

Basic info about quarks and gluons

3 color charges (red, green, blue)

Not real colors but e.g. q_x, q_y, q_z that can be $+q_x$ for quarks (red) and $-q_x$ for anti-quarks (anti-red)

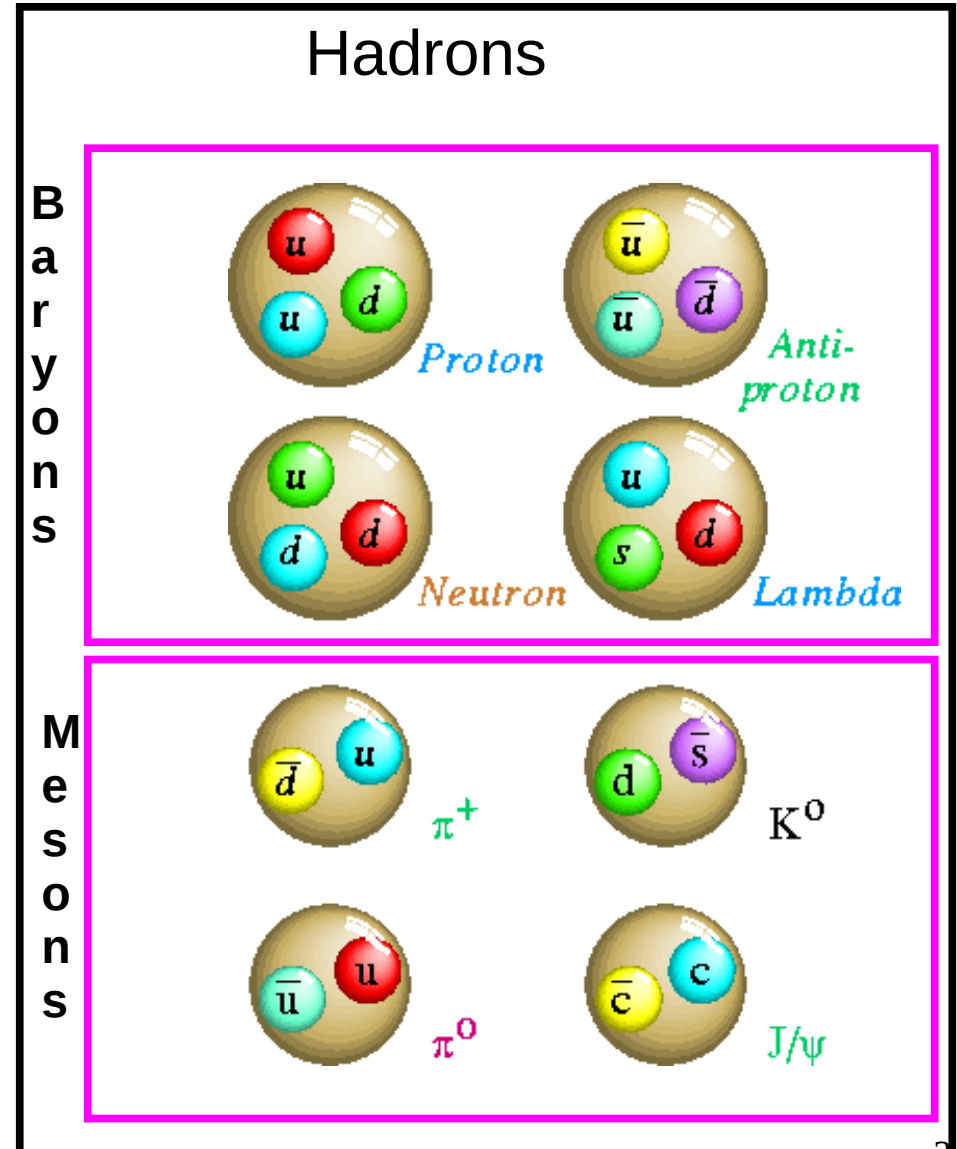
Hadrons have to be colorless

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 \rightarrow
red quark + green-antired gluon



Start with an excursion!

Quark masses?

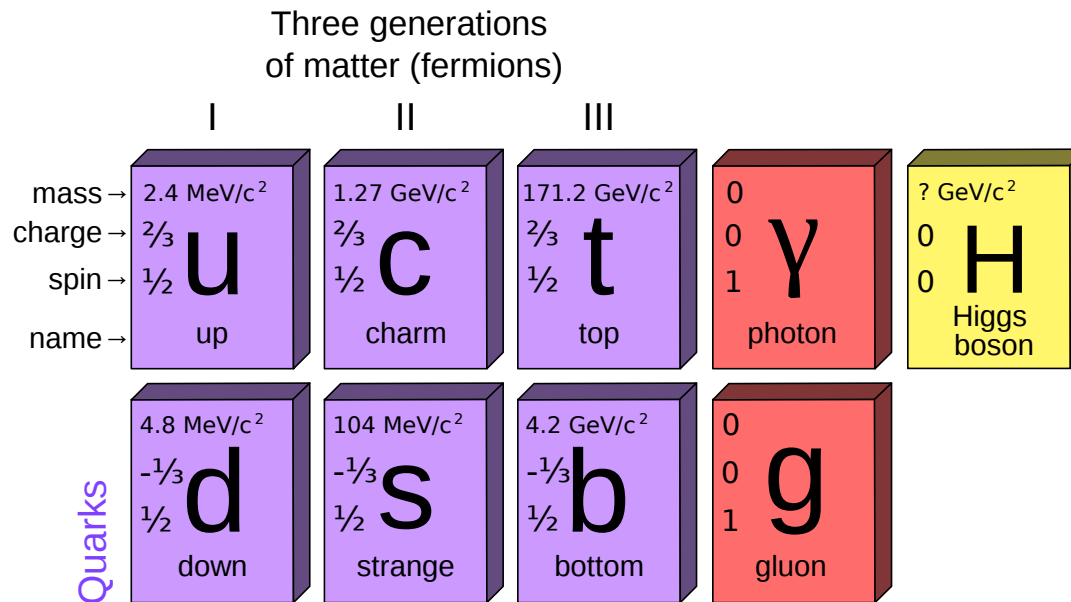


TABLE 3.1 The approximate masses of the quarks in GeV/c² and their electric charges Q in units of e . Also shown are the values of the baryon number B , strangeness S , charm C , bottom \tilde{B} and top T , as defined in Section 3.2. The values for the corresponding antiquarks are equal in magnitude, but opposite in sign.

Name	Symbol	Mass	Q	B	S	C	\tilde{B}	T
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Two definitions

