The physics potential of $\beta$-beams
(and a brief Introduction to GLoBES)

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Technische Universität München

in collaboration with
Patrick Huber, Manfred Lindner, Thomas Schwetz
and Walter Winter

KTH Mathematical Physics Seminar
KTH Stockholm, November 3, 2004
Outline

Part I: Simulation with GLoBES

- AEDL (defining experiments)
- Features
- Applications

Part II: $\beta$-Beams

- Concept of $\beta$-beams
- $\beta$-beam scenarios: low-$\gamma$, medium-$\gamma$ and high-$\gamma$
- Neutrino spectrum at $\beta$-beams
- Sensitivity to $\theta_{13}$
- Sensitivity to CP effects
Neutrino Oscillations

Mixing of neutrinos is described by the unitary leptonic mixing matrix:

\[
U = \begin{pmatrix}
  c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{CP}} \\
-s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{CP}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{CP}} & s_{23}c_{13} \\
  s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{CP}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{CP}} & c_{23}c_{13}
\end{pmatrix}
\]

with \( c_{ij} \equiv \cos \theta_{ij} \) and \( s_{ij} \equiv \sin \theta_{ij} \)

Global Data (at 3\( \sigma \)):

\[
\begin{align*}
\sin^2 2\theta_{12} &= 0.84^{+0.10}_{-0.13} \\
\sin^2 2\theta_{23} &= 1.00^{+0.00}_{-0.13} \\
\sin^2 2\theta_{13} &< 0.18
\end{align*}
\]

\[
\Delta m^2_{21} = 8.1^{+1.0}_{-0.9} \times 10^{-5} \text{eV}^2 \\
|\Delta m^2_{31}| = 2.2^{+1.1}_{-0.8} \times 10^{-3} \text{eV}^2
\]


The CP-phase \( \delta_{CP} \) is completely unknown.
Simulation

All results and plots were produced with

The General Long Baseline Experiment Simulator
developed, documented and maintained by Patrick Huber, Manfred Lindner and Walter Winter


Can be found at: http://www.ph.tum.de/~GLoBES
GLoBES - Structure

AEDL
Abstract Experiment Definition Language
Defines Experiments and modifies them

GLoBES User Interface
C-library which loads AEDL-file(s) and provides functions to simulate experiment(s)

Application software to compute high-level sensitivities, precision etc.
Experiments can be defined individually in

The Abstract Experiment Definition Language
Different neutrino oscillation channels are combined as signal and background to give a **RULE**. An experiment can contain several **RULES** (including different systematics).

GLoBES can handle any number of experiments simultaneously.
GLoBES - Features

C-library which provides GLoBES functions to

- Calculate $\chi^2$ including systematics
- Project $\chi^2$ onto axes/hyperplanes
- Return low level information (event rates, transition probabilities)
- Test various setups and modifications (single experiment or combination of experiments)

GLoBES allows to include matter density uncertainties into the analysis (relevant for long baselines)
GLoBES - Correlations

Example: Correlation between $\sin^2 2\theta_{13}$ and $\delta_{CP}$

![Correlation and Projection Diagrams]

Correlation between $\sin^2 2\theta_{13}$ and $\delta_{CP}$

Projection onto $\sin^2 2\theta_{13}$ – axis
GLoBES - Applications

GLoBES has been used for simulating:

- MINOS, ICARUS and OPERA
- Reactor experiments, Double-CHOOZ
- T2K (formerly called JHF-SK)
- NOνA (formerly called NuMI)
- JHF-HK (T2K upgrade)
- Neutrino Factories
- $\beta$-beams
PART II

$\beta$-Beams
β-Beam: The Idea

Concept originally proposed in

Accelerate beta-decaying isotopes into a decay ring:

CERN Design

Anti-Neutrino-Beam:

\[ ^6He \rightarrow ^6Li + e^- + \bar{\nu}_e \]

Neutrino-Beam:

\[ ^{18}Ne \rightarrow ^{18}F + e^+ + \nu_e \]

