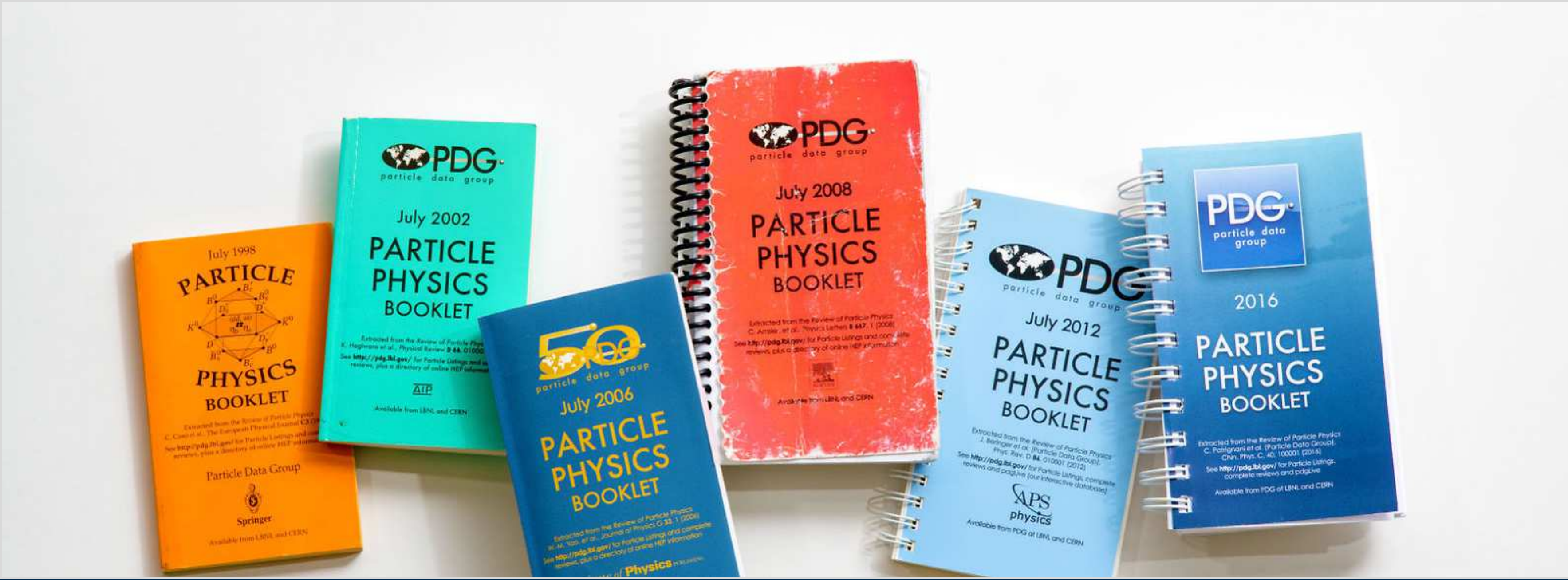


ELEMENTARY PARTICLE PHYSICS

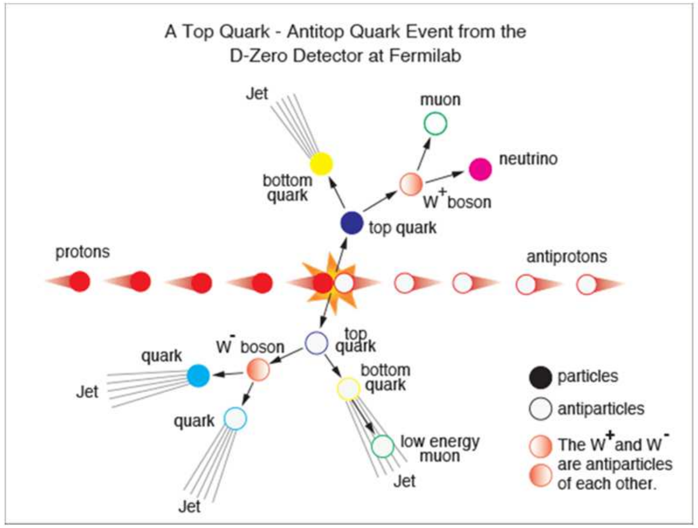
THE PARTICLES (PART III)

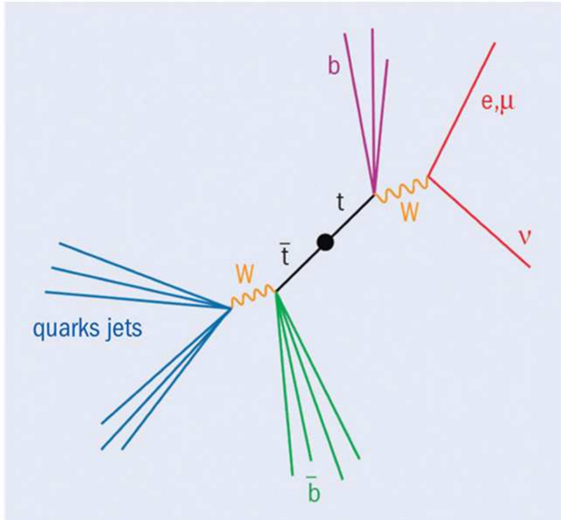
MAY 2020 I HANS STRÖHER (FZ JÜLICH, UNIVERSITY OF COLOGNE)

- Outline:
  - A brief **introduction** (history …)
  - The **tools** (accelerators, targets, detectors … kinematics, …)
  - The **particles** (hadrons, baryons, mesons …)
  - The ***fundamental* particles** (quarks, leptons)
  - The **forces** (gravitation, nuclear forces)
  - The ***fundamental* interactions** (strong and electro-weak IA)
  - The **Standard Model** of EPP
  - Physics **Beyond the Standard Model** (BSM)
  - Spin-offs – **Applications** of EPP

Q: How do we know that the ***top* quark** – the heaviest quark by far (~180 m_p) – is fundamental, i.e. it does not have inner constituents?

