Superbeam activities in the US

- Superbeam Report Summary
- Current Superbeam Ideas
- Snowmass Epiphany
- HEPAP Subpanel Report
- What happens next?
- What's in it for Canada?

Deborah Harris
Fermilab
November 10, 2001
Future Opportunities for
Neutrino Physics
Victoria, BC

Fermilab Superbeam Study

How do superbeams compete with neutrino factories in terms of physics?
Reminder: "Physics", concentrating on $\nu_\mu \rightarrow \nu_e$, assuming LSND is not due to oscillations...

- θ_{13}
- Sign of Matter Effects
- CP violation

Small but Dedicated group:
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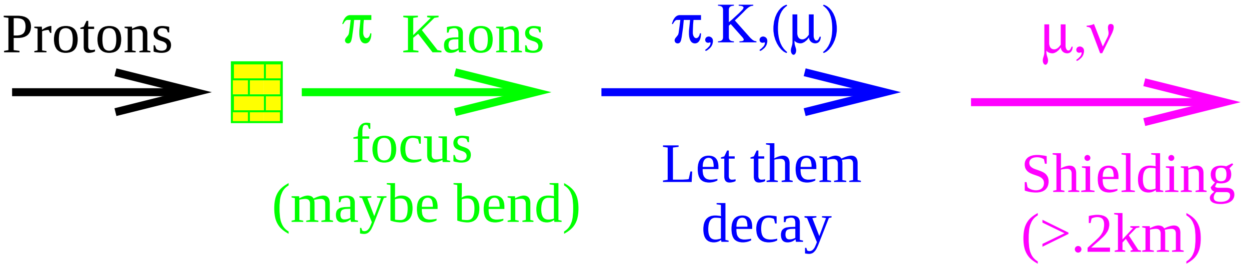
P. Spentzouris, R. Stefanski, K. Whisnant

`hep-ex/0103052`

Making a Conventional Neutrino Beam



For a 2-body decay ($\pi, K \rightarrow \mu\nu_\mu$):
Energy of ν at far detector:

$$E_\nu \approx \gamma m_h \frac{m_h^2 - m_\mu^2}{m_h^2}\left(\frac{1}{1+\gamma^2\theta_{\nu h}^2}\right)$$

Flux of Neutrinos per meson at far detector:

$$\Phi \approx BR\frac{1}{4\pi L_{det}^2}\left(\frac{2\gamma}{1+\gamma^2\theta_{\nu h}^2}\right)^2$$

θ = angle between meson and detector
BR = Branching Ratio, γ = Boost of meson

Events per π, μ decay has same γ^3 dependence as muon storage ring! Oops, except for

1. Production Spectra per MW proton power
2. Length of decay pipe (for $\pi \rightarrow \nu$)

ν_μ Event Rates in Conventional Beam

For 1.6MW proton power, 732km baseline:
(1×10^{20} μ per year or $4\times$ the NUMI POT/year)

Beam	$< E_\nu >$ (GeV)	Events/kt-yr π	μ	E_μ (GeV)
MINOS-LE	3.5	1800	200	4.5
MINOS-ME	7	6000	1900	9.1
MINOS-HE	15	13000	16000	18.2
	20		36000	30

For Conventional Beam, $\nu_\mu \to \nu_e$ signal
For Muon Storage Ring beam, $\nu_e \to \nu_\mu$ signal

Given these event rates for low neutrino energy beams, what's so exciting about storage rings?

It's much easier to look for $\nu_e \to \nu_\mu$ than it is to look for $\nu_\mu \to \nu_e$.

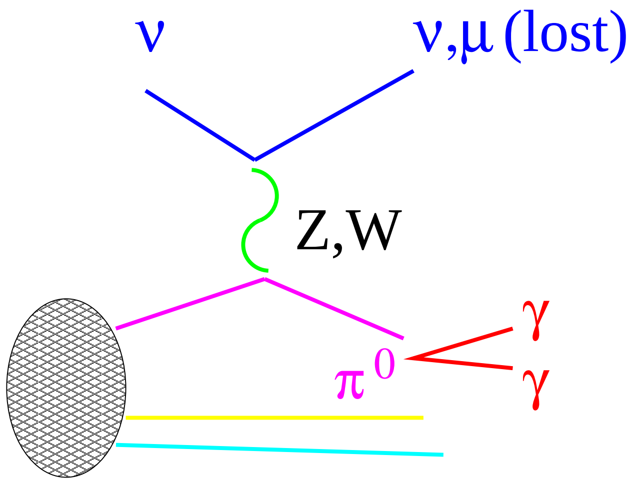
Higher neutrino energies mean higher distances $\to$ Matter effects amplify signal, tell sign of largest mass splitting.

