ν_e appearance studies in MINOS

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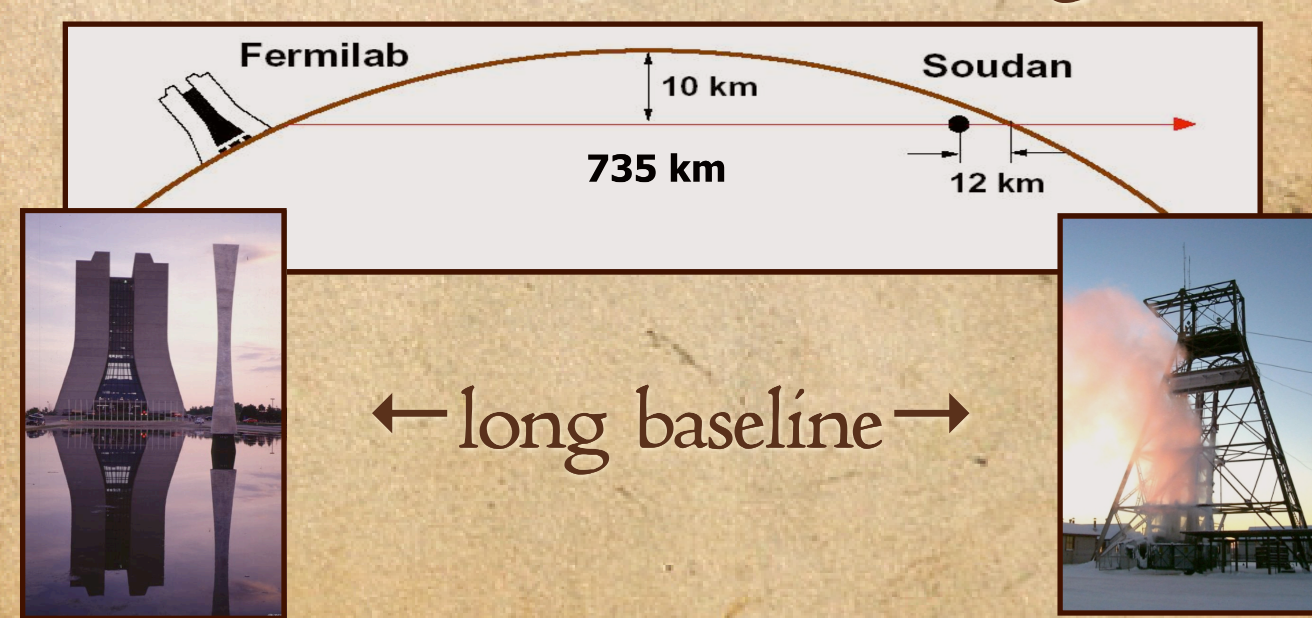
DPF 2006 - October 30, 2006

Seeing ν_e's in MINOS

Main Injector Neutrino Oscillation Search

- Using the NUMI beam from Fermilab.
- Measure and understand the background at the Near detector (Fermilab).
- Search for ν_e signal at the Far detector, 735 km away (Soudan).
- If muon neutrinos oscillate into electron neutrinos, we will see an excess over the predicted background.



Measuring θ_{13}

$$|\nu_\alpha\rangle = \sum_{k=1}^{n} U_{\alpha k} |\nu_k\rangle \quad (\alpha = e,\mu,\tau)$$

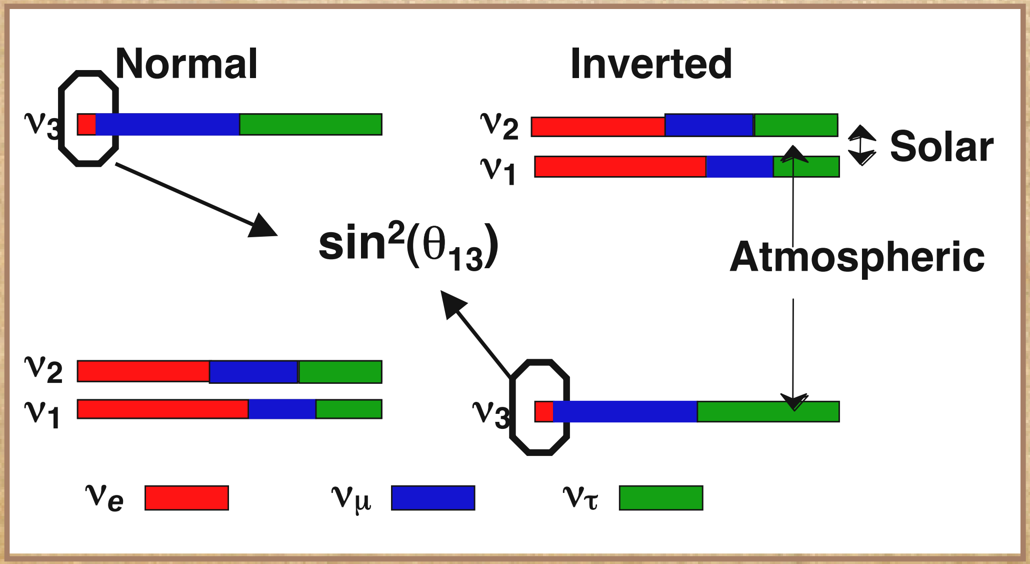
$$\mathbf{U} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} =$$

$\theta_{12}, \theta_{23}, \theta_{13}$, CP phase

Δm^2_{21} Δm^2_{32} , 2 Majorana phases

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \cdot \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{-i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \cdot \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{-i\alpha/2} & 0 \\ 0 & 0 & e^{-i\alpha/2+i\beta} \end{pmatrix}$$

$$\langle \nu_\beta(t)|\nu_\alpha(0)\rangle = \sum_k U^*_{\beta k} U_{\alpha k} e^{-iE_k t} \Longrightarrow P(\nu_\mu \to \nu_e)^* = [\sin^2(\theta_{23})\sin^2(2\theta_{13})] \times [\sin^2(1.27\ \Delta m^2_{13} L/E)]$$



input parameters from the ν_μ disappearance analysis

experimental parameters

* Ignoring matter effects, CP violation and solar terms.

Measuring θ_{13}

past, present and future

$$|\nu_\alpha\rangle = \sum_{k=1}^{n} U_{\alpha k} |\nu_k\rangle \quad (\alpha = e, \mu, \tau)$$

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} =$$

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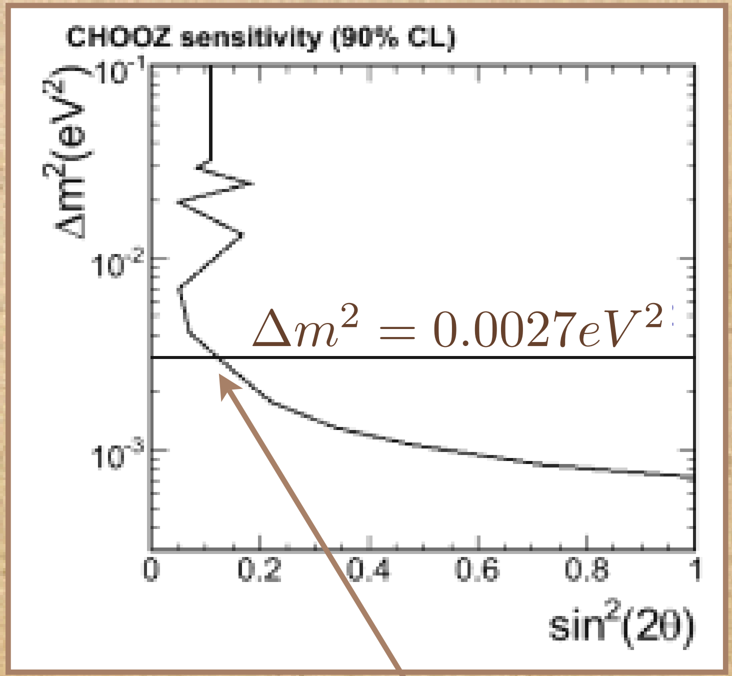
Best limit: Chooz

Future experiments:
Nova, T2K,
Double Chooz,
Daya Bay

MINOS taking data today!



