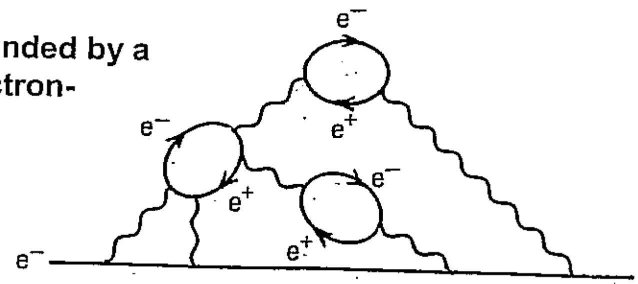
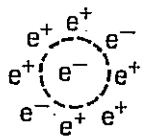
Charge Screening in Quantum Electrodynamics

An electron is surrounded by a "cloud" of virtual electron-positron pairs.

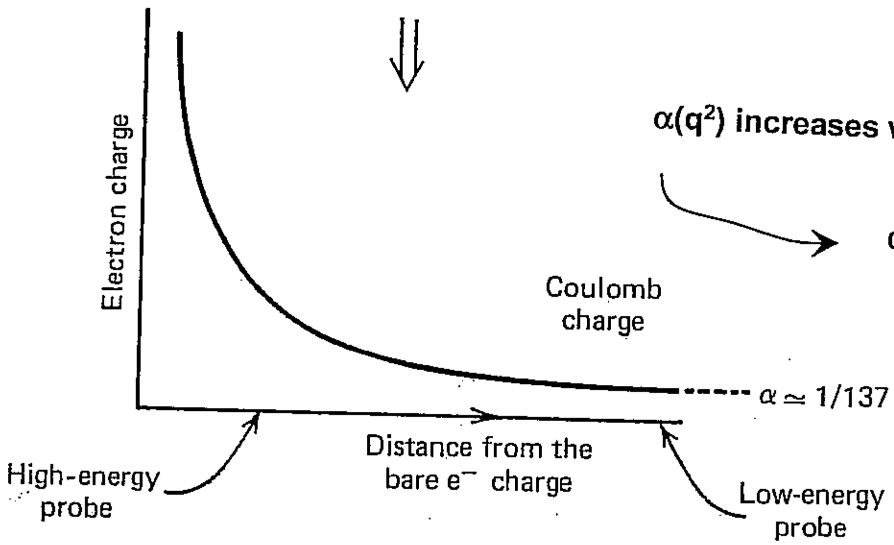


The little e^+e^- pairs can be polarized by the "bare" electron charge



This polarized e+e- cloud shields the charge of the electron. The amount of charge "seen" by an test charge some distance d away depends on d.

e.g. the amount of charge seen increases with the energy of the "probe" particle.

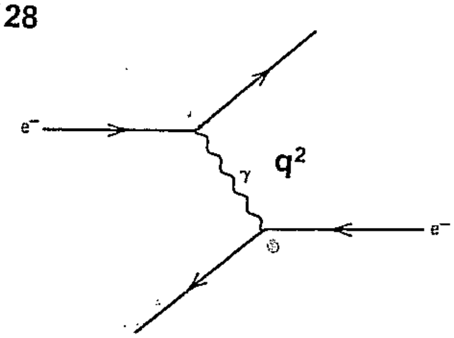


$\alpha(q^2)$ increases with q^2 → QED coupling constant

$$\alpha(Q^2) = \frac{\alpha(\mu^2)}{1 - \frac{\alpha(\mu^2)}{3\pi}\log\left(\frac{Q^2}{\mu^2}\right)}$$

