Particles and Universe

Lecture 3 Properties of particles

Maria Krawczyk, Aleksander F. Żarnecki

Faculty of Physics UW

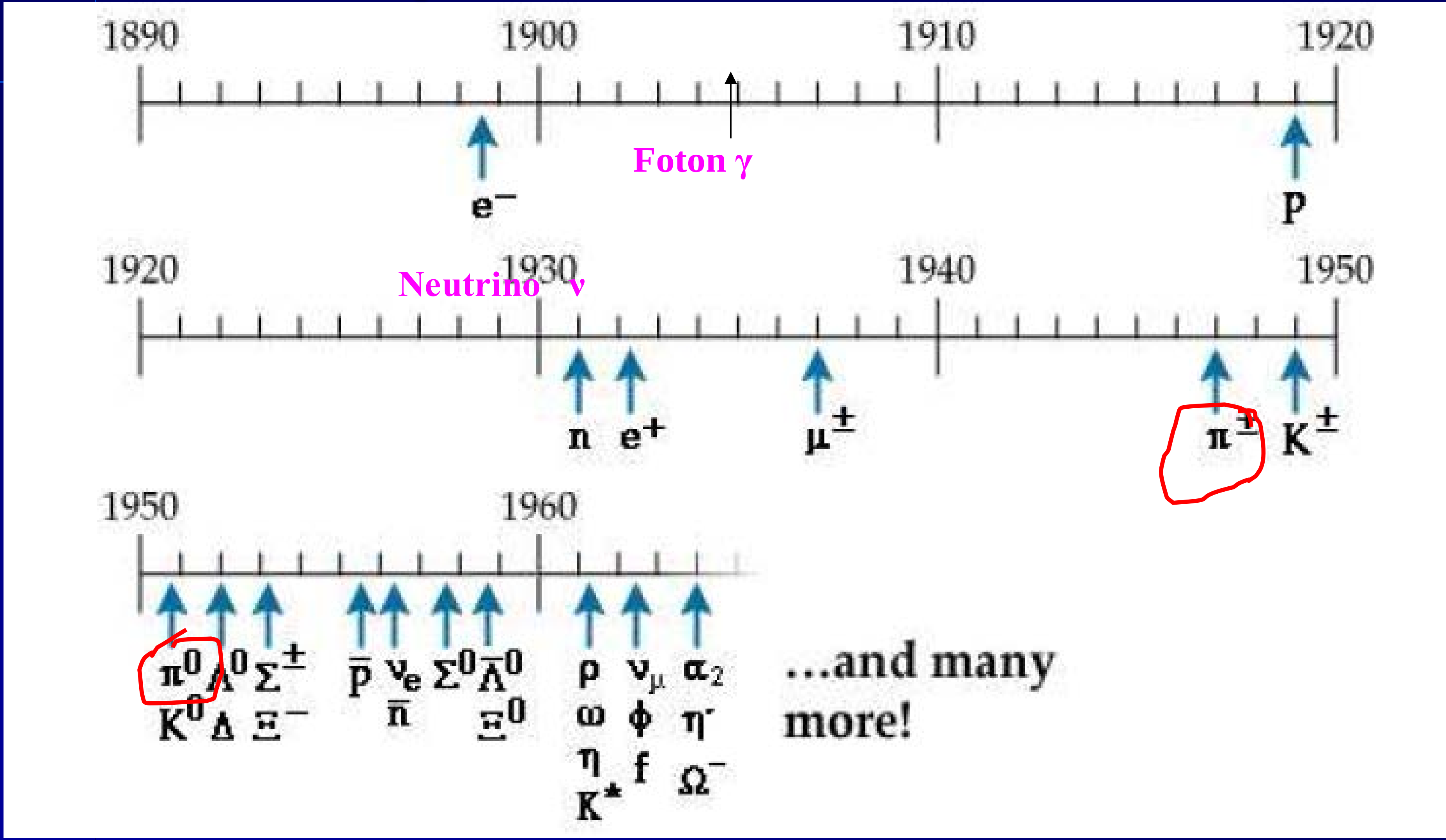
Interactions

Masses and lifetimes of elementary particles

Quarks: flavors and colors

Conservation laws and quantum numbers: baryon number and lepton numbers

Discoveries – flood of particles in 50-60 of XX



Zoo of elementary particles

Definition: elementary particle - object simpler that nucleus (exception the simplest nucleus H(hydrogen), proton, which is an elementary particle)

- Elementary particles – a lot(~1000) and various(Zoo):

  http://pdg.lbl.gov/

  various masses,
  various lifetimes (they can decay !),
  various electric charges,
  various types of interactions,
  various groups (multiplets), etc

Elementary particles can be compound (eg. proton) !
the simplest particles → fundamental particles

Particles of matter and particles of forces

Today we will mainly focus on the matter

Interactions

At macro and micro scales:

- gravitation – acts between all massive particles, only attraction, responsible for Sun system, large astronomical objects, etc.

- electromagnetism (e-m, el-mag) – electric charge of both signs, attraction and repulssion, atoms ...

In microworld in addition there are interactions:

- strong (nuclear) - bounding nucleons in nuclei (pions exchange) range 10^{-15} m
  strong fundamental (color) - between quarks (gluons exchange), range 10^{-15} m

-- weak (nuclear), eg. neutron decay, range smaller than for strong (pointlike interaction)
  weak fundamental between quarks and leptons (exchange of gauge boson W/Z), range 10^{-18} m

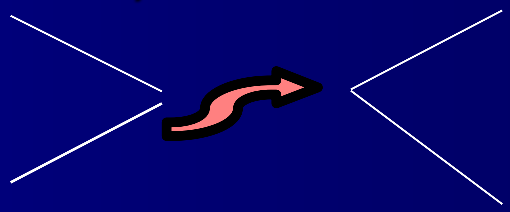
Range of interactions

$c = \hbar = 1$

- Interaction in microworld = emission and absorption of bosons (photon, W/Z, gluons..) → exchange of particles

- Range (Heisenberg, Yukawa) is related to the mass of exchanged particle (carrier of interaction)

$$x \sim 1/M$$



- gravitation and el-mag have an infinite range → graviton mass? photon mass = 0
- color (strong) int. : range ~ proton radius 10^{-15} m (despite of zero mass of gluons, confinement!)
- weak int. range 10^{-18} m, related to the mass of bosons W/Z ~80-90 GeV

Strength of interactions

- gravitation and el-mag are very different - gravitation is very weak (gravitation between two protons 10^{36} times weaker than el-mag)

- Strength's hierarchy at low* energies:

strong> electromagn.> weak > gravitation

** low energies: 1 GeV up to 100 GeV*

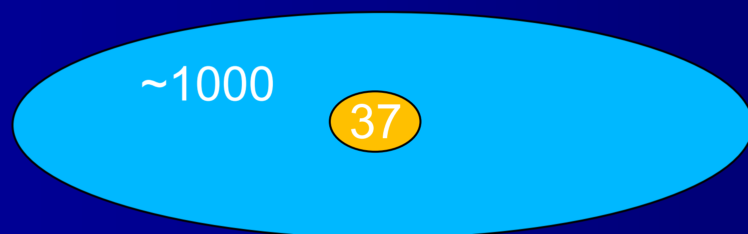
in the Standard Model – no gravitation!

- Parameter of strength of an elementary action

$\rightarrow$ coupling constant

Fundamental particles in the Standard Model

- Particles like proton *p* and neutron *n* are bound states of quarks. Fundamental particles of matter, ie quarks and leptons, have no inner structure
- Carriers of interactions: W+W- Z, γ and gluons - fundamental particles as well



