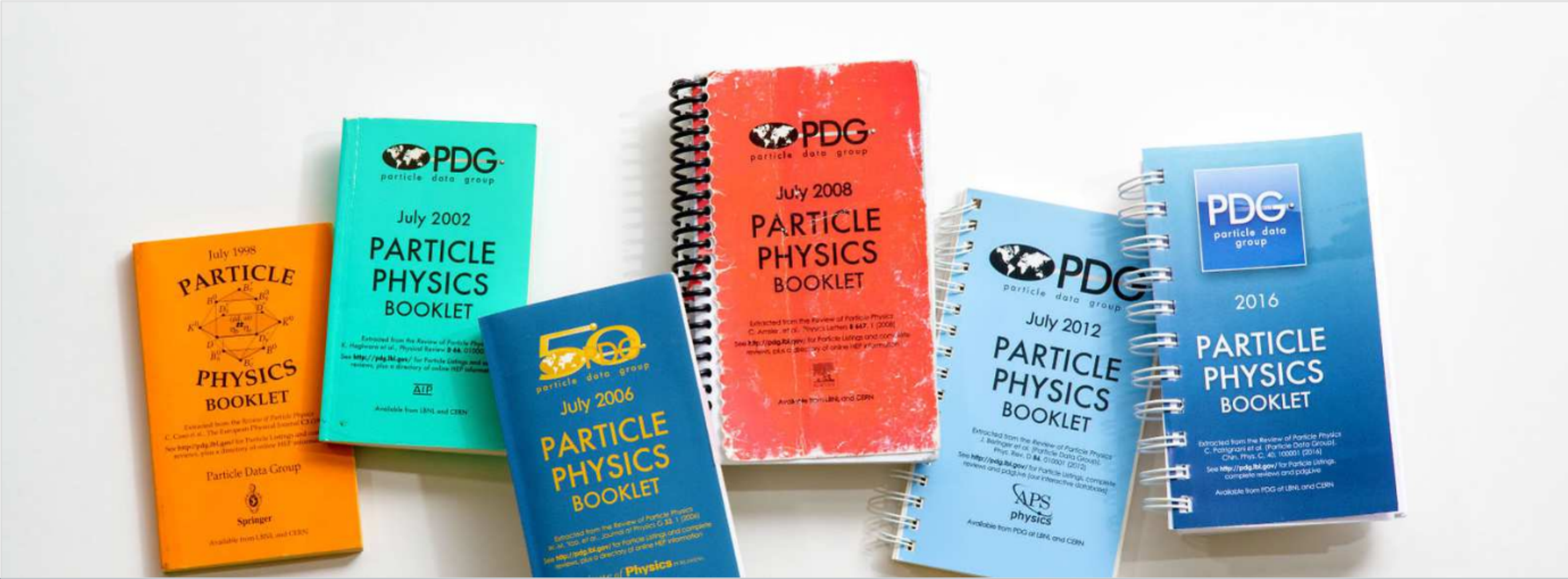


ELEMENTARY PARTICLE PHYSICS

THE PARTICLES (PART II)

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

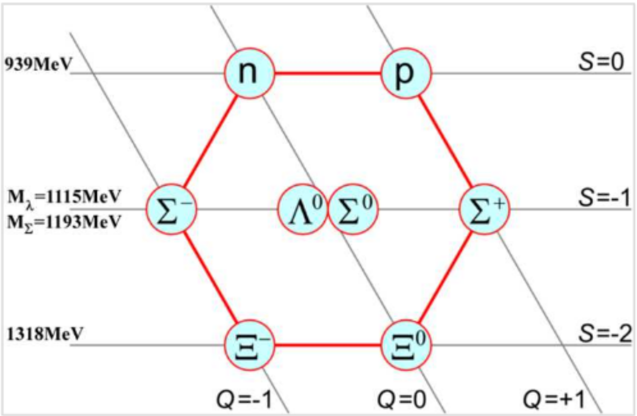
QUARK MODEL

Prelude

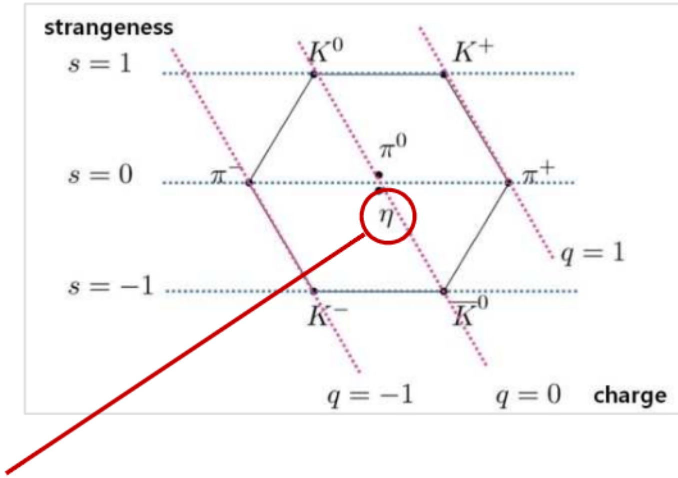
History – The "eightfold way"

When, in the 1960´s hadrons were arranged according to their **electrical charge** and their **strangeness**, they lined up into hexagonal patterns:

baryons (w/ spin ½)



mesons (w/ spin 0)



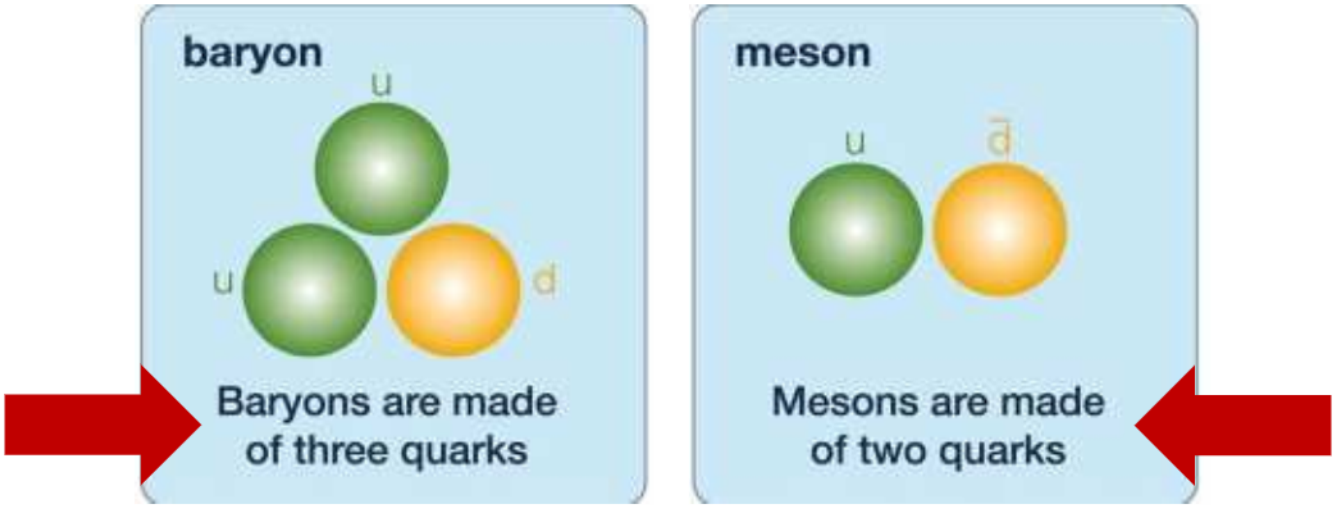
For the mesons, M. Gell-Mann predicted the **gap** would be filled by a particle he called „**eta**“ (η), which was found subsequently …

THE PARTICLES

Prelude

Quark Model – Hadron classification scheme

After early unsuccessful attempts, the **quark model** was eventually invented – in its currently known form by **Murray Gell-Mann**: it is a classification scheme for hadrons in terms of their *valence* quarks – the quarks and antiquarks which give rise to the quantum numbers of the hadrons



more precisely: quark-antiquark pair

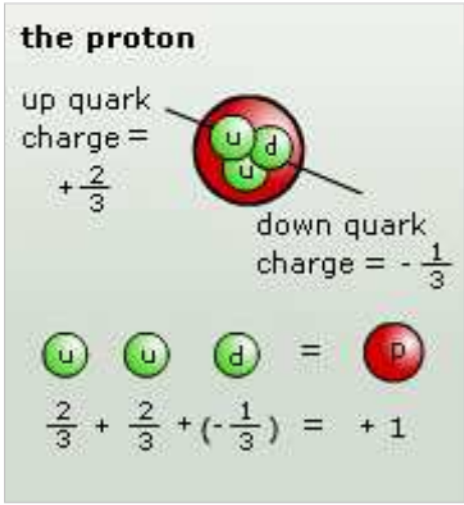
THE PARTICLES

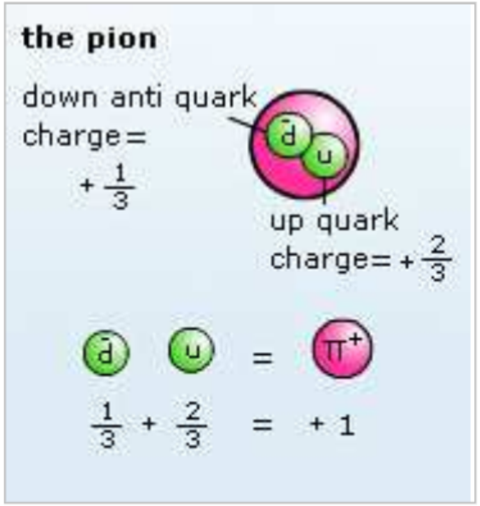
Prelude

Quark Model – fractional charges

The quarks which make up proton, neutron and lightest mesons (pions) were called „**up**“ **(u)** and „**down**“ **(d) quarks**; their strangest property is that they have fractional electric charges: **u (2/3)** and **d (-1/3)** in terms of e_0 (reversed electric charge for the corresponding anti-quarks)

