Neutrino Physics Plans/Dreams at Fermilab

Adam Para
KITP
Santa Barbara

- Physics Motivation 199x
- NuMI Beam
- MINOS
- Physics motivation 200x
- Off-axis NuMI Beam
- Backgrounds and Detector Issues
- Sites
- Sensitivity of NuMI Off-axis Experiments

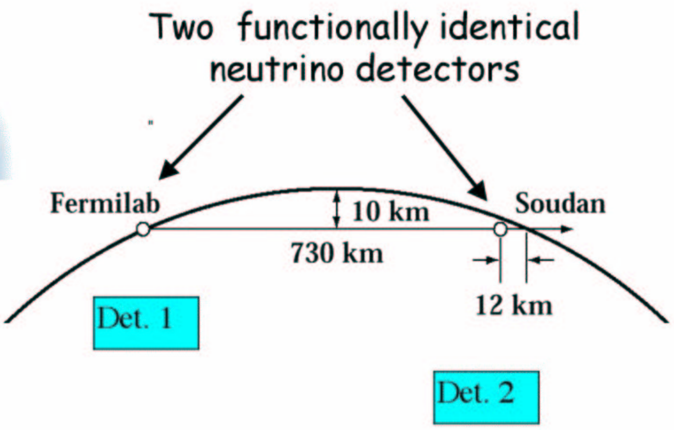
Physics questions, 1990+ε

- Is there an 'atmospheric neutrino anomaly'?
- What is its origin?
- Are there neutrino oscillations with $\Delta m^2 \sim 2\times10^{-2}$ eV^2?

⬇

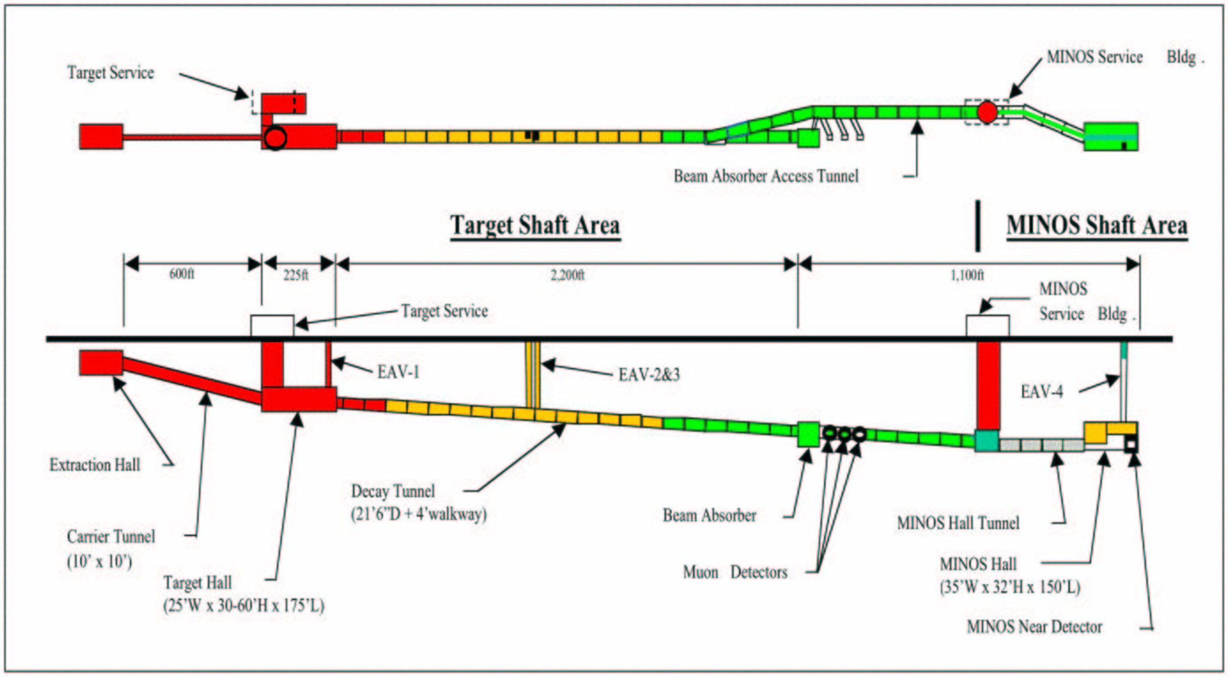
L ~700-800 km, E ~ 10-20 GeV

NuMI + MINOS : a decisive test of the atmospheric anomaly

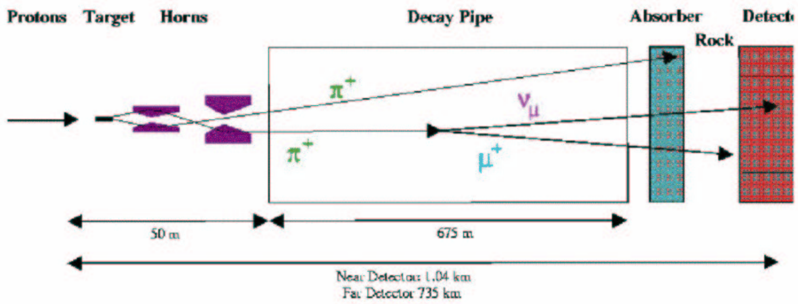


Two functionally identical neutrino detectors

NuMI Beam Layout



NUMI neutrino beam



- 120 GeV protons from the Main Injector
- 4 x 10^{13} protons on target every 1.9 sec => 3.7 x 10^{20} protons/year
- Water cooled graphite target, 2.0-2.4 λ
- Flexible configuration of 2 parabolic magnetic horns
- 675 m long, 1m radius decay pipe
- Muon flux detectors for flux monitoring

