Neutrino factories(*): Detector concepts

*we do not consider conventional “superbeams” (see hep-ph/0103052)

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(ICARUS Collaboration)
Special thanks to A. Bueno & M. Campanelli

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The oscillation physics program at the NF

\[ \mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu \]

Ideal detector should be able to measure **12 different processes as a function of** L and E\(_{\nu}\)

\[ \nu_\mu \rightarrow \nu_e \] **appearance**

\[ \nu_\mu \] **disappearance**

\[ \nu_\mu \rightarrow \nu_\tau \] **appearance**

\[ \bar{\nu}_e \] **disappearance**

\[ \bar{\nu}_e \rightarrow \bar{\nu}_\mu \] **appearance**

\[ \bar{\nu}_e \rightarrow \bar{\nu}_\tau \] **appearance**

Plus their charge conjugates with \(\mu^+\) beam

\[ \begin{cases} 
\nu_\ell N \rightarrow \ell^- + \text{hadrons} \\
\bar{\nu}_\ell N \rightarrow \ell^+ + \text{hadrons}
\end{cases} \]

1. **Particle ID**: charged lepton tags incoming neutrino flavor
2. **Charge ID**: sign of lepton charge tags helicity of incoming neutrino
3. **Energy resolution**: Reconstructed event energy is \(E_\nu = E_\ell + E_{\text{had}}\)
4. **Various baselines** L could help for detector systematics
The Neutrino Factory

$$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu \quad \text{or} \quad \mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$$

Flux scales as $$E_\mu^2 / L^2$$

Total event rate scales as $$\approx E_\mu^3 / L^2$$

A very important feature!

Roughly as many $$\nu_e$$'s as $$\nu_\mu$$'s

The generally adopted consensus (see later) ⇒

high energy $$\nu$$-factory

$$E_\mu = O(30 \text{GeV})$$

P. Lipari, hep-ph/0102046
### Predicted event rates at a Neutrino Factory

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Baseline (km)</th>
<th>$\langle E_{\nu_{\mu}} \rangle$ (GeV)</th>
<th>$\langle E_{\nu_{e}} \rangle$ (GeV)</th>
<th>$N(\nu_{\mu} \text{ CC})$ (per kt–yr)</th>
<th>$N(\bar{\nu}_{e} \text{ CC})$ (per kt–yr)</th>
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</thead>
<tbody>
<tr>
<td>NuMI</td>
<td>732</td>
<td>3</td>
<td>–</td>
<td>458</td>
<td>1.3</td>
</tr>
<tr>
<td>Medium energy</td>
<td>732</td>
<td>6</td>
<td>–</td>
<td>1439</td>
<td>0.9</td>
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<tr>
<td>High energy</td>
<td>732</td>
<td>12</td>
<td>–</td>
<td>3207</td>
<td>0.9</td>
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<tr>
<td>CNGS</td>
<td>732</td>
<td>17</td>
<td>–</td>
<td>2714</td>
<td>1.4</td>
</tr>
<tr>
<td>Muon ring</td>
<td>$E_\mu$ (GeV)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>732</td>
<td>7.5</td>
<td>6.6</td>
<td>1400</td>
<td>620</td>
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<tr>
<td>20</td>
<td>732</td>
<td>15</td>
<td>13</td>
<td>12000</td>
<td>5000</td>
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<tr>
<td>50</td>
<td>732</td>
<td>38</td>
<td>33</td>
<td>$1.8 \times 10^5$</td>
<td>$7.7 \times 10^4$</td>
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<tr>
<td>Muon ring</td>
<td>$E_\mu$ (GeV)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>2900</td>
<td>7.6</td>
<td>6.5</td>
<td>91</td>
<td>41</td>
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<tr>
<td>20</td>
<td>2900</td>
<td>15</td>
<td>13</td>
<td>740</td>
<td>330</td>
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<tr>
<td>50</td>
<td>2900</td>
<td>38</td>
<td>33</td>
<td>11000</td>
<td>4900</td>
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<td>Muon ring</td>
<td>$E_\mu$ (GeV)</td>
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<tr>
<td>10</td>
<td>7300</td>
<td>7.5</td>
<td>6.4</td>
<td>14</td>
<td>6</td>
</tr>
<tr>
<td>20</td>
<td>7300</td>
<td>15</td>
<td>13</td>
<td>110</td>
<td>51</td>
</tr>
<tr>
<td>50</td>
<td>7300</td>
<td>38</td>
<td>33</td>
<td>1900</td>
<td>770</td>
</tr>
</tbody>
</table>

However, in addition to the increased neutrino flux, ambitious oscillation physics program requires detectors in the 10’s kton range to perform experiment with baselines $L \approx 1000$’s km
The goal: detect $\mu^+$, $\mu^-$, $e^+$, $e^-$, $\tau^+$, $\tau^-$ and NC!

