LEPTOGENESIS & CP

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SM+3 massive neutrinos

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix} = U_{PMNS}(\theta_{12}, \theta_{23}, \theta_{13}, \delta, \ldots) \begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

\[\begin{align*}
\theta_{12} & \sim 34^\circ \\
\theta_{23} & \sim 42^\circ \text{ or } 48^\circ \\
\theta_{13} & \sim 8.5^\circ \\
\delta & \sim ?
\end{align*}\]

normal hierarchy

inverted hierarchy

\[7.5 \cdot 10^{-5} \text{eV}^2\]

\[2.5 \cdot 10^{-3} \text{eV}^2\]
New results from T2K

To determine $\delta_{CP}$ intervals, produce the 1-D $\Delta [-2 \ln(L_{marg})]$ curves relative to the global minimum in the two hierarchies.

Critical $\Delta [-2 \ln(L_{marg})]$ values using the Feldman-Cousins prescription.

The 2$\sigma$ confidence interval is:

- Normal hierarchy: $[-2.98, -0.60]$ radians
- Inverted hierarchy: $[-1.54, -1.19]$ radians

CP conserving values (0, $\pi$) fall outside of the 2$\sigma$ intervals!

$\delta=0$, $\pi$ excluded at 2$\sigma$
Why are neutrinos so much lighter?
Neutral vs charged hierarchy?
Why so different mixing?

**CKM**

$$|V|_{\text{CKM}} = \begin{pmatrix}
0.97427 \pm 0.00015 & 0.22534 \pm 0.0065 & (3.51 \pm 0.15) \times 10^{-3} \\
0.2252 \pm 0.00065 & 0.97344 \pm 0.00016 & (41.2^{+1.1}_{-5}) \times 10^{-3} \\
(8.67^{+0.29}_{-0.31}) \times 10^{-3} & (40.4^{+1.1}_{-0.5}) \times 10^{-3} & 0.999146^{+0.000021}_{-0.000046}
\end{pmatrix}$$

**PMNS**

$$|U|_{3\sigma}^{\text{LID}} = \begin{pmatrix}
0.798 \rightarrow 0.843 & 0.517 \rightarrow 0.584 & 0.137 \rightarrow 0.158 \\
0.232 \rightarrow 0.520 & 0.445 \rightarrow 0.697 & 0.617 \rightarrow 0.789 \\
0.249 \rightarrow 0.529 & 0.462 \rightarrow 0.708 & 0.597 \rightarrow 0.773
\end{pmatrix}$$

NuFIT 2016
Why so different mixing?

\[ V_{CKM} \simeq \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \]

PMNS

\[ |V_{PMNS}| \simeq \begin{pmatrix} \sqrt{\frac{2}{3}} & \sqrt{\frac{1}{3}} & 0 \\ \sqrt{\frac{1}{6}} & \sqrt{\frac{1}{3}} & \sqrt{\frac{1}{2}} \\ \sqrt{\frac{1}{6}} & \sqrt{\frac{1}{3}} & \sqrt{\frac{1}{2}} \end{pmatrix} \]

Harrison, Perkings, Scott
A new physics scale?

Neutrinos are different...they can have majorana masses:

\[-\mathcal{L}_{\text{Majorana}} = \bar{\nu}_L m_{\nu} \nu^c_L + h.c. \leftrightarrow \bar{L} \tilde{\Phi} \alpha \tilde{\Phi} L^c + h.c.\]

\[[\alpha] = -1\]

\[\alpha = \frac{\lambda}{\Lambda}\]

\[m_{\nu} = \lambda \frac{v^2}{\Lambda}\]

Scale at which new particles will show up
(mass of the neutrino mass mediators)
Seesaw mechanism:

Minkowski
Gell-Mann, Ramond Slansky
Yanagida, Glashow
Mohapatra, Senjanovic
What originates the neutrino mass?

Could be \( \Lambda \gg \nu \ldots \) the standard lore (theoretical prejudice?)

\[
\begin{align*}
\Lambda &= M_{\text{GUT}} \\
\lambda &\sim O(1) \\
\end{align*}
\]

\[ m_\nu \quad \checkmark \]
Hierarchy problem?

The new scale is stable under radiative corrections due to Lepton Number symmetry but the EW is not!

\[ \delta m_H^2 = \frac{Y^\dagger Y}{4\pi^2} M_N^2 \log \frac{M_N}{\mu} \]

Vissani

\[ M_N \gg m_H \]

not natural in the absence of SUSY/other solution to the hierarchy problem
The Standard Model is healthy as far as we can see...

