2 December 1999
HIMUS99, KEK

Steve Geer
Fermilab

Neutrino Factory Physics Study

1. Motivation
2. Charge and Organization
3. SubGroup: Activities/Results
   - Beam Properties
   - Detector Parameters
   - Oscillation Scenarios
   - Oscillation Measurements
   - Non–Oscillation Physics
4. Summary

http://www.fnal.gov/projects/muon_collider/nu/study/study.html

Motivation

- Growing body of evidence for neutrino oscillations:
  - SuperK atmospheric neutrino results
  - Solar Neutrino Results
  - LSND results

- New generation of accelerator experiments (K2K, MINOS, MiniBooNE, ...) expected to confirm oscillations and begin to measure the associated parameters.

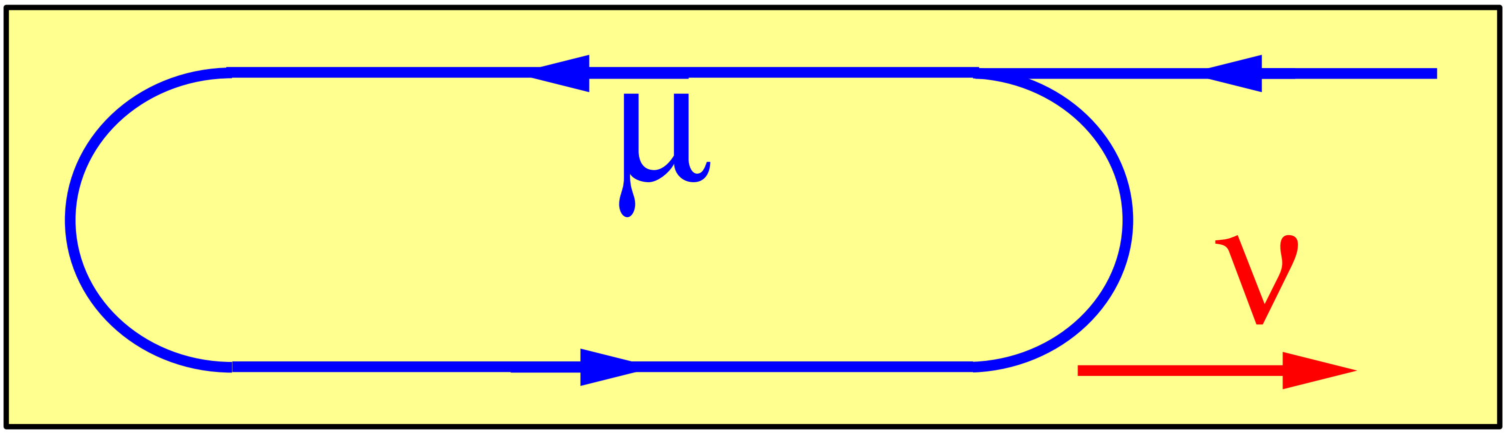
- In the longer term, To ensure we understand the oscillation framework & can measure all of the associated parameters we would like :
  1. ν_e beams as well as ν_μ beams.
  2. Higher intensity beams than available now.

- Conventional neutrino beams (from π/K decays) produce ν_μ beams (with a small annoying ν_e component)

- –> exploit muon decays

Muon Storage Ring Neutrino Source

- To avoid an impractically long decay channel ($\tau_\mu \sim 100\ \tau_\pi$) use a storage ring with long straight sections :



- This is an old idea. Example: The P–860 proposal in 1992 to search for neutrino oscillations using the Fermilab Antiproton Debuncher as a muon storage ring neutrino source. Good idea ... but the problem is to get sufficient neutrino flux to make it really interesting.

- A muon storage ring neutrino source using the muon source required for a Muon Collider, could produce very large neutrino fluxes (*S. Geer, PRD 57, 6989 (1998)*).

Workshops

1. Workshop on Physics at the First Muon Collider & at the Front–End of a Muon Collider, Fermilab, November 6–9, 1997.
   Organizers: S. Geer & R. Raja

2. Workshop on the Potential for Neutrino Physics at Future Muon Colliders, BNL, August 13–14, 1998.
   Organizer: B. King

3. ICFA/ECFA workshop on Neutrino Factories Based on Muon Storage Rings, Lyon (France), 5–9 July 1999.
   Organizer: B. Autin et al.

4. HIMUS99, KEK., 1–4 December 1999.
   Organizers: Y. Kuno

5. NuFact00, Monterey, CA., 22–26 May 2000.
   Organizers: J. Wurtele & S. Wojcicki

Many Questions need answers to understand the physics potential of a nu–factory

1. What are the detectable event rates in a 3–flavor mixing scenario ?
2. How well can the oscillation scheme be determined (3–flavor mixing, sterile νs, ..) ?
3. How do the precision of the oscillation parameter measurements depend on the number of stored muons, L, and E ?
4. What are the dominant systematics & backgrounds for each measurement ?
5. Can matter effects be measured well enough to determine the mass hierarchy ?
6. Are there scenarios in which CP violation could be measured ?
7. Can polarization be effectively exploited ?

To answer these questions, the Fermilab directorate requested a 6 month physics study

(Co–ordinators: H. Schellman, Steve Geer)

Six–Month Physics Study

The charge for the group will be to deliver a concise report by March 31, 2000 that will explicitly include:

1. The physics motivation for a neutrino source based on a muon storage ring, operating in the era beyond the current set of neutrino oscillation experiments.

2. The physics program that could be accomp–lished at a neutrino factory as a function of:

   (a) The stored muon energy, with the maximum energy taken to be 50 GeV.

   (b) The number of muon decays per year in the beam–forming straight section, taken to be in the range from 10^{19} to 10^{21} decays per year.

   (c) The presence or absence of muon polariz–ation within the storage ring.

   (d) For oscillation experiments, the baseline length including investigations evaluating matter effects.

Organization

Group 1: Beam properties (Schellman/Geer)
Defines assumed beam parameters,
e.g. beam divergence, polarization model, etc.

Group 2: Detector parameters (Bernstein)
Defines assumed detector parameters,
e.g. types, mass, efficiencies, resolutions etc.

Group 3: Oscillation theory & scenarios (Parke)
Defines a handful of explicit parameter sets that span the space of likely possibilities & assess for each set what the experimental situation will be in 5–10 years time.

Group 4: Oscillation measurements (Harris)
Performs detector simulations to calculate for each parameter set how well the measurements can be made as a function of L, E, polarization, etc.

Group 5: Non–Oscillation physics (Hawker)
Explores the non–oscillation physics potential as a function of E, fluxes, polarization etc.

Group 1: Beam Properties

C. Crisan
S. Geer
H. Schellman
R. Stefanski

1. Flavor content
2. Differential spectra
3. Fluxes as a function of:
   - Energy
   - Distance
   - Angle
   - Polarization
   - Beam divergence
4. Cross–sections:
   - CC
   - NC
   - ν_τ
5. Interactions rates
6. Lepton and hadron spectra
7. Short baseline beam properties

Neutrinos from Muon Decays

1. Pure ν flavor content with large ν_e component

$$\mu^+ \to e^+ \nu_e \bar{\nu}_\mu \Rightarrow 50\% \; \nu_e \; (\bar{\nu}_\mu)$$

$$\mu^- \to e^- \bar{\nu}_e \nu_\mu \Rightarrow 50\% \; \bar{\nu}_e \; (\nu_\mu)$$

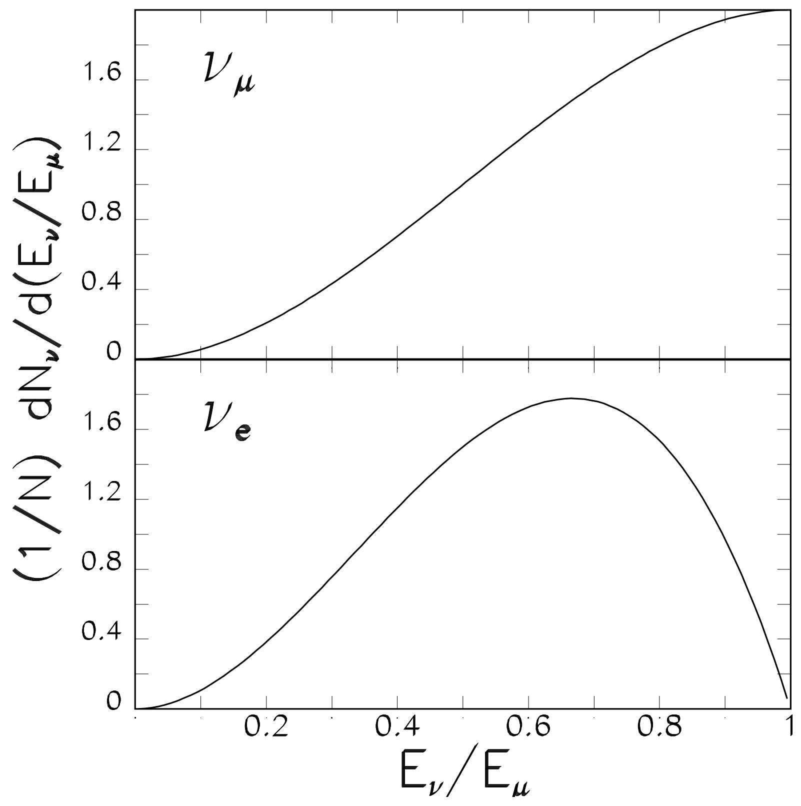
2. Precisely known neutrino fluxes & kinematics