Example:





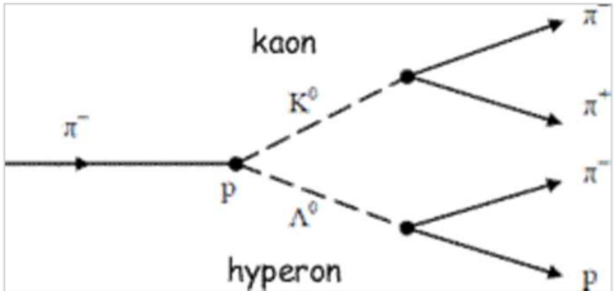
THE PARTICLES

Prelude

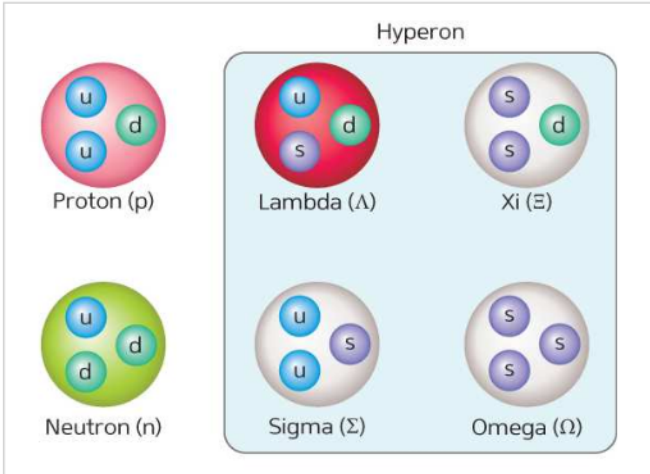
Quark Model – Strangeness

In the course of discovering new particles, some were behaving „strange“, i.e. although created easily in particle collisions, they **decayed much more slowly** than expected – this was ascribed to a property called „**strangeness**“ (introduced by Gell-Mann, Pais and Nishijima): strangeness was conserved in the production, but not in their decay: → necessity of a **new quark** (s):

Example:



↑ **associated strangeness production**



THE PARTICLES

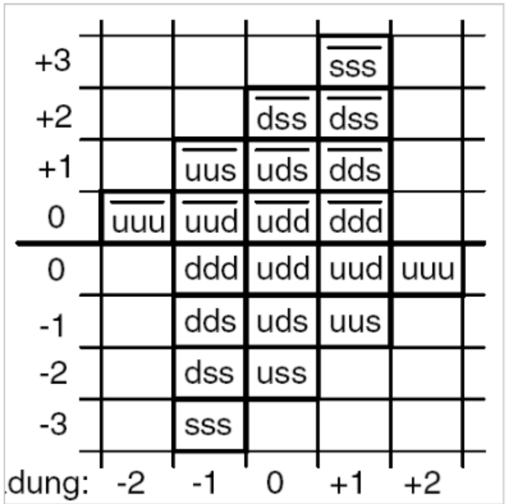
Prelude

Quark Model – A third quark

The **new „strange“ quark** (flavor) has an electric charge of -1/3 e_0.

With 3 quarks (u,d,s), the following 10 states comprising 3-quarks each (i.e. baryons) can be composed (same for anti-quarks) → so called **„multiplets“**

„strangeness“ of the baryon (i.e. number of strange quarks)



charge of the baryon

THE PARTICLES

Prelude

Despite the capability of the quark model to bring order to the „particle zoo“, its status was still unclear (many thought is a mathematical fiction rather than real objects) …

QUARK MODEL

Introduction

The genesis of quarks: Gell-Mann and Zweig

In 1964, Gell-Mann proposed that **hadrons** are **composite particles**, built from more fundamental entities which themselves manifest an **SU(3) symmetry**

2 possible choices:

- 4 elementary entities w/ **electric charge either 0 or 1** (non-elegant)
- scheme w/ **non-integral values of the charges** → **quark model**

(Gell-Mann´s name comes from a phase in James Joyce`s book *Finnegan´s Wake*)

Note: the second scheme was independently proposed by **George Zweig** (PostDoc at CERN) – he called the constituents „aces“

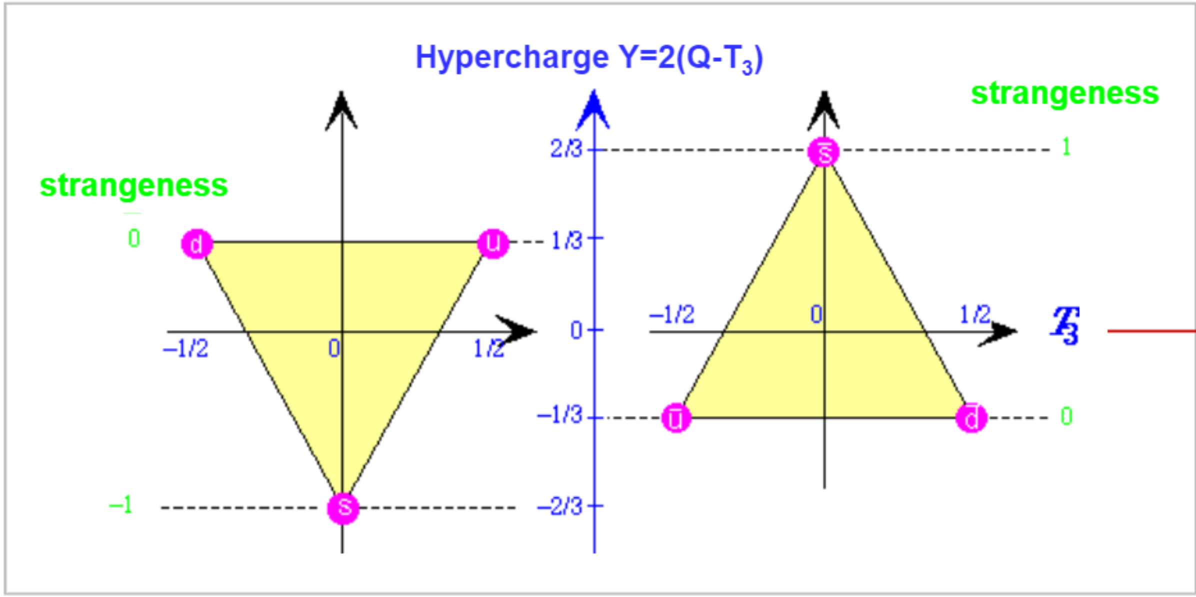
Note: **Murray Gell-Mann** got the physics NP in 1969

QUARK MODEL

Introduction

The genesis of quarks: fundamental representation of SU(3)

According to **SU(3)**, hadrons are expected to fall into **multiplets** containing 1, 3, 6, 8, 10, 27 … members (characteristic of the representations of SU(3)); the **triplet**, containing 3 members, is the **fundamental representation**, i.e. the quarks:



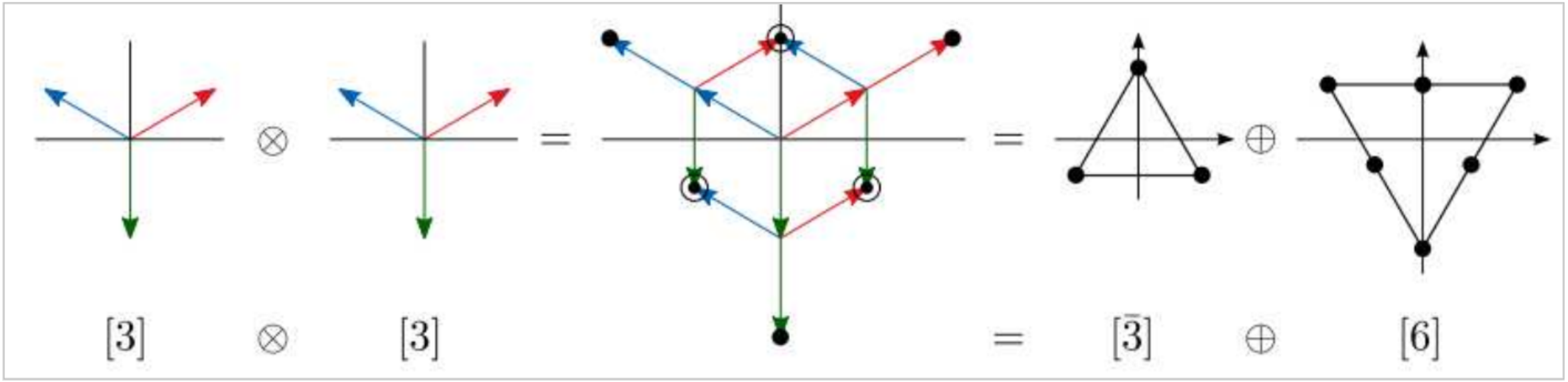
3rd component of isospin

QUARK MODEL

Introduction

The genesis of quarks: making of **baryons** in flavor SU(3)

First: take any two quarks, which arrange in two SU(3) multiplets having **6 symmetric** and **3 anti-symmetric states**:

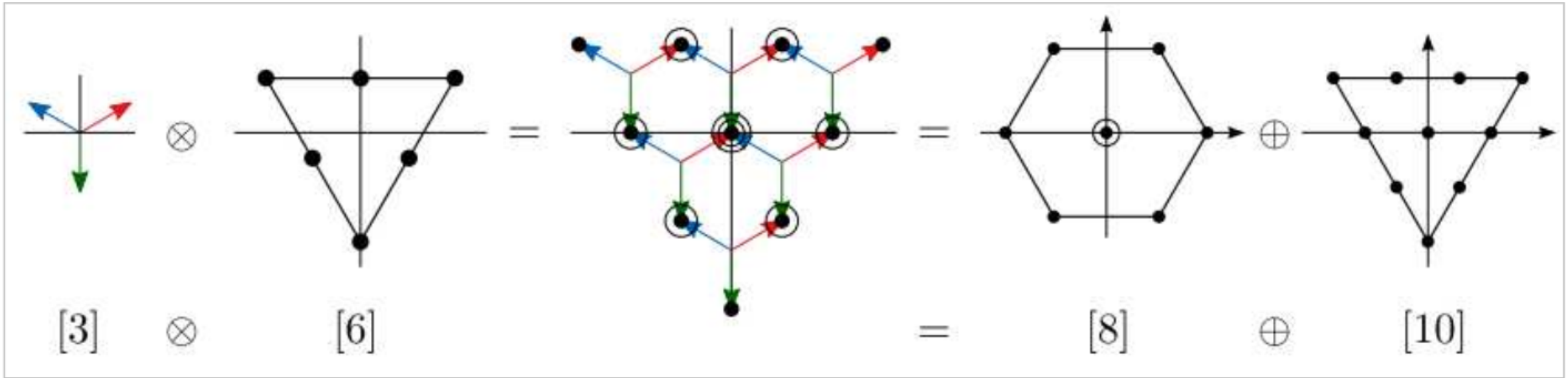


QUARK MODEL

Introduction

The genesis of quarks: making of **baryons** in flavor SU(3)

Second: adding the third quark to the **sextet (6)** results in an **octet (8)** and a **decuplet (10)**:



→ in total:

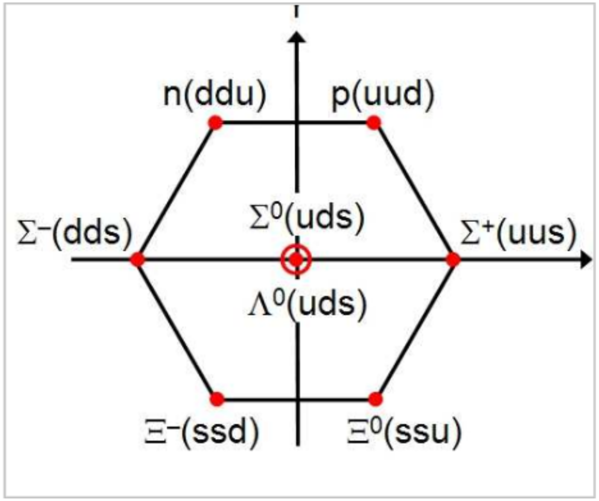
$$3 \otimes 3 \otimes 3 = (6 \otimes 3) \oplus (\bar{3} \otimes 3)$$
$$= 10 \oplus 8 \oplus 8 \oplus 1,$$

QUARK MODEL

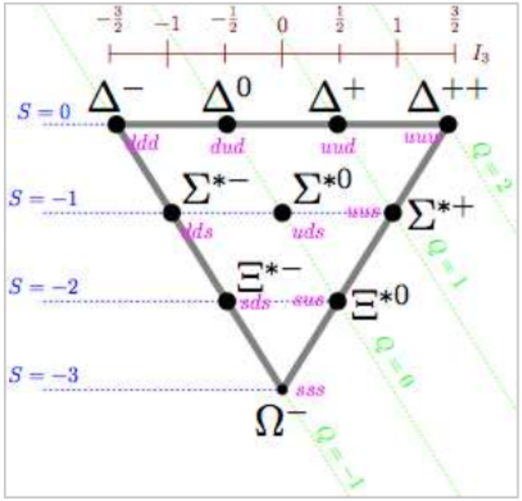
Introduction

The genesis of quarks: making of **baryons** in flavor SU(3)

The **singlet (1)**, **octet (8)** and **decuplet (10)** states are **found experimentally**:



Spin J = 1/2



Spin J = 3/2

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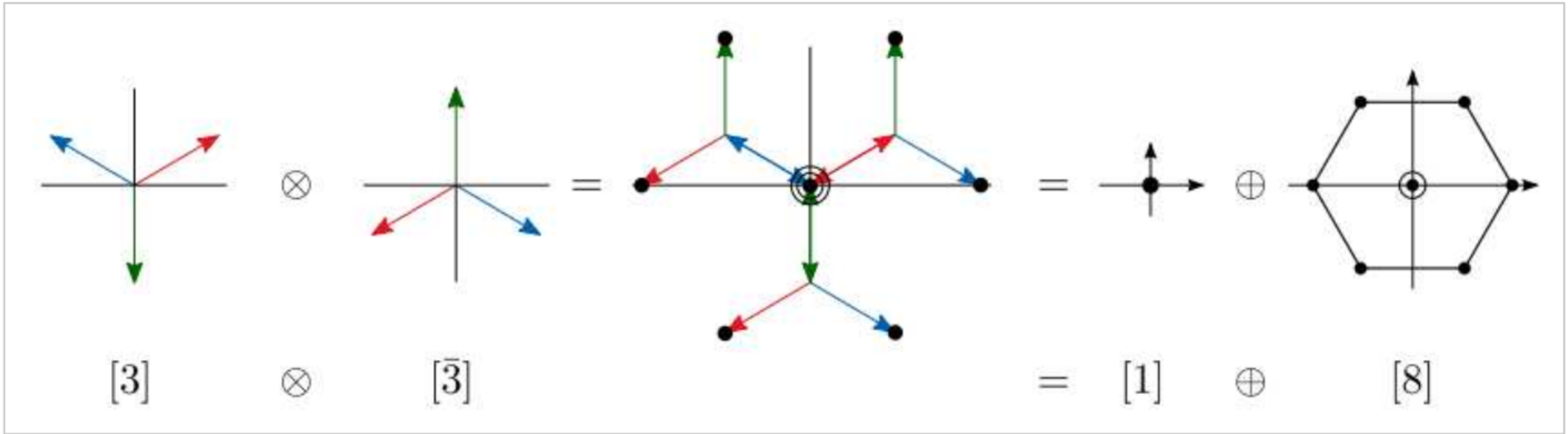
QUARK MODEL

Introduction

The genesis of quarks: making of **mesons** in flavor SU(3)

The nine $q\bar{q}$-states (**nonet**) can be decomposed into a **singlet (1)** and an **octet (8)**:



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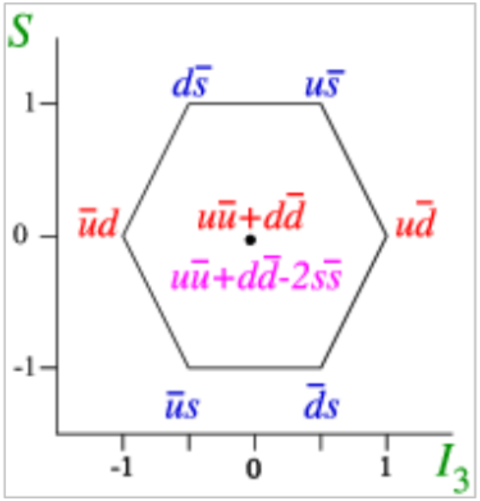
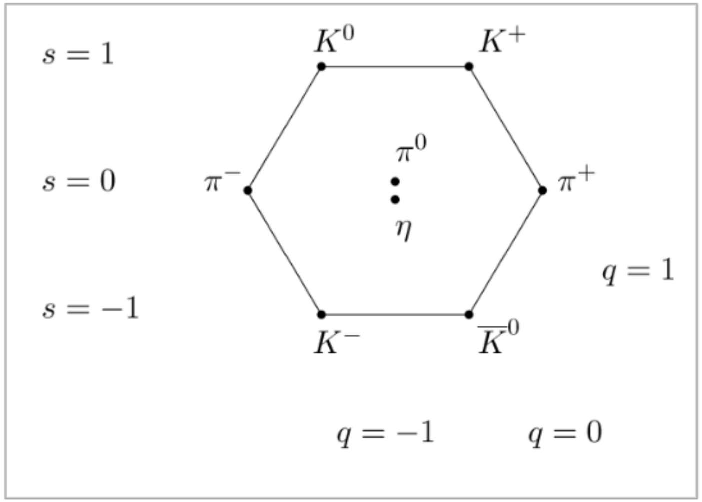
QUARK MODEL

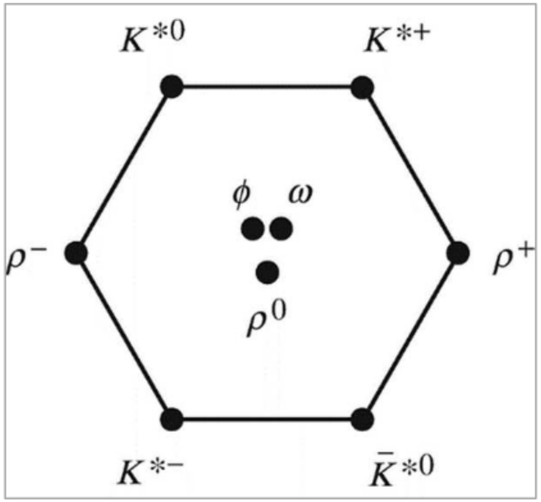
Introduction

The genesis of quarks: making of **mesons** in flavor SU(3)

They are also realized in nature and have been **found experimentally**:







Spin J = 0
(pseudoscalar mesons)

Spin J = 1
(vector mesons)

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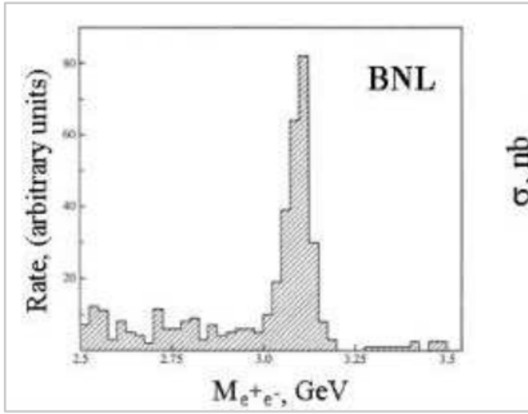
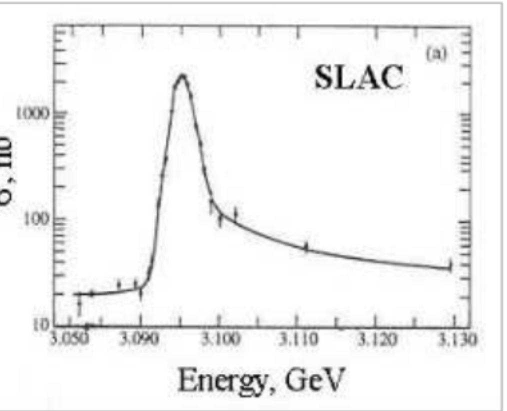
QUARK MODEL

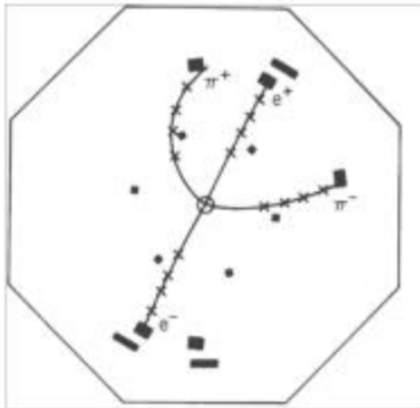
Introduction

The genesis of quarks – “J/Ψ” discovery

In November 1974, the discovery of a **new hadronic state** was simultaneously reported from SLAC (SPEAR) (**B. Richter**) and BNL (AGS) (**S. Ting**) (both received the physics NP in 1976 *"for their pioneering work in the discovery of a heavy elementary particle of a new kind"*); this new particle is now called the **J/Ψ** and has a rest **mass of ~3.1 GeV/*c*²**:







pBe-collisions
decay into e^+e^- X
suggested name „J“

e^+e^- collisions
decay into hadrons, l^+l^-,…
suggested name Ψ

QUARK MODEL

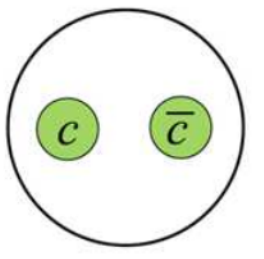
Introduction

The genesis of quarks – the second 2^{nd}-generation quark

The new particle was so heavy that it could not be made out of the known (u,d,s) quarks, but rather a new one: it is called **“charm” (“charmed”) quark (c)**.

The existence of a fourth quark had been speculated by a number of authors around 1964 (J. Bjorken and S. Glashow), but its prediction is usually credited to S. Glashow, J. Iliopoulos and L. Maiani in 1970. Its charge is +2/3 e_0.

It soon became clear that the J/Ψ is a **meson** – a bound state of a so called „**charm quark**“ (**c**) and an „**anti-charm quark**“ ($\bar{c}$) („charmonium“).



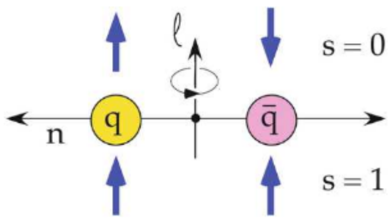
"Charmonium" meson

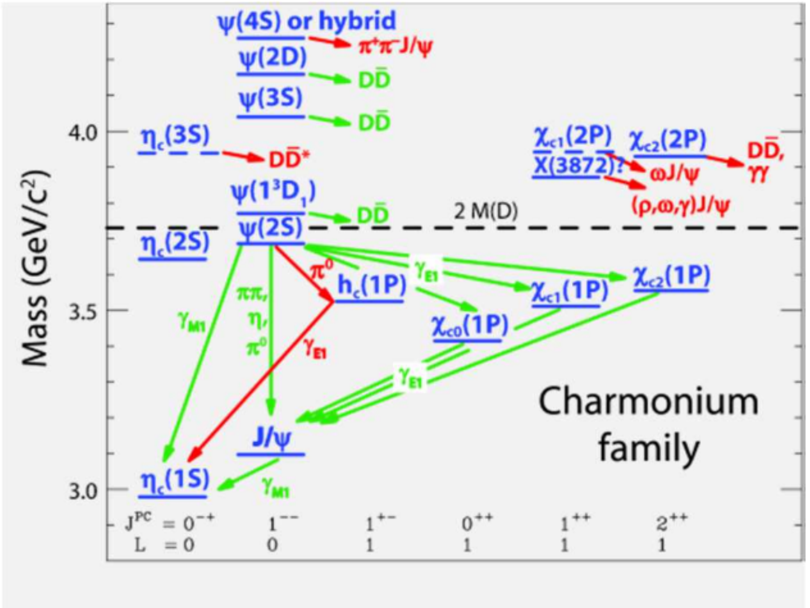
QUARK MODEL

Introduction

The genesis of quarks – charmonium

The charmonium family comprises a large variety of states (actually, the **J/Ψ is not** the **ground-state**):





open charm threshold ($D\bar{D}$)
D-meson = cq

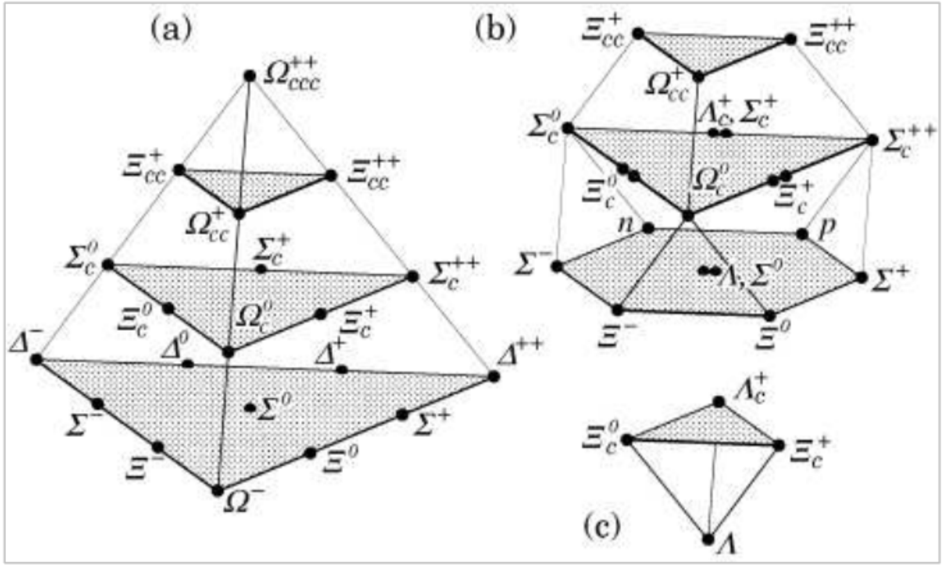
(Note: similar … “bottomonium” ($b\bar{b}$), see below)