J. Bouchez, M. Lindroos and M. Mezzetto, hep-ex/0310059
Three different $\beta$-beam scenarios are discussed:

<table>
<thead>
<tr>
<th>Label</th>
<th>BB@130km</th>
<th>BB@732km</th>
<th>BB@3000km</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline [$km$]</td>
<td>130</td>
<td>732</td>
<td>3000</td>
</tr>
<tr>
<td>Detector Technology</td>
<td>Water Cherenkov</td>
<td>Water Cherenkov</td>
<td>Magn. iron calorim.</td>
</tr>
<tr>
<td>Detector Mass [$kt$]</td>
<td>440</td>
<td>440</td>
<td>40</td>
</tr>
<tr>
<td>$\gamma$-factor $^6He / ^{18}Ne$</td>
<td>60 / 100</td>
<td>350 / 580</td>
<td>1500 / 2500</td>
</tr>
<tr>
<td>$\langle E_\nu \rangle / \langle E_\nu \rangle [GeV]$</td>
<td>0.23 / 0.37</td>
<td>1.35 / 2.18</td>
<td>5.80 / 9.39</td>
</tr>
<tr>
<td>$^6He / ^{18}Ne$ ion decays [$yr^{-1}$]</td>
<td></td>
<td>2.9 $\times 10^{18}$ / 1.1 $\times 10^{18}$</td>
<td></td>
</tr>
<tr>
<td>Running time [$yr$]</td>
<td></td>
<td>10</td>
<td></td>
</tr>
</tbody>
</table>

BB@130km, BB@732km and BB@3000km correspond to Setup-I, Setup-II and Setup-III in:

J. Burguet-Castell, D. Casper, J.J. Gómez-Cadenas, P. Hernández, F. Sánchez

Neutrino Spectrum

Boosted neutrino flux:

\[
\frac{d\phi}{dE_\nu} \propto \frac{E_\nu^2}{\gamma} \left( 1 - \frac{E_\nu}{2\gamma Q} \right) \sqrt{\left( 1 - \frac{E_\nu}{2\gamma Q} \right)^2 - \left( \frac{m_e}{Q} \right)^2}
\]

with \( Q = E_0 + m_e \)

Two \( \beta \) decaying isotopes:

<table>
<thead>
<tr>
<th>Neutrinos</th>
<th>Isotope</th>
<th>( E_0 ) [MeV]</th>
<th>Decay Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \nu_e )</td>
<td>(^{18})Ne</td>
<td>3.4114</td>
<td>0.921</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.3699</td>
<td>0.077</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.7106</td>
<td>0.002</td>
</tr>
<tr>
<td>( \bar{\nu}_e )</td>
<td>(^{6})He</td>
<td>3.5078</td>
<td>1.0</td>
</tr>
</tbody>
</table>

as in


hep-ph/0406132
Neutrino Spectra at $\beta$-beams

unoscillated event rates (1 kt yr)

<table>
<thead>
<tr>
<th></th>
<th>Our Analysis</th>
<th>J. Burguet-Castell et al.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\nu_e$ CC</td>
<td>$\bar{\nu}_e$ CC</td>
</tr>
<tr>
<td>BB@130km</td>
<td>30.3</td>
<td>4.4</td>
</tr>
<tr>
<td>BB@732km</td>
<td>210.6</td>
<td>55.2</td>
</tr>
<tr>
<td>BB@3000km</td>
<td>959.0</td>
<td>273.1</td>
</tr>
</tbody>
</table>

Physics potential of beta-beams - M. Rolinec - Stockholm 2004 – p.16/40
Neutrino Factory Scenarios

$\beta$-beams compared to two different neutrino factory setups introduced in greater detail in:


<table>
<thead>
<tr>
<th>Label</th>
<th>NuFact-I</th>
<th>NuFact-II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parent muon $E_\mu [GeV]$</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>Baseline [km]</td>
<td>3000</td>
<td></td>
</tr>
<tr>
<td>Target Power [MW]</td>
<td>0.75</td>
<td>4</td>
</tr>
<tr>
<td>Useful Muon Decays [yr$^{-1}$]</td>
<td>$1.0 \times 10^{20}$</td>
<td>$5.3 \times 10^{20}$</td>
</tr>
<tr>
<td>Detector Technology</td>
<td>Magn. iron calorim.</td>
<td></td>
</tr>
<tr>
<td>Detector Mass [kt]</td>
<td>10</td>
<td>50</td>
</tr>
<tr>
<td>Running time [yr]</td>
<td>2.5/2.5</td>
<td>4/4</td>
</tr>
</tbody>
</table>