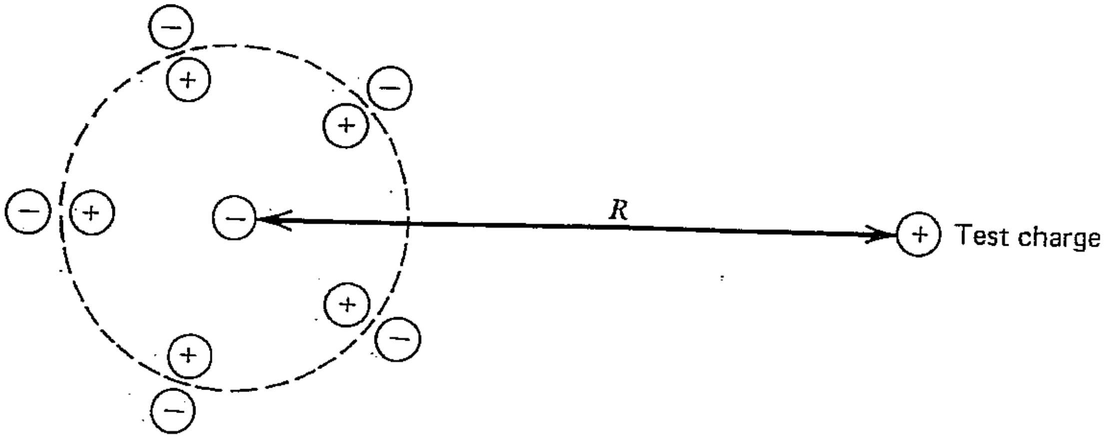
$\alpha(q^2 \sim 0) = 1/137$

$\alpha(q^2 \sim M_Z) = 1/128$

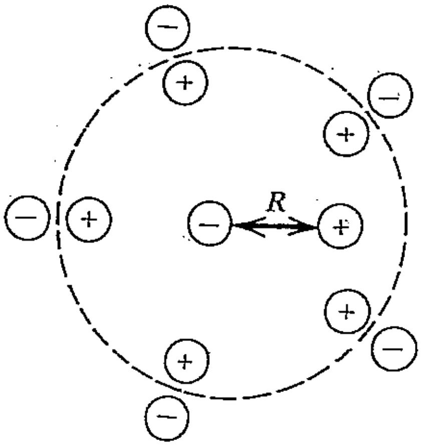


Measuring the charge of an electron

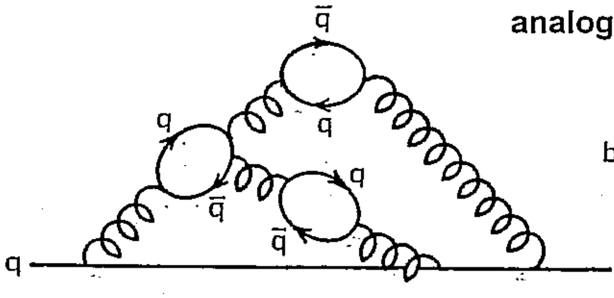
Using a long-distance probe



Using a short-distance probe

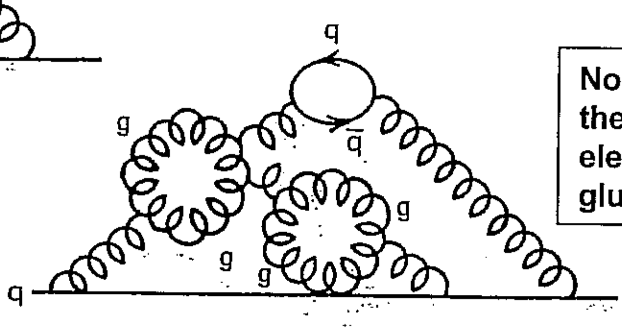


Charge Screening in Quantum Chromodynamics

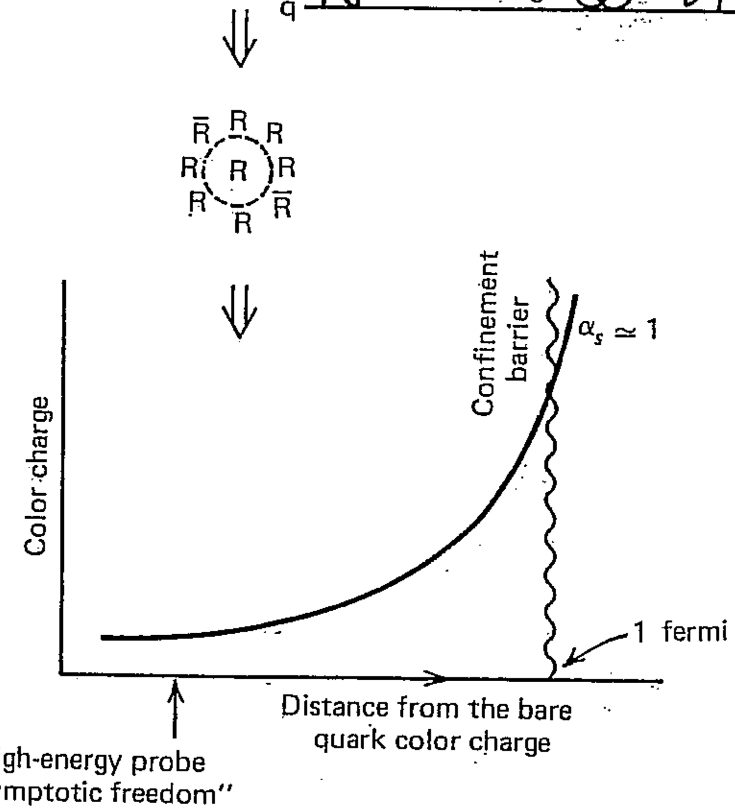


analogous to  in QED

but also



No analogy in QED since the photon does not carry electric charge (but the gluon carries colour)



Quarks must be bound into hadrons at a distance scale small than about 1 *fm*

Recall this is the typical nuclear size

$$\alpha_s(Q^2) = \frac{12\pi}{(33 - 2n_f)\log(Q^2/\Lambda^2)}.$$

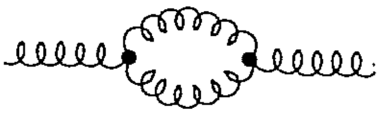
Λ is some energy scale at which QCD is perturbative (i.e. the coupling is small)

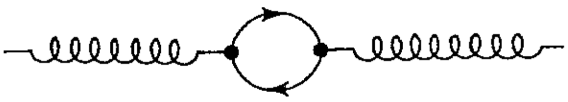
$$\alpha_s(Q^2) = \frac{12\pi}{(33 - 2n_f)\log(Q^2/\Lambda^2)}.$$

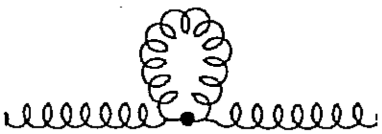
= 11 n_c with n_c = number of coulours

n_f = number of quark flavours

From







screening

(anti-screening)

Any theory with 11 $n_c > 2n_f$ has net anti-screening

(coupling constant decreases with energy instead of increasing as in QED)

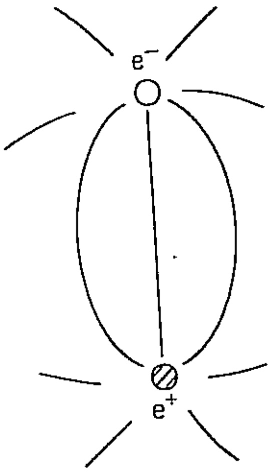
Since coupling becomes weak at short distance scales (high q2), we say that quarks in hadrons are ***asymptotically free***

Forces Between Quarks

Coulomb potential

$$V(r) \propto \frac{1}{r^2}$$

Falls of as 1/ r^2

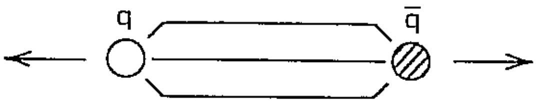


quark-antiquark colour potential

$$V(r) \propto r$$

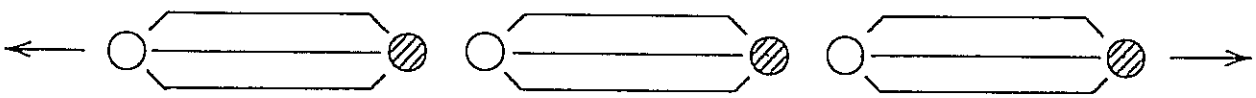
Potential grows linearly with r !