In the $\mu^\pm$ rest–frame, the distribution of neutrinos from muon decay is given by:

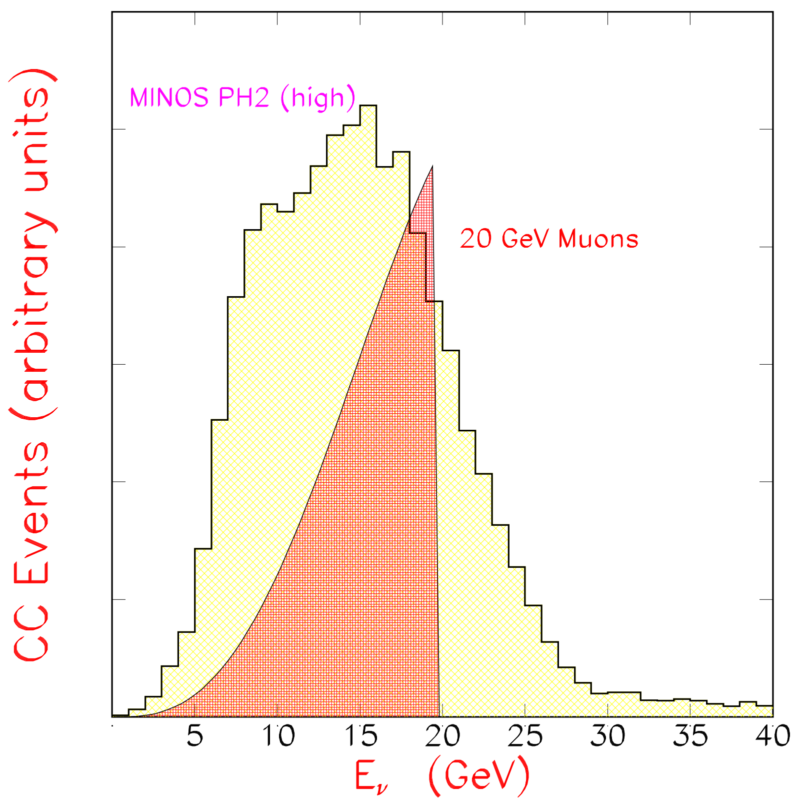
$$\nu_\mu : \quad \frac{d^2N}{dx\, d\cos\theta} \sim \frac{1}{4\pi}\left[2x^2(3-2x) \mp 2x^2(1-2x)\mathcal{P}\cos\theta\right]$$

$$\nu_e : \quad \frac{d^2N}{dx\, d\cos\theta} \sim \frac{1}{4\pi}\left[12x^2(1-x) \mp 12x^2(1-x)\mathcal{P}\cos\theta\right]$$

where $x = 2E_\nu/m_\mu$, θ is the angle between the neutrino and the muon spin, and $\mathcal{P}$ is the muon polarization.



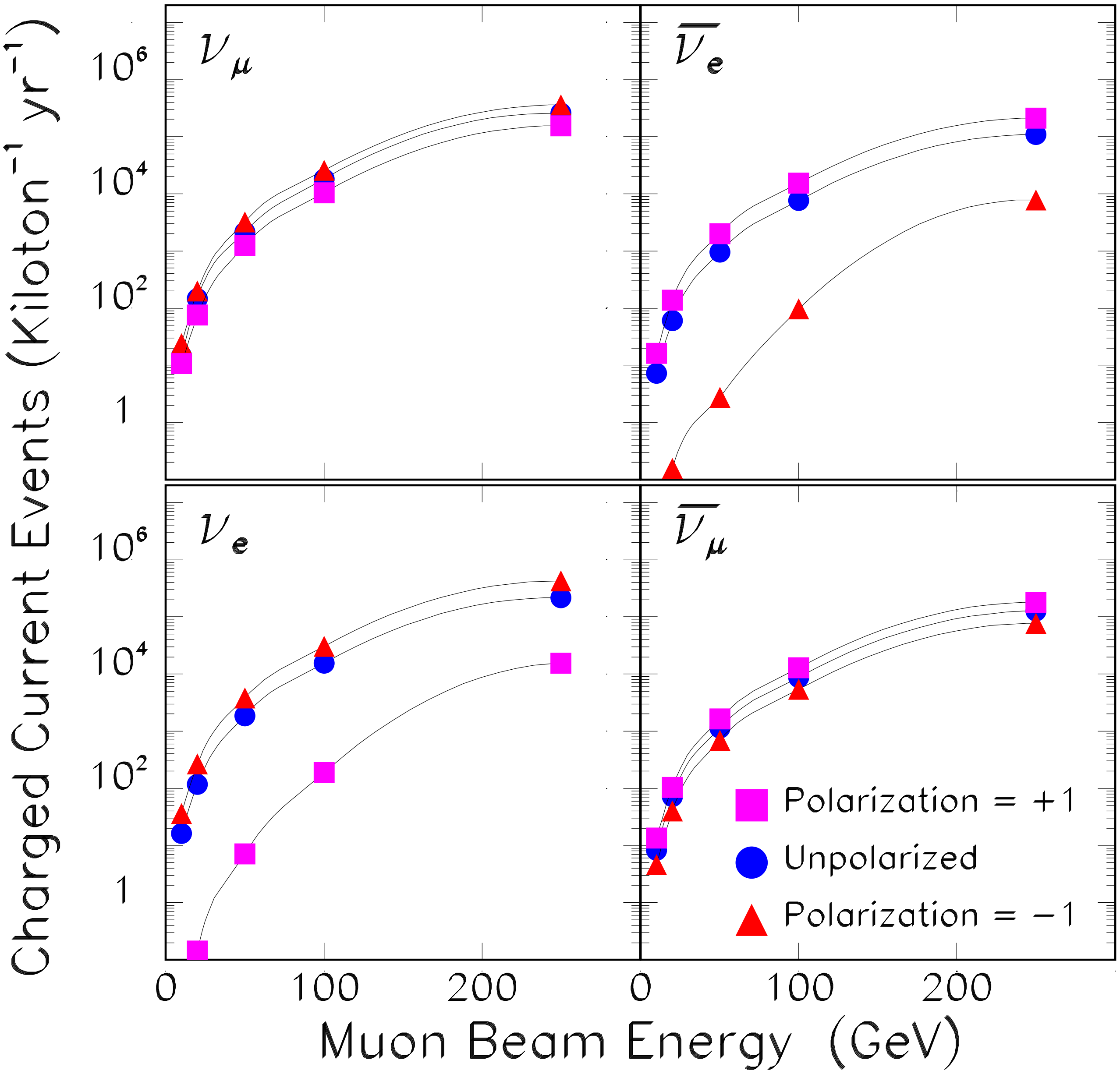
At high muon energies ($E_\mu >> m_\mu$) x –> E_ν/E_μ –> simple expressions for the ν_μ & ν_e spectra



"Narrow–Band" Beam

3. With 10^{20} muon decays per year event rates are high :–

S. Geer, PRD 57,6989 (1998)



Example: For a 30 GeV muon beam there are ~ 3300 ν_μ CC events / yr in a 10 KT detector at L = 10 000 km.

Note: Polarization switches on/off ν_e flux

Long Baseline Event Rates

S. Geer, PRD 57, 6989 (1998)

- Assume 2 x 10^{20} μ^- decays/yr in the beam–forming straight section.

