Workshop Summary

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NuFact 2011, CERN/Université de Genève
August 1–6, 2011
“Neutrino Outlook”
(this is what I signed up for)

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Outline

- Why Is Neutrino Physics Exciting?;
- The Standard Case for Long-Baseline Experiments, Revisited;
- Neutrino Anomalies: Friend or Foe?;
- From Here to There, and Why We Can Make It.

Throughout this talk I will express my opinion regarding a variety of themes about which – oftentimes – I don’t know very much. Corrections, criticisms, and civilized protests are welcome but do keep in mind that many of the surviving participants have planes to catch and all are fairly hungry by now. Finally, my references to different contributions will be very uneven.
What We Are Trying To Understand:

⇐ NEUTRINOS HAVE TINY MASSES

⇓ LEPTON MIXING IS "WEIRD" ⇓

\[
V_{MNS} \sim \begin{pmatrix}
0.8 & 0.5 & 0.2 \\
0.4 & 0.6 & 0.7 \\
0.4 & 0.6 & 0.7
\end{pmatrix}
\]

\[
V_{CKM} \sim \begin{pmatrix}
1 & 0.2 & 0.001 \\
0.2 & 1 & 0.01 \\
0.001 & 0.01 & 1
\end{pmatrix}
\]

What Does It Mean?
Who Cares About Neutrino Masses: Only* “Palpable” Evidence of Physics Beyond the Standard Model

The SM we all learned in school predicts that neutrinos are strictly massless. Massive neutrinos imply that the SM is incomplete and needs to be replaced/modified.

Furthermore, the SM has to be replaced by something qualitatively different.

* There is only a handful of questions our model for fundamental physics cannot explain properly. These are, in order of “palpability” (my opinion):

- What is the physics behind electroweak symmetry breaking? (Higgs or not in SM).
- What is the dark matter? (not in SM).
- Why does the Universe appear to be accelerating? Why does it appear that the Universe underwent rapid acceleration in the past? (not in SM – is this “particle physics?”).
What is the New Standard Model? [$\nu$SM]

The short answer is – WE DON’T KNOW. Not enough available info!

Equivalently, there are several completely different ways of addressing neutrino masses. The key issue is to understand what else the $\nu$SM candidates can do. [are they falsifiable?, are they “simple”?, do they address other outstanding problems in physics?, etc]

We need more experimental input.

This is where NuFact & Friends come in.
Three Flavor Mixing Hypothesis Fits All* Data Really Well.

⇒ Good Measurements of Oscillation Observables [a little outdated...]

| parameter            | best fit ±1σ                      | 2σ                  | 3σ                  |
|----------------------|-----------------------------------|---------------------|---------------------|
| $\Delta m^2_{21} \ [10^{-5}\text{eV}^2]$ | $7.59^{+0.20}_{-0.18}$            | 7.24–7.99           | 7.09–8.19           |
| $\Delta m^2_{31} \ [10^{-3}\text{eV}^2]$ | $2.45 \pm 0.09$                   | 2.28–2.64           | 2.18–2.73           |
|                      | $-(2.34^{+0.10}_{-0.09})$         | $-(2.17–2.54)$      | $-(2.08–2.64)$      |
| $\sin^2 \theta_{12}$ | $0.312^{+0.017}_{-0.015}$         | 0.28–0.35           | 0.27–0.36           |
| $\sin^2 \theta_{23}$ | $0.51 \pm 0.06$                   | 0.41–0.61           | 0.39–0.64           |
|                      | $0.52 \pm 0.06$                   | 0.42–0.61           |                     |
| $\sin^2 \theta_{13}$ | $0.010^{+0.009}_{-0.006}$         | $\leq 0.027$        | $\leq 0.035$        |
|                      | $0.013^{+0.009}_{-0.007}$         | $\leq 0.031$        | $\leq 0.039$        |

Table 2. Neutrino oscillation parameters summary. For $\Delta m^2_{31}$, $\sin^2 \theta_{23}$, and $\sin^2 \theta_{13}$ the upper (lower) row corresponds to normal (inverted) neutrino mass hierarchy. We assume the new reactor anti-neutrino fluxes [5] and include short-baseline reactor neutrino experiments in the fit.

* Modulo short baseline anomalies.

[Schwetz et al, 1103.0734]
Hint For Nonzero $U_{e3}(?)$ Not to be written in stone just yet...

... but next year may prove to be very exciting!

Global evidence for $\theta_{13} > 0$

FIG. 3: Global 3$\nu$ analysis. Preferred $\pm 1\sigma$ ranges for the mixing parameter $\sin^2 \theta_{13}$ from partial and global data sets. Solid and dashed error bars refer to old and new reactor neutrino fluxes, respectively.  

Fogli et al., arXiv:1106.6028.
Good time for experimenta lists

With large $\theta_{13}$ things are easier for EVERYBODY

[H. Minakata]
What We Know We Don’t Know: Missing Oscillation Parameters

- What is the $\nu_e$ component of $\nu_3$? ($\theta_{13} \neq 0$?)

- Is CP-invariance violated in neutrino oscillations? ($\delta \neq 0, \pi$?)

- Is $\nu_3$ mostly $\nu_\mu$ or $\nu_\tau$? ($\theta_{23} > \pi/4$, $\theta_{23} < \pi/4$, or $\theta_{23} = \pi/4$?)

- What is the neutrino mass hierarchy? ($\Delta m_{13}^2 > 0$?)

$\Rightarrow$ All of the above can “only” be addressed with new neutrino oscillation experiments

Ultimate Goal: Not Measure Parameters but Test the Formalism (Over-Constrain Parameter Space)
We need to do this in the lepton sector!

