Identifying ν_e CC events in MINOS

J. Pedro Ochoa
California Institute of Technology

DPF 2009

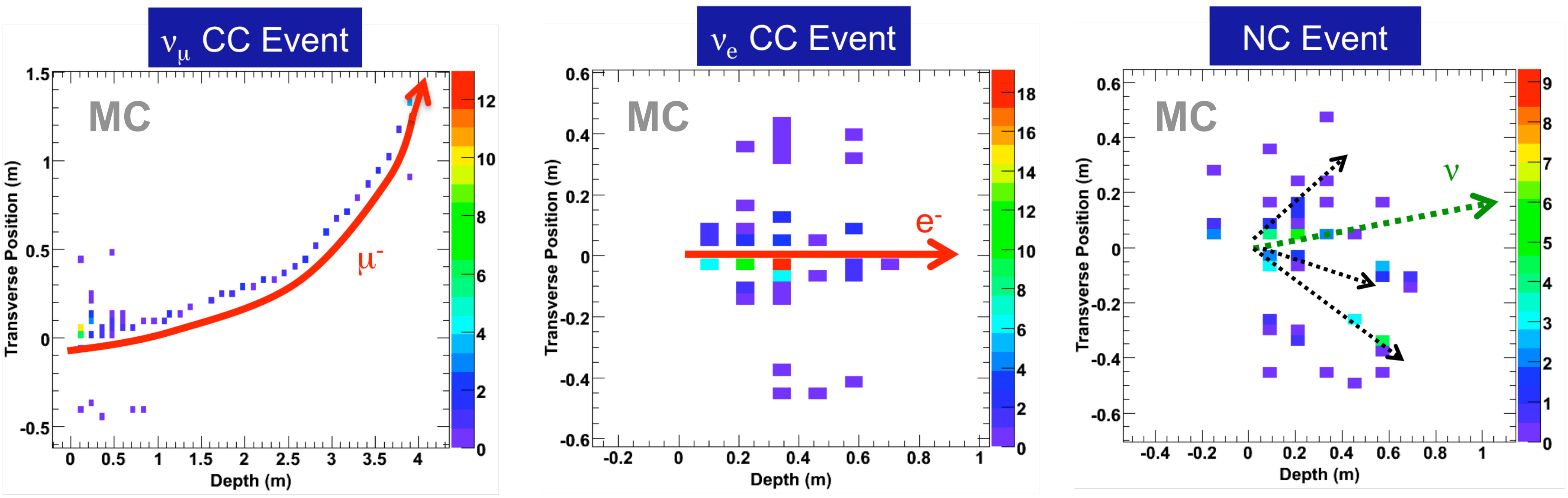
Detroit, MI - July 27th 2009

ν_e CC identification in MINOS

- **ν_e appearance gives us access to θ_{13}**: $P(\nu_\mu \rightarrow \nu_e) \cong \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \frac{\Delta m^2_{23} L}{4E}$

- **Challenge:** our detectors were not designed for this kind of measurement:

EM Showers in MINOS	Detector Parameters
Radiation length: 4.06 cm	Plane separation: 5.95 cm
Molière radius: 3.7 cm	Strip width: 4.12 cm

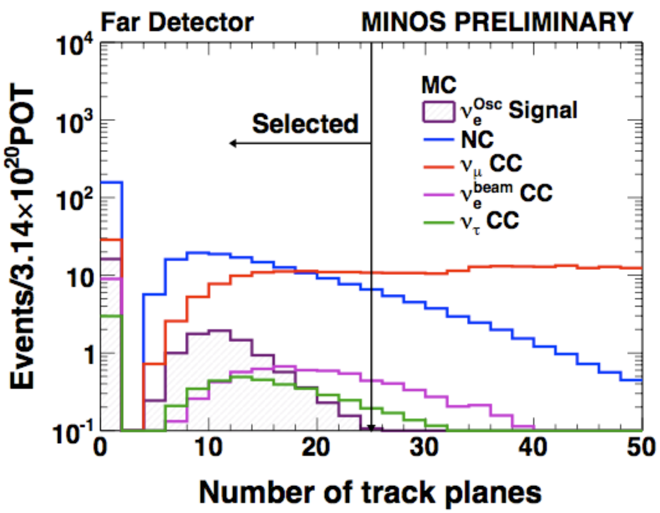


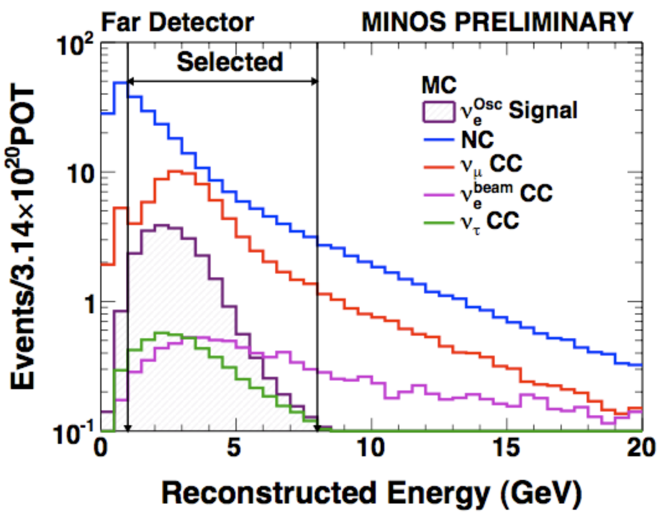
- **ν_e CC**: compact showers with a typical EM profile
- **NC**: typically more diffuse but can contain energetic π^0 that mimics ν_e CC

- **Need to separate the signal from the background as well as possible**

ν_e CC preselection

- It is advantageous to first remove the obvious background through a preselection:



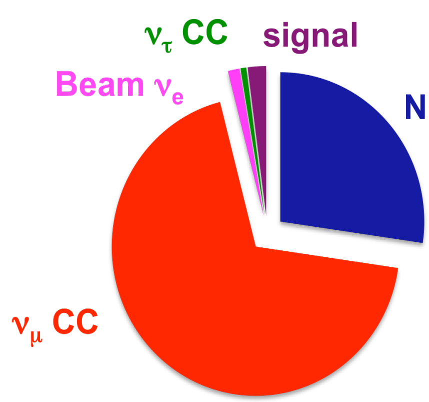


Apply a series of cuts on:

- Track length
- Reconstructed energy
- Existence of reconstructed shower
- Contiguous planes

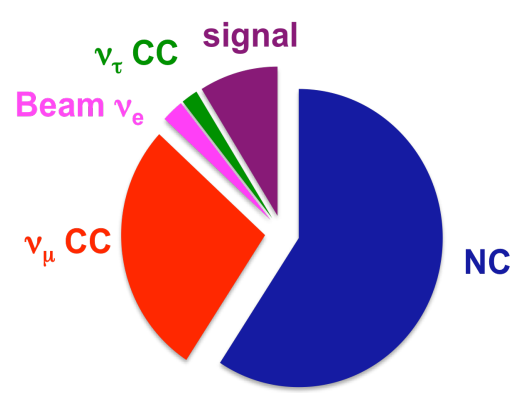
- Only 21% of the signal is removed
- Signal/background ratio goes from 1:55 to 1:12
- A more sophisticated technique is needed to further enhance signal-background separation

