Search for electron neutrino appearance at MINOS

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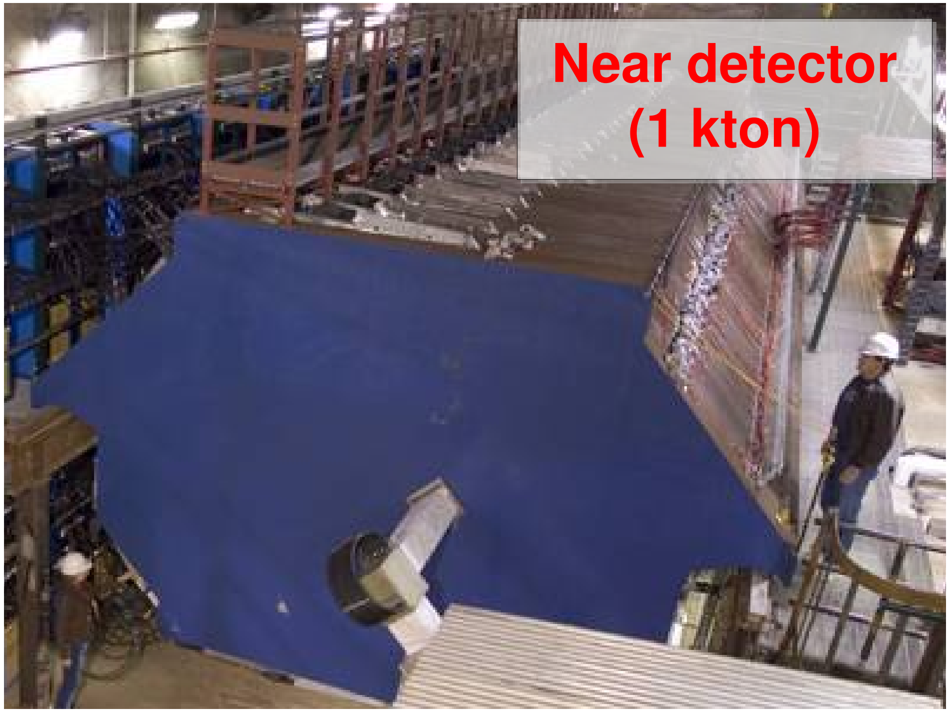
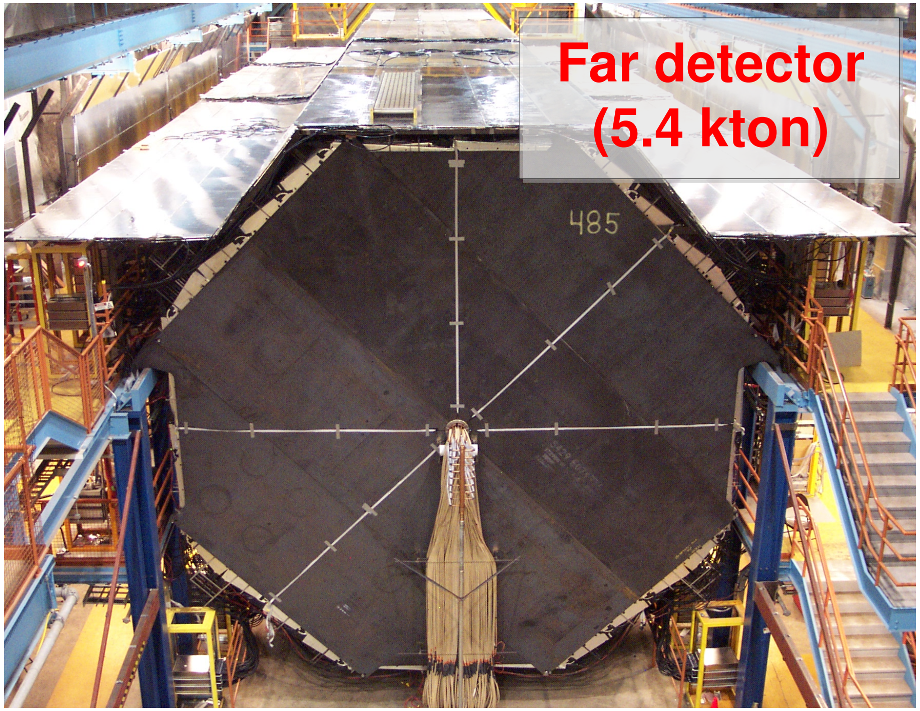
DPF 2009, Detroit

July 27, 2009

Two detectors, 735 km apart

- **Near and far detectors:**
  Magnetized tracking calorimeters
- Alternating layers of **steel** (1” thick) and
  scintillator (1 cm thick, 4.1 cm wide strips)
- Exposed to **NuMI neutrino beam**
  Few-GeV ν_μ beam, FNAL to Soudan

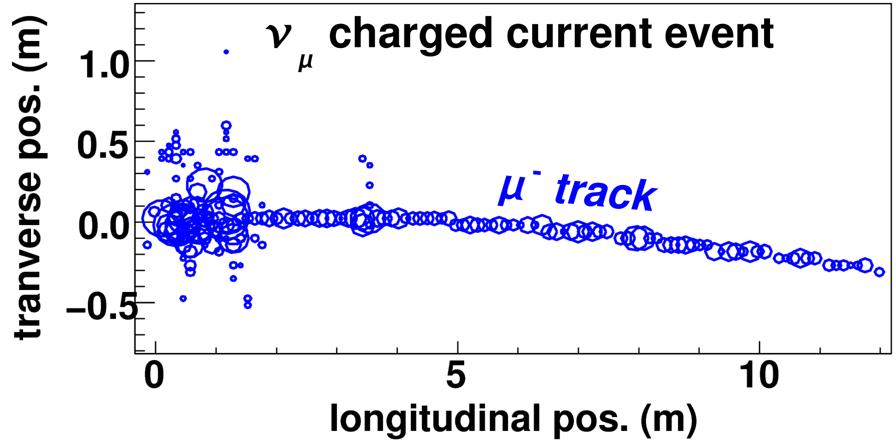




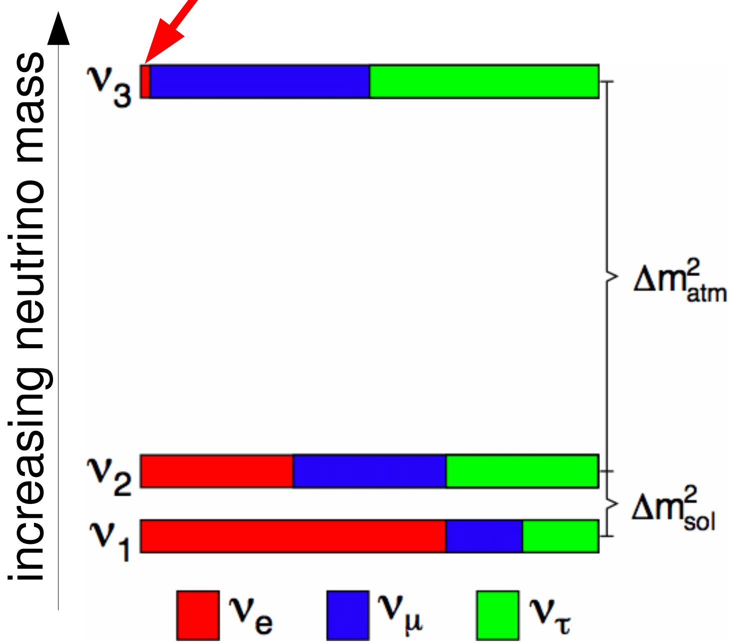
Neutrino oscillations from near to far

- Use events in **near detector** to construct a **far detector** prediction
- ν_μ **disappearance**
  - *clear signature in MINOS*
- Is any of the disappearance due to
  $\nu_\mu \rightarrow \nu_e \Leftrightarrow$ **non-zero θ_{13}** ?

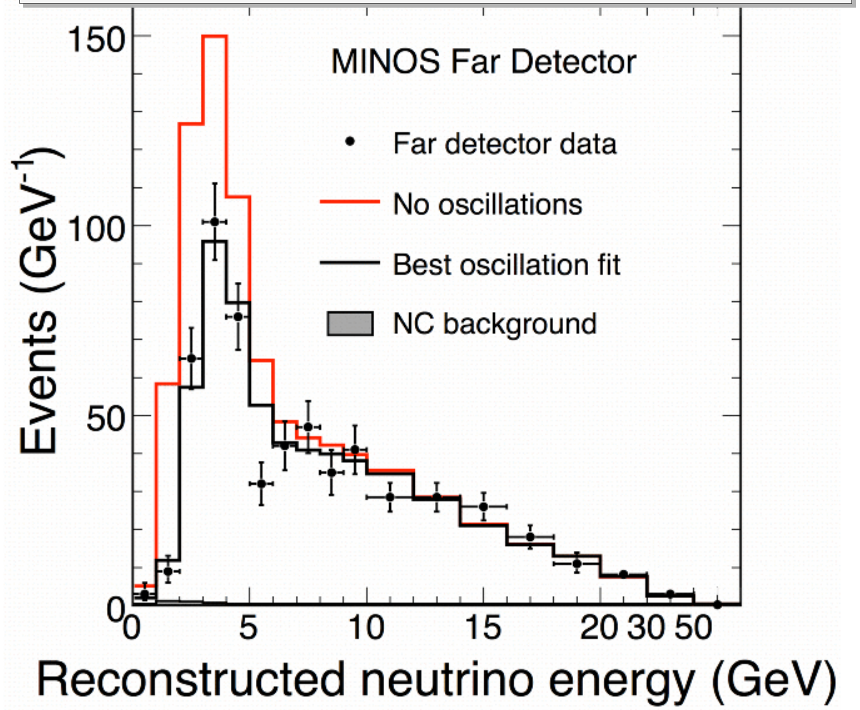
(Monte Carlo)



