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Quarks - ”as we see them”

Kvarky - ”jak je vidíme”

Summary

This lecture briefly overviews the present knowledge of quark physics. The systematic study of many observed elementary particles introduced a symmetry, which leads to the simplification of the nature of particles and represents particles as elements of a group symmetry, $SU(3)$. The base of this symmetry is represented by the hypothetical elements - "quarks". Their properties allow the interpretation the observed particle as composite objects made up of quarks. Electric charges of quarks should be fractional charges of the charge of electron. The real existence of such particles has never been proved despite many searches. The hypothetical quarks, however, could explain the rich nature of observed particles and their properties. In an analogy with nuclear physics spin and orbital momenta have been introduced for quarks. Hence the observed nucleons/antinucleons are composed of three quarks/antiquarks. Mesons are the bound states of quarks and antiquark pairs. The force which binds quarks together to form real particles should have properties different from the known forces, including nuclear forces.

The structure of matter is also manifested in the scattering of particles. Compositeness is shown by the deviation of scattering angles from the usual interactions described by known forces. This effects was first seen in proton-proton interactions at the collider ISR in CERN and later proven in deep inelastic scattering of electrons with protons at SLAC. This dynamical observer "parton" structure of nucleons show that the quarks do not need to be just hypothetical particles, but may really exist inside hadrons. The identity of quarks and partons gives a new understanding to the interactions between quarks with the field of gluons as quanta of these new forces. Therefore Quantum Chomodynamics can explain all the properties of the quark and gluon including their confinement inside hadrons.

Thus the existence of "u" and "d" quarks was established. Together with the electron and electron neutrino they are the basic particles from which is formed 99 percent of matter in our known universe. The existence of the "s" quark explains the observed strange particles (kaons and hyperons) seen in cosmic rays and in high energy particle interactions. These three quarks restored the SU(3) symmetry of observed hadrons. The other heavier "c", "b" and "t" quarks, discovered later in high energy particle interactions, have formed with the muon, muon neutrino, τ lepton and the τ neutrino, three families of elementary particles.

Souhrn

Tato přednáška představuje stručný přehled fyziky kvarků, tak jak je známe v současné době. Systematické studium mnoha pozorovaných částic v kosmickém záření i v interakcích na urychlovačích vedlo k jejich uspořádávání. Ta ukázala, že částice mohou být chápány jako elementy grupy $SU(3)$. Báze této grupy pak může představovat hypotetické částice - "kvarky", které jsou základními kameny pozorovaných částic. Abychom mohli kvarky považovat za částice musely by mít zlomkové elektrické náboje, náboje elektronu. Takovéto částice však nebyly nalezeny, i když k jejich nalezení byla provedena velká řada experimentů. Pokud těmto hypotetickým kvarkům byly přisouzeny spiny a vzájemné orbitalní momenty, v analogii s jadernou fyzikou, pak tyto kvarky vysvětlovaly všechny vlastosti pozorovaných částic. Síly, které je váží dohromady jsou ale jiného charakteru, než síly které vážou nukleony v atomových jádrech.

Struktura hmoty se projevuje v úhlových rozděleních při srážkách částic s vysokými energiemi, jak rovněž ukázal Rutherfodový rozptyl alfa částic na atomových jádrech. První indikace pozorování takového anomálního rozptylu byly pozorovány při srážkách nukleonů v urychlovačích se vtřicnými svazky na ISR v CERNu.

Definitivní potrvrzení "partonové" struktury nucleonu pak bylo pozorováno v nepružných srážkách elekronů s protony ve SLACu. Tato dynamická partonová struktura nucleonu ukázala, že kvarky nemusí být pouze hypotetické částice vyjadřující pozorované symetrie mezi částicemi ale mohou reálně existovat uvnitř nucleonu. Při srážkách elektronů/positronů s protony/neutrony se skutečně potvrdily zlomkové elektrické náboje partonů - kvarků. Ukázalo se rovněž, že kvarky nesou pouze polovinu celkového impulsu srážejících se nucleonů a druhá polovina zůstává skryta před interagujícími leptony. To vedlo k dalšímu předpokladu že tato druhá část představuje partony - gluony, na které leptony neregistrují. Gluony, spolu s kvarky se staly základem kvantové chromodynamiky (QCD). Gluony nemají elekrický náboj, ale jsou nositeli kvantového čísla "barva", která zůstává však skryta uvnitř hadronů, které jsou "nebarevné".

Tak existence kvarků "u" a "d" byla prokázána a spolu s elektronem a elektronovým neutrinem tvoří základní kameny devadesáti devíti procent pozorovatelného vesmíru. Existence kvarku "s" vysvětluje částice pozorované v kosmickém záření a produkované na urychlovačích (kaony a hyperony). Další těžší kvarky "c", "b", "t" byly objevené ve srážkach hadronů na vysokoenergetických urychovačích CERNu FNALu.

Keywords:

quark, gluon, interaction of quarks, interaction of gluons, color, spin, group symmetry, collider, strangeness, charm, beauty, top quark, jet

Klíčová slova:

kvark, gluon, interakce kvarků, interakce gluonů, barva, spin, grupová symetrie, urychlovač se vtřicnými svazky, podivnost, kouzlo, krása, top kvark, trysky

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1 Introduction

The understanding of nature has challenged mankind for a long time. The main attention was always focused on astronomical observations and predictions but since the time of ancient Greece, philosophers have been trying to answer basic questions about the structure of matter and forces acting between objects. Even at that time, philosophers like Epicurus, Democritus and Leucippus (5th to 3rd century BC) proposed that matter consists of *atoms* - the smallest, indivisible parts of the world; configurations and movements of which form everything in the world. This idea was believed to be correct right up to the present day.

There were other theories during history, which dominated over the atomistic view. Aristotle's idea (3rd century BC) that all matter consisted of four elements: earth, water, air and fire. This was accepted until the seventeenth century. The systematic work of physicists e.g. monumental work *Philosophiae Naturalis Principia Mathematica* by Isaac Newton, and by other early scientists eventually lead to later discoveries such as electromagnetism, radioactivity and atomic structure. New experimental methods and equipment during the 20th century have allowed physicists to extend the Democritus picture of the world in terms of elementary particles.

Today the understanding of nature is that matter is made up of six quarks, six leptons (electron, muon, tau and corresponding neutrinos) and their antiparticles. There are three types of forces - the electroweak, strong and gravitational forces , each of which acts between different types of objects, at different distances and strengths, mediated by different particles. While gravitation is described by the stand alone theory of relativity, the strong force is described by a comprehensive theory of Quantum Chromodynamics (QCD), now the most accepted theory of particle physics. This theory gives excellent results in predictions of observations in high energy particle experiments.

The three families of particles, Fig 1, differs by different flavor. Different flavor expresses the different properties of the particles. Quarks also have another hidden quantum number - color. Admitting these three varieties of quark, each with different color is the only way to satisfy the Pauli exclusion principle for fermions. This list of fundamental particles of course also contains the quanta of forces like photon, intermediate bosons (W,Z), gluon and graviton. The interactions of gravitons, however, have not yet been detected in particle interactions.

