Neutrino factories
from muon storage rings

H. Schellman
Northwestern University/FNAL
Several studies of neutrino factory experiments

- **FNAL++ study**
  - 20-50 GeV
  - $10^{19}$-$10^{20}$ muon decays
  - 732km, 3000 km, 7000km

- **CERN/Espana ...**
  - 50 GeV
  - $10^{20}$-$10^{21}$ muon decays
  - 732km, 3500 km, 7000 km

- **Lots of new work shown at NUFACT00**
  - Bueno et al. hep-ph 0005007
  - Cervera et al. hep-ph 0002108
  - Albright et al. FNAL-FN 692
  - Barger et al., hep-ph 9911524 + later
What do we know about electron neutrino oscillations?

- Solar neutrinos give low mass region
- Reactor experiments explore high $\Delta m^2$ region

$\Delta m^2$ (eV$^2$)

$\sin^2 2\theta$

$\nu_e \rightarrow ?$
What we know about muon neutrino oscillations

- From SuperK, Soudan, Macro … know $\sin^2 2\theta_{23} \sim 1$.
- K2K, CGS, MINOS will tell us more.
- Muon neutrino expts require high energy, hence long baselines to be sensitive to low $\Delta m^2$.
3-flavor mixing

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix}
= 
\begin{pmatrix}
U_{e1} & U_{e2} & U_{e2} \\
U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\
U_{\tau 1} & U_{\tau 2} & U_{\tau 3}
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

\[
U = \begin{pmatrix}
c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta} \\
-c_{23}s_{12} - s_{13}s_{23}c_{12}e^{i\delta} & c_{23}s_{12} - s_{13}s_{23}s_{12}e^{i\delta} & c_{13}s_{23} \\
s_{23}s_{12} - s_{13}c_{23}c_{12}e^{i\delta} & -s_{23}s_{12} - s_{13}c_{23}s_{12}e^{i\delta} & c_{13}c_{23}
\end{pmatrix}
\]

3 angles \(\theta_{12}, \theta_{13}\) and \(\theta_{23}\)
and complex phase \(\delta\)

\[
P(\nu_\alpha \rightarrow \nu_\beta) = \left| \langle \nu_\beta | e^{-iH_0 L} | \nu_\alpha \rangle \right|^2 = \sum_{i,j} U_{\alpha i} U_{\beta i}^* U_{\alpha j}^* U_{\beta j} e^{-i\delta m_{ij}^2 L/2E}
\]

3 masses -> only 2 mass differences
So far we know:

- \(\theta_{23}\) is large (atmospheric)
- \(\Delta m_{23}^2\) is > 10^{-3} ev^2 (atmospheric)
- \(\theta_{13}\) is small (reactor)
\[ P(\nu_\mu \to \nu_\mu) \simeq 1 - 4|U_{\mu 3}|^2 (1 - |U_{\mu 3}|^2) \sin^2 \left( \frac{\delta m_{\text{atm}}^2 L}{4E} \right) \]
\[ = 1 - 4 \sin^2(\theta_{23}) \cos^2(\theta_{13}) (1 - \sin^2(\theta_{23}) \cos^2(\theta_{13})) \sin^2 \left( \frac{\delta m_{\text{atm}}^2 L}{4E} \right) , \]

\[ P(\nu_\mu \to \nu_e) \simeq 4|U_{e 3}|^2 |U_{\mu 3}|^2 \sin^2 \left( \frac{\delta m_{\text{atm}}^2 L}{4E} \right) \]
\[ = \sin^2(2\theta_{13}) \sin^2(\theta_{23}) \sin^2 \left( \frac{\delta m_{\text{atm}}^2 L}{4E} \right) \]

\[ P(\nu_\mu \to \nu_\tau) \simeq 4|U_{\mu 3}|^2 |U_{\tau 3}|^2 \sin^2 \left( \frac{\delta m_{\text{atm}}^2 L}{4E} \right) \]
\[ = \sin^2(2\theta_{23}) \cos^4(\theta_{13}) \sin^2 \left( \frac{\delta m_{\text{atm}}^2 L}{4E} \right) \]

\[ P(\nu_e \to \nu_\mu) \simeq 4|U_{e 3}|^2 |U_{\mu 3}|^2 \sin^2 \left( \frac{\delta m_{\text{atm}}^2 L}{4E} \right) \]
\[ = \sin^2(2\theta_{13}) \sin^2(\theta_{23}) \sin^2 \left( \frac{\delta m_{\text{atm}}^2 L}{4E} \right) , \]

\[ P(\nu_e \to \nu_\tau) \simeq 4|U_{\tau 3}|^2 |U_{e 3}|^2 \sin^2 \left( \frac{\delta m_{\text{atm}}^2 L}{4E} \right) \]
\[ = \sin^2(2\theta_{23}) \cos^2(\theta_{23}) \sin^2 \left( \frac{\delta m_{\text{atm}}^2 L}{4E} \right) \]
What we are looking for in 10-15 years?