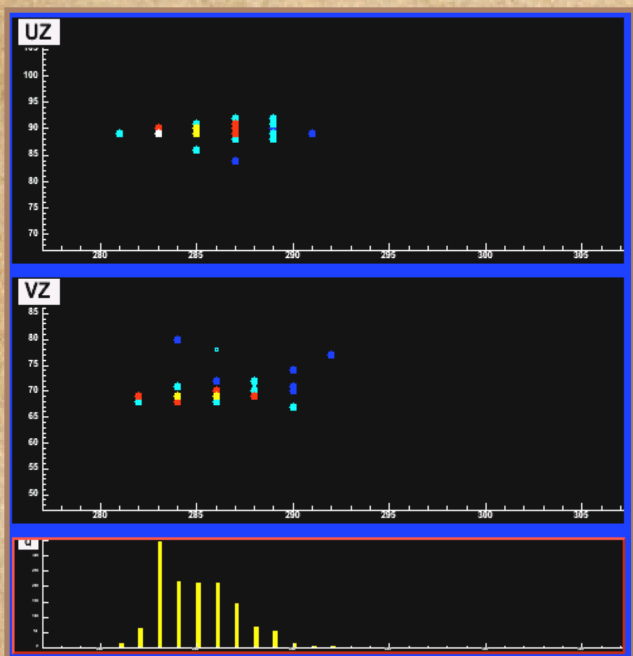
$\sin^2 2\theta_{13} < 0.12$ @ 90%CL

Signal/BG separation

ν_e appearance

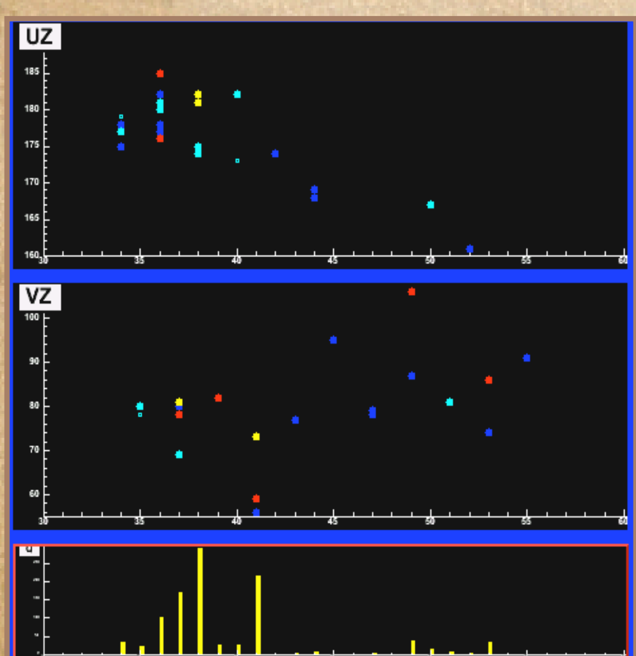
Signal:

ν_e CC interaction: $\nu_e + N \rightarrow e + X$



Primary Background:

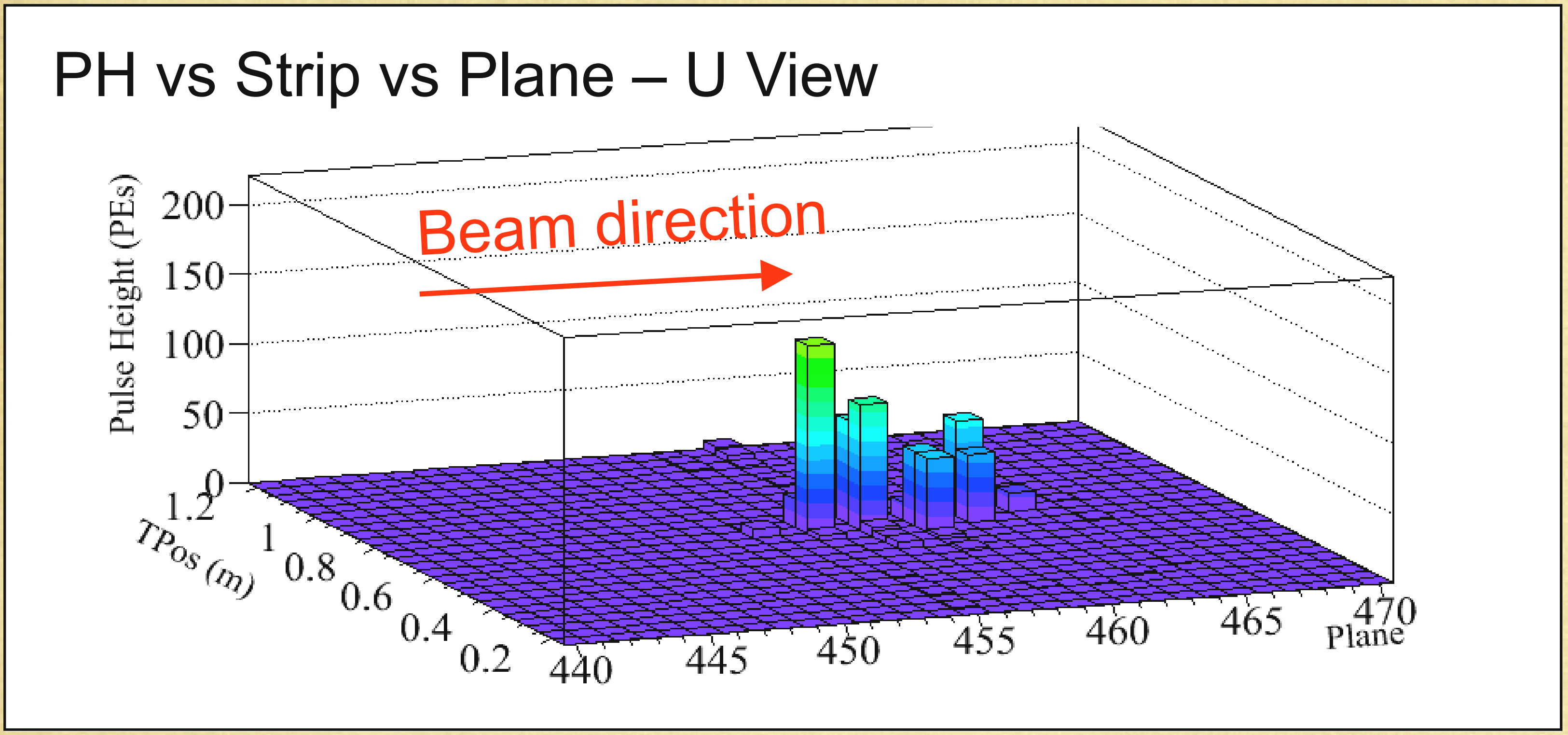
NC interaction $\nu_l + N \rightarrow \nu_l + X$