Remember: NuFact-I is only a modest version of a neutrino factory!
Assumptions

Best Fit Values used:

\[
\begin{align*}
\sin^2 2\theta_{12} &= 0.84 \\
\sin^2 2\theta_{23} &= 1.0 \\
\Delta m_{21}^2 &= 7.9 \times 10^{-5} \text{eV}^2 \\
|\Delta m_{31}^2| &= 2.3 \times 10^{-3} \text{eV}^2
\end{align*}
\]

M. Maltoni, T. Schwetz, M.A. Tórtola, J.W.F. Valle; hep-ph/0405172 (v2)

Further assumptions:

- 10% uncertainty on solar parameters
- 15% uncertainty on \( \theta_{23} \)
- 5% uncertainty on \( |\Delta m_{31}^2| \)
- 5% systematic error
- 5% uncertainty on the matter density
Signal Events

\[ \sin^2 2\theta_{13} = 0.1 \text{ and } \delta_{CP} = 0 \]

<table>
<thead>
<tr>
<th>(\nu)</th>
<th>BB@130km</th>
<th>BB@732km</th>
<th>BB@3000km</th>
<th>NuFact-I</th>
<th>NuFact-II</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td>1950</td>
<td>14928</td>
<td>4845</td>
<td>920</td>
<td>39233</td>
</tr>
<tr>
<td>B</td>
<td>360</td>
<td>1738</td>
<td>12.2</td>
<td>2.4</td>
<td>104.2</td>
</tr>
<tr>
<td>S/B</td>
<td>5.4</td>
<td>8.6.</td>
<td>398.4</td>
<td>376.4</td>
<td>376.4</td>
</tr>
</tbody>
</table>
Signal Events

\[ \sin^2 2\theta_{13} = 0.1 \text{ and } \delta_{CP} = 0 \]

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<table>
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<th>BB@3000km</th>
<th>NuFact-I</th>
<th>NuFact-II</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td>381.2</td>
<td>7414</td>
<td>523.6</td>
<td>241</td>
<td>10270</td>
</tr>
<tr>
<td>B</td>
<td>1</td>
<td>350.2</td>
<td>4.3</td>
<td>4.6</td>
<td>197.2</td>
</tr>
<tr>
<td>S/B</td>
<td>381.2</td>
<td>21.2</td>
<td>121.3</td>
<td>52.1</td>
<td>52.1</td>
</tr>
</tbody>
</table>
Measuring $\theta_{13}$ by $\nu_e \rightarrow \nu_\mu$

The measurement of $\theta_{13}$ with the $\nu_e \rightarrow \nu_\mu$ appearance channel suffers from correlations and degeneracies:

$$P_{e\mu} \simeq \sin^2 2\theta_{13} \sin^2 2\theta_{23} \sin^2 \Delta_{31}$$

$$+ \alpha \sin 2\theta_{13} \sin 2\theta_{12} \sin \delta_{CP} \sin 2\theta_{23} \Delta_{31} \sin^2 \Delta_{31}$$

$$- \alpha \sin 2\theta_{13} \sin 2\theta_{12} \cos \delta_{CP} \sin 2\theta_{23} \Delta_{31} \cos \Delta_{31} \sin \Delta_{31}$$

$$+ \alpha^2 \sin^2 2\theta_{12} \cos^2 \theta_{23} \Delta_{31}^2$$

with $\alpha \equiv \frac{\Delta m_{21}^2}{\Delta m_{31}^2}$ and $\Delta_{31} \equiv \frac{\Delta m_{31}^2 L}{4E_\nu}$

Not $\sin^2 2\theta_{13}$, but only a specific parameter combination is measured very accurately.
How to compute the $\theta_{13}$ Sensitivity

- Simulate data with $\theta_{13} = 0$
- Include statistical errors
- Include systematical errors
- Include correlations
- Include degeneracies

![Graph showing $\theta_{13}$ sensitivity with various error sources including statistical and systematical errors, correlations, and degeneracies.]