Production: strong interaction (quark – anti-quark annihilation in top – anti-top)
(single top production via weak IA has also been observed)





Decay: only through weak interaction (mostly bottom and W), but because of huge mass, lifetime is very short

Note: coupling to W (**tWb**-vertex)

QUARK MODEL

Constituent Quark Model (CQM)

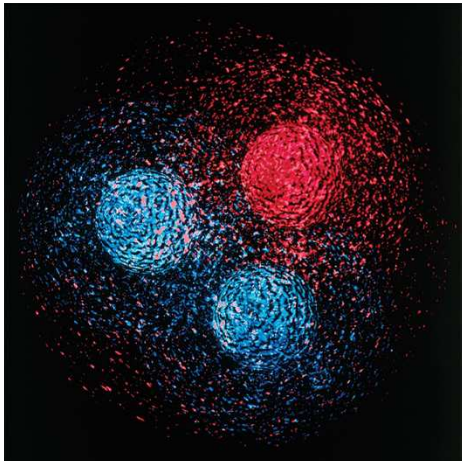
JÜLICH
Forschungszentrum

QUARK MODEL

Constituent Quark Model (CQM)

The reality of quarks – why no observation of free quarks?

Since hadrons are composite objects, made of quarks, one might naively expect that the components can be separated, i.e. it is possible to **observe individual free quarks**:



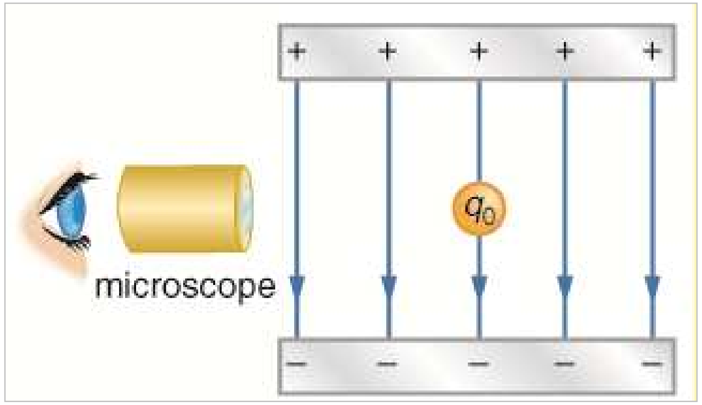
→ After invention of quark-model: many searches for „fractionally charged particles“

QUARK MODEL

Constituent Quark Model (CQM)

The reality of quarks – why no observation of free quarks?

Quarks have **fractional electric charge** values – either $^1/_3$ or $^2/_3$ times the elementary charge e_0, depending on flavor. Thus, in principle, it should be simple to detect them, e.g., in **Millikan-type** experiments (used to identify charge quantization and to detemine the electric elementary charge e_0):



To date, **no fractional charged particles** were found in spite of extensive efforts (see, e.g., Ann. Rev. Nucl. Part. Sci. 59 (2009) 47)

QUARK MODEL

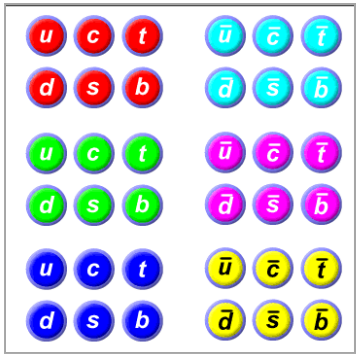
Constituent Quark Model (CQM)

The reality of quarks – why no observation of free quarks?

The negative outcome of searches for free quarks made it clear that some form of **“confinement mechanism”** was required.
“Color” as a new property was introduced – first suggested in connection with the need to satisfy the **Pauli-principle** for baryons like Δ^{++} (uuu), Δ^{-} (ddd) and Ω^{-} (sss):

> **Quarks** are fermions with spin 1/2, they cannot exist in identical states. With 3 identical quarks, the property which distinguishes them must be capable of at least three distinct values – this is usually visualized by the three colors: **red (R), green (G)** and **blue (B)** [Note: color is a nice analogy!]

colors for **quarks**



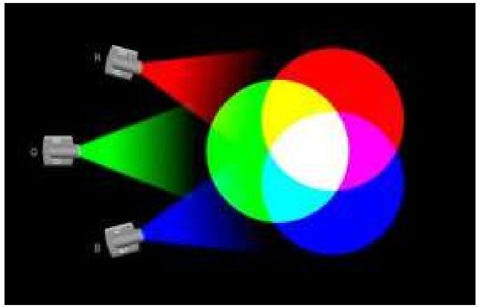
anti-colors for **anti-quarks**

QUARK MODEL

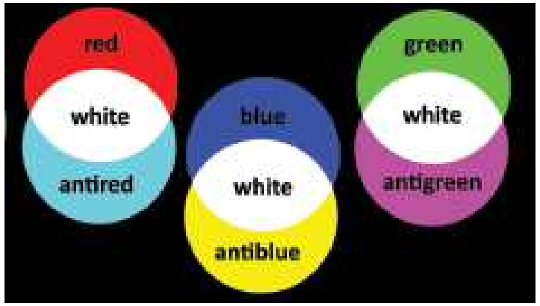
Constituent Quark Model (CQM)

The reality of quarks – why no observation of free quarks?

All quarks have this property and its implications are very profound: it is asserted that the colors of the 3 quarks in a **baryon** at any time must add up to “white”, i.e. **only** “**color-neutral**” (“white”) **objects are observed**:



Likewise for a **meson**: the quark – anti-quark pair colors must add to “white”



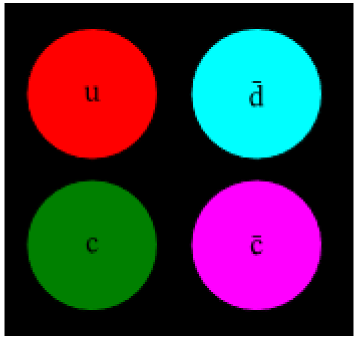
QUARK MODEL

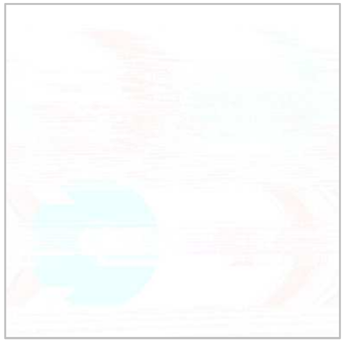
Constituent Quark Model (CQM)

The reality of quarks – why no observation of free quarks?