"normal" mass hiearchy shown



ν_μ disappearance at far detector



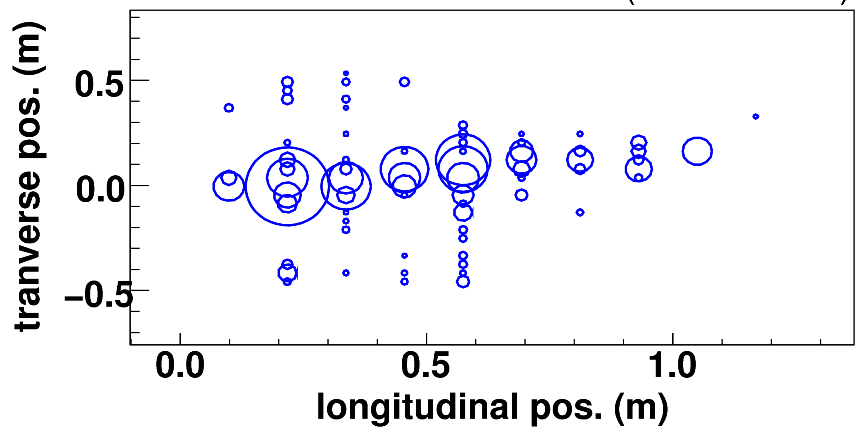
[Phys. Rev. Lett. **101,** 131802 (2008)]

Event topologies in ν_e appearance search

(Monte Carlo)

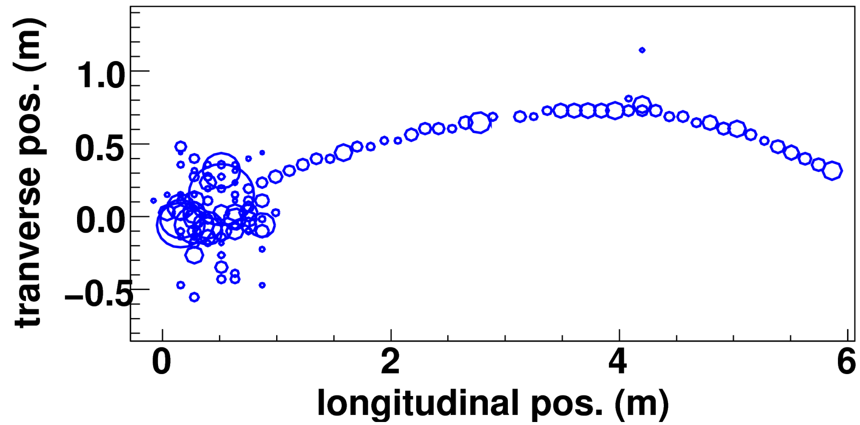
ν_e charged current

- **Signal** (and irreducible beam background)
- Electron leaves characteristic deposition pattern (**compact shower**)



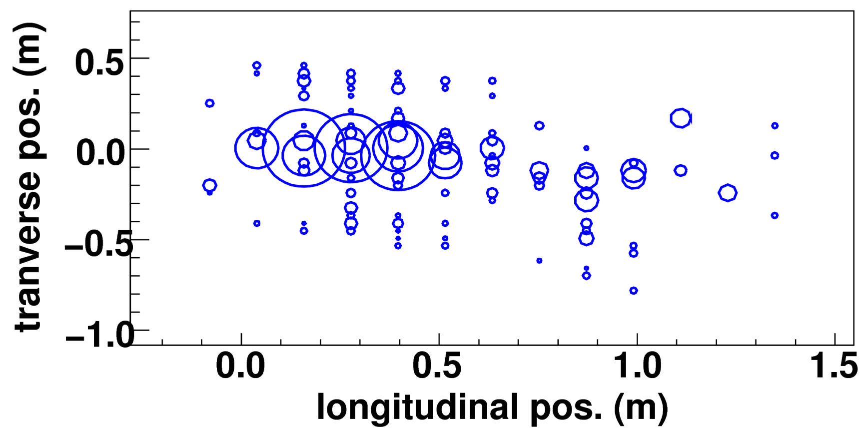
ν_μ charged current

- What MINOS was made for...
- If μ track is very short, event can be mistaken for signal



neutral current

- Esp. with π^0, looks quite like signal!
- Energy deposition more transversely distributed

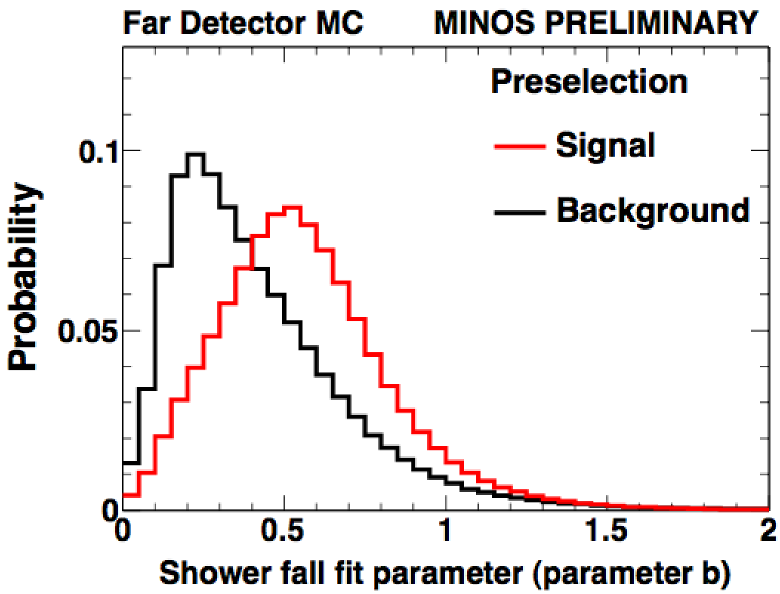


Selecting ν_e charged current events

- **A first round of cuts** removes...
  obvious tracks (via event length, etc.)
  events outside of 1-8 GeV energy range
  events outside fiducial regions

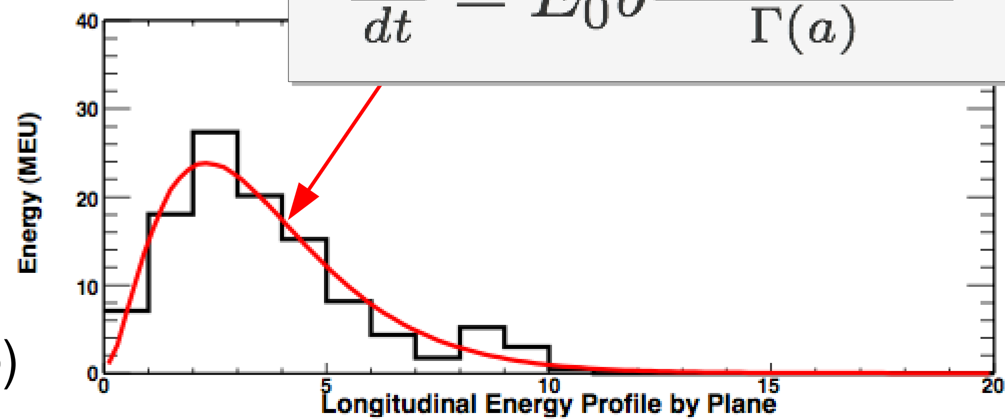
- Followed by a cut on a discriminant (**ANN**) derived from shower profile fits and other spatial variables

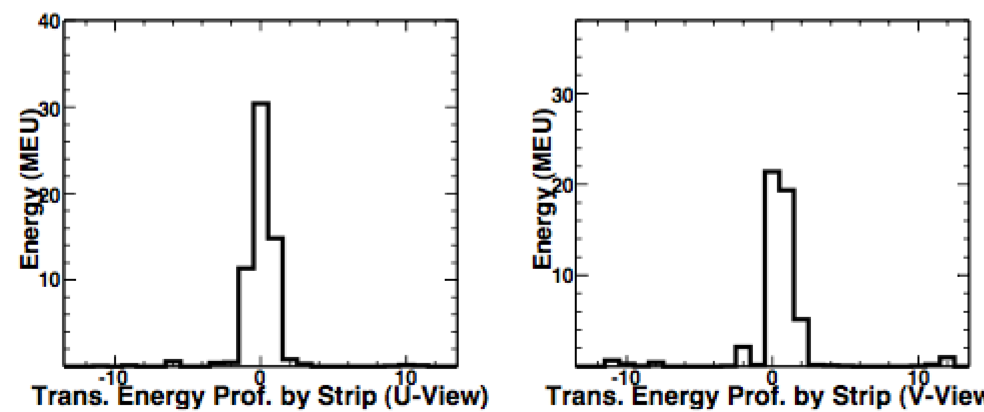
- *Example:* Shower fit fall off (parameter b)