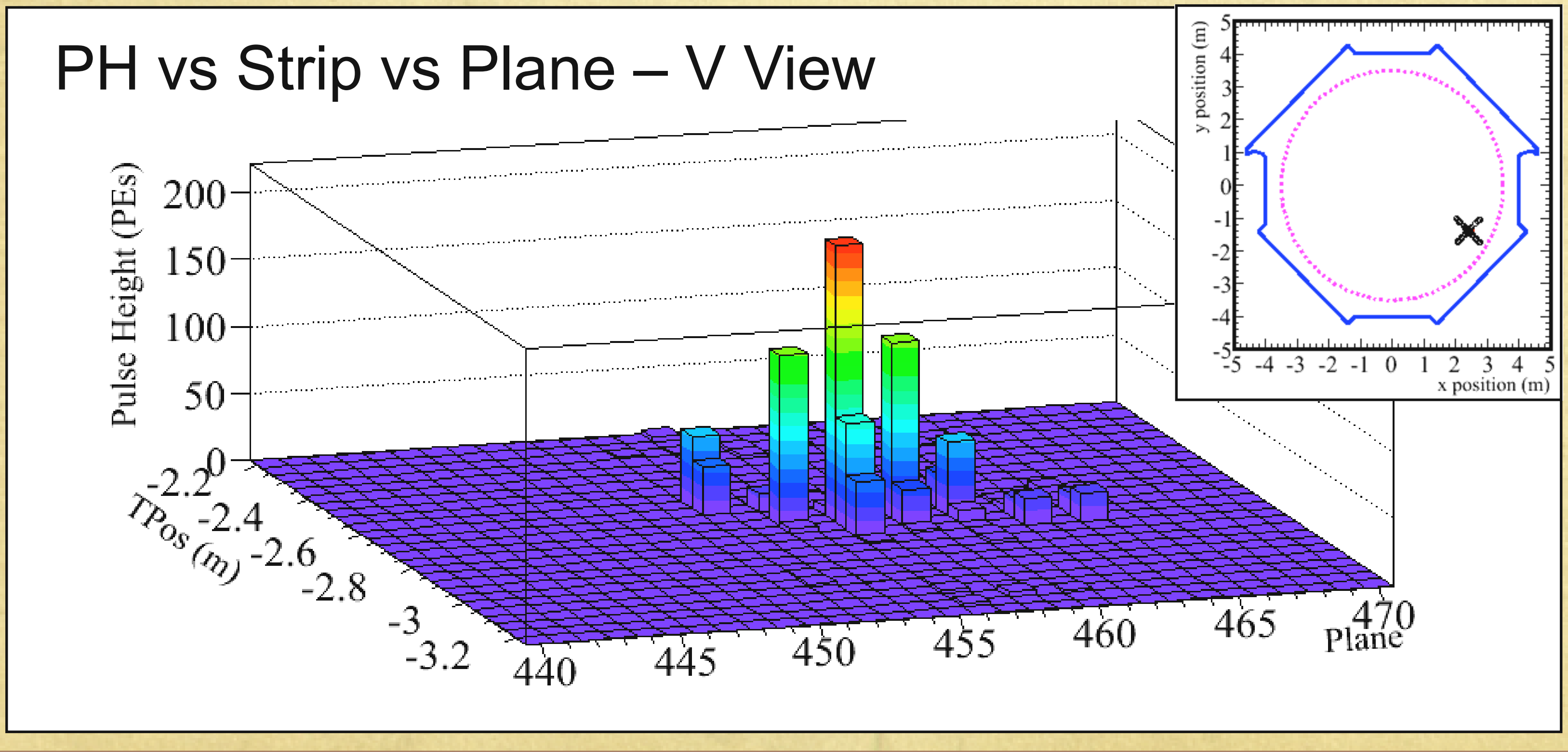


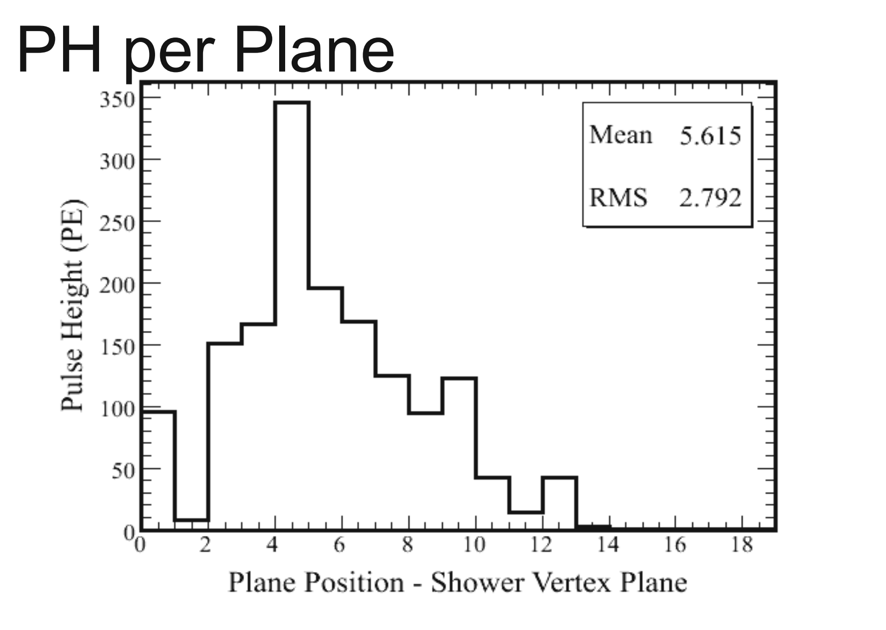
- Main goal is separation between EM and hadronic showers (Neutral Currents).
- Typical EM shower characteristics
  - steel thickness: 2.54cm ~1.44X_0
  - strip width: 4.12cm (Moliere rad ~3.7cm)
- Typical oscillated nue event is contained within a small region: 8 planes x 4 strips for a few GeV.
- Other background components:
  - beam ν_e,
  - high-y ν_μ CC,
  - oscillated ν_τ.

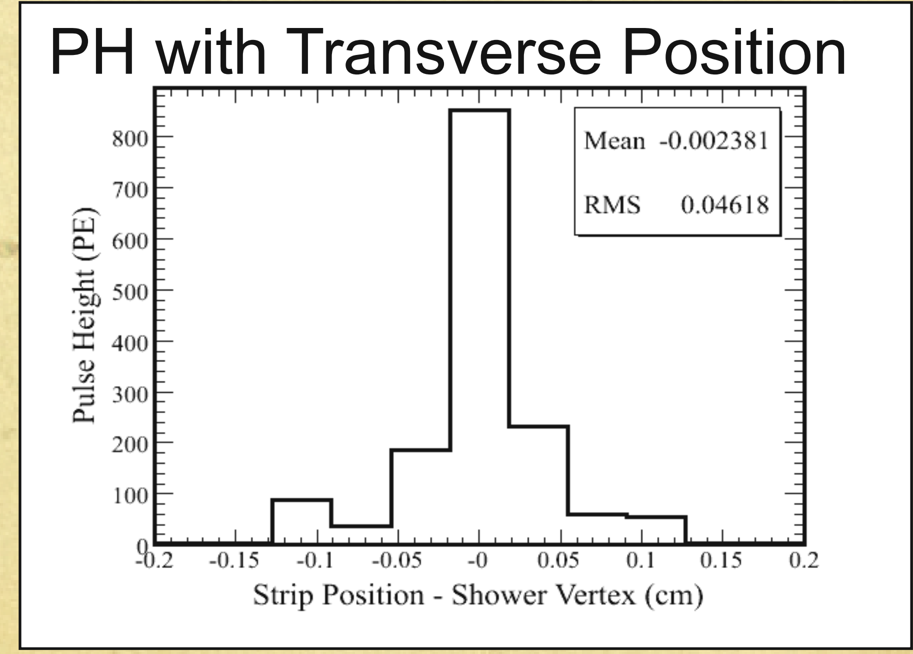
Candidate ν_e in the FD data

Run: 32617 Snarl: 105322
Reco Shower Energy: 8.7 GeV
ANN PID: 0.99









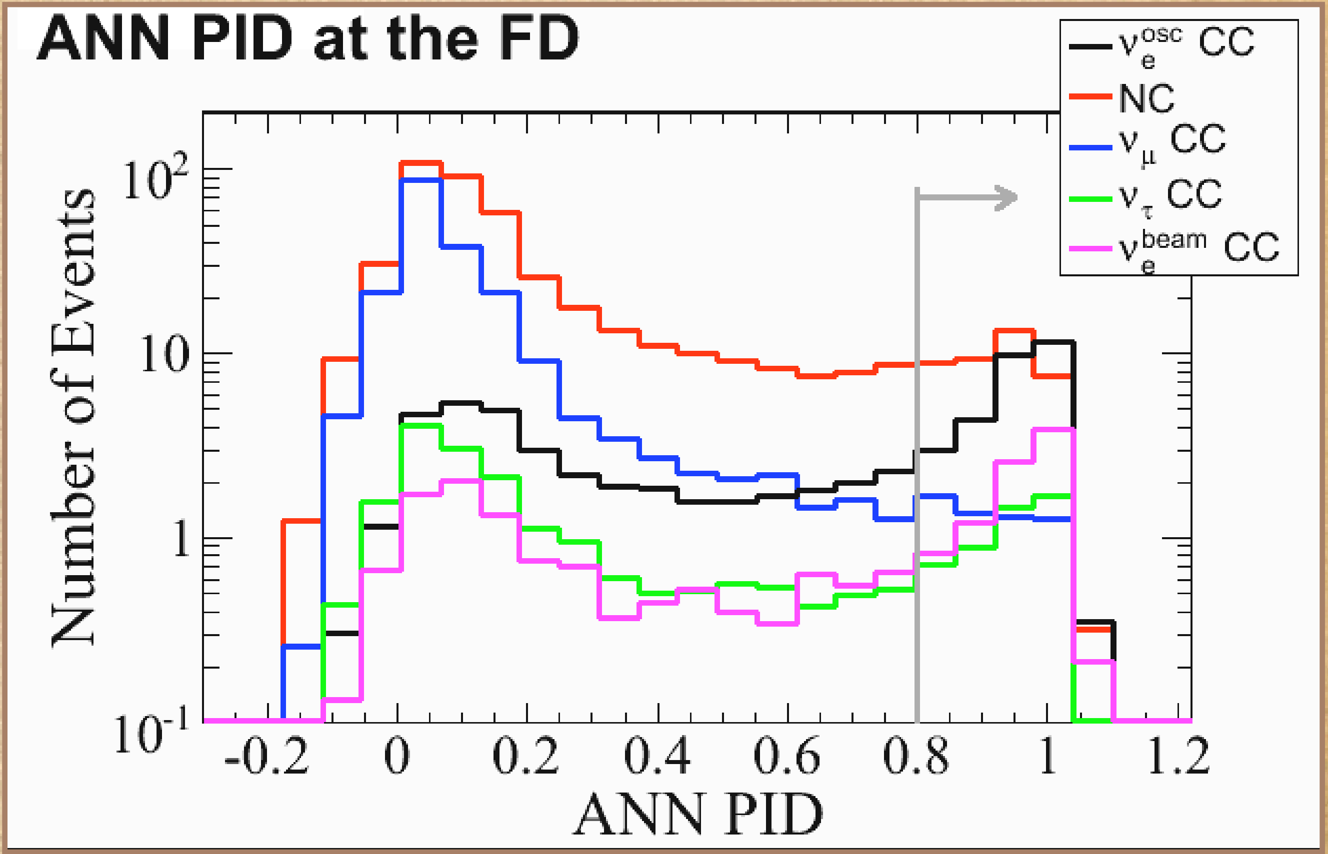
Signal/BG separation

ν_e appearance

$\sin^2\theta_{23}=1.0$, $\Delta m^2_{32}=0.0027$ eV^2

$\sin^2(2\theta_{13})=0.1$ (below Chooz)

- Candidates must contain a compact shower and exhibit characteristic EM profile.
- Intense work has gone into constructing variables and pids that distinguish between EM and hadronic showers.
- Several discriminating techniques have been tried to enhance signal/background separation.
  - Cuts, Multivariate Discriminant Analysis and ANN.
- Neural Net example shows:
  - efficiency 30%
  - signal/$\sqrt{\text{background}}$: ~2 at 4×10^{20}POT



	Signal	Tot. bg.	NC	ν_e^{beam}	ν_μ CC	ν_τ CC
4×10^{20} POT	7.3	14.6	9.8	2.0	1.5	1.3
16×10^{20} POT	29.2	58.2	39.0	8.1	6.1	5.0