Backgrounds in Conventional Beams

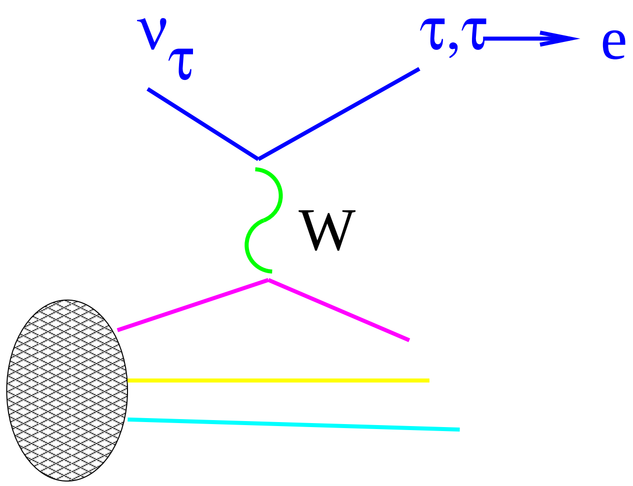
If signal is $\nu_\mu \to \nu_e$ or $\bar{\nu}_\mu \to \bar{\nu}_e$:

Intrinsic ν_e Contamination

$$
\begin{aligned}
K^\pm &\to \pi^0 e^\pm \nu_e(\bar{\nu}_e) \\
\mu^\pm &\to e^\pm \bar{\nu}_\mu(\nu_\mu)\nu_e(\bar{\nu}_e) \\
K_L &\to \pi^\pm e^\mp \nu_e(\bar{\nu}_e) \\
\text{Charm} &\to X e^\pm \nu_e(\bar{\nu}_e)
\end{aligned}
$$



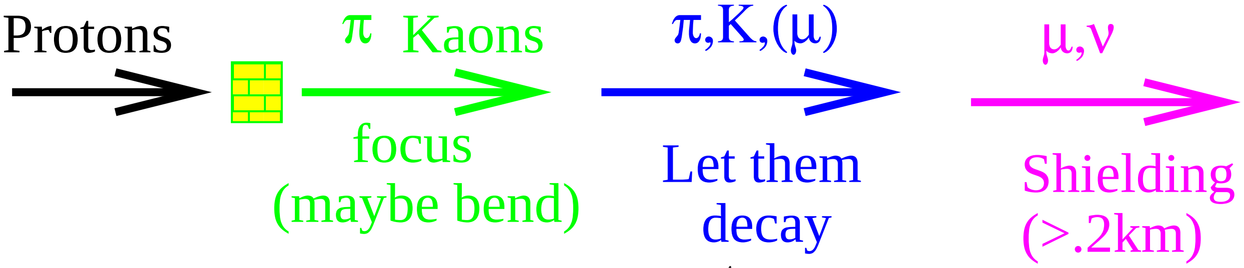
π^0 production in NC and CC (high y) events



