Lecture 8,

QFT3: The Standard Model & Electroweak Theory

Felix Yu

Dec. 3, 2020

Today: Particle lifetimes / decays
Quark / Gluon fragmentation & hadronization
Parton showers

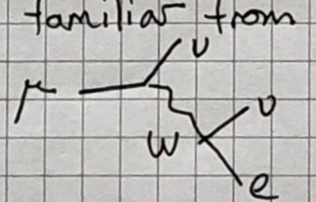
Recall from last time that Γ_W^{tot}, Γ_Z^{tot}, $\Gamma_t^{tot} \sim \mathcal{O}(\text{few})$ GeV
& $\Gamma_h^{tot, SM} \sim 4$ MeV.

So, τ_W, τ_Z, τ_t proper lifetimes were $\mathcal{O}(10^{-24})$ s
& $\tau_h \sim \mathcal{O}(10^{-22})$ s.

Let us understand the longer lifetimes of μ, τ, b, c, s quarks:

Since SM has no FCNCs at tree level, particles cannot generally decay via $f_2 \to f_1 \gamma$ or $f_2 \to f_1 g$.
Hence, the only way to "access" lighter generations @ tree-level is via the charged current interaction.

This is familiar from muons:



Dim. analysis: off-shell & 3-body decay:

$$\Gamma_\mu \sim \frac{g^4}{(4\pi)^2 m_W^4} \cdot m_\mu^5 \cdot \underbrace{\frac{1}{8\pi}}_{\text{phase space suppression factor}}$$

$$\simeq 8.75 \cdot 10^{-19} \text{ GeV} = 1.3 \cdot 10^6 \tfrac{1}{s}$$

$$\tau_\mu \simeq 1\ \mu s$$

What about τ?

Essentially, replace m_μ by m_τ.

$\tau \to \mu\nu\nu$ or $\tau \to e\nu\nu$ are each 17.5% of the τ decay width.

$$\Gamma_\tau \sim \frac{g^4}{(4\pi)^2} \frac{m_\tau^5}{m_W^4} \frac{1}{8\pi}$$

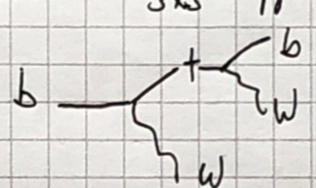
$$\sim 1.22 \cdot 10^{-12}\ \mathrm{GeV} = 1.85 \cdot 10^{12}\ \tfrac{1}{s}$$

$\tau_\tau \sim 10^{-12}\,s$ (compare to $\tau_\tau = 2.903 \cdot 10^{-13}\,s$)

Note, multiplicity in final states (including color factors) $\tau \to \nu\, ud$ + $\tau \to \nu\, cs$ would recover the experimental result even more accurately.

Now, consider b + c+s.

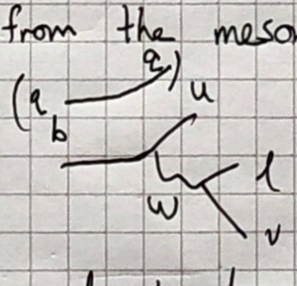
The $V_{CKM} \approx \mathbb{1}_{3\times3}$ approx. leads to a stable b:



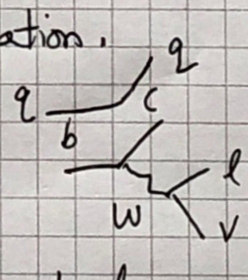
so, must take into account small V_{cb} + V_{ub} elements as <u>leading</u> parameter that scales b lifetime.

We also will "dress up" b quarks with spectator quarks to form mesons, + factorize the EW interaction from the meson creation.

Then,



+



are the dominant tree level decays (also with $W \to ud, cs$).

Then, $\Gamma_b \sim \frac{g^4}{(4\pi)^2} \cdot \frac{m_b^5}{m_W^4} \cdot \frac{1}{8\pi} \cdot (V_{cb})^2$ [or $(V_{ub})^2$]

Recall CKM ~

$$\begin{pmatrix} 0.97446 \pm 10^{-4} & 0.22452 \pm 4.4\cdot10^{-4} & 0.00365 \pm 1.2\cdot10^{-4} \\ 0.22438 \pm 4.4\cdot10^{-4} & 0.97359 \pm {}^{10^{-4}}_{1.1\cdot10^{-4}} & 0.04214 \pm 7.6\cdot10^{-4} \\ 0.00896 \pm {}^{2.4\cdot10^{-4}}_{2.3\cdot10^{-4}} & 0.04133 \pm 7.4\cdot10^{-4} & 0.999105 \pm 3.2\cdot10^{-5} \end{pmatrix}$$

$\Gamma_b \sim 1.44\cdot10^{-13}\ \text{GeV} = 2.2\cdot10^{11}\ \frac{1}{s}$

$\tau_b \sim 4.57\cdot10^{-12}\ s$

(Compare $B^\pm$: $\tau_{B^\pm} = (1.638 \pm 0.004)\cdot10^{-12}\,s$, $c\tau_{B^\pm} = 491.1\,\mu m$)

Note $c\tau_b \sim 1.5\cdot10^{-3}\ m$

(B^0: $\tau_{B^0} = (1.519 \pm 0.004)\cdot10^{-12}\,s$, $c\tau_{B^0} = 455.4\,\mu m$)

So, for $E_b \sim 100$ GeV, then $\frac{E_b}{m_b} = \gamma \approx 25$, giving a lab frame decay length of O(mm – cm).

This is a main design feature of LHC, that B-meson displaced vertices are at O(mm) from the collision vertex.

Finally, c & s are similar.

Exercise: estimate τ_c & τ_s & compare to PDG.

$D^{+/-}$: $M = 1.86965 \pm 0.00005$ GeV

$\tau = (1040 \pm 7)\cdot10^{-15}\,s$

$c\tau = 311.8\,\mu m$

D^0: $M = 1864.83 \pm 0.05$ MeV

$\tau = (410.1 \pm 1.5)\cdot10^{-15}\,s$

$c\tau = 122.9\,\mu m$

$K^{+/-}$: $M = 493.677 \pm 0.016$ MeV

$\tau = (1.2380 \pm 0.0020)\cdot10^{-8}\,s$

$c\tau = 3.711\ m$

$M_{K^0} \simeq 497.611$ MeV

K_S^0: $\tau = 0.8954 \pm 0.0004 \cdot 10^{-10}\,s$, $c\tau = 2.6844$ cm | K_L: $\tau = 5.116 \pm 0.021\cdot10^{-8}\,s$, $c\tau = 15.34$ m

Intuitively, high energy charged particles radiate massless gauge bosons because there is an IR divergence for soft as well as collinear radiation. This should be familiar from the IR divergence in the electron vertex fcn. calculation from QED at 1-loop. We needed to introduce a finite photon mass in order to regulate the IR divergence. To get an IR-safe cross section at 1-loop, though, we had to include the real radiation diagram at tree-level. We will review this and discuss parton showers in the next lecture.