Could be naturally $\Lambda \sim v$?

Yes!

$\lambda$ in front of neutrino mass operator must be small...
Resolving the neutrino mass operator at tree level

**Type I see-saw:**
a heavy singlet scalar

\[ m_\nu = \frac{\alpha v^2}{\Lambda} \equiv Y_N^T \frac{v^2}{M_N} Y_N \]

Minkowski; Yanagida; Glashow; Gell-Mann, Ramond Slansky; Mohapatra, Senjanovic...

\[ \lambda \sim O(Y^2) \]

**Type II see-saw:**
a heavy triplet scalar

\[ m_\nu = \frac{\alpha v^2}{\Lambda} \equiv \frac{\mu_\Delta}{M_\Delta^2} Y_\Delta v^2 \]

Konetschny, Kummer; Cheng, Li; Lazarides, Shafi, Wetterich...

\[ \lambda \sim O(Y \mu/M_\Delta) \]

**Type III see-saw:**
a heavy triplet fermion

\[ m_\nu = \frac{\alpha v^2}{\Lambda} \equiv Y_\Sigma^T \frac{v^2}{M_\Sigma} Y_\Sigma \]

Foot et al; Ma; Bajc, Senjanovic...

\[ \lambda \sim O(Y^2) \]
\[ M_N \sim \text{GUT} \]

\[ M_N \sim \nu \]
Where is the new scale?

“Once you eliminate the impossible, whatever remains, no matter how improbable/unnatural, must be the truth.”
Where is the new scale?

Generic predictions

- there is neutri-noless double beta decay at some level ($\Lambda > 100\text{MeV}$)

  model independent contribution from the neutrino mass
Where is the new scale?

Generic predictions:

- a matter-antimatter asymmetry if there is CP violation in the lepton sector via leptogenesis

model dependent...
Where is the new scale?

Generic predictions:

- there are other states out there at scale $\Lambda$: new physics beyond neutrino masses

potential impact in cosmology, EW precision tests, LHC, rare searches, $\beta\beta0\nu$, ...

model dependent...
Where is the new scale?

The EW scale is an interesting region: new physics underlying the matter-antimatter asymmetry could be tested!
Minimal model of neutrino masses:

Type I seesaw: SM+right-handed neutrinos

\[ \mathcal{L}_\nu = -\bar{l}Y \tilde{\Phi} N_R - \frac{1}{2} \bar{N}_R M N_R + h.c. \]

\[ m_\nu = \frac{\lambda v^2}{\Lambda} \equiv Y^T \frac{v^2}{M} Y \]

Minkowski; Yanagida; Glashow; Gell-Mann, Ramond Slansky; Mohapatra, Senjanovic...
Type I seesaw models

\( n_R = 3 \) : 18 free parameters (6 masses + 6 angles + 6 phases)
out of which we have measured 2 masses and 3 angles...

\[ \begin{align*}
  m_1 & \quad M_1 \\
  m_2 & \quad M_2 \\
  m_3 & \quad M_3
\end{align*} \]  

\( n_R \) Dirac \( M_N \) Seesaw

Light neutrinos
Type I seesaw models

Phenomenology (beyond neutrino masses) of these models depends on the heavy spectrum and the size of active-heavy mixing:

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix}
= U_{ll}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
+ U_{lh}
\begin{pmatrix}
N_1 \\
N_2 \\
N_3
\end{pmatrix}
\]
Type I seesaw models

\[ U_{lh} \sim iU_{PMNS} \sqrt{m_l} R \frac{1}{\sqrt{M_h}} \]

Casas-Ibarra

**R:** general orthogonal complex matrix (contains all the parameters we cannot measure in neutrino experiments)

Strong correlation between active-heavy mixing and neutrino masses:

\[ |U_{lh}|^2 \sim \frac{m_l}{M_N} \]  (but naive scaling too naive for n_R > 1...)
Baryon asymmetry

The Universe seems to be made of matter

\[ \eta \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} = 6.21(16) \times 10^{-10} \]
Baryon asymmetry

Can it arise from a symmetric initial condition with same matter & antimatter?

Sakharov’s necessary conditions for baryogenesis

- ✓ Baryon number violation (B+L violated in the Standard Model)
- ✓ C and CP violation (both violated in the SM)
- ✓ Deviation from thermal equilibrium (at least once: electroweak phase transition)

It does not seem to work in the SM with massless neutrinos ...

