Tracking down the origin of neutrino mass

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Neutrino oscillations

Observation of neutrino oscillations:

→ **Strong** evidence of physics beyond the SM

→ introduced **more parameters** to the model
  (3 angles, at least one phase, 3 masses)

→ **need** to introduce neutrino mass mechanism
Neutrino mass

What is neutrino mass generation mechanism?

**Dirac neutrinos**

\[ m_D = y_\nu \bar{\nu}_L \tilde{H} N_R \]

like other SM fermions
Neutrino mass

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**Majorana neutrinos**

\[ m_M = M_N \tilde{\nu}_L \nu_L^c \]

Neutrinos are the only SM particles that could have such a mass term

Term **not** gauge invariant!
Neutrino mass

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Term not gauge invariant!

In any case need new particles!

→ observation of neutrino oscillations predicts new particles!
Neutrino mass

What is the neutrino mass scale?

→ learn about required couplings in new interaction

identify promising experimental search strategies
Neutrino mass

What is the neutrino mass scale?

Only upper limit on neutrino mass scale so far!

Cosmological sum of neutrino masses:

\[ \sum m_\nu \lesssim 0.1 \text{ eV} \]

Depending on data sets combined

Future cosmological observatories will measure sum of neutrino masses

[Di Valentino, Gariazzo, Mena, 2106.15267]
Neutrino mass

What is neutrino mass scale?

Only upper limit on neutrino mass scale so far!

Mild $(1.6 \, \sigma)$ preference for normal mass ordering from oscillation experiments

![Diagram showing normal and inverted mass orderings with mass eigenstates $\nu_e$, $\nu_\mu$, $\nu_\tau$ for each ordering.](image)

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TAU 2023: Neutrino mass
Neutrino mass

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Neutrinos much lighter than other fermions

Is this a clue about underlying mass mechanism?
Neutrino mass

What is neutrino mass scale?

Neutrinos much lighter than other fermions

Dirac neutrinos: Yukawa coupling $y_\nu \lesssim 10^{-13}$

Dirac neutrinos would have a much smaller Yukawa coupling than other fermions

Direct probe of $H \rightarrow \bar{\nu}\nu$ colliders not possible

Reason for smallness of neutrino mass? [CMS 2009.04363]
Neutrino mass

Majorana mass term arises from higher dimension operators!

→ explains smallness of neutrino mass due to suppression by high scale

Majorana neutrino mass operators occur at odd dimension

\[ \mathcal{O} \propto (LLHH)(H^\dagger H)^n \]

\[ \rightarrow m_\nu \propto c \frac{v^2}{\Lambda} \left( \frac{v}{\Lambda} \right)^{d-5} \]

[Kobach 1604.05726]
Neutrino mass

Majorana mass term arises from higher dimension operators!

→ explains smallness of neutrino mass due to suppression by high scale

Dimension 5 operator
\[ \mathcal{L}_5 = c_5 \frac{(\bar{L}^c \tilde{H}^*) (\tilde{H}^\dagger L)}{\Lambda} \]

Only dim-5 operator that can be build with SM fields alone
Expect first signs of new physics from lowest SMEFT operator
→ neutrino mass

Dimension 7
\[ \mathcal{L}_7 \propto c_7 \frac{(LLHH)(H^\dagger H)}{\Lambda^3} \]

Dimension 9
\[ \mathcal{L}_9 \propto c_9 \frac{(LLHH)(H^\dagger H)(H^\dagger H)}{\Lambda^5} \]

...
Maze of possibilities

Neutrino mass mechanism

Dirac

Majorana

Dimension 5 operator

Dimension 7 operator

Dimension 9 operator

...
Maze of possibilities

Example dimension 5 operator

\[ m_\nu \sim c \frac{\nu^2}{\Lambda} \]

- **\( \Lambda \) large:**
  - small \( m_\nu \)
  - due to suppression of scales
  - No direct probe
  - Hierarchy problem
  - Type I seesaw
  - Type II seesaw
  - Type III seesaw

- **\( \Lambda \) small:**
  - small \( m_\nu \)
  - due to small Wilson coefficient \( c \)
  - testable
  - Type II seesaw
  - inverse seesaw
  - linear seesaw
  - extended seesaw
Maze of possibilities

Neutrino mass mechanism

Dirac

Majorana

Dimension 5 operator

Dimension 7 operator

Dimension 9 operator

Hierarchy: high energy phenomenology

Symmetry: Phenomenology at lower energy
Testing neutrino mass mechanisms

Dirac vs Majorana neutrinos

Majorana mass term violates lepton number
Dirac mass term conserves lepton number
⇒ search for lepton number violating processes

Effect $\propto$ neutrino mass!
Neutrinoless double beta decay experiments aim to provide an answer:

\[(Z, A) \rightarrow (Z + 2, A) + 2 \, e^-\]

Currently just upper limit, no observation.

Large parameter space, depending on absolute mass scale and mass ordering.

