Mauro Mezzetto
INFN, Sezione di Padova

Experimental Outlook
19% of full statistics $\nu: \bar{\nu} = 1:1$

15% of full statistics $\nu: \bar{\nu} = 1:0$

T2K Run1-7b PRELIMINARY

Fixed Mass Hierarchy

<table>
<thead>
<tr>
<th>OBS.</th>
<th>EXPECTED (NH, $\sin^2 \Theta_{23} = 0.528$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\delta_{CP} = -\pi/2$</td>
</tr>
<tr>
<td>$\nu_e$</td>
<td>32</td>
</tr>
<tr>
<td>$\bar{\nu}_e$</td>
<td>4</td>
</tr>
</tbody>
</table>

TRUE PARAMETERS

<table>
<thead>
<tr>
<th>$\delta_{CP} = -\pi/2$, NH</th>
<th>$\delta_{CP} = 0$, NH</th>
</tr>
</thead>
<tbody>
<tr>
<td>90%</td>
<td>0.187</td>
</tr>
<tr>
<td>$2\sigma$</td>
<td>0.089</td>
</tr>
</tbody>
</table>

Global best fit Normal Hierarchy

\[
\delta_{CP} = 1.49\pi \\
\sin^2(\theta_{23}) = 0.40
\]
CP conservation excluded at more than 2 $\sigma$!

T2K alone excludes CP conservation at 90%CL

- By combining with NO$\nu$A and adding the new results of SK
- And fitting all the world data

A. Marrone showed a preliminary global fit where CP conservation is excluded at more than 2 $\sigma$
Next on CP

- HK: 10 years, staged
- Dune: 7 years full conf.
- T2K-II: 3 times T2K stats and several improvements in beam configuration and data analysis
- T2K+Nova: full stats, basically already achieved
- What about Nova-II?

CPV significance for $\delta = -90^\circ$, normal hierarchy

(2 tank staging)

(Based on DUNE CDR, arxiv:1601.05471 Table 2.1, “optimized” beam design)
First generation LBL experiments end

2012: $\nu$-exit, by closing CNGS, Europe leaves accelerator neutrinos

Epilogue
The last ever MINOS beam neutrino

Latest results from the OPERA experiment

D. Duchesneau,
LAPP/CNRS, Université Savoie Mont-Blanc
On behalf of the OPERA Collaboration

• Introduction
• Experimental setup: CNGS and detector
• Data Analysis and Oscillation results
  • $\nu_e$ appearance
  • $\nu_\mu$ disappearance
  • $\nu_\tau$ appearance search
• Conclusions

July 4th 2016

After $2.62 \times 10^{21}$ protons on target
29th June 2016
Third generation are developing fast
Where we are with systematic errors?

They are more efficient than money in improving future experiments CP sensitivities.

<table>
<thead>
<tr>
<th></th>
<th>$\nu$-mode</th>
<th>$\bar{\nu}$-mode</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\mu$</td>
<td>$e$</td>
</tr>
<tr>
<td>FLUX</td>
<td>3.59</td>
<td>3.67</td>
</tr>
<tr>
<td>$\nu$-int</td>
<td>4.10</td>
<td>5.20</td>
</tr>
<tr>
<td>SK detector</td>
<td>4.15</td>
<td>3.50</td>
</tr>
<tr>
<td>osc. par.</td>
<td>0.03</td>
<td>4.16</td>
</tr>
<tr>
<td>post fit</td>
<td>5.13</td>
<td>6.80</td>
</tr>
<tr>
<td>pre fit</td>
<td>11.9</td>
<td>12.6</td>
</tr>
</tbody>
</table>

The magnificent achievement of Daya Bay:

0.11 uncorrelated systematic errors

A factor 2 improvement in anti-$\nu$ in one year.
The impressive efforts behind systematic errors

Theoretical challenges in neutrino scattering studies
Juan M Nieves, IFIC (CSIC & UV), Spain

Review of progress in measurements of neutrino-nucleus scattering
Kendall Mahn, Michigan State University, USA

Recent results from MINERvA
Laura Fields, Fermilab, USA

New Results From MicroBooNE
Matthew Toups, Fermilab, USA

Future experimental programme for neutrino cross sections
Sara Bolognesi, CEA Saclay, France

Hadron production experiments to constrain accelerator-based neutrino flux
Laura Zambelli, Laboratoire d’Annecy-le-Vieux de Physique des Particules (LAPP), France

Not to say the enormous effort of the collaborations in understanding and managing all the other sources of systematics
The impressive efforts behind systematic errors (cross sections)

As an example the summary of Minerva presentation.

