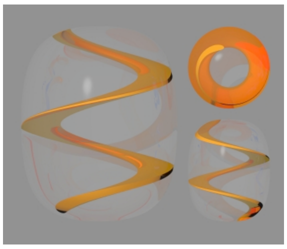
Physics 3:

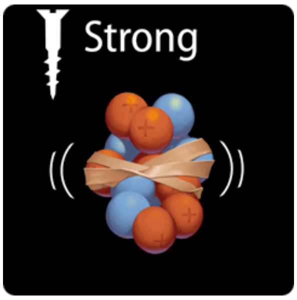
Particle Physics

Lecture 6

The Strong Force: Quantum Chromodynamics

February 28th 2008

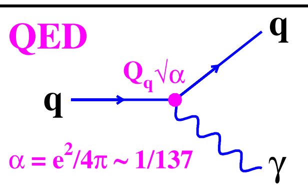
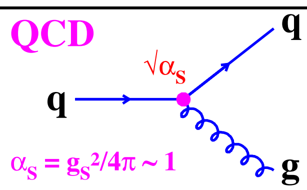




- QCD
- Colour quantum number
- Gluons
- QCD interactions
- Colour confinement
- Hadronisation & Jets
- The cross section ratio ***R***

Quantum Chromodynamics (QCD)

- QCD is the quantum description of the strong force.

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.

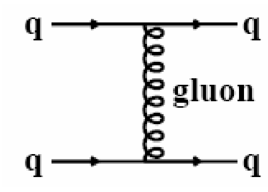
- Quarks always have a colour charge: r , g or b
- Anti-quarks always have an anti-colour charge: $\bar{r}$, $\bar{b}$ or $\bar{g}$

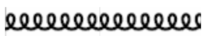
- Leptons and bosons for other forces (γ, W, Z) don't carry colour charge.

- Mesons are colour neutral; colour charges are: $(r\bar{r})$, $(b\bar{b})$ or $(g\bar{g})$
- Baryons are colour neutral; colour charges are: $(r\,g\,b)$

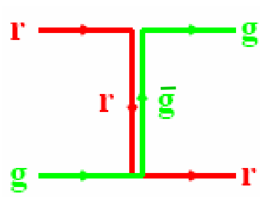
Gluons

- 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.



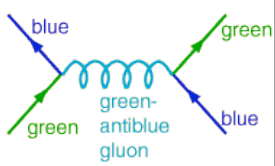
- Number of gluons: there are eight different gluons.
- Symmetry of the strong interaction tell us these are:

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

One big difference between QED and QCD

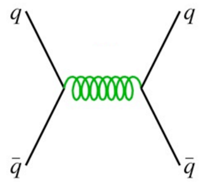
➡ QED propagated by photons: photons no electric charge

➡ QCD propagated by gluons: gluons do have colour charge



Quark & Gluon Interactions

Quark-anti-quark scattering



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

strong force is responsible for holding meson together.

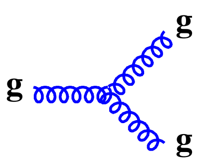
$$V_{\rm QED}(r) = -\frac{q_2\, q_1}{4\pi\epsilon_0 r} = -\frac{\alpha}{r}$$

Short distance potential:

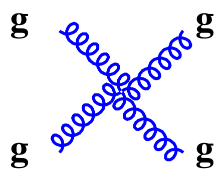
$$V_{\rm QCD}(r) = -\frac{4}{3}\frac{\alpha_s}{r}$$