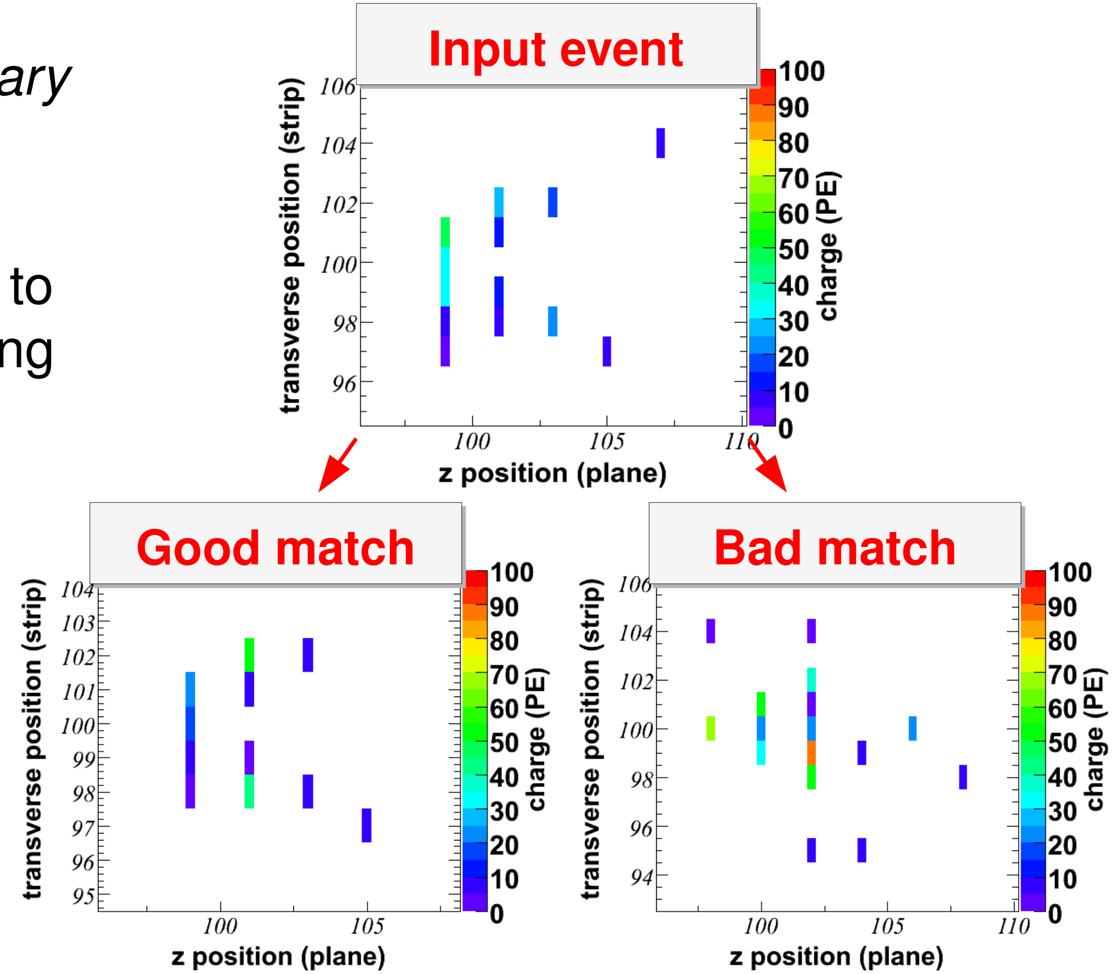
Example EM shower profile

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

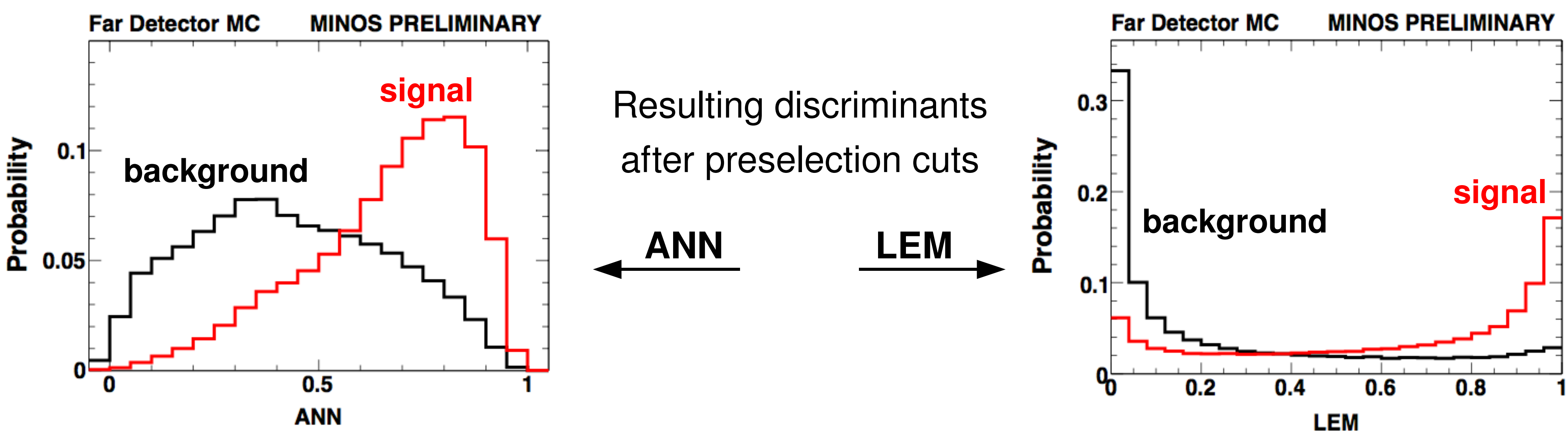




- A **secondary selection** method (*Library Event Matching* or **LEM**) also used
- LEM technique compares input event to large library of simulated events, finding those that are the most similar
- Characteristics of the well-matched events are used to form the LEM discriminant

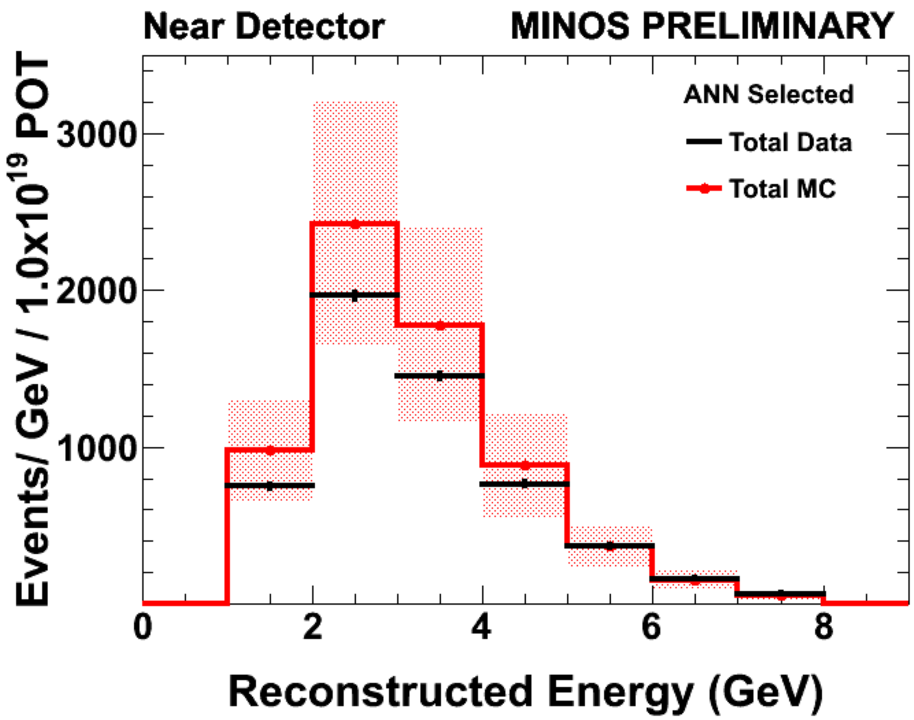


Next talk by **J. P. Ochoa** discusses the **details** of these two selections

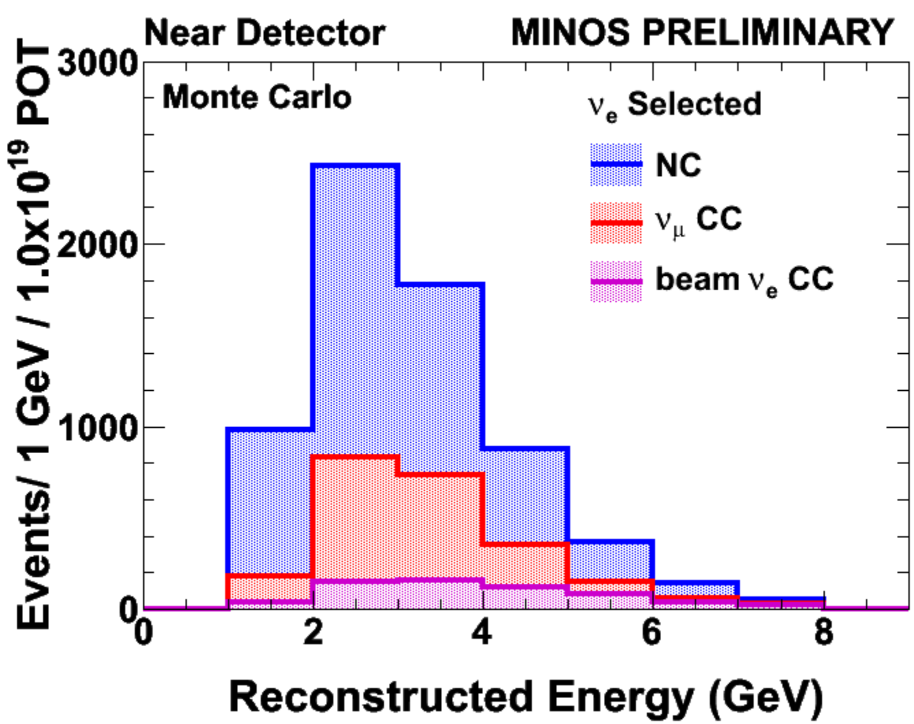


Near detector events

ν_e **candidates** in the **near detector** (ANN selection)