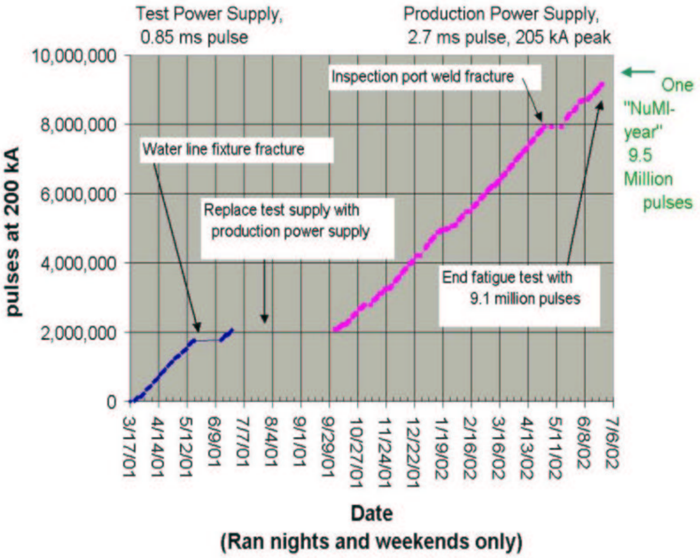
Status of NuMI Tunnel

Beam pipe is now
finished and
cast in concrete

NuMI Horn1: testing

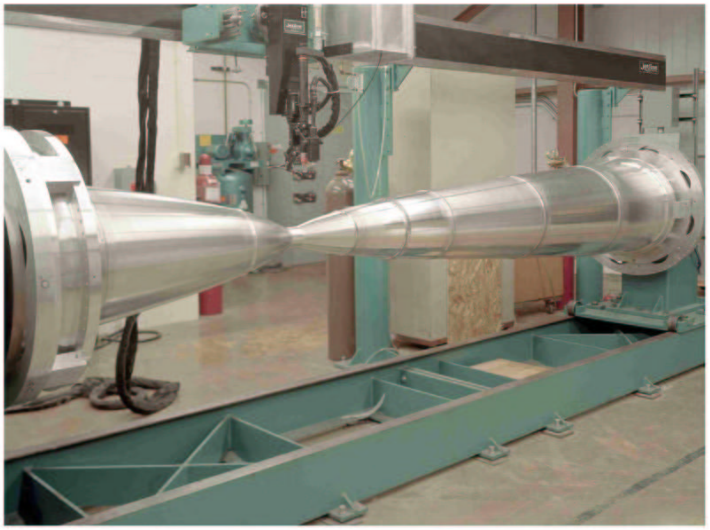
1st Horn under test

1 year worth of pulses



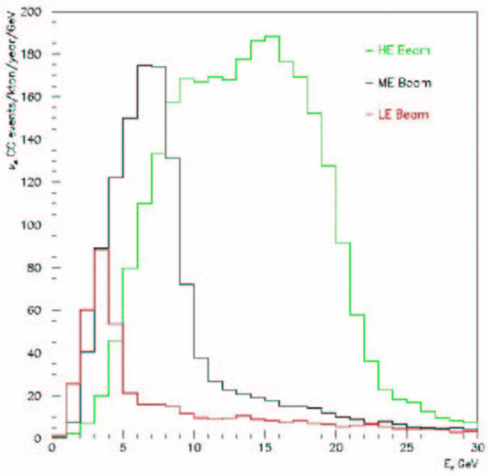
Horn 2: under construction

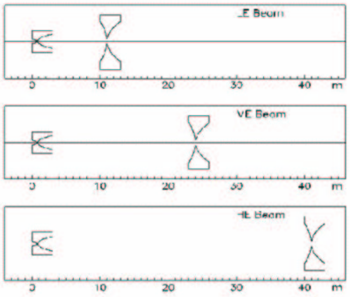
Initial weld samples



Final horn being electron welded

NuMI: Flexible Neutrino Beam



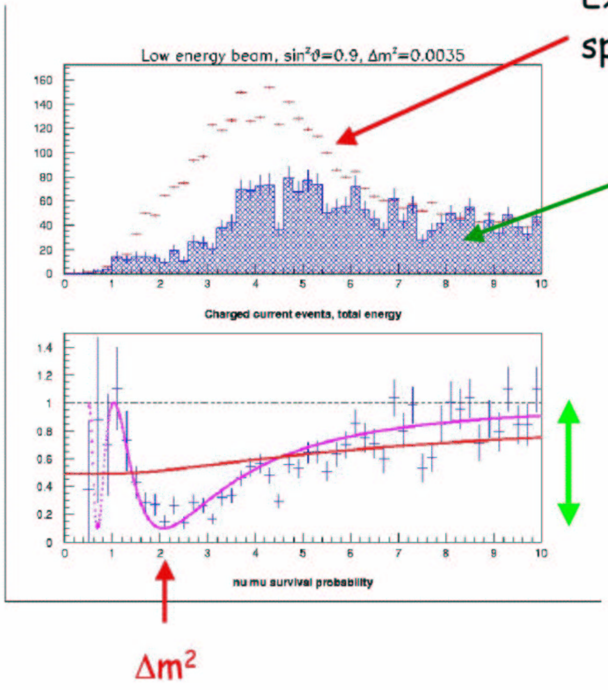


'zoom' lens: Vary the relative distances of the source and focusing elements

Expected CC Events Rates in Minos 5kt detector

- High 16,000 ev/yr
- Medium 7,000 ev/yr
- Low 2,500 ev/yr

Possible result in 2005(?)



Expected event spectrum

Observed event spectrum

Ratio: survival probability as a function of energy

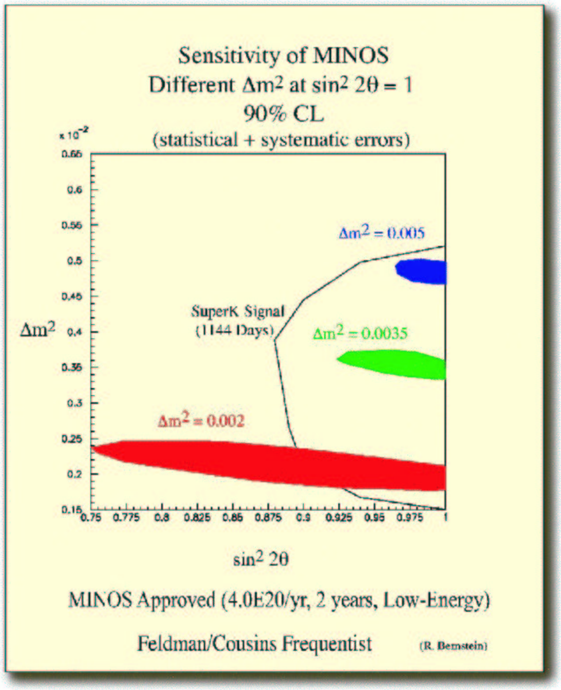
<u>Shape: disappearance mechanism .</u> Oscillations? Decays? Other?

Mixing angle

<u>If</u> oscillations => precise (~10%) measurement of the parameters

MINOS: oscillations parameters

- Will measure Dm2 to ~ 10%
- May improve knowledge of mixing angle, somewhat

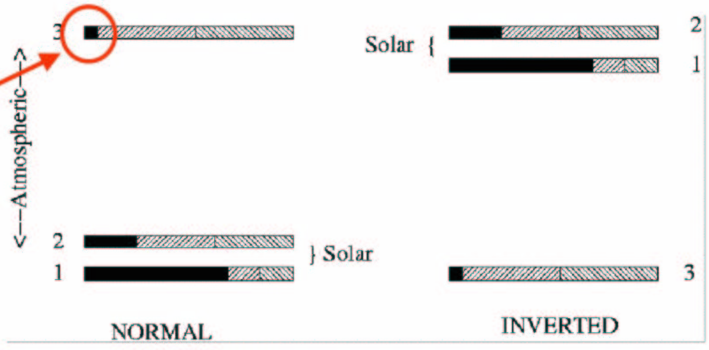


Likely NuMI Schedule

- Far detector _ complete, taking cosmic data
- Near detector assembled in the surface buildong
- The Underground (tunnel, caverns, and shafts) contractor finished
- Surface Building construction and outfitting started
- Outfitting should take about 1 year
- Installation of beam technical components and Near Detector should take about 1 year
- We expect first beam on NuMI target 11/04

Three outstanding questions ~ 2003

- Neutrino mass pattern: This ? Or that?



- Electron component of ν_3 ($\sin^2 2\theta_{13}$)
- Complex phase of s |\ CP violation in a neutrino sector ⇓◊ (?) baryon number of the universe

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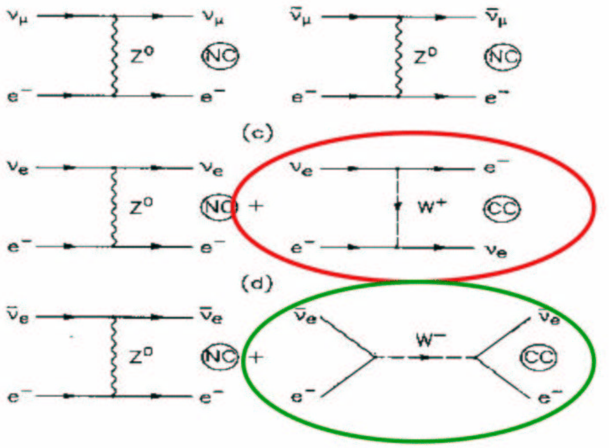
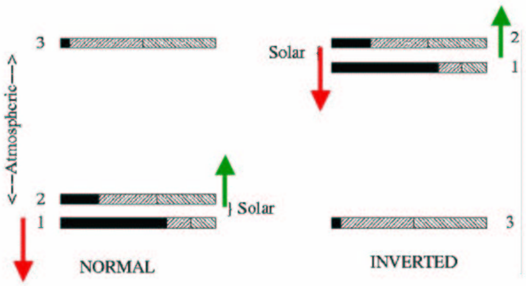
The key: $\nu_\mu \Rightarrow \nu_e$ oscillation experiment

A. Cervera et al., Nuclear Physics B 579 (2000) 17 – 55, expansion to second order in

Neutrino Propagation in Matter





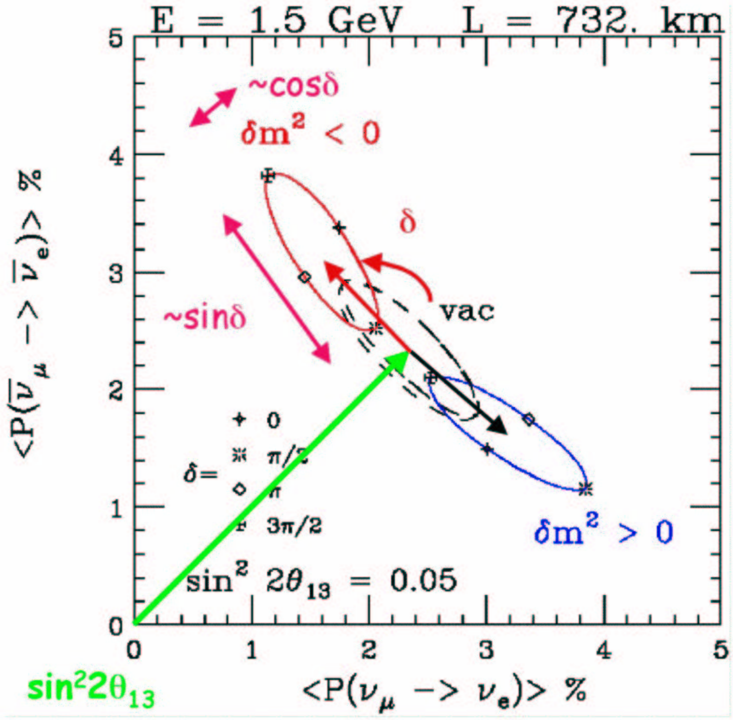
- Matter effects reduce mass of ν_e and increase mass of $\bar{\nu}_e$
- Matter effects increase Δm^2_{23} for normal hierarchy and reduce Δm^2_{23} for inverted hierarchy

Observations

- First 2 terms are independent of the CP violating parameter δ
- The last term changes sign between ν and $\bar{\nu}$
- If θ_{13} is very small ($\lesssim 1^\circ$) the second term (subdominant oscillation) competes with 1st
- For small θ_{13}, the CP terms are proportional to θ_{13}; the first (non-CP term) to θ_{13}^2
- The CP violating terms grow with decreasing E_ν (for a given L)
- CP violation is observable <u>only if all</u> angles ≠ 0

¬ Two observables dependent on several physics parameters: need measurements at different L and E

Anatomy of Bi-probability ellipses



Minakata and Nunokawa, hep-ph/0108085

Observables are:

- •P
- •P

Interpretation in terms of $\sin^2 2\theta_{13}$, δ and sign of Δm^2_{23} depends on the value of these parameters and on the conditions of the experiment: L and E

How large is θ_{13} ???

