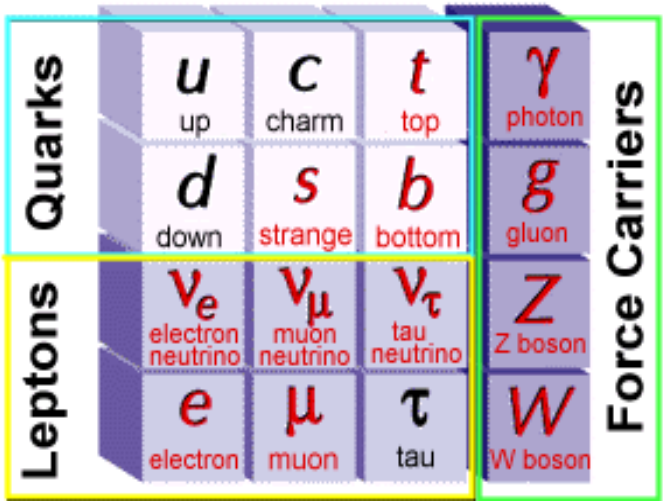
6th Croatian Teachers Programme
CERN, 25-27.3.2024.

Uvod u Fiziku elementarnih čestica



Vuko Brigljević
Institut Ruđer Bošković, Zagreb
CMS Kolaboracija (CERN)

Standard Model of
FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."

FERMIONS

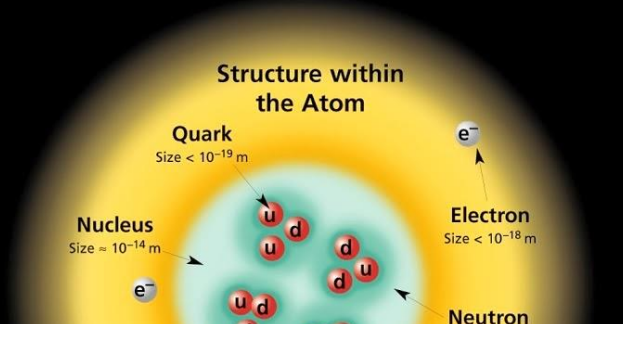
matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	−1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	−1
ν_τ tau neut		
τ tau		

Quarks spin = 1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	−1/3
c charm	1.3	2/3
s strange	0.1	−1/3



BOSONS

force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	−1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Color Charge
Each quark carries one of three types of "strong charge," also called "color charge." These charges have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons. Just as electrically-charged particles interact by exchanging photons, in strong interactions color-charged par- strong

Spin is the quantum u

Electric ch the proton

The **energy** tron in cross $E = mc^2$), w $= 1.67\times10^{-2}$

residual esidual elec- so be

Što znamo o temeljnoj građi svemira

Baryo

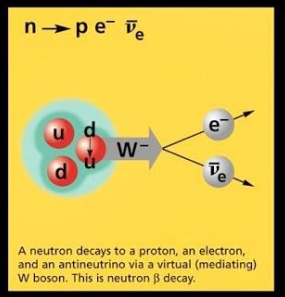
Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	−1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	−1	1.672	3/2

Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
Strength relative to electromag for two u quarks at: 3×10^{-17} m	10^{-41}	10^{-4}	1	60	
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

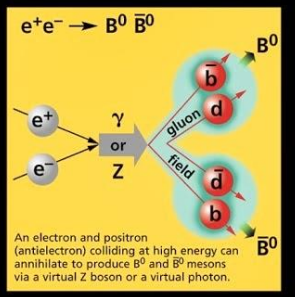
Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	−1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2 .980	0

Matter and Antimatter
For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or − charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z^0, γ, and $\eta_c = c\bar{c}$, but not $K^0 = d\bar{s}$) are their own antiparticles.

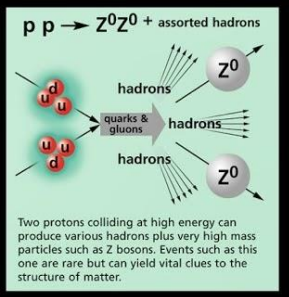
Figures
These diagrams are an artist's conception of physical processes. They are ***not*** exact and have ***no*** meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.



A neutron decays to a proton, an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β decay.



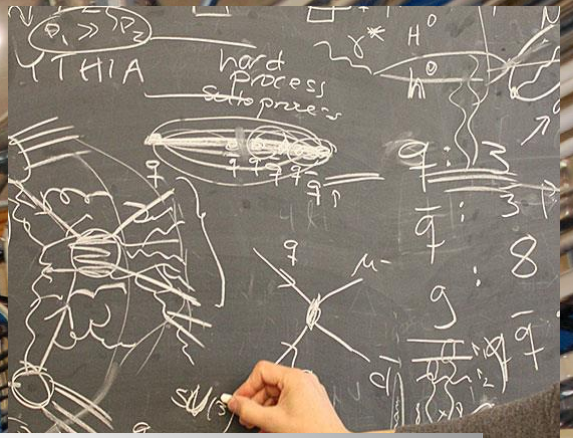
An electron and positron (antielectron) colliding at high energy can annihilate to produce B^0 and $\bar{B}^0$ mesons via a virtual Z boson or a virtual photon.



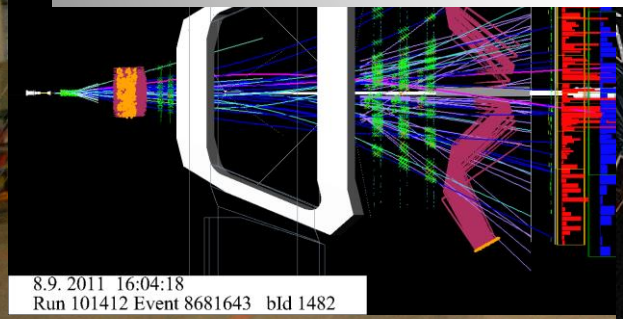
Two protons colliding at high energy can produce various hadrons plus very high mass particles such as Z bosons. Events such as this one are rare but can yield vital clues to the structure of matter.

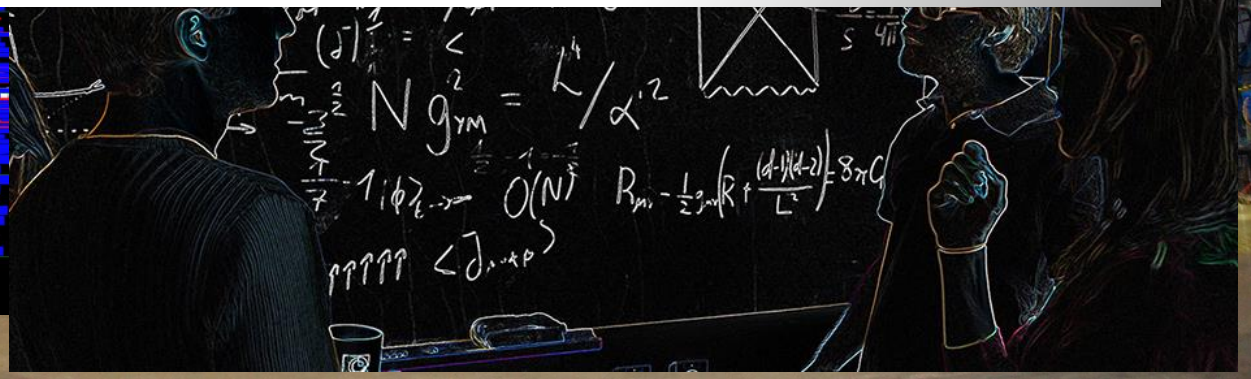
The Particle Adventure
Visit the award-winning web feature *The Particle Adventure* at
http://ParticleAdventure.org

This chart has been made possible by the generous support of:
U.S. Department of Energy
U.S. National Science Foundation
Lawrence Berkeley National Laboratory
Stanford Linear Accelerator Center
American Physical Society, Division of Particles and Fields
BURLE INDUSTRIES, INC.

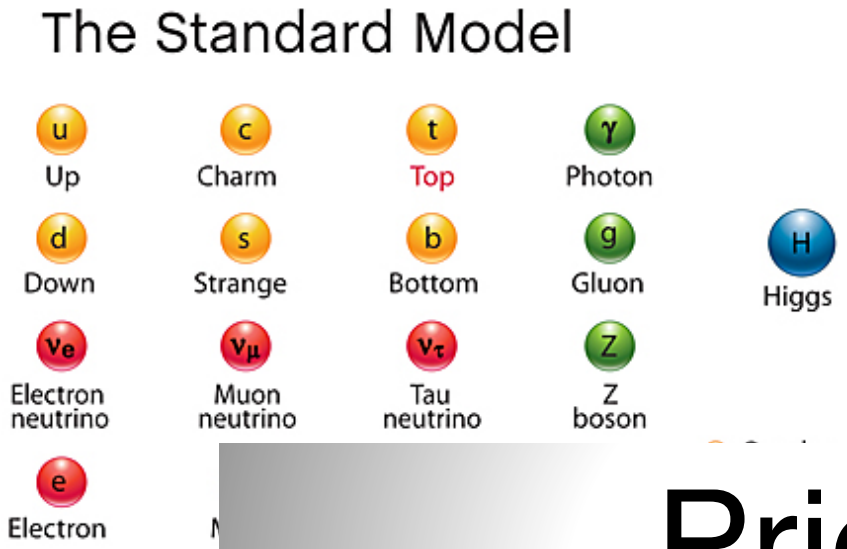


Preko 100 godina plodonosne suradnje Teorije i Eksperimenta





Koja su otvorena pitanja?



