“Future Neutrino Oscillations”

- Introduction.
- The hunting for $\theta_{13}$
- Leptonic CP violation
- Neutrino Factories, SuperBeams, Beta Beams
ν oscillations are the most important discovery in hep of the last 15 years.

They measure foundational parameters of the standard model. Mixing angles, neutrino masses and the CP phase $\delta_{CP}$ are foundational 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: bariogenesis, leptogenesis, galaxies formation, dynamic of supernovae explosion, power spectrum of energy anisotropies, etc.

They open the perspective of the measure of leptonic CP violation.
Most of the parameters are waiting to be measured

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Measured</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta m^2_{23}$</td>
<td>✔️</td>
<td></td>
</tr>
<tr>
<td>$\theta_{23}$</td>
<td>✔️</td>
<td></td>
</tr>
<tr>
<td>$\delta m^2_{12}$</td>
<td>✔️</td>
<td></td>
</tr>
<tr>
<td>$\theta_{12}$</td>
<td>✔️</td>
<td></td>
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<tr>
<td>$\theta_{13}$</td>
<td></td>
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<tr>
<td>$\delta_{CP}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\sum m_v$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mass hierarchy</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dirac/Majorana</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
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 (VERY DIFFERENT from CKM matrix!)

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

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

$\theta_{13}$ drives $\nu_\mu \to \nu_e$ subleading transitions $\Rightarrow$

the necessary milestone for any subsequent search:

neutrino mass hierarchy and leptonic CP violation searches.

M. Mezzetto, "Future Neutrino Oscillations », Moriond, March 17, 2003. . 4
Subleading $\nu_\mu - \nu_e$ oscillations

$p(\nu_\mu \rightarrow \nu_e)$ developed at the first order of matter effects

\[
p(\nu_\mu \rightarrow \nu_e) =
\begin{align*}
&4c_{13}^2s_{13}^2s_{23}^2 \sin^2 \frac{\Delta m_{13}^2 L}{4E} \quad \theta_{13} \text{ driven} \\
&+ 8c_{13}^2s_{12}s_{13}s_{23}(c_{12}c_{23}\cos\delta - s_{12}s_{13}s_{23}) \cos \frac{\Delta m_{23}^2 L}{4E} \sin \frac{\Delta m_{13}^2 L}{4E} \sin \frac{\Delta m_{12}^2 L}{4E} \quad \text{CP - even} \\
&- 8c_{13}^2c_{12}c_{23}s_{12}s_{13}s_{23} \sin \delta \sin \frac{\Delta m_{23}^2 L}{4E} \sin \frac{\Delta m_{13}^2 L}{4E} \sin \frac{\Delta m_{12}^2 L}{4E} \quad \text{CP - odd} \\
&+ 4s_{12}^2c_{13}^2 \{c_{13}^2c_{23} + s_{12}^2s_{23}^2 - 2c_{12}c_{23}s_{12}s_{23}s_{13}\cos\delta\} \sin \frac{\Delta m_{12}^2 L}{4E} \quad \text{solar driven} \\
&- 8c_{12}^2s_{13}^2s_{23}^2 \cos \frac{\Delta m_{23}^2 L}{4E} \sin \frac{\Delta m_{13}^2 L}{4E} \frac{aL}{4E}(1 - 2s_{13}^2) \quad \text{matter effect (CP odd)}
\end{align*}
\]

(1)

where \( a = \pm 2\sqrt{2}G_F n_e E_\nu = 7.6 \cdot 10^{-5} \rho [g/cm^3] E_\nu [GeV] \quad [eV^2] \)

At the first order, neglecting matter effects and CP:

\[
P(\nu_\mu \rightarrow \nu_e) \propto \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \frac{\Delta m_{23}^2 L}{4E}
\]
Why subleading transitions?

\[ <E > = 1.00 \text{ GeV} \]
\[ \sin^2(2\theta_{13}) = 0.01 \]
\[ \sin^2(2\theta_{12}) = 0.8 \]
\[ \delta m^2_{13} = 2.5 \times 10^{-3} \]
\[ \delta m^2_{12} = 7 \times 10^{-5} \]
\[ \delta = 0 \]

Solar peak

\[ \theta_{13} \text{ peak} \]

JHF equivalent baseline

CNGS equivalent baseline

Neutrino Oscillation Experiments

Palo Verde
LSND

Minos
Mini Boone
???? Numi off-axis ????

