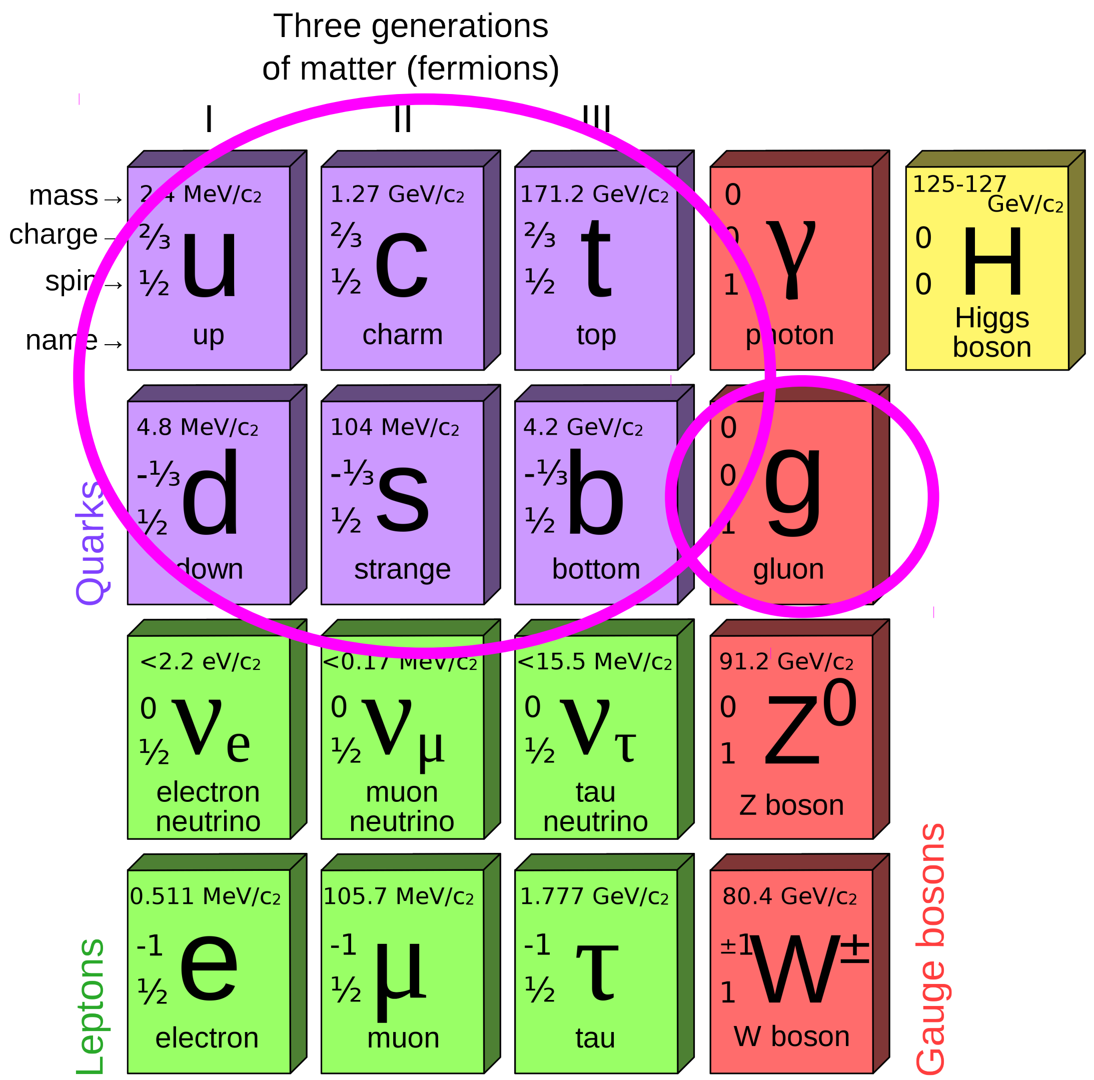
# Quarks and Hadrons

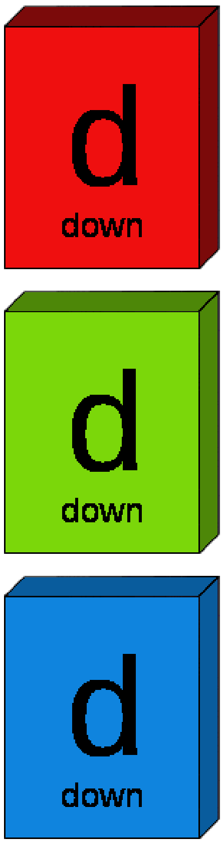


# Do you know what is special about quarks?

# Do you know what is special about quarks?

- They have never been observed directly. We say that they are confined inside the hadrons.
  - Hadrons are particles made up of quarks
- Goal today is to explain how we observe the quarks as bound states called hadrons
  - I will also discuss after this why it is so but this is an advanced argument that we will return to again later in the course

# The interaction of quarks




- For each quark flavor: u, d, s, c, b, t there are 3 charge states: blue, green, and red
- This color is the charge of the strong interaction that binds quarks into e.g. nucleons
- The force is mediated by gluons (that are also colored!) and the theory for the force is called
  Quantum Chromo Dynamics
  or QCD for short

# Hadrons: the “atoms” of particle physics

## QCD:

3 color charges (red, green, blue)

