Физика на елементарните частици

Lecture 1

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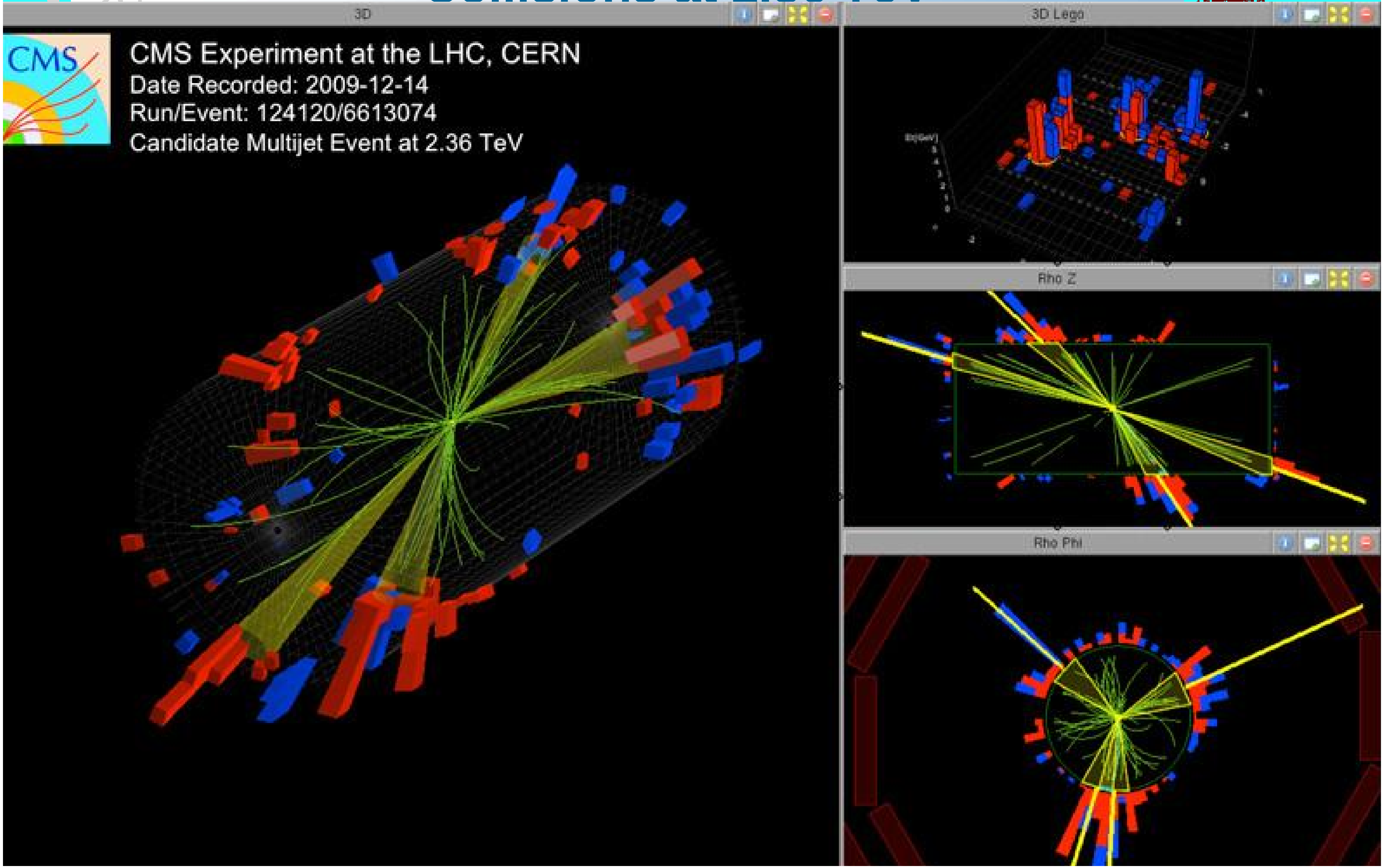
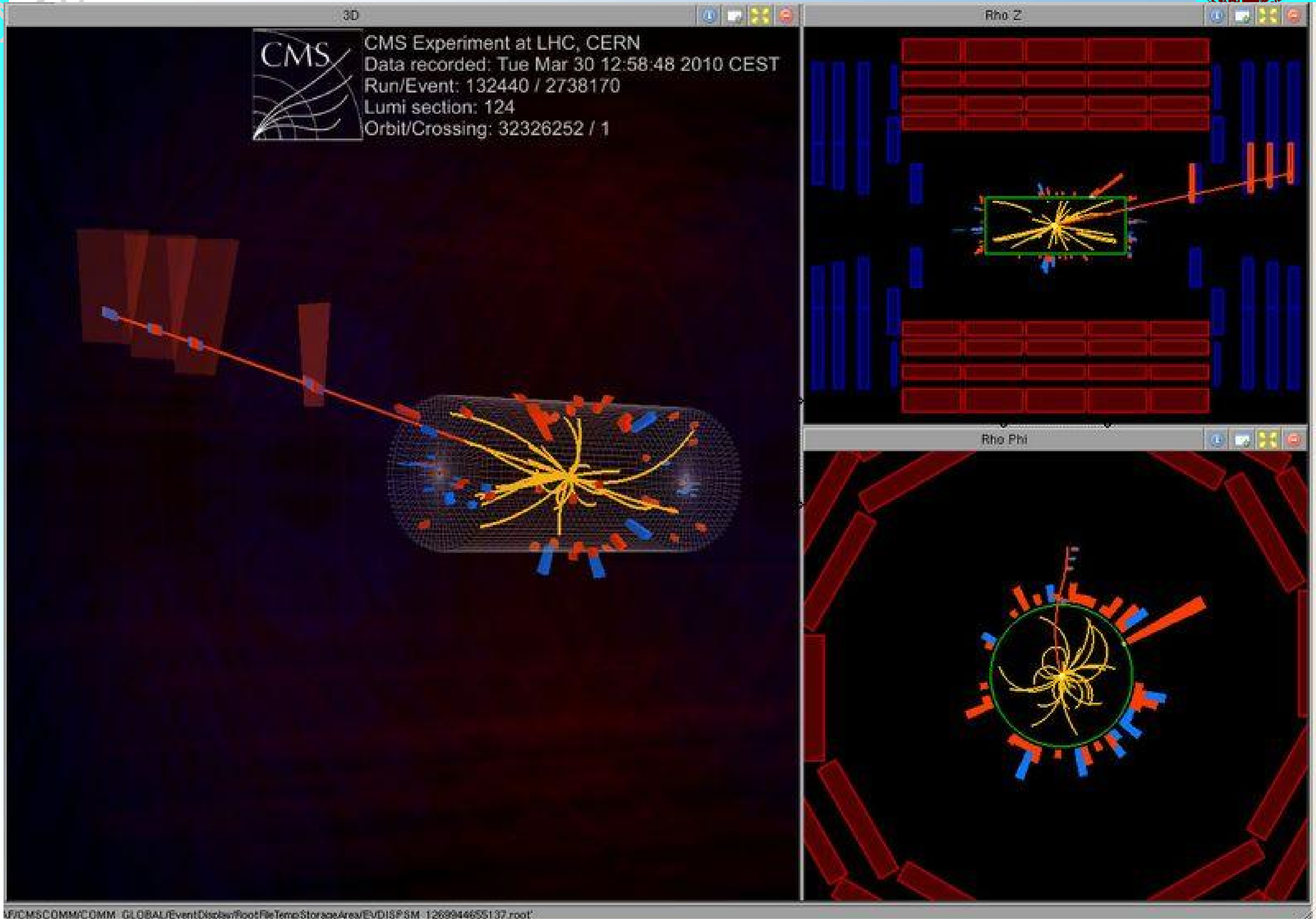
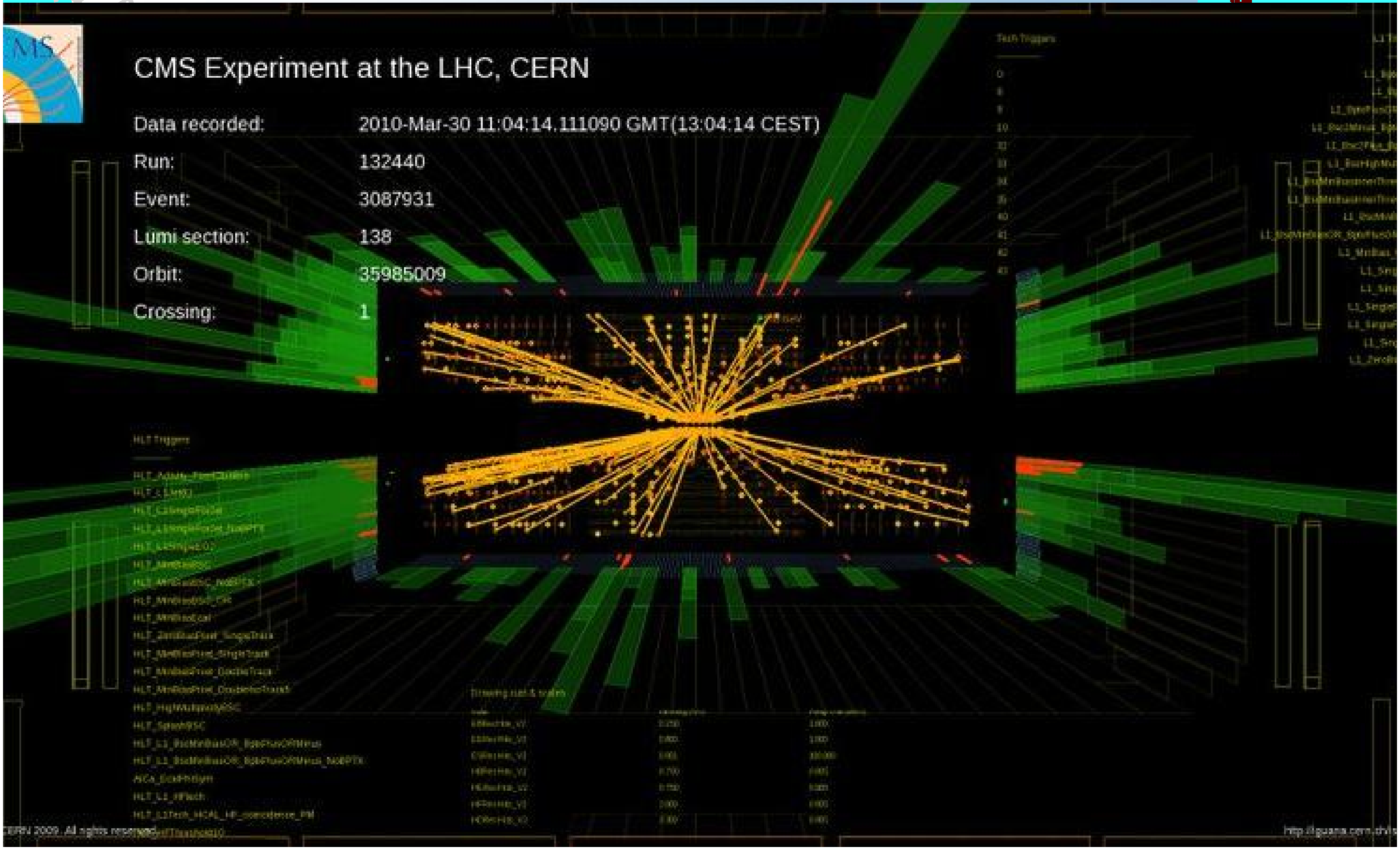
Collisions at 2.36 TeV