number of particles

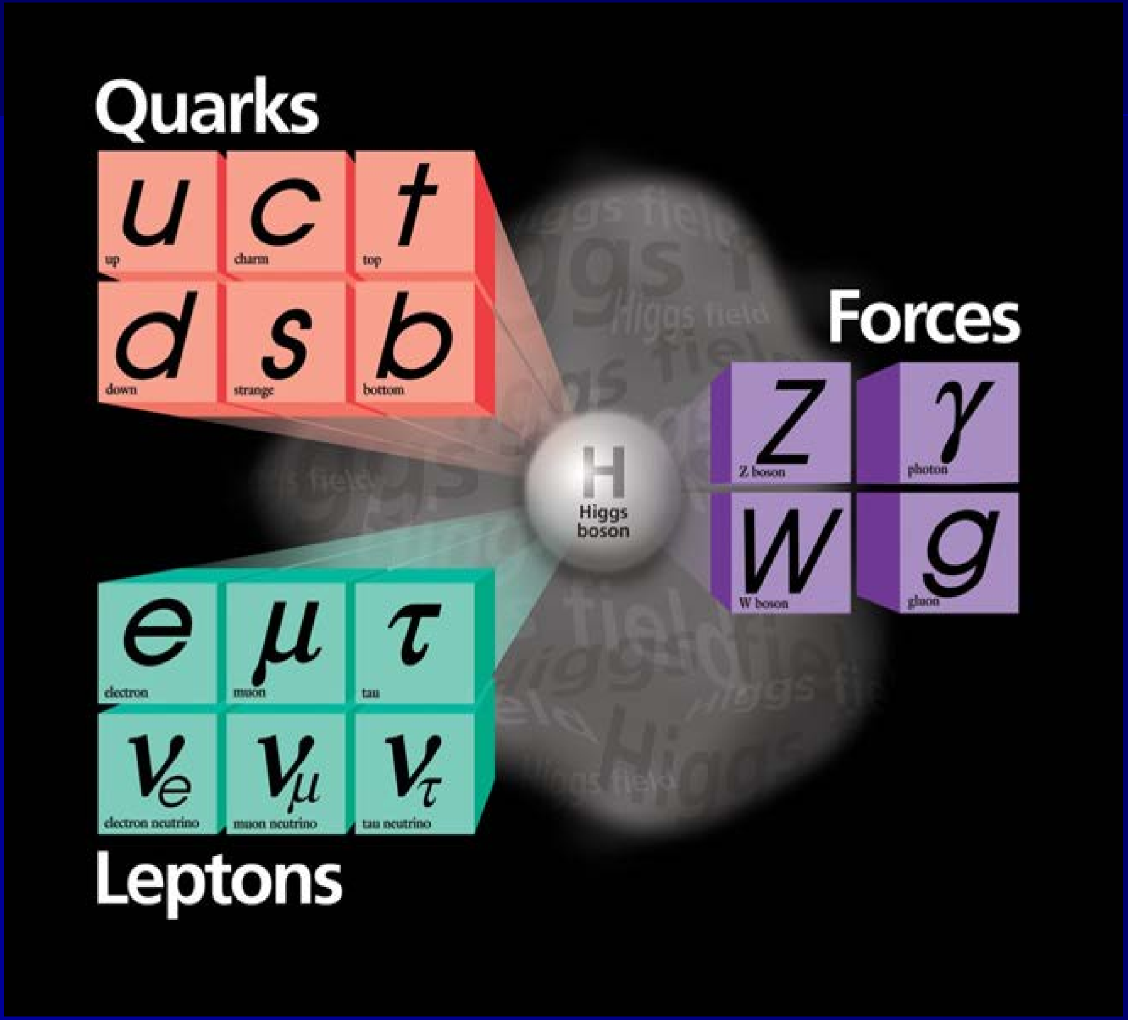
March 2017

- Physics of elementary particles

describes the fundamental level down to 10^{-18} m and energies up to 13 TeV

→ Standard Model

Fundamental particles



Properties of elementary particles

Masses

$E = mc^2$, mass unit = eV/c^2 - we usually neglect c^2 (c=1)

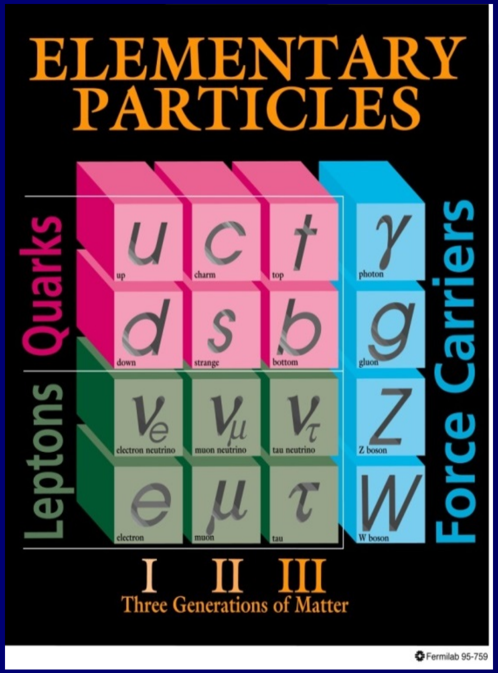
- Neutrino ~ 0 ?
  Electron ~ 0.5 MeV
  Pions (quarks and antiquarks u,d) ~140 MeV
  Proton, neutron (uud, ddu) ~ 1 GeV
  (highest mass ~172 GeV)
- Origin of mass ? – BEH mechanism! (2012)

- Is mass of a particle = sum of constituents' masses ?
  Not always - it is not so for nucleons, pions
  as their masses are coming from strong interaction
  $m = E / c^2$ (masses of u,d quarks negligible)

Masses of quarks and leptons

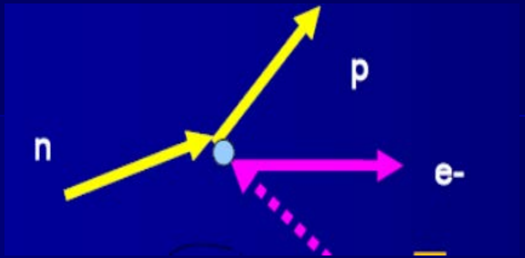
u	c	t
3 MeV	1.25 GeV	172 GeV
d	s	b
7 MeV	150 MeV *	4.5 GeV

ν_e	ν_μ	ν_τ
$<5.10^{-6}$ MeV	<0.27 MeV	<31 MeV
e	μ	τ
0.511 MeV	105.7 MeV	1.78 GeV



Decays

Decay of particles – spontaneous transformation of one particle into others



Eg. neutron decay (β decay)

neutron → proton electron plus ☺?

(lifetime of neutronu 886 s = 14,8 min)

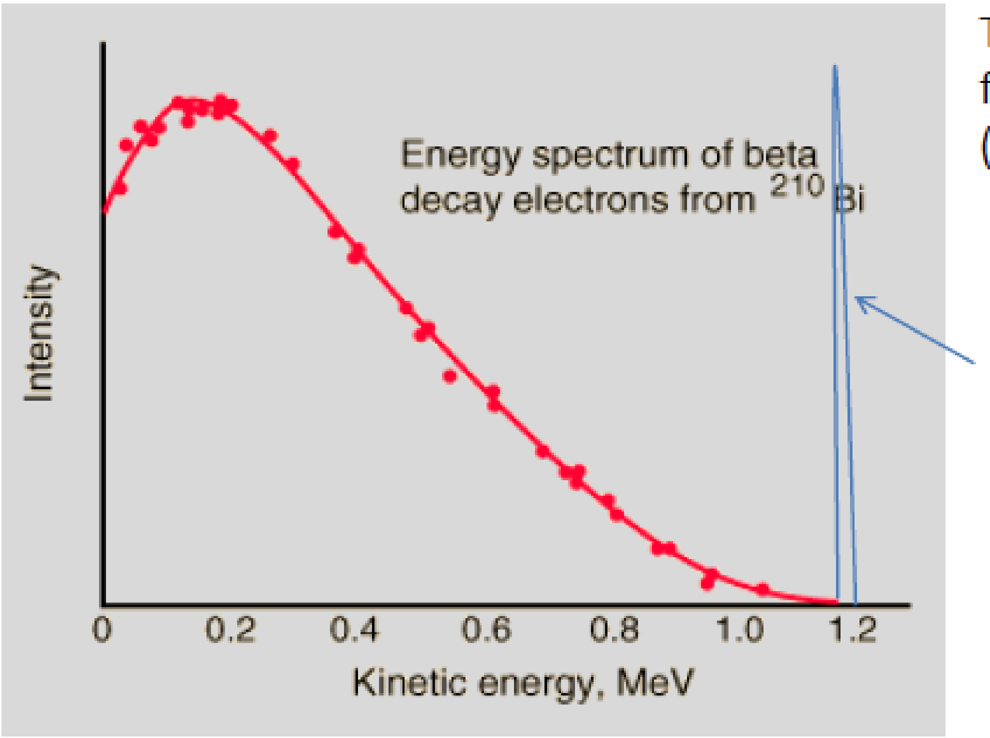
1914 J. Chadwick: in β decay RaB (^{214}Pb) continuous electron energy spectrum - this can not be decay into two particles (energy-momentum conservation)

1927J. Ellis confirms this finding..

…..

N. Bohr – maybe energy is not conserved?

Beta decay 1930



This experimental energy spectrum is from G.J. Neary, Proc. Phys. Soc. (London), A175, 71 (1940).

- **Problem:** nucleus (A,Z) thought to be A protons + (A-Z) electrons
- **Beta decay:** (A,Z) → (A, Z+1) + e- (two body decay, monoenergetic e-)

A. Mirizzi talk at DESY

Pauli 1930

Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

Abschrift

4th December 1930

Dear Radioactive Ladies and Gentlemen,

As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, how because of the "wrong" statistics of the N and ^{6}Li nuclei and the continuous beta spectrum, I have hit upon a desperate remedy to save the "exchange theorem" of statistics and the law of conservation of energy. Namely, the possibility that there could exist in the nuclei electrically neutral particles, that I wish to call neutrons, which have spin and obey the exclusion principle and which further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass (and in any event not larger than 0.01 proton masses). The continuous beta spectrum would then become understandable by the assumption that in beta decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and the electron is constant...

From now on, every solution to the issue must be discussed. Thus, dear radioactive people, look and judge. Unfortunately I will not be able to appear in Tübingen personally, because I am indispensable here due to a ball which will take place in Zürich during the night from December 6 to 7….

Your humble servant,

W. Pauli

Pauli also left in his diaries: "Today I have done something which no theoretical physicist should ever do in his life: I have predicted something which shall never be detected experimentally."

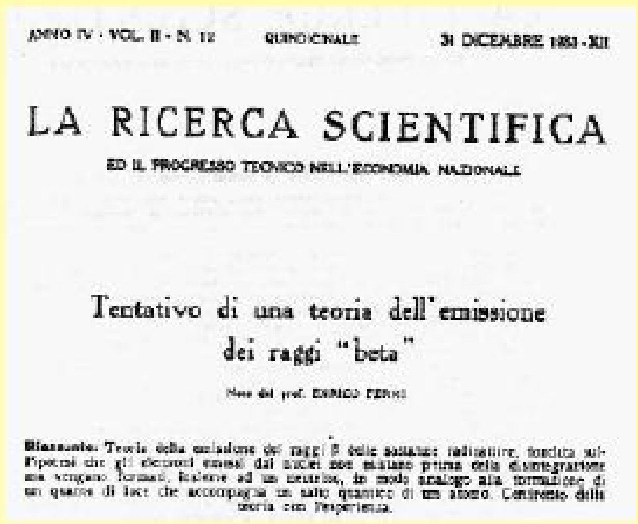
Neutrino and neutron (1932)

Chadwick discovers neutron (1932):

- Mass of neutron similar to mass of proton: not Pauli's particle!