QUARK MODEL

Introduction

The genesis of quarks – Charmed baryons

Charmed **baryons** are composite particles which contain at least one (possibly two or even three) charm quarks; many of them have been discovered; they also can be classified in SU(4) (i.e. arranged in **multiplets**):

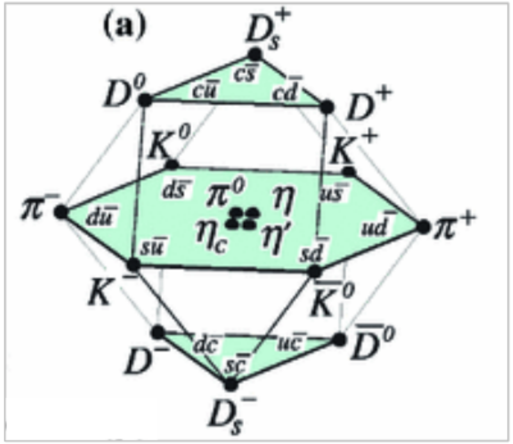


QUARK MODEL

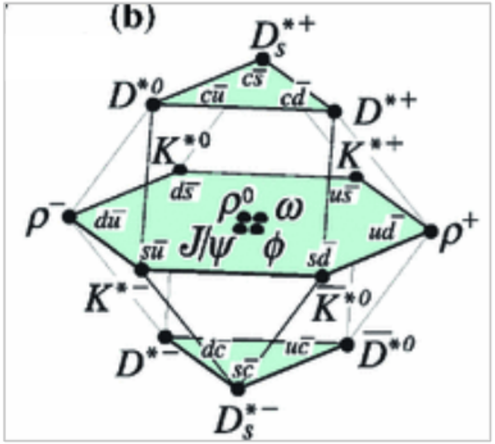
Introduction

The genesis of quarks – Charmed mesons

Charmed **mesons** are composite particles which contain at least one charm quarks; many of them have been discovered; they can be classified in **SU(4) multiplets**:



Spin J = 0
(pseudoscalar mesons)



Spin J = 1
(vector mesons)

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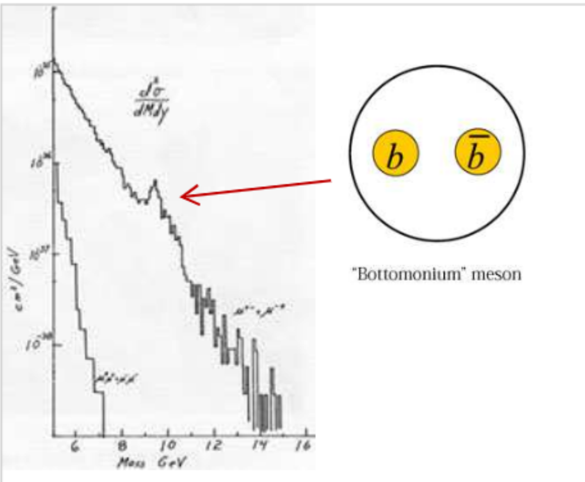
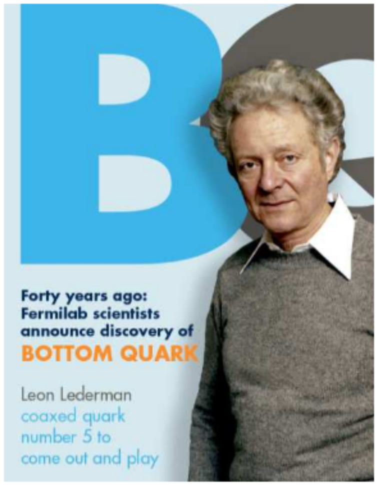
QUARK MODEL

Introduction

The genesis of quarks – the third-generation quarks

The “**bottom” quark** or **b quark** (also: beauty quark) is a third-generation quark with a charge of −1/3 e_0; it was first described theoretically in 1973 by physicists Makoto Kobayashi and Toshihide Maskawa to explain CP violation (more later); it was discovered in 1977 at Fermilab E288 (Leon M. Lederman et al.) in 400 GeV pA collisions producing “**bottomonium**”: its "bare" mass is around **4.2 GeV/c^2** – a bit more than four times the mass of a proton:



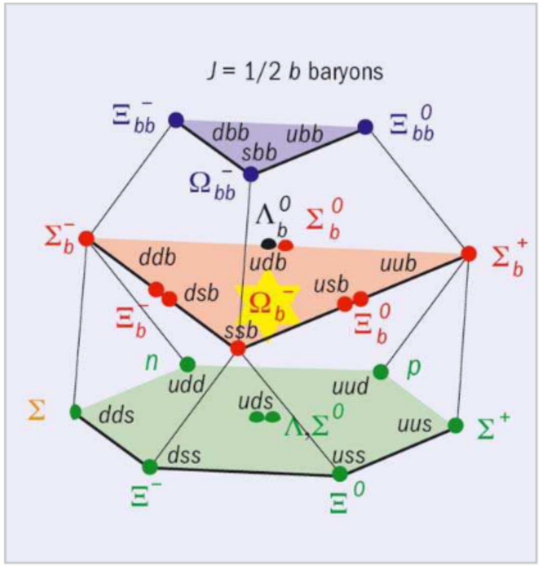


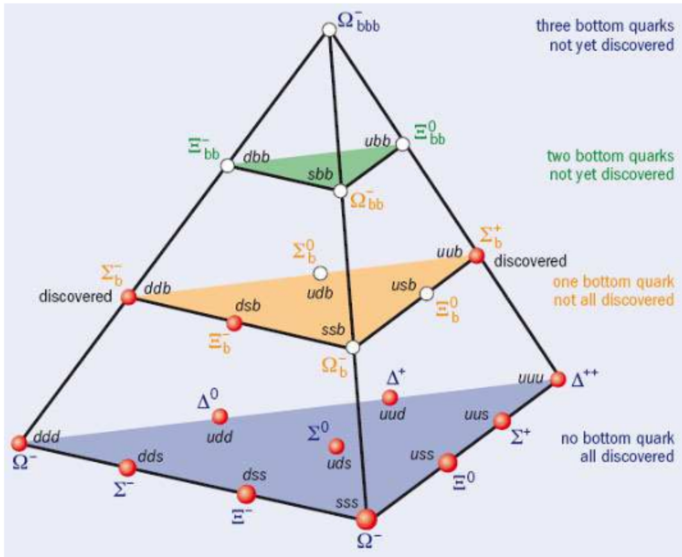
QUARK MODEL

Introduction

The genesis of quarks – the third-generation quarks

The **baryon** states, which include at least one **bottom quark** (“**bottom baryons**”) can be arranged again in SU(4) **multiplets**, but not all of them have been observed up to now:





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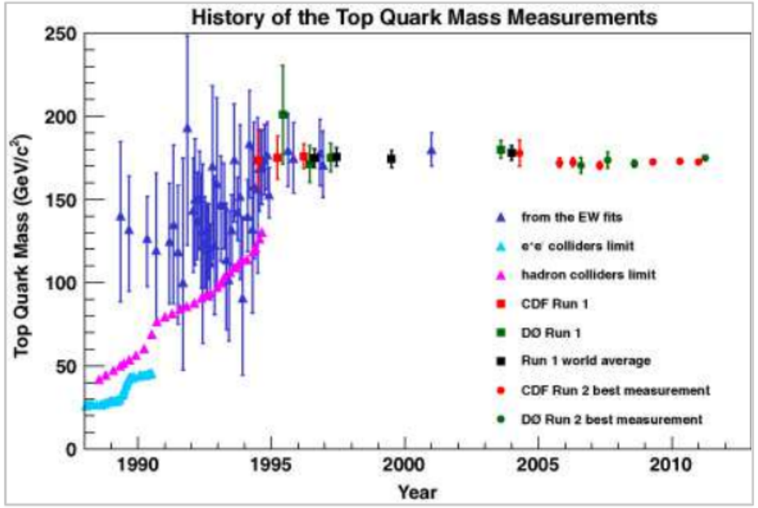
QUARK MODEL