SNO

Kamland
K2K
JHF Fase I
Super Kamiokande

Fase II (?)


Chorus
Nomad
Macro
GNO

Chooz
Borex

Opera
Icarus
Nufact ?
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).
The neutrino beam line is not yet approved. Approval is expected by mid 2003. Start of data taking expected by 2007.

<table>
<thead>
<tr>
<th>K2K</th>
<th>JHF</th>
</tr>
</thead>
<tbody>
<tr>
<td>$6 \cdot 10^{12}$</td>
<td>$3 \cdot 10^{14}$</td>
</tr>
<tr>
<td>2.2 s</td>
<td>3.4 s</td>
</tr>
<tr>
<td>12 GeV</td>
<td>50 GeV</td>
</tr>
<tr>
<td>40</td>
<td>2200</td>
</tr>
<tr>
<td>1.5</td>
<td>0.8</td>
</tr>
</tbody>
</table>
Precision measure of the atmospheric parameters:

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

Ratio of the measured $\nu_\mu$ spectrum with respect to the non-oscillation prediction in case of oscillation (5 years).
5 years, $\delta m^2 = 3 \times 10^{-3}$ eV$^2$ and $\sin^2 2\theta_{\mu e} = 0.05$

<table>
<thead>
<tr>
<th>OAB 2</th>
<th>$\nu_\mu$ C.C.</th>
<th>$\nu_\mu$ N.C.</th>
<th>Beam $\nu_e$</th>
<th>Oscillated $\nu_e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Generated in F.V.</td>
<td>10713.6</td>
<td>4080.3</td>
<td>292.1</td>
<td>301.6</td>
</tr>
<tr>
<td>2) 1R e-like</td>
<td>14.3</td>
<td>247.1</td>
<td>68.4</td>
<td>203.7</td>
</tr>
<tr>
<td>3) $e/\pi^0$ separation</td>
<td>3.5</td>
<td>23.0</td>
<td>21.9</td>
<td>152.2</td>
</tr>
<tr>
<td>4) $0.4 \text{ GeV} &lt; E_{\text{rec}} &lt; 1.2 \text{ GeV}$</td>
<td>1.8</td>
<td>9.3</td>
<td>11.1</td>
<td>123.2</td>
</tr>
</tbody>
</table>

![Graph](image-url)
Two conditions to make Leptonic CP detectable:

- Solar LMA confirmed (DONE by Kamland !)
- $\theta_{13} \geq 0.20$ (see the following).

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

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

This will require:

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

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

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.

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

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.

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

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.
Upgrade the proton driver from 0.75 MW to 4 MW
Upgrade SuperKamiokande by a factor 40 $\implies$ HyperKamiokande

\[ \rho = 2.8 \text{g/cm}^2, \quad L = 300 \text{km}, \]
\[ \Delta m^2_{23} = 3 \times 10^{-3}, \quad \theta_{23} = \pi/4, \]
\[ \Delta m^2_{12} = 1 \times 10^{-3}, \quad \theta_{12} = \pi/8, \]
\[ \sin^2 2\theta_{13} = 0.01 \]
SuperBeams (2) SPL-SuperBeam at CERN

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</th>
<th>Rel. Flux</th>
<th>$\langle E_\nu \rangle$</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>$\overline{\nu}_\mu$</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>$\overline{\nu}_e$</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**: DTL, CC-DTL
- **Superconducting section**: LEP-II