- Data and MC differ by up to 25%, but...
- ... are consistent given the large hadronic model uncertainties (*red error band*)
- **We need not rely on the simulation of the primary backgrounds**
- Observed **near** detector rate is converted to a **far** detector prediction via the Monte Carlo simulation

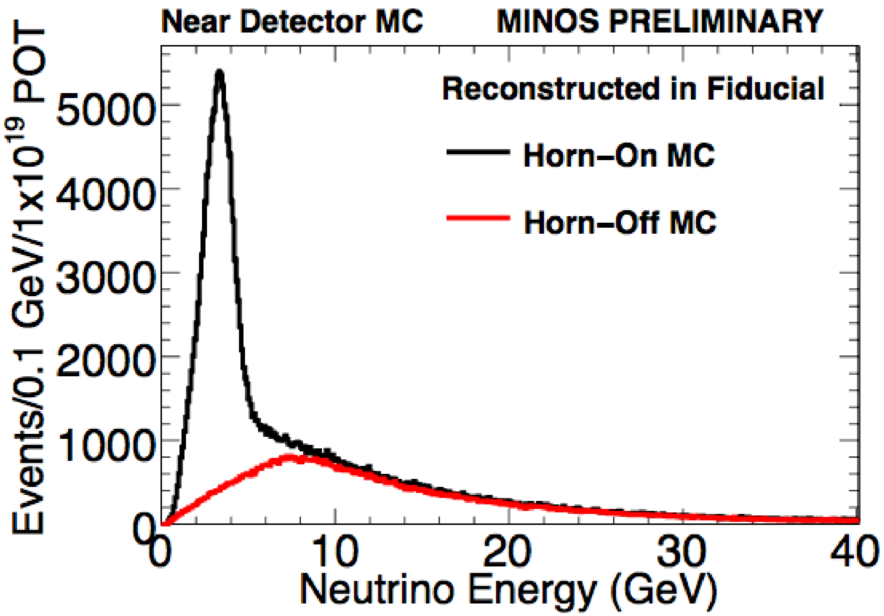


Monte Carlo is needed to incorporate, *e.g.*:

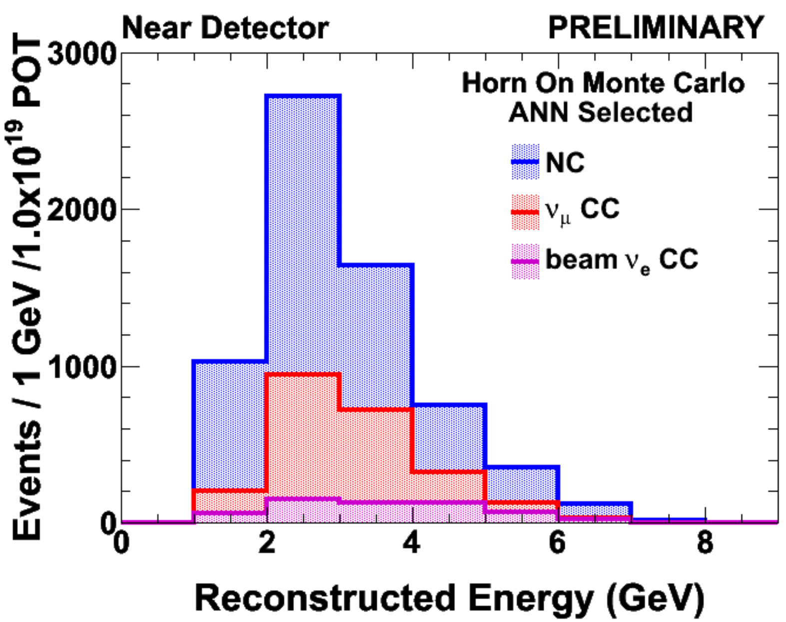
beamline geometry
detector solid angle
readout differences (near vs. far)

Background decomposition

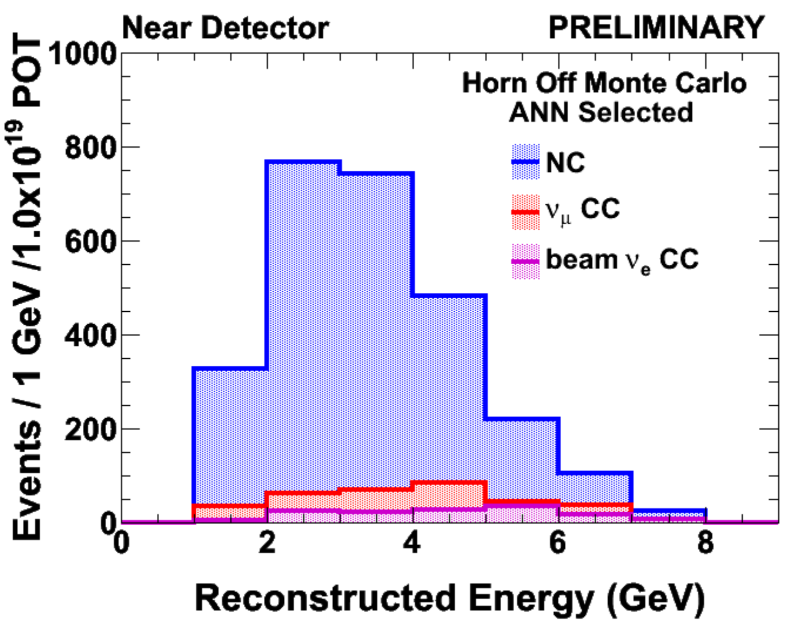
- Transport of ν_μ **CC component** to far det. requires application of $P_{osc}(\nu_\mu \rightarrow \nu_\mu)$
- Could use MC to estimate fraction of background that is ν_μ CC
- *Better:* **measure NC and CC components** by turning off focusing horn, greatly enhancing NC fraction



See **S. Swain** later today for the **details** of this technique.

