MUTAC Review
June 2000

Steve Geer

Neutrino factory physics

Report: FERMILAB–FN–692

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66 Physicists from 22 institutions

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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 accomp–lished at a neutrino factory as a function of:

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

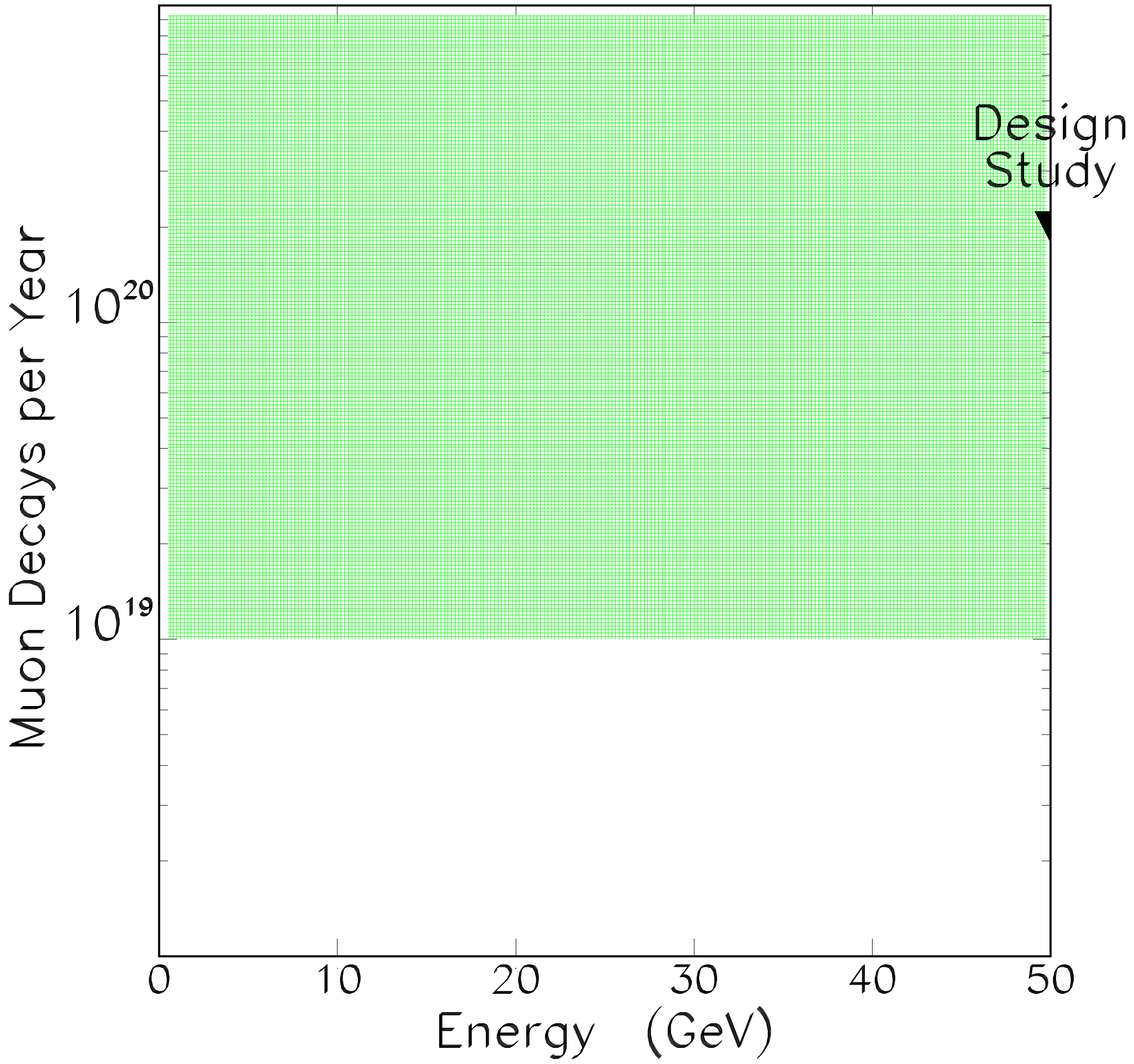
   (b) The number of muon decays per year in the beam–forming straight section, taken to be in the range from 10^{19} to 10^{21} decays per year.

   (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.

Physics Study Charge

Explore the physics potential at a nu factory as a function of muon energy (up to 50 GeV) & instensity (from 10^{19} to 10^{21} decays/yr).



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 :

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

- We have ν_μ beams. We dont have ν_e beams.

- Neutrino factories would –> ν_μ & 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 hundreds of events/yr in a reasonable size detector on the other side of the Earth !

