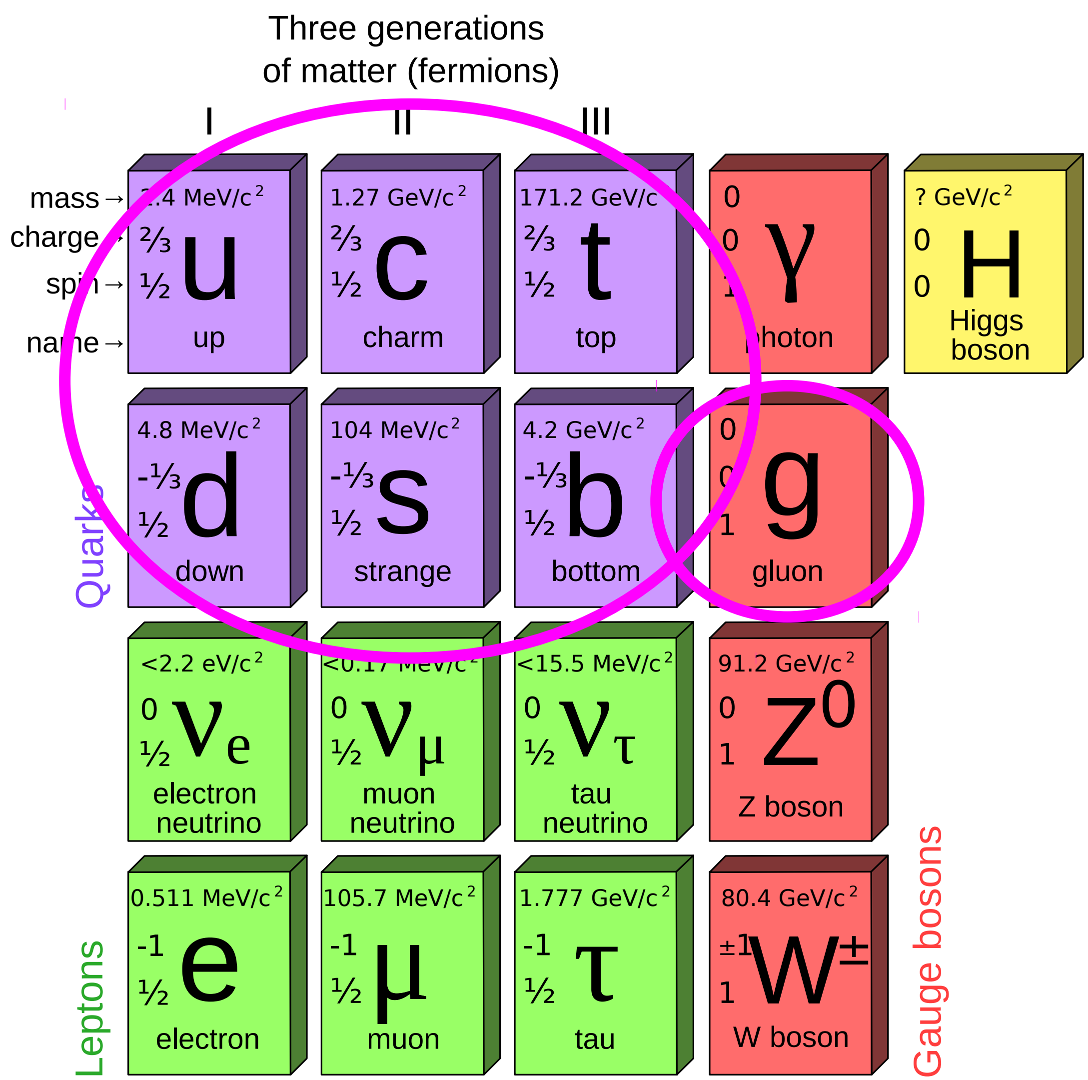
Quarks and Hadrons



Basic info about quarks and gluons

3 color charges (red, green, blue)

<u>Not real colors</u> but e.g. qx, qy, qz that can be +qx for quarks (red) and -qx for anti-quarks (anti-red)

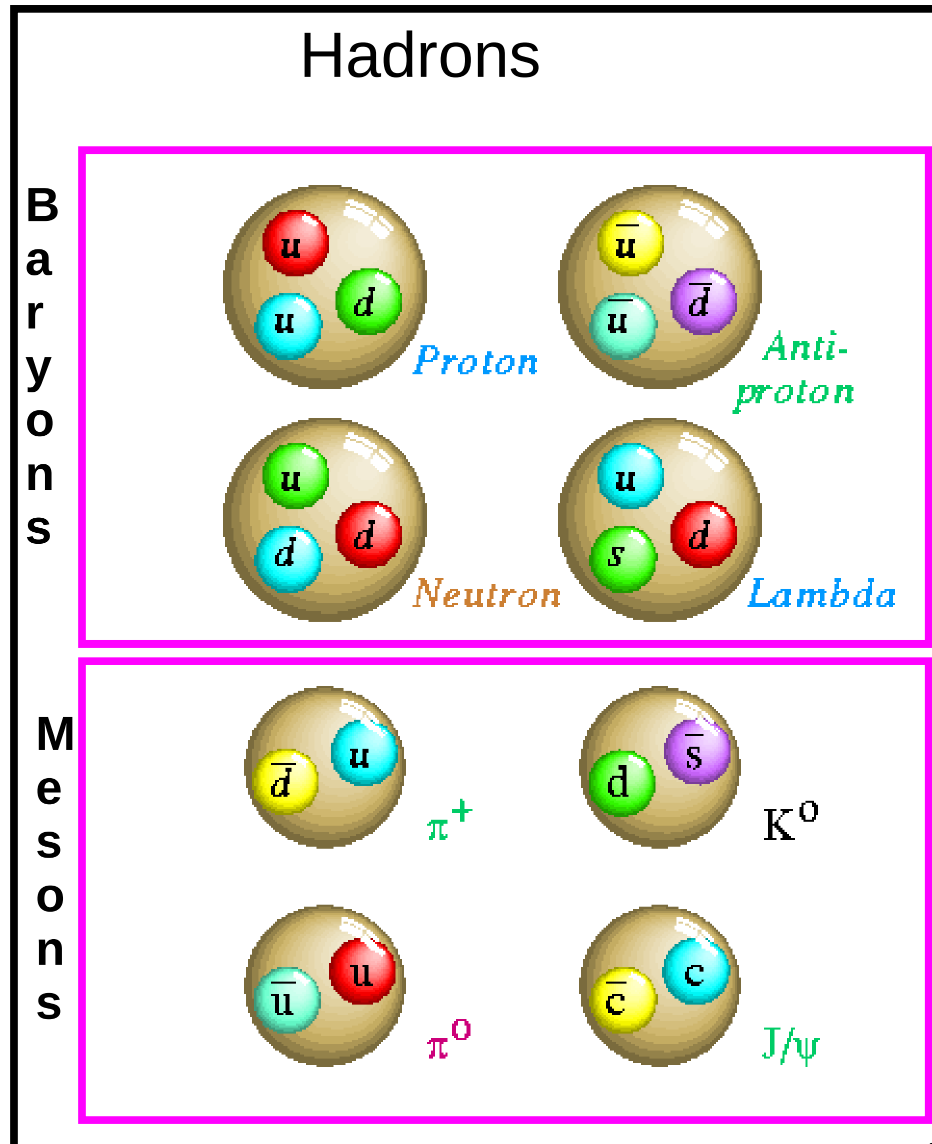
Hadrons have to be colorless

Baryons have all 3 colors

Mesons has a color and an anti-color

There are 8 gluons. They carry a color-anticolor e.g. red-antigreen:

Example of gluon radiation:
green quark →
red quark + green-antired gluon



Start with an excursion!

Quark masses?

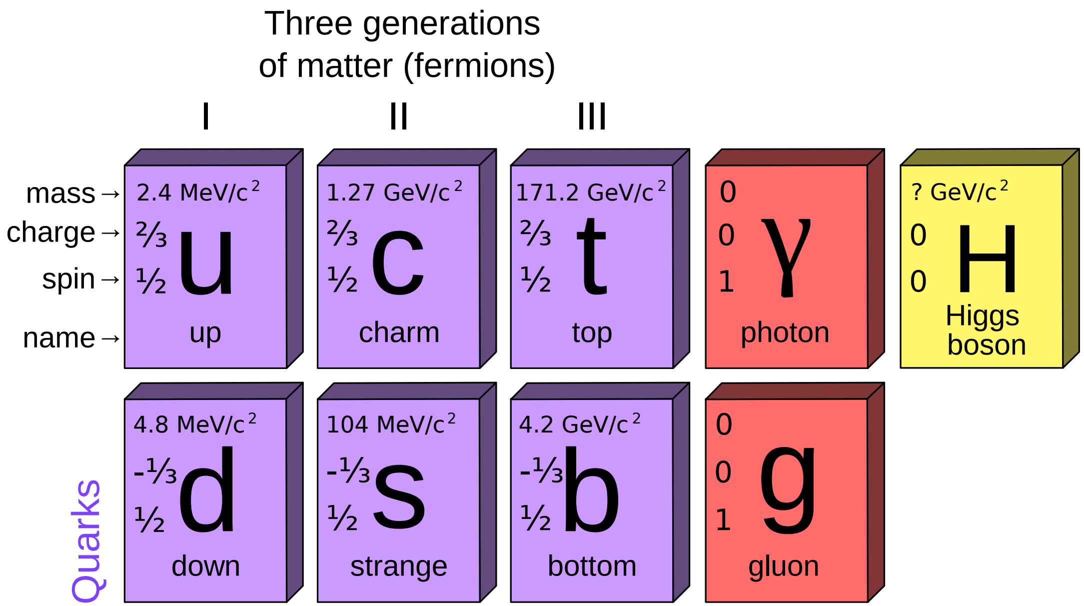


TABLE 3.1 The approximate masses of the quarks in GeV/c^2 and their electric charges Q in units of e. Also shown are the values of the baryon number B, strangeness S, charm C, bottom $\tilde{B}$ and top T, as defined in Section 3.2. The values for the corresponding antiquarks are equal in magnitude, but opposite in sign.