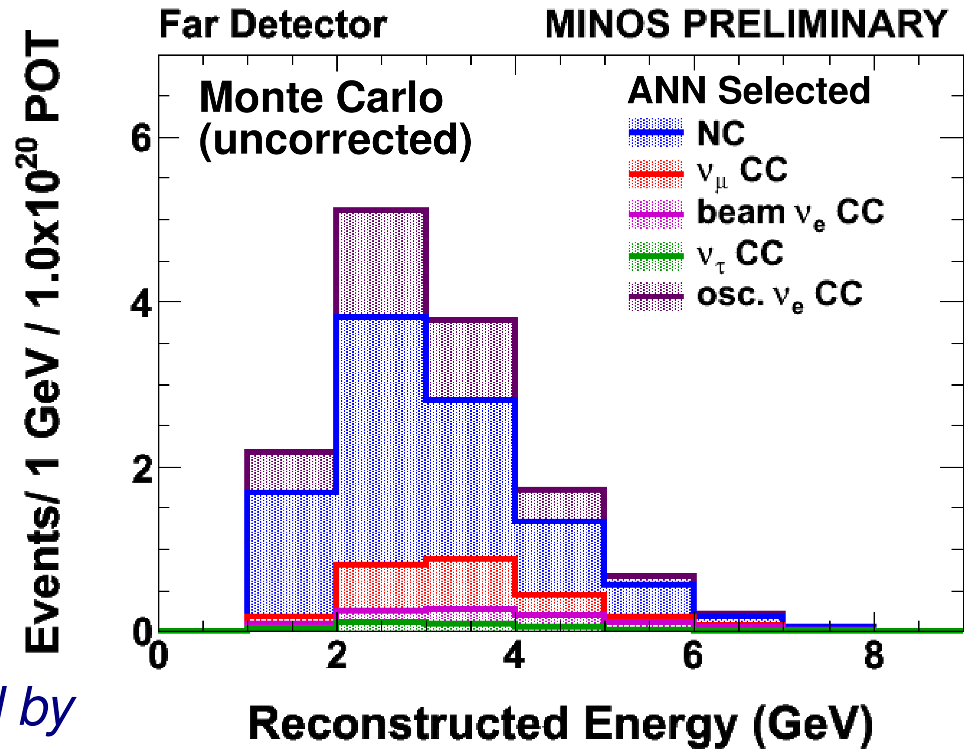


Turn off focusing horn

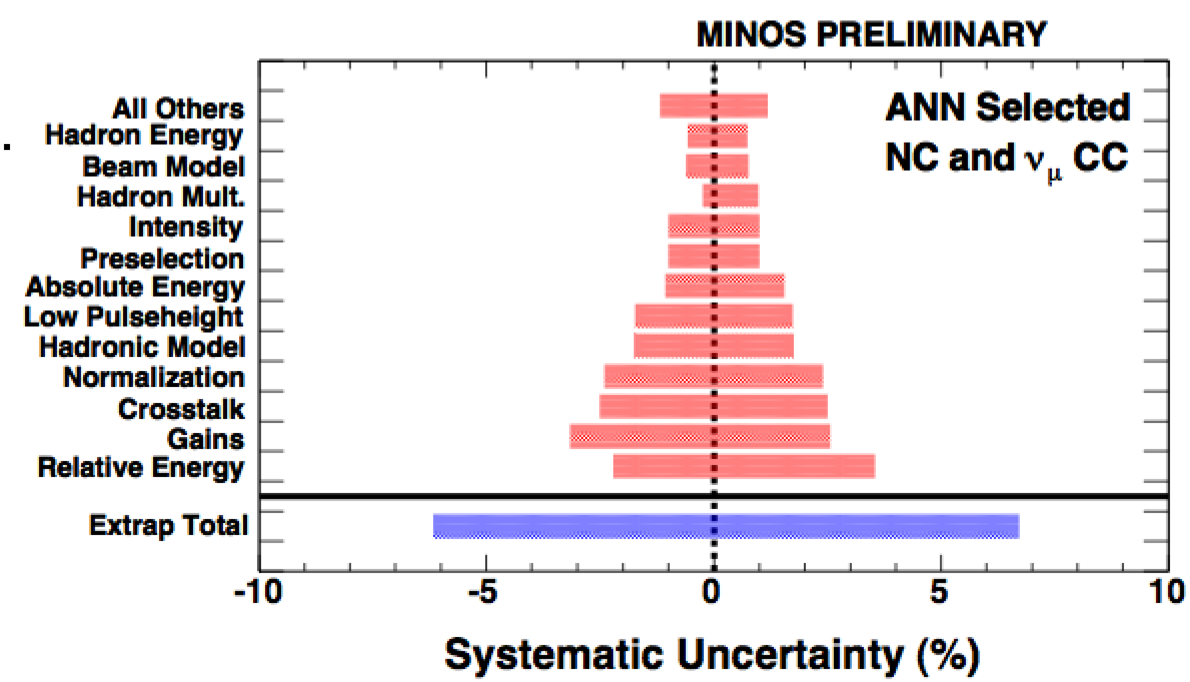


At the far detector

- Two more small but non-negligible backgrounds, with predictions taken from the Monte Carlo:
    - **ν_τ charged current**
      (from $\nu_\mu \rightarrow \nu_\tau$ oscillations)
    - **ν_e charged current**
      (intrinsic beam component; constrained by observed ν_μ rate at near detector)



- **Detector differences** lead to syst. errors when turning the near det. data into a far det. prediction:
  Attenuation
  Readout (single vs. double)
  PMT design
  Crosstalk
  ...



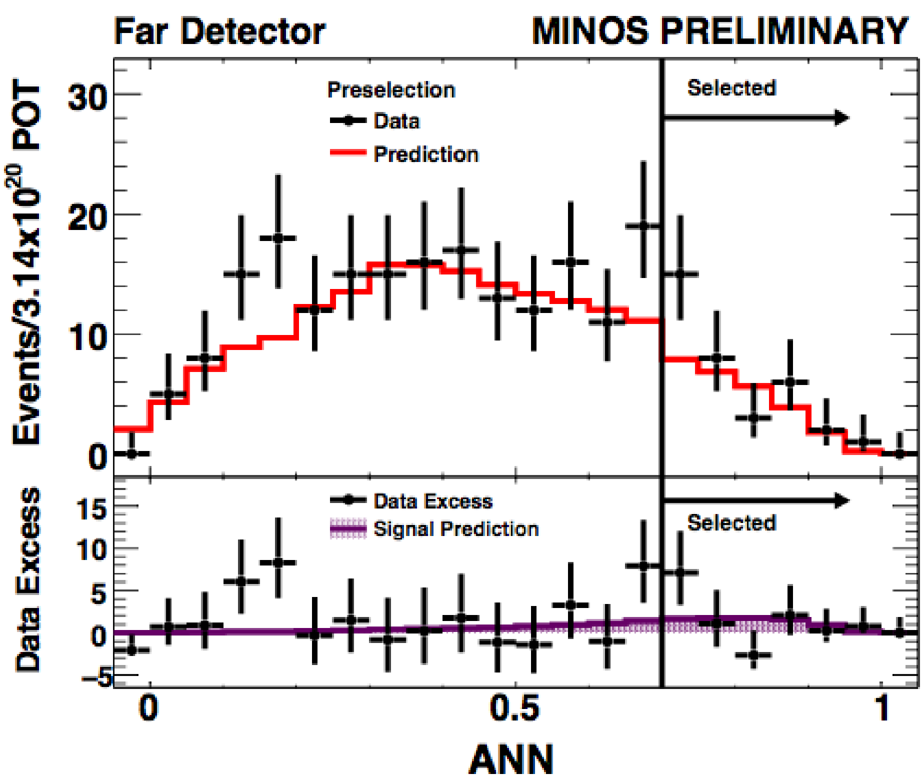
ν_e appearance result

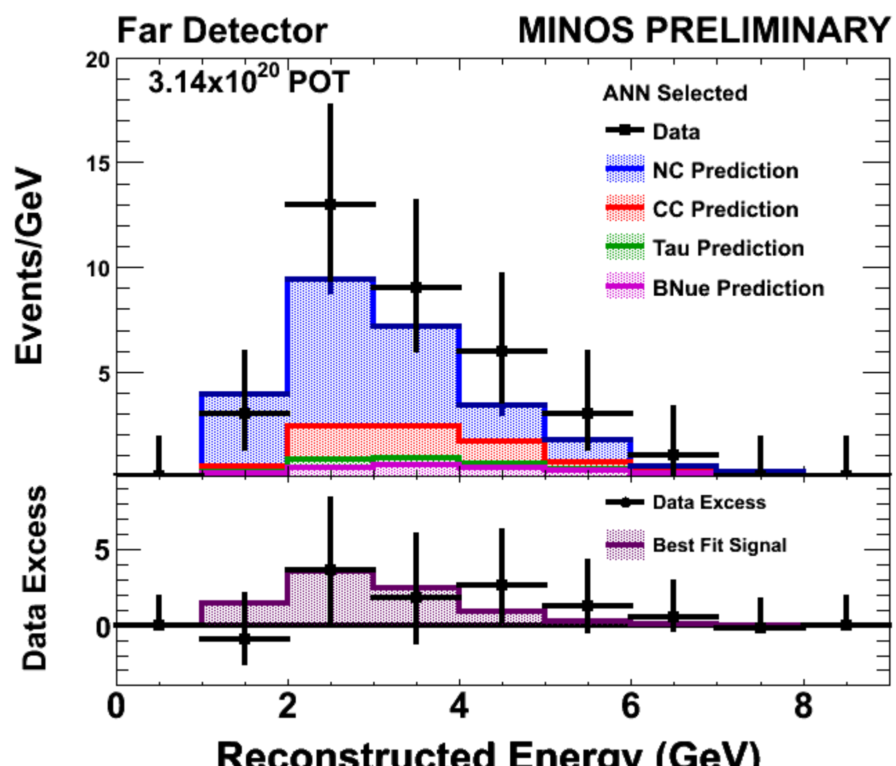
With 3.14×10^{20} protons on target and with the **primary** selector (ANN):

observed ν_e charged current candidate events: **35**

background-only expectation: **27 ± 5(stat.) ± 2(syst.)**

(1.5σ excess)





