Neutrino factory without charge ID

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based on
PH and T.Schwetz, arXiv:0805.2019

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Outline

• The MIND paradigm
• Oscillation helps
• Neutrinos are not their own anti-particles†
• Outlook

† I am not claiming they are Dirac particles.
The need for a magnetic field

The most reliable way to distinguish a $\mu^-$ from a $\mu^+$ is by measuring its charge sign and this is done by bending the muon track in a magnetic field.
The MIND

The use of a magnetic field $\sim 1$ T has following consequences

- iron core magnet
- high target density
- short muon tracks
- most of the detector mass is passive

this results in

- requires a relative long muon track
- puts a severe constraint on the lowest neutrino energy
- mediocre energy resolution
- target mass limited to $\sim 100$ kt

high luminosity, high energy $25$ GeV neutrino
The MIND paradigm

Using a magnetic field a neutrino factory can achieve the ultimate sensitivities to very small probabilities. using MIND

- severe constraints on the minimum usable energy
- relatively small, special purpose detector†

† applies also for TASD and the low-E neutrino factory, see A. Bross, et al., Phys. Rev. D 77:093012, 2008.
Oscillation helps

μ-like QE events for $\delta_{CP} = 90^\circ$ and 0

$\sin^2 2\theta_{13} = 0.1$

$E_{\nu}^{\text{rec}}$ [GeV]

number of events / 100 MeV bin

$\bar{\nu}_\mu$ disapp.

$\nu_\mu$ appear.

GLoBES 2008

μ appearance for $\delta_{CP} = 90^\circ$ and 0

$\sin^2 2\theta_{13} = 0.1$

$E_{\nu}^{\text{rec}}$ [GeV]

events / 100 MeV bin

baseline 1290 km and $\Delta E = 0.05\sqrt{E} + 0.085$ GeV
There are 3 basic differences between $\nu$ and $\bar{\nu}$ events

1. muon lifetime due to $\mu^{-}$ capture
2. $\cos \theta$ distribution
3. outgoing nucleon, either a proton or a neutron
\( \nu \neq \bar{\nu} - \text{muon lifetime} \)

A \( \mu^- \) can be caught by the positively charged nuclei in the target and will undergo muon capture. Since this opens an additional channel for muon decay, the resulting lifetime will be shorter than the one in vacuum.

Moreover, there will be no Michel electron.

\[
\begin{array}{cccc}
\text{Vacuum} & \text{Carbon} & \text{Oxygen} & \text{Argon} \\
\text{lifetime } \mu s & 2.197 & 2.026 & 1.795 & 0.537 \\
\text{capture prob.} & - & 8\% & 18\% & 76\%
\end{array}
\]

Has been used by MiniBooNE (neutrinos) and Kamiokande (cosmic ray muons).
$\nu \neq \bar{\nu} - \cos \theta$

- $\bar{\nu}$ produce more forward leptons
- effect largest around 1 GeV

from MiniBooNE, hep-ex/0602051.

Has been used by MiniBooNE.
Identifying the outgoing nucleon requires the ability to tag at least either the proton or the neutron, ideally both.

Assuming, we have a tag for the proton or neutron, we get two sources of mis-ID

- the tag is not 100% efficient
- the event produced the wrong nucleon
  - because there were more than 1 nucleon
  - because the initial nucleon underwent a charge exchange reaction

Initial estimates indicate, that efficiencies larger than 90% maybe possible and, that charge exchange affects less than 15% of events.
Nucleon tagging

Water Cerenkov

Proton tagging very inefficient due to Cerenkov threshold. However, neutron tagging is possible by adding 0.2% Gadolinium. The neutron will predominantly capture on Gd and the Gd then will emit about 8 MeV of γs. GADZOOKS project is underway to study feasibility in large scale detector. J. Beacom and M. Vagins, hep-ph/0309300.

Liquid Argon

Has demonstrated its ability to see low energy protons in a prototype. F. Arneodo, et al., physics/0609205.
\[ \nu \neq \bar{\nu} – \text{parametrization} \]

In absence of the necessary dedicated MC studies, we parametrize \( \nu/\bar{\nu} \) separation by assuming that we sort each event into either the \( \bar{\nu} \)-like sample \( N_1 \) or the \( \nu \)-like sample \( N_2 \).

\[
N_i^1 = \frac{1 - p}{2} N_\nu^i + \frac{1 + p}{2} N_{\bar{\nu}}^i \\
N_i^2 = \frac{1 + p}{2} N_\nu^i + \frac{1 - p}{2} N_{\bar{\nu}}^i
\]

The efficiency is given by \((1 + p)/2\) and the contamination with the other type by \((1 - p)/2\), with \( p = 0 \) corresponding to no separation at all and \( p = 1 \) is perfect separation.
The beam

