Leptogenesis

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Three birds

Three open questions in physics

- Why is there only matter in the universe?
- How neutrinos acquire their tiny masses?
- Why all the elementary particles have integer electric charges?

It is plausible that one mechanism answers all three questions

Outline

- A short introduction to HEP
- Q1: Matter and anti-matter
- Q2: Neutrinos
- Q3: Electric charge quantization
- Conclude: The answer (?!)

Introduction to HEP

What is HEP

A very simple question

$$\mathcal{L} = ?$$

Building Lagrangians

- Choosing the generalized coordinates (fields)
- Imposing symmetries and choose the fields (input)
- The Lagrangian is the most general that obeys them
- We truncate it at some order, usually x^4

The Standard Model (SM)

- We keep terms up to $O(x^4)$
- The symmetry is $SU(3)_C \times SU(2)_L \times U(1)_Y$
- There are three generations of fermions (flavors)

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

- 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 photon is massless due to a $U(1)_{EM}$ symmetry

Accidental symmetries

Two kinds of symmetries

- Input: symmetries we impose
- Output: symmetries due to the truncation (accidental)
- Example: The period of a pendulum is invariant under change of amplitude
- In the SM Baryon and Lepton numbers are accidental

1: Matter, anti-matter and CPV

Matter, anti-matter and CPV

- We know anti-matter exists
- The positron seems to be an exact “mirror image” of the electron
- The formal transformation is called CP
- Matter and anti-matter cannot coexist. When they meet they annihilate