Try to separate quark-antiquark pair: must pull against linear potential



energy builds up between quark-antiquark

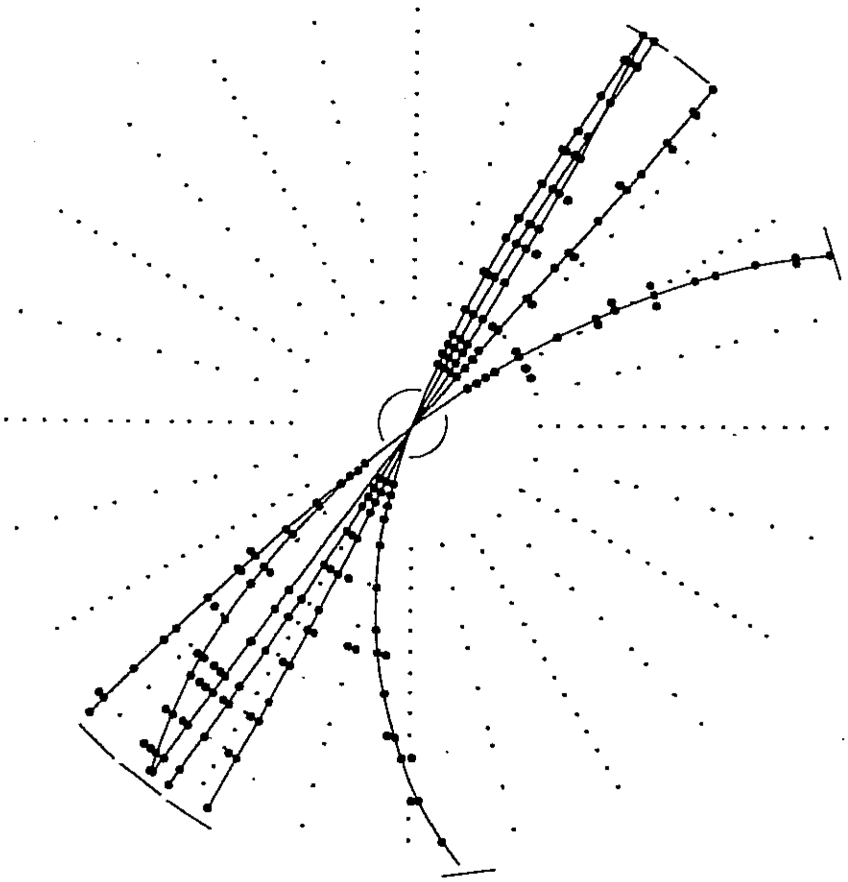
enough energy to produce new quark-antiquark pair

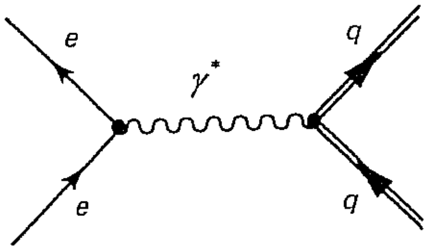


Process continues until no longer enough energy for new quarks (hadronization)

$$e^+e^- \rightarrow \gamma^* \rightarrow q\overline{q} \rightarrow$$ **hadrons**

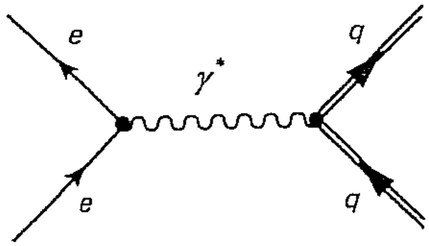
$$e^{+}e^{-} \rightarrow \gamma^{*} \rightarrow q\bar{q} \rightarrow \quad \textbf{hadrons}$$





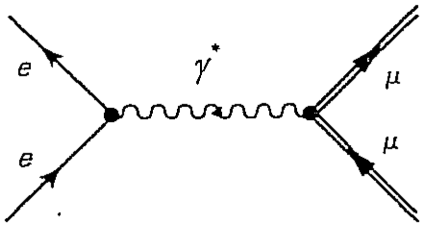
Cylindrical tracking chamber for charged particles
The particles are curved by magnetic field, which is in the beam direction:
Curvature measures the transverse momentum of the particles
electron and positron beams are in and out of the page
(this view is transverse to the beams)

$$e^+e^- \to \gamma^* \to q\overline{q} \to \quad \textbf{hadrons}$$



Amplitude for electron-positron annihilation into a pair of quarks is the same as for any other (charged) fermion pair, such as the muon

(this statement excludes electrons since there are other diagrams contributing to that process)



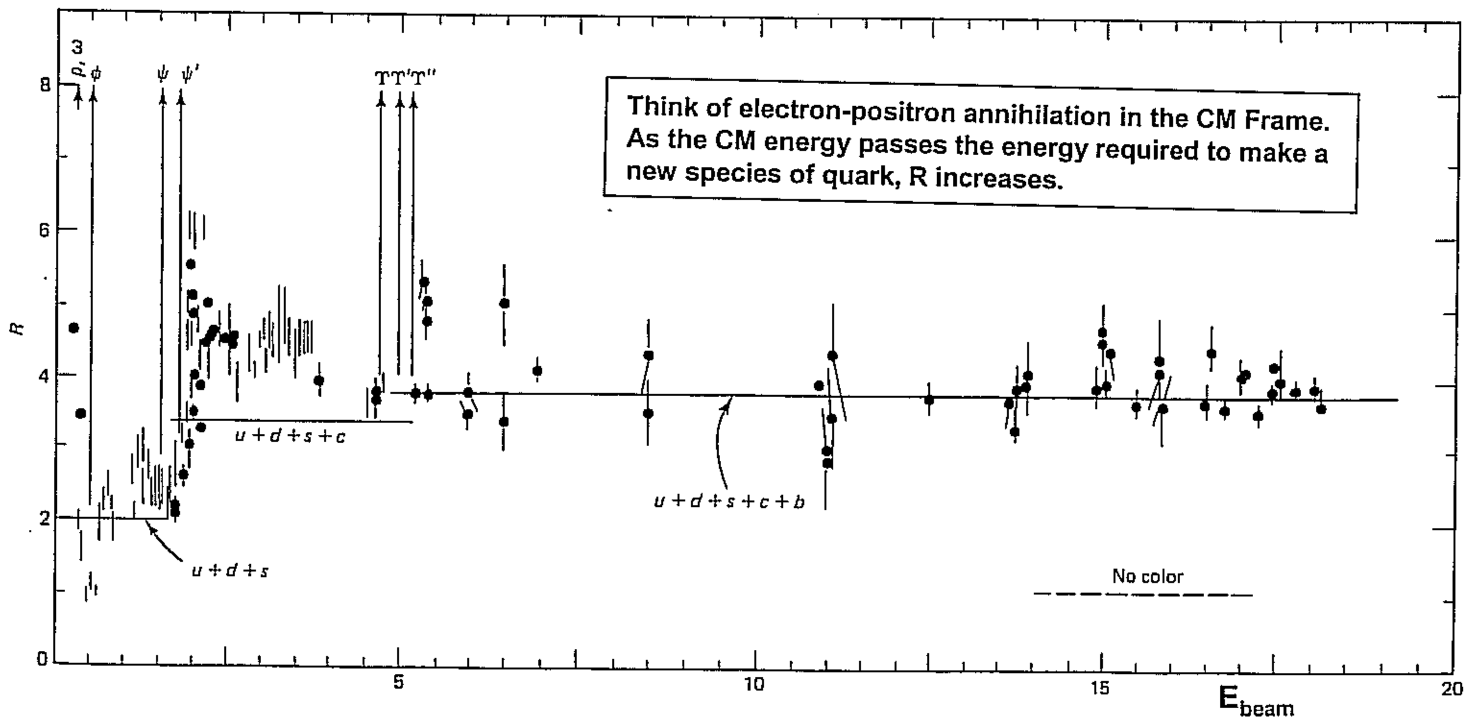
The photon couples to charge, so the only difference is that the quarks are fractionally charged

$$R = \frac{\sigma(e^+e^- \to hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)} \qquad \sigma \propto (\text{Amplitude})^2 \propto (\text{charge } Q)^2$$

$$R = 3\sum_i Q_{q_i}^2$$

Here *i* runs over the kinematically accessible species of quarks (e.g. those with mass < E_{beam})

