



# 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)

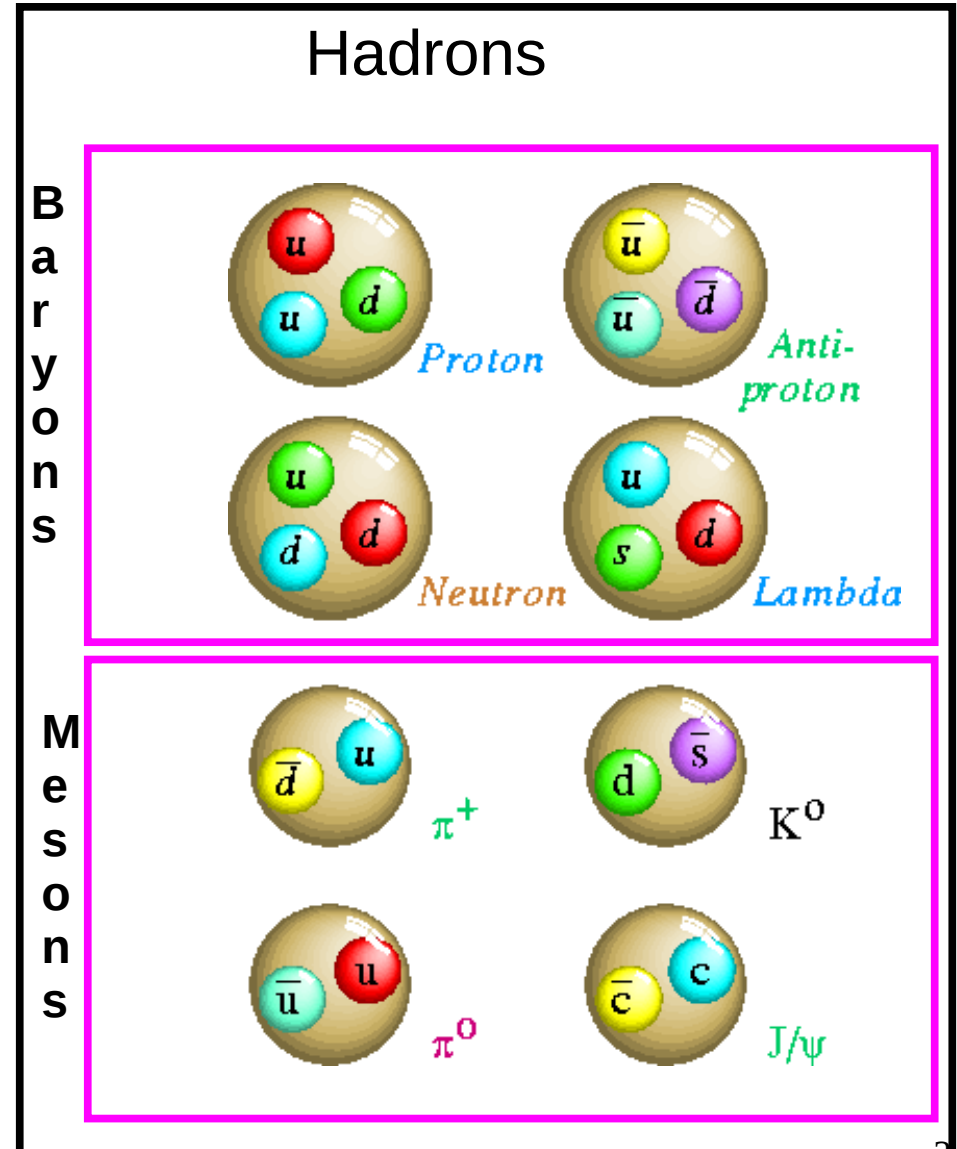
Hadrons have to be colorless

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?

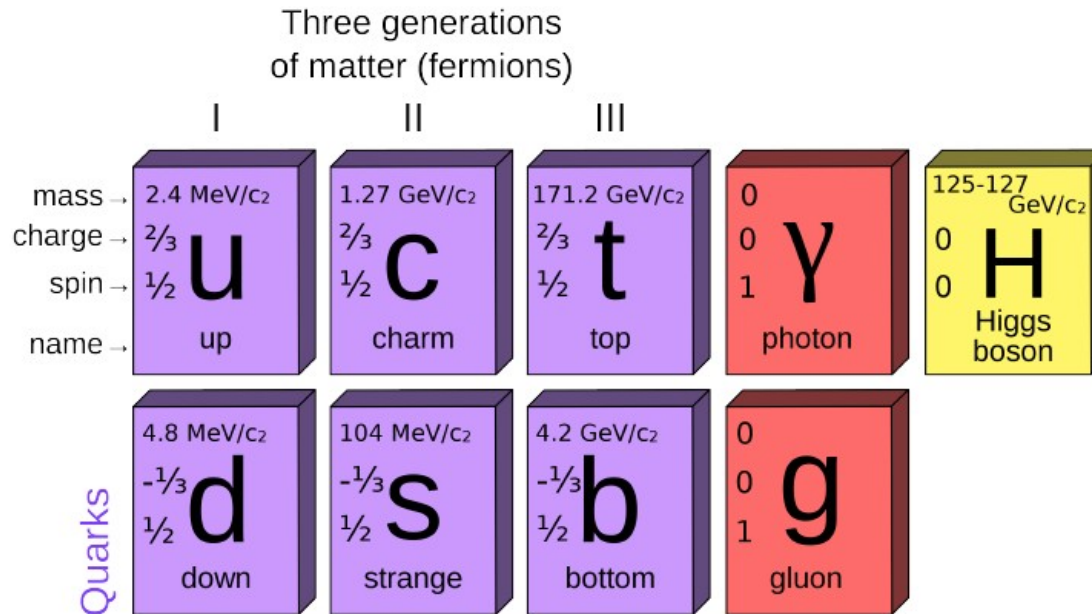


TABLE 3.1 The approximate masses of the quarks in  $\text{GeV}/c^2$  and their electric charges  $Q$  in units of  $e$ . Also shown are the values of the baryon number  $B$ , strangeness  $S$ , charm  $C$ , bottom  $\tilde{B}$  and top  $T$ , as defined in Section 3.2. The values for the corresponding 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
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Bottom	$b$	$m_b \approx 4.5$	$-1/3$	$1/3$	0	0	-1	0
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# Two definitions