Looks like theory runs behind experiments: powerful and innovative models exist but none is capable to explain all the available data in one step.
New concepts on neutrino beams

• In the long term it will be necessary to have neutrino beams with well known fluxes (no other way to push systematics at the 1% level)
• Unfortunately so far major labs don’t support R&D in this direction
• Nevertheless very interesting developments presented at the conference:
  – Future decay-at-rest neutrino sources and their physics opportunities
    Taritree Wongjirad, Massachusetts Institute of Technology (MIT), USA
  – Physics potential of novel neutrino beams from pion and muon decay
    Steve Boyd, University of Warwick, UK
  – Development of muon accelerators for neutrino experiments
    Durga Rajaram, Illinois Institute of Technology (IIT), USA
  – P2.040 High precision neutrino flux measurements with ENUBET
    Michele Pozzato, INFN - Sezione di Bologna, Italy
    ERC Consolidator by A. Longhin, INFN Padova
Neutrino Telescopes: the best long term investment ever

• Following the experience of SK, Kamland, SNO, Borexino, IceCube etc...
• ... in the long term more physics results and better performances than expected
• Physics reach of Dune, HK, Juno: MH, octant, precision on oscillation parameters, proton decay, solar neutrinos, SN neutrinos, relic SN neutrinos, indirect dark matter searches, often in a truly complementary way
• ... and they provide the shortest way to Stockholm
As an example: searches for DM annihilation in the Sun

Limits on the interaction cross-section (SD)

- Most stringent SD cross-section limit for most models
- Complementary to direct detection efforts
- Different astrophysical & nuclear form-factor uncertainties

Graph showing limits on the interaction cross-section for different collaborations and mass scales.
Atmospheric parameters

T2K Run1-7b PRELIMINARY

Fixed Mass Hierarchy

\[ |\Delta m^2_{32}| \]

\[ \sin^2(\theta_{23}) \]

\[ \Delta m^2_{32} (10^{-3} \text{ eV}^2) \]

\[ \sin^2(\theta_{23}) \]

NOvA Preliminary

NOvA 6.05x10^{20} POT-equiv.

Normal Hierarchy

90% C.L. NOvA 2016

90% C.L. NOvA 2015

No FC Correction

SUPERK

\[ |\Delta m^2_{32}| \]

\[ |\Delta m^2_{13}| \]

\[ \sin^2(\theta_{23}) \]

\[ \Delta \chi^2 \]

\[ 0.001 \text{ to } 0.005 \text{ eV}^2 \]

\[ 0.2 \text{ to } 0.8 \]

90% CL contours

IC2014 [NO] - revised

IC2014 [NO]
Mass Hierarchy

Increase of statistics and different exps continue to favor NH

<table>
<thead>
<tr>
<th></th>
<th>NH</th>
<th>IH</th>
<th>SUM</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sin^2\theta_{23} \leq 0.5$</td>
<td>0.218</td>
<td>0.072</td>
<td>0.290</td>
</tr>
<tr>
<td>$\sin^2\theta_{23} &gt; 0.5$</td>
<td>0.529</td>
<td>0.181</td>
<td>0.710</td>
</tr>
<tr>
<td>SUM</td>
<td>0.747</td>
<td>0.253</td>
<td>1.000</td>
</tr>
</tbody>
</table>

$\text{NOvA : } \Delta \chi^2(\text{IH-NH}) = 0.47$

Global fits:

\text{Absolute minimum in NO, } \Delta \chi^2(\text{IO-N0}) = 3.1

$\text{SK : } \Delta \chi^2(\text{IH-NH}) = 4.3$
MH hunters: Orca, Pingu, INO

**MH Hunters**

- **Orca**
- **Pingu**
- **INO**

---

**KM3NeT**

- Mass hierarchy significance [GeV]
- \(\sin(\theta_{23})\)
- 3 yrs

---

**PINGU**

- PINGU

**INO**

- INO

---

**NuFit v2.0**

- "Free + RSBL"

---

**Run-time (years)**

- ICAL only \(\left(E_\mu \cos \theta_\mu, E_\nu\right)\)
- ICAL + T2K + NOvA

---

**Mass hierarchy significance**

- True IH

---

**Run-time (years)**

- 0
- 6
- 12
- 18
- 20

---

**NO (Asimov)**

- NO (LLR)

---

**IO (Asimov)**

- IO (LLR)