Beam properties

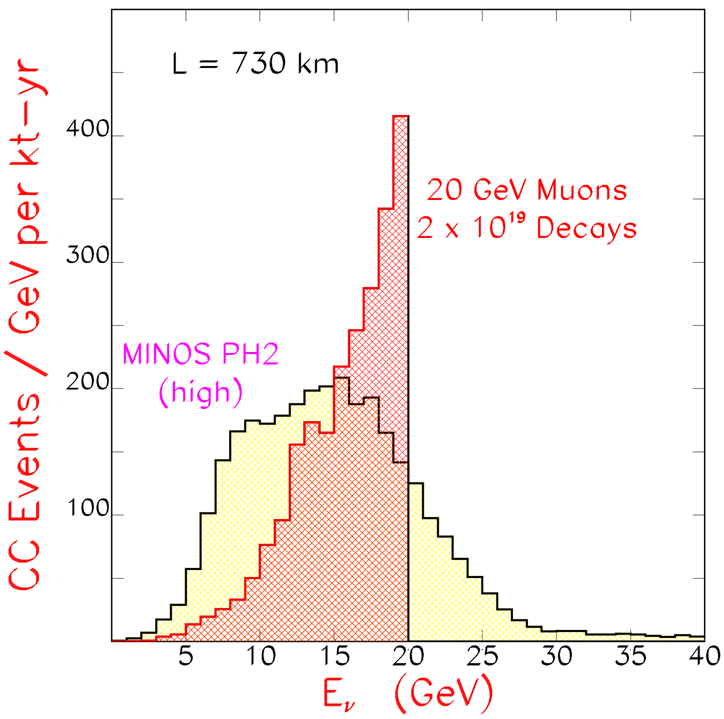
1. Well defined ν flavor content

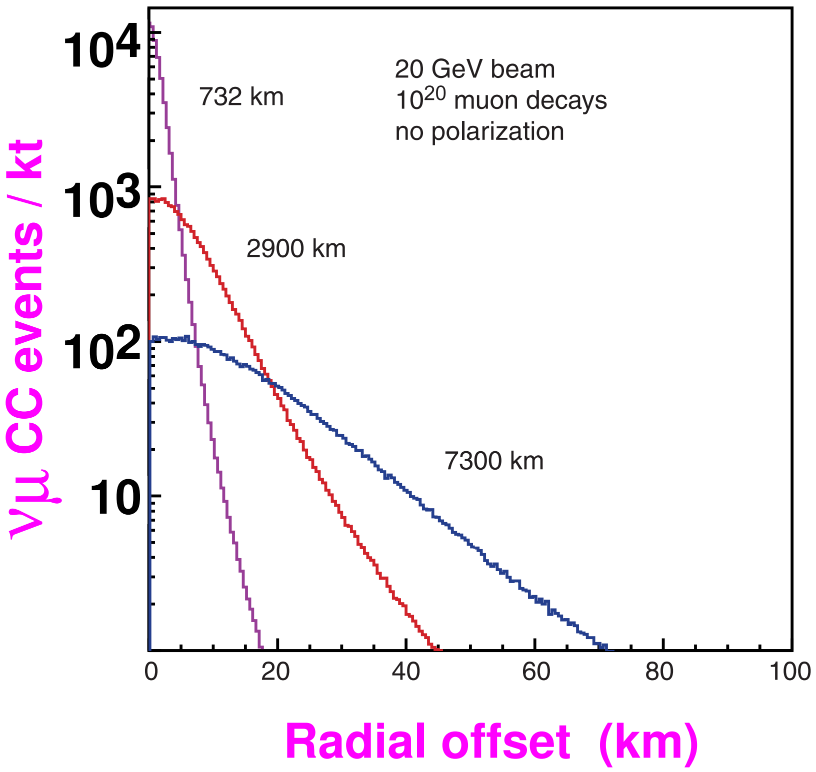
$$\mu^+ \to e^+ \nu_e \bar{\nu}_\mu \quad \Rightarrow \quad 50\% \ \nu_e \ (\bar{\nu}_\mu)$$

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

2. Precisely known neutrino fluxes & kinematics

3. "Narrow–Band" Beam, large event rates





Non Oscillaion Physics

Want neutrino factory energy to be 40–50 GeV (or greater) to be above thresholds (e.g. charm production).

Rates are fantastic. At 50 GeV the rate is ~ 1M events / kg / 10^{20} muons injected into storage ring –> factor of 1000 increase in statistics cf present experiments.

High rates –> possibility of new type of neutrino detectors: polarized targets, silicon pixel targets, good particle ID –> experiments that would not otherwise be possible.

Structure function measurements
Spin structure functions
Precision electroweak measurements
Charm production
Exotic processes
......

Exper–imental program

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) :

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

Getting at the physics – 1

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

m_3^2

Atmos. neutrino deficit
–> ~ 3 x 10^{-3} eV^2/c^4

m_2^2
m_1^2

Solar neutrino deficit
–> $\lesssim O(10^{-5})$ eV^2/c^4

- 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

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

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

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

- Want to measure (or put limits on) ALL of the appearance and ALL of the disappearance modes –> check consistency of the framework & measure δm_{12}^2, δm_{23}^2, δm_{13}^2, δ, θ_{12}, θ_{23}, θ_{13} .

- For this we need 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 !

