NuFact08 Perspectives

Chris Quigg

10th International Workshop on Neutrino Factories, Super beams, and Beta beams
Jaume I
"el conqueridor"
(1208 ÷ 1276)
rei d’Aragó
de mallorquines
de València
comte de Barcelona i d’Urgell
senyor de Montpellier
2008 Premio Rey Jaime I: Investigación Básica
$9.5 M for NOvA
NuFact99: Questions of Identity

Do neutrinos oscillate?
What are the neutrino masses?
Is neutrino mass a sign of (nontrivial) BSM physics?
Does the evidence require more than 3 $\nu$ species?
Can we find evidence for a sterile $\nu$?
Could $\nu$ masses be special (Majorana, scale $\gg$ EW)?

How could light sterile $\nu$ arise?
Are $\nu$ mixing angles large? maximal?
Do $\nu$ masses probe large extra dimensions?
Can we detect CP violation in $\nu$ mixing?
Cl 95%  
Ga 95%  
νμ↔ντ  
νe↔νX  
$10^{-3}$  
$10^{-6}$  
$10^{-9}$  
$10^{-12}$  
$10^2$  
$10^0$  
$10^{-4}$  
$10^{-2}$  
$10^{-1}$  
$\tan^2\theta$  

All limits are at 90% CL unless otherwise noted

http://hitoshi.berkeley.edu/neutrino
Three-neutrino mixing formalism

3 ν masses, $m_1, m_2, m_3$

$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$

3 mixing angles

1 Dirac phase

2 Majorana phases

$30^\circ \lesssim \theta_{12} \lesssim 38^\circ$ solar

$35^\circ \lesssim \theta_{23} \lesssim 55^\circ$ atm

$\theta_{13} \lesssim 10^\circ$

CP phase $\delta$ unconstrained
Neutrino family patterns (representative)

\[ m_1 < m_2; \quad \nu_3 \text{ lies above or below} \]

\[ \theta_{13} = 10^\circ \]
Neutrino family patterns (uncertainties)

\( \delta = 0 \)
Neutrino family patterns (tri-bimaximal mixing)

\[ \theta_{13} = 0, \quad \theta_{23} = \text{maximal}, \quad \sin^2 \theta_{12} = \frac{1}{3} \]
Quark family patterns
Fermion Masses

Running mass $m(m)$
Fermion Masses Run

Running mass $m(m) \ldots m(U)$
Neutrino Masses: oscillations determine $\Delta m^2$, not $m_\nu$

$$m_2^2 - m_1^2 \approx 7.9 \times 10^{-5} \text{ eV}^2; \quad |m_3^2 - m_1^2| \approx 2.5 \times 10^{-3} \text{ eV}^2$$

Absolute scale not known, but $m_\nu \lesssim 10^{-5} m_e$
KATRIN aims at 0.2 eV
Relic ν contributions to mass density of Universe

Pascoli, Pastor
Interactions: $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ gauge symmetries
Why does the muon weigh?

Gauge symmetry allows

\[ \zeta_e \left[ (e_L \Phi) e_R + e_R (\Phi^\dagger e_L) \right] \rightsquigarrow m_e = \zeta_e v / \sqrt{2} \]

After spontaneous symmetry breaking

What does the muon weigh?

\( \zeta_e \) : picked to give right mass, not predicted

Fermion mass implies physics beyond the standard model
How could neutrino mass arise?