Collisions at 7 TeV



Collisions at 7 TeV



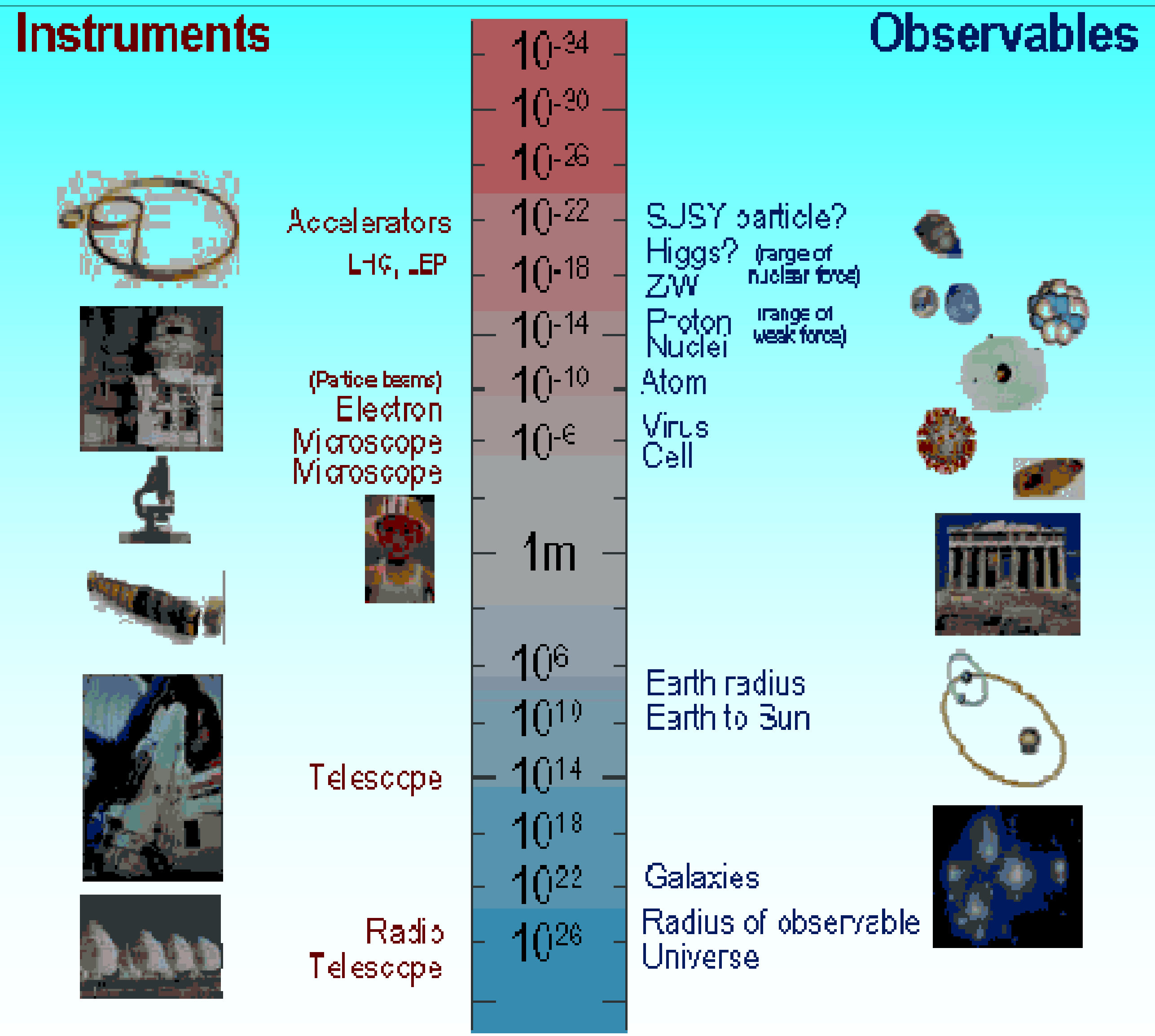
Що е то?

Опитва се да отоговори на на два фундаментални въпроса

-Кои са елементарните съставящи на материята?

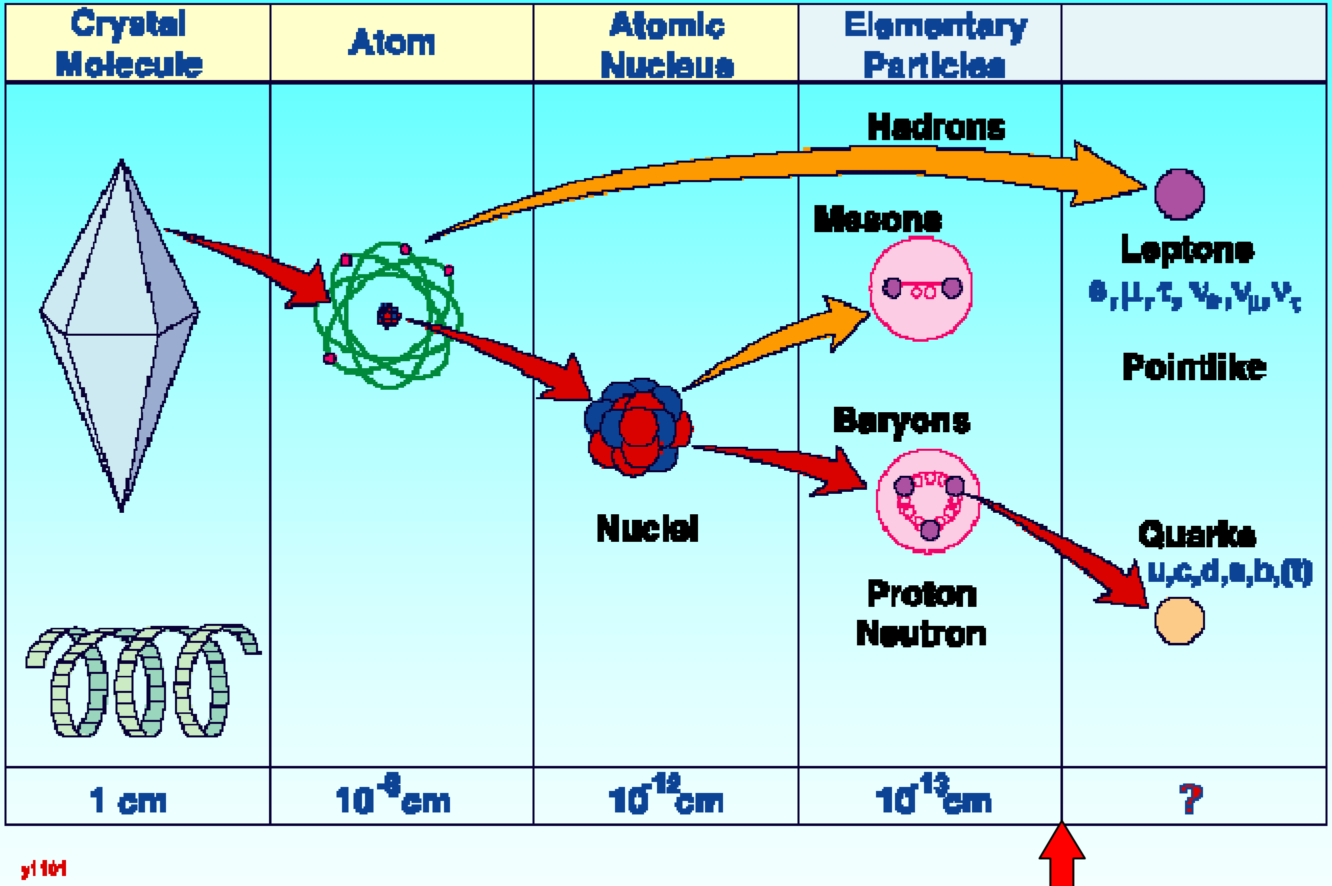
-Кои са фундаменталните сили контролиращи
 тяхното поведение ?

Мащаби



Instruments
Observables
10^{-34}
10^{-30}
10^{-26}
10^{-22}
10^{-18}
10^{-14}
10^{-10}
10^{-6}
1m
10^{6}
10^{10}
10^{14}
10^{18}
10^{22}
10^{26}
Accelerators
LHC, LEP
(Particle beams)
Electron Microscope
Microscope
Telescope
Radio Telescope
SUSY particle?
Higgs?
Z/W
(range of nuclear force)
Proton
Nuclei
(range of weak force)
Atom
Virus
Cell
Earth radius
Earth to Sun
Galaxies
Radius of observable Universe

Структура на материята



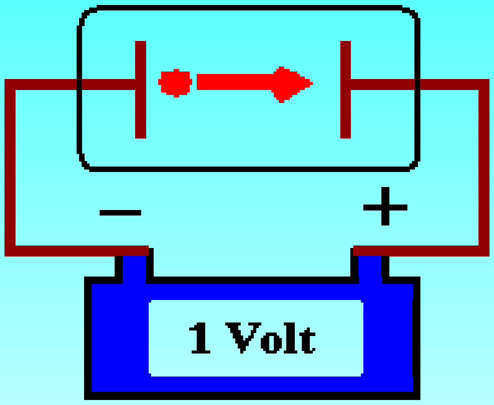
Физика на елементарните частици

Структура на материята

Energy

1 electron-Volt (eV):

the energy of a particle with electric charge = |*e*|, initially at rest, after acceleration by a difference of electrostatic potential = 1 Volt
(*e* = 1.60 x 10 $^{-19}$ C)



1 eV = 1.60 x 10 $^{-19}$ J

Multiples:
1 **keV** = 10^3 **eV ;** 1 **MeV** = 10^6 **eV**
1 **GeV** = 10^9 **eV;** 1 **TeV** = 10^{12} **eV**

Energy of a proton in the LHC :
7 TeV = 1.12 x 10 $^{-6}$ J
(the same energy of a body of mass = 1 mg moving at speed = 1.5 m /s)

Маса, разстояние, енергия, температура

These are related quantities

In particle physics the unit of energy is the electron volt.

1 electron volt (eV) = Energy gained by an electron in passing through a voltage difference of 1 V

$E=mc^2$	$c=3.10^8$ m/s	speed of light
$E=kT$	$k=10^{-4}$ eV K^{-1}	Boltzmann's constant
$E=hc/\lambda$	h=4.10-15 eV s	Planck's constant

Mass of electron	0.5 million eV (MeV)
Mass of proton	1 Giga eV (GeV)

1 eV ~ 10,000 K   1 GeV ~ 1 femtometre (fm) = 10^{-15}m

General Relativity depends on c and G (Newton's constant), QM depends on $\hbar$. Natural unit of length is given by is called Planck length ~ 10^{-35} m

$$\sqrt{\hbar G / c^3}$$

Фундаментални съставящи

1894 – 1897: Откритие на електрона

J.J. Thomson

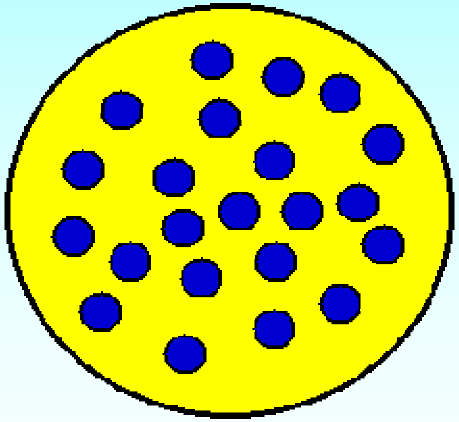
Study of "cathode rays": electric current in tubes at very low gas pressure ("glow discharge")

Measurement of the electron mass: m_e » $M_H/1836$

"Could anything at first sight seem more impractical than a body which is so small that its mass is an insignificant fraction of the mass of an atom of hydrogen?" (J.J. Thomson)

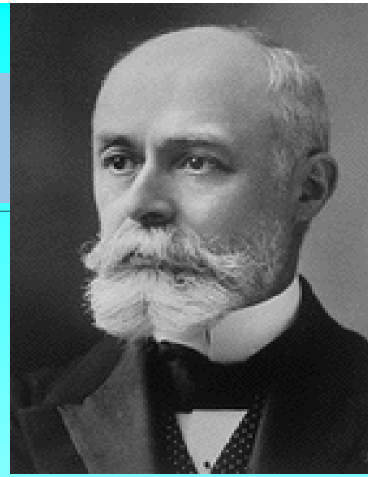
→ **ATOMS ARE NOT ELEMENTARY**

Thomson's atomic model:



- Electrically charged sphere
- Radius ~ 10^{-8} cm
- Positive electric charge
- Electrons with negative electric charge embedded in the sphere