Before Preselection



Signal:background 1:55

After Preselection

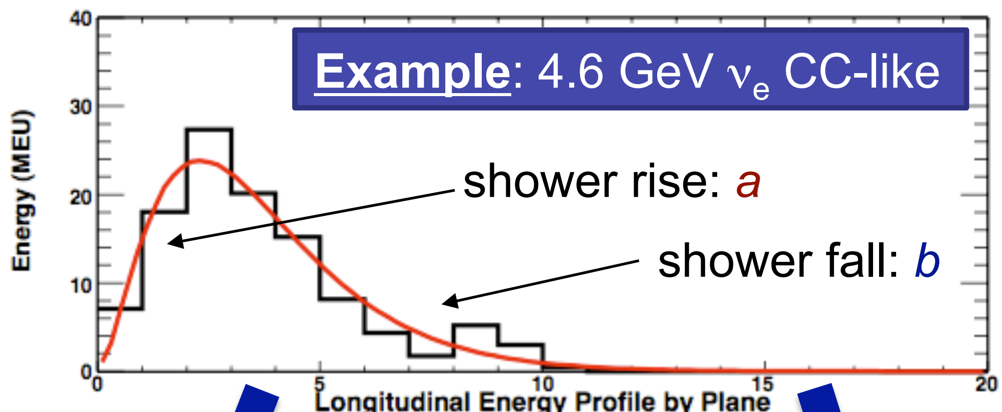


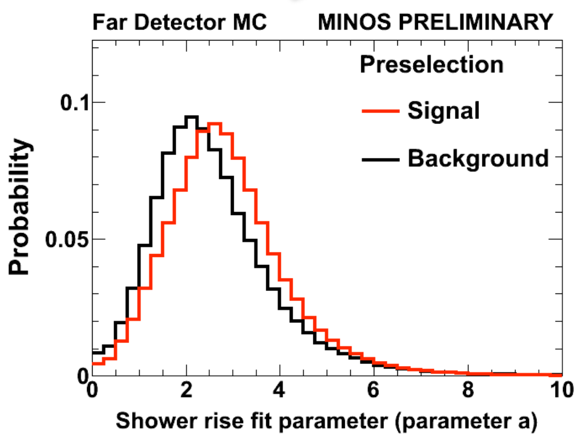
Signal:background 1:12

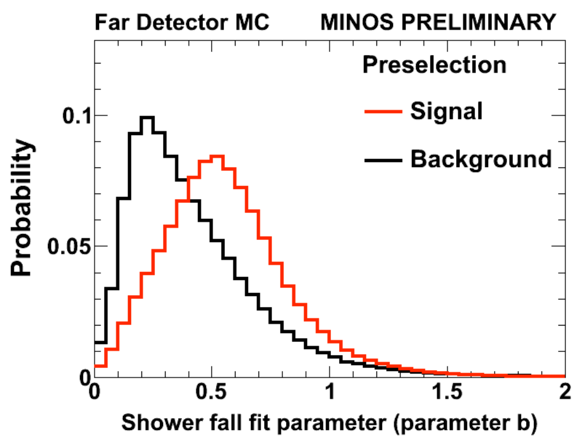
Method #1: a Neural Network

✓ **One approach is to use a neural network.**

❖ **Variables are constructed that characterize showers in the longitudinal and transverse directions**







❖ Longitudinally, the profile is fit to a gamma function:

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

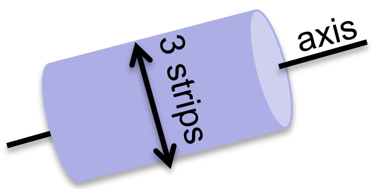
❖ For the longitudinal characterization also use:

- ✓ Fraction of energy deposited within 2, 4, 6 planes.
- ✓ Longitudinal energy projection.

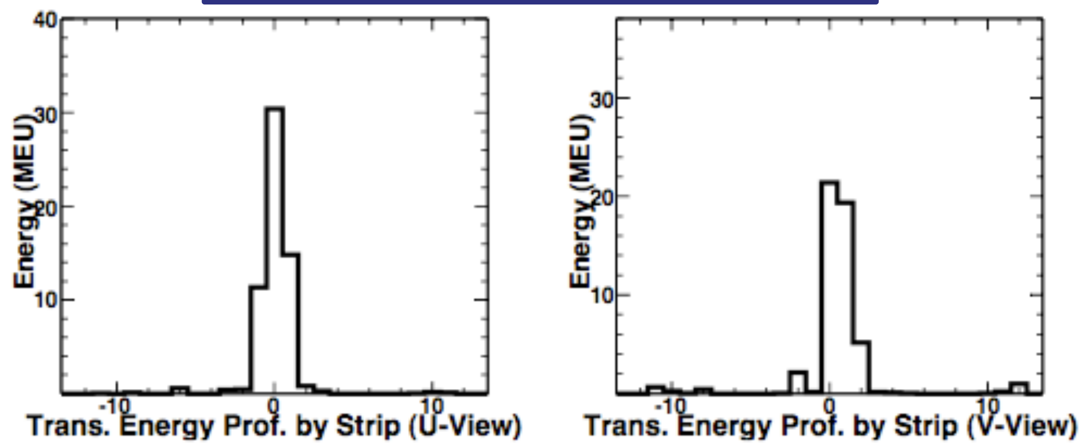
(shown in backup)

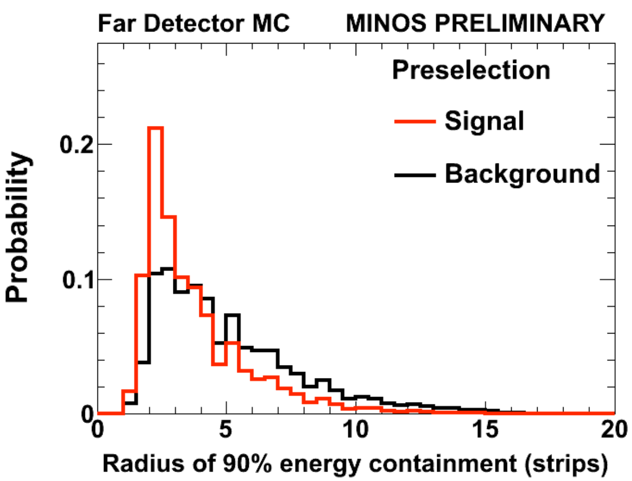
Shower width

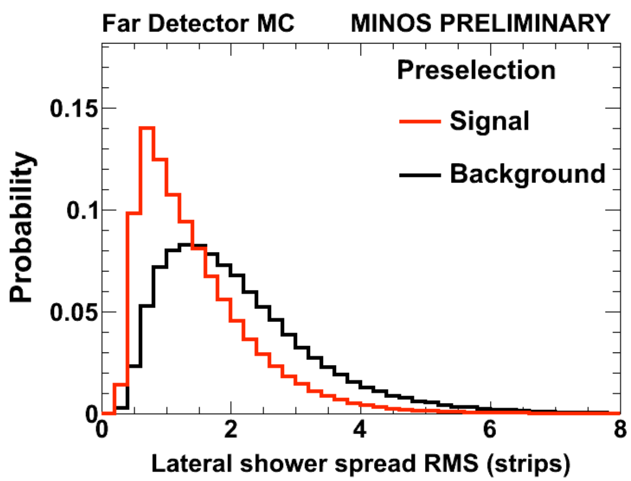
- Transversely, ν_e CC showers are **narrower** than NC showers.
- Quantify that through:
  - ✓ 90% containment radius
  - ✓ Lateral shower spread RMS
  - ✓ Fraction of ph deposited within 3 strips along shower axis

