PHYS 164: Particle Physics

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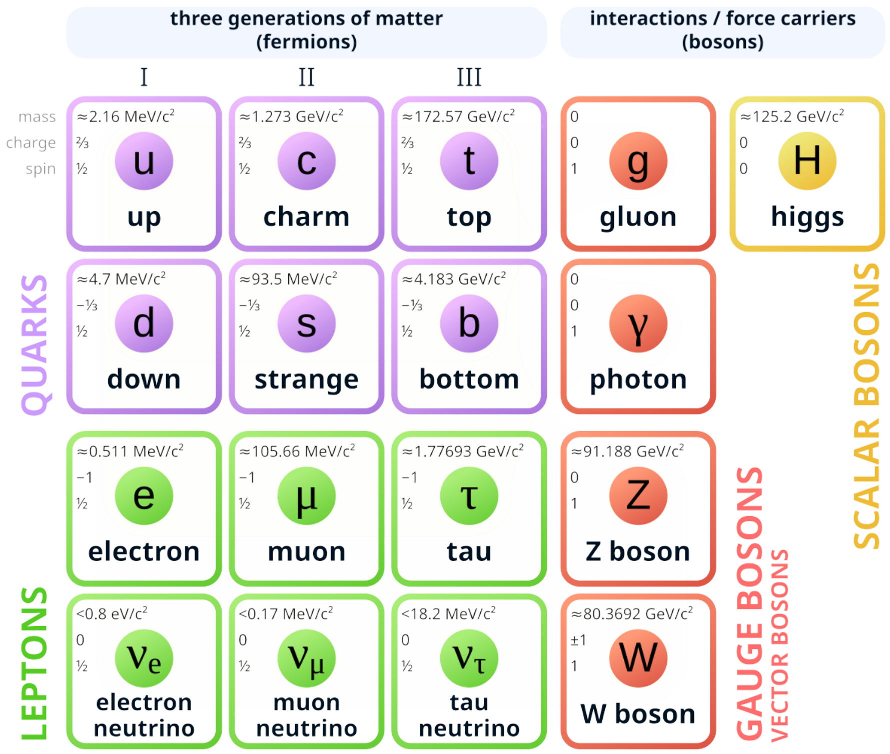
* Adapted from SP25 lectures.

1 Unsorted Notes

1.1 Overview (Lecture 1)

Particle physics is the study of the elementary constituents of matter—that is, of the minimal subset of matter that can explain all the phenomena we see. Our current understanding of these particles is formalized by the Standard Model, which consists of a whole bunch of distinct particles and three forces describing the interactions between them.



Each particle here has a corresponding antiparticle of opposite charge. For example, $e^- \leftrightarrow e^+$, $p^+ \leftrightarrow \overline{p}^-$, and $\gamma \leftrightarrow \gamma$. (Note that neutral particles are not necessarily their own antiparticle!) The gauge bosons mediate force interactions between particles, and the Higgs boson is what gives particles their mass.

A particle's charge determines how it interacts with the electromagnetic force, so some particles feel it and others don't. Particles may or may not also interact with the strong force—quarks do, and leptons don't. All particles interact with the weak force, though the nature of this interaction is complicated.

The behavior of each force depends on two properties: the mass of the force carrier, and some dimensionless coupling strength α. The electromagnetic force, for example, is mediated by the massless photon γ. We can write the electrostatic potential between two electrons as

$$U(\mathbf{r}) = \hbar c \left(\frac{\alpha_{\text{EM}}}{r}\right), \qquad \alpha_{\text{EM}} = \frac{q_e^2}{4\pi\epsilon_0 \hbar c} \approx \frac{1}{137},$$

where α_{EM} is the coupling constant for electromagnetism. As we'll see, the probability of a scattering event occurring is proportional to α_{EM}^2.

