BENE workshop

Resolving parameter degeneracies in long-baseline experiments with atmospheric neutrino data

Thomas Schwetz
SISSA, Trieste

based on:
P. Huber, M. Maltoni, TS, hep-ph/0501037
Outline

- Introduction
- Parameter degeneracies in LBL experiments
- Three-flavour effects in ATM experiments
- Resolving the degeneracies by a combined LBL and ATM analysis
  - simulation of the T2K-II experiment
  - preliminary analysis of CERN-Frejus experiments
- Concluding remarks
Introduction

3-flavour neutrino oscillation parameters:

\[ \Delta m_{31}^2 \]

\[ U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \]

\[ \Delta m_{21}^2 \]

\[ \begin{pmatrix} c_{13} & 0 & e^{-i\theta_{13}} s_{13} \\ 0 & 1 & 0 \\ -e^{i\theta_{13}} s_{13} & 0 & c_{13} \end{pmatrix} \]

\[ \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \]
3-flavour neutrino oscillation parameters:

\[
\Delta m_{31}^2 = \begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{pmatrix},
\quad
\Delta m_{21}^2 = \begin{pmatrix}
c_{13} & 0 & e^{-i\delta} s_{13} \\
0 & 1 & 0 \\
-e^{i\delta} s_{13} & 0 & c_{13}
\end{pmatrix},
\quad
\Delta m_{atm}^2 = \begin{pmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\]

atmospheric + K2K

GHOOZ

solar + KamLAND

Maltoni, Schwetz, Tortola, Valle, hep-ph/0405172
Introduction

3-flavour neutrino oscillation parameters:

\[ |\Delta m^2_{31}| \]

\[
U = \begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{pmatrix}
\]

\[
\Delta m^2_{21} = \begin{pmatrix}
c_{13} & 0 & e^{-i\alpha} s_{13} \\
0 & 1 & 0 \\
-e^{i\alpha} s_{13} & 0 & c_{13}
\end{pmatrix}
\]

\[
\frac{|\Delta m^2_{31}|}{10^{-3}\text{eV}^2} = 2.2^{+0.37}_{-0.27} \\
(14\%)
\]

\[
sin^2 \theta_{23} = 0.50^{+0.06}_{-0.05} \\
(11\%)
\]

atmospheric + K2K

\[
sin^2 \theta_{13} < 0.05 (3\sigma)
\]

CHOOZ

\[
\frac{|\Delta m^2_{21}|}{10^{-5}\text{eV}^2} = 7.9 \pm 0.3 \\
(4\%)
\]

\[
sin^2 \theta_{12} = 0.30^{+0.03}_{-0.02} \\
(9\%)
\]

solar + KamLAND

Maltoni, Schwetz, Tortola, Valle, hep-ph/0405172
Open questions:

How small is $13$?

What is the value of the CP phase $\text{CP}$?

Type of the neutrino mass ordering (sign of $m_{231}$):

\text{INVERTEDNORMAL} \\
\text{MASS} \\
\nu^3 \\
\nu^2 \\
\nu^1 \\
\nu^3 \\
\nu^e \\
\nu^\mu \\
\nu^\tau
Open questions:

- How small is $\theta_{13}$?
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- How small is $\theta_{13}$?
- What is the value of the CP phase $\delta_{CP}$?
- Type of the neutrino mass ordering (sign of $\Delta m_{31}^2$)
Parameter degeneracies in LBL experiments

H. Minakata, H. Nunokawa, JHEP 10 (2001) 001

and many more (I apologize for omissions)
The $\nu_\mu \to \nu_e$ oscillation probability

$P_{\mu e}$ in vacuum to leading order in $\sin^2 2\theta_{13}$ and $\alpha$

\[ P_{\mu e} \simeq \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \Delta_{31} \]
\[ + \alpha \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \Delta_{31} \sin \Delta_{31} \cos(\Delta_{31} \pm \delta_{\text{CP}}) \]
\[ + \alpha^2 \sin^2 2\theta_{12} \cos^2 \theta_{23} \Delta_{31}^2 \]

with

\[ \alpha \equiv \frac{\Delta m_{21}^2}{\Delta m_{31}^2}, \quad \Delta_{31} \equiv \frac{\Delta m_{31}^2 L}{4E_\nu} \]
The **8-fold degeneracy**

