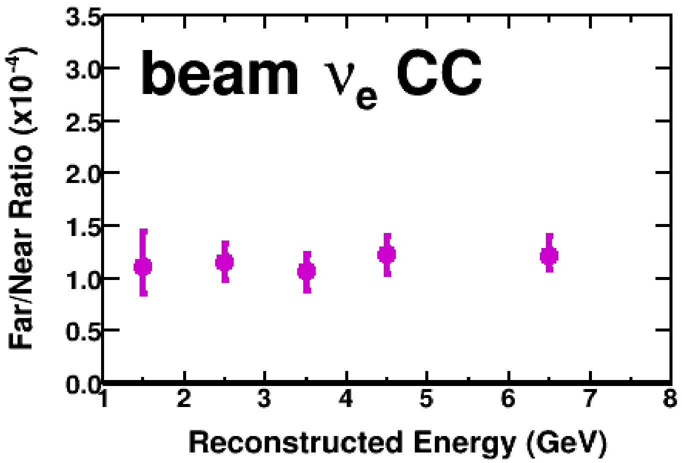
NC: (64±5)%
ν_μ-CC: (23±5)%
ν_e-CC: (13±3)%

Background Extrapolation





Error bars are systematic.



Far Detector Prediction

$$F_i = N_i \times R_i^{F/N}$$

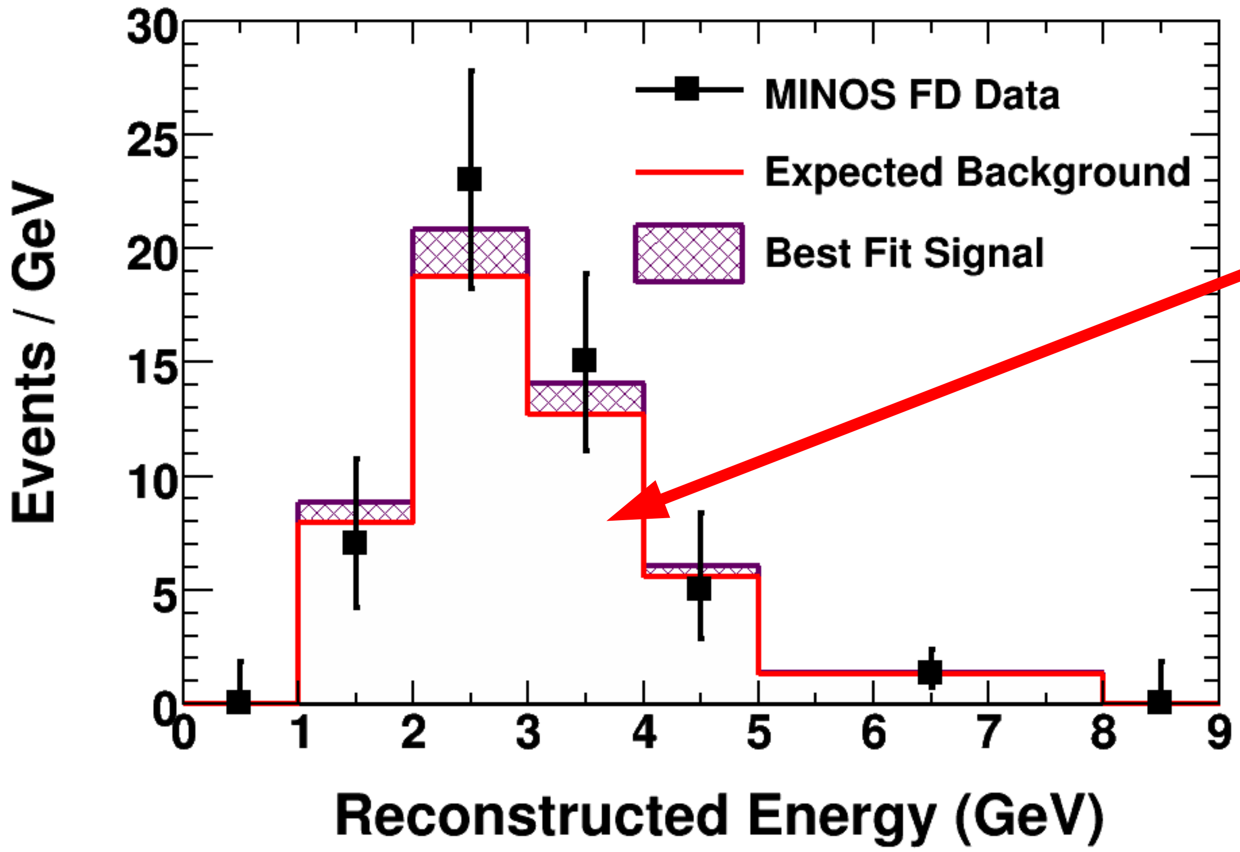
Near Detector Data

MC Far/Near ratio takes care of:

- Flux
- Fiducial volume
- energy smearing
- ν_μ disapp.
- detector effects

F/N ratio method is also used to predict the total FD NC rate for the sterile ν search

