“Physics Potential of Super Beams and Beta Beams”,

Summary:

- Introduction.
- The hunting for $\theta_{13}$
- Leptonic CP violation
- The SPL-Super Beam
- The Beta Beam
- Sensitivity to the CP phase $\delta_{CP}$
ν oscillations are the most important discovery in hep of the last 15 years.

They measure fundamental parameters of the standard model. Mixing angles, neutrino masses and the CP phase $\delta_{CP}$ are fundamental constants of the standard model.

They are a probe of the GUT scales. The smallness of neutrino masses is connected to the GUT scale through the see-saw mechanism.

They are directly linked to many fields in astrophysics and cosmology: baryogenesis, leptogenesis, galaxies formation, dynamic of supernovae explosion, power spectrum of energy anisotropies, etc.

They open the perspective of the measure of leptonic CP violation.
If you are skeptical about that ....

Experimental articles with more than 500 cites in the last 15 years in the QSPIRES database (at 04/04/03):

<table>
<thead>
<tr>
<th></th>
<th>Journal</th>
<th>Title</th>
<th>Cites</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>SK</td>
<td>Evidence for Oscillation of Atmospheric Neutrinos.</td>
<td>1705</td>
</tr>
<tr>
<td>2</td>
<td>SCP</td>
<td>Measurements of $\Omega$ and $\Lambda$ from 42 High Redshift SN.</td>
<td>1311</td>
</tr>
<tr>
<td>3</td>
<td>SST</td>
<td>Observational Evidence from SuperNovae for an Accelerating Universe and a Cosmological Constant.</td>
<td>1293</td>
</tr>
<tr>
<td>4</td>
<td>COBE</td>
<td>Structure in the COBE DMR First Year Maps.</td>
<td>1036</td>
</tr>
<tr>
<td>5</td>
<td>CDF</td>
<td>Observation of TOP Quark Production in $\bar{p} - p$ Collisions.</td>
<td>930</td>
</tr>
<tr>
<td>6</td>
<td>D0</td>
<td>Observation of the Top Quark.</td>
<td>889</td>
</tr>
<tr>
<td>7</td>
<td>SK</td>
<td>Atmospheric $\nu_\mu/\nu_e$ Ratio in the MultiGeV Energy Range.</td>
<td>751</td>
</tr>
<tr>
<td>8</td>
<td>Chooz</td>
<td>Initial Results from CHOOZ.</td>
<td>683</td>
</tr>
<tr>
<td>9</td>
<td>Boomerang</td>
<td>A Flat Universe from High Resolution Maps of the CMB.</td>
<td>644</td>
</tr>
<tr>
<td>10</td>
<td>Chooz</td>
<td>Limits on Neutrino Oscillations from the CHOOZ Experiment.</td>
<td>635</td>
</tr>
<tr>
<td>11</td>
<td>Kamiokande</td>
<td>Observation of a Small Atmospheric $\nu_\mu/\nu_e$ Ratio.</td>
<td>628</td>
</tr>
<tr>
<td>12</td>
<td>CLEO</td>
<td>First Measurement of the Rate for the Inclusive $b \rightarrow s\gamma$.</td>
<td>618</td>
</tr>
<tr>
<td>13</td>
<td>SNO</td>
<td>Measurement of the rate of $\nu_e + d \rightarrow p + p + e^- ...$</td>
<td>592</td>
</tr>
<tr>
<td>14</td>
<td>Homestake</td>
<td>Measurement of the Solar $\nu_e$ Flux ...</td>
<td>565</td>
</tr>
<tr>
<td>15</td>
<td>LSND</td>
<td>Evidence for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ Oscillations from LSND.</td>
<td>563</td>
</tr>
<tr>
<td>16</td>
<td>SK</td>
<td>Measurement of a Small Atmospheric $\nu_\mu/\nu_e$ Ratio.</td>
<td>561</td>
</tr>
<tr>
<td>17</td>
<td>CDF</td>
<td>Evidence for TOP Quark Production in $\bar{p} - p$ ....</td>
<td>550</td>
</tr>
<tr>
<td>18</td>
<td>SK</td>
<td>Study of the Atm. $\nu$ Flux in the MultiGeV Energy Range.</td>
<td>547</td>
</tr>
<tr>
<td>19</td>
<td>IMB</td>
<td>The $\nu_e$ and $\nu_\mu$ Content of the Atmospheric Flux.</td>
<td>535</td>
</tr>
<tr>
<td>20</td>
<td>SK</td>
<td>Solar Neutrino Data Covering Solar Cycle 22.</td>
<td>504</td>
</tr>
<tr>
<td>21</td>
<td>LSND</td>
<td>Neutrino Oscillations from LSND.</td>
<td>500</td>
</tr>
</tbody>
</table>
Most of the parameters are waiting to be measured.