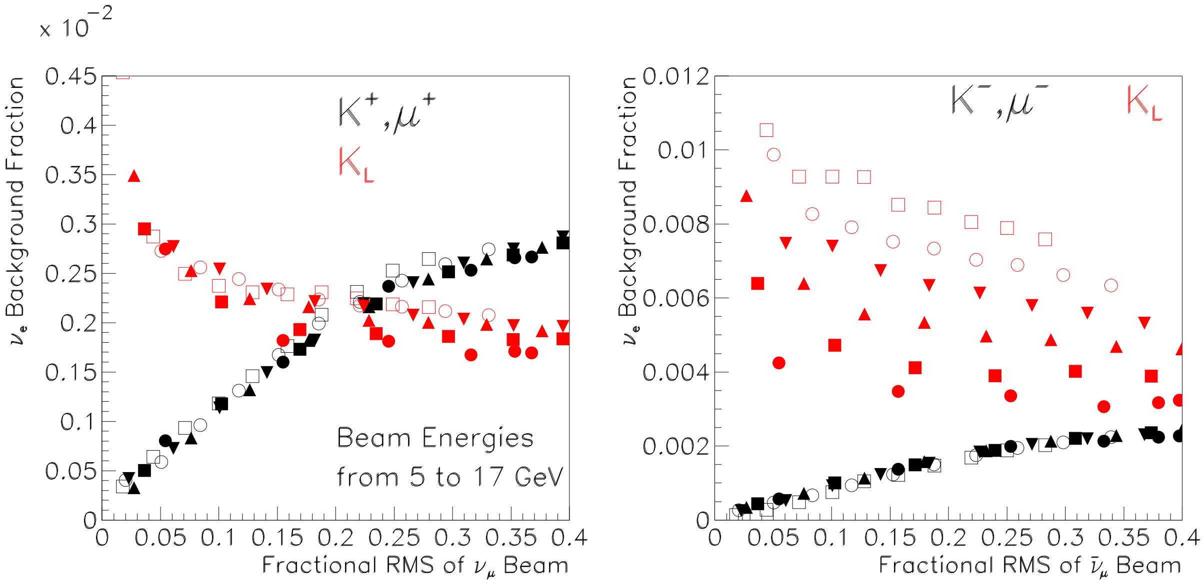
ν_τ Charged Current Events

Important for $E_\nu > 7GeV$

Intrinsic ν_e Background

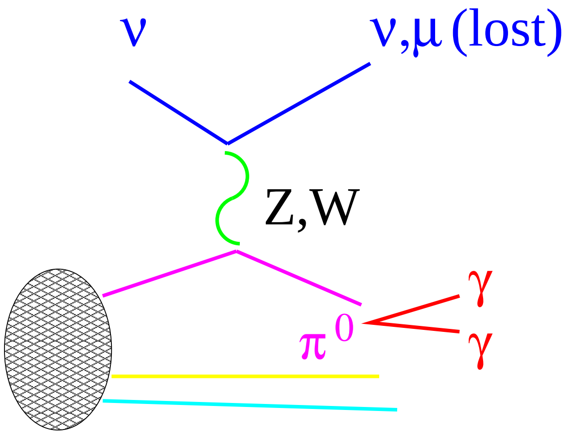


Beamline	Peak ν_μ Energy (GeV)	ν_e/ν_μ event ratio	p Energy GeV
K2K	1.4	0.7%	12
MINOS LE	3.5	1.2%	120
MINOS ME	7	0.9%	120
MINOS HE	15	0.6%	120
CNGS	17	0.8%	400
JHF wide	1	0.7%	50
JHF HE	5	0.9%	50
MiniBoone	0.5	0.2%	8
ORLaND	0.0528	0.05?%	1.3

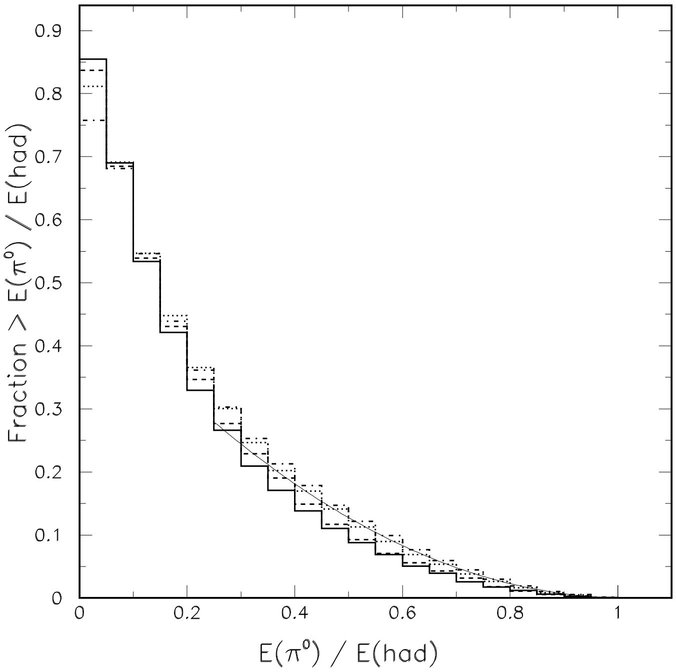


DAH

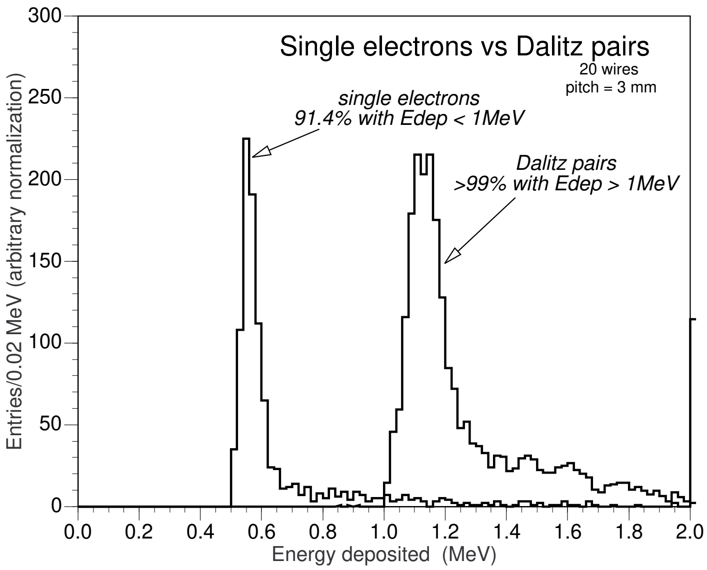
Neutral Current Background



Fritz DeJongh



- Liquid Argon TPC (ICARUS) (1/1000)



Mario Campanelli

- fine-grained steel-drift tubes (THESEUS)
  longitudinal shower development (1/40)

- Water Cerenkov (K2K) (10^{-2} below 1GeV)

