Three questions, one answer

Neutrinos as the key to the universe as we know it

Yuval Grossman

Cornell

Three questions

Three open questions in physics

- How neutrinos acquire their tiny masses?
- Why is there only matter in the universe?
- Why the electron and proton have exactly the same charge?

It is plausible that one mechanism answers all three questions

Outline

- A short introduction to HEP
- Q1: Neutrinos
- Q2: Matter and anti-matter
- Q3: Electric charge quantization
- Conclusion: A possible answer and what next

Introduction to HEP

What is HEP

A very simple question

$$\mathcal{L} = ?$$

Building Lagrangians

- Choosing the generalized coordinates (fields)
- Imposing symmetries and how fields transform (input)
- The Lagrangian is the most general one that obeys the symmetries
- We truncate it at some order, usually fourth

The Standard Model (SM)

It explains almost everything we see in Nature

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

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

- H gives $SU(2)_L \times U(1)_Y \to U(1)_{\rm EM}$
- Each group coressponeds to a force
- $SU(N)$ is non-Abelian while $U(1)$ is Abelian

Accidental symmetries

Two kinds of symmetries

- Input: symmetries we impose
- Output: symmetries due to the truncation (accidental)
- Example: The period of a pendulum does not depend on the amplitude

The accidental symmetries of the SM

- The SM has baryon number and lepton number as accidental symmetries
- That explains why the proton is stable
- There are fundamental differences between baryon number and electric charge conservations
  - Electric charge conservation is imposed while baryon and lepton numbers are not
  - Electric charge comes with a force (the EM force) while baryon and lepton numbers do not

1: Neutrino masses

What are neutrinos

- Neutral fermions
- They appear massless to a very good approximation (we did not detect them traveling slower than light)
- They come with three flavors: ν_e, ν_μ and ν_τ
- Think of flavor as an “new” observable: $\widehat{F}$
- Generally speaking

$$m_\nu = 0 \Rightarrow [H, F] = 0 \qquad m_\nu \neq 0 \Rightarrow [H, F] \neq 0$$

- Non conservation of flavor is a sign for massive neutrinos

Probing neutrino masses

- Direct searches are not sensitive to very small masses
- Neutrino oscillation experiments are sensitive to m_ν
- For example: producing ν_μ and detecting ν_τ far away
- Many different experiments found clear evidences for neutrino oscillations that give

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

- Compared to $m_e \sim 10^6$ eV and $m_P \sim 10^9$ eV

neutrinos have tiny masses

Neutrino masses in the SM

The SM implies that neutrinos are exactly massless

- We need to add something to the SM
- There are several ways to extend the SM such that neutrinos are massive
- One idea: add a “sterile” heavy fermion to the SM, N

Why such a new particle lead to massive neutrinos?

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

- Small corrections to energies due to the whole spectrum
- We can reverse the logic: The correction is a way to probe the high energy states
- Consider a two level system with $E_1 \gg E_0$

$$\Delta E_0 \propto \frac{|\langle 0|\Delta H|1\rangle|^2}{E_0 - E_1} \sim \frac{1}{E_1}$$

- We see the sensitivity to the “heavy” states
- In high energy physics, $E \to m$, and thus

