Neutrino Theory Overview

- Heinrich Päs -

tu dortmund
3 years ago...

The New York Times

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\[ P = \sin^2 2\theta \sin^2 \frac{\Delta m^2 L}{4E_\nu} \]
...2018: Precision Science

\[
U_{3\times3} = \begin{pmatrix}
1 & 0 & 0 \\
0 & \cos \theta_{23} & \sin \theta_{23} \\
0 & -\sin \theta_{23} & \cos \theta_{23}
\end{pmatrix}
\begin{pmatrix}
\cos \theta_{13} & 0 & \sin \theta_{13} e^{-i\delta} \\
0 & 1 & 0 \\
-\sin \theta_{13} e^{i\delta} & 0 & \cos \theta_{13}
\end{pmatrix}
\begin{pmatrix}
\cos \theta_{12} & \sin \theta_{12} & 0 \\
-\sin \theta_{12} & \cos \theta_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\]

- three mixing angles: \( \theta_{12}, \theta_{23}, \theta_{13} \)
- three CP phases: 1 Dirac + 2 Majorana
- three masses: \( m_1, m_2, m_3 \)

\[ \Rightarrow \text{absolute neutrino mass: } m_0 \]

\[ \Rightarrow \text{two mass splittings:} \]

\[ \Delta m^2_{21}, \Delta m^2_{31} \]

\[ |\Delta m^2_{31}|_{\text{NO}} > |\Delta m^2_{31}|_{\text{IO}} \]

Mariam Tortola, Talk at Neutrino2018
Global data fits

Δm^2's and mixing angles determined at the few-% Level

Consistent picture of 3-neutrino mixing

Mariam Tortola,
Talk at Neutrino2018
Open Questions

- **Absolute Mass Scale?**  
  → KATRIN, Cosmology

- **Mass Hierarchy?**  
  → $3\sigma$ preference for NO

- **CP Violation?**  
  → $2\sigma$ (NO)/$3.8\sigma$ (IO) evidence for CPV  
  → Best fit $3\pi/2$

- **Mechanism of Neutrino Mass Generation?**

- **Dirac or Majorana?**  
  → Lepton Number Violation?

- **More than 3 Neutrinos?**  
  → Reactor, Gallium, LSND & MiniBooNE anomalies
Open Questions

- Absolute Mass Scale?
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Why is this interesting?

Why is a non-zero $\nu$ mass physics beyond SM?

EITHER - OR

$m_D \bar{\nu}_L \nu_R$

$m_M \bar{\nu}_L^c \nu_L$

$m_M \bar{\nu}_R^c \nu_R$

Lepton Number Violation

New Symmetry, e.g. Lepton Number

LNV, e.g. Seesaw-I

Lepton Number (Violation) is at the core of the link between $\nu$ mass & physics beyond SM!

[Minkowski’77]
Neutrino Mass Models

Small $m_\nu \leftrightarrow$ neutral elementary fermion

$\leftrightarrow$ large scale unprotected by SM gauge symmetry

**Seesaw-I: Fermion singlet**

Minkowski ‘77

**Seesaw-III: Fermion triplet**

Foot, Lew, He, Joshi ‘89

$\nu, \nu^c, \nu^c, \nu$

**Seesaw-II: Scalar triplet**

Magg & Wetterich ‘80;
Schechter & Valle ‘80;
Lazarides, Shafi, Wetterich ‘81;
Mohapatra & Senjanovic’81;
...

$m_\nu \sim \frac{m_D^2}{M_R}$

$\phi \leftrightarrow \bar{\phi}$

Weinberg ‘77

→ Talk by Oleg Antipin
Neutrino Mass Models

Radiative Neutrino Masses from Leptoquark Loops
Hirsch, Klapdor-Kleingrothaus, Kovalenko ‘96

LHC

v mass

LNV

→ Talk by Lorenzo Capriotti

R_K & other Lepton-Flavor-Non-Universality Anomalies
HP & Schumacher ‘15
Probing LNV

Most prominent: 0vBB decay

\[
\begin{align*}
\nu & \rightarrow \nu \\
W & \rightarrow e^- \\
U_{ei} & \\
\nu & \rightarrow \bar{\nu} \\
U_{ei} & \\
W & \rightarrow e^- \\
d & \rightarrow u
\end{align*}
\]

\[\sim m_\nu\]

“Mass Mechanism”

General Case

\[HP, \text{ Rodejohann, 2015}\]

\[Deppisch, \text{ Hirsch, HP, 2012}\]
$0\nu\beta\beta$ Decay

\[ \text{HP, Hirsch, Kovalenko, Klapdor-Kleingrothaus, 1999 & 2001} \]
\[ F. \text{Deppisch, M. Hirsch, HP, 2012} \]
Model-independent approach also for LNV@LHC?

- Necessary to go beyond effective field theory approach of *HP, Hirsch, Kovalenko, Klapdor-Kleingrothaus, 1999*
- Open up vertices, systematic decomposition of the $d=9$ 0vBB operator *Bonnet, Hirsch, Ota, Winter, 2013*
Taking into account previously unaccounted for physics and detector backgrounds at the LHC, renormalization group evolution, and long-range contributions to $\nu\beta\beta$ nuclear matrix elements

[Helo, Hirsch, Kovalenko, HP, 2013]

[Peng, Ramsey-Musolf, Winslow, 2015]
$0\nu\beta\beta$ vs LHC sensitivities

Complementarity
Neutrino Mass Models

Lepton-Number-Violation:
→ anomaly-free combination B-L

Baryon Asymmetry

LNV

Sphalerons:
B+L-Violation within SM
Baryogenesis

- Baryon Asymmetry as initial condition?