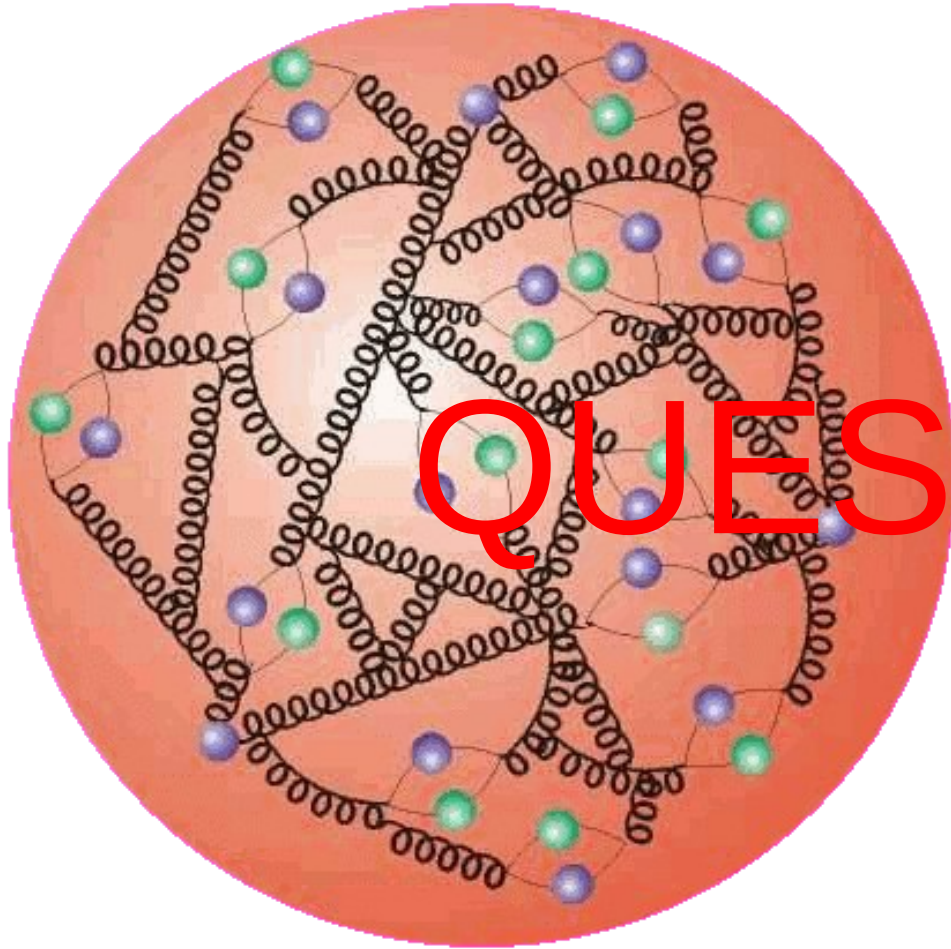
- Constituent quark mass:
  - The effective mass in the hadrons:
    - $M_p \sim 938 \text{ MeV} \rightarrow M_u \sim M_d \sim 300 \text{ MeV}$
- Free quark mass:
  - The mass if the quarks were not bound inside hadrons (the Higgs mass)
- Nonstandard situation:
  - Bound state heavier than non-bound 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  $\Delta x$ 
  - $\Delta x \sim 1 \text{ fm} \rightarrow \Delta p \sim 200 \text{ MeV}$
  - And we know  $E = p^2 + m^2$  so the confinement momentum dominates the energy (effective mass)

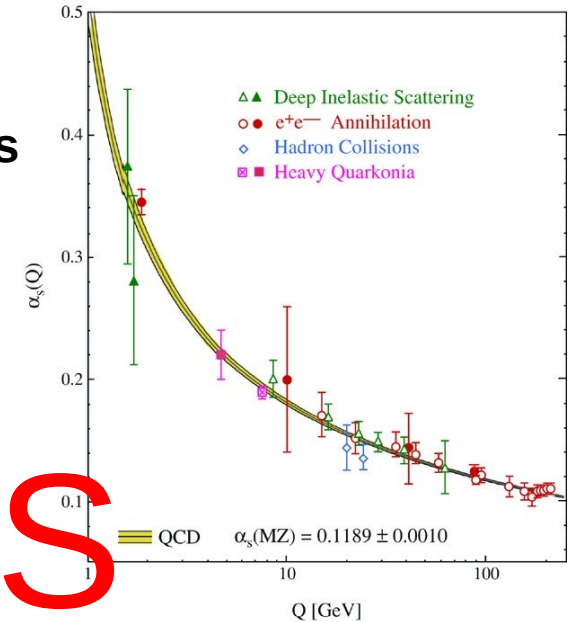
# Many difficult aspects about the strong force

- The strong interaction is very complex!



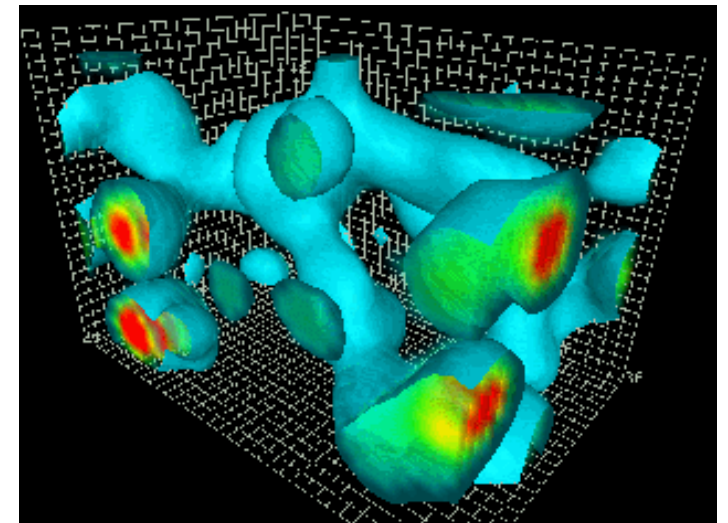
**CONFINEMENT**

Quarks and gluons  
couples strong:



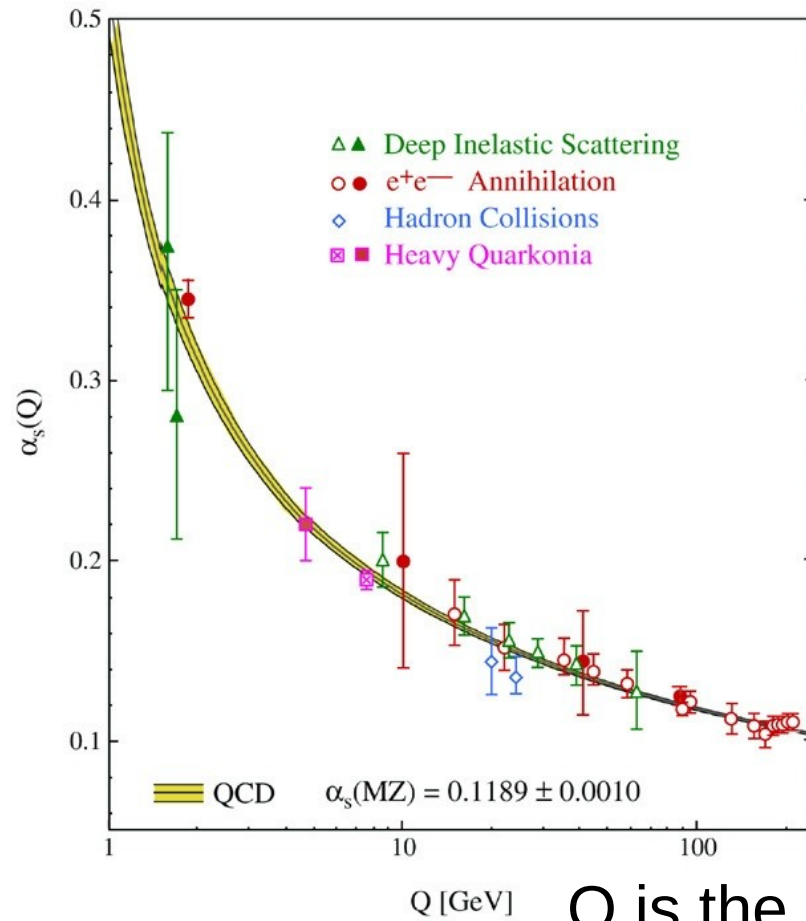
**QUESTIONS**

Complex  
vacuum:



# The coupling is not fixed but runs!

$\alpha_s$



Q is the 4 momentum transfer

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



# Screening/running of the coupling in electromagnetic collisions

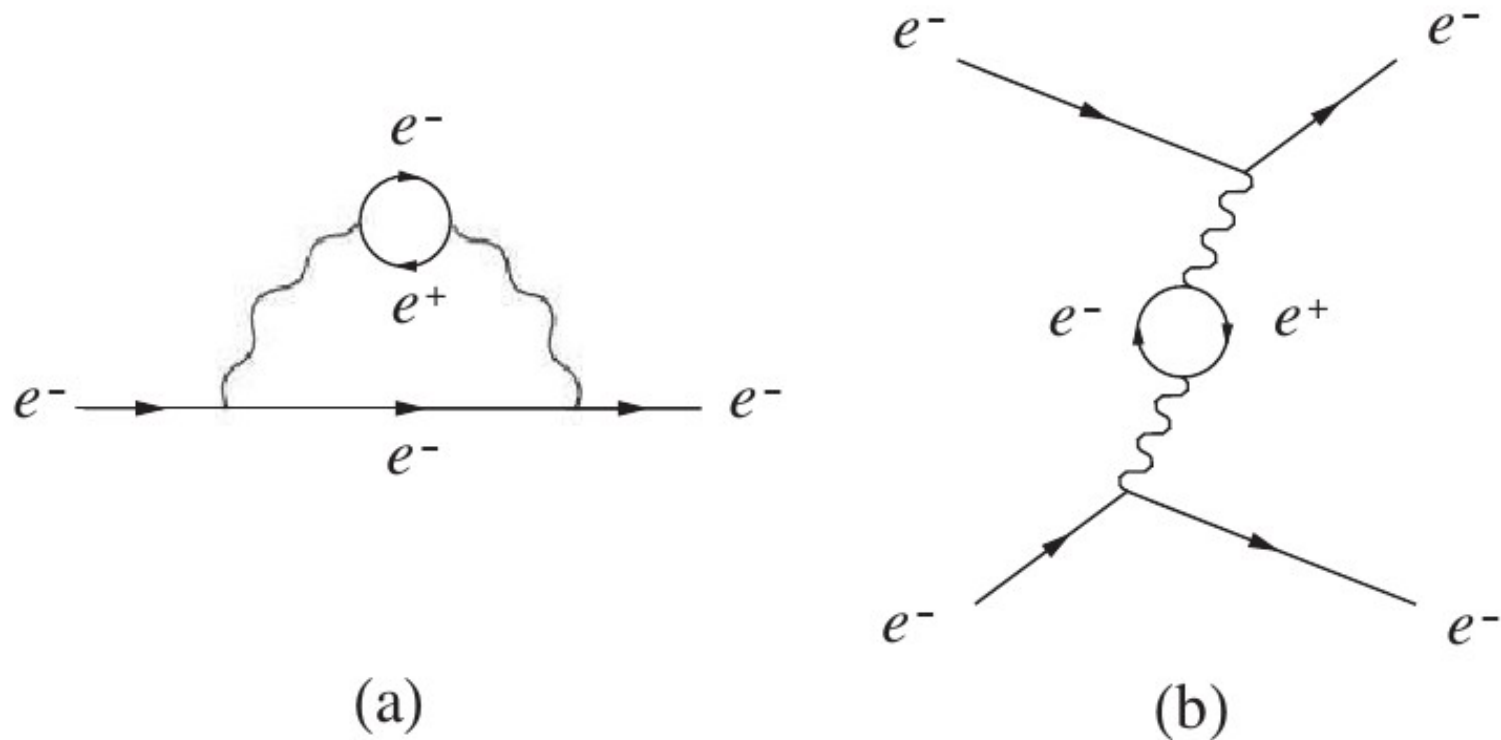


Figure 7.5 A more complicated quantum fluctuation of the electron, together with the associated exchange process.

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

Notice the order: -, +, -!

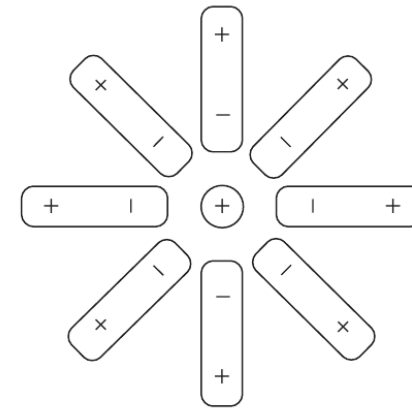
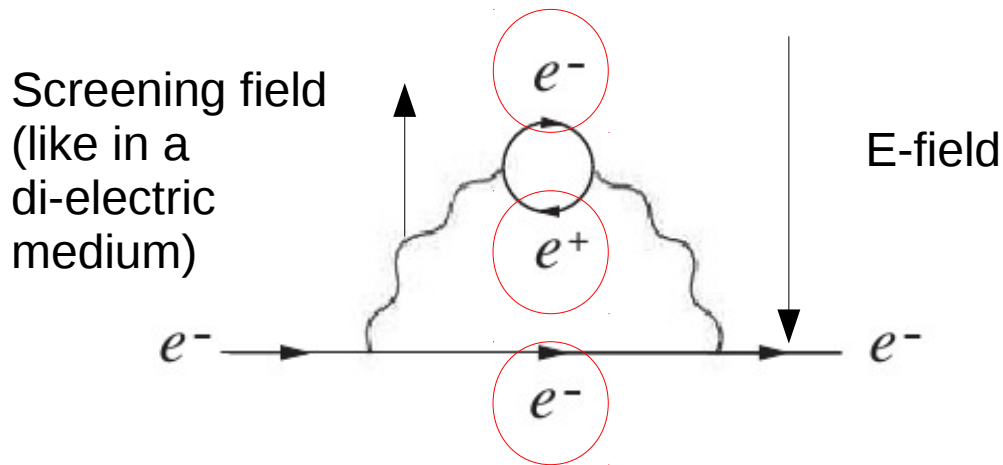


Figure 7.6 Schematic diagram representing the polarization of the molecules of a dielectric by a positive charge placed within it.

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!)

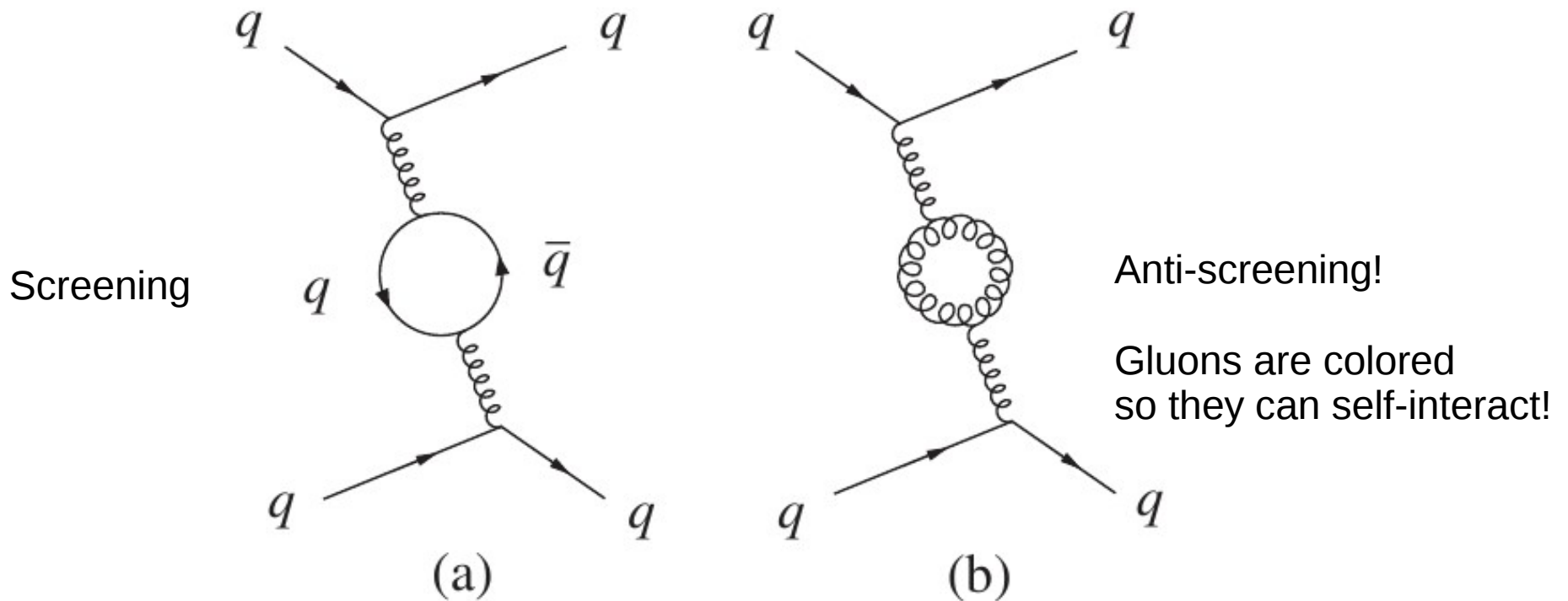


Figure 7.7 The two lowest-order vacuum polarization corrections to one-gluon exchange in quark–quark scattering.