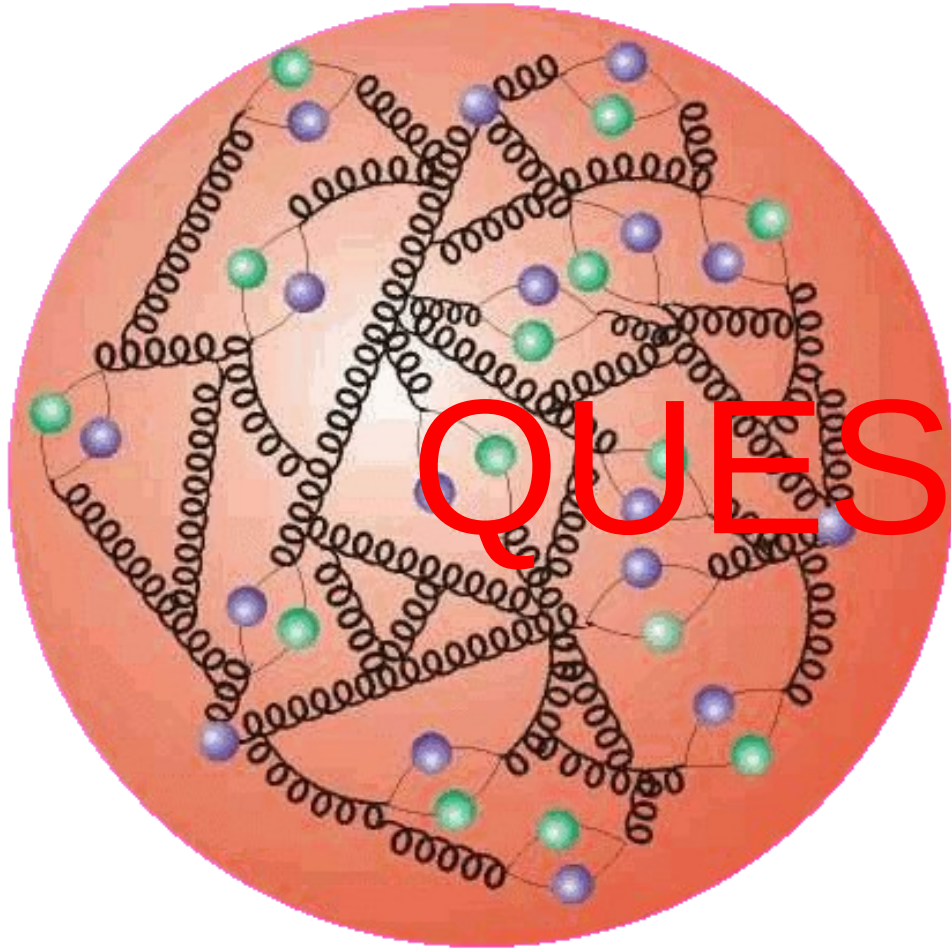
- Constituent quark mass:
 - The effective mass in the hadrons:
 - $M_p \sim 938 \text{ MeV} \rightarrow M_u \sim M_d \sim 300 \text{ MeV}$
- Free quark mass:
 - The mass if the quarks were not bound inside hadrons
- Nonstandard situation:
 - Bound state heavier than non-bound state!
 - Probably we should not say bound but confined!

Mass due to confinement

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

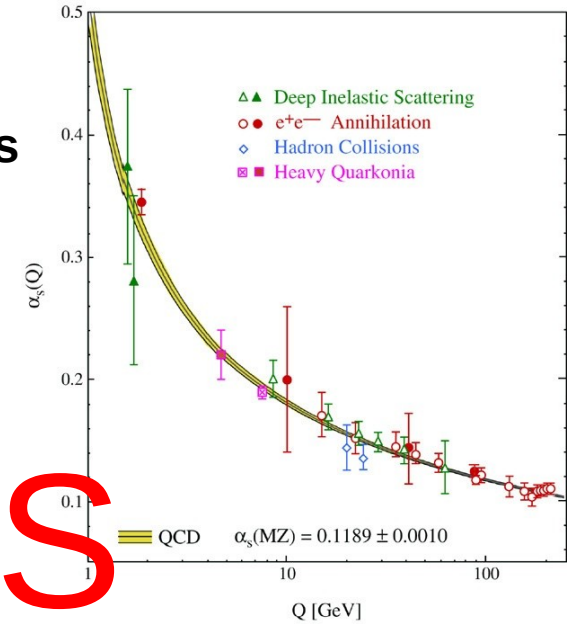
Many difficult aspects about the strong force

- The strong interaction is very complex!



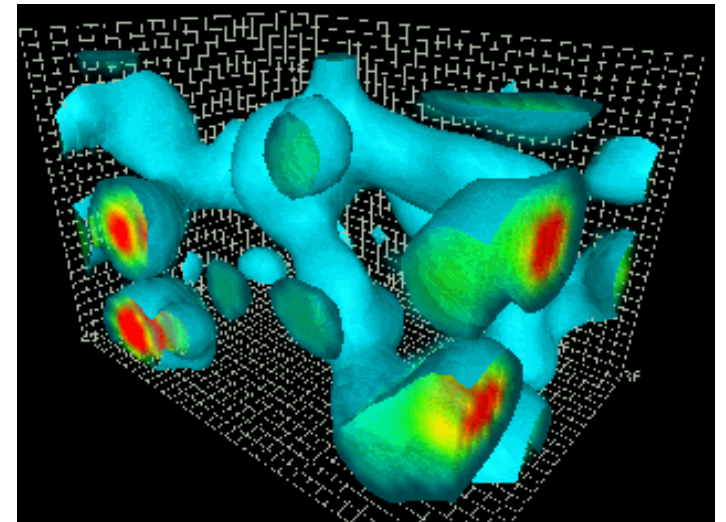
CONFINEMENT

**Quarks and gluons
couples strong:**



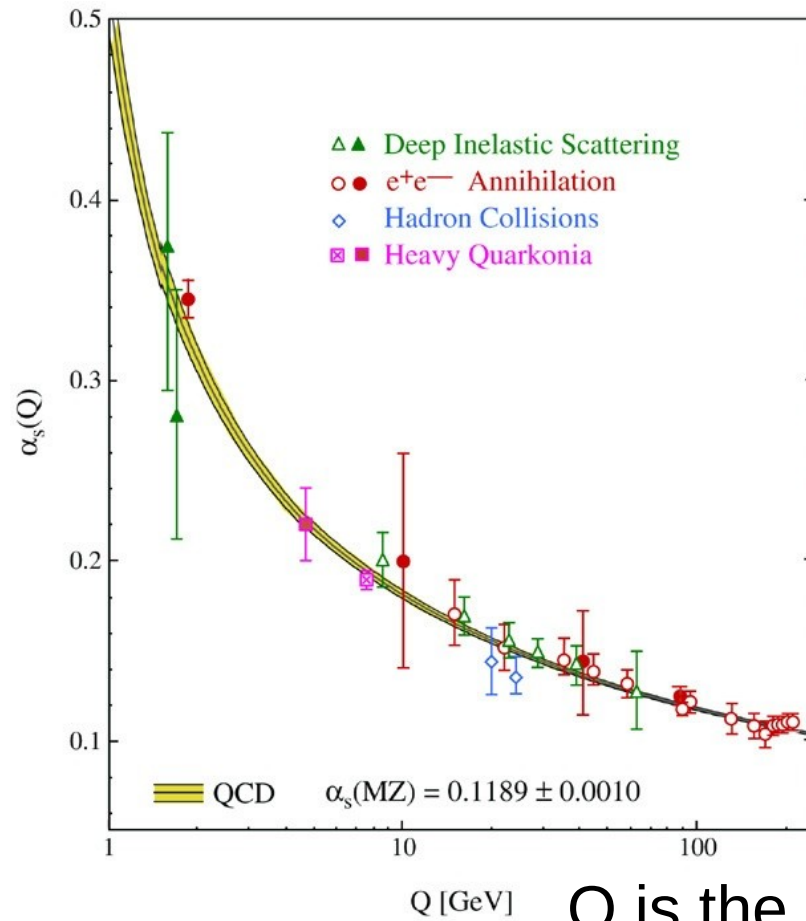
QUESTIONS

**Complex
vacuum:**



The coupling is not fixed but runs!