Baryogenesis

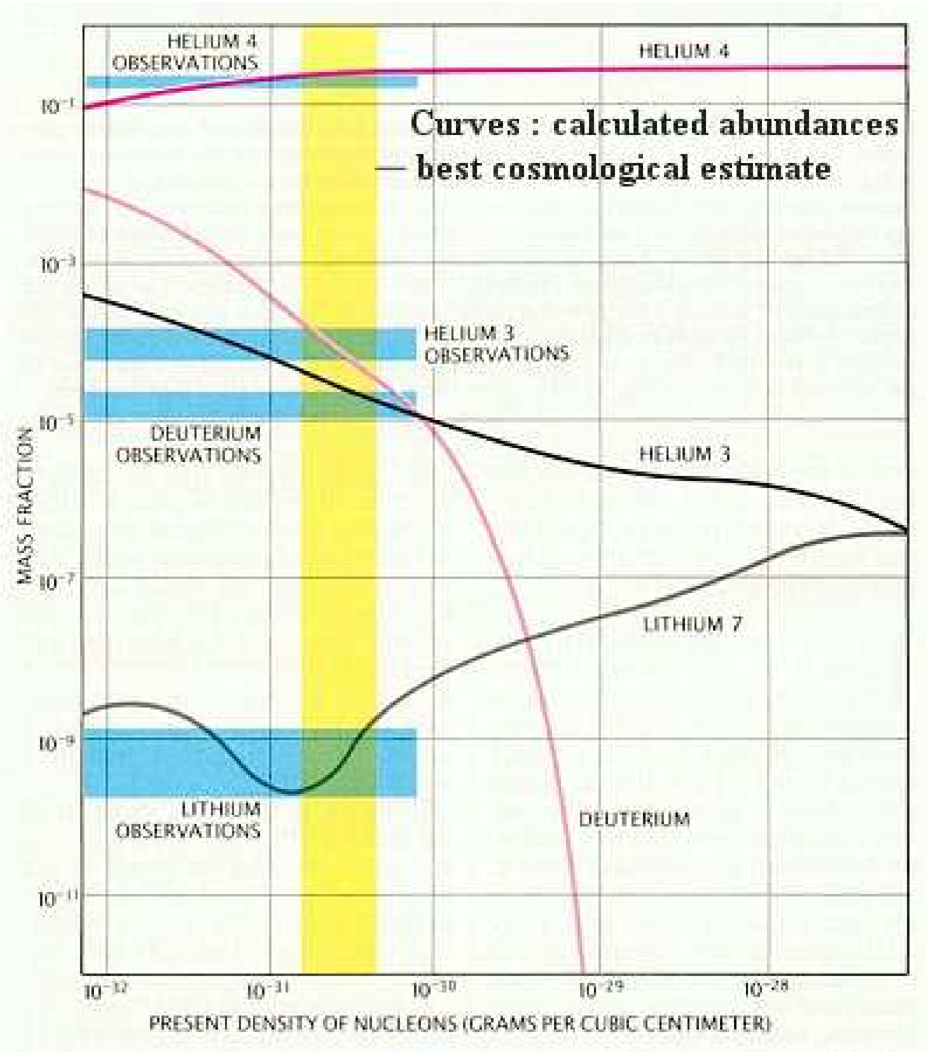
The question

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 seems to be conserved, so we expect the same amount of matter and anti-matter, basically zero
- Can we explain the observed number of baryons

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

Cosmology and particle physics



- Particle physics and cosmology are connected
- BBN and the CMB measurements imply

$$\eta \equiv \frac{n_B}{n_\gamma} = \text{few} \times 10^{-10}$$

Ways to baryogenesis

There are several logical possibilities

- Initial conditions are such that $n_B \neq 0$
- Separation: we are here, they are there
- Dynamical generation of baryons in the early universe

The third possibility looks much more attractive

The Sakharov conditions

The three Sakharov conditions for dynamically generated baryon asymmetry

- 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 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 and 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

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

An open question is therefore:

What is the source of the baryons in the universe?

2: Neutrino masses

What are neutrinos

- Neutral fermions
- They appear massless to a very good approximation
- They come with three flavors: ν_e, ν_μ and ν_τ
- Think of flavor as a new QN

Probing neutrino masses

- Direct searches are not sensitive to very small masses
- In general, flavor eigenstates $\neq$ mass eigenstates $\Rightarrow$
  Flavor is not conserved during propagation

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2 x \qquad x = \frac{\Delta m^2 L}{2E}$$

- Sensitive to Δm^2 and θ
- Many difference experiments found clear evidences for neutrino oscillations that gives

$$m_\nu \sim \text{few} \times 10^{-2}\ \text{eV}$$

Neutrino masses in the SM

The SM implies that neutrinos are exactly massless

- Massive particles must be both LH and RH $\Rightarrow$
  We need RH neutrinos
- Two options:
  - RH neutrino (Dirac mass). [Not there in 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

$m_\nu \neq 0$: A 2nd look at 2nd order PT

- We get sensitivity to high energy states!
- Consider x and y with $E_y \gg E_x$

$$V = \frac{Kx^2}{2} + V_y(y) \qquad V_1 = x^2 f(y)$$

- The second order correction due to y

$$\Delta E_{gs} \propto \frac{\left|\langle 0_x, 0_y | x^2 f(y) | n_x, n_y \rangle\right|^2}{E_{gs} - E_{n_x,n_y}} \sim \frac{x^4}{E_y}$$

- An x^4 term was “generated” and it is suppressed by $1/E_y$

Neutrino masses

- There are many ways to extend the SM such that neutrinos are massive
- One idea: add "sterile" fermions to the SM, N