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

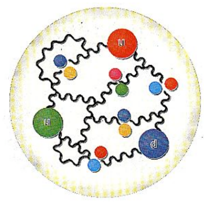
3-gluon vertex



4-gluon vertex



Baryons are really a mix of quarks & gluons

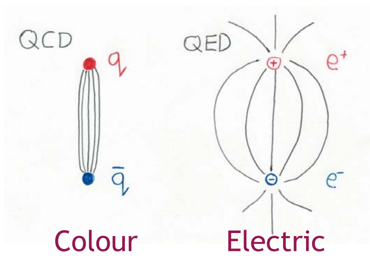


Colour Confinement

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 field lines

Electric field lines

Colour confinement is a direct consequence of gluon self-interactions

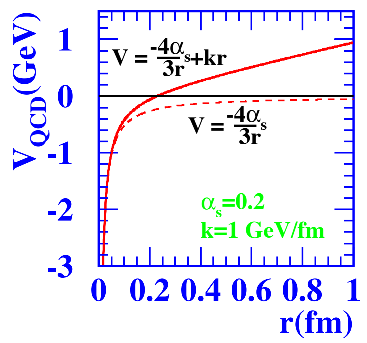
Total potential:

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

Force required to separate quarks:

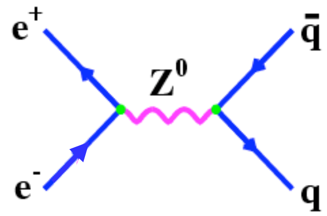
$$F_{\rm QCD} = -\frac{dV}{dr} = \frac{4}{3}\frac{\alpha_s}{r^2} + k$$

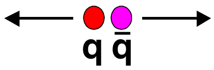
At large distances $F \approx k \approx 100$ GeV/fm = 160,000 N !!!



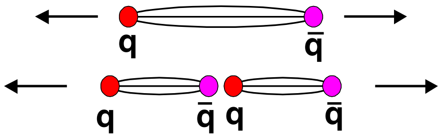
Hadronisation

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

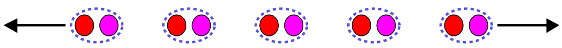




- The energy between the $q\bar{q}$ increases as they move apart $E \approx V(r) \approx kr$
- When $E > 2\,m_q c^2$...



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

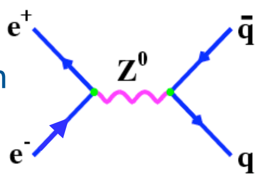


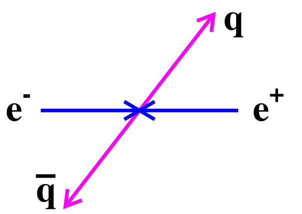
- This process is known as **hadronisation**.

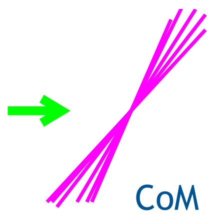
Jets

- 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



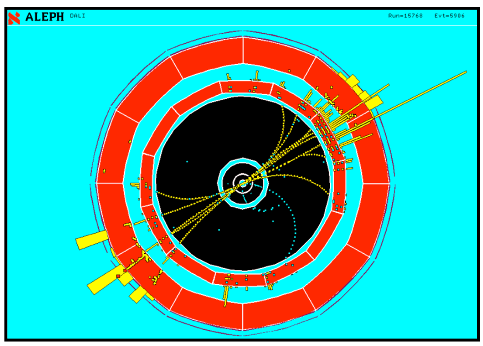




CoM Frame

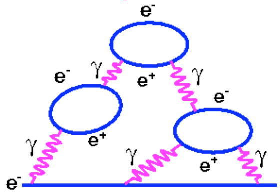
Event from LEP collider
$E_{CM} = 91$ GeV
$e^+e^- \to q\bar{q}$

