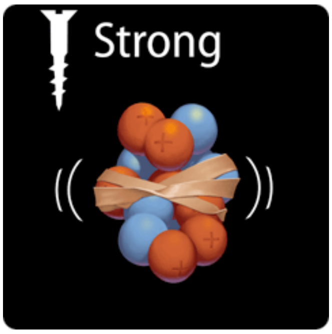
Subatomic Physics:

Particle Physics Handout 7

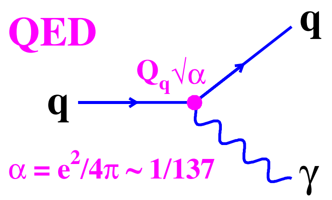
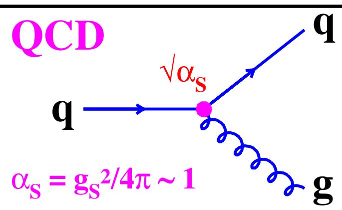
The Strong Force: Quantum Chromodynamics



- QCD
- Colour quantum number
- Gluons
- The parton model
- Colour confinement, hadronisation & jets

Quantum Chromodynamics (QCD)

- QCD is the quantum description of the strong force.

QED	QCD
quantum theory of the electromagnetic interactions	quantum theory of the strong interactions
mediated by the exchange of virtual photons	mediated by the exchange of gluons
acts on all charged particles	acts on quarks only
couples to electrical charge	couples to colour charge
coupling strength $\propto e \propto \sqrt{\alpha}$	coupling strength $\propto g_S \propto \sqrt{\alpha_S}$
	

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 (γ, 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)
  - Anti-baryons have: ($\bar{r}\,\bar{g}\,\bar{b}$)

Formally different colours of quarks are different fundamental particles.
1st generation is: e^- ν_e u_r u_b u_g d_r d_b d_g

Gluons

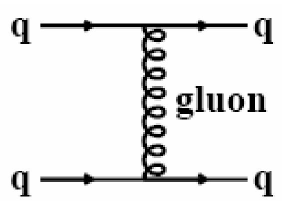
- Gluons are massless, spin-1$\hbar$ bosons.
- They propagate the strong force: exchange momentum between quarks.

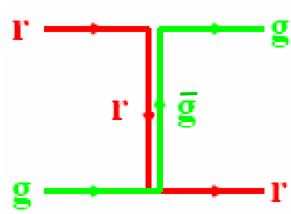
- We draw gluons as curly-wurly lines: 

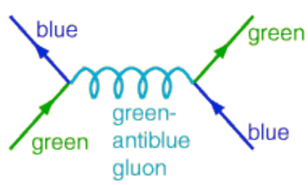
- Gluons also carry colour charge.
- Colour charged is always conserved.

- Number of gluons: there are eight different gluons.
- Symmetry of the strong interaction tell us these are:

$r\bar{b}$ $r\bar{g}$ $b\bar{g}$ $b\bar{r}$ $g\bar{r}$ $g\bar{b}$ $(r\bar{r} - g\bar{g})/\sqrt{2}$ $(r\bar{r} + g\bar{g} - 2b\bar{b})/\sqrt{6}$







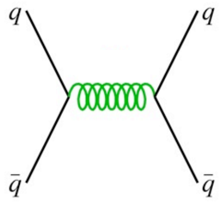
One big difference between QED and QCD

➡ QED propagated by photons: photons no electric charge

➡ QCD propagated by gluons: gluons **have colour charge**

Quark & Gluon Interactions

Quark-anti-quark scattering



$$V_{\rm QED}(r) = -\frac{q_2\, q_1}{4\pi\epsilon_0 r} = -\frac{\alpha}{r}$$

describes a meson: e.g. $\pi^- = \; d\bar{u}$

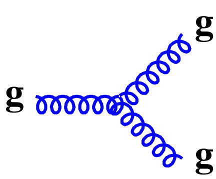
Short distance potential:

$$V_{\rm QCD}(r) = -\frac{4}{3}\frac{\alpha_s}{r}$$

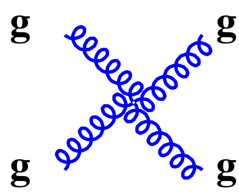
strong force is responsible for holding meson together.

