Lecture 6.

QFT 3: The Standard Model and EW Theory

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Tree-level processes and collider physics.

In principle, after two semesters of QFT + reviewing the tree-level SM interactions, we can calculate any number of $2 \to n$ processes, such as

$$gg \to q\bar{q}, \quad q\bar{q} \to \ell^+\ell^-, \quad q\bar{q} \to \nu\bar{\nu}, \quad q\bar{q}' \to \ell^+\bar{\nu},$$
$$q\bar{q} \to W^{+/-}W^{+/-} \quad \bar{q}\bar{q}$$

These cross sections are responsible for the leading SM interactions that occur in colliders such as the Large Hadron Collider (LHC) in CERN.

But realistically, colliders do not work on individual quarks + gluons. Examples:

LHC :	pp collider at	$\sqrt{s} = 7$ TeV, 8 TeV, 13 TeV (14 TeV)
Tevatron:	$p\bar{p}$ collider at	$\sqrt{s} = 1.8$ TeV, 1.98 TeV
LEP :	e^+e^- collider at	$\sqrt{s} = 91.2$ GeV, 205 GeV
SLC :	e^+e^- collider (w/ pol.) at	$\sqrt{s} = 91.2$ GeV
HERA:	$(e^+/e^-)p$ collider at	$\sqrt{s} = 318$ GeV
$Sp\bar{p}S$:	$p\bar{p}$ collider at	$\sqrt{s} = 630$ GeV

In general, colliders build on top of each other, so previous acceleration infrastructure is used as injection for next collider.

Should also mention B-factories, Babar + Belle, e^+e^- at $\sqrt{s} = \Upsilon_{4S}$, asymmetric.

Should be familiar that protons + anti-protons are composite objects. At $E=0$, $p = (uud)$ bound state, but at higher energies = when using probes at higher energies to interact with the proton, the proton reveals a partonic content that is much richer + dynamic. Intuitively, these parton distribution functions (PDFs) are driven by the virtual behavior of the chiral condensate + virtual gluons as a function of energy.

(You should know that the rest mass of the proton + neutron is mainly driven by the binding energy from gluons + not the consistuent quark masses.)

The main tool / experimental probe for determing PDFs is measurements from $e^- p$ scattering = HERA. Since we expect that electrons are elementary particles with no internal structure, the point-like structure of electrons can be used at different energies to map the parton content of the proton by measuring the final state of the collision. This is analogous to the Rutherford experiment which disproved the Thomson model of atoms. (Ref. Schwartz, Sec. 32.1)

We are interested in understanding how the $2 \to n$ partonic cross sections are related to the measureable cross section for proton-proton scattering, with energies E_{p1}, E_{p2}.

(Peskin 17.40)

$$\sigma(p(P_1) + p(P_2) \to Y + X)$$
$$= \int_0^1 dx_1 \int_0^1 dx_2 \sum_{f_1, f_2} f_{f_1}(x_1) f_{f_2}(x_2) \cdot \hat{\sigma}(f_1(x_1 P) + f_2(x_2 P) \to Y)$$

For comparison, the e^-p formula is

$$\sigma(e^-(k)\,p(P) \to e^-(k') + X) \quad \overset{\kappa}{\text{any hadronic state}}$$

$$= \int_0^1 d\xi \sum_f f_f(\xi)\, \hat{\sigma}(e^-(k)\,q_f(\xi P) \to e^-(k') + q_f(p'))$$

We interpret the PDF as

$$\int dx\; x\, f_j(x) = \langle x\rangle_j \;=\; \text{average fraction of momentum carried by species } j.$$

Note $\sum_j \int_0^1 dx\; x\, f_j(x) = 1$ is a sum rule req. on the PDFs.

In other words,

$$f_j(x)\,dx \;=\; \text{probability of finding constituent } f_j \text{ with (longitudinal) fraction } x.$$

So, the procedure for getting a physically measureable cross section @ LHC requires convolution integrals with PDFs.

Comments: ① Bjorken-scaling − weak + universal $\log Q^2$ (momentum transfer) for $\underline{\text{DIS}}$ cross sections, consequence of asymptotic freedom for partons & RG behavior.

② Factorization.

It is a remarkable statement that we can decompose/factorize the proton-proton cross section into individual partonic cross sections. This is essentially because we operate at $Q \gg \Lambda_{QCD}$, and so the timescale $\frac{1}{Q}$ is much shorter than $\frac{1}{\Lambda_{QCD}}$ where parton consistuents change their nature.

4. Probabilistic nature of σ. Smooths out "hard" cutoffs such as energy-momentum conservation at the partonic level.

5. Dominant PDFs.

At high Q^2, proton is dominantly gluon PDF, with the leading quark ~~to~~ content as u + d.

Terminology: u + d are <u>valence</u> quarks
$\bar{u}, \bar{d}, s, \bar{s}, c, \bar{c}, b, \bar{b}$ are <u>sea</u> quarks.

Hence, $\hat{\sigma}(gg \to Y)$ is usually dominant over $\hat{\sigma}(q\bar{q} \to Y)$, only from PDFs, as long as couplings/multiplicities are equal. (Ex. CTEQ 18, 1912.10053
NNPDF, MSTW)

We have discussed the production side of relating partonic-$\hat{\sigma}$ to pp-σ, but now we focus on the final state.

Can produce any SM particle: u, c, t, d, s, b (+ anti-quark)
g
e, μ, τ
ν
Z
W
γ

Critical to understand characteristic decay lifetimes.

Exercise: Estimate lifetimes of each decaying SM parton or, if it hadronizes, map out dominant hadronization modes.