Future Precision Measurements and Theoretical Implications

M. Lindner

TU Munich & MPI Heidelberg

2nd Scandinavian Neutrino Workshop
May 2-6 2006, AlbaNova University Center
Stockholm, Sweden
Coming Improvements

MINOS: improved oscillation parameters
MiniBOONE ↔ LSND
L/E dependence of oscillations
KATRIN
Better $0\nu2\beta$ limits / signals
...

But why do we need precision measurements?
Solar Neutrinos: Learning About the Sun

**Observables:**
- **optical** (total energy, surface dynamics, sun-spots, historical records, B, ...)
- **neutrinos** (rates, spectrum, ...)

**Topics:**
- nuclear cross sections
- solar dynamics
- helio-seismology
- variability
- composition
Learning from Atmospheric Neutrinos

primary cosmic-ray interaction in the atmosphere

cascade of secondaries $\pi, K$

decay of secondaries

$\nu_\mu$, $\mu$

$\nu_\mu$, $\nu_e$

neutrinos from decays of other particles

Issues (in flux models):
- primaries (...)
- atmosphere
- cross sections
- B-fields
- shower models
- ...

M. Lindner
New Physics Beyond the SM

**Experimental facts:**
- Dark Matter
- Dark Energy
- Baryon asymmetry
- Neutrino masses & mixings
- Precision

**Gauge bosons**

- Higgs
- Quarks
- Leptons

**Gauge hierarchy problem:**
\[ \delta m_H^2 \sim \Lambda^2 \]

**Flavour problem:**
- 3 generations
- Many parameters (\( m_i \), mixings)
- Unification into GUTs

\[ m_\nu = (m_D)^T M_R^{-1} m_D \]

**SUSY**
\[ \sim \text{TeV} \]

**Astrophysics & cosmology**

**~\( \Lambda_{\text{GUT}} \) + seesaw**
Precison with New Neutrino Beams

- **conventional beams, superbeams**
  - MINOS, CNGS, T2K, NO\(\nu\)A, T2H,…
- **\(\beta\)-beams**
  - pure \(\nu_e\) and \(\bar{\nu}_e\) beams from radioactive decays; \(\gamma \sim 100\)
- **neutrino factories**
  - clean neutrino beams from decay of stored \(\mu\)’s

\[
P(\nu_e \rightarrow \nu_\mu) \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin((1-\hat{A})\Delta)}{(1-\hat{A})^2}
\]

\[
\pm \sin \delta_{CP} \alpha \sin 2\theta_{12} \cos \theta_{13} \sin 2\theta_{13} \sin 2\theta_{23} \sin(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}(1-\hat{A})} \sin((1-\hat{A})\Delta)
\]

\[
+ \cos \delta_{CP} \alpha \sin 2\theta_{12} \cos \theta_{13} \sin 2\theta_{13} \sin 2\theta_{23} \cos(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}(1-\hat{A})} \sin((1-\hat{A})\Delta)
\]

\[
+ \alpha^2 \sin^2 2\theta_{12} \cos^2 \theta_{23} \frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2}
\]

- **correlations & degeneracies**
Future Long Baseline Experiments

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Status</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>K2K</td>
<td>finished</td>
<td>establish atmospheric oscillations with beam</td>
</tr>
<tr>
<td>MINOS OPERA</td>
<td>running</td>
<td>expected precision:</td>
</tr>
<tr>
<td></td>
<td>construction</td>
<td>8% for $\Delta m^2_{13}$, 25% for $\sin^2 \theta_{23}$, $\theta_{13}$?</td>
</tr>
<tr>
<td>T2K</td>
<td>approved</td>
<td>4% for $\Delta m^2_{13}$, 15% for $\sin^2 \theta_{23}$, $\theta_{13}$</td>
</tr>
<tr>
<td>NOvA</td>
<td>pre-approved</td>
<td>3% for $\Delta m^2_{13}$, 15% for $\sin^2 \theta_{23}$ (combined with T2K), $\theta_{13}$, $\delta$, $\text{sgn}(\Delta m^2_{13})$</td>
</tr>
<tr>
<td>T2H</td>
<td>R&amp;D</td>
<td>precision neutrino physics</td>
</tr>
<tr>
<td>$\beta$-beams</td>
<td>R&amp;D</td>
<td></td>
</tr>
<tr>
<td>neutrino factory</td>
<td>R&amp;D</td>
<td></td>
</tr>
<tr>
<td>...muon collider</td>
<td>...</td>
<td></td>
</tr>
</tbody>
</table>

- every stage is a **necessary prerequisite** for the next
- continuous line of **improvements for beams, detectors, physics**

- *Simulations with GLoBES*  
- *NF & $\beta$-beam: see talk by M. Rolinec*

M. Lindner  
SNOW 2006  
7
Improvement of $\Delta m^2_{31}$ and $\sin^2 \theta_{23}$

$\Delta m^2_{31}$-precision

$\sin^2 \theta_{23}$-precision

Huber, ML, Rolinec, Schwetz, Winter
Sensitivity Versus Time

β-beams
neutrino factory

proton
driver?

