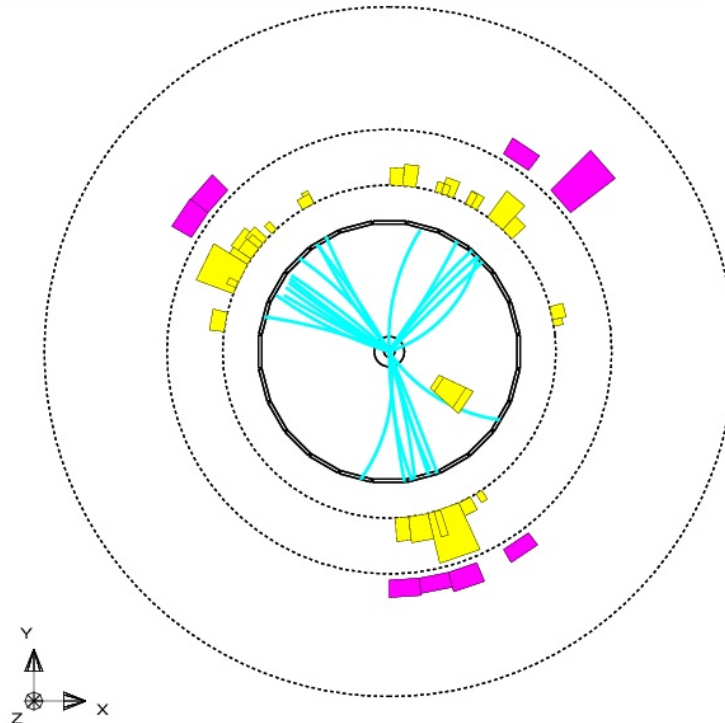


# An Introduction to Modern Particle Physics

**Mark Thomson**  
**University of Cambridge**



**Science Summer School: 30<sup>th</sup> July - 1<sup>st</sup> 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

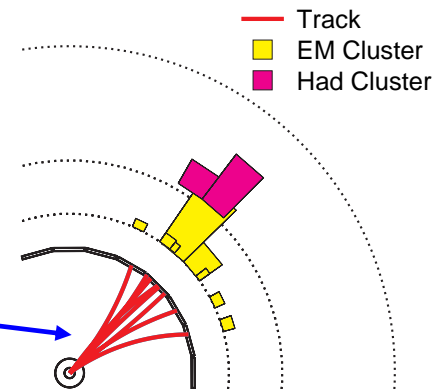
Electron ( $e^-$ )	Muon ( $\mu^-$ )	Tau ( $\tau^-$ )
Electron Neutrino ( $\nu_e$ )	Muon Neutrino ( $\nu_\mu$ )	Tau Neutrino ( $\nu_\tau$ )
Up Quark ( $u$ )	Charm Quark ( $c$ )	Top Quark ( $t$ )
Down Quark ( $d$ )	Strange Quark ( $s$ )	Bottom Quark ( $b$ )

## ★ and 4 fundamental forces

Strong	Weak
Electromagnetic	Gravity

## Last time:

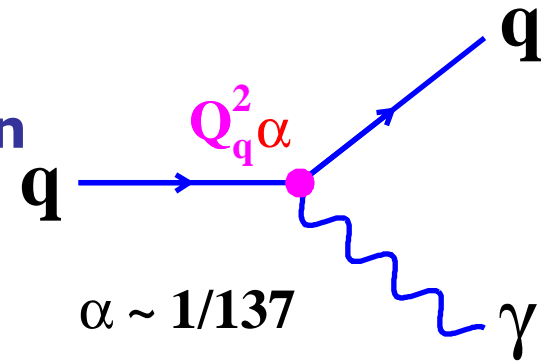
- ★ Discussed the electromagnetic force QED
- ★ Discussed the production and detection of **LEPTONS** at LEP, e.g.,  $e^+e^- \rightarrow \mu^+\mu^-$
- ★ Quarks are also produced at LEP  
- but look **VERY** different
- ★ All due to the nature of the strong interaction (the theory of QCD)



# Quantum Chromodynamics (QCD)

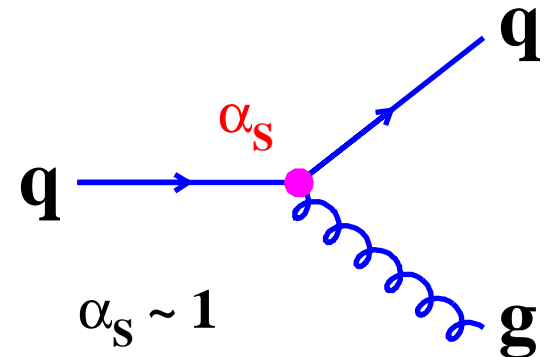
Quantum Electrodynamics (QED): is the quantum theory of the EM interaction

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



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

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

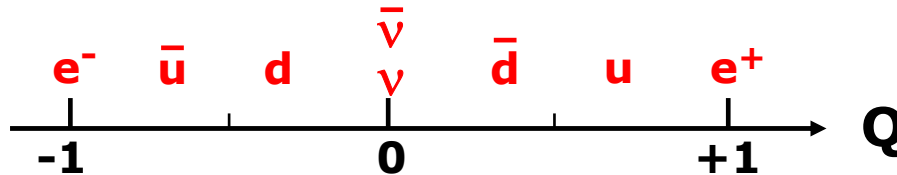


**So far QCD looks just like a stronger version of QED !**

# COLOUR

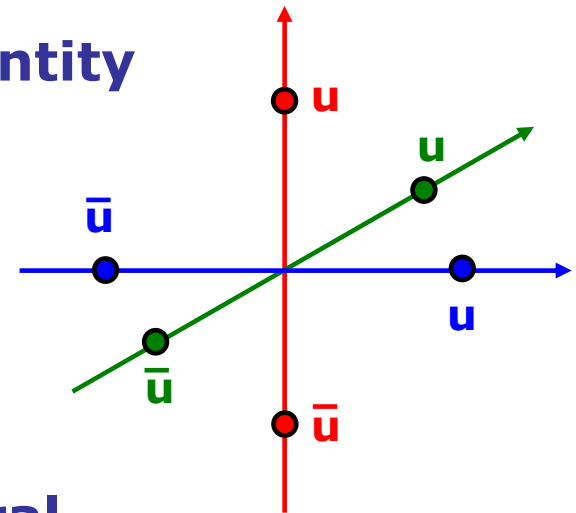
## In QED

- ★ 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  $\bar{r}, \bar{b}, \bar{g}$
- ★ **LEPTONS, PHOTONS** are colour neutral

