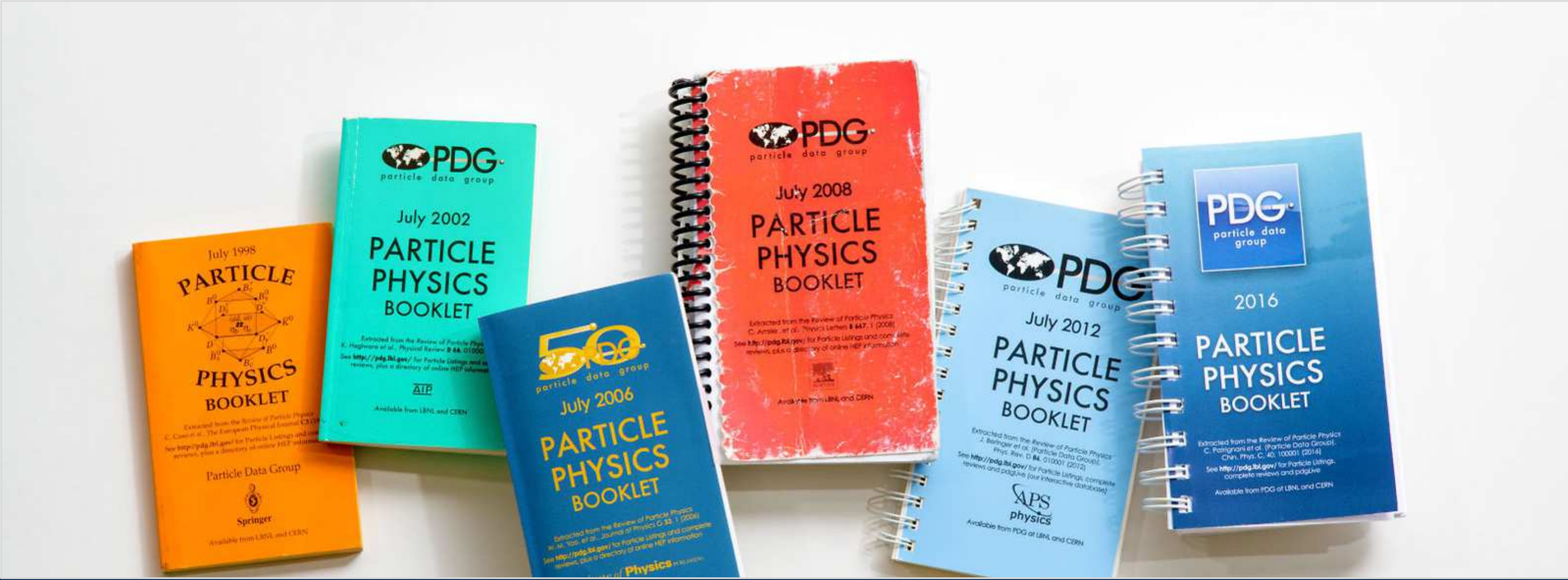


ELEMENTARY PARTICLE PHYSICS

FORCES OF NATURE – FUNDAMENTAL INTERACTIONS (PART III) - QCD

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

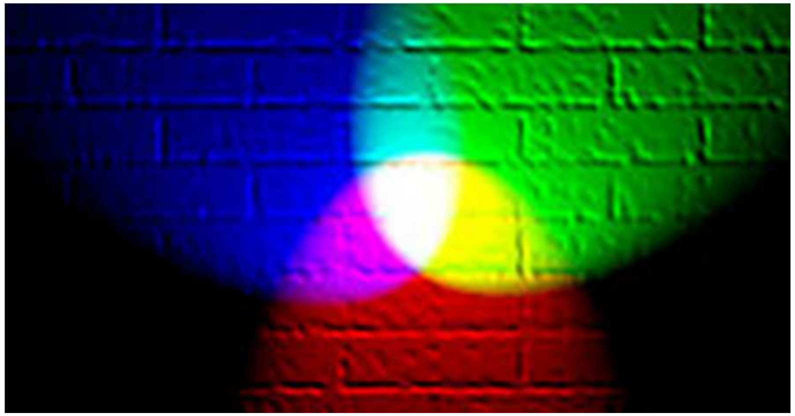
- Outline:
    - A brief **introduction** (history …)
    - The **tools** (accelerators, targets, detectors … kinematics, …)
    - The **particles** (hadrons, baryons, mesons …)
    - The ***fundamental*** **particles** (quarks, leptons)
    - The **forces** (gravitation, nuclear, weak forces)
    -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

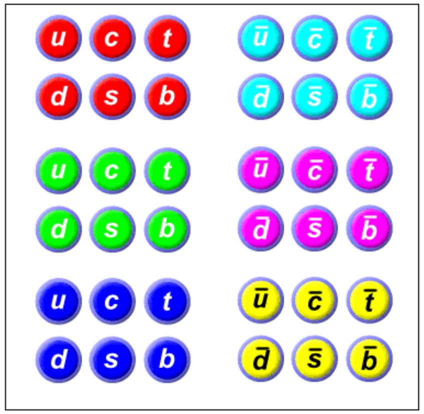
FUNDAMENTAL INTERACTIONS – QCD

Prelude

History – the genesis of QCD (I)

In 1971, **M. Gell-Mann** and **H. Fritzsch** found a solution of the statistics problem (remember the Ω^-): they considered **nine quarks** (as others had done before) (<u>note</u>: **only u,d,s** known at that time), but assumed that the three quarks of the same type had a **new conserved quantum number**, called "color":



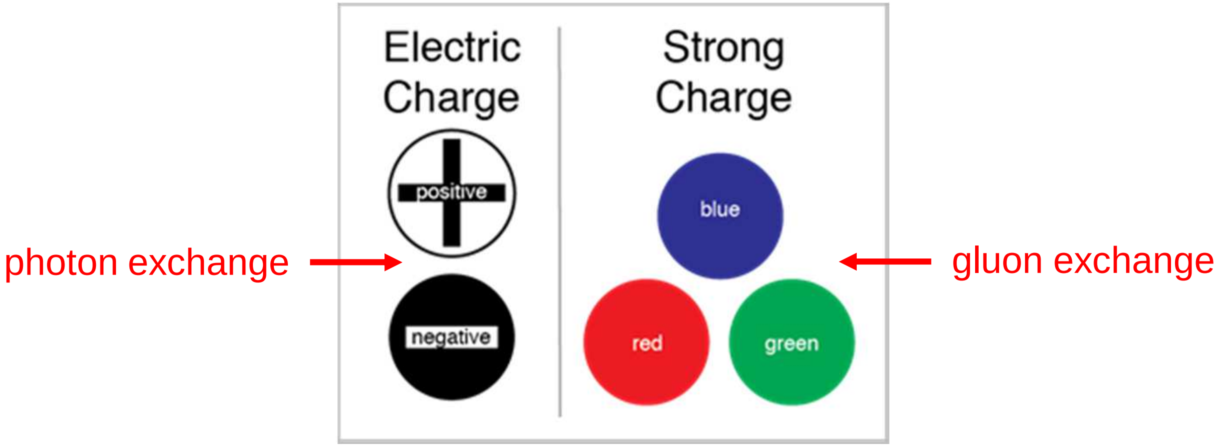


FUNDAMENTAL INTERACTIONS – QCD

Prelude

History – the genesis of QCD (II)

It turns out that **color** is the **charge** of the **strong interaction** (color charge – like the electric charge for the electromagnetic interaction):



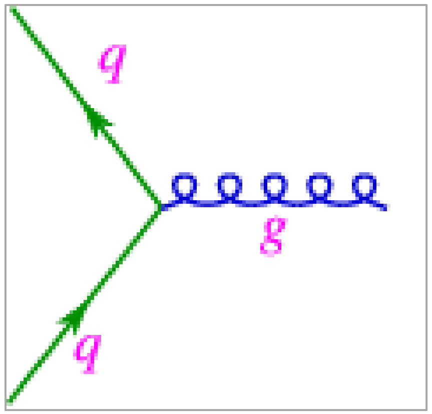
Quarks, which carry color (anti-quarks – anti-color), interact via the exchange of "**gluons**" (analogous to photons which mediate the electro-magnetic interaction).