Pričam profesorima fizike

$$-I_f^3\gamma_5)\Psi_f Z_\mu +$$

$$\partial_\nu W_\mu^+ +$$

$$-ie(W_\mu^+ A_\nu - W_\nu^+ A_\mu) + ig' c_w (W_\mu^+ Z_\nu - W_\nu^+ Z_\mu|^2 +$$

$$-\frac{1}{4}|\partial_\mu Z_\nu - \partial_\nu Z_\mu + ig' c_w (W_\mu^- W_\nu^+ - W_\mu^+ W_\nu^-)|^2 +$$

$$-\frac{1}{2}M_\eta^2\eta^2 - \frac{gM_\eta^2}{8M_W}\eta^3 - \frac{g'^2 M_\eta^2}{32M_W}\eta^4 + |M_W W_\mu^+ + \frac{g}{2}\eta W_\mu^+|^2 +$$

$$+\frac{1}{2}|\partial_\mu \eta + iM_Z Z_\mu + \frac{ig}{2c_w}\eta Z_\mu|^2 - \sum_f \frac{g}{2}\frac{m_f}{M_W}\bar{\Psi}_f \Psi_f \eta$$

Zahvaljujem

- U FEČ smo naučili surađivati
- Jedan dio slajdova, ideja, prikaza sam "ukrao" od:
  - Rolf Landua
  - Marie-Helene Schune
  - Ivica Puljak
  - Bill Murray
  - Caroline Collard
  - i puno drugih...
  - Oni lošiji su vjerojatno moji ☺
- Sad ste dio CERN-ove kulture: možete ih dalje koristiti, kopirati, prilagoditi…
  - pptx će biti na raspolaganju

Fizika: eksperimentalna znanost

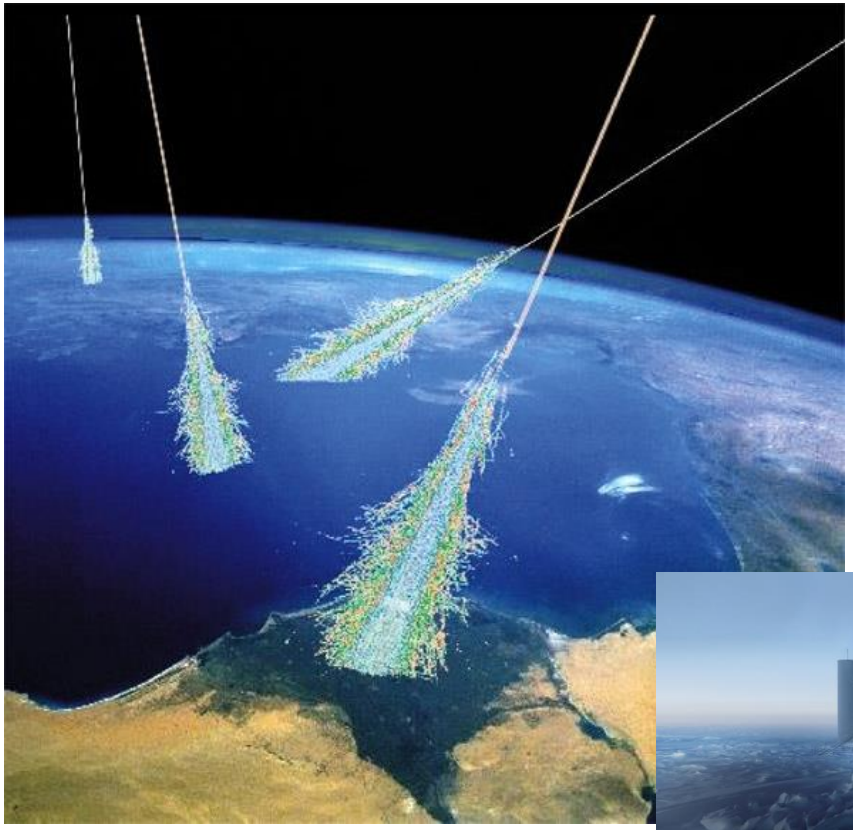
R. P. Feynman

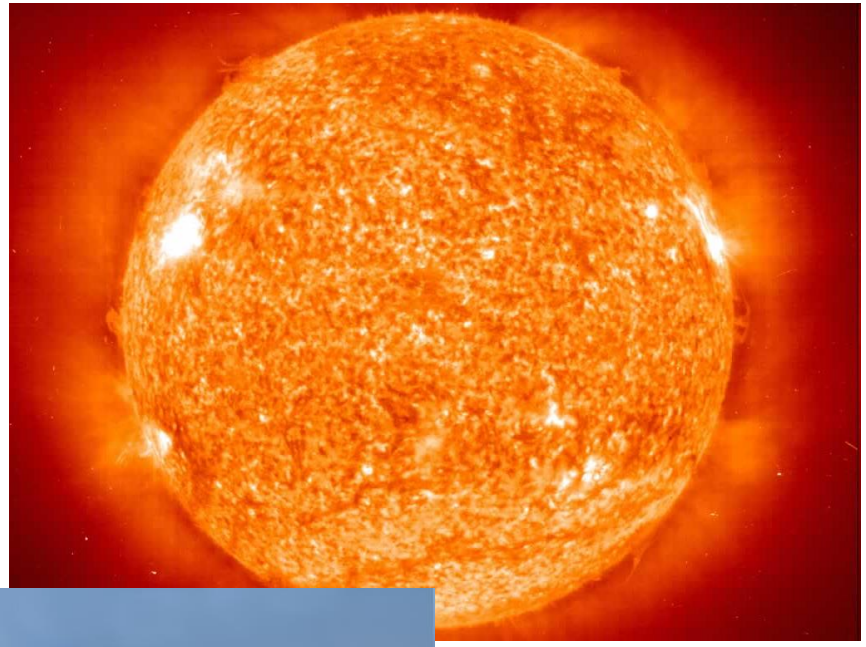
"Physicists learned to realize that whether they like a theory or they don't like a theory is not the essential question. Rather, it's whether or not the theory gives predictions that agree with experiments"