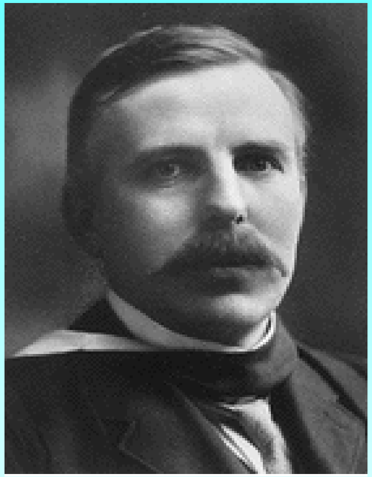
1896: Естествена радиоактивност



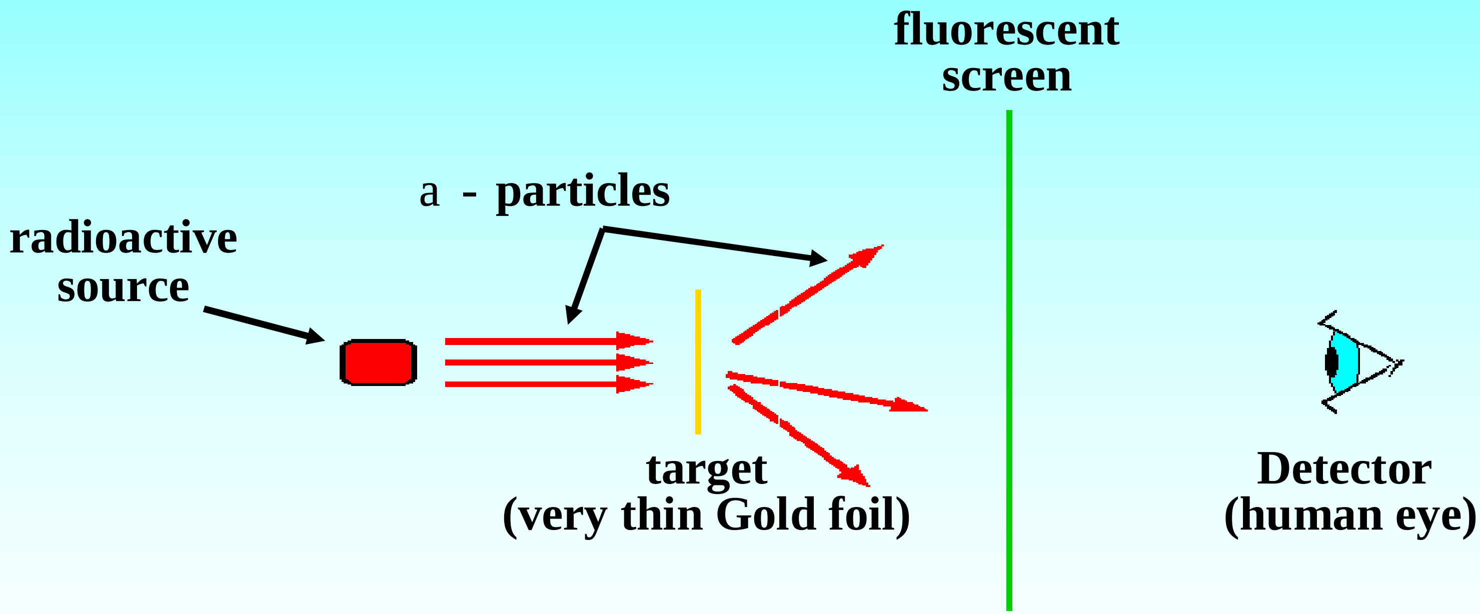
Henri Becquerel

1909 - 13: Rutherford's scattering experiments

Discovery of the atomic nucleus



Ernest Rutherford

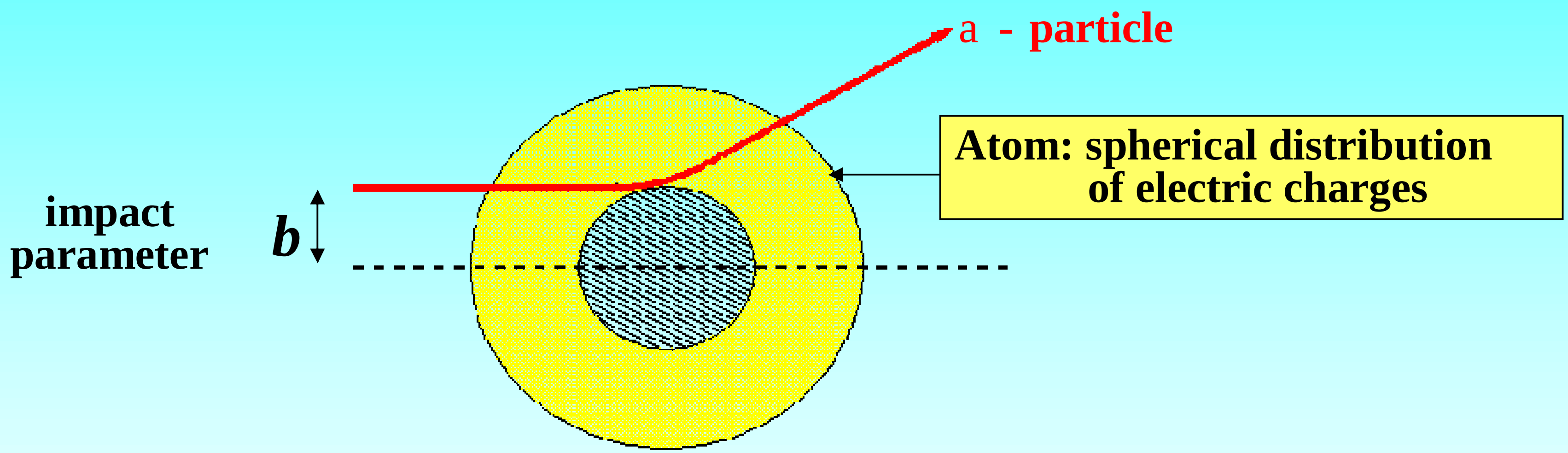


a - particles : nuclei of Helium atoms spontaneously emitted by heavy radioactive isotopes

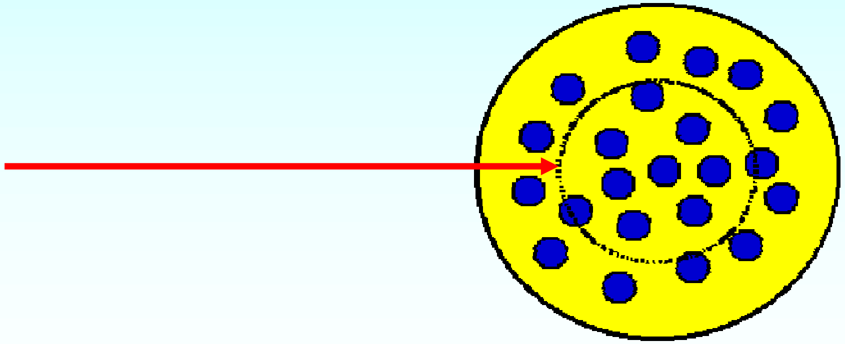
Typical a – particle velocity » 0.05 *c* (*c* : speed of light)

Опити на Ръдърфорд - очаквания

a – atom scattering at low energies is dominated by Coulomb interaction



For Thomson's atomic model the electric charge "seen" by the a – particle is zero, independent of impact parameter

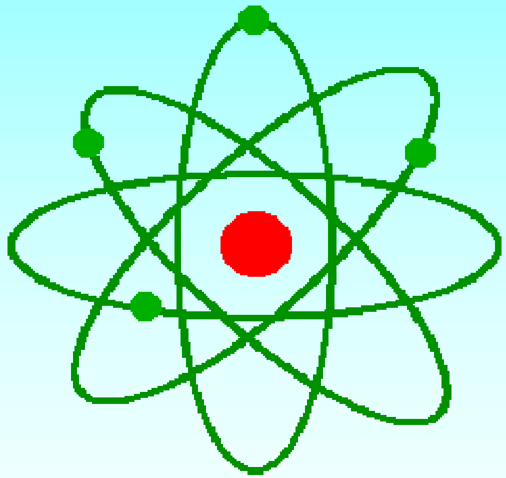


Þ no significant scattering at large angles is expected

Опити на Ръдърфорд - резултати

significant scattering of α – particles at large angles, consistent with scattering expected for a sphere of radius ≈ few x 10^{-13} cm and electric charge = ***Ze***, with ***Z*** = 79 (atomic number of gold) and ***e*** = |charge of the electron|

an atom consists of
a positively charged nucleus
surrounded by a cloud of electrons



Nuclear radius » 10^{-13} **cm** » 10^{-5} x **atomic radius**

Mass of the nucleus » mass of the atom
(to a fraction of 1‰)

Neutron: a particle with mass » proton mass
but with zero electric charge **(Chadwick, 1932)**

Solution to the nuclear structure problem:

Nucleus with atomic number *Z* and mass number *A*:
a bound system of *Z* protons and (*A* – *Z*) neutrons

James Chadwick

Nitrogen anomaly: no problem if neutron spin = ½ħ

Nitrogen nucleus (A = 14, Z = 7): 7 protons, 7 neutrons = 14 spin ½ particles
Þ **total spin has integer value**

Neutron source in Chadwick's experiments: a ^{210}Po radioactive source (5 MeV a – particles) mixed with Beryllium powder Þ emission of electrically neutral radiation capable of traversing several centimetres of Pb:

$$^{4}He_{2} + {}^{9}Be_{4} \text{ ® } {}^{12}C_{6} + \text{neutron}$$

-

α - particle

Принцип на Паули

In Quantum Mechanics the electron orbits around the nucleus are "quantized":
only some specific orbits (characterized by integer quantum numbers) are possible.

$$R_n = \frac{4\pi\varepsilon_0 \hbar^2 n^2}{me^2} \approx 0.53\times10^{-10} n^2 \text{ [m]}$$

$$E_n = -\frac{me^4}{2(4\pi\varepsilon_0)^2 \hbar^2 n^2} \approx -\frac{13.6}{n^2} \text{[eV]}$$

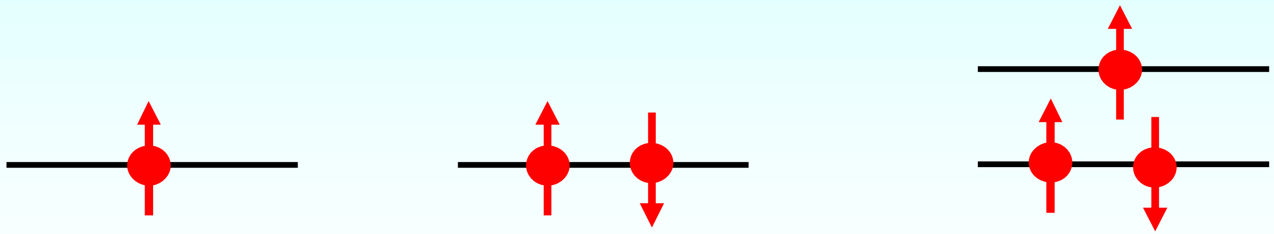
$m = m_e m_p/(m_e + m_p)$
$n = 1, 2, \ldots\ldots$

In atoms with $Z > 2$ only two electrons are found in the innermost orbit – WHY?