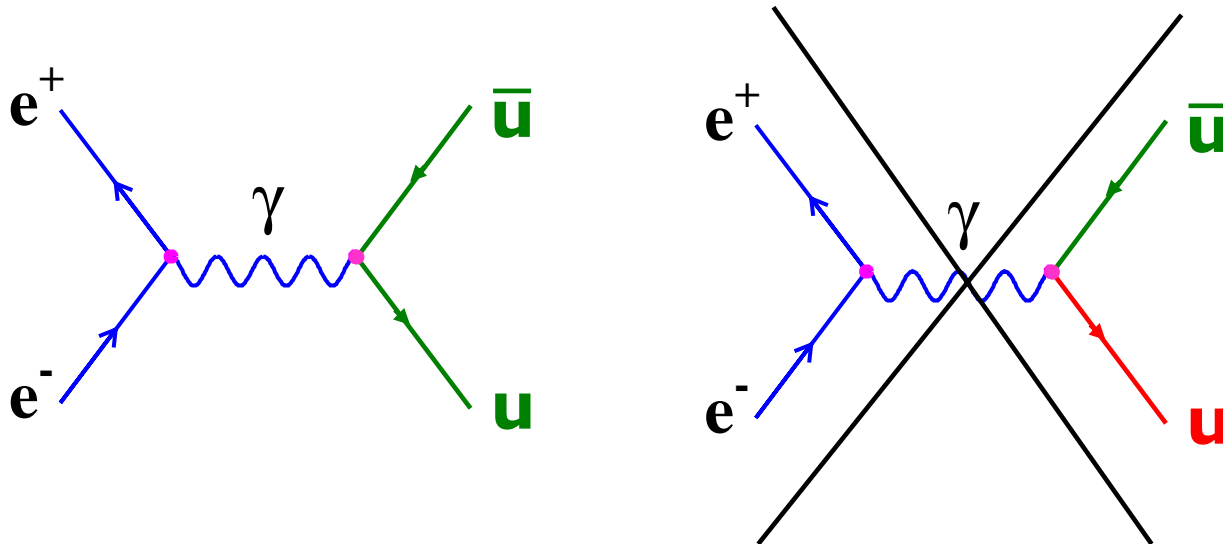


# Colour and the Quarks

- ★ 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.



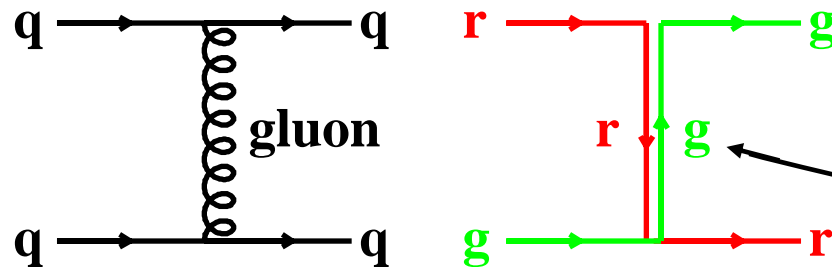
# Gluons

## 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**

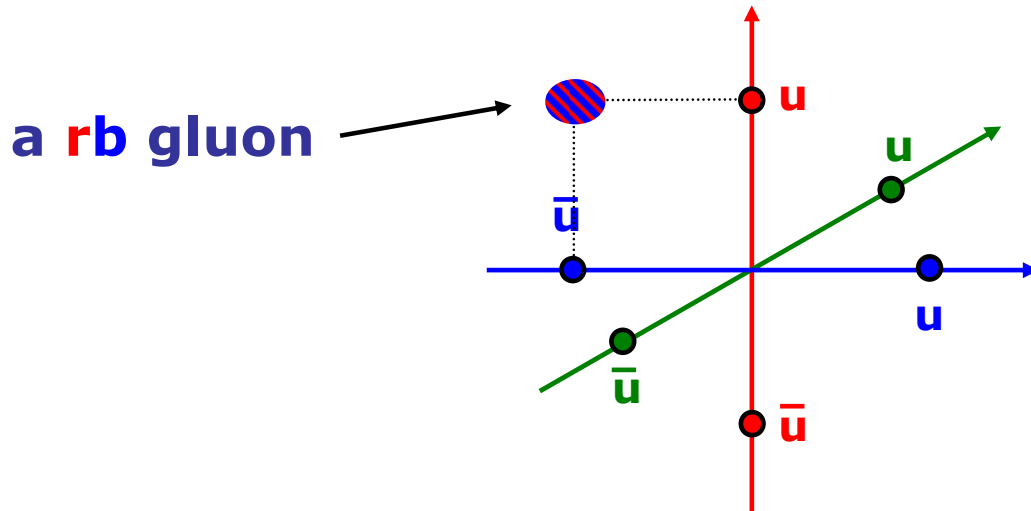


## UNLIKE QED

- ★ 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:



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

However : only 8 allowed combinations

**8 GLUONS**



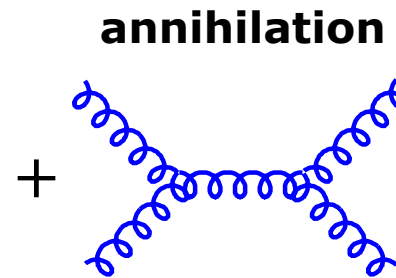
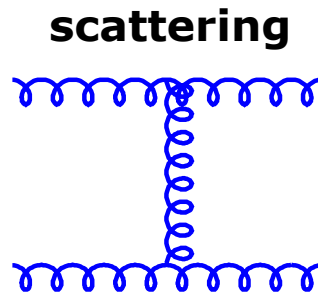
# Gluon Self-Interactions

- ★ 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

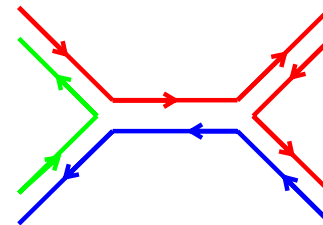
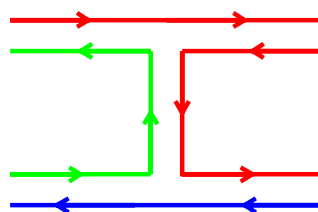
## Interactions between 2 gluons:

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

**This has huge Consequences !**



**Feynman diagrams**



**Colour flow**

# CONFINEMENT

**NEVER OBSERVE:** a single FREE quark or gluon !

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

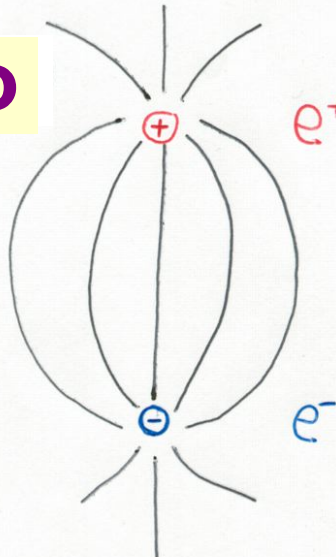
## **QUALITATIVE EXPLANATION:**

“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.”

