Introduction to QCD
and the physics of the LHC (lect 3)

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Michelangelo L. Mangano
TH Unit, Physics Dept, CERN
michelangelo.mangano@cern.ch
Evolution of hadronic final states

Asymptotic freedom implies that at $E_{\text{CM}} \gg 1$ GeV

\[ \sigma(e^+ e^- \rightarrow \text{hadrons}) \quad \leftrightarrow \quad \sigma(e^+ e^- \rightarrow \text{quarks/gluons}) \]

At the Leading Order (LO) in PT:

\[
\begin{align*}
\sigma_0(e^+ e^- \rightarrow q\bar{q}) &= \frac{4\pi \alpha^2}{9s} N_c \sum_{f=u,d,\ldots} e_{q_f}^2 \\
\frac{\sigma_0(e^+ e^- \rightarrow q\bar{q})}{\sigma_0(e^+ e^- \rightarrow \mu^+\mu^-)} &= N_c \sum_{f=u,d,\ldots} e_{q_f}^2 \\
\frac{\sigma_0(e^+ e^- \rightarrow Z \rightarrow q\bar{q})}{\sigma_0(e^+ e^- \rightarrow Z \rightarrow \mu^+\mu^-)} &= N_c \frac{\sum_{f=u,d,\ldots} (v_{q_f}^2 + a_{q_f}^2)}{(v_{\mu}^2 + a_{\mu}^2)}
\end{align*}
\]
Adding higher-order perturbative terms:

\[ \sigma_1(e^+ e^- \rightarrow q\bar{q}(g)) = \sigma_0(e^+ e^- \rightarrow q\bar{q}) \left( 1 + \frac{\alpha_s(E_{CM})}{\pi} + O(\alpha_s^2) \right) \]

+ \geq 2-gluon emissions

\[ O(3\%) \text{ at } M_Z \]

Excellent agreement with data, **provided** \( N_c=3 \)

Extraction of \( \alpha_s \) consistent with the \( Q \) evolution predicted by QCD
Experimentally, the final states contain a large number of particles, not the 2 or 3 which apparently saturate the perturbative cross-section.

$$\langle n_{\text{charged}} \rangle = 20.9$$

Isn't this bizarre?
Look more closely at the structure of these events:

\[ e^+ e^- \rightarrow qq \quad \Rightarrow \quad e^+ e^- \rightarrow 2 \text{ jets} \]

\[ e^+ e^- \rightarrow qqg \quad \Rightarrow \quad e^+ e^- \rightarrow 3 \text{ jets} \]

The puzzle is solved by associating partons to collimated “jets” of hadrons
Jets in hadronic collisions
• Inclusive production of jets is the largest component of high-$Q$ phenomena in hadronic collisions
• QCD predictions are known up to NLO accuracy
• Intrinsic theoretical uncertainty (at NLO) is approximately 10%
• Uncertainty due to knowledge of parton densities varies from 5-10\% (at low transverse momentum, $p_T$) to 100\% (at very high $p_T$ corresponding to high-x gluons)
• Jet are used as probes of the quark structure (possible substructure implies departures from point-like behaviour of cross-section), or as probes of new particles (peaks in the invariant mass distribution of jet pairs)
Phase space and cross-section for LO jet production

\[ d[PS] = \frac{d^3p_1}{(2\pi)^2 p_1^0} \frac{d^3p_2}{(2\pi)^2 p_2^0} (2\pi)^4 \delta^4(P_{in} - P_{out}) \, dx_1 \, dx_2 \]

(a) \[ \delta(E_{in} - E_{out}) \delta(P_{in}^z - P_{out}^z) \, dx_1 \, dx_2 = \frac{1}{2E_{beam}^2} \]

(b) \[ \frac{dp^z}{p^0} = dy \equiv d\eta \]

The measurement of \( p_T \) and rapidities for a dijet final state uniquely determines the parton momenta \( x_1 \) and \( x_2 \). Knowledge of the partonic cross-section allows therefore the determination of partonic densities \( f(x) \).
Quark/gluon composition

Fractional Contribution to $d\sigma/dE_T$ at $\eta=0$

**Tevatron**
The presence of a quark substructure would manifest itself via contact interactions (as in Fermi’s theory of weak interactions). On one side these new interactions would lead to an increase in cross-section, on the other they would affect the jets’ angular distributions. In the dijet CMF, QCD implies Rutherford law, and extra point-like interactions can then be isolated using a fit. With the anticipated statistics of 300 fb$^{-1}$, limits on the scale of the new interactions in excess of 40 TeV should be reached (to increase to 60 TeV with 3000 fb$^{-1}$).
Some more kinematics