Far Detector ν_e-like Data



Prediction based on ND data

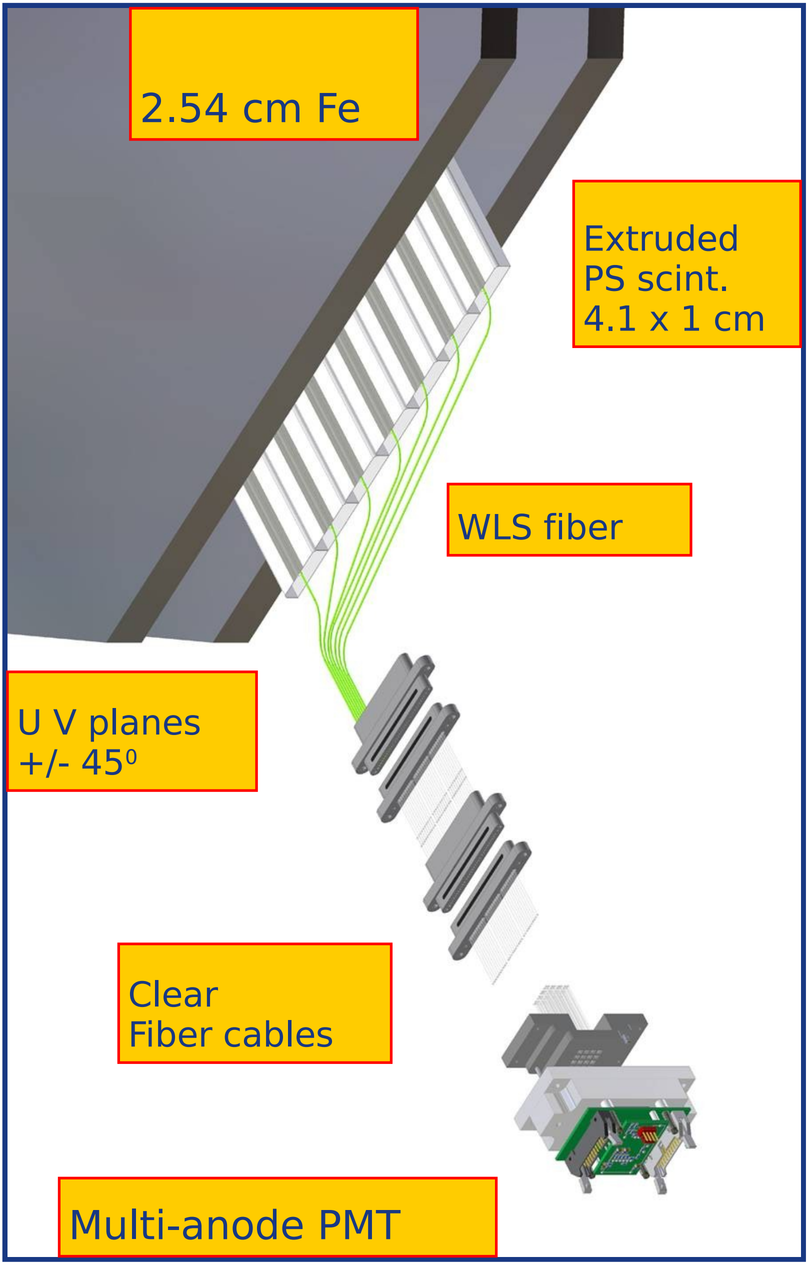
Summary

MINOS uses ND data to tune the beam simulation and make FD predictions for both disappearance and appearance analyses.

Capability of NuMI to run in different configurations is key!

Backup Slides

MINOS detectors



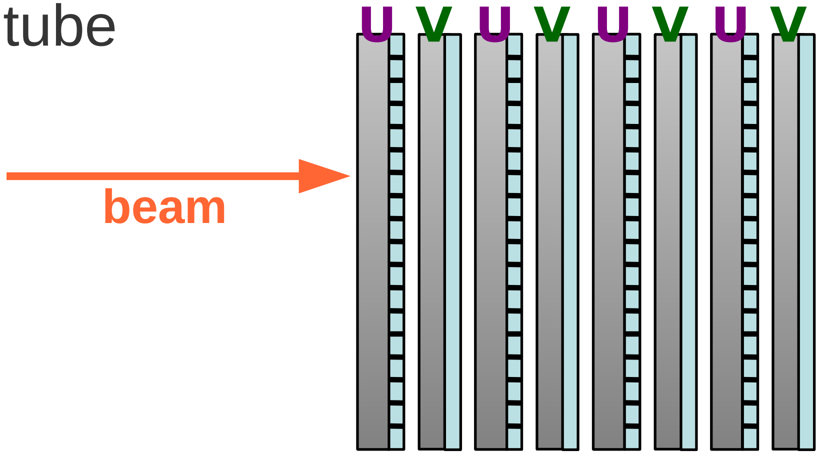