2 jets in detector

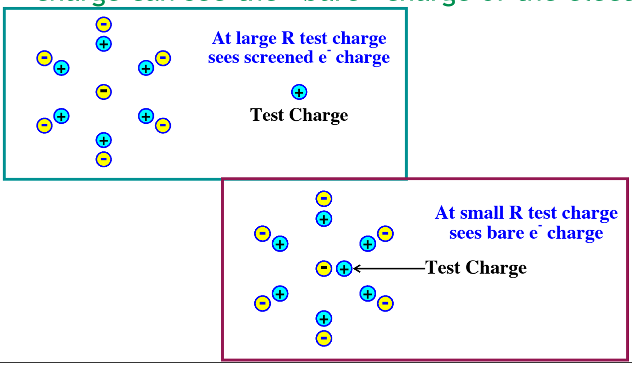


QED Coupling Constant

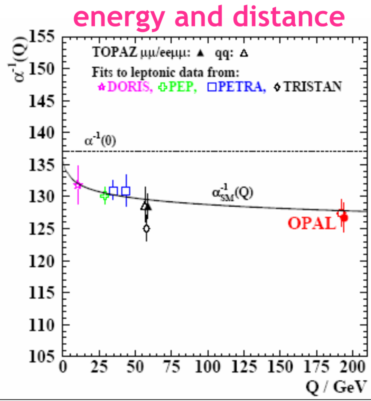
- Strength of interaction between electron and photon $\propto \alpha = \frac{e^2}{4\pi\epsilon_0} \approx \frac{1}{137}$
- However, *α* is not really a constant...
- An electron is never alone:
  - it emits virtual photons, these can convert to electron positron pairs...



- 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.

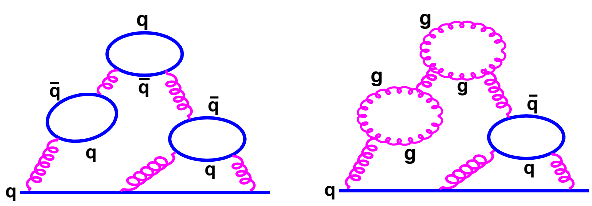


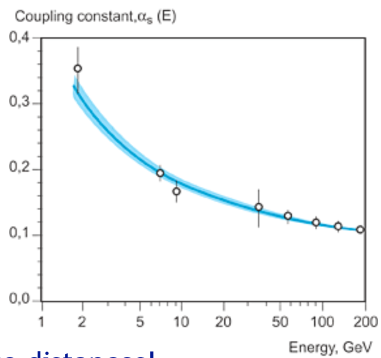
α varies as a function of energy and distance



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.



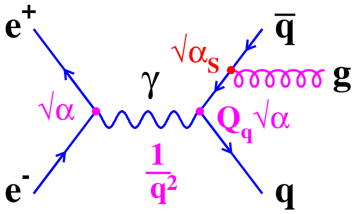


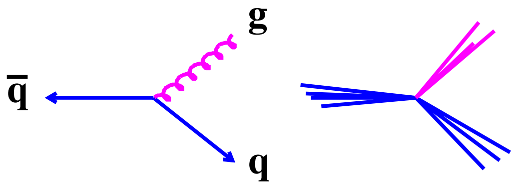
- α_S decreases at high energies! ⇔ α_S increases at large distances!
- At low energies the coupling constant becomes large, $\alpha_S \sim 1$. We cannot use perturbation theory to calculate cross sections!
- The understanding of this phenomena won the Nobel prize in 2004.