α_s



Q is the 4 momentum transfer

In fact it becomes ~ 1 at the scale $\Lambda_{\text{QCD}} \sim 200$ MeV

Screening/running of the coupling in electromagnetic collisions

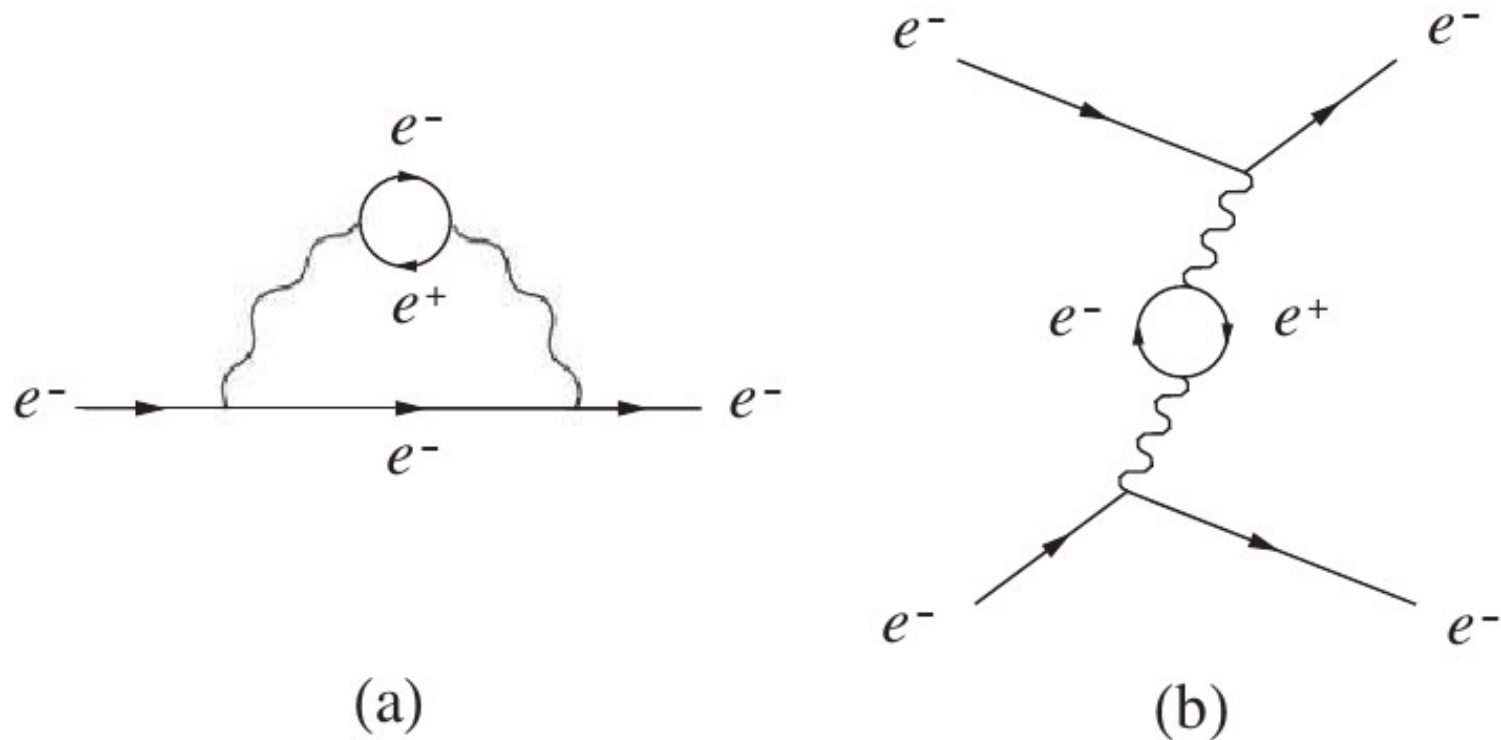


Figure 7.5 A more complicated quantum fluctuation of the electron, together with the associated exchange process.

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

Notice the order: -, +, -!

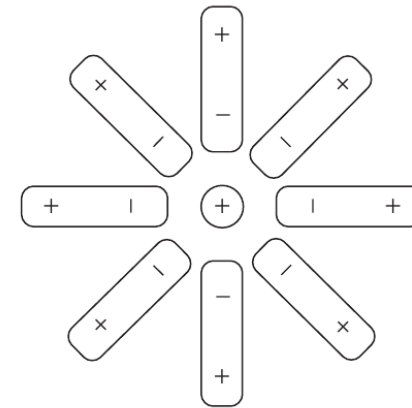
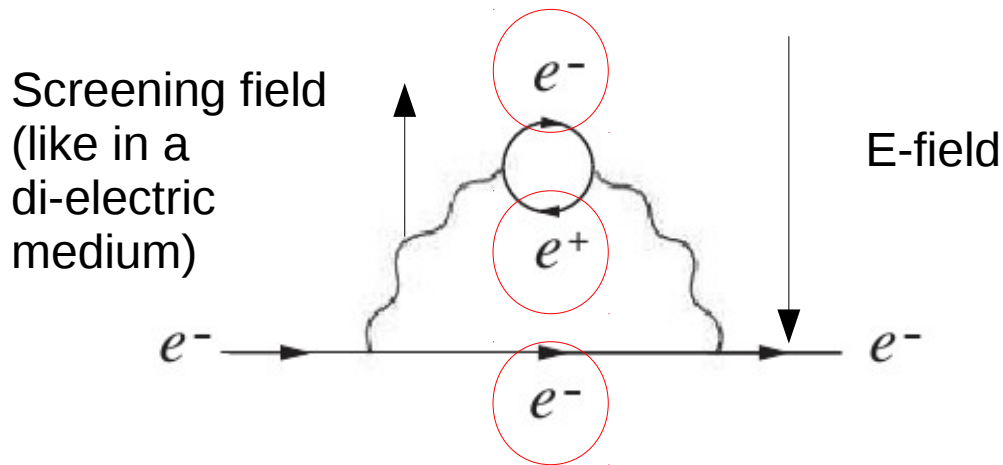


Figure 7.6 Schematic diagram representing the polarization of the molecules of a dielectric by a positive charge placed within it.

The effect is measurable:

At low energy; $\alpha \sim 1/137$

At high energy transfers (mZ): $\alpha \sim 1/127$

This change is fully described by the theory!

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

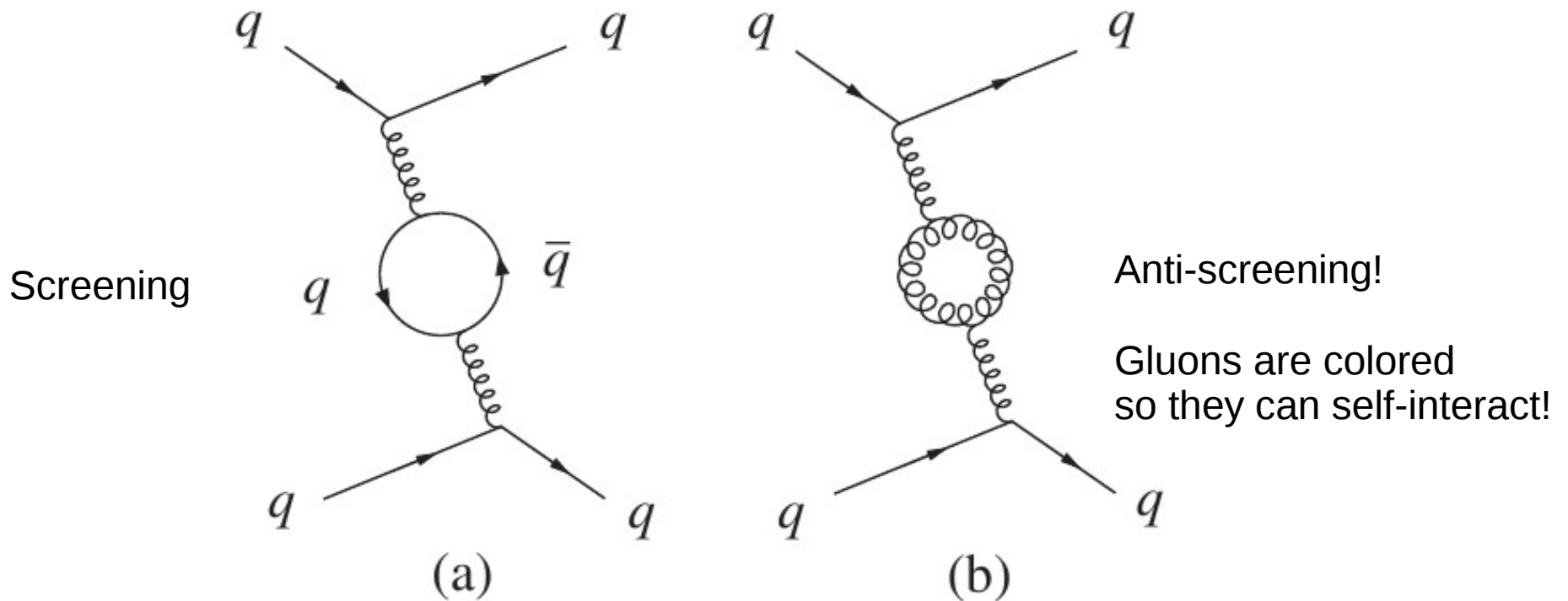


Figure 7.7 The two lowest-order vacuum polarization corrections to one-gluon exchange in quark–quark scattering.