Steel thickness: 2.54 cm (~1.4 radiation lengths)

Strip width: 4.1cm
Moliere radius (radius of 90% containment of EM showers) ~3.7cm

Strips in adjacent planes are oriented orthogonally enabling 3D reconstruction

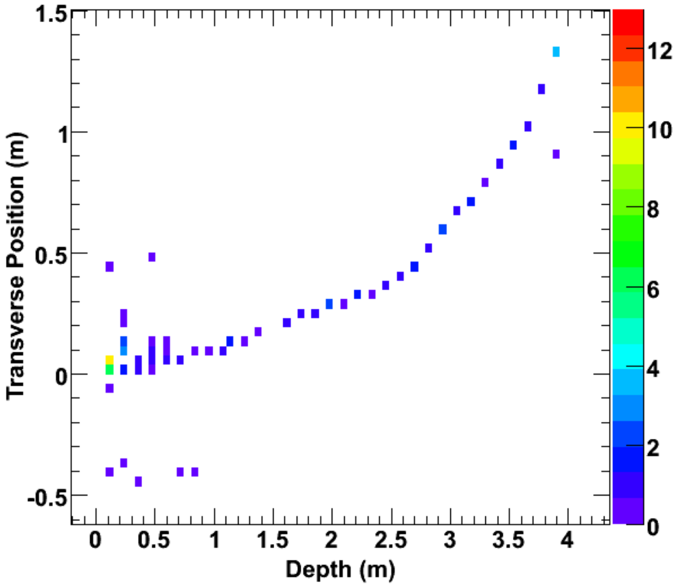
Each strip has a wavelength shifting fiber read out by a multi-anode photomultiplier tube