Range
⇔ ±unknown CP phase

MINOS
CNGS
D-CHOOZ
T2K
NUE
Reactor-II
NUE+FPD

Conventional beams

Reactor experiments

CHOOZ+Solar excluded

Superbeams


Year

$\sin^2 2\theta_{13}$ discovery reach (3σ)

$10^{-3}$

$10^{-2}$

$10^{-1}$

$10^0$
Precision with New Reactor Experiments

\[ P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{31} L}{4E_{\nu}} + \left( \frac{\Delta m^2_{21} L}{4E_{\nu}} \right)^2 \cos^4 \theta_{13} \sin^2 2\theta_{12} \]

- \text{Double Chooz}
- \text{KASKA}
- \text{Braidwood}
- \text{Angra, ...}

no degeneracies
no correlations
no matter effects

\( \bar{\nu}_e \) near detector (170m) \( \bar{\nu}_e \) far detector (1700m)

identical detectors \Rightarrow many errors cancel
Double Chooz

existing far detector hall

... + another existing big hall!
Double Chooz and Triple Chooz

Double Chooz and Triple Chooz

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

- **Chooz limit** \(< 0.20\)
- **Double Chooz** \(< 0.02\)
- **Triple Chooz** \(< 0.008\)
$\theta_{13}$ Sensitivity in the Next Generation

Sensitivity to $\sin^2 2\theta_{13}$ at 90% CL

- one order of magnitude improvement for $\theta_{13}$
- synergies between reactor and accelerator experiments
  - reactor anti-neutrinos $\Rightarrow$ only neutrino beams (x-section)
  - reactor: uncorrelated $\theta_{13}$ $\Rightarrow$ combine with beams & resolve correlations
- synergy between beams $\Rightarrow$ NOvA at larges baseline $\Rightarrow$ matter effects

Compare:
- 5 years each
- 5% flux uncertainty

coming long baseline experiments
Double Chooz Reactor II (...Tripple Chooz)
next generation long baseline experiments
**Leptonic CP-Violation**

**assume:** $\sin^2 2\theta_{13} = 0.1$, $\delta = \pi/2 \Rightarrow$ combine T2K+NOvA+reactor

- $\Delta m^2 > 0$
- $\Delta m^2 < 0$
- 90\% CL
- $\cdots \cdots \cdots 3\sigma$

- bounds or measurements of leptonic CP-violation
- leptonic CP-violation in $M_R \leftrightarrow$ baryon asymmetry via leptogenesis
Double Chooz and $0\nu2\beta$

- $m_{ee}$ versus $m_1$

  for $\sin^2 2\theta_{13} = 0.2$

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

  $\Longrightarrow$ Double Chooz

Bilenky, Pascoli, Petcov
Klapdor, Päs, Smirnov
...
ML, Merle, Rodejohann
precise neutrino parameters

why is this interesting?

unique flavour information
very precise: no hadronic uncertainties
apparent difference: quarks ↔ leptons
tests models / ideas about flavour
History: Elimination of SMA

Was favoured by most theorists
\(\leftrightarrow\) GUTs

preferred by nature
The Value of Precision for $\theta_{13}$

- models of masses & mixings
- input: Known masses & mixings ➔ distribution of $\theta_{13}$ „predictions“

$\theta_{13}$ often close to experimental bounds ➔ motivates new experiments ➔ $\theta_{13}$ controls 3-flavour effects like leptonic CP-violation

for example: $\sin^2 2\theta_{13} < 0.01$ ➔

physics question: why is $\theta_{13}$ so small? ➔ numerical coincidence ➔ symmetry ➔ precision!
Further Implications of Precision

**Precision allows to identify / exclude:**

- special angles: $\theta_{13} = 0^\circ$, $\theta_{23} = 45^\circ$, ... \(\iff\) discrete f. symmetries?
- special relations: $\theta_{12} + \theta_C = 45^\circ$ ? \(\iff\) quark-lepton relation?
- quantum corrections \(\iff\) renormalization group evolution