Width of allowed bands depends on Majorana phases.
Testing neutrino mass mechanisms

Dirac vs Majorana neutrinos

Signs of **lepton number breaking** in the early Universe
Gravitational waves from decay of cosmic strings from breaking of lepton number symmetry

Signature depends on Lepton number breaking scale

[King, Marfatia, Rahat 2306.05389]

[see also Dror, Hiramatsu, Kohri, Murayama, White 2306.05389]
Testing neutrino mass mechanisms

New particles associated to mass generation

New particles are introduced in neutrino mass generation mechanisms
→ search for them!

Identify UV complete models for higher dimensional operators
Testing neutrino mass mechanisms

New particles associated to mass generation

Identify UV complete models for higher dimensional operators

Example: realizations of dim-5 operator

**Type I seesaw**

\[ N_R : \text{SM singlet} \]

“Right-handed neutrino”

**Type II seesaw**

\[ \Delta: SU(2)_L \text{ scalar triplet} \]

**Type III seesaw**

\[ \Sigma: SU(2)_L \text{ fermion triplet} \]
Testing neutrino mass mechanisms

New particles associated to mass generation
Probing the Type I seesaw

Interaction of sterile with SM governed by active-sterile mixing angle

$$\theta \propto \frac{y V}{M_N},$$

neutrino mass

$$m_\nu \propto \theta \times (y V)$$

Phenomenology depends on
mass of sterile

Light sterile: produced at experiments
+ cosmology

Heavy sterile: unitarity of
neutrino mixing matrix
Testing neutrino mass mechanisms

New particles associated to mass generation

Probing the Type II seesaw

Introduce new field charged under $SU(2)_L$, $U(1)_Y$
new neutral, singly and doubly charged scalar particles

$$m_\nu \propto y_\mu \frac{\nu^2}{M^2_\Delta}$$

EWPO, collider phenomenology, cLFV, g-2

[Antusch, Fischer, Hammad, Scherb 1811.03476]
Testing neutrino mass mechanisms

New particles associated to mass generation
Probing the Type III seesaw

Introduce new field charged under $SU(2)_L$, $U(1)_Y$
new neutral, charged fermions with EW gauge interactions

$$m_\nu \propto y_{\nu} \frac{y_{\nu}}{M_\Sigma}$$
(similar to type I seesaw however $\Sigma^0$ couples to EW bosons)

Charged fermion mixing!

L violating and L conserving processes:
Collider constraints, cLFV

[Coy, Frigerio 2110.09126]
Testing neutrino mass mechanisms

New particles associated to mass generation

Alternative neutrino mass mechanisms: radiative neutrino mass models

Smallness of $m_\nu$ due to loop factor

1-, 2-, 3-loop mass models available in literature

Leptoquark model

Zee-Babu model (new charged scalars)

[for a review see Cai, Herrero-Garcia, Schmidt, Vicente. Volkas 1706.08524]

[Leptoquark model: Doršner, Fajfer, Košnik 1701.08322]

[Zee ‘86, Babu ‘88]
Testing neutrino mass mechanisms

Connection to other open questions of SM

Dark Matter
DM particles introduced scotogenic neutrino mass model, realization of inverse seesaw

Baryon asymmetry of the Universe
Leptogenesis: lepton number violating decays of heavy sterile neutrinos → can be realized in parameter space of high scale type I seesaw

Unification of forces
Right-handed neutrinos automatically introduced in SO(10) GUT
High scale type I seesaw scale $\approx$ scale of unification

[Ma, 0601225, De Romeri, Fernandez-Martinez, Machado, Niro, JG 1707.08606]
Summary & Conclusion

- Neutrino oscillations → Very strong evidence for need for additional particles related to neutrino mass generation
- Many possible mass mechanisms with rich phenomenology
- So far no sign of new particles
- If new particle is discovered, need to test if it can reproduce measured neutrino masses and mixing
- Future improved experimental sensitivities and new testable models will hopefully bring us closer to find neutrino mass generation mechanism
Thanks for your attention!
Appendix: Neutrino mass

\[ \Delta \chi^2 \]

\[ m_i \ [\text{eV}] \]

- \( \nu_1 \), 1.78
- \( \nu_2 \), 1.71
- \( \nu_3 \), 1.73

Included:
- Osc data (avg of global fits)
- Preference for NO
- Cosmo constraint

\[ \nu_3 \]

\[ \nu_2 \]

\[ \nu_1 \]

\[ m_i \ [\text{eV}] \]

1, 2, 3 \( \sigma \)
Appendix: Neutrino oscillation parameters

Neutrino oscillation parameters measured over years

[Denton et al 2212.00809]

[Diagram showing neutrino oscillation parameters over time]
Appendix: Neutrino oscillation parameters

Global fits to oscillation data:

mass splittings: $|\Delta m^2_{32}| = 2.5 \cdot 10^{-3} \text{ eV}^2$, $\Delta m^2_{21} = 7.4 \cdot 10^{-5} \text{ eV}^2$

mass ordering unknown

[tau v5.1]