# From Leif's notes

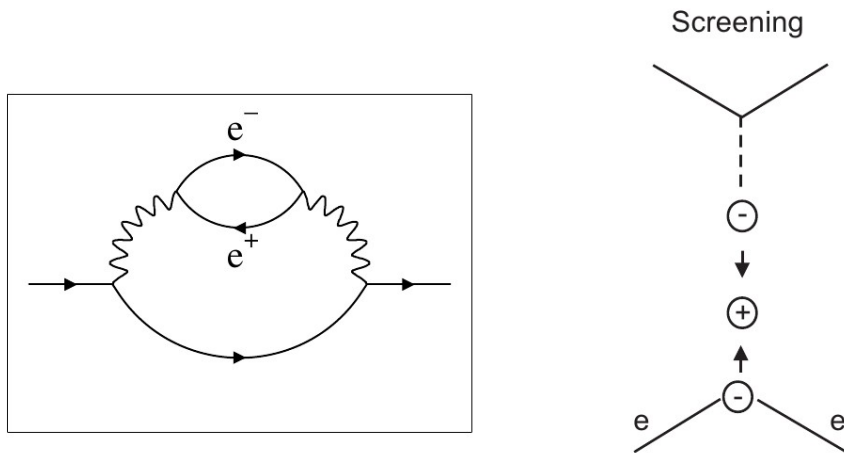


Figure 3.59: Illustration of screening of the electric charge of the electron via the creation of a virtual  $e^+e^-$  pair.

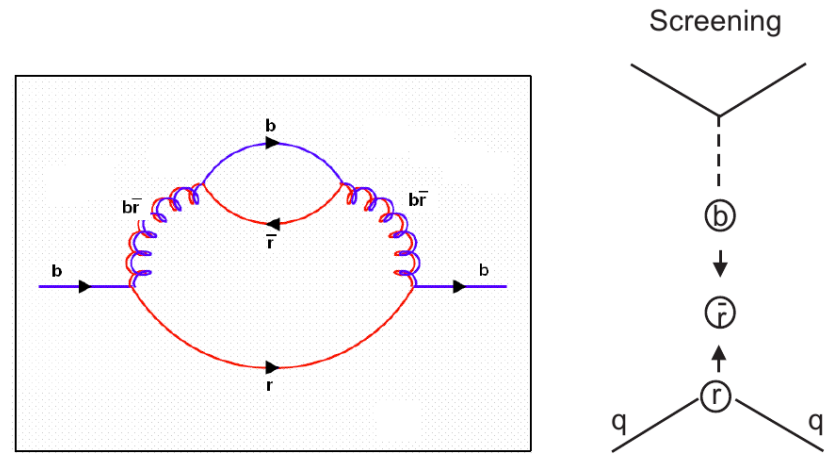


Figure 3.60: Illustration of screening of the colour charge of a quark via the creation of a virtual  $q\bar{q}$  pair.

**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.

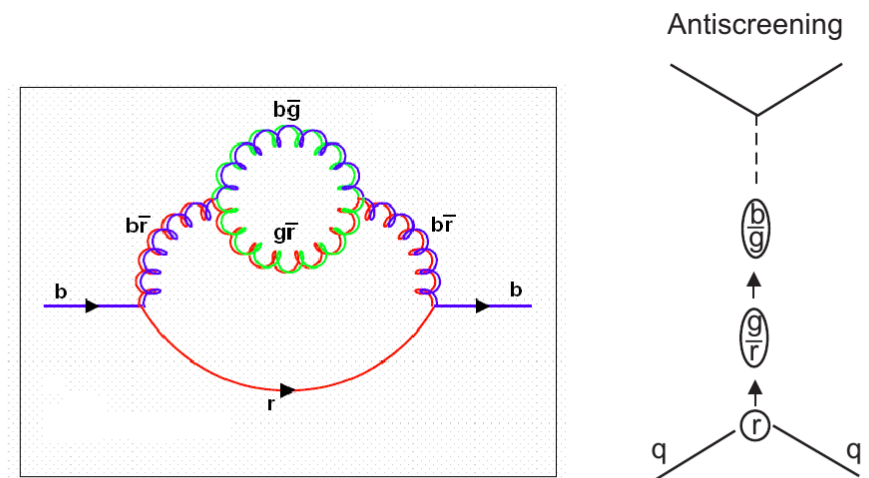
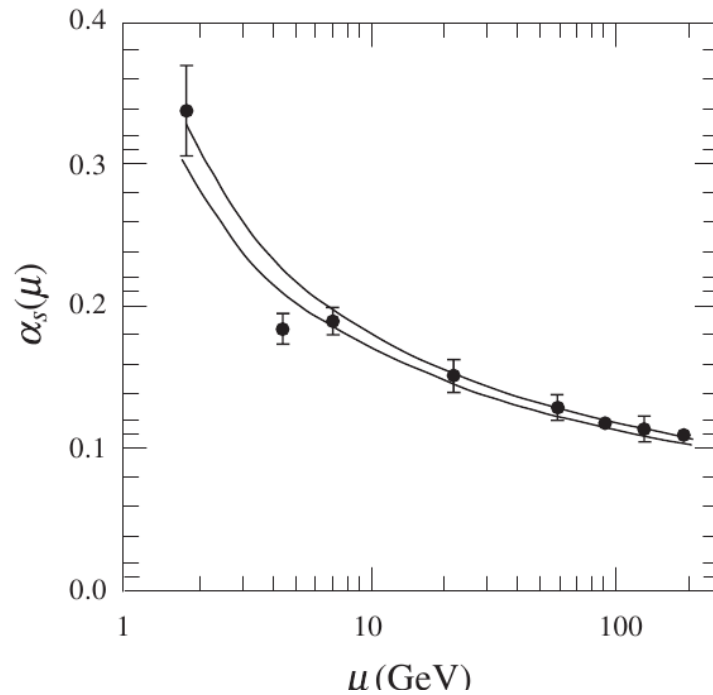


Figure 3.61: Illustration of antiscreening of the colour charge of a quark via the creation of a virtual pair of gluons.