**Provides also measurements or tests of:**

- **MSW effect** (coherent forward scattering and matter profiles)
- cross sections
- 3 neutrino unitarity \(\iff\) sterile neutrinos with small mixings
- neutrino decay (admixture...)
- decoherence
- NSI
- MVN, ...
The larger Picture: GUTs

Gauge unification suggests that some GUT exists

Requirements:
- gauge unification
- particle multiplets $\leftrightarrow \nu_R$
- proton decay

...
Quarks and leptons sit in the same multiplets
- one set of Yukawa coupling for given GUT multiplet
- ~ tension: small quark mixings ↔ large leptonic mixings
- this was in fact the reason for the `prediction’ of small mixing angles (SMA) – ruled out by data

Mechanisms to post-dict large mixings:
- sequential dominance
- type II see-saw
- Dirac screening
- ...
Single right-handed Dominance

\[ m_D = \begin{pmatrix} . & . & . \\ . & a & b \\ . & c & d \end{pmatrix} \quad \quad \quad M_R = \begin{pmatrix} . & . & . \\ . & x & 0 \\ . & 0 & y \end{pmatrix} \]

\[ m_\nu = -m_D \cdot M_R^{-1} \cdot m_D^T = \begin{pmatrix} . & . & . \\ . & \frac{a^2}{x} + \frac{b^2}{y} & \frac{ac}{x} + \frac{bd}{y} \\ . & \frac{ac}{x} + \frac{bd}{y} & \frac{c^2}{x} + \frac{d^2}{y} \end{pmatrix} \]

If one right-handed neutrino dominates, e.g. \( y >> x \)

- Small sub-determinant \( \sim m_2 \cdot m_3 \)
- \( m_2 << m_3 \) i.e. a natural hierarchy
- \( \tan \theta_{23} \sim a/c \) i.e. naturally large mixing
Sequential Dominance

\[ m_D = \begin{pmatrix} a & b & c \\ d & e & f \\ g & e & h \end{pmatrix} \quad M_R = \begin{pmatrix} x & 0 & 0 \\ 0 & y & 0 \\ 0 & 0 & z \end{pmatrix} \]

\[ m_\nu = -m_D \cdot M_R^{-1} \cdot m_D^T = \begin{pmatrix} \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \end{pmatrix} \]

sequential dominance: \( z >> y >> x \)

- small determinant \( \sim m_1 \cdot m_2 \cdot m_3 \)
- \( m_1 \ll m_2 \ll m_3 \) natural
- naturally large mixings

S.F. King
Large Mixings and See-Saw Type II

\[ m_\nu = M_L - m_D M_R^{-1} m_D^T \]

**see-saw type II**

**\( m_D \) and \( M_R \) may possess small mixings and hierarchy**

However: \( M_L \) can be numerically more important

Example: Break GUT \( \rightarrow \) SU(2)_L \times SU(2)_R \times U(1)_{B-L} \( \Rightarrow \) \( M_L \) from LR

\( \Rightarrow \) large mixings natural for almost degenerate case \( m_1 \sim m_2 \sim m_3 \)

\( \Rightarrow \) type I see-saw would only be a correction

**type I – type II interference**

\( \Rightarrow M_L \simeq m_D M_R^{-1} m_D^T \)

\( \Rightarrow \) many possibilities
**Dirac Screening**

**Question:** Do neutrino masses always depend on the Dirac Yukawa couplings? ➔ **no**

Assume: $\nu_L$, $\nu^C_R$, $S$ ➔

$$
\mathcal{M} = \begin{pmatrix}
0 & Y_\nu \langle \phi \rangle & 0 \\
Y_\nu^T \langle \phi \rangle & 0 & Y_N^T \langle \sigma \rangle \\
0 & Y_N \langle \sigma \rangle & M_S
\end{pmatrix}
$$

➔ double seesaw

$$m_\nu^0 = \left[ \frac{\langle \phi \rangle}{\langle \sigma \rangle} \right]^2 Y_\nu (Y_N)^{-1} M_S (Y_N^T)^{-1} Y_\nu^T$$

fit fermions into GUT representations ➔ relation between Yukawa couplings, e.g. E6

$Y_\nu = c \cdot Y_N$
Consequences of Dirac Screening

- Complete screening of Dirac structure

\[ m_\nu = e^2 \left( \frac{\langle \phi \rangle}{\langle \sigma \rangle} \right)^2 M_S \]