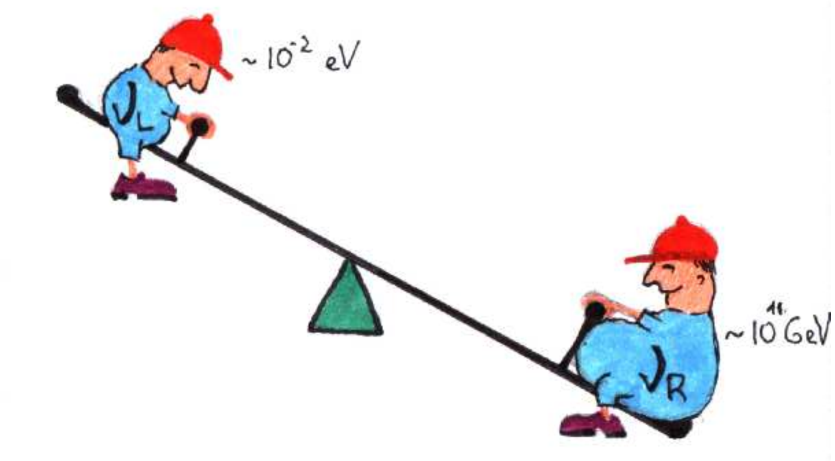
$$m \sim \frac{1}{M}$$

Neutrino masses

- The heavy fermion N gives mass to the light neutrino due to 2nd order perturbation theory

$$m_\nu \sim \frac{m_W^2}{M_N}$$

- The scale is $M_N \lesssim 10^{15}$ GeV



- The see-saw mechanism
- Lepton number is broken

Neutrino masses: the question

What is the mechanism that gives neutrinos their masses? In particular, is it related to N?

2: 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 between them is called CP
- Matter and anti-matter cannot coexist. When they meet they annihilate
- The universe has a net positive baryon number
- In the SM baryon number is an accidental symmetry. We expect the same amount of matter and anti-matter, basically zero
- Measurements (BBN and the CMB) imply

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

Baryogenesis

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

The questions

- Why is there only matter around us?
- Can we explain the measured number?

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

The problem of SM baryogenesis

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?

Leptogenesis

- Using the N that was postulated for neutrino masses
- Dynamic generation of lepton number via N decay
- Since this occurs at very high temperature, the sphalerons convert lepton asymmetry to baryon asymmetry
- For this to work $M_N \gtrsim 10^{11}$ GeV

Baryogenesis: the question

What is the mechanism that generates baryons in the universe? In particular, is it related to N?

Q3: Why $q_e = -q_P$?

Ways for charge quantization

Why all charges are a integert times $q_e/3$ while the masses are all over the place?

Several ideas

- Just an accident
- Dirac quantization
- $U(1)_{\mathrm{EM}}$ is part of a rotation in a larger space

Charge quantization

What is charge? The amount of rotation

$$\psi \to e^{iq\theta}\psi$$

- Think of rotation in 2 and 3 dimensions
- 2d: $r \to e^{iq\theta} r$ for any q a number
- 3d: $r \to e^{iq_i\theta_i} r$ where q_i is a matrix and $[q_i, q_j] = i\epsilon_{ijk}q_k$
- q is quantied if the 2d rotation is part of a 3d rotation

Non-Abelian symmetries imply charge quantization

GUT

- GUT: The SM symmetry group is a part of a bigger group
- In that case, all the SM fields are part of a bigger multiplet (like e and ν in the weak interaction)
- The GUT group is broken to the SM one