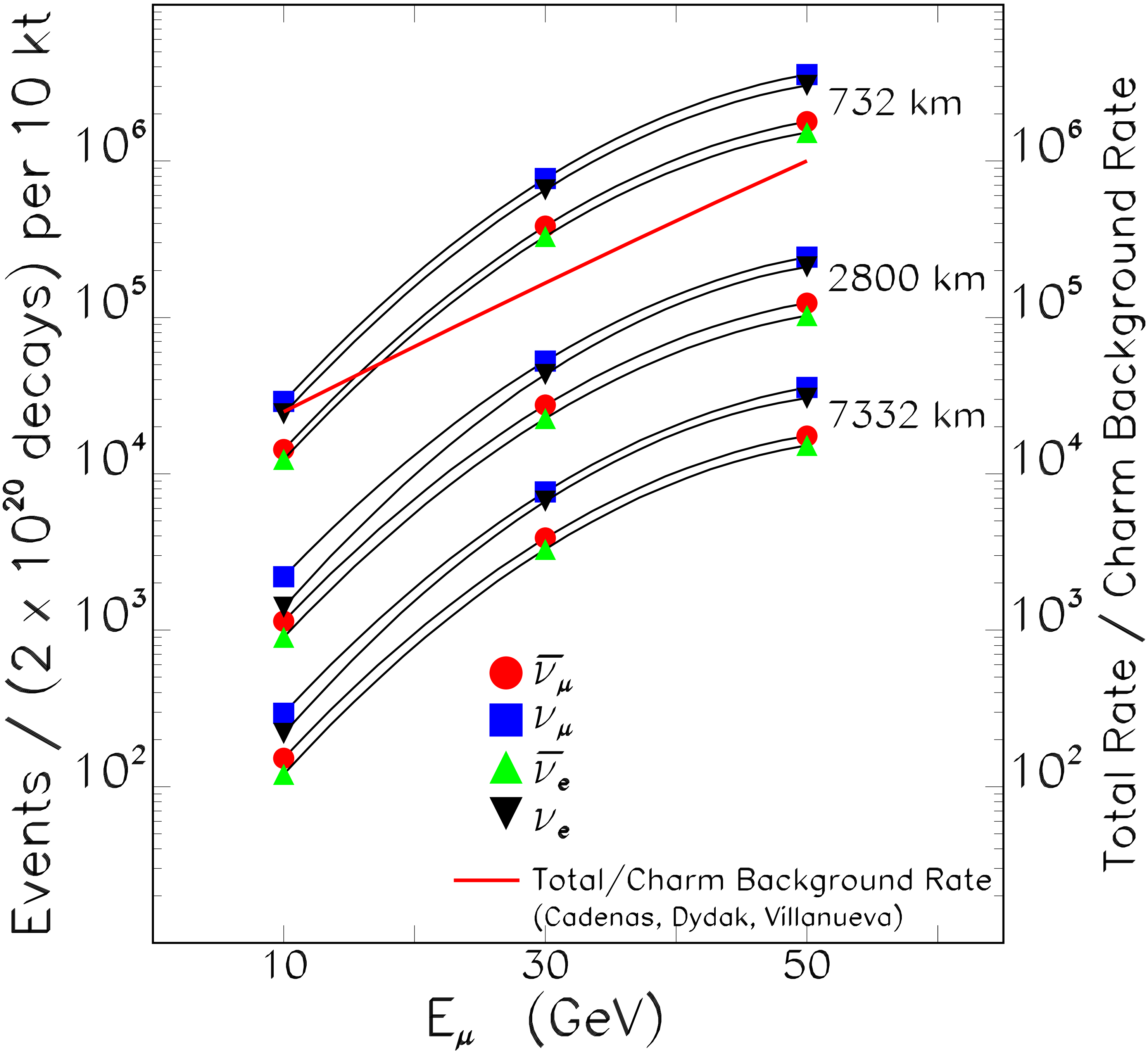
Experiment (L = 732 km)	CC Rates (per kt–yr) ν_μ	$\bar{\nu}_e$
MINOS (WBB)		
Low Energy	458	1.3
Medium Energy	1439	0.9
High Energy	3207	0.9
μ–ring		
10 GeV	2200	1300
20 GeV	18 000	11 000
50 GeV	2.9 x 10^5	1.8 x 10^5
250 GeV	3.6 x 10^7	2.3 x 10^7

Rate ~ E3

- Conclude : muon neutrino intensity become large compared to the next generation of approved beams (MINOS) if the muon energy is high enough (> 20 GeV ?).

Unoscillated CC Event Rates vs Baseline

Barger, Geer, Raja, Whisnant ... Fermilab–PUB 99–341–T



Short Baseline Event Rates

S. Geer, PRD 57, 6989 (1998)

- Consider an unpolarized muon beam stored in a ring with a straight section pointing at an experiment at L = 1 km, consisting of:
  - 1 kg target
  - L=10 cm, r=10 cm Liquid Hydrogen cylinder
  - 300 μm thick, 10 x 10 cm^2 plane of Silicon

E_μ (GeV)	Charged Current Rate / 10^7 secs		
	1 kg Target	10 cm Liq. H_2	Silicon Plane
10	1300	300	10
20	1×10^4	2600	80
30	4×10^4	8600	260 E^3
40	8×10^4	2×10^4	610
50	2×10^5	4×10^4	1200
100	1×10^6	3×10^5	9600
250	2×10^7	5×10^6	1.5×10^5

- Conclude :

  At high energies [E_μ > O(50 GeV)] can use a new sort of neutrino detector –> high granularity, good vertexing, and particle ID.

Group 2: Detector Parameters

R. Bernstein
D. Naples
P. Spentazouris
M. Velasco
D. Harris
E. Prebys
R. Stefanski

1. 10 kt Iron–Scintillator detector

   $\sigma_p(\mu)$ ~ 0.05 p (range)

   σ_E(shower)/E ~ 0.56 (E >3GeV)
   0.80 (E<3 GeV)

2. 10 kt LAr (ICANOE–like) detector

3. Cherenkov detector

4. 1 kt hybrid emulsion detector

Group 3: Oscillation Theory & Scenarios

C. Albright
B. Cahn
Z. Ligeti
H. Murayama
C. Quigg
G. Anderson
S. Geer
J. Lykken
S. Parke
R. Shrock

Define points in parameter space for detailed neutrino factory sensitivity studies.

For each point, estimate how well we will know the parameters in 5–10 years time.

Expect to define 5 – 10 points to cover the likely scenarios.

Neutrino Oscillations

- Within the framework of 3–flavor oscillations, the flavor eigenstates (νe, $\nu\mu$, $\nu\tau$) are related to the mass eigenstates (ν_1, ν_2, ν_3) :

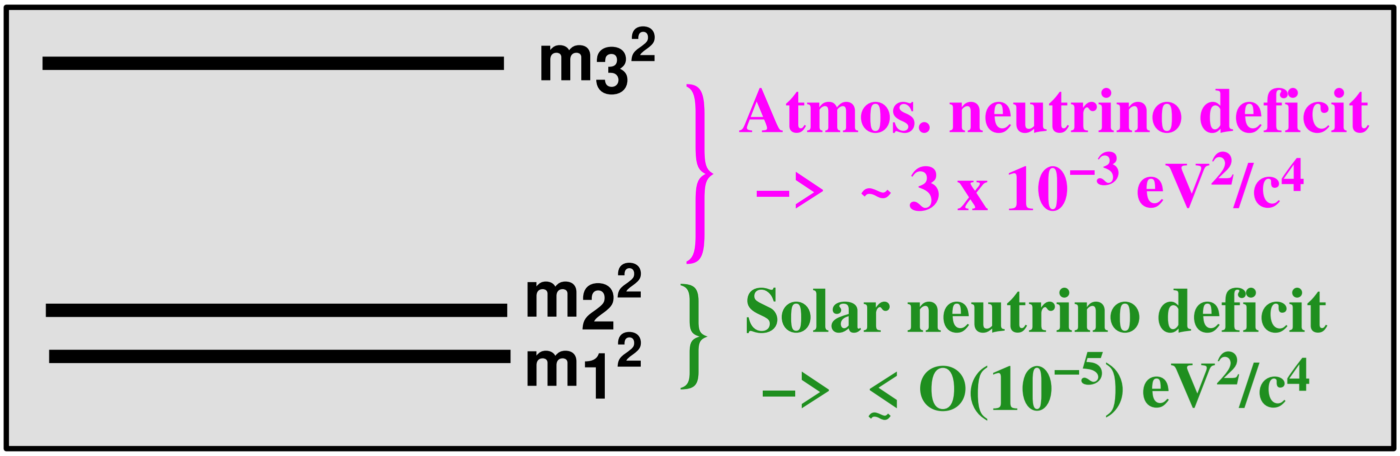
$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \\ \nu_\gamma \end{pmatrix} = \begin{pmatrix} 3 \times 3 \end{pmatrix} \begin{pmatrix} \nu_i \\ \nu_j \\ \nu_k \end{pmatrix}$$