Texture		θ_{13}	$\sin^2 2\theta_{13}$	perturbations
	Degenerate neutrinos, spontaneously broken flavor SO(3)		~0.064	
	Degenerate neutrinos, democratic mass matrix		~0.019	
	Inverted hierarchy		~0.001	
			<<0.001	
	Normal hierarchy		~0.064	
			~0.26	

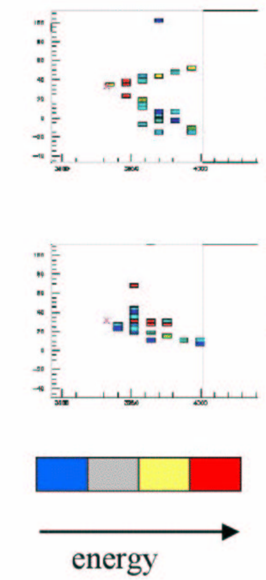
Altarelli,Ferualio, hep-ph/0206077

ν_e Interactions in MINOS?

NC interactions:

- Energy distributed over 'large' volume

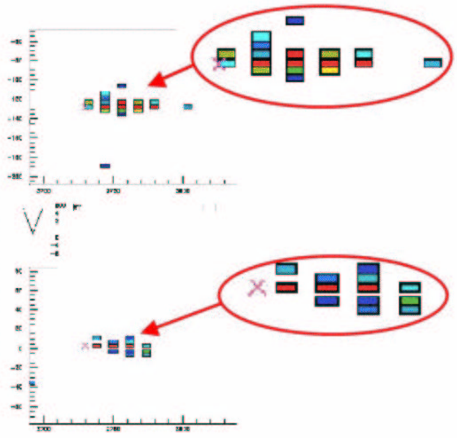
NC, E_{obs} = 3 GeV



ν_e *CC* interactions (low y) :

- Electromagnetic shower:
  - Short
  - Narrow
- Most of the energy in a narrow cluster

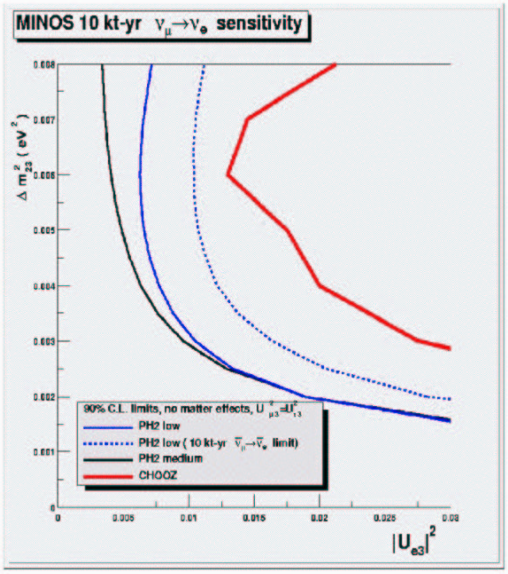
ν_e CC, E_{tot} = 3 GeV



Detector Granularity:

- Longitudinal: $1.5X_0$
- Transverse: $\sim R_M$

MINOS Limits on ν_μ to ν_e Oscillations



10 kton-yr exposure,

Δm^2=0.003 eV^2, $|U_{e3}|^2$=0.01:

Signal (ε = 25%) - 8.5 ev

ν_e background - 5.6 ev

Other (NC,CC,ν_τ) - 34.1 ev

M. Diwan, M. Mesier, B. Viren, L. Wai, NuMI-L-714

90% CL: $|U_{e3}|^2 < 0.01$

Sample of ν_e candidates defined using topological cuts

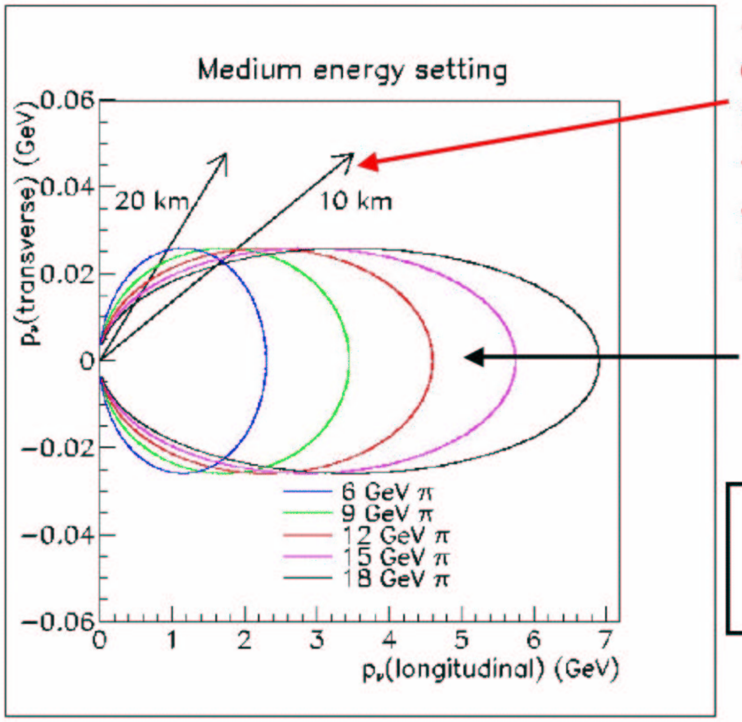
Receipe for a Better Experiment

- More neutrinos in a signal region
- Less background
- Better detector (improved efficiency, improved rejection against background)
- Bigger detector

Lucky coincidences:

- distance to Soudan = 735 km, Δm^2=0.025-0.035 eV^2
- Below the tau threshold! (BR(τ->e)=17%)

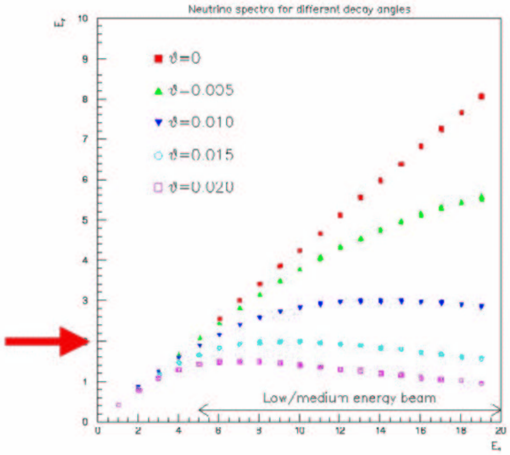
Two body decay kinematics

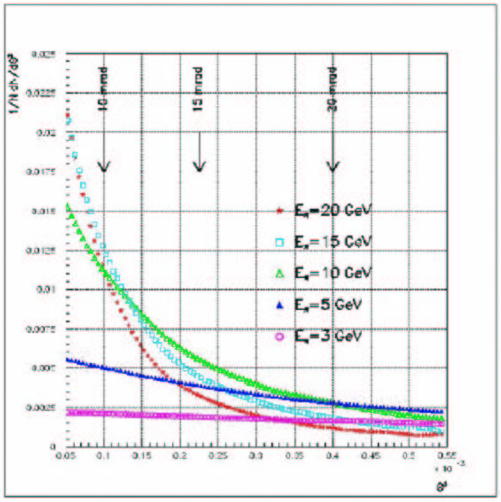


At this angle, 15 mrad, energy of produced neutrinos is 1.5-2 GeV for all pion energies \ very intense, narrow band beam

On axis: $E_\nu=0.43E_\pi$

Off-axis 'magic' (D.Beavis at al. BNL, E-889)