**QCD**



**QED**



# How Strong is Strong ?

**EM Force between two electrons:**

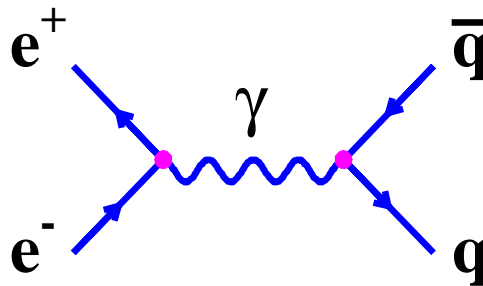
- ★  $1 \times 10^{-15}$  m apart : **200 N** (equivalent weight of small child)
- ★ 1 m apart :  **$2 \times 10^{-28}$  N** (equivalent of a few electrons)

**STRONG Force between two quarks:**

- ★  $1 \times 10^{-15}$  m apart : **160000 N** (weight of large elephant)
- ★ 1 m apart : **160000 N**

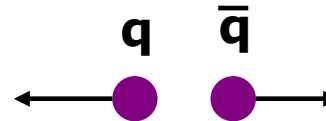
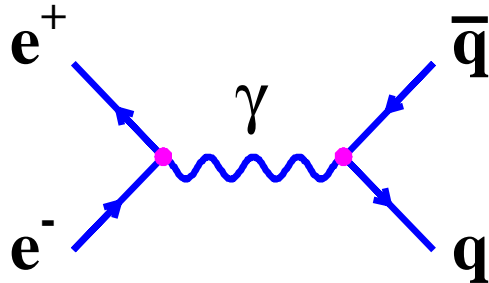
**The main feature of QCD is that the force doesn't decrease with distance !**

**So what happens to the quarks produced in  $e^+e^-$  annihilation ?**

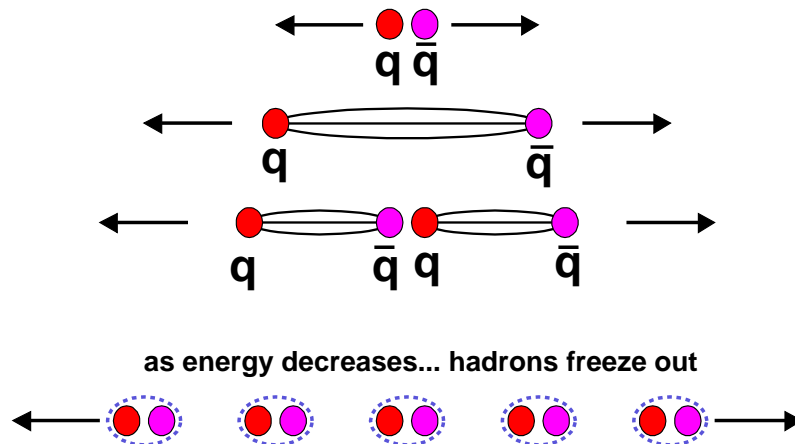


# JETS

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

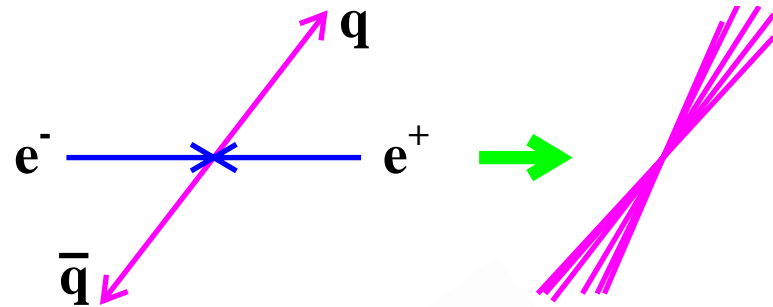


- Initially the quarks are flying apart
- As they do so they are storing up energy in the “force string”
- When there is enough energy stored in the string some of
- ... is – new  $q\bar{q}$  pairs are created

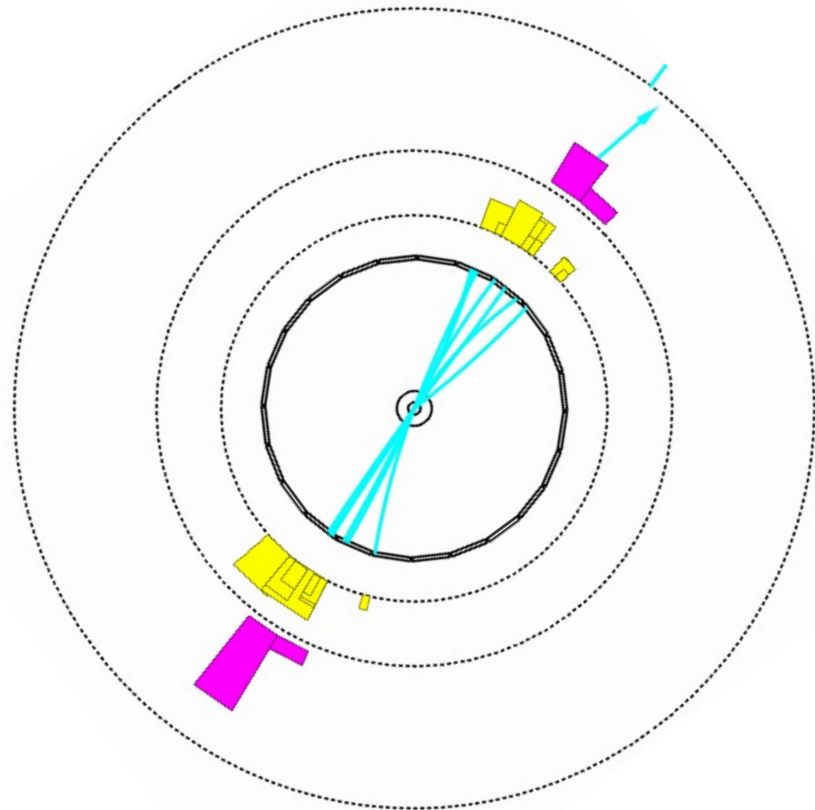


This continues until all the quarks are grouped into hadrons (i.e. colour neutral objects).