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$\theta_{13}$ Sensitivity - Comparison

Sensitivity limit to $\sin^2 2\theta_{13}$ (90% CL)

- Systematics
- Correlations
- Degeneracy

- BB@130km
- BB@732km
- BB@3000km
- NuFact–I
- NuFact–II
$\theta_{13}$ Sensitivity - BB@130km

Dependence on the true value of $\Delta m^2_{31}$ (Remember: true $\theta_{13} = 0$)
$\theta_{13}$ Sensitivity - BB@732km

Dependence on the true value of $\Delta m_{31}^2$ (Remember: true $\theta_{13} = 0$)
$\theta_{13}$ Sensitivity - BB@3000km

Dependence on the true value of $\Delta m_{31}^2$ (Remember: true $\theta_{13} = 0$)

![Graph showing sensitivity limits for $\theta_{13}$]
\( \theta_{13} \) Sensitivity - NuFact-I

Dependence on the true value of \( \Delta m_{31}^2 \) (Remember: true \( \theta_{13} = 0 \))
$\theta_{13}$ Sensitivity - NuFact-II

Dependence on the true value of $\Delta m_{31}^2$ (Remember: true $\theta_{13} = 0$)
Influence of Priors - BB@130km

But: Only Disappearance-Channels considered for MINOS and the SuperBeam!!
Influence of Priors - BB@732km

But: Only Disappearance-Channels considered for MINOS and the SuperBeam!!
Influence of Priors - BB@3000km

But: Only Disappearance-Channels considered for MINOS and the SuperBeam!!
Sensitivity to CP Effects

Basically three scenarios:

- CP conservation: \( \delta_{CP} \equiv 0 \) or \( \delta_{CP} \equiv \pm \pi \)
- Maximal CP violation: \( \delta_{CP} \equiv \frac{\pi}{2} \) or \( \delta_{CP} \equiv -\frac{\pi}{2} \)
- Any CP violation: \( \delta_{CP} \in ]-\pi, 0[ \) or \( \delta_{CP} \in ]0, \pi[ \)

Questions:

- Can one exclude maximal CP violation, if true \( \delta_{CP} = 0 \) at a given CL?
- Can one exclude CP conservation, if there is any CP violation?
CP Violation at BB@130km

\[ \delta_{CP} = \pi/2 \]

BB@130km

- 1 \( \sigma \)
- 2 \( \sigma \)
- 3 \( \sigma \)

true value of \( \Delta m^2_{31} \)

true value of \( \sin^2 2\theta_{13} \)

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CP Violation at BB@732km

\[ \delta_{CP} = \pi/2 \]

\[ \Delta m_{31} < 0 \]

\[ \text{true value of } \sin^2 2\theta_{13} \]

\[ \text{true value of } \Delta m_{31} \]
CP Violation at BB@3000km

\[ \delta_{CP} = \pi/2 \]

\[ BB@3000\text{km} \]

- 1 \(\sigma\)
- 2 \(\sigma\)
- 3 \(\sigma\)

true value of \(\Delta m^2_{31}\)

true value of \(\sin^22\theta_{13}\)
Any CP Violation - BB@130km

![Contour plot showing exclusion limits for CP violation parameters]
Any CP Violation - BB@732km
Any CP Violation - BB@3000km

![Diagram](image-url)

- True value of $\sin^2 2\theta_{13}$
- True value of $\delta_{CP}$
- BB@3000km
Any CP Violation - NuFact-II

![CP Violation Diagram]

The diagram illustrates the true value of CP violation in terms of the phase $\delta_{CP}$ against the true value of $\sin^2 2\theta_{13}$. The contour lines represent different confidence levels: $1\sigma$, $2\sigma$, and $3\sigma$. The NuFact-II region is highlighted, indicating the potential physics reach using beta-beams.
Any CP violation - Comparison

\[ \text{true value of } \sin^2 2\theta_{13} \]

\[ \text{true value of } \delta_{CP} \]

\[ \text{90\% CL} \]

\[ \text{3 \sigma} \]

BB@130km
BB@732km
BB@3000km
NuFact–II

Physics potential of beta-beams - M. Rolinc - Stockholm 2004 – p.39/40
Conclusions

- Results are preliminary!
- The physics potential strongly depends on experimental parameters: Luminosity, efficiencies and background rejection ...
- BB@130km is comparable with Suberbeam experiments
- Only BB@732km and BB@3000km can challenge neutrino factory scenarios ($\sin^2 2\theta_{13}$ and $\delta_{CP}$)
- But: $\beta$-beams cannot measure the atmospheric parameters! $\Rightarrow$ depend on external input (not the case for neutrino factories)
- Not discussed yet: Sensitivity to sign($\Delta m^2_{31}$) (to come ...