ANSWER (Pauli, 1925): two electrons (spin = ½) can never be in the same physical state

Hydrogen ($Z = 1$) **Helium ($Z = 2$)** **Lithium ($Z = 3$) .....**

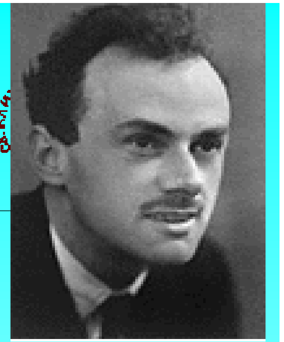
Lowest energy state →



Wolfgang Pauli

Pauli's exclusion principle applies to all particles with half-integer spin (collectively named Fermions)

Антиматерия



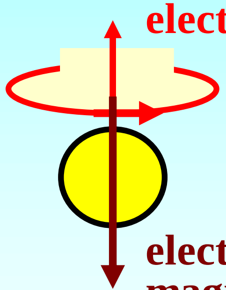
P.A.M. Dirac

Discovered "theoretically" by P.A.M. Dirac (1928)

Dirac's equation: a relativistic wave equation for the electron

Two surprising results:

§ Motion of an electron in an electromagnetic field:
presence of a term describing (for slow electrons) the potential energy of a magnetic dipole moment in a magnetic field
Þ existence of an intrinsic electron magnetic dipole moment opposite to spin

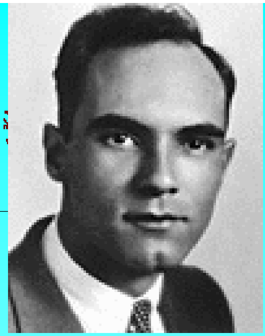


$$\mu_e = \frac{e\hbar}{2m_e} \approx 5.79 \times 10^{-5} \text{ [eV/T]}$$

§ For each solution of Dirac's equation with electron energy $E > 0$ there is another solution with $E < 0$

What is the physical meaning of these "negative energy" solutions ?

Експериментално наблюдение на антиматерия



Carl D. Anderson

(C.D. Anderson, 1932**)**

Measure particle momentum and sign of electric charge from magnetic curvature

<u>Detector</u>: a Wilson cloud – chamber (visual detector based on a gas volume containing vapour close to saturation) in a magnetic field, exposed to cosmic rays

⇒ projection of the particle trajectory in a plane perpendicular to $\vec{B}$ is a circle

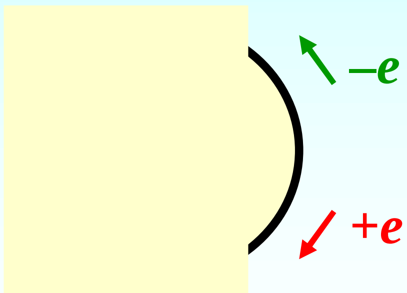
Lorentz force $$\vec{f} = e\vec{v} \times \vec{B}$$

Circle radius for electric charge |*e*|:

$$R\,[\mathrm{m}] = \frac{10\, p_{\perp}\,[\mathrm{GeV/c}]}{3B\,[\mathrm{T}]}$$

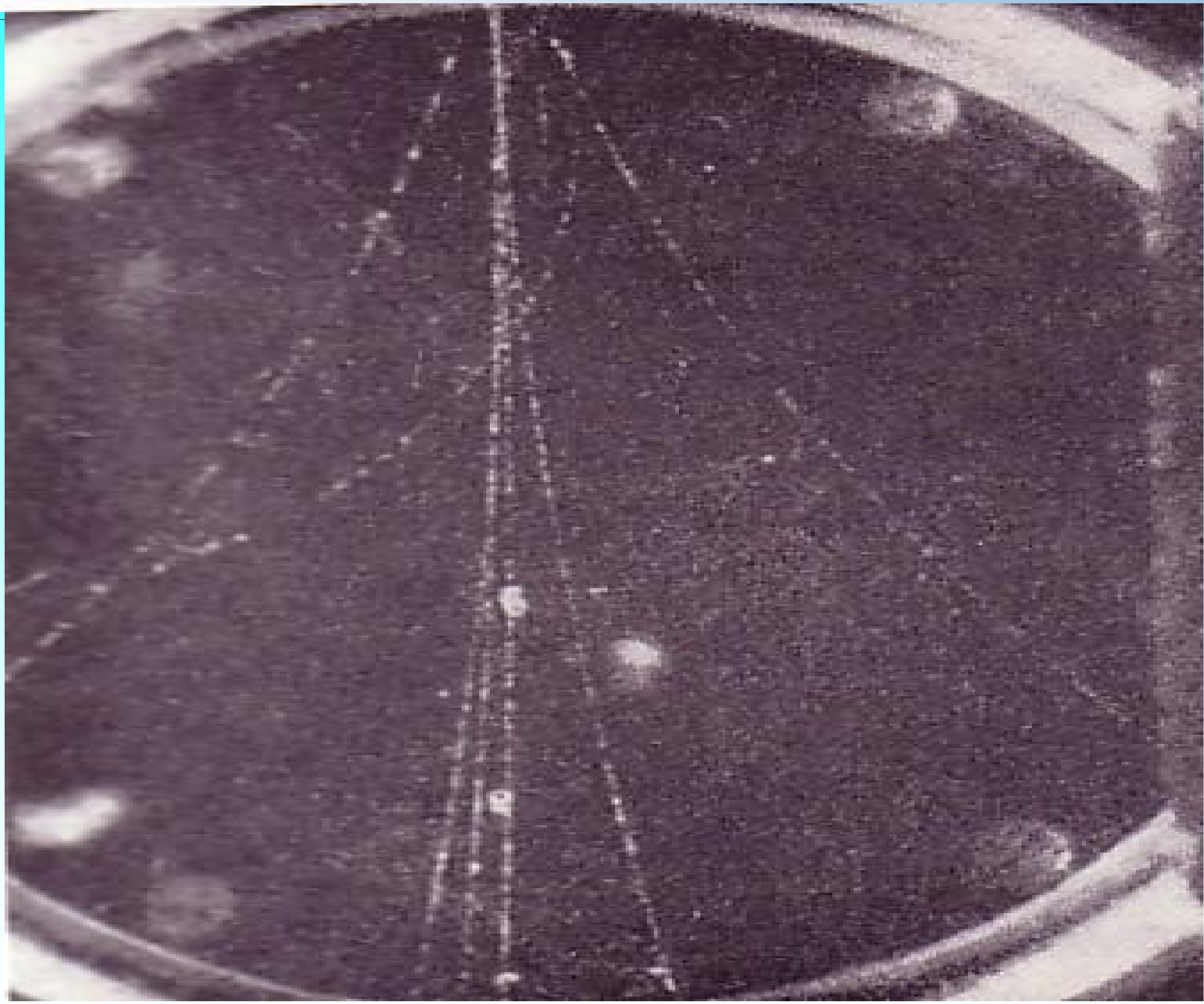
$p_{\perp}$: momentum component perpendicular to magnetic field direction

<u>NOTE</u>: impossible to distinguish between positively and negatively charged particles going in opposite directions



⇒ need an independent determination of the particle direction of motion

Experimental confirmation of antimatter



Cosmic-ray "shower" containing several $e^+ e^-$ pairs

December 1930: public letter sent by W. Pauli to a physics meeting in Tübingen

Zürich, Dec. 4, 1930

Dear Radioactive Ladies and Gentlemen,

...because of the "wrong" statistics of the N and ^{6}Li nuclei and the continuous β-spectrum, I have hit upon a desperate remedy to save 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 ½ and obey the exclusion principle ..... 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 β-spectrum would then become understandable by the assumption that in β-decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and electron is constant.

.... For the moment, however, I do not dare to publish anything on this idea ......

So, dear Radioactives, examine and judge it. Unfortunately I cannot appear in Tübingen personally, since I am indispensable here in Zürich because of a ball on the night of 6/7 December. ....

W. Pauli

Теория на β–разпада (V-A модел)

Enrico Fermi

b$^-$ **decay:** **n ® p + e$^-$ + $\bar{\text{n}}$**

b$^+$ **decay:** **p ® n + e$^+$ +** n (e.g., $^{14}O_8 \rightarrow {}^{14}N_7 + e^+ + \nu$)

n**: the particle proposed by Pauli**
(named "neutrino" by Fermi)
$\bar{\text{n}}$**: its antiparticle (antineutrino)**

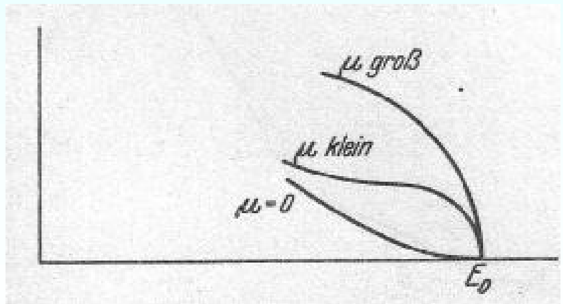
(E. Fermi, 1932-33)

Fermi's theory: a point interaction among four spin ½ particles, using the mathematical formalism of creation and annihilation operators invented by Jordan
Þ **particles emitted in** b **– decay need not exist before emission – they are "created" at the instant of decay**

Prediction of b **– decay rates and electron energy spectra as a function of only one parameter: Fermi coupling constant G_F (determined from experiments)**

Energy spectrum dependence on neutrino mass m
(from Fermi's original article, published in German on Zeitschrift für Physik, following rejection of the English version by Nature)

Measurable distortions for m > 0 **near the end-point**
(E_0 : max. allowed electron energy)