- **The intrinsic or** \( (\delta_{CP}, \theta_{13}) \) **degeneracy**


  several solutions in the \( (\delta_{CP}, \theta_{13}) \) plane

\[
P_{\mu e} \simeq \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \Delta_{31} + \alpha^2 \sin^2 2\theta_{12} \cos^2 \theta_{23} \Delta_{31}^2 \\
+ \alpha \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \Delta_{31} \sin \Delta_{31} \cos(\Delta_{31} \pm \delta_{CP})
\]

The 8-fold degeneracy

- **The intrinsic** or \((\delta_{CP}, \theta_{13})\) degeneracy
  

  several solutions in the \((\delta_{CP}, \theta_{13})\) plane

- **The hierarchy** or \(\text{sgn}(\Delta m_{31}^2)\) degeneracy
  
  H. Minakata, H. Nunokawa, JHEP 10 (2001) 001

  solutions for both signs of \(\Delta m_{31}^2\) (affects mainly \(\delta_{CP}\))

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P_{\mu e} \simeq \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \Delta_{31} + \alpha^2 \sin^2 2\theta_{12} \cos^2 \theta_{23} \Delta_{31}^2
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- **The octant or \(\theta_{23}\) degeneracy**
  \(\nu_\mu\)-disappearance channel gives only \(\sin^2 2\theta_{23}\)
  solutions for \(\theta_{23}\) and \(\pi/2 - \theta_{23}\) (affects mainly \(\sin^2 2\theta_{13}\))

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The 8-fold degeneracy

- **The intrinsic** or $(\delta_{CP}, \theta_{13})$ degeneracy
  several solutions in the $(\delta_{CP}, \theta_{13})$ plane

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  solutions for both signs of $\Delta m_{31}^2$ (affects mainly $\delta_{CP}$)

- **The octant** or $\theta_{23}$ degeneracy
  $\nu_\mu$-disappearance channel gives only $\sin^2 2\theta_{23}$
  solutions for $\theta_{23}$ and $\pi/2 - \theta_{23}$ (affects mainly $\sin^2 2\theta_{13}$)

overall an 8-fold degeneracy

The **T2K-II** long-baseline experiment

4 MW superbeam at JPARC  
mean neutrino energy: 0.76 GeV (2° OA)  
1 Mt Cherenkov detector at Kamioka  
baseline: 295 km

<table>
<thead>
<tr>
<th></th>
<th>$\nu$ (2 Mt yrs)</th>
<th>$\bar{\nu}$ (6 Mt yrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_\mu \to \nu_e$ signal</td>
<td>21 300</td>
<td>16 000</td>
</tr>
<tr>
<td>$\nu_\mu \to \nu_e$ background</td>
<td>2 140</td>
<td>3 260</td>
</tr>
<tr>
<td>$\nu_\mu \to \nu_\mu$ signal</td>
<td>73 200</td>
<td>75 600</td>
</tr>
<tr>
<td>$\nu_\mu \to \nu_\mu$ background</td>
<td>340</td>
<td>320</td>
</tr>
</tbody>
</table>

$\sin^2 2\theta_{13} = 0.05$, $\sin^2 \theta_{23} = 0.5$, $\sin^2 \theta_{12} = 0.3$, $\delta_{CP} = 0$,  
$\Delta m^2_{21} = 8.1 \times 10^{-5}$ eV$^2$, $\Delta m^2_{31} = 2.2 \times 10^{-3}$ eV$^2$
Analysis method

Calculation of event rates for given experiment:

\[ N_i(\alpha) = \Phi \cdot \sigma \cdot R \cdot \epsilon \cdot P(\hat{\theta}) \]

\( \Phi \): neutrino flux
\( \sigma \): detection cross section
\( R \): energy resolution
\( \epsilon \): efficiencies

\( P(\hat{\theta}) \): 3-flavour osc. prob., \( \hat{\theta} = (\Delta m^2_{21}, \Delta m^2_{31}, \theta_{12}, \theta_{23}, \theta_{13}, \delta) \)
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simulate data for “true values” \( \hat{\theta}^{\text{true}} \): \( N_i(\hat{\theta}^{\text{true}}) \)

\[ \chi^2(\hat{\theta}; \hat{\theta}^{\text{true}}) \rightarrow \text{allowed regions for } \hat{\theta} \]

including systematical errors, correlations, degeneracies
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including systematical errors, correlations, degeneracies