**Outcome:**

- Neutrino masses can emerge completely from Planck scale physics ↔ generically different
- Dirac Yukawa structure (small mixings) screened
- Hierarchical neutrino spectrum not required in see-saw
- Quark-lepton complimentarity possible … …with or without degenerate neutrino masses

- Double see-saw predicts for \( M_R \) to be below \( M_{\text{GUT}} \)
  - First see-saw \( M_R \sim \langle s \rangle / M_S \sim 10^{-3} M_{\text{GUT}} \sim 10^{13} \text{ GeV} \)
Flavour Unification

- so far no understanding of flavour, 3 generations
- apparent regularities in quark and lepton parameters
  ➤ flavour symmetries
  ➤ not texture zeros

Examples:

- $O(3)_L \times O(3)_R$
- $SU(3)$
- $SU(2)$
- $U(1)$
- $SO(3)$
- $S(3)_L \times S(3)_R$
- $A_4; Z_3 \approx Z_2$
- $S(3)$
- Nothing

Table:

<table>
<thead>
<tr>
<th>Quarks</th>
<th>1st</th>
<th>2nd</th>
<th>3rd</th>
</tr>
</thead>
<tbody>
<tr>
<td>$u$</td>
<td>2/3</td>
<td>-1/3</td>
<td>2/3</td>
</tr>
<tr>
<td>$d$</td>
<td>-1/3</td>
<td>-1/3</td>
<td>-1/3</td>
</tr>
<tr>
<td>$e$</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Leptons</th>
<th>1st</th>
<th>2nd</th>
<th>3rd</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_1$</td>
<td>-0.511</td>
<td>-1.055</td>
<td>-1.777</td>
</tr>
<tr>
<td>$\nu_2$</td>
<td>-0.511</td>
<td>-1.055</td>
<td>-1.777</td>
</tr>
<tr>
<td>$\nu_3$</td>
<td>-0.511</td>
<td>-1.055</td>
<td>-1.777</td>
</tr>
<tr>
<td>$e$</td>
<td>-0.511</td>
<td>-1.055</td>
<td>-1.777</td>
</tr>
<tr>
<td>$\mu$</td>
<td>-0.511</td>
<td>-1.055</td>
<td>-1.777</td>
</tr>
<tr>
<td>$\tau$</td>
<td>-0.511</td>
<td>-1.055</td>
<td>-1.777</td>
</tr>
</tbody>
</table>
Discrete Flavour Symmetries ↔ flavour structure
Example: Dihedral groups $D_n$

\[ \langle A, B | A^n = 1, B^2 = 1, (AB)^n = 1 \rangle \]

geometric origin of $D_3$
Specific Example: $D_5$

$< A, B | A^n = 1, B^2 = 1, (AB)^n = 1 >$

complex generators

21: $A = \begin{pmatrix} e^{i \frac{2\pi}{5}} & 0 \\ 0 & e^{-i \frac{2\pi}{5}} \end{pmatrix}$  \quad B = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$

22: $A = \begin{pmatrix} e^{i \frac{4\pi}{5}} & 0 \\ 0 & e^{-i \frac{4\pi}{5}} \end{pmatrix}$  \quad B = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$

character table

<table>
<thead>
<tr>
<th>classes</th>
<th>$C_1$</th>
<th>$C_2$</th>
<th>$C_3$</th>
<th>$C_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h_{C_1}$</td>
<td>1</td>
<td>5</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>$n_{C_1}$</td>
<td>1</td>
<td>2</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>$1_1$</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>$1_2$</td>
<td>1</td>
<td>-1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>$2_1$</td>
<td>2</td>
<td>0</td>
<td>$\frac{1}{2}(-1 + \sqrt{5})$</td>
<td>$\frac{1}{2}(-1 - \sqrt{5})$</td>
</tr>
<tr>
<td>$2_2$</td>
<td>2</td>
<td>0</td>
<td>$\frac{1}{2}(-1 - \sqrt{5})$</td>
<td>$\frac{1}{2}(-1 + \sqrt{5})$</td>
</tr>
</tbody>
</table>

Kronecker products

$1_1 \times 1_1 = 1_1$
$1_2 \times 1_1 = 1_2$
$2_1 \times 1_1 = 2_1$
$2_2 \times 1_1 = 2_2$
$1_2 \times 1_2 = 1_1$
$2_1 \times 1_2 = 2_1$
$2_2 \times 1_2 = 2_2$
$2_1 \times 2_1 = 1_1 + 1_2 + 2_2$
$2_2 \times 2_1 = 2_1 + 2_2$
$2_2 \times 2_2 = 1_1 + 1_2 + 2_1$

