Long-Baseline Neutrino Oscillation Phenomenology

Deborah Harris
Fermilab

NuFact09
IIT
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With
Thanks
To Patrick Huber

First, a definition…

According to Wikipedia:

Particle physics phenomenology is the part of theoretical particle physics that deals with the application of theory to high energy particle physics experiments. Within the Standard Model, phenomenology is the calculating of detailed predictions for experiments, usually at high precision (e.g., including radiative corrections).

Outline

- How to measure oscillation probabilities
- Experimental Regimes
  - Conventional Neutrino Beams
    - ν_e appearance
  - Beta Beams
    - ν_μ appearance
  - Neutrino Factories
    - ν_τ and ν_μ appearance
- Example from MINOS: ν_e appearance
- “Phenomenology”: making predictions for future
- What else will be needed in the future

D. Harris
Fermilab
NuFact09

Probabilities

$$N_{far} = \phi_{\nu_\mu} \sigma_{\nu_x} P(\nu_\mu \to \nu_x) \varepsilon_x M_{far} + B_{far}$$

ϕ=flux, σ= cross section ε=efficiency M=mass

$$P(\nu_\mu \to \nu_x) = \frac{N_{far} - B_{far}}{\phi_{\nu_\mu} \sigma_{\nu_x} \varepsilon_x M_{far}}$$

B_{far}= Backgrounds at far detector, from any flux

$$B_{far} = \sum_{i=\mu,e} \phi_{\nu_i} (P) \sigma_{\nu_i} \varepsilon_{ix} M_{far}$$

NuINT matters for Signal and Background Cross sections, and indirectly for efficiencies!

Probabilities, continued

$$\left(\frac{\delta P}{P}\right)^2 = \frac{(N_{far} + (\delta B_{far})^2)}{(\phi_{\nu_\mu}\sigma_{\nu_x}\varepsilon_x M_{far})^2} + \frac{N_{far} - B_{far}}{(\phi_{\nu_\mu}\sigma_{\nu_x}\varepsilon_x)^2}[\delta(\phi_{\nu_\mu}\sigma_{\nu_x}\varepsilon_x)]^2$$

$$\left(\frac{\delta P}{P}\right)^2 = \frac{(N_{far} + (\delta B_{far})^2)}{(\phi_{\nu_\mu}\sigma_{\nu_x}\varepsilon_x M_{far})^2} + (N_{far} - B_{far})\left(\left[\frac{\delta\phi_{\nu_\mu}}{\phi_{\nu_\mu}}\right]^2 + \left(\frac{\delta\sigma_{\nu_x}}{\sigma_{\nu_x}}\right)^2 + \left(\frac{\delta\varepsilon_{\nu_x}}{\varepsilon_{\nu_x}}\right)^2\right)$$

2 Regimes:

$$N_{far} >> B_{far}$$

$$N_{far} \approx B_{far}$$

Problem:

Don’t always know *a priori* which regime you are in

---depends on Δm^2,

---depends on $\sin^2 2\theta_{13}$

Near Detector Strategy

$$B_{far} = \sum_{i=\mu,e} \phi_{\nu_i\ far}(P)\sigma_{\nu_i}\varepsilon_{ix}M_{far}$$

Backgrounds come from several sources

$$N_{near} = \sum_{i=\mu,e} \phi_{\nu_i\ near}\sigma_{\nu_i}\varepsilon_{ix}M_{near}$$

Build near detector with same ε

$$B_{far} = N_{near}\frac{\sum_{i=\mu,e} \phi_{\nu_i\ far}(P)\sigma_{\nu_i}\varepsilon_{ix}M_{far}}{\sum_{i=\mu,e} \phi_{\nu_i\ near}\sigma_{\nu_i}\varepsilon_{ix}M_{near}}$$

Simulations better at predicting ratios absolute levels

$$B_{far} = \sum_{i=\mu,e} N_{near,i}\frac{\phi_{\nu_i\ far}}{\phi_{\nu_i\ near}}\frac{\sigma_{\nu_i}}{\sigma_{\nu_i}}\frac{\varepsilon_{ix}}{\varepsilon_{ix}}\frac{M_{far}}{M_{near}}$$

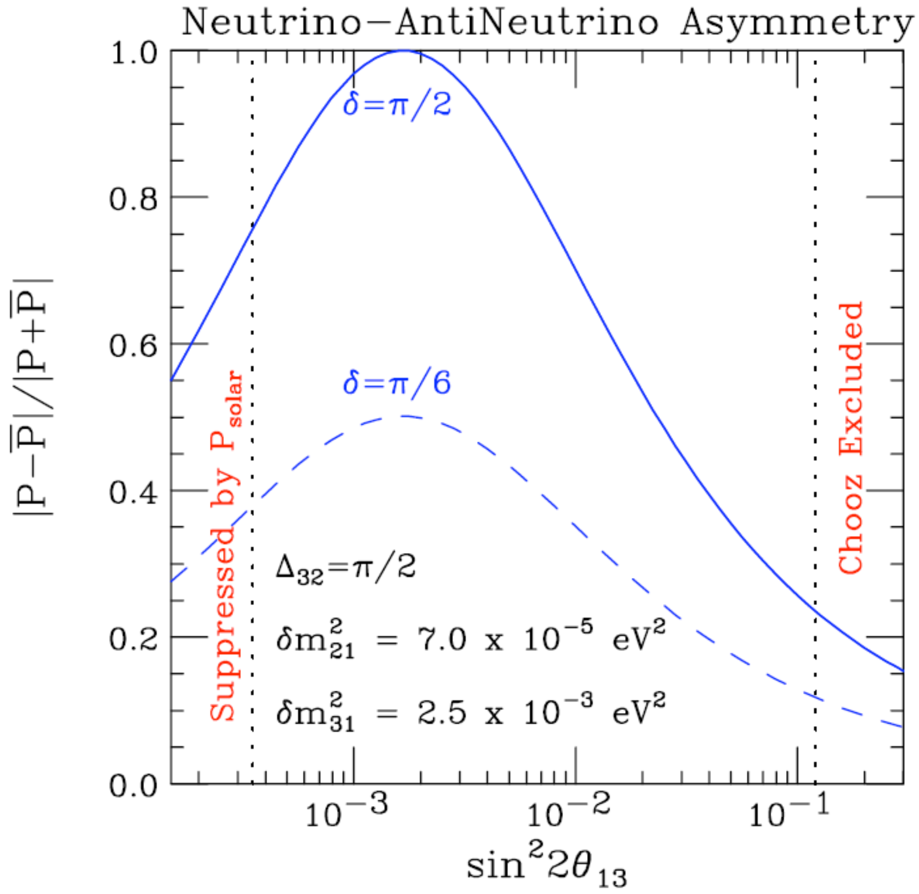
Near Detector Strategy (cont’d)

$$B_{far} = \int dE_\nu \sum_{i=\mu,e} N_{near,i}(E_\nu) \left(\frac{\phi_{\nu_i\ far}}{\phi_{\nu_i\ near}} \right)(E_\nu) \left(\frac{\sigma_{\nu_i}}{\sigma_{\nu_i}} \right)(E_\nu) \left(\frac{\varepsilon_{ix}}{\varepsilon_{ix}} \right)(E_\nu) \frac{M_{far}}{M_{near}}$$

- But ratios don’t cancel everything
- Underlying problem: fluxes are different
  - Near detector: line source, far detector: point source
  - But even if that is solved, still ν_μCC oscillations for conventional beam case
- All of these terms are functions of energy
  - Uncertainties in energy dependence of cross sections translate into far detector uncertainties…

How low should Uncertainties be?