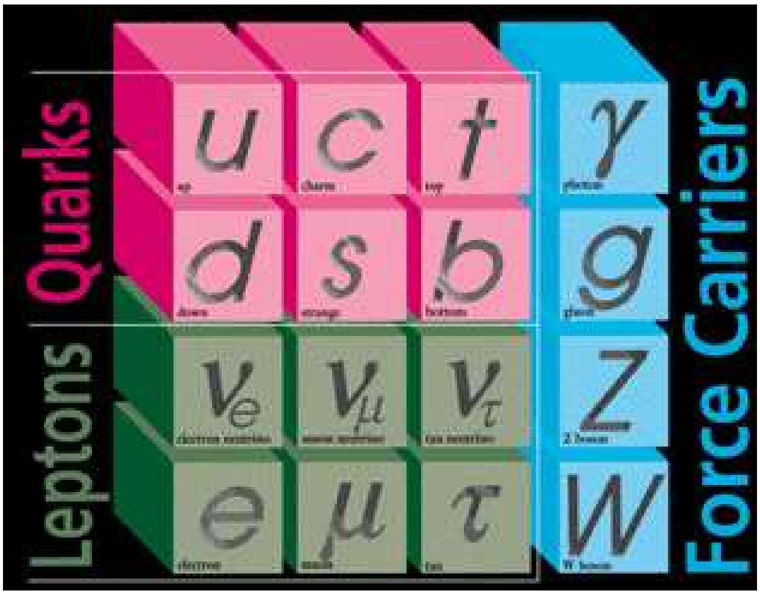


Figure 1: Building bricks of the visible universe according to Standard Model - the Elementary Particles.

There are, however, several properties in which quarks do not resemble ordinary particles like electrons, protons etc. They have fractional electrical charge, and, even more important, they are not seen as free objects. This is referred to as confinement and it could be explained by the QCD coupling constant which increases the binding force between the quarks when an outside interacting particle such as a proton tries to separate them. If the energy of the interacting particle is high new pairs of quark-antiquarks are formed and are seen as newly produced mesons.

The Study of quark properties and their interactions are the main program in high energy particle accelerators like Tevatron in Batavia, USA and LHC collider in CERN, Geneva, which will commence operating this year.

2 Too many elementary particles

While in 1958 the number of particles did not exceeded 30, including some antiparticles (proton, neutron, electron, positron, muon, hyperons Σ, Λ, π,...), in the early sixties the newly discovered resonances have increase this number to hundreds[1]. These resonances are never visible as tracks, like those left by other more long lived particles, as their lifetime $10^{-23}s$ is too short for any detectors. We can only see them because of secondary effects. The discovery of new resonances of baryons and mesons is still going on as the energy of accelerators increases. They usually are observed in the distributions of invariant masses of secondary particles (eg. Dalitz plots, or as cinematics anomalies of recoil particles) Fig. 2 and Fig. 3.

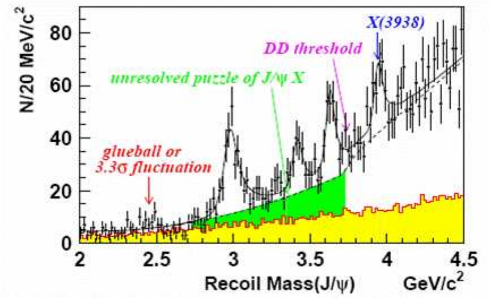


Figure 2: Recoil particle, reflecting existence of resonances.

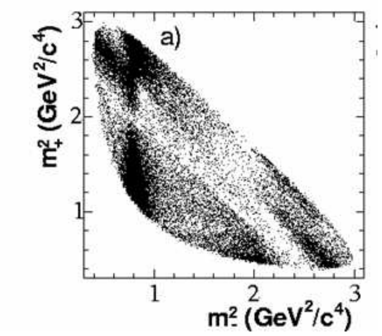


Figure 3: Dalitz plot of effective masses of two hadrons showing evidence of new resonances.

As the energy of the primary interaction of hadrons increases, the cross section also increase Fig. 6 and there is an even greater increase in the number of newly created particles[2] Fig. 4.

Some regularity in multiplicity distributions of secondary particles has been observed. The KNO scaling Fig. 5[4] was inspired by Feynman scaling of longitudinal momenta pl/Plmax. This scaling was, however, violated in the region of collider energy (UA5 experiment in CERN)[3]. Similar scaling was also show in the antiproton-proton annihilation [5] and in electron-positron annihilation. Later, we have observed another regularity in high energy inelastic interactions. The Shannon entropy of particle distribution increases linearly with the logarithms of center of mass energy [6] In electron-positron annihilations in hadrons many new particle flavors were observed. Especially in the ratios cross sections of annihilation into hadron divided by the cross section into leptons R, Fig. 7.

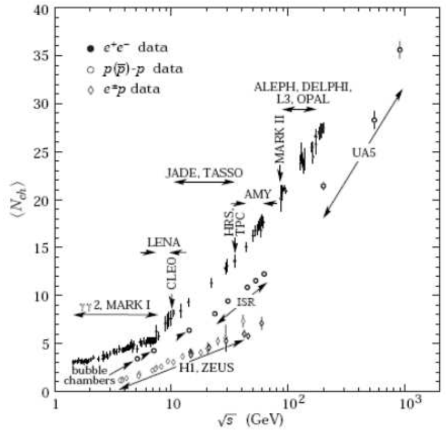


Figure 4: Average multiplicity of charged secondary particles.

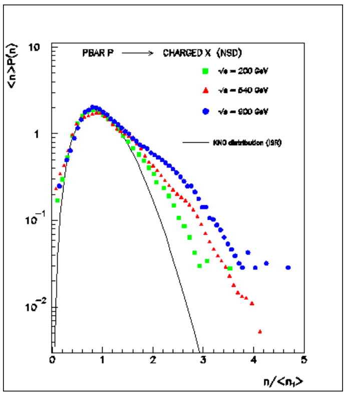


Figure 5: Multiplicity distribution normalized to average multiplicity - KNO

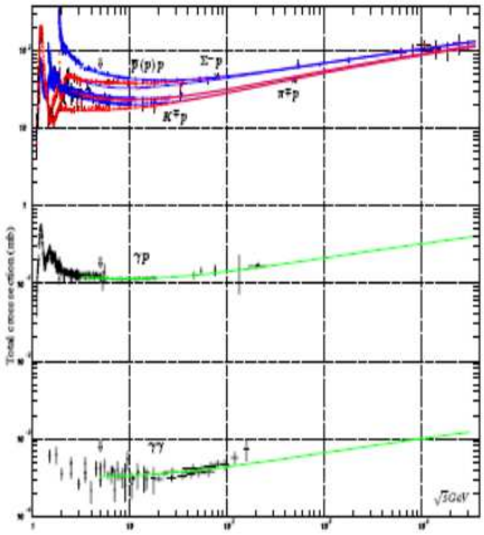


Figure 6: Cross sections of hadron and photon interactions as function of center of mass energy.

