Design Study Meeting,
15thFebruary 2000

Steve Geer

Physics motivation & Neutrino factory parameters

- Physics Motivation
- 6 Month Physics Study
- Sensitivity to oscillation physics versus neutrino factory parameters
- Other considerations
  - Polarization
  - Flux systematics
  - Short baseline physics
  - Other physics possibilities
- Summary

---

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

The primary motivation for a neutrino factory

Growing body of evidence for ν oscillations:

- SuperK atmospheric neutrino results
- Solar Neutrino Results
- LSND results

Interest well motivated -> clues to understanding the family problem, mass hierarchy problem ....

The next generation of accelerator experiments (K2K, MINOS, MiniBooNE, ICANOE, OPERA) are expected to confirm oscillations & begin to measure the associated parameters. However, to fully understand the oscillation framework & measure all of the parameters we will need :

ν_e beams as well as ν_μ beams.
Higher intensity beams than available now.

We have ν_μ beams. We dont have ν_e beams.

If we use a muon–collider type muon source plus a storage ring with long straight sections the ν beam is sufficiently intense to produce

( )!

Beam properties

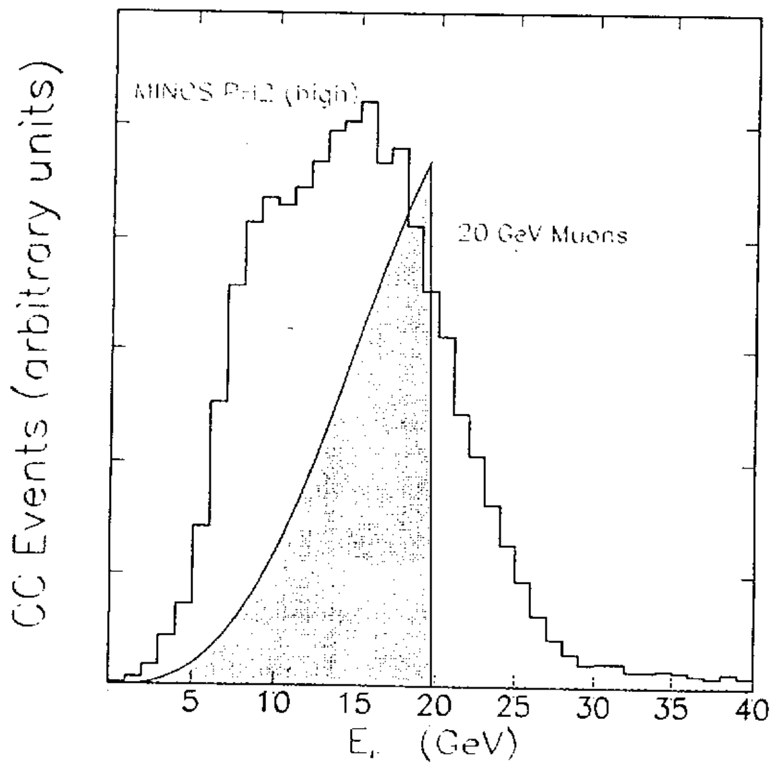
1. **Well defined ν flavor content**

$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu \longrightarrow 50\% \ \nu_e \ (\bar{\nu}_\mu)$$

$$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu \longrightarrow 50\% \ \bar{\nu}_e \ (\nu_\mu)$$

2. **Precisely known neutrino fluxes & kinematics**

3. **"Narrow-Band" Beam**



Neutrino Oscillations

- Within the framework of 3–flavor oscillations, the flavor eigenstates (ν_e, ν_μ, ν_τ) are related to the mass eigenstates (ν_1, ν_2, ν_3) :

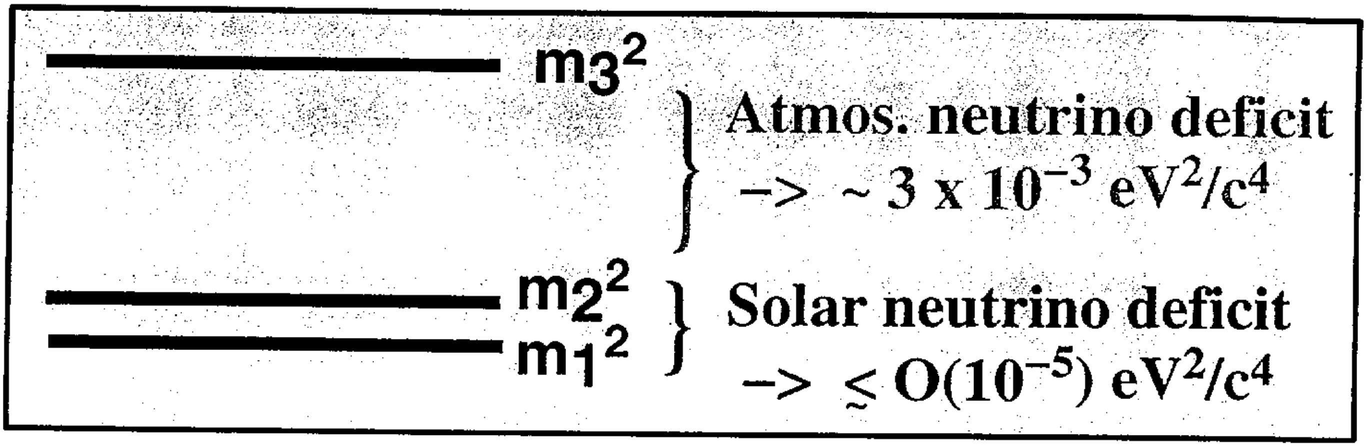
$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \\ \nu_\gamma \end{pmatrix} = \begin{pmatrix} 3 \times 3 \end{pmatrix} \begin{pmatrix} \nu_i \\ \nu_j \\ \nu_k \end{pmatrix}$$