# 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)

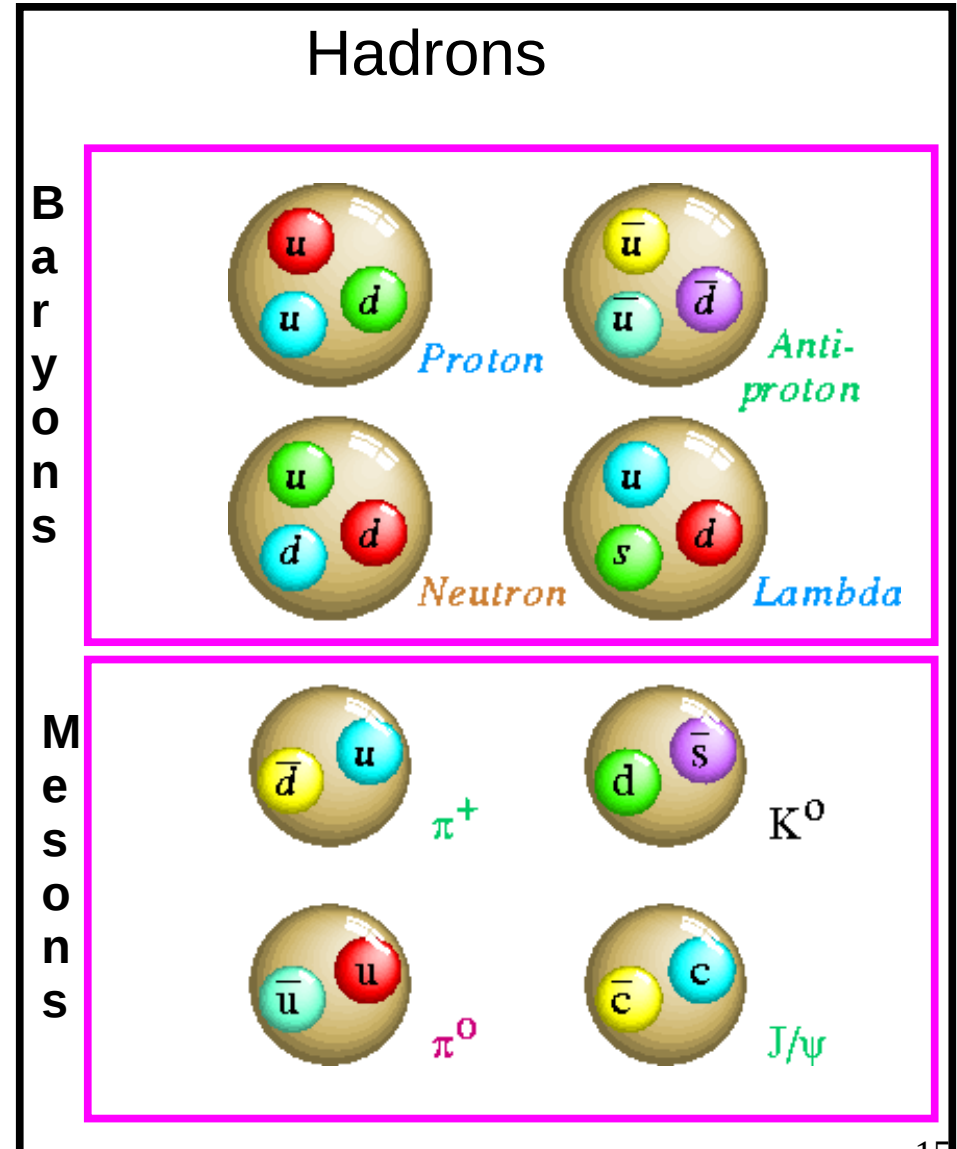
Hadrons have to be colorless

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

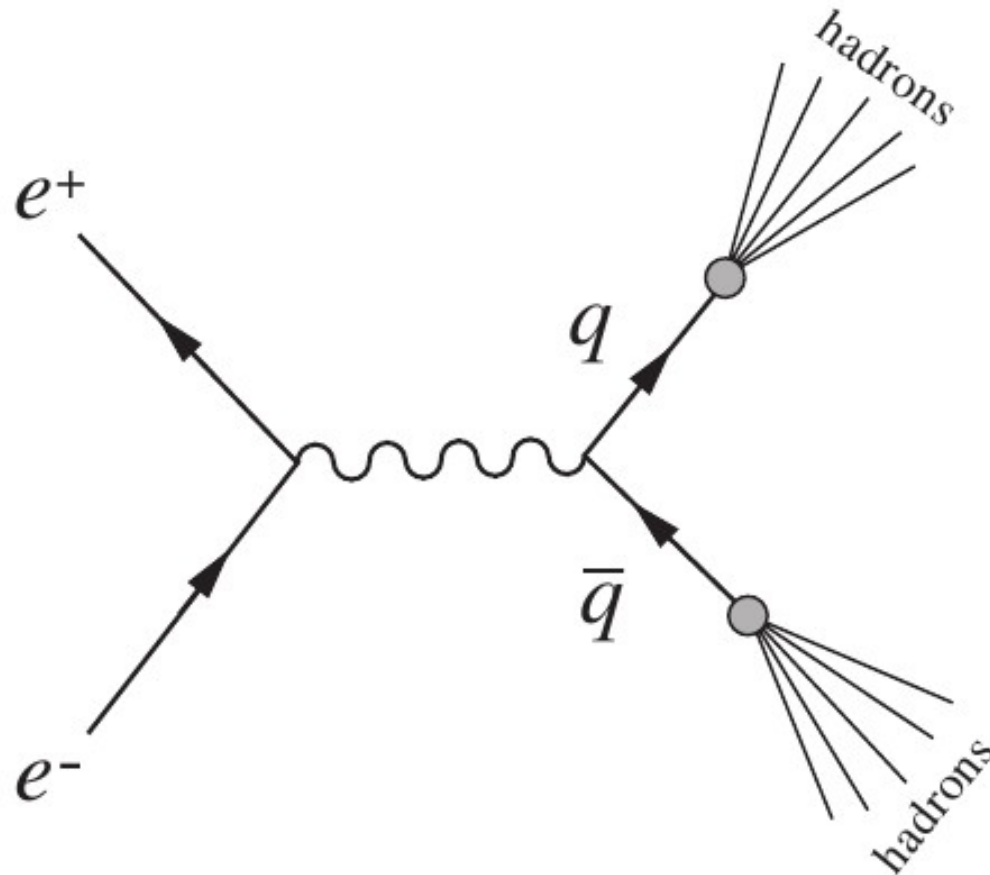
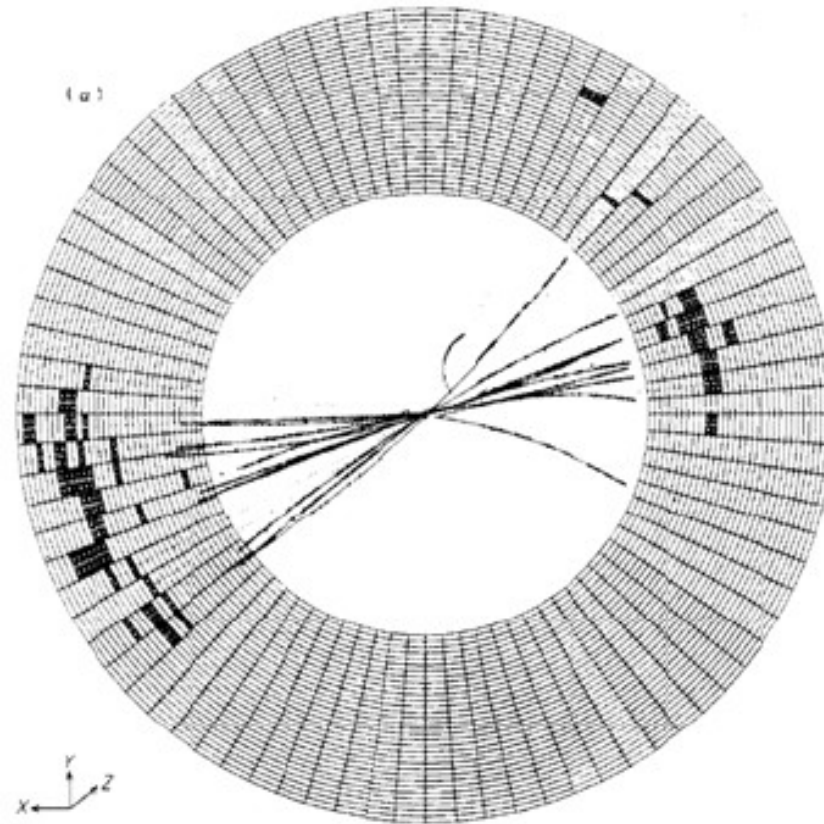


Figure 7.10 Basic mechanism of two-jet production in electron–positron annihilation.