### Key Features
- **Energy Levels**:
  - 45 keV
  - 7 MeV
  - 120 MeV
  - 1.08 GeV
  - 2.2 GeV
- **Lengths**:
  - 13 m
  - 78 m
  - 334 m
  - 345 m

### Re-use superconducting LEP cavities

### Physical Parameters
- **$E_{kin}$**: 2.2 GeV
- **Power**: 4 MW
- **Protons/s**: $10^{16}$
- **Protons/year**: 23

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Super Beams and Leptonic CP (2) SPL SuperBeam

- Assume the upper value of LMA: \( \delta m_{12}^2 = 10^{-4} \ eV^2 \)
- The CP violating observable is \( \frac{N(e^+)-N(e^-)}{N(e^+)+N(e^-)} \), corrected for the different fluxes and cross sections. Here \( e^- (e^+) \) indicates all the e-like events selected with the \( \pi^+ (\pi^-) \) focused beam.
- Run for 2 years with the \( \pi^+ \) focused beam and 10 years with the \( \pi^- \) focused beam, to compensate the unfavorable \( (\bar{\nu}_e/\nu_e) \) cross section ratio
- Fit simultaneously \( \delta \) and \( \theta_{13} \) on \( N(e^+) \) and \( N(e^-) \) separately.
- Take \( \theta_{13} = 5^\circ, 8^\circ, 10^\circ \ (\sin^2 (2\theta_{13}) = 0.03, 0.08, 0.12) \) and a maximally violating CP phase, \( \delta = \pm 90^\circ \)

\[ \downarrow \text{(see figure)} \]

- CP sensitivity does not worsen very much with \( \theta_{13} \).
- In the 40 kton detector, 90\% CL, a maximally violating CP phase \( (\delta = \pm 90^\circ) \) would be just distinguishable from a non violating CP phase \( (\delta = 0^\circ) \).
- With the 400 kton detector the prospects to observe CP violation are much improved.
Preliminary CP sensitivity

40 kton water detector

400 kton water detector
Introducing Neutrino Factories

• The dream beam of every neutrino physicist.
• The first case in which the whole neutrino production chain, including proton acceleration, is accounted on the budget of the neutrino beam construction.
• Beam intensities predicted to be two orders of magnitude higher than in traditional neutrino beams.
• No hadronic MonteCarlos to predict neutrino fluxes.
• Oscillated events $N_{osc}$ at a distance $L$:

$$N_{osc} \sim \text{Flux} \times \sigma_{\nu} \times P_{osc} \sim \frac{E_{\nu}^3}{L^2} \sin^2 \frac{L}{E_{\nu}} \propto E_{\nu}$$

$N_{osc}$ increases linearly with the beam energy. Optimal energy: as high as possible.
• Neutrino beams from muon decays contain ONLY two types of neutrinos of opposite helicities ($\bar{\nu}_e \nu_\mu$ or $\nu_e \bar{\nu}_\mu$). It is possible to search for $\nu_\mu \rightarrow \nu_e$ transitions characterized by the appearance of WRONG SIGN MUONS, without intrinsic beam backgrounds.
In a conventional neutrino beam, neutrinos are produced by pions (and kaons) generated by the proton beam interaction on the target. Given the short life time of the pions \((2.6 \cdot 10^{-8} \text{ s})\), they can only be focused (and charge selected) by means of magnetic horns. Then they are let to decay in a decay tunnel, short enough to prevent most of the muon decays. Hard to predict the details of the neutrino beam, since it derives from hadronic interactions. At least four neutrino flavours are present \(\nu_\mu, \bar{\nu}_\mu, \nu_e, \bar{\nu}_e\).

In a neutrino factory pions decay inside a solenoid, and most of the muons are collected. Muons are longeval enough \((2.2 \cdot 10^{-6} \text{ s})\) to open the possibility to collimate and accelerate them to the desired momentum. Much more efficient way to produce neutrinos BUT a real challenge to accelerate, in a very short time, particles generated with a large emittance.