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

Getting at the physics – 3

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

Two Possible Scenarios

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

$$\boxed{\nu_e \;{-}{>}\; \nu_\mu}$$

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

$$\mu^+ \;{-}{>}\; \nu_e + \bar{\nu}_\mu + e^+$$

$$\nu_e \rightarrow \nu_\mu \xrightarrow[CC]{} \mu^-$$

Wrong–sign muons and long baselines

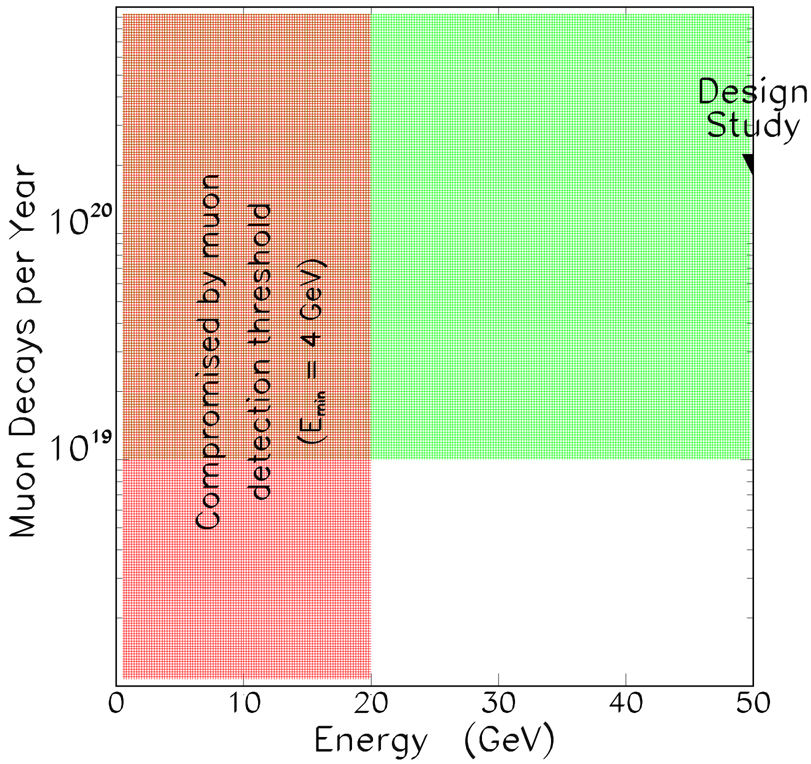
If MiniBooNE does confirm the LSND oscillation result, the world–attention grabbing channel is:

$$\boxed{\nu_e \;{-}{>}\; \nu_\tau}$$

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.

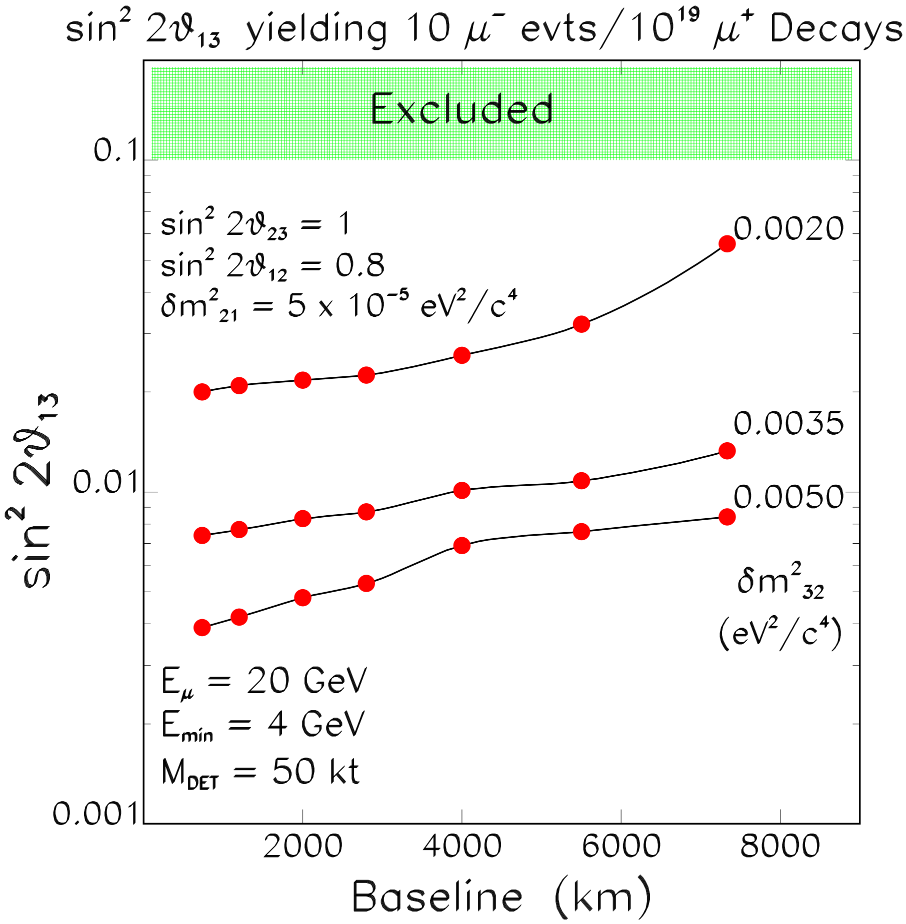


2. Detector mass: Sensitivity ~ detector mass x neutrino flux .... cost optimization needed between detector mass & beam intensity. Nu–factory is O(an order of magnitude) more expen–sive than, for example, the MINOS beam. Guess that the cost optimization –> detectors x10 more massive than MINOS –> 50 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: hep–ph/0003184