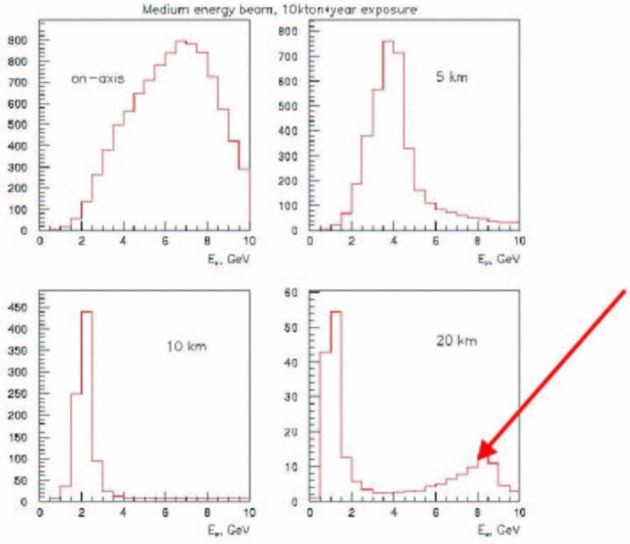




1-3 GeV intense beams with well defined energy in a cone around the nominal beam direction

$$Flux = \left(\frac{2\gamma}{1+\gamma^2\theta^2}\right)^2 \frac{A}{4\pi z^2}$$

Medium Energy Beam: Off-axis detectors

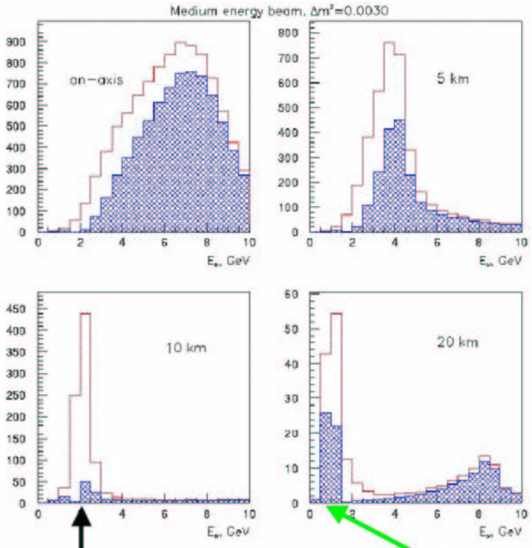


Neutrinos from K decays

Neutrino event spectra at putative detectors located at different locations

Disappearance Experiment, 10 kty
$\Delta m^2 = 0.003\ eV^2$

Three additional detectors at a distance of 5,10 and 20 km (transverse to the beam axis)



$\sim 1-\sin^2 2\theta_{23}$

Oscillatory pattern: re-appearance after a minimum

ν_e Appearance Experiment: a Primer

This determines sensitivity of the experiment

Systematics:

- ·Know your expected flux
- ·Know the beam contamination
- ·Know the NC background*rejection power (Note: need to beat it down to the level of ne component of the beam only)
- ·Know the electron ID efficiency

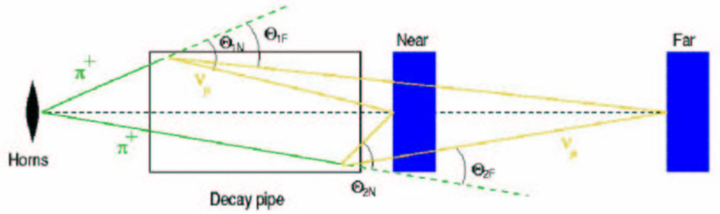
Do we need a dedicated near detector? A.k.a predicting the off-axis spectrum.

Neutrino fluxes detected at the near and far detectors produced by the same parent hadron beam, hence:

every neutrino event observed at the near detector implies a certain flux(E_ν) at the far detector.

Correlation function M depends mostly on the focusing system and the geometry of the beam line (M. Szleper, A. Para hep-exp/011001). It depends on the location of the far detector.

How to predict the off-axis spectrum II

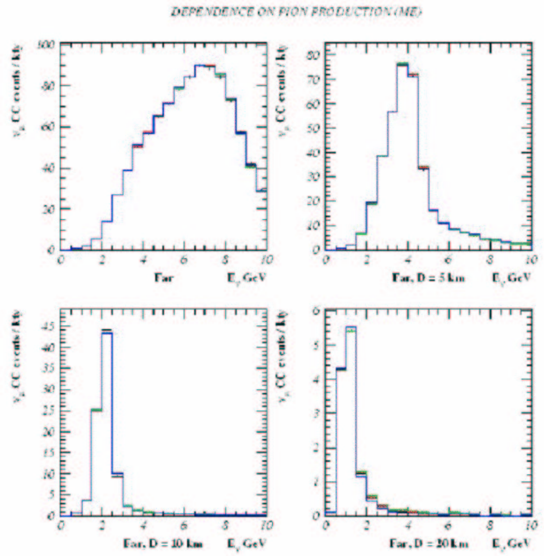


Decay angle $Q^N \neq Q^F$, hence $E^N \neq E^F$.

Take as an example two neutrino energy bins:

- Well focused, parallel beam of pions $M_{11}, M_{22} \neq 0$, $M_{12}=M_{21}=0$
- Realistic beam, far detector on axis $M_{11}, M_{12} \neq 0$, $M_{21}<M_{11}$, $M_{12}\sim 0$
- Off-axis beam $M_{11}, M_{22}, M_{21}\sim 0$, $M_{12} \neq 0$

Beam Systematics: Predict the Spectrum. Medium Energy Beam



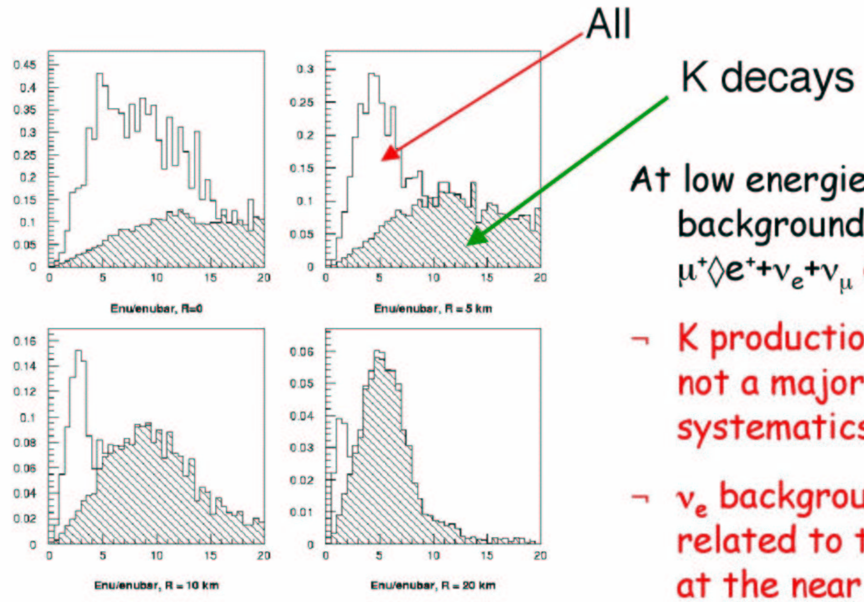
Event spectra at far detectors located at different positions derived from the single near detector spectrum using <u>different particle production models.</u>

Four different histograms superimposed

Total flux predictable to ~1-2 %.

Sources of the ν_e background

$\boxed{\nu_e/\nu_\mu \text{ ~0.5\%}}$

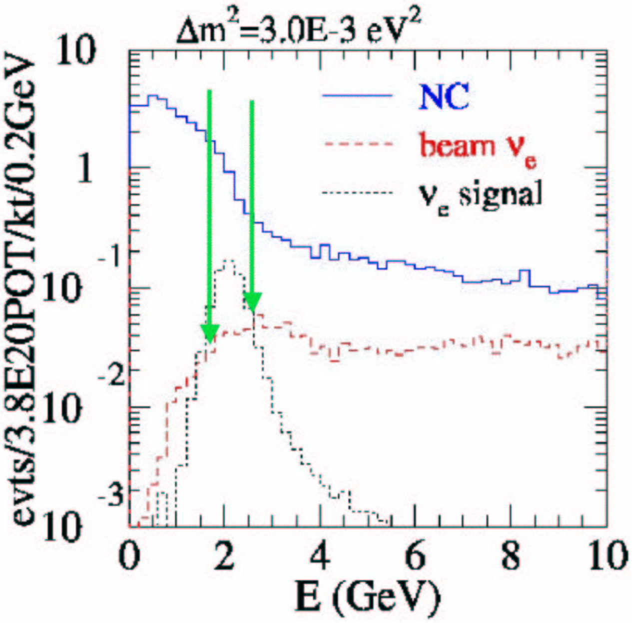


At low energies the dominant background is from μ^+◊$e^+ + \nu_e + \nu_\mu$ decay, hence