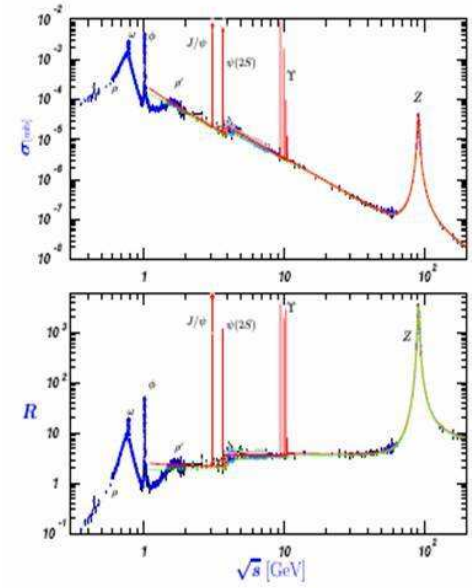
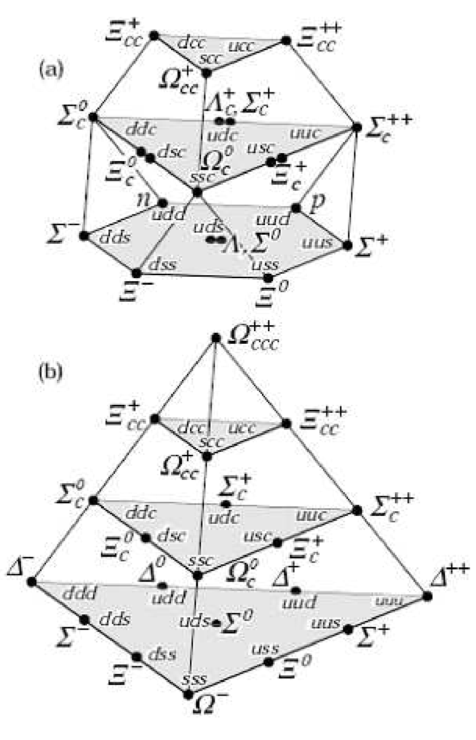


Figure 7: Total cross section of $e^+e^- \to hadrons$ and the ratio $R = \sigma(e^+e^- \to hadrons)/\sigma(e^+e^- \to \mu^+\mu^-)$ as function of center of mass energy.

3 Systematics and particle multiplets

The rich mass spectrum of many observed particles inspired many attempts to classify them according to their masses and other properties. The most successful was "the eight fold way" which arranges particles according to their electrical charge and hypercharge ("strangeness") in two dimensional multiplets. This representation was interpreted as SU(3) group symmetry with three basic elements. These elements, however, should have the particular properties of real observed particles so their combination may explain the nature of particles. As well as strange particles, new particles with a different lifetime were discovered ("charm"). Their mass was much higher and together with the other particles they could belong to group SU(4)[7].



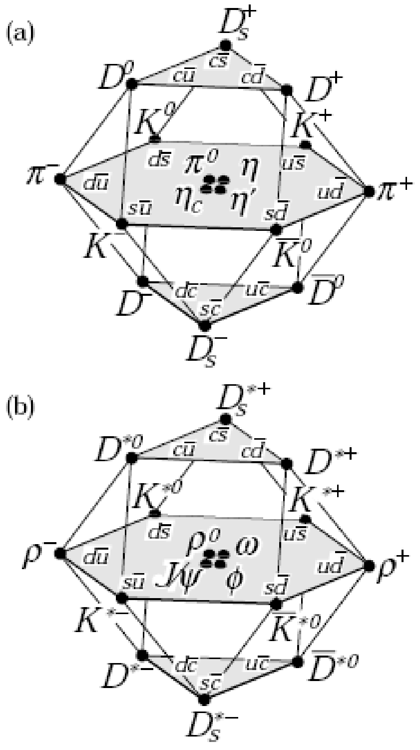
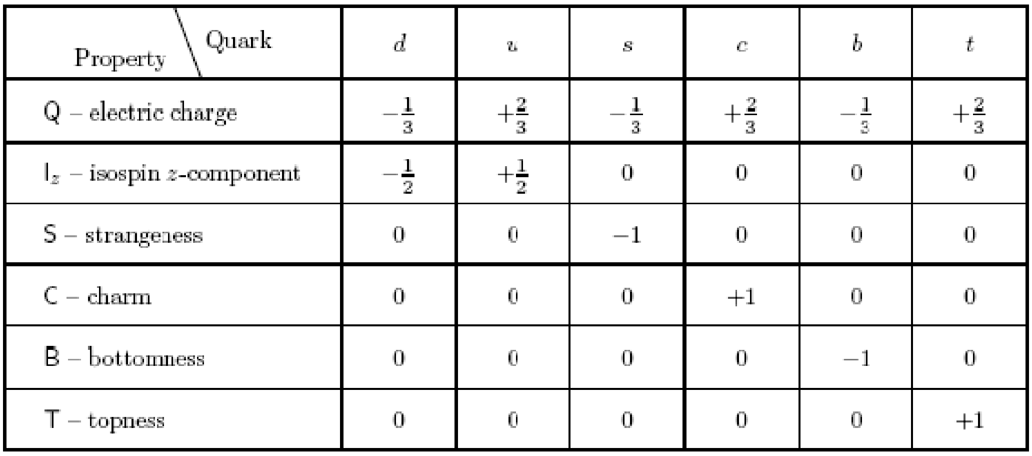


Figure 8: SU(4) multiples of baryons made of u,d,s,c quarks. (a) The 20-plet with SU(3) octet. (b) The 20-plet with SU(3) decuplet.

Figure 9: SU(4) 16-plet for the (a) pseudoscalar mesons and (b) vector mesons made of u,d,s,c quarks.

A three dimensional visualization for baryon and mesons is displayed in Fig. 8 and Fig. 9. The further discovery of yet another heavier particle ("beauty") would force the inclusion of another basic element into the group representation. Hence we have five basic elements which could be considered as the base of group symmetry.



Property \ Quark	d	u	s	c	b	t
Q – electric charge	$-\frac{1}{3}$	$+\frac{2}{3}$	$-\frac{1}{3}$	$+\frac{2}{3}$	$-\frac{1}{3}$	$+\frac{2}{3}$
I_z – isospin z-component	$-\frac{1}{2}$	$+\frac{1}{2}$	0	0	0	0
S – strangeness	0	0	−1	0	0	0
C – charm	0	0	0	+1	0	0
B – bottomness	0	0	0	0	−1	0
T – topness	0	0	0	0	0	+1

Figure 10: Properties of quarks, according to group symmetry in Standard Model.

