“Future CP violation searches in the lepton sector, accelerator based”

- Introduction
- Super Beams
- Beta Beams
- Neutrino Factories

A bottom-up perspective.

International Workshop on “Fundamental Symmetries: from nuclei and neutrinos to the Universe”,
ECT* Trento, 25 - 29 June 2007
Introduction
Near future neutrino oscillations experiments: T2K, Double Chooz (Noνa, Daya Bay), will not be enough to exhaust neutrino oscillations searches: they will be unable to unambiguously measure mass hierarchy and leptonic CP violation, whatever value of $\theta_{13}$.

A new generation of neutrino oscillation experiments will be needed. It could be based again on conventional neutrino beams (SuperBeams) or on neutrino beams of new concept: Beta Beams and/or Neutrino Factories.

Europe it could be the site of next to next generation experiments.
Introduction

Near future neutrino oscillations experiments: T2K, Double Chooz (No\(\nu\)a, Daya Bay), will not be enough to exhaust neutrino oscillations searches: they will be unable to unambiguously measure mass hierarchy and leptonic CP violation, whatever value of \(\theta_{13}\).

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Europe it could be the site of next to next generation experiments.

A list of frequently asked questions:

- Shouldn’t we wait to know \(\theta_{13}\) before proposing these facilities?
- Is it possible to design an optimal facility for a simultaneous measure of \(\theta_{13}\), \(\delta_{\text{CP}}\) and \(\text{sign}(\Delta m^2)\) ?
- Is it possible to design an optimal facility for leptonic CP violation searches regardless of the value of \(\theta_{13}\) ?
- Do we have a clear picture of the R&D, timescales, costs and performances of the proposed new facilities?
- Is it Europe big and coherent enough to propose one of the new facilities?
Most of the neutrino oscillation parameters are waiting to be measured

\[ \delta m_{12}^2 \quad \text{SOLARS+KAMLAND} \quad \delta m_{12}^2 = (7.9 \pm 0.7) \times 10^{-5} \text{eV}^2 \]

\[ \theta_{12} \quad \text{SOLARS+KAMLAND} \quad \sin^2 (2\theta_{12}) = 0.82 \pm 0.055 \]

\[ \delta m_{23}^2 \quad \text{ATMOSPHERICS} \quad \delta m_{23}^2 = (2.4 \pm 0.4) \times 10^3 \text{eV}^2 \]

\[ \theta_{23} \quad \text{ATMOSPHERICS} \quad \sin^2 (2\theta_{23}) > 0.95 \]

\[ \theta_{13} \quad \text{CHOOZ LIMIT} \quad \sin^2 2\theta_{13} < 14^0 \]

\[ \delta_{CP} \quad \text{LSND/Steriles} \]

\[ \Sigma m_\nu \quad \text{Mass hierarchy} \quad \Sigma m_\nu < 6.6 \text{eV} \]

\[ \text{Dirac/Majorana} \]

Addressed by a SuperBeam/Nufact experiment.
Sub leading $\nu_\mu - \nu_e$ oscillations

$$p(\nu_\mu \rightarrow \nu_e) = 4 c_{13}^2 s_{13}^2 s_{23}^2 \sin^2 \frac{\Delta m_{13}^2 L}{4E} \times \left[ 1 \pm \frac{2a}{\Delta m_{13}^2} \left( 1 - 2s_{13}^2 \right) \right] \theta_{13} \text{ driven}$$

$$+ 8 c_{13}^2 s_{12} s_{13} s_{23} (c_{12} c_{23} \cos \delta - s_{12} s_{13} s_{23}) \cos \frac{\Delta m_{23}^2 L}{4E} \sin \frac{\Delta m_{13}^2 L}{4E} \sin \frac{\Delta m_{12}^2 L}{4E} \text{ CPeven}$$

$$+ 8 c_{13}^2 c_{12} c_{23} s_{12} s_{13} s_{23} \sin \delta \sin \frac{\Delta m_{23}^2 L}{4E} \sin \frac{\Delta m_{13}^2 L}{4E} \sin \frac{\Delta m_{12}^2 L}{4E} \text{ CPodd}$$

$$+ 4 s_{12}^2 c_{13}^2 \left\{ c_{12}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2 c_{12} c_{23} s_{12} s_{23} s_{13} \cos \delta \right\} \sin \frac{\Delta m_{12}^2 L}{4E} \sin \frac{\Delta m_{13}^2 L}{4E} \sin \frac{\Delta m_{23}^2 L}{4E} (1 - 2s_{13}^2) \text{ matter effect (CP odd)}$$