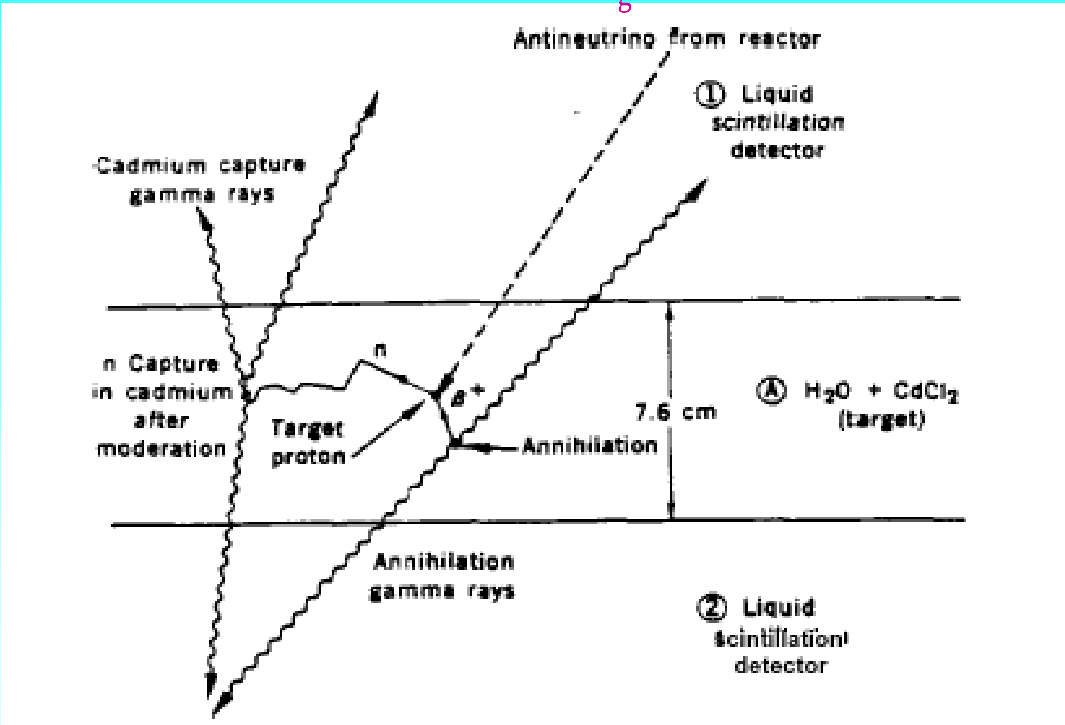


Наблюдение на неутриното

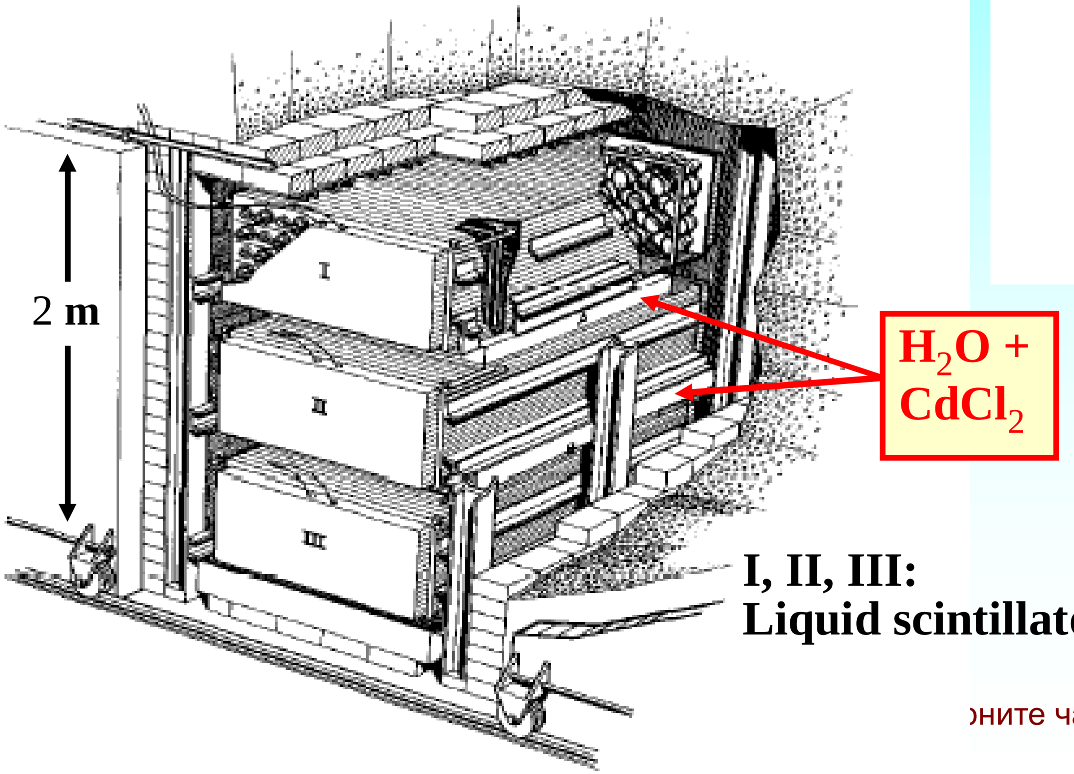
E_g = 0.5 MeV

$\bar{n}$ + p ® e^+ + n

- § detect 0.5 MeV g-rays from e^+e^- ® g g (t = 0)
- § neutron "thermalization" followed by capture in Cd nuclei Þ emission of delayed g-rays (average delay ~30 ms)



(Reines, Cowan 1953)



I, II, III: Liquid scintillator

Event rate at the Savannah River nuclear power plant:

3.0 ± 0.2 **events / hour**

(after subracting event rate measured with reactor OFF)

in agreement with expectations

1947: Откритие на π-мезон

Observation of the p$^+$ ® m$^+$ ® e$^+$ decay chain in
exposed to cosmic rays at high altitudes

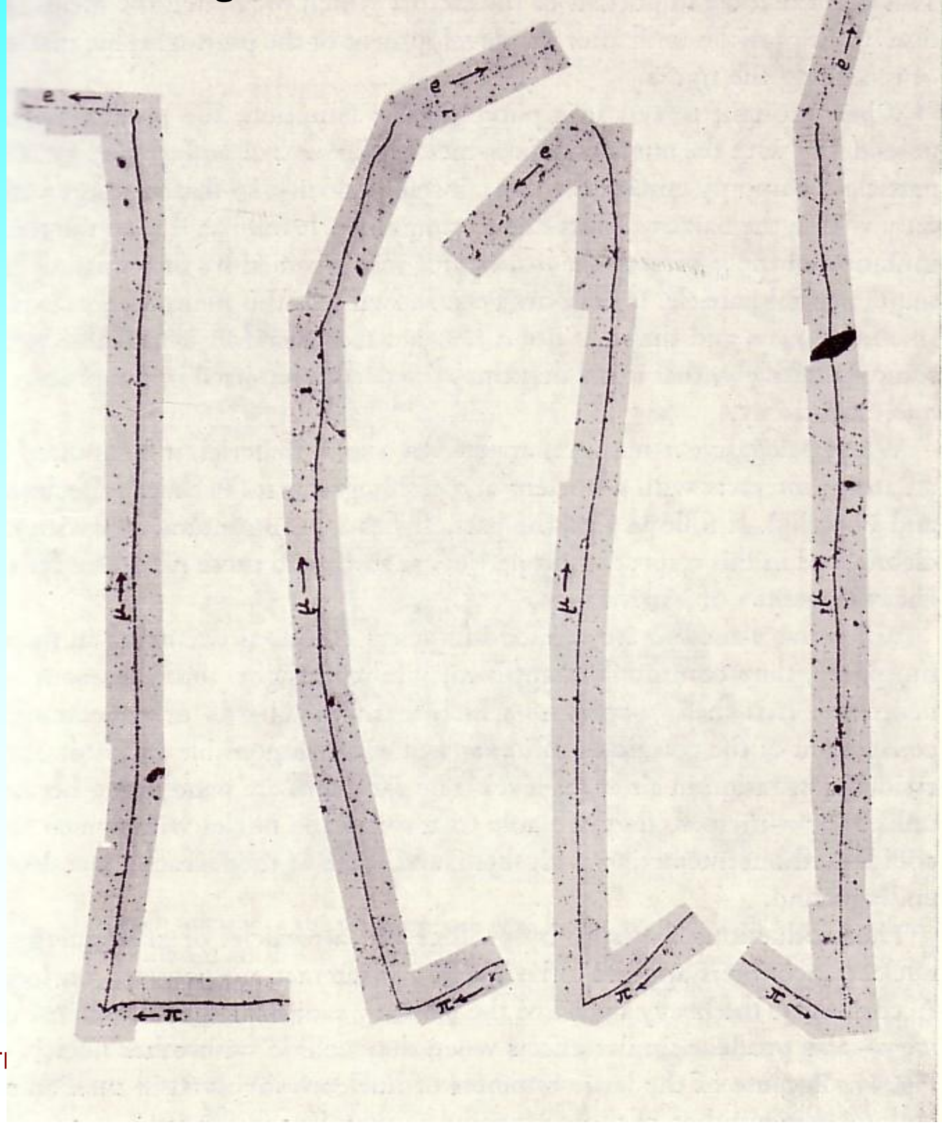
In all events the muon has a fixed kinetic energy (4.1 MeV, corresponding to a range of ~ 600 mm in nuclear emulsion) Þ two-body decay

m_p = 139.57 MeV/c^2 ; spin = 0
Dominant decay mode: p$^+$ ® m$^+$ + n
(and p$^-$ ® m$^-$ + $\bar{n}$)
Mean life at rest: t_p = 2.6 x 10^{-8} s = 26 ns

A neutral p – meson (p°) also exists:
m (p°) = 134. 98 MeV /c^2
Decay: p° ® g + g , mean life = 8.4 x 10^{-17} s

p – mesons are the most copiously produced particles in proton – proton and proton – nucleus collisions at high energies

Four events showing the decay of a p$^+$ coming to rest in nuclear emulsion



Запазващи се квантови числа

Possible proton decay modes (allowed by all known conservation laws: energy – momentum, electric charge, angular momentum):

p ® p° + $\mathbf{e}^{+}$
p ® p° + m^{+}
p ® p^{+} + n
. . . . .

Why is the free proton stable?

No proton decay ever observed – the proton is STABLE

Limit on the proton mean life: $t_{\mathbf{p}} > 1.6 \times 10^{32}$ **years**

Invent a new quantum number : "Baryonic Number" B

B = 1 for proton, neutron

B = -1 for antiproton, antineutron

B = 0 for $e^{\pm}$, $m^{\pm}$, neutrinos, mesons, photons

Require conservation of baryonic number in all particle processes:

$$\sum_{i} B_i = \sum_{f} B_f$$

(***i*** **:** initial state particle ; ***f*** **:** final state particle)

Странност

<u>Late 1940's</u>: **discovery of a variety of heavier mesons (K – mesons) and baryons ("hyperons") – studied in detail in the 1950's at the new high-energy proton synchrotrons (the 3 GeV "cosmotron" at the Brookhaven National Lab and the 6 GeV Bevatron at Berkeley)**

Mass values

Mesons (spin = 0): m(K$^{\pm}$) = 493.68 MeV/c^2 ; m(K$^{\circ}$) = 497.67 MeV/c^2

Hyperons (spin = ½): m(L) = 1115.7 MeV/c^2 ; m(S$^{\pm}$) = 1189.4 MeV/c^2

m(X°) = 1314.8 MeV/c^2; m(X^{-}) = 1321.3 MeV/c^2

Properties

- § **Abundant production in proton – nucleus , p – nucleus collisions**
- § **Production cross-section typical of strong interactions (s > 10^{-27} cm^2)**
- § **Production in pairs (example: p^{-} + p ® K° + L ; K^{-} + p ® X^{-} + K^{+})**
- § **Decaying to lighter particles with mean life values 10^{-8} – 10^{-10} s (as expected for a weak decay)**

Examples of decay modes

K$^{\pm}$ ® p$^{\pm}$ p° ; **K**$^{\pm}$ ® p$^{\pm}$ p^{+}p^{-} ; **K**$^{\pm}$ ® p$^{\pm}$ p° p° ; **K°** ® p^{+}p^{-} ; **K°** ® p° p° ; . . .

L ® **p** p^{-} ; L ® **n** p° ; S^{+} ® **p** p° ; S^{+} ® **n** p^{+} ; S^{+} ® **n** p^{-} ; . . .

X^{-} ® L p^{-} ; X° ® L p°

Странност

(Gell-Mann, Nakano, Nishijima, 1953)

$$\sum_i S_i = \sum_f S_f$$

§ conserved in strong interaction processes:

§ not conserved in weak decays:

$$\left| S_i - \sum_f S_f \right| = 1$$

S = +1: K⁺, K° ; S = –1: L, S±, S° ; S = –2 : X°, X⁻ ; S = 0 : all other particles

(and opposite strangeness –S for the corresponding antiparticles)

Example of a K⁻ stopping in liquid hydrogen:

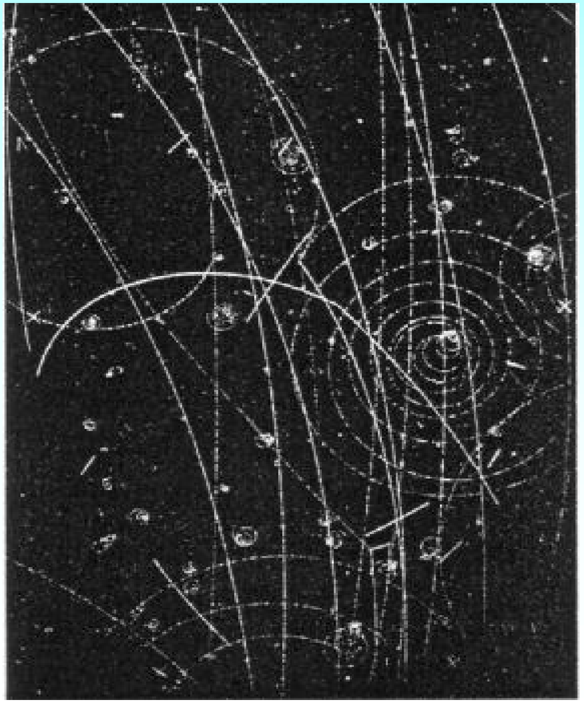
K⁻ + p ® L + p°

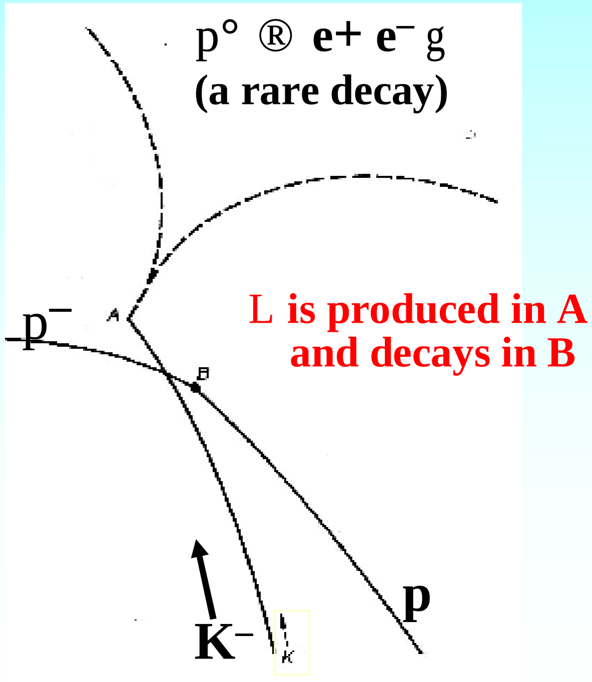
(strangeness conserving)