\[ \delta m_{12} \quad \text{SOLARS+KAMLAND} \quad 5 \times 10^{-5} \lesssim \delta m_{12} \lesssim 3 \times 10^{-4} \text{eV}^2 \]

\[ \theta_{12} \quad \text{SOLARS+KAMLAND} \quad 0.2 < \sin^2(\theta_{12}) < 0.5 \]

\[ \delta m_{23} \quad \text{ATMOSPHERICS} \quad \delta m_{23}^2 = 2.6 \pm 0.4 \text{eV}^2 \]

\[ \theta_{23} \quad \text{ATMOSPHERICS} \quad 0.9 < \sin^2(\theta_{23}) < 1 \]

\[ \theta_{13} \quad \text{CHOOZ LIMIT} \quad \theta_{13} < 14^0 \]

\[ \delta_{CP} \quad \text{Mass hierarchy} \]

\[ \sum m_\nu \quad \text{BETA DECAY END POINT} \quad \sum m_\nu < 6.6 \text{eV} \]

Dirac/Majorana
The capital importance of $\theta_{13}$

Present limit from CHOOZ: $\sin^2 2\theta_{13} \leq 0.1$. Both solar and atmospheric results are compatible with $\theta_{13} = 0$.

Solar+Atmospherics favor a near bi-maximal mixing matrix \textit{(VERY DIFFERENT from CKM matrix!)}

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix},$$

$\theta_{13} \rightarrow 0 \quad \Rightarrow \quad$ The 3x3 matrix is a trivial product of two 2x2 matrixes.

$\theta_{13}$ drives $\nu_\mu \rightarrow \nu_e$ subleading transitions \textit{⇒} the necessary milestone for any subsequent search: neutrino mass hierarchy and leptonic CP searches.
Subleading $\nu_\mu - \nu_e$ oscillations

\[
p(\nu_\mu \rightarrow \nu_e) \text{ developed at the first order of matter effects}
\]

\[
p(\nu_\mu \rightarrow \nu_e) = 4c^2_{13}s^2_{13}s^2_{23}\sin^2 \frac{\Delta m^2_{13}L}{4E} \theta_{13} \text{ driven}
\]

\[
+ 8c^2_{13}s_{12}s_{13}s_{23}(c_{12}c_{23}\cos \delta - s_{12}s_{13}s_{23}) \cos \frac{\Delta m^2_{23}L}{4E} \sin \frac{\Delta m^2_{13}L}{4E} \sin \frac{\Delta m^2_{12}L}{4E} \text{ CP_{Even}}
\]

\[
- 8c^2_{13}c_{12}c_{23}s_{12}s_{13}s_{23} \sin \delta \sin \frac{\Delta m^2_{23}L}{4E} \sin \frac{\Delta m^2_{13}L}{4E} \sin \frac{\Delta m^2_{12}L}{4E} \text{ CP_{Odd}}
\]

\[
+ 4s^2_{12}c^2_{13}\{c^2_{13}c^2_{23} + s^2_{12}s^2_{23}s^2_{13} - 2c_{12}c_{23}s_{12}s_{13}s_{23}\cos \delta\} \sin \frac{\Delta m^2_{12}L}{4E} \text{ solar driven}
\]

\[
- 8c^2_{12}s^2_{13}s^2_{23}\cos \frac{\Delta m^2_{23}L}{4E} \sin \frac{\Delta m^2_{13}L}{4E} \frac{aL}{4E}(1 - 2s^2_{13}) \text{ matter effect (CP odd)}
\]

where

\[
a = \pm 2\sqrt{2}G_F n_e E_\nu = 7.6 \cdot 10^{-5} \rho [g/cm^3] E_\nu [GeV] \quad [eV^2]
\]
Neutrino beam from the 50 GeV - 0.75 MW proton beam at the Hadron Facility at Jaeri, Japan.