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

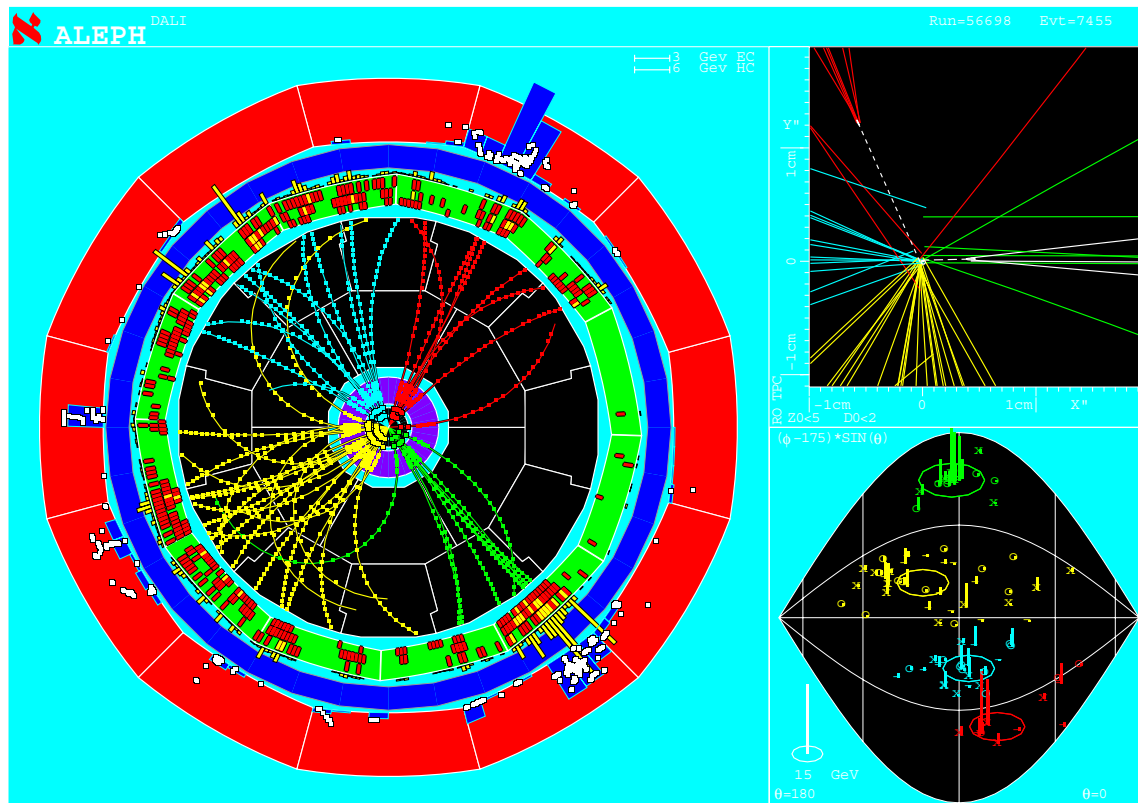


Typical  $e^+e^- \rightarrow q\bar{q}$  at LEP



# Aside :

So what is this event ?



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Filename: D0056698\_007455\_000830\_1723.PS

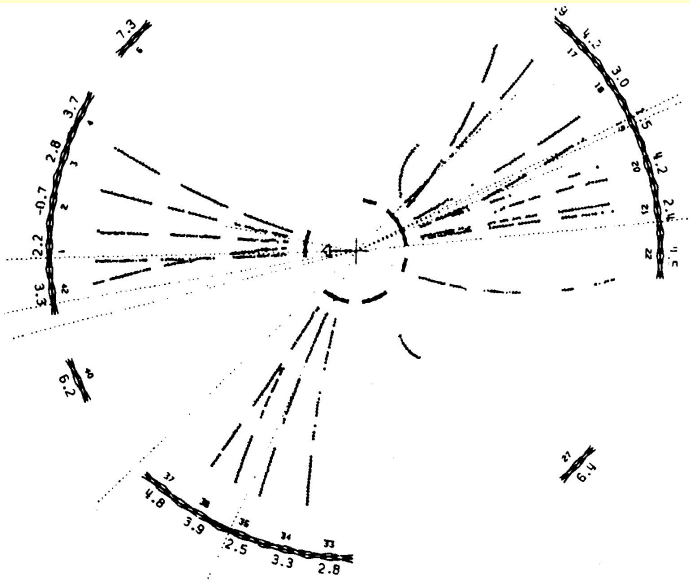
$$e^+e^- \rightarrow \text{something} \rightarrow q\bar{q}q\bar{q}$$

# Evidence for Gluons

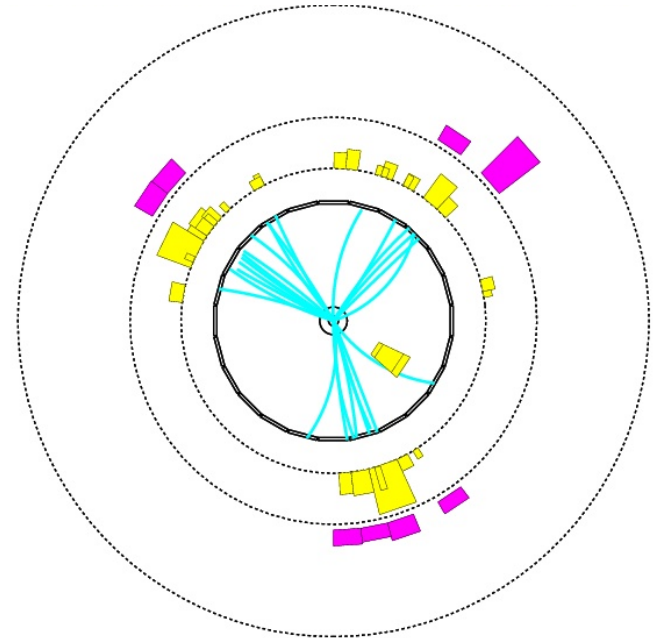
## ★ 3 Jet Events in $e^+e^-$ annihilation

**JADE : 1978**

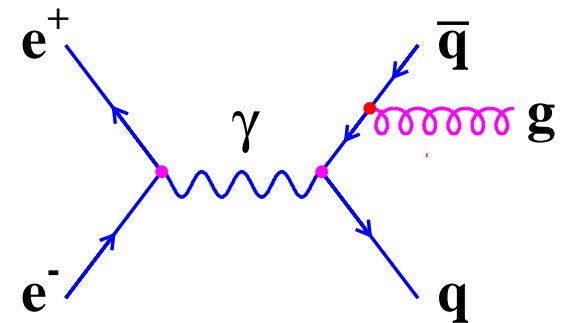
**First direct evidence for gluons**



**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.



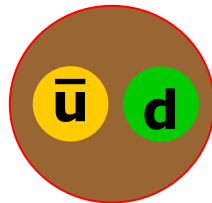
# THE QUARKS

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

★ 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**

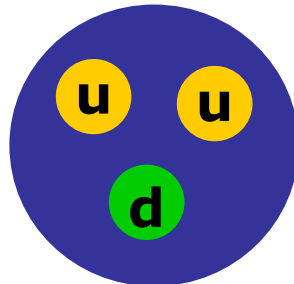


★ bound  $q\bar{q}$  states

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

**BARYONS**

+ anti-baryons



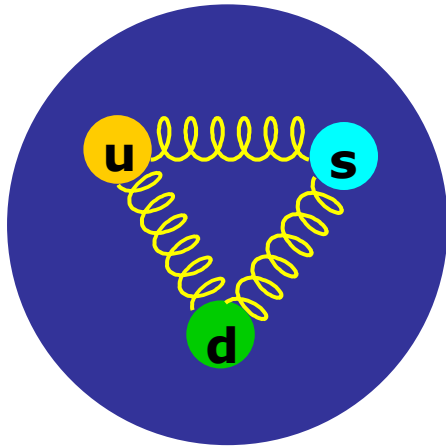
★ bound  $qqq$  states

$rgb$

(this is somewhat of an over simplification)



