Optimization of the Two-Baseline $\beta$-Beam

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Illinois Institute of Technology, Chicago, July 24$^{\text{th}}$ 2009

Based on the collaboration:
Outline

- Leptonic mixing
- Proposed solutions
  - Neutrino Factory
  - β-Beams
- The two-baseline β-Beam
  - The far detector as a degeneracy solver
  - The Li/B alternative
- The ultimate β-beam
  - Our proposal
  - Storage rings: design and feasibility
  - Results & comparison with other facilities
- Conclusions
Leptonic mixing

\[ \mathcal{L}_\nu = \frac{g}{\sqrt{2}} U_{\alpha i}^* (\theta_{12}, \theta_{23}, \theta_{13}; \delta) \left( \bar{l}_\alpha \gamma^\mu \nu_i L W^-_\mu + h.c. \right) + \mathcal{L}_{\text{mass}} (m_{\nu_i}; m_{l_\alpha}) \]
Leptonic mixing

\[ \mathcal{L}_\nu = \frac{g}{\sqrt{2}} U_{\alpha i}^* (\theta_{12}, \theta_{23}, \theta_{13}; \delta) \left( \bar{l}_{\alpha L} \gamma^\mu \nu_{iL} W^-_\mu + h.c. \right) + \mathcal{L}_{\text{mass}} (m_{\nu_i}; m_{l_\alpha}) \]

**What we know:**

\[ \theta_{12}, \Delta m^2_{12} \]

\[ \theta_{23}, |\Delta m^2_{23}| \]

Uncertainties ~\(\mathcal{O}(10\%)\), though...

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Leptonic mixing

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What we know:

\[ \theta_{12}, \Delta m_{12}^2 \]

\[ \theta_{23}, |\Delta m_{23}^2| \]

Uncertainties
\[ \sim \mathcal{O}(10\%), \text{ though...} \]

Shopping list:

\[ \theta_{13} \]

\[ \delta \]

\[ \text{sign}(\Delta m_{23}^2) \]

\[ \delta \theta_{23} = |\theta_{23} - \frac{\pi}{4}| \]

Physics BSM??

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Future proposed facilities

- The Neutrino Factory:

\[ \mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e \]

\[ E_\mu = 25 \text{ GeV} \]

\[ E_\nu \in [1.5, 25] \text{ GeV} \]

→ 5 years/polarity

→ $5 \cdot 10^{20}$ useful muons/baseline per year

→ 2 baselines: 4000, 7500 Km

→ 50 Kton MIND detectors
Future proposed facilities

• The β-Beam:

\[ N(A, Z) \rightarrow N(A, Z + 1) + e^- + \nu_e \]
\[ N(A, Z) \rightarrow N(A, Z - 1) + e^+ + \bar{\nu}_e \]

\[ <E> \sim \gamma E_0 \]

\[ N_{\text{on-peak}}^{\text{events}} \propto N_\beta \left( \frac{\Delta m^2}{2n-1} \right)^2 \frac{\gamma}{E_0} \]

\[ ^6\text{He} / ^{18}\text{Ne} : \gamma = 100 \Rightarrow L_{\text{first-peak}} = 130 \text{ Km} \]
(CERN-FrÉjus)
Future proposed facilities

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The high-γ β-Beam

- $^{6}\text{He}/^{18}\text{Ne}$
  - SPS+: $\gamma = 100 \rightarrow 350$ → $E_\nu \in [0, 2.5] \text{ GeV}$

- $L_{\text{first-peak}} \sim 600 - 700 \text{ Km}$
  - (CERN-Canfranc)

- 1 Mton WC detector
  - (500 Kton fiducial)

- $10^{19}$ total ion decays/year
  - ($\sim 3 \cdot 10^{18}$ useful)

CP discovery reach
(1 d.o.f 3σ C.L.)

GLoBES 3.0

J. Burguet Castell et al, hep-ph/0312068
J. Burguet Castell et al, hep-ph/0503021

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Optimization of the Two-Baseline β-Beam
The high-$\gamma$ $\beta$-Beam

- $^{6}\text{He}/^{18}\text{Ne}
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$\theta_{13}$ discovery reach
(1 d.o.f $3\sigma$ C.L.)