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

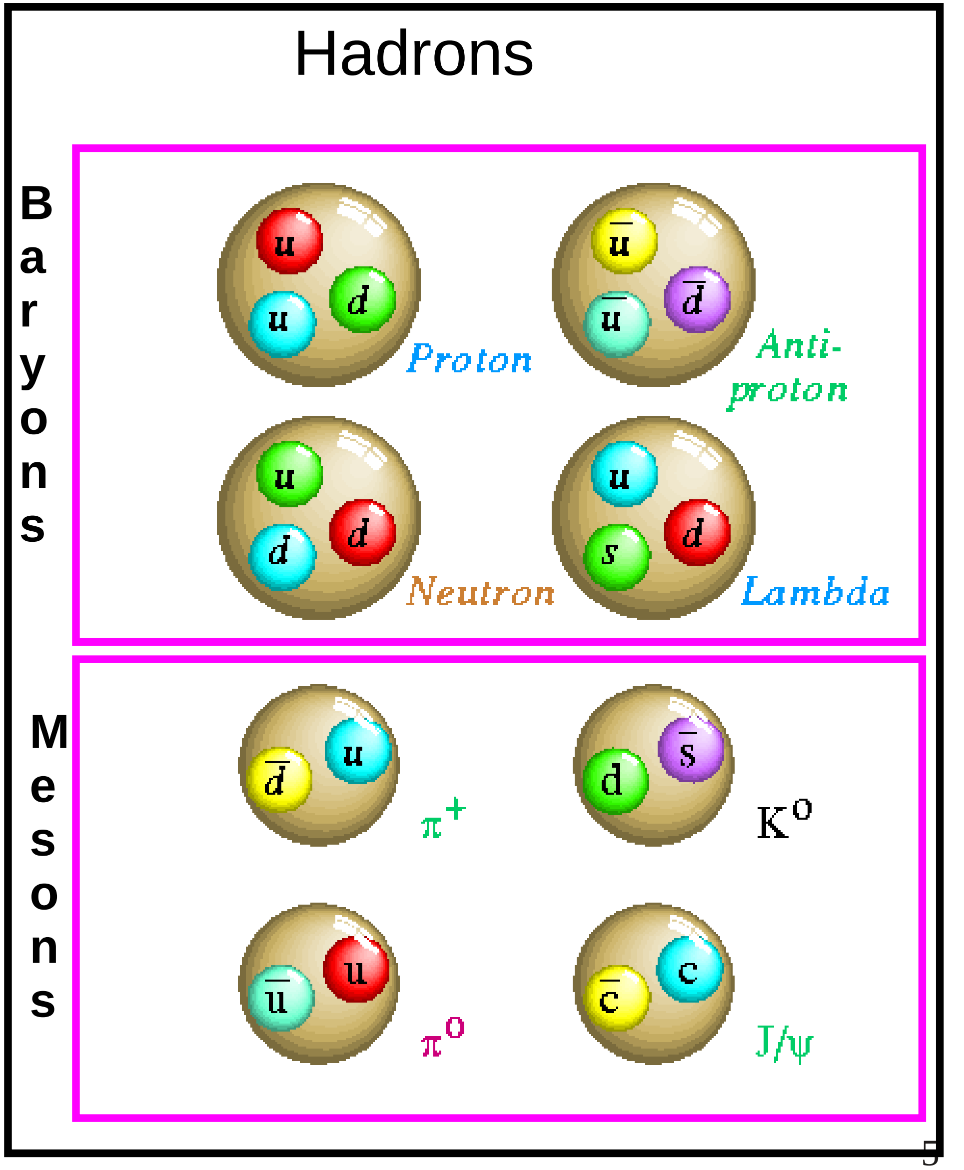
Hadrons have to be colorless

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!



# 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 | $Q$ | $B$ | $S$ | $C$ | $\tilde{B}$ | $T$ |
|---|---|---|---|---|---|---|---|---|
| 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 |

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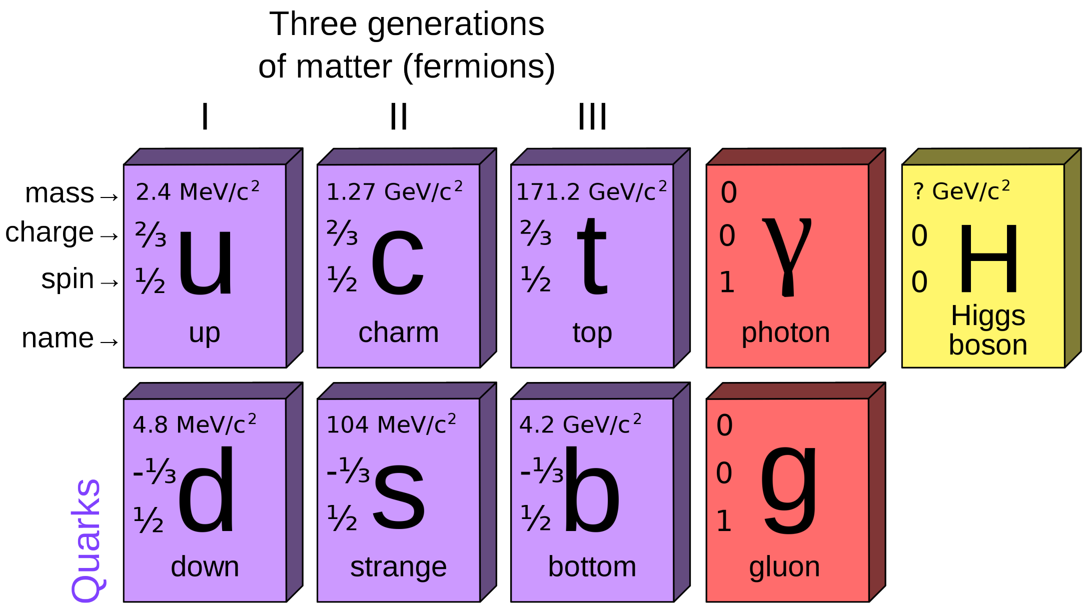
TABLE 3.3 Some examples of mesons, with their quark compositions and the corresponding values of their electric charge $Q$, strangeness $S$, charm $C$ and bottom $\tilde{B}$.

| Particle | | Mass ($MeV/c^2$) | $Q$ | $S$ | $C$ | $\tilde{B}$ |
|---|---|---|---|---|---|---|
| $\pi^+$ | $u\bar{d}$ | 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 |

# What is the relation between quark and hadron masses?

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# 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!
  - That is why we say that quarks are confined

# Mass due to confinement

- From Heisenberg's uncertainty relation:

$$\Delta p \cdot \Delta x \sim \hbar$$

- When we confine we restrict Δx

$$\Delta x \sim 1 fm \rightarrow \Delta p \sim 200\, MeV$$

  - And we know $E=p^2 + m^2$ so the confinement momentum dominates the energy (effective mass)

# 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)
- The reason for this is that all Feynman diagrams we know conserve quark number: a quark “line” never disappears

# 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) + $e^-$ + $\bar{\nu}_e$
    - but quark number is still conserved!

# 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?

# Resonances

- Resonances are hadrons that decays by strong interactions. They are so short lived that they can only be observed indirectly
- They are excited states (like one has excited states in atoms) that we will return to later in more details
- How long do they travel?