Signal/BG separation

ν_e appearance

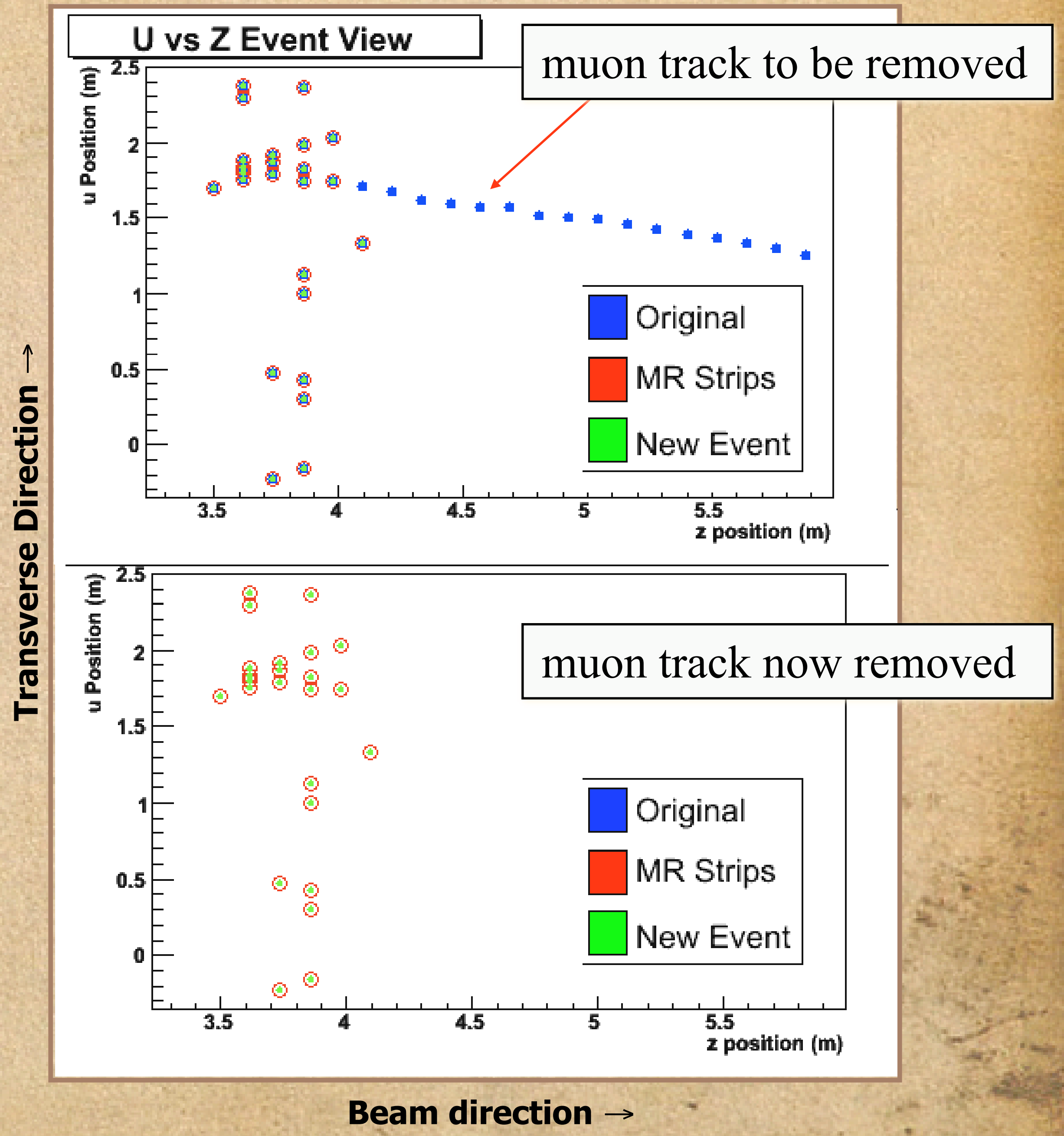
- Expected events from MC for 4×10^{20} POT

NC	9.8 (67%)		$\sin^2\theta_{23}=1.0$
CC	1.5 (10%)		$\Delta m^2_{32}=0.0027\ eV^2$
Beam ν_e	2.0 (14%)		$\sin^2(2\theta_{13})=0.1$
ν_τ	1.3 (9%)		↓
total bg	14.6	⇔	7.3 signal events

- Backgrounds will be estimated from data:
  - Muon removal in CC events: estimating NC bg.
  - Beam ν_e: fit pion and kaon spectrum in ND.
  - Beam ν_e: measure $\bar{\nu}_\mu$ from $\mu^+ \rightarrow e^+\nu_e\bar{\nu}_\mu$ in ND.
  - Horn off data in ND: disentangle NC-CC.
- Signal efficiency for DIS events: combine Muon removed CC events with MC electrons.

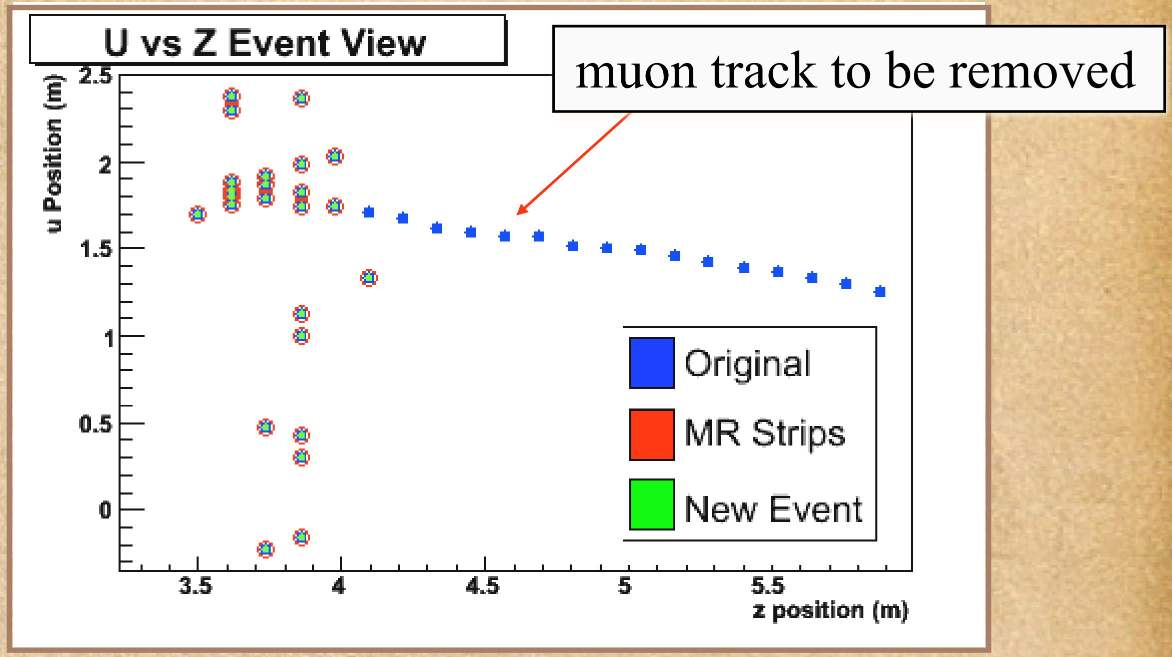
Estimating NC background using muon removal technique

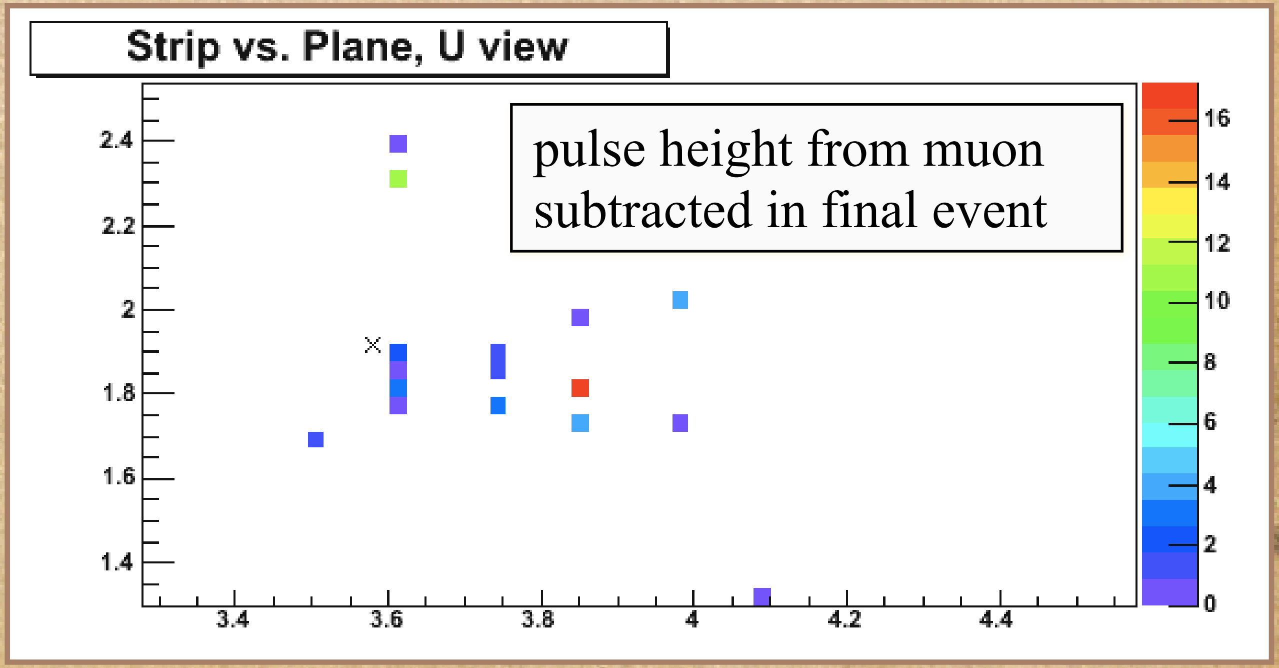
- Remove the muon track in a selected ν_μ CC event and use the rest as a fake NC event.
- We use events that pass our Charged Current event selection, i.e. that have a well defined track.
- We expect a >95% purity in this sample.
- Pulse height from the muon is accounted for and it is subtracted from shower hits.