---

**Null Hypothesis Test**

- \(\Delta \chi^2\)

---

**\(\Delta \chi^2\) (MH)**

- NO
- IO

---

**\(\Delta \chi^2\) vs. \(\sin^2 \theta_{23}\)**

- \(\sin^2 \theta_{23}\)
Probing the unitarity of $U_{PMNS}$ to $\sim 1\%$ more precise than CKM matrix elements

<table>
<thead>
<tr>
<th></th>
<th>Statistics</th>
<th>+BG</th>
<th>+1% b2b</th>
<th>+1% EScale</th>
<th>+1% EnonL</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sin^2 \theta_{12}$</td>
<td>0.54%</td>
<td>0.67%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Delta m^2_{21}$</td>
<td>0.24%</td>
<td>0.59%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Delta m^2_{ee}$</td>
<td>0.27%</td>
<td>0.44%</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**MH sensitivity**

$\Delta T \approx \Delta \chi^2_{MH}$

**Schedule:**

- Civil preparation: 2013-2014
- Civil construction: 2014-2017
- Detector component production: 2016-2017
- Detector assembly & installation: 2018-2019
- Filling & data taking: 2020
Updated: 2365 days

\[
\sin^2 \theta_{12} = 0.311 \pm 0.014
\]

\[
\Delta m_{21}^2 = 4.83^{+1.26}_{-0.62}
\]

\[
\sin^2 \theta_{12} = 0.316^{+0.034}_{-0.026}
\]

\[
\Delta m_{21}^2 = 7.54^{+0.19}_{-0.18}
\]

\[
\sin^2 \theta_{13} = 0.309 \pm 0.013
\]

\[
\Delta m_{21}^2 = 7.48^{+0.19}_{-0.17}
\]

The unit of \( \Delta m_{21}^2 \) is \( 10^{-5} \text{eV}^2 \)

\[
\sin^2 \theta_{13} = 0.0219 \pm 0.0014
\]

For solar global parameter:

\[
A_{DN} = \frac{(Day - Night)}{(Day + Night) / 2}
\]

<table>
<thead>
<tr>
<th>Sun</th>
<th>( A_{DN} )</th>
<th>( A_{DN}^{fit} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>SK-I</td>
<td>-2.0\pm1.8\pm1.0%</td>
<td></td>
</tr>
<tr>
<td>SK-II</td>
<td>-4.4\pm3.8\pm1.0%</td>
<td></td>
</tr>
<tr>
<td>SK-III</td>
<td>-4.2\pm2.7\pm0.7%</td>
<td></td>
</tr>
<tr>
<td>SK-IV</td>
<td>-3.6\pm1.6\pm0.6%</td>
<td></td>
</tr>
<tr>
<td>combined</td>
<td>-3.3\pm1.0\pm0.5%</td>
<td></td>
</tr>
<tr>
<td>non-zero significance</td>
<td>3.0 ( \sigma )</td>
<td></td>
</tr>
</tbody>
</table>
Daya Bay: new results: 1230 days data

\[ \sin^2 2\theta_{13} = [8.41 \pm 0.27(\text{stat.}) \pm 0.19(\text{syst.})] \times 10^{-2} \]

\[ |\Delta m^2_{ee}| = [2.50 \pm 0.06(\text{stat.}) \pm 0.06(\text{syst.})] \times 10^{-3}\text{eV}^2 \]

\[ \chi^2/\text{NDF} = 232.6/263 \]
No positive results on steriles

Daya Bay, Minos and Bugey 3 combined
...except the deficit of absolute reactor neutrino fluxes which compares data with models that failed to predict the 5 GeV bump.
Next generation sterile experiments are almost ready
IceCube initiated $\nu$-astronomy

Energy Spectrum

- 54 events observed with 20±6 expected from atmosphere

- $\sim 7 \sigma$ evidence for extra-terrestrial $\nu$

Antares:

- Observed 19
- Expected 13.5 +/-2, ~ 3 IC

4 yr update of PRL2014, Science 2013
Multi-messenger the new paradigm

The multi-messenger program

- GeV-TeV γ-rays
  - Fermi, HESS, HAWC
  - P2.001
  - S. Celli

- Radio-Visible-X
  - MWA, SUPERB
  - TAROT, ZADKO, MASTER,
  - Swift

- HE neutrinos

- UHECR
  - Auger, TA

- Grav. Waves
  - LIGO-VIRGO-EGO
  - P1.001
  - A. Coleiro

A way to better understand the sources and the related physics mechanisms

A way to increase the detector sensitivities (uncorrelated backgrounds)