3 → Number of colours



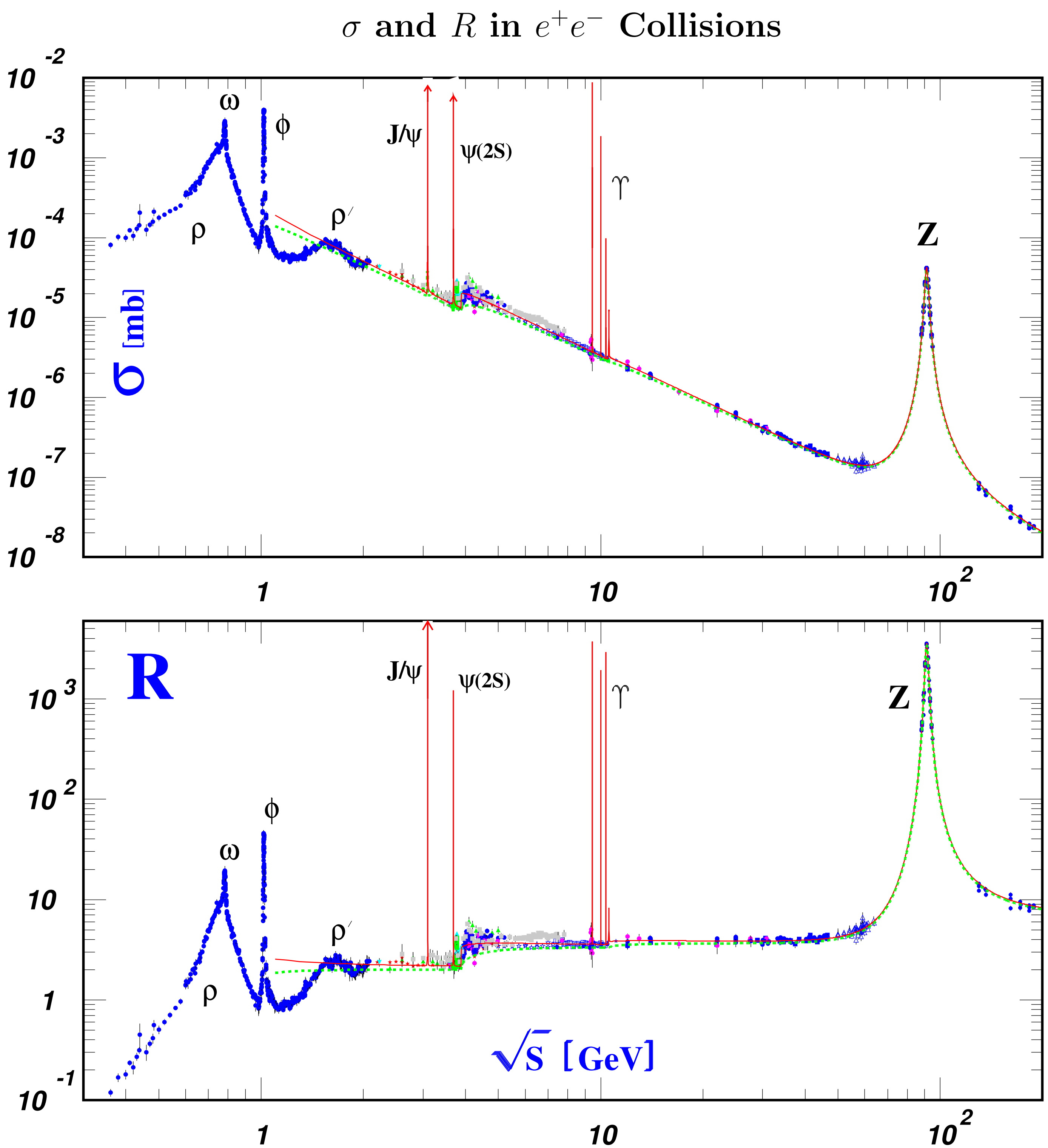


Figure 40.6: World data on the total cross section of $e^+e^- \to hadrons$ and the ratio $R(s) = \sigma(e^+e^- \to hadrons, s)/\sigma(e^+e^- \to \mu^+\mu^-, s)$. $\sigma(e^+e^- \to hadrons, s)$ is the experimental cross section corrected for initial state radiation and electron-positron vertex loops, $\sigma(e^+e^- \to \mu^+\mu^-, s) = 4\pi\alpha^2(s)/3s$. Data errors are total below 2 GeV and statistical above 2 GeV. The curves are an educative guide: the broken one is a naive quark-parton model prediction and the solid one is 3-loop pQCD prediction (see "Quantum chromodynamics" section of this *Review*, Eq. (9.12) or, for more details, K. G. Chetyrkin et al., `hep-ph/0005139`, p.3, Eqs. (1)-(3)). Breit-Wigner parameterizations of J/ψ, $\psi(2S)$, and $\Upsilon(nS), n = 1..4$ are also shown. The full list of references to the original data and the details of the R ratio extraction from them can be found in `hep-ph/0312114`. Corresponding computer-readable data files are available at http://pdg.ihep.su/xsect/contents.html. (Courtesy of the COMPAS(Protvino) and HEPDATA(Durham) Groups, March 2004. Corrections by P. Janot (CERN) and M. Schmitt (Northwestern U.))