FUNDAMENTAL INTERACTIONS – QCD

Prelude

History – the genesis of QCD (III)

"**Quantum chromodynamics**" **(QCD**) is the theory of the **strong interaction** between **quarks** and **gluons**; it has been modeled in analogy to QED; the dynamics of the quarks and gluons are controlled by the QCD *Lagrangian* and visualized by Feynman diagrams; one basic diagram is:



QCD is an important part of the **Standard Model** of particle physics

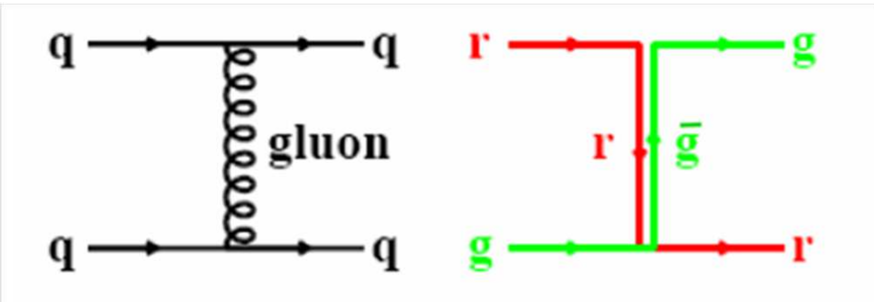
FUNDAMENTAL INTERACTIONS – QCD

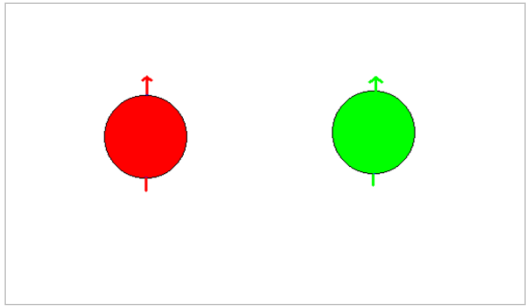
Basics

Facts – the QCD exchange bosons – colored gluons (I)

Gluons act as the exchange particle of the strong force between **colored quarks;** gluons are carrying **both color and anti-color**:

Example:





There are **nine possible combinations** of color and anti-color in gluons: red anti-red, red anti-blue, red anti-green, blue anti-red, blue anti-blue, blue anti-green, green anti-red, green anti-blue, green anti-green.

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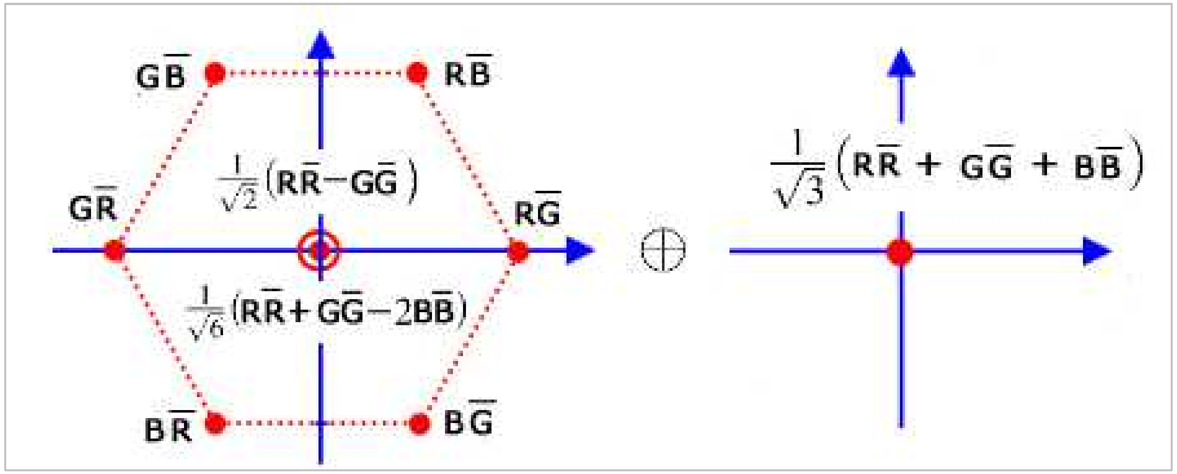
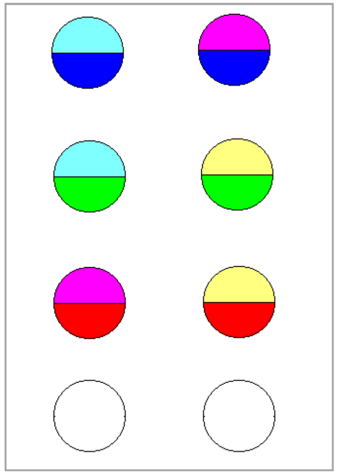
FUNDAMENTAL INTERACTIONS – QCD

Basics

Facts – the QCD exchange bosons – colored gluons (II)

Analogous to the $SU(3)_F$ flavor (for the 3 light quarks (u,d,s) – see: hadron multiplets) the 3 colors can form an $SU(3)_C$ symmetry group with a **color octet** and a **singlet**:





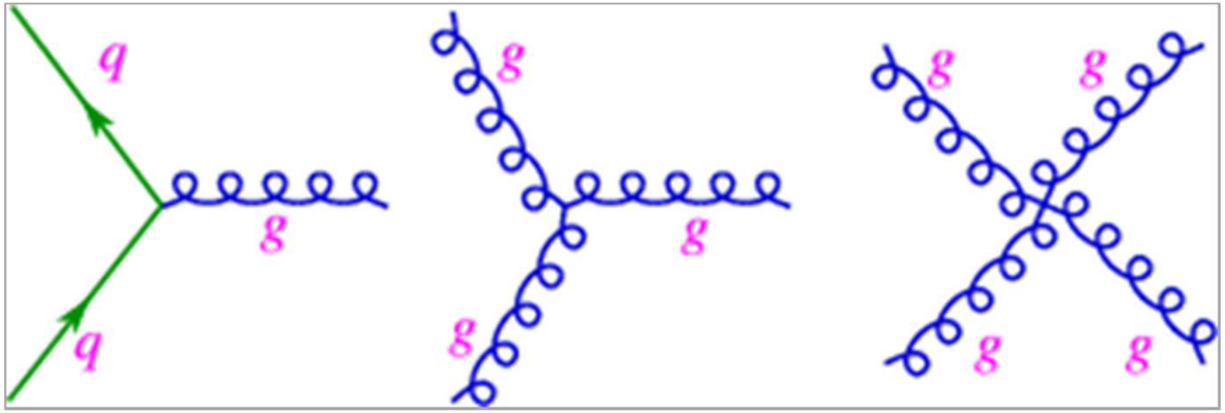
with the **singlet state** not realized in Nature

FUNDAMENTAL INTERACTIONS – QCD

Basics

Facts – the QCD exchange bosons – colored gluons (III)

Since **gluons** carry color – anti-color they not only **interact** with colored quarks, but also **among themselves** (in contrast to photons, which do not carry electric charge):



The "**gluon self interaction**" (gluons themselves take part in strong IA) is the reason for **fundamental differences** between **QED** and **QCD**

FUNDAMENTAL INTERACTIONS – QCD

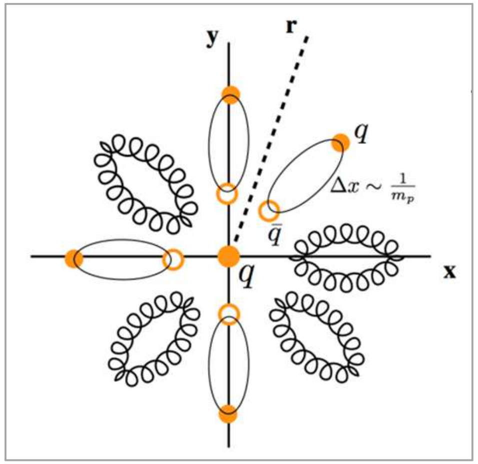
Basics

Facts – the QCD coupling constant (I)

The **strong coupling constant** α_s determines the strength of the strong interaction

In **QED** the bare electric charge is screened by a cloud of virtual (e^+e^-) pairs, leading to the „running“ α (increase with Q), in **QCD** there are two such effects:

- **screening** of the color charge
  by virtual quark-antiquark pairs
- **anti-screening** by a cloud of
  virtual gluons