U/V strips oriented ±45^o from vertical

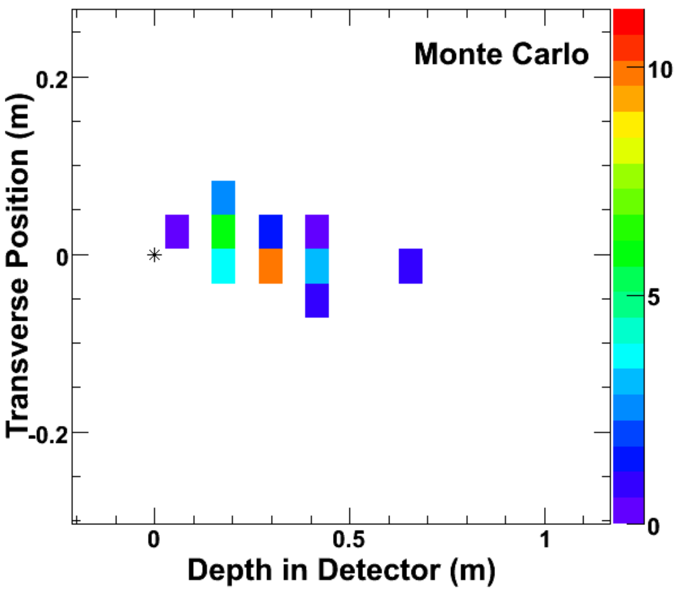


Neutrino Interactions at MINOS

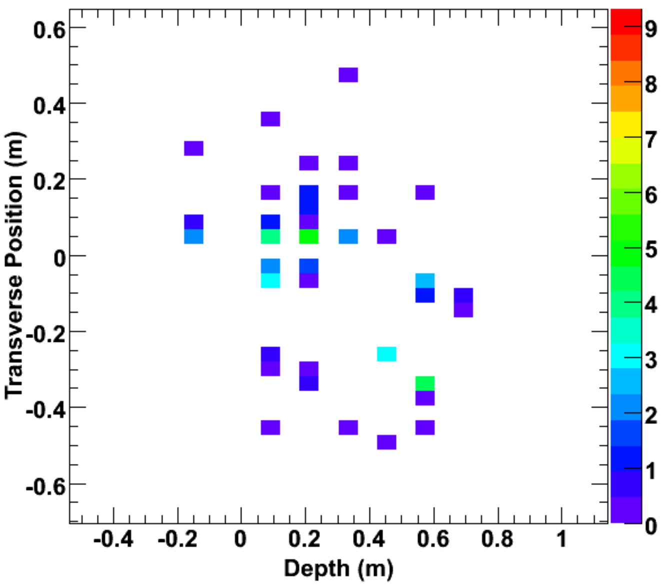
ν_μ Charged Current (CC)



ν_e Charged Current (CC)



Neutral Current (NC)



MC events

Far/Near Differences in MINOS

Far/Near differences (modeled in MC)

difference in fiber length (light level difference)