Name	Symbol	Mass	Q	B	S	C	$\tilde{B}$	T
Down	d	$m_d \approx 0.3$	$-1/3$	1/3	0	0	0	0
Up	u	$m_u \approx m_d$	2/3	1/3	0	0	0	0
Strange	s	$m_s \approx 0.5$	$-1/3$	1/3	-1	0	0	0
Charmed	c	$m_c \approx 1.5$	2/3	1/3	0	1	0	0
Bottom	b	$m_b \approx 4.5$	$-1/3$	1/3	0	0	-1	0
Top	t	$m_t \approx 174$	2/3	1/3	0	0	0	1

Two definitions

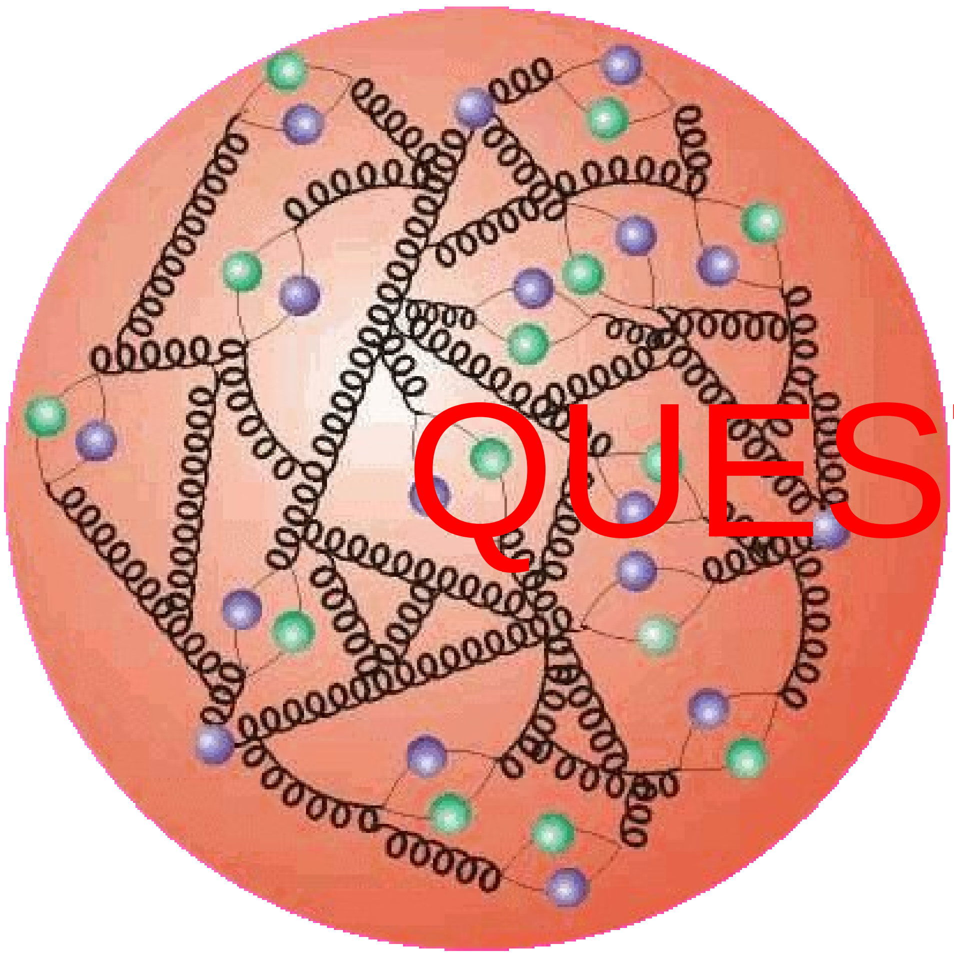
- Constituent quark mass:
  - The effective mass in the hadrons:
    - Mp ~ 938 MeV → Mu~Md~300 MeV
- Free quark mass:
  - The mass if the quarks were not bound inside hadrons
- Nonstandard situation:
  - Bound state heavier than non-bound state!
  - Probably we should not say bound but confined!

Mass due to confinement

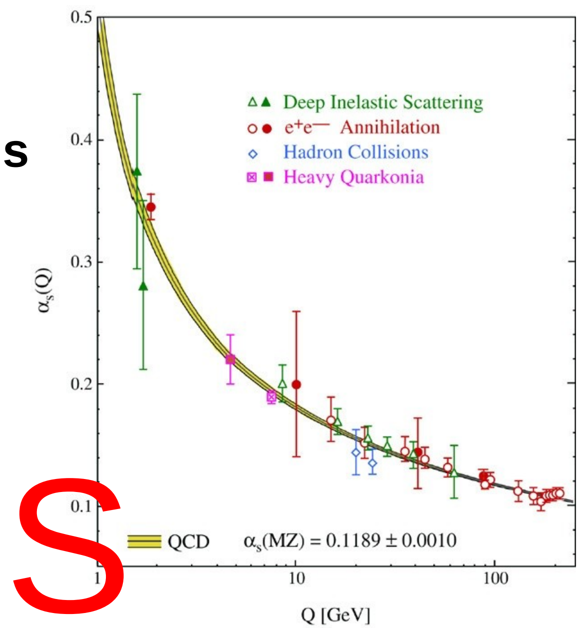
- From Heisenberg's uncertainty relation:
  - $\Delta p * \Delta x \sim$ hbar
- When we confine → restrict Δx
  - $\Delta x \sim 1$ fm → $\Delta p \sim 200$ MeV
  - And we know $E=p^2 + m^2$ so the confinement momentum dominates the energy (effective mass)

Many difficult aspects about the strong force

- The strong interaction is very complex!

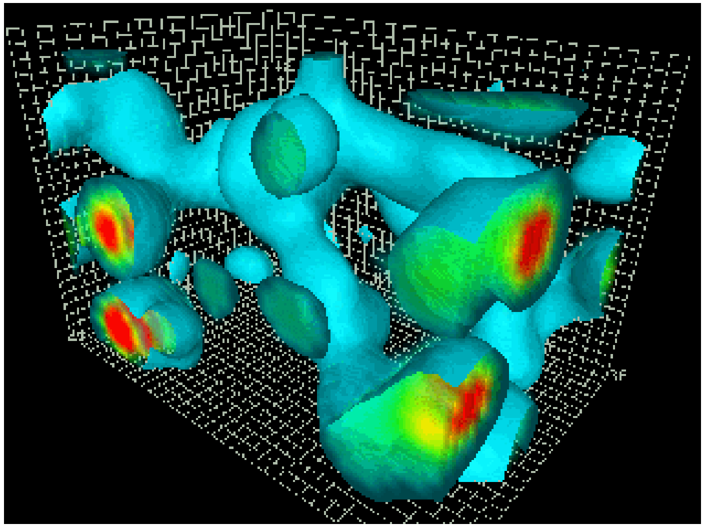


Quarks and gluons couples strong:



QUESTIONS

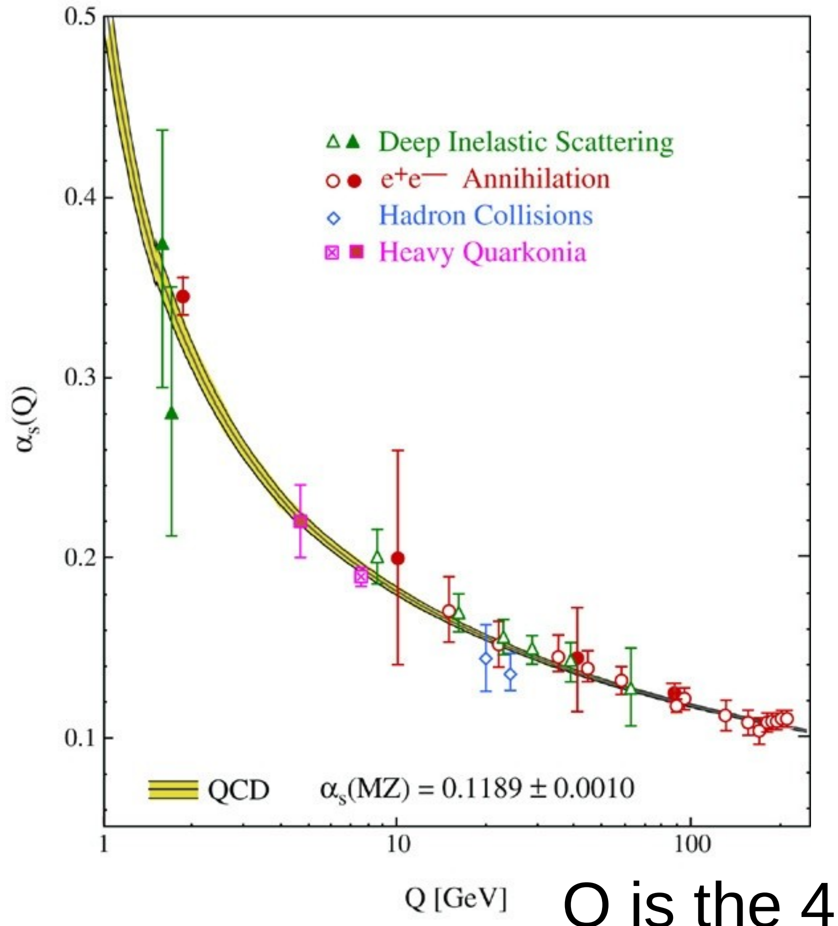
Complex vacuum:



CONFINEMENT

The coupling is not fixed but runs!

