Neutrino Factories:
a probe of oscillation physics

Kara Hoffman
The University of Chicago
Enrico Fermi Institute
On behalf of the Muon Collaboration
Conventional Beams

Wouldn’t it be great if:

• we had a high intensity, collimated neutrino beam of known flavor composition?
• we had a clean source of electron neutrinos?
• a reaction could be compared to its charge conjugate?

Muon Beams

measure $\nu_\mu \rightarrow \nu_e$

small $\nu_\mu$ contamination gives same final state signatures

measure (primarily) $\nu_e \rightarrow \nu_\mu$

unambiguous if you can identify both lepton charge and flavor
For $|\Delta m^2_{32}| \gg |\Delta m^2_{12}|$ and neglecting CP:

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

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

\[
P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\tau) = \cos^4\theta_{13} \sin^2\theta_{23} \sin^2(1.267\Delta m^2_{32} L/E)
\]

$\sin^22\theta_{23}$ will be known to +/- 10%?
Intense cold muon source

- muon magnetic moment
- muonium-antimuonium
- muon spin rotations
- rare decays

Neutrino Factory

\[ \sin \theta_{13} < 10^{-4} \]

sign of \( m^{2}_{32} \) for \( \sin \theta_{13} < 10^{-4} \)

Future Muon Collider

Bowtie offers opportunity to send beams to different sites
Muons Test Area at Fermilab under construction.

Muon Test Area is being built to test components...

Paper designs exist, and real experiments are being built to test new technologies required (i.e. ionization cooling).

\[ \frac{d\Phi_{\mu}}{dz} = \frac{d\Phi_N}{d^2E} \frac{dE}{dz} + \Phi_x (13.6\text{MeV/c})^2 \frac{2dE}{2dE} \text{Em} \text{L}_R \]

Muon Test Area: Science or science fiction?
Conceptual advances since Study II

provides same transverse cooling as sFOFO linear channel considered in neutrino factory Study II

Both could offer better performance and/or significant cost savings

Paschen’s Law the breakdown voltage for a discharge between electrodes in gases is a function of the product of pressure and distance.

Ring Coolers

Gas filled rf cavities

Suppress breakdown in high gradient cavities while cooling beam

6.68 m
d.619 m
45

Bending magnet
45 deg, R = 52 cm
Solenoid coils
D 1.85 m

Direct. of magnetic field

LH2 main absorber

LiH wedge absorber

205 MHz cavity

1.744 m

H2 gas @77K

805 MHz

Muon Collaboration results (2003)

Felici (1948)
Beam energy and intensity needed for physics studies

For 50 kiloton detector

\[ N_{\text{events}} \mu \frac{E^3}{L^2} N M (\text{detector in kilotons}) \]

Important if LSND is confirmed

\[ \nu_e \rightarrow \nu_\tau \]

\[ \nu_e \rightarrow \nu_\mu \]
Choosing a baseline

Mass Hierarchy

Normal?  Inverted?

$\sin^2 2\theta^m = \frac{\sin^2 2\theta}{2\sqrt{2} G_F N_e E_\nu m^2 \cos 2\theta + \sin^2 2\theta}$

enhances $m^2 > 0$

suppresses $m^2 < 0$

Need a long baseline and both $+$ and $-$ beams

Matter Effect

has different effects on electron neutrinos and antineutrinos
Possible if:

\[ \mathbf{m}_{12}^2, s_{12} \text{ large enough (LMA)} \]
\[ \theta_{13} \text{ not too small} \]
As we have seen, oscillation probabilities depend on several parameters simultaneously (i.e. $d$, $q_{13}$). Multiple independent measurements (different L, E, channels) needed to resolve resulting degenerate solutions.

Degeneracies we worry about:

- $\mathbf{d}$, $\mathbf{q}_{13}$
- sign of $\mathbf{m}_{13}$
- $(\mathbf{q}_{23}, \mathbf{p-q}_{23})$ – goes away for current best fit value $\mathbf{q}_{23}=\mathbf{p}/2$

High statistics, low background

Difficult to detect

Emulsion detector needed

Also needed to place limits on sterile neutrinos
Neutrino Factories complement present and near term experiments

- Measurements of oscillation parameters from other experiments will provide valuable input in choice of baseline
- Accelerator (i.e. proton driver) and detector technologies developed will also be invaluable
- Combinations of experiments may be helpful in resolving degeneracies

Neutrino Factories provide clean, high intensity beams which may be necessary in probing some areas of parameter space

- $\Delta CP$ if $\sin^2 \theta_{13}$ is small
- Measurement of small $\sin^2 \theta_{13}$
- Combination of $m^+$ and $m^-$ beams definitively measures mass hierarchy

Staged program provides unique tools for both oscillation and non-oscillation physics

- Precision measurement of neutrino oscillation parameters, cold muon physics, Higgs pole physics

R&D and conceptual advances have the potential to decrease the cost and increase the performance of the design

- "Engineering" experiments are going forward
Extra Plots

Sensitivity to $\text{sgn} (\Delta m^2_{31})$

- ~2005: No sensitivity
  - NuMI@890
  - NuMI@890
  - JHF–SK
- ~2010: ???
  - JHF–HK
  - other SB
- ~?
  - NuFact
  - magic baseline

$E_\mu = 30 \text{ GeV}, L = 2800 \text{ km}, 2 \times 10^{30} \mu^- \text{ Decays}$