Add $N_R$: SU(2)$_L$ singlet with $Y = 0$ — sterile
couple $\nu_L, N_R$ in Dirac mass term, $\zeta_\nu \lesssim 10^{-11}$

$\nu$ has no charge or color,
so $\nu \equiv \bar{\nu}$ is possible (Majorana)

**Dirac & Majorana: explain $m_\nu$?**

Neutrino mass as physics beyond standard model:
may connect with ultrahigh scales (seesaw)
but might also implicate TeV scale
The Importance of the 1-TeV Scale

EW theory does not predict Higgs-boson mass

Thought experiment: conditional upper bound

\[ W^+_L W^-_L, Z^0_L Z^0_L, H H, H Z^0_L \] satisfy s-wave unitarity,

provided

\[ M_H \leq \left( \frac{8\pi\sqrt{2}}{3G_F} \right)^{1/2} = 1 \text{ TeV} \]

• If bound is respected, perturbation theory is everywhere reliable
• If not, weak interactions among \( W^\pm, Z, H \) become strong on 1-TeV scale

New phenomena are to be found around 1 TeV
Imagine a world without a Higgs mechanism
If electroweak symmetry were not hidden ...

- Massless quarks and leptons
- QCD confines quarks into color-singlet hadrons
- \textit{Nucleon mass little changed}
- QCD breaks EW symmetry, gives tiny $W, Z$ masses; weak-isospin force doesn’t confine
- $p$ outweighs $n$: rapid $\beta$-decay
  \[ \Rightarrow \text{lightest nucleus is } n \ldots \text{no hydrogen atom} \]

- Some light elements from BBN, but $\infty$ Bohr radius
- No atoms means no chemistry, no stable composite structures like liquids, solids, ...

\[ \ldots \text{character of the physical world would be profoundly changed} \]
### Parameters of the Standard Model

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<th>Count</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>3</td>
<td>coupling parameters $\alpha_s, \alpha_{\text{em}}, \sin^2 \theta_W$</td>
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<td>parameters of the Higgs potential</td>
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<td>quark masses</td>
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<td>quark mixing angles</td>
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<tr>
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<td>CP-violating phase</td>
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<tr>
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<td>charged-lepton masses</td>
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<tr>
<td>3</td>
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<tr>
<td>3</td>
<td>leptonic mixing angles</td>
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<tr>
<td>1</td>
<td>leptonic CP-violating phase (+ Majorana . . .)</td>
</tr>
<tr>
<td>26$^+$</td>
<td>arbitrary parameters</td>
</tr>
</tbody>
</table>

 Flavor physics may be where we see, or diagnose, the break in the SM.
What is the nature of the mysterious new force that hides electroweak symmetry?

✴ A force of a new character, based on interactions of an elementary scalar
✴ A new gauge force, perhaps acting on undiscovered constituents
✴ A residual force that emerges from strong dynamics among electroweak gauge bosons
✴ An echo of extra spacetime dimensions
Essential step toward understanding the new force that shapes our world:
Find the Higgs boson and explore its properties.

- Is it there? How many?
- Verify quantum numbers (spin, parity, …)
- Does $H$ generate mass for gauge bosons and for fermions?
- How does $H$ interact with itself?
New Physics on the Fermi Scale?

If dark matter interacts weakly …

… its likely mass is 0.1 to 1 TeV: *Fermi scale*
How to separate EW, higher scales?

Does $M_H < 1 \text{ TeV}$ make sense?

The peril of quantum corrections – hierarchy problem

![Diagram showing various loops and their comparisons with tuned input at 5 TeV.](image)
How to separate EW, higher scales?

Traditional: change electroweak theory to understand why $M_H$, electroweak scale $\ll M_{\text{Planck}}$

To resolve hierarchy problem: extend standard model on the 1-TeV scale …

\[ \text{SU}(3)_c \otimes \text{SU}(2)_L \otimes \text{U}(1)_Y \]

composite Higgs boson

technicolor / topcolor

supersymmetry

Ask instead why gravity is so weak, why $M_{\text{Planck}} \gg$ electroweak scale \\
extra dimensions
Look forward to immensely productive conversations among LHC discoveries, neutrino advances, other high-sensitivity accelerator experiments, and astro/cosmo/particle observations.

Many examples of possible connections presented at NuFact08

Lifting the electroweak veil around 1 TeV should help us to see the problem of identity (flavor) and the challenges of other scales more clearly.
How is our thinking too narrow?
New physics *in* the standard model?