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

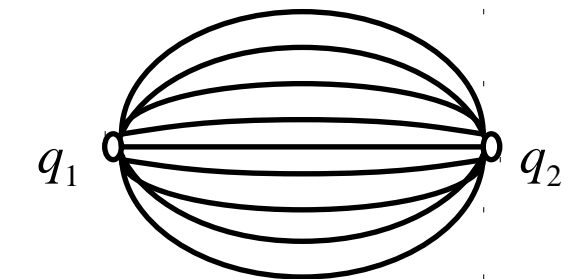


# QCD & Confinement

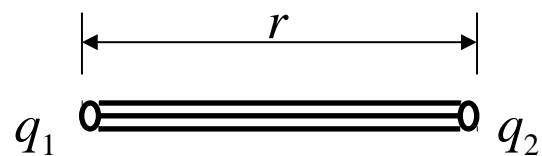
- The strong interaction potential
  - Compare the potential of the strong & e.m. interaction

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

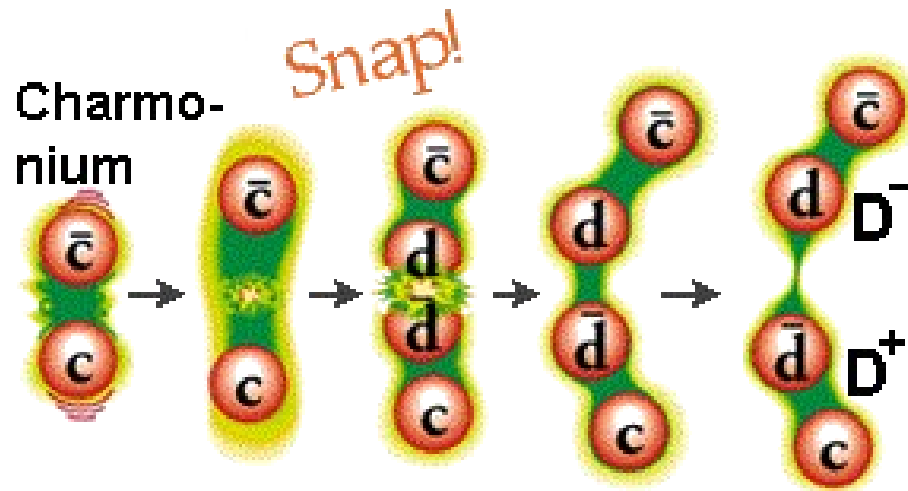
- Confining term arises due to the self-interaction property of the colour field.  $k \sim 1 \text{ GeV/fm}$



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



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



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

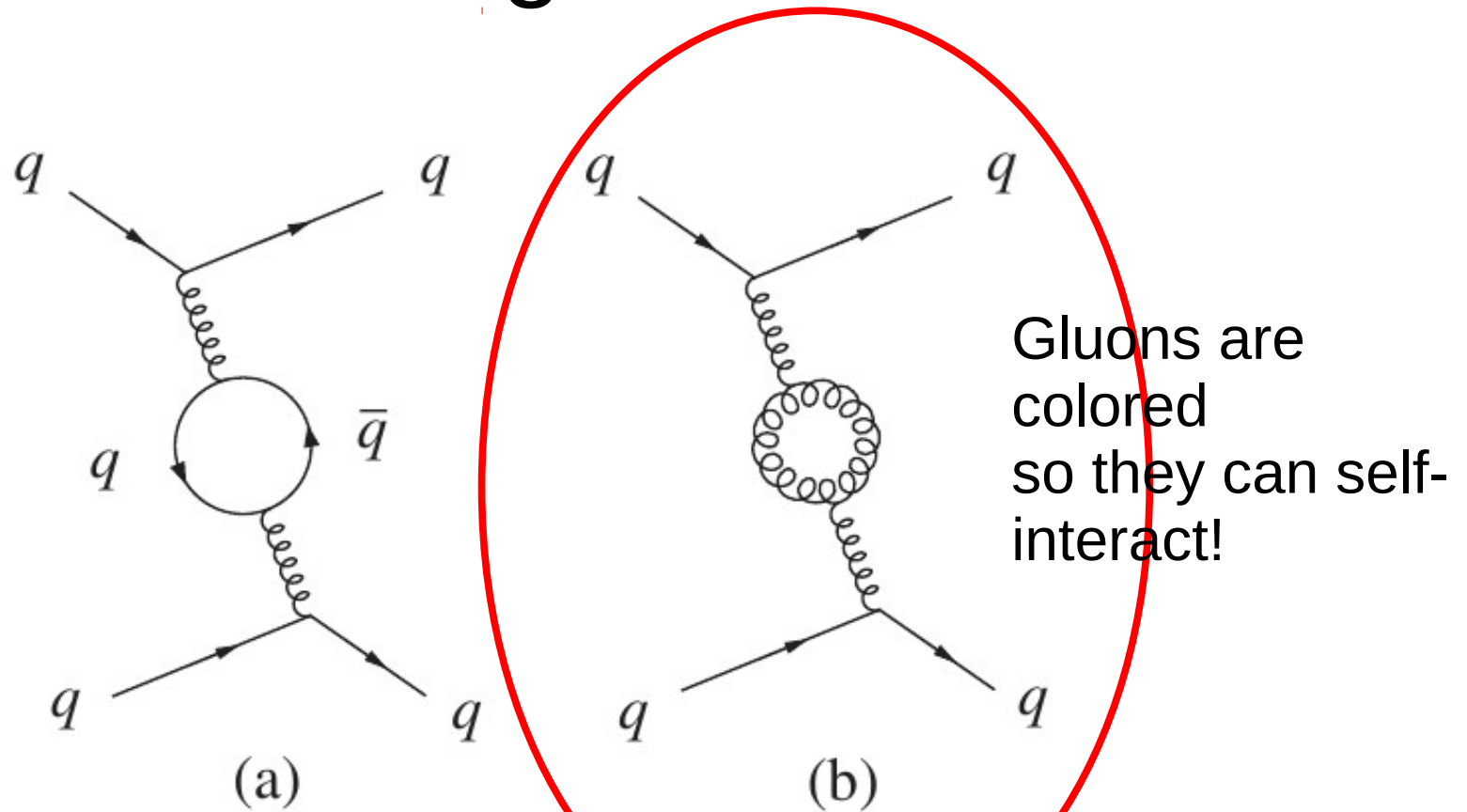


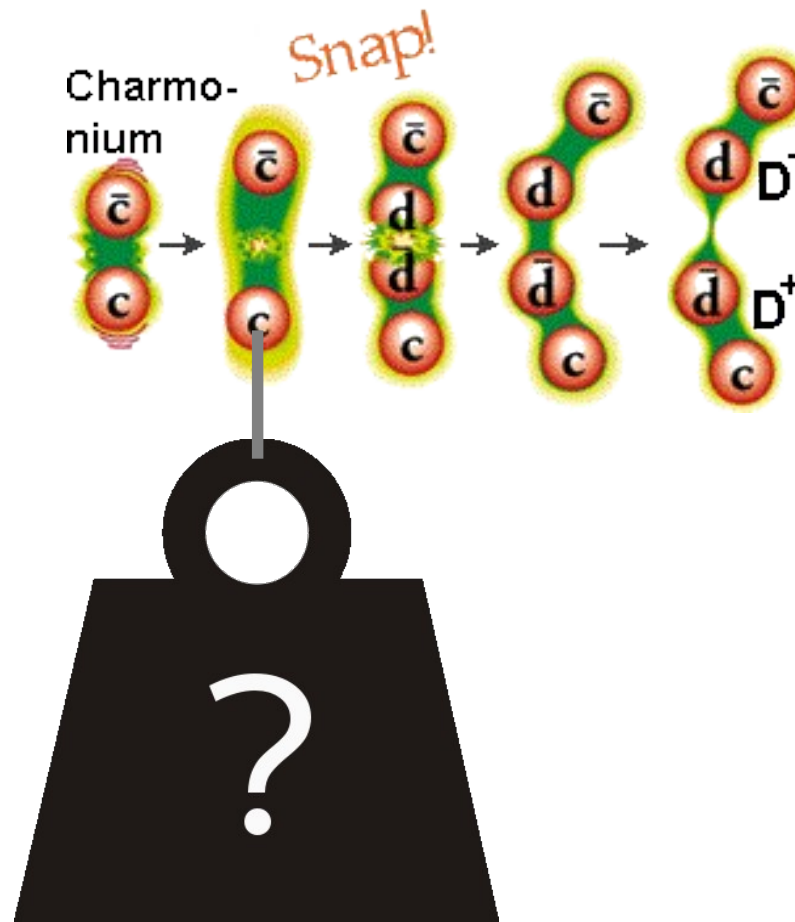
Figure 7.7 The two lowest-order vacuum polarization corrections to one-gluon exchange in quark–quark scattering.

