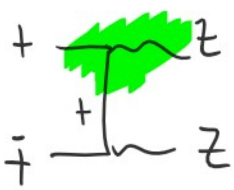
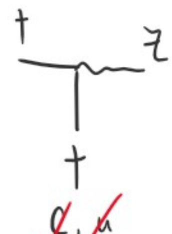
Today: Further w/ tree-level interactions
Begin collider physics
Case study: discover Higgs boson
Case study: discover BSM.

In principle, we know how to calculate a $2 \to n$ tree process in the SM.

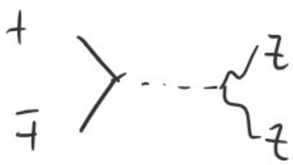
Example:

$t\bar{t} \to ZZ$





No FCNC
@ tree-level



Can calculate $\sigma(t\bar{t} \to ZZ)$.

But at the end of the day, we need to relate these $\sigma(2\to n)$ cross sections to observable cross sections that we measure at colliders.

Large Hadron collider – pp – $\sqrt{s} = 7, 8, 13\ (14)$ TeV

Z-factory ☆ Large Electron Positron collider (LEP) - e^+e^- - $\sqrt{s} = 91.2$ GeV, 205 GeV
2nd run: attempt at Higgs discovery

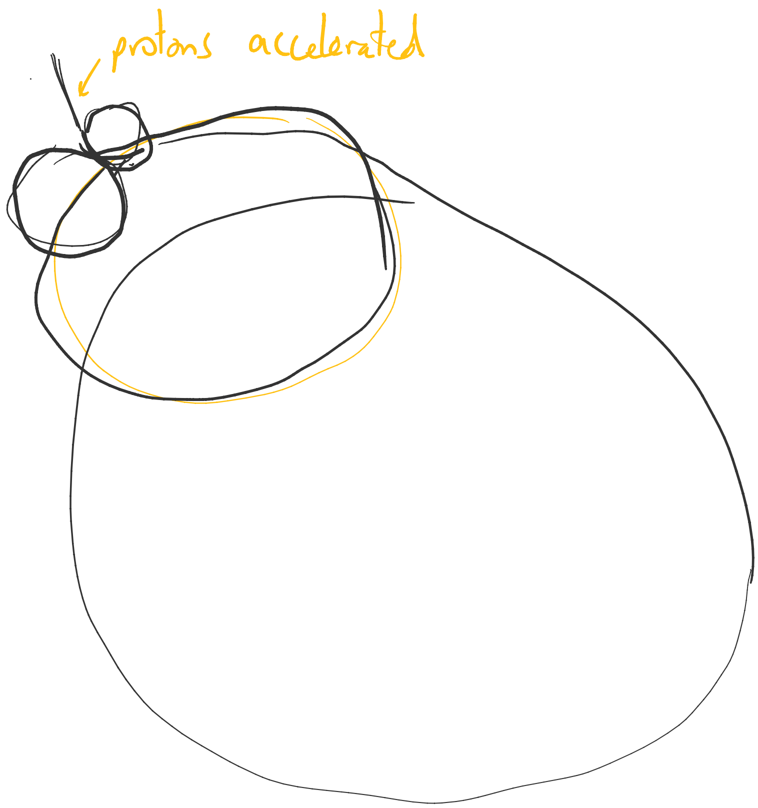
Tevatron - $p\bar{p}$ - $\sqrt{s} = 1.8$ TeV, 1.98 TeV

HERA - $e^{+/-}p$ - $\sqrt{s} = 318$ GeV

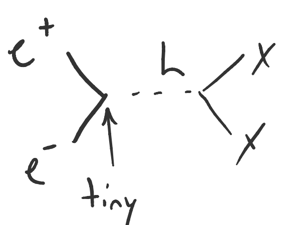
Z-factory ☆ SLC - e^+e^- (pol.) - $\sqrt{s} = 91.2$ GeV

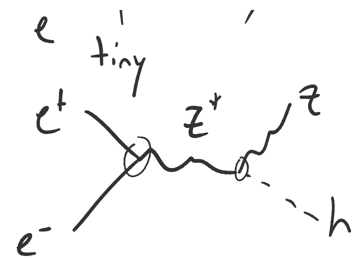
Discovered W, Z boson ☆☆ $Sp\bar{p}S$ - (at CERN) - $p\bar{p}$ - $\sqrt{s} = 630$ GeV

In general, for circular colliders, the earlier machines are reused to become accelerator + injectors for later machines.



How did LEP fail for Higgs discovery, but FCC-ee or CEPC will work, running at $\sqrt{s} = 240$ GeV?





$\sigma(e^+e^- \to Zh) = 0$ unless $\sqrt{s} > m_Z + m_h$.

Should also other colliders at lower energies, dedicated toward precision measurements of known particles.

BaBar, Belle, Belle II $\ni$ e^+e^- (asym), $\sqrt{s} = \Upsilon_{4S}$ to study b-quarks.

Difficulty in calculating cross sections of protons is that protons are <u>composite</u> objects. At $E=0$, $p = (uud)$ bound state, but as we go to higher energies = as we probe the proton structure w/ higher energy probes, we see a much richer structure involving partons besides u & d quarks.

Intuitively, the PDFs are driven by the virtual behavior of the chiral condensate & the virtual gluons as function of energy.