- Fermi introduces name **"neutrino"** (ν_e), which is different to neutron, and beta decay is decay of neutron:

$$n \to p\, e^- \, \bar{\nu}_e$$


ANNO IV - VOL. II - N. 12 QUINDICINALE 31 DICEMBRE 1933 - XII

LA RICERCA SCIENTIFICA

ED IL PROGRESSO TECNICO NELL'ECONOMIA NAZIONALE

Tentativo di una teoria dell'emissione dei raggi "beta"

Fermi 1933

theory.. weak int !

Particle decay

Probability to survive (before decaying)

$$P(t) = e^{-t/(\gamma\tau)}$$

τ = the mean lifetime (lifetime) of the particle (at rest)

(*reduction e-times , e = 2,7*)

(half lifetime if *reduction 2-times*)

$$\gamma = \frac{1}{\sqrt{1 - v^2/c^2}}$$

the Lorentz factor

Decay rate $\Gamma = 1/\tau$

total, if various decay modes (channels), $\Gamma = \Sigma\Gamma_i$

Lifetime of particles

- Lifetime of the particles – exponential decay

(lifetime → *1/e (e= 2.7) particles remain)*

Universe 13,7 mld years

- Lifetime (τ)

  - stable particles (the most stable):

  <u>electron:</u> $\tau > 4.6\ 10^{26}$ y i <u>proton:</u> $\tau > 10^{30}$ y

  - short lived: $\sim 10^{-24}$ s

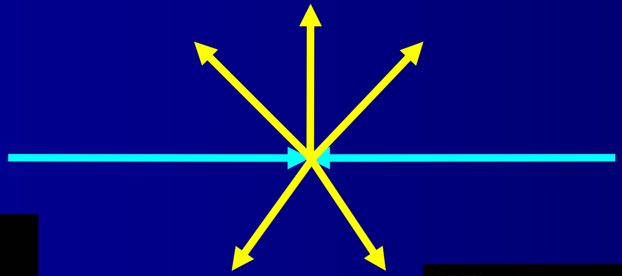
  - long lived : $10^{-6} - 10^{-8}$ s

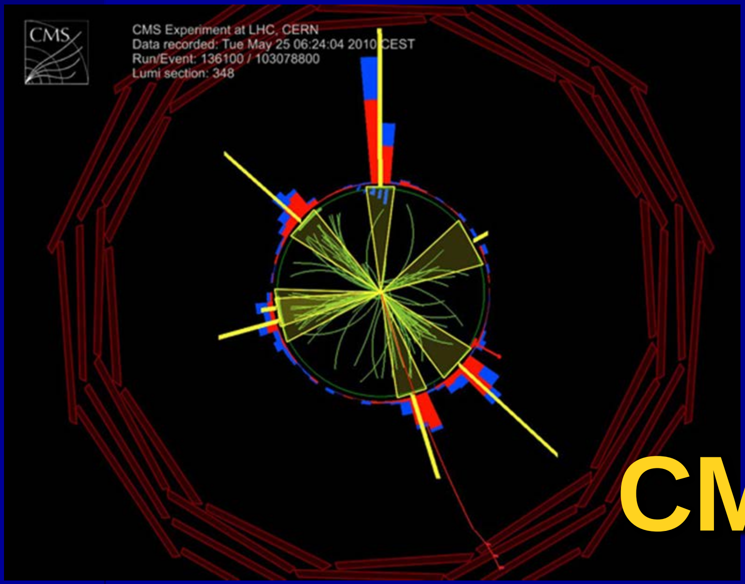
  (eg. mion 2 10^{-6} s, charged pions 2.6 10^{-8} s)

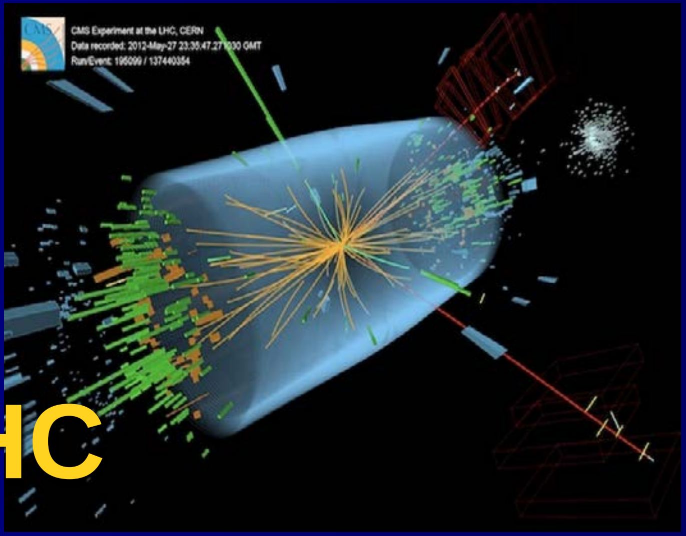
- Probablility of decay small means lifetime long and vise versa (strong int. → short lifetime)

Production of particles

- In collision of particles   two, three,… N particles can be produced – in agreement with energy and momentum conservation



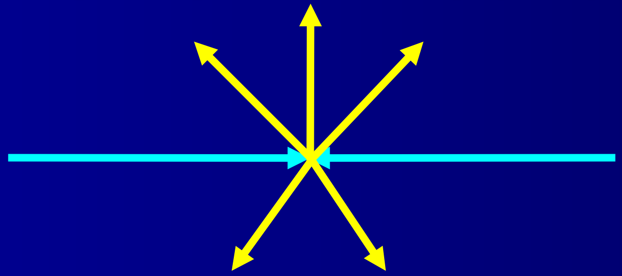




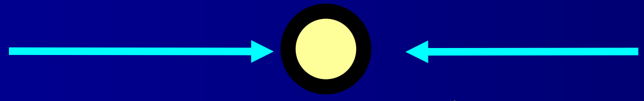
CMS at LHC

Production of particles

- In collision of particles two, three,… N particles maybe be produced – in agreement with energy and momentum conservation

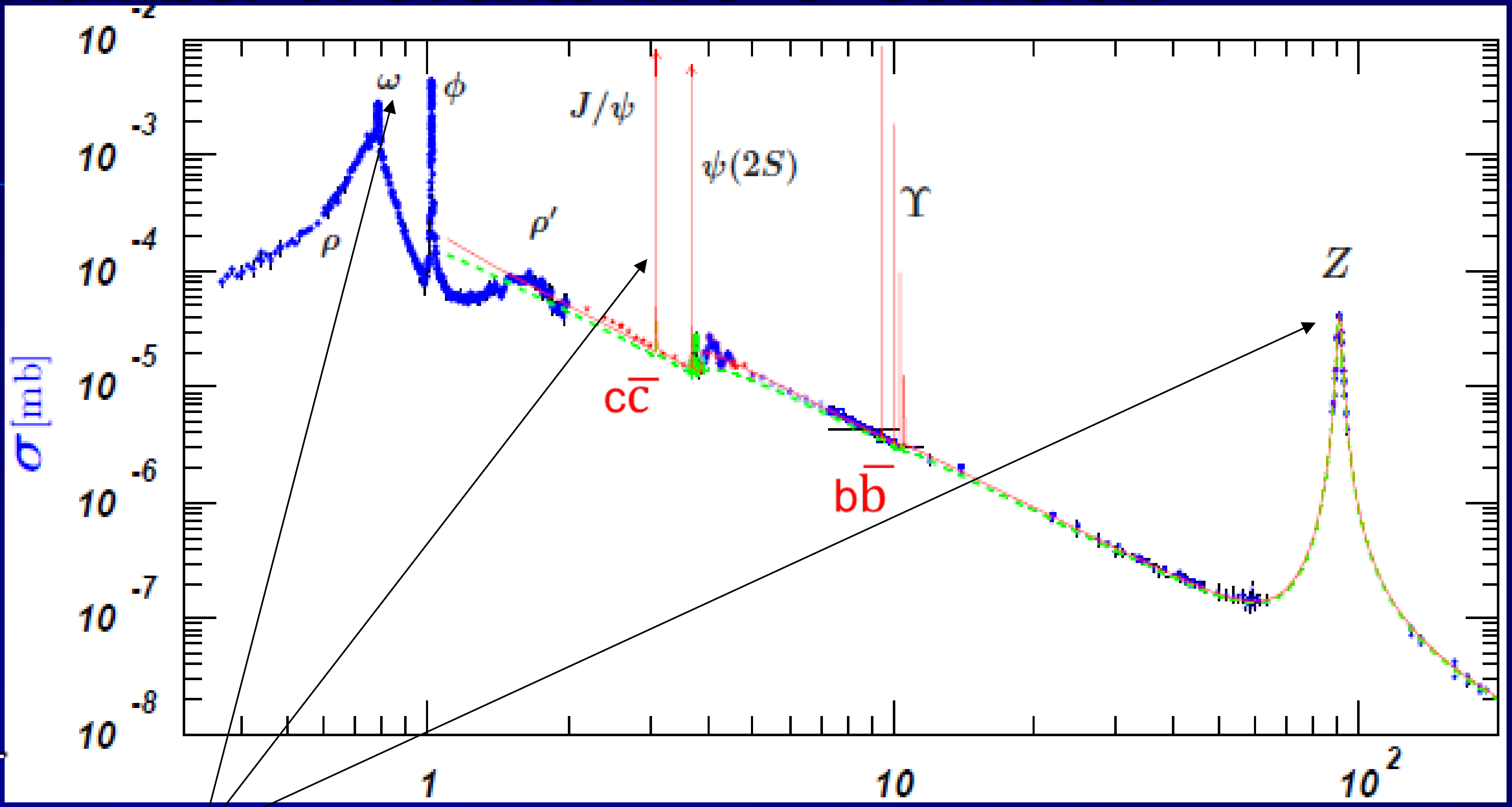


- However energy of collision can be transfered totally into a rest energy of one particle according to $E=mc^2$ - resonanse production :



discovery of many particles

Number of events in e+e- collision



energy of collision (GeV)