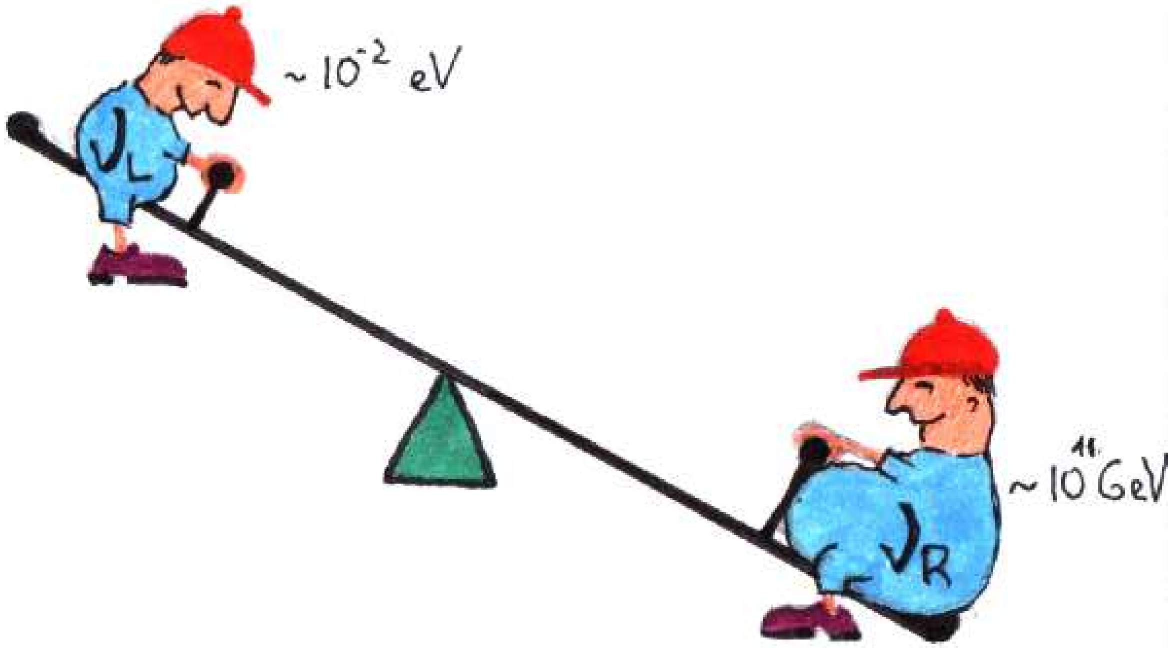
$$m_N \sim M \gg m_W \Rightarrow m_\nu \sim \frac{m_W^2}{M}$$

- Similar to 2nd order perturbation theory

$$m_{\nu_L} = \frac{|\langle \nu | V_1 | N \rangle|^2}{M}$$

- Lepton number is broken by these new particles
- The scale of the new particle is $M_N \sim 10^{14}$ GeV

The see-saw mechanism



$$m_\nu \propto \frac{1}{M_N}$$

The see-saw mechanism predicts very light neutrinos and that Lepton number is broken

Neutrino masses: the problem

What is the mechanism that give neutrino their masses?

Q3: Why Integer charges?

The symmetries of the SM

- $SU(3) \times SU(2) \times U(1)$
- Each symmetry comes with its own “force”
- The force is proportional to a “coupling constant”
- SU(2) is non-Abelian, while U(1) is Abelian
- What is charge?
  - For EM it is a number
  - For SU(2) it is the “size” of the spin: singlet, doublet, etc.

Quantization

- Think of p_i and L_i

$$[P_i, P_j] = 0 \qquad [L_i, L_j] = i\epsilon_{ijk}L_k$$

- While not exactly the same, we know that a non-vanishing commutator implies quantization

Non-Abelian symmetries implies charge quantization

SSB: Hydrogen atom

- The symmetry is rotation in 3d
- Consider an $L = 1$ state
- Magnetic field in an arbitrary direction break the symmetry to rotation in 2d
- The symmetry breaking pattern: $SO(3) \to SO(2)$
- The magnetic field breaks the m_z degeneracy
- It comes with scale: $E \sim muB$