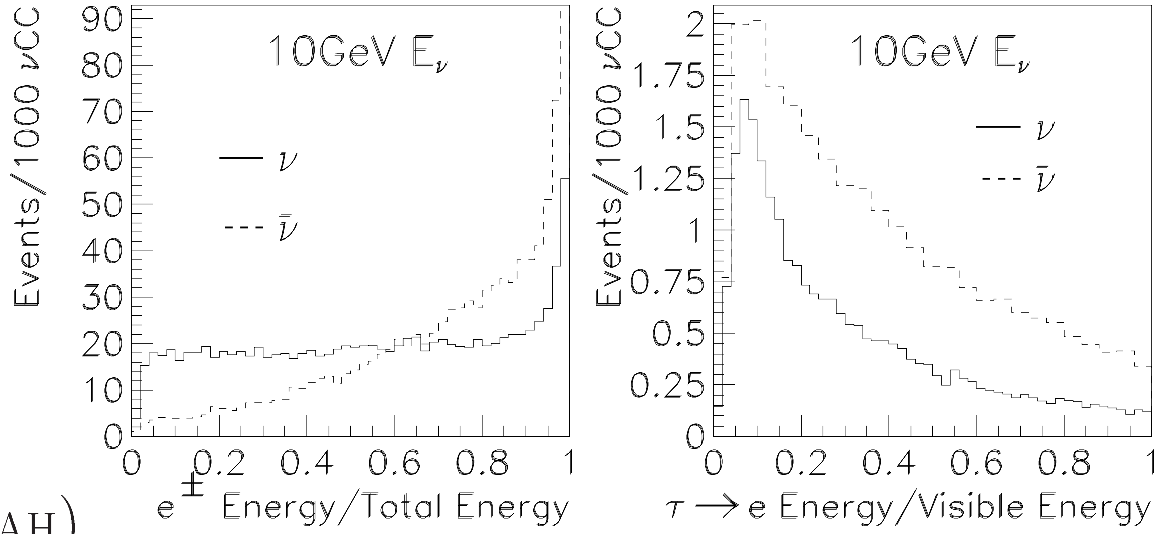
$\nu_\mu \to \nu_T, \tau \to e$

Today's discovery is tomorrow's background...

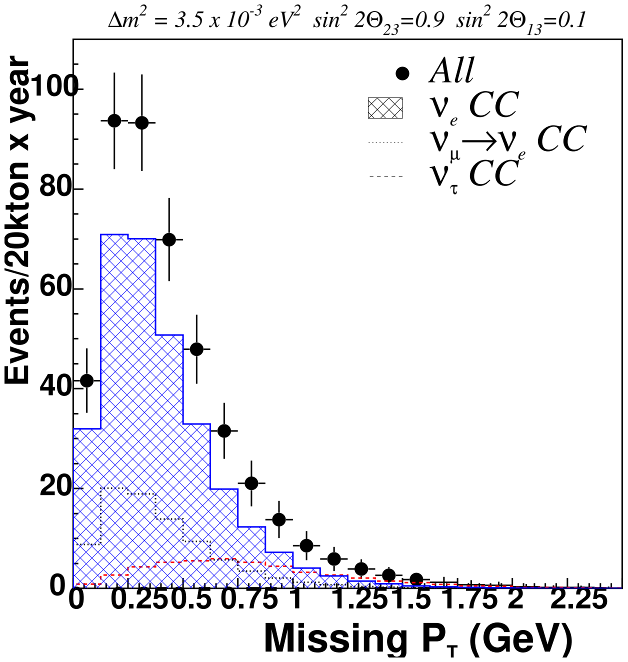
$BR(\tau \to e(\gamma)\nu_\tau\bar{\nu}_e) = 0.20,\ BR(\tau \to n\pi^0 X\nu_\tau) = 0.37,$

ν_τ flux is $\propto \sin^2 2\theta_{23}\sin^2(\delta m_{23}L/E)$ i.e. $\mathcal{O}(1)$...

Kinematic handle on $\tau \to e$: electron energy



(DAH)



Other Kinematic Handles: p_T

ICANOE proposal

$\delta m^2_{23} = 3.5 \times 10{-}3$

$\sin^2 2\theta_{13} = 0.1$

Mario Campanelli

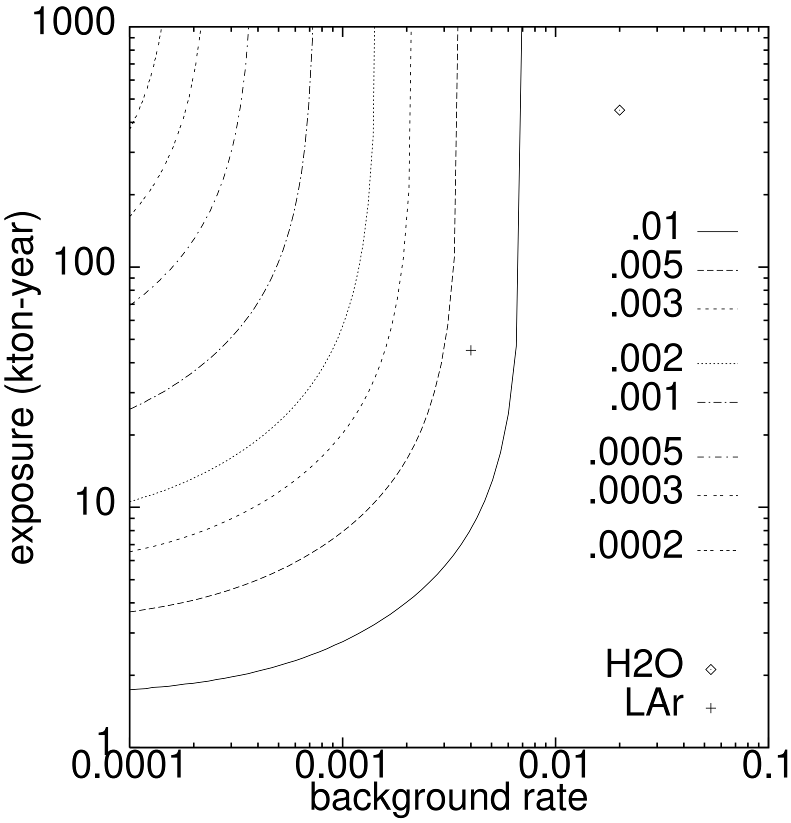
Backgrounds in Conventional Beams
Executive Summary