- 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) :

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

Getting at the physics – 1

- 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:

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

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

Getting at the physics – 2

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

- Want ν_e and ν_μ beams.
- There is a bonus in having ν_e beams if L is a few thousand km. Matter effects modify the oscillations probabilities in a way that depends on the sign of Δm^2 –> who is heavier than who !

$$P(\nu_e \rightarrow \nu_x) = R_m^2 \sin^2 2\theta \sin^2\left[\frac{1.267\,\delta m_{ji}^2}{R_m}\,\frac{L}{E}\right]$$

Want to measure $\delta m_{12}{}^2$, $\delta m_{23}{}^2$, $\delta m_{13}{}^2$, δ, θ_{12}, θ_{23}, θ_{13}, check consistency of the framework, and determine who is heavier than who.

Getting at the physics – 3

Primary Motivation	Beam needed
1. 1st observation of $\nu_e \rightarrow \nu_\mu$ or stringent limit on $\sin^2 2\theta_{13}$	ν_e
2. 1st observation of matter effects	$\nu_e, \bar{\nu}_e$
3. Measurement of sign of δm^2_{32}	$\nu_e, \bar{\nu}_e$
4. Measurement of /limits on δ (CP Violation)	$\nu_e, \bar{\nu}_e$
5. Observation / limits on $\nu_e \rightarrow \nu_\tau, \nu_s$	ν_e
6. Sum of above (1–5) enables test of oscillation scheme consistency	$\nu_e, \bar{\nu}_e$
Additional Motivation (B&B)	
1. High precision measurements of (limits on) $\nu_\mu \rightarrow \nu_\tau, \nu_s$	ν_μ
2. Stru. Fus, spin stru. fus, precision $\sin^2\theta_W$, charm production, D–$\overline{\text{D}}$ mixing, B–physics, exotics, ...	ν_e or ν_μ

Six–Month Physics Study

Co–ordinators: S. Geer, H. Schellman

Conveners: R. Bernstein, D. Harris, E. Hawker, S. Parke

Group 1: Beam properties

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

Group 2: Detectors & backgrounds

R. Bernstein (convener), D. Harris, D. Naples, E. Prebys, P. Spentzouris, R. Stefanski, M. Velasco.

Group 3: Oscillation theory & scenarios

S. Parke (convener), C. Albright, G. Anderson, V. Barger, R. Cahn, Z. Ligeti, J. Lykken, I. Mocioiu, H. Murayama, C. Quigg, R. Shrock, K. Whisnant.

Group 4: Oscillation measurements

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

Group 5: Non–Oscillation physics

E. Hawker (convener), P. Cushman, F. DeJongh, J. Formaggio, D. Harris, G. Garvey, J. Krane, K. McFarland, J. Morfin, S. Parke, H. Schellman, R. Shrock, R. Stefanski, M. Velasco, G. Unel, J. Yu.

---

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

Physics Study Charge

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.