Assume $\Delta m^2_{23}$ and $\theta_{23}$ are well measured the next things to do are:

- Measure $\sin^2\theta_{13}$ to $\sim 0.001$
- See $\nu_e \leftrightarrow \nu_\tau$
- Measure sign of $\Delta M^2$
- Measure CP violation?

- All of these need a measurement of $\nu_e \leftrightarrow \nu_X$

- A complete check of 3-flavor requires

  $\nu_e \leftrightarrow \nu_e, \nu_\mu \leftrightarrow \nu_\mu$ and anti-particles
  $\nu_e \leftrightarrow \nu_\tau, \nu_\mu \leftrightarrow \nu_\tau$
### 3 Flavor Scenarios

<table>
<thead>
<tr>
<th>Parameter</th>
<th>IA1</th>
<th>IA2</th>
<th>IA3</th>
<th>1B1</th>
<th>1C1</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta m^2_{21}$ (eV$^2$)</td>
<td>$3.5 \times 10^{-3}$</td>
<td>$3.5 \times 10^{-3}$</td>
<td>$3.5 \times 10^{-3}$</td>
<td>$3.5 \times 10^{-3}$</td>
<td>$3.5 \times 10^{-3}$</td>
</tr>
<tr>
<td>$\delta m^2_{21}$ (eV$^2$)</td>
<td>$5 \times 10^{-5}$</td>
<td>$1 \times 10^{-5}$</td>
<td>$6 \times 10^{-5}$</td>
<td>$1 \times 10^{-5}$</td>
<td>$1 \times 10^{-5}$</td>
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<tr>
<td>$\sin^2 \theta_{13}$</td>
<td>0.1</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>$\sin^2 \theta_{13}$</td>
<td>0.04</td>
<td>0.04</td>
<td>0.04</td>
<td>0.04</td>
<td>0.04</td>
</tr>
<tr>
<td>$\sin^2 \theta_{23}$</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>$\sin^2 \theta_{23}$</td>
<td>0.04</td>
<td>0.04</td>
<td>0.04</td>
<td>0.04</td>
<td>0.04</td>
</tr>
<tr>
<td>$\sin^2 \theta_{12}$</td>
<td>0,!π/2</td>
<td>0,!π/2</td>
<td>0,!π/2</td>
<td>0,!π/2</td>
<td>0,!π/2</td>
</tr>
<tr>
<td>$\sin^2 \theta_{12}$</td>
<td>0,!π/2</td>
<td>0,!π/2</td>
<td>0,!π/2</td>
<td>0,!π/2</td>
<td>0,!π/2</td>
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<tr>
<td>$\delta$</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
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<tr>
<td>$\sin^2 \theta_{CP}$</td>
<td>0.04</td>
<td>0.04</td>
<td>0.04</td>
<td>0.04</td>
<td>0.04</td>
</tr>
<tr>
<td>$\sin^2 \theta_{CP}$</td>
<td>0.98</td>
<td>0.98</td>
<td>0.98</td>
<td>0.98</td>
<td>0.98</td>
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<tr>
<td>$\sin^2 \theta_{\theta_{S}}$</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>$\sin^2 \theta_{\theta_{L}}$</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
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<tr>
<td>$J$</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
</tr>
</tbody>
</table>
Why not use conventional beam

- Conventional beam is great for measuring $\nu_\mu$ related parameters to ~1%.
- Limitations are electron detection in hadron showers limits $\nu_\mu \rightarrow \nu_e$
- To go beyond 1% on $\nu_\mu \leftrightarrow \nu_e$ or get mass effects and CP violation, need:
  - long baseline,
  - higher energy,
  - way to see $\nu_\mu \leftrightarrow \nu_e$ transitions with better accuracy.
The Neutrino Source