Determining PDFs is typically done by taking measurements from $e^\pm p$ scattering (HERA) but also LHC / Tevatron data. Since we expect electrons are elementary particles & hence point-like, then we can probe composite objects by sending in electrons at higher & higher energies. This is analogous to Rutherford scattering, which disproved Thomson model.

[illegible]

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(Ref. Schwartz, Sec. 32.1)

Break until 3:15pm

Relation between $2\to n$ cross section & pp cross section is

$$\sigma\big(p(P_1)+p(P_2)\to Y+\overset{\text{any hadronic mode}}{X}\big)$$
$$=\int_0^1 dx_1\int_0^1 dx_2 \sum_{f_1,f_2} f_{f_1}(x_1)\,f_{f_2}(x_2)\cdot \underbrace{\hat\sigma\big(f_1(x_1P_1)+f_2(x_2P_2)\to Y\big)}_{2\to n\text{ scattering}}$$

$\hat\sigma$ = partonic cross section

f_1 carries energy x_1P_1

f_2 carries energy x_2P_2

"Weight" of this partonic contribution to the total pp cross section is $f_{f_1}(x_1)\,f_{f_2}(x_2)$.

For reference,

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

We interpret the PDF as

x,ξ are typically used to denote momentum fraction

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

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

So $f_j(x)\,dx$ = "the probability of finding constituent f_j

So $f_j(x)\,dx$ = " the probability of finding constituent f_j with (longitudinal) momentum fraction x.

Key point: σ_{pp} is convolution integral of partonic cross section w/ PDFs.

Comments:

① Bjorken-scaling. Universal + weak $\log Q^2$ (referring to momentum transfer) for DIS cross sections. IOW, at high energies, PDFs can considered as asymptotically free partons, + evolve with RG logarithmically.

$\sigma(pp \to \ell^+\ell^-)$ as fcn. of Q^2;

② Factorization.

It is a remarkable statement that we can decompose/factorize a "composite" cross section into individual partonic cross sections. Intuitive justification is that we typically use $Q^2 \gg \Lambda_{QCD}^2$, and so on the timescale of $\frac{1}{Q}$, the PDFs are "frozen", since they evolve on timescales of $\frac{1}{\Lambda_{QCD}}$.

③ Probabilistic nature of σ. Smooths out "hard" cutoffs in partonic $\hat{\sigma}$, such as energy-momentum conservation.

④ Dominant PDFs.

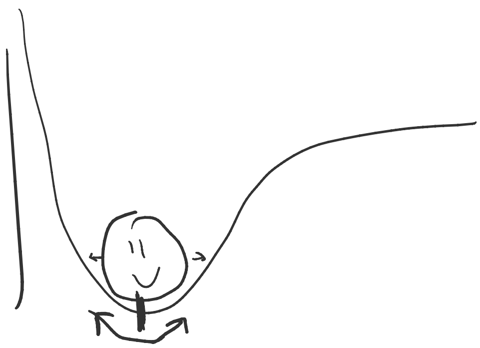
At high Q^2, proton PDFs are dominantly gluon, $\underbrace{u, d}_{\text{valence}}$ PDFs.

$\underbrace{u, d}_{\text{valence}}$ TUFS.

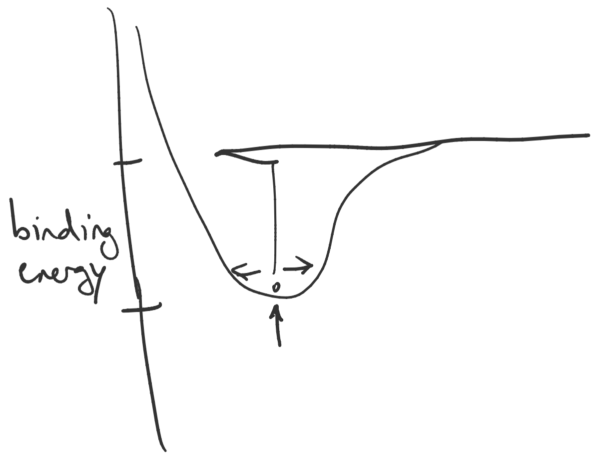
Remaining subleading are "sea" quarks: $\bar{u}, \bar{d}, s, \bar{s}, c, \bar{c}, b, \bar{b}$

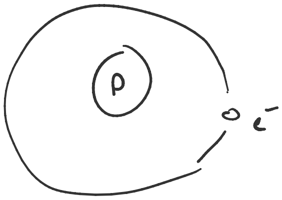
All else being equal, $\hat{\sigma}(gg \to Y)$ gives a larger contribution than $\hat{\sigma}(q\bar{q} \to Y)$.

Ref. CT18, MSTW, NNPDF



curvature of $V''(x_{min})$





$$m(H) = m_p + m_e - 13.7\,\text{eV}$$

$$\underbrace{m_p} = \underbrace{2m_u + m_d}_{\text{lattice}} + \underbrace{X}_{\text{how}}$$

By now, we have the machinery to deal with production side of $\sigma(pp \to Y)$, but now focus on final state.

Selection of what Y can be:

u, d, s, c, b, t
g
e, μ, τ
ν
Z
W

γ

h.

Exercise: understanding decay / hadronization of SM particles.