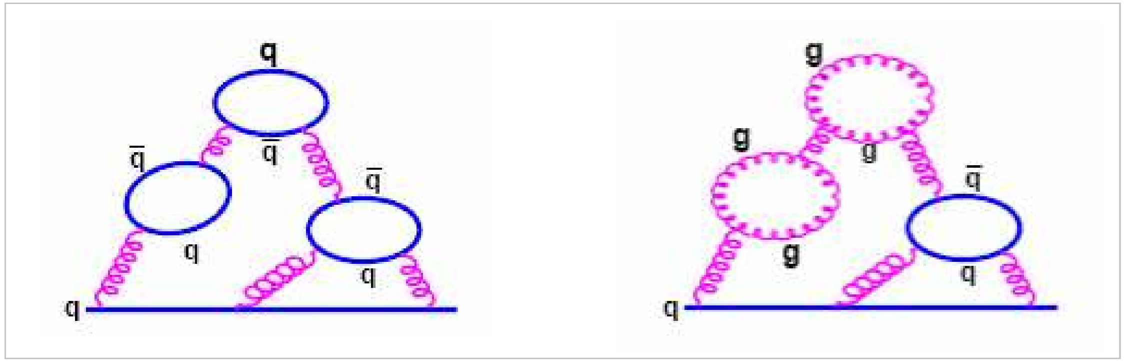


FUNDAMENTAL INTERACTIONS – QCD

Basics

Facts – the QCD coupling constant (II)

The two effects are leading to the „**running**“ **of** α_s, and it turns out: **anti-screening dominates** – the effective **color charge increases with distance**, and **decreases with energy** (momentum transfer):



Screening: color charge decreases with distance

Like in QED

Anti-screening: color charge increases with distance

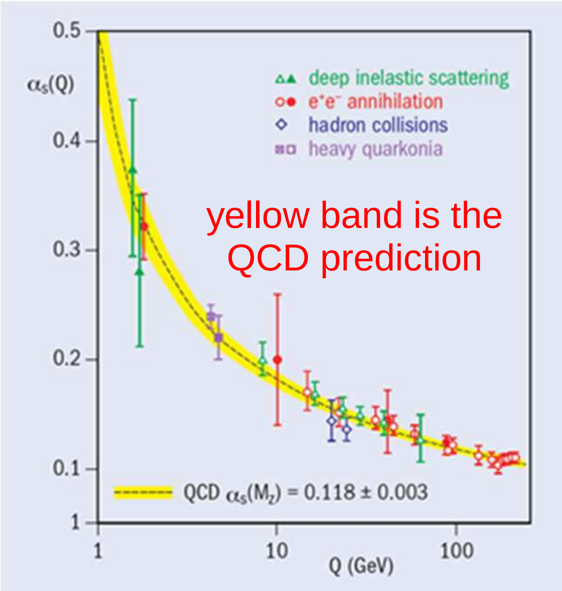
NEW in QCD

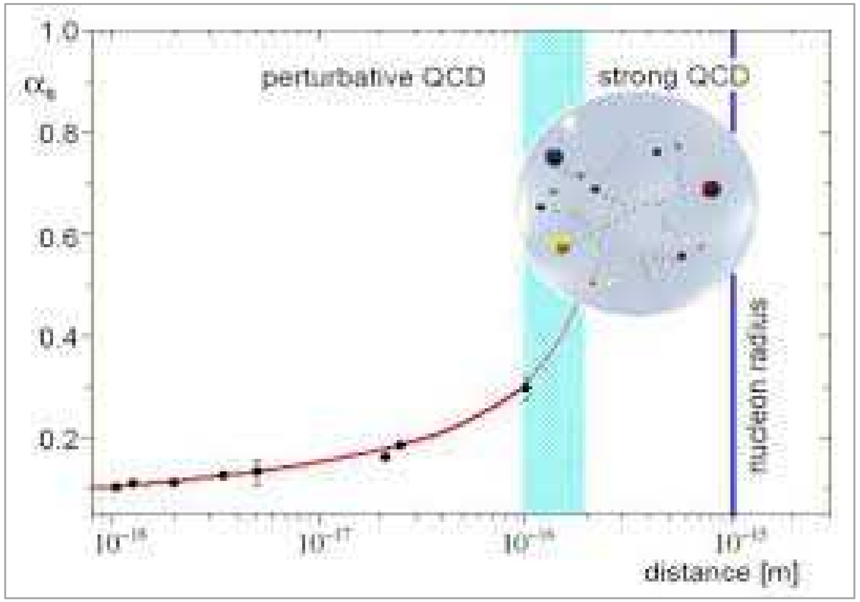
FUNDAMENTAL INTERACTIONS – QCD

Basics

Facts – the QCD coupling constant (III)

The „running“ of α_s is very well **established experimentally**:





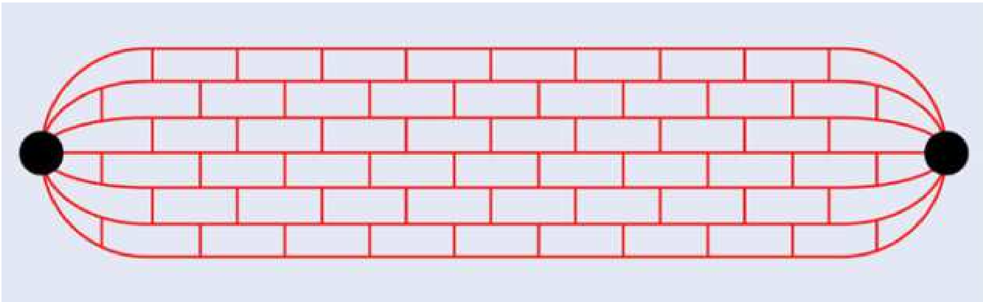
→ 2 regimes: perturbative (α_s<<1), non-perturbative, strong (α_s~1) QCD

FUNDAMENTAL INTERACTIONS – QCD

Basics

Facts – the QCD coupling constant (IV)

In the high-energy/small-coupling regime, the quarks are essentially behaving as free particles: this is called "**asymptotic freedom**"; for low-energy, the coupling becomes so large that quarks cannot be separated: (quark) "**confinement**":



Asymptotic freedom of QCD was discovered by **D. Gross**, **F. Wilczek** and **D. Politzer** (1973) → NP 2004. Quark confinement of QCD has yet to be proven from first principles

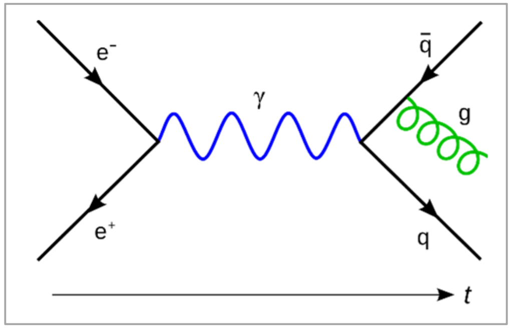
FUNDAMENTAL INTERACTIONS – QCD

Basics

Facts – the QCD exchange bosons – reality of gluons (I)

The process of "**gluon bremsstrahlung**":

Example: **e^+e^- annihilation** to a **photon**; generation of a **qq-pair** fragmenting into hadrons and appears in the detector as **two** back-to-back **hadron jets**. Outgoing quarks can also radiate a **gluon**, creating a third **hadron jet** in the same plane as the other two