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  $\text{GeV}/c^2$  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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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 ( $\text{MeV}/c^2$ )	$Q$	$S$	$C$	$\tilde{B}$
$p$	$uud$	938	1	0	0	0
$n$	$udd$	940	0	0	0	0
$\Lambda$	$uds$	1116	0	-1	0	0
$\Lambda_c$	$udc$	2285	1	0	1	0
$\Lambda_b$	$udb$	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 ( $\text{MeV}/c^2$ )	$Q$	$S$	$C$	$\tilde{B}$
$\pi^+$	$u\bar{d}$	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
$\Upsilon$	$b\bar{b}$	9460	0	0	0	0

# Important facts about hadrons

- All interactions (EM, weak, strong) preserves the total number of quarks:  $N_q - N_{qbar}$ .
  - 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,  $\mu$ ,  $\tau$
  - 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

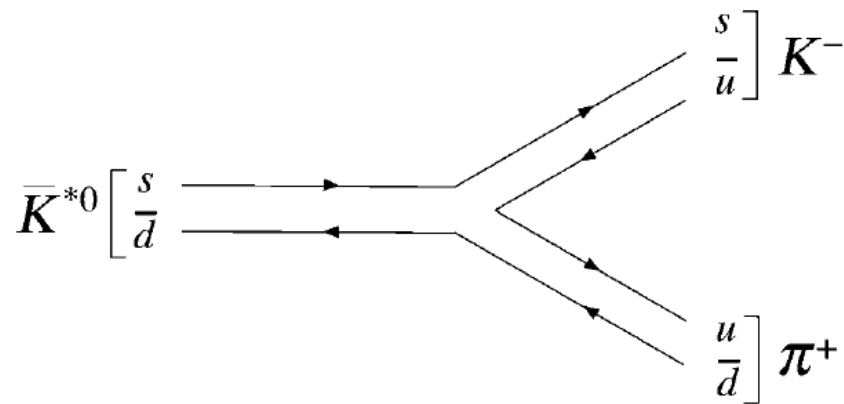


Figure 3.11 Quark diagram for the decay  $\bar{K}^{*0} \rightarrow K^- + \pi^+$ .

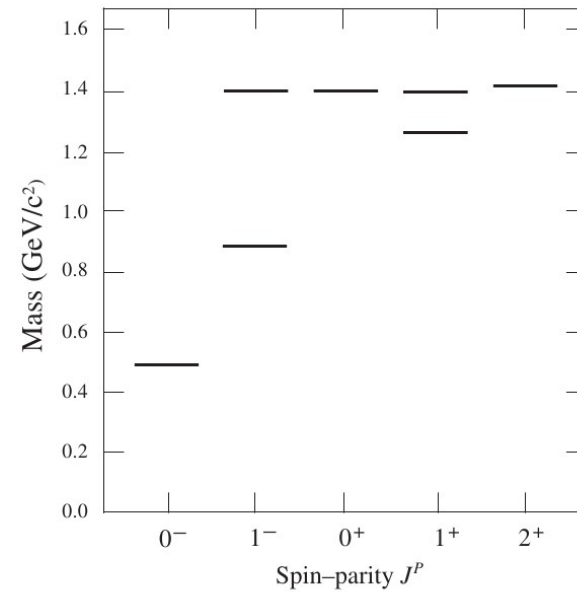
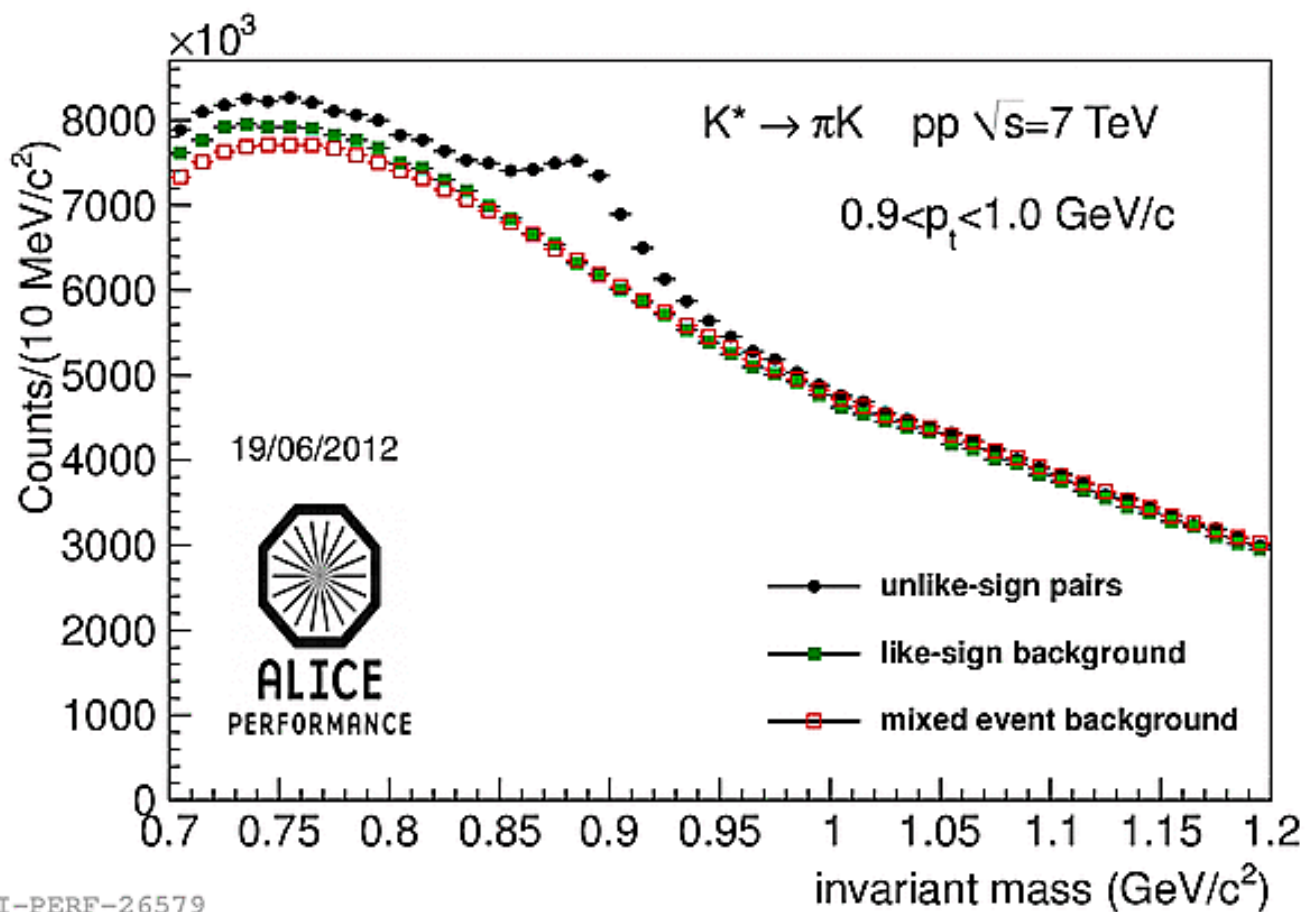