Taken off-axis to better match the oscillation maximum at the SuperKamiokande location (295 km).

<table>
<thead>
<tr>
<th>K2K</th>
<th>JHF</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 \cdot 10^{12}</td>
<td>Protons per pulse</td>
</tr>
<tr>
<td>2.2 s</td>
<td>Cycle</td>
</tr>
<tr>
<td>12 GeV</td>
<td>Proton energy</td>
</tr>
<tr>
<td>40</td>
<td>Events in SK per year (no osc.)</td>
</tr>
<tr>
<td>1.5</td>
<td>Mean neutrino energy</td>
</tr>
</tbody>
</table>
JHF: $\nu_\mu$ disappearance

K2K at half of its statistics:

- $\delta m^2_{23}$ with a resolution of $10^{-4}$ eV$^2$.
- $\sin^2 2\theta_{23}$ at $1 \div 2\%$.

JHF in 5 years

Ratio of the measured $\nu_\mu$ spectrum with respect to the non-oscillation prediction in case of oscillation.
### JHF $\nu_e$ appearance

<table>
<thead>
<tr>
<th>OAB 2°</th>
<th>$\nu_\mu$ CC</th>
<th>$\nu_\mu$ NC</th>
<th>$\nu_e$ CC</th>
<th>Osc. $\nu_e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generated in F.V.</td>
<td>10713.6</td>
<td>4080.3</td>
<td>292.1</td>
<td>301.6</td>
</tr>
<tr>
<td>1R e-like</td>
<td>14.3</td>
<td>247.1</td>
<td>68.4</td>
<td>203.7</td>
</tr>
<tr>
<td>e/$\pi^0$ separation</td>
<td>3.5</td>
<td>23.0</td>
<td>21.9</td>
<td>152.2</td>
</tr>
<tr>
<td>0.4 GeV $&lt; E_{rec} &lt; 1.2$ GeV</td>
<td>1.8</td>
<td>9.3</td>
<td>11.1</td>
<td>123.2</td>
</tr>
</tbody>
</table>

### Sensitivity to $\theta_{13}$

**90% C.L. sensitivities**

- Expected Signal+BG
  \[ (\sin^22\theta_{\mu\nu}=0.05, \Delta m^2=0.003) \]
- Total BG
- BG from $\nu_\mu$

---

Two conditions to make Leptonic CP detectable:

- Solar LMA confirmed
- $\theta_{13} \geq 0.5^0$ (see the following).

A big step from a $\theta_{13}$ search:

\[
\text{from } p(\nu_\mu \rightarrow \nu_e) \neq 0 \text{ to } \begin{cases} 
 p(\nu_\mu \rightarrow \nu_e) \neq p(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \quad \text{(direct CP)} \\
 p(\nu_\mu \rightarrow \nu_e) \neq p(\nu_e \rightarrow \nu_\mu) \quad \text{(T search)} 
\end{cases}
\]

This will require:

1. Neutrino beams of novel conception.
2. Detectors of unprecedented mass
3. Improved control of systematics \(\Rightarrow\) Dedicated experiments on neutrino cross-sections, hadron production, particle ID.
Detecting the $\delta$ phase.

$$A_\delta = [P(\nu_e \rightarrow \nu_\mu, \delta = +\pi/2) - P(\nu_e \rightarrow \nu_\mu, \delta = 0)]/[P(\delta = +\pi/2) + P(\delta = 0)]$$

Compare the measured $\nu_e \rightarrow \nu_\mu$ oscillation probability, as a function of the neutrino energy $E_\nu$, to a "Monte-Carlo" prediction of the spectrum in absence of $\delta$-phase.

