Physics 3:
Particle Physics
Lecture 6
The Strong Force: Quantum Chromodynamics
February 28th 2008

- QCD
- Colour quantum number
- Gluons
- QCD interactions
- Colour confinement
- Hadronisation & Jets
- The cross section ratio $R$

Quantum Chromodynamics (QCD)

- QCD is the quantum description of the strong force.

<table>
<thead>
<tr>
<th>QED</th>
<th>QCD</th>
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</thead>
<tbody>
<tr>
<td>quantum theory of the electromagnetic interactions</td>
<td>quantum theory of the strong interactions</td>
</tr>
<tr>
<td>mediated by the exchange of virtual photons</td>
<td>mediated by the exchange of gluons</td>
</tr>
<tr>
<td>acts on all charged particles</td>
<td>acts on quarks only</td>
</tr>
<tr>
<td>couples to electrical charge</td>
<td>couples to colour charge</td>
</tr>
<tr>
<td>coupling strength $\propto e \propto \sqrt{\alpha}$</td>
<td>coupling strength $\propto g_s \propto \sqrt{\alpha_s}$</td>
</tr>
</tbody>
</table>

QED

$\gamma \rightarrow q \rightarrow q'$

$\alpha = e^2/4\pi \sim 1/137$

QCD

$g \rightarrow q \rightarrow q'$

$\alpha_s = g_s^2/4\pi \sim 1$
Colour

- Colour charge is the charge associated with QCD interactions.
  - Three colours: red, blue, green.
- Like electric charge, it is a conserved quantum number.
- Quarks always have a colour charge: \( r \), \( g \) or \( b \)
- Anti-quarks always have an anti-colour charge: \( \bar{r} \), \( \bar{b} \) or \( \bar{g} \)
- Leptons and bosons for other forces (\( \gamma, W, Z \)) don’t carry colour charge.
- Mesons are colour neutral; colour charges are: \( (r\bar{r}) \), \( (b\bar{b}) \) or \( (g\bar{g}) \)
- Baryons are colour neutral; colour charges are: \( (r\ g\ b) \)

Gluons

- Gluons are massless, spin-1\( h \) bosons.
- They propagate the strong force: exchange momentum between quarks.
- We draw gluons as curly-wurly lines:
  
- Gluons also carry colour charge.
- Colour charged is always conserved.
- Number of gluons: there are eight different gluons.
- Symmetry of the strong interaction tell us these are:
  
One big difference between QED and QCD
  - QED propagated by photons: photons no electric charge
  - QCD propagated by gluons: gluons do have colour charge
**Quark & Gluon Interactions**

Quark-anti-quark scattering

\[
V_{QED}(r) = -\frac{q_2 q_1}{4\pi\epsilon_0 r} = -\frac{\alpha}{r}
\]

Short distance potential:

\[
V_{QCD}(r) = -\frac{4}{3}\frac{\alpha_s}{r} + kr
\]

**Short distance potential:**

\[
\frac{dV}{dr} = \frac{4}{3}\alpha_s r^2 + k
\]

**Total potential:**

\[
V_{QCD}(r) = -\frac{4}{3}\frac{\alpha_s}{r} + kr
\]

**Force required to separate quarks:**

\[
F_{QCD} = \frac{dV}{dr} = \frac{4}{3}\alpha_s r^2 + k
\]

At large distances \( F \approx k \approx 100 \text{ GeV/fm} = 160,000 \text{ N} \)

- Gluons carry colour charge.
- They also feel the strong force \( \rightarrow \) **gluons can interact with other gluons**!

3-gluon vertex

4-gluon vertex

Baryons are really a mix of quarks & gluons

**Colour Confinement**

Experimentally we do not see free quarks: quarks are confined within hadrons

- Gluons attract each other: they self interact
- Gluon-gluon interaction pulls the colour field lines into a narrow tube.
- Potential increases linearly with distance: \( V(r) = kr \)
- Infinite energy is required to separate two quarks.

**COLOUR CONFINEMENT**

Colour confinement is a direct consequence of gluon self-interactions

\[
V_{QCD}(r) = -\frac{4}{3}\frac{\alpha_s}{r} + kr
\]

**Force** required to separate quarks:

\[
F_{QCD} = \frac{dV}{dr} = \frac{4}{3}\alpha_s r^2 + k
\]

At large distances \( F \approx k \approx 100 \text{ GeV/fm} = 160,000 \text{ N} \)
Hadronisation

- What happens when we try to pull apart two quarks?
- At LEP main interactions was $e^+e^- \rightarrow Z \rightarrow q\bar{q}$.
  - $q\bar{q}$ produced at same point in space.
  - $q$ and $\bar{q}$ have very large momentum $\Rightarrow$ they fly apart.

- The energy between the $q\bar{q}$ increases as they move apart $E \approx V(r) = kr$

- When $E > 2m_qc^2$...

- As the kinetic energy decreases ... the hadrons freeze out

- This process is known as hadronisation.

