Lecture 8, December 3, 2020

Thursday, December 3, 2020 2:16 PM

HW 3 is now posted.

Last time: Bjorken scaling
Particle detection.

Today: Particle decays & order of magnitude estimates
Parton showers, fragmentation & hadronization.

Last time,

e, γ, ν, μ are collider stable

$\tau, u, d, c, s, b, g \leftarrow$ today

W, Z, h, t, promptly decaying

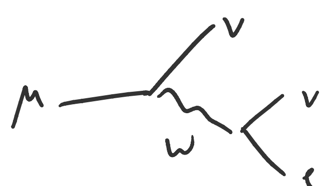
Main figure of merit: decay width ($[\Gamma] = \text{GeV} = \frac{1}{s}$, $[\tau] = \text{GeV}^{-1} = s$)

$1\,\text{GeV} = 1.52 \cdot 10^{24} \frac{1}{s}$

Revisit why μ is collider stable:

Recall $\tau_\mu \sim 2.2 \cdot 10^{-6} s$.

$\mu \to e \nu \nu$ via



For an order of magnitude estimate: approx. ν + e as massless (essentially phase space is already unsuppressed),

$$\Gamma \sim \frac{(g^2)^2 \cdot m_\mu^5}{(4\pi)^2 (m_W^2)^2} \cdot \frac{1}{8\pi}$$

mimic $\left(\frac{g^2}{4\pi}\right)^2$

3 body suppression

Rules: mass dimension
coupling
[Counting π's]

Evaluate $\Gamma \sim 8.75 \cdot 10^{-19}$ GeV $= 1.3 \cdot 10^{6} \frac{1}{s}$

$\tau_\mu \sim 1 \mu s$ compared $\tau_\mu = 2.2 \mu s$ exp.

$c\tau_\mu = 6.6 \cdot 10^2 m$

For 100 GeV μ, γ Lorentz factor is $\gamma = \frac{E}{m} = 10^3$

$\Rightarrow$ lab frame decay length $\gamma c \tau_\mu \sim 6.6 \cdot 10^5 m$.

Next: τ lepton.

In general, particle decays in SM only proceed via the SM charged current because there are no FCNCs at tree level.

$\mu \to e \gamma$ or $t \to g c$ or $g u$.

has least suppressed phase space, but they do not exist at tree level.

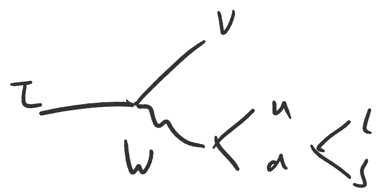
$\mu \to e\gamma$ requires neutrino mass insertion

$t \to gc$ + $t \to gu$ requires 2-loop (?) chromo-magnetic moment.

Redo the discussion of muon with τ lepton:

$\tau \to \nu \nu \mu$ or $\tau \to \nu \nu e$

and also



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

$= 1.22 \cdot 10^{-12}$ GeV $= 1.85 \cdot 10^{12} \frac{1}{s}$

$\tau_\tau = 10^{-12} s$ compare $\tau_\tau = 2.93 \cdot 10^{-13} s$.

Accounting for multiplicity in final states, can recover

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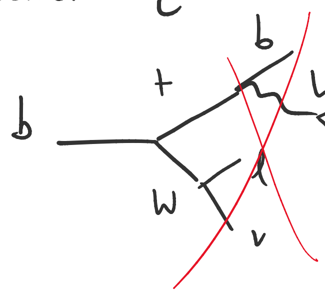
$$\Gamma_{tot} = 2\cdot\left(\Gamma_{\tau\to\nu\nu e} = \Gamma_{\tau\to\nu\nu\mu}\right)$$

$$Br(\tau\to\nu\nu e) \approx Br(\tau\to\nu\nu\mu) = 17.5\%$$

Now, consider bottom quark.