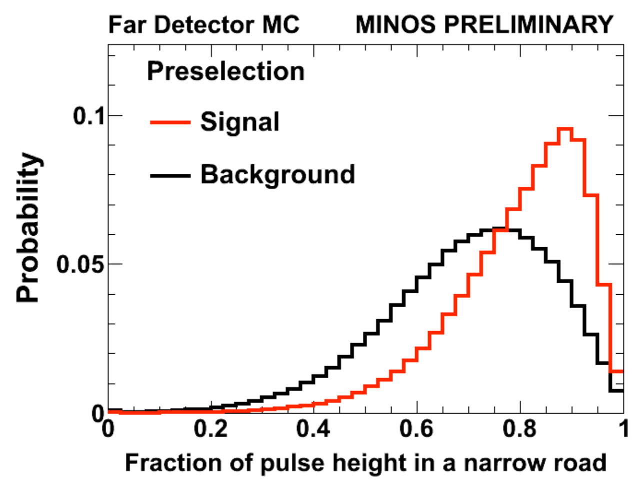


Example: 4.6 GeV ν_e CC-like



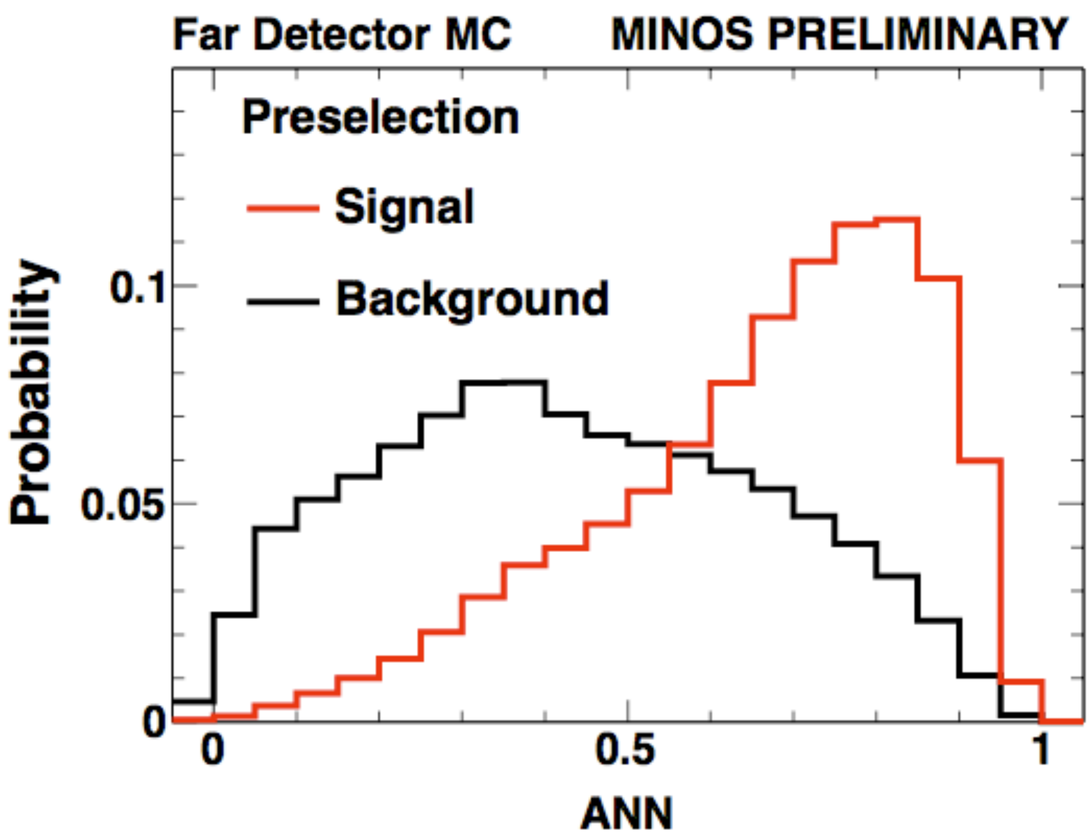






The ANN selection

- 11 variables that describe the shower's width, length and shape are combined into an artificial neural network (ANN):



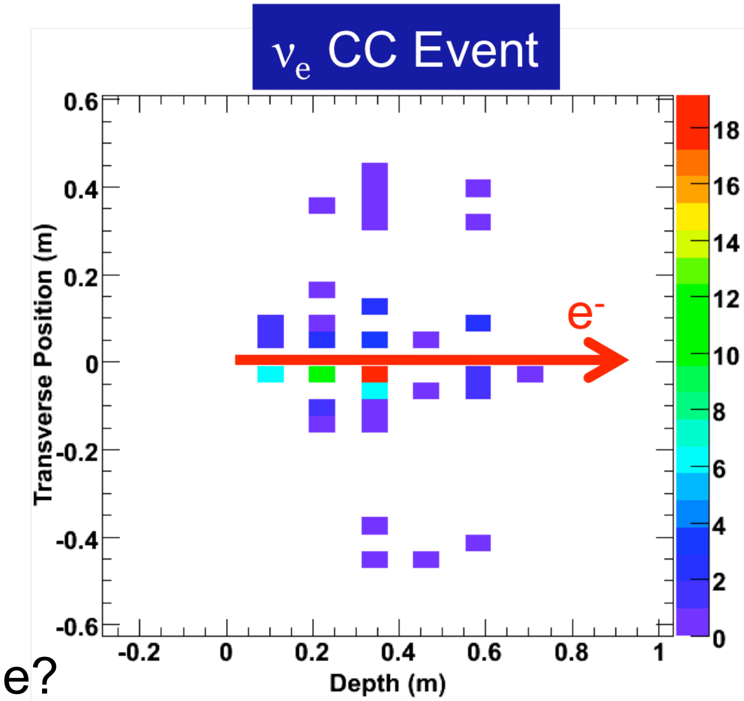
- **Signal/background goes from 1:12 to 1:3 with ANN**

Method #2: a Nearest Neighbors approach

MINOS

✓ **The other approach is to perform event ID based on the hit information alone.**

- The amount of information present in each candidate ν_e CC event is not that large:
  - Only ~25 strips are hit in average during each ν_e CC event in the energy region of interest.
  - Why not use all of the information available?



- **Advantages:**

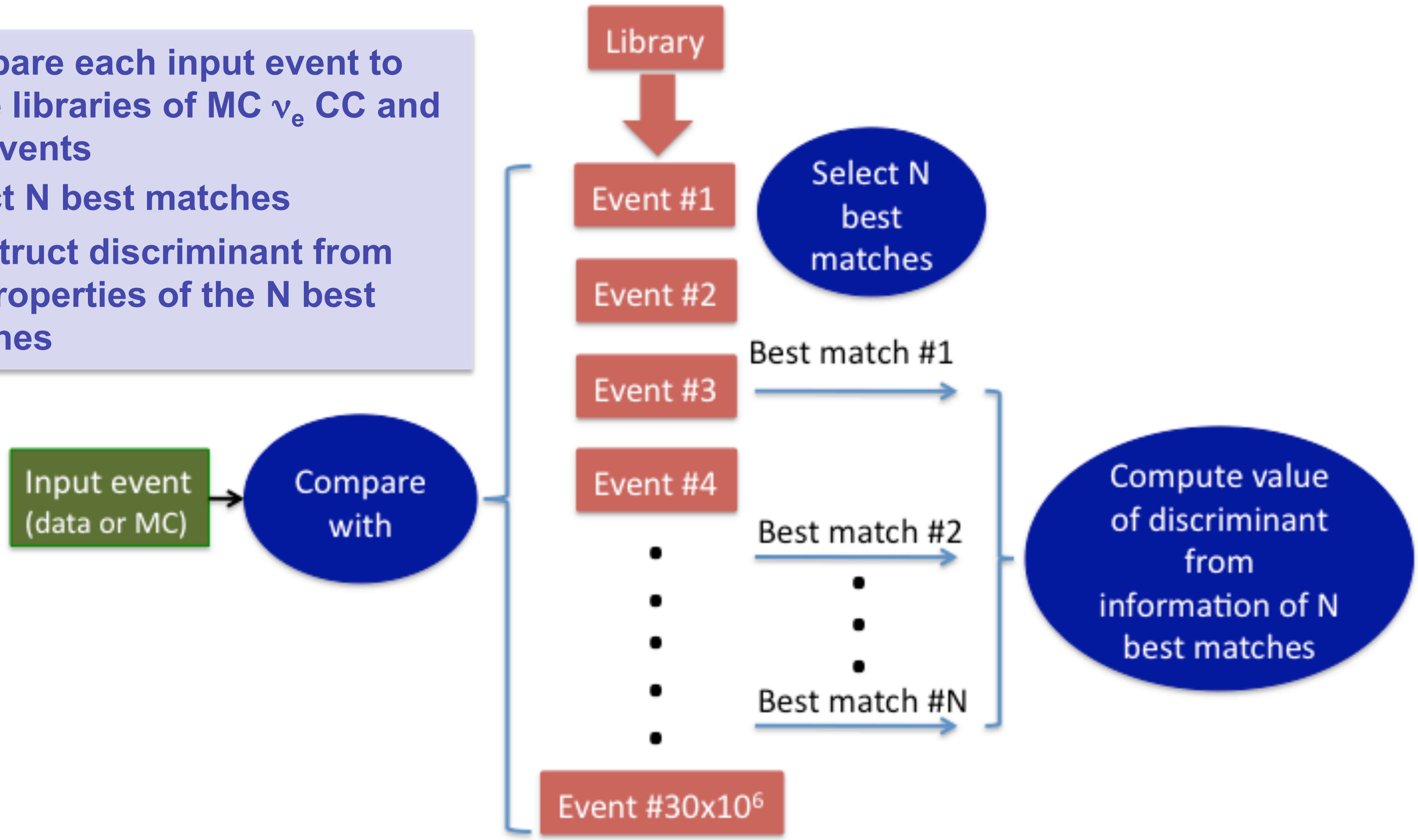
✓ **Can achieve optimal results, as there is no loss of information when going from raw → reconstructed quantities**