**Problems**: it’s model dependent, requires a precise knowledge of the other oscillation parameters, possible degeneracy between solutions and strong correlation with the $\theta_{13}$ parameter.

$$A_{CP}(\delta) = [P(\nu_e \rightarrow \nu_\mu, \delta) - P(\bar{\nu}_e \rightarrow \bar{\nu}_\mu, \delta)]/[P(\nu_e \rightarrow \nu_\mu, \delta) + P(\bar{\nu}_e \rightarrow \bar{\nu}_\mu, \delta)]$$

Compare the appearance of $\nu_\mu$ ($\bar{\nu}_\mu$) in a beam of stored $\mu^+$ ($\mu^-$)decays as a function of the neutrino energy $E_\nu$.

**Problems** It must compete with the fake CP from matter effects. Run time is more than doubled: $\bar{\nu}$ cross sections are half the $\nu$ cross section and matter effects disfavor $\bar{\nu}$ oscillations.

$$A_T(\delta) = [P(\nu_e \rightarrow \nu_\mu, \delta) - P(\nu_\mu \rightarrow \nu_e, \delta)]/[P(\nu_e \rightarrow \nu_\mu, \delta) + P(\nu_\mu \rightarrow \nu_e, \delta)]$$

Compare the appearance of $\nu_\mu$ in a $\nu_e$ beam AND $\nu_e$ in a $\nu_\mu$ beam as a function of the neutrino energy $E_\nu$.

**Problems** Electron charge must be measured in case of a neutrino factory experiment. Systematics of muon and electron efficiencies must be kept to very small values.
A feasibility study of the CERN possible developments

Possible Low Energy Super Beam Layout

Flux intensities at 50 km from the target

<table>
<thead>
<tr>
<th>Flavour</th>
<th>Absolute Flux $\langle E_\nu \rangle$</th>
<th>Rel. Flux (%)</th>
<th>$\langle E_\nu \rangle$ (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_\mu$</td>
<td>$3.2 \cdot 10^{12}$</td>
<td>100</td>
<td>0.27</td>
</tr>
<tr>
<td>$\bar{\nu}_\mu$</td>
<td>$2.2 \cdot 10^{10}$</td>
<td>1.6</td>
<td>0.28</td>
</tr>
<tr>
<td>$\nu_e$</td>
<td>$5.2 \cdot 10^9$</td>
<td>0.67</td>
<td>0.32</td>
</tr>
<tr>
<td>$\bar{\nu}_e$</td>
<td>$1.2 \cdot 10^8$</td>
<td>0.004</td>
<td>0.29</td>
</tr>
</tbody>
</table>

MW-Linac: SPL (Superconducting Proton Linac)

Source Low Energy section DTL Superconducting section dump

Re-use superconducting LEP cavities

Stretching and collimation line
PS / Isolde
Accumulator Ring

45 keV 13m 3 MeV
7 MeV 78m 18MeV
120 MeV 334m 237MeV 389MeV
1.08 GeV 345m

LEP-II

E\text{\tiny{KIN}} = 2.2 \text{ GeV}
Power = 4 \text{ MW}
Protons/s = 10^{16}

23
10 \text{ protons/year}
UNO detector

- Fiducial volume: 440 kton: 20 times SuperK.
- 60,000 PMTs (20") in the inner detector, 15,000 PMTs in the outer veto detector.
- The killer detector for proton decay, atmospheric neutrinos, supernovae neutrinos.
- Energy resolution is poor for multitrack events but quite adequate for sub-GeV neutrino interactions.
- It would be hosted at the Frejus laboratory, 130 km from CERN, in a $10^6 \, m^3$ cavern to be excavated.

Interesting features of a low energy conventional neutrino beam.

\( \nu \) beam:
- \( \langle E_{\nu_\mu} \rangle \approx 0.25 \text{ GeV} \Rightarrow L \sim 100 \text{ km} \Rightarrow \text{NO MATTER EFFECTS.} \)
- \( \nu_e \) production by kaons largely suppressed by threshold effects.
  - \( \nu_e \) in the beam come only from \( \mu \) decays.
    - can be predicted from the measured \( \nu_\mu \) CC spectrum both at the close and at the far detector with a small systematic error of \( \sim 2\% \).