$\theta_{13}$ discovery requires total probability ($\propto \sin^2 2\theta_{13}$) greater than solar driven probability

Leptonic CP discovery requires

$$A_{CP} = \frac{P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}{P(\nu_\mu \rightarrow \nu_e) + P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)} \neq 0$$

Status after the first and second generation: $\theta_{13}$

- **MINOS**: Chooz Excluded
- **World Limit 2006**
- **OPERA**
- **Double Chooz**
- **T2K**

**World limit**

- Computed with: $\delta_{CP}=0$, $\text{sign}(\Delta m^2)=+1$

**T2K**: Start in 2009, latest default beam power curve.

**NO$\nu$A**: Start in 2011, 20 kton, $6 \cdot 10^{20}$ pot/yr

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Status after the first and second generation: $\delta_{CP}$

No hope to see any CP signal at $3\sigma$


\begin{align*}
\text{T2K + NOvA} & \quad 3 \text{ yrs neutrinos + 3 yrs anti-neutrinos} \\
\text{T2K + NOvA + Reactor-II} & \quad \text{T2K + NOvA: 3 yrs neutrinos}
\end{align*}

\begin{align*}
\Delta \chi^2 &= 1.1 \\
\Delta \chi^2 &= 0.8
\end{align*}

(dotted lines: $3\sigma$, solid are 90%CL)

To address leptonic CP violation: improve of at least one order of magnitude the sensitivity of $\sin^2 2\theta_{13}$; two order of magnitudes more neutrinos !!!

...and mass hierarchy

90% CL determination of mass hierarchy
$\Delta m^2 = 2.4 \times 10^{-3} \text{ eV}^2$

From O. Mena et al. hep-ph/0609011

Excluded by global fits: T. Schwetz hep-ph/0510331

T2K+Nova 5 years neutrinos

Proposals based on upgrades of existing facilities:

- T2K $\Rightarrow$ T2HK or T2KK
- No$\nu$a $\Rightarrow$ Super No$\nu$a
- CNGS $\Rightarrow$ off-axis CNGS fired on a gigantic liquid argon detector
- AGS Brookhaven $\Rightarrow$ wide band beam fired on a gigantic water Cerenkov detector.

Proposals based on new facilities

- CERN-SPL SuperBeam
Upgrade the proton driver from 0.75 MW to 4 MW
Upgrade SuperKamiokande by a factor $\sim 20 \Rightarrow$ HyperKamiokande
Both upgrades are necessary to address leptonic CP searches.

The detector would have valuable physics potential in proton decay, SN neutrinos, solar neutrinos.
Its cost: $\sim 0.5 \text{ G$}
Systematics at 2% are difficult
4 MW at 50 GeV/c are difficult
Targetry and optics at 4 MW are difficult and will probably require some compromise


The MODULAr project

- First study of off-axis CNGS to a liquid argon detector by A. Meregaglia and A. Rubbia, JHEP 0611 (2006) 032
- MODULAr is a LoI by the ICARUS collaboration: B. Baibussinov et al., arXiv:0704.1422 [hep-ph].
  - Have $1.2 \times 10^{20}$ pot/yr at the CNGS (about 3 times more than today).
  - Design a new optics (actually cloned by the NuMI optics) to reduce the mean neutrino energy below 10 GeV.
  - Dig a new cavern, shallow depth, at the baseline of 732 km, 10 km off-axis CNGS direction.
  - Install a 20 kton liquid argon detector.
  - Additional details by the recent Cryodet2 workshop at LNGS: http://cryodet.lngs.infn.it/
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  $1.2 \cdot 10^{20}$ pot/yr requires hardware upgrades of the SPS injection chain and the suppression of the fixed target experiments at CERN.
- According to A. Meregaglia and A. Rubbia a CP sensitivity comparable with T2HK can be reached with $4.2 \cdot 10^{20}$ pot/yr and a 100 kton liquid argon detector.
SuperBeams - SPL $\nu$ beam at CERN