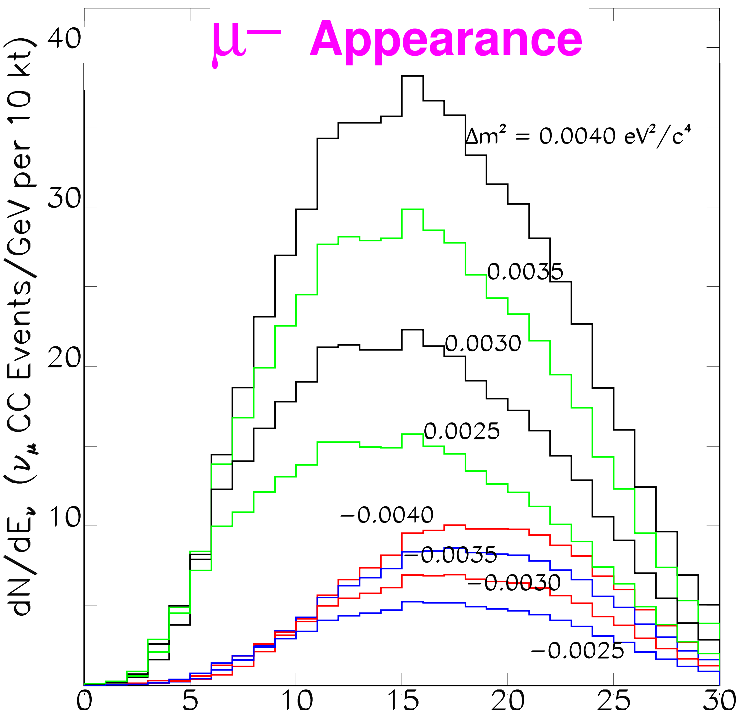


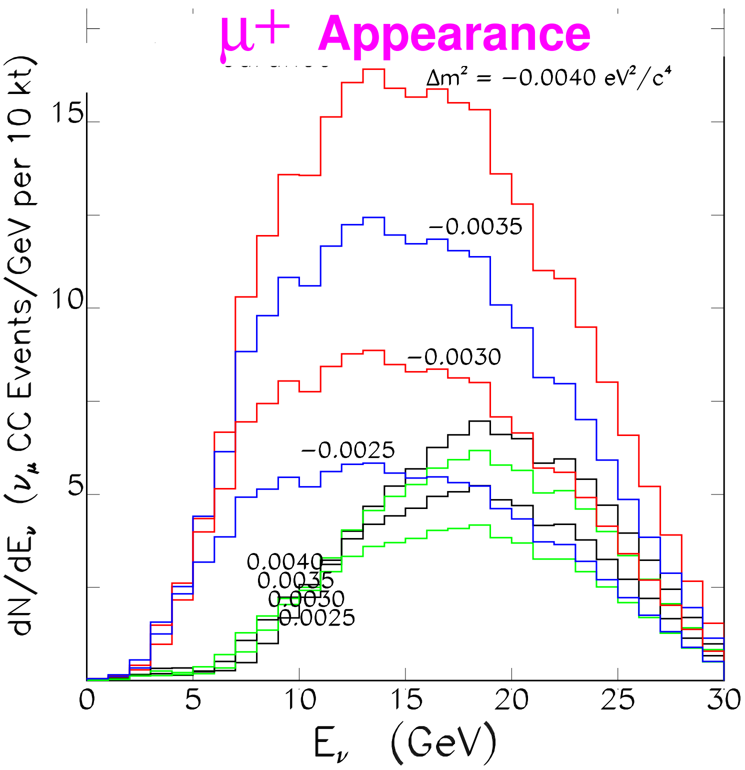
Conclude that 1019 decays/yr would enable the "entry level" goal to be met provided $\sin^2 2\theta_{13} > 0.01$