Muon Storage Ring as a Neutrino Source

50 GeV Muons in many bunches

Medium baseline experiment eg Fermi -> SLAC/LBNL 2900 km

<table>
<thead>
<tr>
<th>Parameters for the Muon Storage Ring</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
</tr>
<tr>
<td>decay ratio</td>
</tr>
<tr>
<td>Designed for inv. Emittance</td>
</tr>
<tr>
<td>Cooling designed for inv. Emitt.</td>
</tr>
<tr>
<td>$\beta$ in straight</td>
</tr>
<tr>
<td>$N_\mu$/pulse</td>
</tr>
<tr>
<td>typical decay angle of $\mu = 1/\gamma$</td>
</tr>
<tr>
<td>Beam angle ($\sqrt{\varepsilon/\beta_0}$) = ($\sqrt{\varepsilon \gamma}$)</td>
</tr>
<tr>
<td>Lifetime $c*\gamma*\tau$</td>
</tr>
</tbody>
</table>

$\gamma = (1-\alpha^2)/\beta$
Properties of neutrino beams from muon decay

\[ \mu \rightarrow P=1 \]

\[ \nu_\mu \rightarrow v_e \]

\[ cm \text{ frame} \]

\[
\frac{dN(\nu_\mu)}{dz d\cos \theta_{CM}} = 2z^2[(3 - 2z) \mp P(1 - 2z)\cos \theta] \\
\frac{dN(\nu_e)}{dz d\cos \theta_{CM}} = 6z^2[(1 - z) \mp P(1 - z)\cos \theta]
\]

\[ z = \frac{E_\nu}{E_{max}} \quad \text{where} \quad E_{max} = m_\mu/2 \]

Single decay mode and well defined kinematics
Neutrino interaction rates as a function of scaled neutrino energy

Beam is a mixture of $\nu_\mu$ and anti-$\nu_e$ or $\nu_e$ and anti-$\nu_\mu$. Peaked towards high energies, polarization is hard to get but can be used to remove backgrounds from the mixture.
Why bother with muon decay?

• **Goal is maximum neutrino/proton**
  - Decay pions/kaons at low energy
  - More decay in decay volume
  (~3% at FNAL high energy ν beam)
  - Then accelerate
  - 40% of muons decay in the right direction

• **Very well understood source**
  - Only one decay process
  - Parent particles ~ monochromatic
  - Around long enough to monitor

See $\nu_e \rightarrow \nu_\mu$ in the $\nu_e \rightarrow \nu_\mu \rightarrow \mu^- + X$ channel ‘Wrong sign muons’

$\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu \rightarrow \mu^+ + X$ is the conventional muon source
Neutrino Event rates vs angle

θ typical is $\sim 1/\gamma$

28km at 2800km

Rate per unit area

Spread of beam scales as $1/E^2$
Event rate/neutrino scales as $E$
For same $L$ event rate/unit area scales as $E^3$

Spread of beam scales as $L^2$
For fixed $E/L$, event rate/unit area scales as $E$
### Event rates for a 10 kton detector

<table>
<thead>
<tr>
<th></th>
<th>$\mu^{-}$ 10$^{20}$ decays</th>
<th>$\mu^{+}$ 10$^{20}$ decays</th>
<th>$E_\mu=30$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rates</td>
<td>$\nu_\mu$ CC</td>
<td>$\bar{\nu}_\mu$ CC</td>
<td>$\bar{\nu}_\mu$ NC</td>
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<tr>
<td></td>
<td>226000</td>
<td>101000</td>
<td>35300</td>
</tr>
<tr>
<td>$\nu_\mu$ NC</td>
<td>67300</td>
<td>6380</td>
<td>2240</td>
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<td></td>
<td>87100</td>
<td>197000</td>
<td>19700</td>
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<tr>
<td>$\bar{\nu}_e$ CC</td>
<td>30200</td>
<td>1990</td>
<td>300</td>
</tr>
<tr>
<td></td>
<td></td>
<td>57900</td>
<td></td>
</tr>
</tbody>
</table>

**No oscillations**

**No polarization**

**No beam divergence**
Experiments can be described by their E/L coverage

- \[ P(\nu_\alpha \rightarrow \nu_\beta) \sim \sin^22\theta \sin^2[1.27\Delta m^2 L/E] \]
- \( m \) in eV, \( L \) in km, \( E \) in GeV

If \( E/L \ll \Delta m^2 \), \( P(\nu_\alpha \rightarrow \nu_\beta) \sim \frac{1}{2} \sin^22\theta \)