**GLoBES software**

P. Huber, M. Lindner, W. Winter, hep-ph/0407333

http://www.ph.tum.de/~globes/
Degeneracies and T2K-II

The intrinsic degeneracy is absent for T2K-II

\[
\sin^2 2\theta_{13} = 0.01 \\
\delta_{CP} = \frac{\pi}{4} \\
\sin^2 \theta_{23} = 0.3
\]

\[
R = \frac{N_i^{tr} - N_i^{deg}}{\sqrt{(N_i^{tr} + N_i^{deg})/2}}
\]
Degeneracies and T2K-II

True values:

\[ \sin^2 2\theta_{13} = 0.03 \]
\[ \delta_{\text{CP}} = -0.85\pi \]
\[ \sin^2 \theta_{23} = 0.4 \]
\[ \Delta m^2_{31} = 2.2 \times 10^{-3}\text{eV}^2 \]
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ambiguities in \( \theta_{13} \) and \( \delta_{\text{CP}} \)
no information on the hierarchy
3-flavour effects in atmospheric neutrinos

3-flavour effects in atmospheric neutrinos

excess of electron-like events:

\[
\frac{N_e}{N_0^e} - 1 \simeq (r s_{23}^2 - 1) P_{2\nu}(\Delta m_{31}^2, \theta_{13}) \quad \theta_{13}\text{-effects}
\]

\[
+ (r c_{23}^2 - 1) P_{2\nu}(\Delta m_{21}^2, \theta_{12}) \quad \Delta m_{21}^2\text{-effects}
\]

\[- 2s_{13} s_{23} c_{23} r \Re(A_{ee}^* A_{\mu e}) \quad \text{interference: } \delta_{CP}
\]

\[
r = r(E_\nu) \equiv \frac{F_\mu^0(E_\nu)}{F_e^0(E_\nu)}
\]

\[
r \approx 2 \quad (\text{sub-GeV})
\]

\[
r \approx 2.6 - 4.5 \quad (\text{multi-GeV})
\]

$\theta_{13}$-effects

$$\frac{N_e}{N_e^0} - 1 \approx (r \ s_{23}^2 - 1) \ P_{2\nu}(\Delta m_{31}^2, \theta_{13})$$

resonant matter effect in $P_{2\nu}(\Delta m_{31}^2, \theta_{13})$ for multi-GeV events ($r \approx 2.6 - 4.5$)

normal hierarchy: enhancement for neutrinos
inverted hierarchy: enhancement for anti-neutrinos

detection cross sections are different for neutrinos and anti-neutrinos

sensitivity to the neutrino mass hierarchy
\[
\frac{N_e}{N^0_e} - 1 \sim (r s^2_{23} - 1) P_{2\nu}(\Delta m^2_{31}, \theta_{13})
\]
$\Delta m_{21}^2$-effects

$$\frac{N_e}{N_0^e} - 1 \approx (r c_{23}^2 - 1) P_{2\nu}(\Delta m_{21}^2, \theta_{12})$$

Peres, Smirnov, hep-ph/0309312

contours of $\frac{N_e}{N_0^e} - 1$

relevant for sub-GeV events

sensitivity to the octant of $\theta_{23}$
Mega ton atmospheric neutrino experiments

projects for Mt water Cherenkov detectors
(SK: 22.5 kt)

UNO (US), Hyper-K (Japan), Frejus (Europe)
Mega ton atmospheric neutrino experiments

projects for Mt water Cherenkov detectors
(SK: 22.5 kt)

UNO (US), Hyper-K (Japan), Frejus (Europe)

multi-purpose experiments:

- far-detector for LBL experiments
- solar and atmospheric neutrinos
- supernova neutrinos
- proton decay
- ...
The HK atmospheric neutrino experiment

assume 9 Mt yrs ATM data (100 × SK-I data)

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<tr>
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<tr>
<td>$e$-like sub-GeV</td>
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</tr>
<tr>
<td>upward going $\mu$</td>
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$\sin^2 2\theta_{13} = 0.05, \sin^2 \theta_{23} = 0.5, \sin^2 \theta_{12} = 0.3, \delta_{\text{CP}} = 0,$