α_s



Q is the 4 momentum transfer

In fact it becomes ~1 at the scale Λ_{QCD}~200 MeV

Screening/running of the coupling in electromagnetic collisions

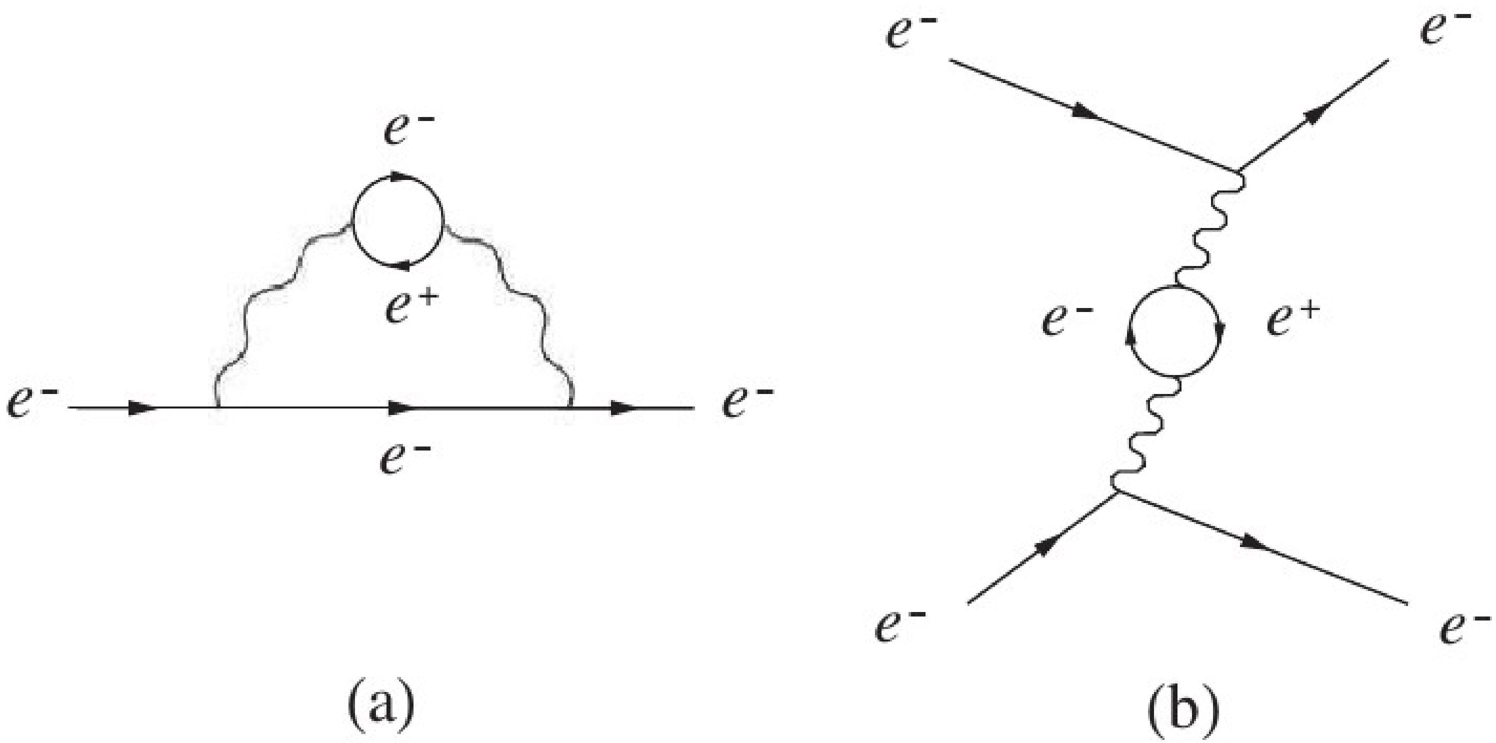
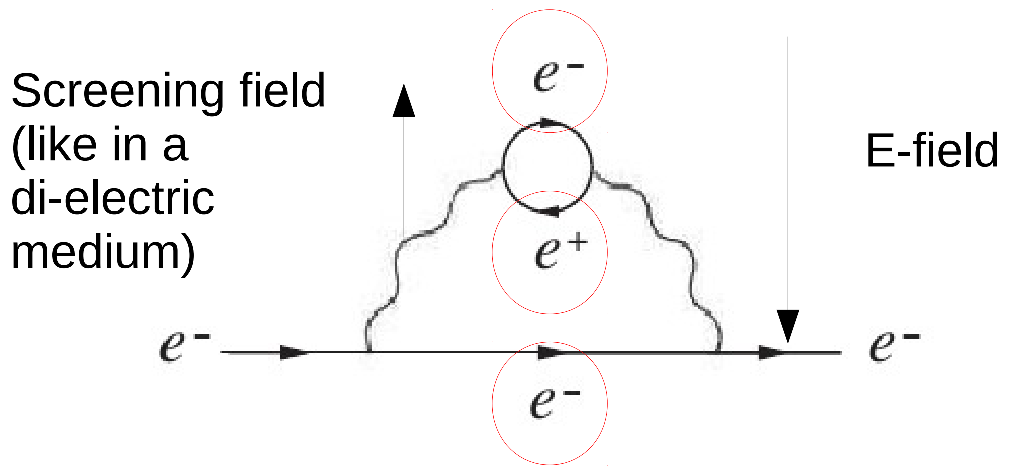


Figure 7.5 A more complicated quantum fluctuation of the electron, together with the associated exchange process.

Due to (polarized) fluctuations the vacuum screens the charge! (vacuum ~ dielectric medium)

Notice the order: -, +, -!



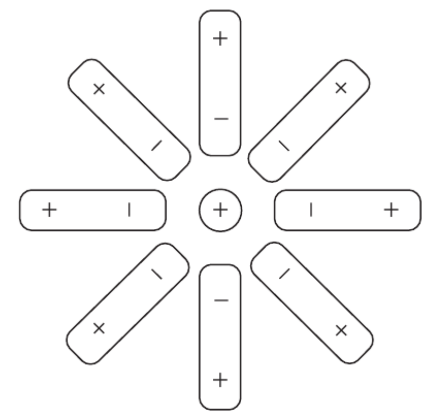
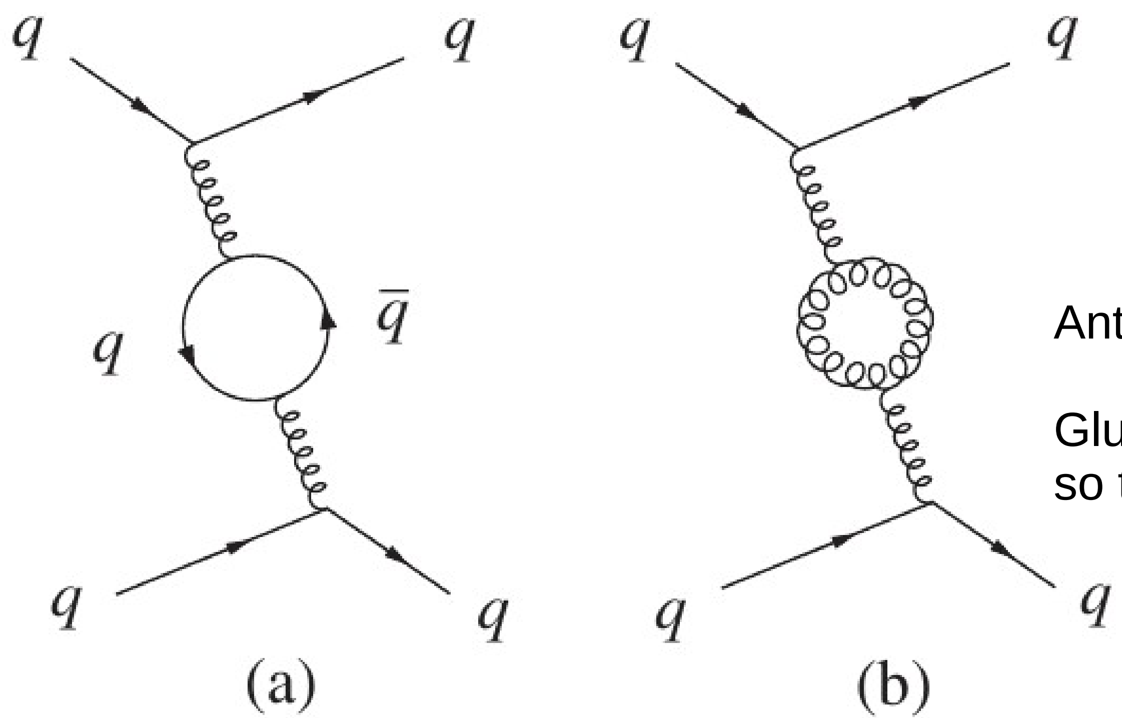


Figure 7.6 Schematic diagram representing the polarization of the molecules of a dielectric by a positive charge placed within it.