Resonances:

collision energy (GeV) = mass of particle

width of resonance line $\Gamma = 1/\tau$ *(in a half of height)*

$$\Delta E \, \Delta t \geq \hbar/2$$

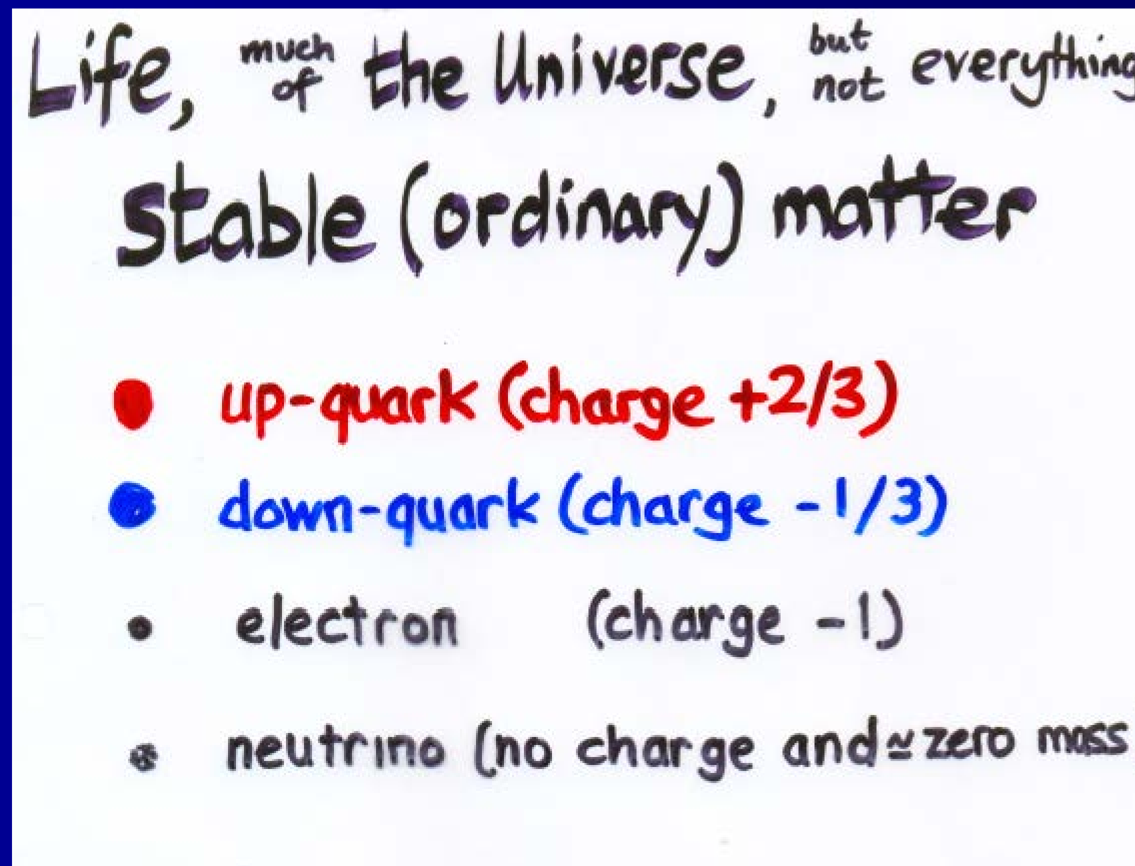
Antiparticels (antimatter)

- Antipartipartiles are particles which may differ from their „partner
by some properties – masses and lifetimes the same!
- Electron i positron – a particle-antiparticle pair (which one is a particle – a convention). They differ by a sign of el. charge (positr is positive..).
Electron discovered in 1897, while positron in 1932
- Existence of antiparticles - a law of Nature.
Theoretical prediction based on symmetry of equation
→ P. Dirac 1928
- Particle and antiparticle may interact violently. A particle-antiparticle pair may disappear (annihilation) or appear (creation)
- Particle can be its own antiparticle (*must be neutral*)
- In Universe almost only matter !!!

Notation: eg. quark u and antiquark $\bar{u}$

Types (flavors) of quarks

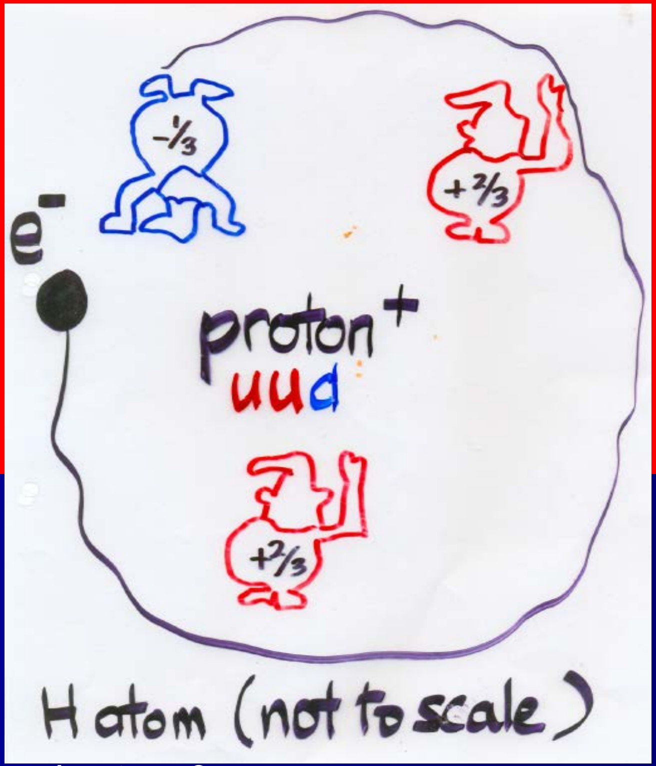
Ordinary matter and ordinary quarks



F. Close

Ordinary quarks u (up) i d (down)

The most populated quarks
in the most populated elementary
particles



from F. Close
lecture at CERN

H atom
(not to scale!)

a miracle of neutrality

electron
balances
uud

hint of unification

Mass difference of quarks u and d

- Proton (uud) i neutron (ddu)

  Masses: m_p=938.3 MeV , m_n=939.6 MeV,

  Δ m=1.3 MeV

  → difference of mass for quarks d and u; other measurements tell us

  mass of u, d – few MeV *(light quarks)*

- Neutron decay (fundamental level) → decay of quark d to quark u (+ electron + antineutrino el.)

  Quark d heavier and decays to a lighter quark u ..

Proton is stable, while neutron not, - very good for us:

- Sun (neutron decay)
- Water exists (proton)

Neutron decay $n \rightarrow p\, e^- \, \bar{\nu}_e$

and ~~$p \rightarrow n\, e^+ \, \nu_e$~~

However question - why proton is stable…?
What about other decays of proton?

Isospin (u,d)

- Heisenberg – 1932 (symmetry of nuclear int.)
- isotopic spin (p,n dublet) -2 states of nucleon
- formalism like for spin ½ (two states ± ½)

- so, isospin ½ for nucleon $I = 1/2$, $I_3 = \pm 1/2$
- for pions - 3 states (triplet)

isospin $I = 1$, $I_3 = 1, 0, -1$

So, p = uud, n = ddu

$\pi^+ = u\,\bar{d}$ $\pi^- = d\,\bar{u}$ $\pi^0 = u\,\bar{u} - d\,\bar{d}$

Relation
electric charge <–> isospin?