- CP violation too small ✗
- EW phase transition too weak ✗

Massive neutrinos provide new sources of CP violation and non-equilibrium conditions
Leptogenesis

Models with massive neutrinos generically lead to generation of lepton and therefore baryon asymmetries

Standard leptogenesis in out-of-equilibrium decay $M_N > 10^7\text{GeV}$

Fukuyita, Yanagida

Can be extended to lower scales at the expense of a extreme degeneracy of the heavy states: resonant leptogenesis

Pilaftsis,...
High-scale leptogenesis

New sources of CP violation and L violation in the neutrino sector can induce CP asymmetries in decays of heavy Majorana $\nu$

\[ \epsilon_1 = \frac{\Gamma(N \to \Phi l) - \Gamma(N \to \Phi \bar{l})}{\Gamma(N \to \Phi l) + \Gamma(N \to \Phi \bar{l})} \]

\[ Y_B = 4 \times 10^{-3} \]

Generic and robust feature of see-saw models for large enough scales $M_N > 10^7-10^9$ GeV (unless an extreme degeneracy exits)
High-scale leptogenesis

\[ \Gamma_N \leq H(M_N) \]

(decay rate < hubble expansion)
Leptogenesis

Leptogenesis from neutrino oscillations
0.1GeV < M < 100GeV

Akhmedov, Rubakov, Smirnov;
Asaka, Shaposhnikov,...
Low-scale Leptogenesis

CP asymmetries arise in production of sterile states oscillations

\[ L_\alpha \rightarrow L_\beta \neq \bar{L}_\alpha \rightarrow \bar{L}_\beta \]

\[ \sum_\alpha \Delta_{CP}^\alpha = 0 \quad Y_B \propto \sum_\alpha \Delta_{CP}^\alpha \eta_\alpha \]

Different flavours different efficiency in transferring it to the baryons
Low-scale leptogenesis

\[ \Gamma_s(T_{EW}) \leq H(T_{EW}) \]

(scattering rate < hubble expansion)
**Testability/predictivity?**

- $Y_B$ cannot be determined from neutrino masses and mixings only

- More information from the heavy sector is needed:
  
  High-scale scenarios: very difficult for $M_N > 10^7$ GeV
  
  Low-scale scenarios: N’s can be produced in the lab and could be in principle detectable!
Full exploration of the minimal model N=2

Bayesian posterior probabilities (using nested sampling Montecarlo Multinest)

\[
\mathcal{L} = -\left( \frac{Y_B(\text{param}) - Y_B^{\text{obs}}}{\sigma_{Y_B}} \right)^2
\]

Use Casas-Ibarra parametrization: fix light neutrino masses and mixings to the best fit oscillation points (IH/NH) and vary

\[
R(\theta + i\gamma); \quad U_{PMNS}(\delta, \phi_1); \quad M_1, M_2
\]

Flat priors in:

\[
\theta = [0, \pi]; \quad \delta = [0, 2\pi]; \quad \phi_1 = [0, 2\pi]; \quad \gamma = [-9, 9]; \\
\log_{10} M_1 \text{ and } \log_{10} M_2 / \log_{10}(M_2 - M_1)
\]
Full exploration of the minimal model N=2

Inverted neutrino ordering (IH)

PH, Kekic, Lopez-Pavon, Racker, Salvado
arxiv:1606.06719
In the minimal model with just $n_R=2$ neutrinos (IH)

Colored regions: posterior probabilities of successful $Y_B$

PH, Kekic, Lopez-Pavon, Racker, Salvado

arxiv:1606.06719
In the minimal model with just $n_R=2$ neutrinos (IH)

Rare meson decays searches

Displaced vertex searches in $Z$ decays
Predicting $Y_B$ in the minimal model $n_R=2$?

Assume a point within SHIP reach that gives the right baryon asymmetry

- SHIP measurement could provide (if states not too degenerate)
  
  \[ M_1, M_2, |U_{e1}|^2, |U_{\mu_1}|^2, |U_{e2}|^2, |U_{\mu_2}|^2 \]

- Future neutrino oscillations: $\delta$ phase in the $U_{PMNS}$
Predicting $Y_B$ in the minimal model $n_R=2$ (IH)

- Grey band: standard light neutrino contribution to $m_{\beta\beta}$ for IH
- Significant interference between light/heavy neutrino contributions to $m_{\beta\beta}$