- The mixing is described by a 3x3 CKM–like matrix which can be parametrized using three mixing angles (θ_{12}, θ_{23}, θ_{13}) and a complex phase (δ) :

$$\begin{pmatrix} C_{12}C_{13} & S_{12}C_{13} & S_{13}e^{-i\delta} \\ -S_{12}C_{23} - C_{12}S_{23}S_{13}\,e^{i\delta} & C_{12}C_{23} - S_{12}S_{23}S_{13}\,e^{i\delta} & S_{23}C_{13} \\ S_{12}S_{23} - C_{12}C_{23}S_{13}e^{i\delta} & -C_{12}S_{23} - S_{12}C_{23}S_{13}\,e^{i\delta} & C_{23}C_{13} \end{pmatrix}$$

Oscillation Probability

- The oscillations are driven by the mass splittings between mass eigenstates :



- If $|\Delta m^2_{32}| >> |\Delta m^2_{12}|$ the oscillation probabilities for the leading oscillations are given by:

$$P(\nu_e \to \nu_\mu) = \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2(1.267\Delta m^2_{32}\, L/E)$$
$$P(\nu_e \to \nu_\tau) = \cos^2\theta_{23} \sin^2 2\theta_{13} \sin^2(1.267\Delta m^2_{32}\, L/E)$$
$$P(\nu_\mu \to \nu_\tau) = \cos^4\theta_{13} \sin^2 2\theta_{23} \sin^2(1.267\Delta m^2_{32}\, L/E)$$

where L = baseline (km), E = ν energy (GeV) and $\Delta m_{ij}^2 = m_j^2 - m_i^2$ (eV^2/c^4)

- Want to measure Δm_{12}^2, Δm_{23}^2, Δm_{13}^2, δ, θ_{12}, θ_{23}, θ_{13}, and check consistency of the framework –> need both ν_e and ν_μ beams !

Matter Effects

- **Electron neutrinos can elastically forward scatter off the electrons in matter via CC interactions –> an additional term in the diagonal element of the mixing matrix corresponding to $\nu_e \to \nu_e$.**

- **Define characteristic matter oscillation length:**

$$L_0 = \frac{2\pi}{\sqrt{2}\, G_F N_e} \sim \frac{1.7 \times 10^7 \text{ m}}{\rho(\text{g/cm}^3)\, Z/A} \sim 10^4 \text{ km}$$

L_0 is the distance over which the phase of the ν_e wavefunction changes by 2π. For antineutrinos $N_e \to -N_e$, a matter induced CP effect !

- **Define ratio of oscillation lengths in matter/vacuum:**

$$R_m = \left[1 + \left(\frac{L_v}{L_0}\right)^2 - 2\frac{L_v}{L_0}\cos 2\theta\right]^{-1/2}$$

$$P(\nu_e \to \nu_x) = R_m^2 \sin^2 2\theta \sin^2\left[\frac{1.267\, \Delta m^2_{ji}}{R_m}\frac{L}{E}\right]$$

The modification to the oscillation probability depends upon the sign of Δm^2 (through L_v).

Need a baseline of a few thousand km.

Scenarios

Three "scenarios" defined so far, all with 3 active neutrinos, no sterile neutrinos, and ...

$\Delta m^2_{32} = 3.5 \times 10^{-3}\ eV^2/c^4$

$\sin^2 2\theta_{23} = 1$

$\sin^2 2\theta_{31} = 0.04$

$\delta = 0$ ... no CP violation

Scenario 1: $\Delta m^2_{21} = 5 \times 10^{-5}\ eV^2/c^4$

$\sin^2 2\theta_{12} = 0.8$

Scenario 2: $\Delta m^2_{21} = 6 \times 10^{-6}\ eV^2/c^4$

$\sin^2 2\theta_{12} = 0.006$

Scenario 3: $\Delta m^2_{21} = 1 \times 10^{-7}\ eV^2/c^4$

$\sin^2 2\theta_{12} = 0.9$

Group 4: Oscillation Measurements

C. Albright
R. Bernstein
S. Geer
K. McFarland
S. Parke
E. Prebys
A. Rubbia
R. Stefanski
G. Unel
V. Barger
M. Campanelli
D. Harris
G. Mills
R. Plunkett
R. Raja
P. Spentzouris
M. Uilesco
K. Whisnant

Explore sensitivity of neutrino factories for measuring oscillations at the points in parameter space defined by Group 3, as a function of :

Muon Energy
Baseline
Polarization
Detector details

$\nu_e \to \nu_\mu$

$$\mu^+ \to \nu_e + \bar{\nu}_\mu + e^+$$

$$\bar{\nu}_\mu \xrightarrow{CC} \mu^+$$

$$\nu_e \to \nu_\mu \xrightarrow{CC} \mu^-$$

1. Wrong–sign muons

Assume Iron–Scintillator detector:

Charge mis–identification ~ $10^{-5} - 10^{-6}$

$$\left.\begin{array}{l} M = 10\ \text{kt} \\ \varepsilon = 33\%\ \ \text{.... pessimistic ?} \end{array}\right\}\ \text{3 year run} \to \text{1 kt–yr data set}$$

2. Backgrounds (*Villanueva et al., Lyon 1999*)

Main background from charm production & decay ($D^- \to \mu^-$) –> reject with kinematic cuts:

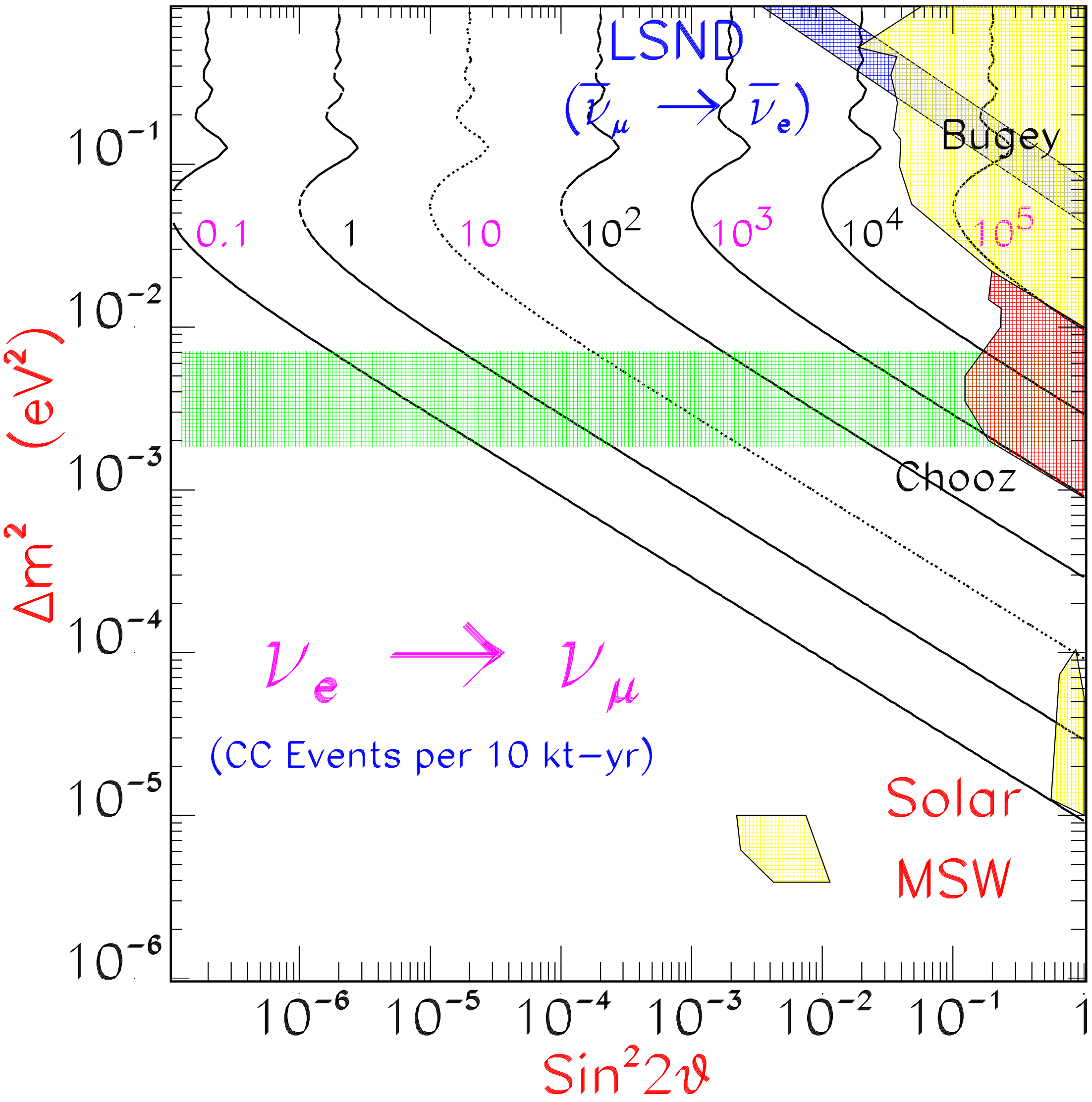
E_μ (GeV)	Background/Total
10	4×10^{-5}
20	6×10^{-6}
50	1×10^{-6}