The effect is measurable:
At low energy; α ~ 1/137
At high energy transfers (mZ): α ~ 1/127
<u>This change is fully described by the theory!</u>

In QCD there is anti-screening! (bare/”naked” charge is smaller!)

Screening



Anti-screening!

Gluons are colored
so they can self-interact!

Figure 7.7 The two lowest-order vacuum polarization corrections to one-gluon exchange in quark–quark scattering.

From Leif's notes

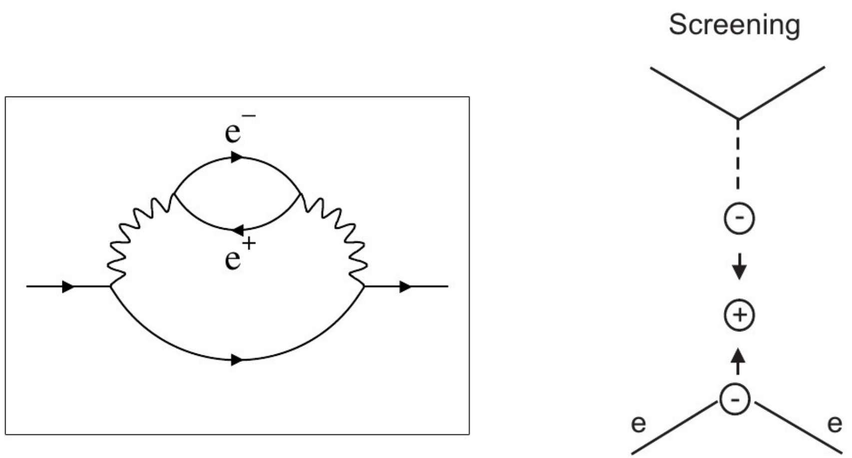


Figure 3.59: *Illustration of screening of the electric charge of the electron via the creation of a virtual e^+e^- pair.*

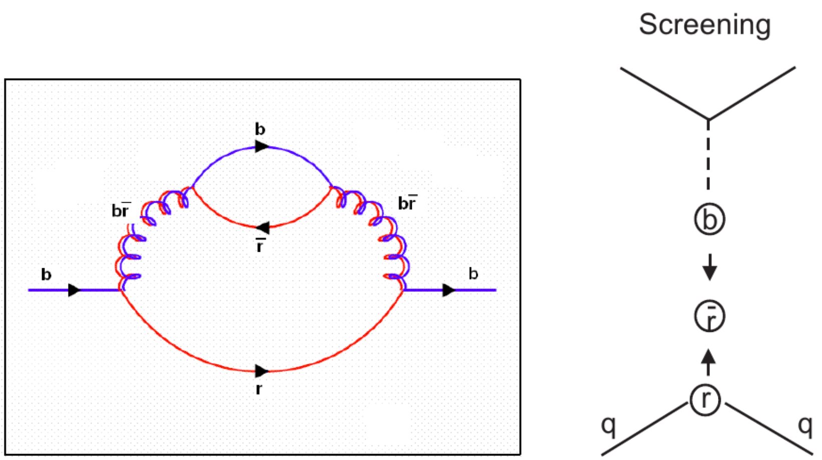


Figure 3.60: *Illustration of screening of the colour charge of a quark via the creation of a virtual $q\bar{q}$ pair.*

NB! In the first calculation (that later gave the nobel prize) they found the wrong sign and gluons was also screening.

So this is not easy to understand.

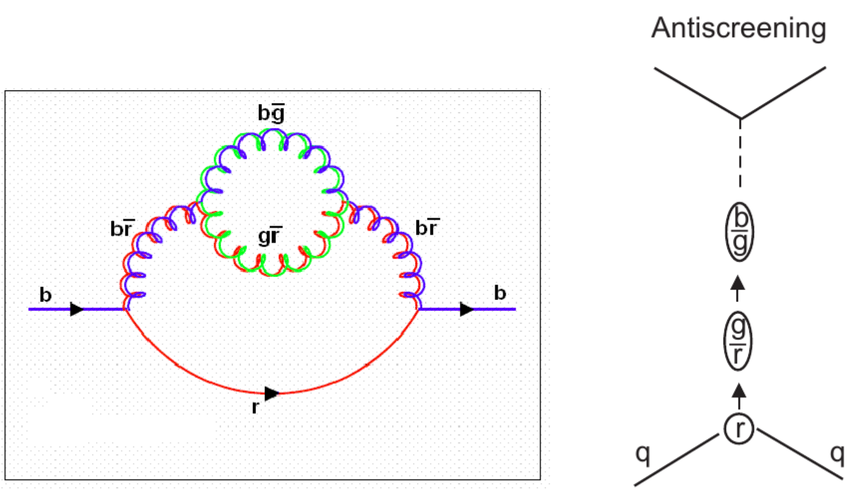
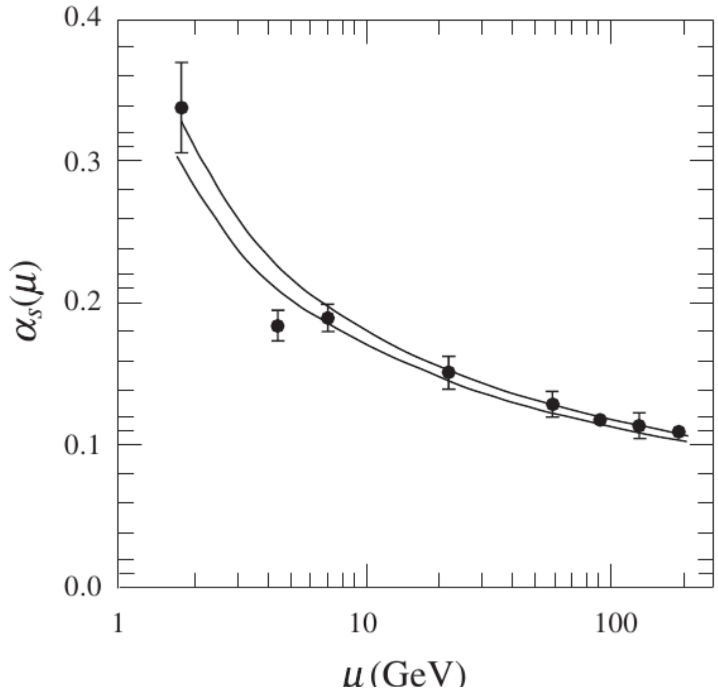


Figure 3.61: *Illustration of antiscreening of the colour charge of a quark via the creation of a virtual pair of gluons.*

Full result for QCD



$$\alpha_s(\mu) = \alpha_s(\mu_0)\left[1 + \frac{(33 - 2N_f)}{6\pi}\alpha_s(\mu_0)\ln(\mu/\mu_0)\right]^{-1} \tag{7.6}$$

Why did we make this excursion?

- Establish background for hadrons
- QCD is very strongly interacting at low energies = everyday life
- In fact so strong that no color charges can exist free
- Instead the color charges (quarks and gluons) are confined inside hadrons!

Quantum Chromo Dynamics (QCD)

3 color charges (red, green, blue)

<u>Not real colors</u> but e.g. qx, qy, qz that can be +qx for quarks (red) and -qx for anti-quarks (anti-red)