From Leif's notes

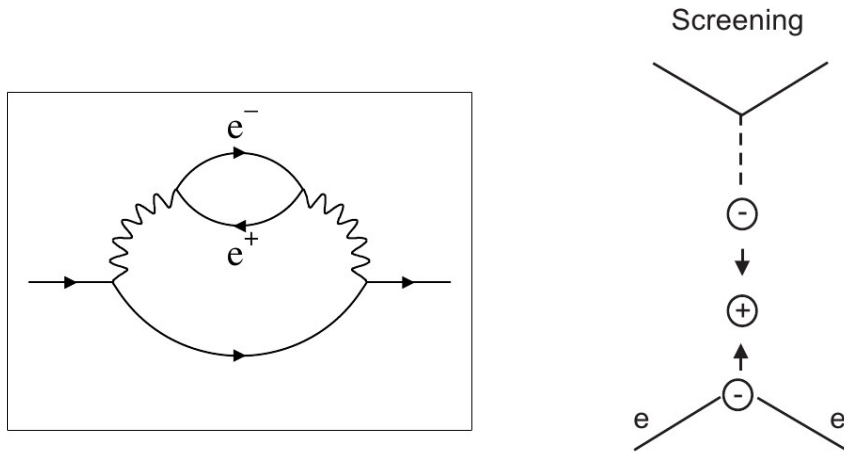


Figure 3.59: Illustration of screening of the electric charge of the electron via the creation of a virtual e^+e^- pair.

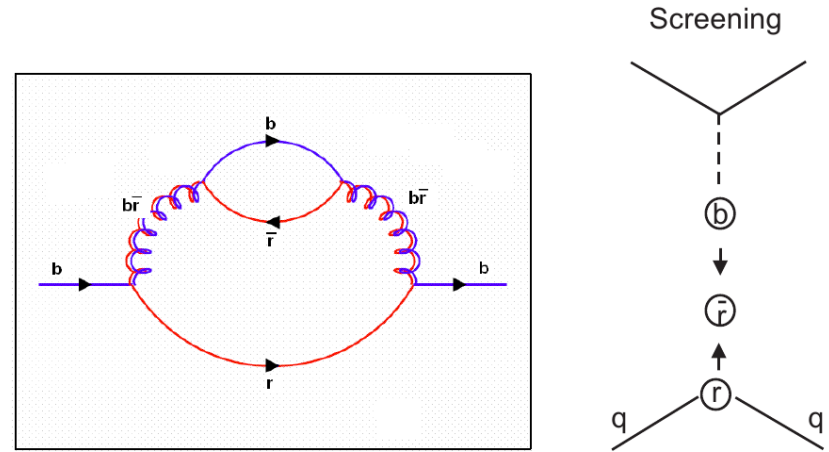


Figure 3.60: Illustration of screening of the colour charge of a quark via the creation of a virtual $q\bar{q}$ pair.

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.

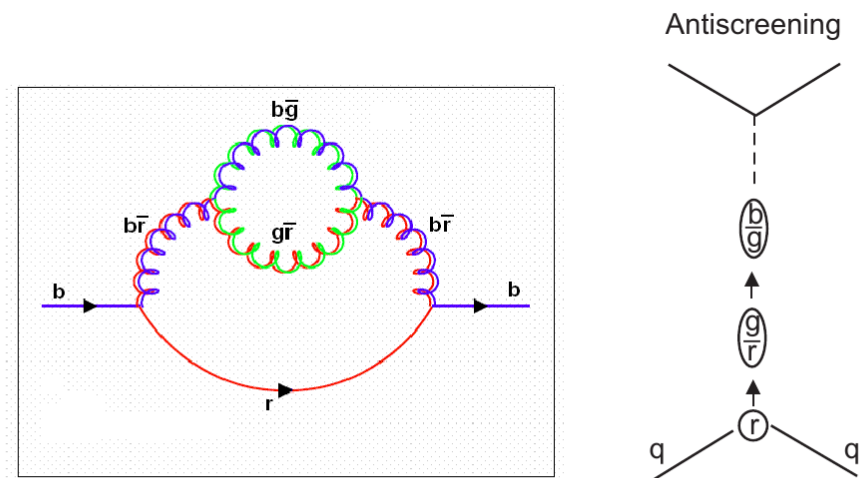
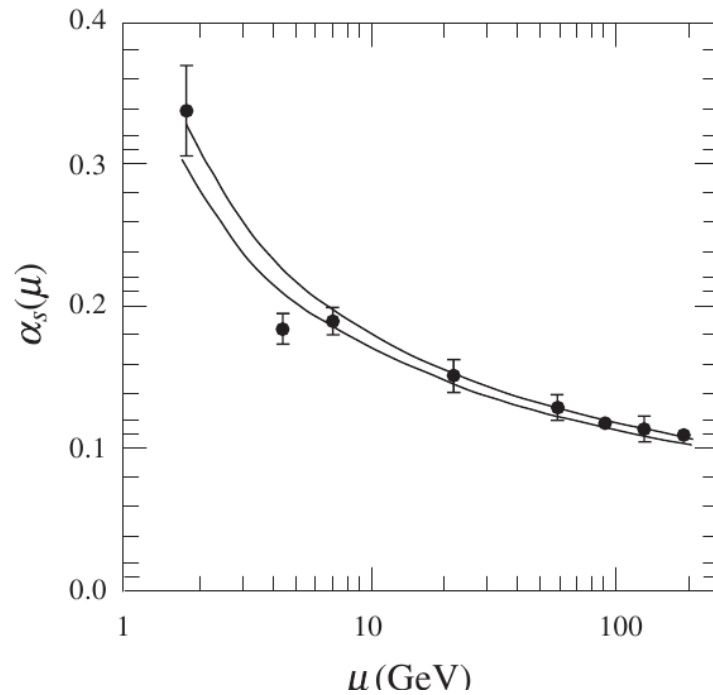


Figure 3.61: Illustration of antiscreening of the colour charge of a quark via the creation of a virtual pair of gluons.

