Neutrino masses, CP violation and Leptogenesis

Yuval Grossman

Technion

Experimental results

- Many difference experiments: Solar, atmospheric reactor and accelerator neutrinos
- All found clear evidence for neutrino oscillation and measure the neutrino masses

$$\Delta m_{12}^2 = (8.2 \pm 0.3) \times 10^{-5}\ \mathrm{eV}^2$$

$$\Delta m_{23}^2 = (2.2 \pm 0.5) \times 10^{-3}\ \mathrm{eV}^2$$

What are the implications of these results?

Outline

- The SM and neutrinos
- Neutrino masses beyond the SM
- Leptogenesis
- Conclusions

The Standard Model

Basics of High Energy Physics

Any model of Nature is based on

- Imposed local symmetries (forces)
- Representations of the fermions and scalars (charges)
- The vacuum state (SSB)

Then, the Lagrangian is

1. the most general one that obeys the symmetries
2. it is renormalizable (no parameters with negative mass dimension)

The question: what is the Lagrangian of Nature?

Namely, what are the forces and particles in Nature?

The SM

- The symmetry is $SU(3)_C \times SU(2)_L \times U(1)_Y$
- There are three generations of fermions

$$Q_L(3,2)_{+1/6} \qquad U_R(3,1)_{+2/3} \qquad D_R(3,1)_{-1/3}$$
$$L_L(1,2)_{-1/2} \qquad E_R(1,1)_{-1}$$

- The vev of the Higgs $H(1,2)_{+1/2}$ breaks the symmetry

$$SU(2)_L \times U(1)_Y \to U(1)_{EM} \qquad m_W \approx 80 \text{ GeV}$$

The SM has accidental global symmetries. In particular, baryon (B) and lepton numbers (L)

Lepton number

- Lepton number is an accidental symmetry of the SM
- Only leptons carry L

$$L(e^-) = 1 \quad L(e^+) = -1 \quad L(\nu) = 1 \quad L(\bar{\nu}) = -1$$

- All processes observed so far conserve L
- Processes that violate it, like $P^+ \to e^+\gamma$, were not observed
- Being an accidental symmetry, lepton number can be broken by non-perturbative effects or by new heavy particles

Neutrino masses in the SM

The SM implies that neutrinos are exactly massless

- The SM has only LH neutrinos
- Massive particles can be both LH and RH $\Rightarrow$

  We need RH neutrinos
- Two options:
  - RH neutrino (Dirac mass). [Not there is the SM]
  - RH anti–neutrino (Majorana Mass). [Violates L]

Unlike the $m_\gamma = 0$ prediction, the $m_\nu = 0$ prediction is accidental; L is an accidental symmetry of the SM

The SM as an effective theory

- There are many reasons not the trust the SM at energies much above what we already probed: gravity, dark matter, coupling unification, baryogenesis, ...
- Very likely, there is new physics

$$O(10^2)\ \mathrm{GeV} \ll \Lambda_{\mathrm{NP}} \leq O(10^{18})\ \mathrm{GeV}$$

- We like to “promote” the SM to an effective theory. This is done by adding non-renormalizable operators that are suppressed by inverse power of Λ_{NP}
- Such terms breaks all the accidental symmetries of the SM. In particular, lepton number is broken and neutrino are massive

The see-saw mechanism

Consider a new, yet unknown, heavy particle, N

- It is a SM singlet with large Majorana mass, $M \gg m_W$
- It couples to the neutrino such that ($m_D \sim m_W$)

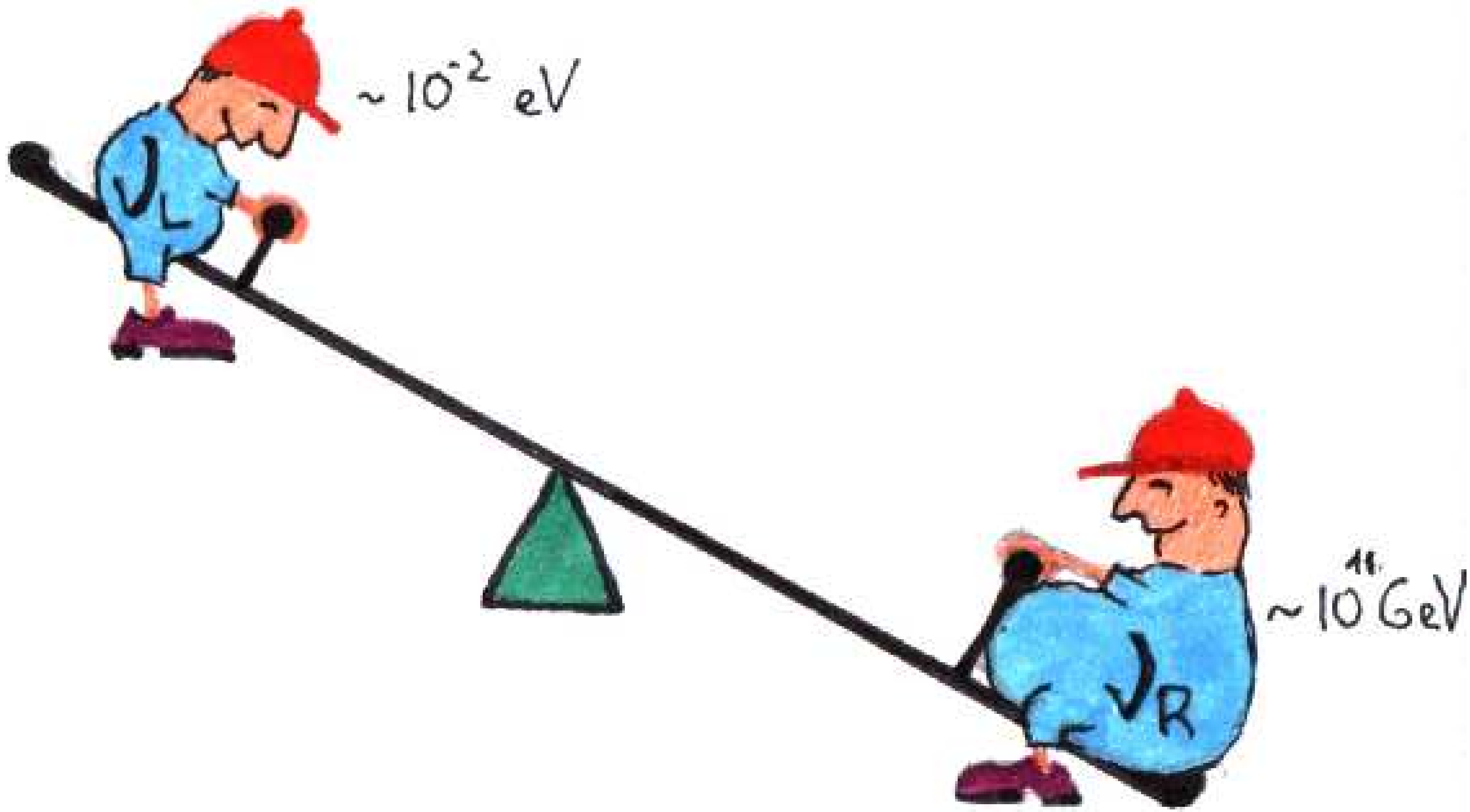
$$m = \begin{pmatrix} 0 & m_D \\ m_D & M \end{pmatrix} \quad \Rightarrow \quad m_\nu = \frac{m_D^2}{M}$$

