An Introduction to Modern Particle Physics

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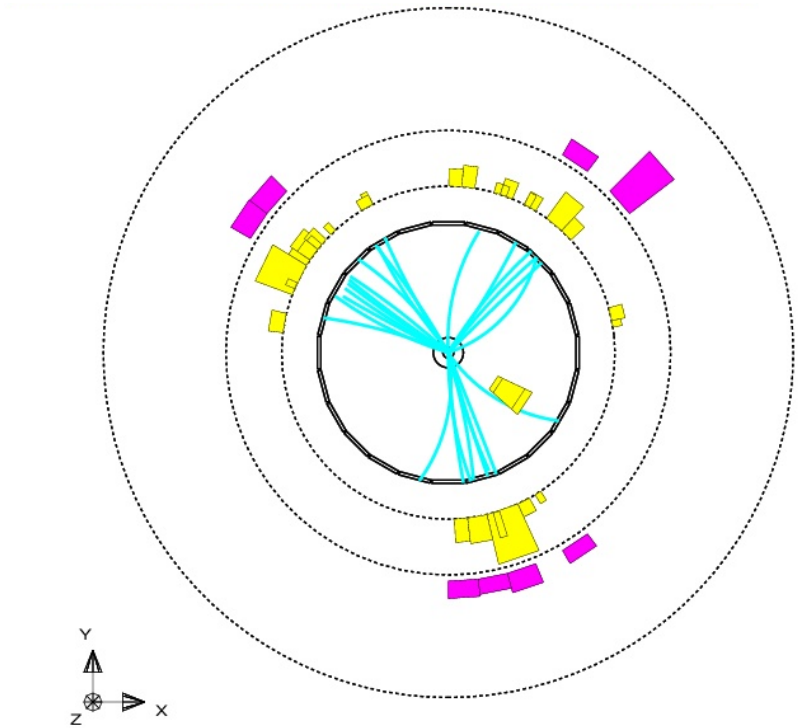


Science Summer School: 30th July - 1st August 2007

Course Synopsis

★ Introduction : Particles and Forces
- what are the fundamental particles
- what is a force

★The Electromagnetic Interaction
- QED and e^+e^- annihilation
- the Large Electron-Positron collider

★The Crazy world of the Strong Interaction
- QCD, colour and gluons
- the quarks

★The Weak interaction
- W bosons
- Neutrinos and Neutrino Oscillations
- The MINOS Experiment

★ The Standard Model (what we know) and beyond
- Electroweak Unification
- the Z boson
- the Higgs Boson
- Dark matter and supersymmetry
- Unanswered questions

Recap

- **There are 12 fundamental particles**

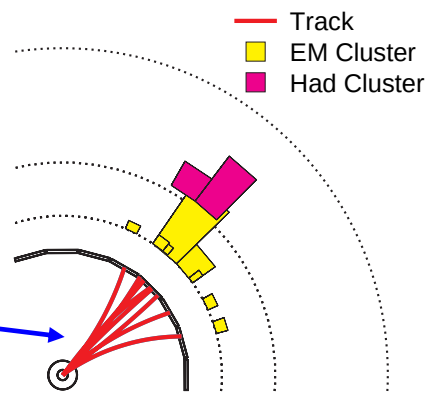
Electron (e^-)	Muon (μ^-)	Tau (τ^-)
Electron Neutrino (ν_e)	Muon Neutrino (ν_μ)	Tau Neutrino (ν_τ)
Up Quark (u)	Charm Quark (c)	Top Quark (t)
Down Quark (d)	Strange Quark (d)	Bottom Quark (b)

- **and 4 fundamental forces**

Strong	Weak
Electromagnetic	Gravity

Last time:

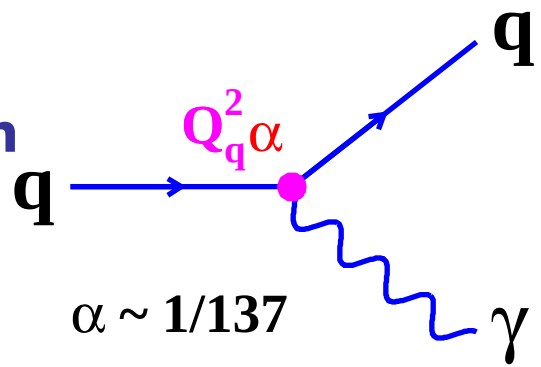
- ★ Discussed the electromagnetic force QED
- ★ Discussed the production and detection of LEPTONS at LEP, e.g., $e^+e^- \rightarrow \mu^+\mu^-$
- ★ Quarks are also produced at LEP - but look VERY different
- ★ All due to the nature of the strong interaction (the theory of QCD)



Quantum Chromodynamics (QCD)

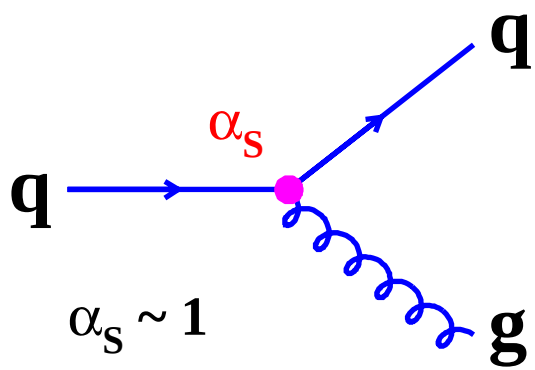
Quantum Electrodynamics (QED): is the quantum theory of the EM interaction

- ★Mediated by massless photons
- ★Photon couples to ELECTRIC charge
- ★Strength of interaction ~ $\alpha = e^2/4\pi$



Quantum Chromodynamics (QCD): is the quantum theory of the strong force

- ★Mediated by massless GLUONS
- ★GLUON couples to "STRONG" charge
- ★Strength of interaction ~ $\alpha_s = g^2/4\pi$
- ★Only QUARKS have non-zero STRONG charge → only quarks feel strong force

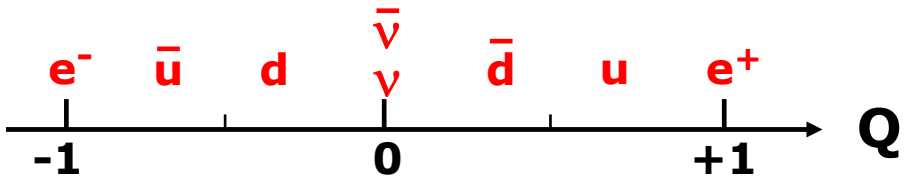


So far QCD looks just like a stronger version of QED !

COLOUR

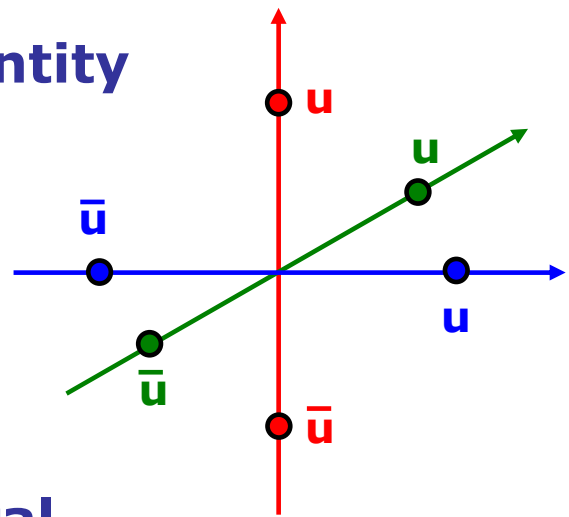
In QED

- ★ Charge of QED is electric charge
- ★ Electrons have charge -1 (in units of e)
- ★ Anti-Electrons have charge +1
- ★ Electromagnetic charge is a (quantised) scalar quantity