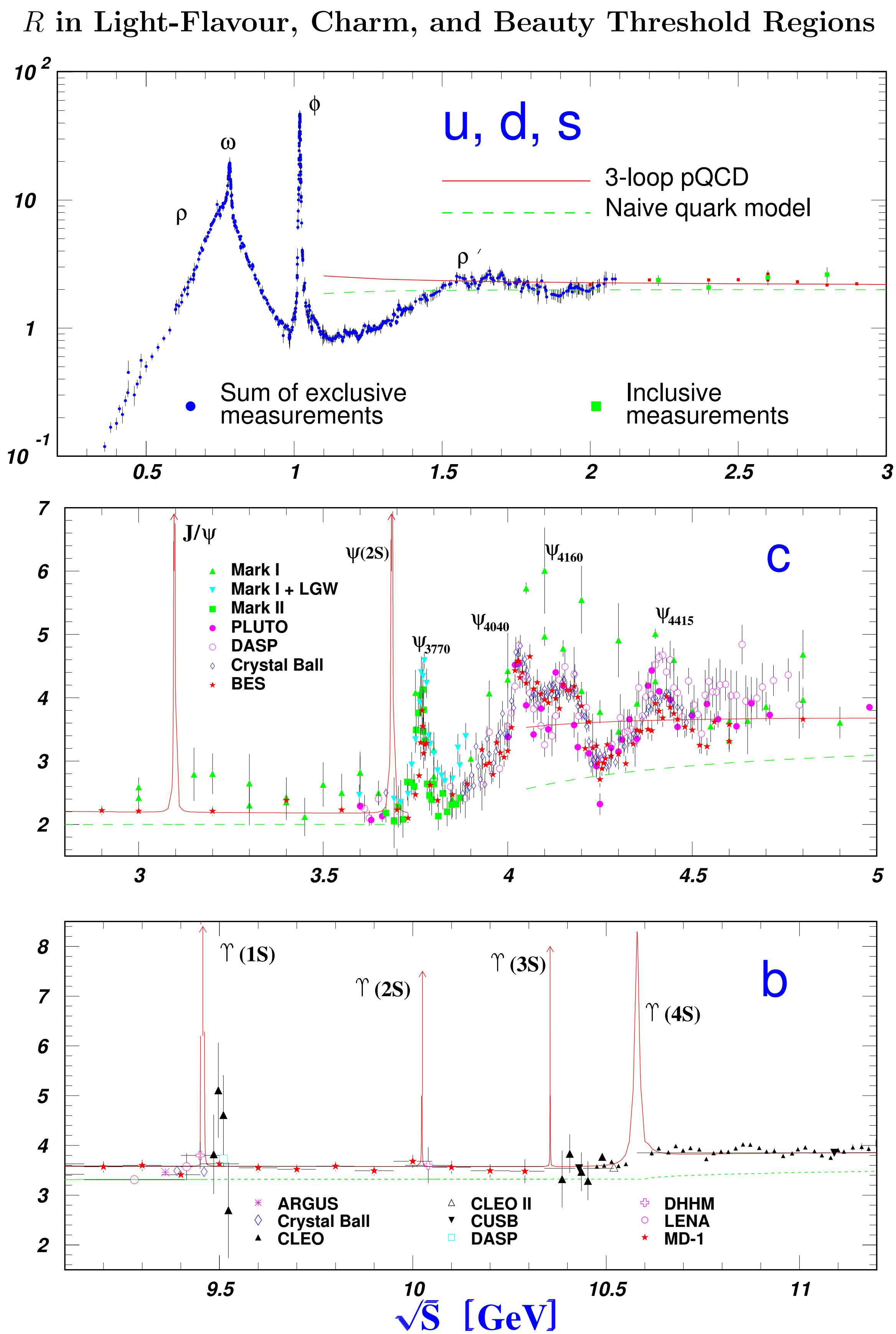


Figure 40.7: R in the light-flavour, charm, and beauty threshold regions. Data errors are total below 2 GeV and statistical above 2 GeV. The curves are the same as in Fig. 40.6. **Note:** CLEO data above $\Upsilon(4S)$ were not fully corrected for radiative effects, and we retain them on the plot only for illustrative purposes with a normalization factor of 0.8 . The full list of references to the original data and the details of the R ratio extraction from them can be found in `hep-ph/0312114`. The computer-readable data are available at http://pdg.ihep.su/xsect/contents.html (Courtesy of the COMPAS(Protvino) and HEPDATA(Durham) Groups, March 2004.)

Hadrons: Mesons and Baryons

So we have seen that quarks cannot exist freely but must be bound inside hadrons

So far we have discussed only $q\overline{q}$ states which are call *mesons* of which the pion is one example

We will see that the issue determining how quarks can bind into hadrons has to do with colour. We will show this once we begin discussing symmetries and spin and other related quantum numbers. For now let us simply adopt the following principle:

All hadrons are "colourless"

(Unlike quarks and gluons)

Mesons:	$q\overline{q}$	one colour and anticolour (e.g. blue quark, antiblue antiquark)
Baryons:	qqq	three quark bound state, one quark of each colour
Antibaryons:	$\overline{q}\overline{q}\overline{q}$	three antiquark bound state, one antiquark of each anticolour

What about electric charge ? → This is an (additive) quantum number that we are already familiar with

up-type (u—type) quarks q_u have charge +2/3

Down-type (d-type) quarks q_d have charge -1/3

Charges are opposite for antiquarks

Electric Charges of Mesons and Baryons

$$Q(q_u) = +\frac{2}{3} \qquad Q(\overline{q}_u) = -\frac{2}{3}$$

$$Q(q_d) = -\frac{1}{3} \qquad Q(\overline{q}_d) = +\frac{1}{3}$$

Mesons

$q_u\overline{q}_u$ $\quad \frac{2}{3} - \frac{2}{3} = 0$

$q_u\overline{q}_d$ $\quad \frac{2}{3} + \frac{1}{3} = 1$

$\overline{q}_u q_d$ $\quad -\frac{2}{3} - \frac{1}{3} = -1$

$q_d\overline{q}_d$ $\quad \frac{1}{3} - \frac{1}{3} = 0$

Mesons all have charge 0 or ± 1

Baryons

$q_u q_u q_u$ $\quad \frac{2}{3} + \frac{2}{3} + \frac{2}{3} = 2$

$q_u q_u q_d$ $\quad \frac{2}{3} + \frac{2}{3} - \frac{1}{3} = 1$

$q_u q_d q_d$ $\quad \frac{2}{3} - \frac{1}{3} - \frac{1}{3} = 0$

$q_d q_d q_d$ $\quad -\frac{1}{3} - \frac{1}{3} - \frac{1}{3} = -1$

Baryons have charges +2, +1, 0, -1

Antibaryon charges are +1, 0, -1, -2

Protons and Neutrons

What can we build just with up-type and down-type quarks ?