Detector Backgrounds
- Good \( e/\pi^0 \) separation following the large \( \pi^0 \rightarrow \gamma \gamma \) opening angle
- Good \( e/\mu \) separation in a Čerenkov detector because \( \mu \) are produced below or just above the Čerenkov threshold.
- Charm and \( \tau \) production below threshold.

Less exiting aspects of a low energy neutrino beam
- Cross sections are small \( \Rightarrow \) large detectors are necessary in spite of the very intense neutrino beam.
- \( \bar{\nu}_\mu \) production is disfavored for two reasons:
  - Smaller \( \pi^- \) multiplicity at the target.
  - \( \bar{\nu}_\mu /\nu_\mu \) cross section ratio is at a minimum (1/5).
- Visible energy is smeared out by Fermi motion \( \Rightarrow \) Counting Experiment.
A comparison of CP sensitivities: Nufact vs. SuperBeam

CP sensitivity, defined as the capacity to separate at 99%CL max CP ($\delta = \pi/2$) from no CP ($\delta = 0$).

Nufact and SPL-SuperBeam sensitivities computed with the same conditions.

![Graph showing CP sensitivity comparison between Nufact and SuperBeam](image)

The limiting factors for the SuperBeam at small $\theta_{13}$ values are:

- The low flux of $\bar{\nu}$ and their small cross section. This limits the overall statistic.
- The beam related backgrounds that increase the statistical errors, hiding the CP signal.

As an example for $\theta_{13} = 3^\circ$, $\delta m_{12}^2 = 0.7 \times 10^{-4} \text{eV}^2$, $\sin^2 2\theta_{12} = 0.8$:

<table>
<thead>
<tr>
<th>Source</th>
<th>$\nu_\mu$ beam (2 years)</th>
<th>$\bar{\nu}_\mu$ beam (8 years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu$CC (no osc)</td>
<td>36698</td>
<td>23320</td>
</tr>
<tr>
<td>Oscillated events (total)</td>
<td>45</td>
<td>133</td>
</tr>
<tr>
<td>Oscillated events (cp-odd)</td>
<td>-84</td>
<td>53</td>
</tr>
<tr>
<td>Intrinsic beam background</td>
<td>140</td>
<td>101</td>
</tr>
<tr>
<td>Detector backgrounds</td>
<td>36</td>
<td>49</td>
</tr>
</tbody>
</table>

Can the SuperBeam+UNO combination be upgraded?

YES
with a novel concept of neutrino beam: BETA BEAM.
1 ISOL target to produce $^6$He, $100 \, \mu A$, $\Rightarrow 2.9 \cdot 10^{18}$ ion decays/straight session/year. $\Rightarrow \bar{\nu}_e$.

3 ISOL targets to produce $^{18}$Ne, $100 \, \mu A$, $\Rightarrow 1.2 \cdot 10^{18}$ ion decays/straight session/year. $\Rightarrow \nu_e$.

The 4 targets could run in parallel, but the decay ring optics requires:

$$\gamma(Ne^{18}) = 1.67 \cdot \gamma(He^6).$$
Beta Beam Backgrounds

Computed with a full simulation and reconstruction program. (Nuance + Dave Casper).

\[ \pi \text{ from NC interactions} \]

The main source of background comes from pions generated by resonant processes (\(\Delta^{++}\) production) in NC interactions.

Pions cannot be separated from muons.

However the threshold for this process is \(\simeq 400\) MeV.

Angular cuts have not be considered.

\[ \frac{e}{\mu} \text{ mis-identification} \]

The full simulation shows that they can be kept well below \(10^{-3}\) applying the following criteria:

- One ring event.
- Standard SuperK particle identification with likelihood functions.
- A delayed decay electron.

\[ \text{Atmospheric neutrinos} \]

Atmospheric neutrino background can be kept low only by a very short duty cycle of the Beta Beam. A reduction factor bigger than \(10^{3}\) is needed.