In QCD

- ★ Charge of QCD is called "COLOUR"
- ★ "COLOUR" charge is a 3D vector quantity
- ★ QUARKS carry one unit of charge
  BUT this can be in one of three "directions" labelled "red", "blue" and "green"
- ★ QUARKS carry COLOUR r, b, g
- ★ ANTI-QUARKS are r̄, b̄, ḡ
- ★ LEPTONS, PHOTONS are colour neutral



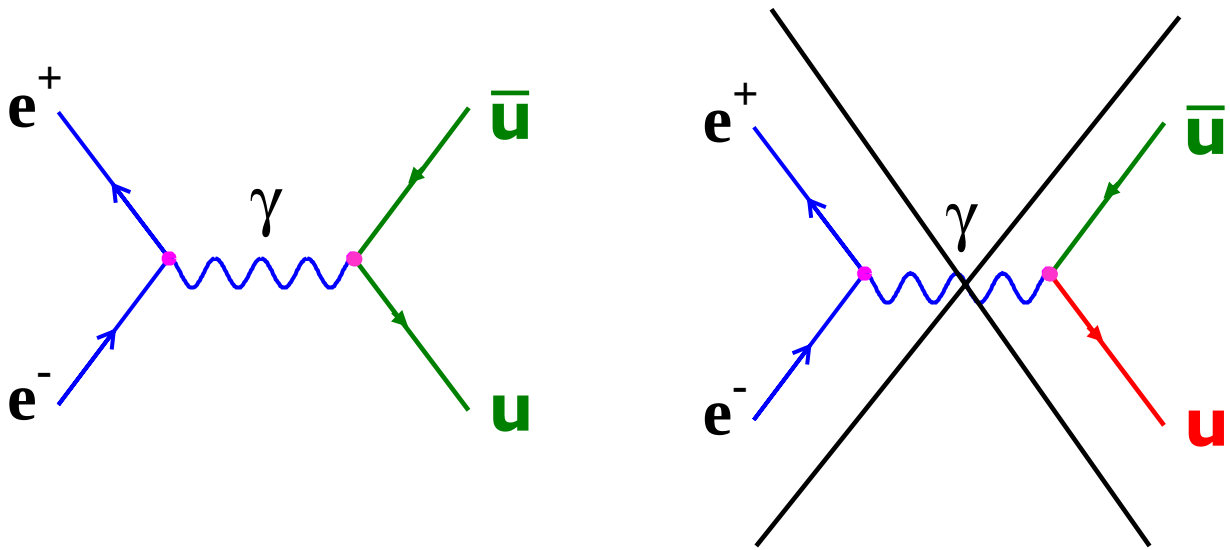
Colour and the Quarks

★ **Each flavour of QUARK (e.g. up, down,….) carries one unit of colour charge which can be in either the "red", "green", or "blue" directions.**

★ **Therefore there are 3 distinct particles of each quark flavour – e.g. u,u,u**

NOTE:

In $e^+e^- \rightarrow q\,\bar{q}$ the photon carries no colour so only r $\bar{r}$ or b $\bar{b}$ or g $\bar{g}$ final states are allowed, e.g.



Gluons

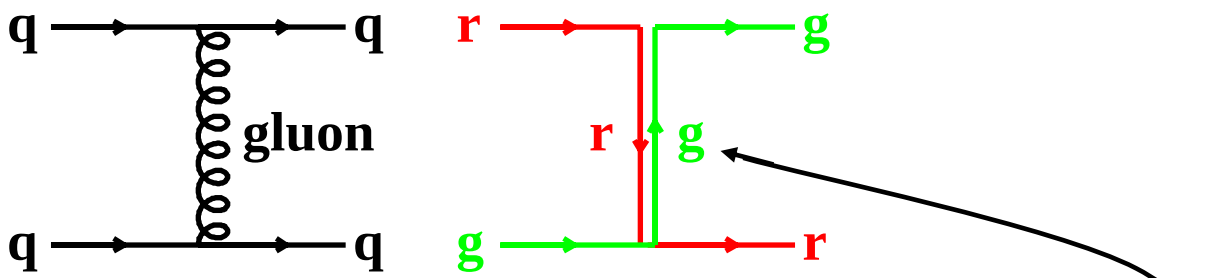
In QED

- photons are exchanged giving rise to the EM force
- photons are massless and neutral

In QCD

- gluons are exchanged giving rise to the STRONG force
- gluons are massless BUT carry colour charge !

e.g. consider scattering of a red quark and a green quark



UNLIKE QED

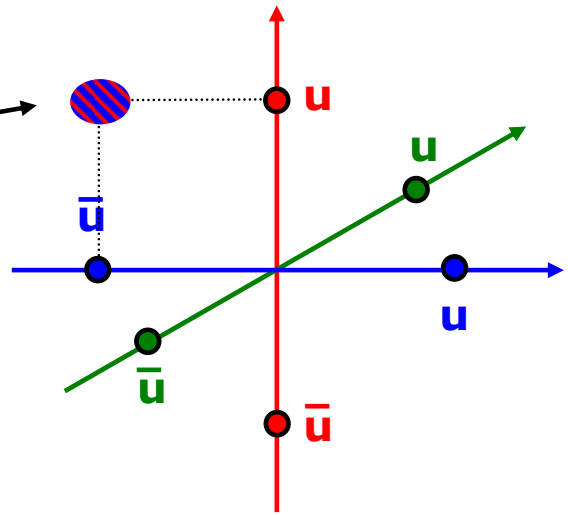
★ Gluons carry the charge of the interaction
- gluons come in different colours, e.g $r\bar{g}$, $g\bar{r}$

★NOTE GLUONS carry both COLOUR and ANTI-COLOUR

8 GLUONS

On the COLOUR diagram:

a rb gluon



One might expect gluons to come in 9 different colour combinations : $r\bar{g}$, $g\bar{r}$, $r\bar{b}$, $b\bar{r}$, bg, $\bar{g}\bar{b}$, gg, $r\bar{r}$, $b\bar{b}$

However : only 8 allowed combinations

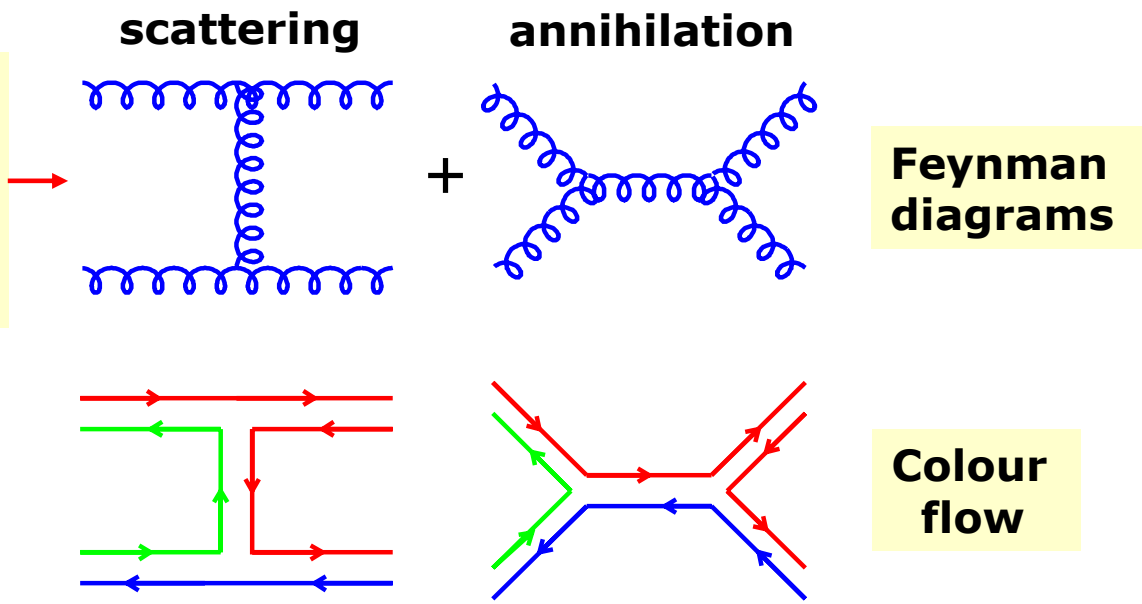
8 GLUONS

Gluon Self-Interactions

- ★At this point QCD looks like a stronger version of QED
- ★**BUT** in practice QCD is **VERY** different because **GLUONS carry colour charge !**
- ★GLUONS can interact with other GLUONS !
- ★In QED photons are neutral and therefore do not interact

Interactions between 2 gluons:

★Note: two gluons travelling in free space attract each other



This has huge Consequences !