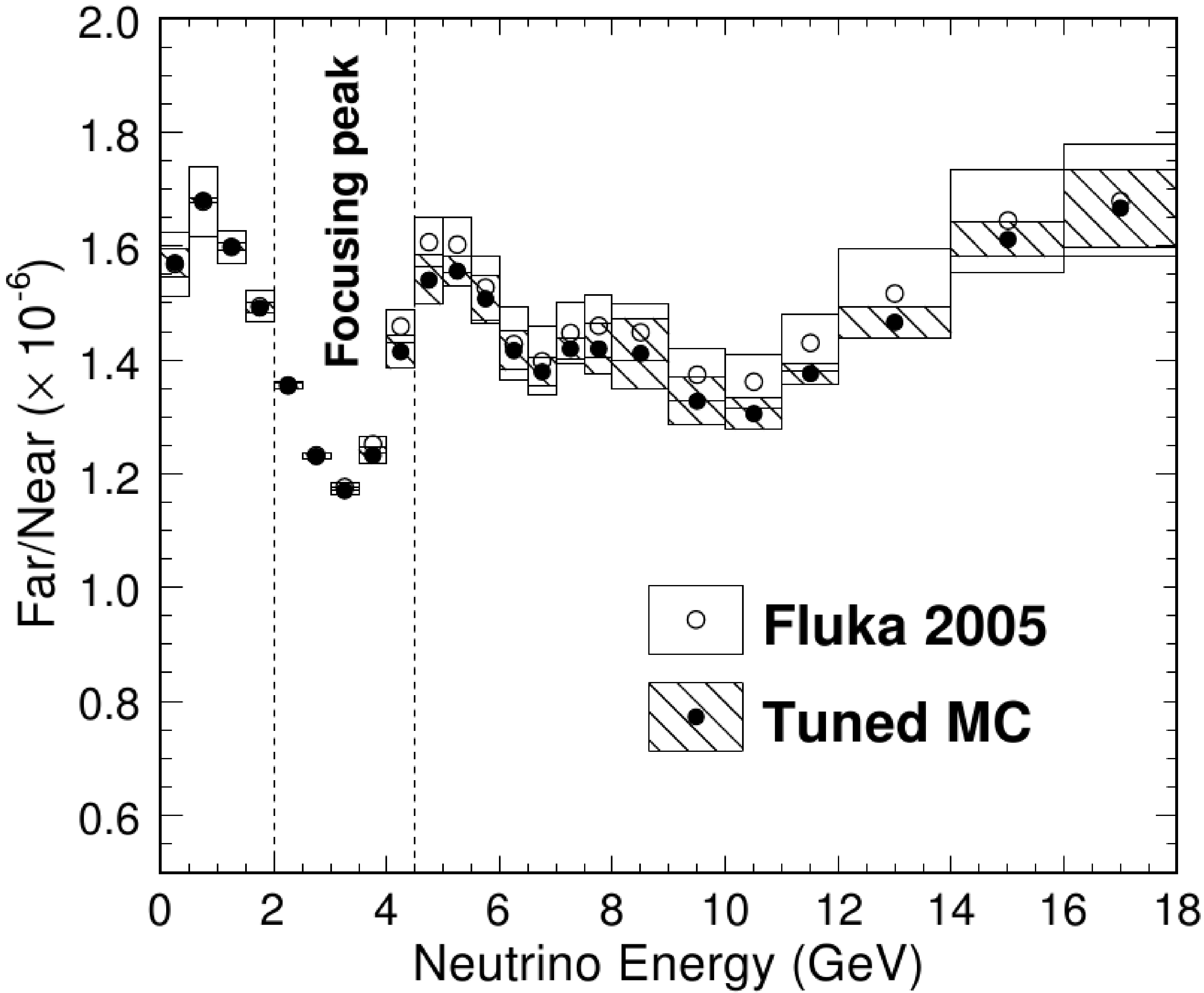
multiplexing in the far detector (8 fibers per PMT channel)