**Particle ID:** $\Rightarrow$ via CC interactions

- **Muons:** *straight-forward*, look for penetrating particles, but beware $\pi^\pm, K^\pm$ and charm decays
- **Electrons:** *harder*, look for large & “short” energy deposition, need good granularity for e/$\pi^0$ separation
- **Taus:** *hardest*, “kink” or kinematical methods (statistical separation), $\tau\rightarrow$hadrons+$\nu$ (Br$\approx$60%) look like “NC”

**Charge ID:** $\Rightarrow$ via magnetic analysis

- **Muons:** *easy*, muon spectrometer downstream or fully magnetized target
- **Electrons:** *hardest*, need to measure significantly precisely the bending in B-field before start of e.m. shower
- **Taus:** easy for $\tau\rightarrow\mu\nu\nu$ (Br$\approx$18%), otherwise *difficult*

This has to be implemented on multi-kton detectors…
various choices & optimizations considered.
1a. Magnetized steel-scintillator sandwich

- **High density**
- **Magnetizable** for $\mu^+/\mu^-$ discrimination
  - Detects: $\mu^+, \mu^-, [e, NC]$
- Good muon and reasonable jet energy resolution $\sigma_{E_h}/E_h \sim 80%/\sqrt{E_h}$
- **Lots of experience**: e.g. CCFR/NuTeV, CDHS. 
  **MINOS** will reach 5.4 kton in 2003.
- Disadvantages:
  - Amount of instrumentation scales with *volume*
  - *Minimum muon energy threshold* (4-6 GeV) in order to separate it from hadrons and muon isolation from jet difficult to tell. Threshold even higher to have excellent wrong-sign-$\mu$ @ $10^{-5}$
  - *e/h discrimination* rather poor
  - Angular resolution determined by transverse readout segmentation, usually rather modest.
The MINOS far detector

- 8m octagonal tracking calorimeter
- 486 layers of 2.45cm Fe
- 2 sections, each 15m long
- 4.1cm wide solid scintillator strips with WLS fiber readout
- 25,800 m² active detector planes
- Magnet coil $<B>=1.3T$
- 5.4kton total mass

Can it be scaled to 40 kton?
<table>
<thead>
<tr>
<th>System</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>MINOS cavern</td>
<td>82.3 m × 13.8 m × 11.6 m (height)</td>
</tr>
<tr>
<td>Supermodules</td>
<td>2 supermodules, each 2.7 metric kt, 14.4 m long × 8 m wide</td>
</tr>
<tr>
<td>Detector mass</td>
<td>5.14 ktons steel + 261 tons scintillator = 5.4 ktons</td>
</tr>
<tr>
<td>Planes/supermodule</td>
<td>486 steel planes and 485 scintillator planes, 2.54 cm pitch</td>
</tr>
<tr>
<td>Detector units/plane</td>
<td>192 scintillator strips packaged in 8 modules</td>
</tr>
<tr>
<td>Readout</td>
<td>2-ended, with 8 × multiplexing</td>
</tr>
<tr>
<td>Channel count</td>
<td>484 planes × 192 strips × 2 ÷ 8 = 23,232 channels</td>
</tr>
<tr>
<td>Photodetectors</td>
<td>1,452 16-channel PMTs in 484 MUX boxes</td>
</tr>
<tr>
<td>Installation rate</td>
<td>1 plane/1.85 shifts or 24 planes/month (maximum)</td>
</tr>
<tr>
<td>Installation time</td>
<td>12 months for first supermodule, 22.5 months for two</td>
</tr>
<tr>
<td>Magnetic field</td>
<td>1.3 T at 2 m radius in steel octagon planes</td>
</tr>
<tr>
<td>Magnet coils</td>
<td>15 kA-turns, water-cooled copper wire, 58 kW total</td>
</tr>
<tr>
<td>Total cavern cooling</td>
<td>292 kW maximum (at the end of the installation period)</td>
</tr>
</tbody>
</table>