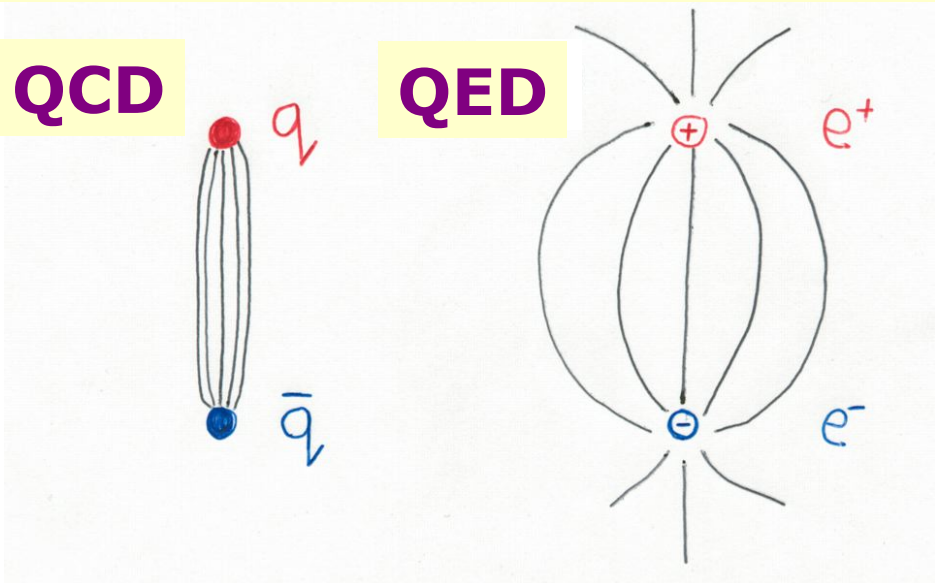
CONFINEMENT

NEVER OBSERVE: a single FREE quark or gluon !

- ★ Quarks are always confined within hadrons
- ★ a consequence of gluon self-interactions

QUALITATIVE EXPLANATION:

"Consider two quarks interacting by exchanging gluons. The gluons mediating the force are attracted to each other – they carry colour charge. These gluon-gluon interactions pull the lines of colour force into a narrow tube (or STRING). In this tube of force has an effective tension. If you pull the quarks further apart the string stores energy. Because the field lines are confined to a tube (and not spreading out) the force doesn't decrease as the quarks are pulled apart. Consequently it requires infinite energy to separate the two quarks to infinity."



How Strong is Strong ?

EM Force between two electrons:

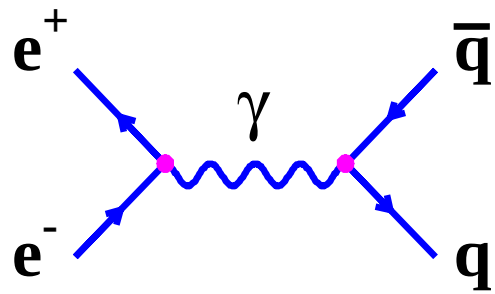
- ★ **1x10^{-15} m apart : 200 N (equivalent weight of small child)**
- ★ **1 m apart : 2x10^{-28} N (equivalent of a few electrons)**

STRONG Force between two quarks:

- ★ **1x10^{-15} m apart : 160000 N (weight of large elephant)**
- ★ **1 m apart : 160000 N**

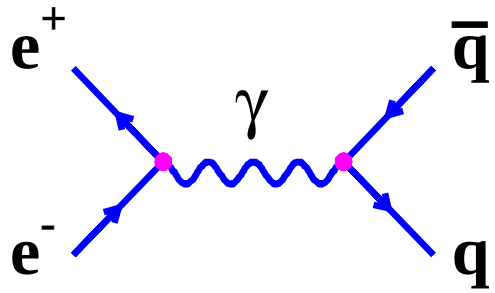
The main feature of QCD is that the force doesn't decrease with distance !

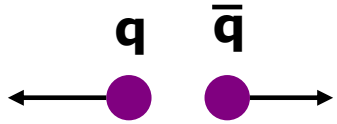
So what happens to the quarks produced in e^+e^- annhilation ?



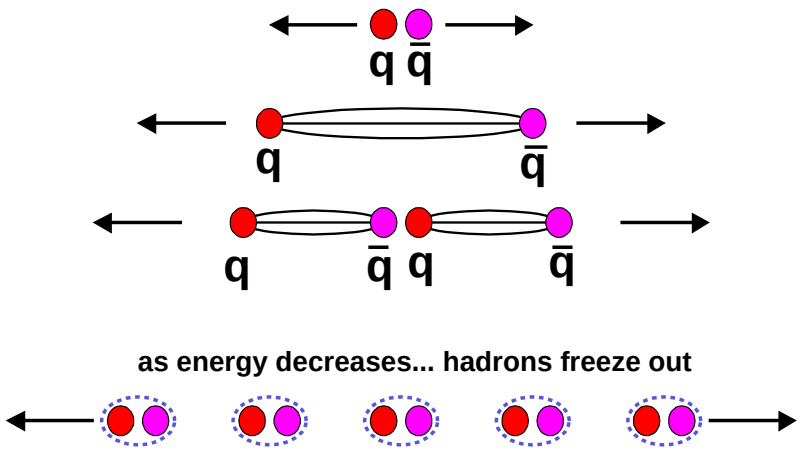
JETS

- Consider the $q\bar{q}$ pair produced in $e^+e^- \rightarrow q\bar{q}$:



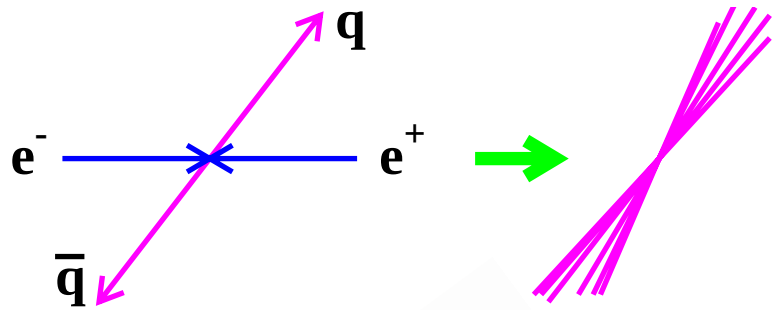


★ Initially the quarks are flying apart
★ As they do so they are storing up energy in the "force string"
★ When there is enough energy stored in the string some of
★ ...s – new $q\bar{q}$ pairs are created

