Lecture 7, December 2, 2020

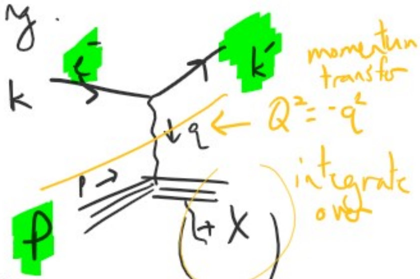
Wednesday, December 2, 2020 2:11 PM

Today: Recap of Bjorken scaling
Particle phenomenology + detecting particles

Bjorken scaling

Schwartz 32.1

$e^- p$ scattering.



θ = angle b/t k + k'

$\theta = 0$ is forward scattering

$$\left(\frac{d^2\sigma}{d\Omega\, dE'}\right)_{lab} = \frac{\alpha_e^2}{4\pi m_p q^4} \frac{E'}{E} L^{\mu\nu} W_{\mu\nu}$$

leptonic tensor ($L^{\mu\nu}$), hadronic tensor ($W_{\mu\nu}$)

For unpolarized scattering,

$$L_{\mu\nu} = \frac{1}{2} \mathrm{Tr}[\not{k}' \gamma^\mu \not{k} \gamma^\nu]$$

($\frac{1}{2}$: avg. init. spins)

$$= \frac{1}{2} \cdot 4 \left(k'^\mu k^\nu - g^{\mu\nu} k\cdot k' + k'^\nu k^\mu\right)$$

$$= 2\left(k^\mu k'^\nu + k'^\mu k^\nu - g^{\mu\nu} k\cdot k'\right)$$

$L_{\mu\nu} = L_{\nu\mu}$

$L_{\mu\nu} L'^{\mu\nu}$

$\mathrm{Tr}[(\not{k}' \gamma^\mu \not{k} \gamma^\nu)]$

$m_e \to 0$

$\mathrm{Tr}[(\not{p}' + m_\mu)\gamma^\mu(\not{p} + m_\mu)\gamma^\nu]$

γ^μ vs. $\gamma^\nu \sigma^{\mu\nu}$

$$\mathrm{Tr}[\gamma^\alpha \gamma^\mu \gamma^\beta \gamma^\nu] = 4\left(g^{\alpha\mu} g^{\beta\nu} - g^{\alpha\beta} g^{\mu\nu} + g^{\alpha\nu} g^{\mu\beta}\right)$$

Hadronic tensor:

1. Since all final states are integrated over, then $W^{\mu\nu}$ can only depend on P^μ + q^μ.
2. Impose Ward identity. $q_\mu W^{\mu\nu} = 0$
3. Unpolarized scattering $W^{\mu\nu} = W^{\nu\mu}$.

$$W_{\mu\nu} = W_1\left(-g_{\mu\nu} + \frac{q^\mu q^\nu}{q^2}\right) + W_2\left(P^\mu - P\cdot q\, q^\mu \ldots\right)\left(P^\nu \ldots\right)$$

 of QED

$$\left[W_{\mu\nu} = W_1\left(-g_{\mu\nu} + \frac{q^\mu q^\nu}{q^2}\right) + W_2\left(p^\mu - \frac{p\cdot q\, q^\mu}{q^2}\right)\left(p^\nu - \frac{p\cdot q\, q^\nu}{q^2}\right)\right.$$

parametrization of $W_{\mu\nu}$.

W_1 + W_2 are form factors + must be Lorentz scalars + can only depend $p^2 = m_p^2$, $p\cdot q$, q^2.

Change notation $Q^2 \equiv -q^2 > 0$, denotes energy transfer.

$$\nu \equiv \frac{p\cdot q}{m_p} = (E - E')_{lab}\,;$$ in proton rest frame, energy lost by electron.

Instead, use Bjorken x:

$$x \equiv \frac{Q^2}{2p\cdot q} \qquad \text{[dimless]}$$

We can contract $L^{\mu\nu} W_{\mu\nu}$:

$$\left(\frac{d^2\sigma}{d\Omega\, dE'}\right)_{lab} = \frac{\alpha_e^2}{8\pi E^2 \sin^4\frac{\theta}{2}}\left[\frac{m_p}{2} W_2(x,Q)\cos^2\frac{\theta}{2} + \frac{1}{m_p} W_1(x,Q)\sin^2\frac{\theta}{2}\right]$$

$\propto$ angular dependence

LHS: Known by detector that covers Ω + measures E' recoiling e^-.
RHS: assign x + Q dependence to extract W_1 + W_2, since x + Q are known by the kinematics.

We can determine W_1 + W_2 by only measuring outgoing electron energy E' + angular dependence.