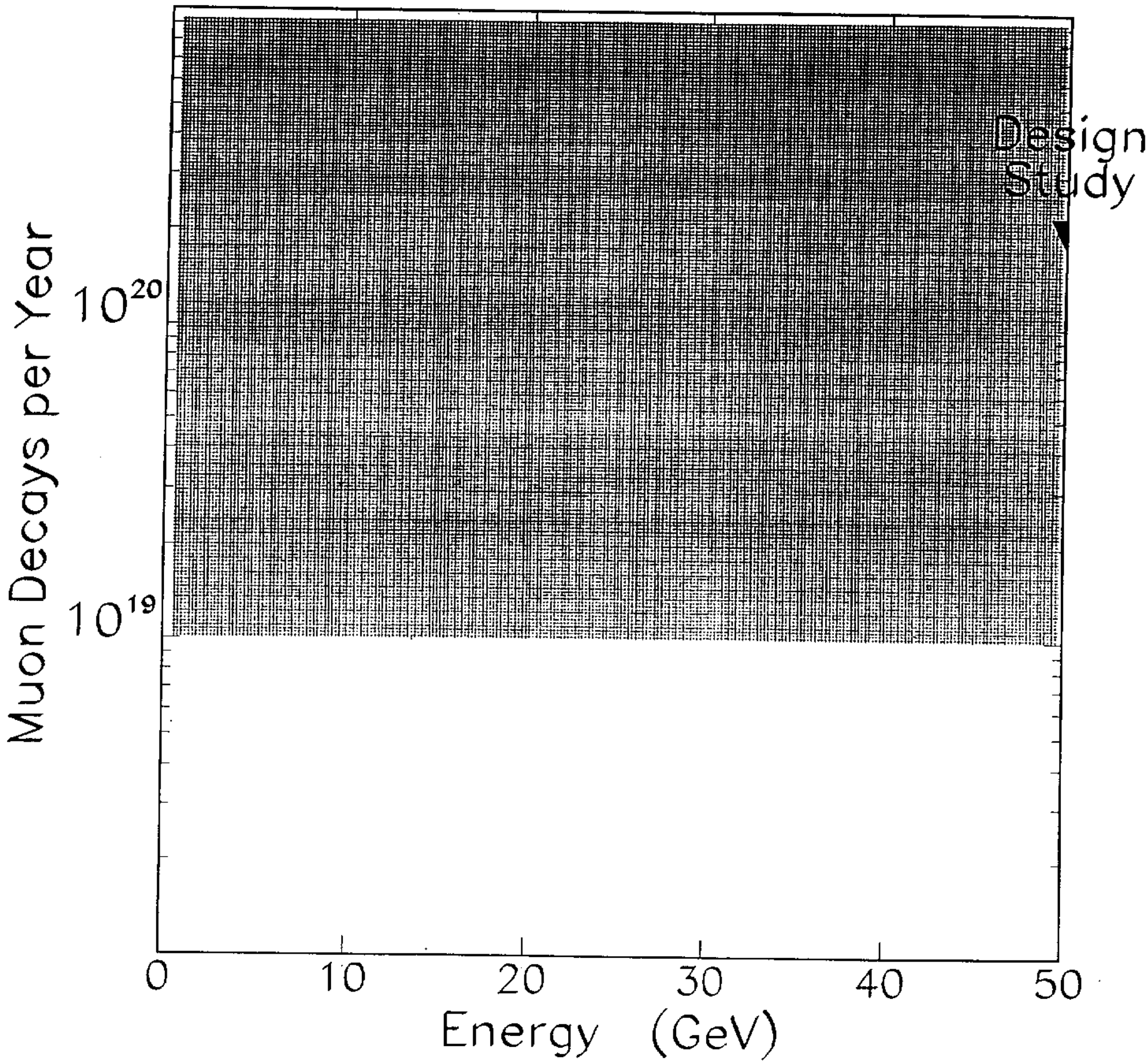
2. The physics program that could be accomplished at a neutrino factory as a function of:

   (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 polarization within the storage ring.

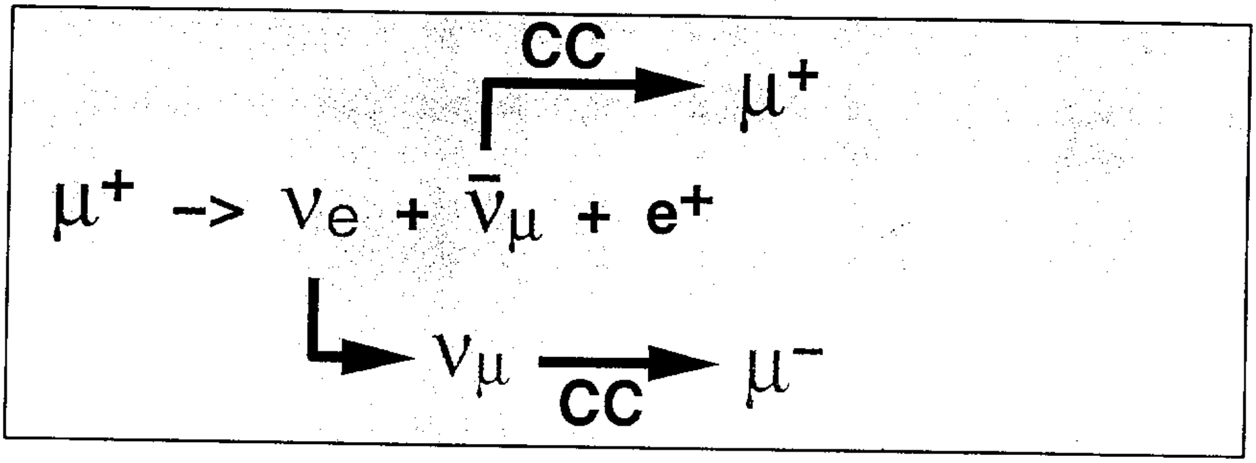
   (d) For oscillation experiments, the baseline length including investigations evaluating matter effects.


Design
Study
Muon Decays per Year
10^{20}
10^{19}
0
10
20
30
40
50
Energy (GeV)

Two Possible Scenarios

If MiniBooNE does not confirm the LSND oscillation result, the world–attention grabbing channel is:

$$\nu_e \rightarrow \nu_\mu$$



Wrong–sign muons and long baselines

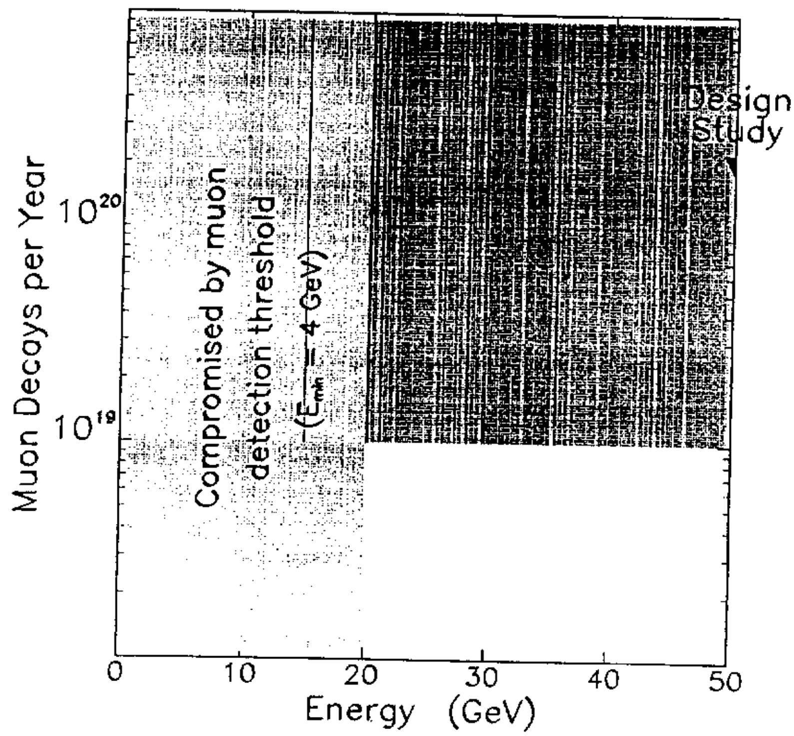
If MiniBooNE does confirm the LSND oscillation result, the world–attention grabbing channel is:

ν_e [illegible]

τ appearance and shorter baselines

Experimental Considerations

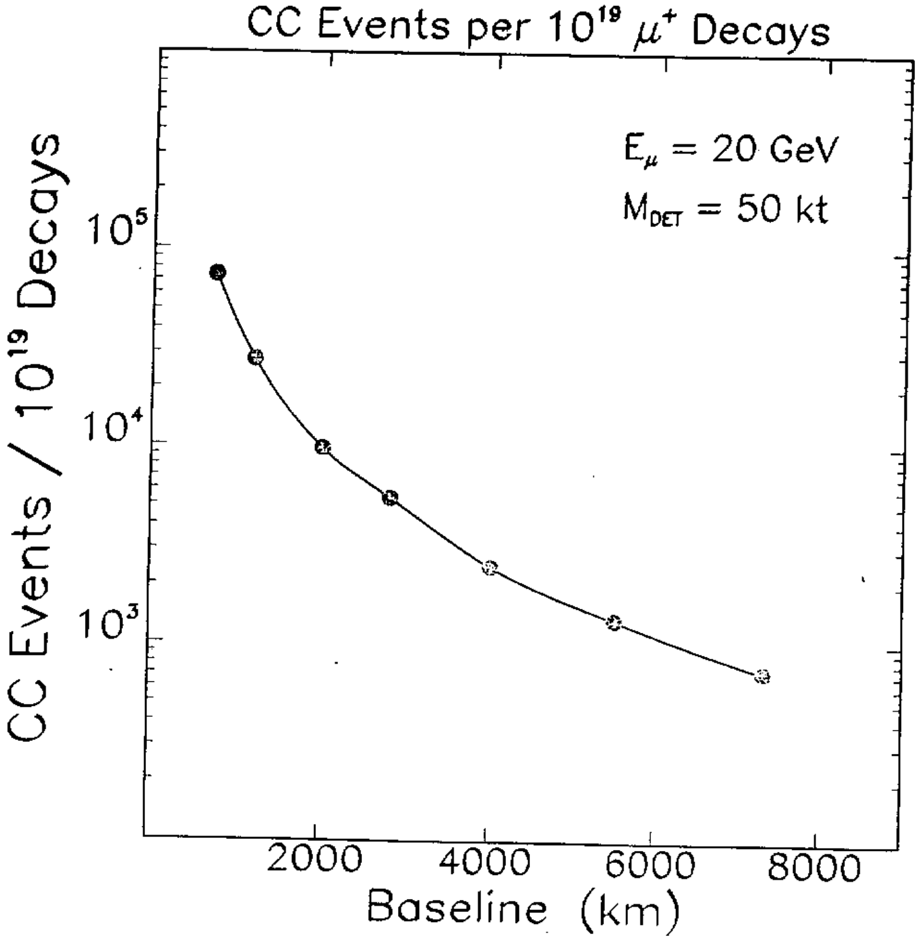
1. Muon Threshold: **To detect & measure wrong–sign muons (the key signature) need to place a threshold on the detected muon energy of ~4 GeV. This puts a limit on the minimum muon storage ring energy of about 20 GeV :**



2. Detector mass: **Sensitivity ~ detector mass x neutrino flux .... so the larger the detector the smaller the number of muons required in the neutrino factory. The next generation nucleon decay detector under discussion is 500 kt ! The nu–factory detector group is considering 50 kt ... also chosen by our European friends.**

Experimental Considerations

3. **Baseline: We want to have small or zero backgrounds. The background / total CC rate may be as high as 10^{-4}** (*P. Spentzouris*)



If the back-ground / total CC rate is ~10^{-4} then L > 2000 km preferred -> < 1 background for 10^{19} decays with a 20 GeV ring