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→ Major drawback: poor sensitivity to mass hierarchy

$\text{sgn}(\Delta m_{31}^2)$ reach in $\sin^2 2\theta_{13}$ (3$\sigma$)

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Optimization of the Two-Baseline $\beta$-Beam
How can we improve this?
Matter effects at the magic baseline

Matter effects at the magic baseline

Matter effects at the magic baseline

$^6\text{He}/^{18}\text{Ne}: \gamma = 100 \rightarrow 350$

$<E_\nu> \sim 1.5 \text{ GeV}$
Matter effects at the magic baseline

\[ ^{6}\text{He}/^{18}\text{Ne} \rightarrow ^{8}\text{Li}/^{8}\text{B} \]

<table>
<thead>
<tr>
<th>Element</th>
<th>( E_0 ) (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \nu )</td>
<td>(^8\text{B})</td>
</tr>
<tr>
<td></td>
<td>(^{18}\text{Ne})</td>
</tr>
<tr>
<td>( \bar{\nu} )</td>
<td>(^8\text{Li})</td>
</tr>
<tr>
<td></td>
<td>(^6\text{He})</td>
</tr>
</tbody>
</table>

\(<E_\nu> \sim 1.5 \text{ GeV} \quad <E_\nu> \sim 5 \text{ GeV}\)
The Two-Baseline $\beta$-Beam: old proposals

P. Coloma, A. Donini, E. Fernández-Martínez and J. López-Pavón,

arXiv: 0712.0796

- **Li/B at 2000 Km:**
  $\gamma = 350$
  50 Kton-MIND detector

- **Li/B at 7000 Km:**
  $\gamma = 350$
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S. Agarwalla, S. Choubey and A. Raychaudhuri,
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- He/Ne at 730 Km:
  $250 < \gamma < 650$
  50 Kton-TASD detector

- Li/B at 7150 Km:
  $\gamma = 650$
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The storage ring for He/Ne: the Long Ring

\[ l = \frac{L_s}{L_r} \]

He/Ne
\[ \gamma = 100 \]

\[ L_s = 2500 \text{ m} \]
\[ L_r = 6884 \text{ m} \]
\[ l = 0.36 \]

\[ B = 5 \text{ T} \]

\[ R = 300 \text{ m} \]
The storage ring for He/Ne: the Long Ring

He/Ne
\(\gamma = 100\)

- \(L_s = 2500\) m
- \(L_r = 6884\) m
- \(l = 0.36\)
- \(B = 5\) T
- \(R = 300\) m

\(l = \frac{L_s}{L_r}\)

\[\implies\]

He/Ne
\(\gamma = 350\)

- \(L_s = 2500\) m
- \(L_r = 8974\) m
- \(l = 0.28\)
- \(B = 8.3\) T
- \(R \sim 633\) m

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Optimization of the Two-Baseline \(\beta\)-Beam
The storage ring: is it feasible?

\[ d = 32 \, m \]

\[ \theta = 0.6^\circ \]

Fréjus
130 Km

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Optimization of the Two-Baseline β-Beam
The storage ring: is it feasible?

\[ d = 32 \text{ m} \]

\[ d = 197 \text{ m} \]

\[ \theta = 0.6^\circ \]

\[ \theta = 3^\circ \]

Fréjus
130 Km

Canfranc
650 Km

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Optimization of the Two-Baseline $\beta$-Beam
The storage ring: is it feasible?

- $d = 32\, m$
- $d = 197\, m$
- $d = 2132\, m$

- $\theta = 0.6^\circ$
- $\theta = 3^\circ$
- $\theta = 34.5^\circ$

Fréjus 130 Km
Canfranc 650 Km
INO 7152 Km
The storage ring: is it feasible?

Notice that for the NF $d$ is much smaller ($d = 423$ m)
The storage ring for Li/B

- Due to a different A/Z, we can reach higher boost factors for Li/B in the LR:

\[ \frac{\gamma^{Li/B}_{max}}{Long \ Ring} = \frac{390}{656} \]
The storage ring for Li/B

- Due to a different A/Z, we can reach higher boost factors for Li/B in the LR:
  \[ \gamma_{max}^{Li/B} \bigg|_{Long \ Ring} = \frac{390}{656} \]
- With only a 10% increase in \( \gamma \), the statistics increase a 50% !
  \[ N_{ev}^{Li}(390) = N_{ev}^{Li}(350) \times 1.5 \]

Li/B
\[ \gamma = \frac{390}{656} \]
\[ L_s = 2500 \text{ m} \]
\[ L_r = 8974 \text{ m} \]
\[ l = 0.28 \]
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\[ R \sim 633 \text{ m} \]
The storage ring for Li/B: the Short Ring