$\nu_e \rightarrow \nu_\mu$ Appearance

FNAL->Soudan
CERN -> Gran Sasso } L=730 km

1.6×10^{20} μ^+ Decays/yr
E_μ = 50 GeV } Search for wrong–sign muons in a 10 kt detector

Barger, Geer, Whisnant ... hep–ph/9906487



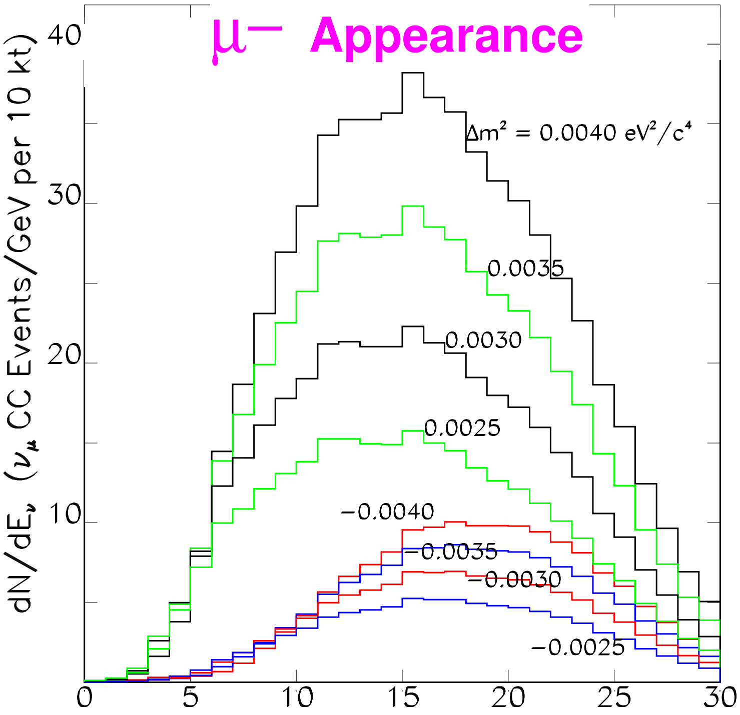
Two–Flavor Mixing Calculation

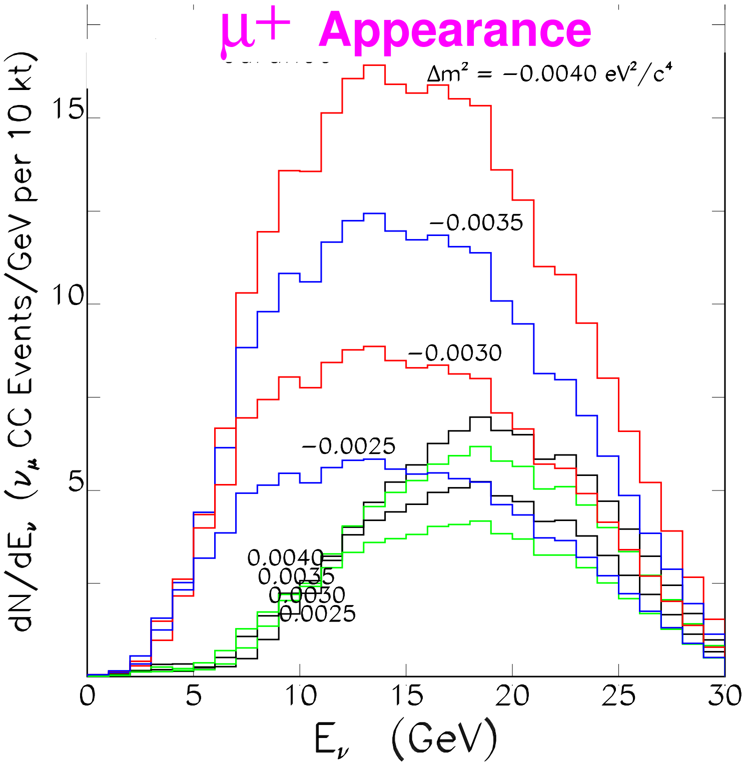
$\nu_e \to \nu_\mu$ Appearance

FNAL–>SLAC/LBNL (L = 2800 km)