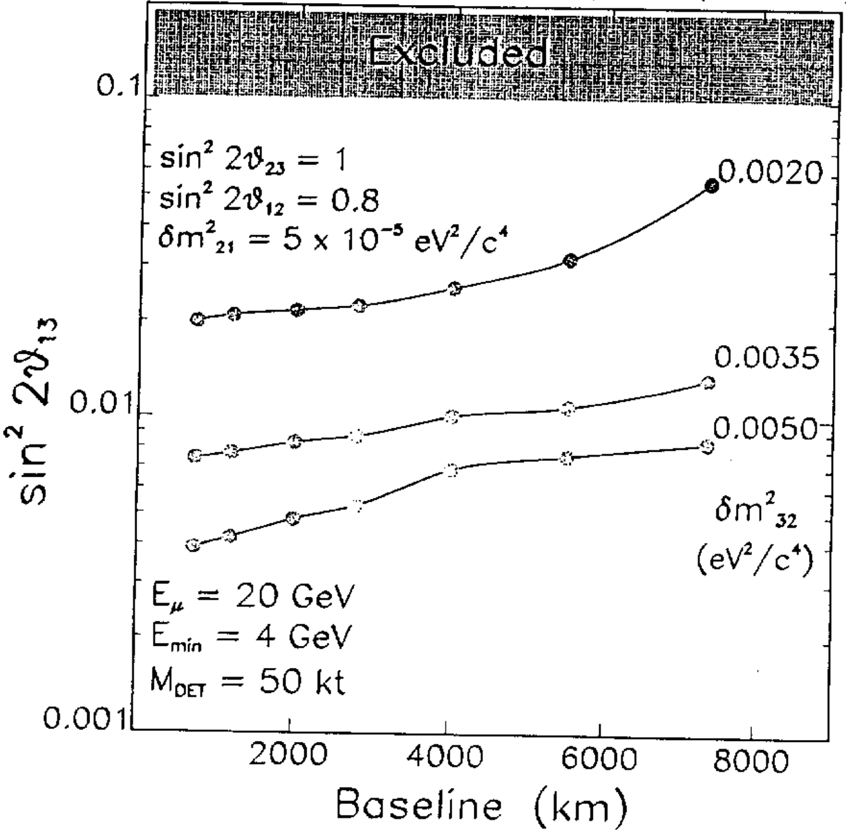
Note that for L = 2800 km the total CC rate is ~5000 events / 10^{19} decays / 50 kt

How many muon decays/year are needed to make contact with the world attention grabbing neutrino oscillation physics if the muon energy is 20 GeV ?

Suppose the "entry–level" physics goal is to make the first observation of $\nu_e \rightarrow \nu_\mu$ at the 10 event level and make the first measurement of $\sin^2 2\theta_{13}$