Full result for QCD



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

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)

Not real colors but e.g. q_x, q_y, q_z that can be $+q_x$ for quarks (red) and $-q_x$ for anti-quarks (anti-red)

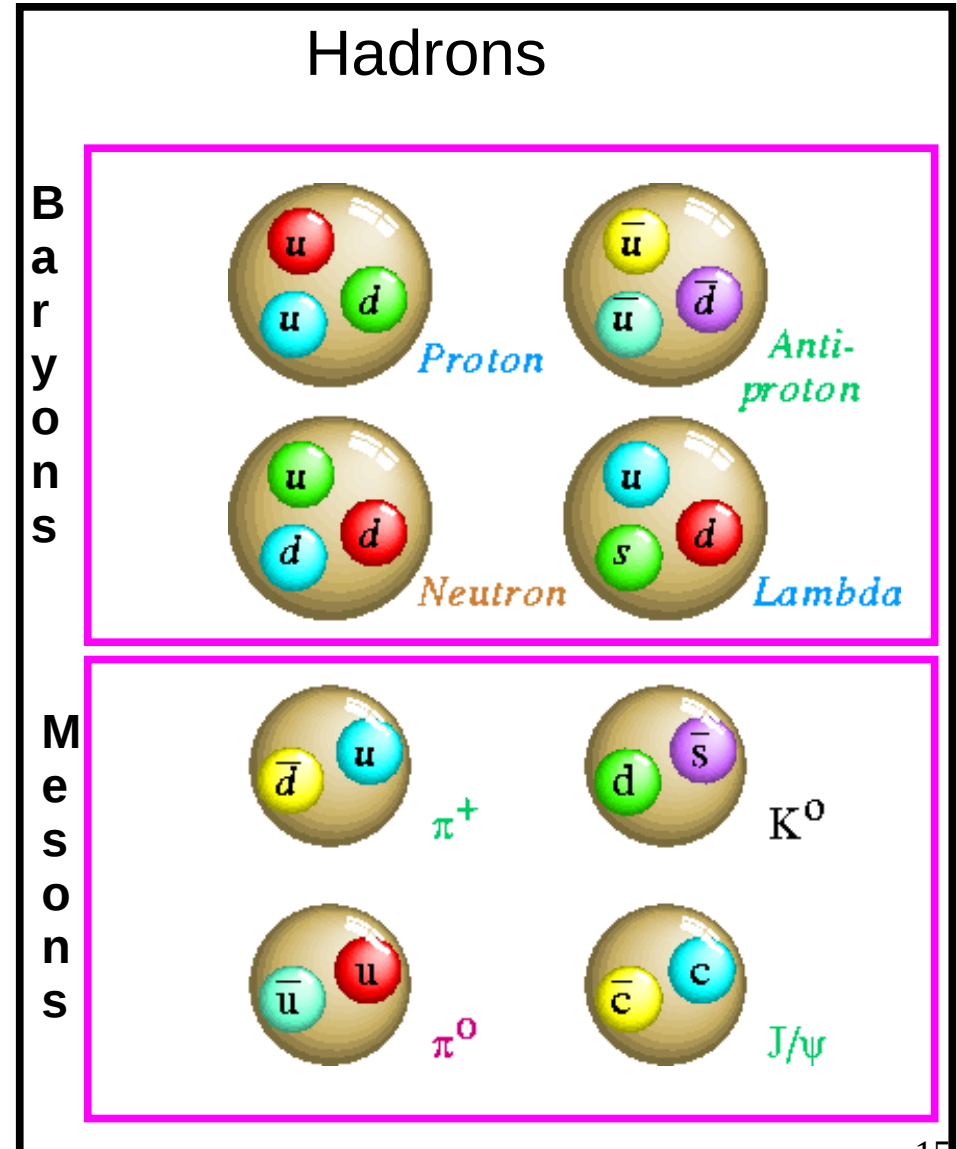
Hadrons have to be colorless

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 \rightarrow quark fragmentation:
example of 2 jet event

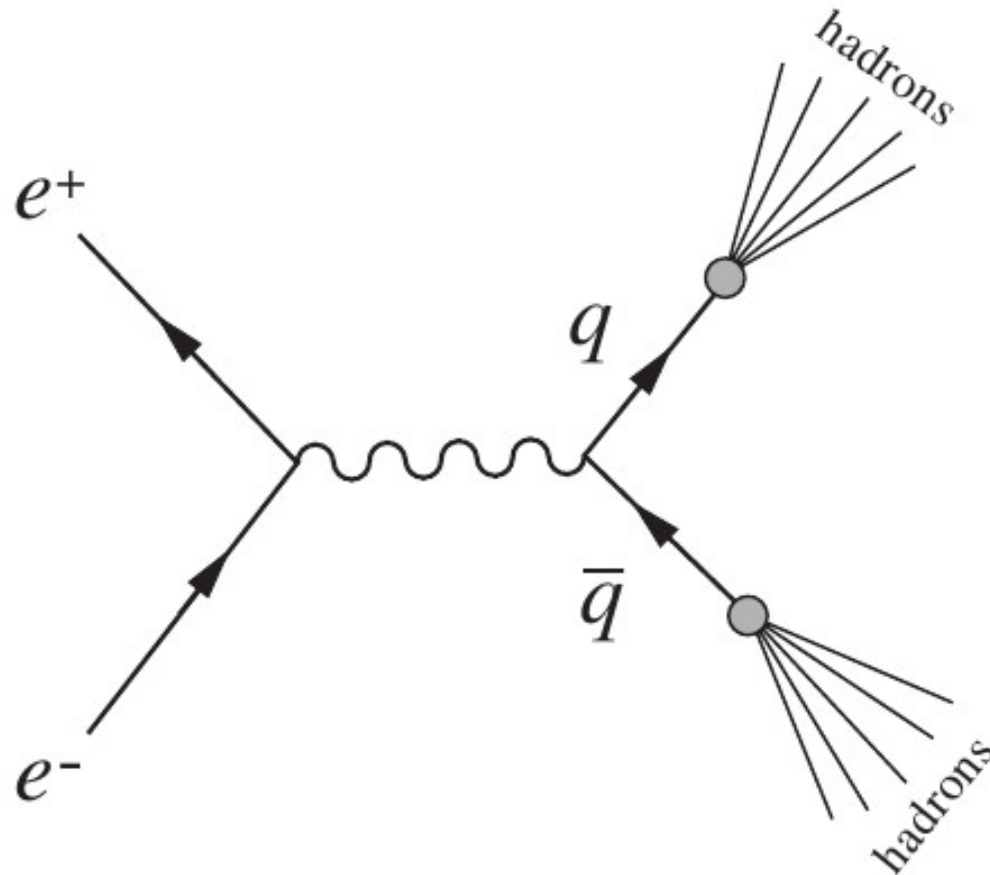
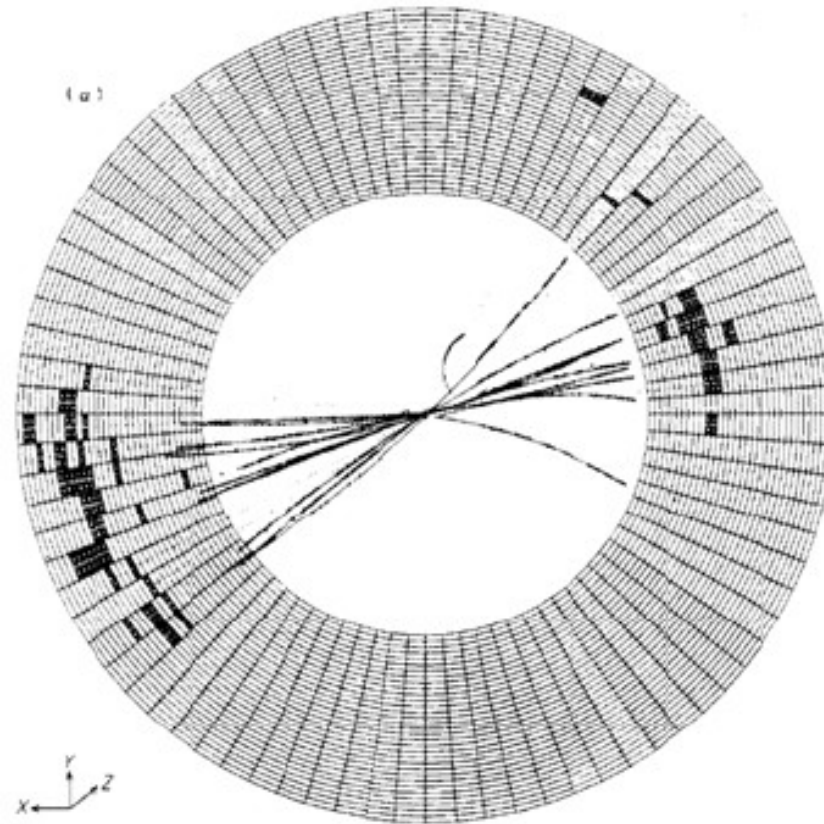


Figure 7.10 Basic mechanism of two-jet production in electron–positron annihilation.