- A 3.5 GeV, 4MW Linac: the SPL.
- A liquid mercury target station capable to manage the 4 MW proton beam. R&D required.
- A conventional neutrino beam optics capable to survive to the beam power, the radiation and the mercury. Already prototyped.
- Up to here is the first stage of a neutrino factory complex.
- A sophisticated close detector to measure at 2% signal and backgrounds.
- A megaton class detector under the Frejus, L=130 km: Memphys.
In the middle of the Frejus tunnel at a depth of 4800 m.w.e a preliminary investigation shows the feasibility to excavate up to five shafts of about 250,000 m$^3$ each ($\Phi = 65 \, m$, full height=80 m).

Fiducial of 3 shafts: 440 kton.

30% coverage by using 12" PMT’s from Photonis, 81k per shaft (with the same photostatistics of SuperKamiokande with 40% coverage)
A coordinated European effort aimed towards conceptual designs for European large underground detectors. Physics focus: proton decay, low energy neutrino astronomy, long baseline neutrino beam.

Three detection techniques are currently investigated:

- Water Cerenkov imaging, $\sim 500$ kton, with synergy with HK (Japan) and UNO (USA).
- Liquid argon time-projection chamber, $\sim 100$ kton. Technology pioneered in Europe by the ICARUS R&D programme.
- Liquid scintillator, $\sim 50$ kton connected to Borexino R&D programme

Feasibility studies for site excavation are mandatory to build the required infrastructure to host these very large detectors, also under controlled cost boundaries.

A request to a European FP7 Design Study has been submitted.
The merits of the “short baselines”

• Absolutely negligible matter effects: the cleanest possible environment for direct leptonic CP violation and $\theta_{13}$ searches.

• Almost all the events are quasi elastics: very reduced problems from the QE-not QE ratios.

• Energy shape it’s not a problem, a reasonable binning can be achieved (see later slides).

• In principle the same energy of a SPS based beta beam. The two beams could be fired to the same detector.

On the other hand

• Mass hierarchy cannot be directly measured. A not trivial sensitivity on $\text{sign}(\Delta m^2)$ can however been recovered combining accelerator neutrino signals with the atmospherics’ (see later slides).

• Small cross sections, loosely known and with important influence of nuclear effects.
Conventional neutrino beams are going to hit their ultimate limitations.

In a **conventional neutrino beam**, neutrinos are produced SECONDARY particle decays (mostly pions and kaons). Given the short life time of the pions ($2.6 \cdot 10^{-8}$ 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.

- Besides the main component ($\nu_\mu$) at least 3 other neutrino flavors are present ($\bar{\nu}_\mu$, $\nu_e$, $\bar{\nu}_e$), generated by wrong sign pions, kaons and muon decays. $\nu_e$ contamination is a background for $\theta_{13}$ and $\delta$, $\bar{\nu}_\mu$ contamination dilutes any CP asymmetry.
- Hard to predict the details of the neutrino beam starting from the primary proton beam, the problems being on the secondary particle production side.
- Difficult to tune the energy of the beam in case of ongoing optimizations.
All these limitations are overcome if secondary particles become primary.

Collect, focus and accelerate the neutrino parents at a given energy. This is impossible within the pion lifetime, but can be tempted within the muon lifetime (Neutrino Factories) or within some radioactive ion lifetime (Beta Beams):

- Just one flavor in the beam
- Energy shape defined by just two parameters: the endpoint energy of the beta decay and the $\gamma$ of the parent ion.
- Flux normalization given by the number of ions circulating in the decay ring.
- Beam divergence given by $\gamma$.