- Be careful what you wish for: at high θ_{13}, you are looking for small differences in probabilities



Graphics courtesy S. Parke

$$P(\nu_\mu \rightarrow \nu_e) \approx$$

$$|\sqrt{P_{atm}}e^{-i(\Delta_{32}+\delta)} + \sqrt{P_{sol}}|^2$$

CP Asymmetry is largest when

$$\sqrt{P_{atm}} = \sqrt{P_{sol}}$$

But small if

$$\sqrt{P_{atm}} > \sqrt{P_{sol}}$$

Asymmetry could be 20% or less with matter effects→ Systematics on difference < < 7%!

Systematic Uncertainties

- Neutrino Flux
  - Hadron Production
    - π/K ratio
    - x and p_t spectrum of produced Pions/Kaons
  - Pion, Muon or Isotope Beam characteristics
    - Focusing uncertainties
    - Alignment Uncertainties
- Neutrino Interactions: Background and Signal!
  - Quasi-elastic Uncertainties
  - Resonance (low W) Uncertainties
  - DIS (high W)
  - Nuclear Effects
- Event Selection
- Event Energy Resolution
  - Important especially for measurements versus neutrino energy
  - Narrow Band beams: energy resolution is key to background rejection

Problem:
uncertainties
all affect the
near and far
detector both,
you can't always
separate
one from the other

Near Detector Design

- Far detector must be massive: the more instrumented it is, the more $/kton…
- Tradeoff between segmentation and far detector mass
- Near Detector Design options:
  - “Identical” to far detector
    - Argue that detector efficiencies and cross sections are the “same”, you just need independent flux measurements
    - Can’t really be identical: different rates, different size detector
    - Also doesn’t see the same flux near as far (line source, osc.)
  - Much more segmented and fine-grained
    - Try to measure fluxes and cross sections as best you can, make far detector prediction
- Ideally, you would do both…

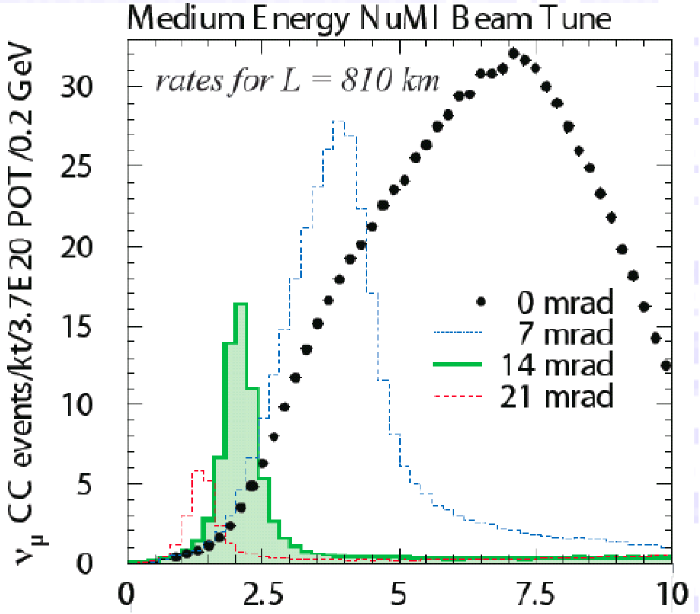
Remainder of Talk

- Next Generation of accelerator searches for θ_{13}
  - T2K and NOvA
  - T2KK and LBNE
  - High Energy Beta Beam
  - Neutrino Factories low and high in energy
- First ν_e Appearance in a Superbeam: MINOS
- Lessons learned
- What the future program will need

The Beamline Options Considered

- Conventional Neutrino Beams
  - Pion focusing and decay in long pipe
  - Mostly ν_μ, few % ν_e
- Beta Beams
  - Collect radioactive isotope and focus and accelerate
  - Decay in long storage ring
  - All ν_e or all anti- ν_e (at given instant in time)
- Neutrino Factories
  - Collect muons, focus, accelerate
  - Decay in long storage ring
  - ν_μ and anti- ν_e or ν_e and anti- ν_μ

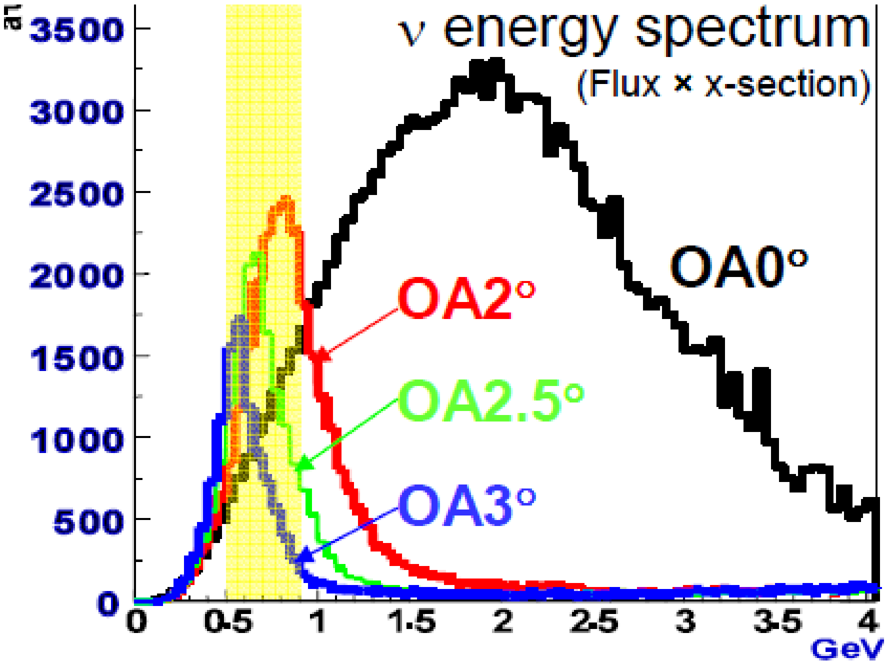
NOvA and T2K Event Samples



	Neutrino Running	Antinetrino Running	Total	Efficiency (Includes fiducial cut)
ν_e signal	75.0	29.0	104	36%
Backgrounds:	14.4	7.6	22	
ν_μ NC	6.0	3.6	9.6	0.23%
ν_μ CC	0.05	0.48	0.53	0.004%
Beam ν_e	8.4	3.4	11.8	14%
FOM	19.8	10.5	22.1	

Numbers generated assuming:
$\sin^2(2\theta_{13}) = 0.10$, $\sin^2(2\theta_{23}) = 1.0$, and $\Delta m_{32}^2 = 0.0024$ eV², no matter effects.

R. Ray, Neutrino 2008



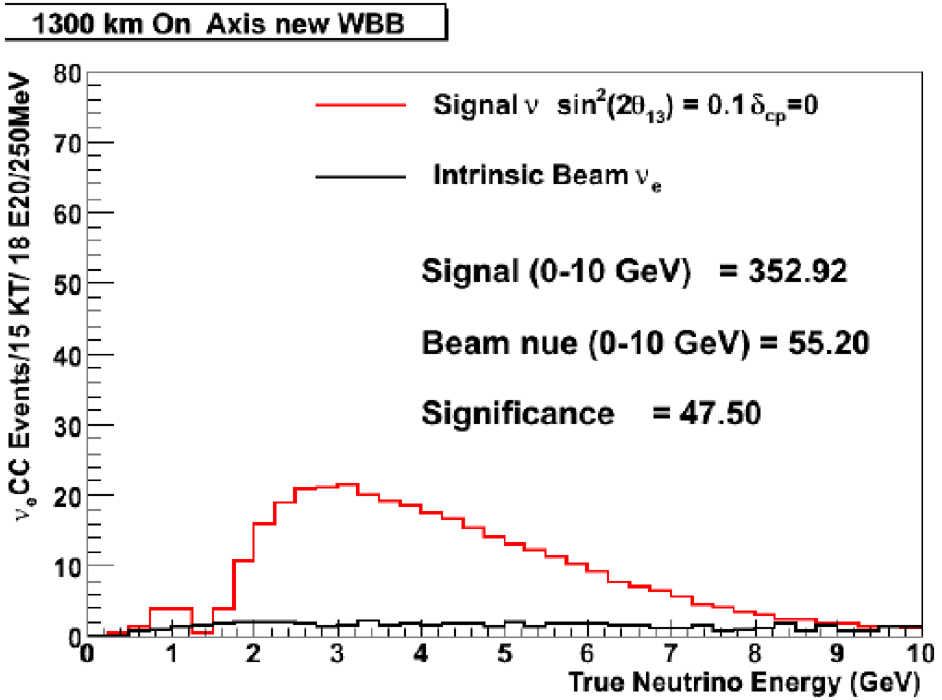
Expected number of events at SK (0.75kW beam x 5yr)