one-sided readout in the near detector

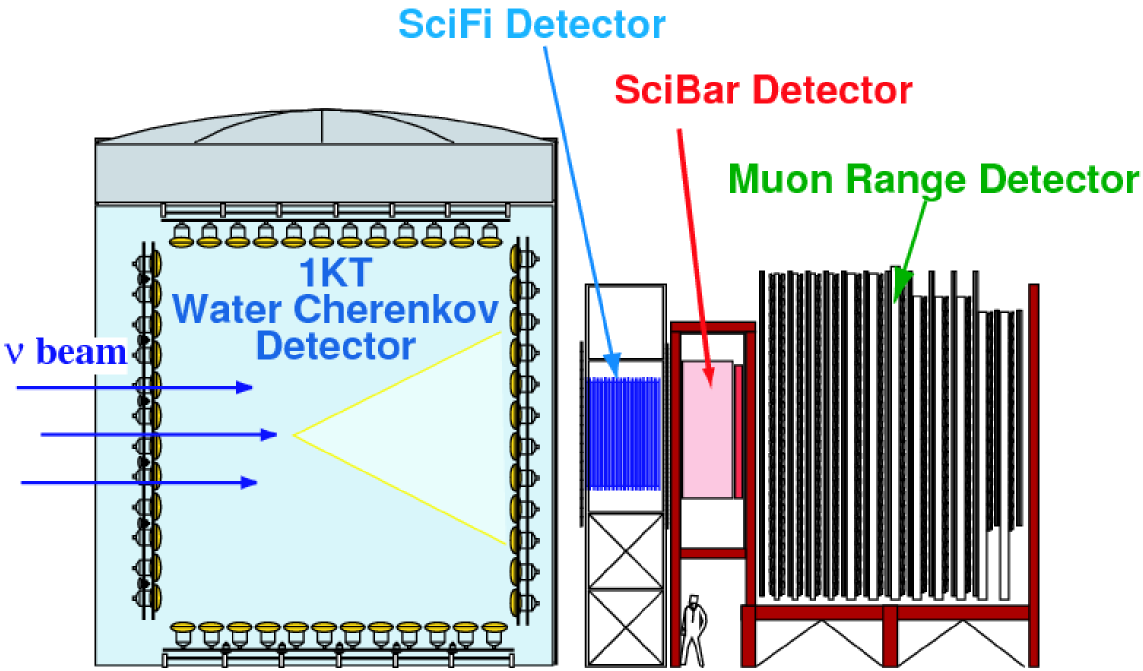
PMTs (64-channel in near, 16-channel in far) - different crosstalk pattern, gains, front end electronics

