Neutrinos and systematic errors

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Hadronic Contributions to New Physics
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Open problems in the SM

Experimental evidence:

- Dark matter
- Neutrino masses
- Matter-antimatter asymmetry
- Gravitational interaction

Naturalness:

- Strong CP problem
- Hierarchy problem
- Flavor puzzle
- Cosmological constant
Current status in neutrino physics

\[ U = \begin{pmatrix}
    1 & 0 & 0 \\
    0 & c_{23} & s_{23} \\
    0 & -s_{23} & c_{23}
\end{pmatrix}
\begin{pmatrix}
    c_{13} & 0 & s_{13}e^{-i\delta} \\
    0 & 1 & 0 \\
    -s_{13}e^{i\delta} & 0 & c_{13}
\end{pmatrix}
\begin{pmatrix}
    c_{12} & s_{12} & 0 \\
    -s_{12} & c_{12} & 0 \\
    0 & 0 & 1
\end{pmatrix}
\times
\begin{pmatrix}
    1 & 0 & 0 \\
    0 & e^{i\alpha_1} & 0 \\
    0 & 0 & e^{i\alpha_2}
\end{pmatrix}
\]

- \[ \theta_{13} \sim 9^\circ \quad \Delta m_{21}^2 \sim 7.5 \times 10^{-5} \text{ eV}^2 \]
- \[ \theta_{23} \sim 45^\circ \quad |\Delta m_{31}^2| \sim 2.5 \times 10^{-3} \text{ eV}^2 \]
- \[ \theta_{12} \sim 33^\circ \]

\[ c_{ij} = \cos \theta_{ij} \]
\[ s_{ij} = \sin \theta_{ij} \]

Pontecorvo, 1957
Maki, Nakagawa, Sakata, 1962

P. Coloma - Neutrinos
Neutrino masses

-neutrinos-

meV  eV  keV  MeV  GeV  TeV

d  s  b
u  c  t

e  μ  τ
Neutrino masses

New fields are required to give neutrinos a mass. Two main ways:

1) Dirac mass: as for the rest of fermions in the SM

\[ Y \overline{L}_L \tilde{\phi} \nu_R \rightarrow m_\nu \bar{\nu}_L \nu_R \]

\[ Y_\nu \lesssim 10^{-12} \]
Neutrino masses

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\[ Y \bar{L}_L \phi \nu_R \rightarrow m_\nu \bar{\nu}_L \nu_R \]

\[ Y_\nu \lesssim 10^{-12} \]

2) A Majorana mass. For example:

\[ m_\nu \bar{\nu}_L \phi \nu_R + \frac{1}{2} M \bar{\nu}_R^c \nu_R \]
Neutrinos as a window to new physics

Goals for the future: complete the neutrino picture, search for lepton number violation, and thoroughly test the standard neutrino scenario.

- Neutrinoless double beta decay is very sensitive to effects from neutrino mass models
- Neutrinos are very sensitive to new physics affecting their oscillation pattern
- Coherent neutrino scattering very sensitive to new mediators with low masses, or to effective operators
$\nu\nu\beta\beta$ decay
Neutrinoless double beta decay

\[ m_{\beta\beta} = \left| \sum_i U_{ei}^2 m_i \right| \]

\[ \left[ T_{1/2}^{0\nu} \right]^{-1} = G_{0\nu}(Q, Z) \left| \mathcal{M}_{0\nu} \right|^2 m_{\beta\beta}^2 \]

For a nice review see e.g., Engel and Menendez, 1610.06548

Depends on the nucleus
Neutrinoless double beta decay

\[
\left[ T_{1/2}^{0\nu} \right]^{-1} = \sum_i G_i^{0\nu}(Q, Z) \left| \mathcal{M}_i^{0\nu} \right|^2 \eta_i^2
\]

Schechter and Valle, PRD25 (1982)

For a nice review see e.g., Engel and Menendez, 1610.06548

Your favorite New Physics Model

Depends on the New Physics model
Neutrinoless double beta decay

For a nice review see e.g., Engel and Menendez, 1610.06548

Kamland-Zen coll., 1605.02889
Neutrinoless double beta decay

See e.g., Giunti and Zavanin, 1505.00978
Huan and Zhou, 1902.03839, Bilenky et al, hep-ph/0104218
and Blennow et al, 1005.3240

→ More on Cirigliano's talk on Friday
Oscillations
Neutrino oscillations

\[ P(\nu_\alpha \rightarrow \nu_\alpha) = 1 - \sin^2 2\theta \sin^2 \left( \frac{\Delta m^2 L}{4E_\nu} \right) \]

\[ E_{peak} = \frac{\Delta m^2 L}{2\pi} \]
CP violation: three families

\[ P_{\mu e} = |U_{\mu 2} U_{e 2}^* (e^{2i \Delta_{21}} - 1) + U_{\mu 3} U_{e 3}^* (e^{2i \Delta_{31}} - 1)|^2 \]

Diwan, Galymov, Qian, Rubbia, 1608.06237
However, neutrinos are...

- **Difficult to produce**
  - No mono-energetic beams available in the few GeV region.
  - Large uncertainties
- **Difficult to detect**
  - Low statistics, few measurements, ...
- **You don't really see the neutrino!**
  - Indirect energy reconstruction methods
However, neutrinos are...

\[ E_{\text{rec}} = \frac{ME_\ell - m_\ell^2/2}{M - E_\ell + |\vec{p}_\ell| \cos \theta_\ell} \]

Image credit: T. Leitner

→ More about this in the talk by M. Vicente Vacas

Martini, Ericson, Chanfray, 1211.152 Nieves, Sanchez, Ruiz Simo, Vicente Vacas, 1204.5404 Lalakulich, Mosel 1208.3678
Direct impact: toy model

\[ P_{\mu\mu} \sim 1 - \sin^2 2\theta \sin^2 \frac{\Delta m^2 L}{4E} \]

Figure from NuSTEC white paper, 1706.03621
(adapted from Coloma and Huber, 1307.1243)
What about calorimetry?

- Using kinematic reconstruction, we are only sensitive to the info carried by the lepton
  - Limited by our assumption of the final state
- At calorimetric detectors in principle we can measure all particles in the final state
  - Limited by undetected particles*

*e.g., neutrons escape detection easily*
Does this improve with calorimetry?

Ankowski, Coloma, Huber, Mariani and Vagnoni, 1507.08561
Summary

- Intensity frontier experiments offer a great opportunity to test for New Physics that is weakly coupled to the SM
- However, we need to make sure we understand our signals very well...
Summary

Circa 1700...
Thank you!!
Backup slides
Ambitious goals

- This figure includes normalization uncertainties at the percent level.
- Reconstructed neutrino energy is assumed to be unbiased.

Diwan, Galymov, Qian, Rubbia, 1608.06237
Possible solutions: nuPRISM

M. Wilking's talk at NNN 2015

Reproduce Super-K Oscillation Pattern at a Near Detector!