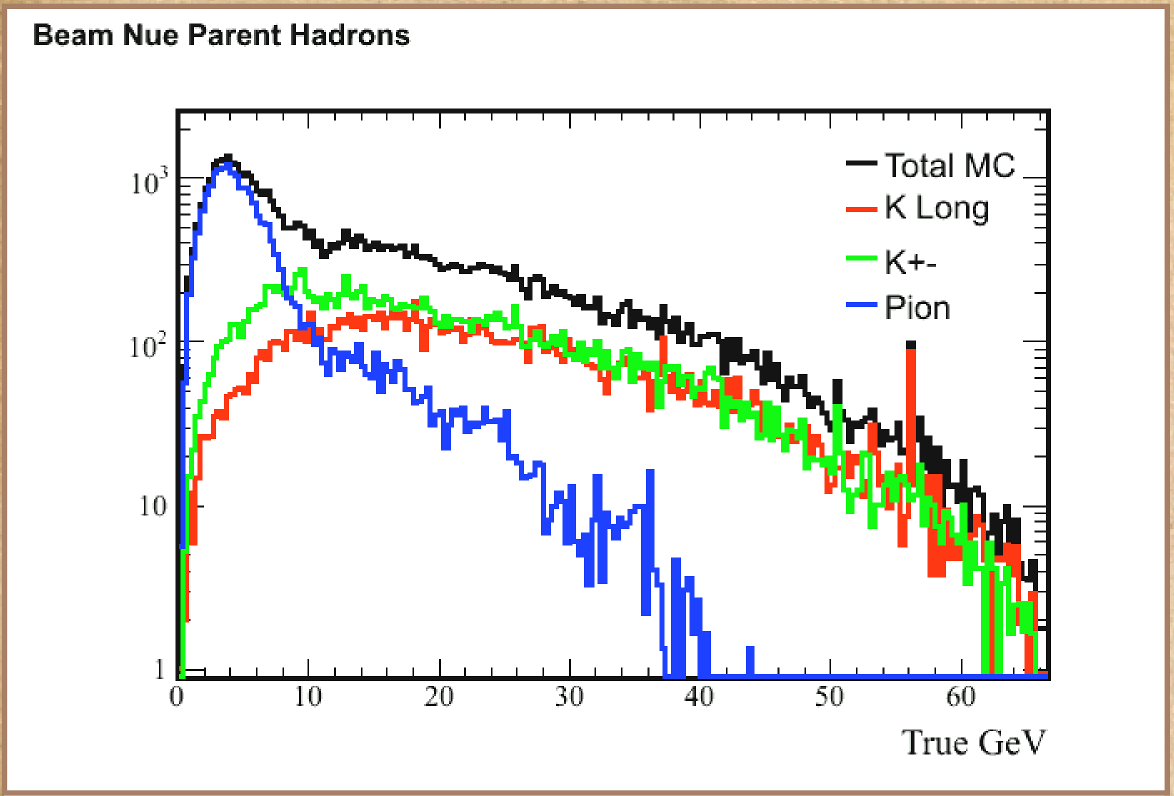
Estimating NC background using muon removal technique

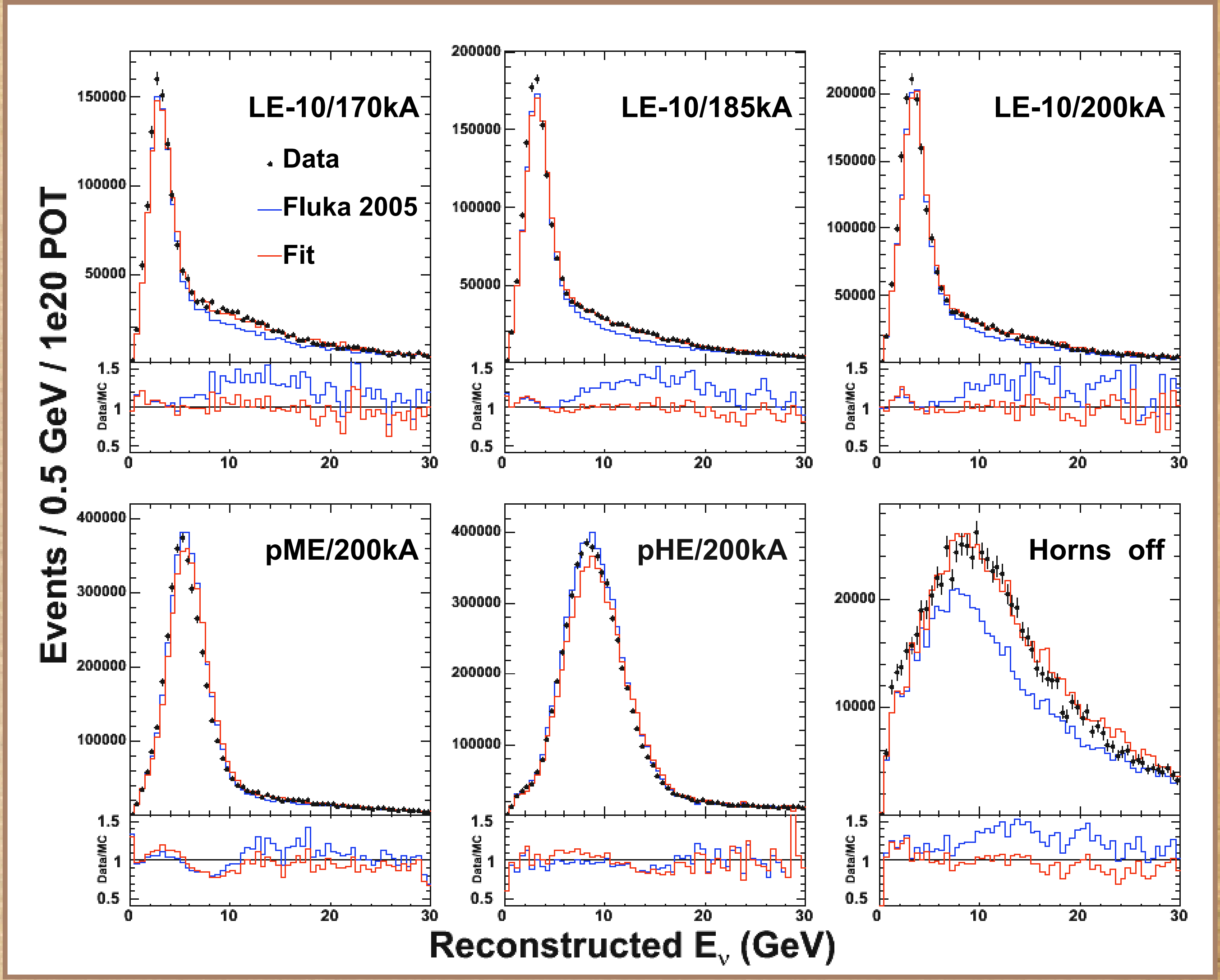
- By applying the PID selection to these events, this technique will verify/measure the NC background using a data/MC ratio of the MRCC events.
- Corrections need to be applied for CC selection efficiency, oscillation in the FD and CC/NC cross-section ratio.
- Relies on the difference in overall charge and multiplicity of the hadronic system not changing the topology too much.
- It can be applied to the Near and the Far data.