Table 13: Summary of some of the major parameters of the far detector and its requirements on the infrastructure systems of the MINOS cavern in the Soudan mine.
Lifting of an instrumented MINOS plane
Cylindrical symmetry, \( R=10 \text{m}, =20 \text{m} \)
6 cm thick iron rods interspersed with 2cm thick scintillators “longitudinally segmented”
Field: 1 T

Mass: 40 kton

⇒ *Muon performance studied with GEANT and assume MINOS-like performance for* \( E_{\text{had}}, \theta_{\text{had}} \)…

\[
\sigma_{E_h} / E_h \approx 76\% / \sqrt{E_h} \oplus 3\%
\]

\[
\sigma_{\theta_h} / \theta_h \approx 17 / \sqrt{E_h} \oplus 12 / E_h
\]
2. Large Water Cerenkov

- Well proven technology, e.g. *Kam, IMB, SuperKamiokande*
  - Detects: $\mu, e, [NC]$
- Low cost target material, only the surface (not volume) needs to be instrumented, but size eventually limited by water properties
- Next generation 1Mton under consideration
- Disadvantages:
  - Reconstructed (pattern) limited to “simple event topologies” (e.g. single-ring)
  - Not compatible with precise reconstruction of high energy neutrinos (e.g. $E_\nu > \approx 5$ GeV ?)
  - Muon charge ID

Simulated neutrino event from a 50 GeV storage ring

FNAL-FN-692, Apr 2000
3. Emulsion/target sandwich

★ **OPERA**: Technique on the ≈1 kton scale to be demonstrated by at LNGS in 2005

→ Detects: $\mu^+$, $\mu^-$, $\tau$ (“kink”), $[\text{e,NC}]$

→ Direct search of $v_e \rightarrow v_\tau$ oscillations, if charge of the tau can be detected to suppress $v_\mu \rightarrow v_\tau$ “background”

★ Disadvantages:

→ Probably difficult to scale to multi-kton mass

→ Scanning (e.g. $v_e \rightarrow v_\tau$ to $\sin^2 2\theta_{13} \approx 10^{-4}$ ?)

→ Possibly severe charm background from $v_e$ interactions
4. Liquid Argon imaging TPC

**ICARUS**: mature technique, demonstrated up to 15 ton prototype

**Features provided:**

- Detects: $\mu^+$, $\mu^-$, e, NC, $[\tau]$
- Fully homogeneous, continuous, precise *tracking device* with high resolution dE/dx *measurement* and full sampling *electromagnetic and hadronic calorimetry*
- Excellent *e identification/measurement* and *e/hadron* separation
- Very good hadronic energy resolution

**600 ton prototype construction** *very advanced*

- After the foreseen series of technical tests to be performed in Pavia within the summer 2001, *the T600 module will be ready to be transported into the LNGS tunnel*

**Disadvantages:**

- Muon charge discrimination: target cannot be easily magnetized (but...)
- Rely on *down-stream muon spectrometer* (low threshold since $dE/dx \approx 240$ MeV/m)

Idea first implemented in the ICANOE proposal
The LAr TPC technique is based on the fact that ionization electrons can drift over large distances (meters) in a volume of purified liquid Argon under a strong electric field. If a proper readout system is realized (i.e. a set of fine pitch wire grids) it is possible to realize a massive "electronic bubble chamber", with superb 3-D imaging.
Liquid Argon imaging on large scales