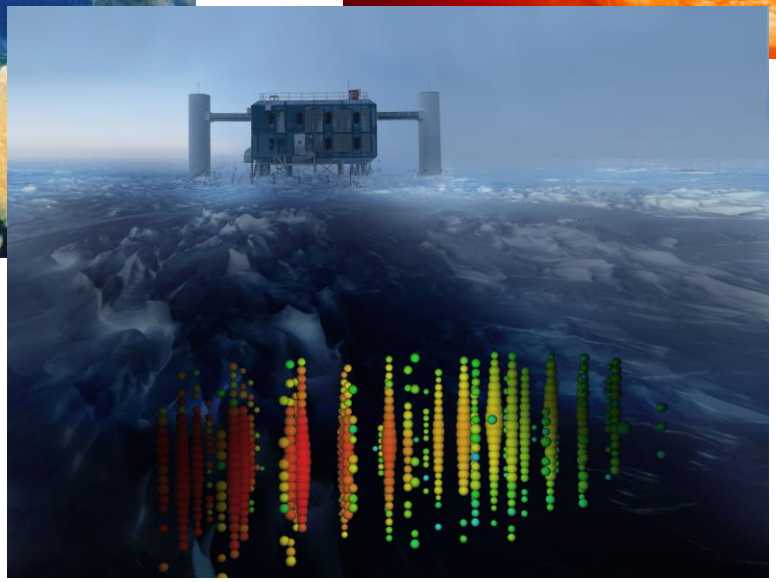
Richard Feynman

Fizika elementarnih čestica: Moderno ime za stara pitanja

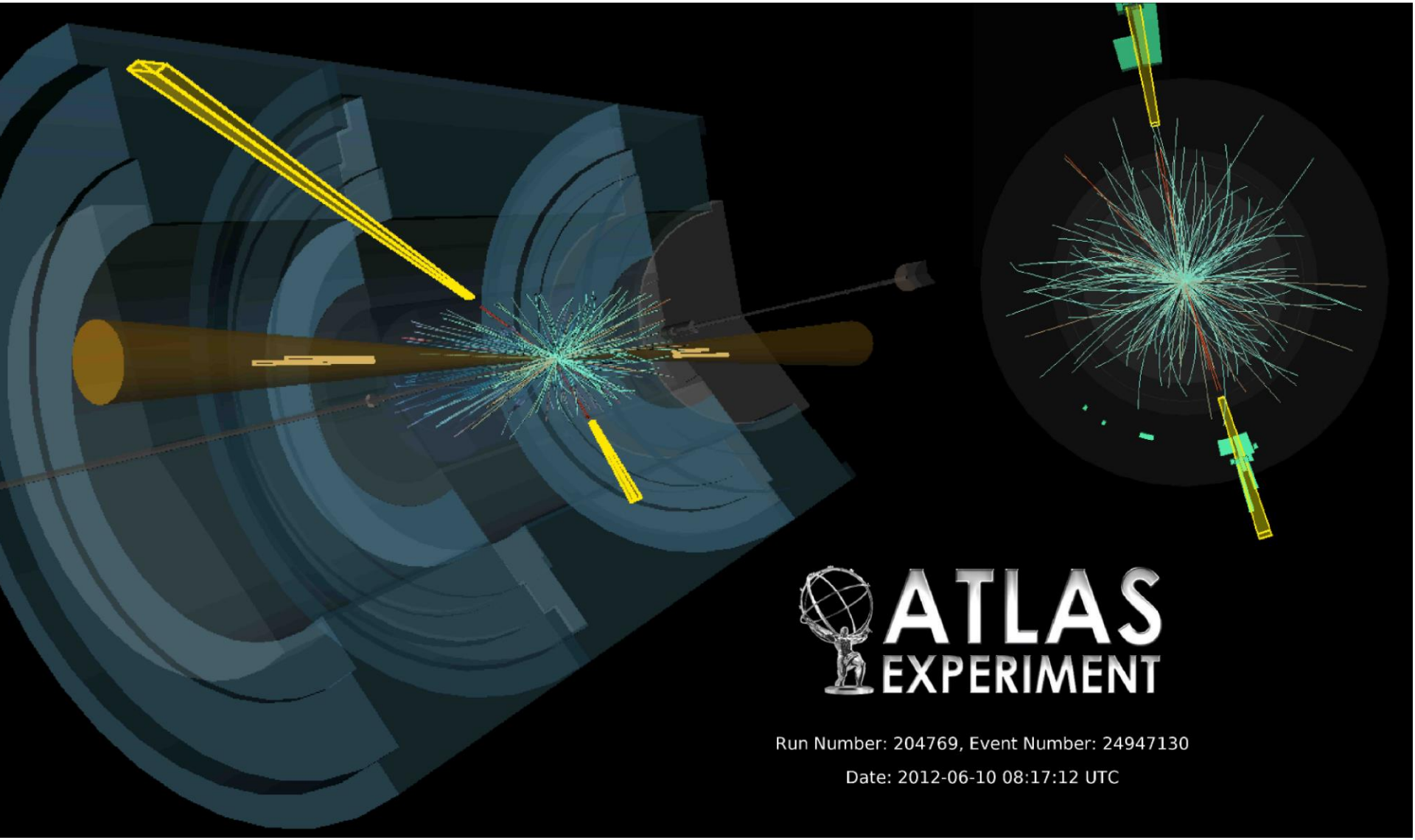
Fenomeni: u prirodi





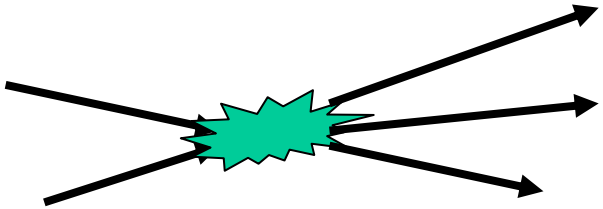


Fenomeni: u laboratoriju



Kako eksperimentalno pristupiti EČ

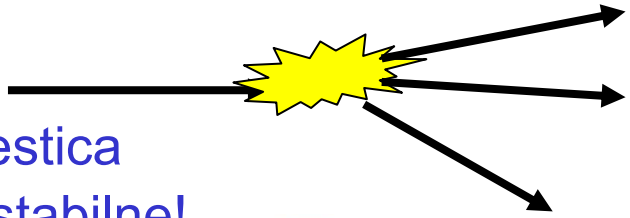
Sve informacije o elementarnim česticama potječu iz triju izvora:



1. Raspršenja

   Čestica na metu ili sudar dviju snopa

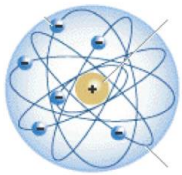
   Informacija o interakciji se dobiva iz mjerenja čestica koje proizlaze iz raspršenja (masa, energija, pravac, impuls, spin, …)



2. Raspadi

   Mjerenje ostataka spontanog raspada čestica

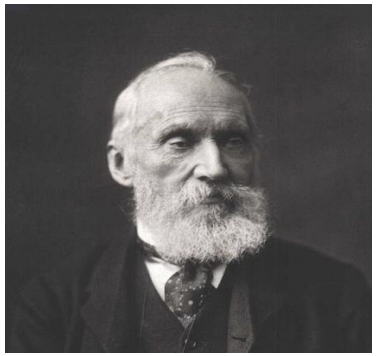
   Od svih poznatih čestica: gotovo sve nestabilne!



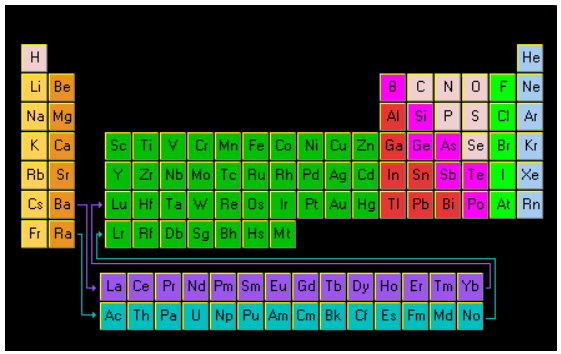
3. Vezana stanja

   Mjerenje svojstava objekata složenih od više čestica (masa, spin, …)

Fizika na kraju 19. stoljeća



William Thomson
(Lord Kelvin)



- Cijela fizika opisana kroz:
  - Mehanika (Newton)
  - Termodinamika
  - Elektrodinamika (Maxwell)

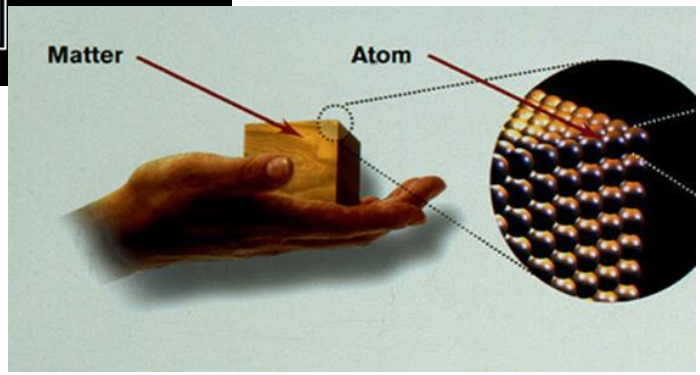
"There is nothing new to be discovered in Physics now. All that remains is more and more precise measurements."
(Lord Kelvin, 1900)

- Samo nekoliko oblaka na inače vedrom nebu fizike:
  - Materija sastavljena od atoma?
  - Spektar zračenja crnog tijela?
  - Michelson-Morley Eksperiment?

Elementarne čestice: do 1897.

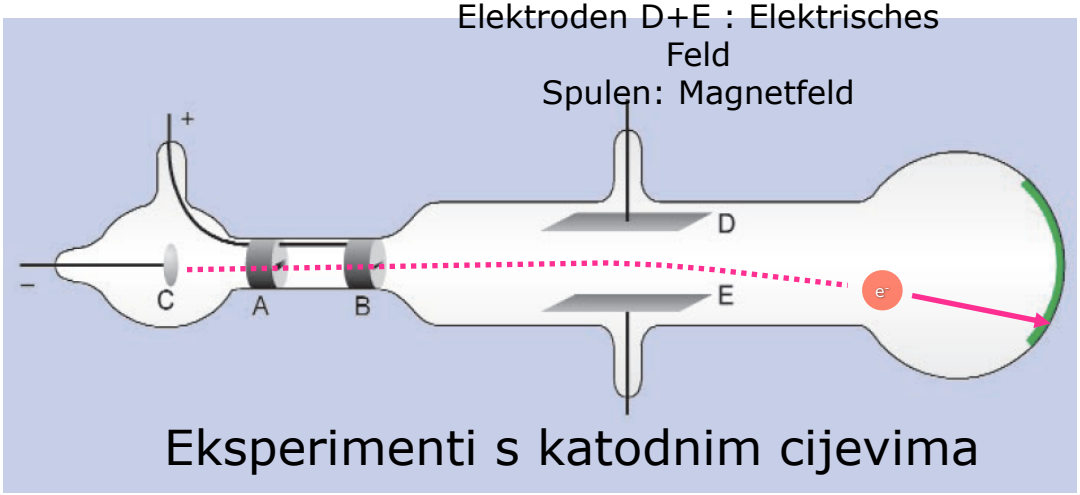
	IA											IIIA	IVA	VA	VIA	VIIA	0
1	1 H	IIA															2 He
2	3 Li	4 Be										5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg	IIIB	IVB	VB	VIB	VIIB	—VIIB—		IB	IIB	13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	57 *La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	89 +Ac	104 104	105 105	106 106	107 107	108 108	109 109	110 110	111 111	112 112		114 114		116 116		118 118

*Lanthanide Series	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
+Actinide Series	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr



1897., prva elementarna čestica: Elektron

J.J. Thomson



1893. - 1897. Otkriće elektrona (J.J. Thomson)

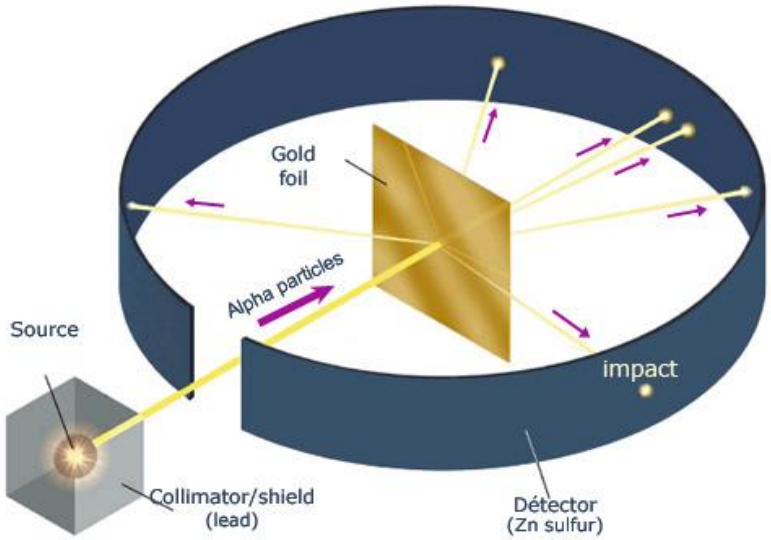
(Struje u katodnim cijevima se sastoje od čestica)

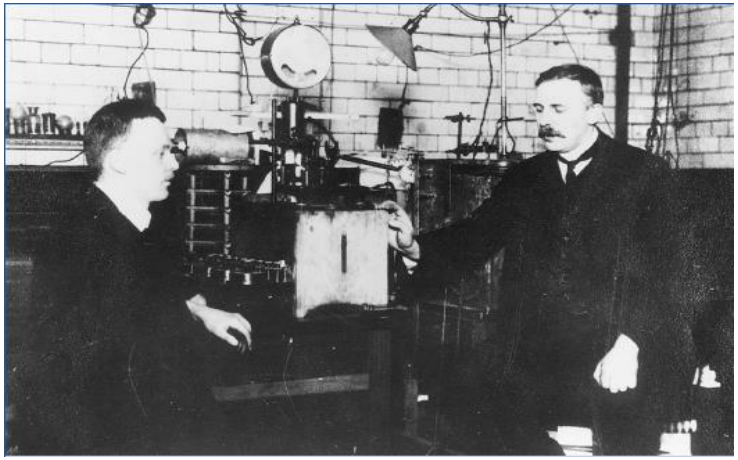
$$m_e \approx M_H/1836$$

"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)

ATOMI NISU ELEMENTARNI!