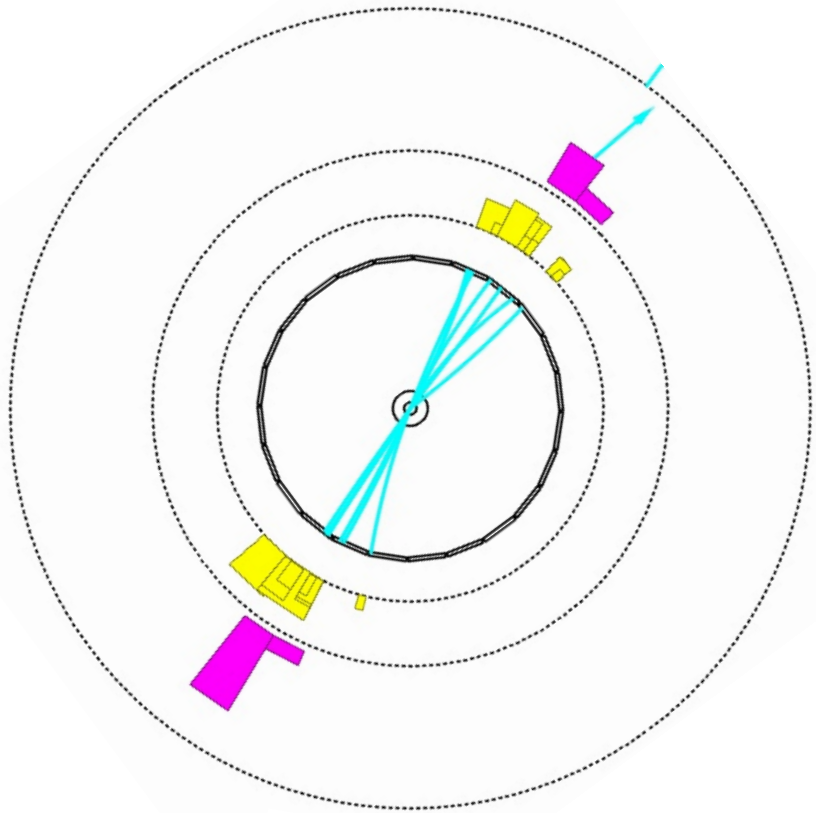


This continues until all the quarks are grouped into hadrons (i.e. colour neutral objects).

Start out with quarks and end up with collimated JETS of hadrons

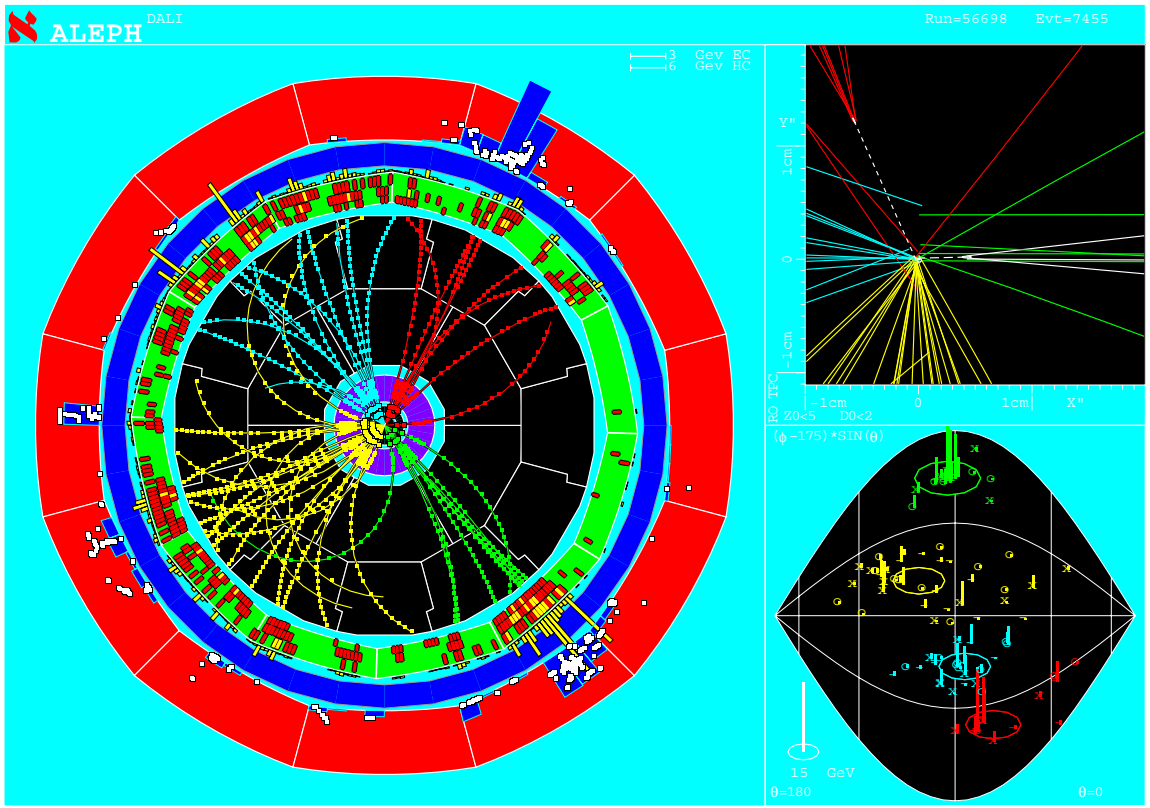


Typical $e^+e^- \rightarrow q\bar{q}$ at LEP



Aside :

So what is this event ?

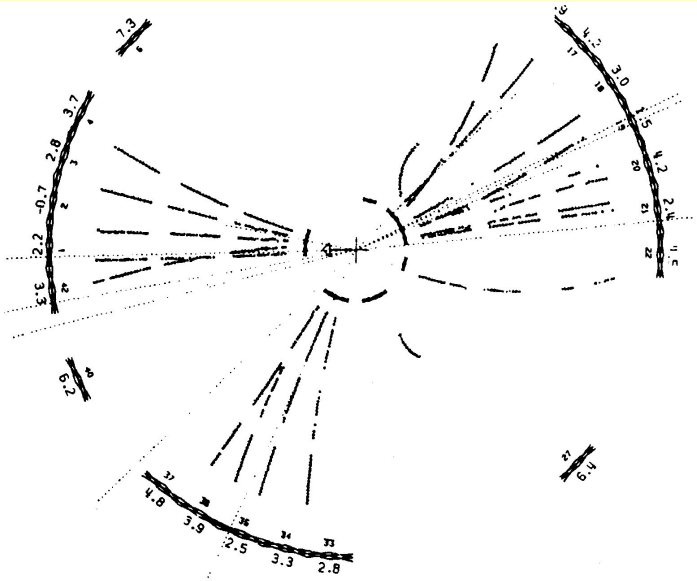


$e^+e^- \rightarrow$ something $\rightarrow q\bar{q}q\bar{q}$

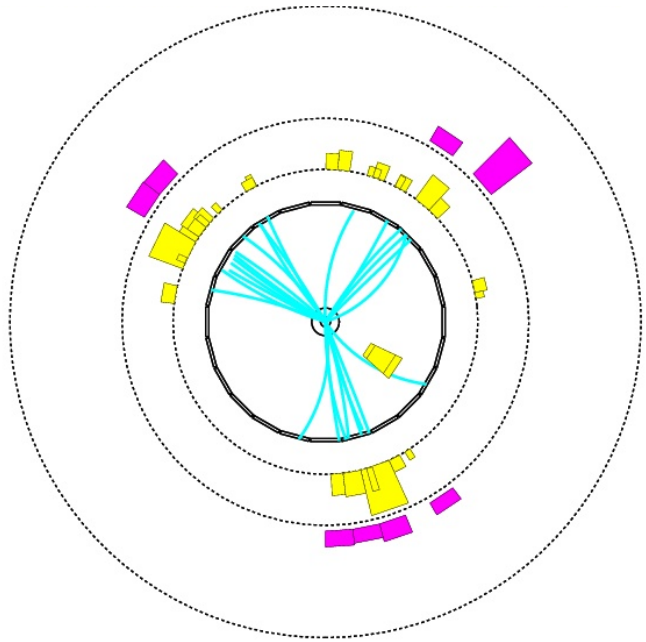
Evidence for Gluons

★3 Jet Events in e^+e^- annihilation

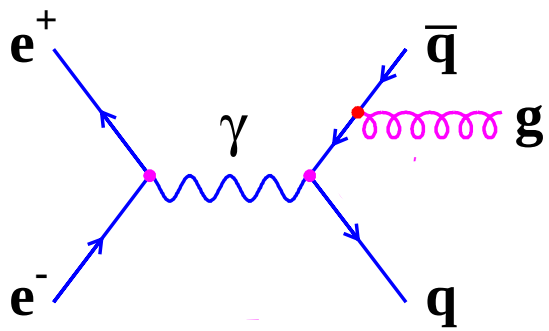
JADE : 1978
First direct evidence for gluons