This is achieved by building 10 ns long Ion bunches.
Optimizing the Lorentz Boost $\gamma$ (L=130 km): preferred values: $\gamma = 55 \div 75$

Higher $\gamma$ produce more CC interactions
More collimated neutrino production and higher cross sections.

Background rate rises much faster than CC interactions
From resonant pion production in $\nu_e$ NC interactions

$\nu$ flux must match the CP-odd oscillating term

Detection efficiency as function of $\nu$ energy

### Fluxes

- SPL $\nu_\mu$
- SPL $\bar{\nu}_\mu$
- Beta $\bar{\nu}_e$ (He$^6$)
- Beta $\nu_e$ (Ne$^{18}$)

### CC Rates

- SPL $\nu_\mu$
- SPL $\bar{\nu}_\mu$
- Beta $\bar{\nu}_e$ (He$^6$)
- Beta $\nu_e$ (Ne$^{18}$)

<table>
<thead>
<tr>
<th>Fluxes @ 130 km $\nu/m^2/yr$</th>
<th>$&lt;E_\nu&gt;$ (GeV)</th>
<th>CC rate (no osc) events/kton/yr</th>
<th>$&lt;E_\nu&gt;$ (GeV)</th>
<th>Years</th>
<th>Integrated events (440 kton $\times$ 10 years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_\mu$</td>
<td>$4.78 \cdot 10^{11}$</td>
<td>0.27</td>
<td>41.7</td>
<td>0.32</td>
<td>2</td>
</tr>
<tr>
<td>$\bar{\nu}_\mu$</td>
<td>$3.33 \cdot 10^{11}$</td>
<td>0.25</td>
<td>6.6</td>
<td>0.30</td>
<td>8</td>
</tr>
<tr>
<td>Beta $\bar{\nu}_e$ (He$^6$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beta $\nu_e$ (Ne$^{18}$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The SuperBeam - BetaBeam synergy: CP, T and CPT

No other realistic scenario can offer CP, T and CPT searches at the same time in the same detector!!!!

**CP Searches**
- SuperBeam running with $\nu_\mu$ and $\bar{\nu}_\mu$.
- Beta Beam running with $^6\text{He} (\bar{\nu}_e)$ and $^{18}\text{Ne} (\nu_e)$.

**T searches**
- Compare Super Beam $p(\nu_\mu \rightarrow \nu_e)$ with Beta Beam $^{18}\text{Ne} p(\nu_e \rightarrow \nu_\mu)$
- Compare Super Beam $p(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ with Beta Beam $^6\text{He} p(\bar{\nu}_e \rightarrow \bar{\nu}_\mu)$.

**CPT searches**
- Compare Super Beam $p(\nu_\mu \rightarrow \nu_e)$ with Beta Beam $^6\text{He} p(\bar{\nu}_e \rightarrow \bar{\nu}_\mu)$.
- Compare Super Beam $p(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ with Beta Beam $^{18}\text{Ne} p(\nu_e \rightarrow \nu_\mu)$.
The SuperBeam - BetaBeam synergy: a benchmark on $\theta_{13}$ sensitivity

Computed for $\delta_{CP} = 0$ and 5 years running.

- Super Beam $\rightarrow$ 96 × CHOOZ.
- Super Beam + Beta Beam $\rightarrow$ 160 × CHOOZ.

- Beta Beam can measure $\theta_{13}$ both in appearance and in disappearance mode. All the ambiguities can be removed for $\theta_{13} \geq 3.4^\circ$
Beta Beam - Super Beam synergy: CP sensitivity

\[ \delta m_{12}^2 = 7 \cdot 10^{-5} \, eV^2, \quad \theta_{13} = 1^\circ, \quad \delta_{CP} = \pi/2 \]