The full $^6$He flux MonteCarlo code

```plaintext
Function Flux(E)
Data Endp/3.5078/
Data Decays /2.9E18/
ye=me/EndP
c ...For ge(ye) see hep-ph0312068
ge=0.0300615
2gE0=2*gamma*EndP
c ... Kinematical Limits
If(E.gt.(1-ye)*2gE0)THEN
   Flux=0.
   Return
Endif

Flux=Decays*gamma**2/(pi*L**2*ge)*(E**2*(2gE0-E))/+
     2gE0**4*Sqrt((1-E/2gE0)**2-ye**2)
Return
```

• 1 ISOL target to produce He$^{6}$, 100 $\mu$A, $\Rightarrow$ $2.9 \cdot 10^{18}$ ion decays/straight session/year. $\Rightarrow \bar{\nu}_e$.

• 3 ISOL targets to produce Ne$^{18}$, 100 $\mu$A, $\Rightarrow$ $1.1 \cdot 10^{18}$ ion decays/straight session/year. $\Rightarrow \nu_e$.

• These fluxes apply if the two ions are run separately.
C. Rubbia et al., hep-ph/0602032
C. Rubbia hep-ph/0609235

- It could deliver up to two order of magnitudes more radioactive ions than the Eurisol targets.
- $^8$B and $^8$Li have a Q factor about 8 times larger than $^6$He and $^{18}$Ne, allowing higher neutrino energies for the same $\gamma$ value (on the other hand for the same neutrino energy the relative flux is lower by $1/\gamma$ due to the smaller Lorenz boost.)
- They have a more favorable Z/A factor, allowing for higher $\gamma$ at the same accelerator.
- If realistic, this production method could bring to a completely different Beta Beam optimization scheme.
The pion background: a potential Beta Beam killer?

The pions generated in NC events can fake the muon signal. **They are the main concern.**

To estimate these backgrounds

- Generate CC and NC events with Nuance
- Count events with a pion and no other track above the Čerenkov threshold (single ring events)
- Apply the particle identification cuts of SuperKamiokande
- Follow pions in water (Geant 3.21) to compute the probability for $\pi \rightarrow \mu \rightarrow e$.
- Reconstruct the neutrino energy from the survived pions treating them as the signal muons
The pion background (cont.)

Pion production cross sections and nuclear effects can heavily change these numbers and the overall experimental sensitivity. Potentially the worst source of systematic errors.
### Oscillation signals


<table>
<thead>
<tr>
<th></th>
<th>(\beta B)</th>
<th>SPL</th>
<th>T2HK</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(\delta_{\text{CP}} = 0)</td>
<td>(\delta_{\text{CP}} = \pi/2)</td>
<td>(\delta_{\text{CP}} = 0)</td>
</tr>
<tr>
<td>(\nu) appearance</td>
<td>(\sin^2 2\theta_{13} = 0)</td>
<td>143</td>
<td>600</td>
</tr>
<tr>
<td></td>
<td>(\sin^2 2\theta_{13} = 10^{-3})</td>
<td>72</td>
<td>81</td>
</tr>
<tr>
<td></td>
<td>(\sin^2 2\theta_{13} = 10^{-2})</td>
<td>310</td>
<td>339</td>
</tr>
<tr>
<td>(\bar{\nu}) appearance</td>
<td>(\sin^2 2\theta_{13} = 0)</td>
<td>157</td>
<td>500</td>
</tr>
<tr>
<td></td>
<td>(\sin^2 2\theta_{13} = 10^{-3})</td>
<td>82</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>(\sin^2 2\theta_{13} = 10^{-2})</td>
<td>346</td>
<td>125</td>
</tr>
</tbody>
</table>

Computed with \(\Delta m_{31}^2 = +2.4 \times 10^{-3} \text{ eV}^2\), \(\sin^2 \theta_{23} = 0.5\), \(\Delta m_{21}^2 = 7.9 \times 10^{-5} \text{ eV}^2\), \(\sin^2 \theta_{12} = 0.3\). with an accuracy of 10\% for \(\theta_{12}, \theta_{23}, \Delta m_{31}^2\), and 4\% for \(\Delta m_{21}^2\) at 1\sigma.
$3 \sigma$ discovery of a non-zero $\theta_{13}$

![Graph showing $\sin^2 \theta_{13}$ vs. true $\delta_{CP}$]

Line width: 2% and 5% systematic errors.