V. Barger, S. Geer, R. Raja, K. Whisnant

$\sin^2 2\vartheta_{13}$ yielding 10 μ^- evts/10^{19} μ^+ Decays

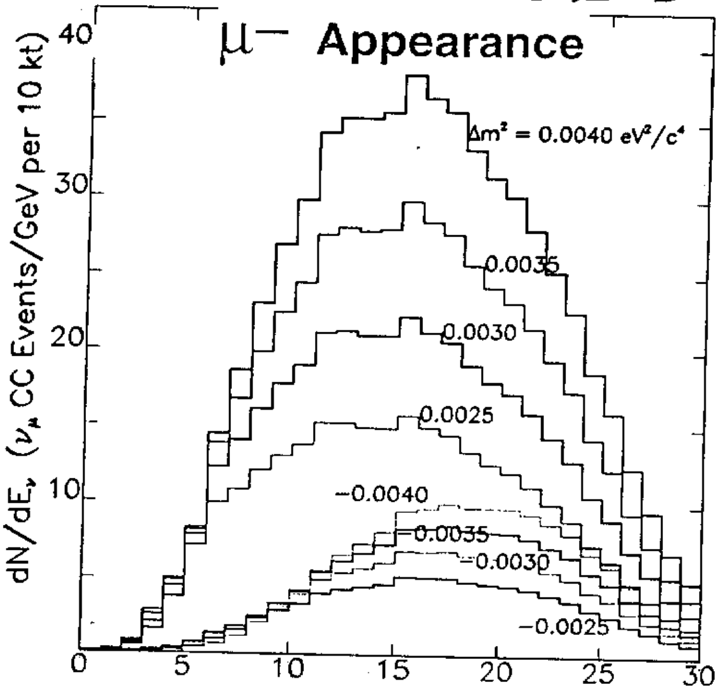


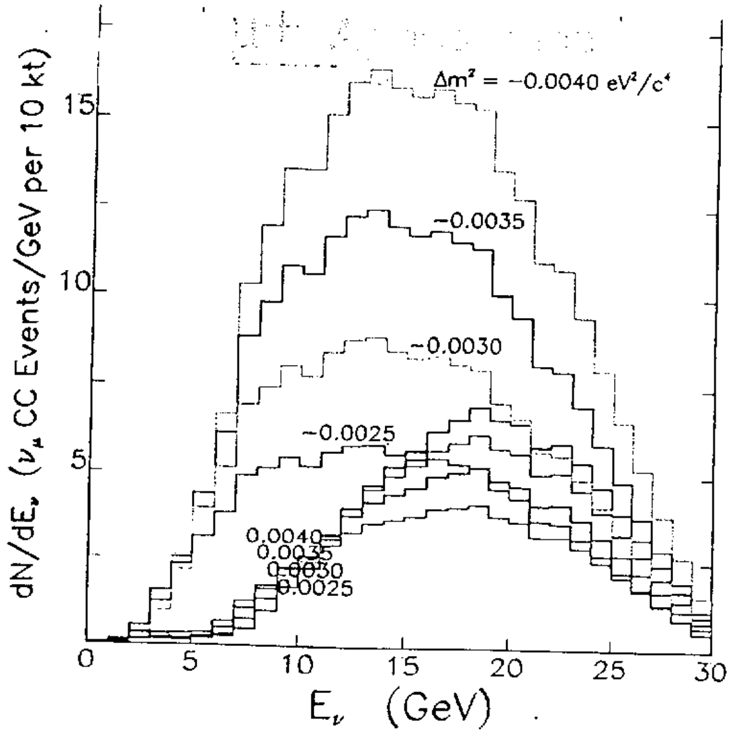
Conclude that 1019 decays/yr would enable the "entry level" goal to be met provided $\sin^2 2\theta_{13} > 0.01$

With more data we could determine the sign of δm^2

L = 2800 km, E_μ = 30 GeV, 2 x 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

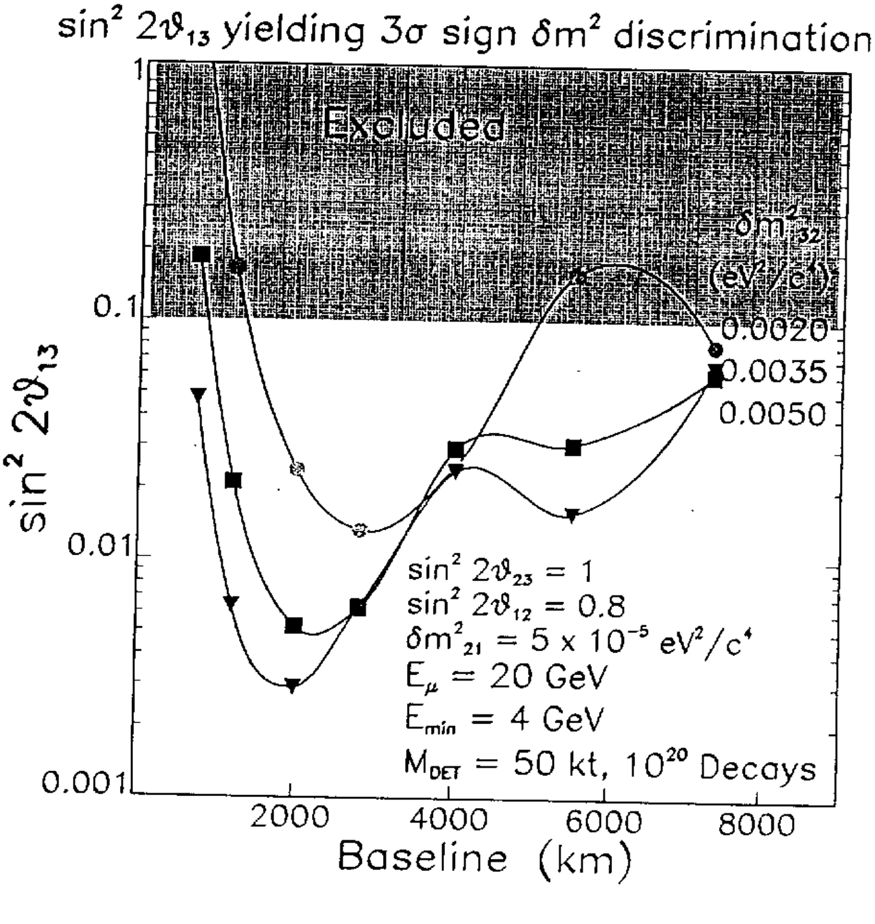
+tve Δm^2_{32} gives smaller rate & harder spectrum than –tve Δm^2_{32}

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

How many muon decays/year are needed for a "beyond the entry level" neutrino factory if the muon energy is 20 GeV ?

Suppose the "upgrade" physics goal is to make the first measurement of matter effects & determine who is heavier than who at 3σ.