✓ **Less reconstruction dependent.**

LEM's basic concept

❖ We achieve this through the "Library Event Matching" (LEM) selection:

1) Compare each input event to large libraries of MC ν_e CC and NC events
2) Select N best matches
3) Construct discriminant from the properties of the N best matches



→ ν_e identification is turned into a pattern recognition problem!

Event comparison

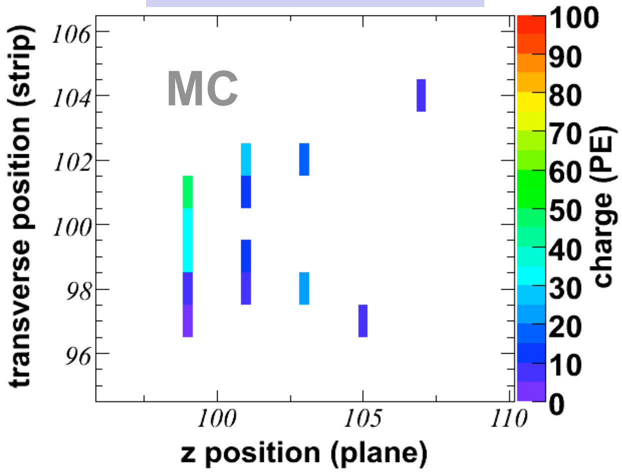
❖ **We quantify how well two events match by asking:**

"what is the likelihood that the two events come from the same energy deposition pattern?"

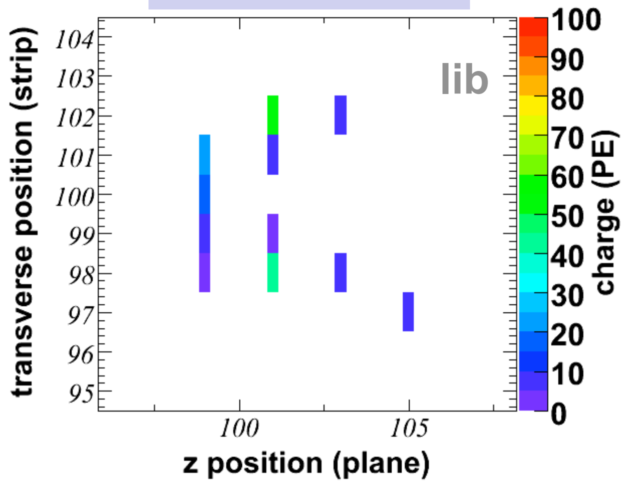
$$\mathcal{L} = \sum_{pl}\sum_{st} \ln\left(\int_0^\infty P(n_1,\lambda)P(n_2,\lambda)\,d\lambda\right)$$