Otkriće atomske jezgre: Rutherfordov eksperiment





Ernest Rutherford (r) und Hans Geiger (l) in Manchester

<u>Bitni elementni eksperimenta</u>

- Snop
- Meta
- Detekcija
- Izbor podataka (u našem žargonu: *triggering*)

Modeli atoma: Thomson vs Rutherford

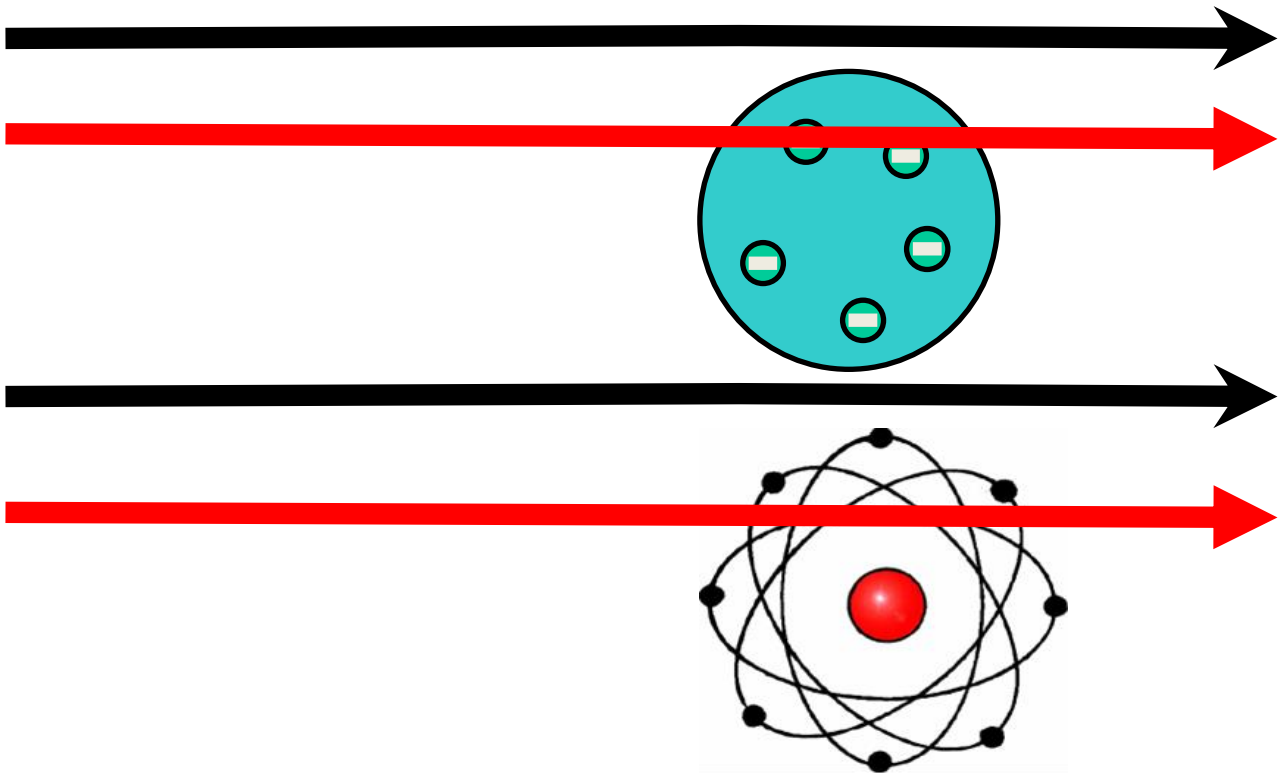
Thomson

+ naboj homogeno raspodjeljen u cijelom atomu

Rutherford

Sav + naboj Koncentriran u maloj jezgri

$R_{jezgra} << R_{atom}$



Kakve eksperimentalne rezultate predviđaju jedan i drugi model?

U kojem će slučaju α čestica vidjeti veću odbojnu silu jezgre:

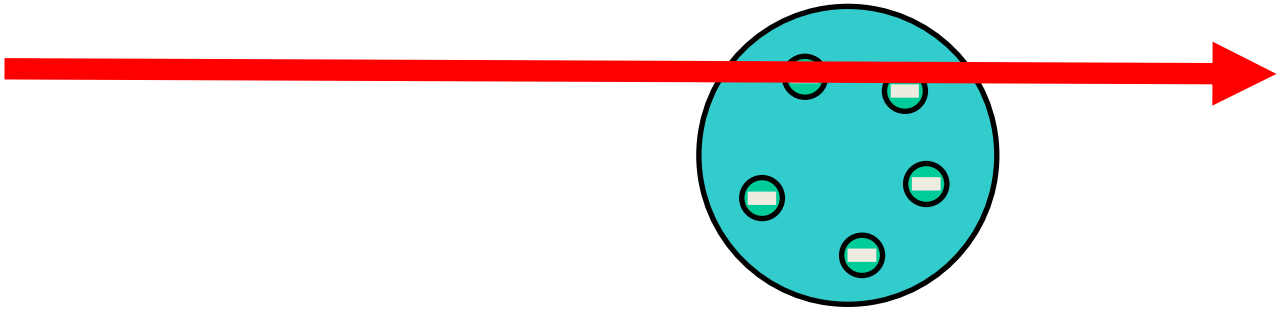
Ako prođe van radiusa atoma?

Ako uđe unutar radisua atoma?

Modeli atoma: Thomson vs Rutherford

Thomson

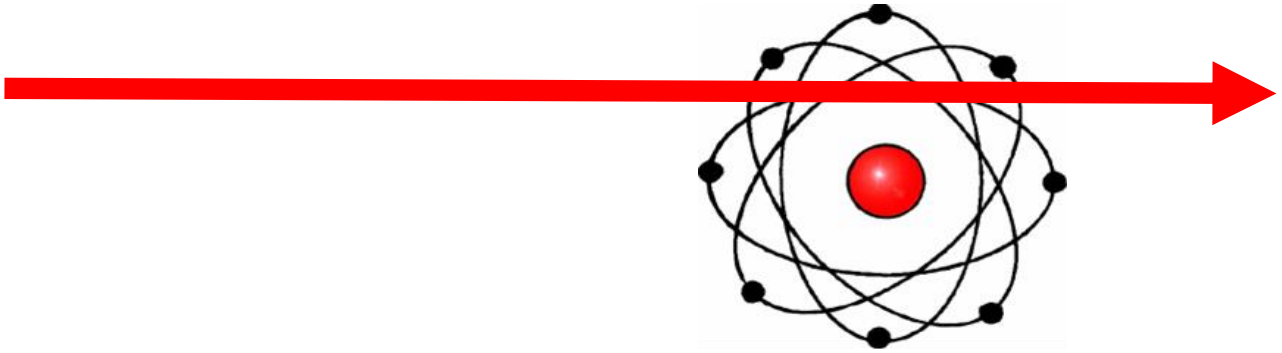
+ naboj homogeno raspodjeljen u cijelom atomu



Rutherford

Sav + naboj Koncentriran u maloj jezgri

$R_{jezgra} << R_{atom}$



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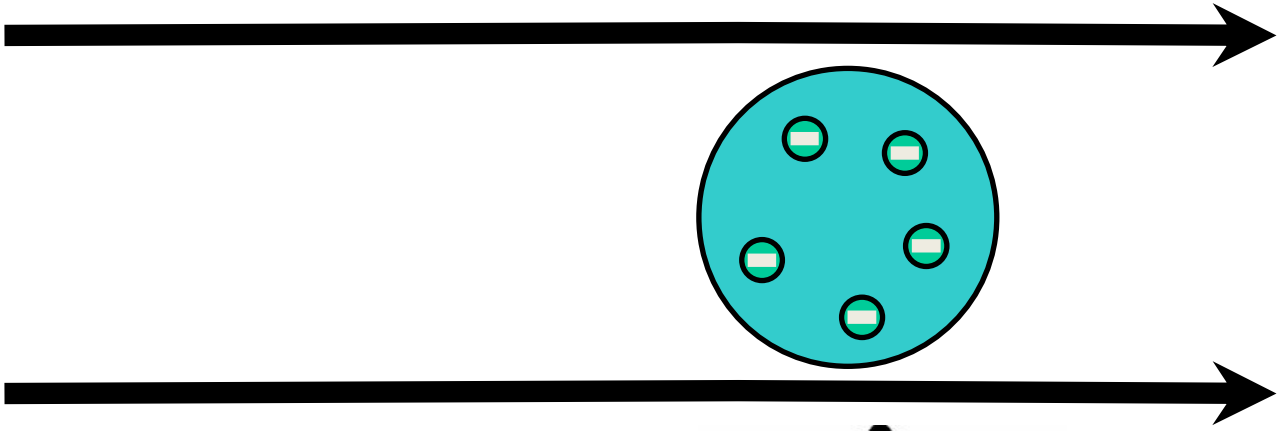

Rutherford

Sav + naboj Koncentriran u maloj jezgri

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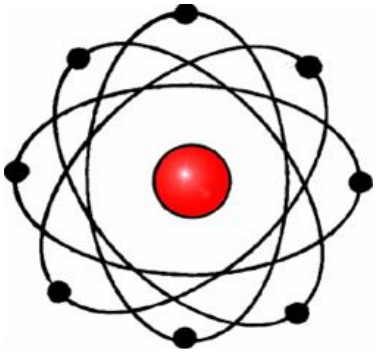

Kakve eksperimentalne rezultate predviđaju jedan i drugi model?