- Gluons carry colour charge.
- They also feel the strong force ➔ **gluons can interact with other gluons!**

3-gluon vertex



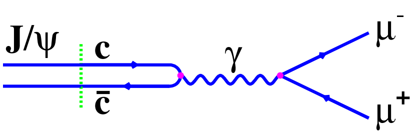
4-gluon vertex



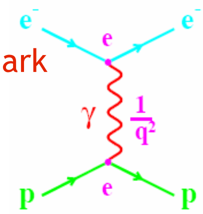
The Parton Model

- The parton model proposes that, in high energy interactions, hadrons interact as if they were made of their constituent parts. *e.g.*:

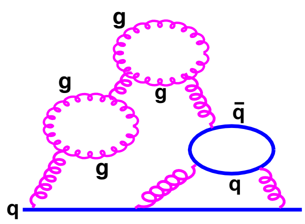
- (Problem sheet 2, Q3) $J/\psi \to \mu^+\mu^-$ decay

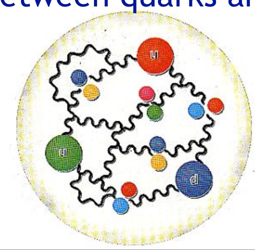


- (Handout 4, p11) $ep \to ep$ scattering.
  Proton interacts as if it were three independent quarks.
  Electron scatters off one quark



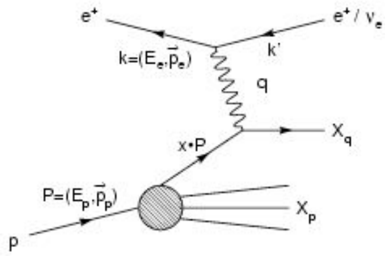
- At higher energies, proton consist of more than three quarks: quarks are constantly exchanging gluons. Gluons can convert into quark–anti-quark pairs.
  - Proton consists of three "**valance quarks**" plus **gluons** and "**sea quarks**".
  - The sea quarks are exactly balanced between quarks and anti-quarks.
  - Net quark content of proton is **u, u, d**.



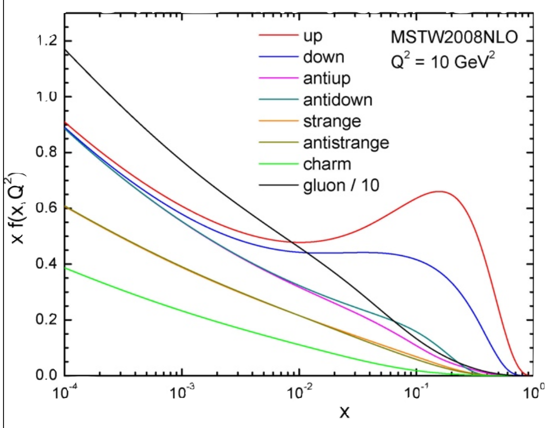


Parton Distributions in the Proton

- Positron-proton scattering measurements (at HERA accelerator) have measured the valance and sea quarks and gluon in the proton.
- Key parameter is "Feynman x": $x = \frac{|\vec{p}_{\text{parton}}|}{|\vec{p}_{\text{proton}}|}$



- Graph shows measured fraction, f, of each parton (**u-, d-, s-, c-**quarks & gluons) as a function of x.



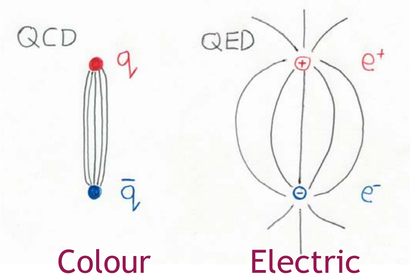
- f also depends on momentum, $Q^2 = -(\underline{q})^2$ transferred by the boson (γ).
  - ➡ The higher the Q^2, the more energetic the partons.
  - ➡ At LHC energies, proton contain lots of gluons!
- LHC collisions will be a mixture of: quark-quark, quark-gluon, gluon-gluon, anti-quark–quark, anti-quark–gluon etc.
- One challenge: for each individual collision we do not know the **flavour** or **momentum** of the interacting partons!

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 field lines

Electric field lines

Colour confinement is a direct consequence of gluon self-interactions

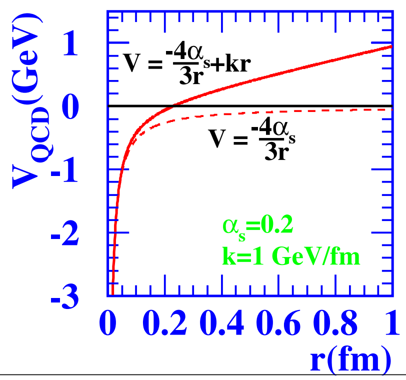
Total potential:

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

Force required to separate quarks:

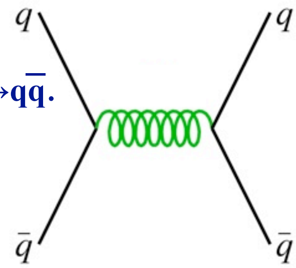
$$F_{\text{QCD}} = -\frac{dV}{dr} = \frac{4}{3}\frac{\alpha_s}{r^2} + k$$

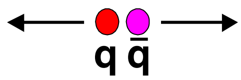
At large distances $F \approx k \approx 100$ GeV/fm = 160,000 N !!!