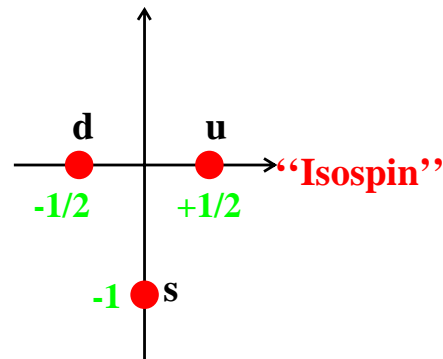
# The Light Quarks (uds)



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

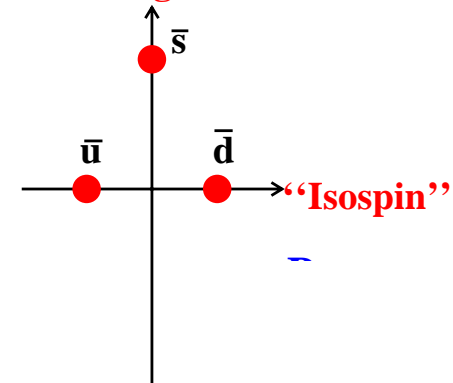
## QUARKS

“Strangeness”



## ANTIQUARKS

“Strangeness”

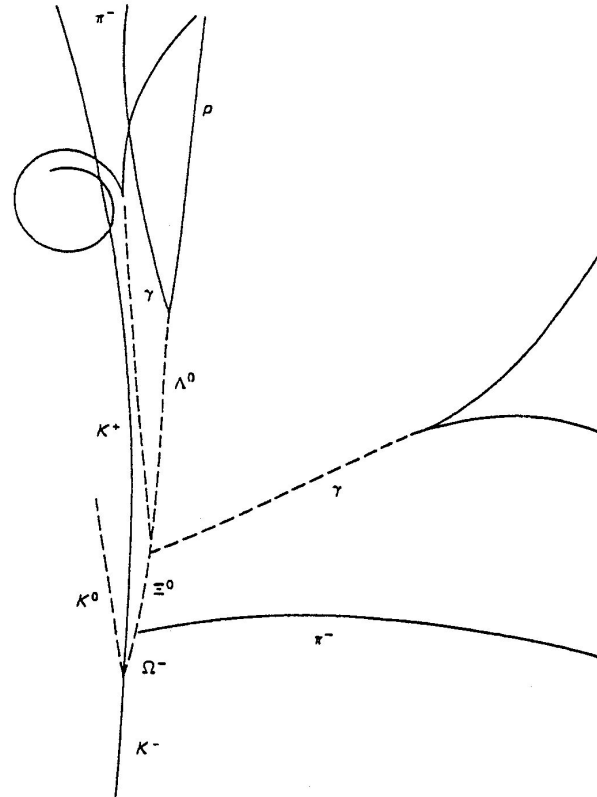
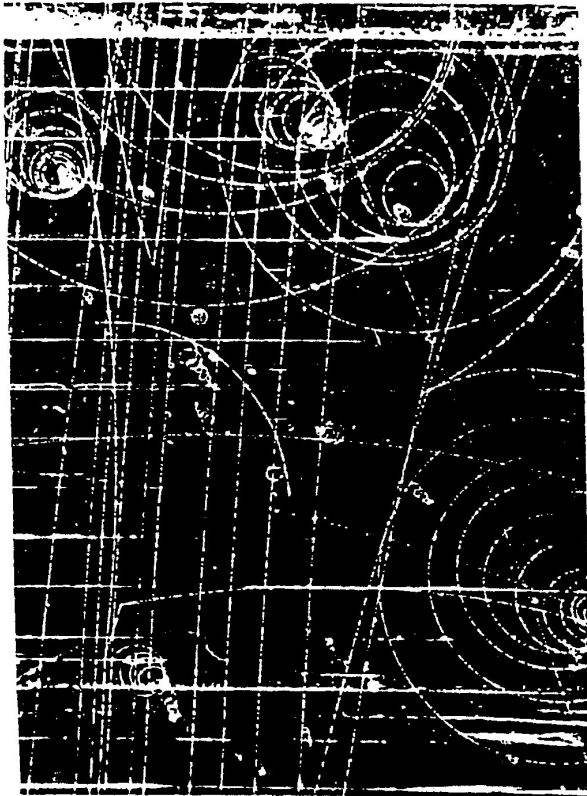


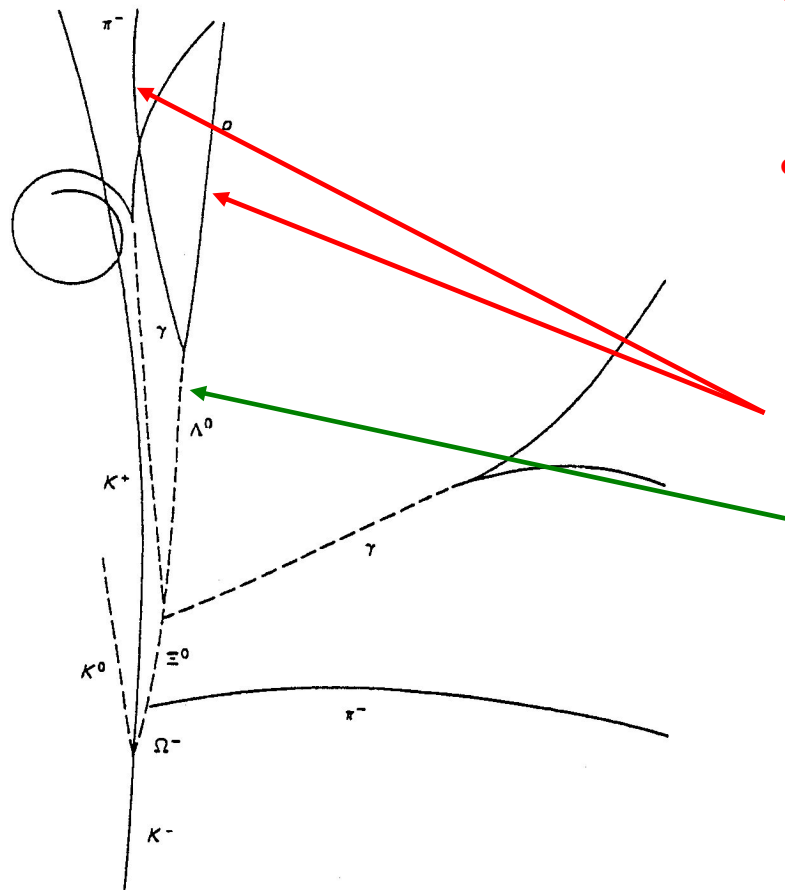
★  $\text{Isospin} = \frac{1}{2} \{N(u) - N(d)\}$