The weak force has coupling constant $\alpha_W = 0.032$. This is very clearly larger than α_{EM}, which suggests that the weak force is actually stronger than the electromagnetic force. We resolve this apparent misnomer by noting that the mediators of the weak force—the $W^\pm$ and Z bosons—are very heavy, much heavier than even a proton. We thus modify the potential to get the Yukawa potential

$$U(r) = -\hbar c \left(\frac{\alpha_W}{r}\right) e^{-r/R_W}, \qquad R_W = \frac{\hbar}{c m_Z}.$$

So heavy mediators give rise to short-range forces. For particles with very large de Broglie wavelengths compared to R_W the potential looks more like

$$U(\mathbf{r}) = -4\pi\alpha_W R_W^2\, \delta^3(\mathbf{r}),$$

and in this case the coupling is modified to $4\pi\alpha_W R_W^2$. To get a dimensionless scattering probability we introduce the wavenumber k to get $P \sim (\pi\alpha_W k^2 R_W^2)^2$, and since $p \approx E/c$ for a relativistic particle, we find

$$P \sim \left(4\pi\alpha_W \frac{E^2}{m_W^2 c^4}\right)^2.$$

We can see that the weak force is "weak" at everyday energies, which are much lower than $m_W c^2$ and $m_Z c^2$. But at high energies the weak force is actually stronger than electromagnetism!

The strong force, mediated by the gluon, has "color charges" red, green, and blue (along with their corresponding anti-colors). Its coupling constant is $\alpha_S \approx 0.1$, which isn't that much larger than α_W. The reason we call it the strong force, then, has to do with the fact that the coupling α is not actually constant!

α_{EM}, for example, increases with increasing energy. (This has to do with vacuum polarization—when a charged particle and antiparticle spontaneously come into existence they create a dipole moment for a very small amount of time, which may be oriented depending on how close it is to a nearby charge.) The strong force, in contrast, gets weaker at higher energies as quarks and gluons get bound up into color-neutral hadrons. This effectively "binds up" the strong force into larger particles, so we don't see its effects in everyday life.

1.2 Feynman Diagrams (Lecture 2)

Suppose we observe an electron and positron with momenta $\mathbf{p}_1, \mathbf{p}_2$ turn into a muon and antimuon with $\mathbf{p}_3, \mathbf{p}_4$; the amplitude of this occurring is denoted by $\langle \mu^-(\mathbf{p}_3), \mu^+(\mathbf{p}_4) | e^-(\mathbf{p}_1), e^+(\mathbf{p}_4)\rangle$. But we can only observe the initial and final state of these particles—in principle, a whole variety of things could've happened in between! We can represent this by inserting the identity operator between the bra and ket:

$$\left\langle \mu^-(\mathbf{p}_3), \mu^+(\mathbf{p}_4) \middle| e^-(\mathbf{p}_1), e^+(\mathbf{p}_4)\right\rangle = \sum_X \left\langle \mu^-(\mathbf{p}_3), \mu^+(\mathbf{p}_4) \middle| X\right\rangle \left\langle X \middle| e^-(\mathbf{p}_1), e^+(\mathbf{p}_4)\right\rangle.$$

We describe the intermediate stages using Feynman diagrams. Each vertex of such a diagram represents an interaction with a force mediator, and at each vertex a number of quantities is conserved:

- energy and momentum,
- electric charge and color charge,
- quark number $(N_q, N_{\overline{q}})$ and baryon number $B = \frac{1}{3}(N_q - N_{\overline{q}})$, and
- lepton number, including electron number, muon number, and tau number:

$$\begin{aligned} L_e &= (N_e + N_{\nu_e}) - (N_{\overline{e}} + N_{\overline{\nu}_e}), \\ L_\mu &= (N_\mu + N_{\nu_\mu}) - (N_{\overline{\mu}} + N_{\overline{\nu}_\mu}), \\ L_\tau &= (N_\tau + N_{\nu_\tau}) - (N_{\overline{\tau}} + N_{\overline{\nu}_\tau}). \end{aligned}$$

We'll start simple with the electromagnetic vertex, drawn below. (Positive time flows in the rightward direction.) Notice how we can orient this vertex in a number of ways to get different processes, being careful to conserve charge.

[small, horizontal = i1 to c] i1[particle = γ] –[photon] c, c –[fermion] f1[particle = e^-], c –[anti fermion] f2[particle = e^+] ; [small, horizontal = c to f1] i2[particle = e^-] –[fermion] c, i1[particle = e^+] –[anti fermion] c, c –[photon] f1[particle = γ] ; [small] i1[particle = γ] –[photon] c, c –[fermion] f1[particle = e^-], c –[anti fermion] f2[particle = e^-] ; [small] i1[particle = γ] –[photon] c, c –[fermion] f1[particle = e^+], c –[anti fermion] f2[particle = e^+] ;

We can combine these vertices to create more complex processes, like electron-electron scattering.