Evidence for Gluons

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

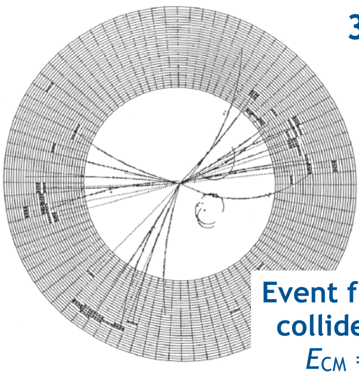
Feynman Diagram





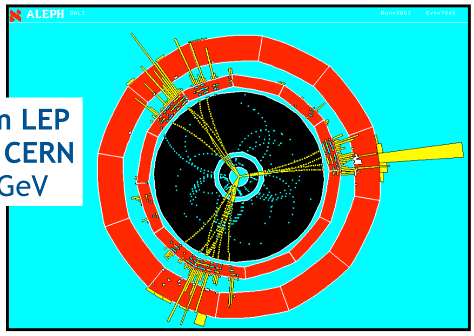
CoM Frame

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

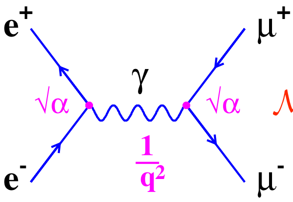


Evidence for three Colours: the ratio *R*

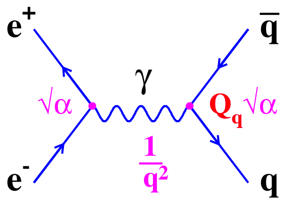
Consider the ratio, ***R***, we calculated on problem sheet 2:

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

- Write the charge of the quarks as $Q_q e$, where $Q_q = -⅓$ or $+⅔$



$\mathcal{M} = e^2/\underline{\underline{q}}^2$



$\mathcal{M} = Q_q e^2/\underline{\underline{q}}^2$

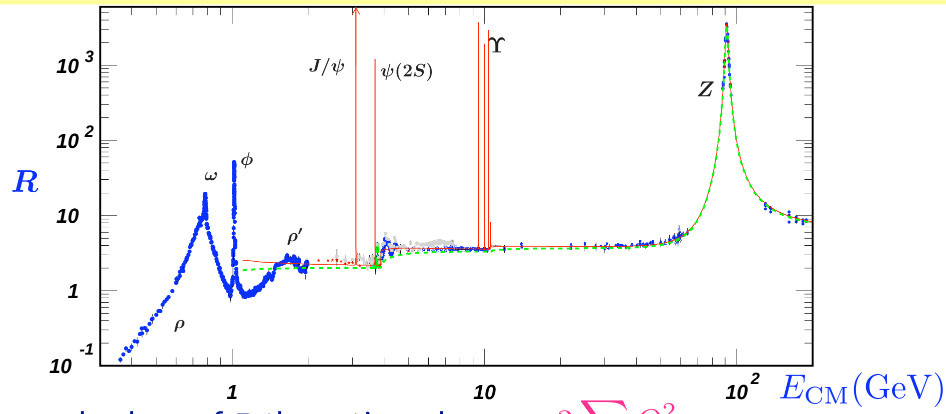
For one type of quark, $R = \dfrac{Q_q^2 e^4/\underline{\underline{q}}^4}{e^4/\underline{\underline{q}}^4} = Q_q^2$

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

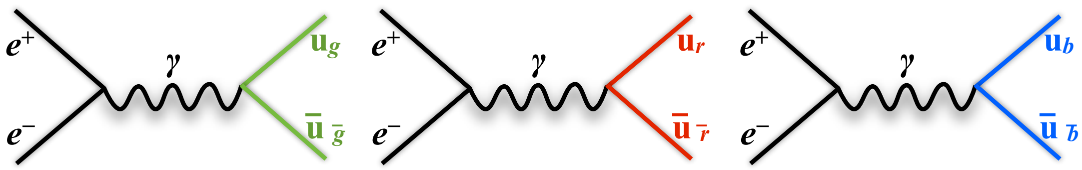
- *e.g.* at E_{CM} = **5 GeV** we can produce **u, d, s** and **c** quarks.

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

The Ratio R



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

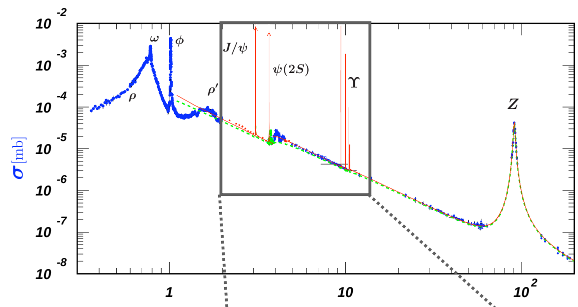


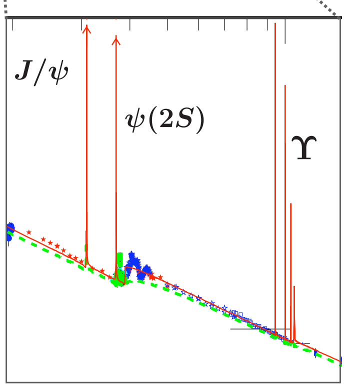
Resonances in R

At certain values of E_{CM}, there is a large spike in $\sigma(e^+e^- \to \mathbf{hadrons})$.