Obs. $Y_B = 8.6 \times 10^{-11}$

PH, Kekic, Lopez-Pavon, Racker, Salvado
arxiv:1606.06719
Predicting $Y_B$ in the minimal model $n_R=2$

Heavy states also contribute to the $\beta\beta_{0\nu}$ amplitude...

\[
m_{\beta\beta} = \sum_{i=1}^{3} \left[ (U_{PMNS})_{ei} \right]^2 m_i + \sum_{i=j}^{3} U_{ej}^2 M_j \frac{M^{0\nu\beta\beta}(M_j)}{M^{0\nu\beta\beta}(0)}
\]

the heavy contribution is sizeable for $M_i$ of $O(\text{GeV})$

\[M_j \rightarrow \infty \quad \frac{M^{0\nu\beta\beta}(M_j)}{M^{0\nu\beta\beta}(0)} \propto \left( \frac{100 \text{ MeV}}{M_j} \right)^2\]

The non standard contributions bring essential information of some CP phases and other unknown parameters

Blennow, Fernandez-Martinez, Lopez-Pavon, Menendez; Lopez-Pavon, Pascoli, Wong; Lopez-Pavon, Molinaro, Petcov
Predicting $Y_B$ in the minimal seesaw model $M \sim \text{GeV}$

The GeV-miracle: the measurement of the mixing to $e/\mu$ of the sterile states, neutrinoless double-beta decay and $\delta$ in neutrino oscillations have a chance to give a prediction for $Y_B$.
Sample point

\[ \delta = 234^\circ \quad \alpha = 254^\circ \]

\[ M_1 \sim M_2 \sim 0.77 \text{ GeV} \quad \Delta M/M \sim 10^{-2} \]
How fine-tunned is the range of parameters for successful leptogenesis?

The very degenerate regions could be understood in terms of an approximate global symmetry $U(1)_L$

$$L(N_1) = +1, \quad L(N_2) = -1$$

$$-\mathcal{L}_\nu \supset \bar{N}_1 M N_2^c + Y \bar{L} \tilde{\Phi} N_1 + h.c.$$
How natural is the range of parameters for successful Leptogenesis?

The very degenerate regions could be understood in terms of an approximate global symmetry $U(1)_L$

Wyler, Wolfenstein; Mohapatra, Valle; Branco, Grimus, Lavoura, Malinsky, Romao; Kersten, Smirnov; Abada et al; Gavela et al....many others

$$
\begin{pmatrix}
0 & Y_1 \nu & \epsilon Y_2 \nu \\
Y_1 \nu & \mu' & M_N \\
\epsilon Y_2 \nu & M_N & \mu
\end{pmatrix}
$$

- How small must the small entries be?
How natural is the range of parameters for successful ARS leptogenesis?

- Blue region prefers a mild hierarchy in all $U(1)_L$ breaking terms
- Red region points require $\mu, \mu'$ entries significantly smaller than $\epsilon$
How large can the mixing be (even if less probable) and still have successful baryogenesis?

Figure 9: The solid, dark blue lines show the largest and smallest value of $U_{2}$ we find to be consistent with neutrino oscillation data and the requirement to explain the observed BAU as a function of $\bar{M} = (M_1 + M_2) / 2$. They are compared to the upper bound from direct search experiments summarised in Ref. [14] (solid black line), the lower bound from neutrino oscillation data (gray dashed "seesaw" line) and the lower bound from the requirement that the $N_i$ have a lifetime of less than $\frac{1}{10}$ that their decay does not modify primordial nucleosynthesis (dotted gray "BBN" line). The upper panel corresponds to normal neutrino mass hierarchy, the lower panel corresponds to inverted hierarchy.

Drewes, Garbrecht, Gueter, Klaric arxiv: 1606.06690

Abada, Arcadi, Domcke, Lucente arxiv: 1709.00415
The seesaw path to leptonic CP violation: flavour ratios of heavy lepton mixings strongly correlated with ordering, $U_{\text{PMNS}}$ matrix: $\delta, \phi_1$

In minimal model:

![Diagram showing correlation between leptonic CP violation and heavy lepton mixings.](image)

Caputo, PH, Lopez-Pavon, Salvado arxiv:1611.05000

Superb sensitivity to Majorana CP phases: complementary to oscillations
If SHIP/FCC-ee measures the heavy neutrinos and their mixings to $e/\mu$:

Can we exclude a real $U_{PMNS}$ matrix i.e.
discover leptonic CP violation in mixing?

$$(\delta, \phi_1) \neq (0/\pi,0/\pi)$$
Leptonic CP violation $5\sigma$ CL discovery regions (SHIP)

$R_{CP} = 5\sigma$ CP-fraction =
fraction of the area of the CP rectangle which is colored

Caputo, PH, Lopez-Pavon, Salvado  arxiv:1611.05000
Beyond the minimal model

Many possibilities:

Examples: type I \( +W', Z' \), left-right symmetric models, GUTs, etc

Keung, Senjanovic; Pati, Salam, Mohapatra, Pati; Mohapatra, Senjanovic; Ferrari et al + many recent refs...