First we need to know (a little) about spin (more next class)

Quarks are fermions, with spin 1/2

Inside a hadron each of these spins can be either spin-up (↑) or spin down (↓)

A proton is a uud baryon with charge +1 and spin 1/2 (↑↑↓ or ↑↓↑ or ↓↑↑)

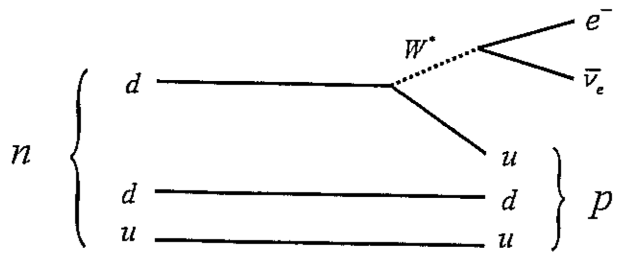
Proton wavefunction will be a linear combination of the various possible spin states with spin 1/2

For now just write this as ↑↑↓

A neutron is a udd baryon with charge 0 and spin 1/2 (↑↑↓)

Radioactive β-decay $^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + e^- + \bar{\nu}_e$ **is actually** $n \rightarrow p + e^- + \bar{\nu}_e$

Underlying fundamental interaction is $d \rightarrow u + W^* \rightarrow u + e^- + \bar{\nu}_e$



Hadrons with u, d quarks cont'd

$uuu = \Delta^{++}$ charge +2 spin 3/2 (↑↑↑ or ↓↓↓) We will come back to this state later

Ground State Mesons with u,d quarks

spin 0 (↑↓, ↓↑)

$u\bar{d}, \bar{u}d \quad \pi^{\pm}$

$u\bar{u}, \bar{d}d \quad \pi^{0}$ $\qquad \pi^0 = \frac{1}{\sqrt{2}}(u\bar{u} + \bar{d}d)$

spin 1 (↑↑, ↓↓)

$u\bar{d}, \bar{u}d \quad \rho^{\pm}$

$u\bar{u}, \bar{d}d \quad \rho^{0}$ $\qquad \rho^0 = \frac{1}{\sqrt{2}}(u\bar{u} + \bar{d}d)$

For a time, only protons, neutrons, pions, rho mesons and other low lying "resonances" were known.

Resonances are excited states that decay quickly (via the strong interaction) on timescales typical of that interaction (~ 10^{-23} s)

For instance say we do an experiment in π p scattering $\pi^+ + p \to \pi^+ + p$

We will dicsuss such experiments later, but if there are higher-mass particles that can decay into π^+ p, these states (with well defined quantum numbers) will show up as "resonances".

Strangeness

Hypothesize some conserved quantum number: Strangeness

In collision (strong interaction) produce s = 1 and s = -1 states simulataneously (so that strangeness is conserved)

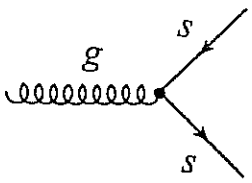
$\pi^- + p \rightarrow$ particles with strange quark + particle with anti-strange quark + other particles

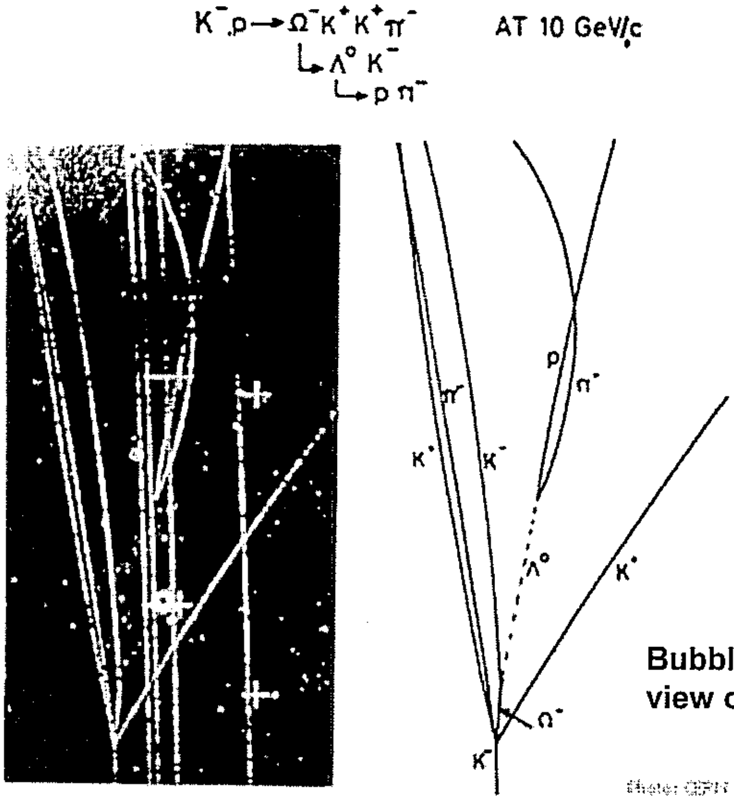
$\pi^- + p \rightarrow \Lambda^0 K^0$ $\qquad \bar{u}d + uud \rightarrow uds + \bar{s}u$ $\qquad$ **Associated production**

Alternatively, scattering of a strange particle from a proton

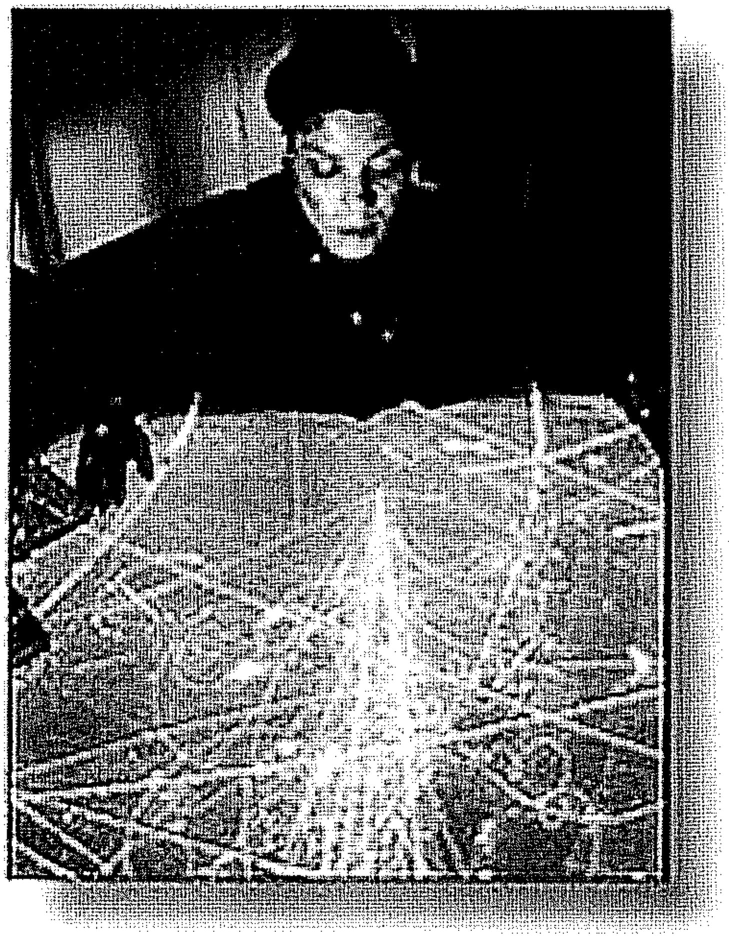
$K^- + p \rightarrow \Xi^- + K^+$ $\qquad s\bar{u} + uud \rightarrow dss + \bar{s}u$