Poisson

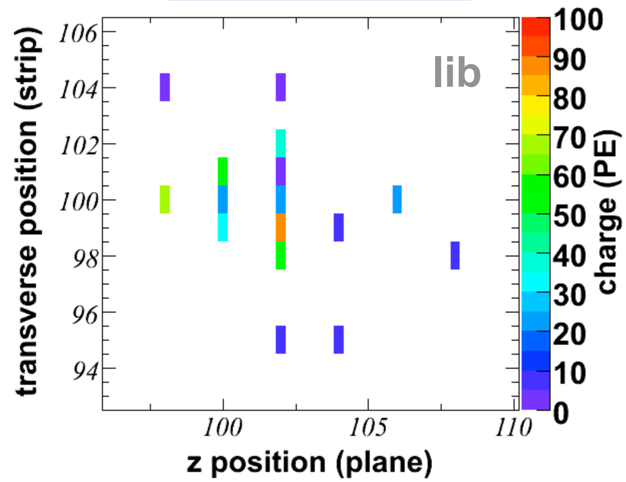
Original event



✓Good match



X Bad match

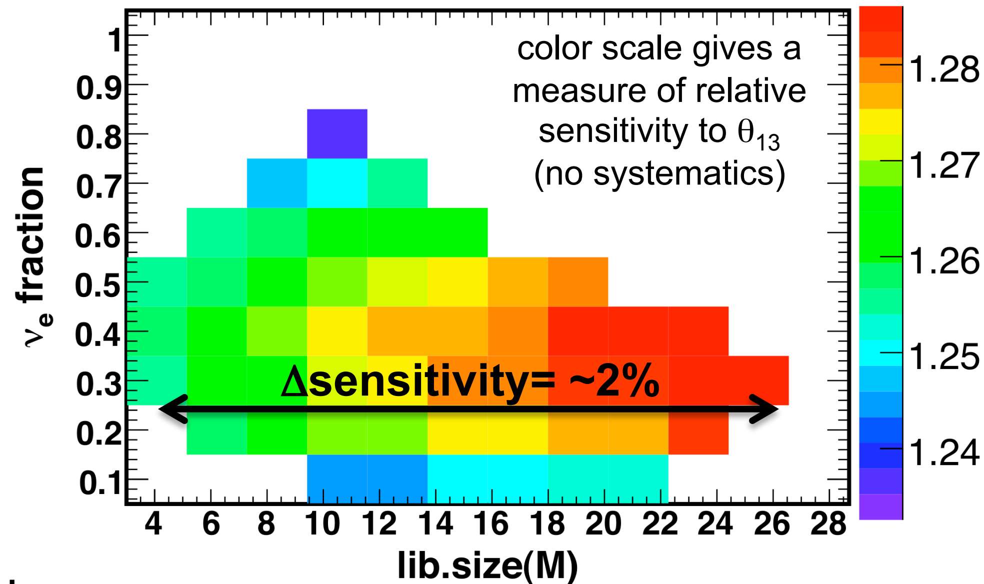


Making the most of LEM

- **LEM has undergone a full optimization:**

Note: ν_e fraction is the fraction of signal events in the library

Sensitivity vs. lib size and ν_e fraction

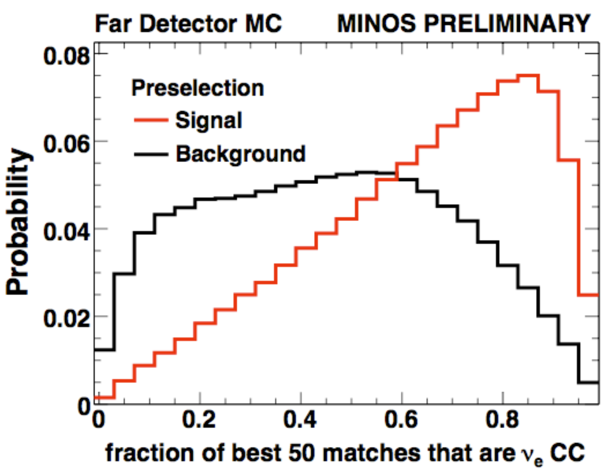


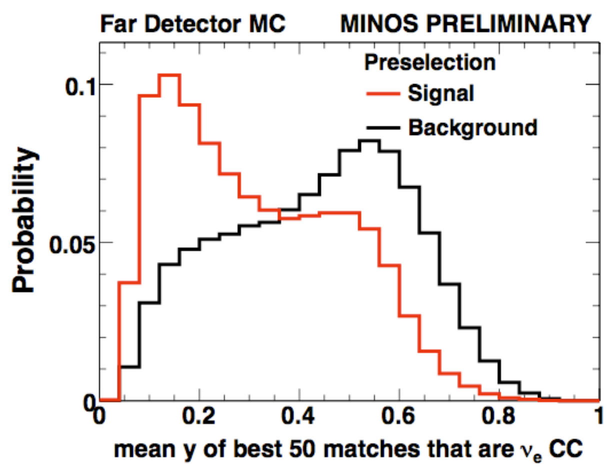
- Some important lessons learned:

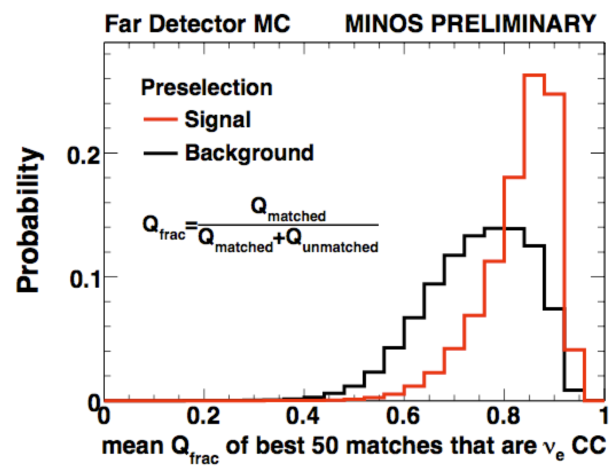
  - ✓ **Performance is <u>largely insensitive</u> to the number of best matches N used (small maximum at N≈50).**
  - ✓ **As expected, sensitivity <u>increases with library size</u> (for this analysis used 30M events)**
  - ✓ **Sensitivity <u>peaks when signal-background mixture in library is about 1/3 - 2/3</u>**

Making the most of LEM

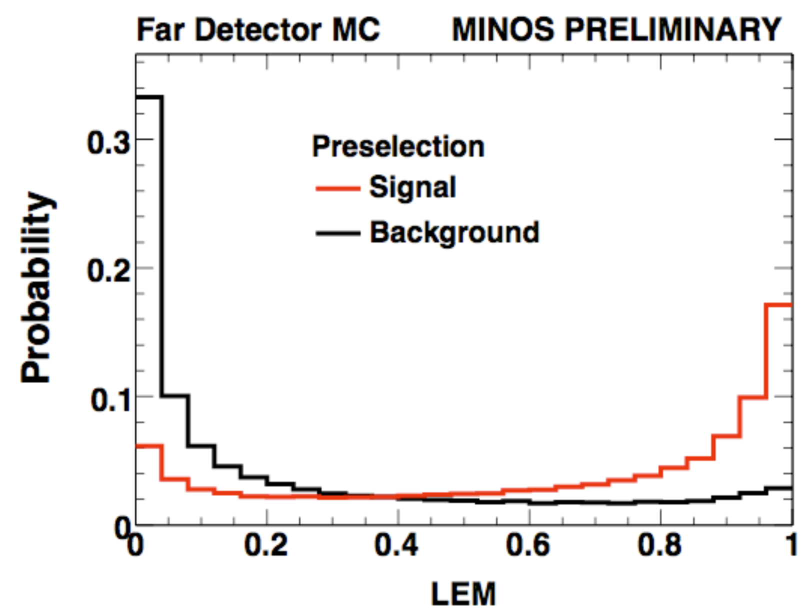
- **To maximize the sensitivity need to use the information of the N best matches, which is very rich:**







- More information than just the event type is useful as some signal events look like background (and vice versa).
- These three variables are combined into an energy binned likelihood with a bin width of 0.5 GeV.



Overall performance

MINOS

- **Number of FD predicted events:**

	Signal*	Total background	Systematic error on background
LEM	**11.0**	**21.4**	**12%**
ANN	**10.3**	**26.6**	**7%**

(* signal assuming θ_{13} at the CHOOZ limit, with no CP violation and no matter effects)

- **Both methods have an average sensitivity that is better than CHOOZ for the full analysis with 7.0×10^{20} POT**

  - **And LEM has at least 10% higher sensitivity to θ_{13} than other selection methods, with at least ~30% higher signal to background ratio.**

- LEM is still under development:
  - LEM was not used to derive the contours on θ_{13} for our first analysis, but was still used as a secondary selection method.
  - Very promising work is underway to reduce the systematic error in LEM, further improving its sensitivity.

Summary & Outlook

- **The task of ν_e CC identification is challenging in MINOS**
  - It is also the main key to MINOS' reach in θ_{13}
- **Two methods have been developed and fully optimized that enhance signal to background separation:**
  - The ANN method combines 11 variables that characterize the shower's shape.
  - The LEM method performs event ID based on the energy deposition pattern alone.
- **Both methods were used in the first analysis, and are undergoing improvements for the full analysis with 7×10^{20} POT.**

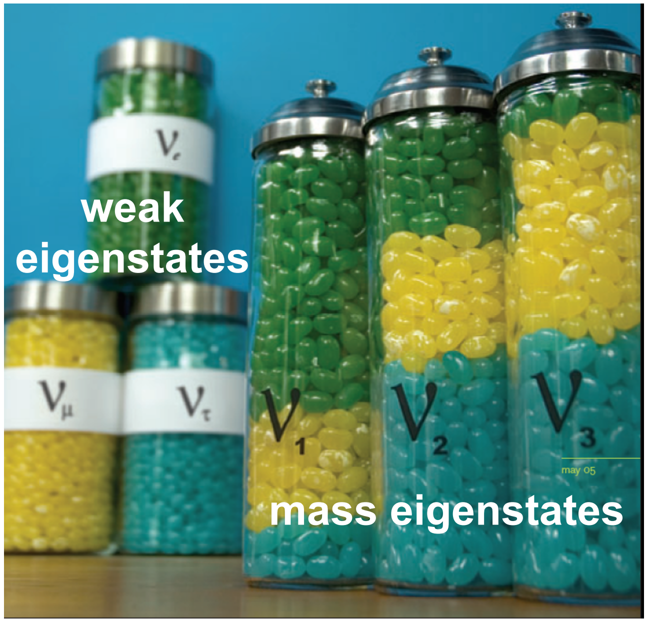
With these methods, MINOS is making the most of its full dataset for the ν_e appearance search.