¬ K production spectrum is not a major source of systematics

¬ ν_e background directly related to the ν_μ spectrum at the near detector

Fighting NC background:the Energy Resolution



Cut around the expected signal region to improve signal/background ratio

M. Messier, Harvard U.

Backgrounds Summary

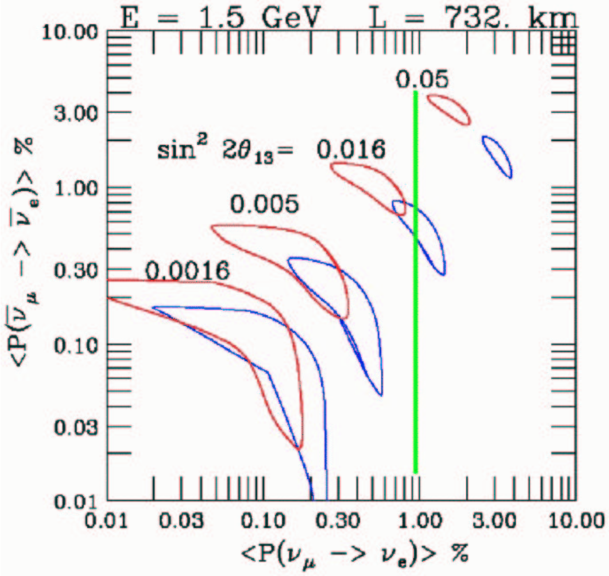
- ν_e component of the beam
  - Constrained by ν_μ interactions observed in the near MINOS detector (π)
  - Constrained by ν_μ interactions observed in the near MINOS detector (μ)
  - Constrained by pion production data (MIPP)
- NC events passing the final analysis cuts (π^0?)
  - Constrained by neutrino data from K2K near detector
  - Constrained by the measurement of EM 'objects' as a function of E_{had} in the dedicated near detector
- Cosmics
  - Cosmic muon induced 'stuff' overlapped with the beam-induced neutrino event
  - (undetected) cosmic muon induced which mimics the 2 GeV electron neutrino interaction in the direction from Fermilab within 10 μsec beam gate

- Expected to be very small
- Measured in a dedicated setup (under construction)

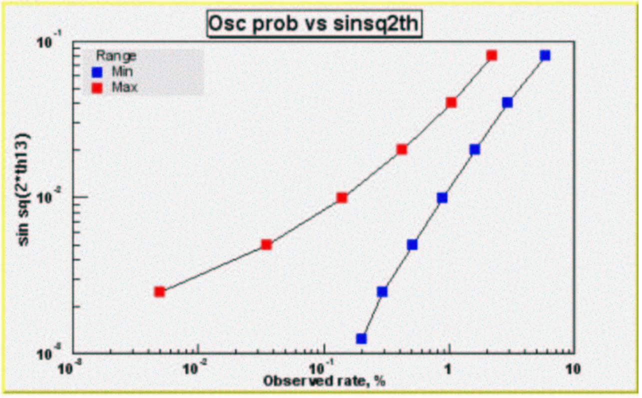
Important Reminder

- Experiment measures oscillation probability. It is not unambigously related to fundamental parameters, θ_{13} or $U_{e3}{}^2$
- At low values of $\sin^2 2\theta_{13}$ (~0.01), the uncertainty could be as much as a factor of 4 due to matter and CP effects
- Measurement precision of fundamental parameters can be optimized by a judicious choice of running time between ν and ν

Oscillation probability vs physics parameters



Parameter correlation: even very precise determination of P_ν leads to a large allowed range of $\sin^2 2\theta_{23}$ \ antineutrino beam is more important than improved statistics



Antineutrinos are very important

Antineutrinos are crucial to understanding:

- Mass hierarchy
- CP violation
- CPT violation

High energy beams experience: antineutrinos are 'expensive'.

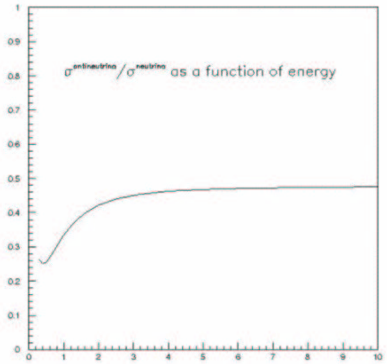
For the same number of POT ← Ingredients: $\sigma(\pi^+)\sim3\sigma(\pi^-)$ (large y)

NuMI ME beam energies:

$\sigma(\pi^+)\sim1.15\sigma(\pi^-)$ (charge conservation!)

Neutrino/antineutrino events/proton ~ 3

Backgrounds very similar to the neutrino case (smaller NC background)



(no Pauli exclusion ~25% at 0.7 GeV)

Detector(s) Challenge

- Surface (or light overburden)
  - ϖ High rate of cosmic μ's
  - ϖ Cosmic-induced neutrons
- But:
  - ϖ Duty cycle 0.5×10^{-5}
  - ϖ Known direction
  - ϖ Observed energy > 1 GeV

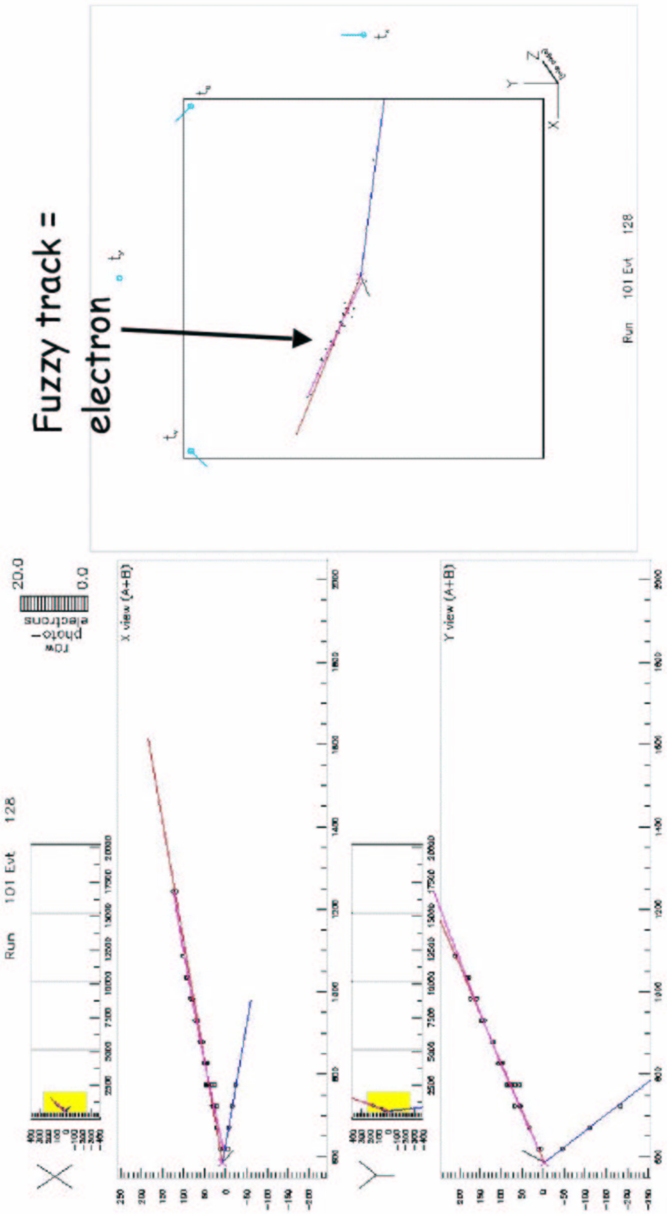
Principal focus: electron neutrinos identification

- Good sampling (in terms of radiation/Moliere length)

Large mass:

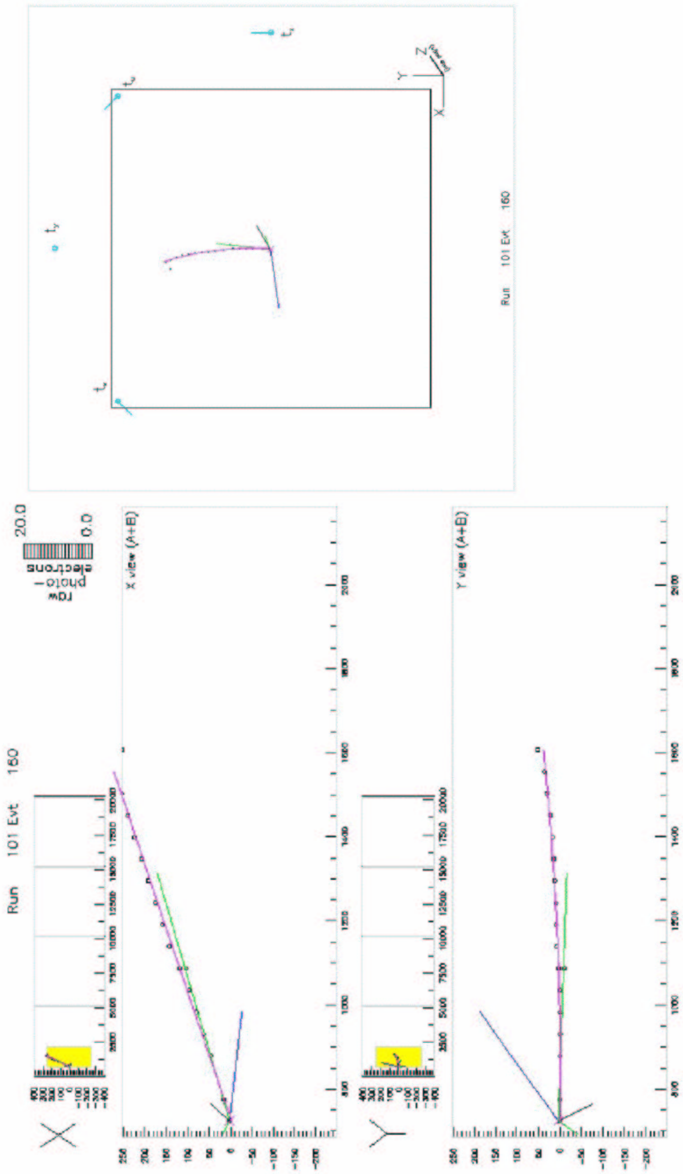
- maximize mass/radiation length
- cheap