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

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# Resonance states are excited states that decays via the strong interaction

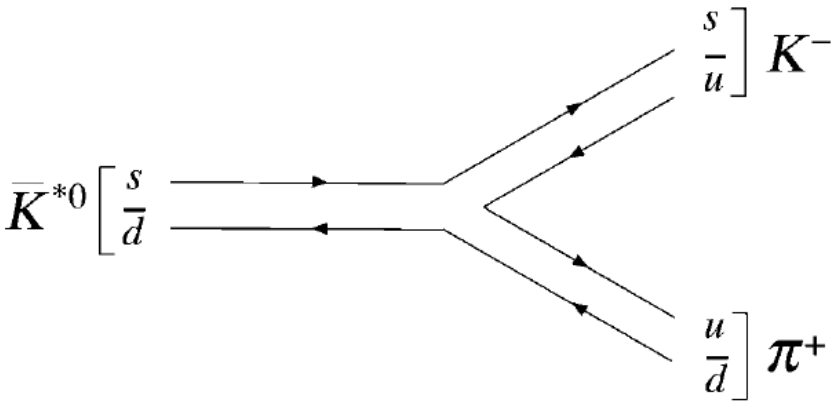



Figure 3.11 Quark diagram for the decay $\bar{K}^{*0} \to K^- + \pi^+$.

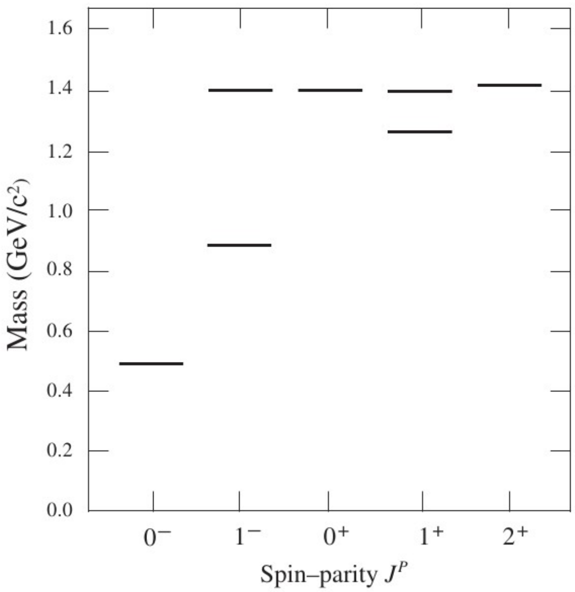
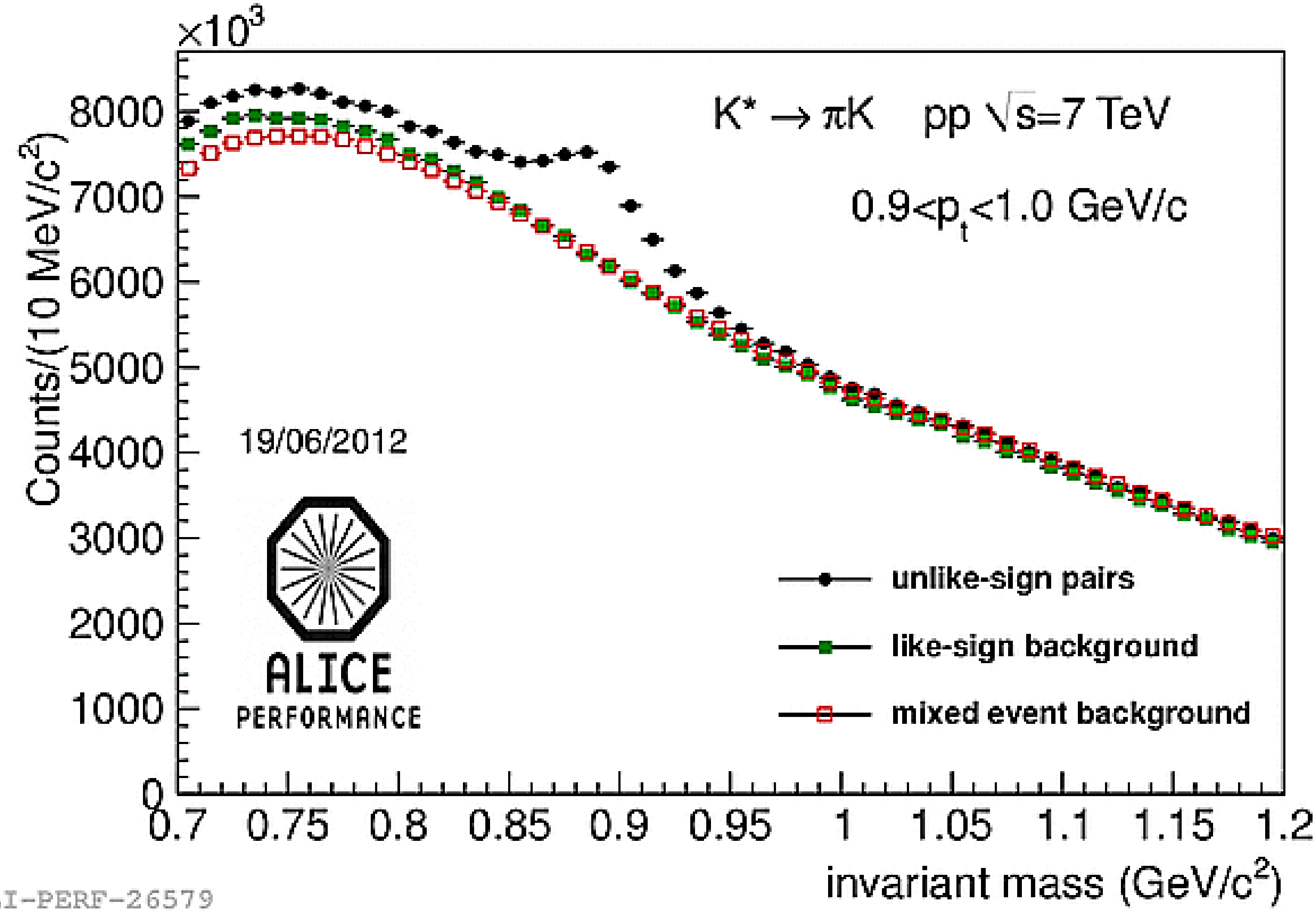



Figure 3.12 Observed bound states of the $s\bar{u}$ system with masses below 1.5 GeV/c$^2$, together with values of their spin-parities[9] $J^P$. The ground state is the $K^-(494)$ and the others can be interpreted as its excited states.