Jets

- A collision produces energetic quarks, which hadronise.
  - The produced hadrons decay... (into more hadrons and maybe leptons)
  - In the detector this appears as a collimated “jet” of particles.

Event from LEP collider
$E_{CM} = 91$ GeV
$e^+e^- \rightarrow q\bar{q}$

2 jets in detector
QED Coupling Constant

- Strength of interaction between electron and photon.
- However, $\alpha$ is not really a constant.
- An electron is never alone:
  - it emits virtual photons, these can convert to electron-positron pairs.
- Any test charge will feel the $e^+e^-$ pairs: true charge of the electron is screened.
- At higher energy (shorter distances) the test charge can see the “bare” charge of the electron.

QCD Coupling Constant

- In QCD the interaction strength is $\alpha_S$ - also not really a constant.
- Quark emit gluons: which can form virtual quark - anti-quark pairs.
- However the gluons themselves also carry colour charge, which effects the screening.
- $\alpha_S$ decreases at high energies! $\Rightarrow \alpha_S$ increases at large distances!
- At low energies the coupling constant becomes large, $\alpha_S \approx 1$. We cannot use perturbation theory to calculate cross sections!
- The understanding of this phenomena won the Nobel prize in 2004.
Evidence for Gluons

- $\alpha_s$ is large at high energy (high $q^2$) quarks are very likely to emit a gluon.
- High energy gluons also hadronise, and also form jets.

3 jets event: $e^+e^-\rightarrow q\bar{q}g$

Event from LEP collider at CERN $E_{CM} = 91$ GeV

Event from PETRA collider at DESY $E_{CM} = 35$ GeV

Evidence for three Colours: the ratio $R$

Consider the ratio, $R$, we calculated on problem sheet 2:

$$R(E_{CM}) = \frac{\sigma(e^+e^- \rightarrow q\bar{q})}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)} = \frac{\sigma(e^+e^- \rightarrow \text{hadrons})}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)}$$

- Write the charge of the quarks as $Q_q e$, where $Q_q = -\frac{1}{3}$ or $+\frac{1}{3}$

For one type of quark, $R = \frac{Q_q^2 e^4}{e^4/\bar{Q}^4} = Q_q^2$

If there is enough energy, can produce > 1 type of quark: $R = \sum_q Q_q^2$

- e.g. at $E_{CM} = 5$ GeV we can produce u, d, s and c quarks.

$$R(E_{CM} = 5 \text{ GeV}) = \left(\frac{1}{3}\right)^2 + \left(\frac{2}{3}\right)^2 + \left(\frac{1}{3}\right)^2 + \left(\frac{2}{3}\right)^2 = \frac{10}{9}$$
The Ratio $R$

- Observed values of $R$ three times larger $\sim 3 \sum_q Q_q^2$
- Photon couples equally to the three different colours of quark, each diagram has $\mathcal{M} = Q_q e^2/q^2$

\[
e^+ \gamma u_g \to e^+ \gamma u_r \to e^+ \gamma \gamma \to e^+ \gamma \bar{u}_b \gamma \bar{u}_b
\]

Resonances in $R$

At certain values of $E_{CM}$, there is a large spike in $\sigma(e^+e^-\to\text{hadrons})$. This is due to production of:
- $c\bar{c}$ bound states at $E_{CM} \approx 2m_c$
- $b\bar{b}$ bound states at $E_{CM} \approx 2m_b$

These states have a relatively long lifetime, compared to other hadrons. e.g. $\tau(J/\psi) = 7.6 \times 10^{-21}$ s
- Width, $\Gamma = \hbar/\tau$ is narrow.

EM decay also has a chance
$\Gamma(J/\psi \to \mu^+\mu^-) \propto \alpha^2$

Strong decay requires exchange of three gluons:
$\Gamma(J/\psi \to \text{hadrons}) \propto \alpha s^6$
**R Summary**

\[
R(E_{CM}) = \frac{\sigma(e^+e^- \rightarrow \text{hadrons})}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)} = 3 \sum_q Q_q^2 \quad \text{for } 2 < E_{CM}/\text{GeV} < 30
\]

- Need **three colours** of quarks to explain observed ratio.
- Jumps at \(E_{CM} \approx 2m_e\) and \(E_{CM} \approx 2m_h\) when we can start to produce extra quark flavour.
- Narrow resonances due production of \(q\bar{q}\) bound states at \(E_{CM} \approx 2m_h\) threshold.
- For peak at \(E_{CM}\) around 90 GeV … see lecture on weak force.

**QCD Summary**

**QCD:** Quantum Chromodynamics is the quantum description of the strong force.

*Only quarks feel the strong force.*

- Electromagnetic coupling constant \(\alpha\) **decreases** as a charged particles get further apart.
- Strong coupling constant \(\alpha_s\) **increases** as further apart quarks become.

**Gluons are the propagator of the strong force**

**Quarks and gluons carry colour charge.**

Colour charge is conserved.

Gluons self-interact:

- Quarks and gluons produced in collisions hadronise: hadrons are produced.
- The decay products of the hadrons appear in the detector as jets.