The particles could be considered as composite objects of some basic entities corresponding partially to the nature of seen particles. As the baryons have spin $1/2\hbar$ the number of basic particles, considered also as fermions, which can build a nucleon must be odd and at least 3. The mesons, particles with an even spin could be composed of a basic fermion and an antifermion. The properties of these basic particles known as "quarks" are listed in Fig. 10. The particles and resonances with higher masses or spins could be considered as composite objects of quarks/antiquarks with additional orbital momenta between them.

The 5 quarks and 5 antiquarks explained the nature of all observed particles. The last quark was discovered much later (top quark with mass of 175 masses of nucleon), but it completed the symmetry basic elements - quarks - "Standard Model". In each fermion and antifermion family in SM the electric charge must fulfill the relation: $-1(electron)+3(2/3(u-quak)-1/3(d-quark)) = 0$, and similarly for the other families. The t-quark with a charge $+2/3$ completed the nature of hypothetical quarks.

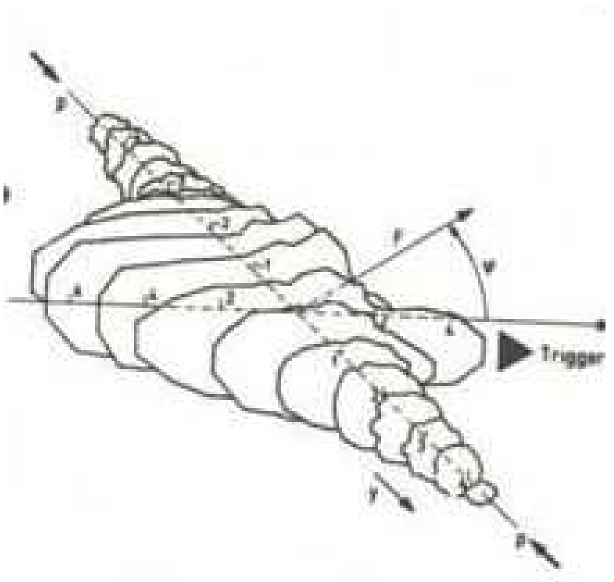


Figure 11: ISR - exes of particles opposite to high p_t trigger.

4 Dynamic partons

Quarks have appeared as basic entities in the systematic classification of observed elementary particles. Their actual existence in the physical world can only be proven by dynamics effects. The structure of a proton should be seen in the scattering of particles at very high energies, in a similar way to the anomalous angular distributions of scattered particles in Rutherford's experiment with alpha particles and a gold foil.

In 1975 in CERN the accelerator with two proton colliding beams (ISR experiment[9]) could reach the center of mass energy up to 60 GeV. The structure of a proton should show an excess of particles in the central region and with large transverse momenta. The experiment, where the events with high p_t trigger particle were observed have indeed shown an excess of secondary particles in the opposite direction to the triggered particles Fig. 11. Simple energy and momenta conservation could not explain this effect completely. The possibility of an internal structure of a proton was the only plausible explanation. The energy of ISR was too small to show the further details of interaction as effect of high p_t was seen as integrated from many events.

In the SLAC laboratories at the beginning of the seventies experiments with high energy

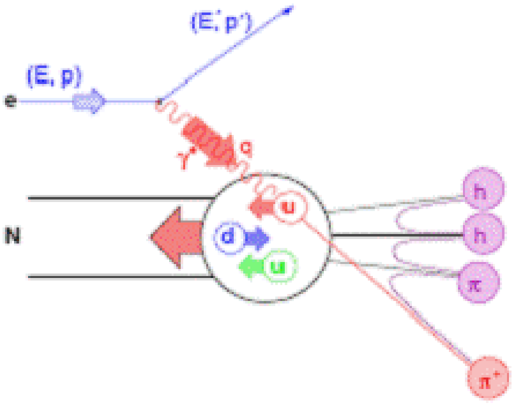


Figure 12: Deep inelastic scattering of electron with proton.

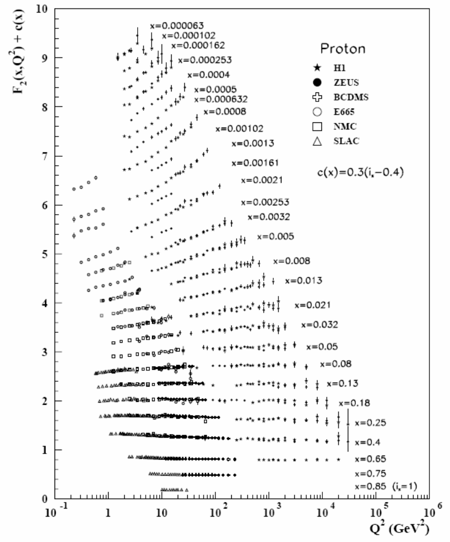


Figure 13: The proton structure function F_2^p measured in electromagnetic scattering of positron on proton in SLAC and HERA experiments.

electrons were performed. The electrons with an energy of 20 GeV were shot at a nucleon target and the final angular distributions of scattered electrons indicated the complex structure of nucleons Fig. 12. The interaction of the electrons could only probe the electromagnetic structure of nucleons but the comparison of interaction of an electron or a positron with a proton or a neutron, in deep inelastic scattering (DIS)[10], has proved the composite structure of nucleons. Nucleons are composed from ”partons”.

The distributions of the longitudinal part of protons ($x = p_l/P_p$)in interactions with electrons seems to be independent of the energy of the electrons (rather momentum transverse of electrons Q) in the broad energy region Fig. 13 and that indicated the permanent structure of a proton (Bjorken scaling[11]). The measurements of structure functions in the small x region, however, exhibit this scaling Fig. 14. The structure functions of nucleons measured in SLAC and later in HERA experiments in DESY, supported the compositeness of nucleons. The properties of this parton, however, did not immediately correspond to quarks whose properties were extracted from particle symmetry.

5 Quarks and partons

The pictures of partons and quarks, however, presented two different scenarios and only a detailed study on both of them could merge them together. In further DIS experiments the electromagnetic of interactions has shown difference between proton and neutron.

The separation of the positive and negative parts of partons indicate that in the proton there are twice as many positive charged partons as negative ones, while in the neutron the situation was the opposite. This supported the quark picture where the proton has 2 $u-quarks$ and 1 $d-quark$. The separation of measured "Structure functions" according to the charge confirmed that the parton are quarks Fig. 15[12].

The integration of the structure functions of parton/quarks should give a full picture of the nucleon. The experiments, however have shown that the electrons see only just half of total momenta of interacting nucleons.

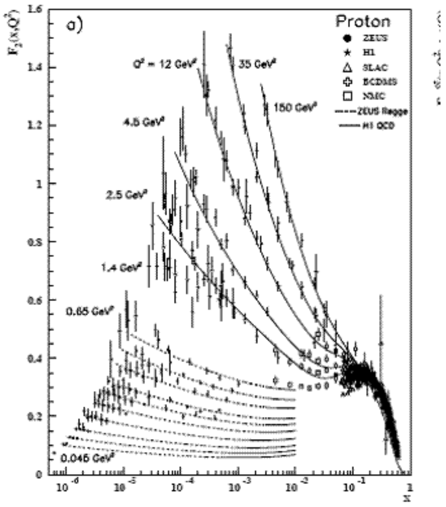


Figure 14: The parton structure function F_2^p at various values Q^2, which exhibit scaling at $x \approx 0.14$.