$\Delta m_{21}^2 = 8.1 \times 10^{-5} \text{ eV}^2, \Delta m_{31}^2 = 2.2 \times 10^{-3} \text{ eV}^2$
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**WARNING:**
- same systematics as SK-I
**The HK atmospheric neutrino experiment**

assume 9 Mt yrs ATM data (100 \times SK-I data)

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**WARNING:**

- same systematics as SK-I
- same binning (zenith angle, energy) as SK-I
The ATM analysis

- Full numerical three-flavour analysis
  - both $\Delta m^2_{31}$ and $\Delta m^2_{21}$ taken into account
  - realistic treatment of earth matter effects

based on:
The ATM analysis

- Full numerical three-flavour analysis
  - both $\Delta m^2_{31}$ and $\Delta m^2_{21}$ taken into account
  - realistic treatment of earth matter effects

based on:

- Combined with LBL data by using a generalized version of the GLoBES software
Resolving the degeneracies
Resolving the degeneracies

True values:
\[
\sin^2 2\theta_{13} = 0.03, \quad \delta_{CP} = -0.85\pi, \quad \Delta m^2_{31} = 2.2 \times 10^{-3} \text{eV}^2
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Resolving the degeneracies

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Resolving the degeneracies

True hierarchy: normal

True hierarchy: inverted

$\delta_{CP}^{true} = 0$

$\text{sng}(\Delta m^2)$-deg.
Resolving the degeneracies

True hierarchy: normal

True hierarchy: inverted

\[ \delta_{\text{CP}}^{\text{true}} = \pi \]

\[ \delta_{\text{CP}}^{\text{true}} = 0 \]

\[ \delta_{\text{CP}}^{\text{true}} = \pi/2 \]
Which are the relevant ATM data samples?

true value of $\sin^2 \theta_{23}$

true value of $\sin^2 \theta_{13}$

$\delta_{CP} = 0$

$\delta_{CP} = -\pi/2$
Identifying the mass hierarchy
Identifying the mass hierarchy

solid: LBL-only, dashed: ATM-only, shading: LBL+ATM
Identifying the mass hierarchy

solid: LBL-only, dashed: ATM-only, shading: LBL+ATM
Identifying the mass hierarchy

solid: LBL-only, dashed: ATM-only, shading: LBL+ATM
Do we really need a Mt experiment?
Luminosity scaling

True values: $\sin^2 \theta_{13} = 0.04$, $\sin^2 \theta_{23} = 0.4$, $\delta_{CP} = 0$, normal hierarchy.
Preliminary BB/SPL analysis

CERN-Frejus LBL experiments (PRELIMINARY)
simulation from Huber, Lindner, Rolinec, Winter, work in progress
Preliminary BB/SPL analysis

CERN-Frejus LBL experiments (PRELIMINARY)
simulation from Huber, Lindner, Rolinec, Winter, work in progress

- **Beta Beam**
  similar to the setups from Bouchez, Lindros, Mezzetto, hep-ex/0310059;
  Burguet-Castell et al., hep-ph/0312068; Donini et al., hep-ph/0406132

\[ \bar{\nu}: \quad ^6\text{He} \quad (\gamma = 60, \, 3 \times 10^{18} \text{ decays/yr}), \]
\[ \nu: \quad ^{18}\text{Ne} \quad (\gamma = 100, \, 1 \times 10^{18} \text{ decays/yr}), \]
10 yrs running
Preliminary BB/SPL analysis

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- **SPL Superbeam**
  similar to SB from Gomes-Cadenas et al., hep-ex/0105297; Donini et al., hep-ph/0406132
  2.2 GeV proton beam from 4 MW SPL, 2 yrs \(\nu\), 8 yrs \(\bar{\nu}\)
Preliminary BB/SPL analysis

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simulation from Huber, Lindner, Rolinec, Winter, work in progress

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  2.2 GeV proton beam from 4 MW SPL, 2 yrs \( \nu \), 8 yrs \( \bar{\nu} \)

- **450 kt water Cherenkov detector at Frejus**
main difference to T2K:

- baseline: 130 km
- \( E_\nu \simeq 0.2 - 0.3 \) GeV
- no spectral information available
Preliminary BB/SPL analysis

main difference to T2K:

- baseline: 130 km
- $E_\nu \simeq 0.2 - 0.3$ GeV
- no spectral information available

$(\theta_{13}, \delta_{CP})$-degeneracy cannot be resolved
Preliminary BB/SPL analysis

90% CL regions for the \( (H^{tr}\ O^{tr}) \), \( (H^{tr}\ O^{wr}) \), \( (H^{wr}\ O^{tr}) \), \( (H^{wr}\ O^{wr}) \) solutions

Dashed: LBL only, Solid: LBL+ATM

True values: \( \delta_{CP} = -0.85\pi \), \( \sin^2 \theta_{13} = 0.03 \), \( \sin^2 \theta_{23} = 0.6 \), 5% external precision on \( \Delta m^2_{31} \), \( \Delta m^2_{21} \), \( \theta_{23} \).
Preliminary BB/SPL analysis

90% CL regions for the $(H^{tr}O^{tr})$, $(H^{tr}O^{wr})$, $(H^{wr}O^{tr})$, $(H^{wr}O^{wr})$ solutions

True values: $\delta_{CP} = -0.85\pi$, $\sin^2 2\theta_{13} = 0.03$, $\sin^2 2\theta_{23} = 0.6$, 5% external precision on $\Delta m^2_{31}$, $\Delta m^2_{21}$, $\theta_{23}$
Preliminary BB/SPL analysis

90% CL regions for the \((H^{tr}O^{tr}), (H^{tr}O^{wr}), (H^{wr}O^{tr}), (H^{wr}O^{wr})\) solutions

True values: \(\delta_{CP} = -0.85 \pi\), \(\sin^2 \theta_{13} = 0.03\), \(\sin^2 \theta_{23} = 0.4\), 5% external precision on \(\Delta m^2_{31}, \Delta m^2_{21}, \theta_{23}\)

Dashed: LBL only, solid: LBL+ATM
Concluding remarks
Combined analysis of LBL and ATM data provides an interesting method to resolve degeneracies.
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- good sensitivity to the *octant of $\theta_{23}$*
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given the Mt detector for the LBL experiment, ATM data come for free!
Concluding remarks

Complementarity of LBL and ATM data:

Three-flavour effects in ATM data provide sensitivity to mass ordering and octant of $\theta_{23}$.

The determination of $m_{23}$ and $\sin^2\theta_{23}$ at the sub-percent level and a constraint on $\sin^2\theta_{13}$ from LBL data is necessary.

Thank you for your attention!

P. Huber, M. Maltoni, TS, hep-ph/0501037
Complementarity of LBL and ATM data:

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Complementarity of LBL and ATM data:

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Concluding remarks

Complementarity of LBL and ATM data:

- Three-flavour effects in ATM data provide sensitivity to mass ordering and octant of $\theta_{23}$
- The determination of $\Delta m^2_{31}$ and $\sin^2 2\theta_{23}$ at the sub-percent level and a constraint on $\sin^2 2\theta_{13}$ from LBL data is necessary

Thank you for your attention!

P.Huber, M.Maltoni, TS, hep-ph/0501037
Additional slides

True hierarchy: normal

- LBL only
- ATM only

True hierarchy: inverted

- wrong hierarchy ($\Delta \chi^2 = 10.4$)
- true solution

- wrong hierarchy ($\Delta \chi^2 = 6.6$)
- true solution

T. Schwetz, BENE workshop, CERN, 16-18 march 2005 – p.33
True $\theta_{13} = 0$

Resolving the octant-degeneracy:

![Graph showing $\Delta \chi^2$ vs. True value of $\sin^2 \theta_{23}$ with LBL+ATM, ATM only, and LBL only lines.](image)
\( \text{True } \theta_{13} = 0 \)

The limit on \( \sin^2 2\theta_{13} \):

![Graph showing sensitivity to \( \sin^2 2\theta_{13} \).](image)

- (a) right octant of \( \theta_{23} \)
- (b) wrong octant of \( \theta_{23} \)
- (c) combined

Dashed: LBL only, solid: LBL+ATM

\[ P_{\mu e} \simeq \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \Delta_{31} + \ldots \]