2 jet event in e^+e^-

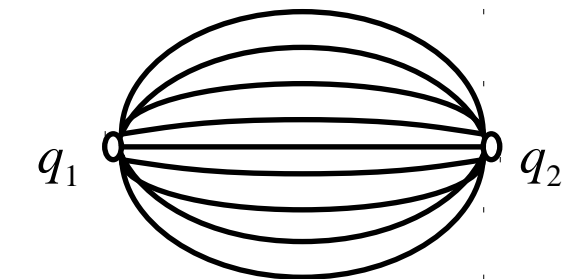


QCD & Confinement

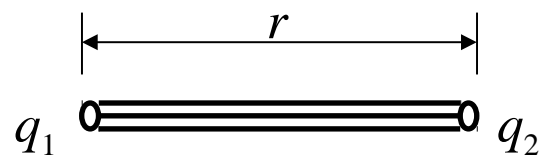
- The strong interaction potential
 - Compare the potential of the strong & e.m. interaction

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

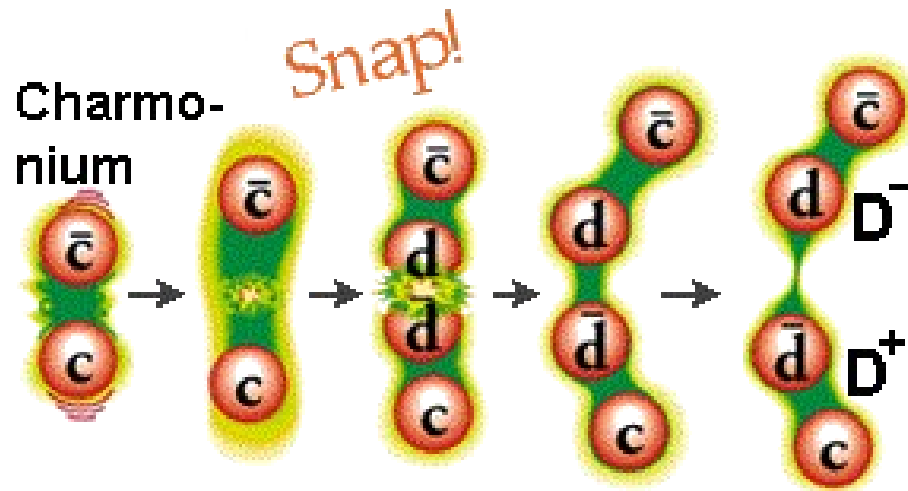
- Confining term arises due to the self-interaction property of the colour field. $k \sim 1 \text{ GeV/fm}$



a) QED or QCD ($r < 1 \text{ fm}$)



b) QCD ($r > 1 \text{ fm}$)



The “self-interaction property” of the strong force!