What phenomena are implied by the standard model, but too subtle to have attracted our notice?

**Known example:** sphaleron for $B$-violation

**Recent case:** $Z\gamma\omega$ anomaly-mediated $\nu\gamma$ interaction in presence of baryons (Harvey, Hill, & Hill)

*Added motivation to measure & understand* 
$\nu$ cross sections, hadroproduction at low energies 
HARP, MIPP, SciBooNE, Minerva, MiniBooNE, T2K, …

Catanesi, Harris, Nakaya, Petti, …
What preconceptions must we reexamine?
Enormously impressive progress reported here

Coherence of experimental results
Breadth of scientific opportunities
Creativity of machine designers

Much incentive to stretch our minds,
think “blue-sky” thoughts
about machines, detectors, baselines, strategies …

and even to ask how little we could require
Super Beams

J-PARC facility in Japan:
- Phase I for T2K (2009):
  0.75 MW 30 GeV, 10 \times 10^{20} \text{ pot/y};
- Phase II upgrade (2015):
  4MW 50 GeV, 50 \times 10^{20} \text{ pot/y}

Project-X at Fermilab:
- NuMI for NO\nu A:
  400kW, 700kW MI 120 GeV, 6 \times 10^{20} \text{ pot/y};
- New GeV linac + recycler + MI (2016):
  2.3 MW 120 GeV, 30 \times 10^{20} \text{ pot/y}.

(see talk by D. Harris & A. Jansson)
Megawatt proton source of few GeV for pion production

Neutrinos produced from decay of 25-50 GeV stored muons

Useful decays achievable $3 \div 5 \times 10^{20}$ per year

Path toward Muon Collider
Megawatt proton driver of few GeV to produce radioactive ions (ISOL target)

Neutrinos originated from $\beta$ decay of accelerated ions (EURISOL)

$\Rightarrow$ Rates of $2.9 \times 10^{18}\nu\ (^6\text{He})$ and $1.1 \times 10^{18}\nu\ (^{18}\text{Ne})$ per year at $\gamma = 100$

+ $^8\text{Li}$, $^8\text{B}$, EC monochromatic beams

Wildner
From existing detectors to a new generation

Magnetized iron
Water Cherenkov
Magnetized emulsion
Totally active scintillator
Liquid argon

...
Where do we want to go?
How can we get there?
Practical considerations will intervene

Cavern size, structural integrity, excavation time
Detector cost, fabrication time
Difficulty, cost of steep dip angles

What compromises will get us to the essential physics results in the shortest time?
Realizing Neutrino Factory or $\beta$ Beam

When will needed demonstrations be in hand?
When will experimental specification be needed?

When might we hope to ask for funding?
How long to operations?
Bagnères-de-Bigorre, 1953
the “last” cosmic-ray conference
the coming of the BNL Cosmotron

C. F. Powell: “Gentlemen, we have been invaded!
The accelerators are here.”

Louis Leprince-Ringuet: « Mais nous devons aller vite, nous devons courir sans ralentir notre cadence : nous sommes poursuivis … nous sommes poursuivis par les machines ! »
NuFact08: Updated Questions of Identity

What are subdominant neutrino transitions?
What is the neutrino hierarchy, absolute mass scale?
Is neutrino mass a sign of nontrivial BSM physics?

Bottom line on LSND & MiniBooNE?
Can we find evidence for a sterile ν?

Dirac or Majorana (L-number), scale $\gg$ EW, GUTs?

Connection between ν mass, LFV, what else?
How could light sterile ν arise?

$\theta_{23}$: is $\nu_3$ mostly $\nu_\mu$ or $\nu_\tau$? How small is $\theta_{13}$?

Do ν masses probe large extra dimensions?
Can we detect CP violation in ν mixing?

Does leptogenesis explain matter excess?

How do neutrinos shape the universe?
ν decay, EDM, MDM, discrete symmetry violation?
Thanks to all!