Electric charge Q

$$Q = I_3 + \tfrac{1}{2} Y$$

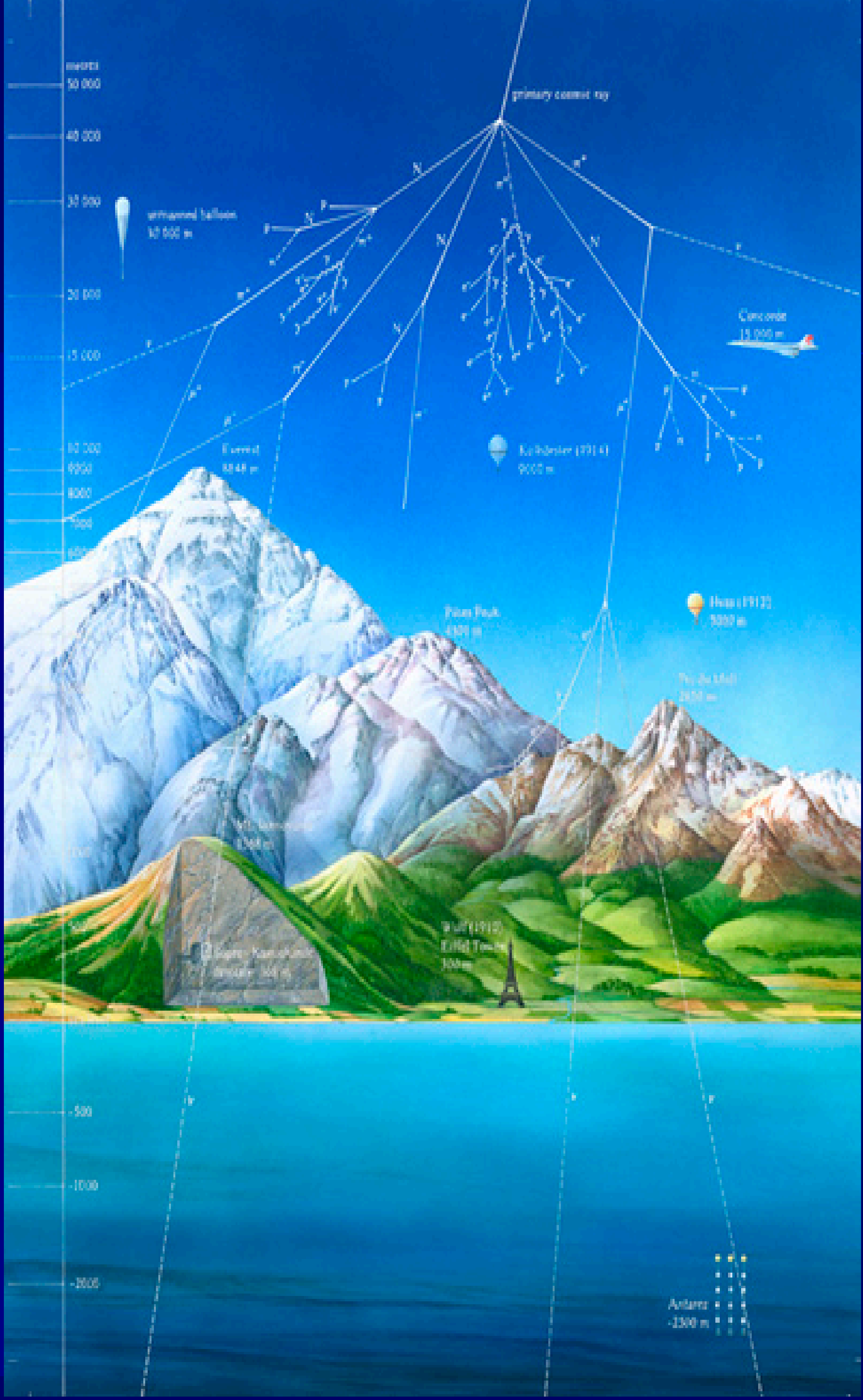
Y – hypercharge

Y= S + B *(see below)*

Strange particle

Strange particles were discovered in cosmic rays ~ 1950 r

later
in laboratory
- first K (kaon)



Strange particles

- Life time longer than for „similar" particles
- produced in pairs in collision of nucleons

$$\Lambda \quad \rightarrow \quad p + \pi^-$$
$$\tau \approx 3 \cdot 10^{-10} s$$

$$\Delta \quad \rightarrow \quad p + \pi^-$$
$$\tau \sim 10^{-23} s$$

To describe new „category" of particles new quantum number S (strangeness) has been introduced

Strangeness

Strange particle $S \neq 0$; observed S = 1,2,3;-1.-2,-3

nucleons= proton, neutron S=0

pions S=0

For a system of particles stangeness adds (additivity); in processes with nucleons, pions it is conserved:

S_initial = S_final.

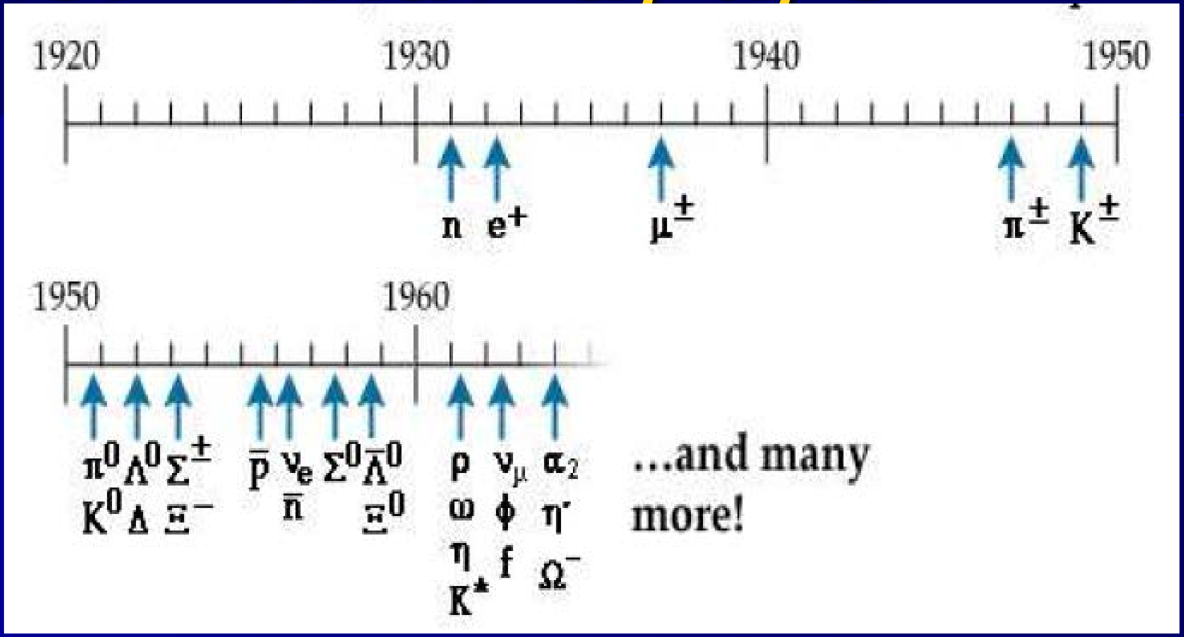
On fundamental level: quark s (S = -1).

The lightest elementary particle contains one strange quark - kaon K (mass 500 MeV):

$K^+ = u\bar{s}$, $K^- = \bar{u}s$, $K^0 = d\bar{s}$; Λ(1116 MeV)=uds

$\rightarrow$ mass s quark ~150 MeV

Quark Model – with u, d, s



In 60-ties XX (multiplets)

Gell-Mann and Zweig:

quark hypothesis

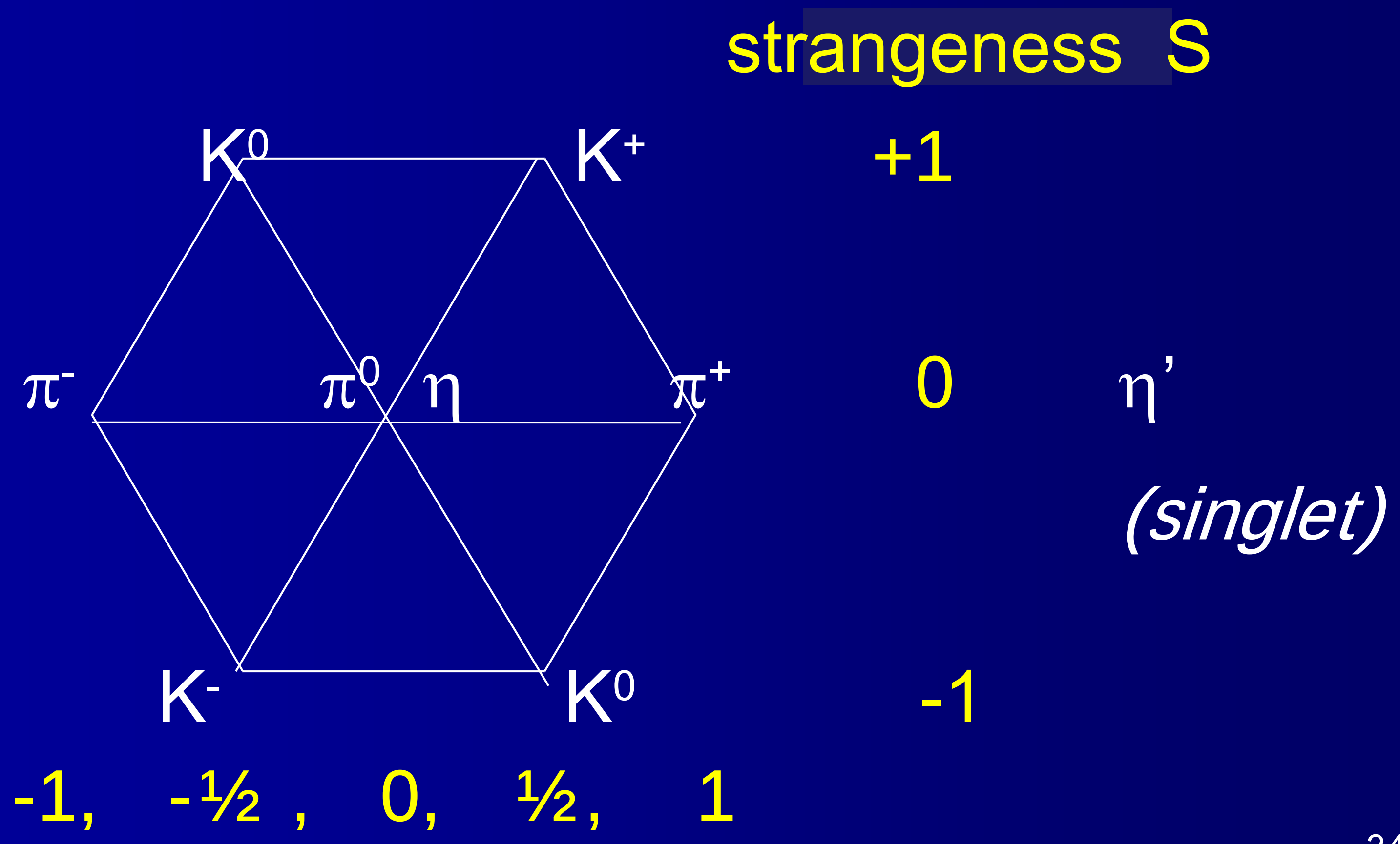
$q\ \bar{q}$ (mesons)

qqq (baryons)