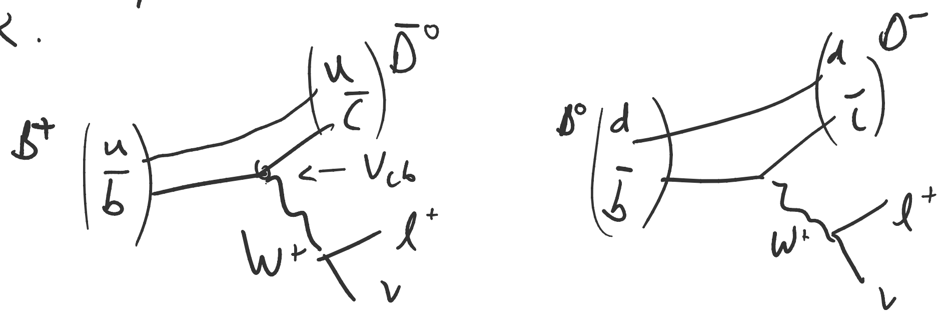
Note that $V_{CKM} = \mathbb{1}_{3\times3}$ will result in a stable bottom quark.



violates decay kinematics

It is necessary to account for non-identity CKM to get a bottom quark decay. V_{ub} + V_{cb} CKM elements drive the leading parameter dependence in bottom decay widths.

For our purposes, we are always going to factorize the meson decay as a b-quark interaction dressed with a spectator quark.



$$\Gamma_b = \left[\frac{(g^2)}{4\pi\, m_W^2}\, V_{cb}\right]^2 \cdot m_b^5 \cdot \frac{1}{8\pi}$$

Why V_{cb} + not V_{ub}?

$$V_{CKM} = \begin{array}{c} \begin{pmatrix} 0.97446 & 0.22452 & 0.00365 \\ 0.22438 & 0.97359 & 0.04214 \\ 0.00896 & 0.04133 & 0.999105 \end{pmatrix} \\ \begin{array}{ccc} \overset{\shortparallel}{V_{ub}} & \overset{\shortparallel}{V_{cb}} & \end{array} \end{array}$$

$$\Gamma_b = 1.44 \cdot 10^{-13}\,\text{GeV} = 2.2 \cdot 10^{11}\,\frac{1}{s}$$

$$\tau_b = 4.57 \cdot 10^{-12}\,s\,, \quad c\tau \sim 1.5\,\text{mm}$$

Compare to $B^{+/-}$: $\tau_{B^{+/-}} \sim (1.638 \pm 0.004) \cdot 10^{-12}\,s$

$c\tau \sim 491.1\,\mu m$

B^0 : $\tau_{B^0} \sim (1.519 \pm 0.004) \cdot 10^{-12}\,s$

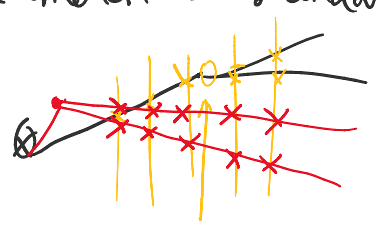
$c\tau \sim 455.4\,\mu m$

For 100 GeV B-meson, $\gamma = \frac{E}{m} \sim 25$,

$$\gamma c\tau \sim 25 \cdot 0.5\,\text{mm} \Rightarrow 12.5\,\text{mm} = 1.25\,\text{cm}$$

Exactly why the tracking layers (pixel detectors) start at $\mathcal{O}(\text{cm})$ from primary interaction vertex.

Leads to phenomenon of secondary vertices.



identify secondary vertex as long you capture hits before + after

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Break: Return @ 3:20pm

Finish off with charm + strange

Exercise: estimate τ_c + τ_s + compare to PDG

Exercise: estimate τ_c & τ_s + compare to PDG.

$D^{+/-}$: $\tau = (1040 \pm 7) \, 10^{-15} s$

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

D^0 : $\tau = (410.1 \pm 1.5) \cdot 10^{-15} s$

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

$K^{+/-}$: $M = 493.7$ MeV

$\tau = (1.238 \pm 0.0020) \cdot 10^{-8} s$

$c\tau = 3.711 m$

K^0 : $M = 497.611$ MeV

K^0_S $\tau = 0.8954 \pm 0.0004 \cdot 10^{-10} s$

$c\tau = 2.6844 \, cm$

K^0_L $\tau = 5.116 \pm 0.021 \cdot 10^{-8} s$

$c\tau = 15.34 m$

Now, having developed an understanding of the timescales of particle decays in SM, we turn to QCD fragmentation and parton showers.