E_μ = 30 GeV
2×10^{20} Decays

Barger, Geer, Raja, Whisnant
Fermilab–Pub 99–341–T





Three–Flavor Mixing

$\Delta m^2_{21} = 5 \times 10^{-5}$ eV^2/c^4

$\sin^2 2\theta_{23} = 1$ $\delta = 0$

$\sin^2 2\theta_{12} = 0.8$

$\sin^2 2\theta_{31} = 0.04$

μ^- Appearance

+tve Δm^2_{32} gives larger rate & softer spectrum than –tve Δm^2_{32}

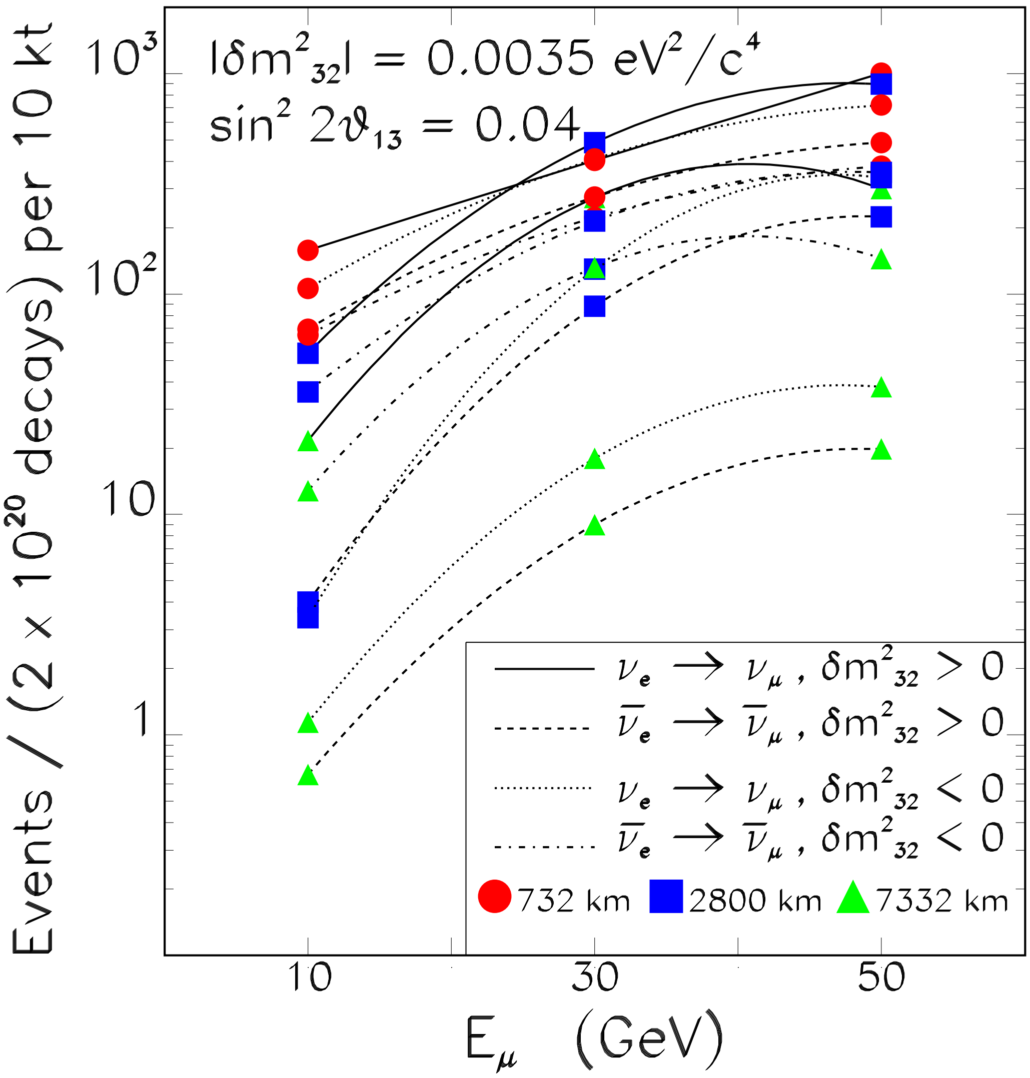
μ^+ Appearance

+tve Δm^2_{32} gives smaller rate & harder spectrum than –tve Δm^2_{32}

Data with stored μ^+ and stored μ^- would enable sign of Δm^2_{32} to be determined !

Wrong–Sign Muon Rates

Barger, Geer, Raja, Whisnant ... Fermilab–PUB 99–341–T



If we want >100 wrong–sign muon events then 7332 km is too far & Eμ must be ~30 GeV or more.

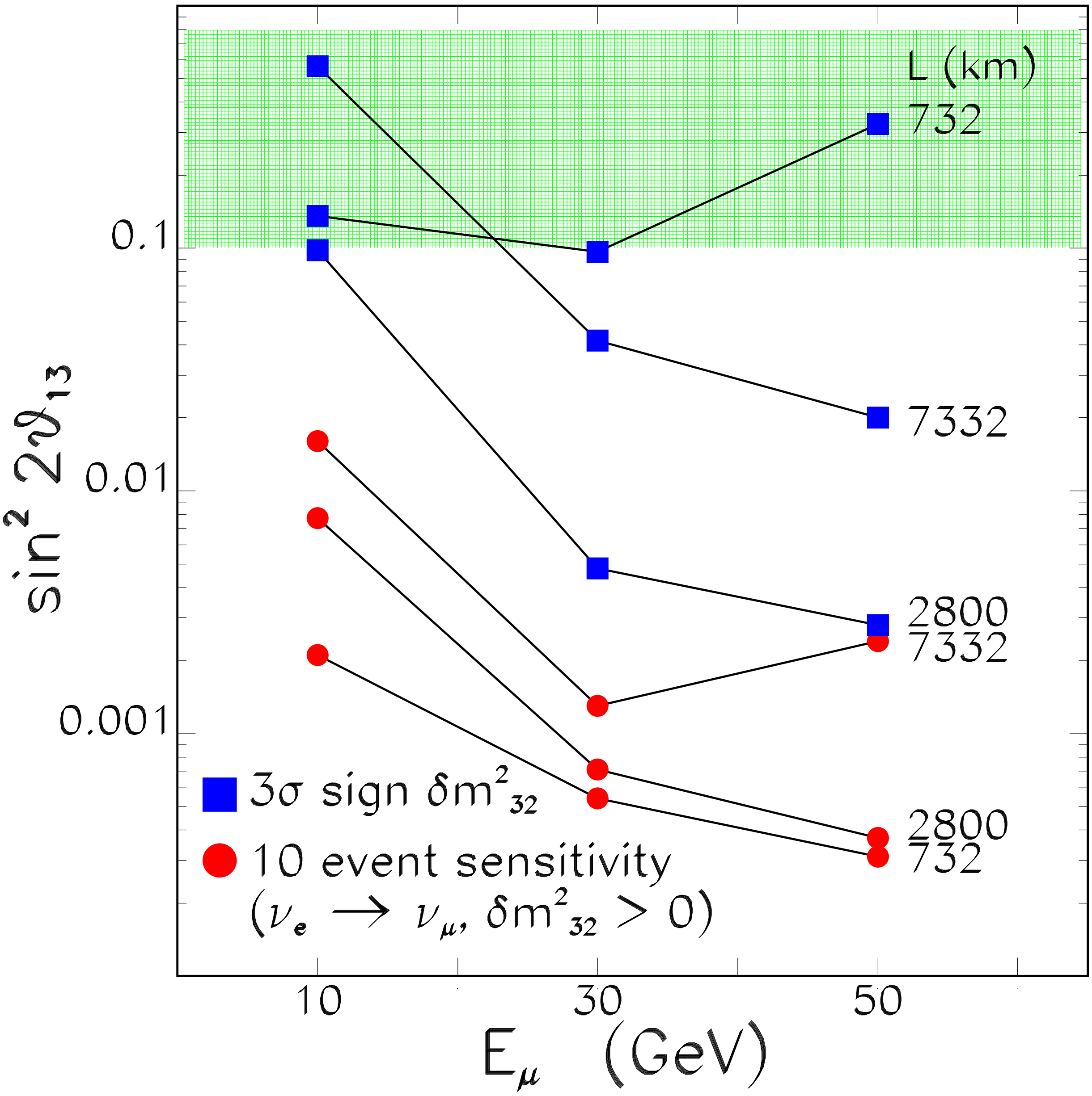
Note: Can scale to other $\sin^2 2\theta_{13}$ using the approximate expression:

$$P(\nu_e \rightarrow \nu_\mu) = \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2(1.267\Delta m^2_{32} L/E)$$

$\nu_e \rightarrow \nu_\mu$ Sensitivity

2 x 10^{20} μ decays **10 kt detector** **δm^2_{32} = 0.0035 eV^2/c^4**

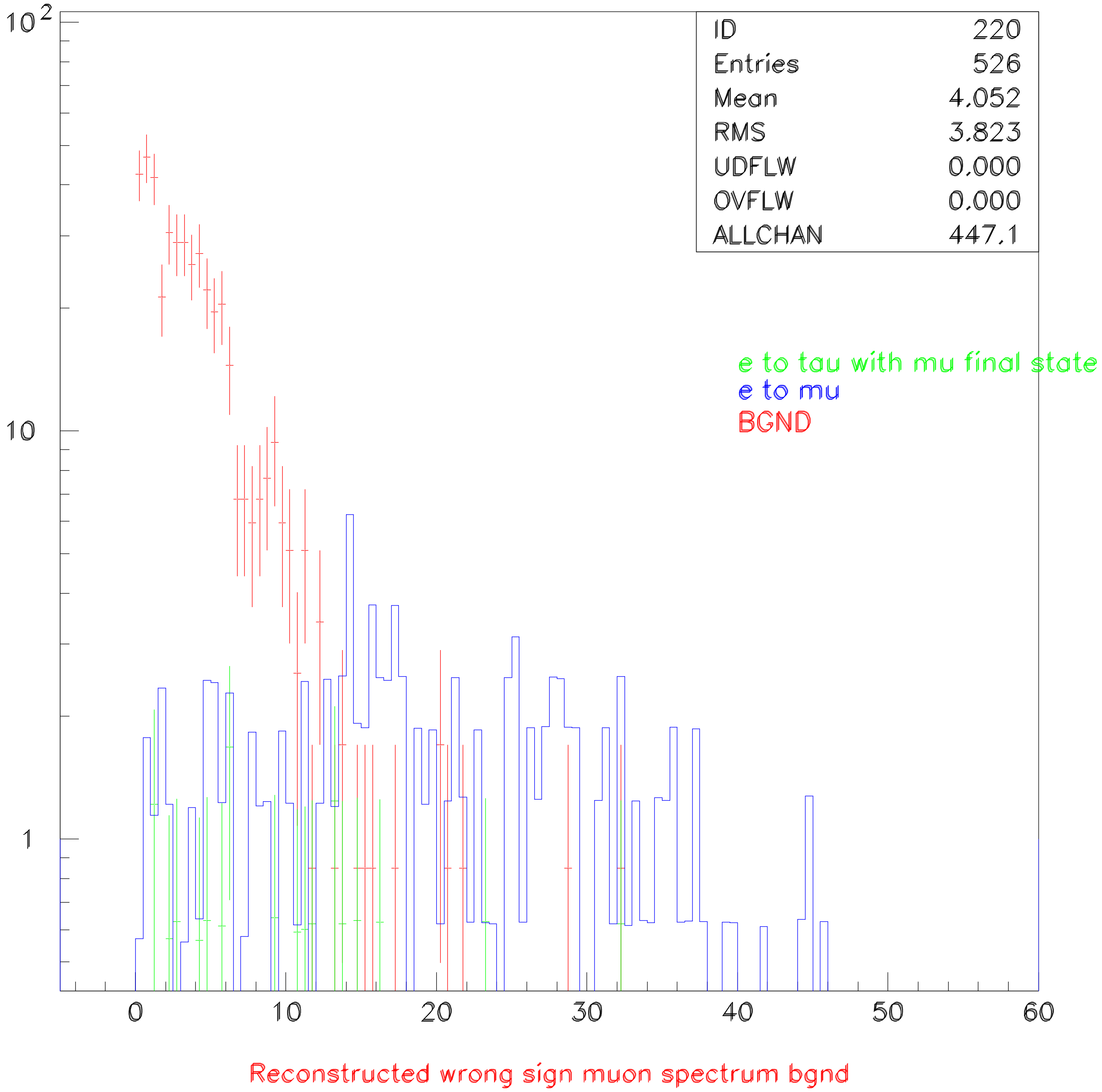
Barger, Geer, Raja, Whisnant ... Fermilab–PUB 99–341–T