<table>
<thead>
<tr>
<th>10 yrs (4400 kton/yr)</th>
<th>SuperBeam</th>
<th>Beta Beam</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \nu_\mu )</td>
<td>1.7</td>
<td>0.5</td>
</tr>
<tr>
<td>( \overline{\nu}_\mu )</td>
<td>33.3</td>
<td>84.2</td>
</tr>
<tr>
<td>( \overline{\nu}_e ) (He(^{6}))</td>
<td>-25.5</td>
<td>-11.9</td>
</tr>
<tr>
<td>( \overline{\nu}_e ) (Ne(^{18}))</td>
<td>16.9</td>
<td>41</td>
</tr>
</tbody>
</table>

| CC events (no osc, no cut) | 36698 | 23320 |
| Total oscillated | 1.7 | 0.5 |
| CP-Odd oscillated | -25.5 | -11.9 |
| Beam backgrounds | 141 | 113 |
| Detector backgrounds | 37 | 50 |
| Statistical Error | 13.4 | 1.5 |
| Error on \( \theta_{23} \) | 2.1 | 0.5 |
| Error on \( \delta m_{12}^2 \) | 2.8 | 0.3 |
| Total Error | 13.9 | 1.7 |

The asymmetric statistics and background rates in the $\nu_e$ and $\bar{\nu}_e$ beams produce an asymmetric response to the positive and negative values of $\delta$.

Even if the matter effects are negligible, the $p(\nu_\mu \to \nu_e)$ formula contains odd $\text{sign}(\delta m_{13}^2)$ terms.

The change of $\text{sign}(\delta m_{13}^2)$ produces non negligible changes in the oscillation formula. No attempt made so far to fit $\text{sign}(\delta m_{13}^2)$, $\theta_{13}$ and $\delta$ at the same time.

Results are shown in the following for positive values of $\delta$ and $\text{sign}(\delta m_{13}^2)$.

- $\sin^2 2\theta_{23} = 1.0$
- $\delta m_{23}^2 = 2.5 \cdot 10^{-3} \text{ eV}^2$.
- $\sin^2 2\theta_{12} = 0.8$
A comparison of CP sensitivities: Beta Beam vs. Nufact

CP sensitivity, defined as the capacity to separate at 99%CL max CP ($\delta = \pi/2$) from no CP ($\delta = 0$). Nufact sensitivity as computed in J. Burguet-Castell et al., Nucl. Phys. B 608 (2001) 301:

- 50 GeV/c $\mu$.
- $2 \cdot 10^{20}$ useful $\mu$ decays/year.
- 5+5 years.
- 2 iron magnetized detectors, 40 kton, at 3000 and 7000 km.
- Full detector simulation, including backgrounds and systematics.
Some comments about the comparison

The sensitivity computation depends from many implicit assumptions, input parameters, degeneracy treatment, statistical methods, tricks, bugs etc. A fair comparison should be made by the same group using the same methods for the different facilities (a call for collaboration ...)

The plot doesn’t tell anything about the fits in a arbitrary \((\theta_{13}, \delta)\) point.

\begin{align*}
\theta_{13} &= 0.80, \quad \Delta m^2_{223} = 2.5 \times 10^{-3}, \quad \sin^2 \theta_{13} = 0.90, \quad L = 130 \\
\theta_{13} &= 70, \quad \Delta m^2_{223} = 2.5 \times 10^{-3}, \quad \sin^2 \theta_{13} = 0.90, \quad L = 130
\end{align*}

The small \(\theta_{13}\) region is particularly delicate: going the absolute probabilities down to zero, it’s very sensitive to:

- Background levels.
- Statistical treatment of data
- Input parameters and their errors.

In the large \(\theta_{13}\) region the CP asymmetry is small. This favours the Super-Beta Beams, because they don’t have to compete with matter effects.
Conclusions

The next ($4^{th}$, $5^{th}$?) generation of accelerator $\nu$ oscillation experiments will address the problem of measuring $\theta_{13}$

Then the difficult, long and very expensive searches for Leptonic CP violations

Beta Beam is a (CERN based) realistic facility that could profit of very deep synergies with:
- Nuclear physicists aiming at a very intense source of radioactive ions.
- A gigantic water Cerenkov detector with great physics potential in its own.

The Super-Beta Beams combination can address $\delta_{CP}$ discovery with a sensitivity similar to the Neutrino Factory having the distinctive possibility of:
- Combine CP, T and CPT searches
- Use $\nu_e$ disappearance to solve all the ambiguities for reasonable large values of $\theta_{13}$.