Discovered at DESY (Hamburg, Germany) in 1979

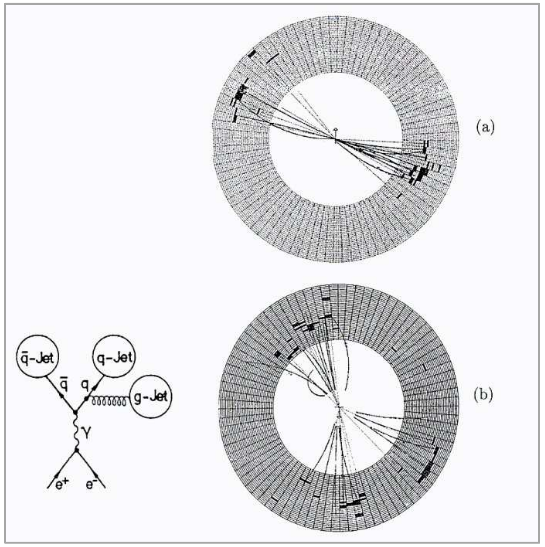
FUNDAMENTAL INTERACTIONS – QCD

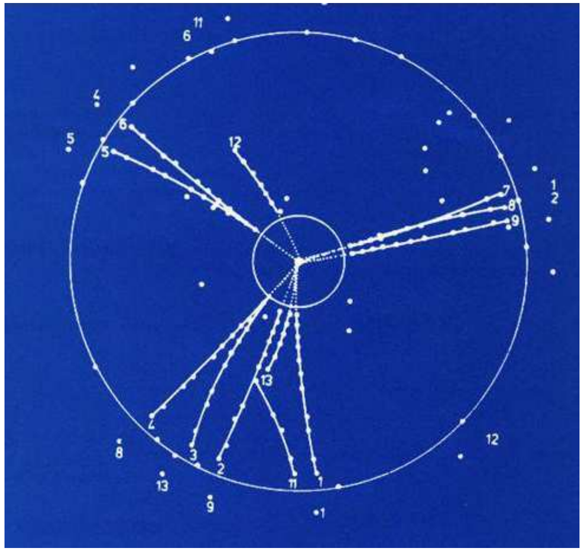
Basics

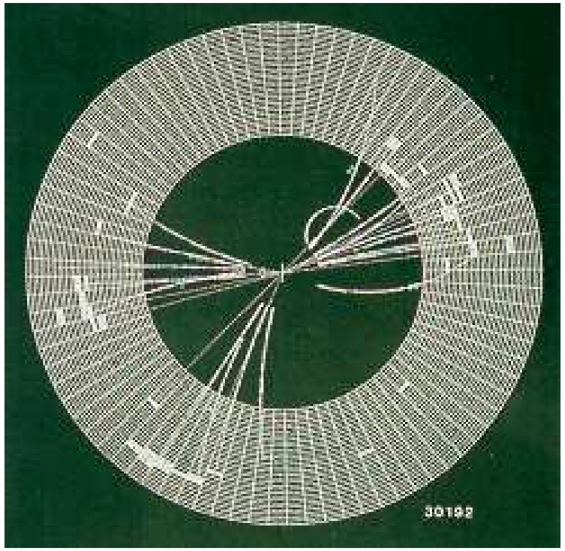
Facts – the QCD exchange bosons – reality of gluons (II)

The process of "**gluon bremsstrahlung**":

Example: 2- and 3-jet events







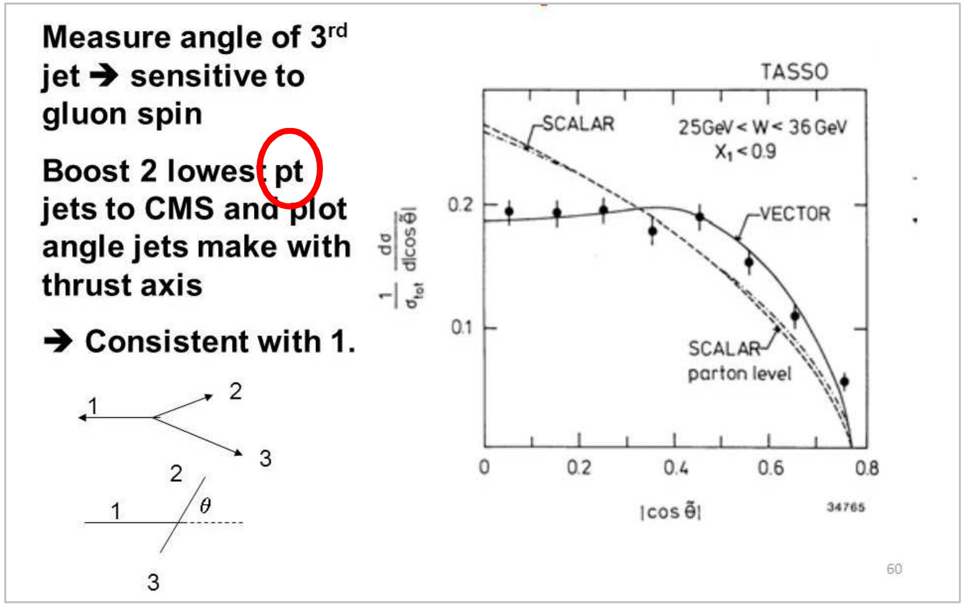
FUNDAMENTAL INTERACTIONS – QCD

Basics

Facts – the QCD exchange bosons – reality of gluons (III)

The **angular distribution** of the jets depends on the **gluon spin**:

pt …
transverse
momentum



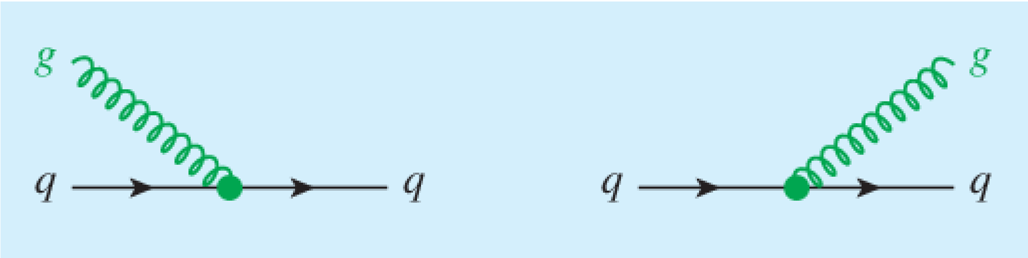
Experiments find that **gluons** are **vector bosons** (spin-1) as expected for exchange particles

FUNDAMENTAL INTERACTIONS – QCD

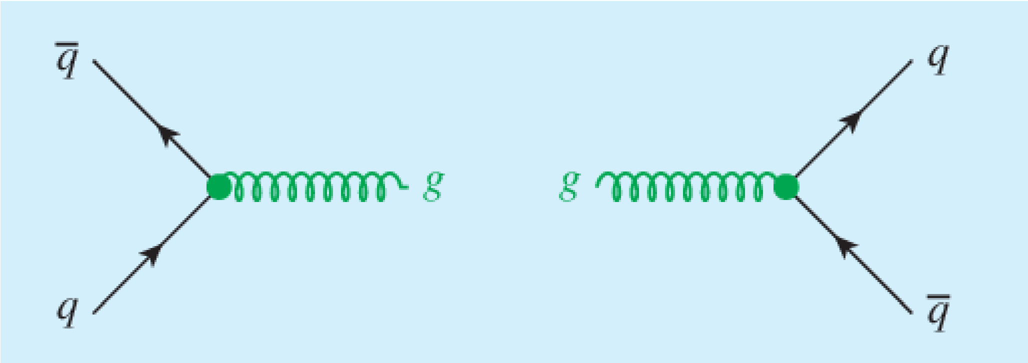
Basics

Facts – the basic vertices of QCD

Gluon absorption and **emission**:



Quark – anti-quark annihilation and **pair production**:



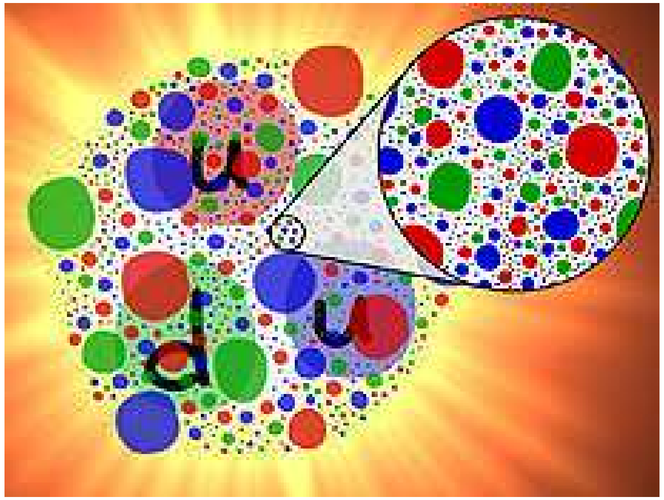
Note: the vertices do not yet represent physical processes (require a combination)

FUNDAMENTAL INTERACTIONS – QCD

Basics

Facts – Feynman´s partons

R. Feynman postulated (in 1969) that protons (→ hadrons) were made of pointlike constituents, he called "**partons**". Later, it was recognized that partons describe the same objects now more commonly referred to as **quarks** and **gluons**:



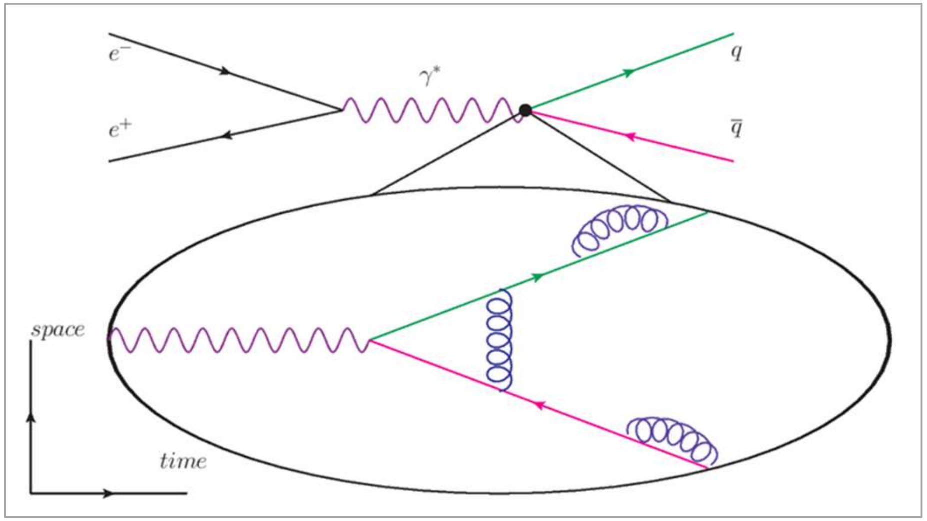
Note: When probed at smaller scales, e.g. in **DIS** (see below), protons seem to contain more and more **partons** (quarks and gluons), represented here as colored blobs.