- Cosmic inflation: \( a(t) \sim \exp \left( \frac{\Lambda}{3} t \right) \)
  - Universe flat, homogenous and empty
  - Necessity of Baryogenesis after reheating

- 3 Sakharov conditions:
  - Non-Equilibrium
  - C and CP violation
  - Baryon Number Violation

- Prominent example - Leptogenesis:
  - Right-handed neutrino decay in early Universe

\[ \rightarrow \text{Lepton Asymmetry} \]

Fukugita, Yanagida, 1986
Can Leptogenesis be falsified?

“Falsifying Leptogenesis at the LHC”
F. Deppisch, J. Harz, M. Hirsch, PRL 112 (2014) 221601

- LNV @ LHC
- Lower bound on washout of Lepton Number Asymmetry
- No out-of-equilibrium condition in early universe!
But EVEN WORSE: consider Sphalerons

Leptogenesis:

\[ \text{B-L} \] \quad \text{v}_R \text{ decay} \quad \text{\textbf{+}} \quad \text{B+L} \quad \text{Sphalerons} \]

In Reverse:

\[ \text{B-L} \] \quad \text{e.g. LHC} \quad \text{\textbf{+}} \quad \text{B+L} \quad \text{Sphalerons} \]

\[ \text{B washout} \]
Long range mechanism e.g. \( m_v \)

Short range mechanism

LNV @ LHC

Low-Scale Baryogenesis

also detectable @ LHC?

“2 for one”
Asymmetric dark matter, baryon asymmetry and lepton number violation

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We study the effect of lepton number violation (LNV) on baryon asymmetry, generated in the early Universe, in the presence of a dark sector with a global symmetry $U(1)_X$, featuring asymmetric dark matter (ADM). We show that in general LNV, observable at the LHC or in neutrinoless double beta decay experiments, cannot wash out a baryon asymmetry generated at higher scales, unlike in scenarios without such dark sector. An observation of LNV at the TeV scale may thus support ADM scenarios. Considering several models with different types of dark matter (DM), we find that the DM mass is of the order of a few GeV or below in our scenario.

Problem

\[ v \text{ mass generation} \quad @ \quad 1 \text{ TeV} \]

Baryon Asymmetry of the Universe
Baryons, Dark Matter & Lepton Number Violation

Problem

- $v$ mass generation @ 1 TeV
- Baryon Asymmetry of the Universe
- Asymmetric Dark Matter
- eight chemical potentials
- free parameter
- solved !!!
Sterile Neutrinos?

Gallium Anomaly

En-Chuan Huang, Talk at Neutrino 2018

“MSW-like resonance model”

4.8σ/6.1σ
Sterile Neutrinos?

Appearance versus Disappearance Experiments

Dentler, Hernandez-Cabezudo, Kopp, Machado, Maltoni, Martinez-Soler, Schwetz, 2018
Consider an asymmetrically warped extra dimension with a sterile neutrino in the bulk.

\[ ds^2 = dt^2 - e^{-2k|u|} dx^2 - du^2 \]

Chung, Freese, 1999, 2000
Csaki, Erlich, Grojean, 2001

\[ E = p + m^2/2E + \text{new terms} \]

[Döring, HP, arXiv:1808.07734]

[HP, Pakvasa, Weiler, PRD72, 2005]
In a 3+3 model with democratic mixing the sterile neutrino decouples completely at high energies.
Neutrinos as Messengers

IceCube neutrinos point to long-sought cosmic ray accelerator

→ E.g.: Flavor Ratios: Feedback into fundamental Physics
Summary

- Neutrinos: Consistent 3v picture
- Open Questions: Origin? Dirac/Majorana?
- \( v \) Mass ↔ LNV ↔ Physics BSM
- LNV ↔ Baryogenesis ↔ Dark Matter
- Various Anomalies: Sterile Neutrinos
- Neutrinos as Probes ↔ Multi-Messenger Astronomy
What is $0\nu\beta\beta$ decay?

$2n \rightarrow 2p + 2e^-$

Lepton Number Violation

$A=76$

Ge

As

$\beta^- \beta^-\beta^+\beta^-$

Z=32 33 34

In general: Every operator

$\bar{p} \bar{p} e^+ e^- nn / M^5$

will generate $0\nu\beta\beta$ decay

Mass mechanism:

$[T_{1/2}^{0\nu}]^{-1} \propto \left| \sum_i U_{ei}^2 m_i \right|^2$

[SUSY KK-modes $N_R$

[HP, W. Rodejohann, NJP 17 (2015) 115010]

Apply the decomposition of \[\text{Bonnet, Hirsch, Ota, Winter, 2013}\] to 0νBB @ LHC:

- Results for Scalars and Vectors very similar
- Concentrate on Scalars & Topology 1:
  
  \[S_{\text{charge}}, \quad S_{\text{LQ charge}}^{\text{charge}} (L \neq 0, B \neq 0), \quad S_{\text{DQ charge}}^{\text{charge}} (B = \pm 2/3)\]

[Helo, Hirsch, Kovalenko, HP, 2013]