# ALICE reconstruction



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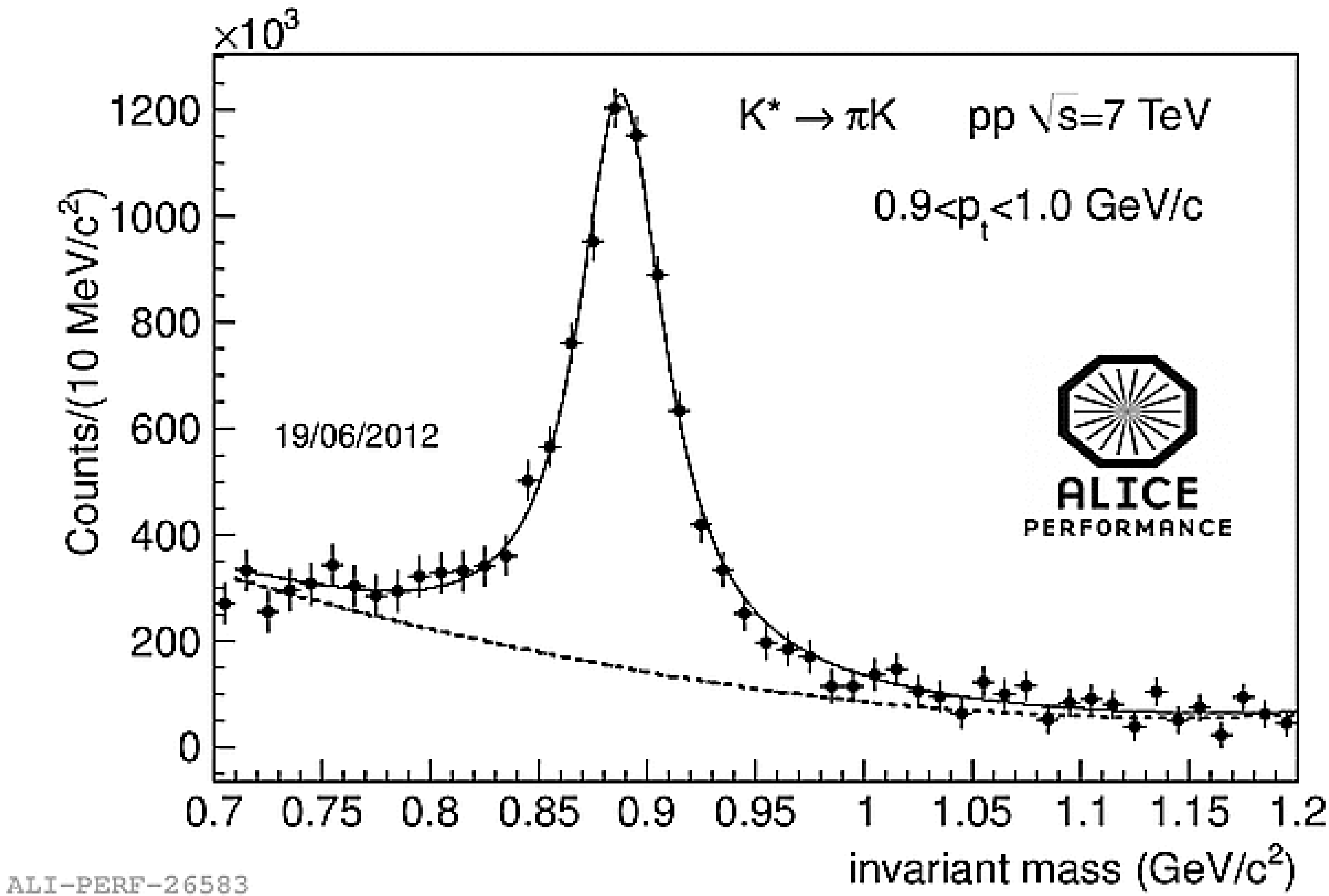
# Notice that mass is not fixed!



# The mass width is an indication of the lifetime

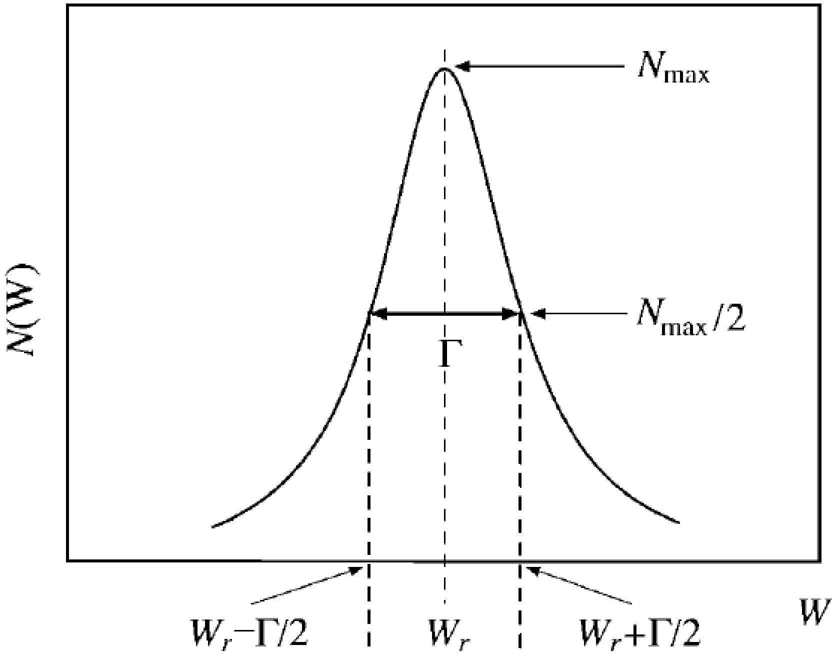



Figure 3.10 Plot of the Breit–Wigner formula (3.26).