$\sin^2 2\theta_{13}$	Backgrounds			Signal
	ν_μ induced	Beam ν_e	Total	
0.1	10	13	23	103
0.01				10

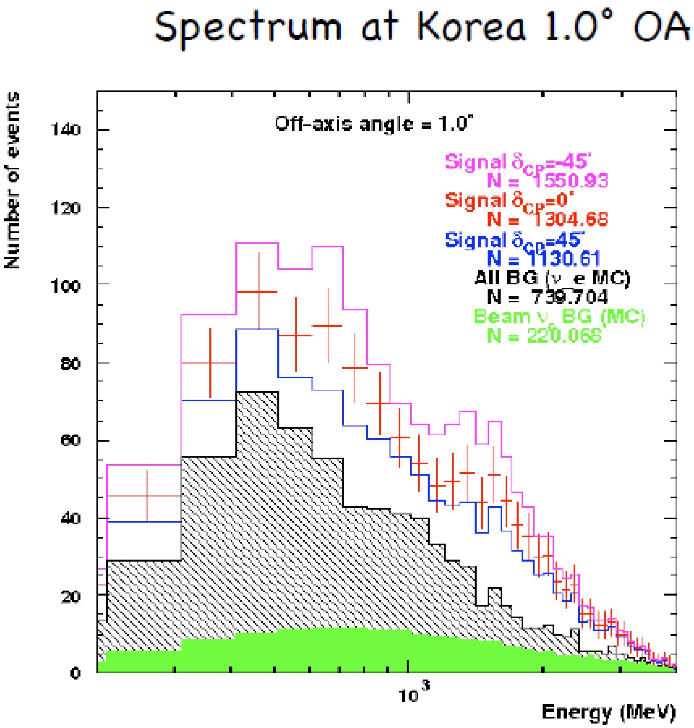
I. Kato, Neutrino 2008

T2KK and LBNE Event Samples

- Water Cerenkov in T2KK, assume Liquid Argon in LBNE (assumed in plot below)
- Few Hundred signal events, 5% systematic uncertainties assumed on signal and background predictions



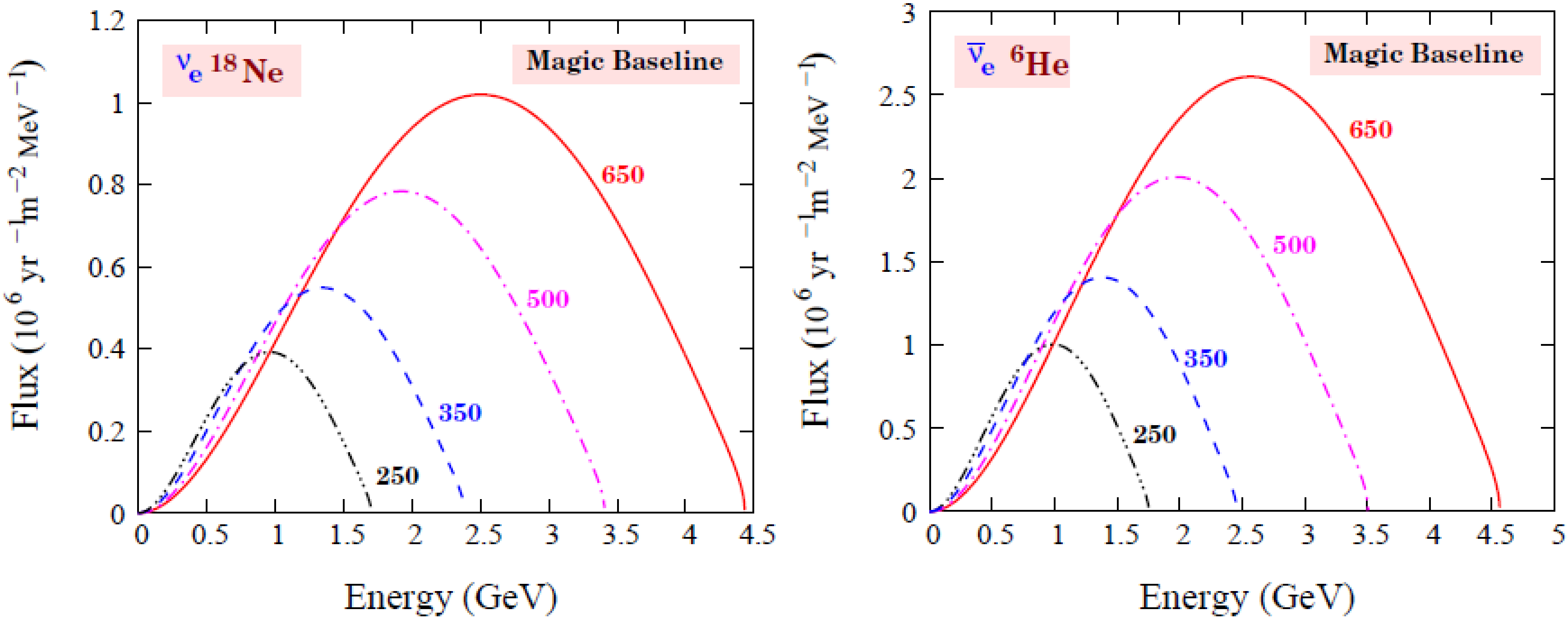
N. Saoulidou, Neutrino 08



F. Dufour, NOW 08

Beta-Beam Event Samples

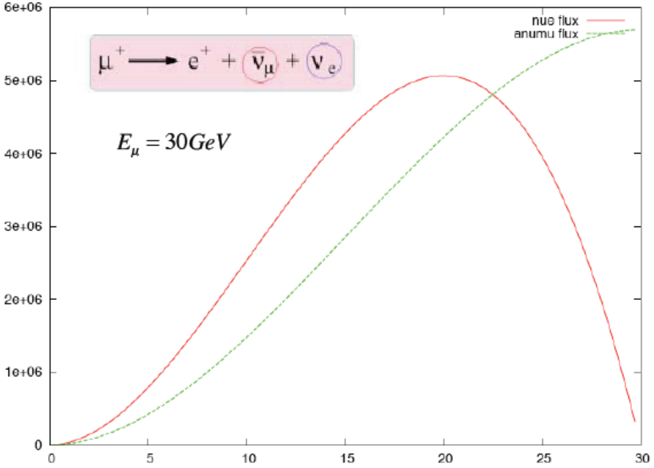
- Greenfield optimization: pure electron neutrino fluxes
- Signal error assumed: 2.5%, Background error, 5%