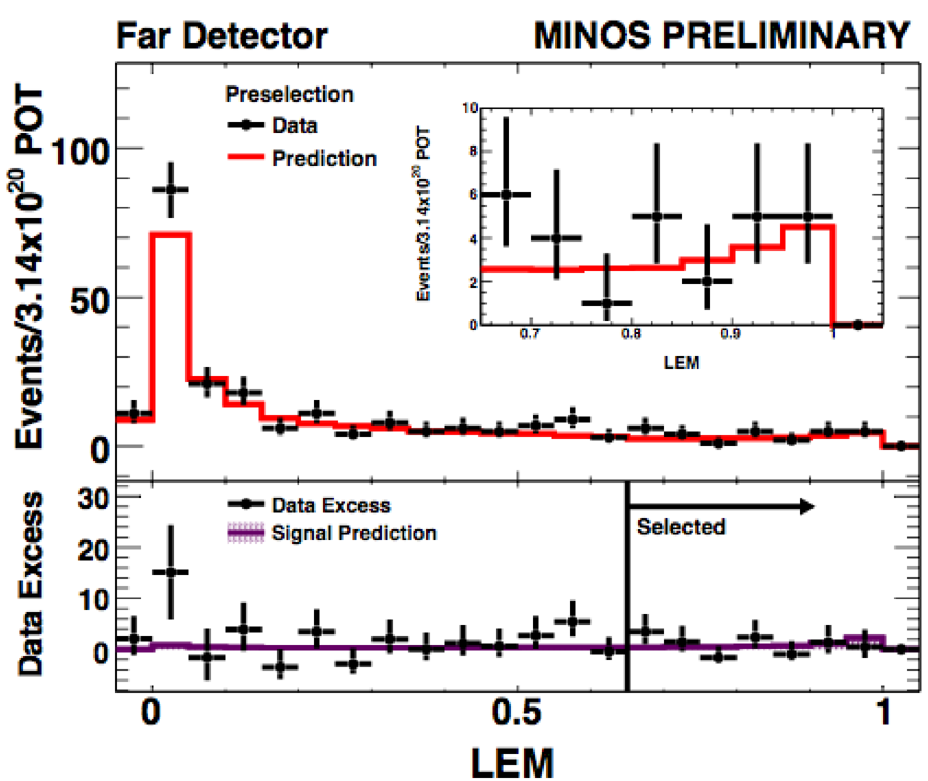
Using secondary selector

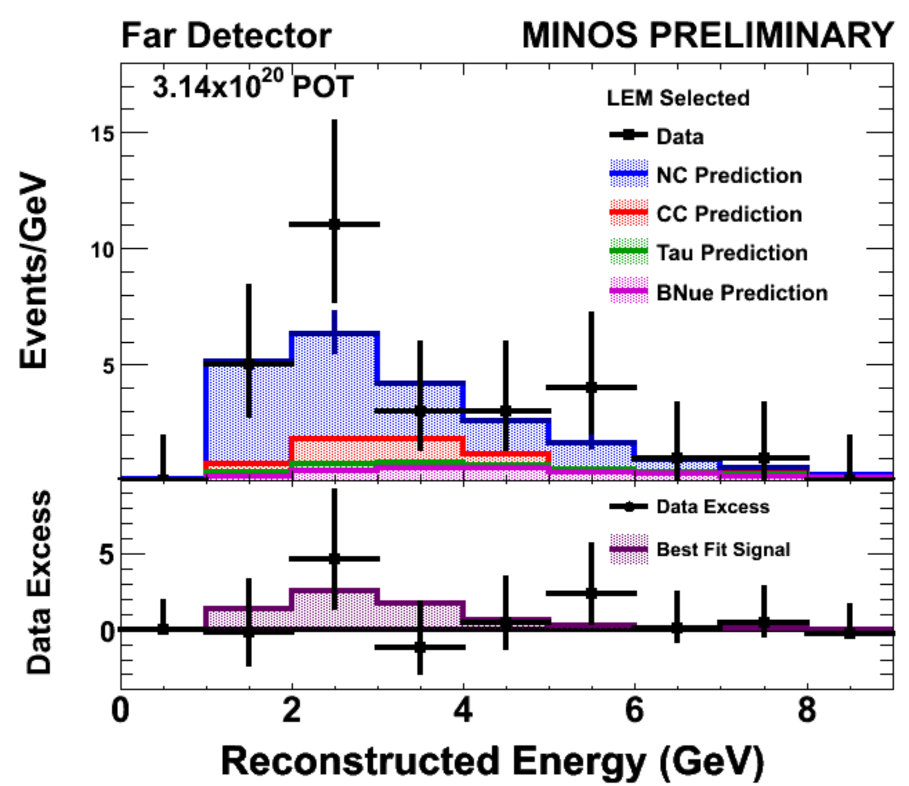
LEM selector gives consistent result:

observed ν_e charged current candidate events: **28**

background-only expectation: **22 ± 5(stat.) ± 3(syst.)**

(1.0σ excess)





Oscillation interpretation

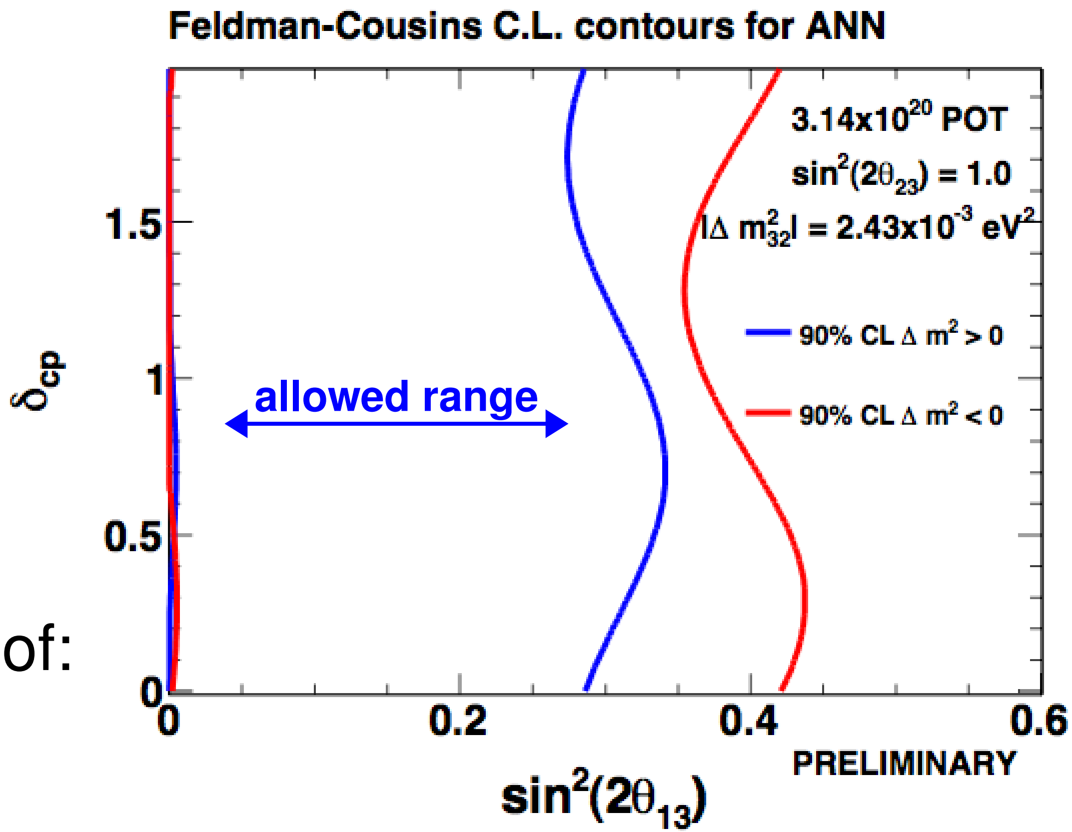
- **$\sin^2(2\theta_{13})$ allowed range** depends on **CP-phase δ** and **mass hierarchy** [sign(Δm^2)]

- **90% C.L.** allowed ranges →

- Assumes MINOS best-fit values of:

$$|\Delta m_{32}^2| = 2.43 \text{ eV}^2$$

$$\sin^2(2\theta_{23}) = 1.0$$



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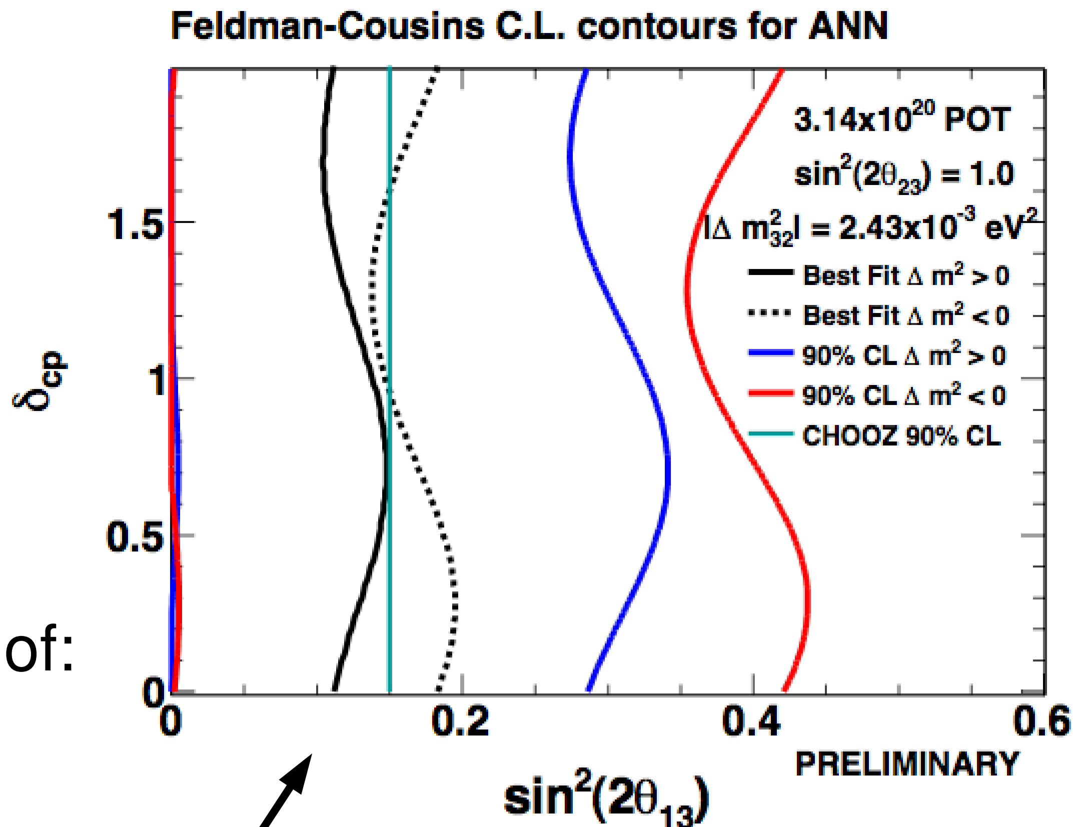
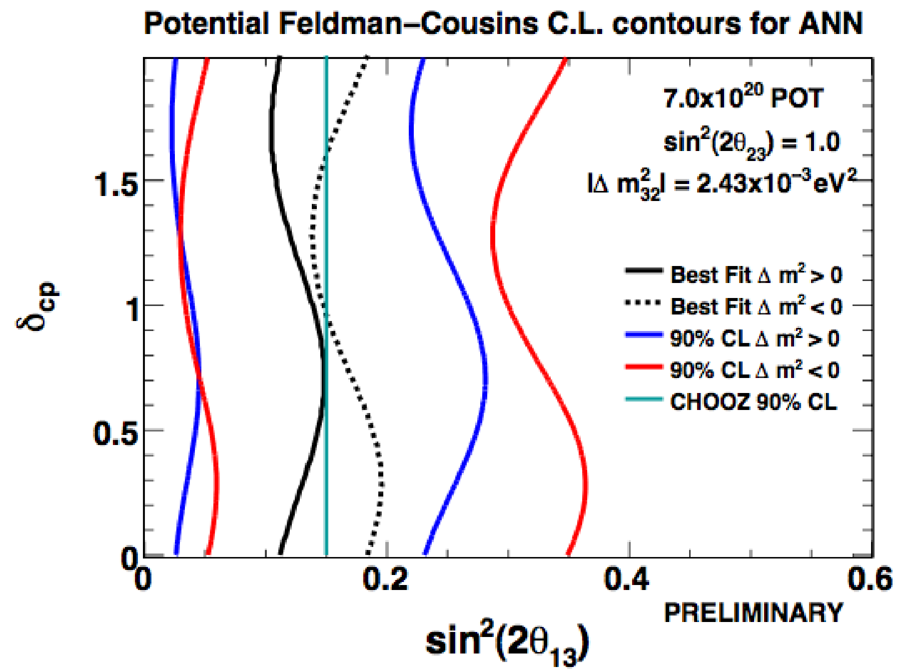