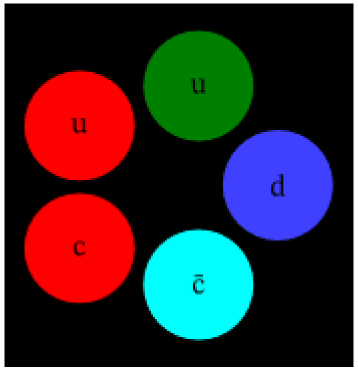
Other quark combinations with total color “white” can be constructed:

- **Tetraquark**:





- **Pentaquark:**



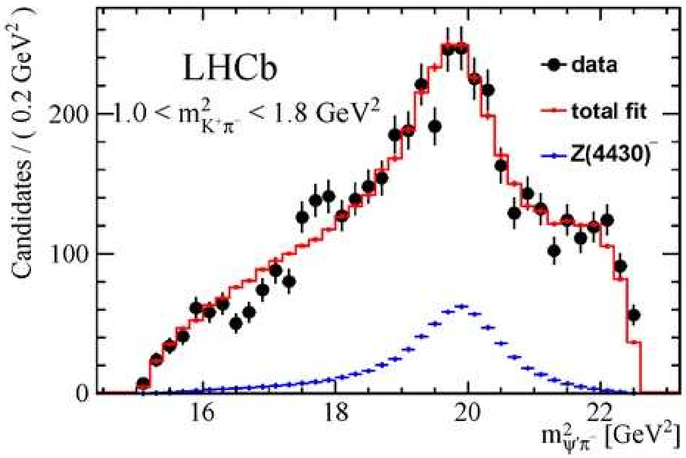
… and have recently been observed

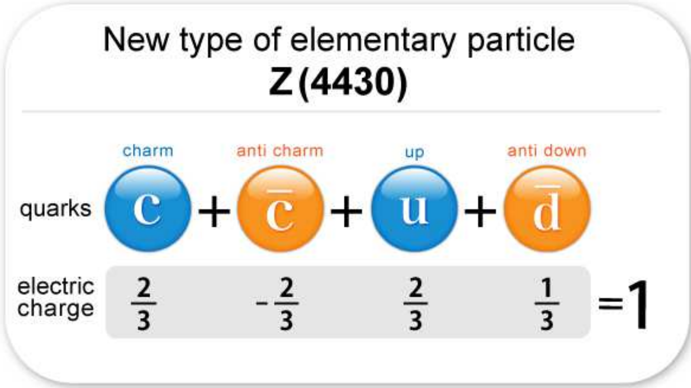
QUARK MODEL

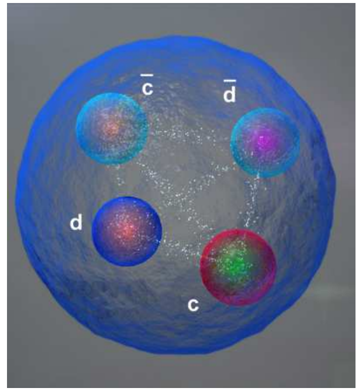
Constituent Quark Model (CQM)

New developments – X,Y,Z states

Example: The **Z(4430)$^{+-}$** is a **mesonic resonance** discovered by Belle confirmed by the LHCb experiment. It has a mass of 4430 MeV/c^2:







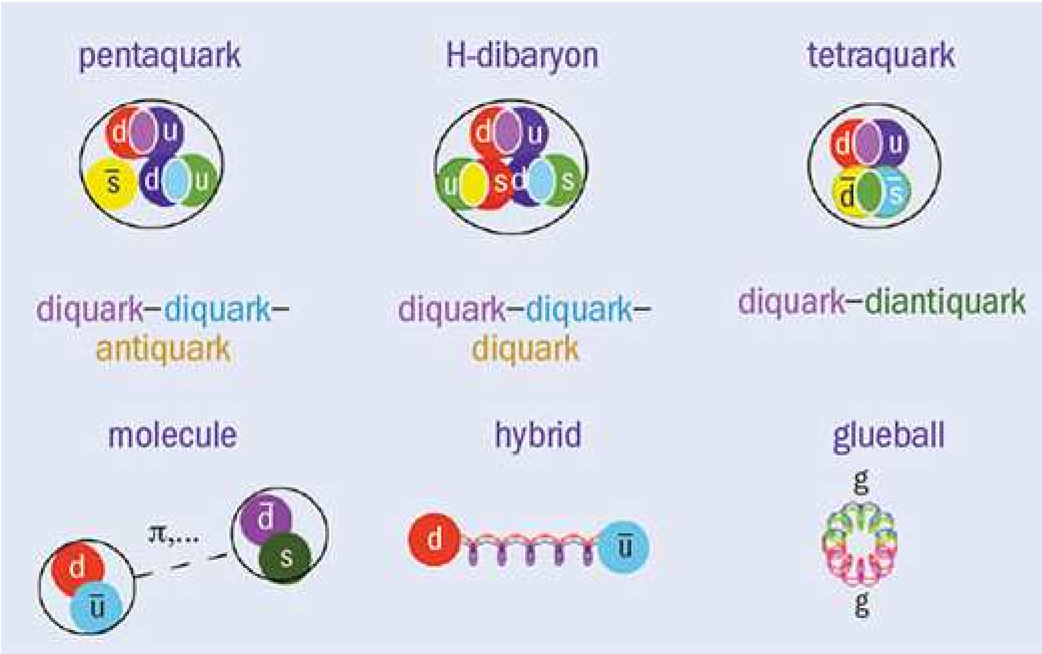
The particle is **charged** (i.e. no charmonium state) and is thought to be a **tetra-quark candidate**. It has the spin-parity quantum numbers $J^P = 1^+$.
→ The issue of **non-(3q)** and **non-($q\bar{q}$)** states is open/rapidly developing …

QUARK MODEL

Constituent Quark Model (CQM)

New developments – exotic quark (and gluon) bound states

Possibilities:



JÜLICH
Forschungszentrum

Scientific American, July 1979

The Bag Model of Quark Confinement

Quarks appear to be real, and yet they have not been observed in isolation. One hypothesis for why they have not been is that they are confined in bags analogous to the bubbles in a liquid

by Kenneth A. Johnson

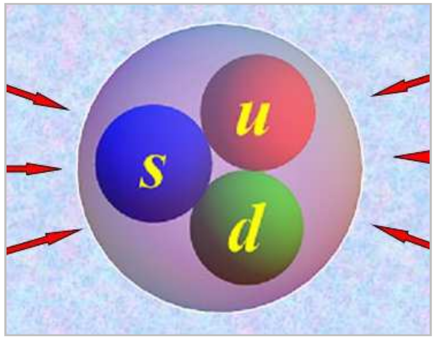
QUARK MODEL

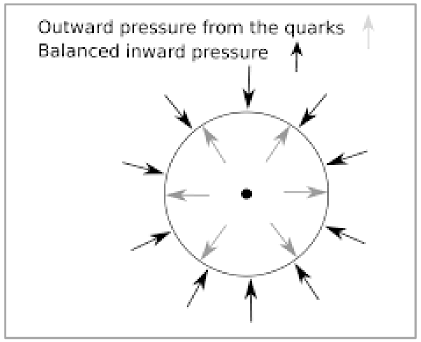
Constituent Quark Model (CQM)

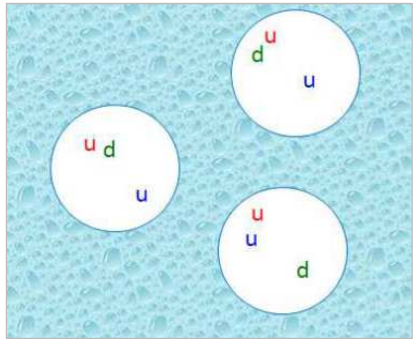
The reality of quarks – why no observation of free quarks?

In the mid-1970´s a **phenomenological model** for confinement, the so called “**MIT bag model**” was developed:

$$V(r) = \begin{cases} 0 & r < a \\ +\infty & r > a \end{cases}$$







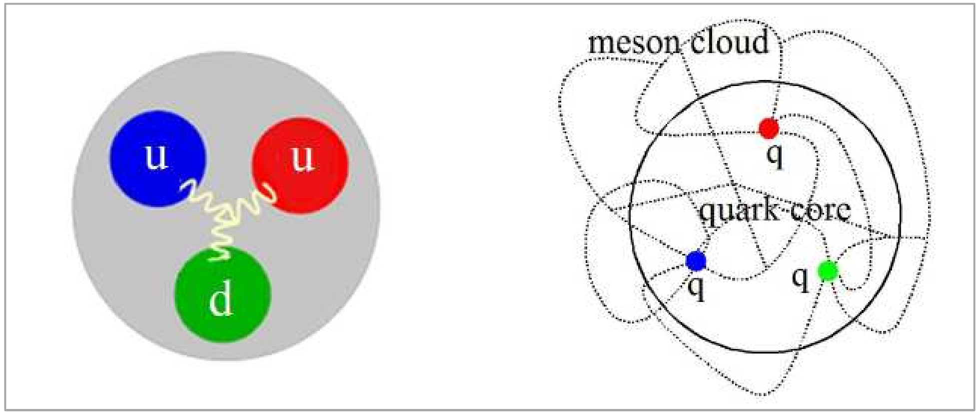
Quarks are forced by a fixed **external pressure** (vacuum pressure and surface tension) to move only inside a given spatial region (“bag”); its shape is spherical if all quarks are in the ground state. Inside the bag, the quarks are allowed to move quasi-free; boundary conditions at the bag surface guarantee that **no quark can leave the bag**.

QUARK MODEL

Constituent Quark Model (CQM)

The reality of quarks – why no observation of free quarks?

In the "**cloudy bag model**", hadrons are treated as quarks confined in an MIT bag, which is surrounded by a cloud of pions (mesons):



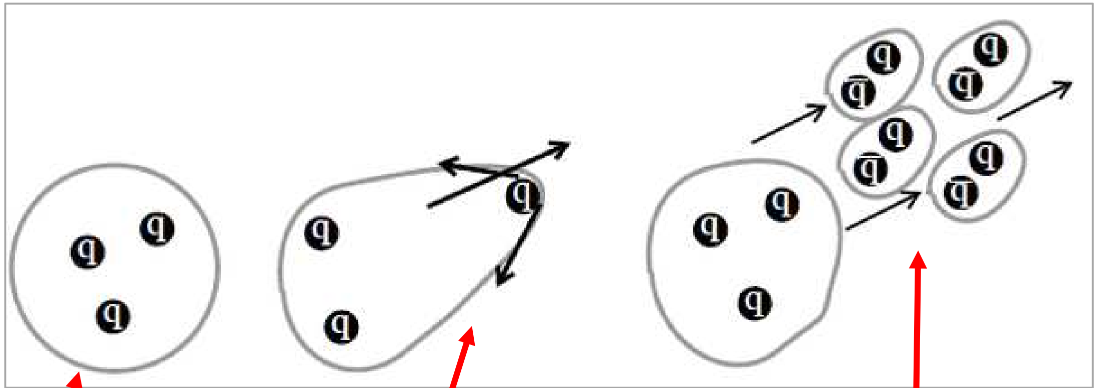
The only free parameter of the model is the **bag radius** which is fixed by a fit to be about 0.8 fm. With this phenomenological model, e.g. the **magnetic moments of neutron and proton** are in very good agreement with the experimental values.

QUARK MODEL

Constituent Quark Model (CQM)

The reality of quarks – why no observation of free quarks?

Trying to **isolate a colored quark** out of a baryon is **not possible**; instead:



A baryon: 3 quarks free to move within an „elastic bag“

A quark tries to leave the bag; bag stretches and applies a restoring force

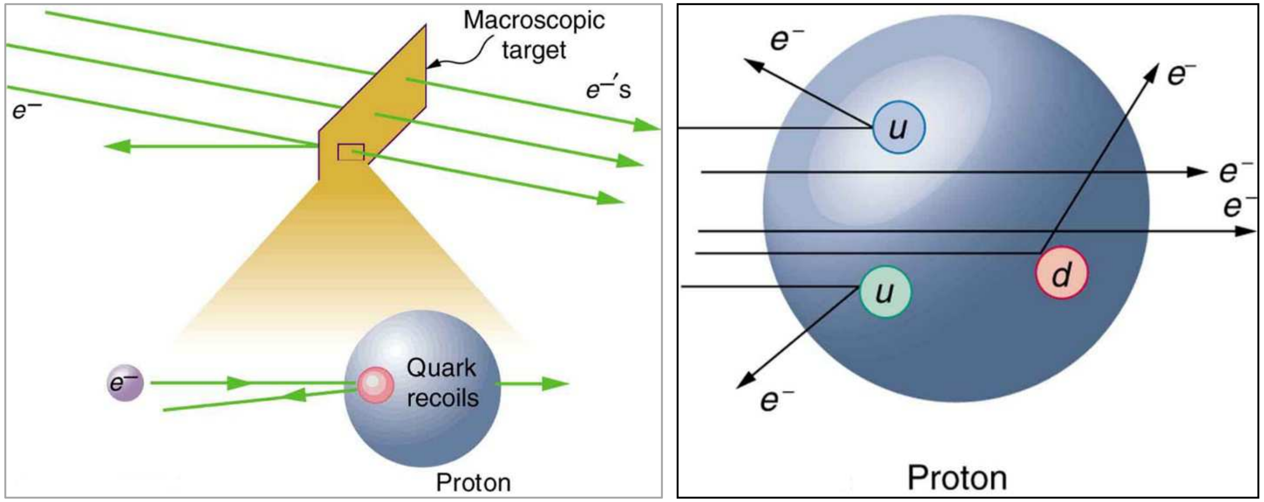
If energy high enough to break out of the bag, another quark is created in the bag, producing a meson (can also be more than one … a jet)

QUARK MODEL

Constituent Quark Model (CQM)

The reality of quarks – experimental evidence for quarks

In **scattering** experiments, e.g. of high energy electrons on protons, the electron sometimes hits a quark:



The **recoiling quark** is not observed – rather a meson or (for high energies) a “jet” of particles is observed in a detector. Will be discussed in more detail later.

JÜLICH
Forschungszentrum

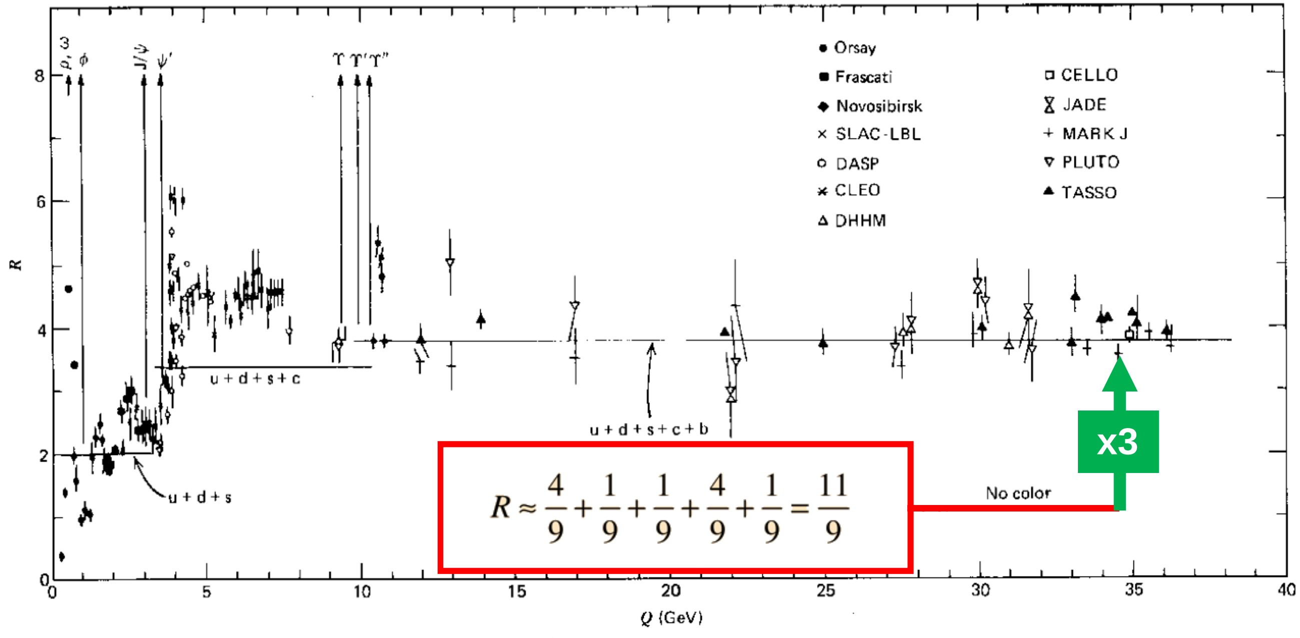
QUARK MODEL

Constituent Quark Model (CQM)

The reality of quarks – experimental evidence for color (I)

The experimental **cross section ratio R** (electron-positron annihilation into hadrons and muons)

$$R = \frac{\sigma_{hadrons}}{\sigma_{muons}} = \frac{\sum \sigma_{q\bar{q}}}{\sigma_{muons}} = \sum \left(\frac{q_q}{e}\right)^2$$



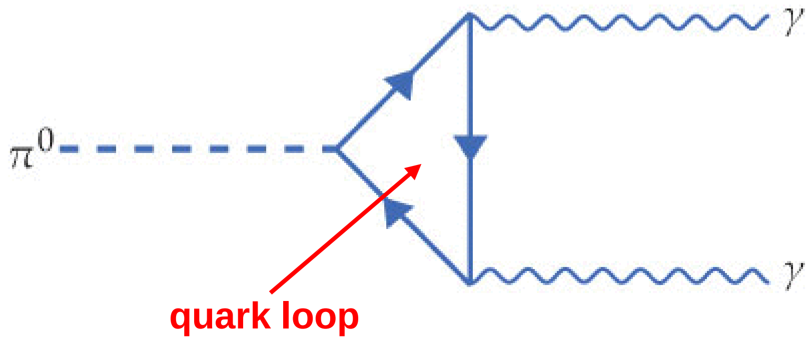
provides **overwhelming evidence for three colors** of quarks

QUARK MODEL

Constituent Quark Model (CQM)

The reality of quarks – experimental evidence for color (II)

The **neutral pion** (π^0) mostly decays into 2 photons: $\pi^0 \rightarrow \gamma\gamma$;