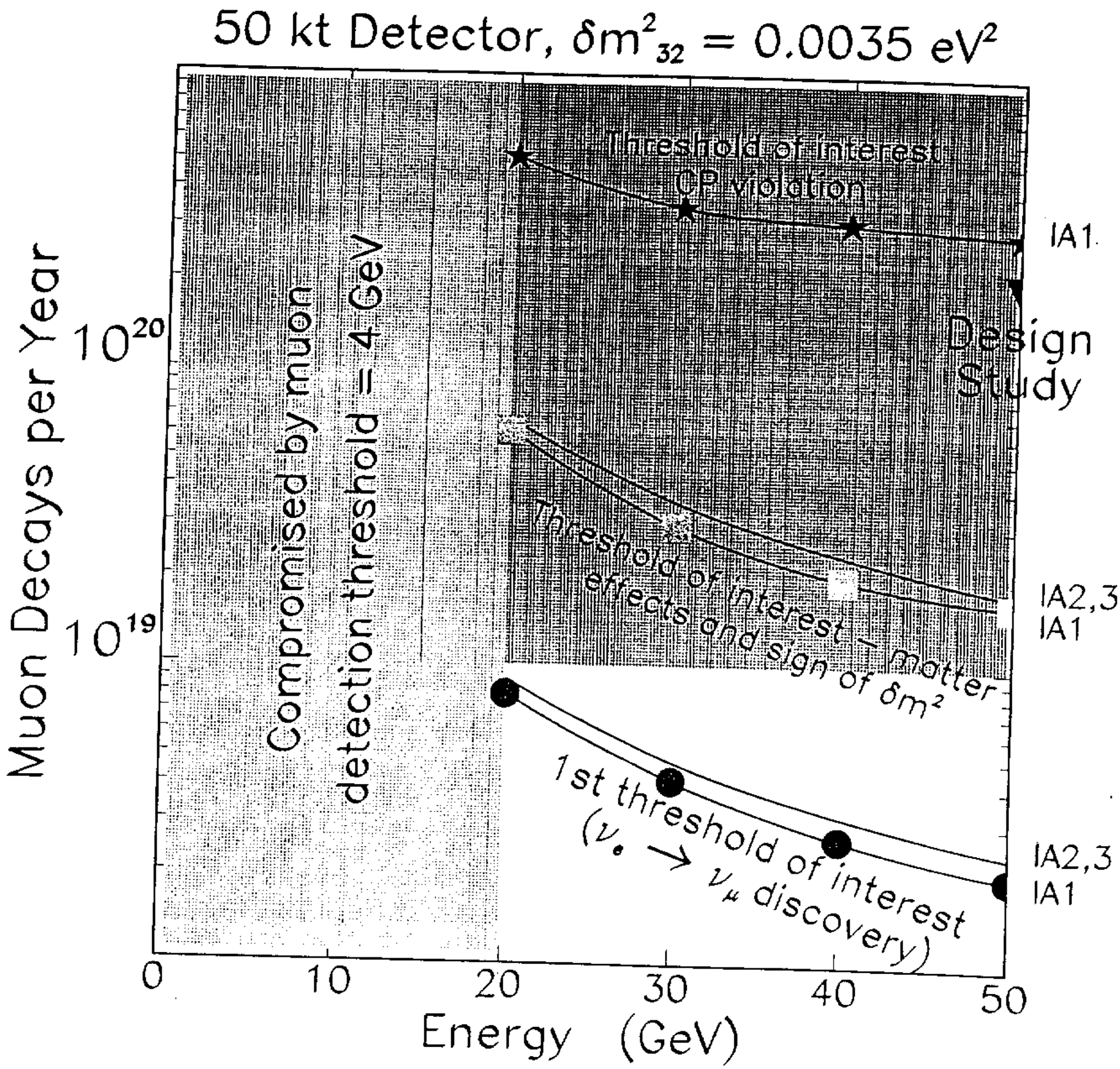
V. Barger, S. Geer, R. Raja, K. Whisnant



Conclude that 1020 decays/yr would enable "upgrade level" goals to be met provided $\sin^2 2\theta_{13} > 0.01$

Conclude that there appears to be a staging strategy for neutrino factories

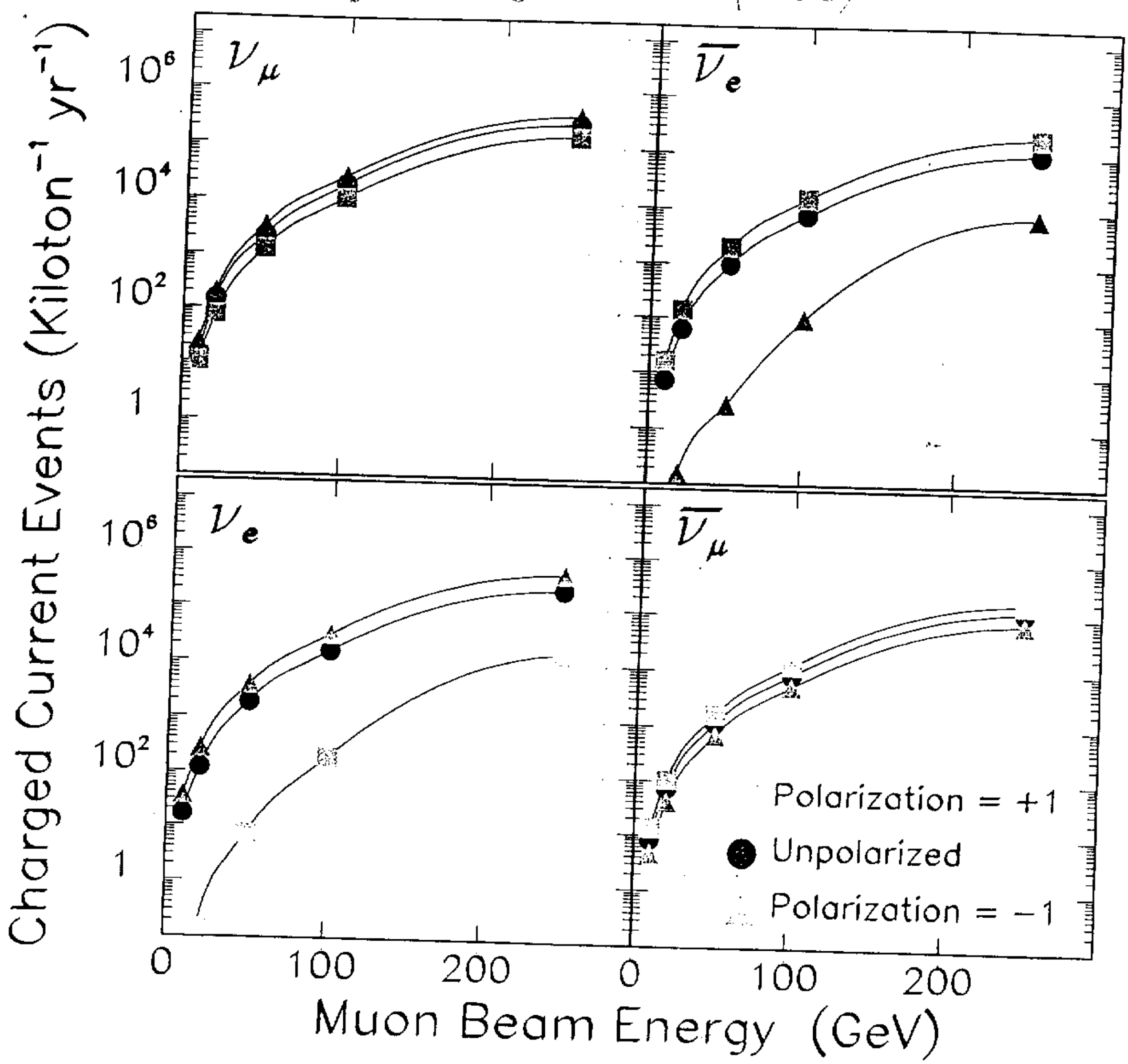
V. Barger, S. Geer, R. Raja, K. Whisnant