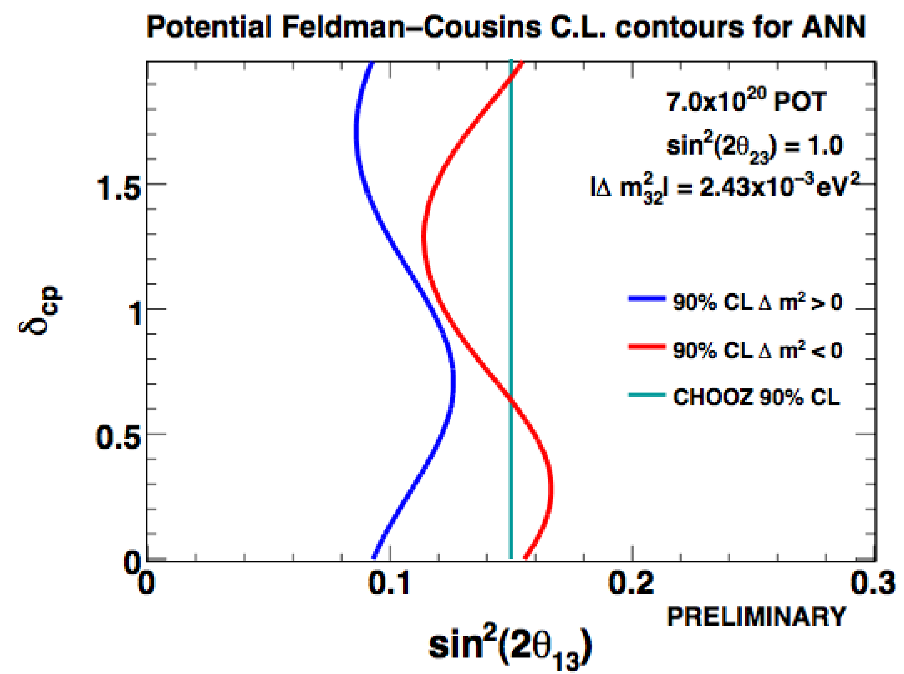
MINOS <u>best-fit</u> $\sin^2(2\theta_{13})$ [**black curves**] along with <u>CHOOZ upper limit</u> [**cyan line**].

What's next?

- **Full analysis** currently underway with more than twice the data (**7×10^{20} protons on target**)

Full data sample's sensitivity if...
...best fit stays **the same**
...or best fit shifts to **$\sin^2(2\theta_{13})=0$**



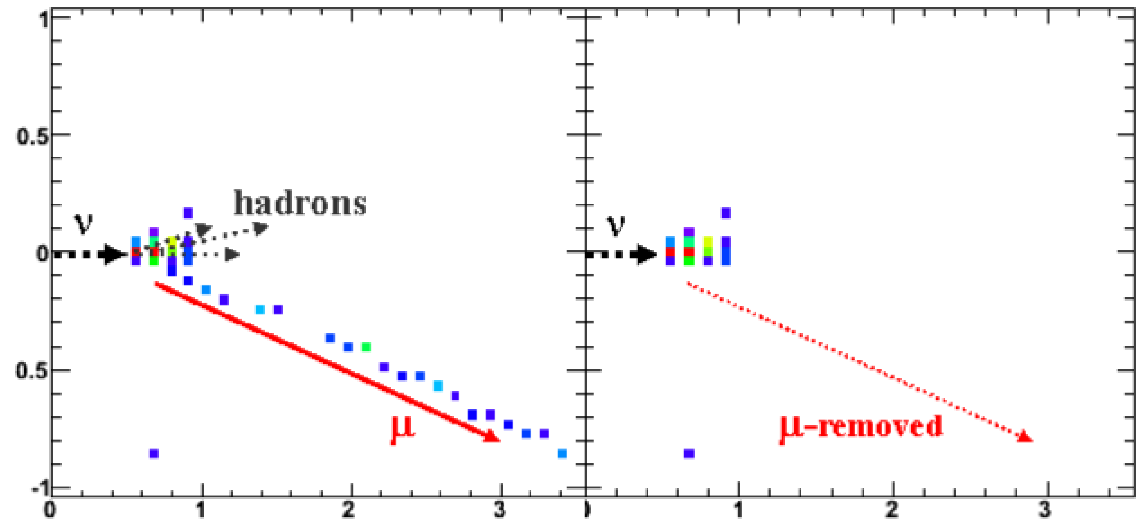


- These sensitivities do not include **several improvements** expected for full analysis:
  - Enhanced ν_e selection algorithm
  - Better cross talk handling
  - Reduction of key systematics (*e.g.*, PMT gains)
- Look for the clarifying 7×10^{20} p.o.t. result next year!

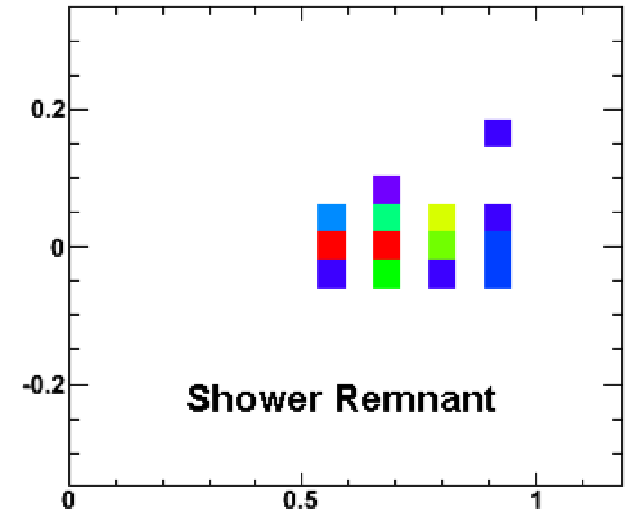
Backup slides

Muon-removed sample

- Start with an identified ν_μ **charged current event** (clean muon track)



- **Remove the hits** associated with the muon track
- If a track hit is also part of the shower, subtract out expected muon contribution, leaving some charge remaining
- ***The result:***
  A sample of "mock" neutral current events →