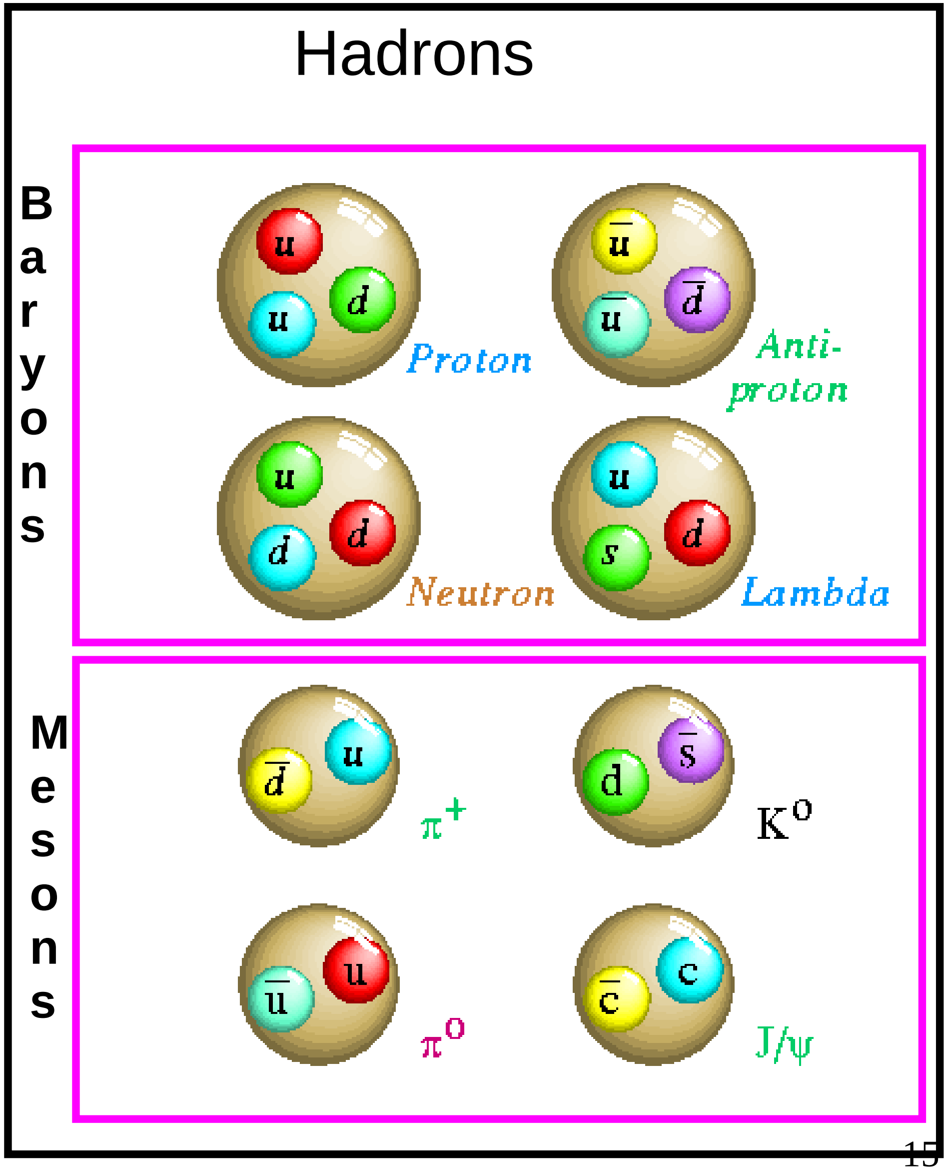
Hadrons have to be colorless

Baryons have all 3 colors

Mesons has a color and an anti-color

A single quark cannot be observed because it has color!

The quarks are confined inside the hadrons!



We cannot observe colored objects in nature → quark fragmentation: example of 2 jet event

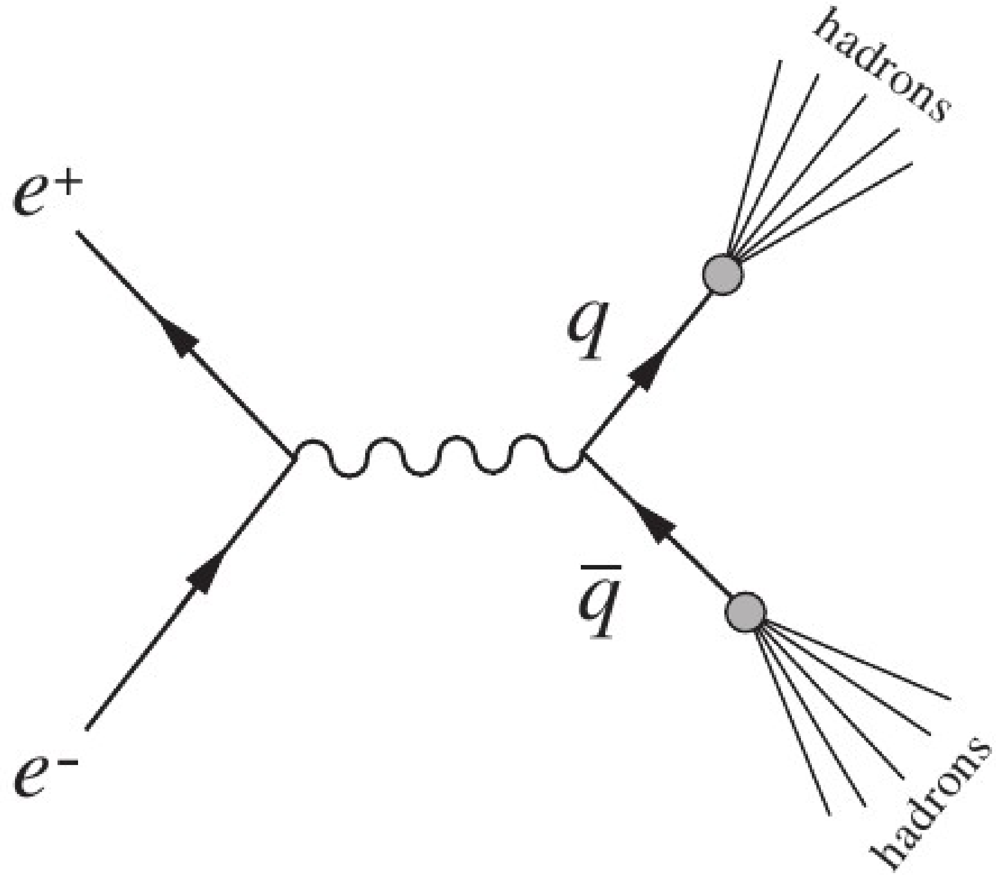
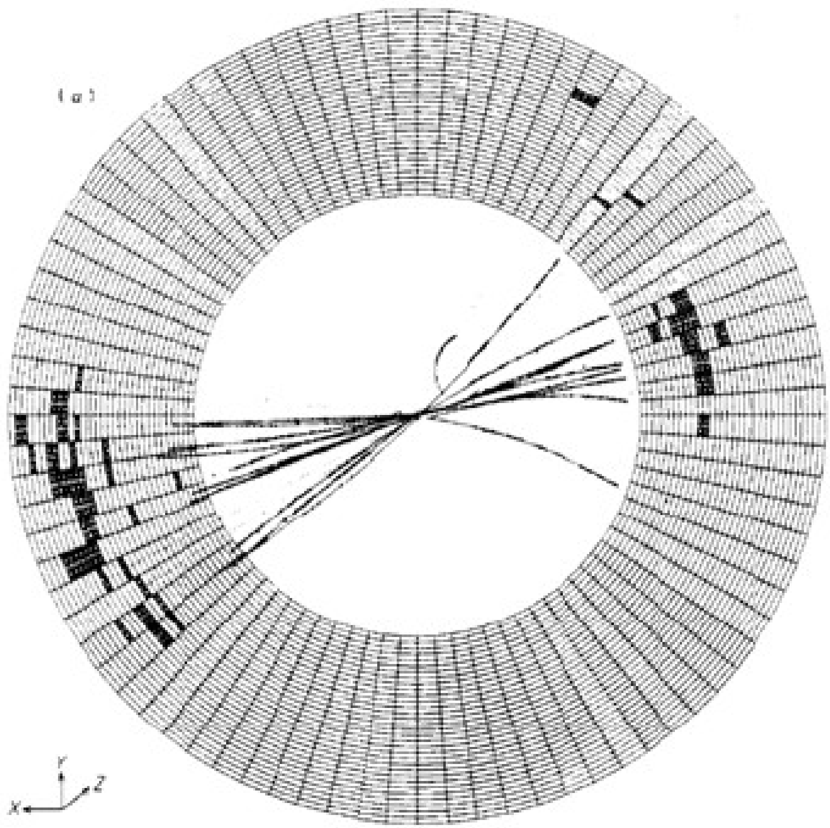


Figure 7.10 Basic mechanism of two-jet production in electron–positron annihilation.

2 jet event in $e^+ + e^-$

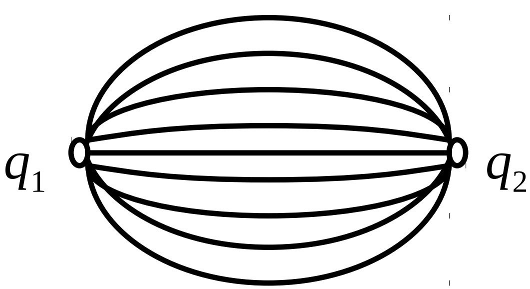


QCD & Confinement

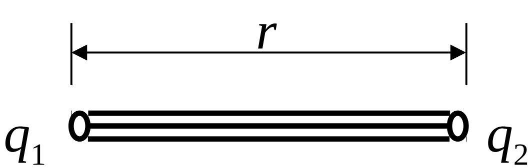
- The strong interaction potential
  - Compare the potential of the strong & e.m. interaction

$$V_{em} = -\frac{c}{r} \qquad V_s = -\frac{c'}{r} + kr \qquad c, c', k \text{ constants}$$