followed by the decay

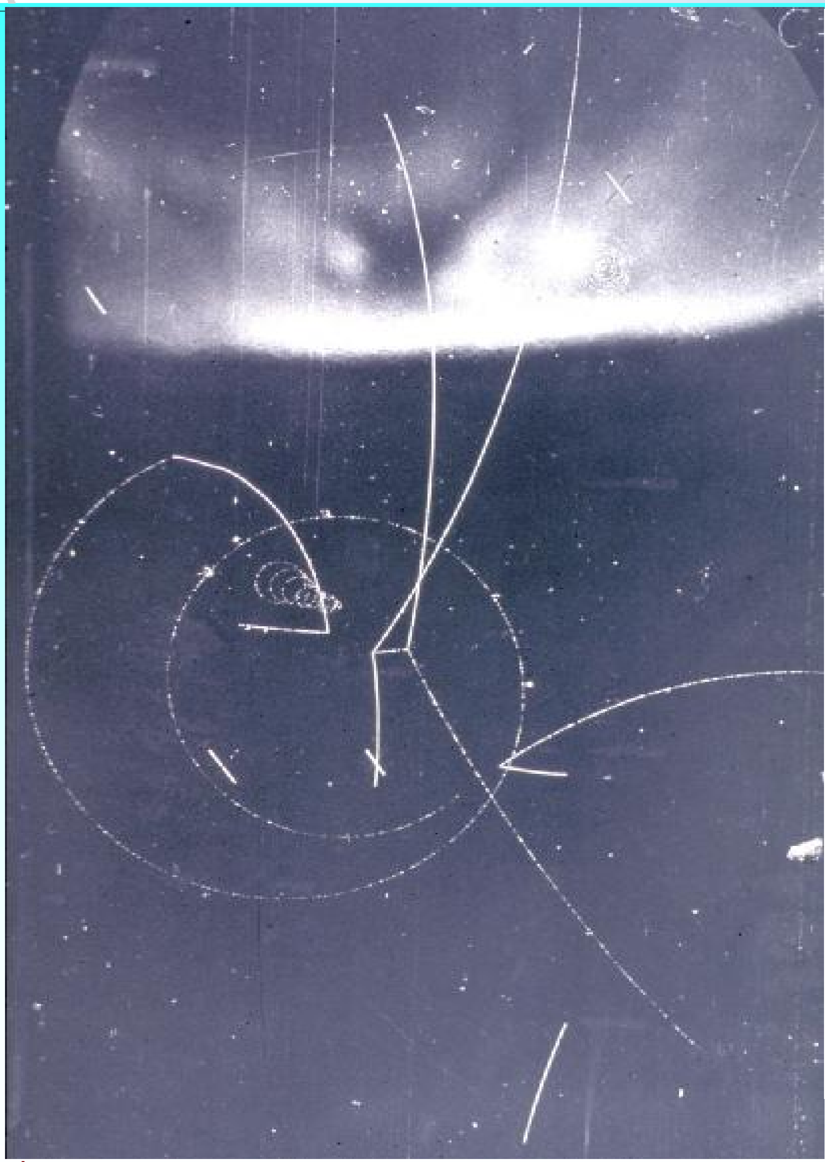
L ® **p** + p⁻

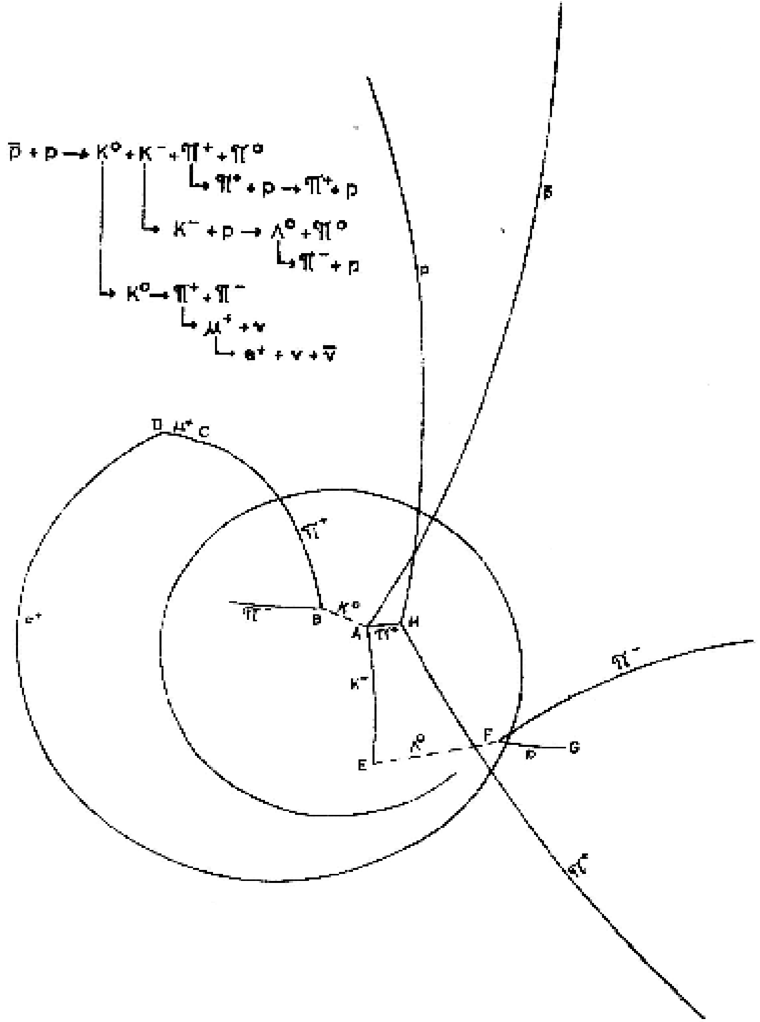
(strangeness violation)





Откритие на антипротона





Лептонно число

A puzzle of the late 1950's: the absence of $\mu \to e \gamma$ decays

Experimental limit: < 1 in 10^6 $\mu^+ \to e^+ \nu \bar{\nu}$ decays

A possible solution: existence of a new, conserved "muonic" quantum number distinguishing muons from electrons

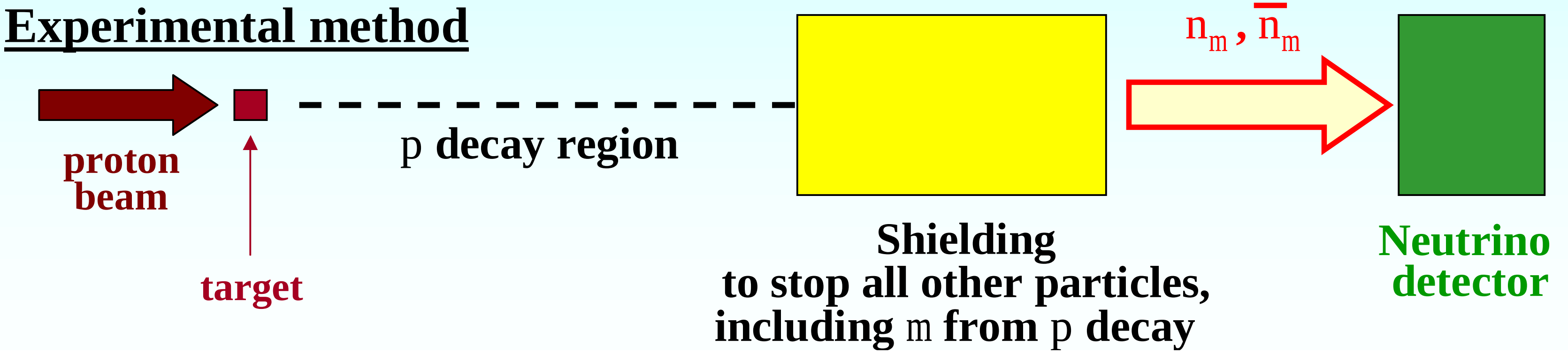
To allow $\mu^+ \to e^+ \nu \bar{\nu}$ decays, $\bar{\nu}$ must have "muonic" quantum number but not ν $\Rightarrow$ in μ^+ decay the $\bar{\nu}$ is not the antiparticle of ν

$\Rightarrow$ two distinct neutrinos (ν_e, ν_μ) in the decay $\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$

Consequence for π – meson decays: $\pi^+ \to \mu^+ \nu_\mu$; $\pi^- \to \mu^- \bar{\nu}_\mu$
to conserve the "muonic" quantum number

High energy proton accelerators: intense sources of $\pi^\pm$ – mesons $\Rightarrow$ ν_μ, $\bar{\nu}_\mu$

<u>Experimental method</u>



If $\nu_\mu \neq \nu_e$, ν_μ interactions produce μ^- and not e^- (example: $\nu_\mu + n \to \mu^- + p$)

Кварков модел

Late 1950's – early 1960's: discovery of many strongly interacting particles at the high energy proton accelerators (Berkeley Bevatron, BNL AGS, CERN PS), all with very short mean life times (10^{-20} – 10^{-23} s, typical of strong decays)

Þ catalog of > 100 strongly interacting particles (collectively named "hadrons")

ARE HADRONS ELEMENTARY PARTICLES?

1964 (Gell-Mann, Zweig): Hadron classification into "families"; observation that all hadrons could be built from three spin ½ "building blocks" (named "quarks" by Gell-Mann):

	u	d	s
Electric charge (units $\|e\|$)	+2/3	-1/3	-1/3
Baryonic number	1/3	1/3	1/3
Strangeness	0	0	-1

and three antiquarks ($\bar{u}$, $\bar{d}$, $\bar{s}$) with opposite electric charge and opposite baryonic number and strangeness

Кварков модел

Mesons: quark – antiquark pairs

Examples of non-strange mesons:

$$p^{+} \equiv u\bar{d} \quad ; \quad p^{-} \equiv \bar{u}d \quad ; \quad p^{0} \equiv (d\bar{d} - u\bar{u})/\sqrt{2}$$

Examples of strange mesons:

$$K^{-} \equiv s\bar{u} \quad ; \quad \bar{K}^{0} \equiv s\bar{d} \quad ; \quad K^{+} \equiv \bar{s}u \quad ; \quad K^{0} \equiv \bar{s}d$$

Baryons: three quarks bound together

Antibaryons: three antiquarks bound together

Examples of non-strange baryons:

$$\text{proton} \equiv uud \quad ; \quad \text{neutron} \equiv udd$$

Examples of strangeness –1 baryons:

$$\Sigma^{+} \equiv suu \quad ; \quad \Sigma^{0} \equiv sud \quad ; \quad \Sigma^{-} \equiv sdd$$

Examples of strangeness –2 baryons:

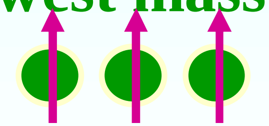
$$\Xi^{0} \equiv ssu \quad ; \quad \Xi^{-} \equiv ssd$$

A success of the static quark model

The "decuplet" of spin $\frac{3}{2}$ baryons

Strangeness					Mass (MeV/c^2)
0	N^{*++} *uuu*	N^{*+} *uud*	$N^{*\circ}$ *udd*	N^{*-} *ddd*	1232
–1	S^{*+} *suu*	$S^{*\circ}$ *sud*	S^{*-} *sdd*		1384
–2	$X^{*\circ}$ *ssu*	X^{*-} *ssd*			1533
–3	W^- *sss*				1672 **(predicted)**

W^-: the bound state of three *s* – quarks with the lowest mass with total angular momentum = 3/ 2 Þ



Pauli's exclusion principle requires that the three quarks cannot be identical

A success of the static quark model

<u>The first W⁻ event</u> (observed in the 2 m liquid hydrogen bubble chamber at BNL using a 5 GeV/c K⁻ beam from the 30 GeV AGS)