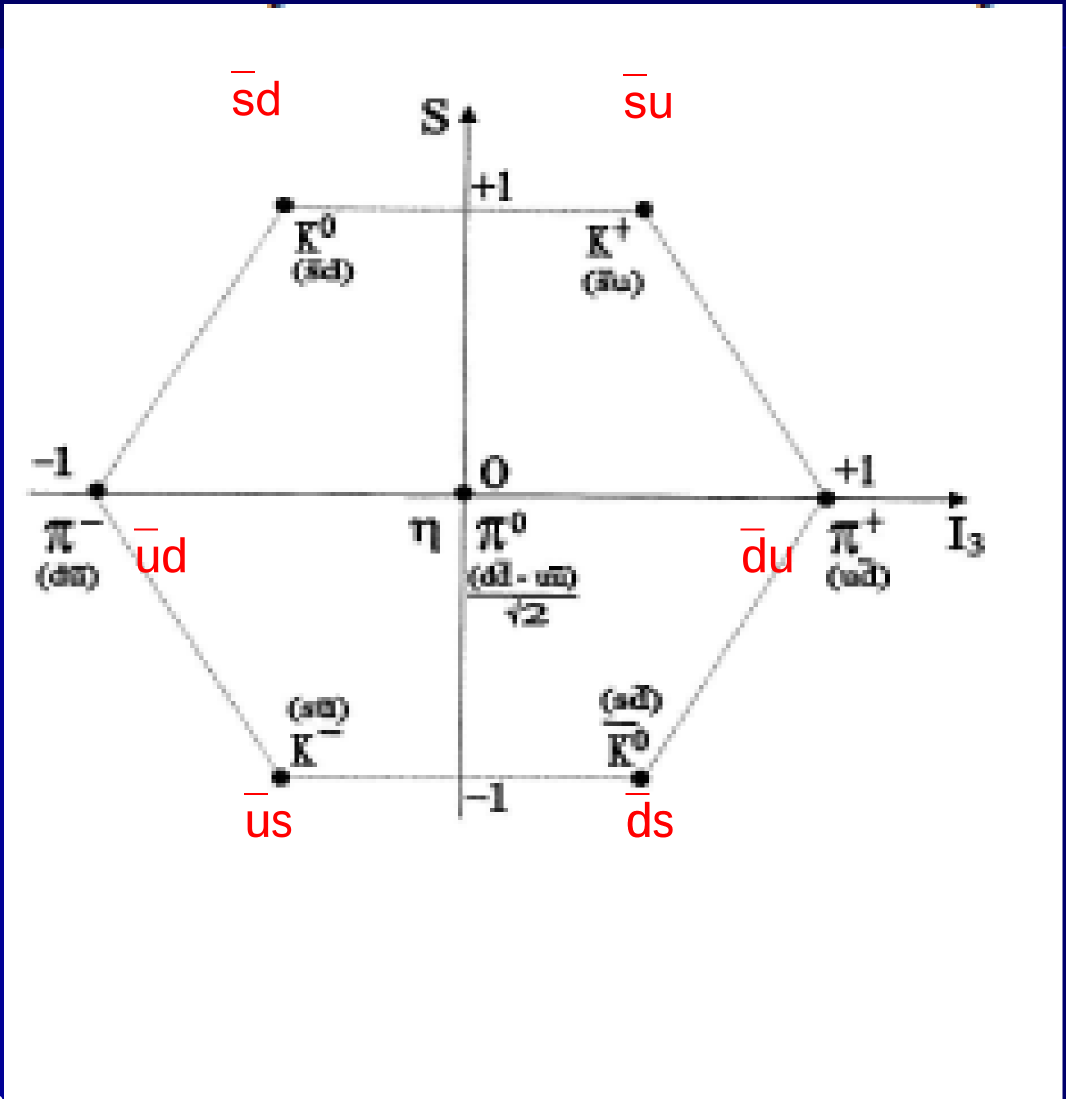
Quark diagrams

Octet: mesons K, π i η

masses~500 MeV



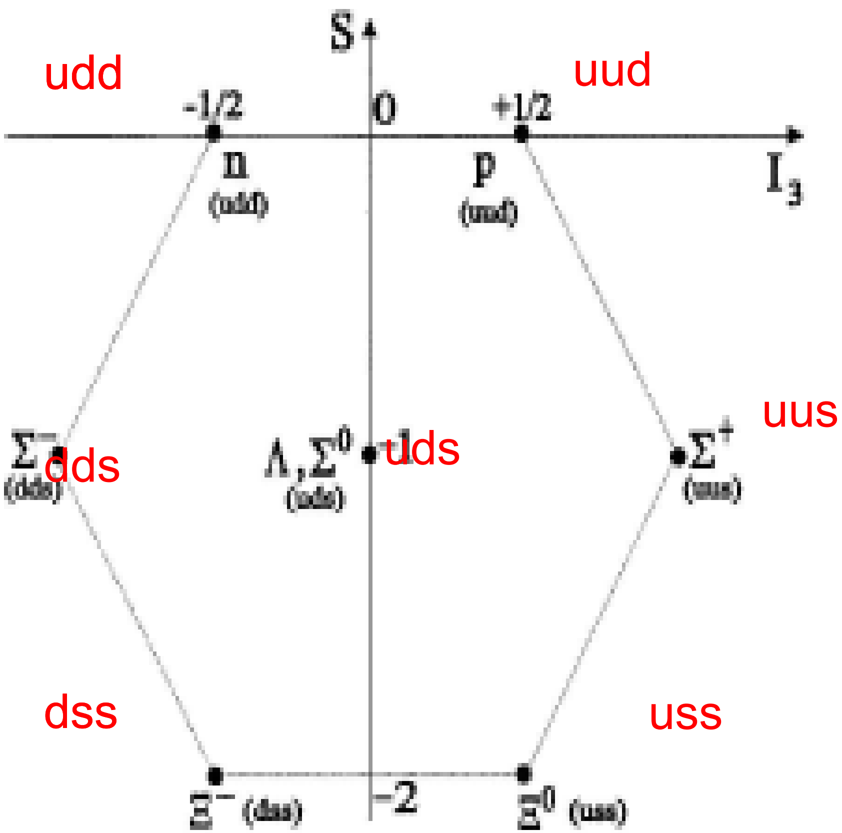
Octet ($q\bar{q}$)