★  $\text{Strangeness} = N(\bar{s}) - N(s)$

# Particle Physics in the 1960s

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





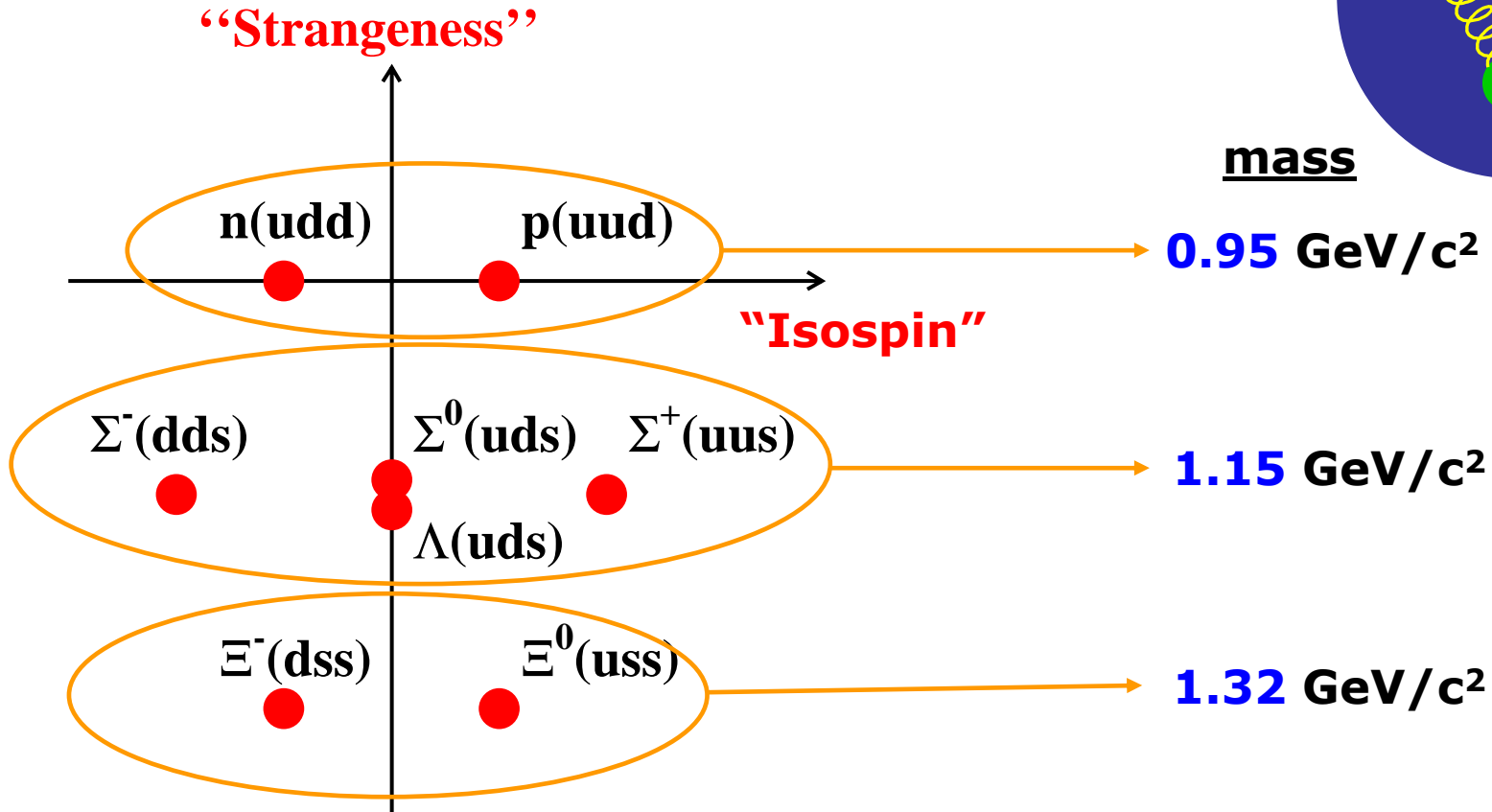
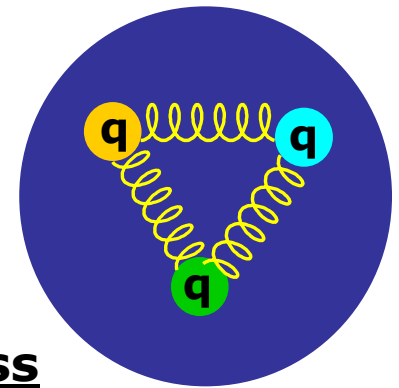
- By measuring curvature in a magnetic field can determine momentum of particles.
- Allows particle masses to be determined.

**measure momentum**

**mass**

- ★ **MANY** particles with different masses observed
- ★ **Observed patterns....**