FUNDAMENTAL INTERACTIONS – QCD

Examples

Hadronic processes – generic reaction

A **virtual photon** (γ^*) (produced, e.g., in e^+e^- annihilation) produces a **quark – anti-quark pair**:



Not only **electric charge** but also **color charge** of quarks and **gluons** are involved

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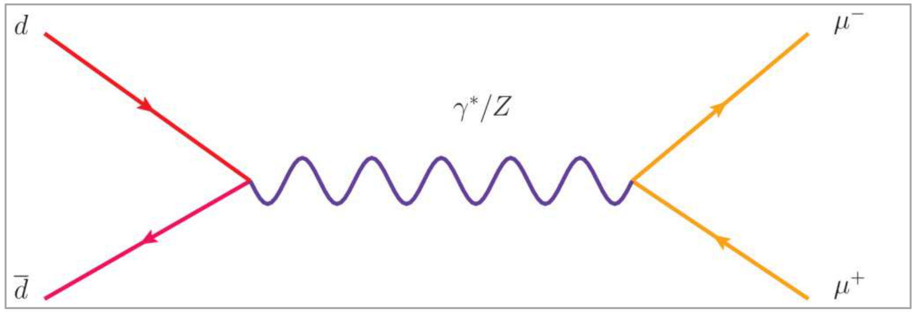
FUNDAMENTAL INTERACTIONS – QCD

Examples

Hadronic processes – Drell-Yan process (I)

In **pp-collisions** the so called "**Drell-Yan**" (DY) process occurs: a quark from one proton and an antiquark from the other proton (note: a "sea quark"!) annihilate into a **virtual photon** (γ^*). The photon can split into a lepton and its antiparticle partner, for example into an e^+e^- or $\mu^+\mu^-$ pair, provided the γ^* energy is sufficient:



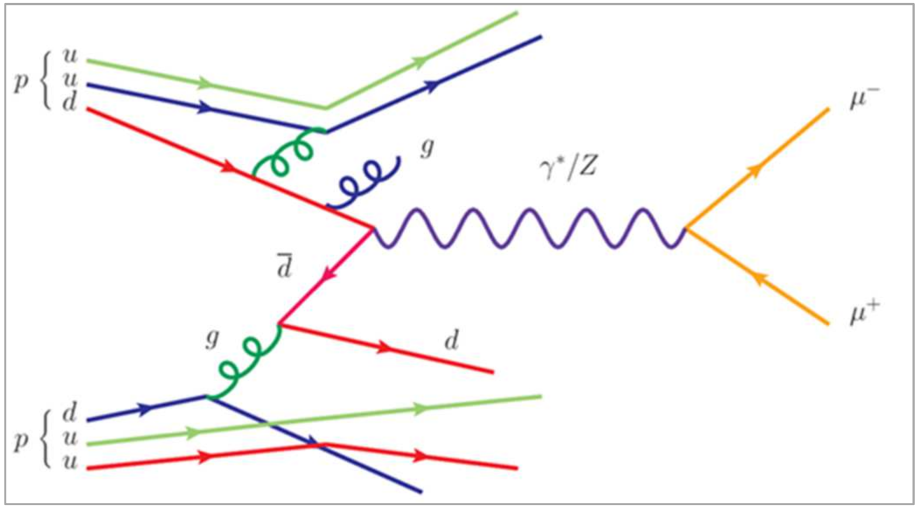
(DY can also happen via an **intermediate Z-boson** (weak IA, later …))

FUNDAMENTAL INTERACTIONS – QCD

Examples

Hadronic processes – Drell-Yan process (II)

The Drell-Yan process is not so simple due to the **complexity of the proton**: real collisions also include the **remnants** of the scattered protons:



Notes: (i) complex final state; identification of (μμ)-pair simple

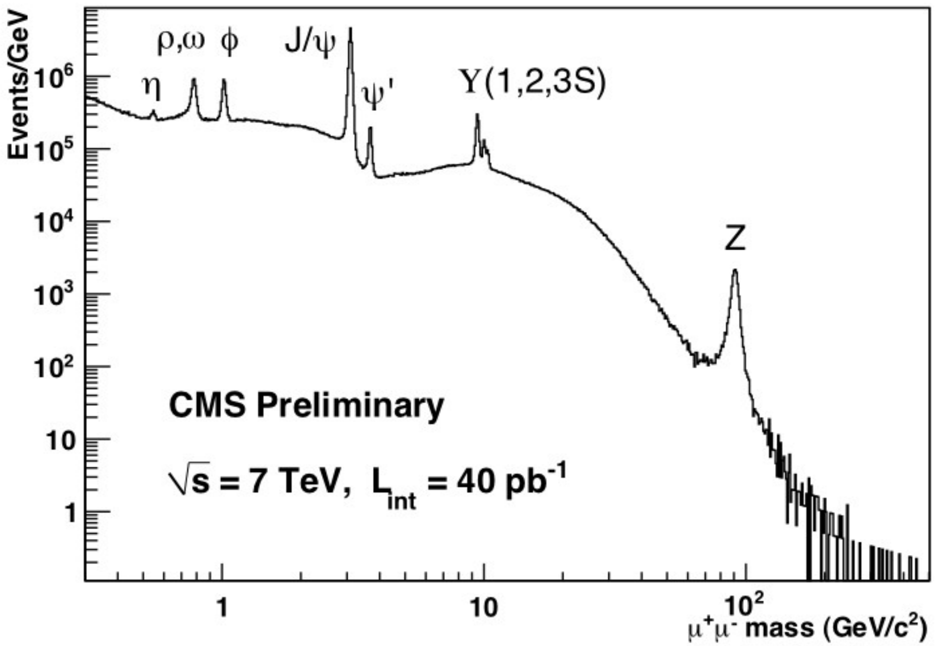
(ii) many more graphs (loops …)

FUNDAMENTAL INTERACTIONS – QCD

Examples

Hadronic processes – Drell-Yan process (III)

Example: $M_{\mu+\mu-}$ spectrum in pp-collisions at LHC



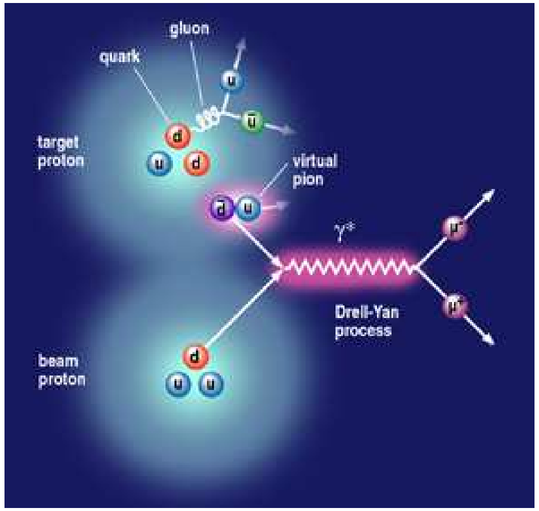
The rightmost peak at about 90 GeV (~90 times the proton mass!) is a peak corresponding to the production **Z bosons** (→ weak IA). The other peaks represent the production of well-known particles that have decayed into a muon-antimuon pair.