U kojem će slučaju α čestica vidjeti veću odbojnu silu jezgre:

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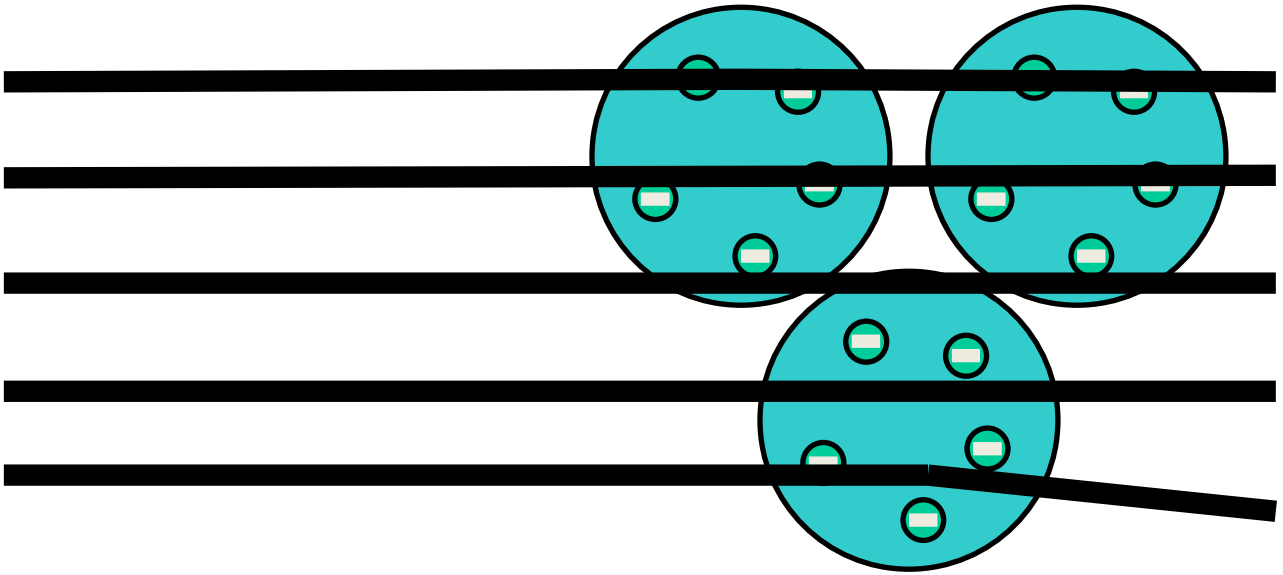
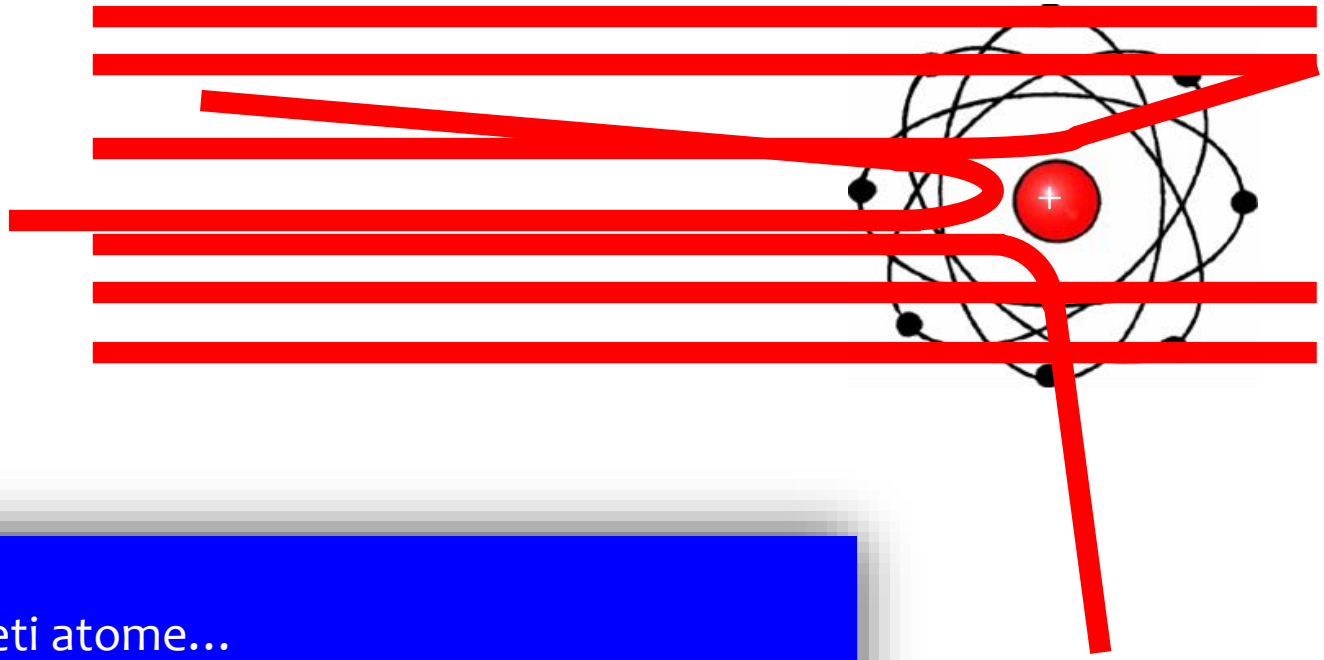
Thomsonov model atoma



Elektroni izmiješani s ostatkom atoma.
Atome ne možemo vidjeti… ali možemo tražiti dokaze da su tu
Kakve eksperimentalne rezultate predviđa model?

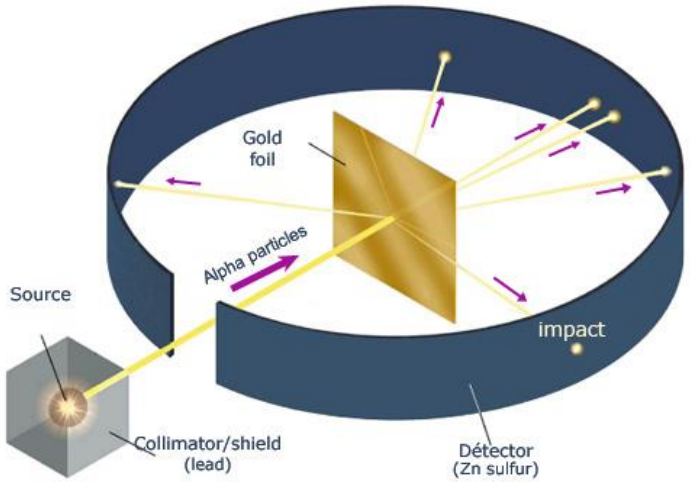
Rutherfordov model atoma

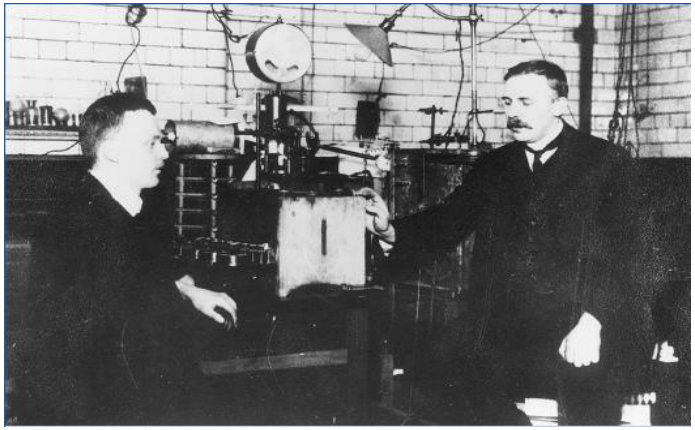


Rutherford model:
I dalje ne možemo vidjeti atome…
Negativni elektroni oko malog, gustog pozitivnog centra
Kakve eksperimentalne rezultate predviđa ovaj model?

Jezgra atoma je 100 000 puta manja od promjera atom!

Otkriće atomske jezgre

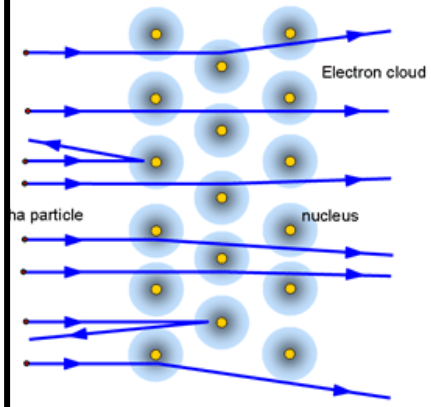




Ernest Rutherford (r) und Hans Geiger (l)
in Manchester

It was quite the most incredible event that has ever happened to me in my life. It was almost as incredible as if you fired a 15-inch shell at a piece of tissue paper and it came back and hit you. On consideration, I realized that this scattering backward must be the result of a single collision, and when I made calculations I saw that it was impossible to get anything of that order of magnitude unless you took a system in which the greater part of the mass of the atom was concentrated in a minute nucleus. It was then that I had the idea of an atom with a minute massive centre, carrying a charge.

—Ernest Rutherford[19]



Gotovo cijela masa atoma koncentrirana u jako maloj jezgri : $< 27 \times 10^{-15}$ m

2 revolucije u ranom 20. stoljeću

RELATIVNOST

Fizika visokih energija

brzine ~ c

Einstein (1905.)

Masa / Energija

$E = M c^2$

Stvaranje novih čestica

KVANTNA FIZIKA

Fizika najmanjih dimenzija

Val / Čestica

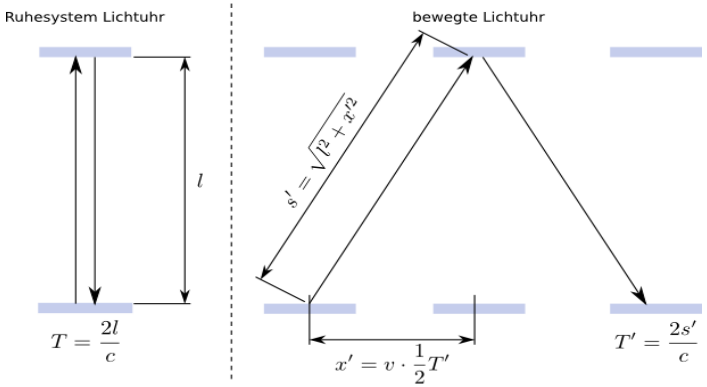
$p = h / \lambda$

Bohr (1913.)