Agarwalla, Choubey, Raychaudhuri, Winter arxiv: 0802.3621

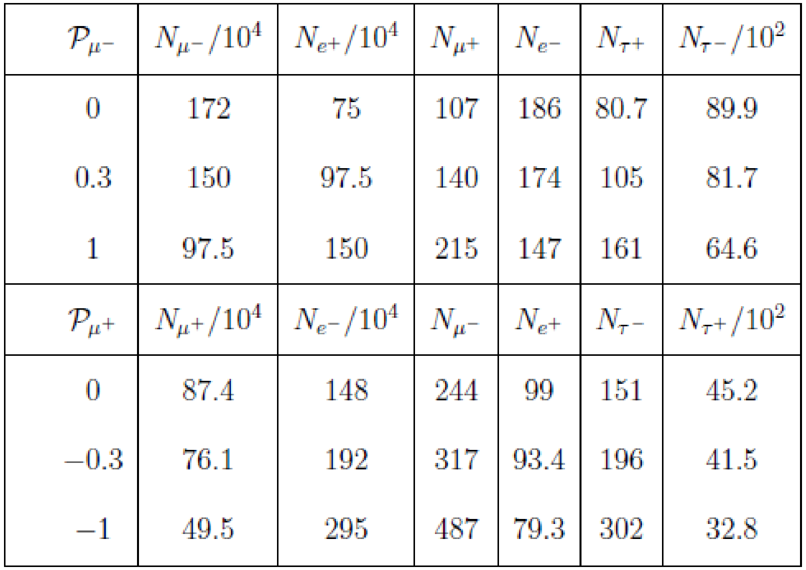
Neutrino Factory Event Samples

- Gold Channel: $\nu_e \rightarrow \nu_\mu$ in magnetized iron+readout (a la MINOS): MIND (50 kton)
- Silver Channels: $\nu_e \rightarrow \nu_\tau$ in Possible magnetized OPERA detector (10 kton)
- Low energy neutrino factory option: TASD



1kton magnetized OPERA, $\theta_{13}=5^o$, $\delta=90^o$, 732km, 10^{21} muon decays

Thousands of events, systematics assumed vary from 2 to 5%



$\mathcal{P}_{\mu^-}$	$N_{\mu^-}/10^4$	$N_{e^+}/10^4$	N_{μ^+}	N_{e^-}	N_{τ^+}	$N_{\tau^-}/10^2$
0	172	75	107	186	80.7	89.9
0.3	150	97.5	140	174	105	81.7
1	97.5	150	215	147	161	64.6
$\mathcal{P}_{\mu^+}$	$N_{\mu^+}/10^4$	$N_{e^-}/10^4$	N_{μ^-}	N_{e^+}	N_{τ^-}	$N_{\tau^+}/10^2$
0	87.4	148	244	99	151	45.2
−0.3	76.1	192	317	93.4	196	41.5
−1	49.5	295	487	79.3	302	32.8

Autiero et al, arXiv: 0305185

Phenomenology…

- These studies include allowances that there are uncertainties, often categorized as follows:
  - “signal” uncertainties
  - “background” uncertainties
- We need to start looking at how to achieve these 2-5% uncertainties, considering all the factors that go into them
  - Neutrino Flux
  - Detector Efficiencies for Signal and Backgrounds
  - Cross Sections
  - Detector Mass (i.e. Fiducial Volume)
- New Case Study since last NuFact: MINOS search for $\nu_\mu \rightarrow \nu_e$

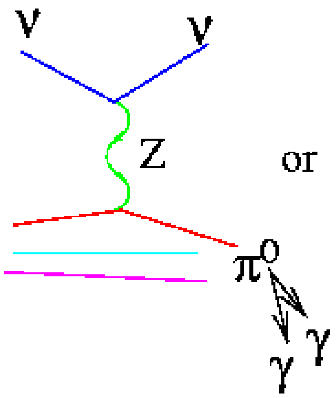
Challenges to conventional beam ν_e Appearance

Problem: looking for a ν_e in a beam of ν_μ's

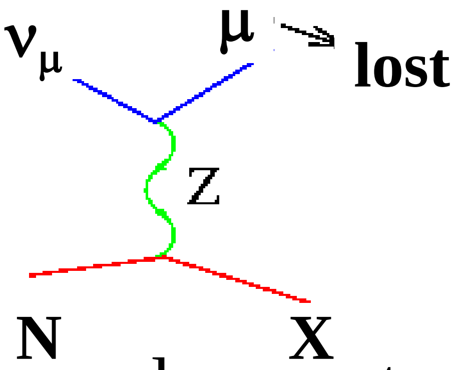
- Intrinsic beam ν_e
  - K decays

    $K \rightarrow \pi e \nu_e$
  - μ decays

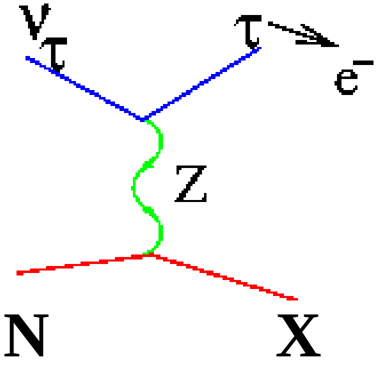
    $\pi \rightarrow \mu \rightarrow e \nu_e \nu_\mu$
- Neutral Current events



- ν_μ charged current events

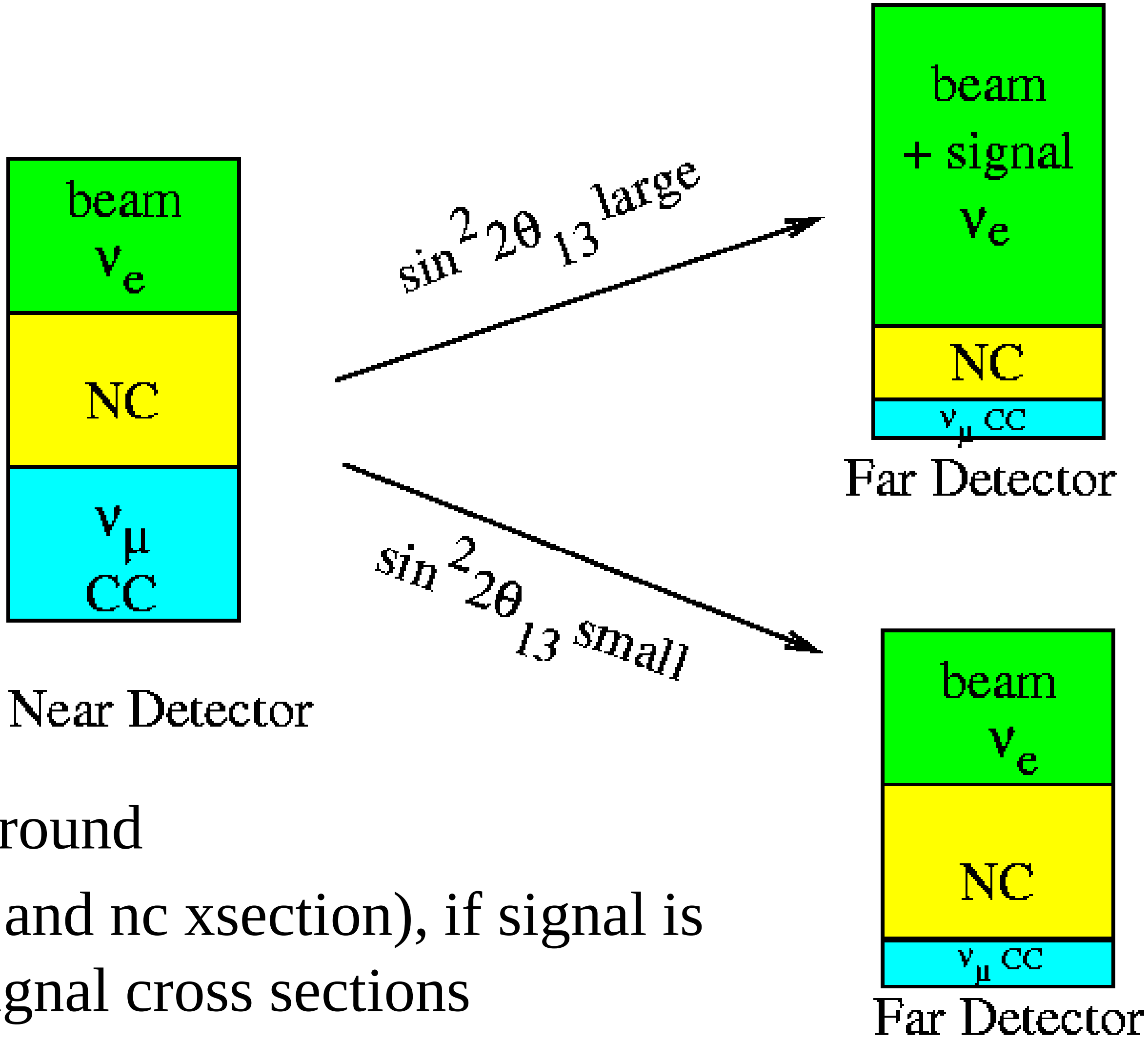


- ν_τ charged current events



ν_e Appearance Analysis

Summary:
Event Samples are different
Near to far, so
Uncertainties
In cross sections
Won’t cancel