Estimating beam ν_e background fitting the hadronic production



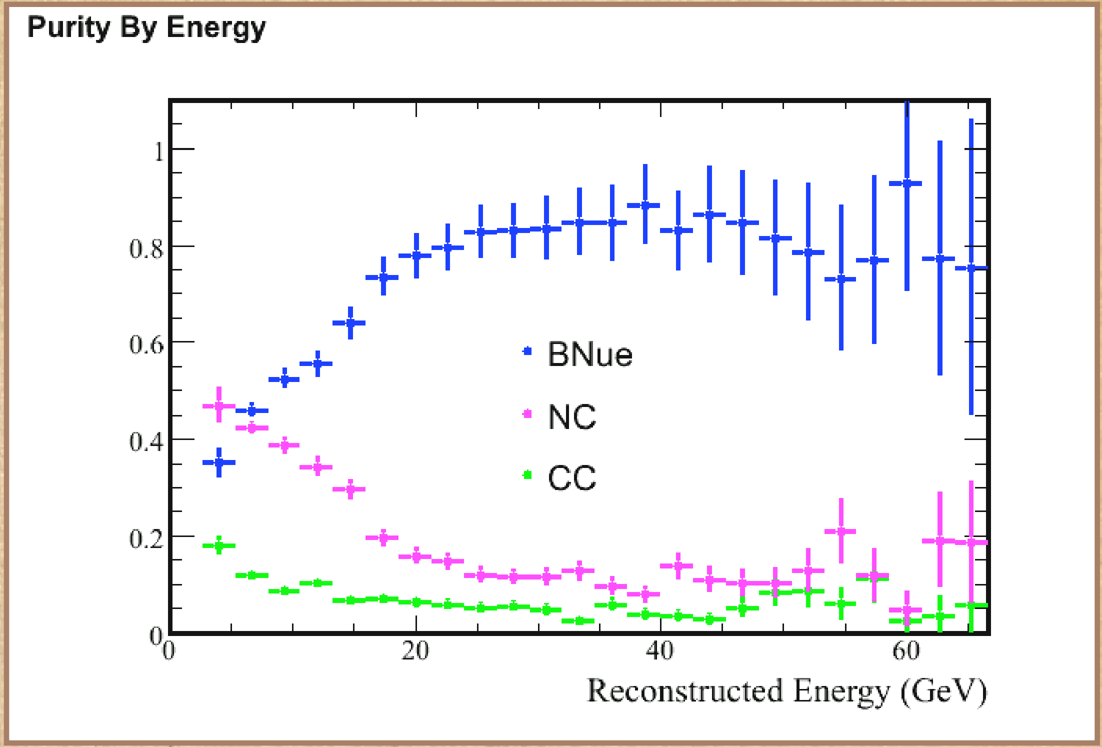


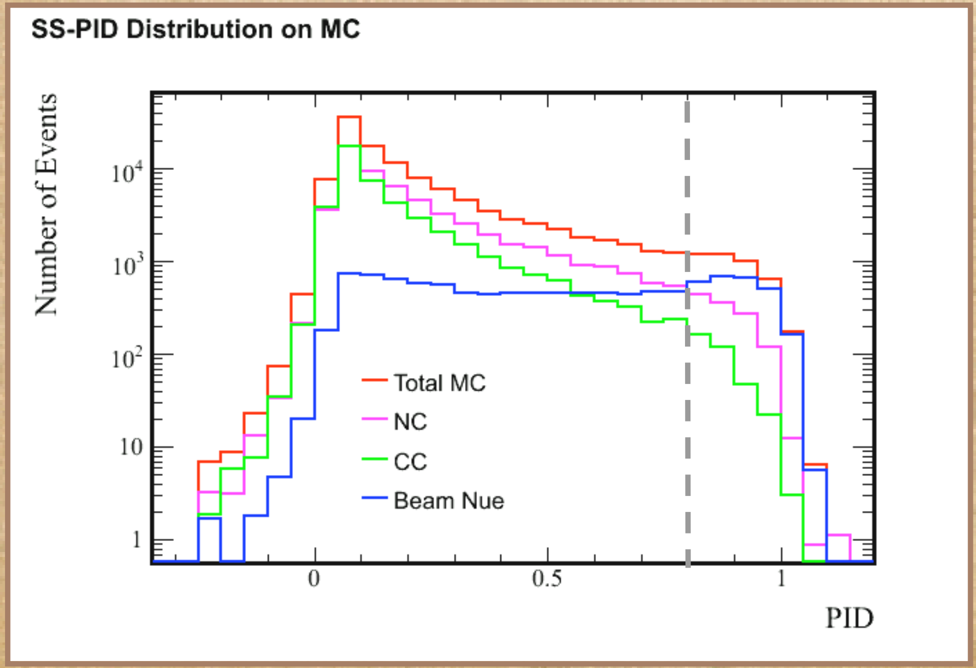
- The ν_e contamination in the beam derives from both pion and kaon decays
- Fitting hadronic production parameters using data in the Near Detector provides a first estimate of the beam nue background.

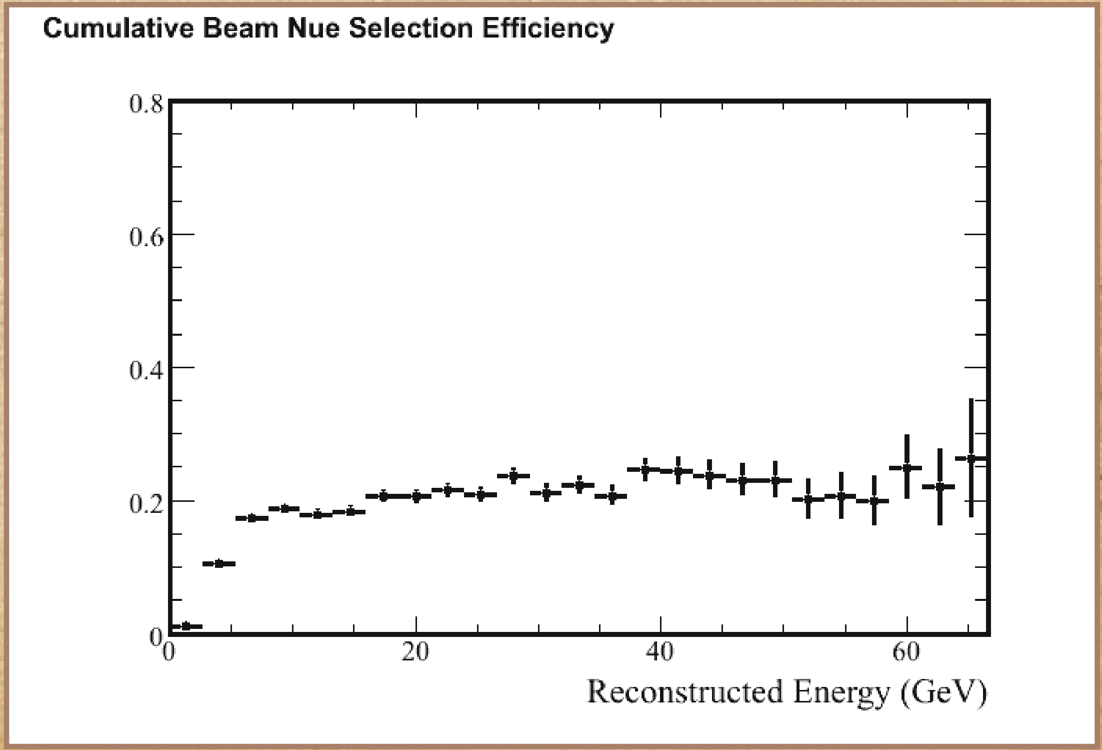
- $\pi^+ \rightarrow \nu_\mu \mu^+, \quad \mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$
- $K^+ \rightarrow \nu_e \pi^0 e^+$
- $K_L^0 \rightarrow \nu_e e^+ \pi^-$

Estimating beam ν_e background fitting the hadronic production

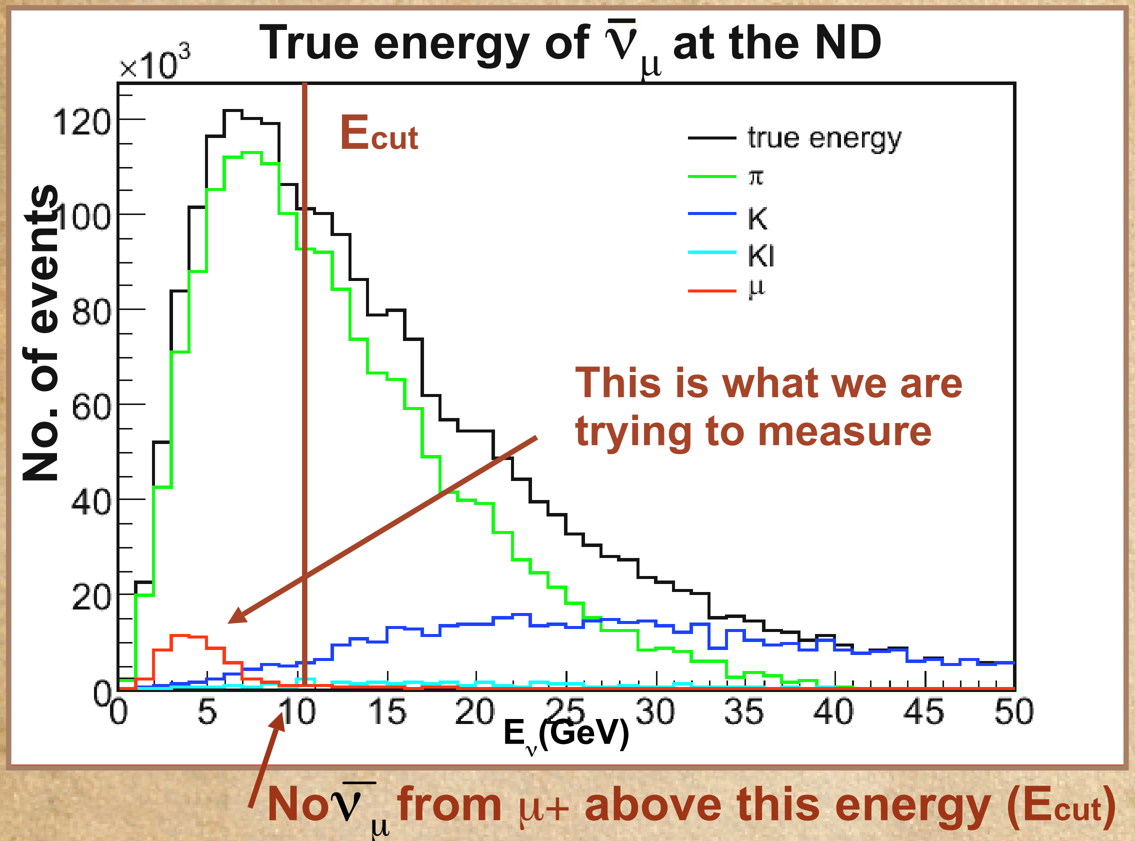
- The higher end of the spectrum allows us to add a separate set of constraints to the kaon production.
- A PID tuned to higher energy events can be used to extract kaon dominated beam nues.
- Very high purity and a flat efficiency for >10GeV.