10m$^3$ Module at LNGS

Cosmic Ray tracks recorded during the 10 m$^3$ operation

“Big track” in T600 semimodule expected soon...
T600 assembly schedule

★ Completed *site preparation* in Pavia for the T600 cryostat (**Nov 1999**)
   → “clean room”, “assembly island”, floor, ...
★ Delivery of the *1st cryostat* by AirLiquide (**Feb 2000**)
   → Successful vacuum tightness and mechanical stress tests
★ Beginning of *assembly of the internal detector mechanics* (**Mar 2000**)
★ Completion of assembly and positioning of inner detector frames (**Jul 2000**)
★ Installation of *30000 wires + signal cables* (**Jul 2000-Oct 2000**)
★ Delivery of the *2nd cryostat* of AirLiquide (**Aug 2000**)
   → Successful vacuum tightness and mechanical stress tests
★ Installation of *scintillation light* and all *slow control devices* (**Jul 2000-Dec 2000**)
★ *H.V. and field electrodes system* installation (**Oct 2000- Jan 2001**)
★ Installation of the *48 electronic racks* on top of dewar (**Dec 2000-ongoing**)
★ Installation of *external heat insulation* (for both dewars) and *LAr and LN₂ cryogenic circuits* (**Dec 2000-Jan 2001**)
★ Semi-module now ready to be sealed.
The ICARUS T600 module

Number of independent containers = 2
Single container Internal Dimensions: Length = 19.6 m, Width = 3.9 m, Height = 4.2 m
Total (cold) Internal Volume = 534 m$^3$
Sensitive LAr mass = 476 ton

Number of wires chambers = 4
Readout planes / chamber = 3 at 0°, ± 60° from horizontal
Maximum drift = 1.5 m
Operating field = 500 V / cm
Maximum drift time ≈ 1 ms
Wires pitch = 3 mm
Total number of channels = 58368
First half-module delivery in Pavia (Feb 29, 2000)
Assembly of the T600 internal detector (Mar-Jul 2000)
Second half-module (delivered Aug 2000)

Thermal insulation panels

Thermal floor
Nomex honeycomb panels (heat insulation)

Dewar

Readout electronics
Wire installation in T600 internal detector (Jul-Oct 2000)
The three wire planes at $0^\circ, \pm 60^\circ$ (wire pitch = 3mm)

and one PMT
Drift H.V. and field electrodes system

Drift distance
1.5 m

Horizontal wires readout cables

Race-track

–75kV
Slow control sensor (behind wire planes)
Man-hole (after sealing, the only way to get inside!)
The first ICARUS T600 prototype

- The T600 module is to be considered as a fundamental milestone on the road towards a total sensitive mass in the multi-kton range
  - First piece of the detector to be complemented by further modules of appropriate size and dimension ⇒ Goal is to reach a multikton mass in LNGS tunnel in a most efficient and rapid way
- It has a physics program of its own, immediately relevant to neutrino physics, though limited by statistics (see hep-ex/0103008)
Proposed setup ICARUS 5kt in LNGS Hall B

Two possible options:
A) \( \approx 8 \times T600 \)
B) \( 4 \times T1400 \) (better for physics)
We consider a design in which the muon escaping the liquid Argon is bent by a magnetized piece of iron.

\[ B = 2.0 \, \text{T}, \quad L_{\text{iron}} = 2.5 \, \text{m} \]

The bending angle $\theta$ is measured with the tracks observed in two subsequent liquid argon module.

\[ \Delta p/p \approx 25\% \quad \text{Charge confusion: } \sim 10^{-4} \]

A simpler solution than in the ICANOE proposal.
**Muon charge misidentification**

- **μ momentum resolution:**
  - 25% for a 2.5m long Fe spectrometer with B=2T
- **Wrong sign contamination**
  - Charge confusion: $\sim 10^{-4}$
- **Large detection efficiency for low energy beam**
  - $\mu$ detection threshold ($dE/dx = 240$ MeV/m)
An interesting possibility, **to be further understood**, is the creation of the B-field over the large volume encompassing the LAr with the help of a very large solenoid coil. 

\[
\vec{B} \perp \vec{v}_{\text{drift}} \perp \vec{p}
\]

Joule Power (non-superconducting):

\[
P = \rho \frac{2(a + b)hB^2}{md\mu_0^2}
\]

- \(d\) = coil thickness, \(m\) = # windings, \(h\) = height, \(a\) = width, \(b\) = length

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Argon volume</td>
<td>(8 \times 8 \times 16 m^3)</td>
</tr>
<tr>
<td>Argon mass</td>
<td>1.4 kton</td>
</tr>
<tr>
<td>Magnetic field</td>
<td>1.0 T</td>
</tr>
<tr>
<td>Current</td>
<td>2000 A</td>
</tr>
<tr>
<td>Conductor length</td>
<td>150 km</td>
</tr>
<tr>
<td>Resistance</td>
<td>1 (\Omega)</td>
</tr>
<tr>
<td>Dissipated power</td>
<td>4 MW</td>
</tr>
<tr>
<td>Iron mass</td>
<td>5 kton</td>
</tr>
</tbody>
</table>
Precise determination of $\Delta m^2_{23}$ and $\Theta_{23}$