OPAL: 1990



★Interpreted as $e^+e^- \rightarrow qq$ events where one of the quarks emits a gluon. The two quarks and the gluon are seen as jets.



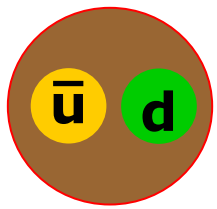
THE QUARKS

Gen	Flavour		Q	Mass
1st	Down	d	-1/3	0.3 GeV/c^2
1st	Up	u	+2/3	0.3 GeV/c^2
2nd	Strange	s	-1/3	0.5 GeV/c^2
2nd	Charm	c	+2/3	1.5 GeV/c^2
3rd	Bottom	b	-1/3	4.5 GeV/c^2
3rd	Top	t	+2/3	175 GeV/c^2

★ Due to the nature of the strong interaction all observed particles are either colourless or are confined to colourless objects

★ Two ways this can happen:

MESONS

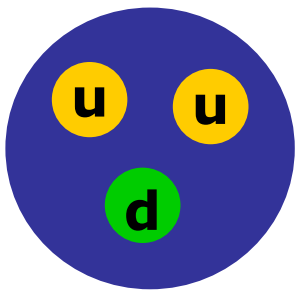


★bound $q\bar{q}$ states

$r\bar{r}$, $g\bar{g}$, $b\bar{b}$

BARYONS

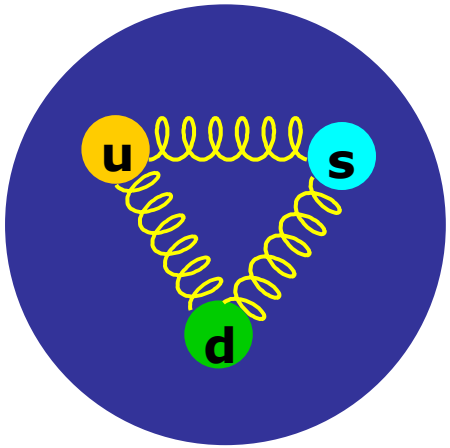
+ anti-baryons



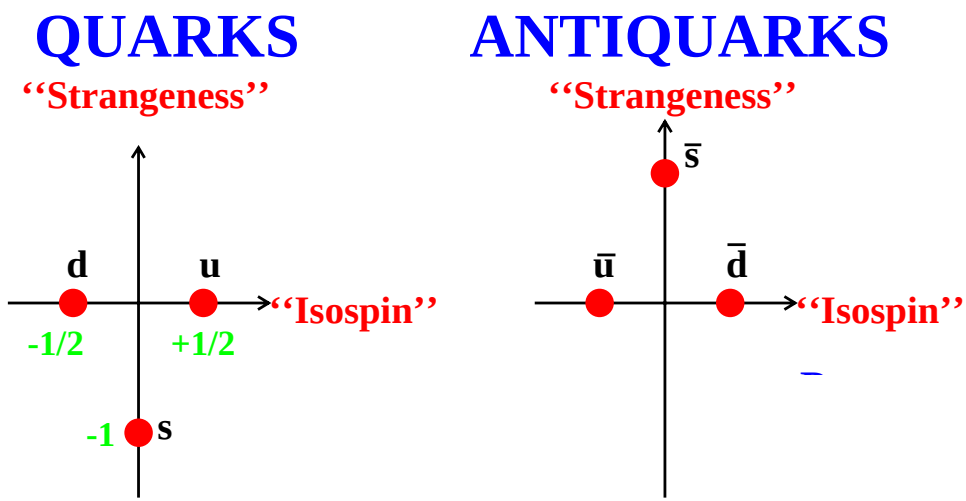
★bound qqq states

rgb (this is somewhat of an over simplification)

The Light Quarks (uds)



- Historically it was realised that baryons had substructure because of symmetries amongst the particles
- Plot observed particles in terms of "strangeness" and "isospin"