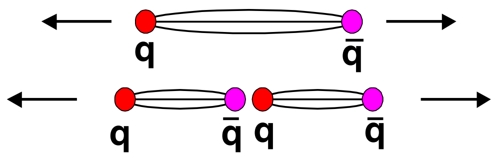
Hadronisation

- What happens when we try to pull apart two quarks?
- At LHC production of energetic quarks is common e.g. $q\bar{q} \rightarrow g \rightarrow q\bar{q}$.
  - $q\bar{q}$ produced at same point in space.
  - q and $\bar{q}$ have very large momentum ➔ they fly apart.

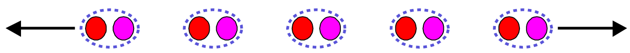




- The energy between the $q\bar{q}$ increases as they move apart $E \approx V(r) \approx kr$
- When $E > 2\, m_q c^2$...



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

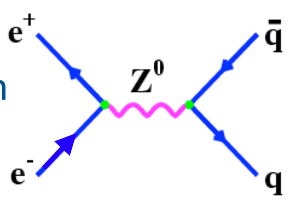


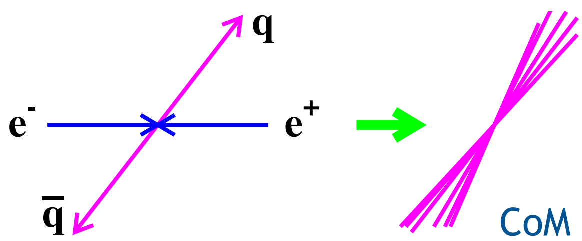
- This process is known as **hadronisation.**

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.

Feynman Diagram

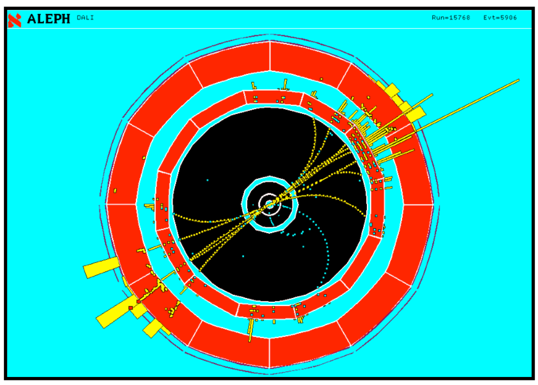




CoM Frame

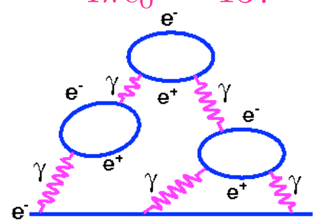
Event from LEP collider
$E_{CM} = 91$ GeV
$e^+e^- \rightarrow q\bar{q}$

2 jets in detector

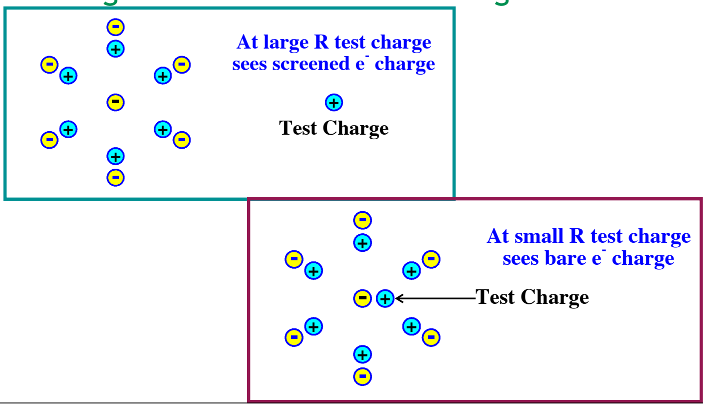


Review: QED Coupling Constant

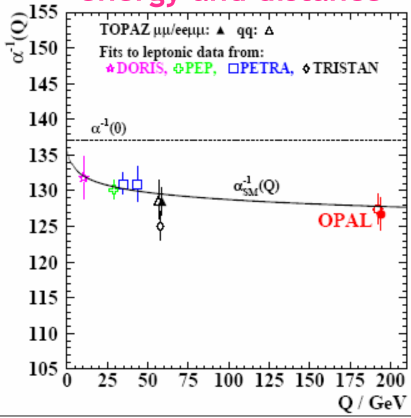
- Strength of interaction between electron and photon $\propto \alpha = \dfrac{e^2}{4\pi\epsilon_0} \approx \dfrac{1}{137}$
- However, α is not really a constant...
- An electron is never alone:
  - it emits virtual photons, these can convert to electron positron pairs...