How can we 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

Δm^2_{21} = 5 x 10^{-5} eV^2/c^4

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

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

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

μ^- Appearance

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

μ^+ Appearance

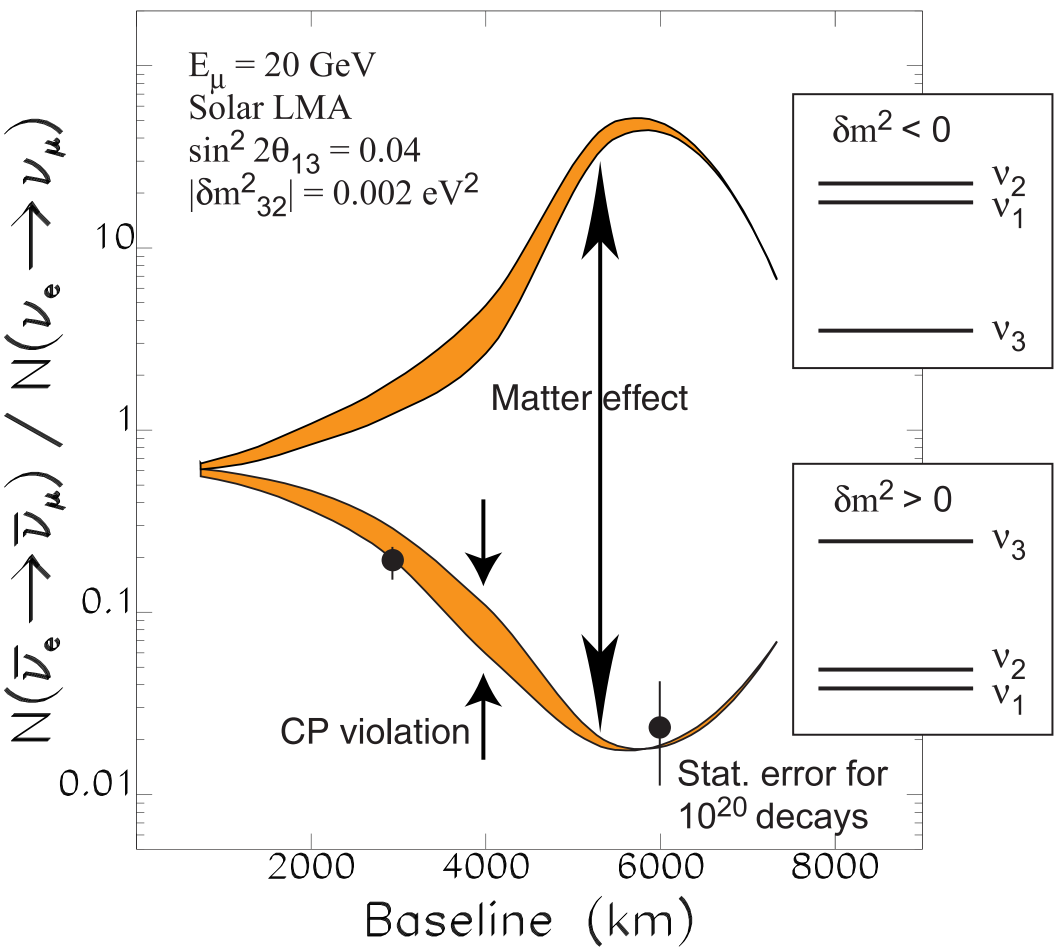
+tve Δm^2_{32} gives smaller rate & harder spectrum than –tve Δm^2_{32}

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

With O(10^{19}) decays/year can determine the sign of δm^2 provided $\sin^2 2\theta_{13} > 0.01$, and with O($10^{20}$) decays/year can begin to be sensitive to CP violation provided solar solution = LMA MSW

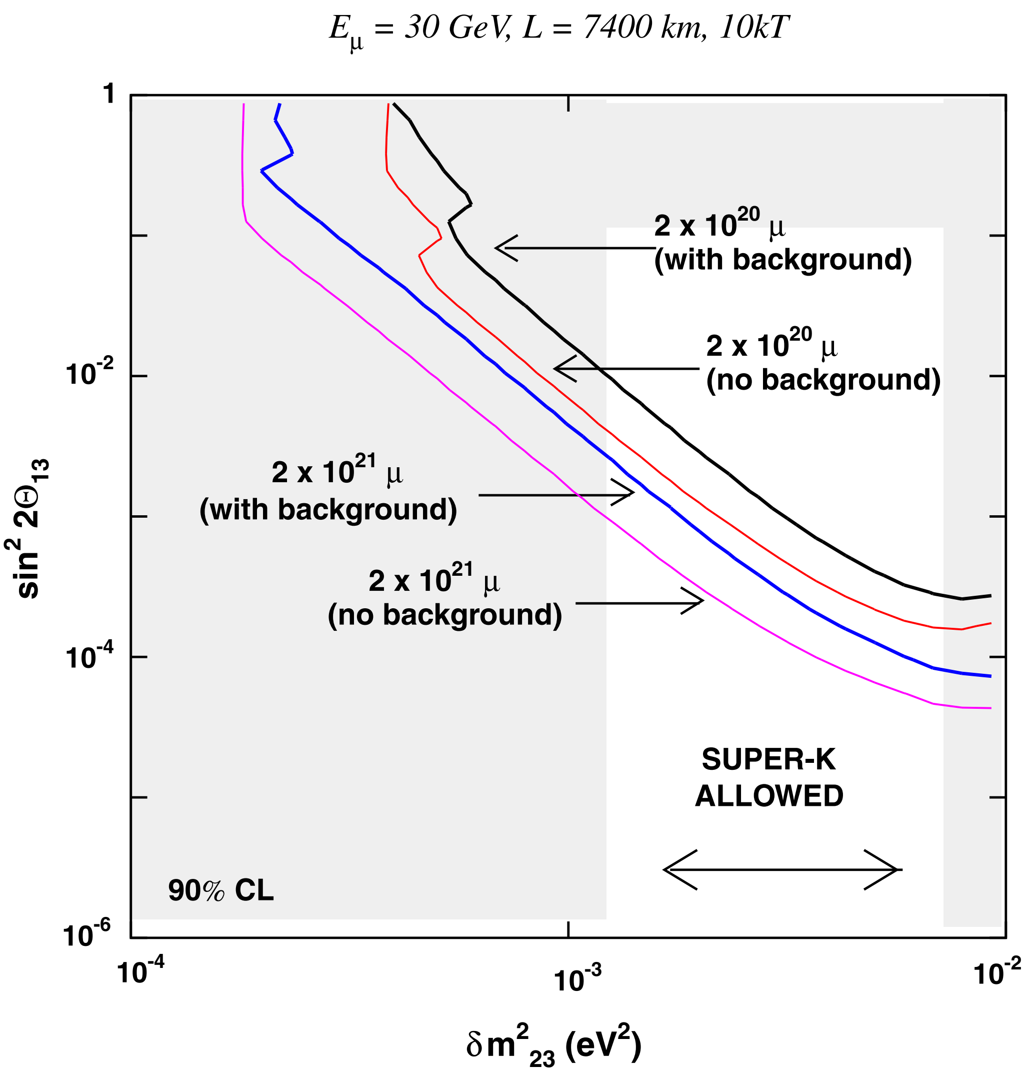
V. Barger, S. Geer, R. Raja, K. Whisnant: hep–ph/0003184