GUT implies $q_e = -q_P$

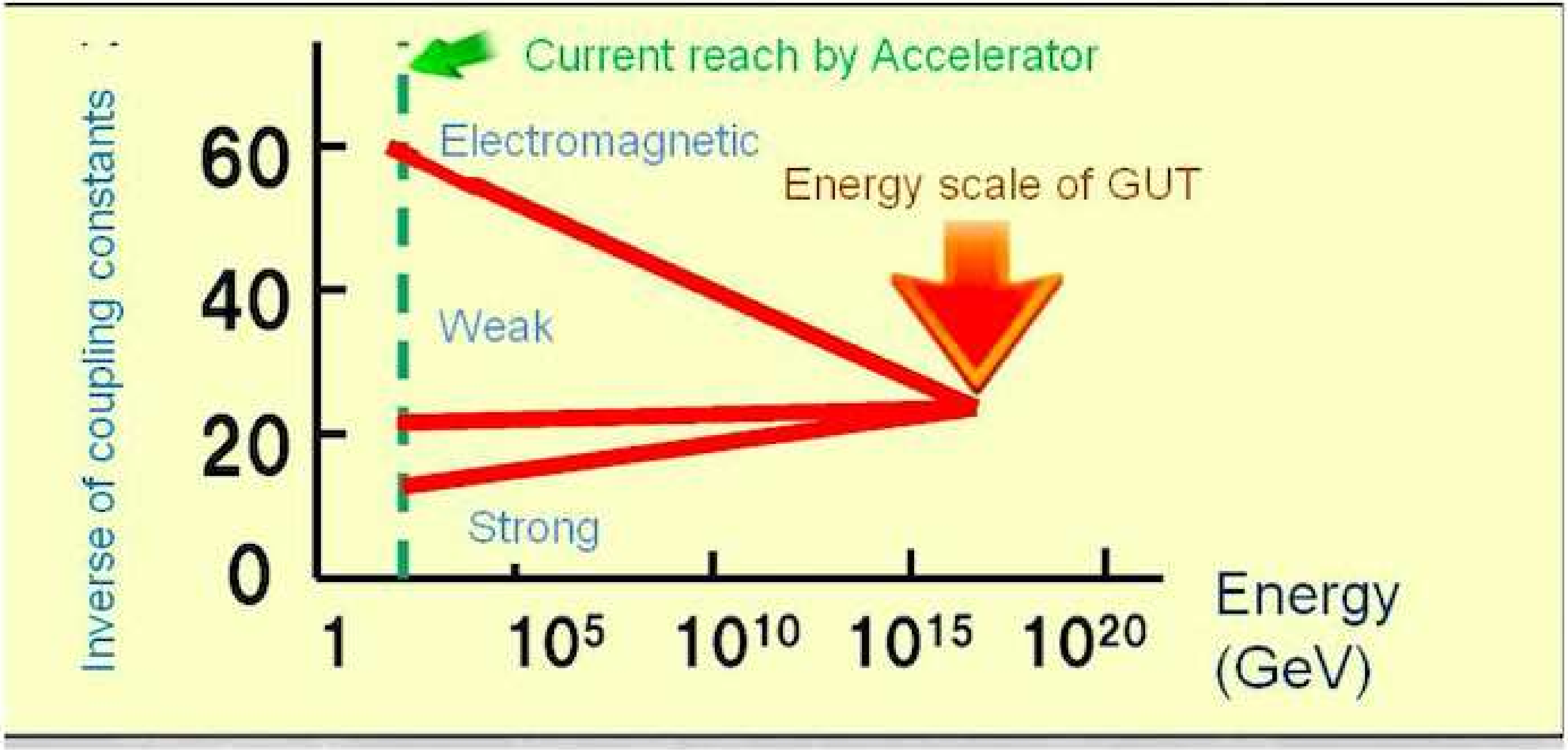
GUT: how it works?

- All the SM fields are part of a bigger group
- Our best candidate for GUT is $SO(10)$

$$SO(10) \to SU(3) \times SU(2) \times U(1)$$

- In the SM we have 15 DoF, and in $SO(10)$ we need 16
- The one more field that we need is not charged under the SM. It has the same properties as N
- Its mass is of the order of the GUT breaking scale
- What is the scale associated with the breaking?

GUT scale



$$M_{GUT} \sim 10^{16}\ \text{GeV} \ \Rightarrow\ M_N \lesssim 10^{16}\ \text{GeV}$$

GUT: the question

Is GUT realized in Nature?
In particular, is N part of it?

All together now

All together now

- Why are neutrinos massive?
- How we ended up in a universe with matter?
- Do we have a GUT?

It all points to that new particle, N

Can the same N do it all?

Can the same N do it all?

YES!

What next?

Many experiments are running and others are planed

- to look for CP violation in neutrino oscillations
- to search for proton decay
- to observe neutrinoless double beta decay

We expect to see signals in all of them

Conclusions

Conclusions

(maybe) Thanks the neutrinos that we are here