Ispitivanje strukture materije

Relativnost: postulati

1. Zakoni fizike su isti u svim inercijalnim sustavima
2. Brzina svjetlosti (u vakuumu) je konstantna i ista za sve promatrače



$$
\begin{aligned}
T' &= \frac{2\sqrt{l^2 + \frac{1}{4}v^2T'^2}}{c} \\
T'^2 &= 4\frac{l^2}{c^2} + \frac{v^2}{c^2}T'^2 \\
\left(1 - \frac{v^2}{c^2}\right) \cdot T'^2 &= 4\frac{l^2}{c^2} \\
T' &= 2\frac{l}{c} \cdot \sqrt{\frac{1}{1 - \frac{v^2}{c^2}}} = \gamma \cdot T
\end{aligned}
$$

- Nema apsolutnog vremena ni prostora
- Dilatacija vremena - duljine

Masa i Energija

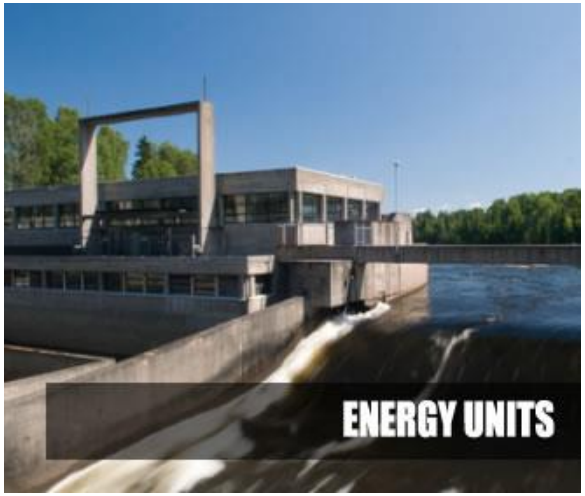
- Masa:
  - Spremište energije čestica
  - Ne ovisi o brzini
  - "definirana" $M^2c^4 = E^2 - p^2c^2$
  - U miru: **E = M c²**
  - M je **Lorentz invarianta**: ista u svim sustavima (E i p općenito nisu)
  - c velik: mala masa= velika količina energije

Jedinica za masu (SI): kg

masa elektrona $\approx 10^{-30}$ kg

masa čovjeka $\approx$ 100 kg

masa Sunca $\approx 10^{30}$ kg



Jedinica za energiju (SI): J

Često se koristi u fizici:

eV (elektron volt)

1 eV = 1.6×10^{-19} J

1 GeV = 10^9 eV

$$E = m$$

$$E = mc^2$$

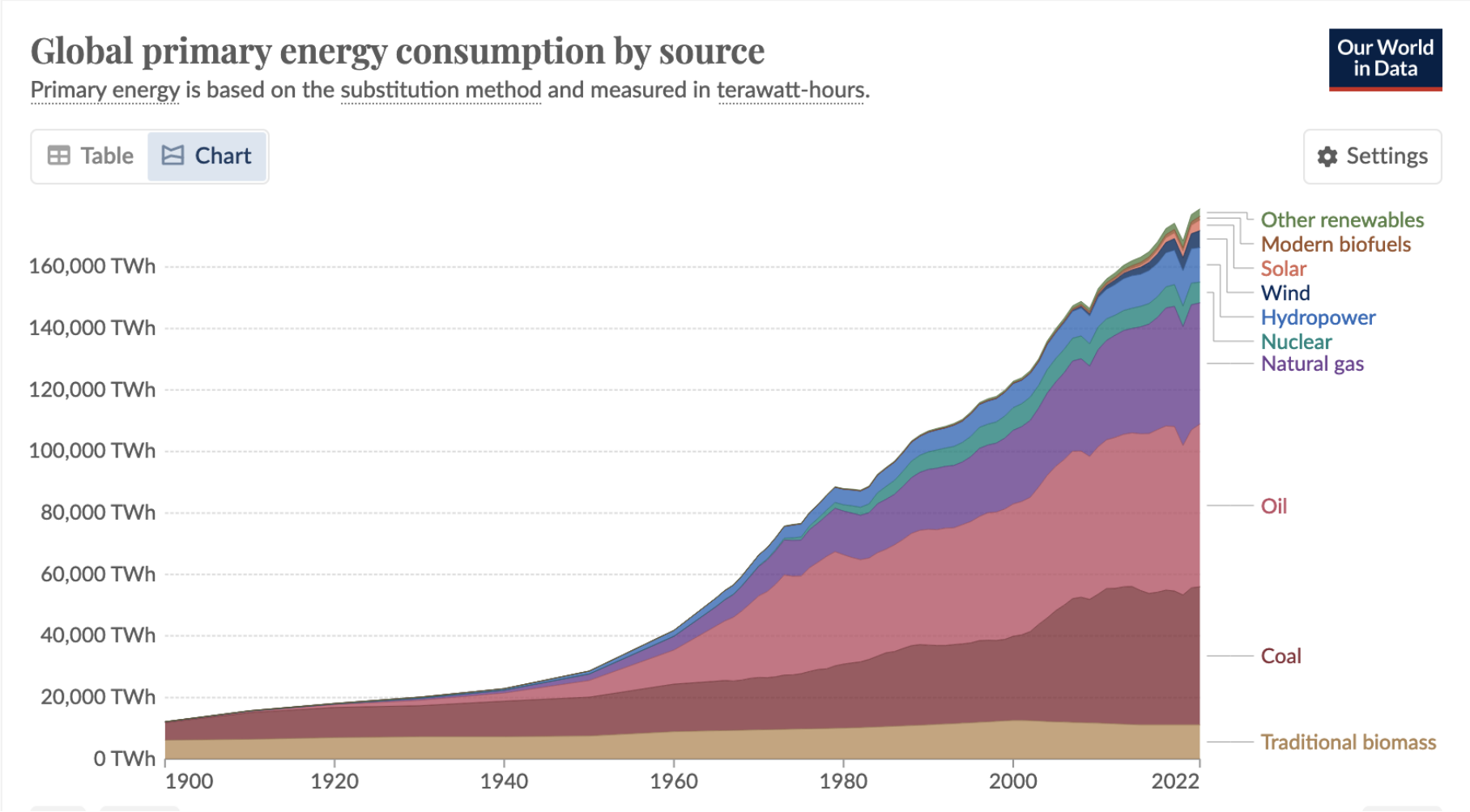
$E = mc^2$

$c = 300\ 000\ km/h = 10^8\ m/s$

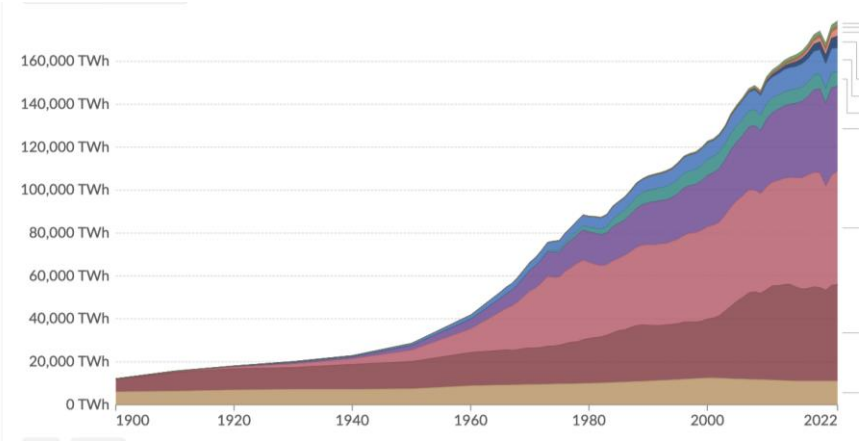
$c^2 = 9 \times 10^{16}\ m^2/s^2 \approx 10^{17}\ m^2/s^2$

$m = 100\ kg$

$E = mc^2 \approx 10^{19}\ J$



$$2022: 178899\ \text{TWh} = 6.44 \cdot 10^{20}\ \text{J} = 7155\ \text{kg} \cdot c^2$$


160,000 TWh
140,000 TWh
120,000 TWh
100,000 TWh
80,000 TWh
60,000 TWh
40,000 TWh
20,000 TWh
0 TWh
1900
1920
1940
1960
1980
2000
2022

=

~ 3 x

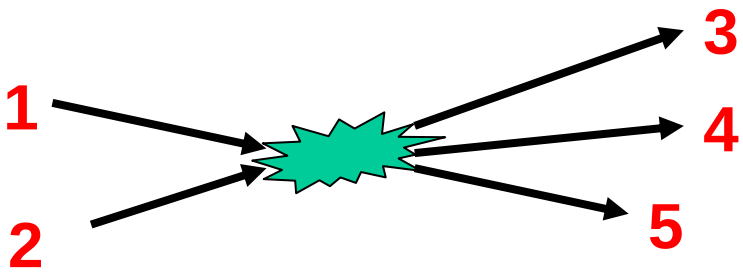
U fizici visokih energija

$E = mc^2$ ➡ $[m] = GeV/c^2$

$c = 1$ ➡ $E = m$ ➡ $[m] = GeV$

Očuvane veličine

- Očuvane veličine u svakoj reakciji:
  - Energija, količina gibanja
- Npr. reakcija 1+2 -> 3 +4 +5