Wrong-Sign Muon Measurements



What if $\sin^2 2\theta_{13}$ very small ?

A. Bueno, M. Campanelli, A. Rubbia: hep–ph/0005007



With 2 x 10^{21} kt–decays (for example 2 x 10^{19} decays/year, 50kt detector, 2 years running) and δm^2 in center of SuperK range would be sensitive to $\sin^2 2\theta_{13} > 0.001$ –> cover SMA MSW region.

Entry–level Neutrino Factory

$O(10^{19})$ useful decays / year at 20 GeV

–> sign of δm^2 if $\sin^2 2\theta_{13} > 0.01$

–> Limit on $\sin^2 2\theta_{13}$ –> > 0.001 if $\nu_e \to \nu_\mu$ not observed

... but need to better understand capabilities of an upgraded conventional super–beam (en–route to a high–performance nu–factory).

High–performance Neutrino Factory

$O(10^{20})$ useful decays / year at 50 GeV

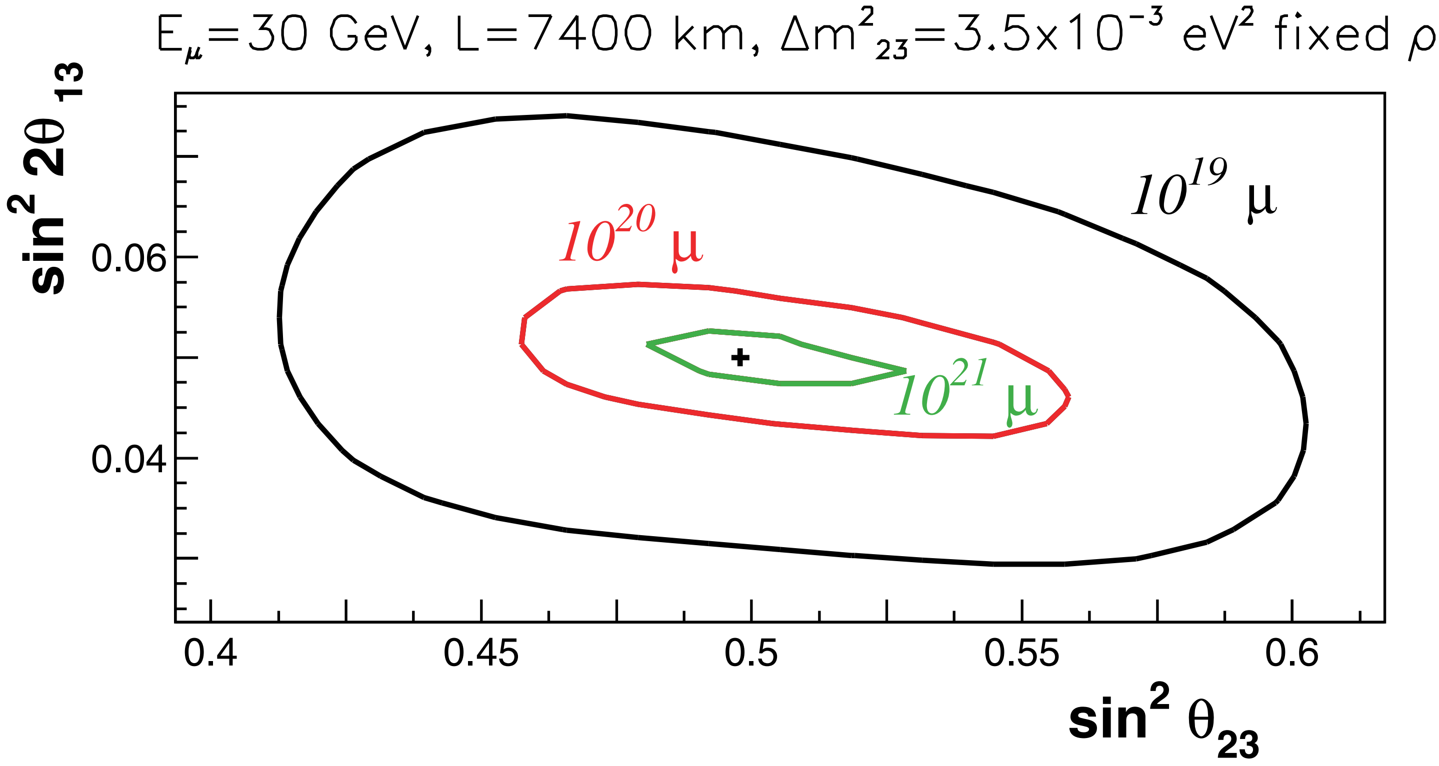
–> CP violation in lepton sector if $\sin^2 2\theta_{13} > 0.01$ and LMA solution.