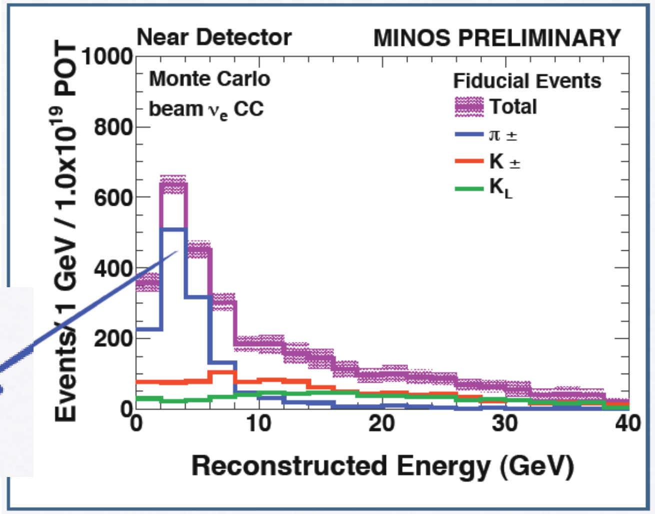
If signal is small,
Worry about background

Prediction (ν_e flux and nc xsection), if signal is
Big, worry about signal cross sections

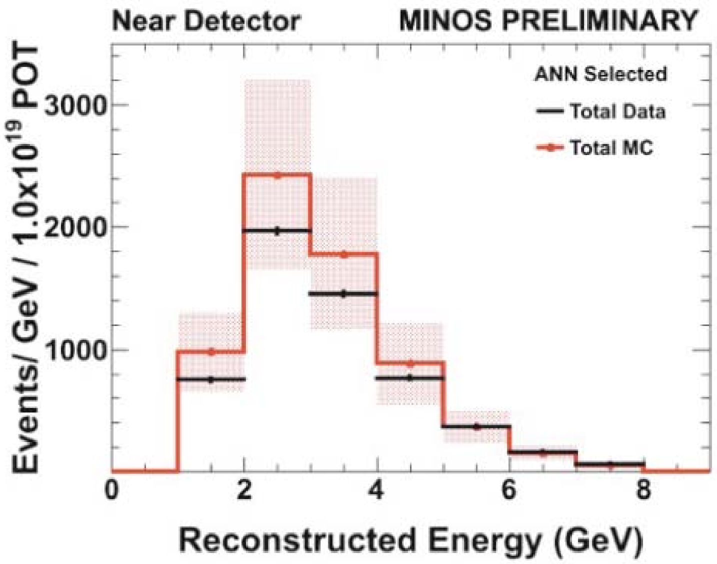
First "Superbeam" $\nu_\mu \rightarrow \nu_e$: MINOS

- Electron neutrinos dominated by muon decay

$$\begin{aligned} \pi^+ &\rightarrow \mu^+ \nu_\mu \\ &\hookrightarrow e^+ \bar{\nu}_\mu \nu_e \end{aligned}$$



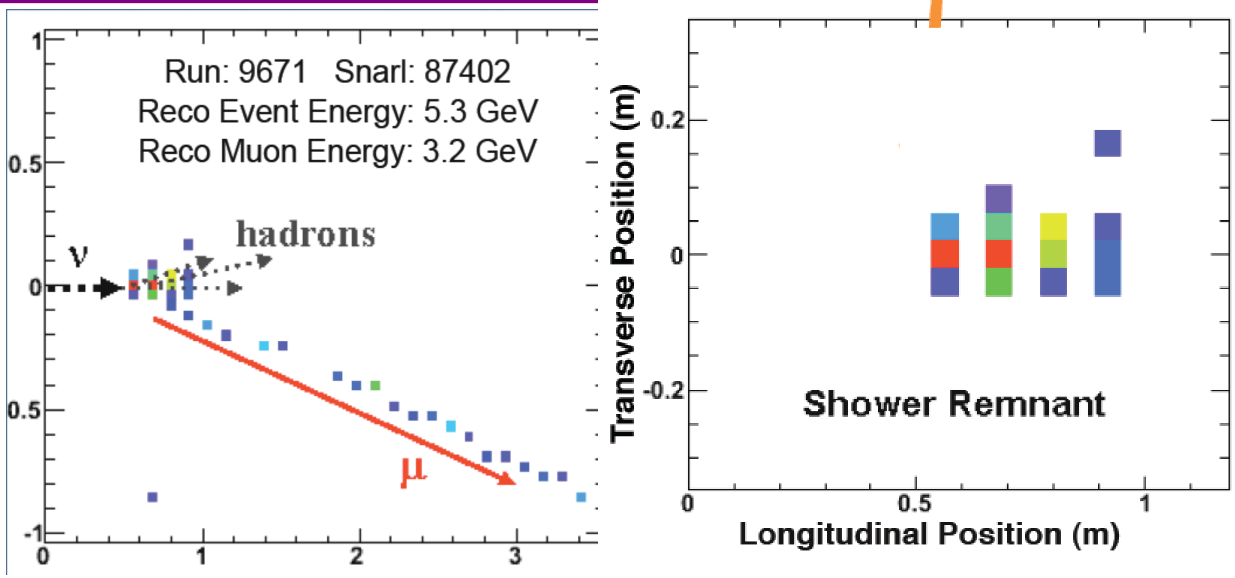
- Problem: when analysis was "done", the near detector data and prediction did not agree