- Generically gauge interactions can enhanced the production in colliders
- But they make leptogenesis more challenging (out-of-equilibrium condition harder to meet)
Interesting possibility:

TeV: Extra interactions (LR, etc)

EW: SM + neutrino mass mediator (N)

Effective theory SM+N’s
Model independent approach: EFT

\[ \mathcal{L}_{BSM} = \mathcal{L}_{mSS} + \sum_{d,i} \frac{1}{\Lambda^{d-4}} O^{(d)}_i \]

The seesaw portal to BSM:

\[ O_W = \sum_{\alpha,\beta} \left( \frac{\alpha_W}{\Lambda} \right)_{\alpha\beta} \bar{L}_\alpha \tilde{\Phi} \Phi^\dagger L_\beta + h.c., \]

\[ O_{N\Phi} = \sum_{i,j} \left( \frac{\alpha_{N\Phi}}{\Lambda} \right)_{ij} \bar{N}_i N_j^c \Phi^\dagger \Phi + h.c., \]

\[ O_{NB} = \sum_{i \neq j} \left( \frac{\alpha_{NB}}{\Lambda} \right)_{ij} \bar{N}_i \sigma_{\mu\nu} N_j^c B_{\mu\nu} + h.c. \]

S. Weinberg ‘79; M. Graesser ‘07; F. Del Aguila et al ‘09; Aparici et al, ‘09; Caputo et al ‘17
The cosmic muon background. In the case of muons a constraint in the opening angle cuts on transverse momentum, pseudorapidity and isolation of the two tracks: selection is done by requiring two lepton tracks, the higgs decays just to one neutrino). We consider a parton-level Monte Carlo analysis using Madgraph5. The production cross section has been done in the context of gluon fusion higgs production and we consider the production of just one neutrino species, a center-of-mass energy of 13TeV and 300 fb⁻¹. For simplicity we will consider only semileptonic decays of the Higgs. These operators could appear at tree level in extensions with scalar singlets, such as the Higgs portal. On the other hand the operator could lead to spectacular signals at LHC/colliders of two displaced vertices from higgs decays (production independent of U). For the analyses: 1) a search of displaced tracks in the inner tracker where at least one or more displaced lepton, 2) a search for displaced tracks opposite sign leptons are possible. In the muon chambers and outside the inner tracker where at least one displaced lepton, 3) a search for displaced tracks from searches of higgs decays to two displaced vertices at LHC. A closely related calculation performed following recent searches by the CMS collaboration. The exchange of the singlet scalar leads at tree level to the operator as a function of .

$LHC: 300 \text{ fb}^{-1}, 13 \text{TeV}$

\[
\left| \frac{\alpha_{N\Phi} v}{\sqrt{2} \Lambda} \right| \leq 10^{-3} - 10^{-2} \rightarrow \frac{\alpha_{N\Phi}}{\Lambda} \leq 6 \times (10^{-3} - 10^{-2}) \text{TeV}^{-1}.
\]
could lead to spectacular signals at LHC/colliders of two displaced vertices from higgs decays (production independent of U)

A large hierarchy between the coefficients would be needed since the Weinberg operator is much more strongly suppressed: technically natural with \( U(1)_L \)
Conclusions

• Exploring the EW-> TeV region for NP related to neutrino masses is very well motivated

• A minimal model of neutrino masses with a new scale near GeV can explain the baryon asymmetry and might do so in a testable way (IH more promising)

• Testability in simplest model will require the contribution of very different type of experiments:

  SHIP/FCCee: masses and mixings of the heavy neutrino states

  DUNE/HyperK: CP violation $\nu$ neutrino oscillations

  $\beta\beta0\nu$: non-standard contributions from heavy sector

• Flavour mixings of the heavy states high sensitivity to CP phases in $U_{PMNS}$ (in particular Majorana phases!)

• Mediators of neutrino mass at the EW provide a new portal to BSM physics