If \( E/L \gg \Delta m^2 \), \( P(\nu_\alpha \rightarrow \nu_\beta) \sim 0 \)

If \( E/L \sim \Delta m^2 \), can measure both \( \Delta m^2 \) and \( \sin^22\theta \)
Numbers of muon neutrino interactions for fixed number of muon decays
$\Delta m^2 = 0.0035 \text{ eV}^2$

**Oscillation Probability**

Solid is $\sin^2 \theta = 0$, Dashed is $\sin^2 \theta = 1$ (disappearance)

2800 km, 50 GeV
7000 km, 50 GeV
2800 km, 20 GeV

$\Delta m^2 = 0.0035 \text{ eV}^2$
$0.0050 \text{ eV}^2$
$0.0020 \text{ eV}^2$
Numbers of electron neutrino interactions for fixed number of muon decays

$\Delta m^2 = 0.0035 \text{ eV}^2$

- Solid is $\sin^2 \theta = 0$
- Dashed is $\sin^2 \theta = 1$ (appearance)

- $0.0035 \text{ eV}^2$
- $0.0050 \text{ eV}^2$
- $0.0020 \text{ eV}^2$

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

- 7000 km, 50 GeV
- 2800 km, 50 GeV
- 2800 km, 20 GeV

$E/L$, GeV/km

flux*energy

6/14/00
Detectors

`Protons are cheaper than muons`

- **Tau detection**
  - Emulsion/msgc ~ 1-20 kTons
  - Tau id, electron id
- **Liquid argon drift**
  - 10-20 kTons
  - Electron id!
- **Magnetized Iron Scintillator**
  - 20-100 kTons
  - Good muon id!
- **Water Cerenkov with magnet tail**
  - 50-500 kTons
  - Electron id, limited muon charge
Liquid Argon with drift readout

$\nu_e$ event
Steel-Scintillator
MINOS/MONOLITH/anon.

50 kT version of MINOS
10xSuperK?

Water detector followed by analyzing magnet

Dave Kasper, Kevin McFarland, Debbie Harris
$10^{20}$ muon decays

$E_\mu = 30 \text{ GeV}, L = 7400 \text{ km}, 10^{20} \mu^-$ decays

- Right sign muons
  - Dip due to oscillation
- Tau's contribute
  - Signal?
  - Background?

$\nu_e N \rightarrow e^+ X$

Bueno et al.

6/14/00
Disappearance Experiment $\nu_\mu \rightarrow \nu_\tau$

$E_\mu = 30 \text{ GeV}, \ 2 \times 10^{20} \mu \text{ decays}$

$E_\text{visible}$ (GeV)

$L=732 \text{ km}$

$L=2900 \text{ km}$

$L=7400 \text{ km}$

- No oscillations
- $\Delta m^2=3.5 \times 10^{-3} \text{ eV}^2$
- $\Delta m^2=5 \times 10^{-3} \text{ eV}^2$
- $\Delta m^2=7 \times 10^{-3} \text{ eV}^2$

Mario Campanelli, ETH Zurich
What determines the machine energy?

• We’re interested in $\nu_e \rightarrow \nu_\mu$

• Need to tag wrong sign muons with very low backgrounds

• There are also anti-$\nu_\mu$ in the beam

• Wrong sign muons from
  - Hadron decay
  - Charm decay
  - Non-interacting hadrons
  - Charge confusion

• How do you tell a 2 GeV pion from a 2 GeV muon at the 0.01% level?
Backgrounds to $\bar{\nu}_e \rightarrow \bar{\nu}_\mu \rightarrow \mu^+$

Pions which do not interact!
Wrong sign muon signal
10 kt Iron-scintillator detector
20 GeV muon decay
$10^{20}$ decays

Bernstein, Harris, McFarland, Spetzouris
$E_\mu = 30 \text{ GeV}, L = 7400 \text{ km, } 10^{21} \mu^+ \text{ decays}$

Wrong Sign $\mu$

- $\nu_\mu + \nu_\tau \text{ CC } + \text{ background}$
- $\nu_\mu \text{ CC}$
- $\nu_\tau \text{ CC}$
- Background

$\Delta m^2_{23} = 3.5 \times 10^{-3} \text{ eV}^2$

$\sin^2 \theta_{23} = 0.5$

$\sin^2 2\theta_{13} = 0.05$
Limits on $\sin^2 \theta_{13}$ for a 10kt detector 7400 km away.