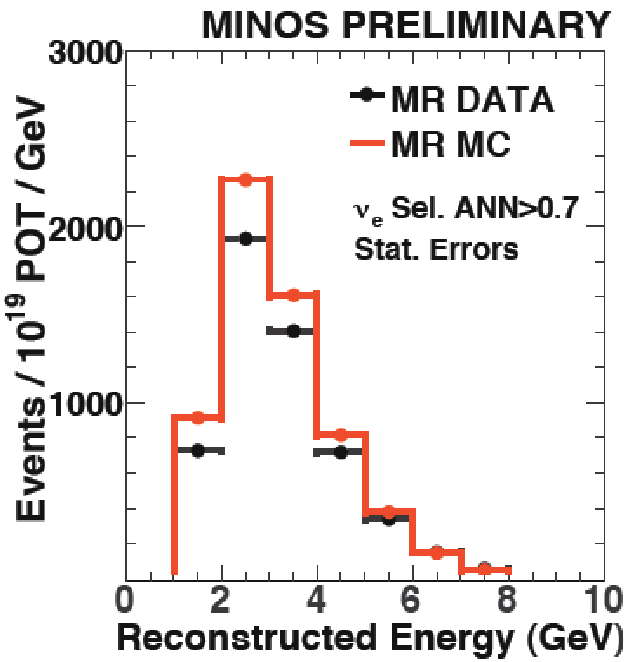


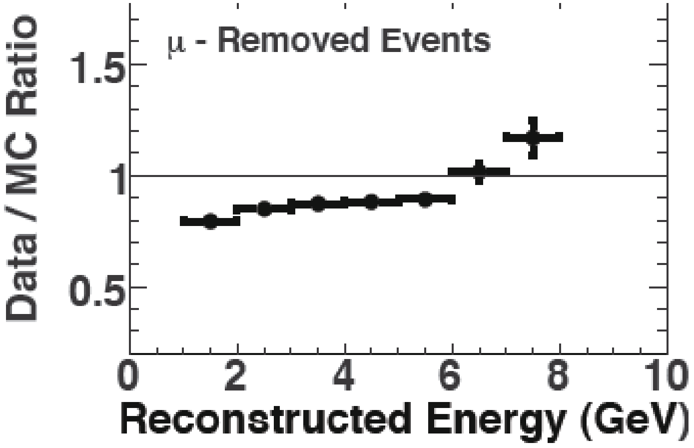
M. Sanchez, W&C, February 2009

Fixing ν_e Candidate Discrepancy, I

- Technique #1: Take ν_μ Charged Current events in data and remove muon to use "hadron shower" data







- Additional uncertainty in translating from Charged Current hadron shower to Neutral Current hadron shower

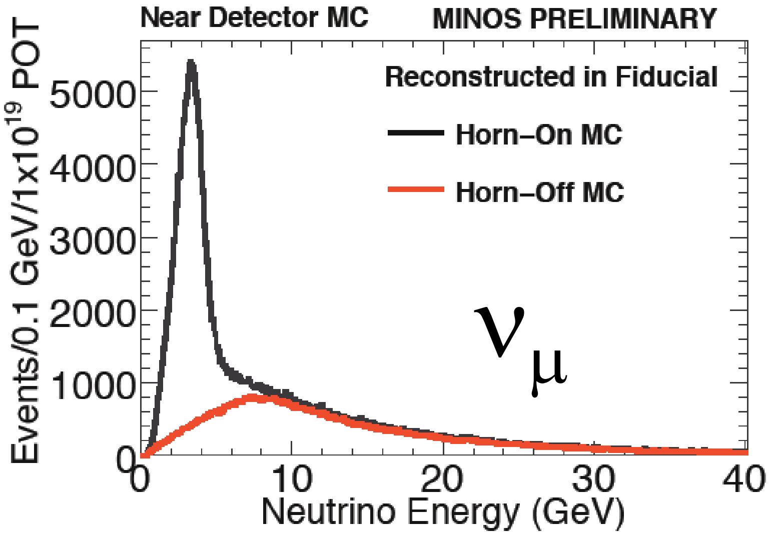
M. Sanchez, W&C, February 2009

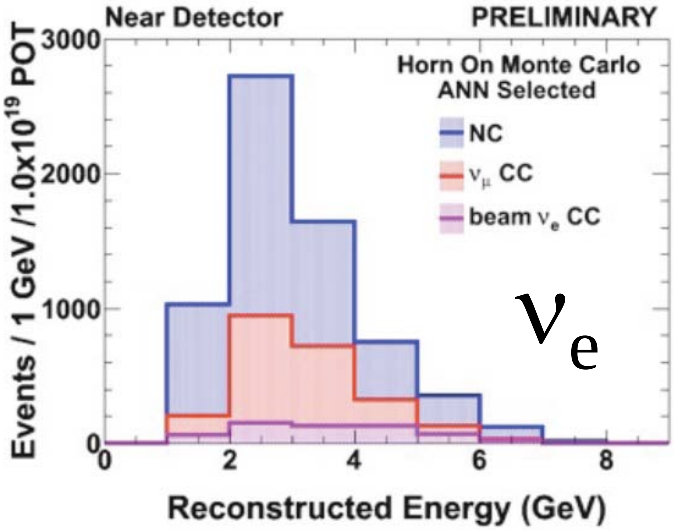
Beta-Beam and Neutrino Factory

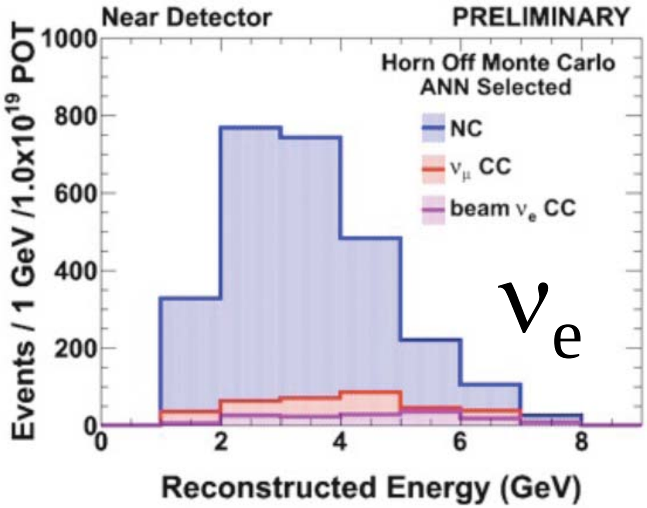
- Question: how will we study hadron showers in beta beams and neutrino factory era?
- What if we just wait and fix it then?
  - Beta beam: will be much harder to “remove the electron” in the near detector event samples
  - Neutrino Factory: will be hard because if the signal will be from ν_e to ν_μ, you only have anti-ν_μ in the beam
- What can we do instead (and do now!)?
  - Measure hadron showers in fine grained well-understood detectors with good energy resolution and particle ID:
    - At the energies of interest
    - On the same nuclei as the future far detectors
  - Develop better models for effects of nucleus on outgoing hadrons in the interactions, then test them with data

Fixing ν_e Candidate Discrepancy, II

- Run beamline with very different incoming flux to change the near detector background fractions





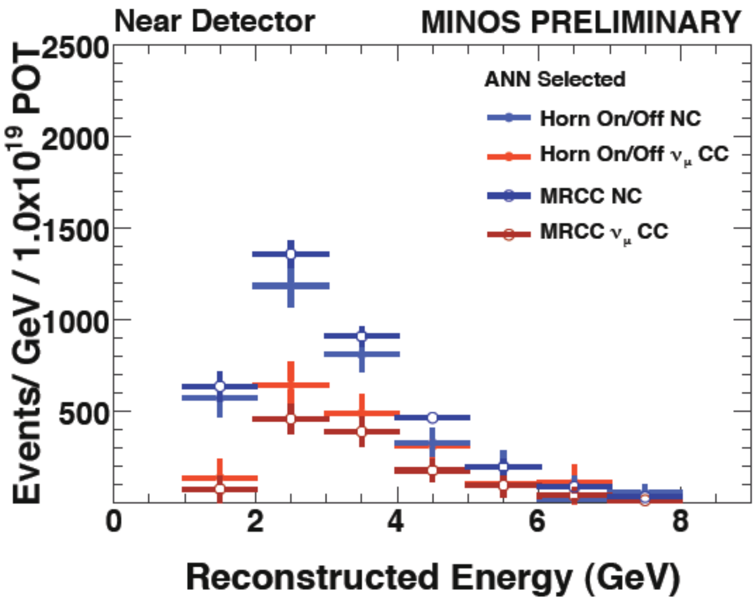


Betabeam and Neutrino Factory

- What changes can be made to the muons or radioactive isotopes to make changes in the flux?
  - Neutrino Factory: have investigated muon polarization to change relative amounts of ν_e and ν_μ in the beam
    - Does this change the background or signal fractions enough?
- Beta Beams and neutrino factories: can energy of particles in storage ring be changed enough to do a systematic check in finite time?
- Aside on Superbeams:
  - NOvA will not have the capability to move target around, will changing horn current be enough?
  - T2K: beamline can take several off-axis angles, is this still a possibility for systematic studies?