[small, vertical = c1 to c2] i1[particle = $e^-(\mathbf{p}_1)$] –[fermion] c1, i2[particle = $e^-(\mathbf{p}_2)$] –[fermion] c2, c1 –[photon] c2, c1 –[fermion] f1[particle = $e^-(\mathbf{p}_3)$], c2 –[fermion] f2[particle = $e^-(\mathbf{p}_4)$] ; [small, vertical = c11 to c12, remember picture] i1[particle = $e^-(\mathbf{p}_1)$] –[fermion] c11, i2[particle = $e^-(\mathbf{p}_2)$] –[opacity=0] c12, c11 –[opacity=0] c12, c21 –[opacity=0] c22, c11 –[opacity=0] c21, c12 –[opacity=0] c22, c22 –[fermion] f2[particle = $e^-(\mathbf{p}_4)$], c21 –[opacity=0] f1[particle = $e^-(\mathbf{p}_3)$], ;

Feynman diagram vertices—rules in the slides! Electron-positron scattering is easy to see from the diagram.

Electron-electron scattering has a couple of possibilities. We encapsulate both of these possibilities with a purely vertical Feynman diagram.

In principle, there are infinitely many diagrams for the same process. But diagrams with more vertices have smaller amplitudes (since there is a $\sqrt{\alpha}$ for each vertex), so their contributions are subdominant. (We might only add the "leading-order" diagrams, which contain only what is required for an interaction to occur.)

Everything we've said here is true not only for electrons, but also everything that carries electric charge. See the slide on Electromagnetic Vertices!

1.3 Lecture 2

So we've talked about electromagnetic vertices. Now let's dive into the gluon vertices.

Slide - Gluon Vertices (spring-like line because gluons act like springs at long distances):

- We can start with a gluon and it can split into a quark and antiquark of the same type. This vertex has amplitude $\sqrt{\alpha_S}$.
- We can start with a gluon and it can split into two gluons. This vertex has amplitude $\sqrt{\alpha_S}$.
- We can start with two gluons and they can produce two gluons. This vertex has amplitude α_S. (This kind of vertex and the previous one characterize gluon self-interaction!)

((See onenote (A) for leading-order gg -> t tbar process))

Sometimes scattering can actually proceed through two different forces. These are technically different process, and so we have to sum all the Feynman diagrams, even though the strong-force diagrams are dominant.

Now, having all these square root factors flying around can get annoying. Factors of 4π will be flying everywhere too, so we define

$$g \equiv \sqrt{4\pi\alpha}.$$

The E&M coupling constant is denoted g_e, or simply e. This notational ambiguity might not be important for this class, but it's good to keep in mind in general!

Now let's talk about weak vertices.

- Vertices involving Z-bosons are very similar to EM vertices—Z-bosons are coupled to a fermion and its antifermion. For both quarks and leptons, there is no cross-generational coupling (it is generation-diagonal).
- The coupling of W-bosons to SM leptons is also generation-diagonal. But the coupling of SM quarks to W bosons can change generations! (Any time there's a change in generation, it's because there's a W-boson involved.)

Slide - Weak Vertices: W-leptons, CKM Matrix.

- We can define down-type quarks in two different ways, and these two bases are relayed by a unitary transformation.
- The CKM matrix used to transform between them is evidence that our three-generation theory is closed (the probabilities sum nicely)!

- The diagonal entries of the CKM matrix are very close to 1, suggesting that our two basis definitions are almost the same but not quite!

The weak force has self-interacting vertices, too. (Slide - Weak Vertices: Gauge) Note that we cannot "freely" rotate vertices like these—we'd need to change our labels a bit to conserve charge!

((Examples - Allowed and Forbidden Processes—see more detailed reasoning later in slides))

Slide - Conservation Laws

- Electric charge (and color)
- Quark number, baryon number $B = \frac{1}{3}(N_q - N_{\overline{q}})$
- Lepton number (electron number, muon number, tau number)—one separate conserved quantity for each generation!

1.4 Lecture 3