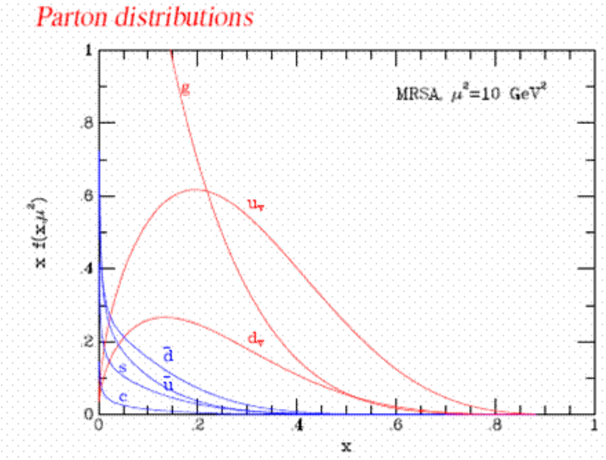


Figure 15: Distribution of x times the proton structure function F_2^p decomposed into quarks and gluon.

The gluon structure function represents the remaining half of the momentum carried by a proton Fig. 15.

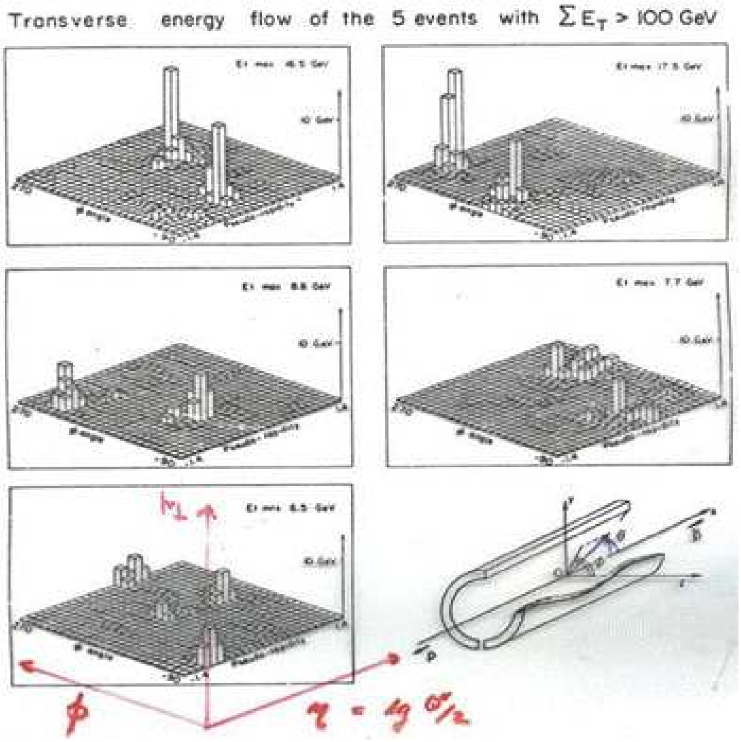


Figure 16: CERN experiment UA2 have discovered quark jets in antiproton-proton interactions at SPS.

6 Quark and QCD

The invisible part of nucleons corresponds to partons - ”gluons”, which interact with quarks, but have no electric charge. The interactions of gluons resemble electromagnetic interaction of photons, but they have to have other properties - ”colors”.

Color quantum numbers are not visible in the observed particles, but the existence of them is indicated by the number of newly creating quarks in the electron - positron annihilations. The ratio of hadrons (quark pairs) to lepton production is 3 times larger than the simple production of quark-antiquark pairs Fig. 17

The SPS collider, where the antiproton interacted with proton at the 630 GeV of center of mass energy, the quarks and gluons interaction appeared as jets with transverse momenta very much above the normal secondary particles Fig. 16[13].

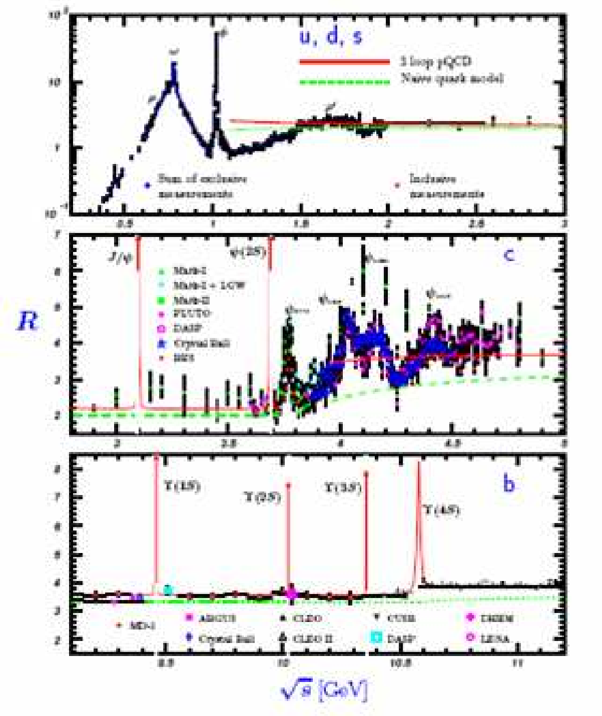


Figure 17: Ratio $R = \sigma(e^+e^- \to hadrons)/\sigma(e^+e^- \to \mu^+\mu^-)$ as function of center of mass energy with indicated regions of quarks creation.

$$
\begin{aligned}
L_{\mathrm{QCD}} &= -\frac{1}{4} F^{(a)}_{\mu\nu}\, F^{(a)\mu\nu} + i \sum_q \overline{\psi}^i_q\, \gamma^\mu\, (D_\mu)_{ij}\, \psi^j_q \\
&\quad - \sum_q m_q\, \overline{\psi}^i_q\, \psi_{qi}\ , \\
F^{(a)}_{\mu\nu} &= \partial_\mu A^a_\nu - \partial_\nu A^a_\mu - g_s f_{abc} A^b_\mu A^c_\nu\ , \\
(D_\mu)_{ij} &= \delta_{ij}\, \partial_\mu + i g_s \sum_a \frac{\lambda^a_{i,j}}{2} A^a_\mu\ ,
\end{aligned}
$$

Figure 18: QCD lagrangian, where the summation is over quark flavor and also for all possibilities of color exchanges. The g_s corresponds to coupling constant.