Sensitivity to CP violation at 3σ

\[ \Delta \chi^2 (\delta_{CP} = 0, \pi) = 9 \]

- \( \delta_{CP} \sim \pi \)
- \( \sigma_{syst} = 2\% - 5\% \)

- T2HK
- SPL
- \( \beta B \)

The degeneracy problem

The sub-leading $\nu_\mu \to \nu_e$ formula leaves room for clone solutions of the fit to $\theta_{13}$ and $\delta_{\text{CP}}$. The eightfold degeneracies arise from

- $\text{sign}(\Delta m^2)$: Changing $\text{sign}(\Delta m^2)$ the $P(\nu_\mu \to \nu_e)$ terms $\propto \sin(\Delta m^2_{23})$ change sign. Two separate solutions can be created by $(\theta_{13}, \delta_{\text{CP}}, \text{sign}(\Delta m^2))$ and by $(\theta_{13}', \delta_{\text{CP}}', -\text{sign}(\Delta m^2))$.

- $\pi/2 - \theta_{23}$ (octant): $\nu_\mu$ disappearance measures $\sin^2 2\theta_{23}$ but some terms in the oscillation formula depend from $\sin \theta_{23}$. At present the experimental best fit is $\sin^2 2\theta_{23} = 1$ allowing no ambiguity, but the experimental not excluded values smaller than unity allow for a twofold $\pi/2 - \theta_{23}$ ambiguity.

- Mixed: The product of the above two

These eightfold discrete degeneracies (or twofold in case $\sin^2 2\theta_{23} \approx 1$) can be solved by combining information of different experiments running at different energies or looking to different processes (i.e. combining $\nu_\mu \to \nu_e$ transitions with $\nu_e$ disappearance or with $\nu_e \to \nu_\tau$ transitions). A single experiment cannot solve all these degeneracies by itself.
The synergy with atmospheric neutrinos

P. Huber et al., hep-ph/0501037: Combining Long Baseline data with atmospheric neutrinos (that come for free in the megaton detector):

- Degeneracies can be canceled, allowing for better performances in $\theta_{13}$ and LCPV searches
- The neutrino mass hierarchy can be measured
- The $\theta_{23}$ octant can be determined.

The main reasons are:

- **Octant** e-like events in the Sub-GeV data is $\propto \cos^2 \theta_{23}$
- **Sign** e-like events in the Multi-GeV data, thanks to matter effects, especially for zenith angles corresponding to neutrino trajectories crossing the mantle and core where a resonantly enhancement occurs.

**NOTE:** LBL and atmospherics are a true synergy. They add to each other much more that a simple gain in statistics. Atmospherics alone could not measure the hierarchy, the octant, $\theta_{13}$ and LCPV. While the Beta Beam at short baselines could not measure the hierarchy as well as the octant.

In the following sensitivities of the Beta Beam combined with the atmospherics are taken from J.E.Campagne, M.Maltoni, M.M., T.Schwetz, hep-ph/0603172
The red region is what is left after the atmospheric analysis.