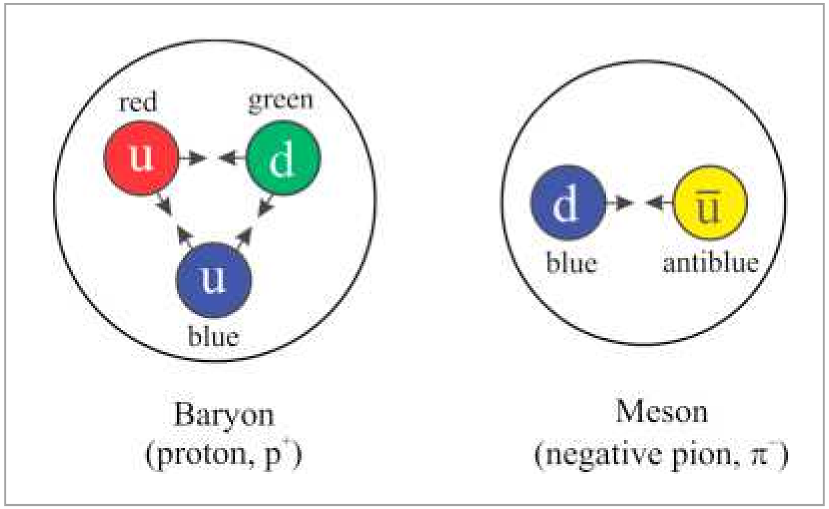
This decay involves **virtual quarks** (see fig.). Because quarks come in **3 colors**, the measured **decay rate is three times** what it would be in a theory with colorless quarks.

QUARK MODEL

Constituent Quark Model (CQM)

Holding hadrons together – the interaction between quarks (I)

In order to go beyond the **phenomenological bag model**, one needs to understand how quarks interact; it turns out that the interaction, called the **“strong interaction”** is mediated by **exchange bosons**, called **“gluons”**:



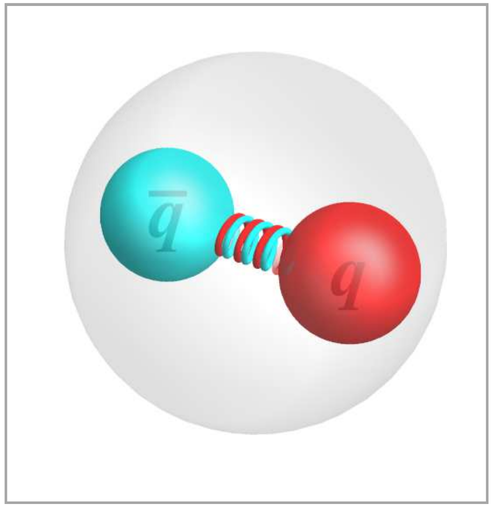
→ **Color** is the charge of the **strong interaction** (will be discussed in “interactions”)

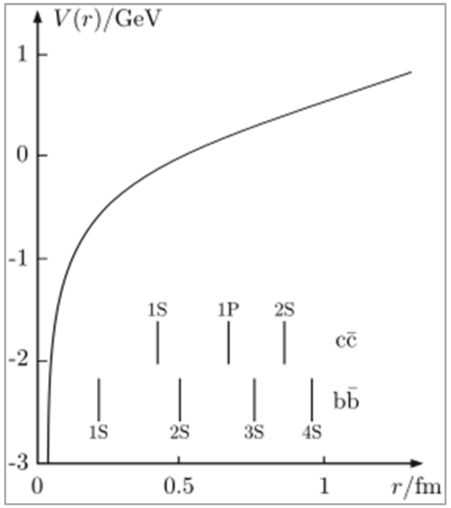
QUARK MODEL

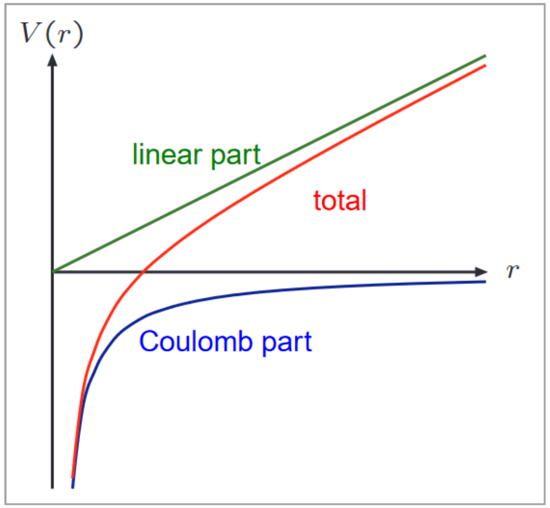
Constituent Quark Model (CQM)

Holding hadrons together – the interaction between quarks (II)

In order to obtain information about the **quark – anti-quark potential**, the bound $c\bar{c}$- ("**charmonium**") and $b\bar{b}$-states ("**bottomonium**") have been studied:







→ **Small distance**: V ~ 1/r ; **large distance**: V ~ r (→ confinement); more later …

JÜLICH
Forschungszentrum

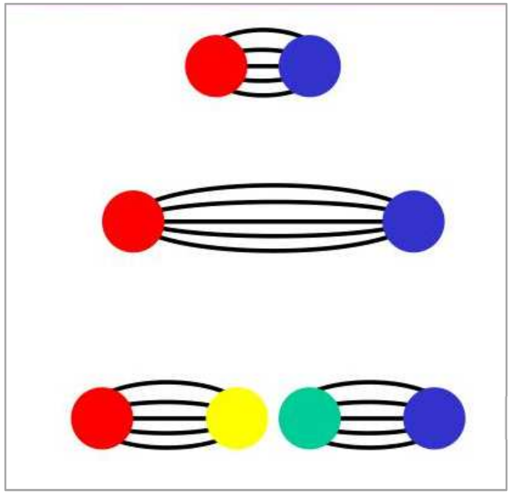
QUARK MODEL

Constituent Quark Model (CQM)

Holding hadrons together – the interaction between quarks (III)

The Japanese theorist **Y. Nambu** proposed that the quarks inside hadrons are "tied" together by color-lines ("**strings**"): start with a quark – anti-quark pair:

→ Breaking of the string into a $q\bar{q}$-pair (a meson) …



When quarks pulled apart, the color lines stretch; potential energy stored in strings increases by ($\frac{1}{2}$ B r^2) (with B … string tension)