Consider now parton instead of full proton.

parton momentum $p_i^\mu = \xi p^\mu$

Momentum conservation:

$$p_i^\mu + q^\mu = p_f^\mu$$

$$\Rightarrow m_q^2 + 2p_i\cdot q + q^2 = m_q^2$$

$$\Rightarrow 2p_i\cdot q = -q^2 = Q^2$$

$$\Rightarrow \frac{Q^2}{2p_i\cdot q} = 1$$

$x \equiv Q^2 \quad Q^2$

$$x \equiv \frac{Q^2}{2P\cdot q} = \frac{Q^2}{2\left(\frac{p_i}{\xi}\right)\cdot q} = \xi \quad \text{is momentum fraction}$$

Assuming partons are free, aside from the photon interaction, the $e^- q \to e^- q$ scattering is exactly analogous to $e^-\mu \to e^-\mu\ (+\gamma)$ scattering in QED. Recall that form factors only get $\log Q^2$ dependence because of 1-loop vertex correction, as long as we fix x. This is the origin of Bjorken scaling: cross section (or form factors W_1 & W_2) only has $\log Q^2$ dependence for fixed x, & so increasing Q^2 & keep x fixed, the cross grows only as $\log Q^2$.

Break until 3:18 pm

Now, we have discussed the hard interaction and how partons are modeled as parton distribution functions, We now focus on the decay and detection side of SM particles.

Basic detector physics:

Competition between two ideals:

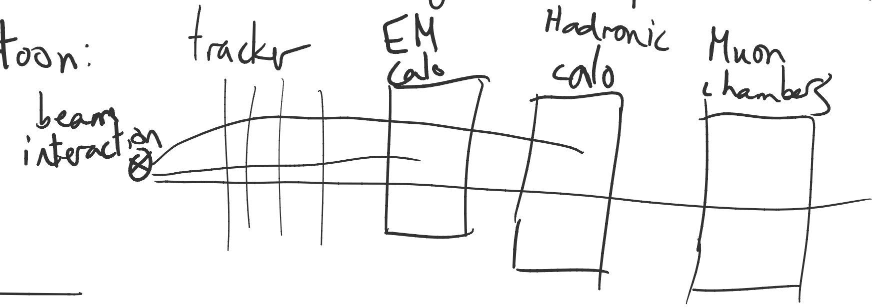
Measuring energy: Ideally, destroy/absorb particle in order to capture/stop it completely & measure energy deposition. This necessarily washes out energy deposition. This necessarily washes out directional information.

Measuring momentum: (angles + trajectories).

Ideally, charged particles are deflected by magnetic fields, or uncharged particles can have very soft interactions. By registering many soft hits, we can map out trajectory. But many soft hits cause a loss in particle energy. For high resolution momentum measurement, need to "kick" the particle at a significant fraction of its momenta.

Thus, the best detectors balance these competing principles, and most importantly, try to have as wide of a dynamic range as practical. This is also driven by the beam energies that power the entire apparatus.

Cartoon:



We'll start w/ basic decays of SM particles.

Colored (next time): u, c, t, d, s, b, g

Fragmentation + Hadronization, perform jet finding & jet algorithm.

EW bosons: W, Z

Higgs,

γ

e, μ, τ

Which are stable on collider timescales?

γ, μ, e.

γ: $\tau_\gamma \to \infty$.

e: $\tau_e \to \infty$

μ: $\tau_\mu = 2.2\,\mu s$ $\Rightarrow$ $\gamma c \tau = \gamma(2.2 \cdot 10^{-6}\,s \cdot 3 \cdot 10^{8}\,m/s)$ (decay displacement)

$= \gamma(6.6 \cdot 10^{2}\,m)$

$= \underline{660\,m \cdot \gamma}$

Recall, $\Gamma_{tot} = \tau^{-1}$

Width

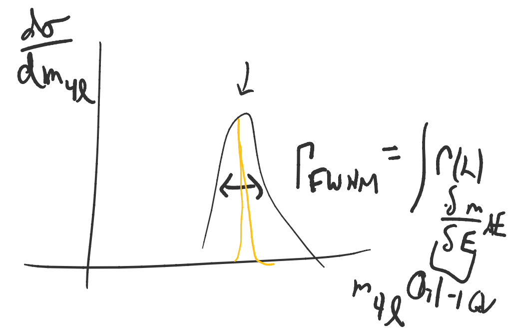
τ : $\tau = 2.903 \cdot 10^{-13}\,s$

W : $\Gamma(W) = 2.085 \pm 0.042\,\text{GeV}$

Z : $\Gamma(Z) = 2.4952 \pm 0.0023\,\text{GeV}$

h : $\Gamma(h) = 4\,\text{MeV}$ (theory)

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



For W, Z, h, & any resonance decaying at tree-level,
quick + dirty est. for $\Gamma \sim \frac{g^2}{(4\pi)} \cdot m\,(N_c)$

Inverse of Γ $\Rightarrow$ lifetime

$$\left.\begin{aligned} \tau_W &\sim 10^{-24}\,s \\ \tau_Z &\sim 10^{-24}\,s \\ \tau_h &\sim 10^{-21}\,s \end{aligned}\right] \quad \gamma c \tau \sim \gamma \cdot \begin{pmatrix} 3 \cdot 10^{-16}\,m \\ 3 \cdot 10^{-16}\,m \\ 3 \cdot 10^{-13}\,m \end{pmatrix}$$

Unless $\gamma \sim 10^{7-10}$, these decay vertices are not observable. Hence, "prompt" decays, where vertex of collision = vertex W, Z, h decay.

This is less true for b quark, & possibly c + τ.

Will discuss displaced vertices tomorrow.

… fine for … , & possibly … .
Will discuss displaced vertices tomorrow.