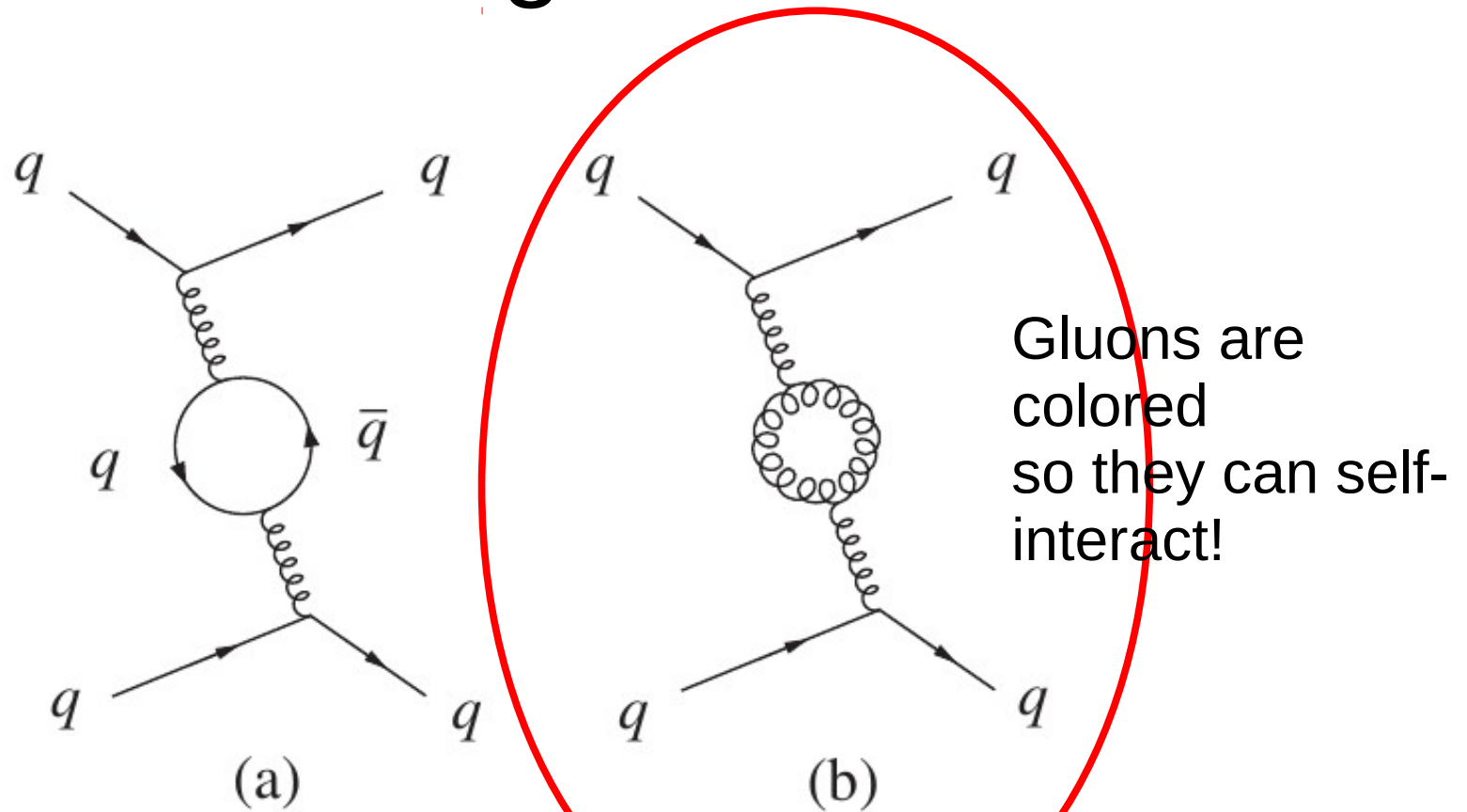


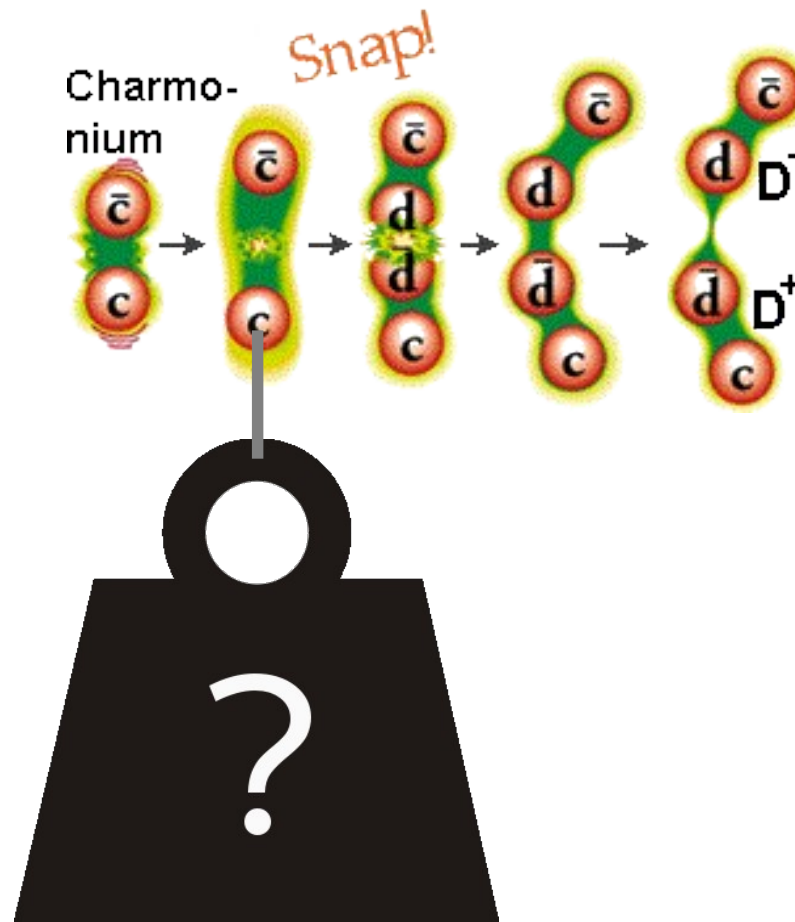
Figure 7.7 The two lowest-order vacuum polarization corrections to one-gluon exchange in quark–quark scattering.

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?

- $k=1\text{GeV}/\text{fm}$
- What force does that correspond to in kilograms?
 - $mg=1\text{ GeV}/\text{fm} \Rightarrow m=?$



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 $\ll 1$ 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.

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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

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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
K^-	$s\bar{u}$	494	-1	-1	0
D^-	$d\bar{c}$	1869	-1	0	-1
D_s^+	$c\bar{s}$	1969	1	1	1
B^-	$b\bar{u}$	5279	-1	0	0
Υ	$b\bar{b}$	9460	0	0	0

Important facts about hadrons

- All interactions (EM, weak, strong) preserves the total number of quarks: $N_q - N_{q\bar{}}$.
 - 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 $e^- \leftrightarrow \nu_e$
- **The mass only affects kinematics!**

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?

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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Resonance states can be excited states

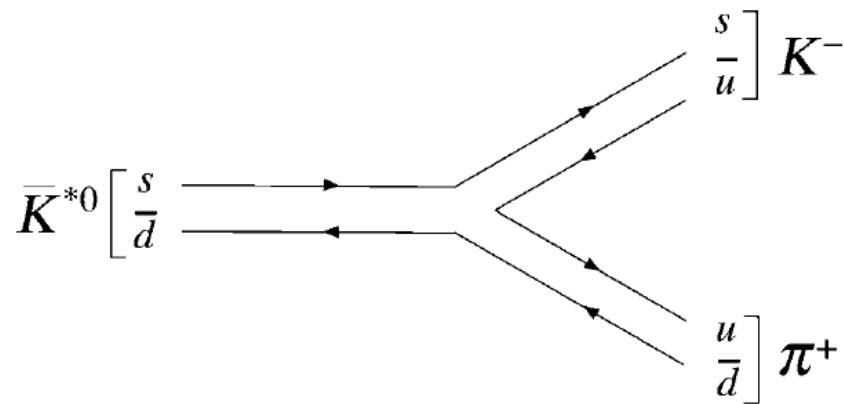


Figure 3.11 Quark diagram for the decay $\bar{K}^{*0} \rightarrow K^- + \pi^+$.

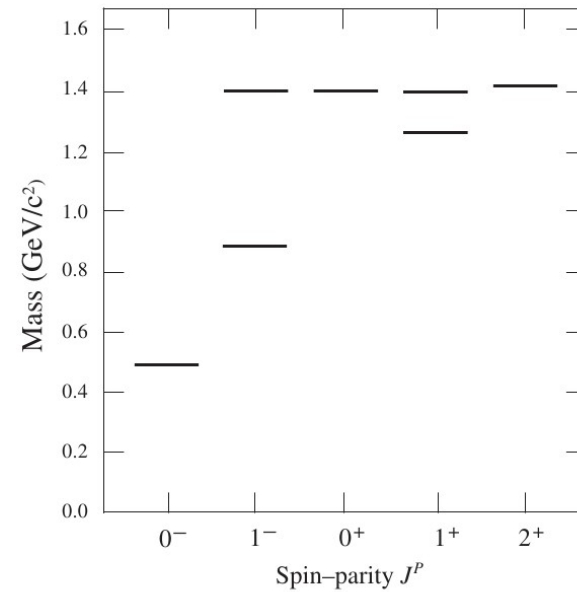
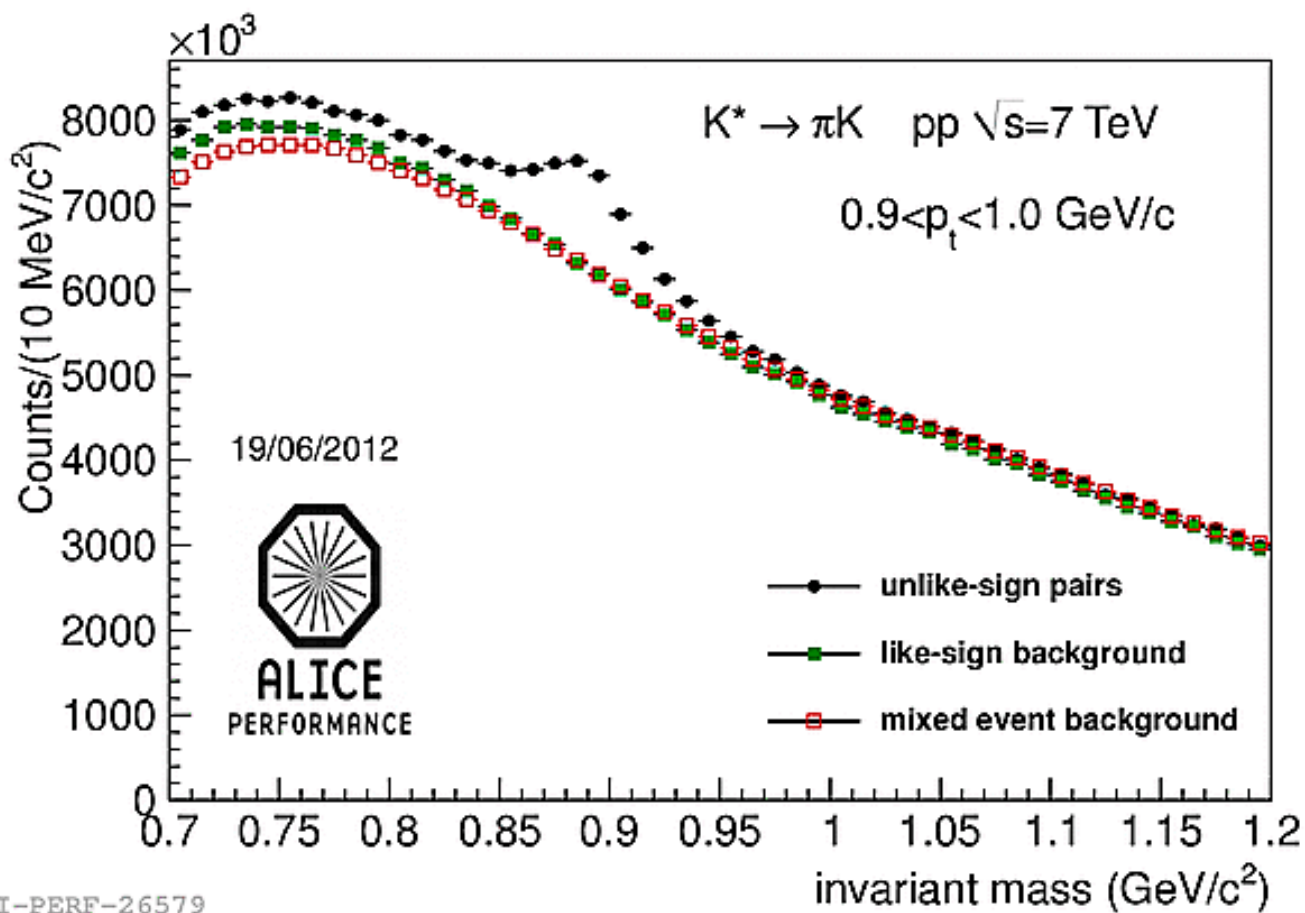