A 'typical' signal event



Fuzzy track = electron

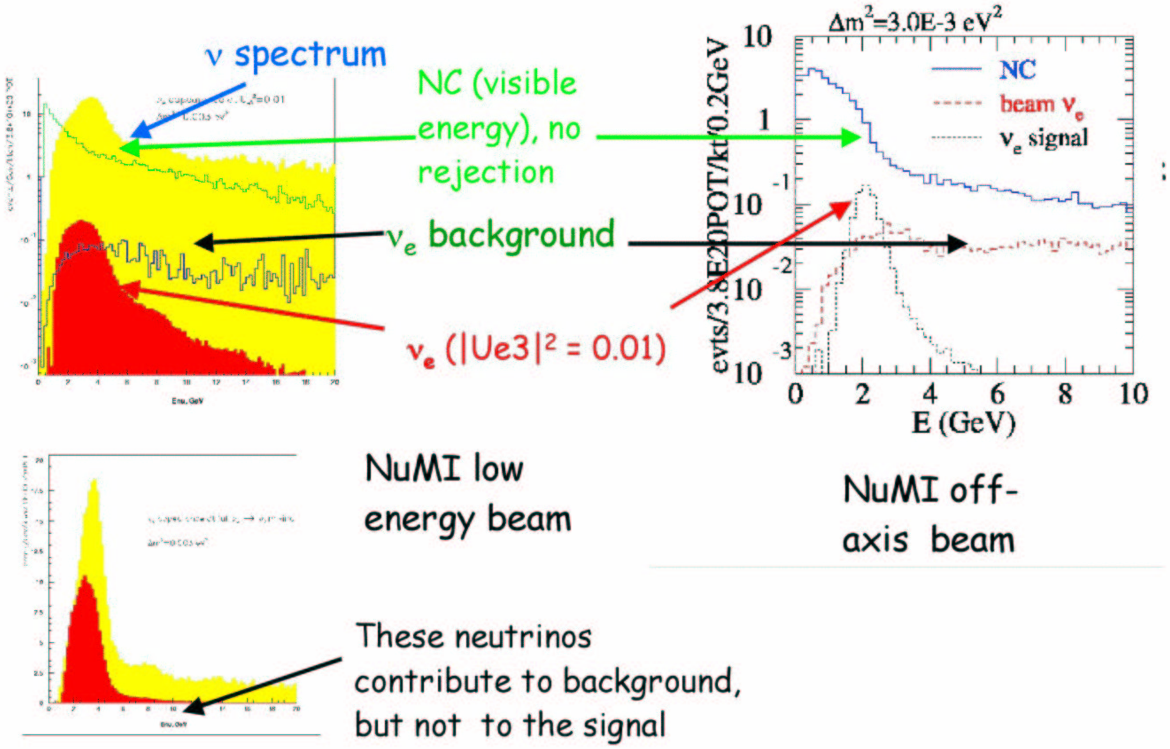
A 'typical' background event



NuMI Off-axis Detector

- Different detector possibilities are currently being studied
- The goal is an eventual 50 kt fiducial volume detector
- The possibilities are:
  - Low Z imaging calorimeter with RPC's, drift tubes or scintillator
  - Liquid Argon (a large version of ICARUS)

Background rejection: beam + detector issue



ν spectrum

NC (visible energy), no rejection

ν_e background

ν_e ($|Ue3|^2$ = 0.01)

NuMI low energy beam

NuMI off-axis beam

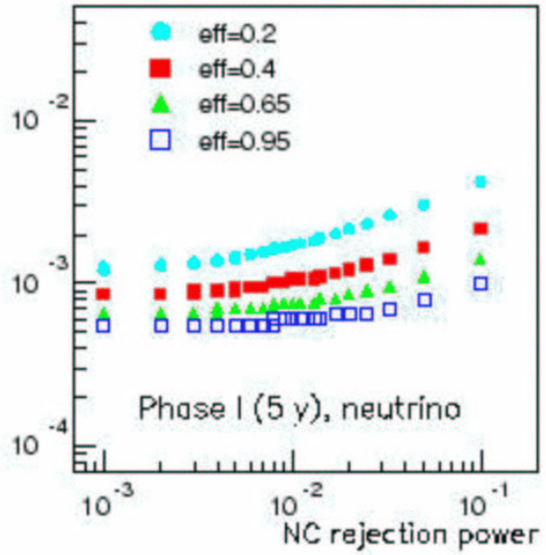
These neutrinos contribute to background, but not to the signal

Sensitivity: ν_e efficiency and NC rejection

Major improvement of sensitivity by improving ID efficiency up to ~50%

Factor of ~ 100 rejection (attainable) power against NC sufficient

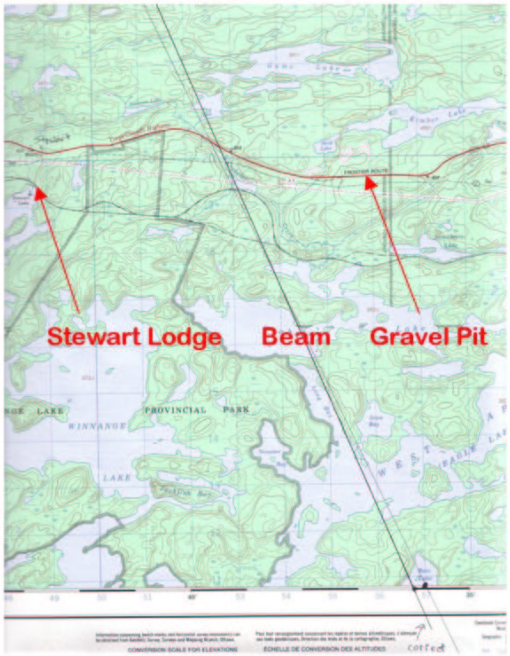
NC background not a major source of the error, but a near detector probably desirable to measure it



NuMI Beam: wide range of possible sites

- Collection of possible sites, baselines, beam energies
- Physcis/results driven experiment optimization
- Complementarity with other measurements (Cluster of detectors? JHF? => K. Whisnant's talk)

Location of Canadian Sites



A Closer Look

Stewart Lodge

Compressor station
and
Gravel pit

Two Most Attractive Sites

- Closer site, in Minnesota
  - About 711 km from Fermilab
  - Close to Soudan Laboratory
  - Unused former mine
  - Utilities available
  - Flexible regarding exact location
  - CNA study
- Further site, in Canada, along Trans-Canada highway
  - About 985 km from Fermilab
  - There are two possibilities:
    - About 3 km to the west, south of Stewart Lodge
    - About 2 km to the east, at the gravel pit site, near compressor station

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Two phase program

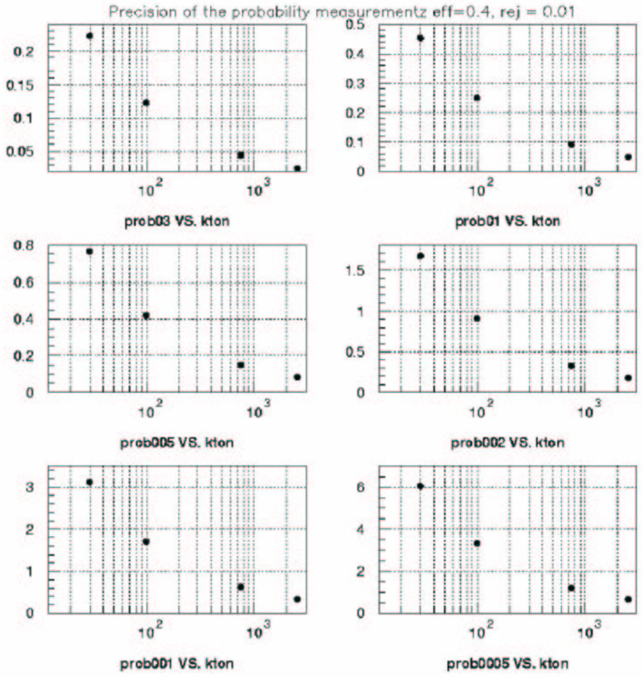
Phase I (~ $150 M, running 2007 - 2014)