–> Limit on $\sin^2 2\theta_{13}$ –> > 0.0001 if $\nu_e \to \nu_\mu$ not observed

–> Precise parameter measurements

Measurement capability steadily improves with increasing beam intensity :

A. Bueno, M. Campanelli, A. Rubbia: hep–ph/0005007

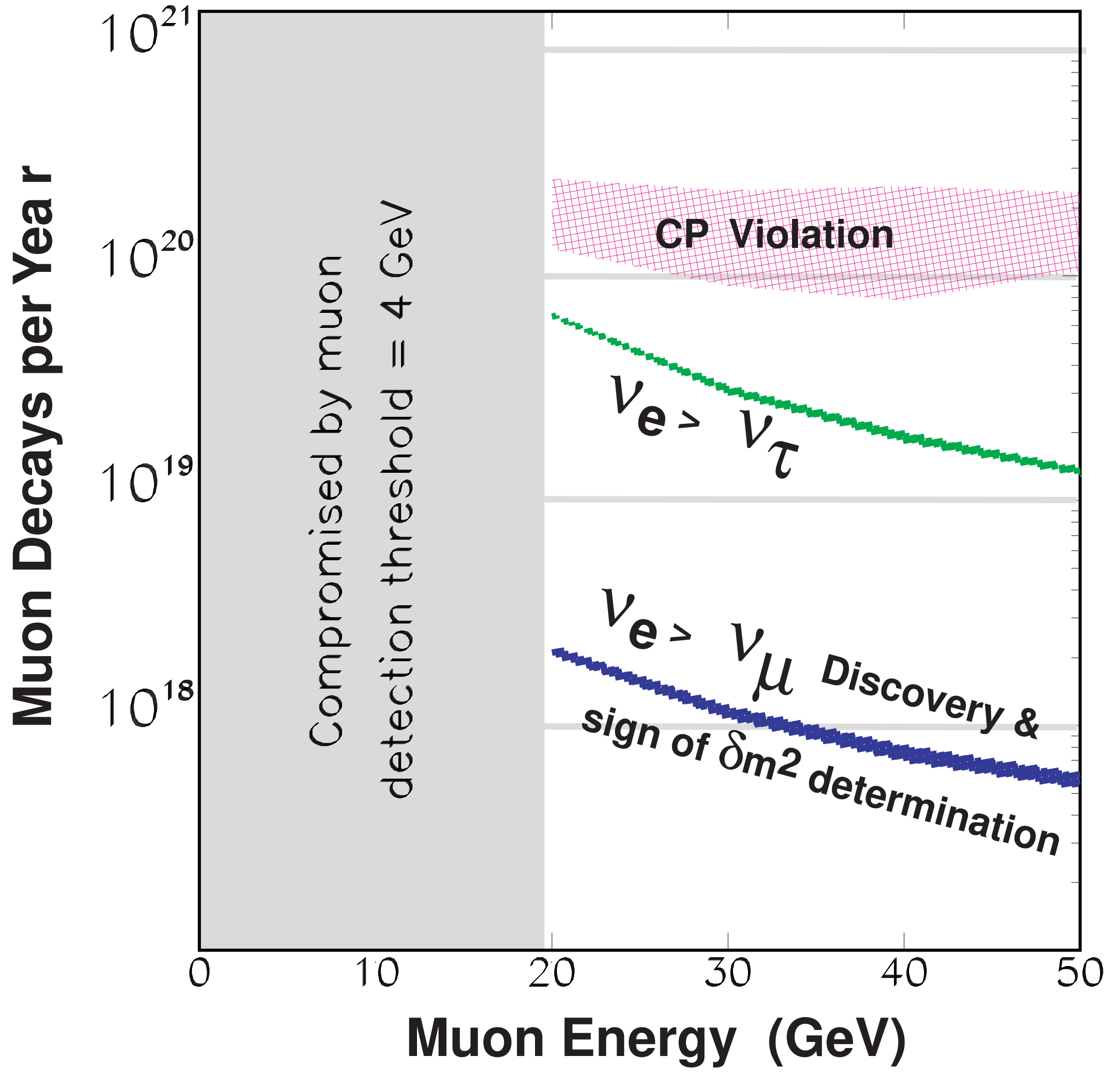


High performance neutrino factory –> few % measurements of the oscillation parameters.