Masses 140- 500 MeV

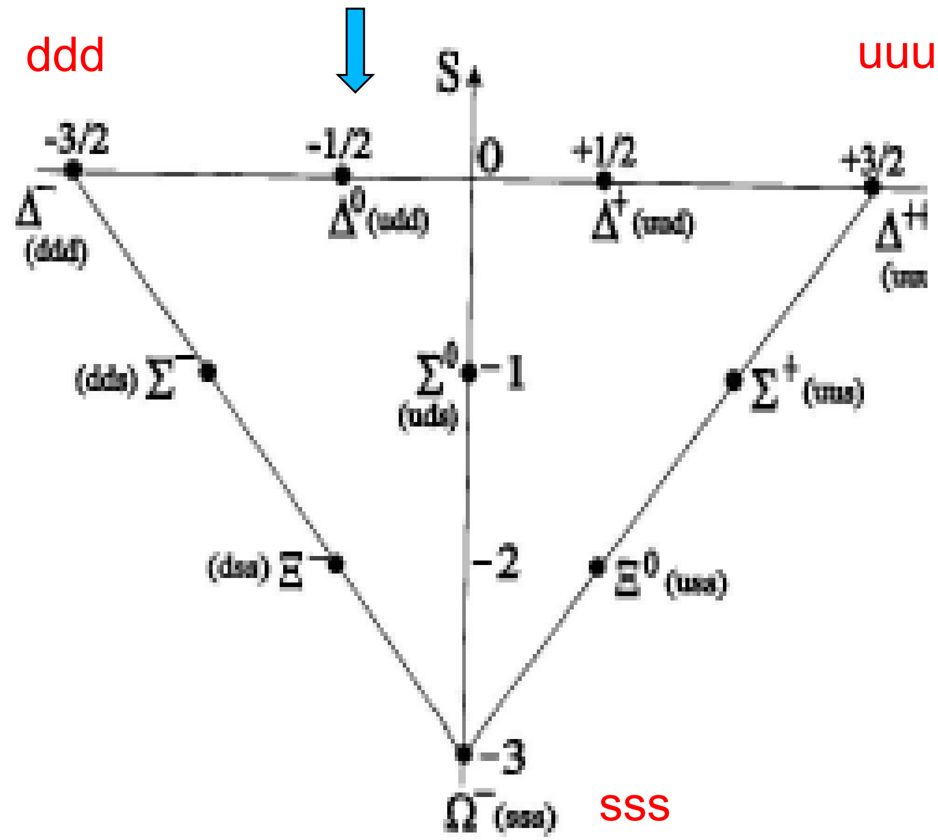
Multiplety cząstek qqq

octet



Mass around 1 GeV

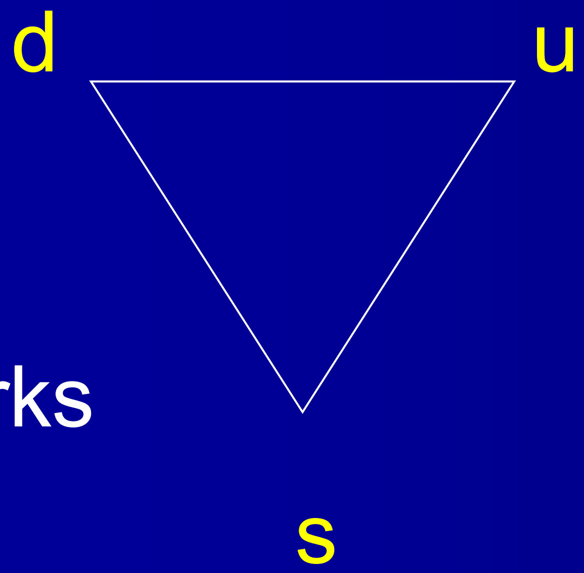
decouplet



Mass around 1.7 GeV

Quarks Model: quarks – fundamental representation of SU(3)_flavor

quark diagrams

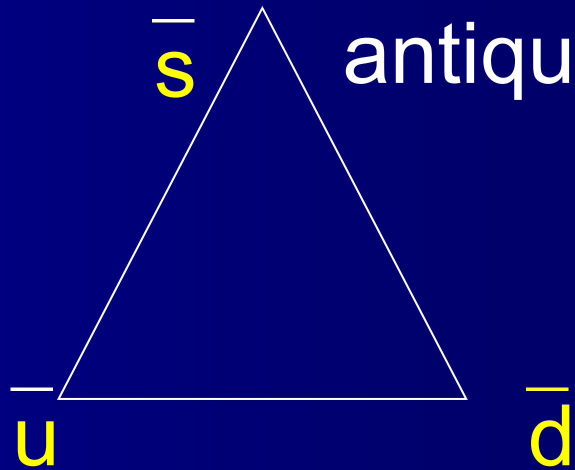


$3 \times 3 \times 3 = 1+8+8+10$

$3 \times \bar{3} = 1 + 8$

quarks

antiquarks



Heavy flavors

Other phenomena – a need to introduce other flavors

(additive quantum numbers):

1974 (charm) C → quark c

1977 (beauty, bottom) B* → quark b

1995 (true, top) T* → quark t

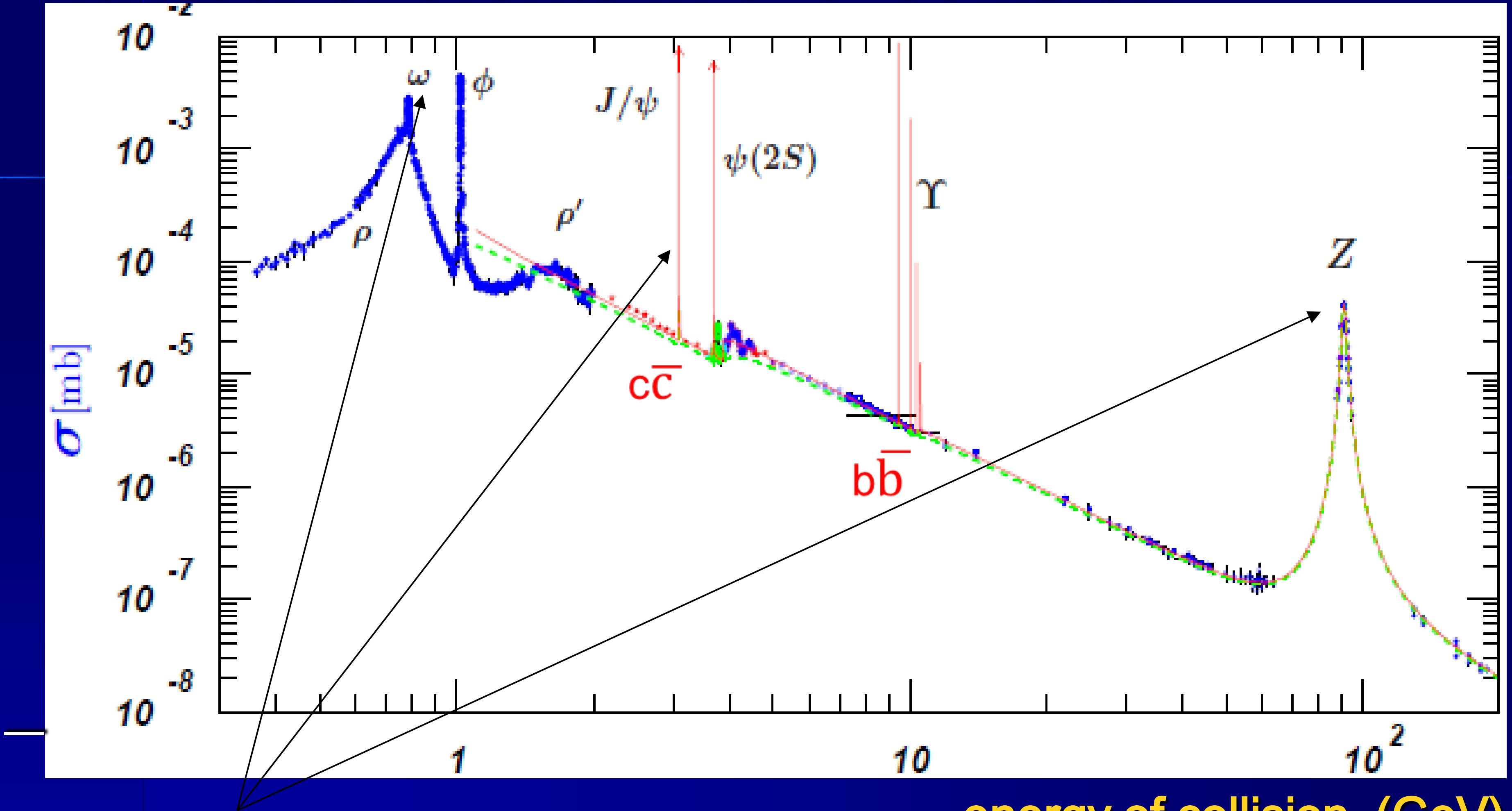
- Particle J/ψ mass 3 GeV. In collision e+e- very narrow resonans. Why so narrow ? Does contain new type of quarks ? Charmonium $J/\psi = c\,\bar{c}$ (C=0). There are charmed particles with C=±1, $D^+ = c\,\bar{d}$. Mass of c quark ~ 1.5 GeV (half of mass J/ψ).

http://capp.iit.edu/hep/bquarkfound.html

- Particle Υ (9.5 GeV) - bound state $b\,\bar{b}$ (B*=0) - bottonium. Particles with B*≠0 exist . Quark b mass ~ 4.5 GeV

- Quark mass t ~ 172 GeV → there are no bound state.

Number of events in e+e- collision



energy of collision (GeV)

Resonances:

collision energy (GeV) = mass of particle

$\Delta E \, \Delta t \geq \hbar/2$

width of resonance line Γ = 1/ τ *(in a half of height)*

Particle Data Group

http://pdg.lbl.gov/

CHARMED MESONS
$(C = \pm 1)$

$D^+ = c\overline{d}$, $D^0 = c\overline{u}$, $\overline{D}^0 = \overline{c}\,u$, $D^- = \overline{c}\,d$, similarly for D^*'s

CHARMED, STRANGE MESONS
$(C = S = \pm 1)$

$D_s^+ = c\overline{s}$, $D_s^- = \overline{c}\,s$, similarly for D_s^*'s

BOTTOM MESONS
$(B = \pm 1)$

$B^+ = u\overline{b}$, $B^0 = d\overline{b}$, $\overline{B}^0 = \overline{d}\,b$, $B^- = \overline{u}\,b$, similarly for B^*'s

BOTTOM, CHARMED MESONS
$(B = C = \pm 1)$

$B_c^+ = c\overline{b}$, $B_c^- = \overline{c}\,b$, similarly for B_c^*'s

Also BOTTOM, STRANGE MESONS...

Baryons…

BOTTOM BARYONS

$(B = -1)$

$\Lambda_b^0 = u\,d\,b$, $\Xi_b^0 = u\,s\,b$, $\Xi_b^- = d\,s\,b$, $\Omega_b^- = s\,s\,b$