Backup

The search for θ_{13}

MINOS

❖ The discovery that neutrinos have mass has **revolutionized** their place in physics and in our universe:



weak eigenstates ≠ mass eigenstates ➡ $|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric $\theta \sim 45°$ | Cross-Mixing | Solar $\theta \sim 34°$ | Majorana CPV phases

❖ A pressing question: **is the θ_{13} mixing angle zero or just very small?**

- ➢ **θ_{13} is inextricably linked to leptonic CP violation.**
- ➢ **Leptonic ~~CP~~ could have important implications in cosmology (i.e. leptogenesis)**
- ➢ **Through θ_{13}-driven ν_e appearance experiments like NOvA and T2K have a chance to address the neutrino mass hierarchy.**
- ➢ **A zero θ_{13} could point to an unknown symmetry in physics.**

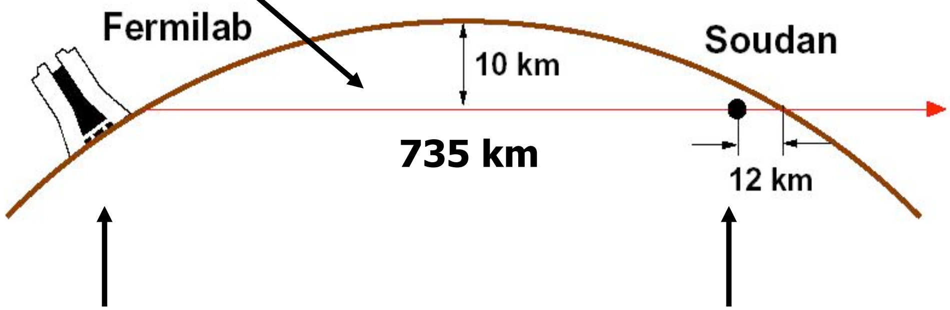
❖ The world's best limit is set by CHOOZ: $\sin^2(2\theta_{13}) < 0.15$ (for $|\Delta m_{32}|^2 = \sim 2.5\times10^{-3}\,eV^2$)

➢ **MINOS has a chance of making the first measurement of a non-zero θ_{13}**

The MINOS Experiment

- **MINOS (<u>M</u>ain <u>I</u>njector <u>N</u>eutrino <u>O</u>scillation <u>S</u>earch)** is a long-baseline neutrino oscillation experiment:

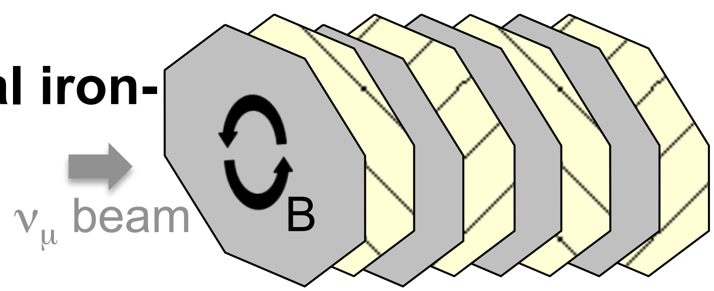
The <u>NuMI ν_μ beam</u> provided by 120 GeV protons from the Fermilab Main Injector



A <u>Near detector</u> at Fermilab to measure the beam composition and energy spectrum.

A <u>Far detector</u> at the Soudan Mine in Minnesota to search for neutrino oscillations.

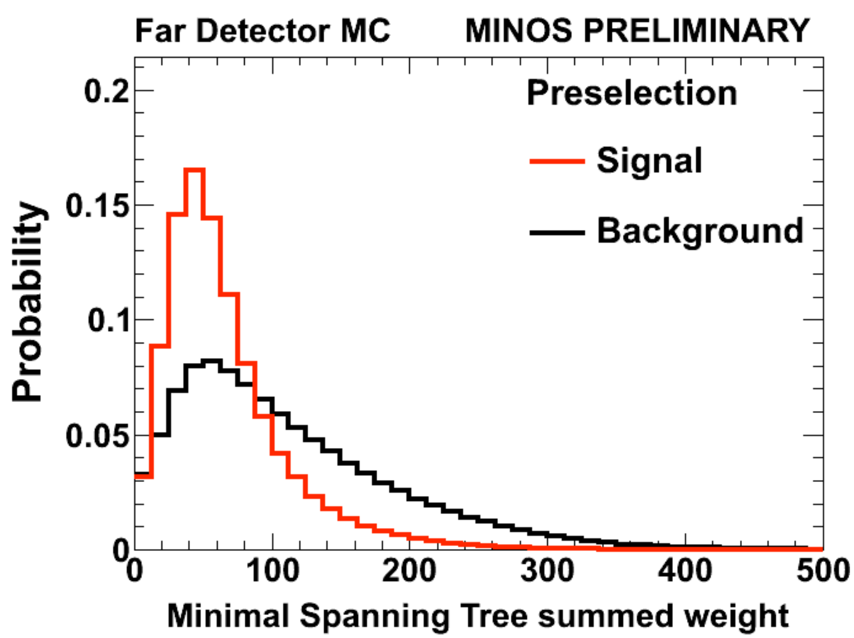
- **Both detectors are functionally identical iron-scintillator sampling calorimeters**
  - **Alternating scintillator planes have strips perpendicular to one another.**