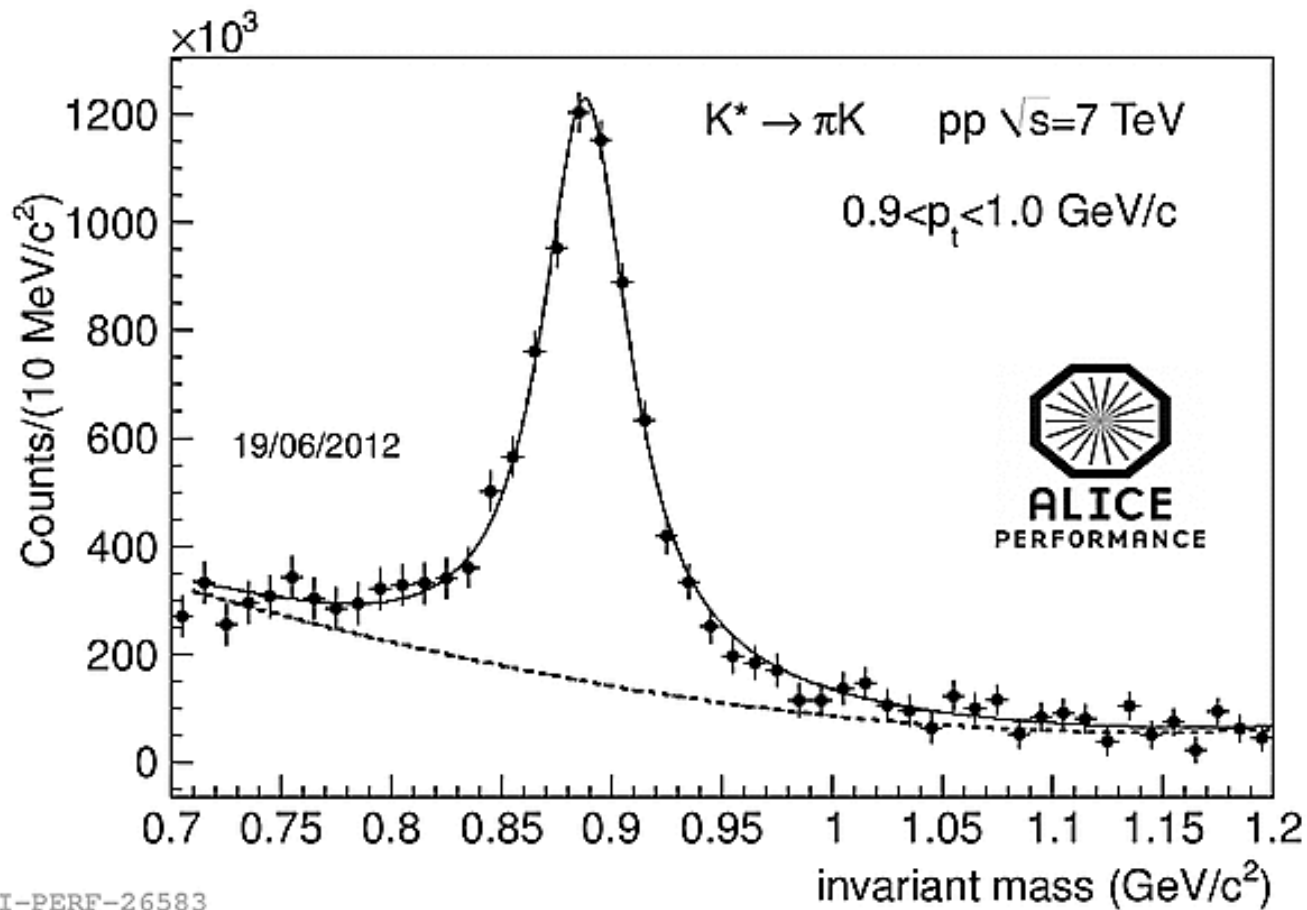
Figure 3.12 Observed bound states of the  $s\bar{u}$  system with masses below  $1.5 \text{ GeV}/c^2$ , together with values of their spin-parities<sup>9</sup>  $J^P$ . The ground state is the  $K^-$  (494) and the others can be interpreted as its excited states.

# ALICE reconstruction



ALI-PERF-26579

# Notice that mass is not fixed!



ALI-PERF-26583

# 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  
 $W \sim \hbar / \text{lifetime}$

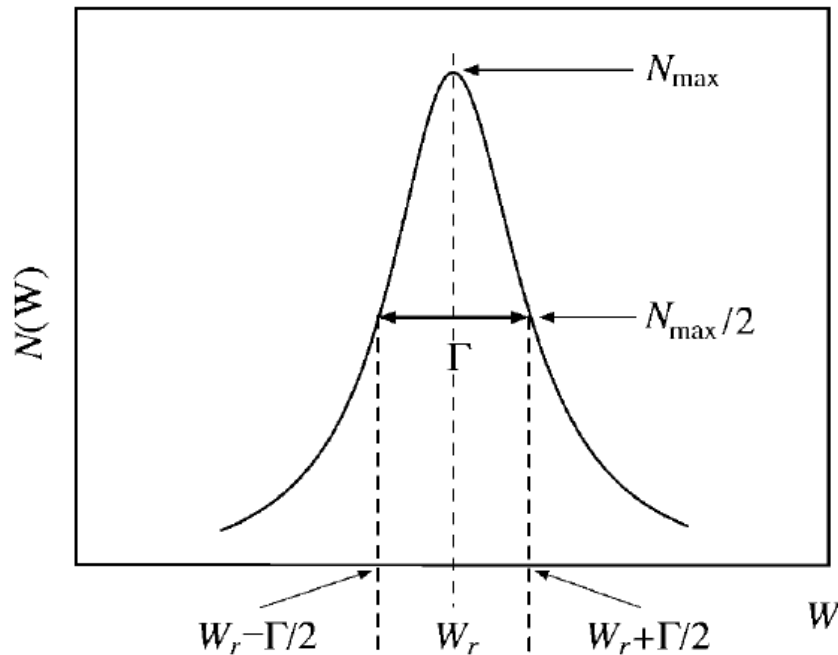


Figure 3.10 Plot of the Breit-Wigner formula (3.26).

# Summary

Three generations of matter (fermions)

	I	II	III		
mass →	2.4 MeV/c <sup>2</sup>	1.27 GeV/c <sup>2</sup>	171.2 GeV/c <sup>2</sup>	0	125-127 GeV/c <sup>2</sup>
charge →	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0	0
spin →	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	0
name →	<b>u</b> up	<b>c</b> charm	<b>t</b> top	<b>γ</b> photon	<b>H</b> Higgs boson
	4.8 MeV/c <sup>2</sup>	104 MeV/c <sup>2</sup>	4.2 GeV/c <sup>2</sup>	0	
	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	0	
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
Quarks	<b>d</b> down	<b>s</b> strange	<b>b</b> bottom	<b>g</b> gluon	
	<2.2 eV/c <sup>2</sup>	<0.17 MeV/c <sup>2</sup>	<15.5 MeV/c <sup>2</sup>	91.2 GeV/c <sup>2</sup>	
	0	0	0	0	
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
	<b>ν<sub>e</sub></b> electron neutrino	<b>ν<sub>μ</sub></b> muon neutrino	<b>ν<sub>τ</sub></b> tau neutrino	<b>Z<sup>0</sup></b> Z boson	
	0.511 MeV/c <sup>2</sup>	105.7 MeV/c <sup>2</sup>	1.777 GeV/c <sup>2</sup>	80.4 GeV/c <sup>2</sup>	
	-1	-1	-1	±1	
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
Leptons	<b>e</b> electron	<b>μ</b> muon	<b>τ</b> tau	<b>W<sup>±</sup></b> W boson	Gauge bosons

# Exercise 3.1