Background	Baseline	Detector	Beamline	Rate
	Dependence on			
NC/CC π^0 production	$1/L^2$	a lot	some	$10^{-1} \rightarrow 10^{-3}$
$\nu_\mu \rightarrow \nu_\tau$ $\tau \rightarrow e$	flat	some	some	$10^{-1} \rightarrow 0$
Intrinsic ν_e	$1/L^2$	barely	all	$10^{-2} \rightarrow 10^{-3}$

Two Regimes:

1. 1GeV beam (JHF Study)
   - ν_e, NC only
   - Could use water Čerenkov or LAr TPC
2. Multi-GeV beams (3-15GeV)
   - ν_e, NC, and maybe τ
   - Liquid Argon TPC or fine-grained steel
   - Would water Čerenkov work?

Measuring of $\nu_\mu \to \nu_e$ at 3σ



3.5GeV beam (NUMI LE) Baseline 732km

syst. error: 0.1

1.6MW Source

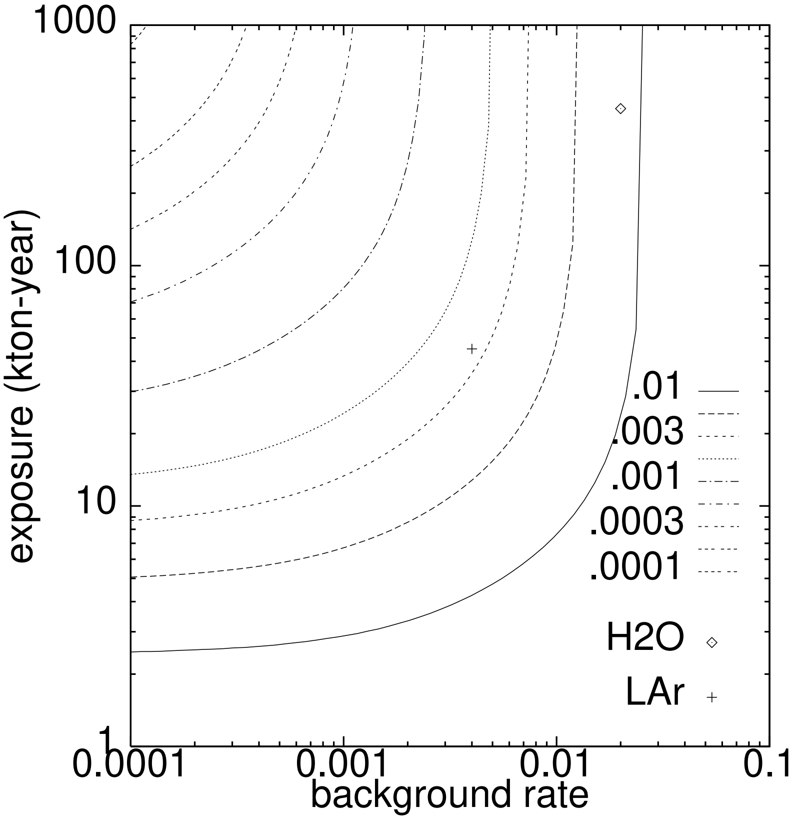
$\delta m^2_{23} = 3.5 \times 10^{-3}$

MADPH-00-1199

and

`hep-ex/0103052`

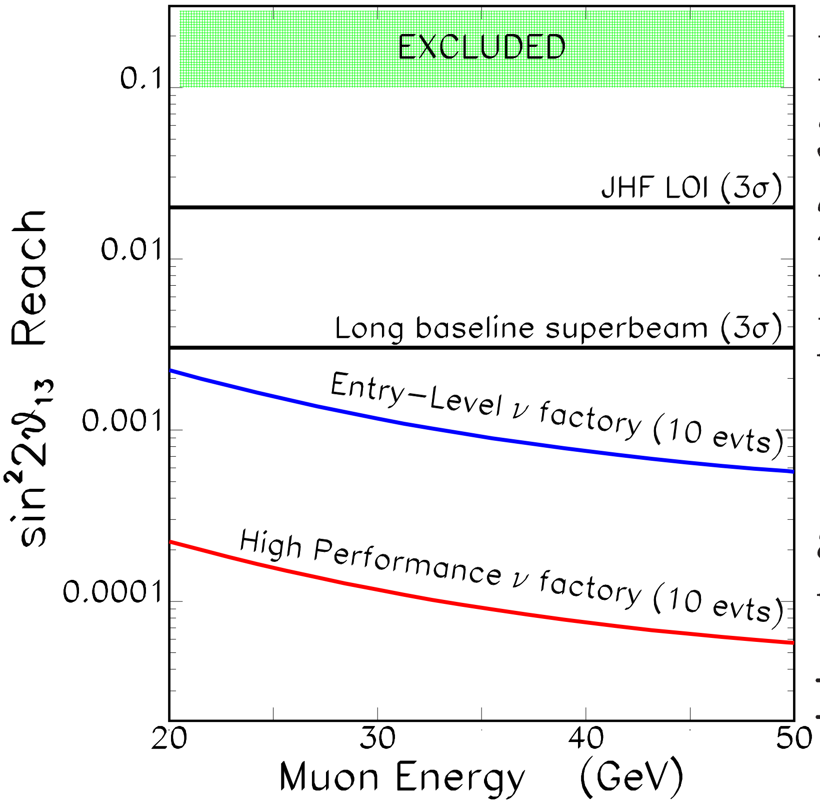
Barger *et al*



7GeV beam (NUMI ME) Baseline 2800km –see matter effects!

syst. error: 0.1

Upgraded Conventional Beam ($\geq 1GeV$) Conclusions



Best Bet:
30kton-yr LAr,
2800km,
NUMI-ME
beam
1.6MW Source
assume 0.3% background
`hep-ex/0103052`

- Beam backgrounds are never at 1 event level
- Detector technology has a **huge impact** on backgrounds
- If $\sin^2 2\theta_{13} < 0.01$, $\nu_\mu \rightarrow \nu_e$ will be hard!
- Unambiguous CP violation only in small region of parameter space
- unambiguous sign of δm^2_{23} in limited scenarios

Snowmass Cry: We are in the middle of a fundamental discovery!

Oscillations can:

- Give insight into the theory of flavor
- Tell us about the origin of fermion masses
- suggest a high mass scale of new physics
- contribute to understanding the origin of baryon asymmetry in the universe

To understand mass and mixing...

- New Facilities
  - Upgraded proton source (1-4MW)
  - Very intense ν beams
  - Ultimately, a ν factory
- New Detectors
  - Focus on ν_e appearance
  - If LSND is oscillations: ν_τ appearance

The Case for a High Energy Superbeam

- $\nu_\mu \to \nu_e$ is extremely important for detemrining the mixing matrix structure
  - at any one baseline the error will be due to a combination of syst. and stat. errors on background levels
  - Two baselines and energies will ensure that oscillations are occurring and not something completely different
- The mass hierarchy may be different from what people naively expect!
  - if so the matter effects will enhance the $\sigma(\bar{\nu})$ not $\sigma(\nu)$
  - You would want the longer baseline to see it for the first time
- If JHF-HyperK sees CP violation, there would still be a 8° ambiguity due to matter effects