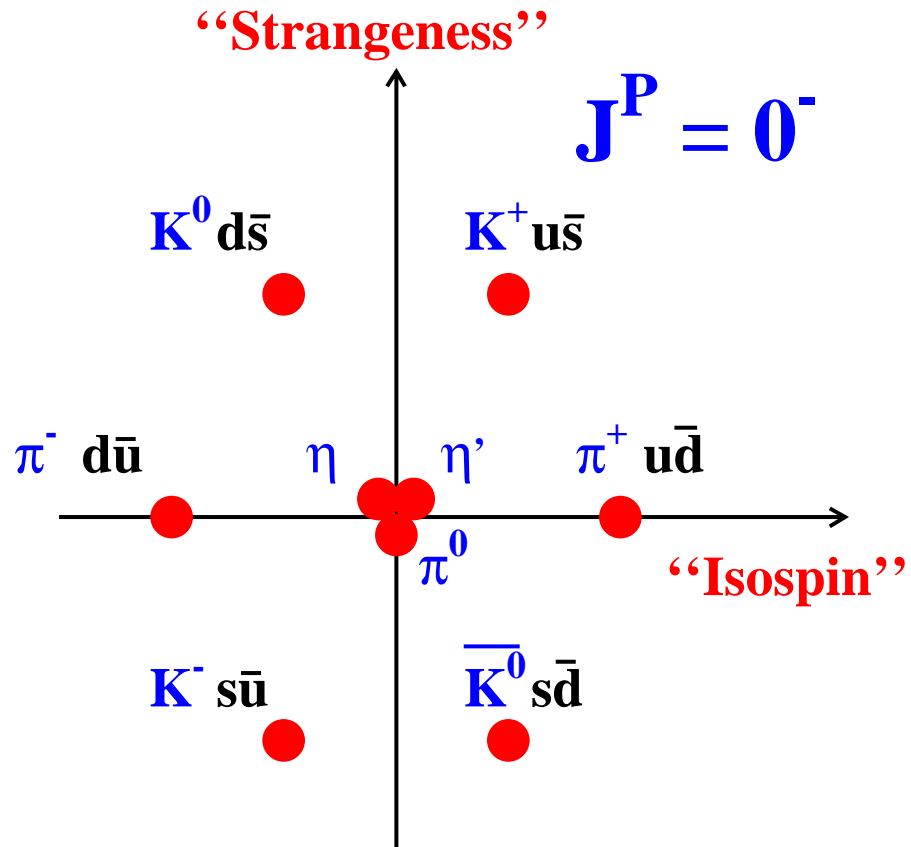
# uds Baryons



- ★ Masses can be explained assuming:
- mass of the **up** and **down** quarks =  $0.3 \text{ GeV}/c^2$
  - mass of the **strange** quark =  $0.5 \text{ GeV}/c^2$

# uds Mesons

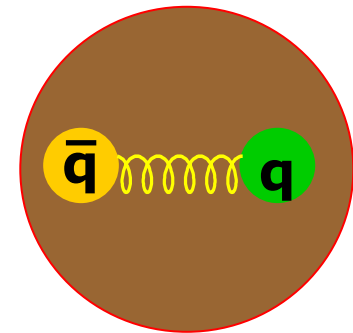
★ Again mass patterns can be seen  
e.g.  $K^-$ ,  $K^+$ ,  $K^0$ ,  $\bar{K}^0$  have mass  $0.495 \text{ GeV}/c^2$



Masses/MeV:

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

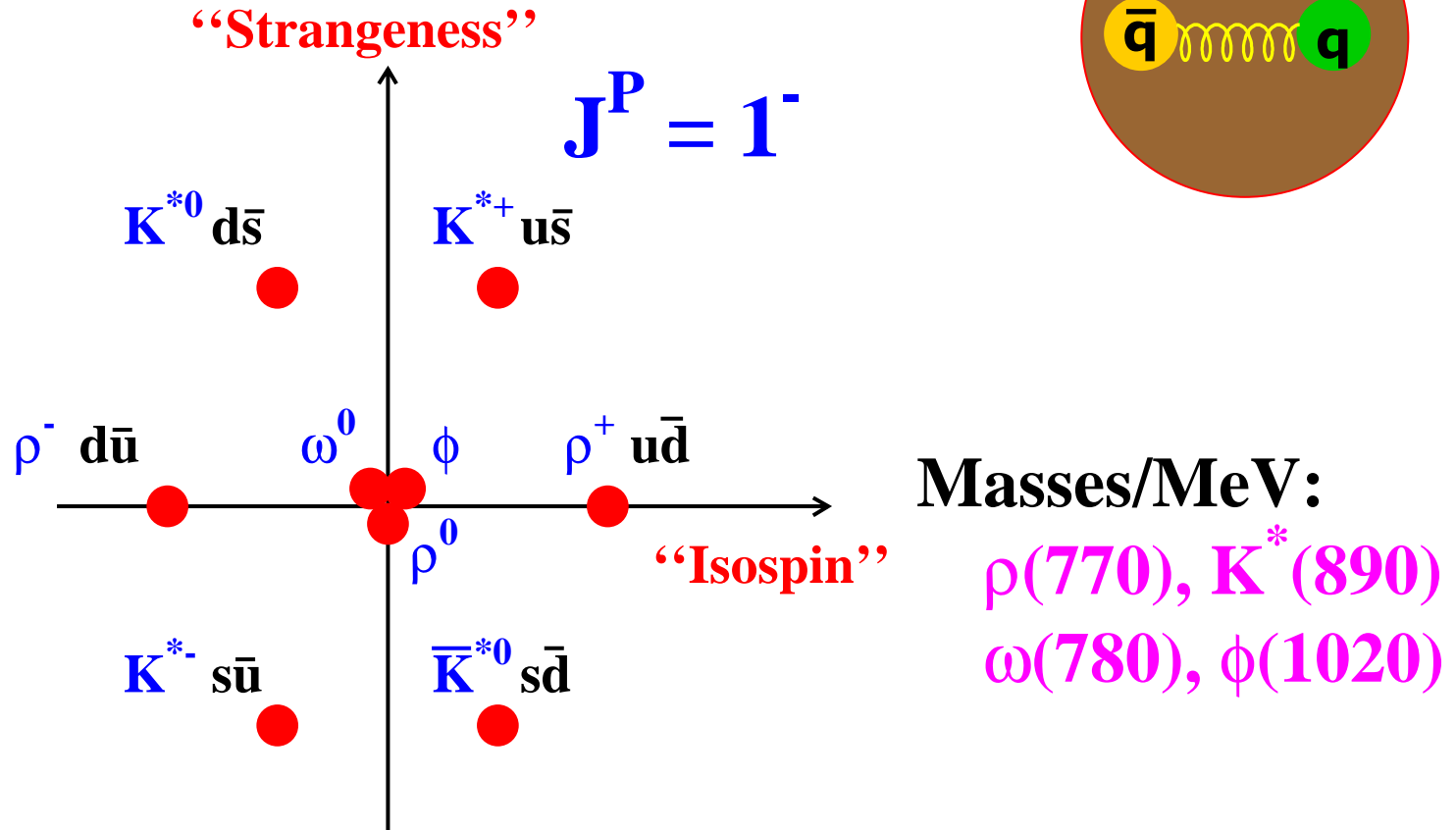
$\eta(550)$ ,  $\eta'(960)$



- ★ We have so far only considered the ground states...
- ★ There are also **excited states** !
- ★ States with “**ORBITAL ANGULAR MOMENTUM**”