- From Heisenberg uncertainty relation we have:

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

So that the width

$$W \sim \frac{\hbar}{\tau}$$

Where τ is the lifetime

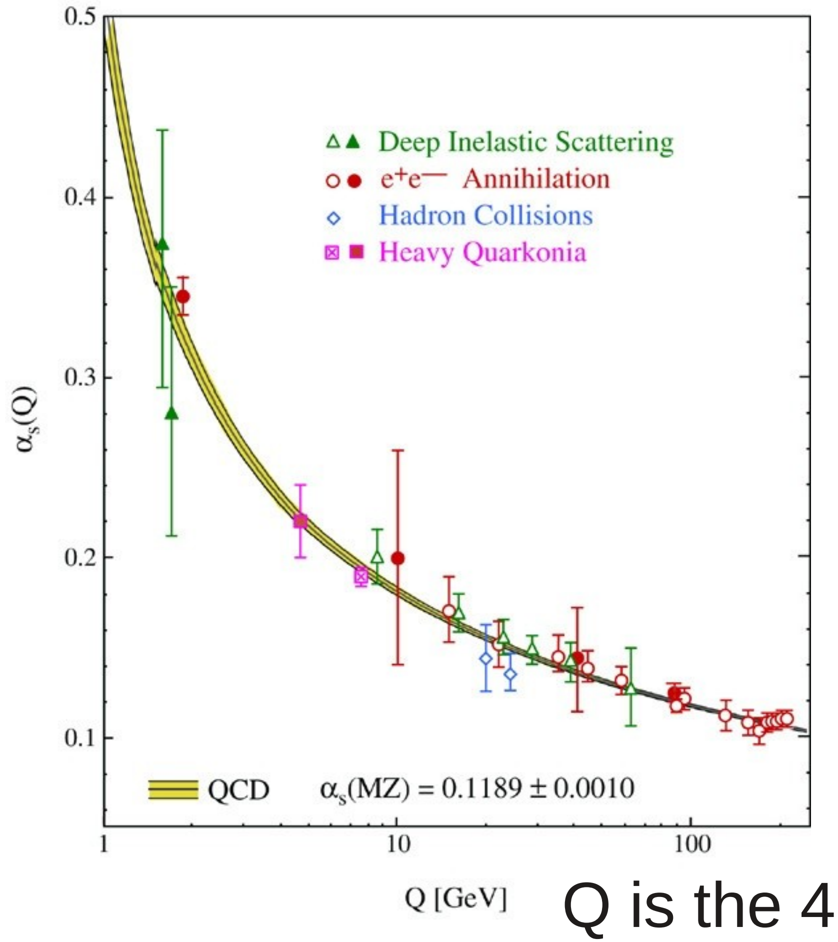
# This completes the basic introduction of hadrons

- It is a good idea to solve some of the questions in the book on what processes are allowed

- But we now only understand how nature works, not why it is so!

# The coupling is not fixed but runs!

$\alpha_s$




Q is the 4 momentum transfer

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

# Screening/running of the coupling in electromagnetic collisions

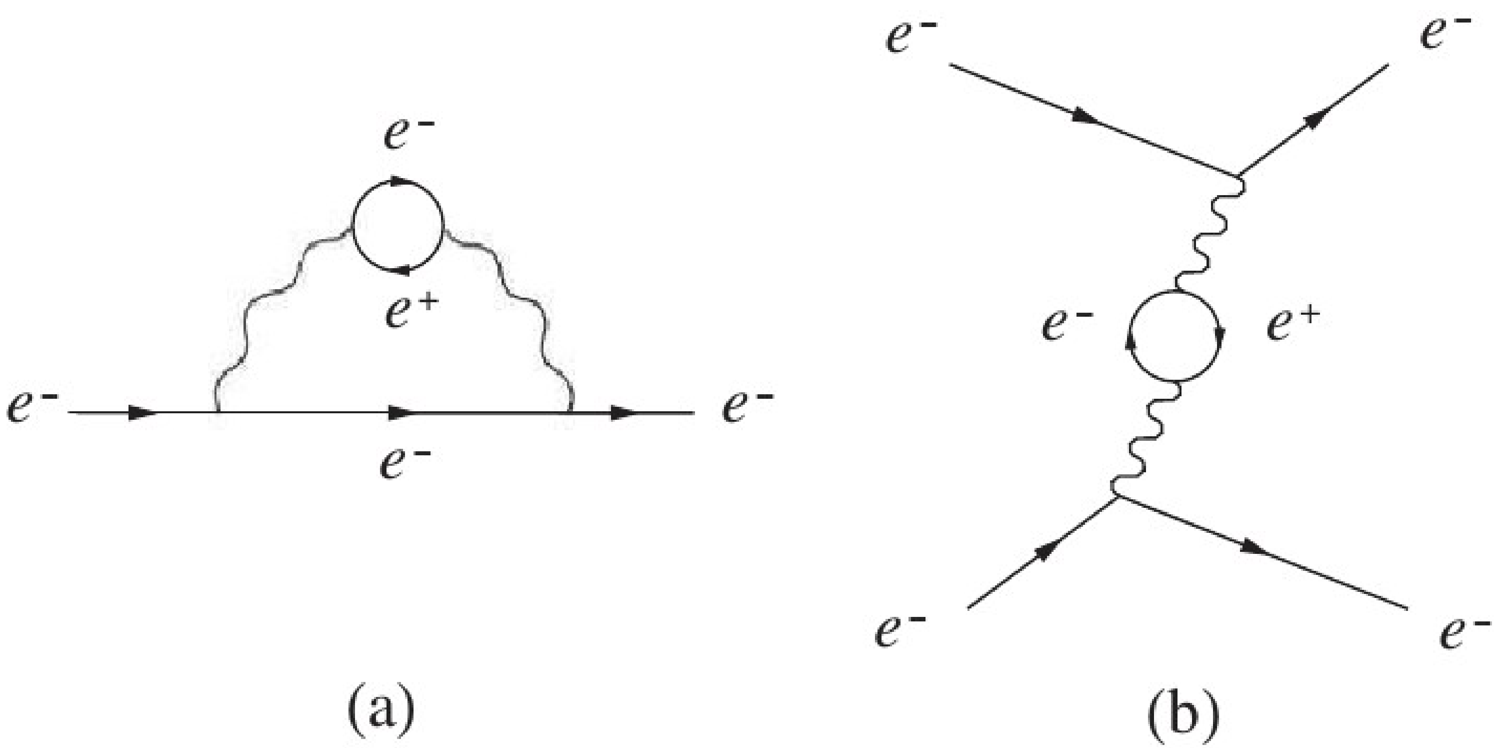
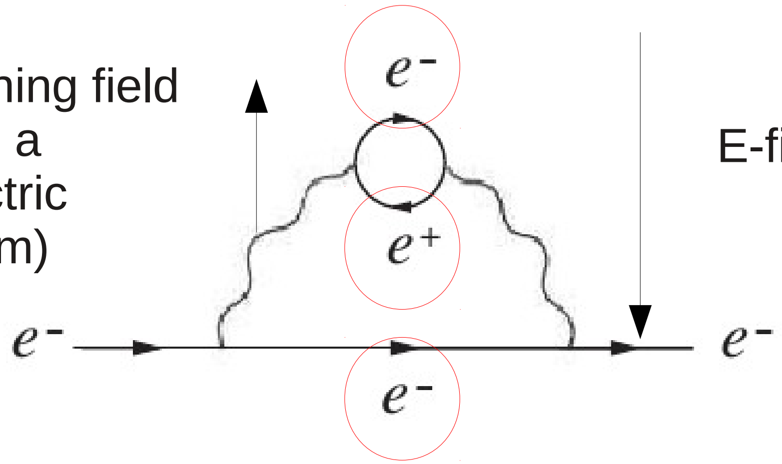



Figure 7.5 A more complicated quantum fluctuation of the electron, together with the associated exchange process.