  - Vrijedi

$$E_1 + E_2 = E_3 + E_4 + E_5$$

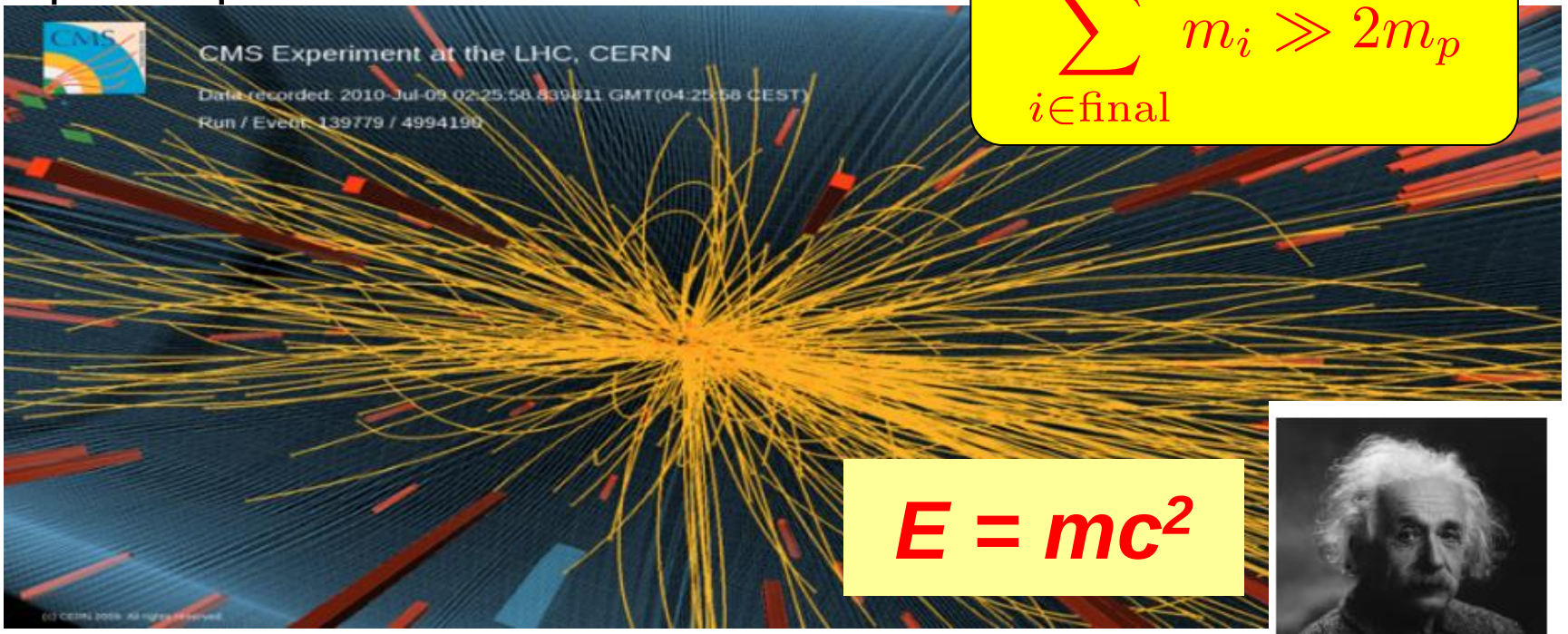
$$\vec{p}_1 + \vec{p}_2 = \vec{p}_3 + \vec{p}_4 + \vec{p}_5$$

  - Ali općenito: $M_1 + M_2 \neq M_3 + M_4 + M_5$

Masa nije očuvana veličina!

Sudari na LHC-u: Masa nije očuvana

proton proton sudar na LHC-u



$$\sum_{i \in \text{final}} m_i \gg 2m_p$$

$E = mc^2$

U KEMIJI

“Ukupna masa tvari koje ulaze u kemijsku reakciju jednaka je ukupnoj masi tvari koje nastaju tom reakcijom.

Ta se zakonitost naziva **zakon o očuvanju mase** i temeljni je kemijski i prirodni zakon.”

NE VRIJEDI ZA FIZIKU NA VISOKIM ENERGIJAMA!

Relativnost i raspadi: Test

- Mase:
  - Proton: 938 MeV
  - Λ barion: 1116 MeV
  - Pion □⁺: 140 MeV
- Ako proton miruje, je li dopušten raspad

$$p \rightarrow \Lambda \pi^+$$

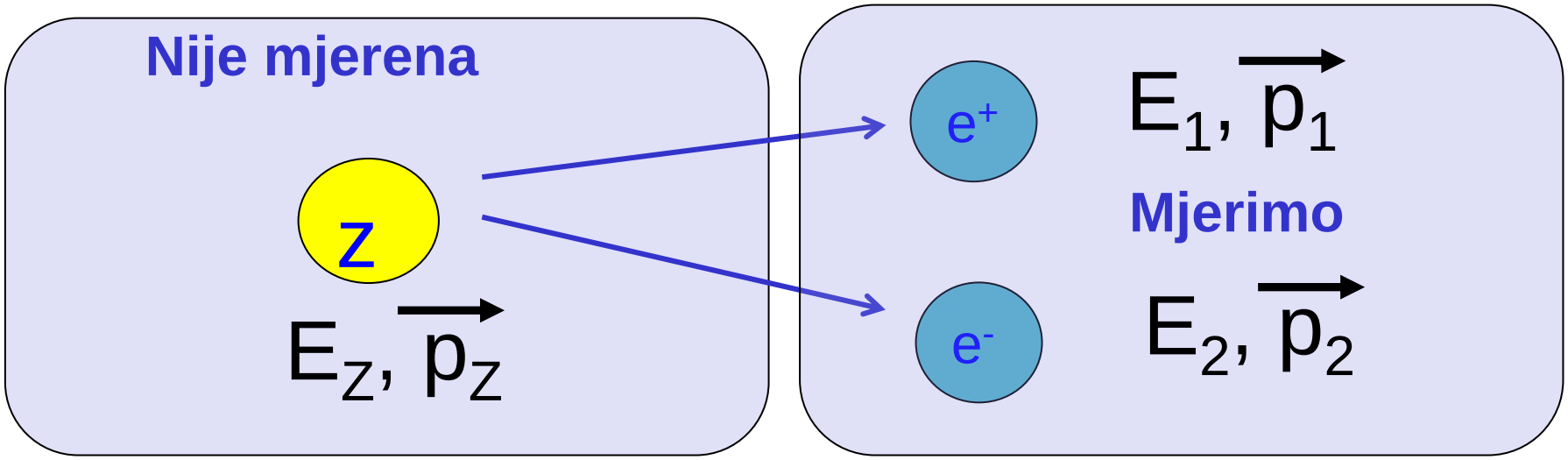
a) DA

b) NE

Relativnost i raspadi: Test

- Zbog očuvanja energije se proton u miru ne može raspasti na način $p \rightarrow \Lambda\pi^+$
  - M(p) 938 MeV, M(Λ): 1116 MeV, M(□⁺): 140 MeV
- Na koju kinetičku energiju moram ubrzati proton za omogućiti taj raspad:
  a) 318 MeV
  b) 1256 MeV
  c) 2512 MeV
  d) Nikad neće biti moguće

Kako identificirati nevidljive čestice



Očuvanje energije i impusa

$$E_Z = E_1 + E_2$$

$$\vec{p}_Z = \vec{p}_1 + \vec{p}_2$$

Invarijantna masa

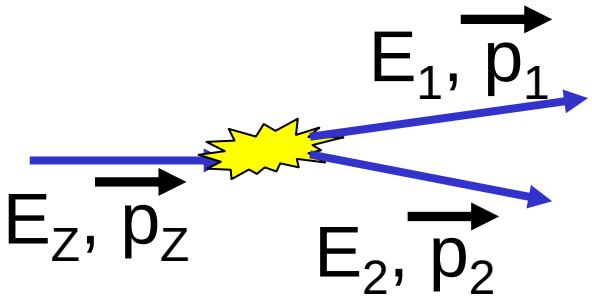
$$M_Z^2 = E_Z^2 - p_Z^2 = (E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2$$

Vježba: dodajte nedostajuće c faktore (dimenzionalna analiza!)

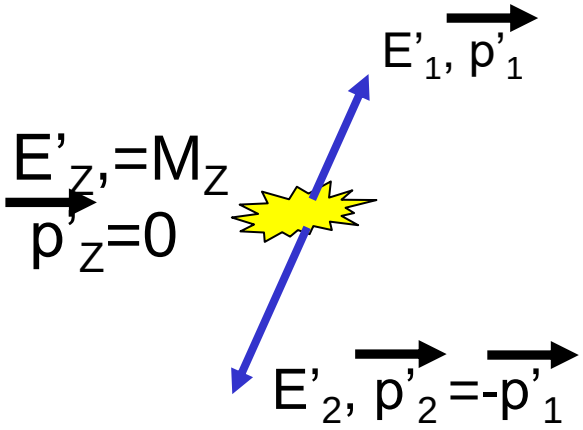
Izbor sustava

Možemo promatrati raspad u više mogućih sustava

Raspad u letu



Raspad u mirovanju



Općenito: E_i i E'_i nisu jednaki

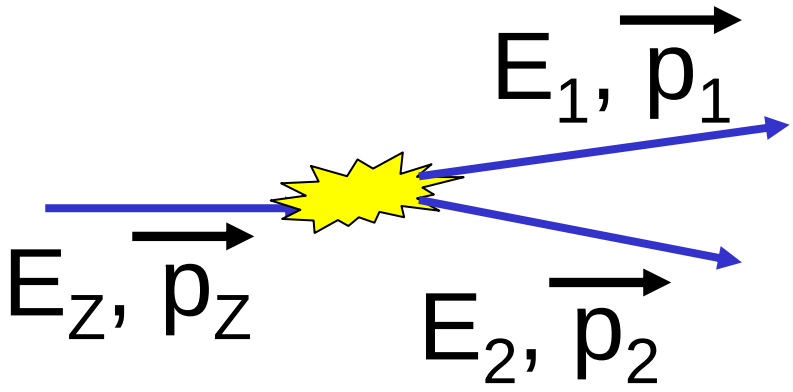
U kojem sustavu računati inv. masu za dobiti pravu masu čestice?