How do we do it?

Need NuFact (I think)
\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix} =
\begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu1} & U_{\mu2} & U_{\mu3} \\
U_{\tau1} & U_{\tau2} & U_{\tau3}
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

What we have **really measured** (very roughly):

- Two mass-squared differences, at several percent level – many probes;
- \(|U_{e2}|^2 – solar data;\)
- \(|U_{\mu2}|^2 + |U_{\tau2}|^2 – solar data;\)
- \(|U_{e2}|^2|U_{e1}|^2 – KamLAND;\)
- \(|U_{\mu3}|^2(1 – |U_{\mu3}|^2) – atmospheric data, K2K, MINOS;\)
- \(|U_{e3}|^2(1 – |U_{e3}|^2) (upper bound) – reactors (1 km);\)
- \(|U_{e3}|^2|U_{\mu3}|^2 (upper bound?) – MINOS, T2K(?).\)

We still have a ways to go!
Evidence(?) For Physics Beyond the Three–Massive–Neutrinos Paradigm

- LSND $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$;
- MiniBooNE $\nu_\mu \rightarrow \nu_e$;
- MiniBooNE $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$;
- Reactor Anomaly;
- MINOS $\nu_\mu$ versus $\bar{\nu}_\mu$ oscillations;
- …

[Bross, Djuricic, Louis, Mention, Pietropaolo, Wark]
(Some) Phenomenological Explanations

- Sterile Neutrinos (light, stable variety); LSND, MB, Reactor
- New Neutrino Interactions; MINOS
- Lorentz Invariance/CPT-Violation; “all”
- Sterile Neutrinos (heavy, unstable variety [Gninenko]). LSND, MB

Most important: how do we tell which (if any) are correct?

Answer is in the intensity frontier, especially in new short-baseline neutrino experiments.
[new mixing parameters: $|U_{e4,5}|, |U_{\mu 4,5}| \sim 0.13 - 0.16$]
Short-Baseline Neutrino Experiments

Short: GeV neutrino energies, baselines of $\sim 100 - 1000$ m. This is “near-detector” physics!

The goals are well-defined and include:

- $\nu_\mu$ disappearance at the few percent level. Aiming at $4|U_{\mu4,5}|^2 \sim 0.06$.

- $\nu_e$ appearance in the Mini-BooNE LSND range, more accurate. Aiming at $4|U_{e4,5}|^2|U_{\mu4,5}|^2 \sim 0.001$.

- Can we see an oscillation? Challenging for these short (only upper bounds for now) baselines...

- How about $\nu_\tau$? If $|U_{\tau4,5}| \sim 0.1$, expect $P(\nu_\mu \rightarrow \nu_\tau) \sim 0.001$. 

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Q: Should We Worry About These “Anomalies”? 

Here is my attempt at an answer:

- Don’t affect “vanilla” physics in a destructive way. E.g. LSND effect really small (for appearance), but potentially interesting for disappearance (unless the near detector blinds us to it . . . )!

- Furthermore, efforts to elucidate these anomalies will certainly end up teaching us a lot. They have already taught us that neutrino experiments can be quite tricky, especially when we are trying to see very small effects! [subliminal message: going forward, you must understand your fluxes and your cross-sections really well!]

- If confirmed however, we are in hog heaven!
  - New Physics!
  - New Physics that can mostly be studied via neutrino oscillations!
Sterile Neutrinos Aren’t So Bad After All [P. Hernandez, M. Shaposhnikov, H. Zhang]

– could be “side effect” of mechanism behind neutrino masses!

[AdG, Huang, Jenkins, arXiv:0906.1611]
Getting from Here to There, and Why We Can Make It

- There? I’ll assume ‘there’ is a Neutrino Factory. Which one (low energy, high energy, which baselines, etc) will be decided by the Physics we will learn along the way.

- The Physics case for the Neutrino Factory can be made very clearly now. It does not depend on what the LHC will discover, but the LHC may help (?).

- Somewhere along the way, in the not too distant future, someone will build and run a superbeam experiment, unless $|U_{e3}|$ is not large. We will learn a lot, and the Physics Case for the Neutrino Factory will only get stronger.

- Step zero may be taken “today”: the VLENF [A. Bross] is a great opportunity to address current “anomalies” and will teach us a lot, including cross-section measurements ($\nu_e$). Should be considered very seriously.
• The Neutrino Factory is a very powerful facility. Lots of Physics to be done with lots of muons, and well characterized neutrino beams. CLFV, in particular, may teach us a lot about the physics behind neutrino masses. (I’ll echo J. Ellis regarding this. Taking advantage of the muon fluxes at a Neutrino Factory isn’t just a good idea. It is probably mandatory.)

Note that this may include addressing the burning questions we will be worried about 10+ years from now (I can assure you, none of these can be found in this talk!) – “Be Prepared”

• After we get there, we may choose to move on. The Neutrino Factory is a (probably necessary) step towards a Muon Collider [V. Shiltsev]. In the near future, it will be clear whether the Physics Case for the Muon Collider is strong enough. In this case, we will need input from the LHC!
Dénouement

• A lot of progress made over the past 10+ years.
• New neutrino oscillation data keeps coming. Look forward to very exciting next few years – MiniBooNE, MINOS, Ice-Cube/Deep Core, T2K, Double-CHOOZ, RENO, Daya Bay, Nova are all real experiments.
• Simulations much more sophisticated. Good level of communication and cooperation between experimentalists and phenomenologists.
• NuFact R&D experiments becoming a reality.
• I thank the organizers and working group conveners for a very stimulating meeting and really look forward to the next NuFact meetings!

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