- 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.

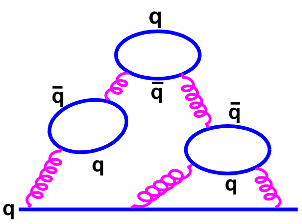


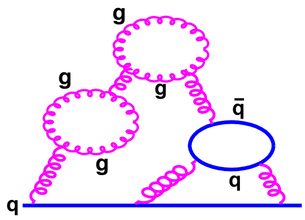
α varies as a function of energy and distance

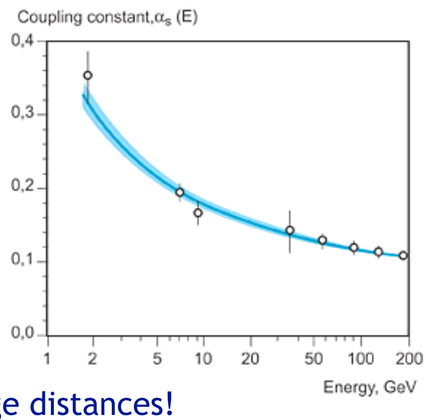


QCD Coupling Constant

- In QCD the interaction strength is α_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.





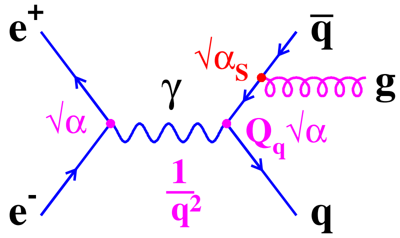


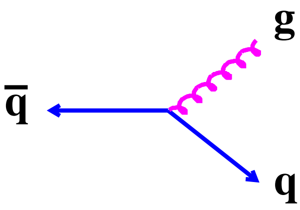
- α_S decreases at high energies! ⇔ α_S increases at large distances!
- At low energies the coupling constant becomes large, $\alpha_S \sim 1$. We cannot use perturbation theory to calculate cross sections!
- The understanding of this phenomena won the Nobel prize in 2004.

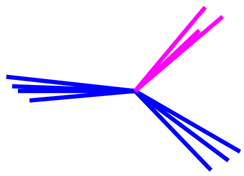
Evidence for Gluons

- α_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.

Feynman Diagram

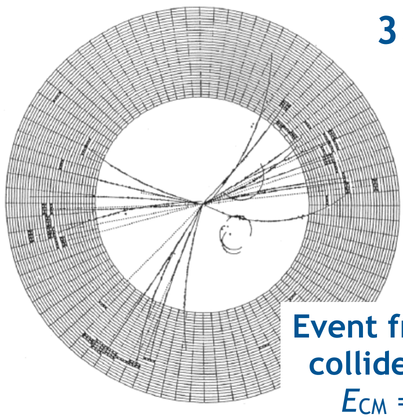






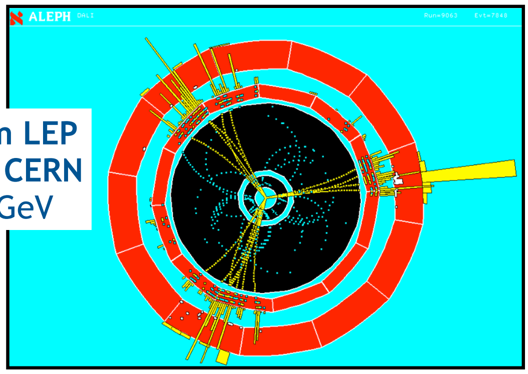
CoM Frame

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



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

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

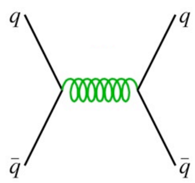


QCD Summary

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

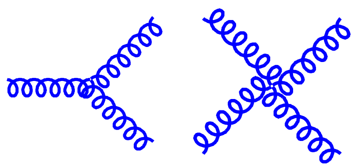
Only quarks feel the strong force.

Gluons are the propagator of the strong force



Quarks and gluons carry **colour charge.**

Gluons self-interact:



- Electromagnetic coupling constant α **decreases** as a charged particles get further apart.
- Strong coupling constant α_S **increases** as further apart quarks become.

Hadrons can be described as consisting of **partons**: quarks and gluons, which interact independently

Colour Confinement
energy required to separate quarks $\to \infty$
quarks are confined to hadrons

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

Notes

Notes