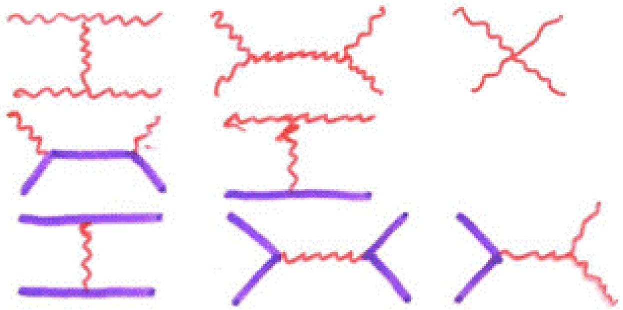


Figure 19: Feynman's diagrams corresponding first order of quarks and gluon interactions.

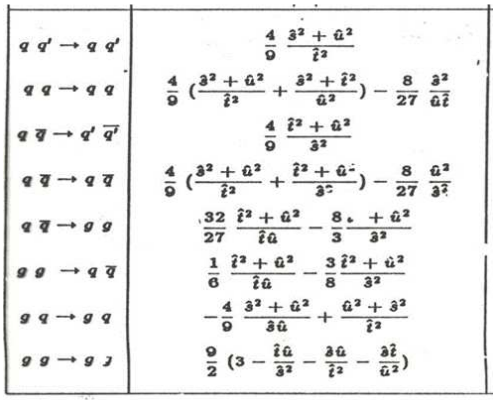
For the quantitative description of partons (quarks and gluons)was found to be Lagrangian in analogy with electromagnetic interaction. In addition to the electric charge an additional quantum number color has to be implemented.

The freedom in colors appears to be very important. The conservation of 3 colors together with the coupling constant could explain the confinement of quarks inside hadrons. Contrary to photons which interact with a charged particle, the gluons could interact not only with quarks but also between themselves exchanging color quantum numbers.

The Lagrange formalism Fig. 18 allows the calculation of matrix elements of interactions, Fig. 20 and thus quantitatively compared prediction of Quantum Chomodynamics. The exchange of colors is a basic feature of partons, compared to electrodynamics.

In real descriptions of interacting partons, the structure functions of quarks should be taken into account Fig. 21. For the high p_t distribution of jets (as represented by partons) the agreement of QCD with the experiment is remarkable, Fig. 22 and Fig. 23[14]. QCD together with electromagnetic interaction, the so called "Standard Model" (SM), is a big success in the understanding of particle physics.

QCD can explain all the observed properties of jets but only with high p_t, where the coupling constant g_s is reasonably small and the perturbative summation of feynman's diagrams converge. QCD can not, however, describe the creation of real particles as it is the region of low p_t physics.



$q\,q' \rightarrow q\,q'$	$\frac{4}{9}\,\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}$
$q\,q \rightarrow q\,q$	$\frac{4}{9}\,(\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}+\frac{\hat{s}^2+\hat{t}^2}{\hat{u}^2})-\frac{8}{27}\,\frac{\hat{s}^2}{\hat{u}\hat{t}}$
$q\,\overline{q} \rightarrow q'\,\overline{q'}$	$\frac{4}{9}\,\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}$
$q\,\overline{q} \rightarrow q\,\overline{q}$	$\frac{4}{9}\,(\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}+\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2})-\frac{8}{27}\,\frac{\hat{u}^2}{\hat{s}^2}$
$q\,\overline{q} \rightarrow g\,g$	$\frac{32}{27}\,\frac{\hat{t}^2+\hat{u}^2}{\hat{t}\hat{u}}-\frac{8}{3}\,\frac{\quad+\hat{u}^2}{\hat{s}^2}$
$g\,g \rightarrow q\,\overline{q}$	$\frac{1}{6}\,\frac{\hat{t}^2+\hat{u}^2}{\hat{t}\hat{u}}-\frac{3}{8}\,\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}$
$g\,q \rightarrow g\,q$	$-\frac{4}{9}\,\frac{\hat{s}^2+\hat{u}^2}{\hat{s}\hat{u}}+\frac{\hat{u}^2+\hat{s}^2}{\hat{t}^2}$
$g\,g \rightarrow g\,g$	$\frac{9}{2}\,(3-\frac{\hat{t}\hat{u}}{\hat{s}^2}-\frac{\hat{s}\hat{u}}{\hat{t}^2}-\frac{\hat{s}\hat{t}}{\hat{u}^2})$

Figure 20: First order of matrix elements for interactions of quarks and gluons in Mandelstam invariants s, t, u.

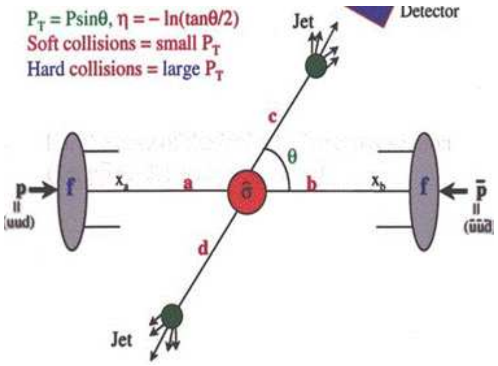


Figure 21: Interactions of partons are decomposed into QCD matrix elements and structure functions of partons inside nucleons. Two partons in final states are observed as two high p_t jets.

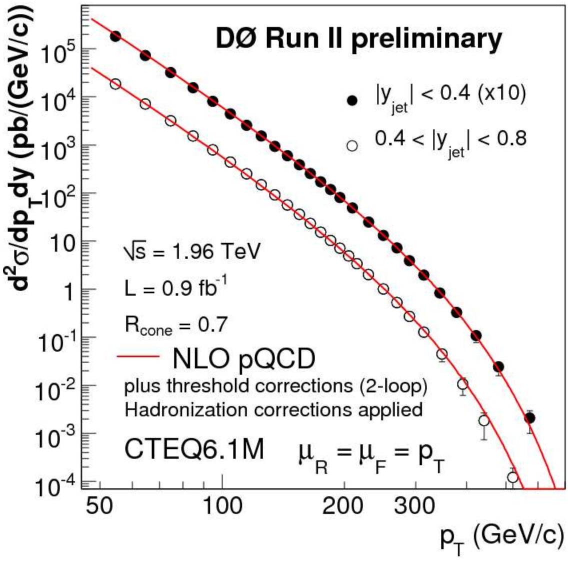


Figure 22: Inclusive spectrum of high p_t jets in proton - antiproton interactions in experiment D0 compared with theoretical calculation from QCD.