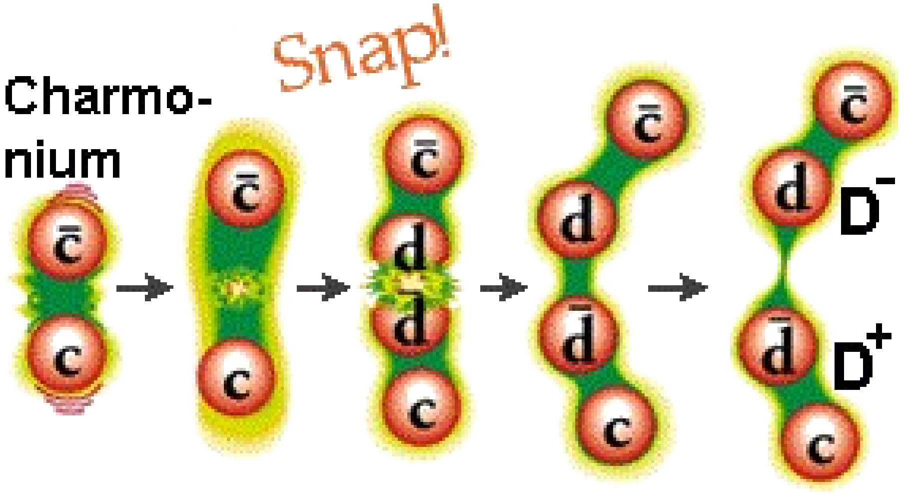
  - Confining term arises due to the self-interaction property of the colour field. k~1GeV/fm



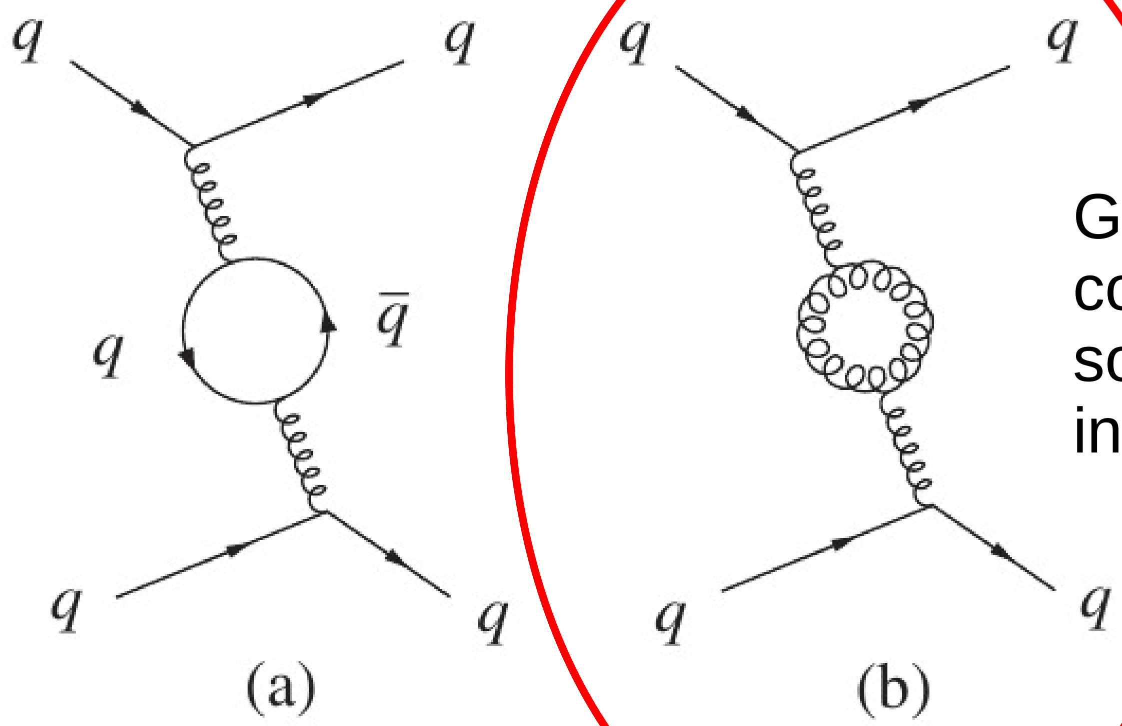
a) QED or QCD (r < 1 fm)



b) QCD (r > 1 fm)



The "self-interaction property" of the strong force!



Gluons are colored
so they can self-interact!

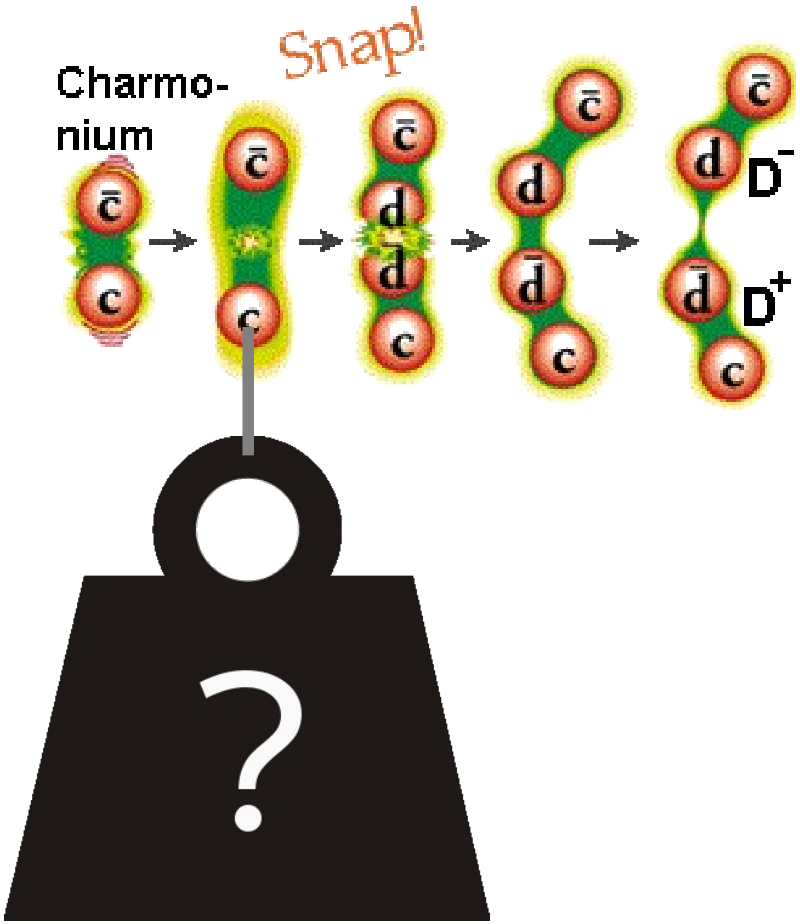
Figure 7.7 The two lowest-order vacuum polarization corrections to one-gluon exchange in quark–quark scattering.

What is the different between a photon (EM force) and a gluon (strong force)

Gluons are colored so they can self-interact!

Exercise: How big is k?

- k=1GeV/fm
- What force does that correspond to in kilograms?
  - mg= 1 GeV/fm => m=?



Consequences of 10 ton force!

- This is why QCD is also called the strong interaction
  - QCD can bind together quarks even though they are EM repulsed
- QCD is for low energies non-perturbative
  - We know the theory but we cannot solve it!
  - We don't know how to describe hadronic properties with QCD
- But at high energies (small distances << 1 fm) we can use perturbative QCD
- Idea: Can we create high energy matter where the quarks and gluons are the fundamental degrees of freedom
  - This is also the phase of matter in the universe around 1 micro second after the big bang!
  - It is first after this time that quarks and gluons “crystallize” into hadrons

Back to the book:-)

Some examples of baryons

TABLE 3.1 The approximate masses of the quarks in GeV/c^2 and their electric charges Q in units of e. Also shown are the values of the baryon number B, strangeness S, charm C, bottom $\tilde{B}$ and top T, as defined in Section 3.2. The values for the corresponding antiquarks are equal in magnitude, but opposite in sign.

Name	Symbol	Mass	Q	B	S	C	$\tilde{B}$	T
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Top	t	$m_t \approx 174$	2/3	1/3	0	0	0	1

TABLE 3.2 Some examples of baryons, with their quark compositions and the corresponding values of their electric charge Q, strangeness S, charm C and bottom $\tilde{B}$.

Particle		Mass (MeV/c^2)	Q	S	C	$\tilde{B}$
p	uud	938	1	0	0	0
n	udd	940	0	0	0	0
Λ	uds	1116	0	-1	0	0
Λ_c	udc	2285	1	0	1	0
Λ_b	udb	5624	0	0	0	-1

Some example of mesons

TABLE 3.1 The approximate masses of the quarks in GeV/c^2 and their electric charges Q in units of e. Also shown are the values of the baryon number B, strangeness S, charm C, bottom $\tilde{B}$ and top T, as defined in Section 3.2. The values for the corresponding antiquarks are equal in magnitude, but opposite in sign.

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TABLE 3.3 Some examples of mesons, with their quark compositions and the corresponding values of their electric charge Q, strangeness S, charm C and bottom $\tilde{B}$.