What about u, d, or rather how do quarks + gluons behave after being produced in hard interaction & flying to the detector?

Basic story: At high energies ($E \gg \Lambda_{QCD}$), quarks + gluons interact via perturbative QCD, and it is readily calculable. Once you produce a fast, high energy quark or gluon, they will radiate gluons or split into $q\bar{q}$ pairs and lose energy in the process, leading to fragmentation.

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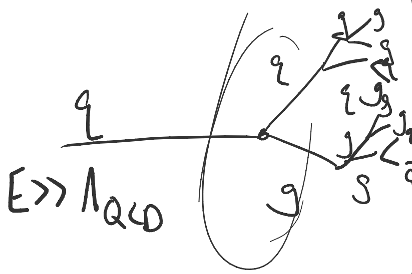


hadronize + color singlets form

$E \sim \Lambda_{QCD}$

Everything confines.

$\pi^{+/-}$, π^0, ρ, K^0_S, K^0_L, $K^{+/-}$

$D^0, D^{+/-}$

$B^0, B^{+/-}$ ...

$\Lambda, p, \Lambda, \ldots$

$\pi^{+/-}$: $\tau = 2.6 \cdot 10^{-8} s \Rightarrow c\tau = 7.8 m$

π^0 : $\tau = 8.4 \cdot 10^{-17} s \Rightarrow c\tau = 2.64 \cdot 10^{-8} m$

But also note, π^0 can be produced in decay of long-lived parent (like $\tau^+ \to \nu \pi^+ \pi^0$)

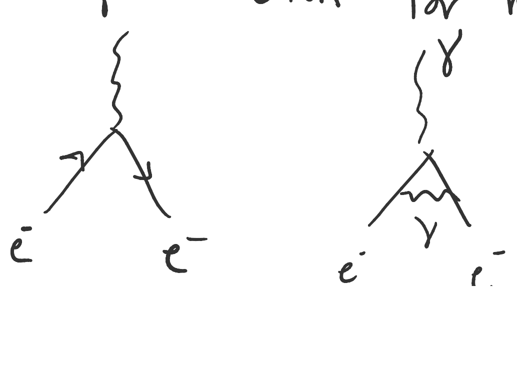
Aside: Detector (calorimeter) figure of merit is effective number of radiation lengths that "attenuate" flux of particles produced in primary interaction.

First splitting: why does high energy quark radiate gluon?

Trivial answer: Similar to QED bremstrahlung.

Equivalent: why does high energy electron radiate photon?

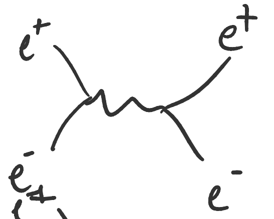
Consequence of resolving IR divergence in vertex correction for massless photon (+electron)



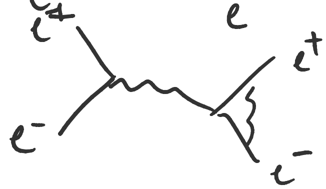
IR divergence: fictitious photon mass

Match between photon mass IR

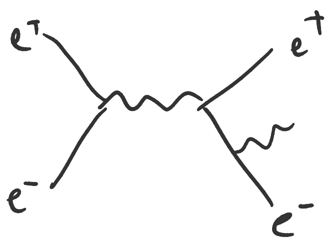
Match between photon mass IR divergence in vtx correction + regulator photon mass incollinear emission (real radiation) from $e^+e^- \to e^+e^-\gamma$ scattering.



$O(\alpha^2)$



$O(\alpha^3)$



real radiation cancels IR divergence.

Req: $\sigma(e^+e^- \to e^+e^-(+\gamma))$ finite regulates vertex IR divergence.

Exactly same for quark + gluon vtx + gluon radiation.

Q: Why happens for high energy electrons?