Two possible solutions,
- Ionization cooling (stochastic cooling is too slow).
- Very large aperture accelerators (FFAG)

Both solutions have never been implemented and require R&D.

No need of hadronic MC to predict the fluxes and only two \(\nu\) flavours in the beam.
The basic concept of a neutrino factory (the CERN scheme)

- High power (4 MW) proton beam onto a liquid mercury target.
- System for collection of the produced pions and their decay products, the muons.
- Energy spread and transverse emittance have to be reduced: “phase rotation” and ionization cooling
- Acceleration of the muon beam with a LINAC and Recirculating Linear Accelerators.
- Muons are injected into a storage ring (decay ring), where they decay in long straight sections in order to deliver the desired neutrino beams.
- **GOAL:** $\geq 10^{20}$ $\mu$ decays per straight section per year
**MICE**

- **Muon Ionisation Cooling Experiment**
- Collaboration of 40 institutes from Europe, Japan, US
- LOI recently reviewed by international panel at RAL
- Enthusiastically supported MICE
- Asked for a proposal by end 2002

**Construction:** 2002-2004

**First beam:** 2004/5

**New collaborators welcome!**
Detector

Iron calorimeter
Magnetized
Charge discrimination
B = 1 T
R = 10 m, L = 20 m
Fiducial mass = 40 kT

Also: L Arg detector: magnetized ICARUS
Wrong sign muons, electrons, taus and NC evts

Events for 1 year

<table>
<thead>
<tr>
<th>Baseline</th>
<th>CC</th>
<th>e CC</th>
<th>signal ($\sin^2 \theta_{13} = 0.01$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>732 Km</td>
<td>$3.5 \times 10^7$</td>
<td>$5.9 \times 10^7$</td>
<td>$1.1 \times 10^5$</td>
</tr>
<tr>
<td>3500 Km</td>
<td>$1.2 \times 10^6$</td>
<td>$2.4 \times 10^6$</td>
<td>$1.0 \times 10^5$</td>
</tr>
</tbody>
</table>

(cf 40 in JHF-SK)

Alain Blondel, Venice, March 2003
Precision measurements at the Neutrino Factories

Improve up to 4 orders of magnitude the Chooz sensitivity on $\theta_{13}$

Measure the $\Delta m_{23}^2$ sign

Measure the atmospheric parameters at 1%.

- Matter effects must be separated from genuine CP-odd effects.
- Strong correlations in the simultaneous fit of $\theta_{13}$ and $\delta$.
- The errors of all the other mixing matrix parameters influence the precision of the measure of $\delta$. On the other hand a $\nu F$ can measure $\theta_{23} e^{\Delta m_{23}^2}$ at 1% through the $\nu_\mu$ disappearance.
- Backgrounds and efficiencies computed for a 40 kton large magnetic detector (full simulation, full reconstruction).

Two detectors at two different baselines are the optimal solution for the Leptonic CP detection. Best combination: 3000+7000 km.

CP sensitivity, defined as the capacity to separate at 99%CL max CP ($\delta = \pi/2$) from no CP ($\delta = 0$) computed as function of the two critical parameters $\theta_{13}$ and $\delta m_{12}^2$.
SuperBeam vs. Nufact

**PROS**

- Negligible matter effects: it can be run at the optimal baseline
- Negligible matter effects: reduced correlations between $\theta_{13}$ and $\delta$
- Less influenced by uncertitudes on the other mixing matrix parameters

**CONS**

- Smaller CC rate
- Higher systematic errors
- Intrinsic beam contamination
A comparison of CP sensitivities of 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.

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

- The low flux of $\nu$ 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 $\theta_{13} = 3^\circ$, $\delta m_{12}^2 = 0.7 \cdot 10^{-4} \text{ eV}^2$, $\sin^2 2\theta_{12} = 0.8$:

<table>
<thead>
<tr>
<th></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.
Muons are not the only unstable particles that decay into neutrinos, there are also $\beta$ emitter nuclei.