E1 Working Group Position Paper

- The recent evidence for neutrino oscillations is a profound discovery. The US should strengthen its lepton flavor research program by expediting construction of a high-intensity conventional neutrino beam ("superbeam") fed by a 1-4MW proton source.

- A superbeam will probe the neutrino mixing angles and mass hierarchy, and may discover leptonic CP violation. The full program will require neutrino beams at a number of energies, and massive detectors at a number of baselines. These facilities will also support a rich program of other important physics, including proton decay, particle astrophysics, and charged lepton CP and flavor-violating physics.

- The ultimate laboratory for neurino oscillation measurements is a neutrino factory, for which the superbeam facility serves as a strong foundation. The development of the additional needed technology for neutrino factories and muon colliders requires an ongoing vigorous R& D effort in which the US should be a leading partner.

Superbeam Ideas

Ref.	Beamline	Baseline (km)	Detector
1	NUMI off axis	500,732	steel/scint
2,6	NUMI off axis	500	$H_2 0$ Č
3	BNL to Cornell	300	LAR TPC
4	FNAL → WIPP	1770	LAR TPC
5	FNAL → NUSL	1290*	$H_2 0$ Č
6	BNL → NUSL	2540*	$H_2 0$ Č

* Distances assume NUSL in Homestake, SD. [1]A. Para, M.Szleper `hep-ex/0110032` , [2]L.Wai, D.Petyt, A.Habig, NuMI-NOTE-GEN-0780, [3]S.Kahn,K.McDonald, [4]D.Cline, J.Learned, [5] F.DeJongh FNAL study group, [6] M.Diwan, B.Viren.

Strategy for most: reduce backgrounds with "designer" beamline suited for measurement at only one energy.

- Off-axis beam
- Dipole in beamline

Strategy for LAR TPC: reduce backgrounds with "designer" detector–bubble chamber like image quality.

How well could 70kton ideal detector do?

L(km)	E(GeV)	Beam ν_e	3σ reach $\sin^2 2\theta_{13}$	sign Δm^2_{23}	3σ δ
350	0.57	116	0.0020	-	26
730	1.18	56	0.0026	0.10	35
1290	2.09	32	0.0031	0.036	49
1770	2.86	23	0.0033	0.020	67
2900	4.70	14	0.0038	0.011	-

$$\Delta m^2_{23} = 2 \times 10^{-3} eV^2, \quad \delta m^2_{12} = 5 \times 10^{-5} eV^2$$

70kton, 50%efficient detector, 0.2*MINOS LE flux at 732km x 4 for proton source upgrade, scale vs L^2 , 2 years run ν, $2n$ years run at $\bar{\nu}$ mode. $0.4 \pm 0.04\%$ total background (beam ν_e +NC)

Barger, Marfatia, Whisnant `hep-ph/0108090`

Going to Higher Energies if you can keep the background low isn't crazy, and is necessary to see matter effects!