Introduction

The genesis of quarks – completing the list of quark flavors: t

The "**top" quark** (symbol: t, also **truth quark)** is the most massive of all observed elementary particles. Like all quarks, the top quark is an elementary fermion with spin ½; it has an **electric charge of +2/3 e_0** and a large **mass of 172 GeV/c^2**, which is about the mass of a tungsten (W) atom; it was discovered in 1995 by the CDF and DØ experiments at Fermilab; single top-quarks first produced in 2006 (DØ);



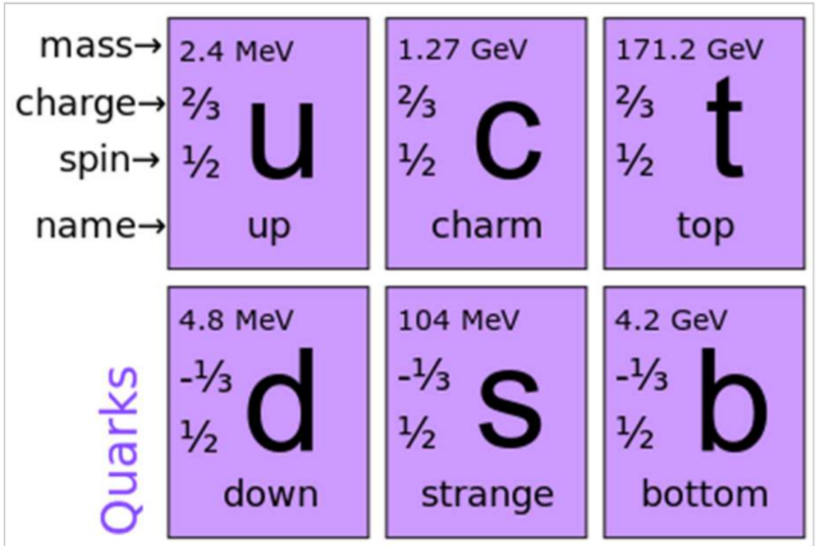
The lifetime of the **top quark** is about **4 x 10^{-25} s** – this is **too short** to create a strongly bound state.

QUARK MODEL

Introduction

Summary: three quark generations (families)

According to our current understanding, the **6 quarks** and the corresponding anti-quarks account for all hadronic matter in our universe (no further quark family)



Quark	Date	Where	Mass [GeV/c^2]	Comment
up, down	-	-	~0.005, ~0.010	Constituents of hadrons, most prominently, proton and neutrons.
strange	1947	-	~0.2	discovered in cosmic rays
charm	1974	SLAC/ BNL	~1.5	Discovered simultaneously in both *pp* and e^+e^- collisions.
bottom	1977	Fermi-lab	~4.5	Discovered in collisions of protons on nuclei
top	1995	Fermi-lab	~175	Discovered in pp collisions

<u>Note:</u> vastly different mass; why 3 generations?

QUARK MODEL

Introduction

Summary: three quark generations (families)

The table gives the relevant **properties/quantum numbers** of the six quarks:

Flavor	I	I_3	S	C	B^*	T	Q/e
u	1/2	1/2	0	0	0	0	+2/3
d	1/2	-1/2	0	0	0	0	-1/3
s	0	0	-1	0	0	0	-1/3
c	0	0	0	1	0	0	+2/3
b	0	0	0	0	-1	0	-1/3
t	0	0	0	0	0	1	+2/3

For **anti-quarks** all the **signs are changed**.

Note: quantum numbers are conserved in **electromagnetic**, **strong interactions**

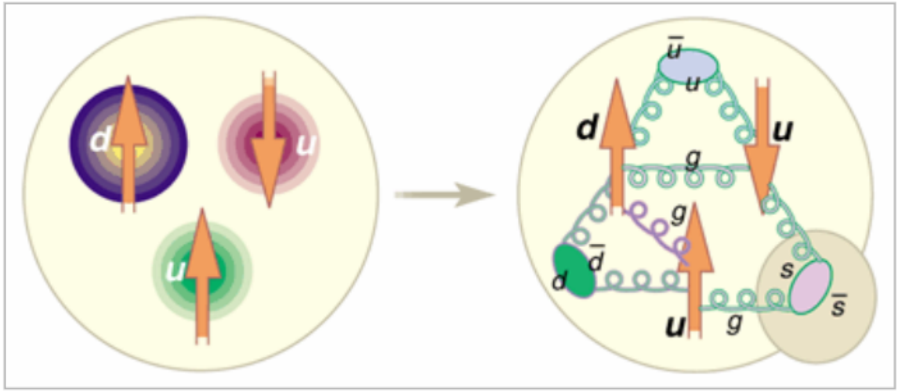
QUARK MODEL

Constituent Quark Model (CQM)

The reality of quarks

The (non-relativistic) constituent quark model treats the substructure of hadrons (today known to be very complex – see below) as **quasi-particles**, which have the same quantum numbers (electric charge, baryon number, color, flavor, spin) as the quarks of Quantum-Chromodynamics (QCD – theory of strong interactions).

They can be seen as the QCD quarks (the „bare“ quarks or „current“ quarks) dressed by clouds of quark-antiquark pairs („sea“ quarks) and gluons and are called **„constituent“ („valence“) quarks**:



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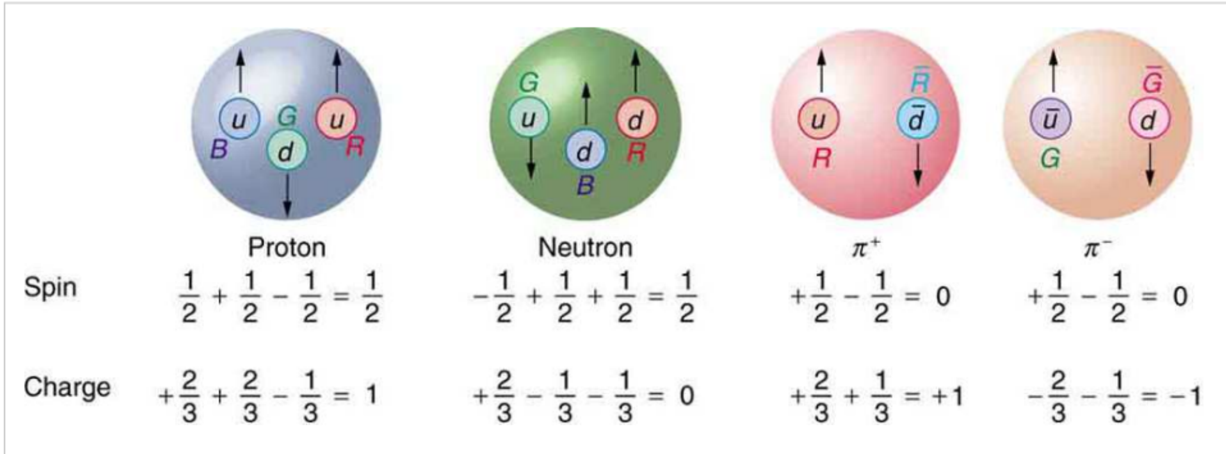
QUARK MODEL

Constituent Quark Model (CQM)

The reality of quarks – properties of constituent quarks

Their **mass** is of the order of **340 MeV/c²** (for **u** and **d**) and **490 MeV/c²** (for **s**); they have **spin ½**, i.e. they are fermions and **fractional charge** (1/3 e_0, 2/3 e_0).

Examples:



(Note: R,G,B („color“) etc. will be introduced later)

QUARK MODEL

Constituent Quark Model (CQM)

The reality of quarks – achievements: magnetic moments of baryons

Historically,the prediction of **baryon magnetic moments** was one of the striking successes of the quark model; they are the **vector sum** of the constituent quark magnetic moments:

<u>Examples</u>: proton and neutron

$$\propto = e/2m\ s$$

p (uud): $\propto_p = 2/3\ (2 \propto_u - \propto_d) + 1/3 \propto_d$

n (udd): $\propto_n = 2/3\ (2 \propto_d - \propto_u) + 1/3 \propto_u$

Quark model magnetic moment predictions and measurements

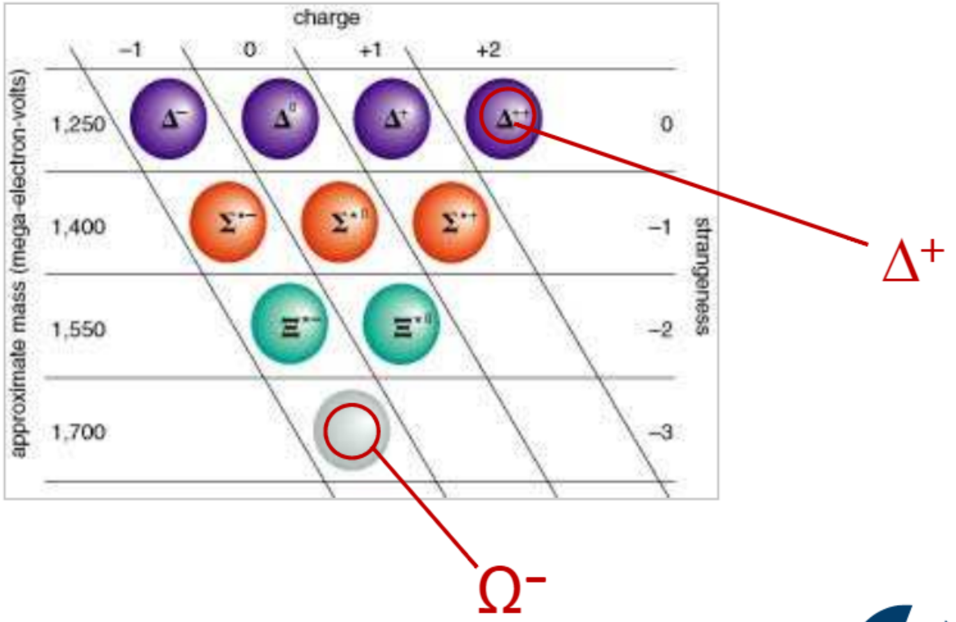
Particle	Predicted μ	Predicted in μ_N	Measured
p	$\frac{4}{3}\mu_u - \frac{1}{3}\mu_d$	+2.79	+2.793
n	$\frac{4}{3}\mu_d - \frac{1}{3}\mu_u$	−1.86	−1.913
Λ	μ_s	−0.61	-0.613 ± 0.004
Σ^-	$\frac{4}{3}\mu_d - \frac{1}{3}\mu_s$	−1.04	-1.160 ± 0.025
Σ^0	$\frac{2}{3}(\mu_d + \mu_u) - \frac{1}{3}\mu_s$	+0.82	Lifetime too short
Σ^+	$\frac{4}{3}\mu_u - \frac{1}{3}\mu_s$	+2.69	$+2.458 \pm 0.010$
Ξ^-	$\frac{4}{3}\mu_s - \frac{1}{3}\mu_d$	−0.51	-0.651 ± 0.003
Ξ^0	$\frac{4}{3}\mu_s - \frac{1}{3}\mu_u$	−1.44	-1.250 ± 0.014
Ω^-	$3\mu_s$	−1.83	-2.20 ± 0.05

QUARK MODEL

Constituent Quark Model (CQM)

The reality of quarks – achievements: validity of SU(3): the Ω^- (sss) (I)

A major **prediction by Gell-Mann** was that a particle, an isotopic singlet with spin = 3/2, positive parity, mass of roughly 1,700 MeV, negative charge, baryon number +1, strangeness = -3, and stable to strong decay, should exist to complete the J^P = $3/2^+$ baryon **decuplet**:



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QUARK MODEL

Constituent Quark Model (CQM)

The reality of quarks – achievements: validity of SU(3): the Ω^- (sss) (II)

It was therefore a major triumph for the scheme when the **omega-minus**, a baryon with the mass, charge and strangeness predicted, was **discovered in 1964** at BNL by N. Samios et al. using the 80-inch bubble chamber:

Production:

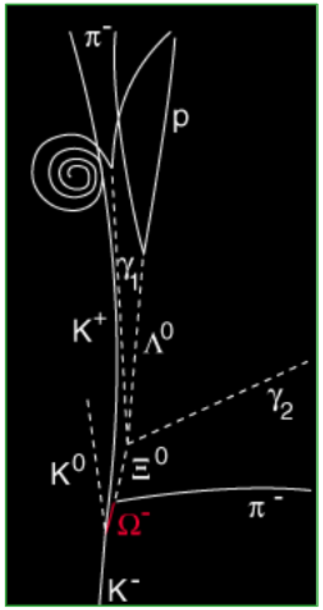
K^-	+	p	$\rightarrow$	Ω^-	+	K^+	+	K^0
$\bar{u}s$		uud		sss		$u\bar{s}$		$d\bar{s}$

Decay:

Ω^-	$\rightarrow$	Ξ^0	+	π^-
sss		uss		$\bar{u}d$

Ξ^0	$\rightarrow$	Λ^0	+	2γ
uss		uds		

Λ^0	$\rightarrow$	p	+	π^-
uds		uud		$\bar{u}d$



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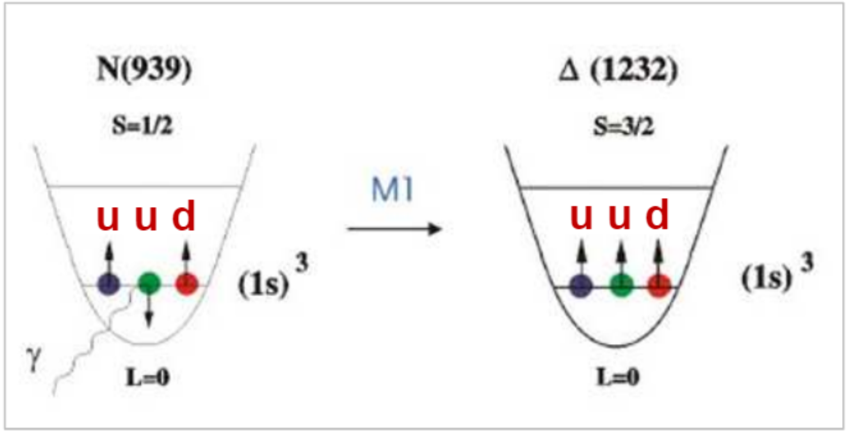
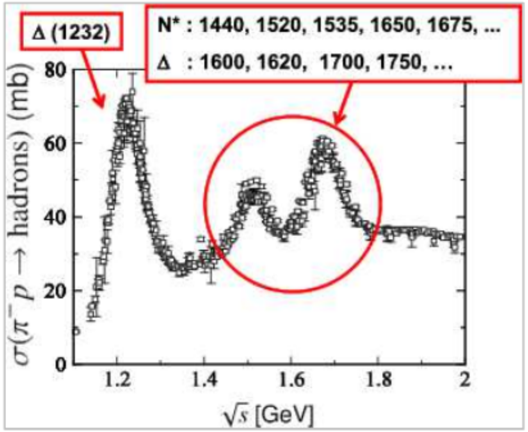
QUARK MODEL

Constituent Quark Model (CQM)

The reality of quarks – achievements: nucleon resonances (N*, Δ*, ...)

Example: The „Δ-resonance“ is interpreted as a **flip of one of the quark spins**, which „costs“ about 200 MeV of energy:





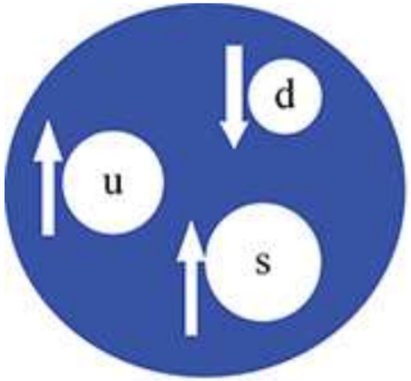
Higher-mass resonances (N* (I = ½), Δ (I = 3/2) …) are considered as higher quantum excitations (e.g. larger total angular momentum …)

QUARK MODEL

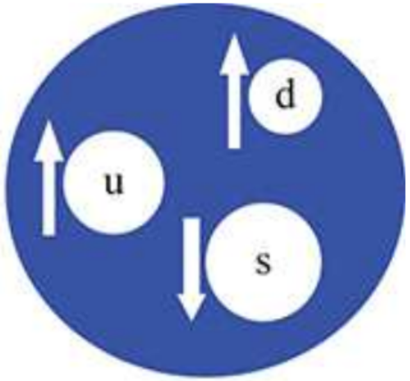
Constituent Quark Model (CQM)

The reality of quarks – achievements: spin direction in quarks

Example: Ground-state neutral hyperons (Λ, Σ) have both the quark content (u,d,s), but **different mass** – why?