This is due to production of:

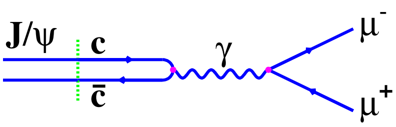
- $c\text{-}\bar{c}$ bound states at $E_{\mathrm{CM}} \approx 2m_c$
- $b\text{-}\bar{b}$ bound states at $E_{\mathrm{CM}} \approx 2m_b$



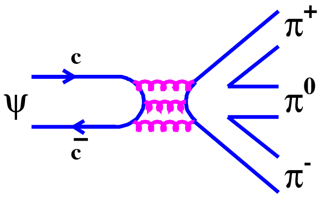


These states have a relatively long lifetime, compared to other hadrons.
e.g. $\tau(J/\psi) = 7.6 \times 10^{-21}$ s

- Width, $\Gamma = \hbar/\tau$ is narrow.

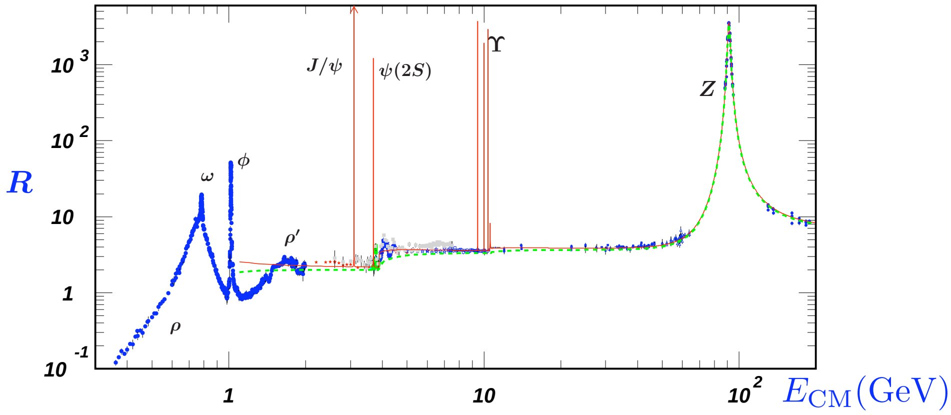


EM decay also has a chance
$\Gamma(J/\psi \to \mu^+\mu^-) \propto \alpha^2$



Strong decay requires exchange of three gluons:
$\Gamma(J/\psi \to \mathbf{hadrons}) \propto \alpha_S^6$

R Summary



$$R(E_{\mathrm{CM}}) = \frac{\sigma(e^+e^- \to \mathrm{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)} = 3\sum_q Q_q^2 \qquad \text{for } 2 < E_{\mathrm{CM}}/\mathrm{GeV} < 30$$

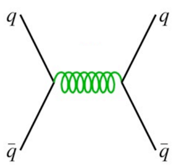
- Need **three colours** of quarks to explain observed ratio.
- Jumps at $E_{CM} \approx 2m_c$ and $E_{CM} \approx 2m_b$ when we can start to produce extra quark flavour.
- Narrow resonances due production of $\mathbf{q\text{-}\bar{q}}$ bound states at $E_{CM} \approx 2m_q$ threshold.
- For peak at E_{CM} 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.

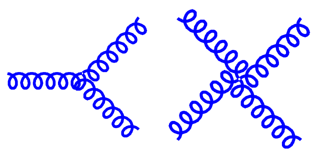
Gluons are the propagator of the strong force



Quarks and gluons carry **colour charge.**

Colour charge is conserved.

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.

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

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