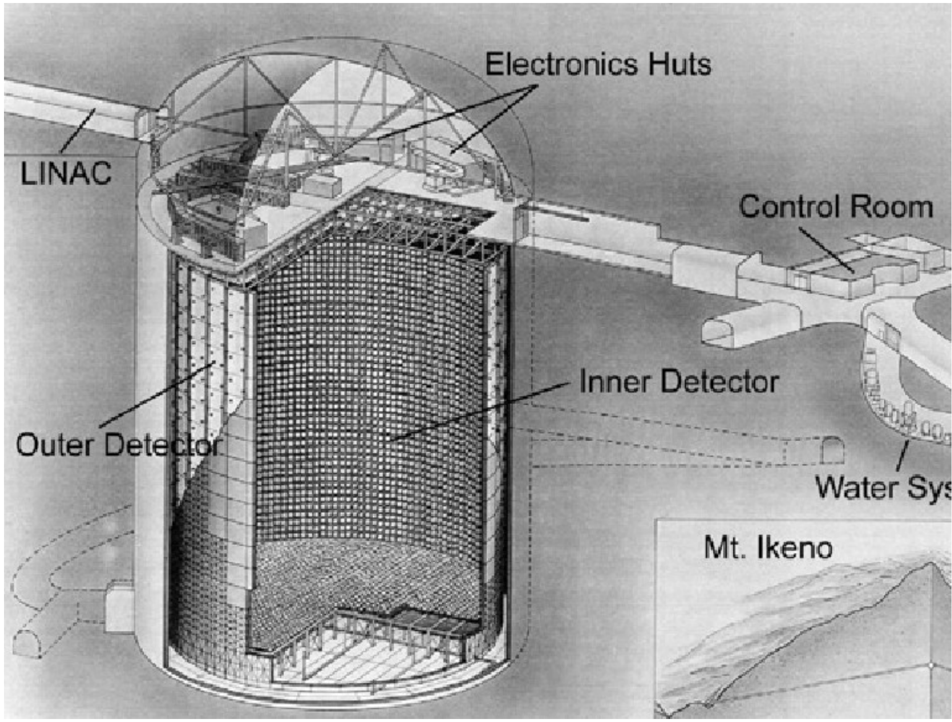
faster readout in near detector

MINOS Far/Near Flux Ratio



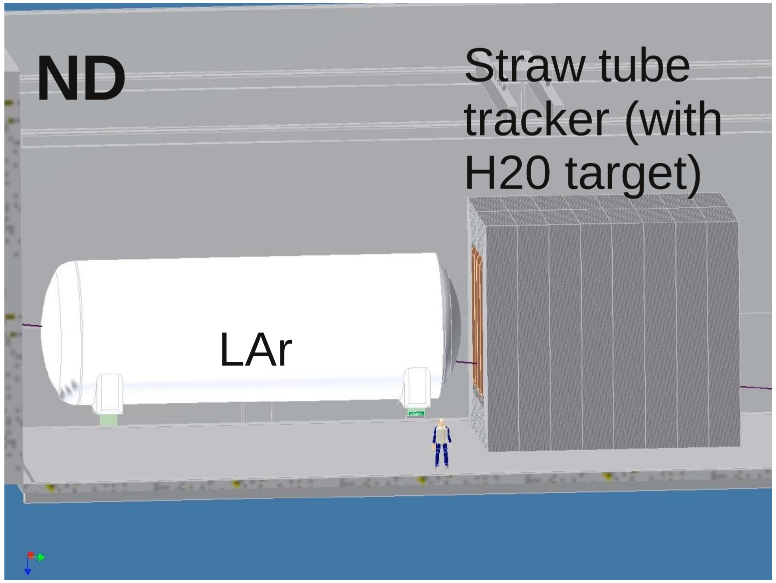
K2K



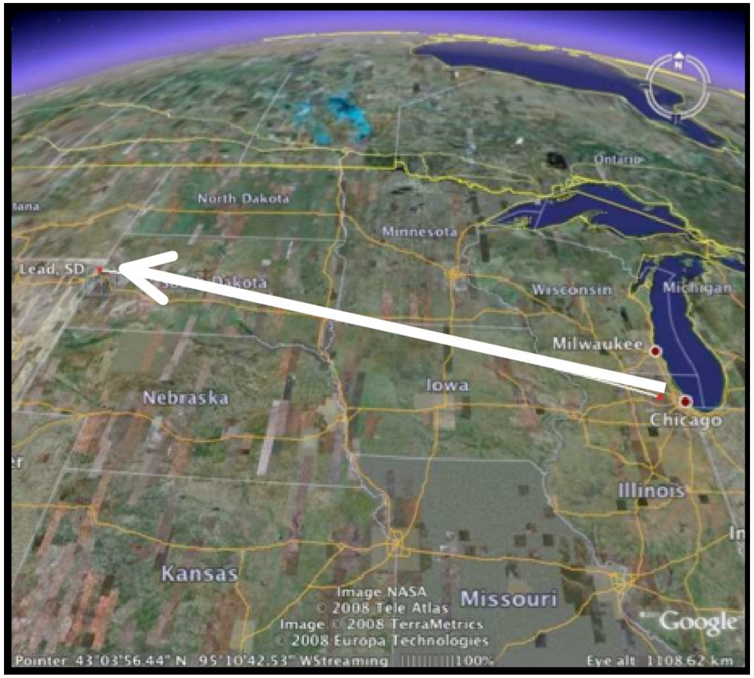


- Suite of near detectors at KEK, including 1 kton WC
- Super-Kamiokande (50 kton WC) as far detector
- 250 km baseline
- 1.3 GeV peak neutrino energy
- Near WC detector data used for SuperK prediction
- Data from all near detectors used to tune the flux simulation

LBNE



See yesterday's talk by S. Mishra



- Both water and LAr targets in the ND
- Measure ν_μ, ν_e, $\bar{\nu}_\mu$, $\bar{\nu}_e$, components of the beam
- Identify event classes important for oscillation analysis: e.g. ν_μCCQE, ν_eCCQE, NC π^0
- Possibility of having several beam configurations like NuMI?