Prove as an exercise that

\[ x_{1,2} = \frac{p_T}{E_{\text{beam}}} \cosh y^* \ e^{\pm y_b} \]

where

\[ y^* = \frac{\eta_1 - \eta_2}{2}, \quad y_b = \frac{\eta_1 + \eta_2}{2} \]

We can therefore reach large values of x either by selecting large invariant mass events:

\[ \frac{p_T}{E_{\text{beam}}} \cosh y^* \equiv \sqrt{\tau} \to 1 \]

or by selecting low-mass events, but with large boosts \((y_b \ \text{large})\) in either positive or negative directions. In this case, we probe large-x with events where possible new physics is absent, thus setting consistent constraints on the behaviour of the cross-section in the high-mass region, which could hide new phenomena.
Example, at the Tevatron

DO jet data, and PDF fits

CDF data, using fits from high-\(\eta\) region
Tevatron,
Run 2 results
Detecting the Higgs boson

Like any other medium, the Higgs continuum background can be perturbed. Similarly to what happens if we bang on a table, creating sound waves, if we “bang” on the Higgs background (something achieved by concentrating a lot of energy in a small volume) we can stimulate “Higgs waves”. These waves manifest themselves as particles*, the so-called Higgs bosons.

What is required is that the energy available be larger than the Higgs mass ⇒ LHC !!!

* Even the sound waves in a solid are sometimes identified with “quasi-particles”, called “phonons”
Higgs interactions

\[ \propto m_{W,Z} \]

\[ \propto m_f \]

\[ \propto m_H \]
Four main production mechanisms at the LHC:

Gluon-gluon fusion (NNLO):
- Largest rate for all m(H).
- Proportional to the top Yukawa coupling, $y_t$
- $gg$ initial state

Vector-boson (W or Z) fusion (NLO):
- Second largest, and increasing rate at large m(H).
- Proportional to the Higgs EW charge
- mostly $udd$ initial state

W(Z)-strahlung (NNLO):
- Same couplings as in VB fusion
- Different partonic luminosity (uniquely qqbar initial state)

$ttH/bbH$ associate production (NLO):
- Proportional to the heavy quark Yukawa coupling, $y_Q$
- dominated by $ttH$, except in 2-Higgs models, such as SUSY, where $b$-coupling enhanced by the ratio of the two Higgs expectations values, $\tan\beta^2$
- Same partonic luminosity as in gg-fusion, except for different $x$-range
Higgs production rates at the LHC

\[ \sigma(pp \rightarrow H+X) \]
\[ \sqrt{s} = 14 \text{ TeV} \]
\[ m_t = 175 \text{ GeV} \]
CTEQ4M

\[ \sigma (\text{pb}) \]

Events for \(10^5 \text{ pb}^{-1}\)

M. Spira et al.
NLO QCD
Higgs decays

\[ \propto m_f^2 \] (evaluated at \( m_H \), including QCD running effects)

\[ \propto m_f^2 \] (dominated by top-quark loops)

\[ \propto \alpha_W \] (sharp threshold at \( m_H = 2m_W \), but large BR even down to 130 GeV). Similar processes with \( W \leftrightarrow Z \).

Dominated by the EW couplings, only minor contribution from top loop \( m \Rightarrow \) correlated to \( H \rightarrow WW \).
Higgs decays

Not all decay modes are accessible at a given mass. Very high luminosity is required to thoroughly investigate the Higgs couplings.
How can we detect the Higgs?

**Example:** If $m(H) > 2m(Z) \Rightarrow H \rightarrow ZZ$

Each $Z$ will decay. Assume for example $Z \rightarrow \mu^+ \mu^-$

Search for events with 4 muons $(\mu^+_1 \mu^-_2 \mu^+_3 \mu^-_4)$ subject to the condition that:

$$m(\mu^+_1 \mu^-_2) = m(\mu^+_3 \mu^-_4) = m(Z)$$

The invariant mass of the 4-muon system will then give $m(H)$

A computer simulation of how the signal will appear, for $m_H = 200$ GeV
Summary of SM Higgs discovery potential

Within 2-3 yrs from startup we should have an answer