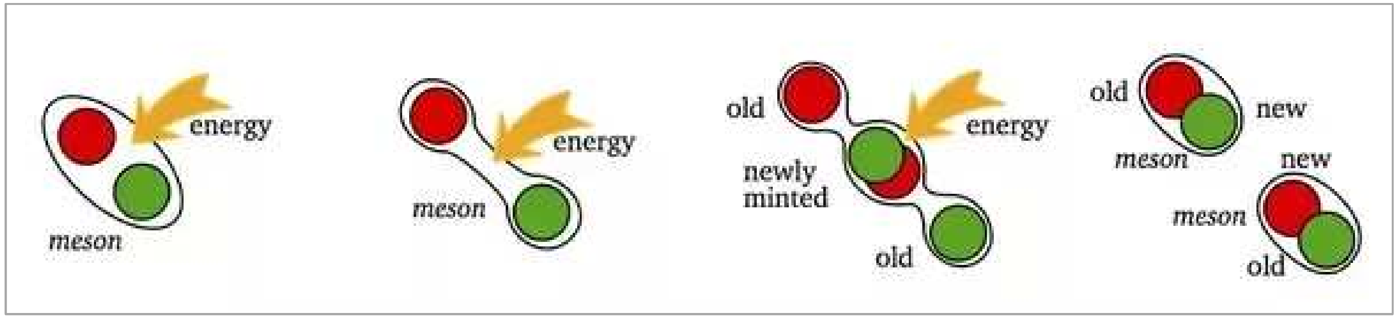
When ($\frac{1}{2}$ B r^2) > m(π), a quark – anti-quark pair can be created from the vacuum; instead of free quarks, the result is two colorless hadrons (mesons)

QUARK MODEL

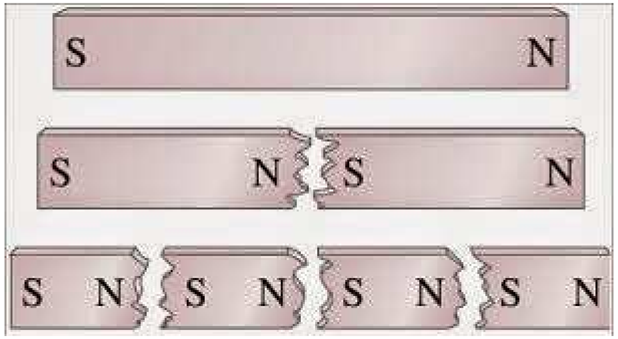
Constituent Quark Model (CQM)

Holding hadrons together – the interaction between quarks (IV)

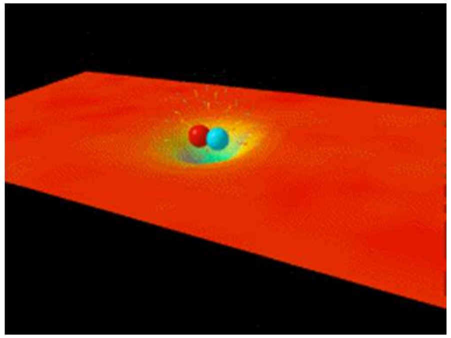
Trying to **isolate a colored quark** out of a meson is also **not possible**:



Analogy:
no magnetic
monopoles



Note:
Flux tube
in QCD

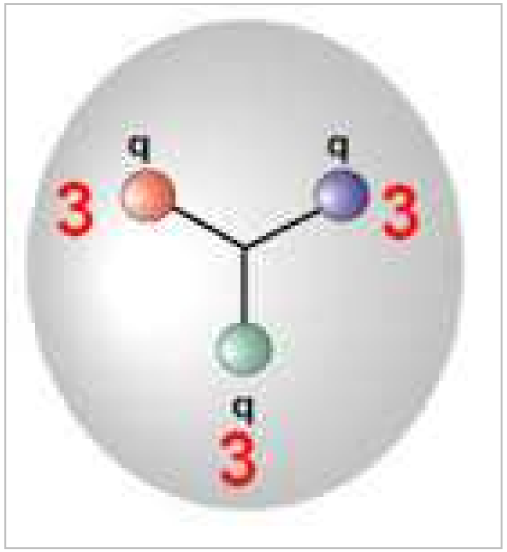


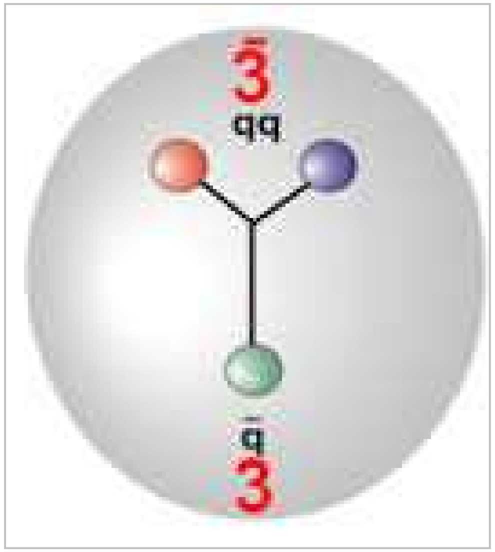
QUARK MODEL

Constituent Quark Model (CQM)

New developments – di-quark quark model of baryons

There is evidence that, e.g. in the proton, one of the up quarks and the only down quark appear to combine into a **di-quark**, while the remaining up quark hangs out on its own:





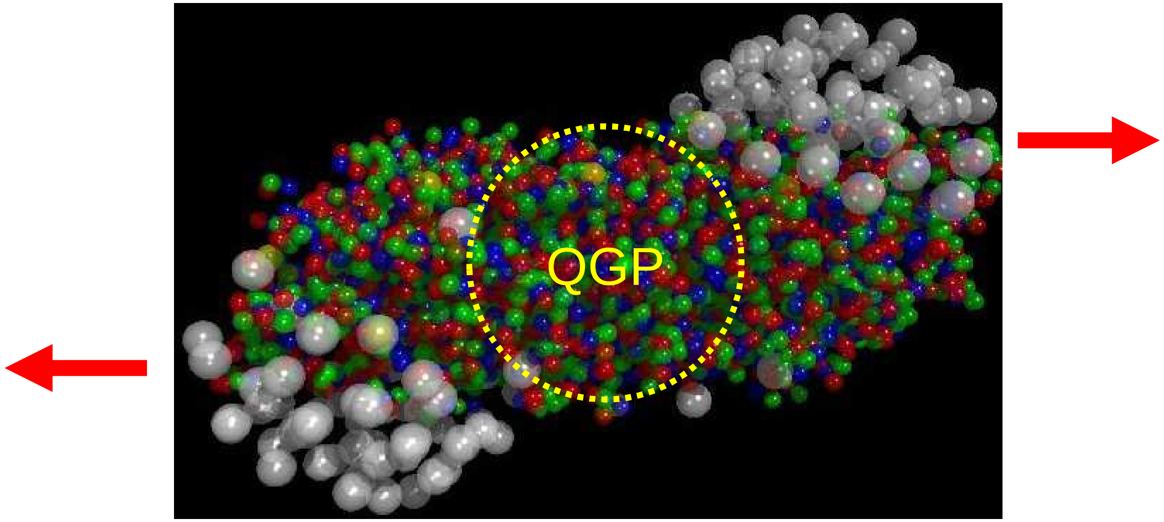
→ This reduces the symmetry (and the **number of** the **excited states**) …