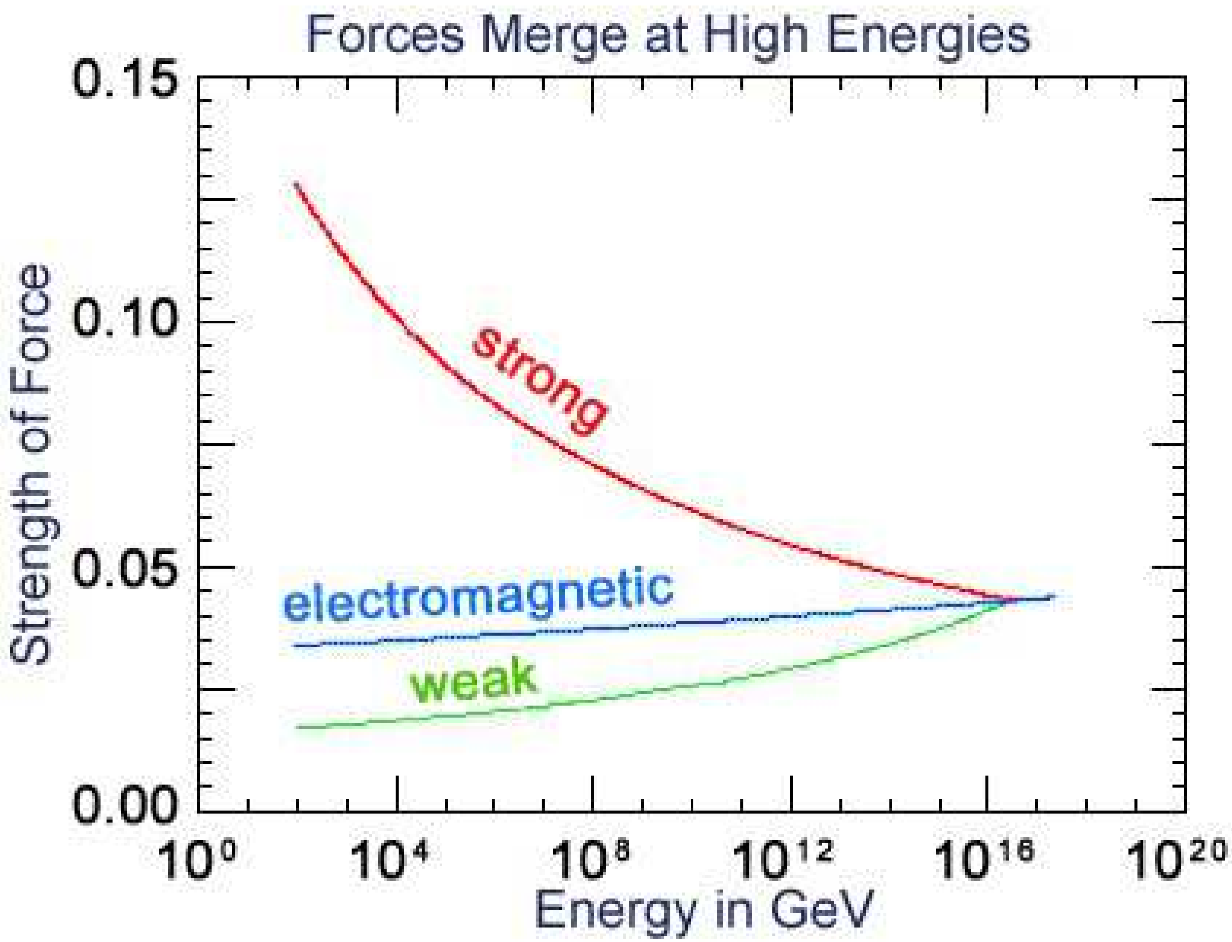
SSB: the SM

- The EM symmetry is part of the bigger $SU(2) \times U(1)$ one
- The electron and the neutrinos are degenerate due to the SU(2) symmetry
- The Higgs “chooses” a direction so we can tell them apart
- The breaking comes with scale, m_W
- EM is part of $SU(2) \times U(1)$ in that $Q = S_Z + Y$
- $SU(2) \times U(1)$ is “little unified theory”

GUT

- The SM symmetry maybe the unbroken part of a bigger symmetry
- In that case the SM particles are part of a bigger multiplet (like e and ν in the weak interaction)
- It work best for 10d rotation: $SO(10)$
- In the SM we have 15 DoFs, and in $SO(10)$ we need 16
- The one more field that we need is not charged under the SM
- What is the scale associated with the breaking?