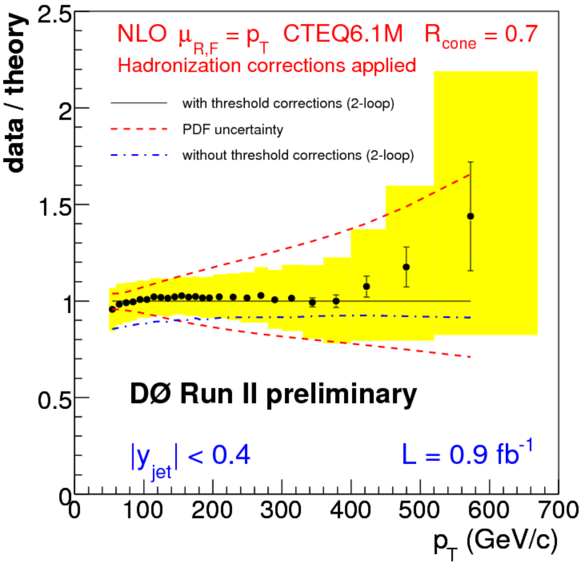


Figure 23: The ratio experiment/theory for inclusive jets in experiment D0 at 1.98 TeV energy, The yellow band corresponds to experimental errors.

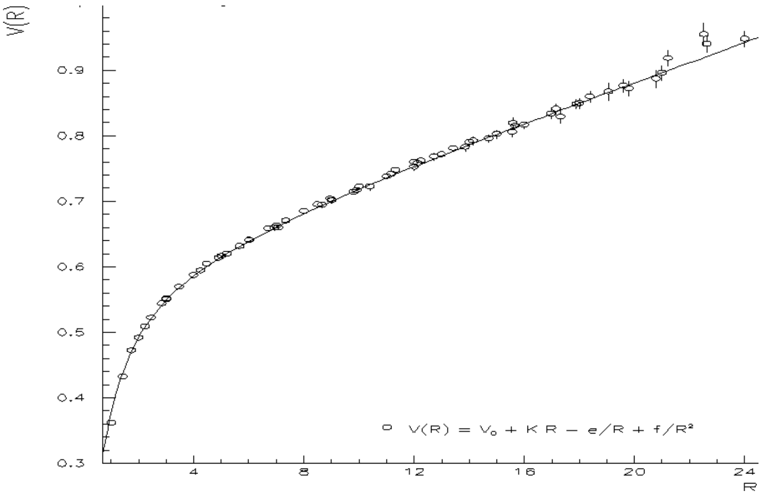


Figure 24: Potential of force between quarks inside hadron.

7 Quark interactions and particle creation

The force between quarks inside the nucleons is negligible. Quarks behave as free particles but the forces increase when the quarks are forced out of a hadron. There the force is directly proportional to the distance between them. This could be understood as the potential of force which increases with the distances between quarks Fig. 24.

But how the new real particles are created is not known. One of the possible models of particle creation is represented by the Lund string model[15]. In this model, between quarks there is a color string, which, with increasing tension , as they move apart, could break. The newly created quark pairs(quark +antiquark) are seen as a new meson. As the interaction energy increases the multiple strings could produce multiple final states as has been observed in experiments, Fig. 25.

Another model assumed that the particles are creating in clusters with no open color and they decay into observed particles seen in the final states (Herwig model)[16] Fig. 26.

Both models, however, for comparison with experimental results need experimentally determined fragmentation functions, which describe the energy flow of newly created particles. Of course all of the particle properties should also be included in these models.

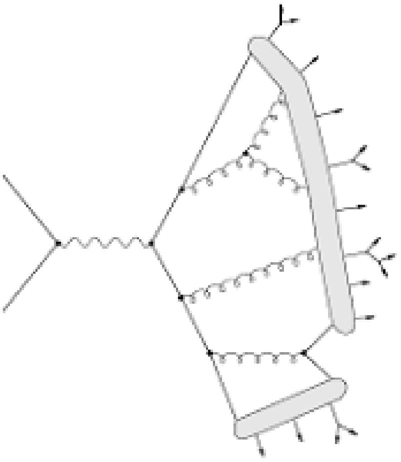


Figure 25: String fragmentation model.

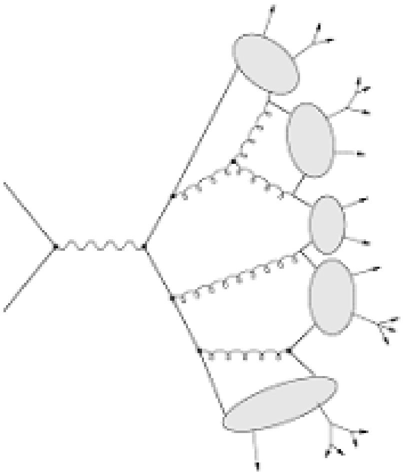


Figure 26: *Cluster fragmentation model*

8 Last quark - top

The three family of quarks would not be complete without the last one *topquark*. The symmetry in the Standard Model without a complete doublet with a b-quark would spoil the nice relation between the quarks and leptons charges: $-1(taon) + 3(2/3(t - quak) - 1/3(b - quark)) = 0$, which is a basic assumption of SM.

The first indirect evidence of its existence came from the LEP experiments. The increase of production of b and anti-b quark pairs in electron-positron annihilation indicated the exchange of a virtual particle with mass about 150 - 190 GeV.

In 1994 the discovery of the top quark at Tevatron [17] confirmed the predictions. The top quark mass is anomalously large at 173 GeV compared to other quarks, Fig. 27and Fig. 28. It decays into a W boson and a b-quark. As it decays very quickly, $10^{-23}s$, it can not create bound states with other quarks.

The hadronisation time in which the hadrons are created is longer than its lifetime. This, however, gives advantages in seeing dynamics for quark production unspoiled by the hadronisation processes. For example, from the spin correlations of the top-antitop quarks we can learn the properties of virtual or real particles from which the top-antitop quarks are created[18, 19, 20, 21].

According to SM the top/antitop quark could be produced as a single particle due to elec-

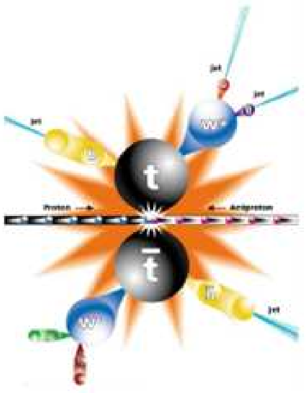


Figure 27: Top quark production in antiproton-proton collisions.

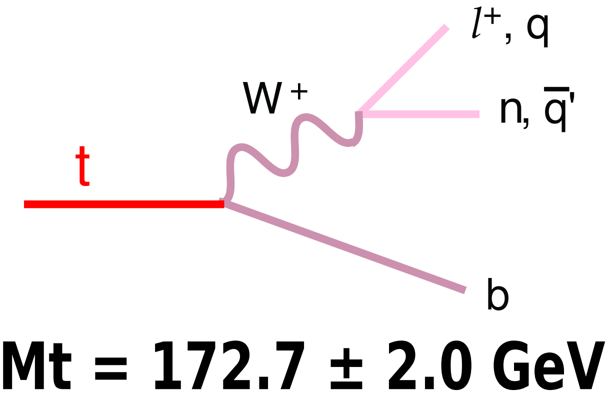


Figure 28: Top quark decay into W boson and b-quark.

troweak interaction and not only in pairs as ordinary hadrons This important prediction was last year confirmed by experiment [22].