Λ (1120 MeV/c²)



Σ (1193 MeV/c²)

→ Obviously (although the total spin of both is ½), it is important which of the 2 quark-spins are parallel

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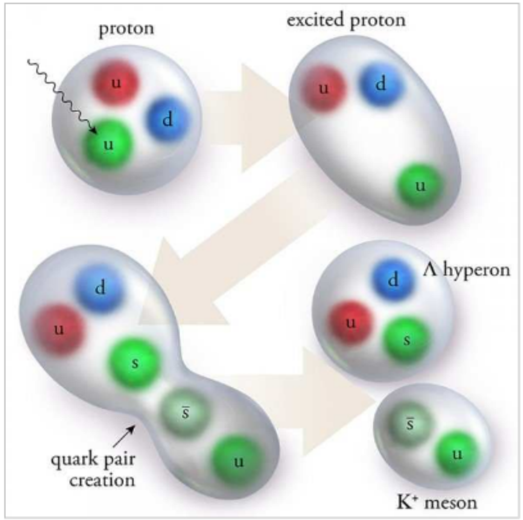
QUARK MODEL

Constituent Quark Model (CQM)

The reality of quarks – achievements: strangeness production

In the CQM, the **associated strangeness production** is easily understood in terms of an $s\bar{s}$-pair, which is produced and separated into two distinct final state particles

Example:



associated production

Note: A obvious question is why the **u-quark** is not flying away, but a $q\bar{q}$-pair must be produced

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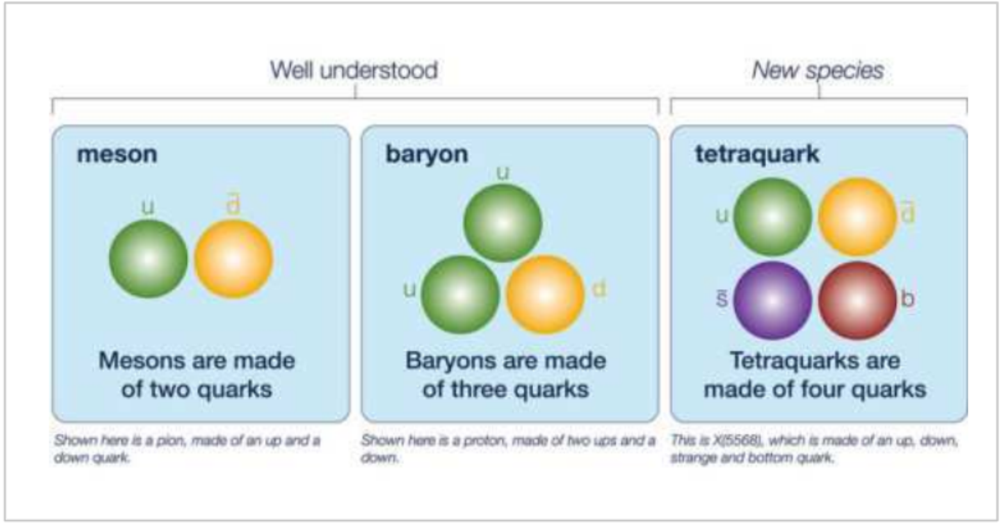
QUARK MODEL

Constituent Quark Model (CQM)

The reality of quarks – achievements: further quark bound-states

Besides **mesons** and **baryons**, there should be other hadrons

<u>Example</u>: tetraquark

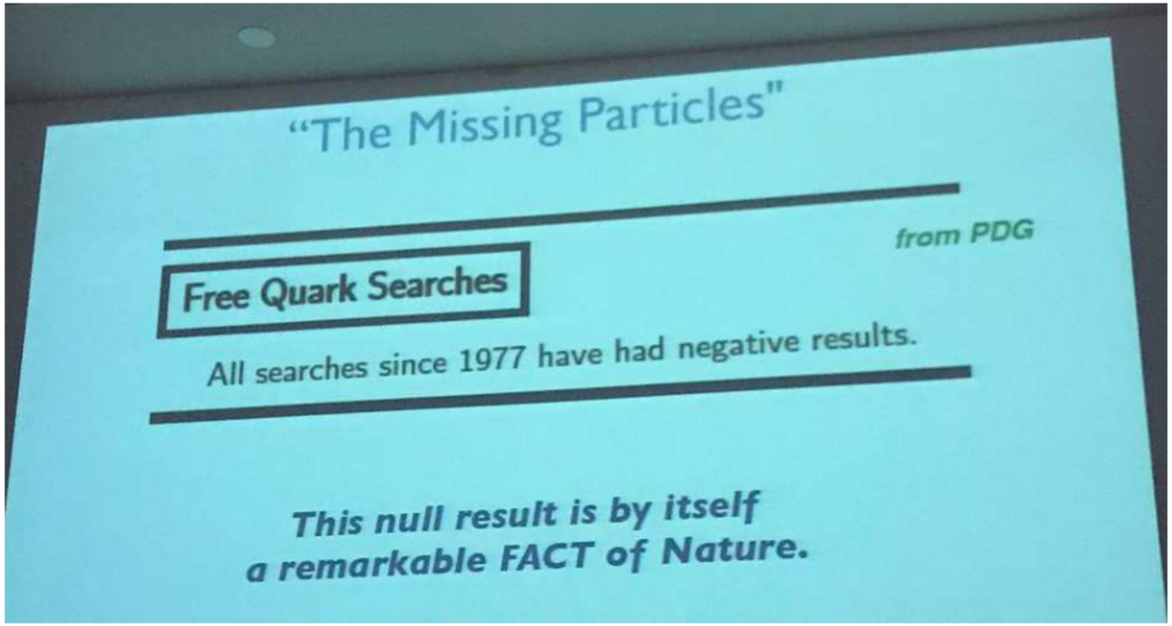


Recently discovered; not clear yet, whether genuine **4-quark state** or a **di-meson molecule**; also pentaquark (5q) and di-baryon (6q).

QUARK MODEL

Constituent Quark Model (CQM)

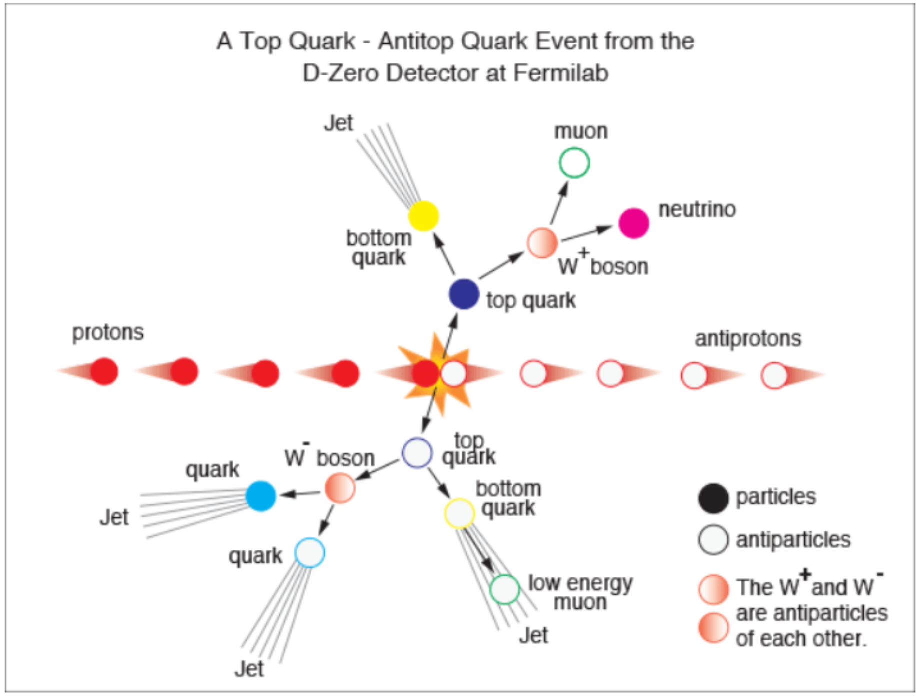
The reality of quarks – why no observation of free quarks?

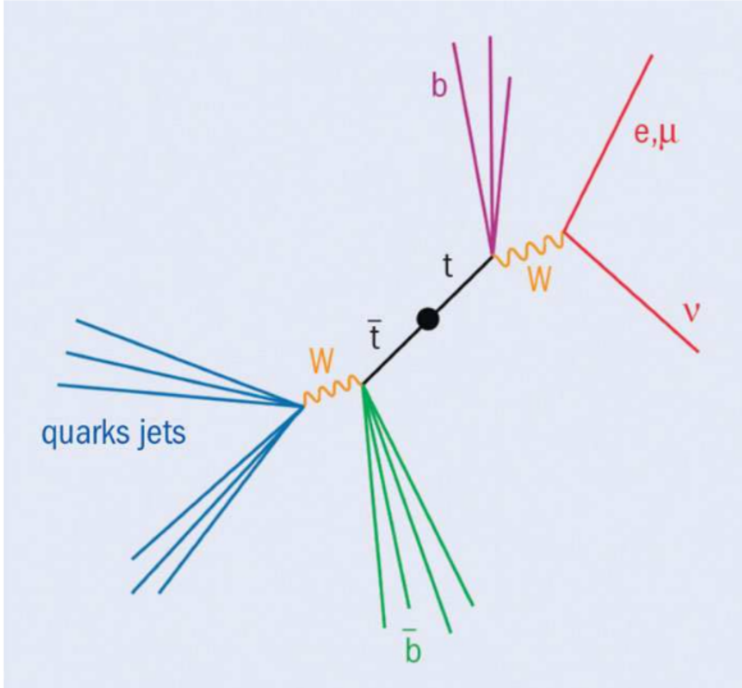


→ free quarks **cannot be observed** (quarks are „**confined**“ inside hadrons)

THE PARTICLES

That´s it for today





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