Note how degeneracies were not influencing LCPV sensitivity too much.

\[ \delta = -0.85 \pi \]
\[ \sin^2(2\theta_{13}) = 0.03 \]
\[ \sin^2(2\theta_{23}) = 0.6 \]
Beta Beam plus atmospherics: determining mass hierarchy and the octant


2σ sensitivity to normal hierarchy

Sensitivity of to the octant of \(\theta_{23}\)

The high energy options

Several papers explored the physics potential of higher energy beta beams, showing how the experimental sensitivities can be improved if a higher energy accelerator than the SPS could be used (performances shown in later slides):

- P. Huber, M. Lindner, M. Rolinec and W. Winter, Phys. Rev. D 73,053002 (with a discussion of fluxes vs. \(\gamma\)).
- S. Agarwalla, S. Choubey, A. Raychaudhuri, hep-ph/0610332

- Need a proton machine of 1 TeV energy (LHC cannot be used at such high fluxes)
- Assume the same ion decay rates of the SPS option.
- The decay ring length rises linearly with \(\gamma\)
Electron capture beams

Radioactive ions can produce neutrinos also through electron capture.

Monochromatic, single flavor neutrino beams!


- The same complex could run either beta or electron capture beams.
- No way to have $\bar{\nu}_e$ beams.
- Ions should be partially (and not fully) stripped. Technologically challenging.
- Ion candidates are much heavier than beta candidates and have longer lifetimes (more difficult to stack them in the decay ring)
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:** \( \sim 10^{21} \) \( \mu \) decays per straight section per year
Oscillation signals at the neutrino factory

\( \mu^- (\mu^+) \) decay in \((\nu_\mu, \bar{\nu}_e) \) \((\bar{\nu}_\mu, \nu_e)\).

**Golden channel:** search for \(\nu_e \rightarrow \nu_\mu \) \((\bar{\nu}_e \rightarrow \bar{\nu}_\mu)\) transitions by detecting wrong sign muons.

Default detector: 40-100 kton iron magnetized calorimeter (Minos like)

**Silver channel:** search for \(\nu_e \rightarrow \nu_\tau\) transitions by detecting \(\nu_\tau\) appearance.

Ideal detectors: 4 × Opera or 10 Kton LAr detector.

All these detectors can be accommodate at LNGS.
Ideal baseline for a 50 GeV Neutrino Factory is \(\sim 3000\) km.
ISS stands for International Scoping study, an international effort started about 2 years ago to fully establish the possibilities and the physics potential of future neutrino beam facilities. The final document will be ready soon. Next ISS plenary meeting: CERN 29-30 March.

The neutrino physics community has produced a EU FP7 request for a design study of future neutrino beam facilities: EuroNu.

Line widths reflect different assumptions on machine configuration, fluxes, detector performances and systematic errors.
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Developments in this field are up to now a bottom-up process, driven by the foundamental importance of neutrino oscillations and the enthusiasm of neutrino physicists.
Backup Slides
Effects of systematic errors

Preliminary results of a study of P. Huber, M.M. and T. Schwetz

![Graph showing sensitivity to $\sin^2 2\theta_{13}$ at 3$\sigma$ vs. luminosity for T2K-I and T2K-II.](image)

Smallest $\delta_{CP}$ in $[0, \pi/2]$ for which CPV can be established at 3$\sigma$

$\sin^2 2\theta_{13} = 0.03$

preliminary
\[ 1 - P_{ee} \simeq \sin^2 2\theta_{13} \sin^2 (\Delta m_{31}^2 L/4E) + (\Delta m_{21}^2/\Delta m_{31}^2)^2 (\Delta m_{31}^2 L/4E)^2 \cos^4 \theta_{13} \sin^2 2\theta_{12} \]

- Much simpler connection between \( P_{ee} \) and \( \theta_{13} \), no interference with \( \delta_{\text{CP}} \) and \( \text{sign}(\Delta m^2) \).
- No way to directly measure leptonic CP violation and mass hierarchy.
- Truly complementary to the accelerator experiments.
- Disappearance experiments: systematic errors dominate over statistics.
Evolution of the Double Chooz sensitivity

Start the operation of the far detector, 10 m³, at $t_0$. With no close detector, systematics dominate.

Start the operations of an identical close detector after 1.5 yrs. Reactors flux is identical in the two detectors. Systematics reduced.


Time 0: scheduled to be 2008