In each case in the strong interaction we have a vertex





Bubble chamber photograph and "cleaned-up" view of interesting interaction

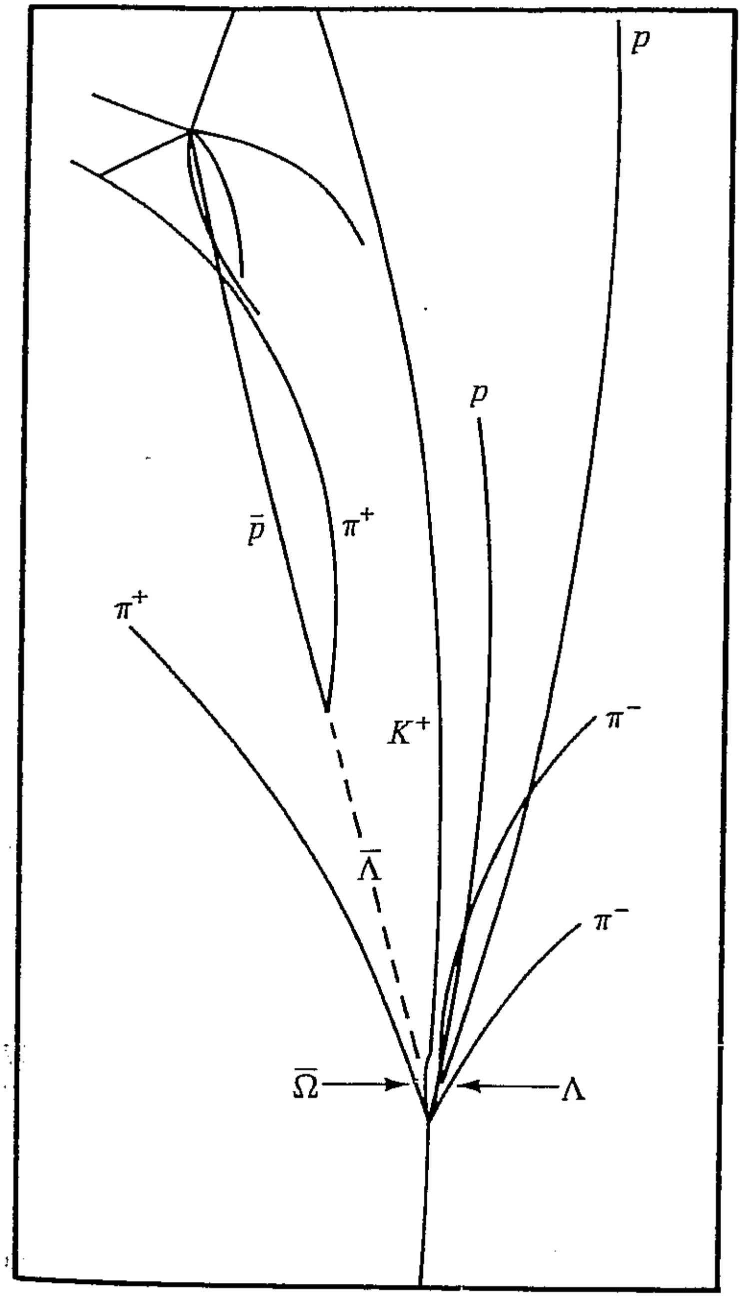


Bubble chamber photograph scanning

Originally done manually

Discovery of "Strange" Particles

Event recorded in a Bubble Chamber
(essentially a proton target)



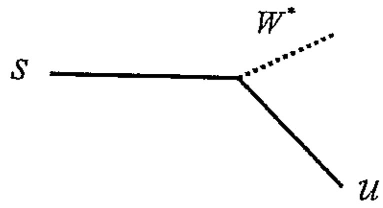
Neutral " V^0 " particle produced in hadronic collisions via the strong interaction

But cannot *decay* via the strong interaction……leads to an anomalously long lifetime (compared to other particles known at the time)

Quark Flavours

Ground state baryons & mesons containing a strange quark can only decay to lighter particles via decay of the strange quark

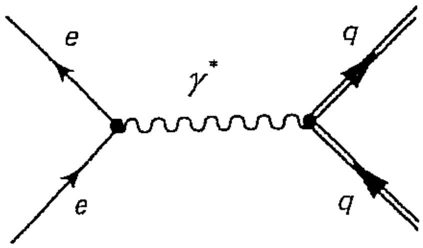
which occurs via the weak interaction (typical $\tau \sim 10^{-13}$ s)



10 orders of magnitude slower than the strong interaction

Fourth and fifth quarks discovered in the 1970's, in electron-positron collisions (and in aother process as well)

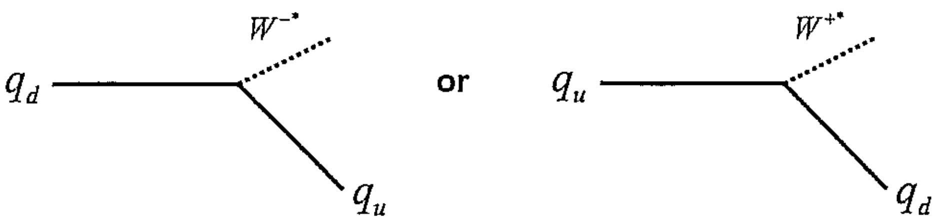
$e^+e^- \to \gamma^* \to q\overline{q} \to$ hadrons



here $qq = u\overline{u}, d\overline{d}, s\overline{s}, c\overline{c}, b\overline{b}$ N.B. NEVER (for instance) $u\overline{c}$

The only interaction that can mix flavours of quarks is the

<u>charged weak interaction</u>



Quarks and hadrons cont'd

6^{th} quark (the top quark) discovered in high-energy proton-antiproton collision at Fermilab in 1995

top quark (t) does not form hadrons (e.g. $t\overline{u}$) because it decays on a shorter timescale (~ 10^{-25}) that that assciated with the strong interaction (~ 10^{-23} s) which is responsible for hadronization

So all known hadrons are made of $q\overline{q}, qqq,$ and $\overline{q}\overline{q}\overline{q}$ bound states of u,d,s,c and b quarks, in all possible combinations.