Bueno et al.
$\nu_e > \nu_\mu$ Appearance

FNAL>SLAC/LBNL
(L = 2800 km) $E_\mu = 30$ GeV
$2 \times 10^{20}$ Decays

ThreeFlavor Mixing
$\Delta m^2_{21} = 5 \times 10^5$ eV$^2$/c$^4$
$\sin^2 2\theta_{23} = 1$  $\delta = 0$
$\sin^2 2\theta_{12} = 0.8$
$\sin^2 2\theta_{31} = 0.04$

Sign of $\Delta m^2$ can be determined thanks to matter effects

Barger Geer Raja Whisnant
FermilabPub 99341
CP violation?

$E_{\mu} = 20 \text{ GeV}$
$E_{\text{min}} = 4 \text{ GeV}$

Relative wrong-sign muon rates $\mu^+$ cf $\mu^-$

$\delta m^2_{21} = 5 \times 10^{-5} \text{ eV}^2/c^4$
$\sin^2 2\theta_{23} = 1$
$\sin^2 2\theta_{12} = 0.8$
$\sin^2 2\theta_{13} = 0.04$

Density effect

CP violation

$\delta = \pi/2$
$\delta = 0$

$\delta m^2_{32} \text{ (eV}^2/c^4\text{)}$

$-0.0050$
$-0.0020$
$+0.0020$
$+0.0050$
What optimal CP violation looks like

Assume Solar LMA solution, large $\theta_{12}, \theta_{13}$

Wrong-sign muons

$10^{21}$ $\mu$, 3500 km
Fit to $\delta$, all other parameters free.

- $P = 0$ : $\delta = 1.57 \pm 0.20$
- $P = \pm 40\%$ : $\delta = 1.57 \pm 0.15$
- $P = \pm 100\%$ : $\delta = 1.57 \pm 0.10$

Blondel NUFACT00 - CP/polarization
Kinematic cuts can increase sensitivity at high event rates.

Cervera et al.

\[ Q_t = P_\mu \sin \theta \]
Near Experiments

• Place detectors 50 m from end of straight section
• Get 1000 times current statistics!
  - Hydrogen targets
  - Polarized targets
  - Charm
  - Beauty? (not at 50 GeV)
  - Rare phenomena
At 50 GeV, 7.9M events/gr/cm²/year
But only 22% are within 20 cm radius
(82% pass loose kinematic cuts)

1000 times current experiments!
Detector like NOMAD

10 kg targets in front of tracking/calorimetry
140 Si wafer target
17 M CC events
-> .5-1M charm

1 ton target
120 M charm
Conclusions

• Baselines of ~3000-7000 are very interesting
• Large detectors are needed (and the cheap way to go)
• Intensities >~ 10^{20}/year open allow
  – very accurate measure of $\Delta m^2_{23}$ and $\theta_{23}$
  – Measure $\sin^2 2\theta_{13}$ and sign of $\Delta m^2_{23}$
• May be sensitive to CP violation if
  $\sin^2 2\theta_{13}, \sin^2 2\theta_{12}$ and $\Delta m^2_{12}$ are large (lucky LMA solution)

Near detector physics factor of 1000 better than present or foreseen expts.
# Standard Model of Elementary Particles

### 3 Generations of Fermions

<table>
<thead>
<tr>
<th>Quarks</th>
<th>Leptons</th>
<th>Force Carriers</th>
</tr>
</thead>
<tbody>
<tr>
<td>u, c, t</td>
<td>ν₁, ν₂, ν₃</td>
<td>g, γ, Z⁰, W⁺⁻</td>
</tr>
<tr>
<td>q, ~5</td>
<td>~5</td>
<td>0</td>
</tr>
<tr>
<td>~1350</td>
<td>~175</td>
<td>0</td>
</tr>
<tr>
<td>175000</td>
<td>~4500</td>
<td>0</td>
</tr>
</tbody>
</table>

**Charge**

- u, c, t: 2/3
- d, s, b: –1/3
- ν₁, ν₂, ν₃: 0
- e, μ, τ: 0

**Masses are in MeV**

- e = 0.511
- μ = 105.66
- τ = 1777.2
- Z⁰ = 91187
- W⁺⁻ = 81400

**Notes**

- Strong Interactions
- Electromagnetism
- Weak Interactions

**June 2000**