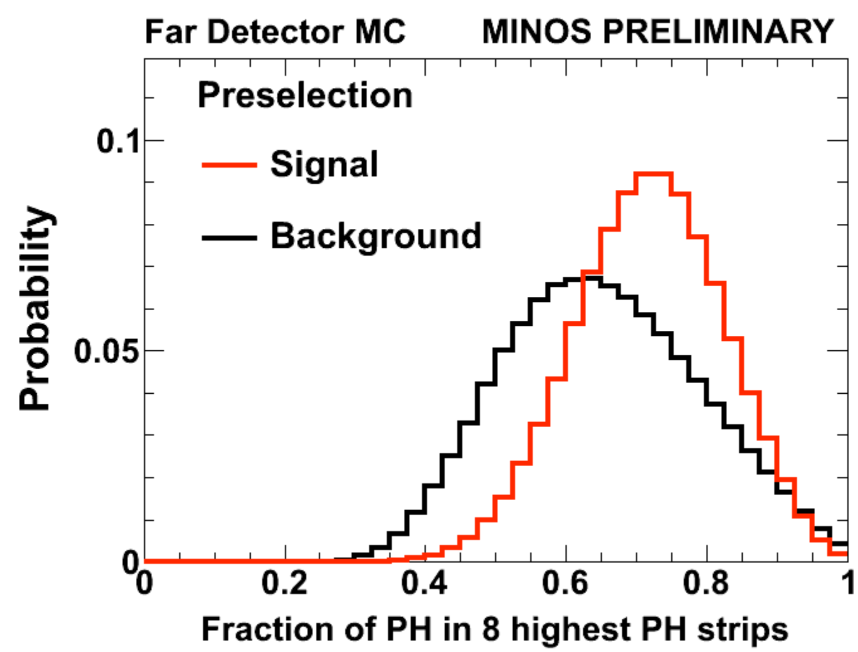


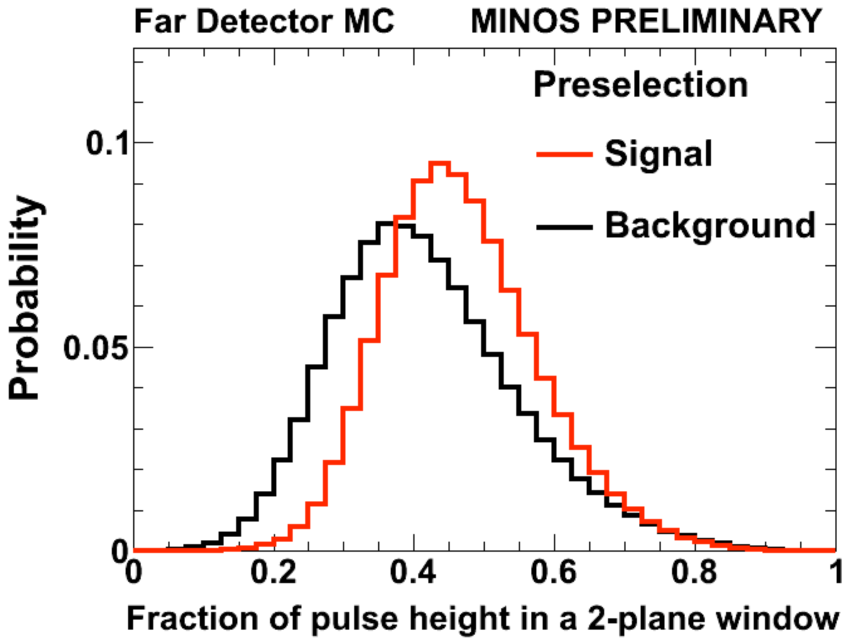
Two other variables in ANN

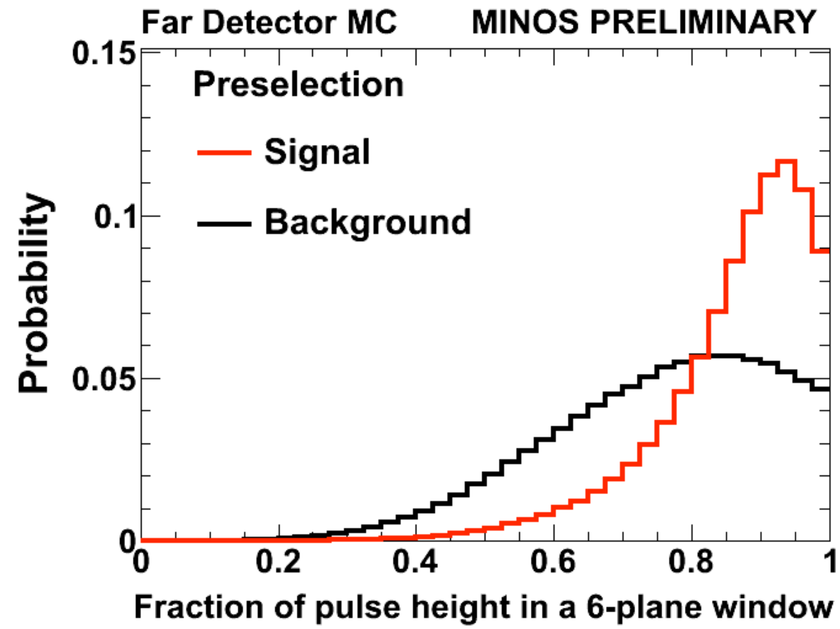
MINOS

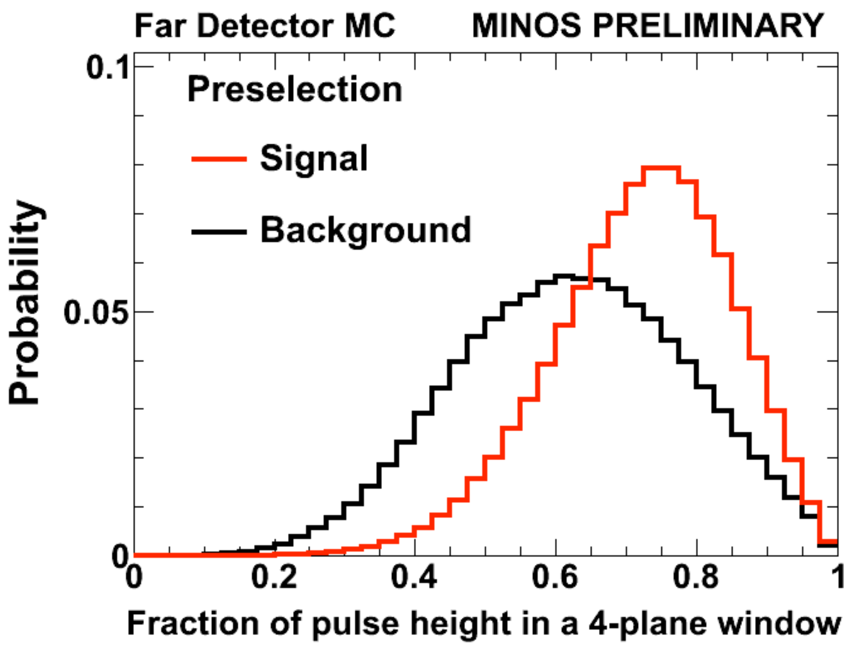
- **Minimal spanning tree summed weight:** the sum of the minimum distances that join the hits of larger than average pulseheight hits in an event.
- **Fraction of pulseheight in 8 highest PH strips:** the fraction of pulseheight in the highest 8 strips divided by the event energy.

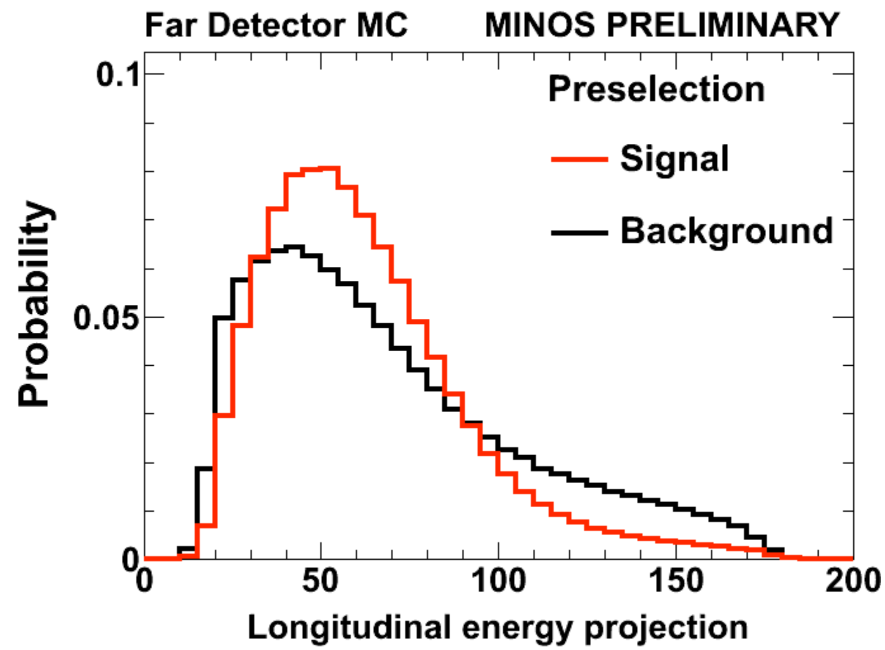





Far Detector MC
MINOS PRELIMINARY
Preselection
Signal
Background
Probability
0.1
0.05
0
0.2
0.4
0.6
0.8
1
Fraction of pulse height in a 2-plane window


Far Detector MC
MINOS PRELIMINARY
Preselection
Signal
Background
Probability
0.15
0.1
0.05
0
0.2
0.4
0.6
0.8
1
Fraction of pulse height in a 6-plane window


Far Detector MC
MINOS PRELIMINARY
Preselection
Signal
Background
Probability
0.1
0.05
0
0.2
0.4
0.6
0.8
1
Fraction of pulse height in a 4-plane window

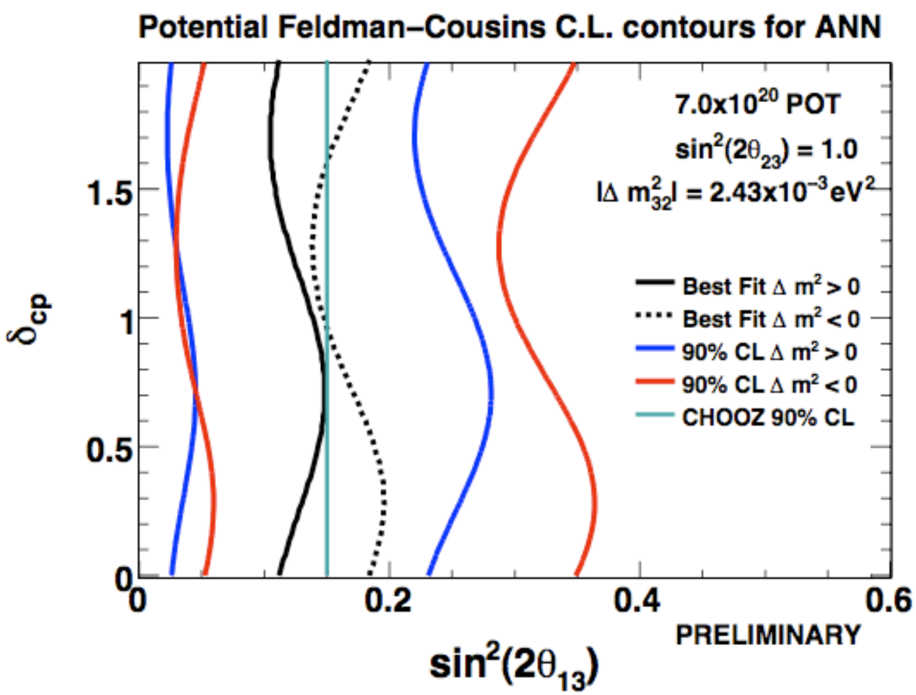

Far Detector MC
MINOS PRELIMINARY
Preselection
Signal
Background
Probability
0.1
0.05
0
50
100
150
200
Longitudinal energy projection