Stringent limit/precise measurement of $\Theta_{13}$

Determination of $\Delta m^2_{23}$ sign

Study matter effects

First detection of $\nu_e \rightarrow \nu_\tau$ oscillations

Over-constrain the oscillation parameters

Study CP violation in the leptonic sector

Try to show three concrete examples where detector considerations could be relevant...
Looking at the $\theta_{13}$ term

$$P(v_e \rightarrow v_\mu) = \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2(\Delta m_{32}^2 L/4E)$$

A realistic assumption at the NF $\Rightarrow$ for $\Delta m_{21}^2 (L/4E) << 1$

$$\approx \sin^2 2\theta_{13} \sin^2 \theta_{23} (\Delta m_{32}^2)^2 (L/4E)^2$$

Not always a correct assumption at the NF $\Rightarrow$ for $\Delta m_{21}^2 (L/4E) << \Delta m_{32}^2 (L/4E) << 1$

Similarly,

$$P(v_e \rightarrow v_\tau) = \sin^2 2\theta_{13} \cos^2 \theta_{23} \sin^2(\Delta m_{32}^2 L/4E)$$

For $\Delta m_{21}^2 (L/4E) << 1$

In contrast,

$$P(v_\mu \rightarrow v_\tau) = \cos^4 \theta_{13} \sin^2 2\theta_{23} \Delta_{32}^2$$
Wrong-sign muon optimization

Optimization of $E_\mu$ and $L$ depends on detector background considerations
⇒ gain with $E_\mu$, since rate increases like $E_\mu^3$ until background becomes relevant

$$\nu_e \rightarrow \nu_\mu \text{ oscillations}$$

\[ \Delta m^2_{32} = 3 \times 10^{-3} \text{ eV}^2 \]
\[ \Delta m^2_{21} = 1 \times 10^{-4} \text{ eV}^2 \]
\[ \sin^2 \theta_{23} = 0.5 \quad \sin^2 \theta_{12} = 0.5 \]
\[ \sin^2 2\theta_{13} = 0.05 \quad \delta = 0 \]

Statistical significance

$$S = \frac{N_{ws\mu}}{B}$$

$$B = \left\{ \begin{array}{ll}
\sqrt{N_{rs\mu} \times e_{BKG}} & \text{if } N_{rs\mu} \times e_{BKG} > 10 \\
\text{Poisson} & \text{otherwise}
\end{array} \right.$$
Over-constraining the parameters (I)

Combining all classes $\Rightarrow$ (over-constrained) sensitivity to all oscillations!

Over-constraining the parameters (II)

Check consistency between different observed oscillation processes

Proof/rule out the existence of sterile neutrinos

First observation of $\nu_e \rightarrow \nu_\tau$

Ability to detect $\tau$ appearance is crucial

$E_\mu = 30$ GeV, $L=2900$ km, $2 \times 10^{20}$ $\mu$ decays

$\chi^2$

$\Delta m_{32}^2 = 3.5 \times 10^{-3}$ eV$^2$
$\Delta m_{21}^2 = 1 \times 10^{-4}$ eV$^2$

$\sin^2 \theta_{23} = 0.5$
$\sin^2 \theta_{13} = 0.5$
$\sin^2 2\theta_{13} = 0.05$

A way to rescale probabilities...

\[ p \equiv P(\nu_e \rightarrow \nu_\mu) \times \frac{E_\nu^2}{L^2} \]

1. \( p \rightarrow \text{const} \) when \( E_\nu \rightarrow \infty \)
2. It correctly “weighs” the probabilities with the \( E_\nu \) dependence of the NF \( \nu \) spectrum
3. \( p \) can be directly compared at different baselines

\[ E_\nu \]

\[ L=730 \text{ km} \]

\[ L=730 \text{ km}, \rho=2.8 \text{ g/cm}^3 \]

\[ \Delta m^2_{32} = 3 \times 10^{-3} \text{ eV}^2 \]
\[ \Delta m^2_{21} = 1 \times 10^{-4} \text{ eV}^2 \]
\[ \sin^2 \phi_{32} = 0.5 \quad \sin^2 \phi_{13} = 0.5 \]
\[ \sin^2 2\phi_{13} = 0.05 \quad \delta = 0 \]