GUT scale



$$M_{GUT} \sim 10^{16 GeV}$$

Some tests of GUTs

- Proton decay
- That one extra particle

Can we test for GUT?

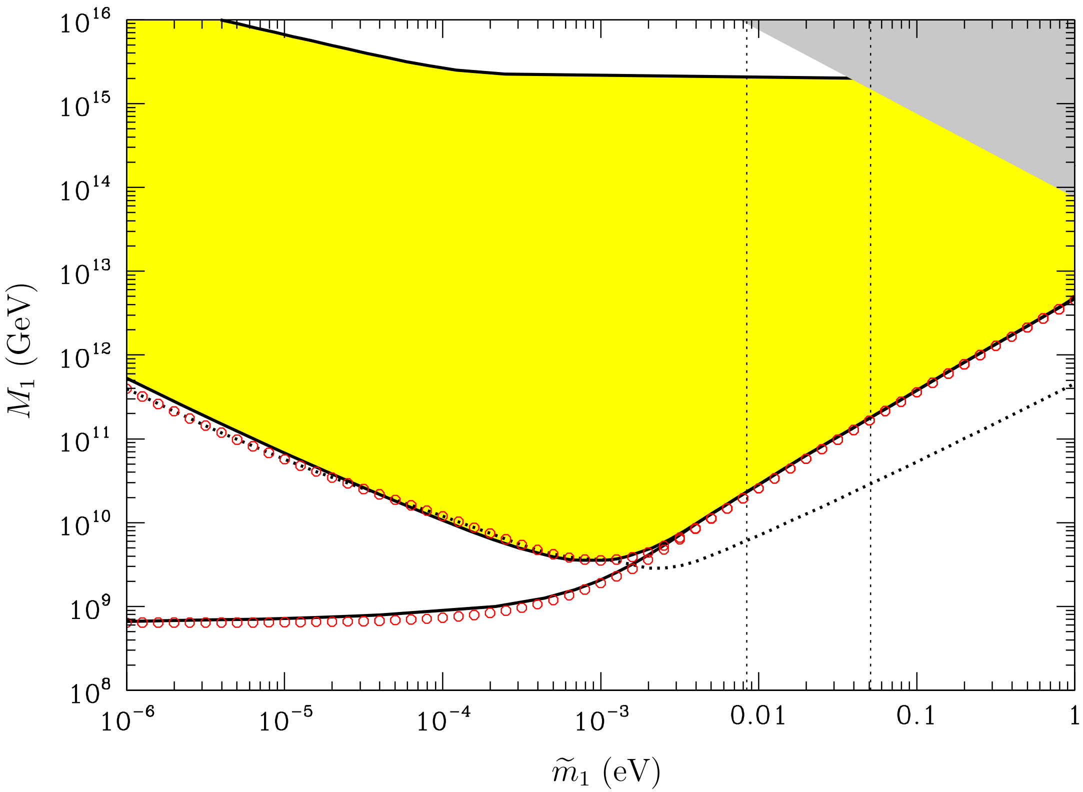
Leptogenesis

All together

- How was matter created?
- Why are neutrinos massive?
- Do we have GUT?

It all point to that new particle N

Numerical prediction



- A GUT scale N can generate the observed neutrino masses and matter in the universe!

Tests of this idea

- It is not easy to look for N since it is too heavy
- Observing proton decay will be amazing
- Leptogenesis predicts very small lepton asymmetry in the universe. Very hard to check
- Since leptogenesis requires CP violation, we would like to find CP violation also in neutrino oscillation
- Majorana mass for the neutrinos can be probed with neutrinoless double beta decay
- The neutrino mass provided a non trivial test

$$\text{Leptogenesis} \quad \Rightarrow \quad m_3 \lesssim 0.15 \text{ eV}$$
$$\text{Atmospheric neutrinos} \quad \Rightarrow \quad m_3 \sim 0.05 \text{ eV}$$

Conclusions

Conclusions

- It smells like we must have this extra particle
- Yet, can we get better to prove it?