Constraining the ν_e flux from $\bar{\nu}_\mu$ measurement



- Primary source of low energy beam ν_e is: $\mu^+ \rightarrow e^+\nu_e\bar{\nu}_\mu$
- A measurement of the low energy $\bar{\nu}_\mu$ can be used as another means to constrain the ν_e flux.
- Work on a PID and understanding of these events in the ND is in progress.
- The technique:

$$\phi_{\bar{\nu}}(\mu^+) = \phi_{\bar{\nu}}^{data}(\mu^+, \pi^-, K^{-/0}) - \phi_{\bar{\nu}}(\pi^-, K^{-/0})$$

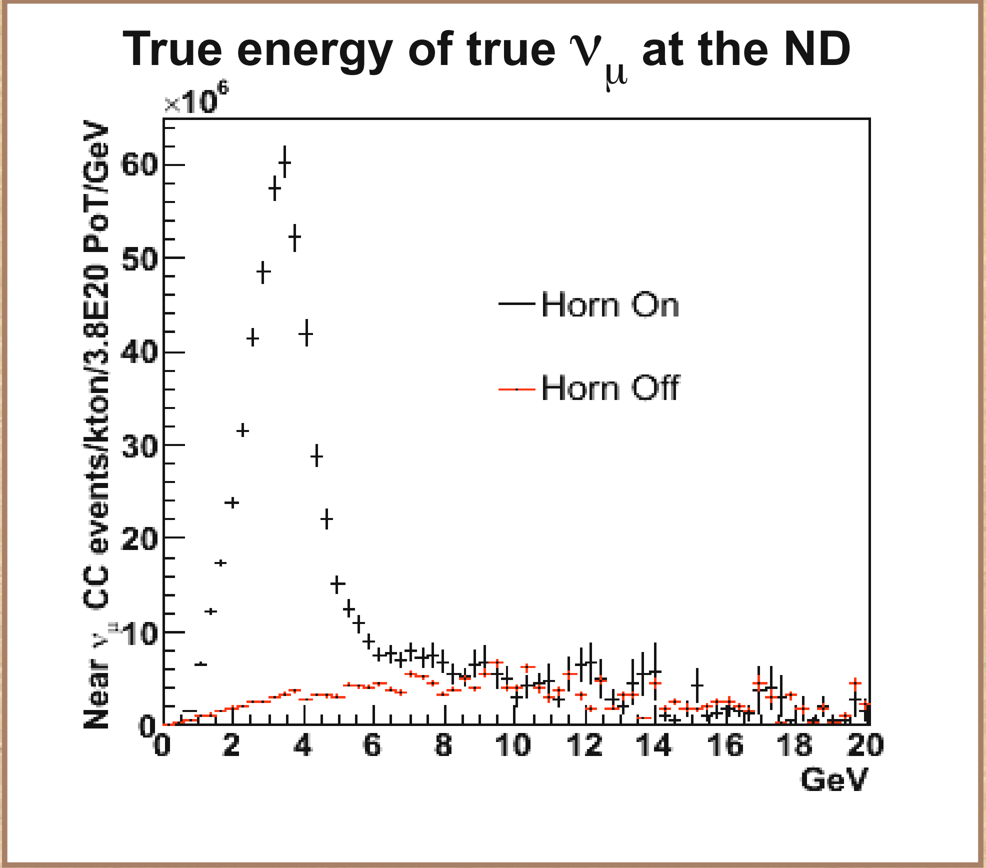
- Estimating pion and kaon antineutrino flux can be done from different techniques: horn off, beam fits, etc.

Estimating background uncertainties using horn off data

- If we turn off the horns, the pions will not get focused and the peak in the neutrino energy spectrum will disappear.
- Once we apply the ν_e selection cuts, we will get a NC-enriched sample.
- The measured flux of ν_e candidates with horns on and horns off can expressed as:

$$N^{on} = N_{NC} + N_{CC} + N_e \quad (1)$$
$$N^{off} = r_{NC} * N_{NC} + r_{CC} * N_{CC} + r_e * N_e \quad (2)$$

which can be solved to get the NC and ν_μ CC background.



N_{NC}, N_{CC}: NC, ν_μ CC background with horn on – will be calculated based on eqn. (1) and (2)

N_e: beam ν_e background with horn on – **from MC or data**

$r_{NC(CC,e)} = N_{NC(CC,e)}^{off} / N_{NC(CC,e)}$ – **from MC**

Estimating background uncertainties using horn off data

- The advantage of this technique: it can separate different backgrounds and estimate the uncertainty of each component.
- Using a MC simulation with: 8.0×10^{18} POT horn off and 1.4×10^{19} POT horn on data; scaled to horn off data taken.
- We measure:

$N^{on} = 1752.6 \quad \delta N^{on} = 16.2$; $N^{off} = 681.0 \quad \delta N^{off} = 26.1$

- We input and calculate:

$r_{NC} = 0.532 \quad r_{CC} = 0.129 \quad r_e = 0.192$, $\delta r/r = 10\%$

$N_e = 199.2 \qquad \delta N_e = 39.8$ – assign a 20% systematic error

Expected background at ND for 2.73×10^{18} POT

	NC	ν_μ CC	Tot. bg.
background	1096.9±159.7	456.5±164.4	**1752.6±232.6**
error	14.6%	36.0%	**13.3%**

The optimistic scenario

Estimating background uncertainties using horn off data

- The advantage of this technique: it can separate different backgrounds and estimate the uncertainty of each component.
- For a MC simulation with: 8.0×10^{18} POT horn off and 1.4×10^{19} POT horn on data.
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$N^{on} = 1752.6 \quad \delta N^{on} = 16.2$; $N^{off} = 681.0 \quad \delta N^{off} = 26.1$

- We input and calculate:

$r_{NC} = 0.532 \quad r_{CC} = 0.129 \quad r_e = 0.192$, $\delta r/r = 10\%$

$N_e = 199.2 \quad \delta N_e = 199.2$ – assign a 100% systematic error

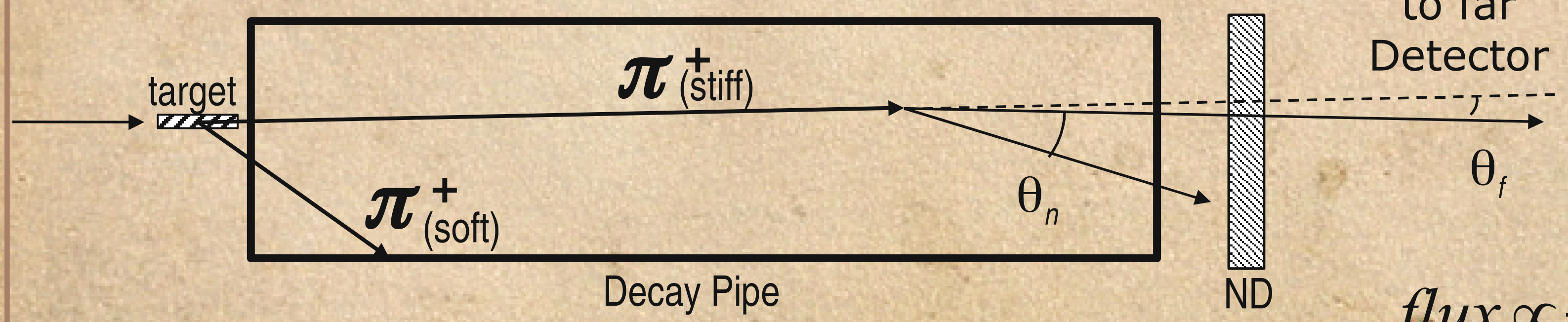
Expected background at ND for 2.73×10^{18} POT

	NC	ν_μ CC	Tot. bg.
background	1096.9±162.5	456.5±232.8	**1752.6±346.8**
error	14.8%	51.0%	**19.8%**

NC uncertainty under control, total bg. error ranges from 13-20%

Predicting the FD background for the ν_e measurement

- As in the Charged Current analysis we will use the Near Detector data to perform extrapolation between Near and Far.
- We will use our knowledge of pion/kaon decay kinematics and geometry of our beamline to predict the FD expected background rate from the measured ND background components.