\( \nu \) in matter

\( \bar{\nu} \) in matter

in vacuum
Matter effects

\[ \sin^2 2\theta_m(D) = \frac{\sin^2 2\theta}{\sin^2 2\theta + \left( \pm \frac{D}{\Delta m^2} - \cos 2\theta \right)^2} \]

\[ \lambda_m = L \times \sqrt{\sin^2 2\theta + \left( \pm \frac{D}{\Delta m^2} - \cos 2\theta \right)^2} \]

+ for neutrinos
– for antineutrinos

where

\[ D(E_\nu) = 2\sqrt{2}G_F n_e E_\nu \approx 7.56 \times 10^{-5} \ eV^2 \left( \frac{\rho}{gcm^{-3}} \right) \left( \frac{E}{GeV} \right) \]

For example, for neutrinos:

**Resonance:** \[ D \approx \Delta m^2 \cos 2\theta \]
\[ \sin^2 2\theta_m(D) \approx 1 \]

**Suppression:** \[ D > 2\Delta m^2 \cos 2\theta \]
\[ \sin^2 2\theta_m(D) < \sin^2 2\theta \]

Mixing in matter smaller than in vacuum

Effect tends to become “visible” for \( L > \approx 1000 \text{ km} \)
At large distances, matter effect suppresses oscillations!

\[ D \approx 2\Delta m^2 \cos 2\theta \]

\[ D \approx \Delta m^2 \cos 2\theta \]
Looking for effects of $\delta$!

One of the main motivations of NF is to try to look for effects induced by the phase $\delta$.

Effect "largest" when beat of three sin-functions:

$$\Delta m^2_{21} \left( \frac{L}{4E_\nu} \right) > 1$$
&

$$\Delta m^2_{32} \left( \frac{L}{4E_\nu} \right) > 1$$

$\Rightarrow$ $L/E$ of "solar"!
The “CP-odd” term

\[ \Delta CP = \frac{P(\nu_e \rightarrow \nu_\mu) - P(\overline{\nu}_e \rightarrow \overline{\nu}_\mu)}{2} \]

Complex term in matrix

Need LA MSW

Oscillation P goes like \( \sin^2 \theta_{13} \)

hence, \( \Delta CP / \sqrt{P} \) independent of \( \theta_{13} \)

\[ \propto \cos \theta_{13} \sin \delta \sin 2 \theta_{12} \sin 2 \theta_{13} \sin 2 \theta_{23} \times \]

\[ \sin(\Delta m^2_{12} L/4E_\nu) \sin(\Delta m^2_{13} L/4E_\nu) \sin(\Delta m^2_{23} L/4E_\nu) \]

\[ \approx f \times \Delta m^2_{12} (L/4E_\nu) \times \sin^2(\Delta m^2_{23} L/4E_\nu) \]

for \( \Delta m^2_{21} (L/4E_\nu) \ll 1 \)

\[ \approx f \times \Delta m^2_{12} (\Delta m^2_{23})^2 (L/4E_\nu)^3 \]

for \( \Delta m^2_{21} (L/4E_\nu) \ll \Delta m^2_{32} (L/4E_\nu) \ll 1 \)
So what to do at high energy?

See also P. Lipari, hep-ph/0102046

\[ P\left(\nu_e \rightarrow \nu_\mu\right) \times \frac{E_\nu^2}{L^2} \]

1. The \( E_\nu^2 \) term takes into account that the NF likes to go to high energy \( \Rightarrow \) damps the part \( \Delta m_{21}^2 \frac{L}{4E_\nu} \approx 1 \)

2. At “high energy”, i.e. \( \Delta m_{21}^2 \frac{L}{4E_\nu} \ll 1 \) & \( \Delta m_{32}^2 \frac{L}{4E_\nu} \ll 1 \), there is no more oscillation \( \Rightarrow \) change of \( \delta \) = change of \( \theta_{13} \) !!!