Other Considerations

1. Polarization

S. Geer, PRD 57, 6989 (1998)



For a 30 GeV muon beam with 10^{20} muon decays there are ~ 3300 ν_μ CC events / yr in a 10 KT detector at L = 10 000 km.

Polarization switches on/off ν_e flux.
-> can be exploited if signal statistics are large enough – open question.

Other Considerations

2. Flux Systematics

For precision measurements (B&B physics ?) would like precise knowledge of flux at the detector. For example, if we want the flux uncertainty to be < 1% –>

C. Crisan & S. Geer, FERMILAB–TM–2101

Muon Beam Property	Event Rate Dependence	Required Precision
Energy (E_μ)	$\Delta N/N = 3\Delta E_\mu/E_\mu$	$\Delta E_\mu < 0.003 E_\mu$
Divergence $\sigma_\theta \sim 0.1/\gamma$	$\Delta N/N \sim 0.03 \Delta\sigma_\theta/\sigma_\theta$	$\Delta\sigma_\theta < 0.2\,\sigma_\theta$
Direction	$\Delta N/N < 0.01$ for $\Delta\theta < 0.6\,\sigma_\theta$	$\Delta\theta < 0.6\,\sigma_\theta$
Energy spread	$\Delta N/N = 0.06 \Delta\sigma_E/\sigma_E$	$\Delta\sigma_E < 0.17\sigma_E$
Polarization	$\Delta N/N = \Delta P$ for ν_e	$\Delta P < 0.01$

Are these precisions attainable ? Needs study and ideas.

Other Considerations

3. Short baseline physics

   Stru. Fus, spin stru. fus, precision $\sin^2\theta_W$, charm production, D–D mixing, B–physics, exotic processes .....

- **Many of these physics topics primarily need high event rates –> benefit from high energy muons. Consider a 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

S. Geer, PRD 57, 6989 (1998)

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
40	8×10^4	2×10^4	610
50	2×10^5	4×10^4	1200

(Silicon Plane rates: ↓ E^3)

- Need ~100m shielding before detectors

Other Considerations

4. Additional physics possibilities

1. A 1 MW proton driver.
   Kaon, conventional neutrino, ...
2. Intense stopped muon source (no cooling).
   $\mu \to e\gamma$, $\mu \to e$ conversion, hyperfine splitting, muonium–antimuonium, μ decay parameters
3. Low energy muon source (some cooling).
   g–2, μ EDM, ...

At a neutrino factory complex there are many supplementary physics possibilities.

Summary

We have a strong physics incentive to try and develop neutrino factories

If MiniBooNE does not confirm the LSND result, it looks as if a 20 GeV ring with 10^{19} decays/yr might be a good entry–level nu–factory ... our 2–day physics meeting will provide an opport–unity to discuss this.

Eventually we will want a more intense neutrino factory ... certainly O(10^{20}) decays/yr, and if we are in the very special scenario in which CP violation is detectable, then we may one day want O(10^{21}) decays/yr.

Scenarios in which MiniBooNE confirms LSND are now under study.

Non–oscillation physics will require detectors ~ 100m downstream of the beam–forming straight section. Much of this physics would benefit from the highest achievable beam energy.

Beam flux systematics may be important for some of the precision (bread & butter type) oscillation measurements.

Invitation

We have a 2–day neutrino factory physics meeting in 1 West on Thursday/Friday.

Starts 9:00 AM Thursday 17th Feb.

Lots of interesting talks & discussion.

You are welcome.