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

Notice the order: -, +, -!

Screening field (like in a di-electric medium)



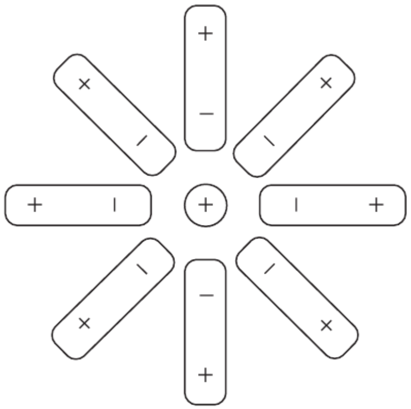
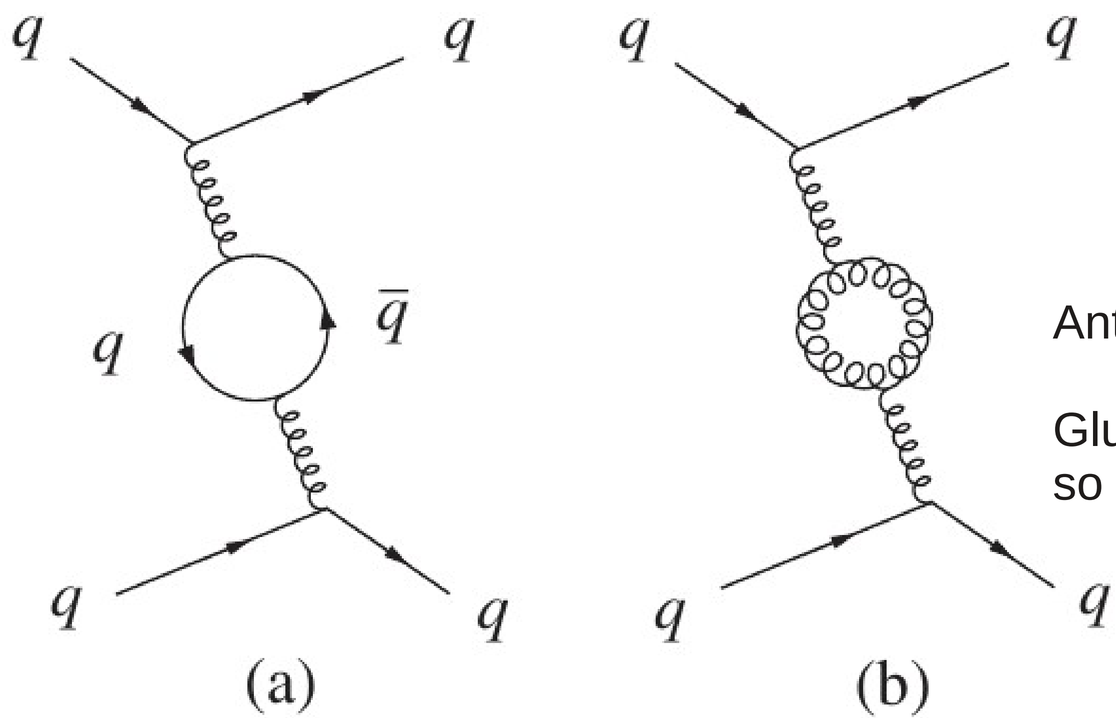



Figure 7.6 Schematic diagram representing the polarization of the molecules of a dielectric by a positive charge placed within it.

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

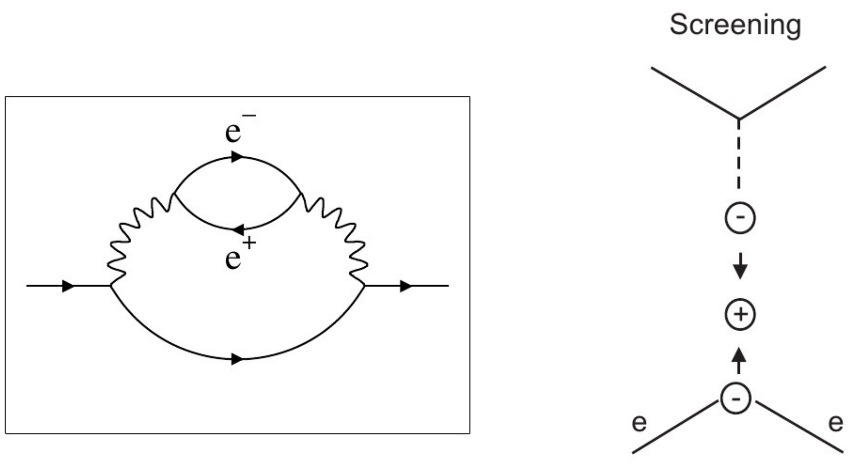



Figure 3.59: *Illustration of screening of the electric charge of the electron via the creation of a virtual* $e^+e^-$ *pair.*

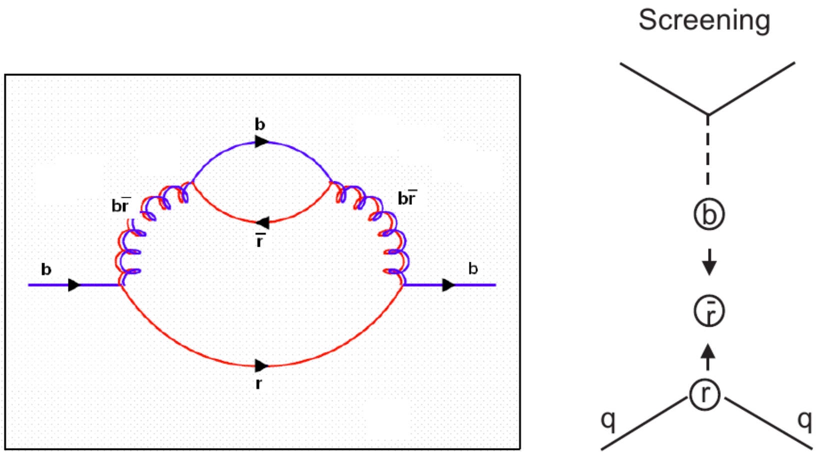



Figure 3.60: *Illustration of screening of the colour charge of a quark via the creation of a virtual* $q\overline{q}$ *pair.*