QUARK MODEL

Other Issues

Quark-Gluon Plasma – a new state of matter

In relativistic heavy-ion collisions (RHIC), a **quark–gluon plasma (QGP**) is created: the elementary particles that make up the hadrons of baryonic matter are **freed of their strong attraction** under extremely high energy densities:



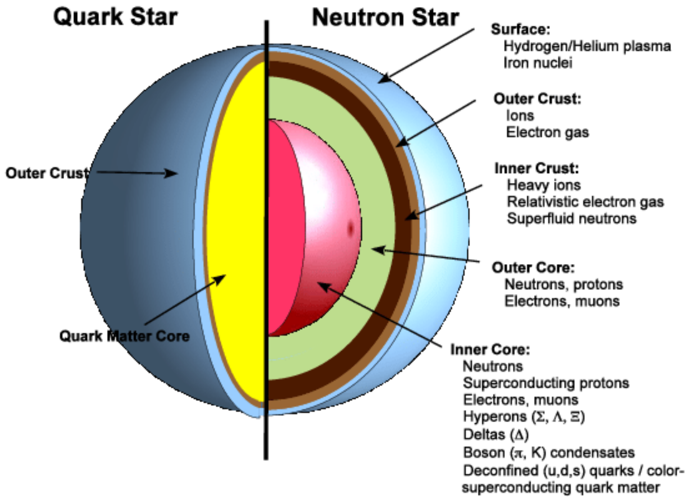
The QGP in RHICs exists for a brief instant and then **"hadronizes"** …

QUARK MODEL

Other Issues

Quark Matter – speculative interior of extreme stars

A quark star is a *hypothetical* type of compact, exotic star, where **extremely high core temperature and pressure** has forced hadrons to form quark matter, a continuous state of matter consisting of free quarks.

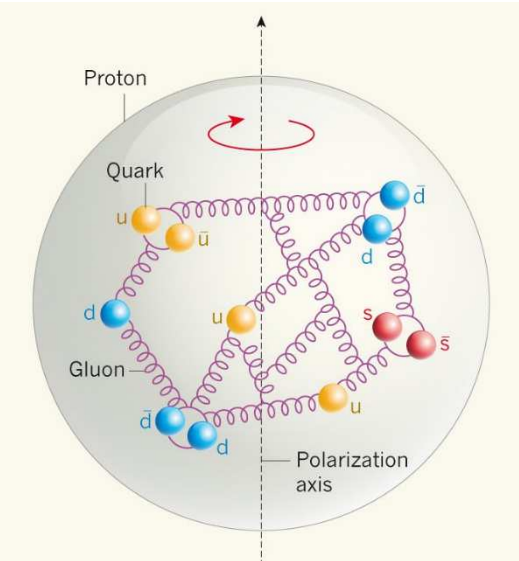


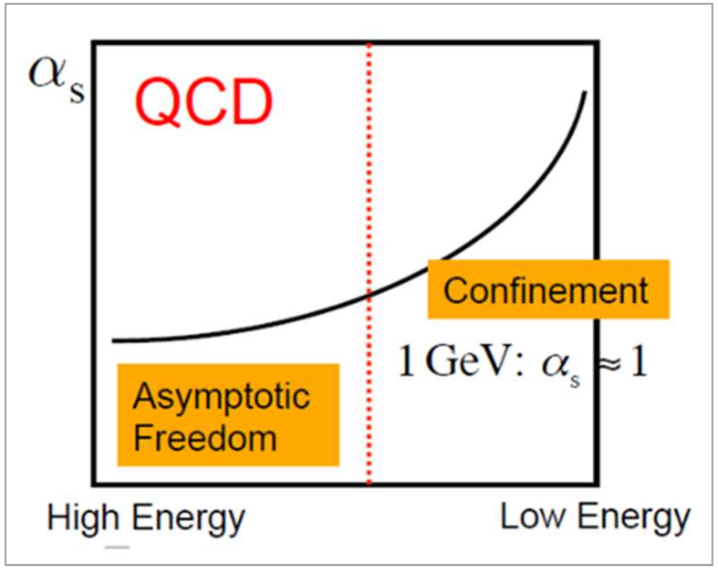
QUARK MODEL

Outlook

Quantum Chromodynamics (QCD) – theory of strong interactions

In **QCD** the hadrons are **complex objects**, comprising valence and “sea quarks” as well as “gluons”:





THE PARTICLES

That´s it for today

$$R = 3 \sum_i Q_i^2$$

Energy	Expected ratio R
$\sqrt{s} > 2m_s, \quad \sim 1\ \mathrm{GeV}$	$3\left(\frac{4}{9}+\frac{1}{9}+\frac{1}{9}\right) = 2$ uds
$\sqrt{s} > 2m_c, \quad \sim 4\ \mathrm{GeV}$	$3\left(\frac{4}{9}+\frac{1}{9}+\frac{1}{9}+\frac{4}{9}\right) = 3\frac{1}{3}$ $udsc$
$\sqrt{s} > 2m_b, \quad \sim 10\ \mathrm{GeV}$	$3\left(\frac{4}{9}+\frac{1}{9}+\frac{1}{9}+\frac{4}{9}+\frac{1}{9}\right) = 3\frac{2}{3}$ $udscb$
$\sqrt{s} > 2m_t, \quad \sim 350\ \mathrm{GeV}$	$3\left(\frac{4}{9}+\frac{1}{9}+\frac{1}{9}+\frac{4}{9}+\frac{1}{9}+\frac{4}{9}\right) = 5$ $udscbt$