- Similar to second order perturbation (two level system)

$$E_L = \frac{|\langle \nu | H_2 | N \rangle|^2}{E_R - E_L} \qquad m_\nu = \frac{|\langle \nu | H_2 | N \rangle|^2}{M}$$

- L is broken

The see-saw mechanism



Summary: theoretical expectations

- In the SM $m_\nu = 0$ due to an accidental symmetry
- Generally, lepton number is broken in extensions of the SM $\Rightarrow$ these models predict massive neutrinos
- There are many reasons to believe that the SM is an effective low energy theory

$$\Downarrow$$

It is likely that the neutrinos are massive

$$m_\nu \sim \frac{m_W^2}{\Lambda_{\rm NP}} \qquad 10^{-5}\ {\rm eV} \leq m_\nu \leq 1\ {\rm eV}$$

- Neutrino masses probe high energy/short distance physics. Data implies that it is likely that $M \sim 10^{11-15}\ {\rm GeV}$

Leptogenesis

Baryogenesis

The question

Why is there only matter around us?

- The universe has a net positive baryon number. (We do not know the lepton number of the universe)
- In the SM baryon number is an accidental symmetry, so we expect the same amount of matter and anti-matter, basically zero
- Can we explain the observed number of baryons

$$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} = \frac{n_B}{n_\gamma} \sim 10^{-10}$$

The Sakharov conditions

The likely scenario is that baryons are dynamically generated in the early universe. For this the three Sakharov conditions have to be fulfilled

- Baryon number violating process

$$X \to p^+ e^-$$

- C and CP violation

$$\Gamma(X \to p^+ e^-) \neq \Gamma(\overline{X} \to p^- e^+)$$

- Deviation from thermal equilibrium

$$\Gamma(X \to p^+ e^-) \neq \Gamma(p^+ e^- \to X)$$

SM baryogenesis

The three Sakharov conditions are satisfied in the SM

- Baryon number violating process: sphalerons
- The weak interaction violates C. With three generations it also violates CP
- Out of equilibrium from the electroweak phase transition

In principle, the SM can generate a world with matter

Baryogenesis: the problem

While the SM "makes" baryons, it is not efficient enough

$$\eta_{\rm SM} \sim 10^{-25} \ll 10^{-10}$$

Q: Can we extend the SM in a way that we get enough baryons?

A: The same mechanism that give neutrinos masses via the see-saw mechanism also generates baryonic universe via leptogenesis

Leptogenesis

Leptogenesis

- Dynamic generation of lepton number from decays of the heavy neutrino N
- The requirement that N generates neutrino masses implies leptogenesis
- Since all this occurs at very high temperature, the sphalerons convert the lepton asymmetry to baryon asymmetry
- The non trivial fact is that the observed baryon asymmetry and neutrino masses can be explained simultaneously

The Sakharov conditions for leptogenesis

- Lepton number violating process

$$N \to H^+ e^-$$

- C and CP violation

$$\Gamma(N \to H^+ e^-) \neq \Gamma(\overline{N} \to H^- e^+)$$

- Deviation from thermal equilibrium. N decays late enough

$$\Gamma(N \to H^+ e^-) \neq \Gamma(H^+ e^- \to N)$$

N implies both neutrino masses and baryonic universe

Tests of leptogenesis

- It is not easy to directly test leptogenesis as the heavy neutrino is too heavy, $m_N > 10^{11}$ GeV
- Leptogenesis predicts very small lepton asymmetry in the universe. Very hard to even detect the neutrino background
- Since leptogenesis require CP violation, we like to find CP violation also in neutrino oscillation
- Majorana masses for the neutrinos can be probed with neutrinoless double beta decay

Conclusions

Conclusions

- The fact that neutrinos are massive is a confirmation that the SM is an effective theory of Nature
- The fact that neutrinos are massive could be crucial to our existence
- Better understanding of the neutrino sector can shed light on the physics at very high scale and the question of baryogenesis