- 50 kton (fiducial) detector with $\varepsilon \sim 40\%$
- 4×10^{20} protons per year
- 1.5 years neutrino (6000 ν_μ CC, 70-80% 'oscillated')
- 5 years antineutrino (7000 ν_μ CC, 70-80% 'oscillated')

Phase II (~ $500M, running 2014-2020)

- 200 kton (fiducial) detector with $\varepsilon \sim 40\%$ or 100 kton Liquid Argon
- 20×10^{20} protons per year
- 1.5 years neutrino (120000 ν_μ CC, 70-80% 'oscillated')
- 5 years antineutrino (130000 ν_μ CC, 70-80% 'oscillated')

Expected precision of Phase I and II (statistical)



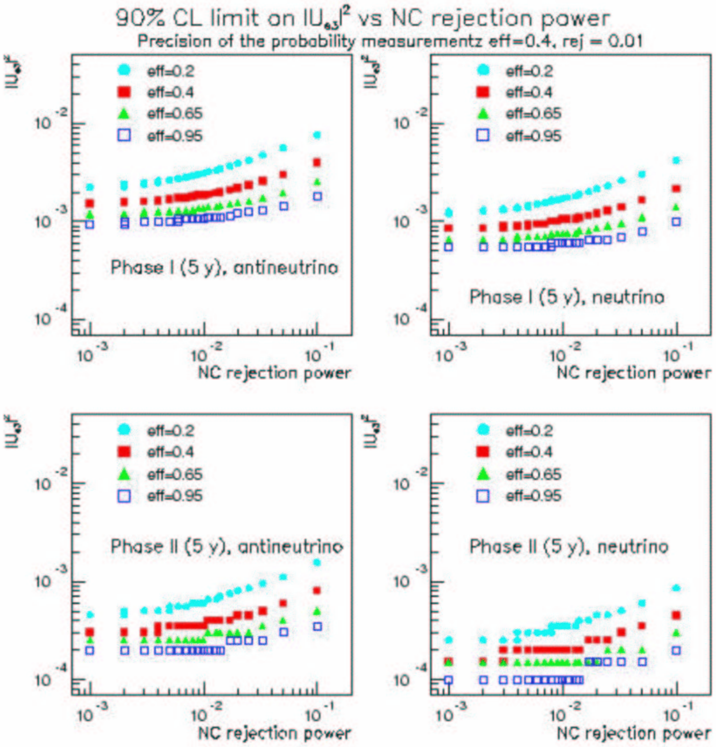
Phase I:

- Measure 0.01 probability to 25% (ν)

Phase II:

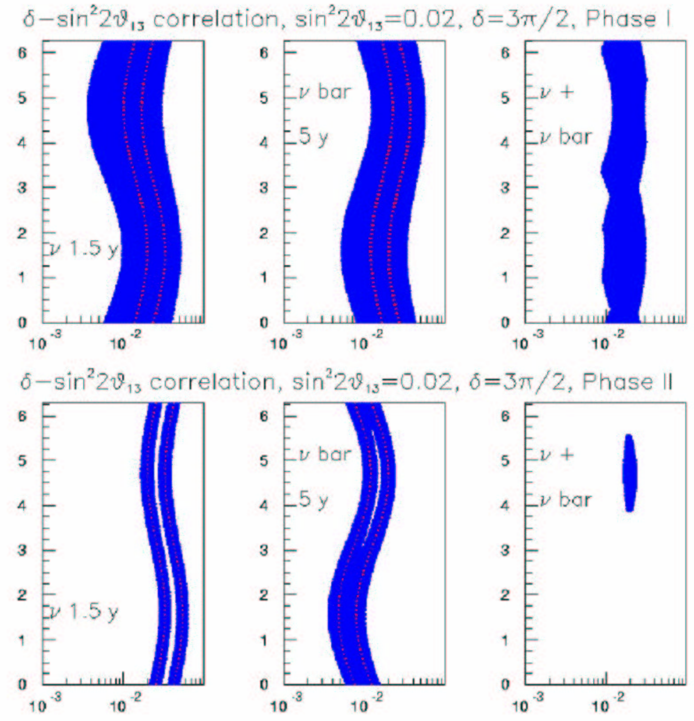
- Measure 0.01 probability to 5% (ν)
- Measure 0.02 probability to 20% (ν)

Sensitivity of the off-axis experiment



Sensitivity to 'nominal' $|U_{e3}|^2$ (I.e. neglecting CP phase δ) at the level 0.001 (phase I) and 0.0002 (phase II)

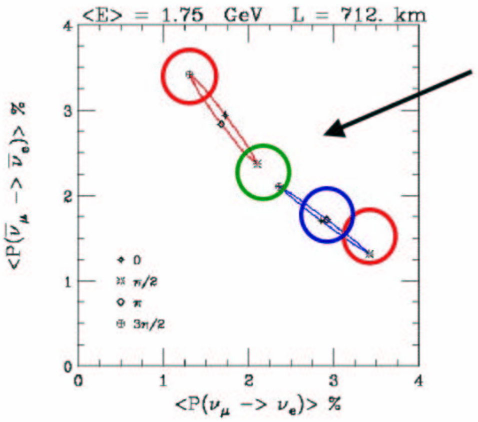
NuMI Of-axis Sensitivity for Phases I and II



We take the Phase II to have 25 times higher POT x Detector mass

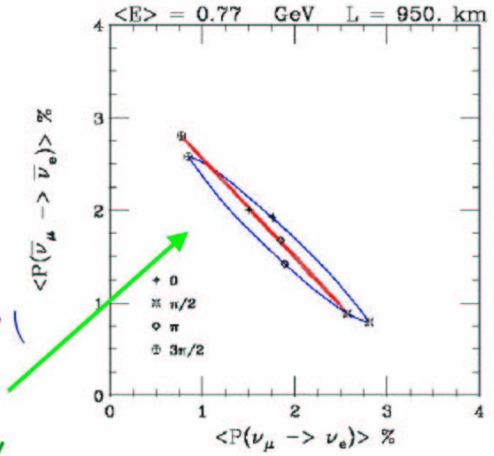
Neutrino energy and detector distance remain the same

Result-driven program: L, E flexibility



Phase I: run at 712 km, oscillation maximum

Where to locate Phase II detector?



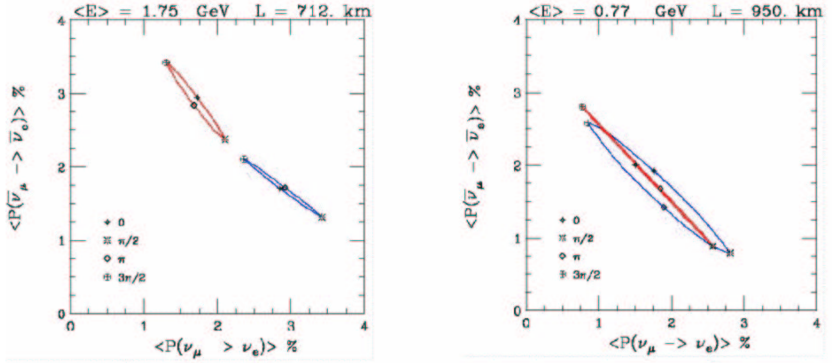
Matter effects amplify the effect:
 increase statistics at this location

Osc. Maximum induces δ=0/δ=π ambiguity \
 move to lower/higher energy

Matter induces δ=π/2 vs δ=3π/2 ambiguity
 \ move to the second maximum

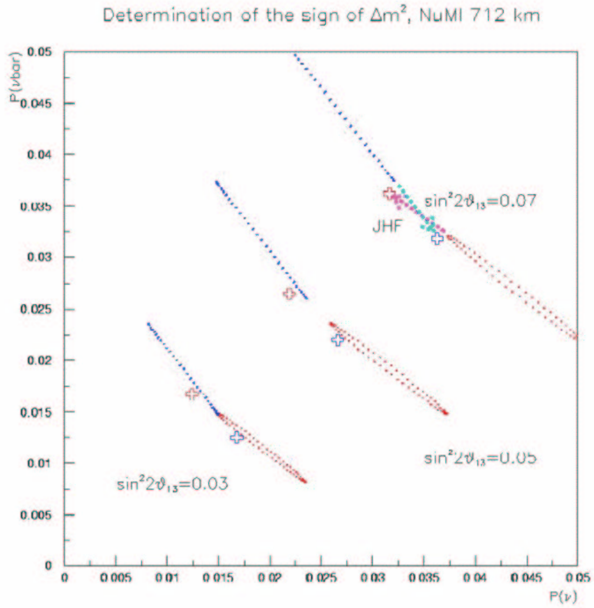
Modular, transportable detector

$Sin^2 2\theta_{13}=0.05$



Super-superbeam somewhere? Here we come!