Looking to the future (ANN)

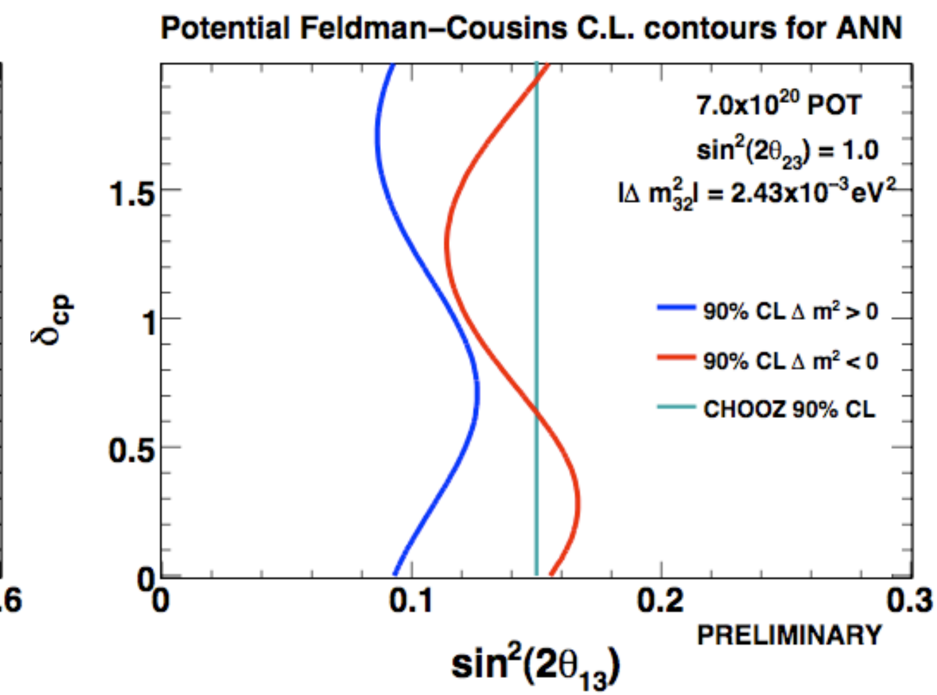
MINOS

- Future 90% C.L. exclusion contours for ANN at 7×10^{20} POT:

if excess persists



if data=expectation



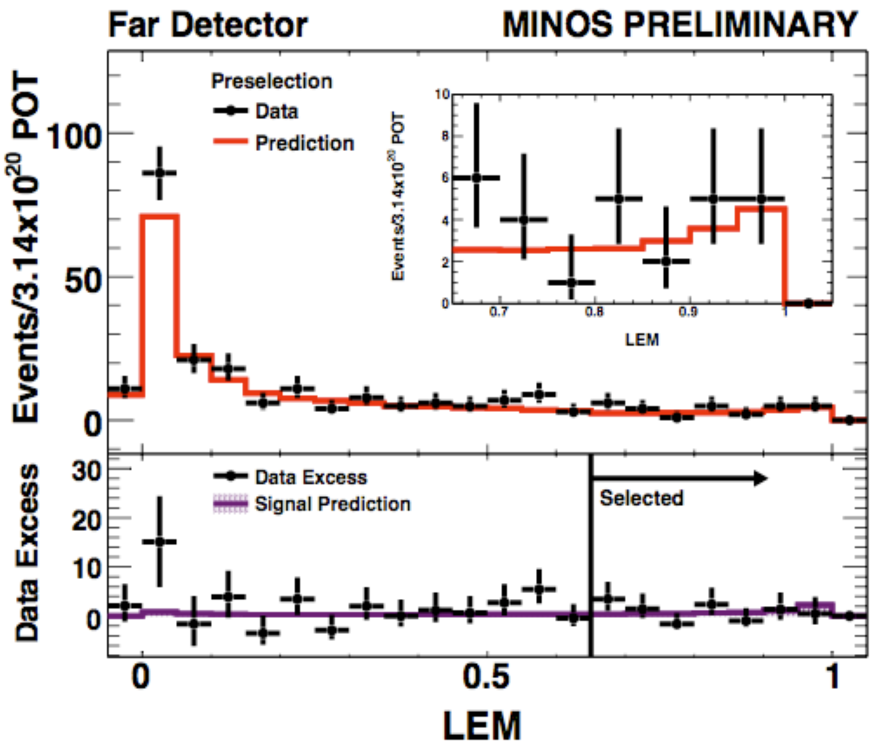
- **With ANN, if the excess persists it would be distinguishable from $\theta_{13}=0$ at 90% C.L.**

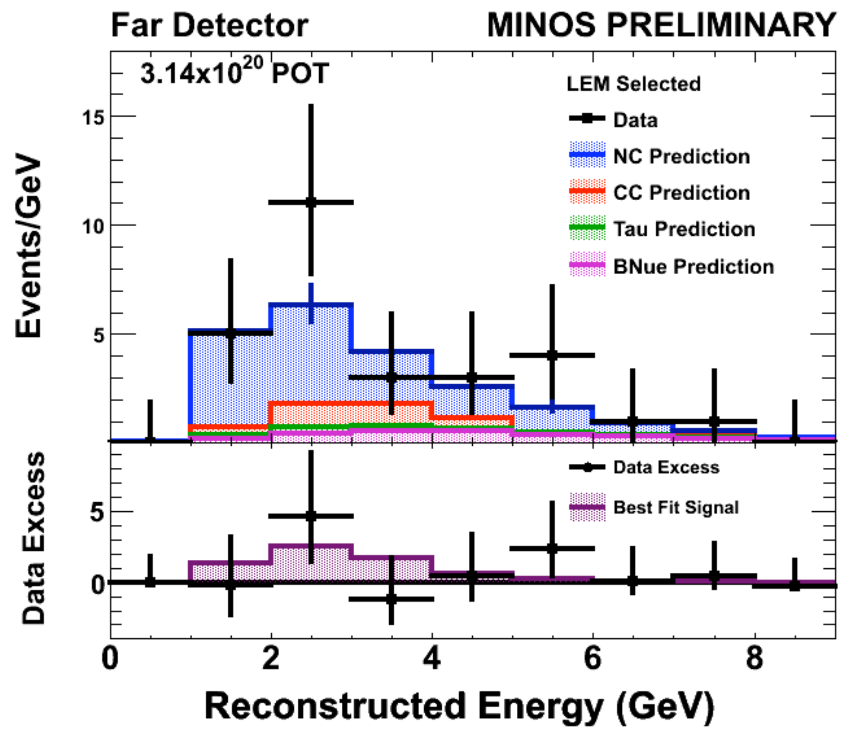
Box opening

MINOS

- Used LEM to look for ν_e appearance in 3.14×10^{20} POT of MINOS data:

Expected 21.4 ± 4.6(stat) ± 2.5(syst) background events, observed 28





- **The results are consistent with the no signal hypothesis at 1.2σ**

- **With ANN we expected 26.6 ± 5.2(stat) ± 1.8(syst) background events, observed 35 (1.5σ away from the no-signal hypothesis)**