Ground state mesons ALWAYS have spin 0 or spin 1

Next time we will look at how we add orbital angular momentum to produce excited states.

Orbital angular momentum always comes in integer units, so mesons always have integer spin

All mesons are BOSONS

Ground state baryons ALWAYS have either spin 1/2 or 3/2

Adding orbital angular momentum still leaves us with half-integer spin

All baryons are FERMIONS

Pauli-exlcusion principle applies to protons and neutrons in the nucleus

BARYONS (Spin $\frac{1}{2}$)

Baryon	Quark content	Charge	Mass	Lifetime	Principal decays
N p	uud	+1	938.280	∞	—
N n	udd	0	939.573	900	$pe\bar{\nu}_e$
Λ	uds	0	1115.6	2.63×10^{-10}	$p\pi^-$, $n\pi^0$
Σ^+	uus	+1	1189.4	0.80×10^{-10}	$p\pi^0$, $n\pi^+$
Σ^0	uds	0	1192.5	6×10^{-20}	$\Lambda\gamma$
Σ^-	dds	−1	1197.3	1.48×10^{-10}	$n\pi^-$
Ξ^0	uss	0	1314.9	2.90×10^{-10}	$\Lambda\pi^0$
Ξ^-	dss	−1	1321.3	1.64×10^{-10}	$\Lambda\pi^-$
Λ_c^+	udc	+1	2281	2×10^{-13}	not established

BARYONS (Spin $\frac{3}{2}$)

Baryon	Quark content	Charge	Mass	Lifetime	Principal decays
Δ	uuu, uud, udd, ddd	+2, +1, 0, −1	1232	0.6×10^{-23}	$N\pi$
Σ^*	uus, uds, dds	+1, 0, −1	1385	2×10^{-23}	$\Lambda\pi$, $\Sigma\pi$
Ξ^*	uss, dss	0, −1	1533	7×10^{-23}	$\Xi\pi$
Ω^-	sss	−1	1672	0.82×10^{-10}	ΛK^-, $\Xi^0\pi^-$, $\Xi^-\pi^0$

PSEUDOSCALAR MESONS (Spin 0)

Meson	Quark content	Charge	Mass	Lifetime	Principal decays
$\pi^\pm$	$u\bar{d}$, $d\bar{u}$	+1, −1	139.569	2.60×10^{-8}	$\mu\nu_\mu$
π^0	$(u\bar{u}-d\bar{d})/\sqrt{2}$	0	134.964	8.7×10^{-17}	$\gamma\gamma$
$K^\pm$	$u\bar{s}$, $s\bar{u}$	+1, −1	493.67	1.24×10^{-8}	$\mu\nu_\mu$, $\pi^\pm\pi^0$, $\pi^\pm\pi^\pm\pi^\mp$
K^0, $\bar{K}^0$	$d\bar{s}$, $s\bar{d}$	0, 0	497.72	K_S^0 0.892×10^{-10}; K_L^0 5.18×10^{-8}	$\pi^+\pi^-$, $\pi^0\pi^0$; $\pi e\nu_e$, $\pi\mu\nu_\mu$, $\pi\pi\pi$
η	$(u\bar{u}+d\bar{d}-2s\bar{s})/\sqrt{6}$	0	548.8	7×10^{-19}	$\gamma\gamma$, $\pi^0\pi^0\pi^0$, $\pi^+\pi^-\pi^0$
η'	$(u\bar{u}+d\bar{d}+s\bar{s})/\sqrt{3}$	0	957.6	3×10^{-21}	$\eta\pi\pi$, $\rho^0\gamma$
$D^\pm$	$c\bar{d}$, $d\bar{c}$	+1, −1	1869	9×10^{-13}	$K\pi\pi$
D^0, $\bar{D}^0$	$c\bar{u}$, $u\bar{c}$	0, 0	1865	4×10^{-13}	$K\pi\pi$
$F^\pm$ (now $D_s^\pm$)	$c\bar{s}$, $s\bar{c}$	+1, −1	1971	3×10^{-13}	not established
$B^\pm$	$u\bar{b}$, $b\bar{u}$	+1, −1	5271	14×10^{-13}	$D + ?$
B^0, $\bar{B}^0$	$d\bar{b}$, $b\bar{d}$	0, 0	5275	14×10^{-13}	$D + ?$
η_c	$c\bar{c}$	0	2981	6×10^{-23}	$KK\pi$, $\eta\pi\pi$, $\eta'\pi\pi$

VECTOR MESONS (Spin 1)

Meson	Quark content	Charge	Mass	Lifetime	Principal decays
ρ	$u\bar{d}$, $d\bar{u}$, $(u\bar{u}-d\bar{d})/\sqrt{2}$	+1, −1, 0	770	0.4×10^{-23}	$\pi\pi$
K^*	$u\bar{s}$, $s\bar{u}$, $d\bar{s}$, $s\bar{d}$	+1, −1, 0, 0	892	1×10^{-23}	$K\pi$
ω	$(u\bar{u}+d\bar{d})/\sqrt{2}$	0	783	7×10^{-23}	$\pi^+\pi^-\pi^0$, $\pi^0\gamma$
ϕ	$s\bar{s}$	0	1020	20×10^{-23}	K^+K^-, $K^0\bar{K}^0$
J/ψ	$c\bar{c}$	0	3097	1×10^{-20}	e^+e^-, $\mu^+\mu^-$, 5π, 7π
D^*	$c\bar{d}$, $d\bar{c}$, $c\bar{u}$, $u\bar{c}$	+1, −1, 0, 0	2010	$>1\times10^{-22}$	$D\pi$, $D\gamma$
Υ	$b\bar{b}$	0	9460	2×10^{-20}	$\tau^+\tau^-$, $\mu^+\mu^-$, e^+e^-