Predicting Far Detector ν_e Candidates

- Two strategies for "predicting" near detector ν_e candidates agree within errors, total background error quoted (after millions of ND events taken): 7.3%, statistical error is 23%

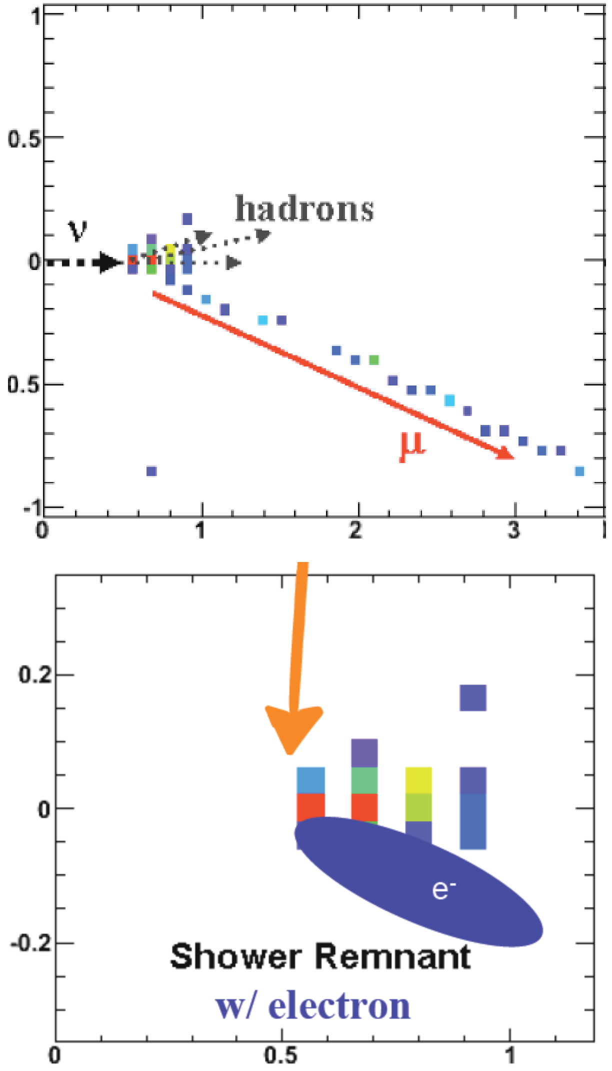


	Total	NC	ν_μ CC	ν_τ CC	ν_e beam
Horn on/ off	**27**	**18.2**	**5.1**	**1.1**	**2.2**
MRCC	28	21.1	3.6		

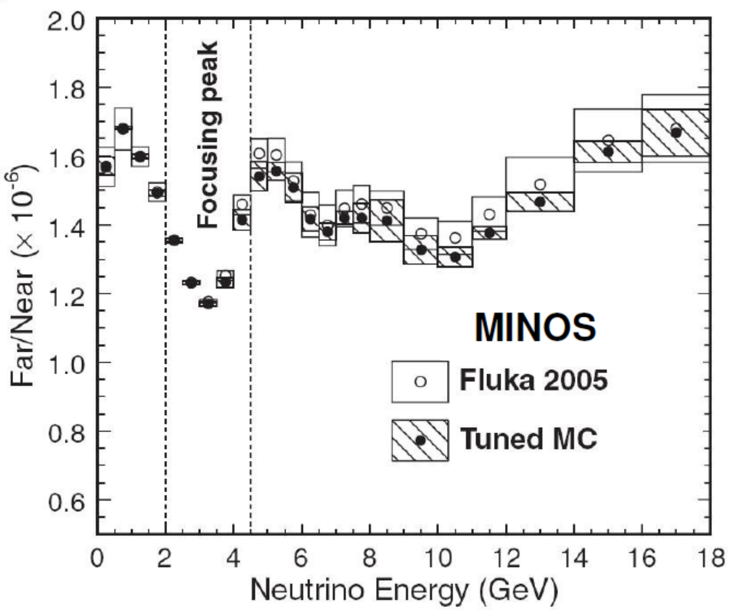
How can MINOS predict
Signal efficiency when it can't
See individual ν_e CC events?

ν_e Signal efficiency at MINOS

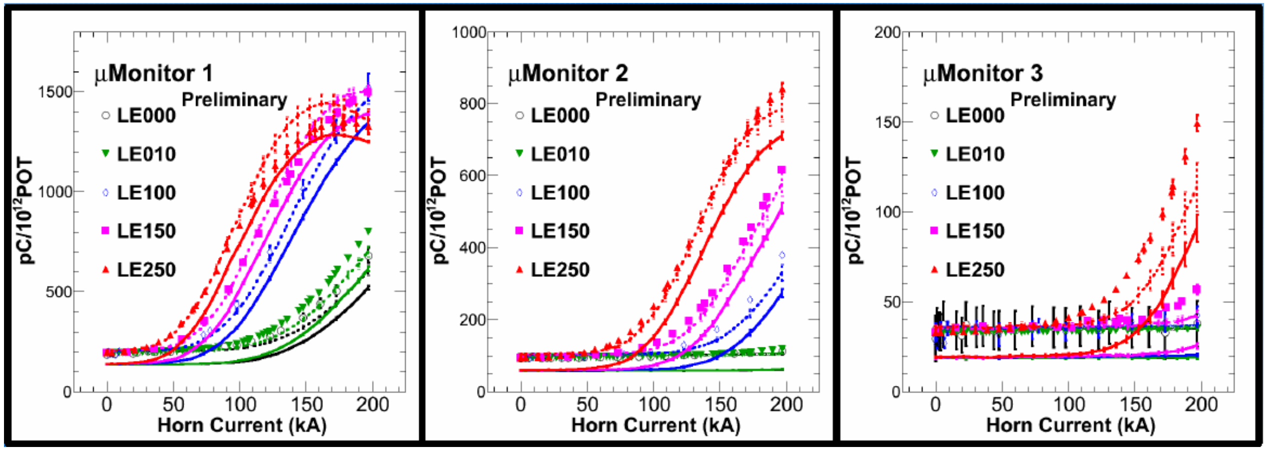
- Combine test beam information on electrons with neutrino beam information on hadron showers
- Note: this procedure assumes you know ratio of signal cross sections to normalization cross sections perfectly
- Note: this would be much harder in a near detector in a β beam: can't simply "remove" an electron shower and look at the remaining hadron shower
- Also note: in neutrino factory, the "ν_μ" is an antineutrino…



Need Absolute Flux Measurements!

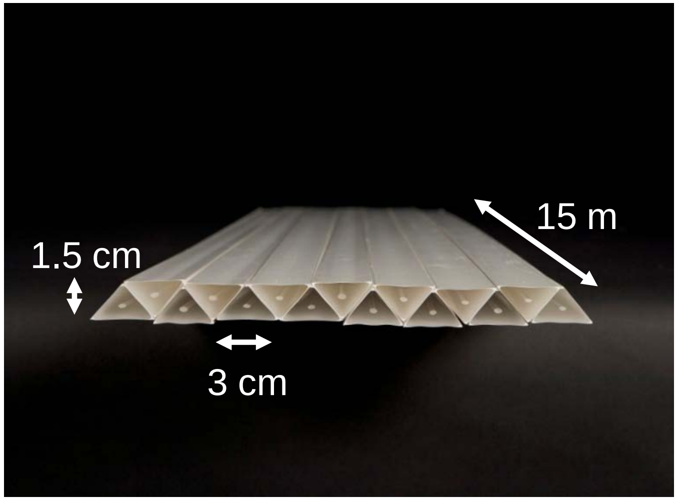


- MINOS ran with several different horn currents and target positions to best understand the far/near ratio (previous NuFact presentations)
- Currently evaluating muon monitor response versus focusing as well (Loiacono, Tuesday session)
- NuMI has flux measurements for 3 different populations of muons
- Plan for variable beam energy running resulted in much lower flux systematics