Determination of mass hierarchy



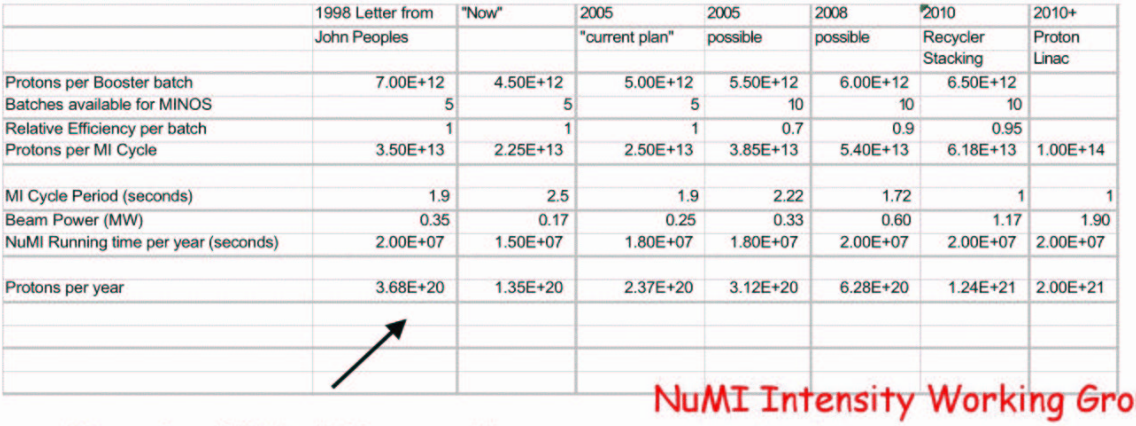
Matter effects can amplify the effect, $[sgn(\Delta m^2_{13}=+1), \delta=3\pi/2]$, or reduce the effect $[sgn(\Delta m^2_{13}=-1), \delta=\pi/2]$, and induce the degeneracy at smaller values of $\sin^2 2\theta_{13}$.

In the latter case a measurement at the location where matter effects are small (even with neutrinos only!) breaks the degeneracy and extends the hierarchy determination to lower values of $\sin^2 2\theta_{13}$. |\ complementarity of NuMI and JHF

Beam-Detector Interactions

- Optimizing beam can improve signal
- Optimizing beam can reduce NC backgrounds
- Optimizing beam can reduce intrinsic ν_e background
  - Easier experimental challenge, simpler detectors
- # of events ~ proton intensity x detector mass
  - Split the money to maximize the product, rather than individual components

A Quest for NuMI Proton Intensity



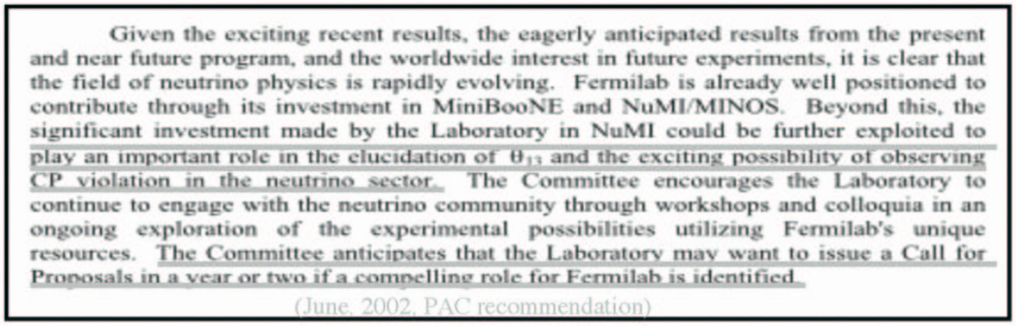
	1998 Letter from John Peoples	"Now"	2005 "current plan"	2005 possible	2008 possible	2010 Recycler Stacking	2010+ Proton Linac
Protons per Booster batch	7.00E+12	4.50E+12	5.00E+12	5.50E+12	6.00E+12	6.50E+12	
Batches available for MINOS	5	5	5	10	10	10	
Relative Efficiency per batch	1	1	1	0.7	0.9	0.95	
Protons per MI Cycle	3.50E+13	2.25E+13	2.50E+13	3.85E+13	5.40E+13	6.18E+13	1.00E+14
MI Cycle Period (seconds)	1.9	2.5	1.9	2.22	1.72	1	1
Beam Power (MW)	0.35	0.17	0.25	0.33	0.60	1.17	1.90
NuMI Running time per year (seconds)	2.00E+07	1.50E+07	1.80E+07	1.80E+07	2.00E+07	2.00E+07	2.00E+07
Protons per year	3.68E+20	1.35E+20	2.37E+20	3.12E+20	6.28E+20	1.24E+21	2.00E+21

NuMI Intensity Working Group,
D. Michael/P. Martin

Nominal "NuMI year"

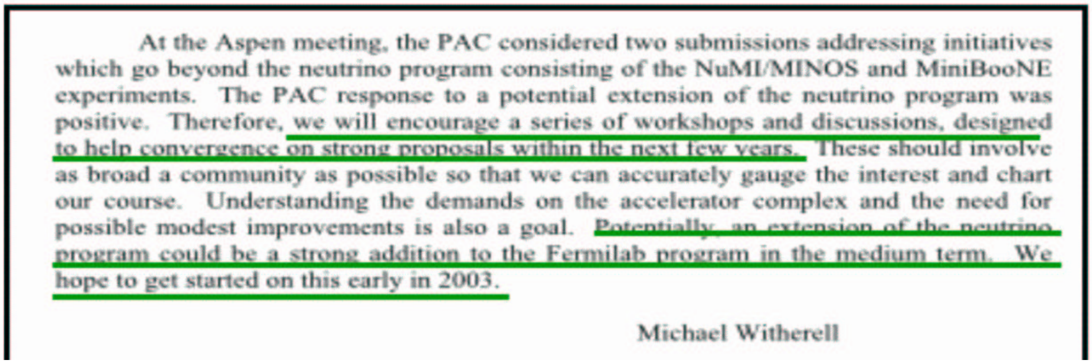
Investment level	Very Rough Cost	120 GeV Protons in 2005	120 GeV Protons in 2008
≈None	≈ $0	1.3×10^{20}	1.3×10^{20}
Small	≈ $5 M	2.8×10^{20}	3.0×10^{20}
Medium	≈ $15 M	4.0×10^{20}	4.5×10^{20}
Substantial	≈ $45M	5.0×10^{20}	8.0×10^{20}

Fermilab Official Reaction



Given the exciting recent results, the eagerly anticipated results from the present and near future program, and the worldwide interest in future experiments, it is clear that the field of neutrino physics is rapidly evolving. Fermilab is already well positioned to contribute through its investment in MiniBooNE and NuMI/MINOS. Beyond this, the significant investment made by the Laboratory in NuMI could be further exploited to play an important role in the elucidation of θ_{13} and the exciting possibility of observing CP violation in the neutrino sector. The Committee encourages the Laboratory to continue to engage with the neutrino community through workshops and colloquia in an ongoing exploration of the experimental possibilities utilizing Fermilab's unique resources. The Committee anticipates that the Laboratory may want to issue a Call for Proposals in a year or two if a compelling role for Fermilab is identified.

(June, 2002, PAC recommendation)



At the Aspen meeting, the PAC considered two submissions addressing initiatives which go beyond the neutrino program consisting of the NuMI/MINOS and MiniBooNE experiments. The PAC response to a potential extension of the neutrino program was positive. Therefore, we will encourage a series of workshops and discussions, designed to help convergence on strong proposals within the next few years. These should involve as broad a community as possible so that we can accurately gauge the interest and chart our course. Understanding the demands on the accelerator complex and the need for possible modest improvements is also a goal. Potentially, an extension of the neutrino program could be a strong addition to the Fermilab program in the medium term. We hope to get started on this early in 2003.

Michael Witherell

Conclusions

¬ ν_μ -> ν_e oscillations provide a powerful tool to determine fundamental parameters of the neutrino sector

¬ NuMI neutrino beam offers an unique laboratory for an optimal ν_μ -> ν_e oscillation experiment:

ϖ Matter effects

ϖ L/E optimization

¬ Off-axis detector(s) in combination with a realistic upgrades of the Fermilab proton intensity will improve our sensitivity by two orders of magnitude over the CHOOZ limit

¬ Determination of the mass hierarchy and a discovery of the CP violation in the neutrino sector may be well within our reach

¬ Neutrino beam will start in 2004. Large affordable detector(s) can be constructed in 4-5 years. Let's do it!