Outstanding Detector Issues

- Liquid Argon TPC
  - getting a large enough cryogenic volume underground
  - What is the largest module you could build?
  - does it work as well in data as in MC?
  - How does it work at energies above 1GeV?
  - could you add a magnetic field and use for ν factory?
- Steel/Scintillator
  - How much segmentation is needed for enough NC rejection (at 2-3GeV)?
- Water Čerenkov
  - what do events look like at 1-3GeV?
  - where do backgrounds come from? (ν_μ CC, etc?)
- For all: how can we optimize cost/kton?

HEPAP Subpanel Report

Charge:

- Review central scientific issues defining HEP
- Develop 20 year plan for US HEP program

Draft Response:

- Next Big machine for the field is e^+e^- linear collider, and we need only 1 on the planet
- BUT... ν physics is a central scientific issue, should be pursued
- AND... National Underground Laboratory should go ahead
  (Homestake or San Jacinto)
- AND... keep ν factory R& D at current level
- AND... BTeV not recommended at this point
- Two scenarios:
  - LC in US (No superbeam in US)
  - LC not in US (Superbeam in US)

HEPAP Subpanel Report Rebuttal

- Decision on where to house LC will happen in a few years
  - too late to join JHF to SK effort in meaningful way
  - maybe not too late to join CERN to UNO?
  - if no LC in the US, then want to start designing superbeam now...
    - Need Beam design work now!
    - Need Detector R& D now!
- Doesn't take advantage of current beamlines

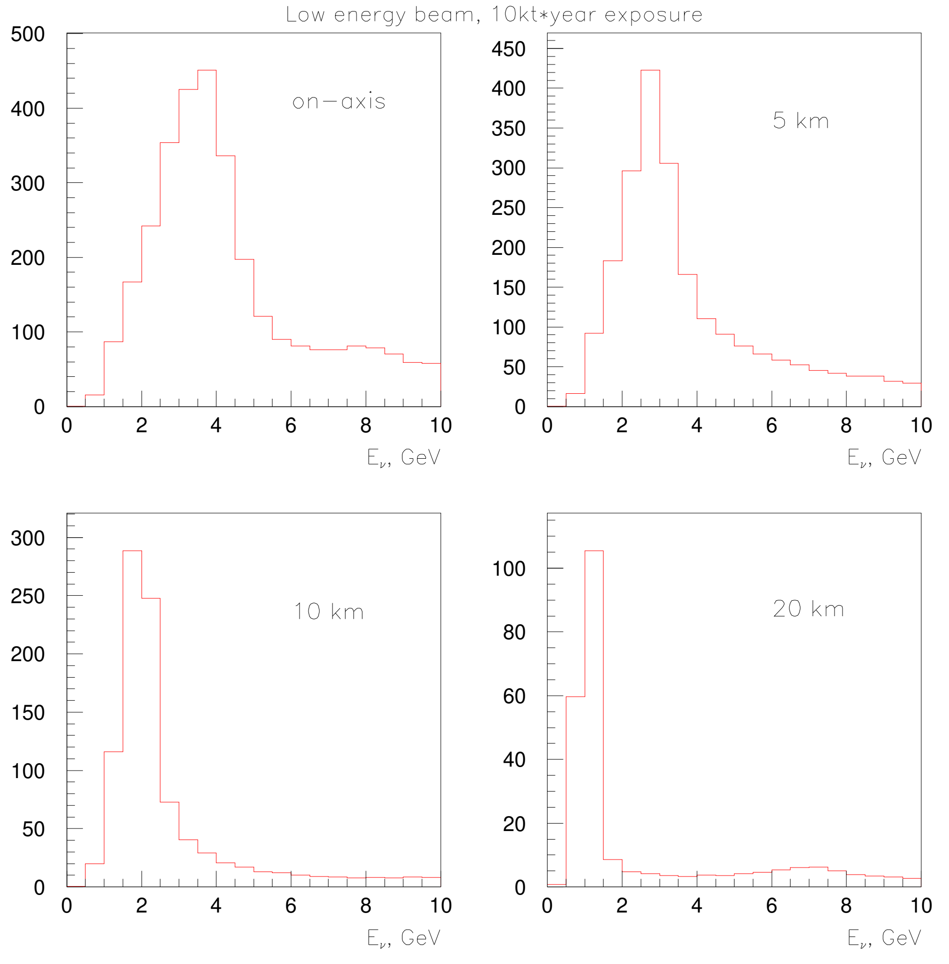
Letters being composed and signed now...
Some are still forging ahead working out details of what next US experiment could be...