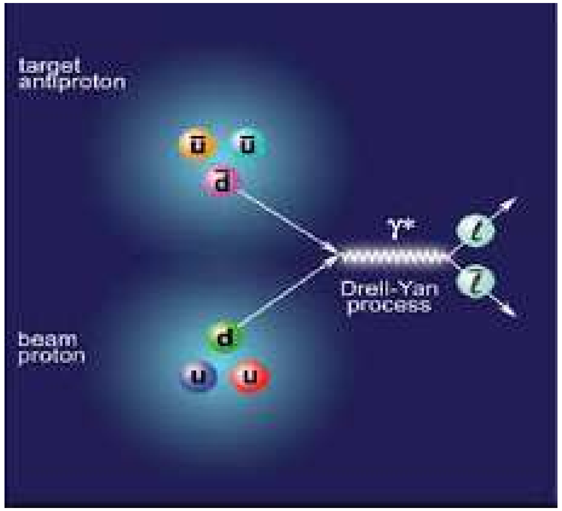
FUNDAMENTAL INTERACTIONS – QCD

Examples

Hadronic processes – Drell-Yan process (IV)

The use of **proton – anti-proton** collisions is advantageous, because the anti-proton contains valence anti-quarks:





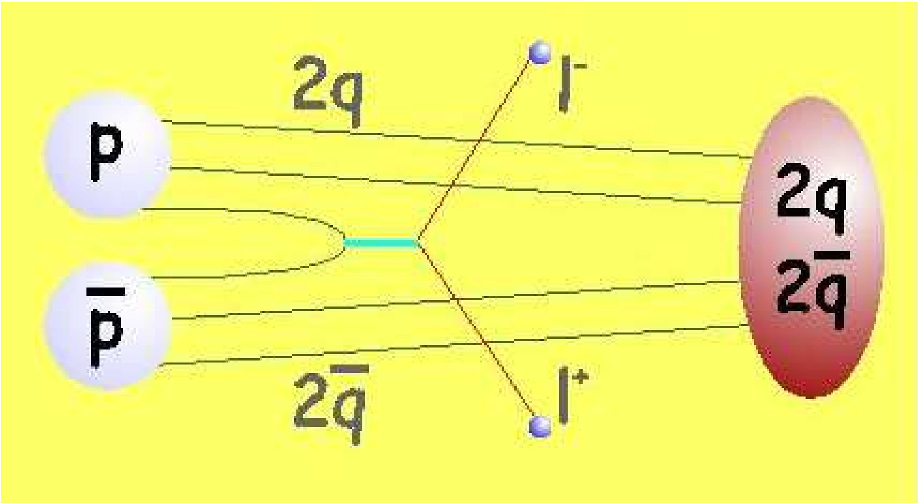
→ In addition: polarization as an additional/new degree of freedom (our project: production of **polarized anti-protons** …)

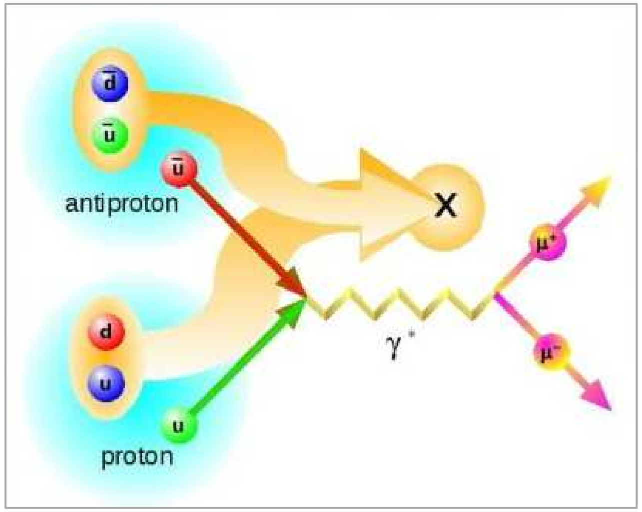
FUNDAMENTAL INTERACTIONS – QCD

Examples

Hadronic processes – Drell-Yan process (V)

DY in **proton** – **anti-proton** collisions may also be used to search and investigate **exotics** (like tetraquarks):





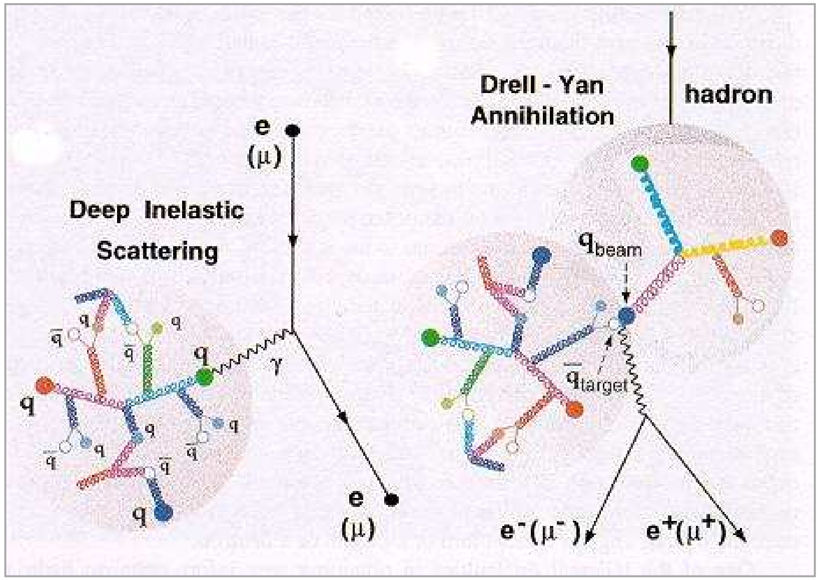
→ Possible science case for **PANDA at HESR** (FAIR) …

FUNDAMENTAL INTERACTIONS – QCD

Examples

Hadronic processes – deep-inelastic scattering (DIS) (I)

Make things simpler: use an electromagnetic probe (i.e **high-energy scattering** of **charged leptons** on nucleons (avoid complexity of second nucleon):

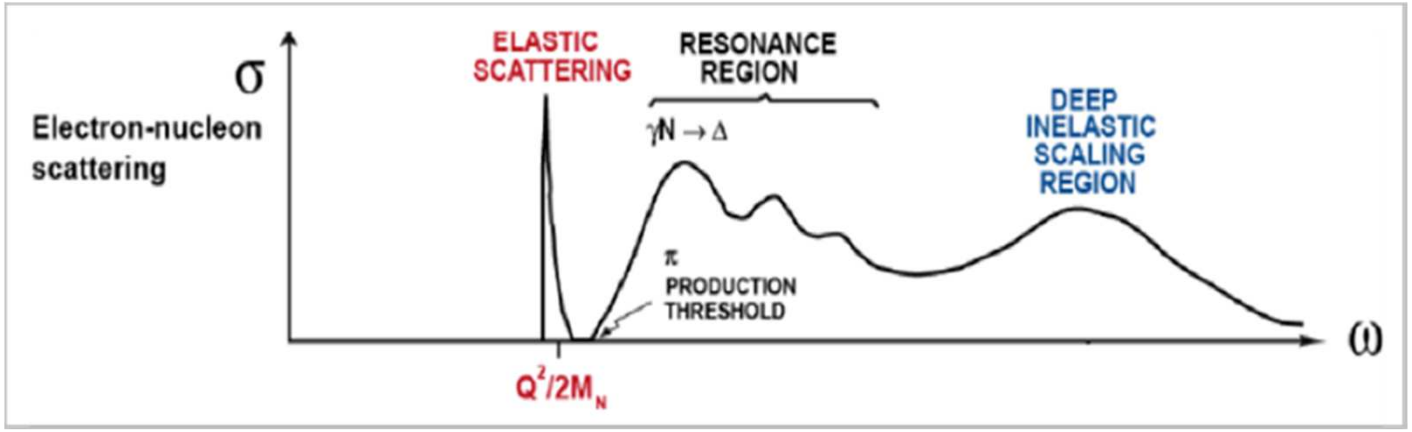


FUNDAMENTAL INTERACTIONS – QCD

Examples

Hadronic processes – deep-inelastic scattering (DIS) (II)

Elastic electron scattering (eN → eN; form factors) and excitation of nucleon resonances (eN → eN* → eN X) already discussed; at **higher energy** (smaller virtual photon wave length), on probes the **internal constituents**; at same time strong coupling constant becomes small → use of **perturbative approximation** (like in QED):

