Introduction to the SM

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Extending the SM

Why extending and not replacing?

The SM is doing very well!

- The gauge sector
- The flavor sector
- Anything new has to save what we have
- The basic idea: add new heavy particles that “solve” some of the things the SM cannot explain, with very little impact on the SM successes

Open problems

Different kind of “problems”

- Gravity
- Inflation
- Baryogenesis
- Dark matter
- The cosmological constant problem
- The hierarchy problem
- The strong CP problem
- Gauge coupling unification
- The flavor puzzles

Problems are good

Gravity

We have to quantize gravity!

- Cannot write a QFT for gravity
- The reason is that the fundamental coupling, G_N is NR
- String theory is the only alternative
- In general we do not care much. For us, as “low energy people” all we know is that we need to include NR terms with suppression scale of $M_{\rm PL}$
- In models with extra dimensions, the scale of quantum gravity can be low and we can have interesting effects

Cosmology

- Standard cosmology works very good
- We know we had some inflation in the early universe
- Inflation is driven by some scalar fields
- “Dark energy”. Maybe just a cosmological constant, but maybe more

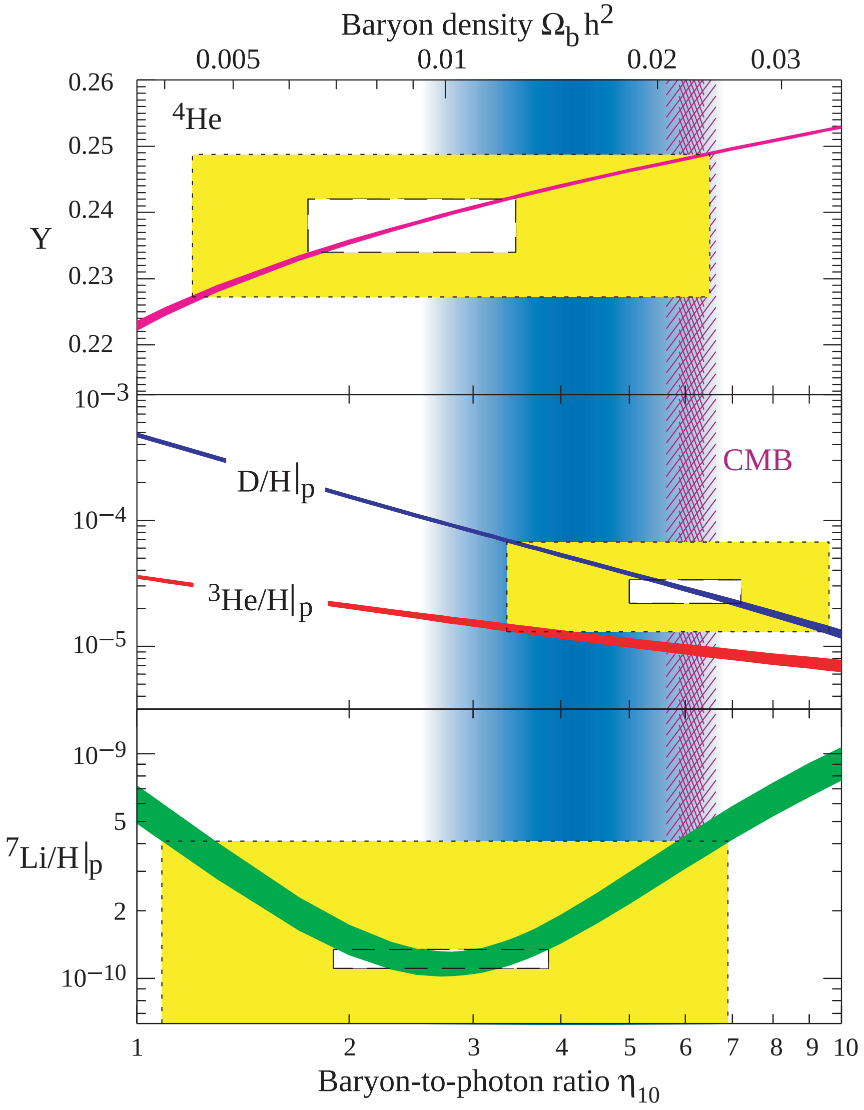
Baryogenesis

- The SM cannot explain why there are baryons and not anti-baryons around us
- Amazing that it predicts non-zero effect, just too small
- What is the number?

$$\eta \sim \frac{n_B}{n_\gamma}$$

- How we measure it? BBN and CMB

BBN determination of η



- Particle physics and cosmology are connected
- Big Bang Nucleusynthesis (BBN) works and measured

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

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 is much more attractive

Sakharov's conditions

Sakharov's 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 thermal equilibrium