Particle		Mass (MeV/c^2)	Q	S	C	$\tilde{B}$
π^+	$u\bar{d}$	140	1	0	0	0
K^-	$s\bar{u}$	494	-1	-1	0	0
D^-	$d\bar{c}$	1869	-1	0	-1	0
D_s^+	$c\bar{s}$	1969	1	1	1	0
B^-	$b\bar{u}$	5279	-1	0	0	-1
Υ	$b\bar{b}$	9460	0	0	0	0

Important facts about hadrons

- All interactions (EM, weak, strong) preserves the total number of quarks: Nq-Nqbar.
  - As this number is 0 for mesons this leads to baryon number conservation
  - Example: at LHC we collide 2 protons (baryons). In the final state there has to be exactly 2 baryons more than anti-baryons (but not necessarily 2 protons)

Important facts about hadrons (2/2)

- The quark flavor (u, d, s, c, b, t) is conserved in strong and EM interactions
  - Example:

    Nu = #u quarks - # anti-u quarks is conserved
- It is not necessarily conserved in weak interactions!
  - Example:

    n (udd) $\rightarrow$ p (uud) + e- + $\bar{\nu}_e$

Important facts about specie dependence of interactions

- Strong interactions are mediated via color: quark flavor does not matter!
  - All quarks: u, d, s, c, b, t interacts strongly in the same way
- EM interactions are mediated via EM charge
  - Charge -1: e, μ, τ
  - Charge +2/3: u, c, t
  - Charge -1/3: d, s, b
- Weak interactions are mainly in the same generation, e.g.: $u \leftrightarrow d$ and $e^- \leftrightarrow \nu_e$
- <u>**The mass only affects kinematics!**</u>

Hierarchy of interactions

TABLE 3.4 Typical lifetimes of hadrons decaying by the three interactions.

Interaction	Lifetime (s)
Strong	$10^{-22} - 10^{-24}$
Electromagnetic	$10^{-16} - 10^{-21}$
Weak *	$10^{-7} - 10^{-13}$

* The neutron lifetime is an exception, for reasons explained in Section 3.2.

- If a decay can be strong it will be strong
  - Only exception is OZI rule
- If not strong but EM is allowed then it will be EM
- If not strong and EM then it can be weak

Questions?

Exercise 2.1, 2.2, and 2.4

Resonances

- Resonances are hadrons that decays by strong interactions. They are so short lived that they can only be observed indirectly
- How long do they travel?

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Electromagnetic	$10^{-16} - 10^{-21}$
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Resonance states can be excited states

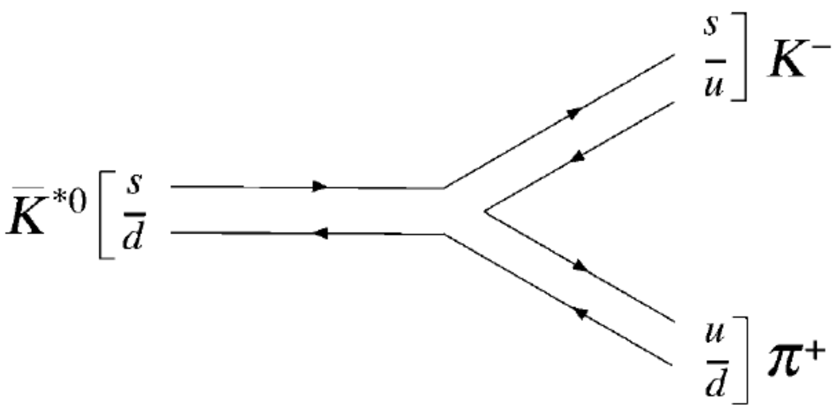


Figure 3.11 Quark diagram for the decay $\bar{K}^{*0} \to K^- + \pi^+$.

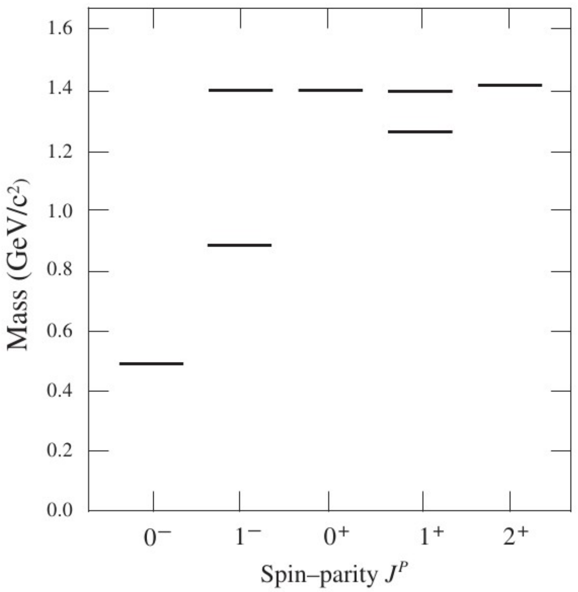
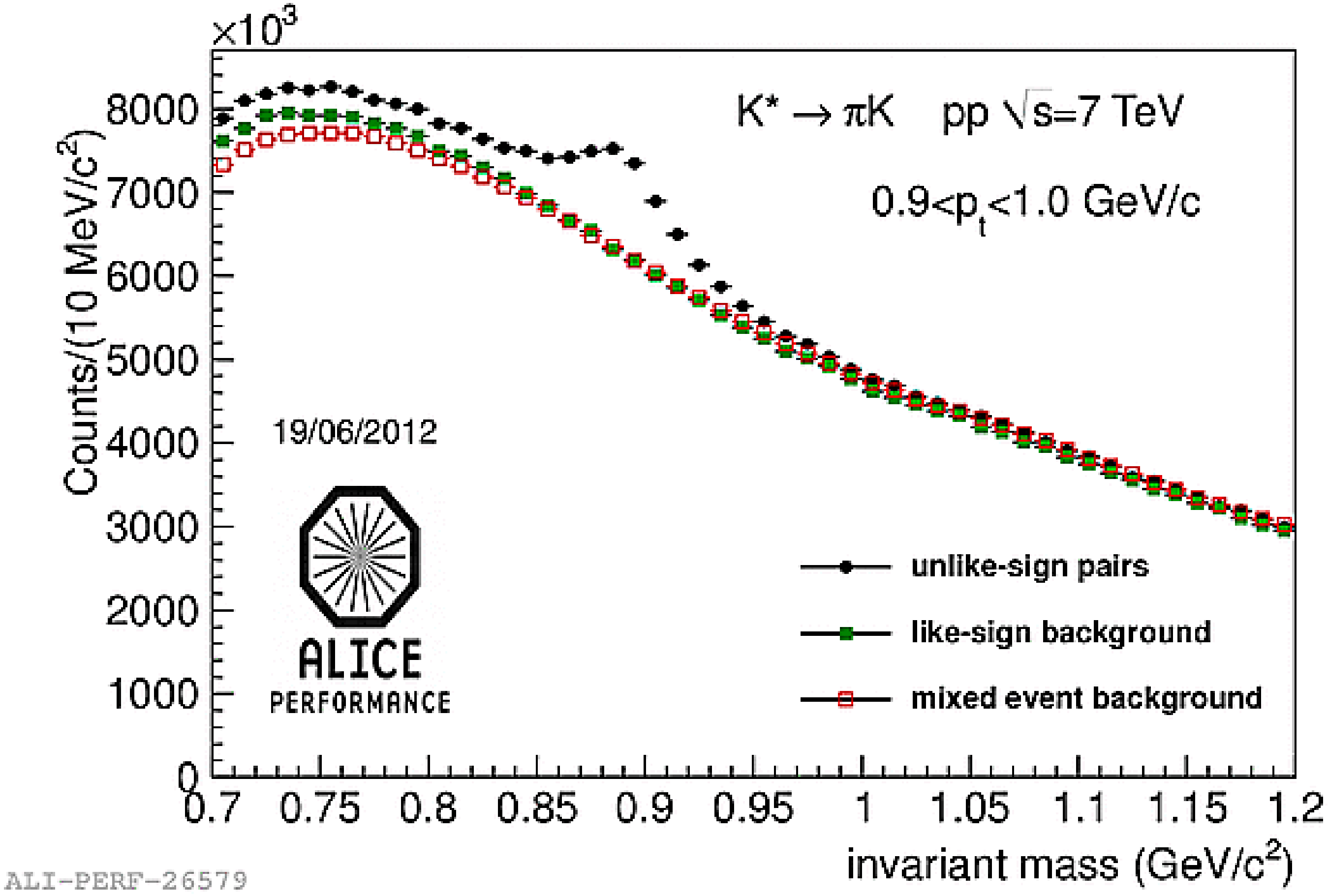
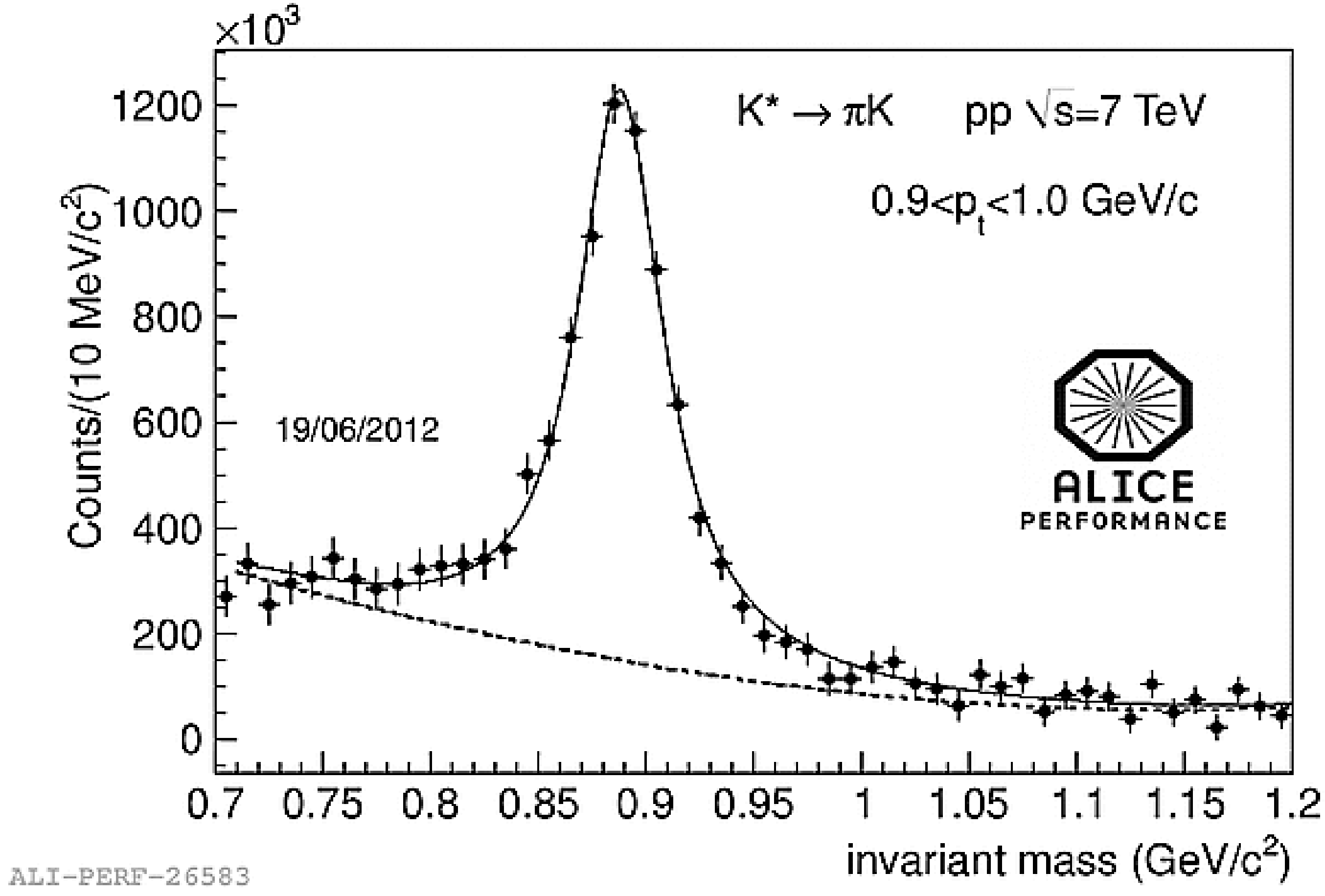