3. At “high energy”, the CP-effect goes like \( \cos \delta \), as pointed out by Lipari \( \Rightarrow \) cannot measure sign of \( \delta \)

\[ \delta = 0 \text{ (matter)} \]
\[ \delta = 0 \text{ (vacuum)} \]
\[ \delta = +\pi/2 \text{ (matter)} \]
\[ \delta = +\pi/2 \text{ (vacuum)} \]
\[ \delta = -\pi/2 \text{ (matter)} \]
\[ \delta = -\pi/2 \text{ (vacuum)} \]

\[ P\left(\nu_e \rightarrow \nu_\mu, \delta = \frac{\pi}{2}\right) - P\left(\nu_e \rightarrow \nu_\mu, \delta = 0\right) \propto \cos \delta \]
So where is the compromise in L/E?

We must compromise at “medium” energy to

1. This means $\Delta m^2_{21} (L/4E_{\nu}) < 1$ & $\Delta m^2_{32} (L/4E_{\nu}) \approx 1$

2. To gain from the $E_\mu^3$ behavior of the NF

3. To guarantee the possibility to disentangle $\delta$ from $\theta_{13}$

$$\frac{L}{E_\nu} \approx \frac{4\pi}{2\Delta m^2_{32}}$$

$E_{\nu,\text{MAX}} \approx 2 \text{ GeV for } L=732 \text{ km}$

$E_{\nu,\text{MAX}} \approx 8 \text{ GeV for } L=2900 \text{ km}$
If L/E$_{\nu}$ is fixed, what should be L and E$_{\nu}$?

The magnitude of the CP effect (given by J) is known to be unaffected by matter:

$$J = \cos\theta_{13} \sin\delta \sin2\theta_{12} \sin2\theta_{13} \sin2\theta_{23} / 8$$

Our “choice-point” for CP is at the fixed L/E$_{\nu,\text{max}}$ given by:

$$E_{\nu,\text{max}} = \frac{2 \times 1.27 \times \Delta m^2 L}{\pi}$$

When the neutrino energy becomes close to the MSW resonance, the effective oscillation wavelength increases, hence the CP effect at a fixed distance L becomes less visible.

Hence, we gain until the MSW resonance region and then loose

$$2\sqrt{2}G_F n_e E_{\nu} < \Delta m^2 \cos 2\theta$$

$$\Rightarrow 2\sqrt{2}G_F n_e \frac{2 \times 1.27 \Delta m^2 L}{\pi} < \Delta m^2 \cos 2\theta$$

$$L < \frac{\pi \cos 2\theta}{2 \times 1.27 \times 7.56 \times 10^{-5} \text{ eV}^2 \left( \frac{\rho}{\text{gcm}^{-3}} \right)} \approx 1.5 \times 10^4 \text{ km} \approx 5000\text{ km}$$
The “scaling” with $L/E_\nu$ of the probabilities is destroyed when $E_{\nu,\text{max}} > E_{\nu,\text{resonance}}$ due to matter effects.

\[ D \approx 2\Delta m^2 \cos 2\theta \]

**Dependence of probability on $L/E_\nu$**

- $\Delta m^2_{32} = 3 \times 10^{-3}$ eV$^2$
- $\Delta m^2_{21} = 1 \times 10^{-4}$ eV$^2$

**Conditions:**
- $\sin^2 \theta_{23} = 0.5$
- $\sin^2 \theta_{12} = 0.5$
- $\sin^2 2\theta_{13} = 0.05$
- $\delta = 0$

**Graph Details:**
- Black line: $L=2900$ km
- Red line: $L=730$ km
- Blue line: $L=7400$ km

**Equation:**
\[ P(\nu_e \rightarrow \nu_\mu) E_\nu E_\mu / L^2 \]

**Axes:**
- $x$-axis: $L/E_\nu$ (km/GeV)
- $y$-axis: $P(\nu_e \rightarrow \nu_\mu) E_\nu E_\mu / L^2$ (GeV$^2$/km$^2$)
The T-violation term dependence on $L/E_\nu$

$\Delta m^2_{32} = 3 \times 10^{-3} \text{ eV}^2$
$\Delta m^2_{21} = 1 \times 10^{-4} \text{ eV}^2$
$\sin^2 \theta_{23} = 0.5 \quad \sin^2 \theta_{12} = 0.5$
$\sin^2 2\theta_{13} = 0.05$
$\delta = +\pi/2 \text{ and } -\pi/2$
The CP-violation term dependence on $L/E_\nu$

\[
D \approx \Delta m^2 \cos 2\theta
\]