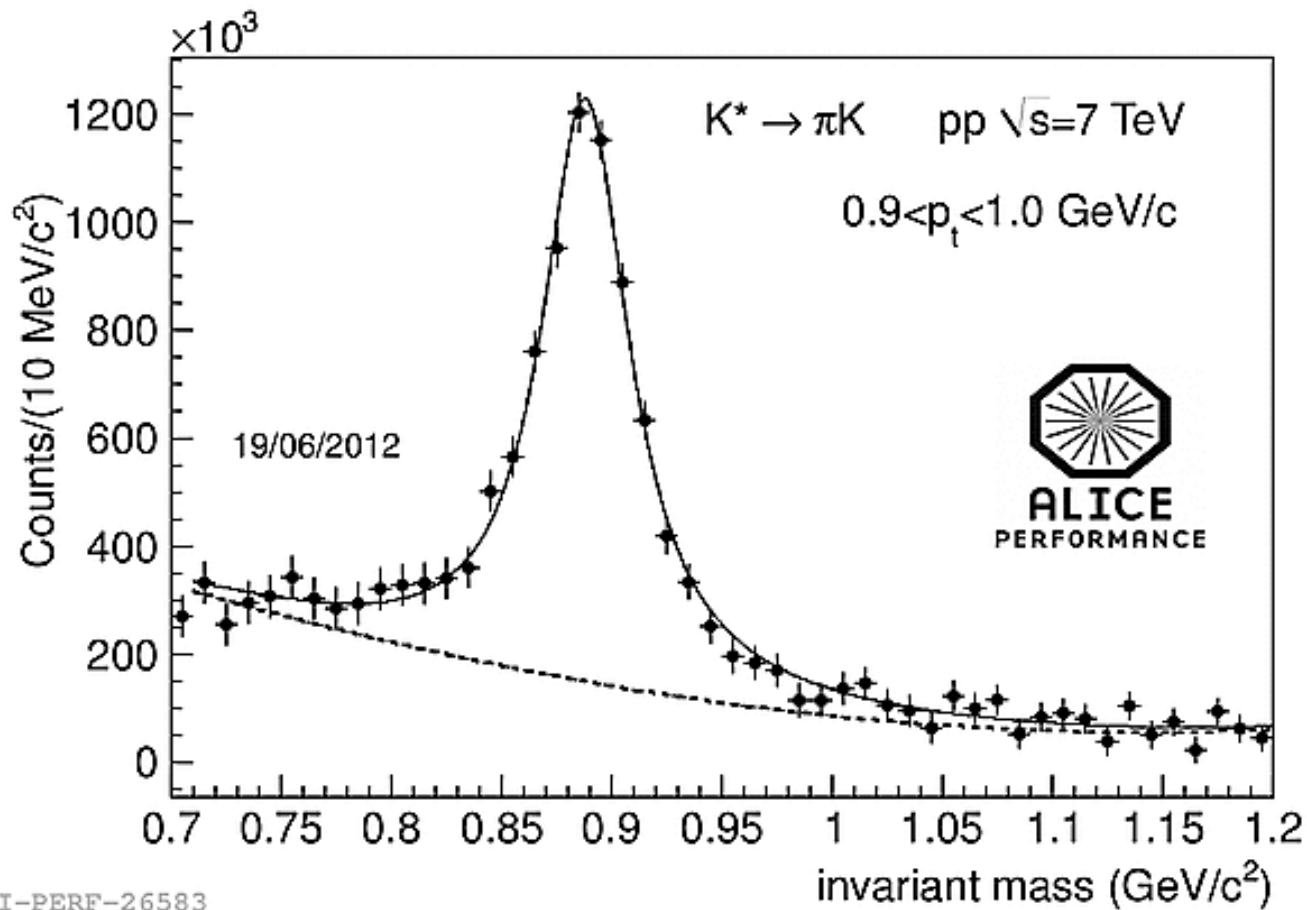
Figure 3.12 Observed bound states of the $s\bar{u}$ system with masses below $1.5 \text{ GeV}/c^2$, together with values of their spin-parities⁹ J^P . The ground state is the K^- (494) and the others can be interpreted as its excited states.

ALICE reconstruction



ALI-PERF-26579

Notice that mass is not fixed!



The mass width is an indication of the lifetime

- From Heisenberg uncertainty relation we have:

$$\Delta E \cdot \Delta t \sim \hbar \rightarrow$$

The width
 $W \sim \hbar / \text{lifetime}$

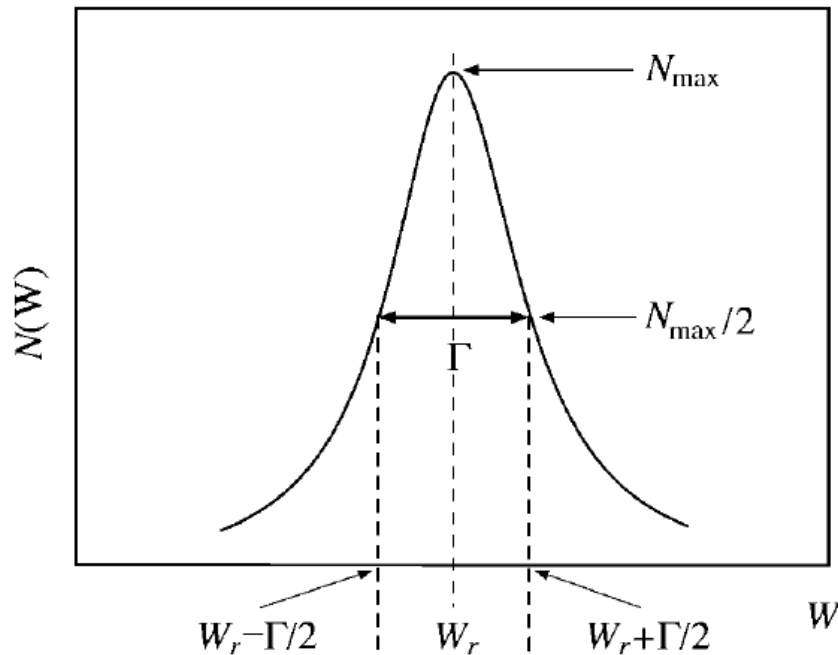


Figure 3.10 Plot of the Breit-Wigner formula (3.26).

Summary

Three generations of matter (fermions)

	I	II	III		
mass →	2.4 MeV/c ²	1.27 GeV/c ²	171.2 GeV/c ²	0	? GeV/c ²
charge →	2/3	2/3	2/3	0	0
spin →	1/2	1/2	1/2	1	0
name →	u up	c charm	t top	γ photon	H Higgs boson
	4.8 MeV/c ²	104 MeV/c ²	4.2 GeV/c ²	0	
	-1/3	-1/3	-1/3	0	
	1/2	1/2	1/2	1	
Quarks	d down	s strange	b bottom	g gluon	
	<2.2 eV/c ²	<0.17 MeV/c ²	<15.5 MeV/c ²	91.2 GeV/c ²	
	0	0	0	0	
	1/2	1/2	1/2	1	
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	Z⁰ Z boson	
	0.511 MeV/c ²	105.7 MeV/c ²	1.777 GeV/c ²	80.4 GeV/c ²	
	-1	-1	-1	±1	
	1/2	1/2	1/2	1	
Leptons	e electron	μ muon	τ tau	W[±] W boson	Gauge bosons