9 Quarks and open problems

The quark structure of hadrons opened new windows into the structure of matter. Enormous simplification of particle nature and their interactions enable the prediction of many new results which are compared with experiments in high energy accelerators. This put the physics of quarks (QCD) into the similar category as electromagnetic and electroweak interactions.

This opened up a set of new problems. We may list some of them:

- why the quarks have fractional electric charge?
- what is color quantum number?
- structure functions of hadrons and confinement of quarks inside nucleons?
- why masses of quarks are so different and still there may be reactions among them, Fig. ???
- what is behind B and K mesons oscillation and CP violation?

- do super partners of quarks exist?

Some of those questions may be answered in the new generation of experiments on LHC in next years, where the center of mass energy of proton-proton collisions reaches 14 TeV.

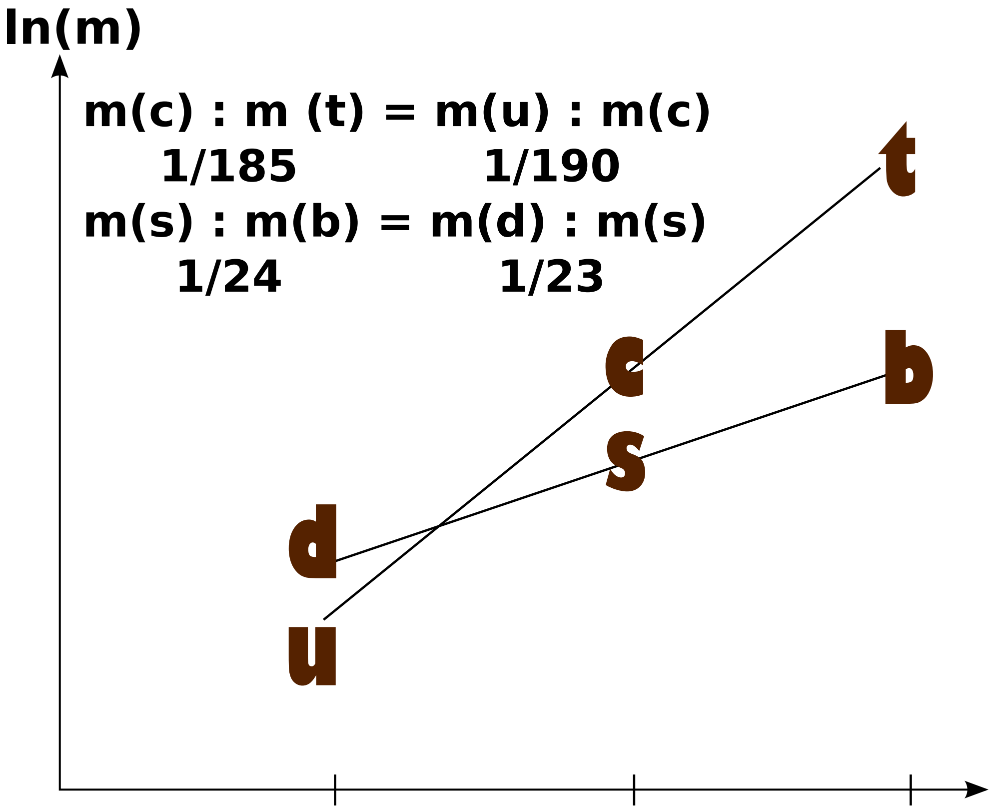


Figure 29: Some unexplained regularities between masses of quarks.

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- born 20. April 1934 in Tbor in Czechoslovakia
- Schools: Grammar school and Gymnasium in Tbor.
- 1953-1958 in Faculty of mathematics and physics at Charles University in Prague. Diploma work was devoted to the study of cosmic rays Jets. PhD. finished in 1960 with theme "Interaction of protons of cosmic rays and at 9 GeV in nuclear Emulsions".
- 1958-1960 assistant at the Faculty of Nuclear and Technical Physics at the Charles University. Since 1961 employed as a research physicist in the Institute of Physics of the Czech Academy of Scieces in the department of Cosmic rays, later department of high energy physics
- 1963-1965 fellowship of IAEC-Vienna and CERN in the department of bubble chamber physics in CERN. Study of antiproton proton interaction and spectroscopy of hadrons
- 1967-1968 leader of the high energy physics department in the Institute of Physics, organizing collaboration on antiproton physics with CERN
- 1969-1970 research in CERN and MIT-Cambridge USA, in the department of high energy physics
- 1971-1989 in the Institute of Physics of Czech Academy of Sciences, working on experiments with antiprotons and antideuterons via collaboration JINR-Dubna at Serpuchov accelerator
- 1990-1991 six months associated member in CERN on the collider experiment with antiproton proton interactions at 630 GeV (Experiment UA2)
- 2001-now Czech Technical University in Prague, Faculty of Nuclear Sciences and Physical Engineering. Experiment ATLAS in CERN and experiment D0 inFNAL

Regular lectures

- Exercise in nuclear physics (1959-1960) at FJFI CVUT
- seminaires on selected topics in subnuclear physic (1960-1961) MFF UK
- selected topics in subnuclear physic (1966-1968, 1972-1999) MFF UK
- Introduction particle physics -UFEC (2003-now) FJFI CVUT
- Modeling of particle production EMEC (2003-now) FJFI CVUT

Experiments

- Interactions of cosmic rays in nuclear emulsions (1957-1961)
- Interactions of proton-proton at 9 GeV (JINR Dubna) in nuclear emulsion (1961-1963)
- Interactions of antiproton-proton at 3-4 GeV (CERN) in hydrogen bubble chamber (1963-1966)
- Interactions of atiproton-proton at 5.7 GeV in 2m hydrogen bubble chamber (CERN) (1966-1970)
- Interactions of proton-proton at 15 and 303 GeV (MIT - SLAC)in hydrogen bubble chamber (1970-1971)
- Interactions of atiproton-proton at 5.7 GeV in 2m hydrogen bubble chamber (CERN) (1966-1970)
- Interactions of atiproton-proton at 5.7 GeV in 2m hydrogen bubble chamber (CERN) (1966-1970)
- Interactions of atiproton-proton at 22.4 GeV in 2m hydrogen bubble chamber Lubmila (Serpuchov IHEP, JINR Dubna) (1971-1985)

- Preparation of experiment H1 for study of interactions of electron-proton at HERA DESY (1985-1988)
- Collider experiment UA2 (CERN) on antiproton-experiment at 630 GeV center of mass energy
- Preparation of experiment ATLAS at CERN (1994-)
- Experiment D0 of antiproton-proton interactions on Tevatron at 1.9 TeV center of mass experiment (1997-)

Other activities

- author or coauthor of 280 publication in international scientific journals
- author of 40 articles with popularization of particle physics and recencies
- author of book "High Energy Physics" (ILIFE - 1968) and "Fyzika vysokých energií" (SNTL - 1967)
- organization of many international conference and member of conference committees (ISMD, PIC)
- member of EPS, APS, JMF