- Due to a different A/Z, we can reach higher boost factors for Li/B in the LR:

\[ \gamma_{max}^{Li/B} \bigg|_{Long \ Ring} = 390/656 \]

- With only a 10% increase in \( \gamma \), the statistics increase a 50% !

\[ N_{ev}^{Li}(390) = N_{ev}^{Li}(350) \times 1.5 \]

- We can use this to reduce the ring size:

\[ l = 0.6 \times 0.28 \sim 0.17 \Rightarrow \begin{cases} L_s = 998 \text{ m} \\ d = 1282 \text{ m} \end{cases} \]
Our proposal

**He/Ne @ WC**

- $E_o \sim 3$ MeV;
- $\gamma = 350$;
- 500 Kton fiducial mass;
- 650 Km (first osc. peak);
- 2.5 years/ion;
- $10^{19}$ total $\Rightarrow 3 \cdot 10^{18}$ useful decays/year;
- 6 energy bins with $\Delta E = 0.25$ GeV; last bin with $\Delta E = 0.5$ GeV; $E_\nu \in [0.5, 2.5]$ GeV;
- Migration matrices from hep-ph/0503021;
- Uncorrelated systematic errors: 2.5% and 5%.

**Li/B @ MIND**

- $E_o \sim 13$ MeV;
- $\gamma = 350 \cdot (A/Z)$;
- 50 Kton;
- 7000 Km (matter resonance);
- 2.5 years/ion;
- $10^{19}$ total $\Rightarrow 1.7 \cdot 10^{18}$ useful decays/ year;
- $E_\nu \in [1.0, 18.55]$ GeV ;
- MIND-efficiencies optimized for the IDS-NF;
- Energy smearing: $0.55 \sqrt{E_\nu}$
- Uncorrelated systematic errors: 2.5% and 5%. 
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Comparative sensitivity reach

$\sin^2 2\theta_{13}$ vs $\delta$

- He/Ne WC
- B/Li iron
- 4 ions iron/TASD
- Our proposal

CP discovery reach (1 d.o.f $3\sigma$ C.L.)
Comparative sensitivity reach

\[ \sin^2 2\theta_{13} \]

\[ \theta_{13} \text{ discovery reach} \]

(1 d.o.f 3\sigma C.L.)

GLoBES 3.0

He/Ne WC

B/Li iron

4 ions iron/TASD

Our proposal
Comparative sensitivity reach

\[ \text{sgn}(\Delta m^2_{31}) \text{ reach in } \sin^2 2\theta_{13} (3\sigma) \text{ for NH} \]

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\[ \sin^2 2\theta_{13} \]

Optimization of the Two-Baseline $\beta$-Beam

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Comparison with the Neutrino Factory

\[ \text{cp fraction} \]

\[ \sin^2 2\theta_{13} \]

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He/Ne WC
Our proposal
IDS–NF

CP discovery reach
(1 d.o.f 3\(\sigma\) C.L.)

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Optimization of the Two-Baseline \(\beta\)-Beam
Comparison with the Neutrino Factory

$\theta_{13}$ discovery reach
(1 d.o.f 3\(\sigma\) C.L.)
Comparison with the Neutrino Factory

\[ sgn(\Delta m_{31}^2) \text{ reach in } \sin^2 2\theta_{13} \text{ (3\sigma) for NH} \]

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Optimization of the Two-Baseline \( \beta \)-Beam
Conclusions

• We believe that the β-Beam we propose here represents an **optimal setup**:  
  
  • It has the advantages of the high-γ He/Ne β-Beam, but **solving the degeneracies** that affected this setup for \( \sin^2(2\theta_{13}) \sim 10^{-2} \)
  
  • It uses the **magic baseline** to achieve good sensitivity to the mass hierarchy

• We have addressed the issue of the **storage ring** for a β-Beam aimed at the magic baseline, proposing a realistic setup
Conclusions

• β-Beams still cannot compete with the NF for extremely small values of $\theta_{13}$, but our proposal is better optimized for regions with $\sin^2(2\theta_{13}) > 10^{-3}$
  • The sensitivity is unaffected by the poor efficiencies for the lower energy bins

• However, we still are limited...
  • By the number of ions that can be produced: all the setups presented here are strongly limited by statistics
  • A study of the MIND detector performance when exposed to a β-Beam is lacking