To determine the sign of δm^2, 732 km too short (matter effects small), & 7332 km too far (no statistics). So choose L = 2800 km. Sensitivity improves with $E\mu$ ... but 30 GeV almost as good as 50 GeV.

Wrong–Sign Muon Appearance with Detector Simulation

Panagiotis Spentzouris



ν_τ Appearance

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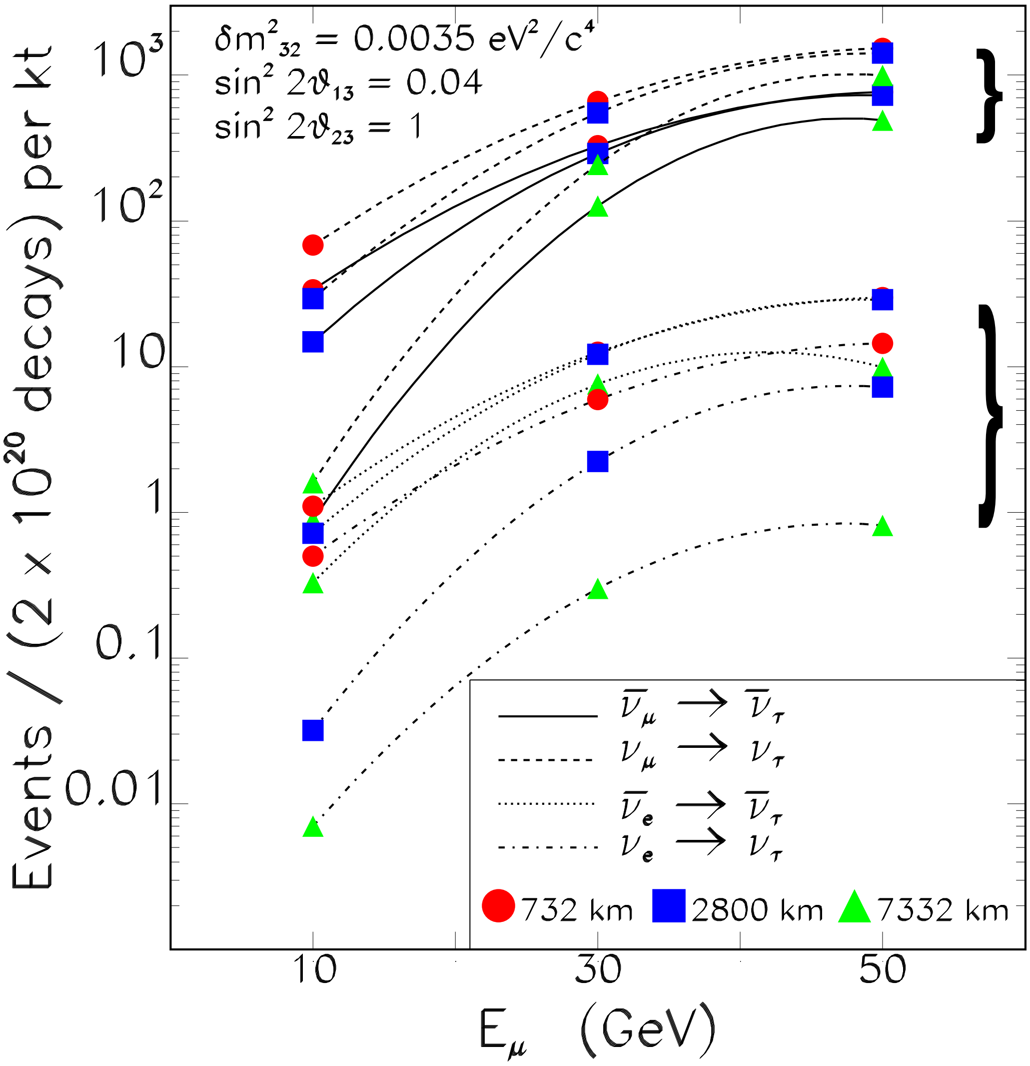


$\nu_\mu \to \nu_\tau$

Hundreds of events

$\nu_e \to \nu_\tau$

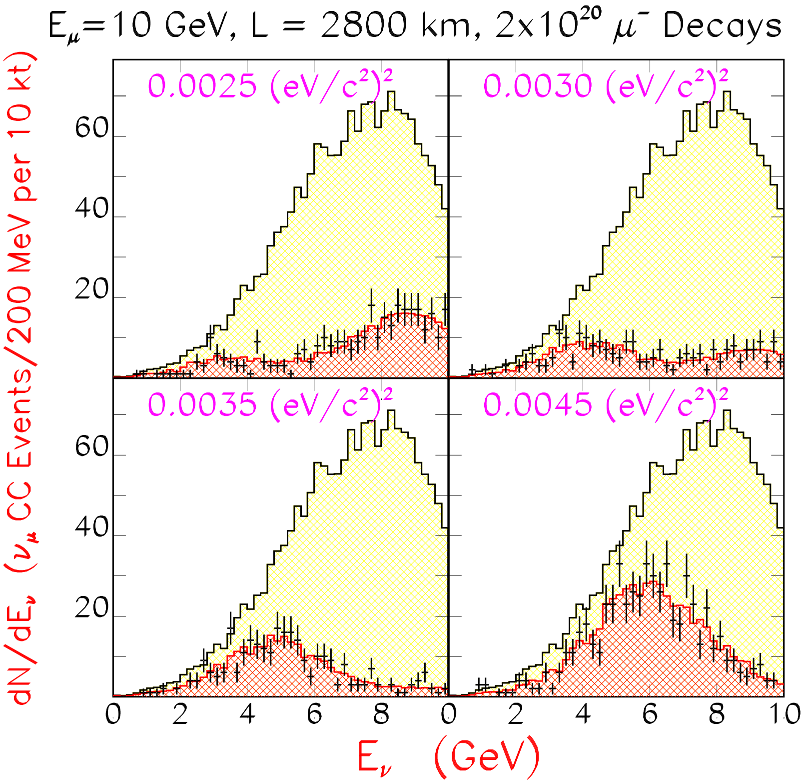
Hard with 2×10^{20} decays / yr

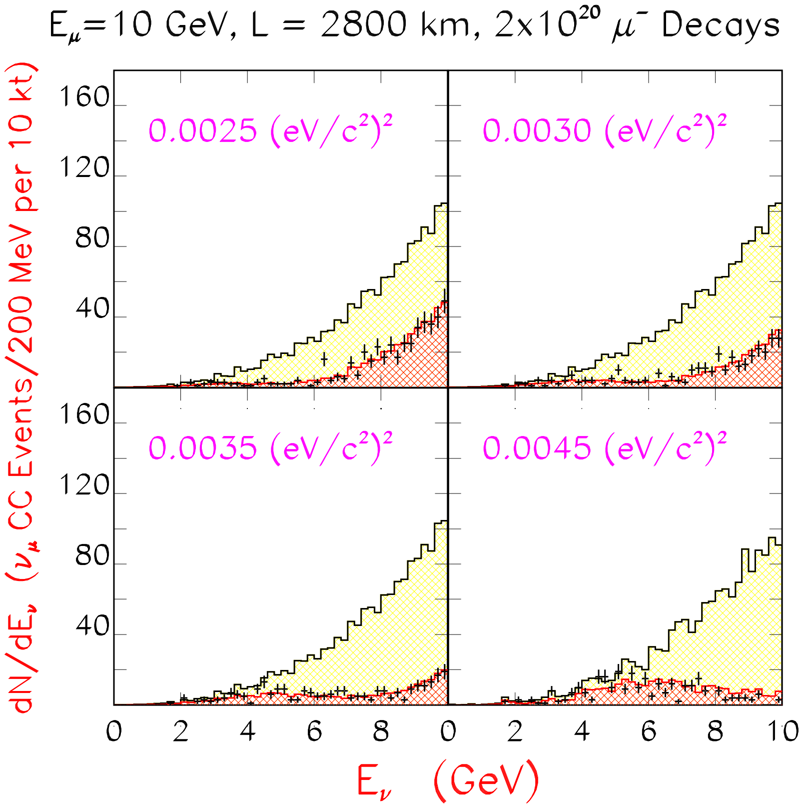
Note: Can scale to other $\sin^2 2\theta_{13}$ and δm^2_{32} using the approximate expressions:

$$P(\nu_e \to \nu_\tau) = \cos^2\theta_{23} \sin^2 2\theta_{13} \sin^2(1.267 \delta m^2_{32} L/E)$$

$$P(\nu_\mu \to \nu_\tau) = \cos^4\theta_{13} \sin^2 2\theta_{23} \sin^2(1.267 \delta m^2_{32} L/E)$$

ν_μ Disappearance





Barger, Geer, Raja, Whisnant ... Fermilab–PUB 99–341–T

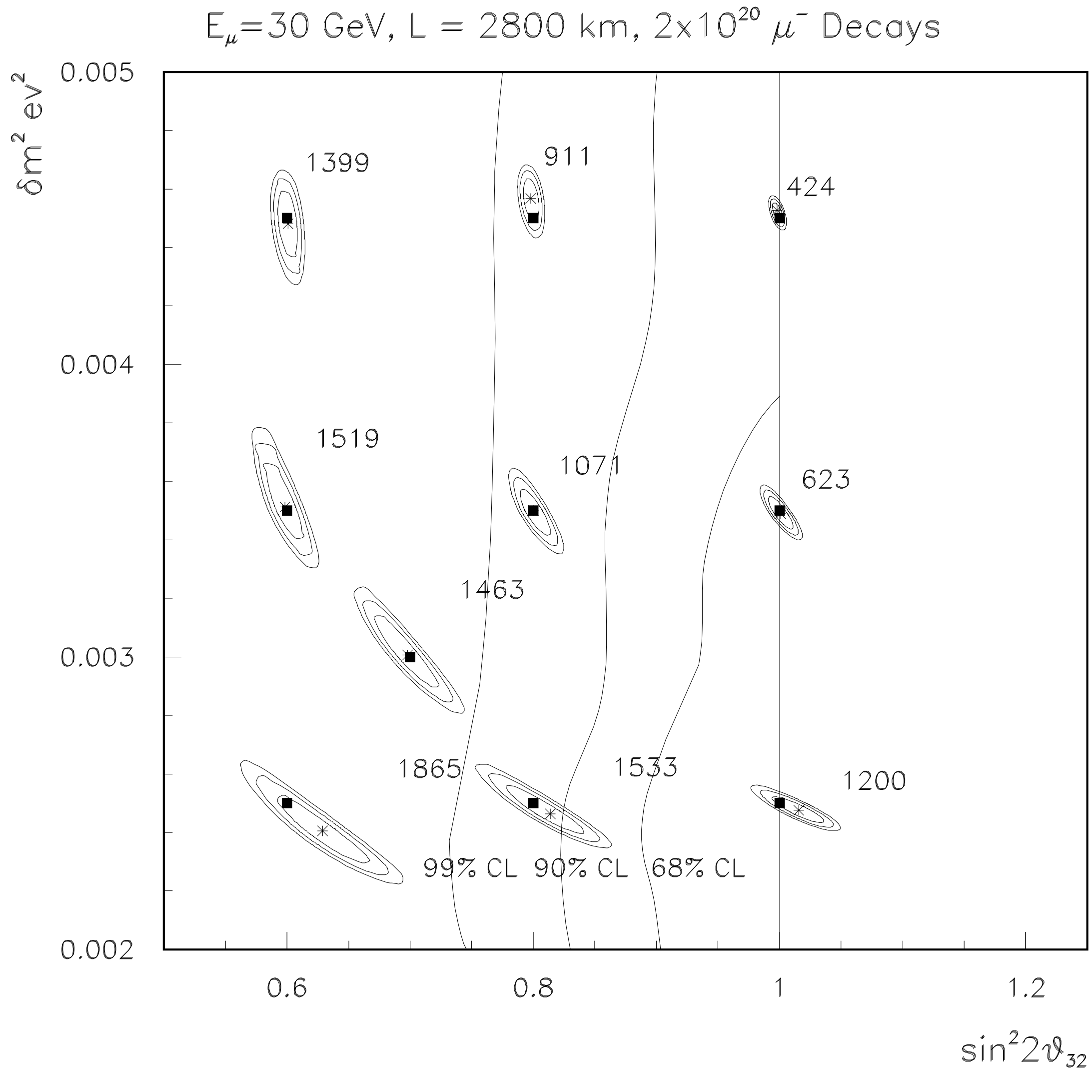
$\delta m^2 \sim 3 \times 10^{-3}$ eV^2
L = 2800 km

–> first Osc. Max at E ~ 10 GeV ... too low for appearance measurements.

However, with Eμ ~ 30 GeV there is still a striking disappear–ance signal, and we are now in business for the appearance measurements.

ν_μ Disappearance

Barger, Geer, Raja, Whisnant ... Fermilab–PUB 99–341–T



–> See talk by R. Raja

Optimizing E and L for Long–Baseline Experiments

Barger, Geer, Raja, Whisnant ... Fermilab–PUB 99–341–T

L km	E_μ GeV	Disappearance stat. precision $\sin^2\theta_{23}$	δm^2_{32}	Wrong–Sign μ minimum $\sin^2\theta_{13}$ 10 Evt/yr	3σ sign δm^2_{32}
732	10	7.6%	6.7%	0.002	> 0.1
	30	14 %	8.9%	0.0005	0.1
	50	17 %	12 %	0.0003	> 0.1
2800	10	1.1%	2.4%	0.008	0.1
	30	2.0%	3.2%	0.0007	0.005
	50	1.8%	4.9%	0.0004	0.003
7332	10	13 %	6.3%	0.02	> 0.1
	30	0.57%	1.2%	0.001	0.04
	50	0.64%	1.4%	0.002	0.02

1. Optimizing for finding the sign of δm^2
   L = 732 km too short (matter effects small)
   L = 7332 km too far (statistics small).
   Sensitivity improves linearly with E_μ –>
   tradeoff between energy, detector size, and muon beam intensity.

2. Statistical precision of disappearance measurements –> O(1%) precision on $\sin^2\theta_{23}$ and δm^2_{32}

Group 5: Non–Oscillation Physics

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J. Krane
J. Morfin
H. Schellman
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G. Unel
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D. Harris
G. Garvey
K. McFarland
S. Parke
R. Shrock
M. Velasco
J. Yu

Physics:

Rare processes (e.g. multiplicative lepton no.)

Precision $\sin^2\theta_W$

Structure functions

Charm production

...

Not the driving force behind neutrino factories, but a bonus.

Summary

- At first sight it seems that:

1. Neutrino beams from neutrino factories (as currently envisioned) are sufficiently intense to shoot a beam anywhere on the planet & detect thousands of events/year –> matter effects and the sign of δm^2.
2. Neutrino factories could enable the measurement of $\nu_e \to \nu_\mu$ oscillations driven by the atmospheric neutrino deficit Δm^2 with oscillation amplitudes approaching $O(10^{-4})$.
3. $\nu_\mu \to \nu_\tau$ appearance & $\nu_\mu \to \nu_\mu$ disappearance measurements could enable δm^2 & $\sin^2\theta_{23}$ to be determined with a precision of $O(1\%)$.
4. There is also an extensive non–oscillation physics program–>bonus (not driving force)

Six–months study in progress to more fully explore the possibilities, understand impact of backgrounds & systematics, & understand if there is a an optimal L, E, & the case for polarization .. theres lots to do .. please join us !