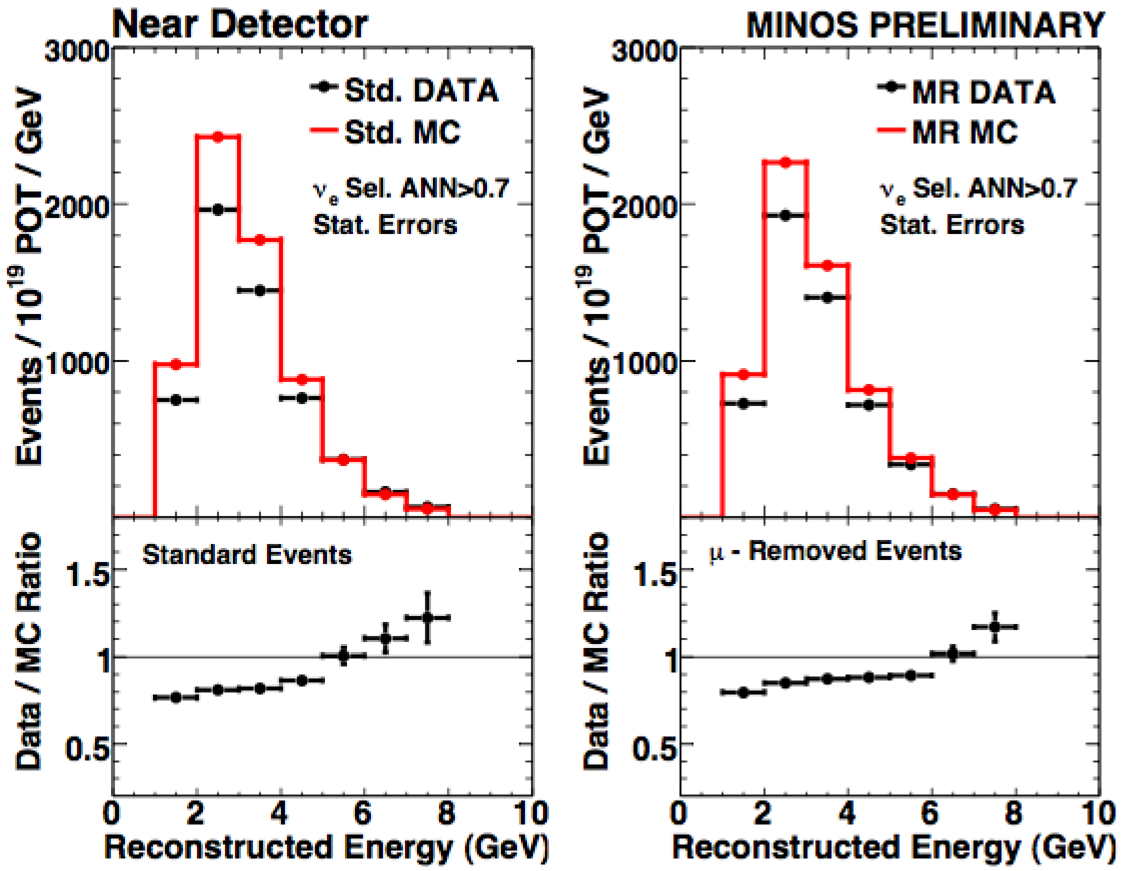


- Use these to **test** or **adjust the simulation**

Muon-removed events in near detector

- Apply ν_e selection to muon-removed events in the near detector

- Disagreement is consistent with that seen in "standard" events



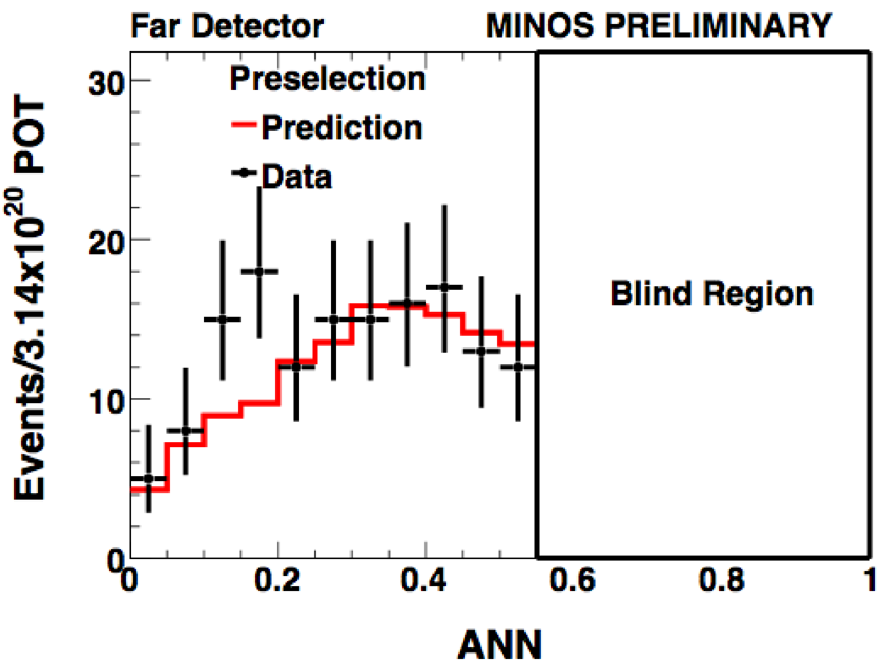
Far detector prediction

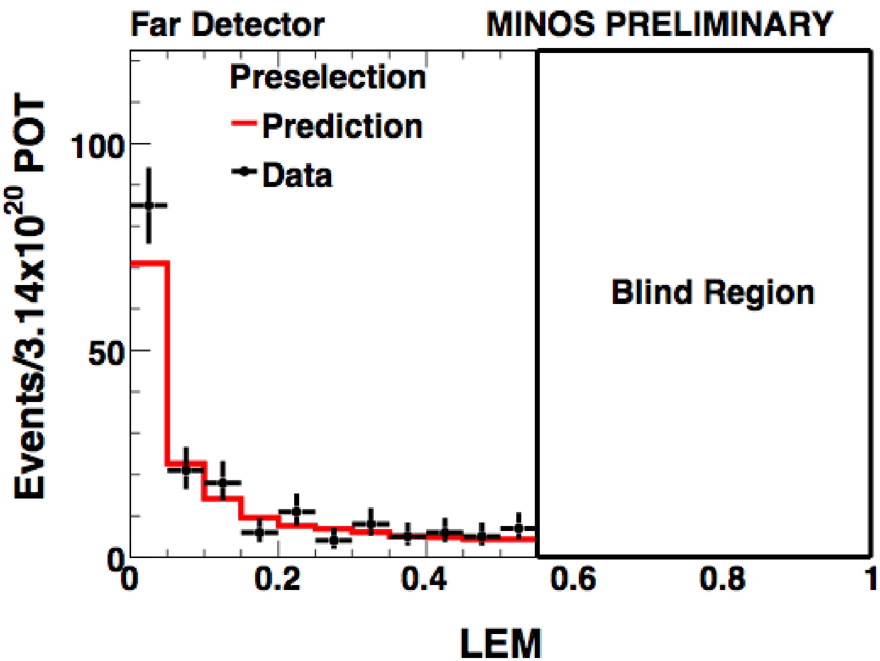
- Breakdown of far detector background prediction below
- Two decomposition methods:
  1. **Horn on/off** – *official method (p. 8)*
     - Changing the spectrum changes proportions of CC and NC
     - Extract the CC and NC fractions from data
  2. **MRCC** – *independent cross check*
     - Correct Monte Carlo events using PID response of muon-removed showers in data
- **Answers are consistent!**

<table>
<tr><th></th><th>Total</th><th>NC</th><th>ν_μ CC</th><th>ν_τ CC</th><th>ν_e beam</th></tr>
<tr><td>Horn on/off</td><td>27</td><td>18.2</td><td>5.1</td><td rowspan="2">1.1</td><td rowspan="2">2.2</td></tr>
<tr><td>MRCC</td><td>28</td><td>21.1</td><td>3.6</td></tr>
</table>

Inverting the PID cut

- Before looking at the signal region, we tested the signal-free region
- No problems seen (insignificant excess for both selectors)





events observed: 146

events expected: 132 ± $12_{stat.}$ ± $8_{syst.}$

(1.0σ excess)

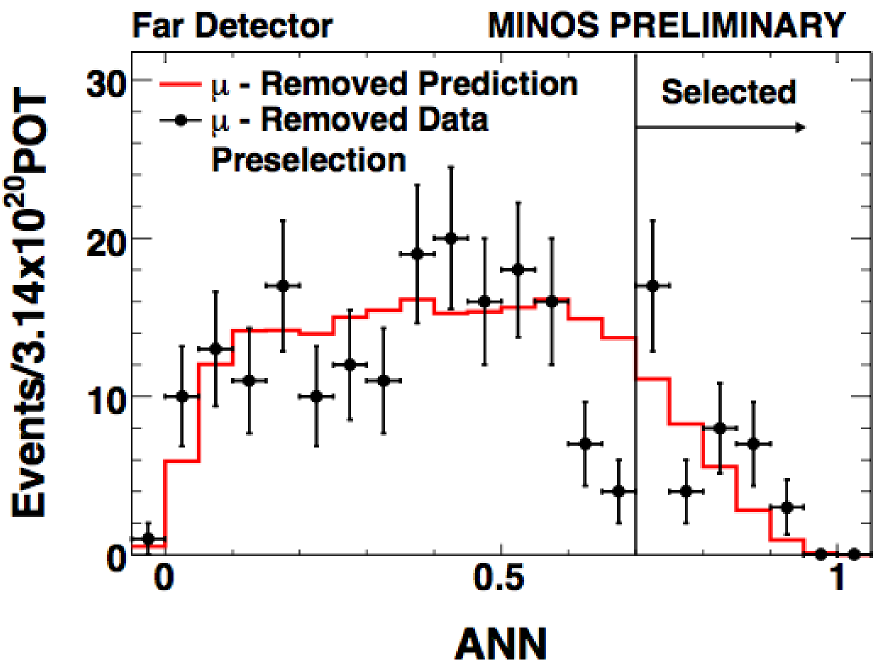
events observed: 176

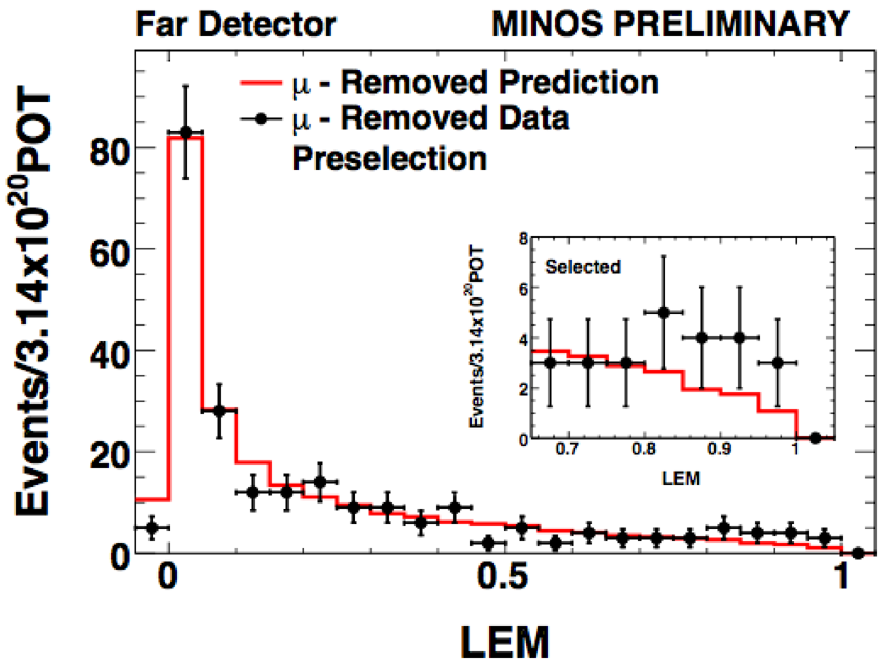
events expected: 157 ± $13_{stat.}$ ± $3_{syst.}$

(1.4σ excess)

Applying selection to muon-removed events

- Before looking at the signal region, we tested the signal-free region
- Slight excess for both selectors; more data should clarify situation





events observed: 39

events expected: $29 \pm 5_{stat.} \pm 2_{syst.}$

(1.9σ excess)

events observed: 25

events expected: $17 \pm 4_{stat.} \pm 2_{syst.}$

(1.8σ excess)