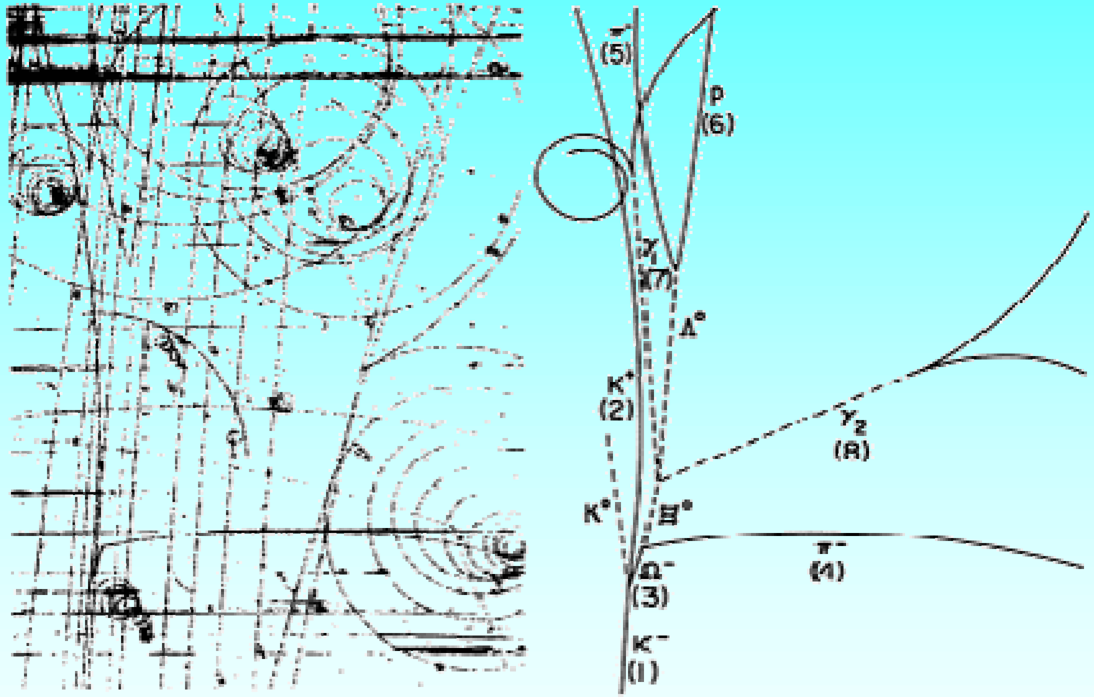
Chain of events in the picture:

K^- + p ® W⁻ + K^+ + K°
(strangeness conserving)

W⁻ ® X° + p⁻
(DS = 1 weak decay)

X° ® p° + L
(DS = 1 weak decay)

L ® p⁻ + **p**
(DS = 1 weak decay)



p° ® g + g **(electromagnetic decay)**
with both g – rays converting to an e^+e^- in liquid hydrogen
(very lucky event, because the mean free path for g ® e^+e^- in liquid hydrogen is ~10 m)

W⁻ mass measured from this event = 1686 ± 12 MeV/c^2

Дълбоко нееластично разсейване

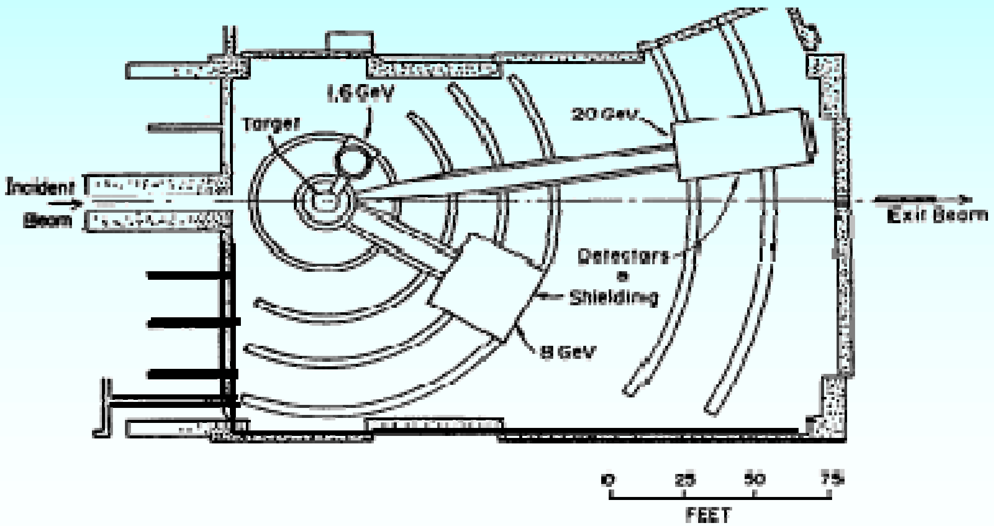
Electron – proton scattering using a 20 GeV electron beam from the Stanford two – mile Linear Accelerator (1968 – 69).

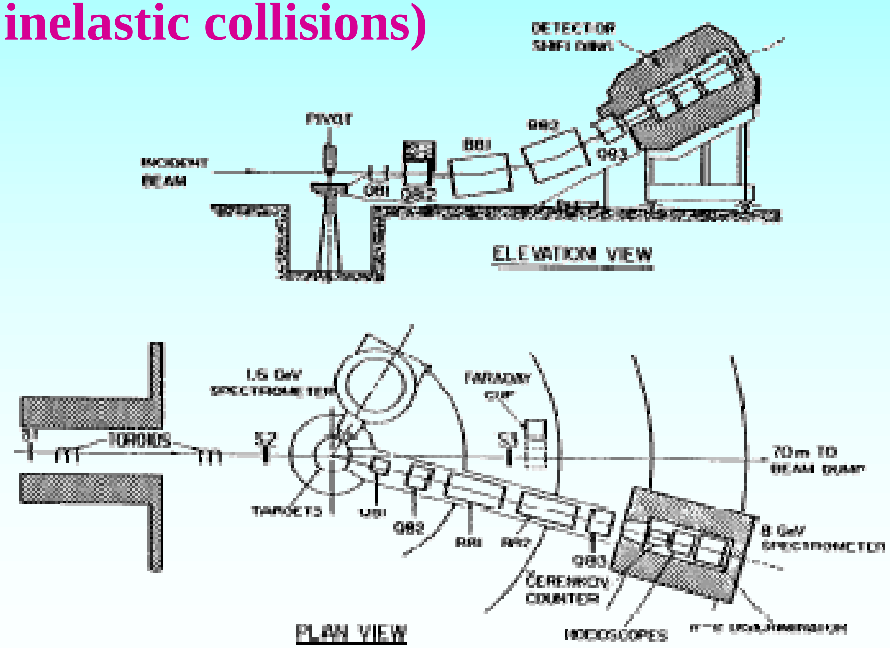
The modern version of Rutherford's original experiment:

resolving power » wavelength associated with 20 GeV electron » 10^{-15} cm

Three magnetic spectrometers to detect the scattered electron:

- **20 GeV spectrometer (to study elastic scattering $e^- + p$ ® $e^- + p$)**
- **8 GeV spectrometer (to study inelastic scattering $e^- + p$ ® e^- + hadrons)**
- **1.6 GeV spectrometer (to study extremely inelastic collisions)**





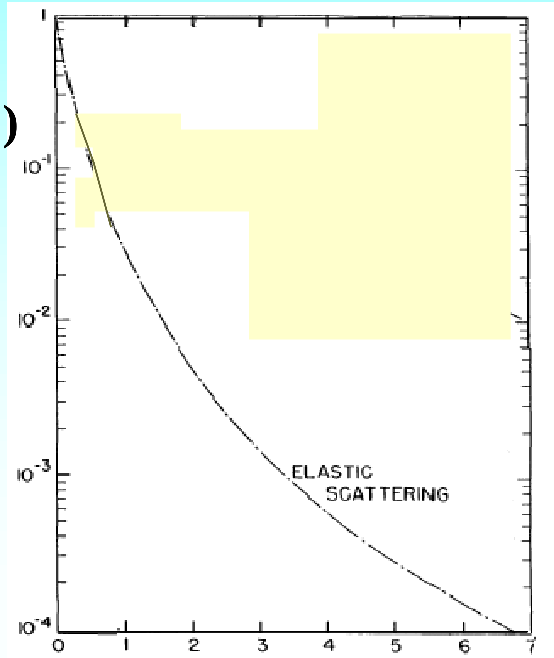
Дълбоко нееластично разсейване

Electron elastic scattering from a point-like charge |*e*| at high energies: differential cross-section in the collision centre-of-mass (Mott's formula)

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2 (\hbar c)^2}{8E^2} \frac{\cos^2(\theta/2)}{\sin^4(\theta/2)} \equiv \sigma_M \qquad \left(\alpha = \frac{e^2}{\hbar c} \approx \frac{1}{137} \right)$$

Scattering from an extended charge distribution: multiply s$_M$ by a "form factor":

$F(|Q^2|)$



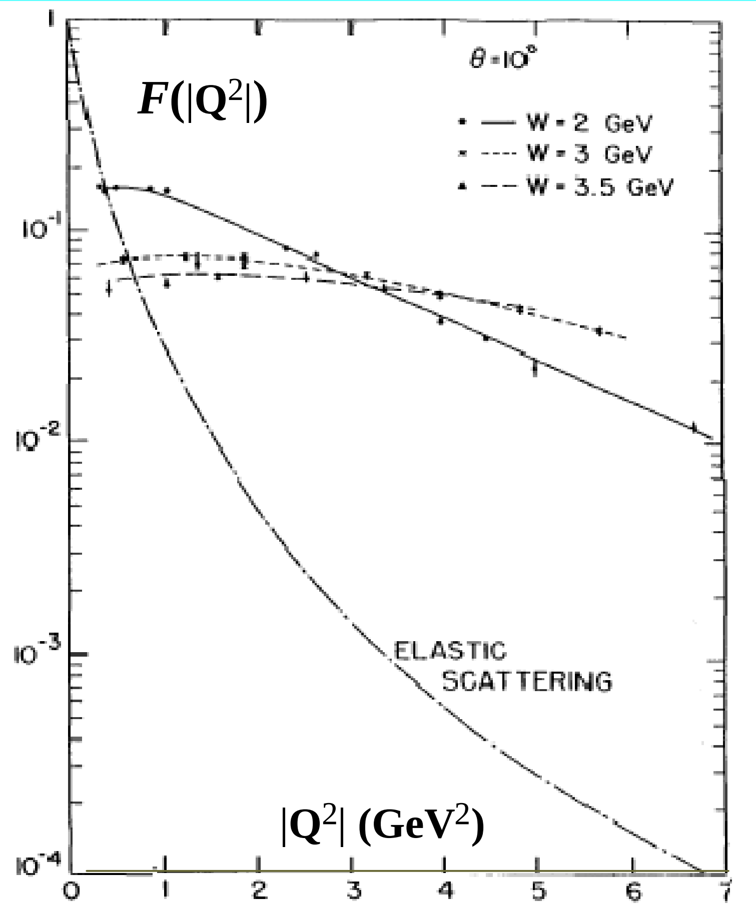
$|Q^2|$ (GeV^2)

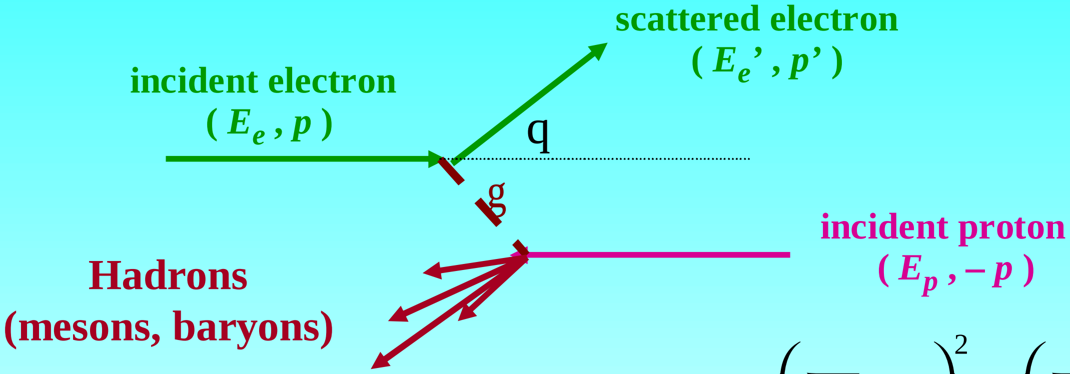
$$\frac{d\sigma}{d\Omega} = F(|Q^2|)\sigma_M$$

|Q| = ħ / D : mass of the exchanged virtual photon
D: linear size of target region contributing to scattering
Increasing |Q| Þ decreasing target electric charge