$$E_\nu = \frac{0.43\, E_\pi}{1+\gamma^2\theta^2}$$

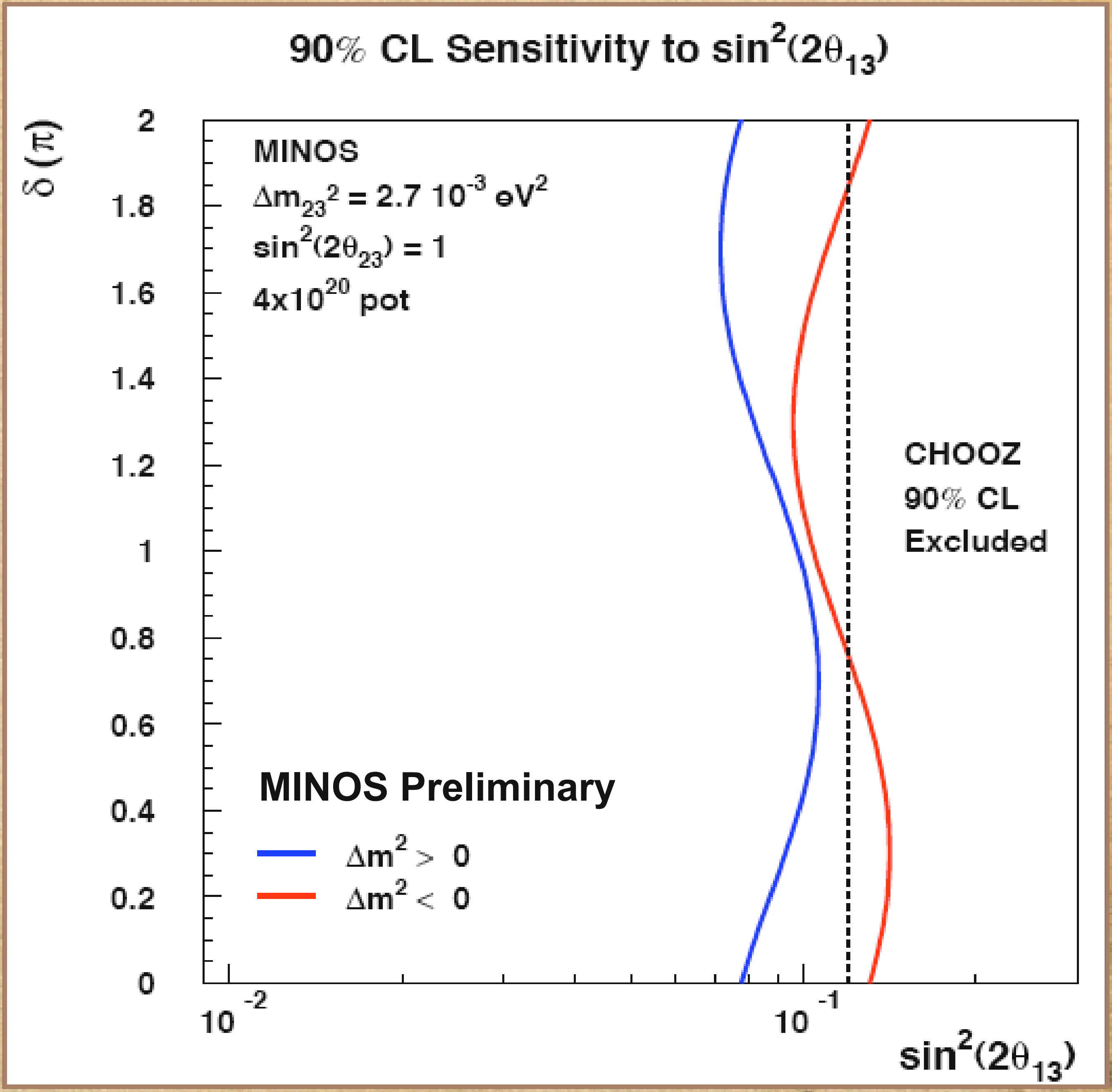
$$flux \propto \frac{1}{L^2}\left(\frac{\gamma}{1+\gamma^2\theta^2}\right)^2$$

- The ν_τ background will instead be estimated from MC to be: 1.3±1.1(stat)± 0.5(syst) for $4\mathrm{x}10^{20}$POT.

Physics reach of MINOS

ν_e appearance

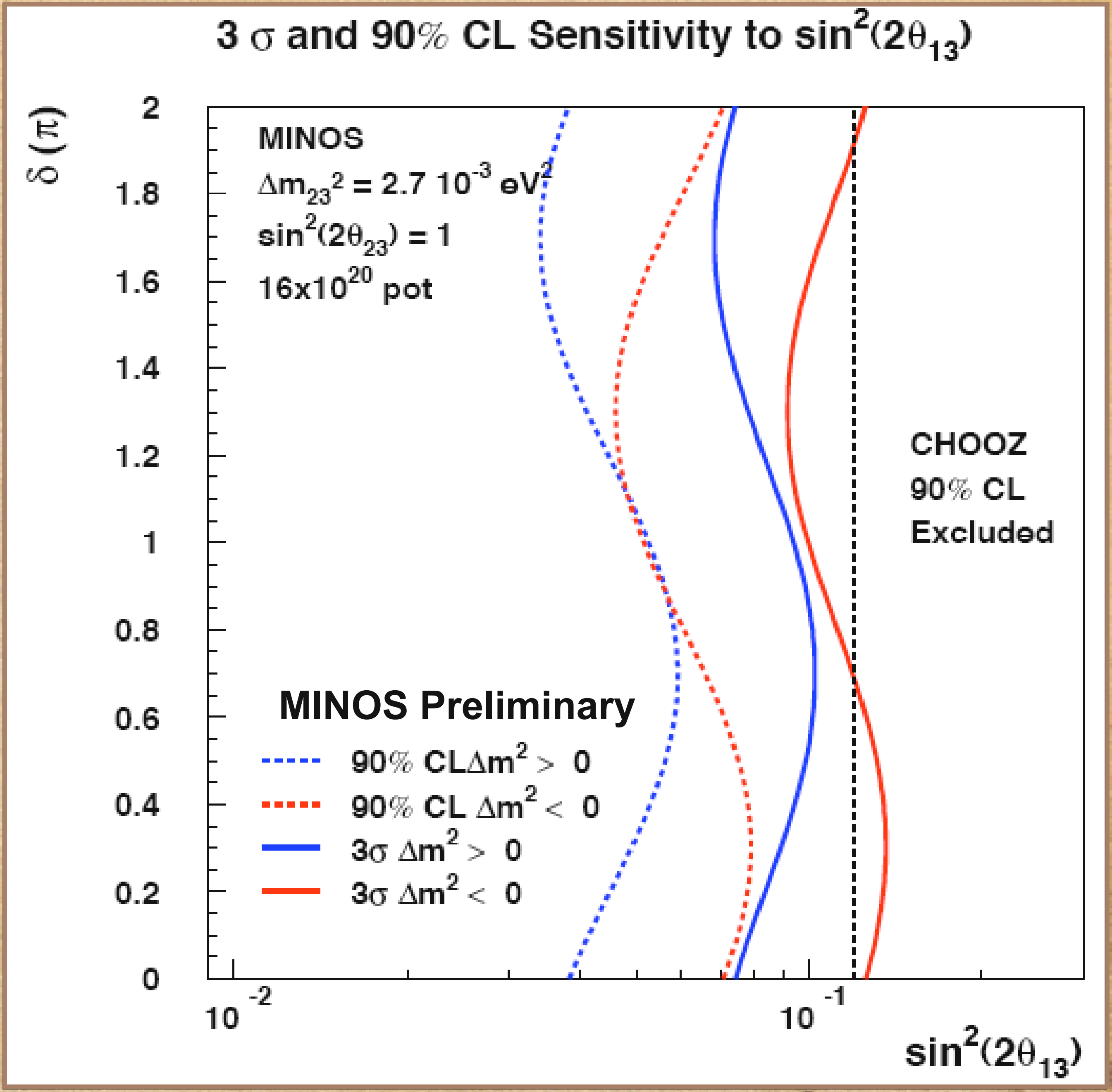
- We have a chance at making the first measurement of θ_{13}.
  - Matter effects can change ν_e yield by as much as ±20%
- Plot shows δ_{CP} vs. $\sin^2 2\theta_{13}$ for both hierarchies for MINOS best fit value at 4×10^{20} POT
  - 10% systematic effect included
- We can improve on current best limit (Chooz).



Physics reach of MINOS

ν_e appearance

- We have a chance at making the first measurement of θ_{13}.
  - Matter effects can change ν_e yield by as much as ±20%
- Reach depends on POT
  - With 16x10^{20} POT we can make significant improvements to the current best limit and improve the chances of a discovery.



Summary

- We have a number of independent techniques to evaluate the background components for the ν_e appearance measurement.
- We will extrapolate these measurements in order to predict the background rate in the Far Detector.
- Expect $4x10^{20}$POT next year!

Backup Slides

Systematics for CC analysis

- Normalization: ± 4 %
  - POT counting, Near/Far selection efficiency
- Relative shower energy scale: ± 3%
  - Inter-Detector calibration uncertainty
- Muon energy scale: ±2%
  - Uncertainty in dE/dX in MC
- NC contamination of CC-like sample: ± 30%
  - From shape and normalization of ND PID distributions
- CC cross-section uncertainties
  - M_A(QEL) and M_A (RES): ± 5%
  - KNO RES-DIS scaling factor: ± 20%
- Intranuclear rescattering: ± 10% shower energy scale uncertainty
- Beam uncertainty: difference between fits and weighted/ unweighted MC