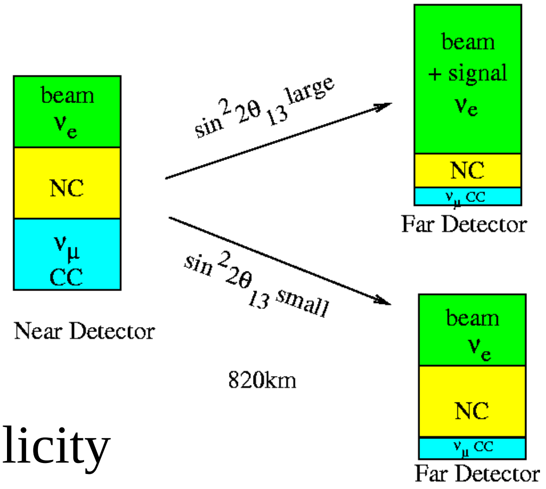
Understanding detector acceptance and background rejection

- Totally Active Scintillator Detector prototyping: trying to figure out how to put “MINERvA bars” in a large magnetic field
  - Can understand wrong sign backgrounds in low energy neutrino factory experiments
  - Need to understand ideal density for electron charge sign measurements ($\nu_\mu \rightarrow \nu_e$)
  - Hadron Shower studies in B field
- Liquid Argon Prototyping: MicroBooNE
  - Can study hadron showers and MiniBooNE low energy excess



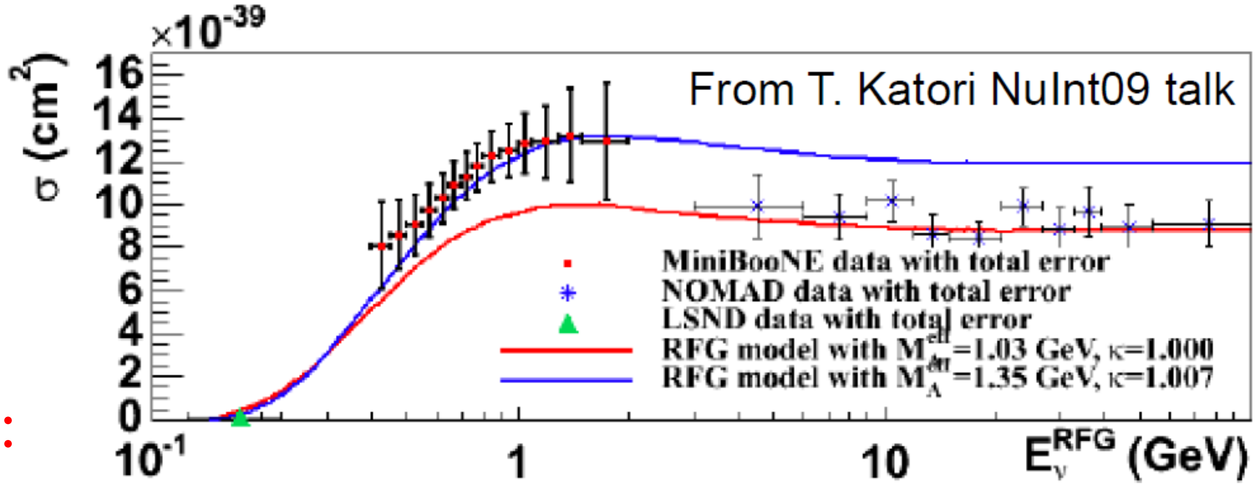
A. Bross

Need to Understand Cross Sections



- Remember, near detector and far detector cross section processes are very different
  - Conventional beam: ν_μ’s oscillated away
  - Beta-beam: there are no ν_μ’s in near detector to normalize to at all
  - Neutrino Factories: only neutrinos of the wrong helicity or the wrong flavor in the near detector compared to the far detector
- Recall that the cross sections themselves are far from known:

  Quasielastic news:

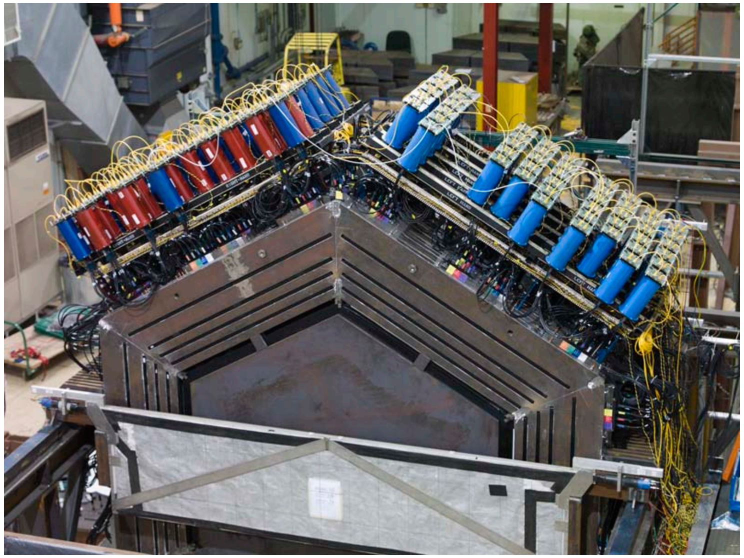


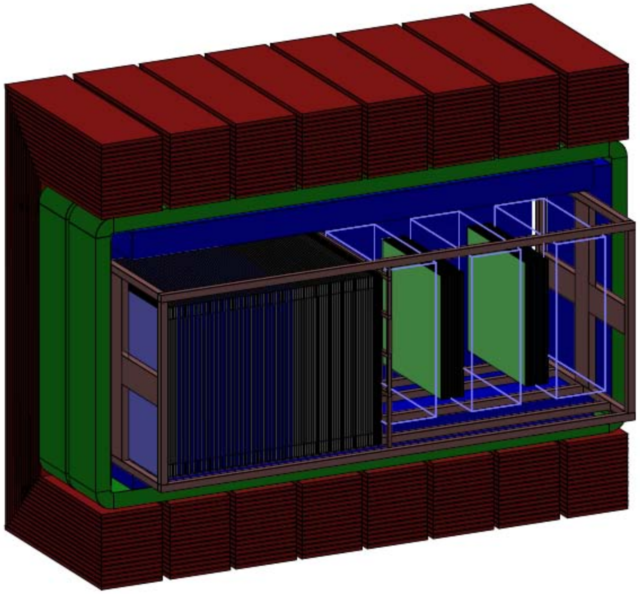
From T. Katori NuInt09 talk

- See Dave Schmitz’s Talk, Friday 9:45AM

Help is on the way…soon!

- MINERvA: exclusive final state measurements, 4 nuclear targets, to run in NuMI beamline in time for MINOS and NOvA (and T2K's) data





- T2K 280m Off axis detector to run in T2K beamline: inclusive π^0 measurements and some exclusive states, water target

Conclusions and Homework Assignments

- Many ideas for getting thousands of oscillated events in search of CP Violation & Mass Hierarchy
- To the Accelerator Physicists
  - Design in ability to cross-check the neutrino flux!
    - Muon monitoring stations for conventional beams
    - Varying polarization for muon storage rings
    - Measurements of ion and muon divergence in storage ring
- To the Theoretical Physicists
  - Develop/Improve description of neutrino interactions
    - Not just Quasi-elastic cross sections
    - Secondary particle production spectra: $\pi^\pm$, π^0
    - Signal and Background processes both important
- To the Experimental Particle Physicists
  - Measure your cross sections before you start, figure out hadron showers
  - Measure your detector response before you decide to build 100 ktons
  - Measure it again when design is final, in a test beam