***F* (|Q²|) = 1 for a point-like particle**
Þ the proton is not a point-like particle

Дълбоко нееластично разсейване





Total hadronic energy : $W^2 = \left(\sum_i E_i\right)^2 - \left(\sum_i \vec{p}_i\right)^2 c^2$

For deeply inelastic collisions, the cross-section depends only weakly on $|Q^2|$, suggesting a collision with a <u>POINT-LIKE</u> object

Партонен модел

Deep inelastic electron – proton collisions are elastic collisions with point-like, electrically charged, spin ½ constituents of the proton carrying a fraction *x* of the incident proton momentum

Each constituent type is described by its electric charge e_i (units of $|e|$) and by its *x* distribution (dN_i/dx) ("structure function")

If these constituents are the *u* and *d* quarks, then deep inelastic e – p collisions provide information on a particular combination of structure functions:

$$\left(\frac{dN}{dx}\right)_{\mathrm{e-p}} = e_u{}^2 \frac{dN_u}{dx} + e_d{}^2 \frac{dN_d}{dx}$$

Comparison with n_m – p and $\overline{n}_m$ – p deep inelastic collisions at high energies under the assumption that these collisions are also elastic scatterings on quarks

n_m + **p** ® m^- + **hadrons :** n_m + ***d*** ® m^- + ***u*** **(depends on dN_d/dx)**

$\overline{n}_m$ + **p** ® m^+ + **hadrons :** $\overline{n}_m$ + ***u*** ® m^+ + ***d*** **(depends on dN_u/dx)**

(Neutrino interactions do not depend on electric charge)

All experimental results on deep inelastic e – p , n_m – p, n_m – $\overline{\mathrm{p}}$ collisions are consistent with $e_u^2 = 4/9$ and $e_d^2 = 1/9$

→ the proton constituents are the quarks

Цвят

Problem with

J=3/2 barion $\Delta^{++} \Rightarrow u\uparrow u\uparrow u\uparrow$

It has symmetric wave function, but it is a fermion

Contradiction with Pauli exclusion principle –

the wave function should be antisymmetric

The way out - new quantum number – colour

$N_c = 3$ q^{α} , $\alpha = 1,2,3$

Then

$$\Delta^{++} = \frac{1}{\sqrt{6}} e^{abg} u_a \uparrow u_b \uparrow u_g \uparrow$$

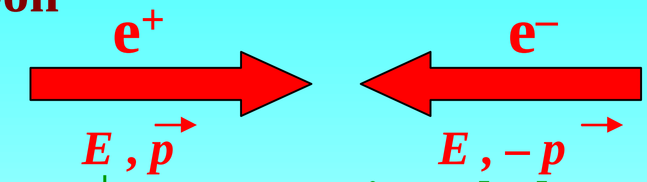
In general case

$$B = \frac{1}{\sqrt{6}} e^{abg} \,|\, q_a q_b q_g >$$

$$M = \frac{1}{\sqrt{3}} d^{ab} \,|\, q_a \bar{q}_b >$$

Експериментална проверка на хипотезата за цвят

Two beams circulating in opposite directions in the same magnetic ring and colliding head-on



A two-step process: $e^+ + e^- \rightarrow$ virtual photon $\rightarrow f + \bar{f}$

f **: any electrically charged elementary spin ½ particle (μ , quark)**

(excluding e^+e^- elastic scattering)

Virtual photon energy – momentum : $E_\gamma = 2E$, $p_\gamma = 0 \Rightarrow Q^2 = E_\gamma^2 - p_\gamma^2 c^2 = 4E^2$

Cross - section for $e^+e^- \rightarrow f\bar{f}$:

$$\sigma = \frac{2\pi\alpha^2\hbar^2c^2}{3Q^2} e_f^2 \beta(3-\beta)$$

$\alpha = e^2/(\hbar c) \approx 1/137$

e_f **: electric charge of particle f (units |*e* |)**

$\beta = v/c$ **of outgoing particle *f***

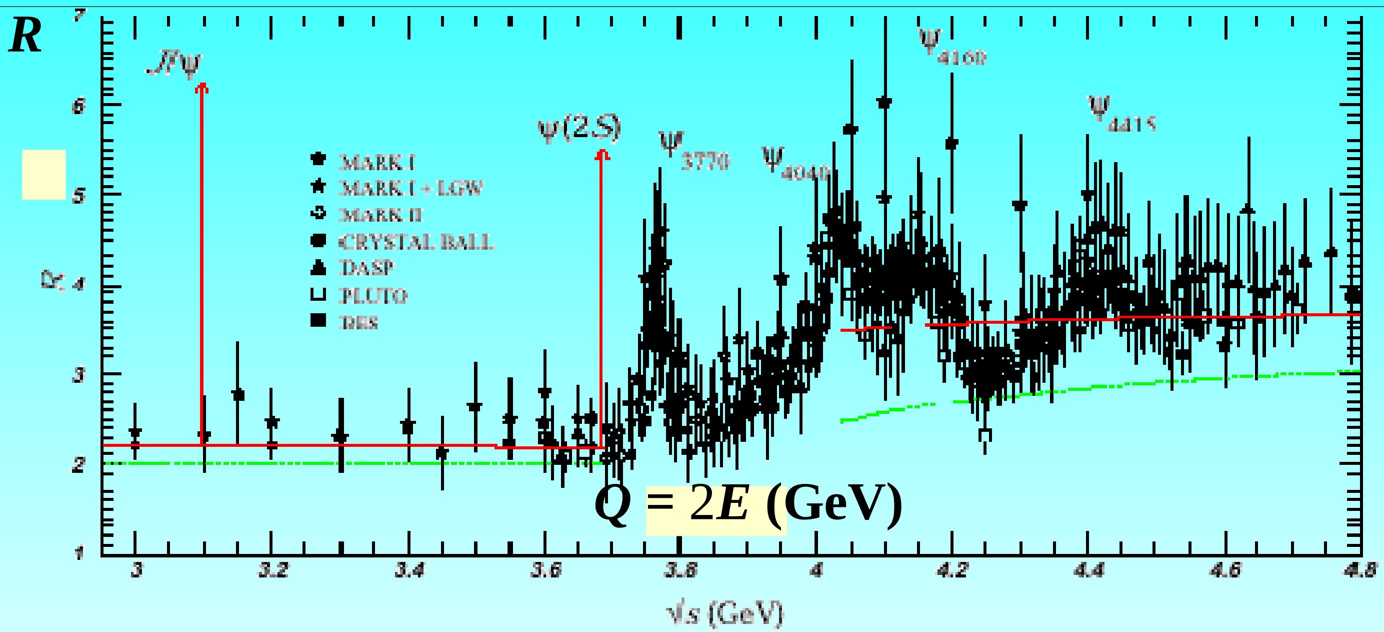
(formula precisely verified for $e^+e^- \rightarrow \mu^+\mu^-$)

Assumption: $e^+e^- \rightarrow$ quark (q) + antiquark ($\bar{q}$) $\rightarrow$ hadrons

$\Rightarrow$ **at energies $E >> m_q c^2$ (for $q = u , d , s$)** $\beta \approx 1$**:**

$$R \equiv \frac{\sigma(e^+e^- \rightarrow \text{hadrons})}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)} = e_u^2 + e_d^2 + e_s^2 = \frac{4}{9} + \frac{1}{9} + \frac{1}{9} = \frac{2}{3}$$

Stanford e^+e^- collider SPEAR (1974 –75):

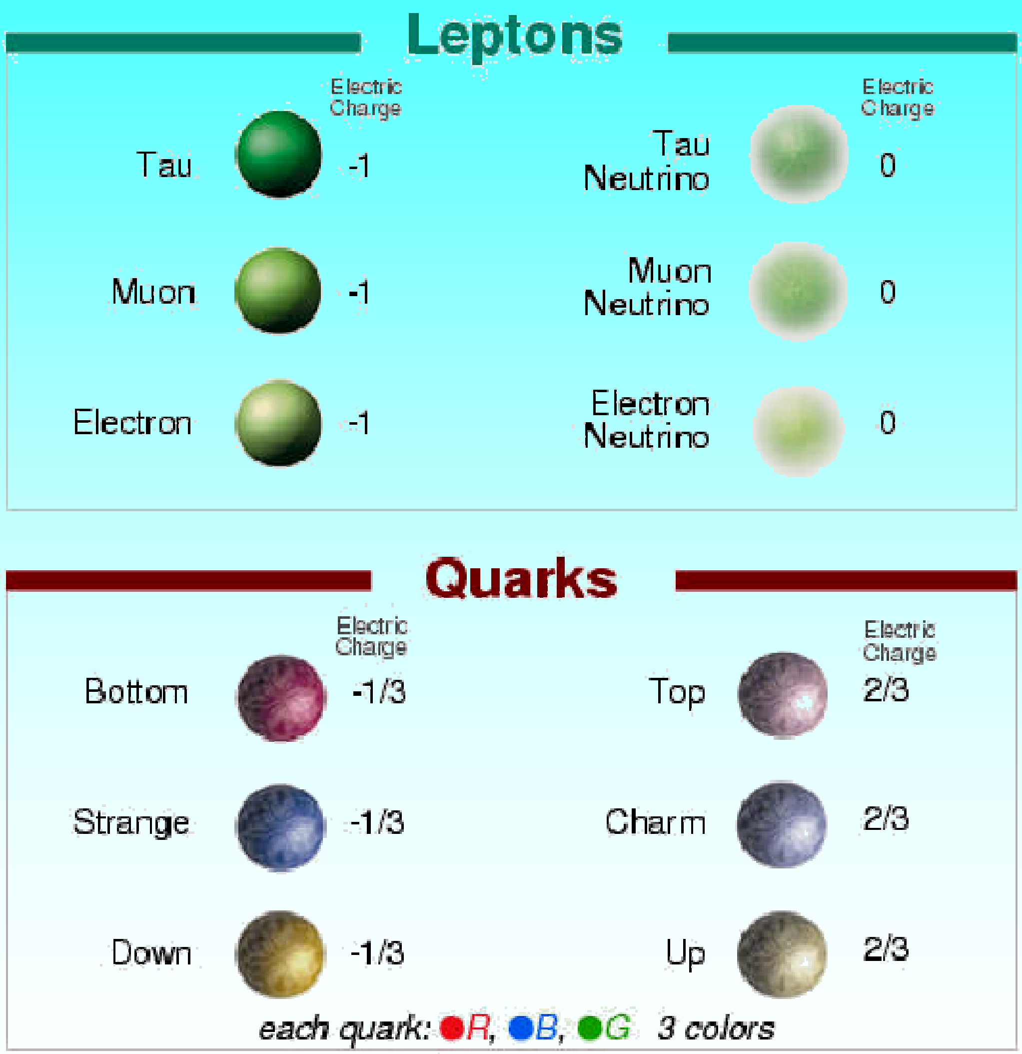


§ **For *Q* < 3. 6 GeV *R* » 2. If each quark exists in three different states, *R* » 2 is consistent with 3 x (2 / 3). This would solve the W⁻ problem.**

§ **Between 3 and 4.5 GeV, the peaks and structures are due to the production of quark-antiquark bound states and resonances of a fourth quark ("charm", *c*) of electric charge +2/3**

§ **Above 4.6 GeV *R* » 4.3. Expect *R* » 2 (from *u, d, s*) + 3 x (4 / 9) = 3.3 from the addition of the *c* quark alone. So the data suggest pair production of an additional elementary spin ½ particle with electric charge = 1 (later identified as the t – lepton (no strong interaction) with mass » 1777 MeV/c^2).**

Фундаментални частици



The particle drawings are simple artistic representations