Two Approaches to the next ν experiment

- MINOS Off-axis beam
  - 500 to 900 km
  - 1.5 to 4 GeV
  - Beamline will be running in 2005
  - On Axis near and far detectors there
  - detector possibilities:
    - segmented steel/scint
    - water cerenkov (use Lake Superior)
  - Modest upgrade: new proton driver?
- FNAL/BNL to NUSL
  - Baselines could be 1290 to 2540 or more
  - Take advantage of running on second peak (Marciano `hep-ph/0108181`) for larger CP-violating effectss
  - New target station, proton driver, etc.
  - Use whatever large proton decay detector is there (UNO?)

MINOS Off-axis Beam

Following example from JHF-SK (and BNL 889 D. Beavis et al., BNL No. 52459, April 1995):
off-axis beams can potentially give high fluxes between 1 and 2.5GeV...



(ref. Para, Szleper) 540 (1380) Events/10kton-years at 1.5 to 2.5GeV, without oscillations in Low (Medium) energy beam.

ν_e background at the peak: 0.6% (0.3%) for Low (Medium) energy beam.

Proposal for Canadian Involvement

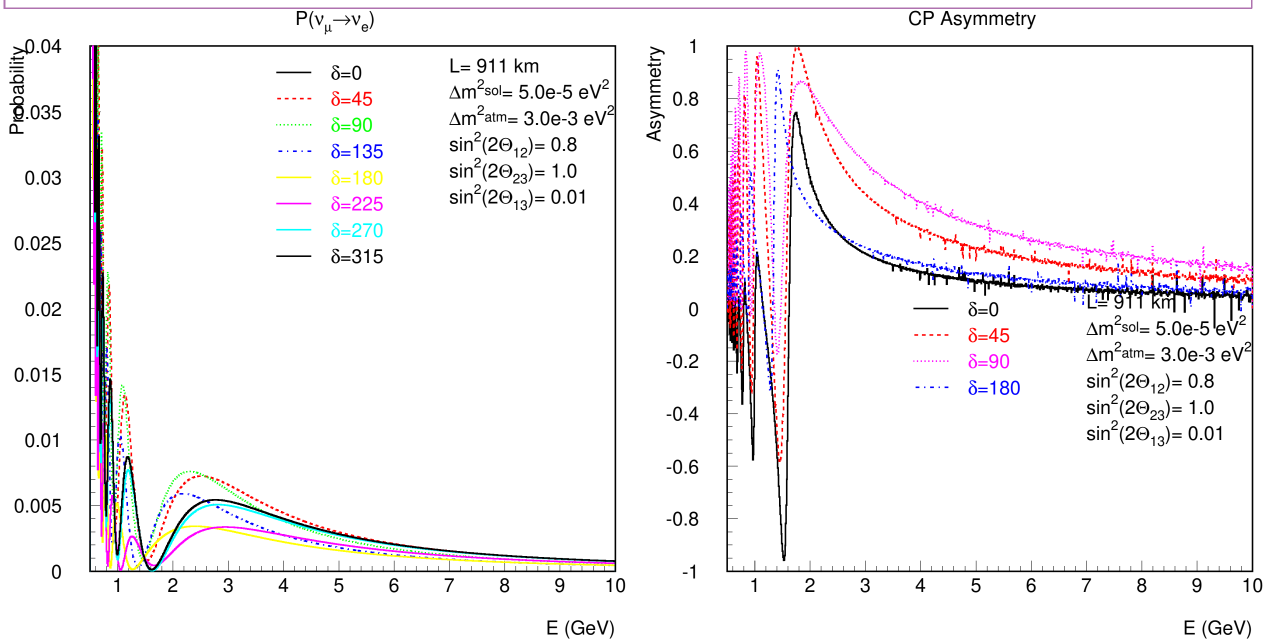
10km off of FNAL to Soudan Axis: Could be as far as 911km away from Fermilab, or Canada!

For ALL of these studies, we need your help!

- Full Detector Simulations tools
- Proposal for Detector R& D tests (possibly in MINOS near detector hall?)

What does 25% longer baseline get you?

Oscillation Probabilities at 911km



Brett Viren, using formulae from I. Mocioiu, R. Shrock PR**D62** (2000)

- Off-axis beams at ~2GeV
- at this baseline, the matter effects are large compared to the CP-violating effects
- determine the sign of the largest mass splitting with relatively coarse measurements at ν_μ and $\bar{\nu}_\mu$ beams
- if $\Delta m^2_{23} = 2 \times 10^{-3}$ we may need this longer baseline...

Conclusions

Superbeams can take the next step in oscillation physics

BUT..

- need background rejection at 10^{-3}
- can combine this physics with other areas
  - detector
  - beam (proton source)
- HEPAP subpanel report is challenging
- **BUT...**..the US will have invested 100M$ in a beamline, and there are a few obvious reasons to think of how to extend its use...
  - if LSND is due to oscillations
  - if θ_{13} evidence seen at MINOS or CNGS
  - if Δm^2_{23} is $2 \times 10^{-3} eV^2$
- there's LOTS of ways YOU CAN contribute– we're a small group looking for expertise, esp. in low energy ν interactions...
- the reward is so large we can't give up now!