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

V. Barger, S. Geer, R. Raja, K. Whisnant: hep–ph/0003184

L = 2800 km, $\sin^2 2\theta_{13}=0.04$



NOTE: Curves ~ scale with $\sin^2 2\theta_{13}$ ...
so if $\sin^2 2\theta_{13}$ = 0.01 slide curves up by x 4.

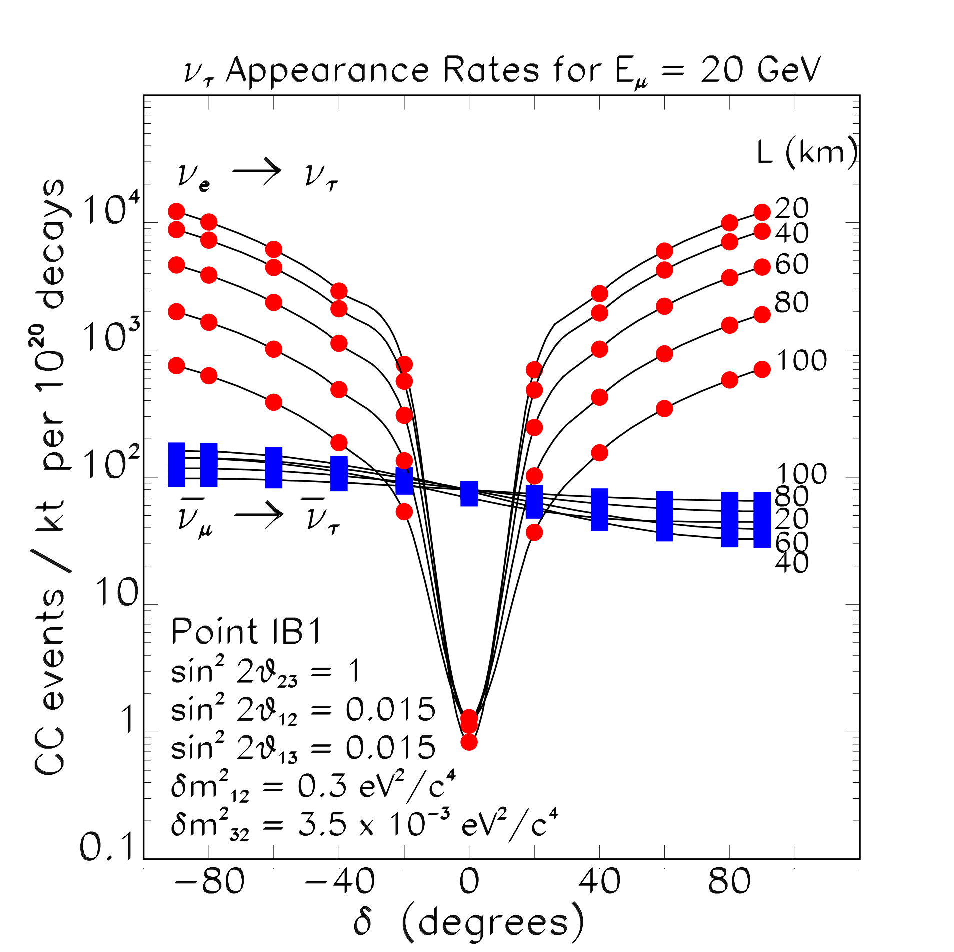
MiniBooNE does not confirm LSND

What if MiniBooNE confirms LSND ?

$\nu_e \rightarrow \nu_\tau$ **is likely to be the world attention grabbing channel**

Example: Assume mass splittings correspond to atmospheric deficit and LSND signal:

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



2×10^{19} decays/yr, 3 years run with 5 kt detector with 30% tau efficiency.

Rates sensitive to the phase δ !

Summary

Entry–level Neutrino Factory

$O(10^{19})$ useful decays / year at 20 GeV

–> sign of δm^2 if $\sin^2 2\theta_{13} > 0.01$

–> Limit on $\sin^2 2\theta_{13}$ –> < 0.001 if $\nu_e \to \nu_\mu$ not observed

... but need to better understand capabilities of an upgraded conventional super–beam (en–route to a high–performance nu–factory).

High–performance Neutrino Factory

$O(10^{20})$ useful decays / year at 50 GeV

–> CP violation in lepton sector if $\sin^2 2\theta_{13} > 0.01$ and LMA solution.

–> Limit on $\sin^2 2\theta_{13}$ –> < 0.0001 if $\nu_e \to \nu_\mu$ not observed

–> Precise parameter measurements

–> Tremendous for non–oscillation physics

Baseline needs to be ~3000km or greater

If MiniBooNE confirms LSND then $\nu_e \to \nu_\tau$ searches will be important ... $O(10^{19})$ decays per year interesting in medium baseline expt.