As for the neutrino factory the neutrino spectrum is completely defined by the parent decay properties and by the Lorentz boost $\gamma$.

To produce a Beta Beam:

1. Produce $\beta$ radioactive ions with a lifetime of the order of $\sim 1$ s. Best candidate: $^6$He, $\beta^-$ emitter $(E_0 \simeq 3.5 \text{ MeV}, T/2 \simeq 0.8 \text{ s})$.
2. Accelerate them to high energies in a conventional way (PS).
3. Accumulate them in a decay ring with long straight sections (SPS like).
4. **Just ONE neutrino flavour is produced:** $\nu_e$ or $\overline{\nu}_e$.

CERN ISOLDE, if injected by SPL, could produce $7 \cdot 10^{13}$ $^6$He/s by using 1/8 of the SPL duty cycle.

PS + SPS (modified to have 2.5 km long straight sections). Today they are already accelerating heavy ions up to $\gamma = 150$.

The complexity of the FAST muon acceleration is absent (simply $4 \times 10^5$ more time).

It is technologically feasible to build neutrino beams with intensities comparable with SuperBeams.

CERN is the only place with the complete Beta Beam know-how:

- Isotopes production (ISOLDE)
- Ion acceleration (PS+SPS+LHC)
- Neutrino Experiments (EP)
The SuperBeam - BetaBeam synergy

Run two neutrino beams to the same detector at the same time.

Both beams need SPL, but the BetaBeam requires at most 3% of the SPL
protons $\rightarrow$ the two beams can run together.

Both beams produce sub-GeV neutrinos $\rightarrow$ same baseline and same
detector.

CP, T and CPT searches at the same time !!!!
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 $^6$He ($\nu_e$) and $^{18}$Ne ($\nu_e$).

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

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

In case of small values of $\theta_{13}$ the most powerful combination to discover Leptonic CP would be however a single T search with neutrinos (SuperBeam $\nu_\mu$ with BetaBeam $\nu_e$).
The SuperBeam - BetaBeam synergy: results

A test point running SuperBeam with $\nu_\mu$ for 10 years and Beta Beam with $\nu_e$ for 10 years.

$\theta_{13} = 3^\circ$, $\delta m_{12}^2 = 0.6 \cdot 10^{-4} \text{eV}^2$:

<table>
<thead>
<tr>
<th></th>
<th>SuperBeam</th>
<th>Beta Beam</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 yrs (4400 kton/yr)</td>
<td>$\gamma = 75$</td>
<td></td>
</tr>
<tr>
<td>CC events (no osc, no cut)</td>
<td>183488</td>
<td>18583</td>
</tr>
<tr>
<td>Total oscillated</td>
<td>263</td>
<td>64</td>
</tr>
<tr>
<td>CP-Odd oscillated</td>
<td>-360</td>
<td>22</td>
</tr>
<tr>
<td>Beam background</td>
<td>705</td>
<td>0</td>
</tr>
<tr>
<td>Detector bkg.</td>
<td>181</td>
<td>10</td>
</tr>
</tbody>
</table>

How two particular solutions can be improved by the combination of Super + Beta Beam (99%CL curves)
Final CP sensitivity.

CONCLUSIONS

- Still a long trip to the leptonic CP violation.
- Next generation experiments probably will tell us if the experimental conditions for the search of leptonic CP violation are fulfilled and how difficult the search.
- Neutrino Factories are the most powerful instrument for this searches.
- The first stage of Neutrino Factories, neutrino SuperBeams, could provide the necessary informations for the final searches.
- Beta Beams, a truly new concept, could represent a powerful complementary alternative to Neutrino Factories.
- **If you are interested in Beta Beams you may have a look at the workshop starting tomorrow here at Les Arcs.**