See talk by
I. Bartos & A. Franckowiak
New results in $0\nu\beta\beta$

► 3–4 keV energy resolution at $Q_{\beta\beta}$

► lowest background in ROI ever achieved:
  $35^{+21}_{-15} \cdot 10^{-4}$ cts/(keV·kg·yr) for Coax
  $7^{+11}_{-5} \cdot 10^{-4}$ cts/(keV·kg·yr) for BEGe

► combined Phase I+II sensitivity:
  $T^{0\nu}_{1/2} > 4.0 \cdot 10^{25}$ yr (90% C.L.)*

► blind analysis, no $0\nu\beta\beta$ signal:
  $T^{0\nu}_{1/2} > 5.2 \cdot 10^{25}$ yr (90% C.L.)*
  $|m_{ee}| < [160, 260]$ meV (90% C.L.)*

(*) preliminary, $\epsilon_{coax}^{PSD}$ to be finalized

<table>
<thead>
<tr>
<th></th>
<th>Period-1</th>
<th>Period-2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(270.7 days)</td>
<td>(263.8 days)</td>
</tr>
<tr>
<td>Observed events</td>
<td>22</td>
<td>11</td>
</tr>
<tr>
<td>Background</td>
<td>Estimated</td>
<td>Best-fit</td>
</tr>
<tr>
<td>$^{136}$Xe $2\nu\beta\beta$</td>
<td>-</td>
<td>5.48</td>
</tr>
<tr>
<td>Residual radioactivity in Xe-LS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{214}$Bi ($^{238}$U series)</td>
<td>$0.23 \pm 0.04$</td>
<td>$0.25$</td>
</tr>
<tr>
<td>$^{208}$Tl ($^{232}$Th series)</td>
<td>-</td>
<td>$0.001$</td>
</tr>
<tr>
<td>$^{110m}$Ag</td>
<td>-</td>
<td>$8.5$</td>
</tr>
<tr>
<td>External (Radioactivity in IB)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{214}$Bi ($^{238}$U series)</td>
<td>-</td>
<td>2.56</td>
</tr>
<tr>
<td>$^{208}$Tl ($^{232}$Th series)</td>
<td>-</td>
<td>0.02</td>
</tr>
<tr>
<td>$^{110m}$Ag</td>
<td>-</td>
<td>0.003</td>
</tr>
<tr>
<td>Spallation products</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{10}$C</td>
<td>2.7 ± 0.7</td>
<td>3.3</td>
</tr>
<tr>
<td>$^6$He</td>
<td>0.07 ± 0.18</td>
<td>0.08</td>
</tr>
<tr>
<td>$^{12}$B</td>
<td>0.15 ± 0.04</td>
<td>0.16</td>
</tr>
<tr>
<td>$^{137}$Xe</td>
<td>0.5 ± 0.2</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Limits (90% C.L.)

$T^{0\nu}_{1/2} > 1.07 \times 10^{26}$ yr

$\langle m_{\beta\beta} \rangle < (61 - 165)$ meV

$m_{\text{lightest}} < (180 - 480)$ meV
This plot assumes $g_A = 1.27$

- What’s going on about $g_A$ quenching?
- Which strategies to have this parameter fixed?
- ... IH not favored
$0\nu\beta\beta$ medium term perspectives

EXO-200 Phase-II started April 2016

CUORE will start operations by the end of 2016

5-y sensitivity (@ 90% C.L.)

$T_{1/2}^{(130}\text{Te}) > 9.5 \times 10^{25}$ y

$m_{\beta\beta} < 50-130$ meV
Waiting for new lab data on $\nu$ masses

Source and transport systems
- Test of source beamtube cooling system
- Completion of closed tritium loops
- Cold commissioning of full source beamline: first with D2(T2)

Full system integration
- Final commissioning of spectrometer & detector section
- “First light” planned for autumn 2016
- First tritium data in 2017
Conclusions

• The great success of this conference, both attendance and physics results, is a manifestation of the vitality of neutrino physics
• For the first time robust indication of CP violation in the leptonic sector
• Important new results by several experiments
• Very ambitious projects becoming true
• New ideas in many many fields
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• For the first time robust indication of CP violation in the leptonic sector
• Important new results by several experiments
• Very ambitious projects becoming true
• New ideas in many many fields
• Let me thanks the chairpersons for the invitation and the wonderful organization.