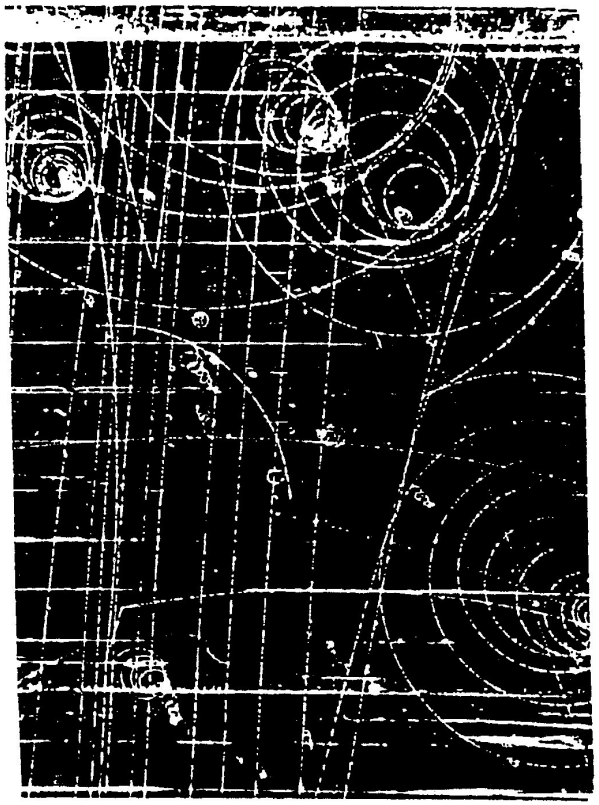


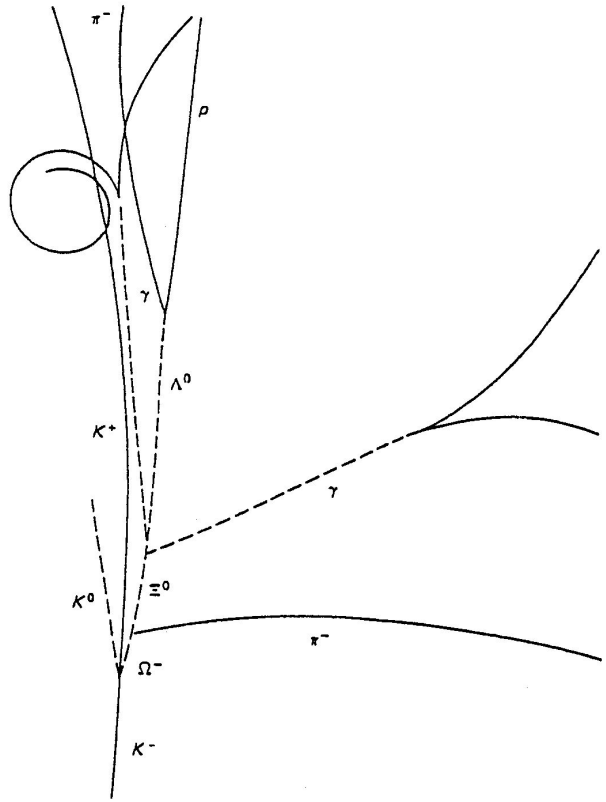
★ Isospin = $\frac{1}{2}$ {N(u) – N(d)}

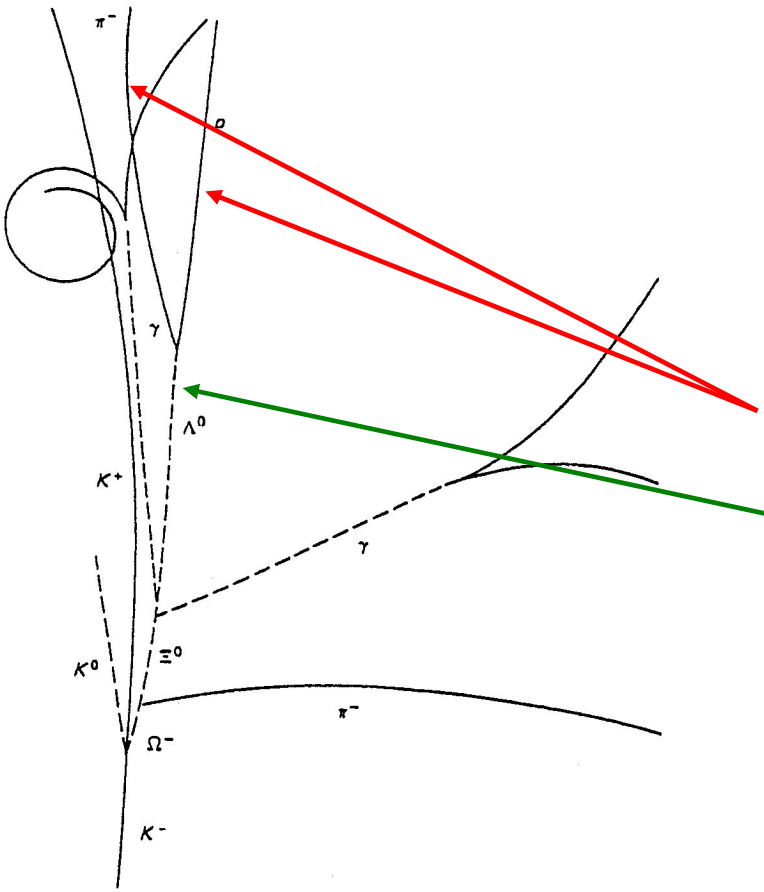
★ Strangeness = N($\bar{s}$) – N(s)

Particle Physics in the 1960s

- **Bubble chamber experiments allowed physicists to view charged particle tracks from interactions:**







- **By measuring curvature in a magnetic field can determine momentum of particles.**
- **Allows particle masses to be determined.**