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

SM baryogenesis

The three Sakharov’s 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

A moment for the environment

- It is tempting to conclude that we “must” have 3 generations, as they are the minimal number that is needed in order to get CPV

Baryogenesis: the problem

While the SM “makes” baryons, it is not efficient enough

$$\eta_{\rm SM} \sim 10^{-20} \ll 10^{-10}$$

Thus, we need to extend the SM

- New particles that can do it at high energy
- New particles that can do it at the EW scale
- Leptogenesis

Few words about leptogenesis

Very attractive idea

- The same RH neutrinos that we add for the seesaw mechanism, also give baryogenesis
- The idea is that they decay out of equilibrium and generate lepton asymmetry
- Then the sphalerons convert it to baryon asymmetry

Dark matter

DM in the SM

- In the SM we do not have DM (really?)
- We should have new particles for it
- Can we instead change gravity?
- Mond and all that...

The WIMP miracle

WIMP=Weakly Interacting Massive Particle

How much DM we have?

- Depend on the coupling and the mass
- The “WIMP miracle” is the fact that in order to get the right amount of DM we need a particle with

$$m \sim m_W \qquad g_{DM} \sim g$$

- Very nice for the LHC
- Of course, not the end of the story...

The hierarchy problem

Introduction to problems

Unlike what I talked before, this problem is purely a matter of taste!

- The Higgs mass get radiative corrections
- They are very sensitive to the cutoff, $m_h^2 \sim \Lambda^2$
- Since in the SM $\Lambda \sim M_{Pl}$ we see that we need to “fine tune” the tree level mass and the loop mass
- Is it a problem?

Hierarchy vs fine tuning

- Why the electron mass is so small?
  - Set and forget!
- Why the Higss mass so small?
  - Set and set and set...

Hierarchy problems are “set and forget”. Fine tuning problems are those that we cannot do it

The Higgs, again

We like to think about the Hierarchy problem as a hint for something new

- Something that cancel the quadratic divergences in the SM
- In the SM the important loop is with internal top quarks
- In SUSY the problem is solve by stop loops. Negative sign due to fermions
- Not easy to argue that the Higgs hierarchy problem is solve by an anthropic arguments

The cosmological constant problem

In a way, the most “severe” one

- We can add a constant to the Einstein equation
- Any vev add to this constant
- Numerically, we measure it to be $\sim 10^{-3} eV$
- EW breaking gives $\sim 10^{11} eV$
- No idea why it is not M_{Pl} to start with
- No mechanism to make it zero

The CC and the anthropic principle

- Maybe the reason for the small CC is that with large CC we will not be here
- With a slightly larger CC galaxies were unable to form and no life
- Prediction of the anthropic principle: the CC is not zero but very small. This prediction was confirmed
- Is it physics?

The NP flavor problem

The new physics scale

- Baryon and lepton number violating operators. From proton decay data

$$\frac{QQQL}{\Lambda^2} \Rightarrow \Lambda \gtrsim 10^{16}\ \mathrm{GeV}$$

- Flavor and CP violating operators

$$\frac{QQQQ}{\Lambda^2} \Rightarrow \Lambda \gtrsim 10^{7}\ \mathrm{GeV}$$

- Electroweak data

$$\Lambda \gtrsim 10^{3}\ \mathrm{GeV}$$

Exact and broken symmetries

There is a fundamental difference between the first and the last two

- Baryon and lepton numbers may be exact symmetries. Thus, the new operators may be small due to the high scale or due to a symmetry.
- Flavor symmetry and custodial symmetry are known to be broken by the SM. There cannot be an exact symmetry that protects the new operators

These two scales are associated with hierarchy problems

- The new physics flavor problem
- The little hierarchy problem

The flavor bounds

Q: Why the flavor bounds are so tight, $\Lambda \gtrsim 10^4~\mathrm{TeV}$?

A: Because in the SM there are many suppression factors (and the data agree with the SM)

$$\epsilon_K \sim \frac{m_c^2}{m_W^2}\,\frac{1}{16\pi^2}\,\alpha_W^2\,V_{us}^2\,\arg(V_{us}) \sim 10^{-10}$$

- The naive scale of the operator that generate ϵ_K is $\Lambda \sim 10^4~\mathrm{TeV}$
- In the SM there is a suppression of 10^{-10}, so the mass scale is five order of magnitudes smaller, $100~\mathrm{GeV}$

The new physics flavor problem

There is tension:

- The hierarchy problem $\Rightarrow \; \Lambda \sim 1$ TeV
- Flavor bounds $\Rightarrow \; \Lambda \gtrsim 10^4$ TeV

Any TeV scale NP has to deal with the flavor bounds

If there is time...

- The little hierarchy problem
- The SM flavor puzzle
- The strong CP problem
- Gauge coupling unification