- $\Delta m_{22}^2 = 3 \times 10^{-3}$ eV$^2$
- $\Delta m_{21}^2 = 1 \times 10^{-4}$ eV$^2$
- $\sin^2 \theta_{23} = 0.5$
- $\sin^2 \theta_{12} = 0.5$
- $\sin^2 2\theta_{13} = 0.05$
- $\delta = \pm \pi/2$ and $-\pi/2$

Graph showing the CP-violation term dependence on $L/E_\nu$ for different values of $L$: L=2900 km, L=730 km, L=7400 km.
As long as \( L < \approx 5000 \text{ km} \), the effects scale with \( L/E_\nu \).

However, keeping \( L/E_\mu \) constant, we gain linearly with \( E_\mu \) because of the NF flux dependence \( E_\mu^3/L^2 \).

At lower \( E_\mu \) must compensate with higher muon intensities.

\[ E_\mu = 30 \text{ GeV} \text{ & } L = 2900 \text{ km} \]
\[ \rightarrow 2.5 \times 10^{20} \text{ decays} \]

\[ E_\mu = 7.5 \text{ GeV} \text{ & } L = 732 \text{ km} \]
\[ \rightarrow 10^{21} \text{ decays} \]
On the possibility to measure the electron charge

The presence of a magnetic field surrounding the LAr should allow to even determine the charge of electrons

$e^+$

$2.5 \text{ GeV}$

$B=1\text{T}$

Hard bremsstrahlung
Wrong-sign lepton spectra

Main background for WSE:
- $\mu^- \to \nu_\mu \Rightarrow \nu_\tau \to \tau^- \to e^-$
- Wrong-sign electrons from $\tau$ decays not suppressed as in the WSM case:
  - $\mu^- \to \bar{\nu}_e \Rightarrow \bar{\nu}_\tau \to \tau^+ \to \mu^+$

One more reason to go to lower energies where $\tau$ production is suppressed
Measured oscillation probabilities

- $\Delta m^2_{23}=3.5 \times 10^{-3} \text{ eV}^2$
- $\Delta m^2_{12}=1. \times 10^{-4} \text{ eV}^2$
- $\sin^2 2\theta_{13}=0.05$
- $\sin^2 2\theta_{23}=1.$
- $\sin^2 2\theta_{12}=1.$
- $\delta_{13}=\pi/2$
- $10^{21} \mu$ decays $E_\mu=5 \text{ GeV}$
- 10 kton detector

Direct comparison of oscillation probabilities for neutrinos and antineutrinos

$\varepsilon=20\%, \text{ w.s. background } 10^{-3}$
Probability difference

Difference is significant for neutrinos (antineutrinos are matter-suppressed) after evaluation of statistical and systematic errors (5% variation in \( \tau \) contribution)

\[
P(\bar{\nu}_e \rightarrow \bar{\nu}_\mu) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)
\]

* Direct measurement of the CP-odd component.

\[
P(\nu_e \rightarrow \nu_\mu) - P(\nu_\mu \rightarrow \nu_e)
\]

\( \approx 3\sigma \) effect!
Conclusion

> The richness of the NF oscillation physics calls for *multikton detectors capable of measuring all leptons and their charges*!

> **A difficult task**, leading to *different optimizations*, but

  > → *MINOS*-like (20kt?) & *ICARUS*-like (10kt?) (they would cost $\approx$ the same!) are more than just detector concepts

  > → They could be envisaged, but they will be expensive and to build either of them will be a great enterprise!

> The physics output will depend on the detector, *different optimizations*? e.g.

  > → For the *best $\theta_{13}$ sensitivity* ($10^{-5}$? the small mixing angle syndrome) it would suffice to have large mass (statistics!) and good muon capabilities at the highest energies

  > → For more subtle effects like *the study of $\delta$-phase*, a detector with more redundancy and excellent detection in the range 1–15 GeV is favored

  > → If *energy cannot be afforded*, must go closer, keeping L/E constant (at the price of increasing the muon intensity!)

  > → Charge discrimination for electrons could provide a “*direct” proof of T-violation*!