# Excited States

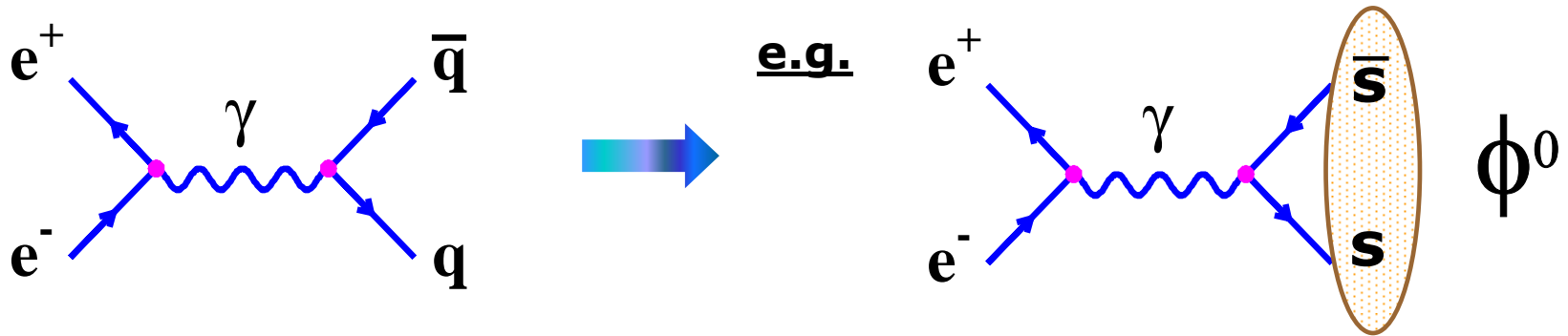
- ★ Again mass patterns can be seen  
e.g.  $K^-, K^+, K^0, \bar{K}^0$  have mass  $0.495 \text{ GeV}/c^2$



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

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

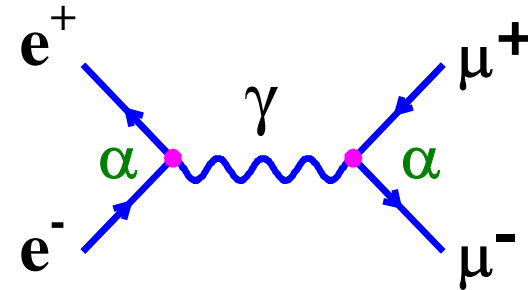
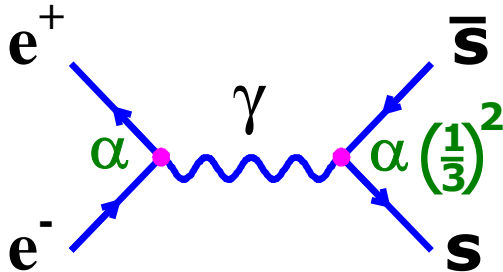
- ★ Previously we discussed how jets are produced in  $e^+e^- \rightarrow q\bar{q}$
- ★ Start with **coloured quarks** and end up with jets of **colourless hadrons**
- ★ There is another way of ending up with a colourless final state
- ★ If the energy of the  $e^+e^-$  collision is “**just right**”
- ★ 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

$R_\mu$

- Compare  $e^+e^- \rightarrow s\bar{s}$  with  $e^+e^- \rightarrow \mu^+\mu^-$



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

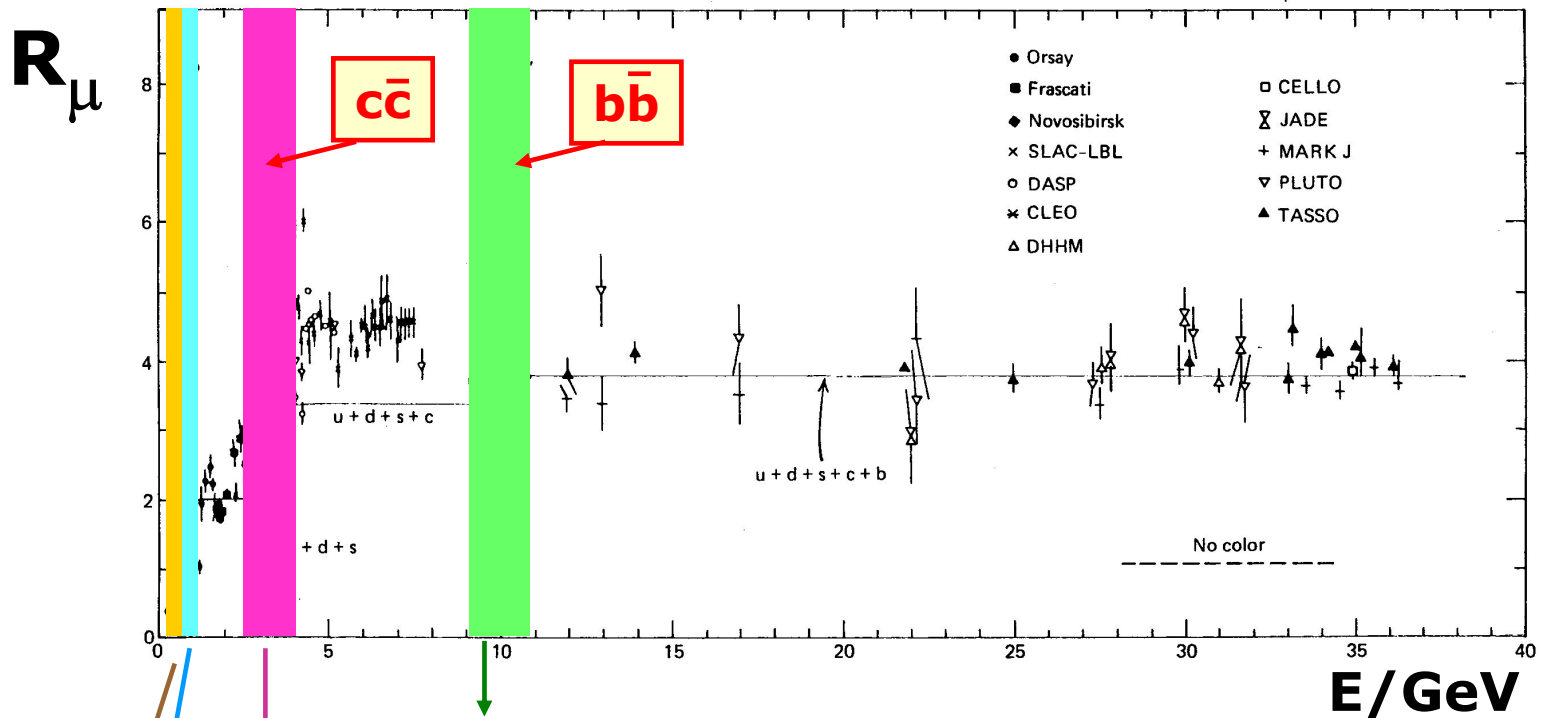
$$\text{Ratio} = Q_s^2 = \left(\frac{1}{3}\right)^2$$

QED interaction strength proportional to charge<sup>2</sup>

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



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



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

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

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

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

# 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
1 <sup>st</sup>	Down	d	-1/3	0.3 GeV/c <sup>2</sup>
1 <sup>st</sup>	Up	u	+2/3	0.3 GeV/c <sup>2</sup>
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3 <sup>rd</sup>	Top	t	+2/3	175 GeV/c <sup>2</sup>

# For further discussion....

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