Figure 3.12 Observed bound states of the $s\bar{u}$ system with masses below 1.5 GeV/c^2, together with values of their spin-parities[9] J^P. The ground state is the $K^-(494)$ and the others can be interpreted as its excited states.

ALICE reconstruction



Notice that mass is not fixed!



The mass width is an indication of the lifetime

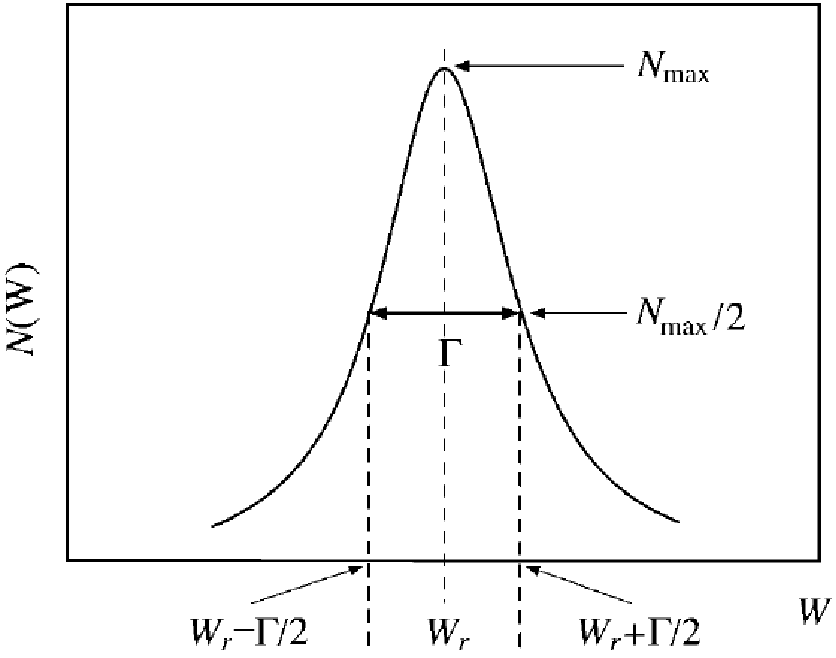


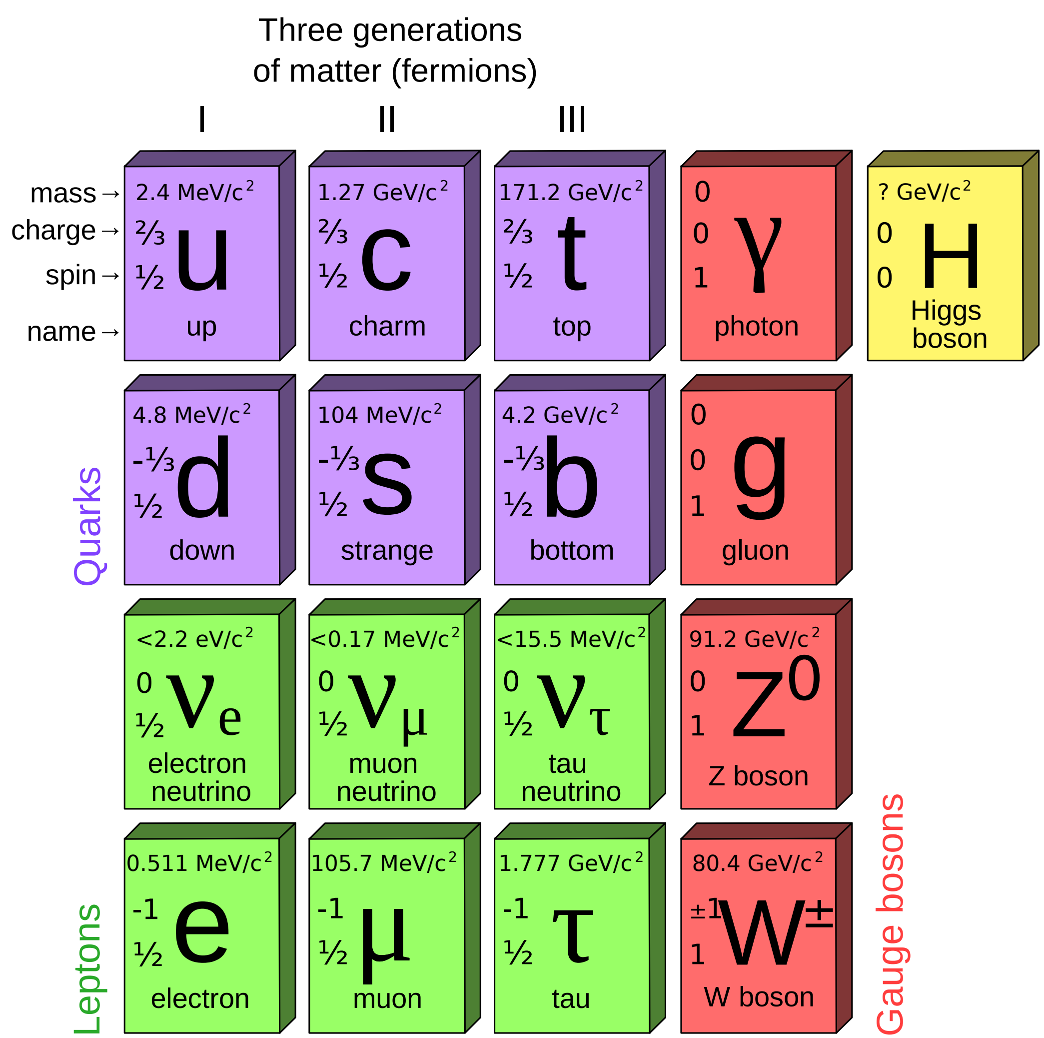
Figure 3.10 Plot of the Breit–Wigner formula (3.26).

- From Heisenberg uncertainty relation we have:

  ΔE*Δt~hbar →

  The width W~hbar/lifetime

Summary


Three generations
of matter (fermions)
I
II
III
mass→
charge→
spin→
name→
2.4 MeV/c²
⅔
½
u
up
1.27 GeV/c²
⅔
½
c
charm
171.2 GeV/c²
⅔
½
t
top
0
0
1
γ
photon
? GeV/c²
0
0
H
Higgs
boson
4.8 MeV/c²
-⅓
½
d
down
104 MeV/c²
-⅓
½
s
strange
4.2 GeV/c²
-⅓
½
b
bottom
0
0
1
g
gluon
<2.2 eV/c²
0
½
νe
electron
neutrino
<0.17 MeV/c²
0
½
νμ
muon
neutrino
<15.5 MeV/c²
0
½
ντ
tau
neutrino
91.2 GeV/c²
0
1
Z0
Z boson
0.511 MeV/c²
-1
½
e
electron
105.7 MeV/c²
-1
½
μ
muon
1.777 GeV/c²
-1
½
τ
tau
80.4 GeV/c²
±1
1
W±
W boson
Quarks
Leptons
Gauge bosons