Introduction to the SM

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General remarks

- Please ask questions
- I will tell you things that you know. But if you do not know them, ask...
- Do your “homeworks”
- I will cover only the main ideas. For details look at reviews and books

Outline

1. The SM (or how we built models)
2. The gauge+Higgs sector
3. The flavor sector
4. Beyond the SM

What is HEP?

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Very simple question

$$\mathcal{L} = ?$$

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$$\mathcal{L} = ?$$

Not a very simple answer

Basics of model building

$$\boxed{\mathcal{L} = ?}$$

Axioms of physics

1. Gauge symmetry
2. representations of the fermions and scalars (irreps)
3. SSB (relations between parameters)

Then $\mathcal{L}$ is the most general renormalizable one

Remarks

- We impose Lorentz symmetry (in a way it is a local symmetry)
- We assume QFT (that is, quantum mechanics is also an axiom)
- We do not impose global symmetries. They are “accidental,” that is, they are there only because we do not write NR terms
- The basic fields are two components Weyl spinors
- A model has a finite number of parameters. In principle, they need to be measured and only after that the model can be tested

A working example: the SM

- Symmetry: $SU(3)_C \times SU(2)_L \times U(1)_Y$
- irreps: 3 copies of QUDLE fermions

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

- SSB: one scalar with negative μ^2

$$\phi(1,2)_{+1/2} \qquad \langle\phi\rangle = \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix}$$
$$\Rightarrow \quad SU(2)_L \times U(1)_Y \to U(1)_{EM}$$

Then Nature is given by...

the most general $\mathcal{L}$

$$\mathcal{L} = \mathcal{L}_{kin} + \mathcal{L}_{Higgs} + \mathcal{L}_{Yukawa}$$

- Kinetic terms give rise to the gauge interactions.
  - The Gauge interactions are universal (better emphasis that!)
  - 3 parameters, g, g' and g_s
  - In the SM only LH fields participate in the weak interaction
- The Higgs part gives the vev and the Higgs mass. 2 parameters
- Yukawa terms: $H\bar{\psi}_L\psi_R$. This is where flavor is. 13 parameters

Renormalzabilty and all that

What is a renormalizable field theory?

Please write it down!

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No negative dimension operators

- $m\bar{\psi}\psi$
- $Y_h H\bar{\psi}\psi$
- $G(\bar{\psi}\gamma_\mu\psi)(\bar{\psi}\gamma^\mu\psi)$

But what is the physics?

IR, UV and renormalizability

- The dimension tells us when an operator is important
- Consider standard dispersion relation

$$E^2 = p^2 + m^2$$

  - At the IR, low energy, $E \approx m$
  - At the UV, high energy, $E \approx p$
- What if

$$E^2 = m^2 + p^2 + \frac{p^4}{\Lambda^2}\ ?$$

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It is all about Λ

- For $p \ll \Lambda$ the last term in not important
- For $p \gg \Lambda$ the last term is important

MDR: Modified Dispersion Relation

$$E^2 = m^2 + p^2 + \frac{p^4}{\Lambda^2}$$

- Is the MDR Lorentz invariance?
- Is the MDR excluded experimentally?
- What can we say about Λ?

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- What can we say about Λ?

- All we can say is that experimentally Λ is large compare to any scale we probed
- This is not the same as saying that we know $\Lambda \to \infty$. We set $\Lambda \to \infty$ since we deal with “low energy”

Back to QFT

- NR terms just refer to terms that are important at the UV
- When we construct a theory, at first we set all the NR terms to zero since we care about low energy
- At later stages, when we care about small corrections at “low” energies, we may add them
- Important: We are modest! We do not try to explain physics at energies we cannot probe
- The issue of mathematical consistency is just the above statement. It is inconsistent to use NR theories to explain physics at very high scale.

Global and Accidental symmetries

We only impose gauge (or local) symmetries

- Well, they are nicer (think about it...)
- There is an argument that quantum gravity always break them (so what?)
- We like to think that all global symmetries are accidental. They are there just because the field choices and the requirement of renormalizability
- We think all symmetries are either local or broken!

Accidental symmetry: an example

Consider a school where all the rules are kept

- Rule: all groups should have even numbers of persons
- Rule: boys have blue shirts, girls have red shirts and teachers white shirts
- Rule: only children are playing

$$\Downarrow$$

New rule: the difference between the number of red and blue shirts in any play group is even

This new rule is accidental. If also teachers use to play the new rule is broken

Lepton and baryon numbers

- The SM has a $U(1)_B \times U(1)_e \times U(1)_\mu \times U(1)_\tau$ global symmetry
- Only leptons carry L and only quarks carry B
- All processes observed so far conserve L and B
- Processes that violate it, like $P^+ \to e^+\gamma$, were not observed
- Baryon and lepton number are accidental symmetries of the SM
- They are broken by NR operators. Can you think of such operators?

Discrete space time symmetries

C, P, and T

- Any Local Lorentz invariant QFT conserves CPT
- No theoretical reason for C, P or T to be conserved separately
- In the SM the weak interaction breaks them all. This is also what we see in Nature.
- Any chiral theory break C and P.
- The condition for CP violation is more complicated: a phase in $\mathcal{L}$

Some summary

- Model building is based on axioms: Gauge symmetries, field content and SSB
- The Lagrangian is the most general renormalizable one
- Renormalizability is really the point that we don't try to explain physics at very short distance
- Now that we have the Lagrangian, what can we do with it?
  - Measure its parameters
  - Make predictions and test them