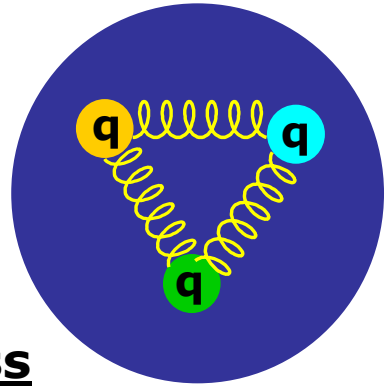
measure momentum

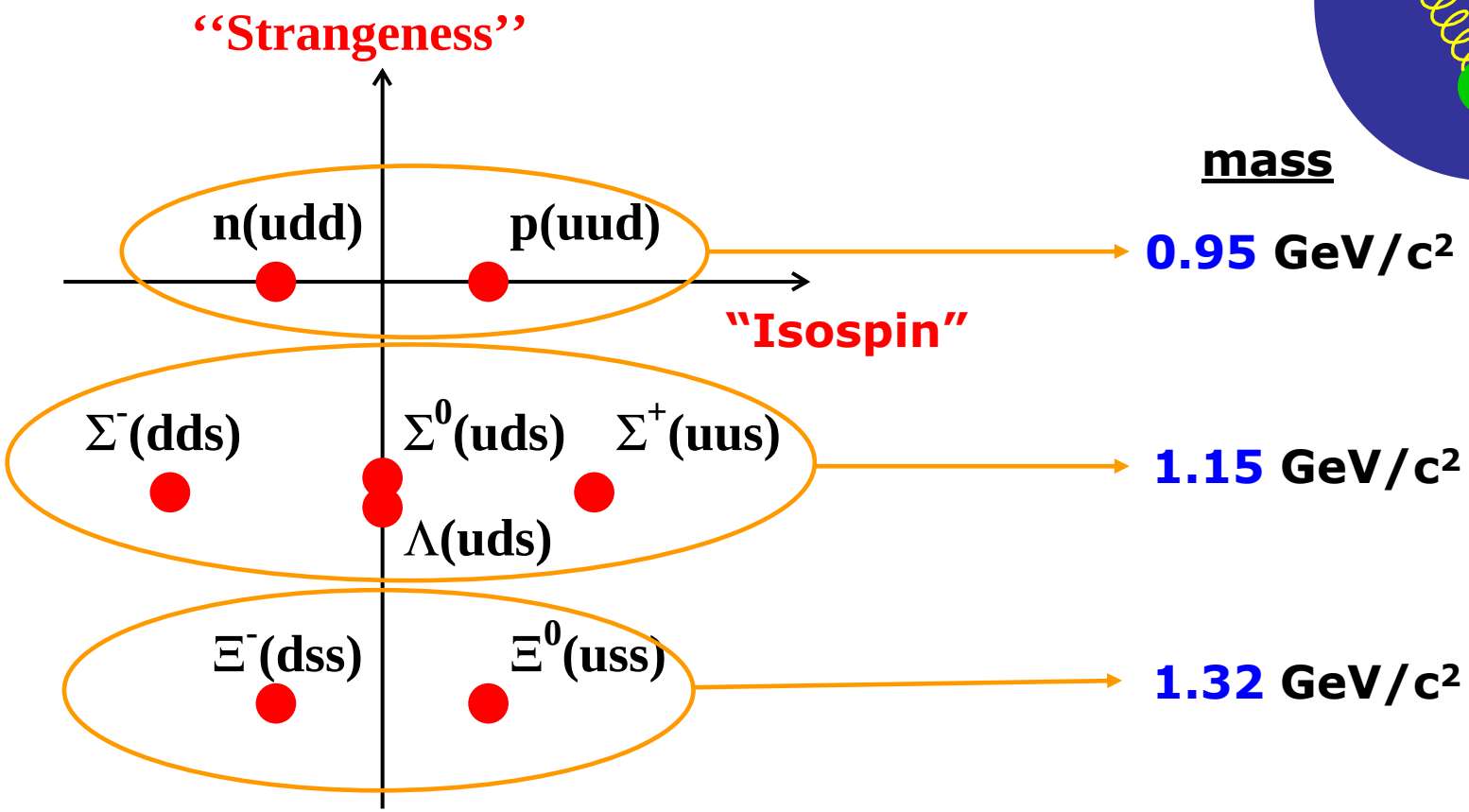
mass

★ **MANY particles with different masses observed**

★ **Observed patterns….**

uds Baryons





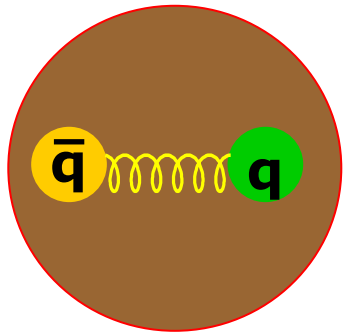
★**Masses can be explained assuming:**

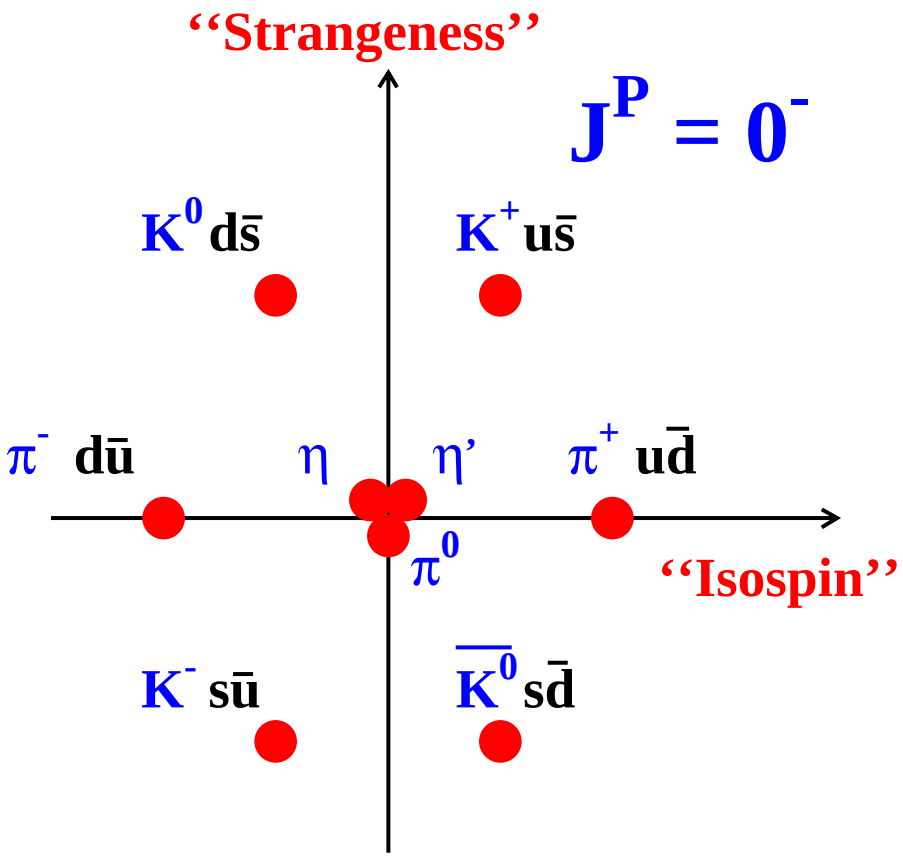
mass of the up and down quarks = 0.3 GeV/c²

mass of the strange quark = 0.5 GeV/c²

uds Mesons

★Again mass patterns can be seen
e.g. K^-, K^+, K^0, $\bar{K}^0$ have mass 0.495 GeV/c^2





Masses/MeV:

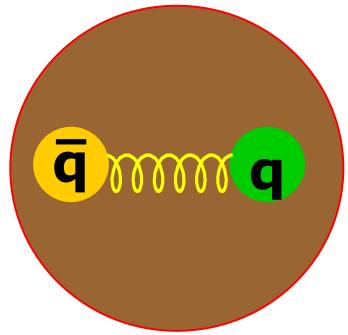
$\pi(140)$, K(495)

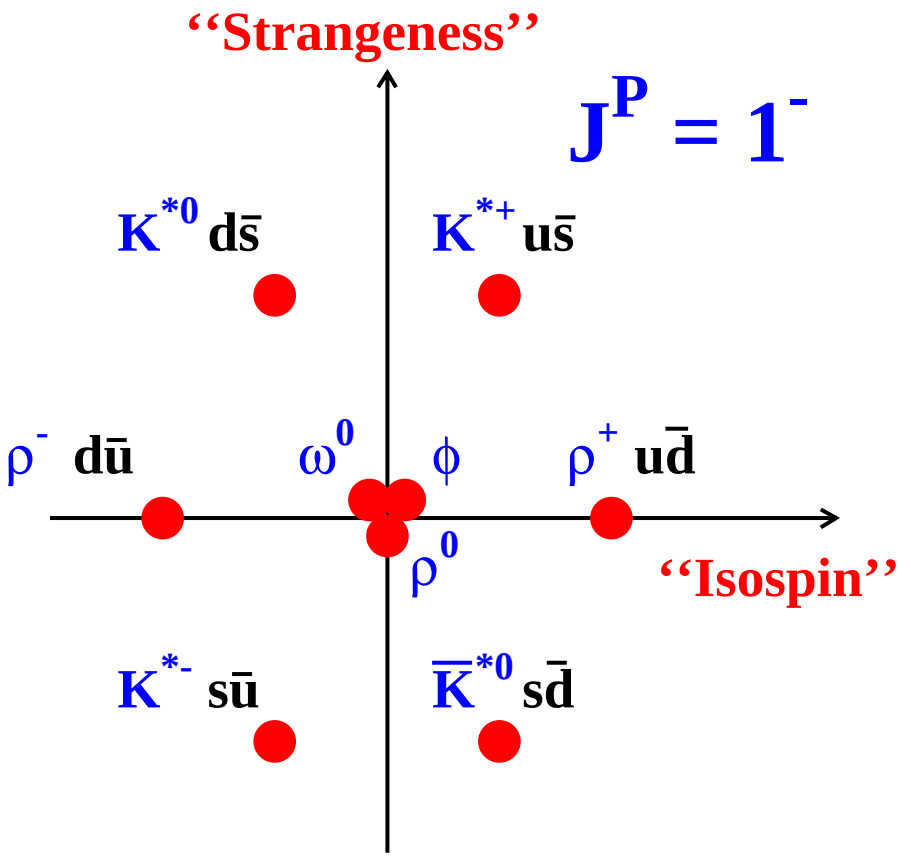
$\eta(550)$, $\eta'(960)$

★ We have so far only considered the ground states…
★ There are also excited states !
★ States with "ORBITAL ANGULAR MOMENTUM"

Excited States

★Again mass patterns can be seen
e.g. K^-, K^+, K^0, $\bar{K}^0$ have mass 0.495 GeV/c^2





Masses/MeV:

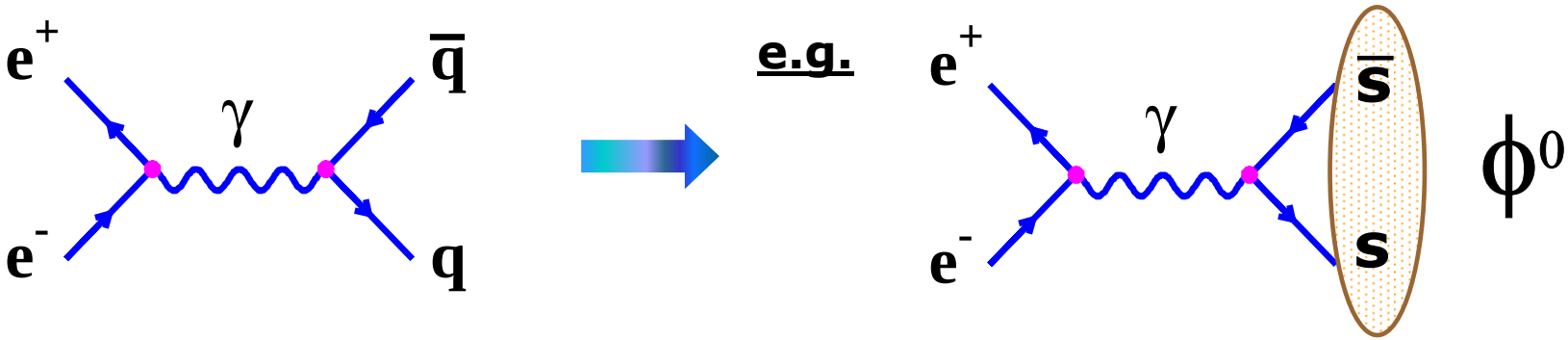
$\rho(770)$, $K^*(890)$

$\omega(780)$, $\phi(1020)$

★ The properties of the light mesons/baryons can only be explained by the quark model