Clebsch-Gordan Coefficients …
D$_5$ Allowed Mass Terms

Task: search for mass terms which are suitable Higgs singlets under D$_5$

Notation:
\( i_{th} \) generation fermions

\[ L = \{ L_1, L_2, L_3 \} \]

Dirac mass terms:
\[ \lambda_{ij} L_i^T (i\sigma_2) \phi L_j^c \]

Majorana mass terms:
\[ \lambda_{ij} L_i^T \equiv \phi L_j \]

with
\[ \equiv = \begin{pmatrix} \xi^0 & -\frac{\xi^+}{\sqrt{2}} \\ -\frac{\xi^+}{\sqrt{2}} & \xi^{++} \end{pmatrix} \]
### Resulting D$_5$ Symmetry Texture

<table>
<thead>
<tr>
<th>$L$</th>
<th>$L^C$</th>
<th>Mass Matrix</th>
</tr>
</thead>
<tbody>
<tr>
<td>$(1_2, 1_1, 1_1)$</td>
<td>$(2_1, 1_1)$</td>
<td>$egin{pmatrix} \kappa_1 \psi_2^1 &amp; -\kappa_1 \psi_1^1 &amp; \kappa_4 \phi^2 \ \kappa_2 \psi_2^1 &amp; \kappa_2 \psi_1^1 &amp; \kappa_5 \phi^1 \ \kappa_3 \psi_2^1 &amp; \kappa_3 \psi_1^1 &amp; \kappa_6 \phi^1 \end{pmatrix}$</td>
</tr>
</tbody>
</table>

D$_5$ singlet mass terms require the following quantum numbers for the scalars:

\[ \phi_1 \sim 1_1 , \]
\[ \phi_2 \sim 1_2 \text{ and} \]
\[ \psi_1 \sim 2_1 . \]

➤ Check if phenomenological successful predictions arise
GUT *and* Flavour Unification

Example: SO(10) x SU(3)

- up-type quarks
- down-type quarks
- charged leptons
- neutrinos

\[
\begin{align*}
&u \times 10^{-3} \\
&d \times 10^{-3} \\
&e \times 10^{-3} \\
&\nu_1 \times 10^{-12} \\
&\nu_2 \times 10^{-12} \\
&\nu_3 \times 10^{-11} \\
&\mu \times 10^{-2} \\
&\tau \times 10^{-1} \\
&c \times 10^{-1} \\
&s \times 10^{0} \\
&b \times 10^{1} \\
&t \times 1 \end{align*}
\]

\[SU(3)\]
\[SO(10)\]
GUT $\times$ Flavour Unification

- GUT group $\times$ continuous, gauged flavour group
  - for example $SO(10) \times SU(3)_{\text{flavour}}$
  - Generations are $3_F$
  - SSB of $SU(3)_{\text{flavour}}$ between $\Lambda_{\text{GUT}}$ and $\Lambda_{\text{Planck}}$
    - all flavour Goldstone Bosons eaten
    - discrete (ungauged) sub-group survives $\leftrightarrow$ SSB potential
    - e.g. $Z_2$, $S_3$, $D_5$, $A_4$, ...
    - structures in flavour space

GUT $\times$ flavour is rather restricted
  - small quark mixings
  - large leptonic mixings

- from unified GUT $\times$ flavour representations
GUT ⊗ Flavour Challenges

- Difficulty grows with
  - size of flavour symmetry
  - size of the GUT group

⇒ so far only a few viable models
  e.g. \( \text{SO}(10) \otimes S_4 \)  \( \text{Hagedorn, ML, Mohapatra} \)

⇒ limited number of possibilities

⇒ phenomenological success non-trivial

Aim: Distinguish models by future precision
Conclusion: The Interplay of Topics

SM extensions: SUSY, …
flavour symmetries
unification
fundamental interactions
CPT & Lorentz inv.
extra dimensions
…

leptogenesis
supernovae
BBN
structure formation, UHE neutrinos
dark matter & energy
…

precision
neutrino properties:
masses, mixings,
CP-phases, ...

mass spectrum, mixings, CP-phases, lepton flavour violation, 0ν2β–decay, ...

⇒ $\nu$-parameters extremely valuable
⇒ long term: most precise flavour info

M. Lindner
SNOW 2006
35