- 5GeV neutrino factory
- $10^{21}$ useful decays per year
- 5 years $\mu^-$
- 5 years $\mu^+$
- baseline 1290km

Note: this luminosity requires 4MW for $10^7$ s per year, which is about the same than FNAL’s Project X which would deliver 2.3MW for $1.7 \cdot 10^7$ s a year.
## Detector parameterization

|                        | TASD | WC | LAr |
|------------------------|------|----|-----|
| fiducial mass [kt]     | 20   | 500| 100 |
| efficiency             | 0.73 | 0.9\(^a\) | 0.8 |
| magnetized             | yes  | no | no |
| \(\Delta E\) at 2.5 GeV [MeV] | 165 | 300\(^b\) | 165 |
| \(p\) for muons       | 0.999| 0 \(-\)0.7 | 0.7 \(-\)0.9 |
| \(p\) for electrons   | 0    | 0  | 0.7 \(-\)0.9 |

\(^a\) on top of the single ring selection efficiency and an efficiency of 82% for \(\nu_\mu\) events

\(^b\) equivalent Gaussian width
CP sensitivity

\[ \sin^2 2\theta_{13} > 0.03 \]
WBB better than NF with TASD

\[ \sin^2 2\theta_{13} > 0.004 \]
WC and LAr with some \( \nu/\bar{\nu} \) separation equivalent or better than TASD

\[ \sin^2 2\theta_{13} < 0.004 \]
TASD is the best solution

WBB – 120 GeV proton beam from FNAL to DUSEL at 0.5 mrad
Outlook

- Oscillation provides a right sign muon suppression of 1 : 10 down to 1 : 100, depending on energy resolution
- Neutrinos are not anti-neutrinos: muon lifetime, $\cos \theta$ and nucleon tagging
- Moderate separation efficiencies and purities of 50%-90% allow to use very large general purpose detectors down to $\sin^2 2\theta_{13} \approx 0.004$
- This may be very useful in the context of staging

Caveat emptor: all of this requires detailed simulations and a precise understanding of nuclear effects.
A neutrino factory may be mindless – but still can be reasonable.
Backup Slides
Size matters – detector mass

CP violation at 3σ

Normal hierarchy at 3σ

fraction of $\delta_{\text{CP}}$

detector mass [kt]

$\sin^2 2\theta_{13} = 0.01$

GLoBES 2008
The TASD

To overcome the low energy constrain:

• air core magnet
• lower target density
• longer muon tracks
• all of the detector is active

this results in

• requires a relatively short muon track
• low energy neutrinos can be used as well
• very good energy resolution
• target mass limited to \( \sim 20 \text{ kt} \)
• high luminosity, low energy 5 GeV neutrino source
A word about backgrounds

The statistical error in a bin \( i \) of sample \( N_2 \) is given by

\[
\sigma^2_{\text{stat}} = \frac{1 + p}{2} N^i_\nu + \frac{1 - p}{2} N^i_\bar{\nu} + \frac{B_i}{2}
\]

In the limit of vanishing signal, this error is determined by the background of 'right sign’ events plus any other background \( B_i \)

\[
\sigma^2_{\text{stat}} \xrightarrow{N^i_\nu \rightarrow 0} \frac{1 - p}{2} N^i_\bar{\nu} + \frac{B_i}{2}
\]

Thus the permissible background \( B_i \) will depend on \( 1 - p \).
A word about backgrounds

The worst case is when events from the peak of the right sign event distribution migrate into its minimum. We call the ratio between the events in the minimum to the events in the maximum \( r \). Depending on the energy resolution we have \( r = 1/100 - 1/10 \).

Thus whenever

\[
f = \frac{B_i}{N_\nu} \lesssim r(1 - p)
\]

we safely can neglect \( B_i \). Thus we obtain \( f \lesssim 0.001 \) for LAr and \( f \lesssim 0.03 \) for WC, which seems to be fulfilled in both cases.

Note: Muons from \( \nu_\tau \) events also do not play a role for a 5GeV NF.
Non-maximal $\theta_{23}$

Variation of the true $\theta_{23}$ within its current $3\sigma$ range.
Small $\theta_{13}$

**CP violation at 3$\sigma$**

- GLoBES 2008
- $p = 0.999$
- LAr $p = 0.9$
- LAr $p = 0.7$
- WC $p = 0.9$
- WC $p = 0.7$
- WC $p = 0.5$
- WC $p = 0$
- TASD
- $\sin^2 2\theta_{13} = 0.003$

**Normal hierarchy at 3$\sigma$**

- $p = 0.999$
- LAr $p = 0.9$
- LAr $p = 0.7$
- WC $p = 0.9$
- WC $p = 0.7$
- WC $p = 0.5$
- WC $p = 0$
- TASD
- $\sin^2 2\theta_{13} = 0.003$