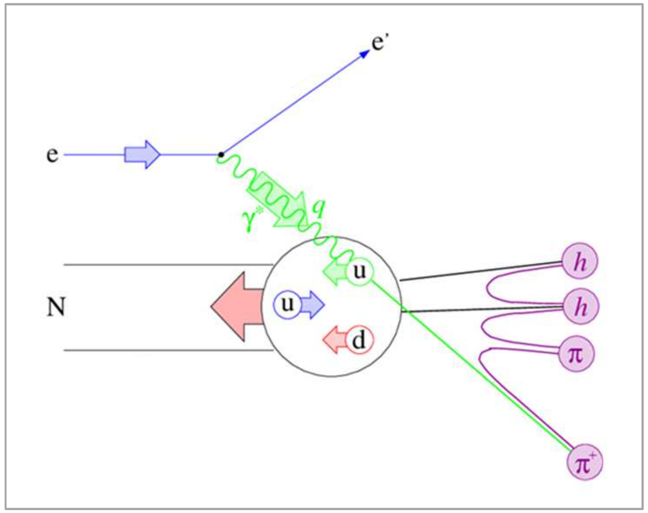


FUNDAMENTAL INTERACTIONS – QCD

Examples

Hadronic processes – deep-inelastic scattering (DIS) (III)

DIS is **elastic scattering on a quark** inside a nucleon:



Since quarks are supposed to be point-like, the corresponding form-factors should be constant (→ "**Bjorken scaling**", J. Bjorken, 1968; Feynman´s point-like partons) → this inspired QDC

FUNDAMENTAL INTERACTIONS – QCD

Examples

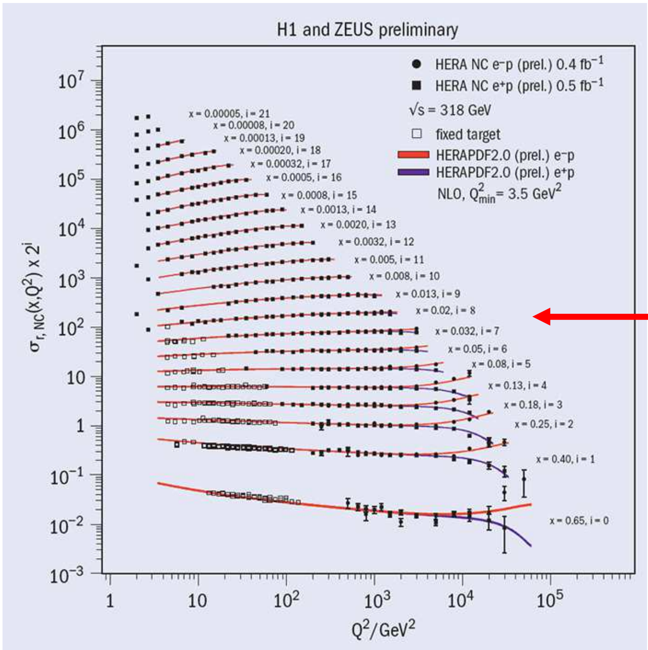
Hadronic processes – deep-inelastic scattering (DIS) (IV)

Bjorken scaling (independence of "**structure functions**" on momentum transfer) is experimentally observed:

Example:

HERA (DESY)

e^+p and e^- p data



x („**Bjorken-x**“) is the kinematic scaling variable

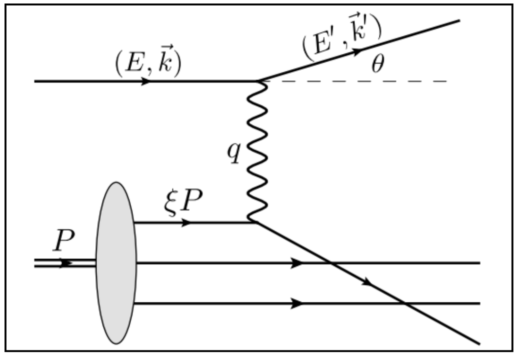
FUNDAMENTAL INTERACTIONS – QCD

Examples

Hadronic processes – deep-inelastic scattering (DIS) (V)

Bjorken scaling is not exact; deviations from strict scaling is required in quantum field theory; **QCD can predict** the detailed form of **violations of the scaling behavior** of the relevant physical quantities.

Quarks inside a nucleon have a **momentum distribution** – each one carries a varying fraction of the energy/momentum of the nucleon; the momentum distribution can be determined by looking at the scattered electrons:



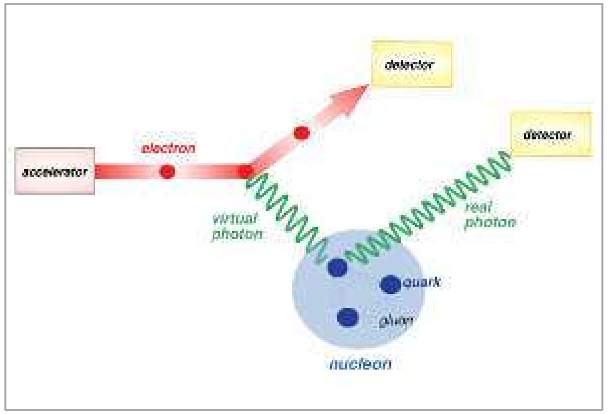
Expt´l finding: **quarks** carry about **50%** of the proton momentum; **gluons** carry another **~50%**

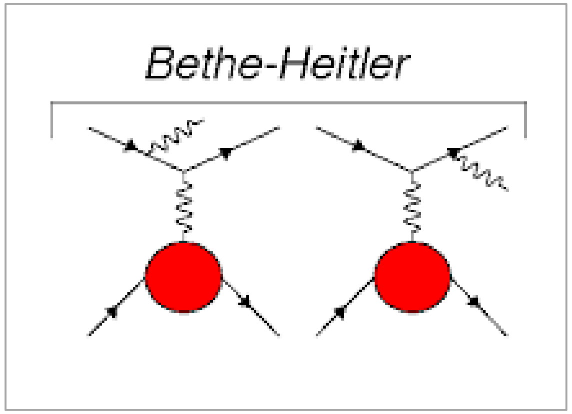
FUNDAMENTAL INTERACTIONS – QCD

Examples

Hadronic processes – deeply-virtual Compton scattering (DVCS)

Even simpler: in "**Deeply Virtual Compton Scattering**" (DVCS), a high-energy electron probes a nucleon by exchanging a **virtual photon** with the quarks inside. The final-state **real photon** carries information about the nucleon structure:





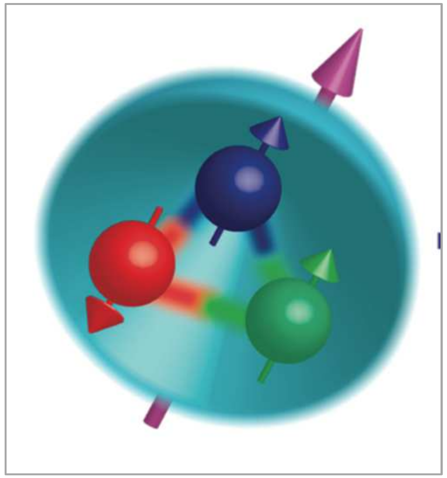
Experimental problem: separation of "**Bethe-Heitler**" background

FUNDAMENTAL INTERACTIONS – QCD

Examples

Hadronic processes – nucleon spin (I)

In the simple CQM, the spin S_N = ½ of the nucleon is just the vector sum of the 3 quark spins of S_q = ½ (with two parallel and the 3rd one anti-parallel):



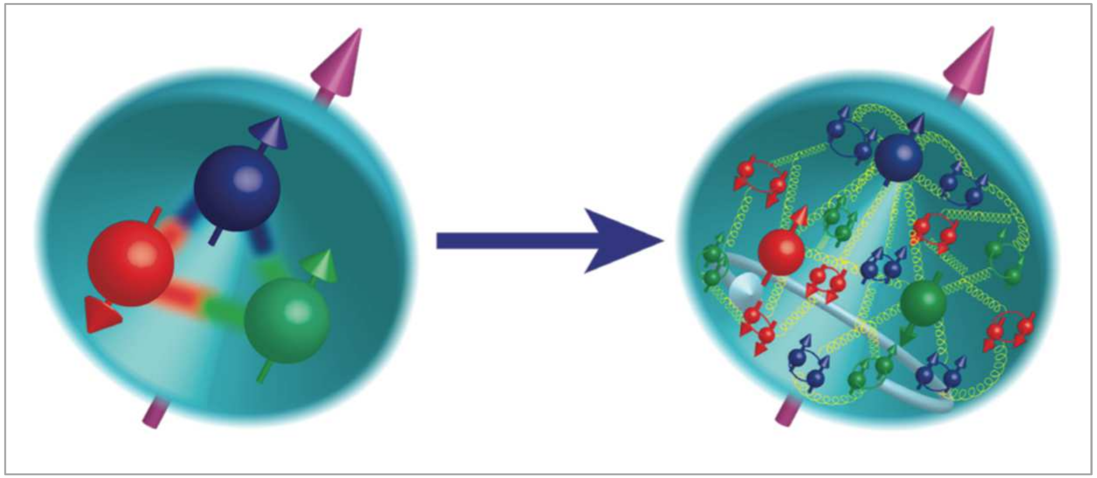
But: the nucleon is a much more complex object (valence and sea-quarks, gluons) → what is their contribution?