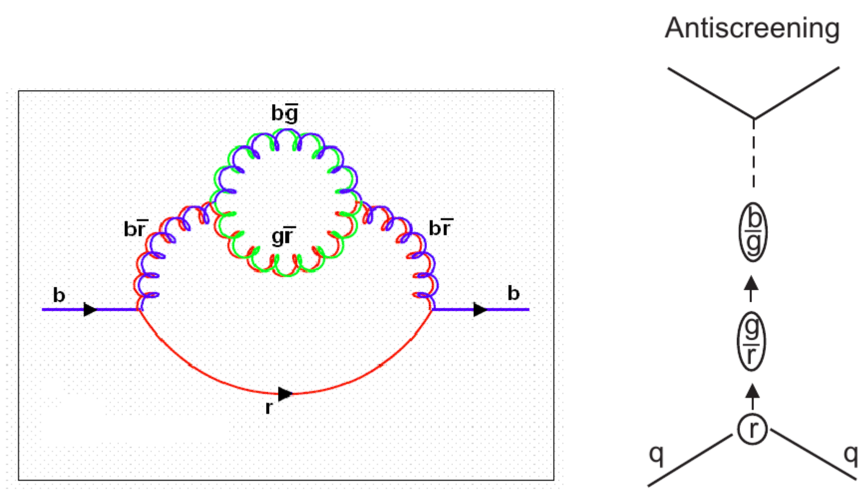
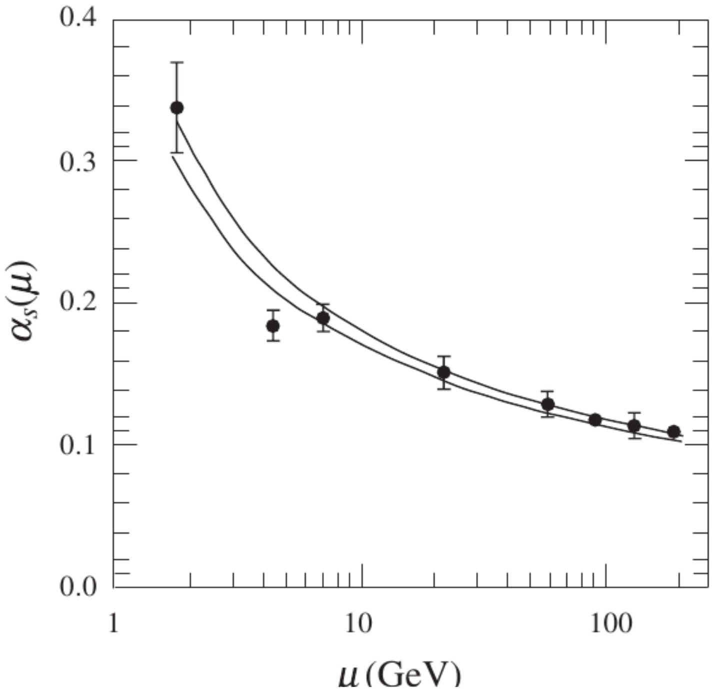



Figure 3.61: *Illustration of antiscreening of the colour charge of a quark via the creation of a virtual pair of gluons.*

# Full result for QCD




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

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

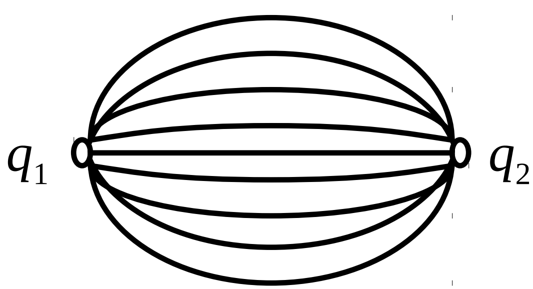
Gluons are colored so they can self-interact!

# QCD & Confinement

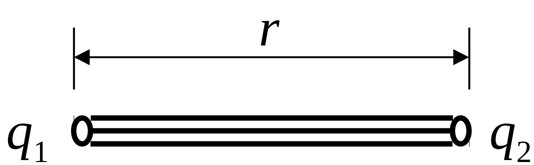
- The strong interaction potential
  - Compare the potential of the strong & e.m. interaction

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

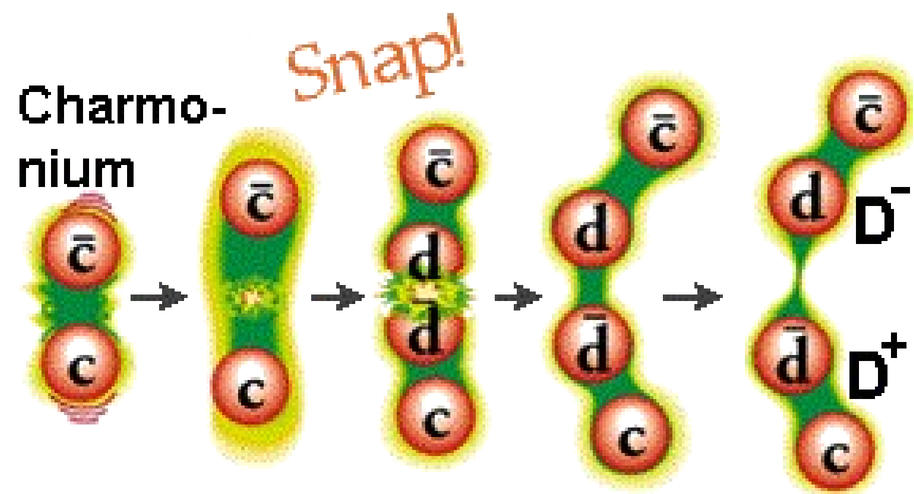
  - Confining term arises due to the self-interaction property of the colour field. k~1GeV/fm




a) QED or QCD ($r$ < 1 fm)