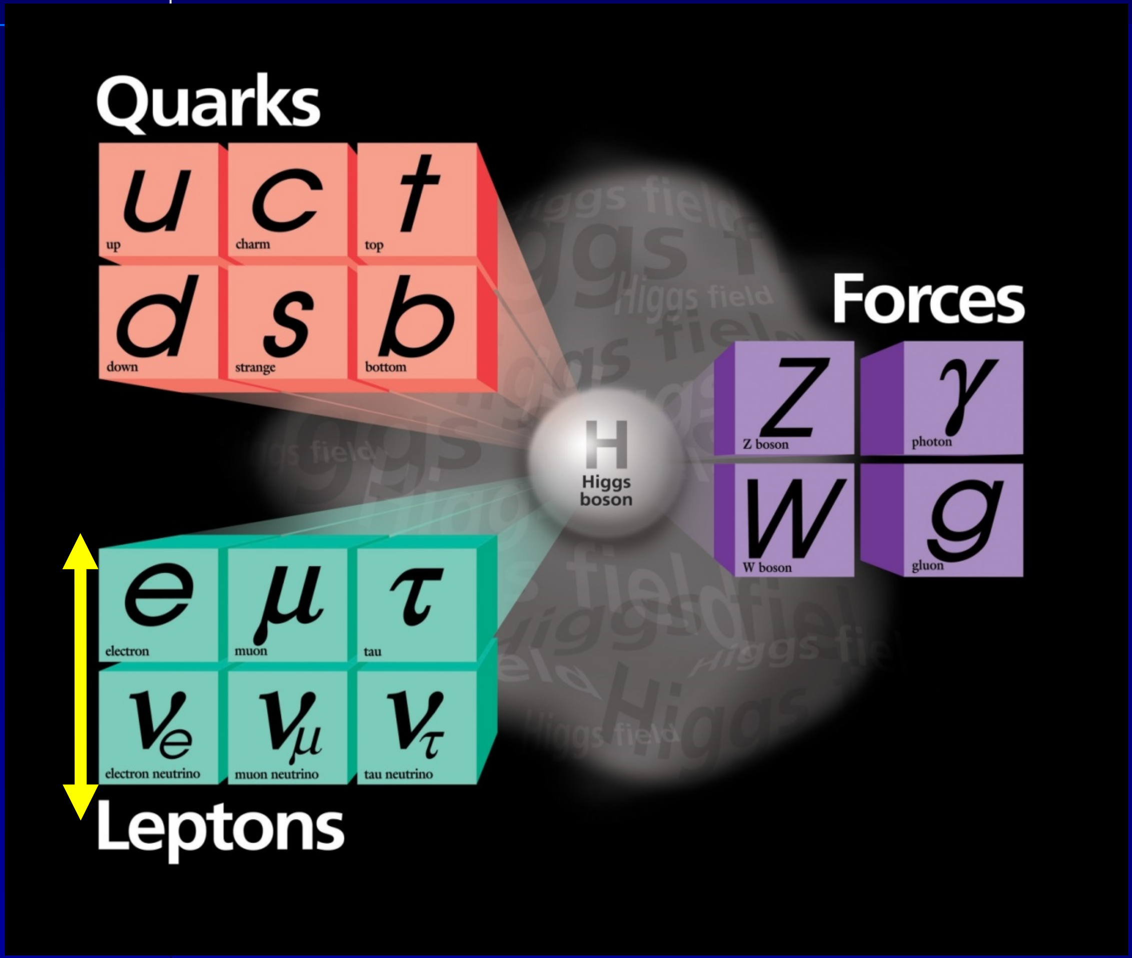
etc

Particle Data Group

u,d,s + c,b,t

- Multiplets with quarks uds –
  mass of these particles close
  (differences below 1 GeV)
- Multiplets with udsc ?, udscb ?
  differences larger
  symmetry broken...
- Quark t too heavy to make a bound state

Carriers of flavors are quarks



In this table
quarks and leptons
are in doublets

Why?

This is dictated
by weak interaction
eg. in beta decay :
d → u,
neutrino → e

Exotics (not q qbar, qqq)

http://www.wired.com/2014/09/tetraquark-quantum-feud/

- New type of hadrons

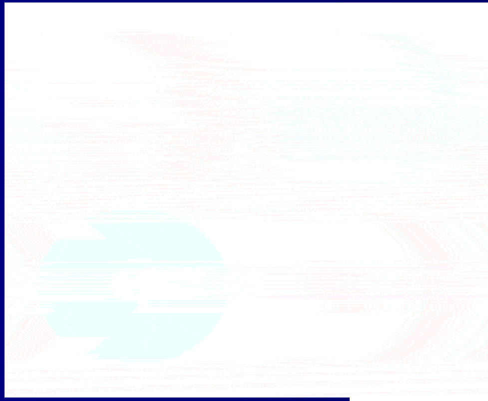
- X(3872)
- Zc(3900)
- Y(4140)

four-quark system

$c\ \bar{c}\ d\ \bar{u}$

tetraquark

How to get white hadrons?



Conservation laws and other quantum numbers

Energy-momentum conservation

- In any process (collision, decay) a total energy :

  energy_final = energy_initial

For free particles (3-momentum $\bar{p}$, m- mass at rest)

$$E^2=(\bar{p}c)^2+(mc^2)^2$$

(often we put c=1)

In relativistic theory 4-vector (E, $\bar{p}$) is conserved

- Particle with mass m has at rest energy $E=mc^2$ and massive particles have more chances to decay

- Energy, momentum and angular momentum are conserved

Charge conservation

- Electric charge is conserved in Nature

  that why eg. proton can not decay into electron (plus antyneutrino)

- Charge of elementary particles – only in definite portions (quanta) → charge quantisation (charge quantum number)

- If in some units el. charge of electron = -1, than el. charge of protonu = +1,

  (then for *u* quark = 2/3, for *d* quark -1/3!)

- Observed elementary particles have el. charge - multiplication of el. charge of electron, so

  n = 0, 1, 2...or -1,-2,..(n = 0 neutral particle)

Baryonic quantum number B

- Proton decay is not forbidden by el. charge conservation, nor energy conservation, eg

  $p \rightarrow$ e+ neutrino el. – what wrong?

  It seems that p and leptons are not „relatives"

- New idea: Stückelberg (1938r)

  New quantum number to count nucleons (conserved)
- Tests of this hypothesis:

  eg.lack of neutron decay → e-e+?

  (baryon, z greckiego ciężki)

New (additive) quantum number B: baryonic number

proton=+1,neutron=+1 ($\bar{p}$, $\bar{n}$ = -1); baryons B ≠ 0

B is conserved in Nature

Hadrons = bound states of quarks

Hadrons

Baryons ($B \neq 0$)
3 quarks

Mesons ($B=0$)
quark-antiquarks

Hadron- gruby, mocny

np. piony

mezon - pośredni

Quantum numbers of quarks cd.

- Baryonic quantum number B for p, n = +1

  Quarks have B = 1/3, antiquarks B = - 1/3

- Electric charge for p = +1 and for n= 0

  quarks q = 2/3 lub -1/3

  antiquarks $\bar{q}$ = -2/3 lub 1/3

  np.. u = 2/3, d= -1/3

- Flavor quantum numbers

Color – new quantum number

flavor (u,d,s...) – classification/structure of particles
color – dynamics of interaction between quarks

- all quarks in 3 color states
- gluons – double color (color and anticolor , eg. gluon red- antiblue), 8 different gluons
- photon „feels" el. charge (→ *quantum electrodynamics*), gluon – color (color charge) (→ *quantum chromodynamics*)
- Free color charge is not observed → there are no free quarks, they are confined permanently

...

Confinement of color ?!

Quarks and gluons are colored, but hadrons are „white". Since they are of types

$$(qqq) \;\; \text{i} \;\; (q\,\bar{q})$$

$N_c=3$ is needed to make these combinations (hadrons) colorless (*color singlet*)

$$3 \times 3 \times 3 = 1 + 8 + 8 + 10 \qquad 3 \times \bar{3} = 1 + 8$$

Confinement – new phenomenon leading to the end of a ladder :

molecule →atom →nucleus→ nucleon→ quark?

Possibly...

Electron quantum number L_e

- In many processes electron is accompanied by neutrino (or antineutrino) eg. neutron decay

- Electron number (additive): electron e = +1,
  electron neutrino ν_e = +1
- For their antiparticles = -1; other particles =0
  If electron quantum number is conserved
  neutron decay must be: $n \rightarrow p\, e^- \, \bar{\nu}_e$
- „ Crossing reaction" exists: $\nu_e\, n \rightarrow p\, e^-$
  Observation of crossing process $\bar{\nu}_e\, p \rightarrow n\, e^+$
  -a discovery of electron (anti)neutrino ν_e
  Covan, Reines'1956 (Nobel 1995)

Before neutrino it was only hypothesis (Pauli 1930)

Muon and taon quantum number

Massive copies of electron and el. neutrino ν_e

muon (1937 - *„Who ordered that?"* I. Rabi *)*,

taon (1975, M. Perl, Nobel 1995)

and their neutrinos

ν_μ 1962, Schwartz, L. Lederman, J. Steinberger (Nobel 1988)

ν_τ 2000

LEPTONS: (*lepton - „lekki")*

electron, mion, taon and their neutrinos

Similarly to L_e one introduces

muon L_μ and taon L_τ quantum number

Lepton quantum number L

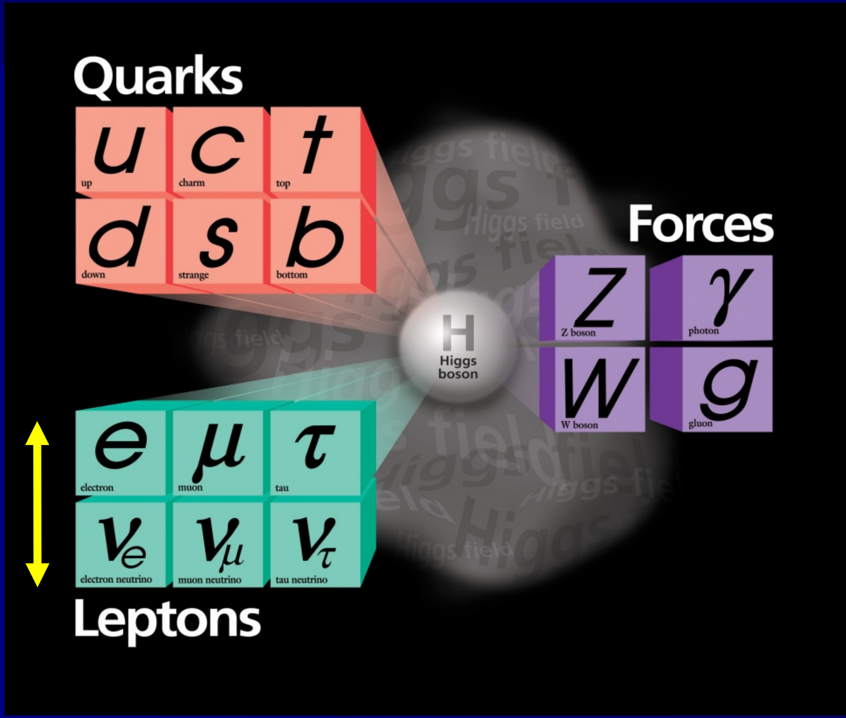
Lepton quantum number = sum over individual quantum numbers

$$L = L_e + L_\mu + L_\tau$$

L – conserved in Nature…

Standard Model

Quarks (all) :
Baryonic number B=1/3
Leptons (all) :
Leptonic number L =1



Antiquark s B = -1/3
Antileptons L= - 1

Individual quantum numbers for electron, muon and taon

and for quarks (flavors)