The Heavy Quarks and $e^+e^- \rightarrow q\bar{q}$

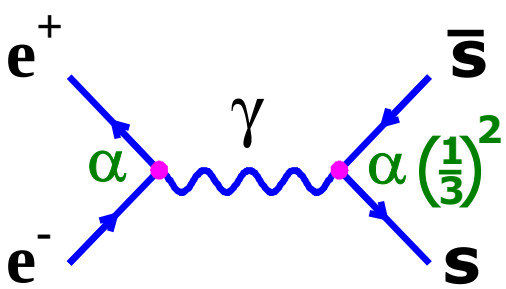
- ★ Previously we discussed how jets are produced in $e^+e^- \rightarrow q\bar{q}$
- ★ Start with coloured quarks and end up with jets of colourless hadrons
- ★ There is another way of ending up with a colourless final state
- ★ If the energy of the e+e- collision is "just right"
- ★ i.e. precisely equal to $E = mc^2$ of a $q\bar{q}$ meson then can produce a single bound state

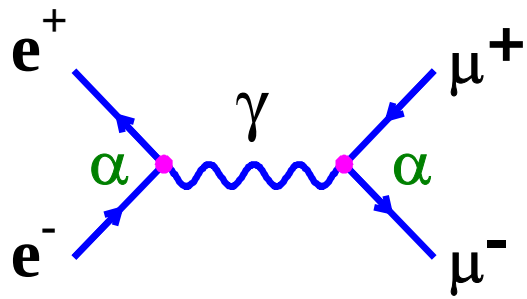


- ★ This type of process is termed "RESONANT" production - just the right energy to produce the particle
- ★ When this happens the CROSS-SECTION increased rapidly

R_μ

- Compare $e^+e^- \rightarrow s\,s$ with $e^+e^- \rightarrow \mu^+\mu^-$





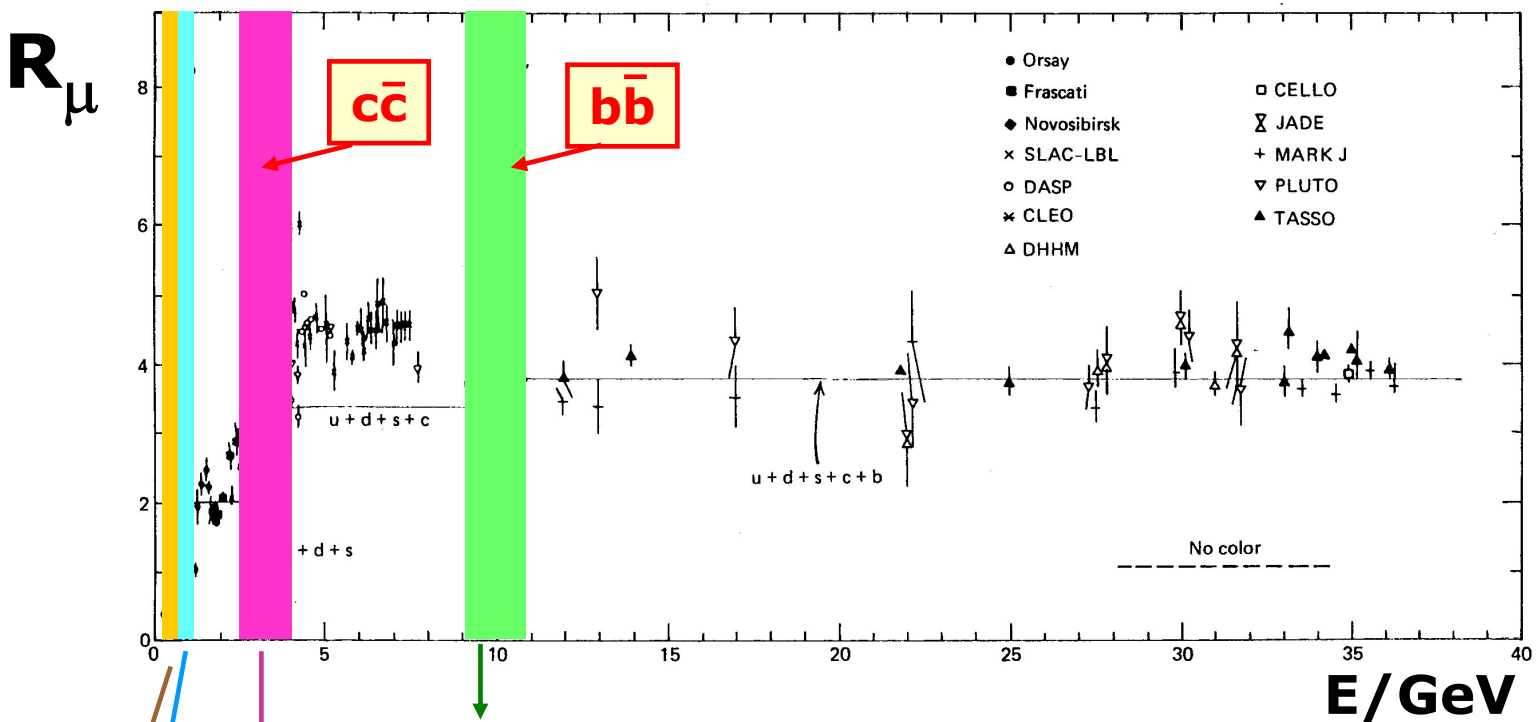
- What is ratio of $\sigma(e^+e^- \rightarrow s\,s)$ to $\sigma(e^+e^- \rightarrow \mu^+\mu^-)$?

$$\text{Ratio} = Q_s^2 = \left(\tfrac{1}{3}\right)^2$$

QED interaction strength proportional to charge^2

- At the resonant energy rate increases hugely.....

$$R_\mu = \frac{e^+e^- \to q\,\bar{q}}{e^+e^- \to \mu^+\mu^-}$$



E = 9.1 GeV: $b\bar{b} \to m_b \sim 4.5$ GeV/c^2

E = 3.1 GeV: $c\bar{c} \to m_c \sim 1.5$ GeV/c^2

E = 1.0 GeV: $s\bar{s} \to m_s \sim 0.5$ GeV/c^2

E = 0.7 GeV: $u\bar{u}/d\bar{d} \to m_u/m_d \sim 0.35$ GeV/c^2

Summary

★ QCD superficially like QED
★ Quarks come in three colours
★ The force carrying particles, 8 gluons, which carry the charge of the interaction → interact
★ Self interactions → quarks must be confined in colourless states

★Clear evidence for quarks in hadron structure/e^+e annihilation - and elsewhere
★ Good idea of quark masses..... although yet to discuss top

Gen	Flavour		Q	Mass
1st	Down	d	-1/3	0.3 GeV/c^2
1st	Up	u	+2/3	0.3 GeV/c^2
2nd	Strange	s	-1/3	0.5 GeV/c^2
2nd	Charm	c	+2/3	1.5 GeV/c^2
3rd	Bottom	b	-1/3	4.5 GeV/c^2
3rd	Top	t	+2/3	175 GeV/c^2

For further discussion....

$$R_\mu = \frac{e^+e^- \to q\,\bar{q}}{e^+e^- \to \mu^+\mu^-}$$