FUNDAMENTAL INTERACTIONS – QCD

Examples

Hadronic processes – nucleon spin (II)

Experimentally, it is found that the **quark spin contributes about 30%** to the spin of the nucleon (→ "**nucleon spin crisis**"); a major topic of expt´l particle physics is to find the missing part, believed to be carried either by **gluon spin**, or by **gluon** and **quark orbital angular momentum**:



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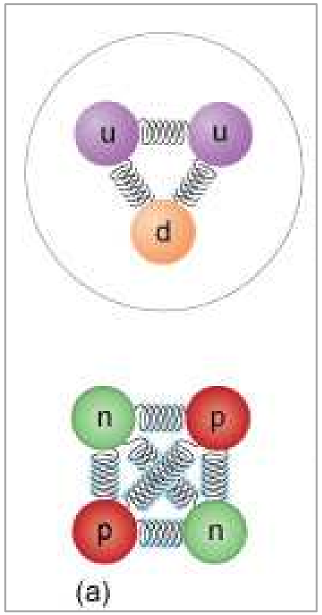
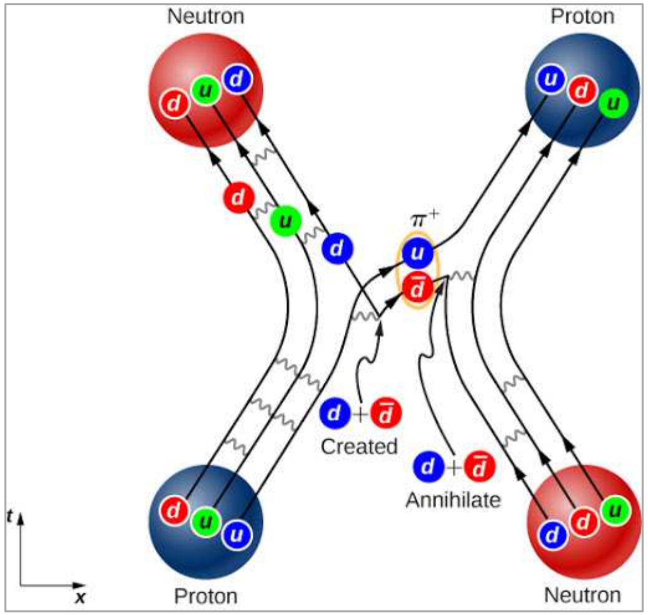
FUNDAMENTAL INTERACTIONS – QCD

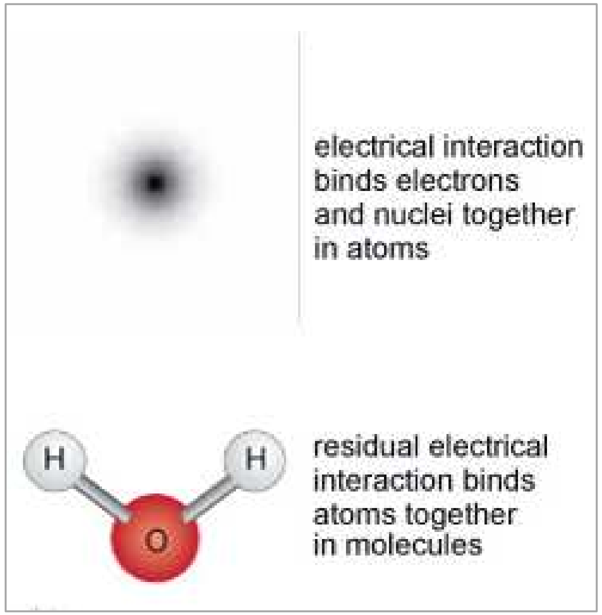
Examples

Hadronic processes – from the qq interaction to the nuclear force

The strong interaction binds quarks inside nucleons, and the **residual strong force** (nuclear force) binds nucleons in nuclei:





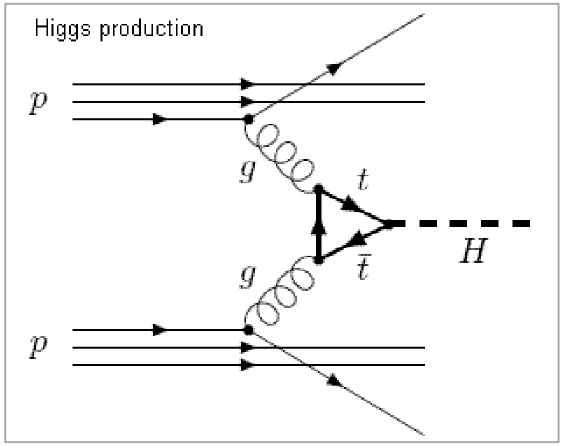


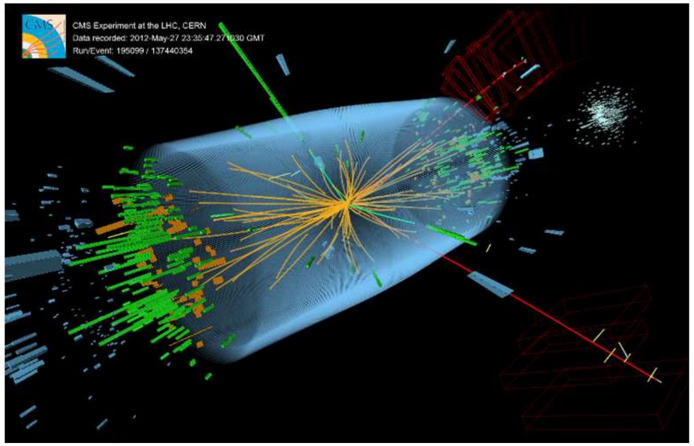
FUNDAMENTAL INTERACTIONS – QCD

Examples

Hadronic processes – production of the Higgs boson

The dominant **Higgs boson production mechanism** (~88%) at the elementary level by **gluon fusion** and a quantum loop process involving a **top quark**; discovery at the **LHC** in pp collisions (2012):





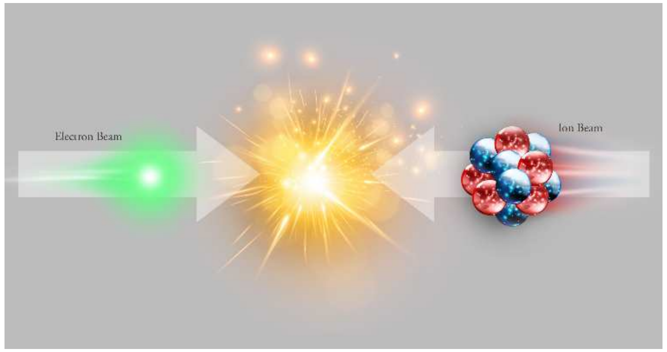
Talk about (wish for) a **Higgs-factory** … highest priority for the particle physics community: CLIC, FCC, ILC, …

FUNDAMENTAL INTERACTIONS – QCD

Outlook

Hadronic processes – new (upcoming) experimental facilities

EIC (Electron-Ion Collider) – Brookhaven (USA)



FAIR (Facility for Antiproton and Ion Research) – GSI (Germany)

FUNDAMENTAL INTERACTIONS – QCD

Summary

Quantum Chromodynamics (QCD) – main features

- **Confinement**
  - At large distances the effective coupling between quarks is large, resulting in confinement.
  - Free quarks are not observed in nature.
- **Asymptotic freedom**
  - At short distances the effective coupling between quarks decreases logarithmically.
  - Under such conditions quarks and gluons appear to be quasi-free.
- **(Hidden) chiral symmetry**
  - Connected with the quark masses
  - When confined quarks have a large dynamical mass - constituent mass
  - In the small coupling limit (some) quarks have small mass - current mass

THE FORCES

That´s it for today

გმადლობთ

JÜLICH
Forschungszentrum

The coupling between quarks and gluons depends strongly on the energy scale of the process. The same is true for the masses of the quarks. This effect – the so-called “running” of the strong coupling constant and the quark masses – is described byquantum chromodynamics (QCD). The experimental verification is both an important test of the validity of QCD and an indirect search for unknown physics