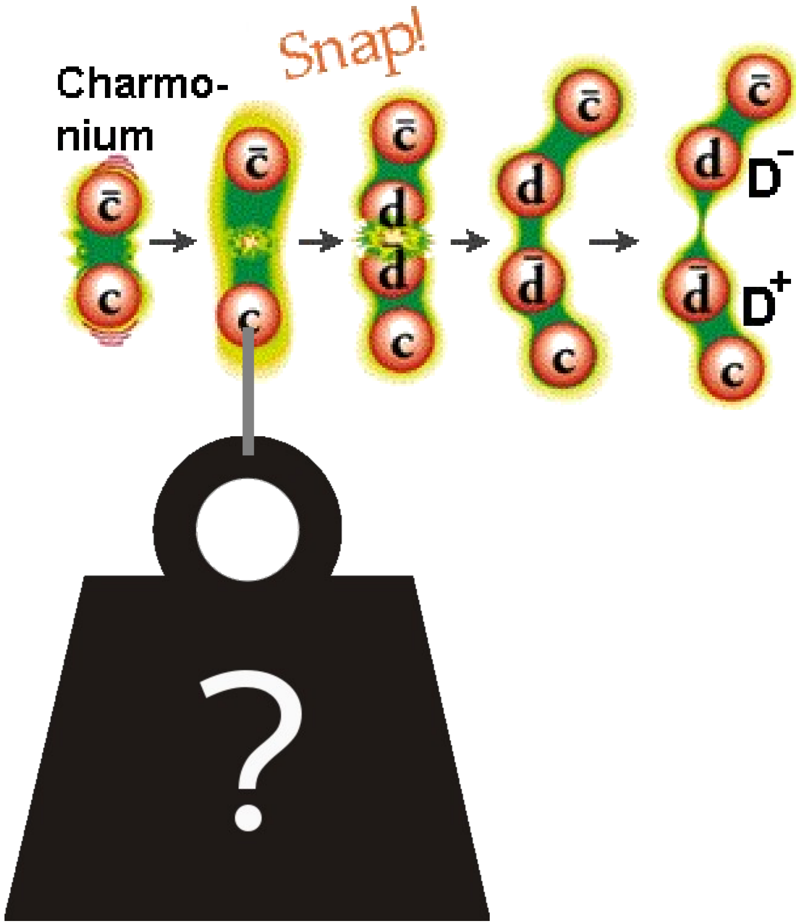



b) QCD ($r$ > 1 fm)



# Exercise: How big is k?

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

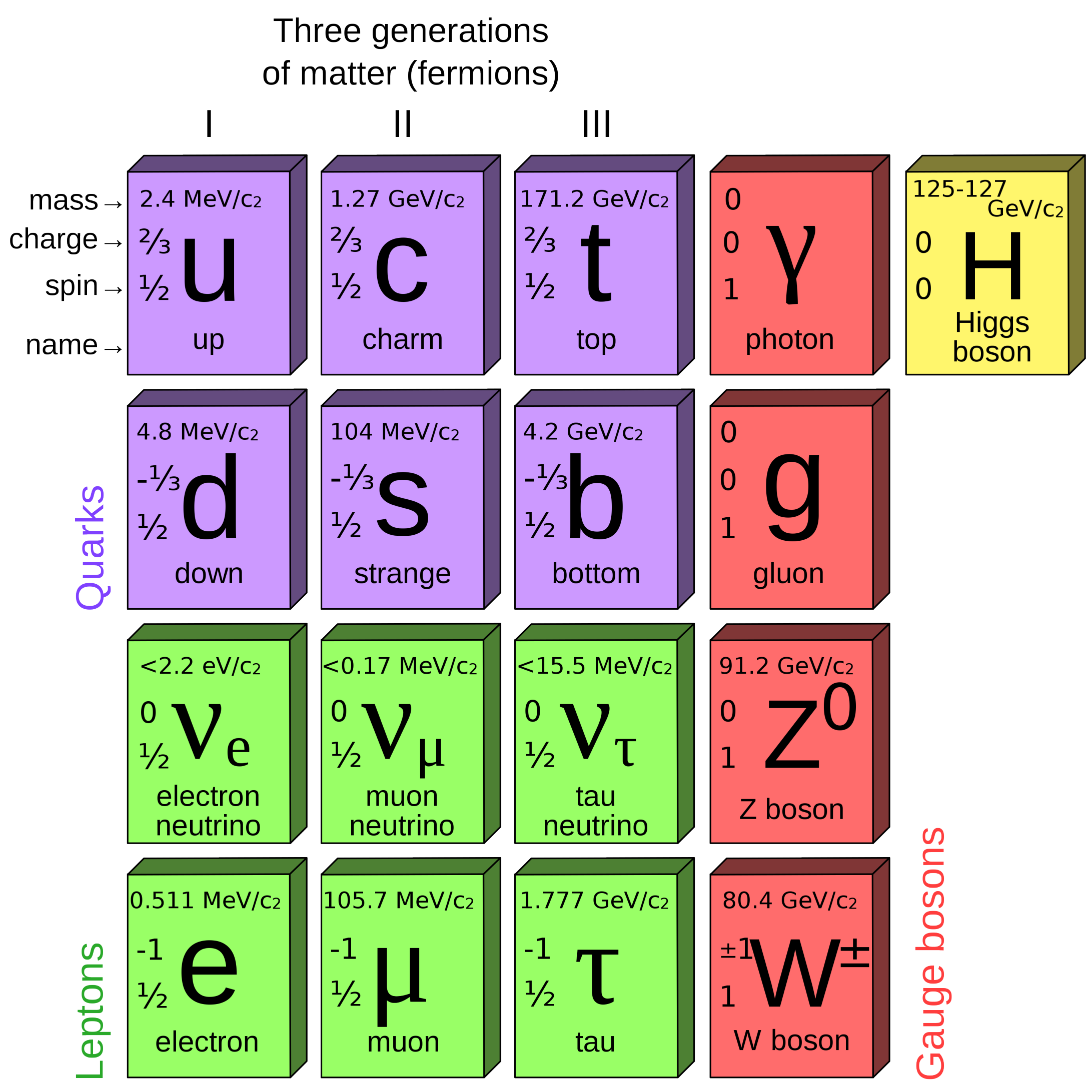


# Consequences of 10 ton force!

- This is why QCD is also called the strong interaction
  - QCD can bind together quarks even though they are EM repulsed

- **Confinement**
  - QCD is for low energies non-perturbative ($\alpha \sim 1$ so the series of Feynman diagrams does not converge)
    - We know the theory but we cannot solve it!
    - We don't know how to describe hadronic properties with QCD
- **Asymptotic freedom**
  - But at high energies (small distances << 1 fm) we can use perturbative QCD ($\alpha \ll 1$ so the series of Feynman diagrams converges)

# 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
125-127
GeV/c2
0
0
H
Higgs
boson
Quarks
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
Leptons
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
Gauge bosons