1) **U sustavu laboratorija**
2) **U sustava mirovanja**
3) **U nekom trećem sustavu**
4) **U bilo kojem od navedenih**

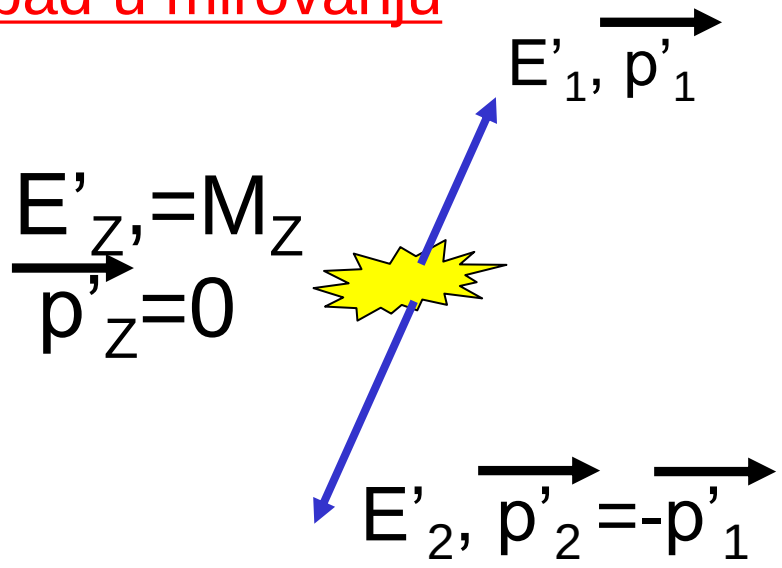
Izbor sustava

Možemo promatrati raspad u više mogućih sustava

Raspad u letu



Raspad u mirovanju



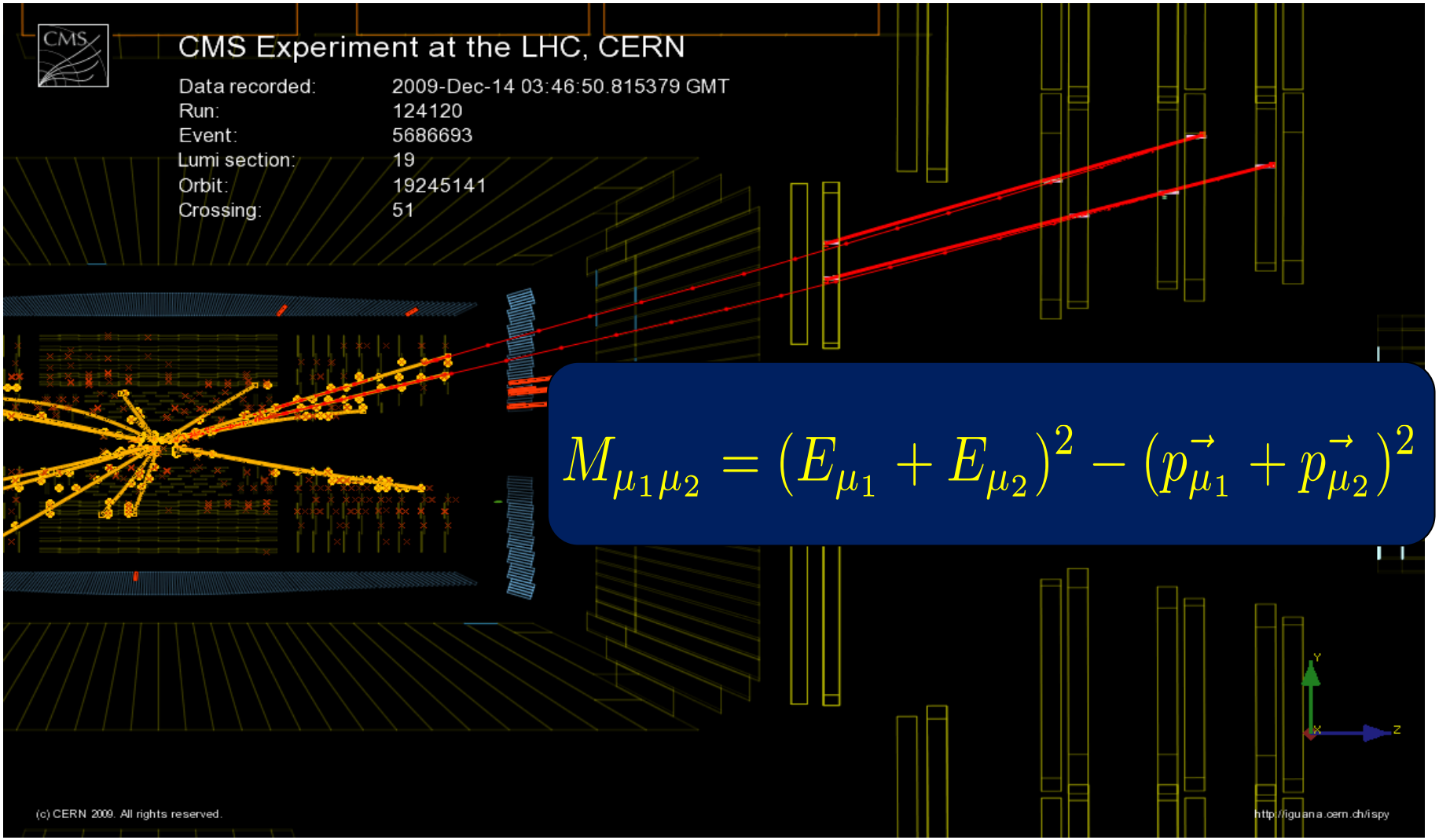
Općenito: E_i i E'_i nisu jednaki

U kojem sustavu računati inv. Masu?

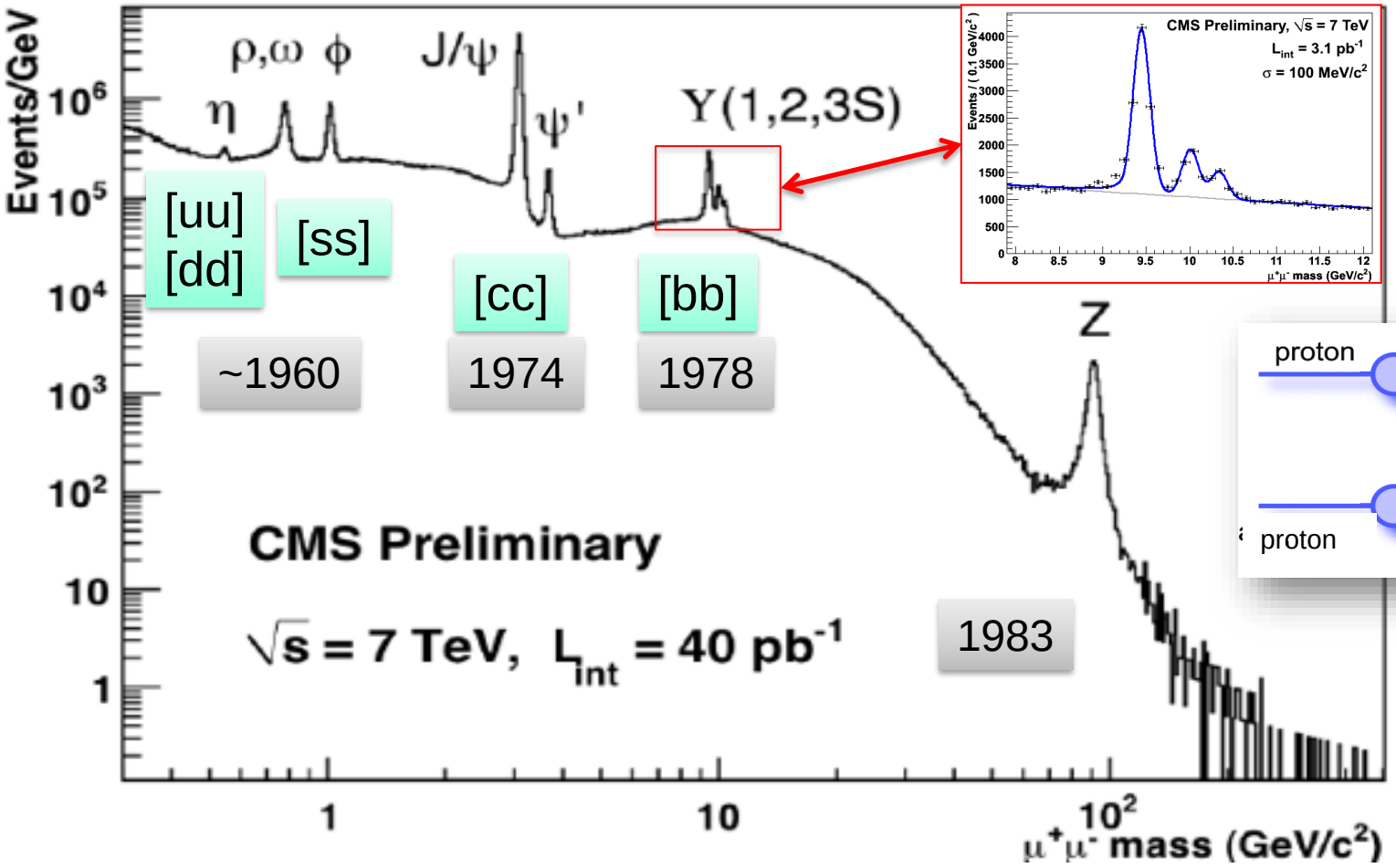
$$\text{Einstein} : (E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2 = (E'_1 + E'_2)^2 - (\vec{p'}_1 + \vec{p'}_2)^2$$

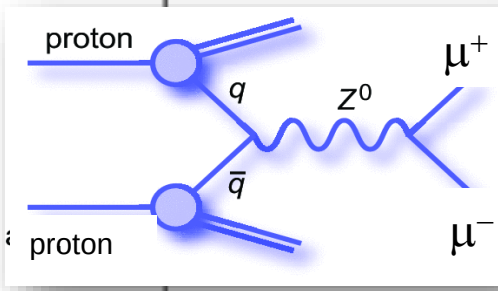
NIJE BITNO: INVARIJANTNA MASA NE OVISI O PROMATRAĆU

Događaji sa 2 miona



Ponovno otkriće SM na LHC-u



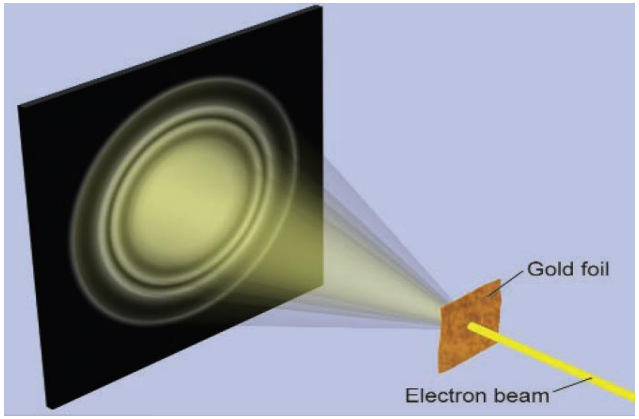


40 pb^{-1} collected in 2010

Elementarne čestice: kvantni objekti

- Svim česticama pripadaju svojstva čestica:
  - Energija, količina gibanja, masa
  - Za svjetlo (fotone) **$E=h\nu$**
- Sve imaju i valnu narav:

$$\lambda = h / p$$



Louis de Broglie (1924)

Kvantna neodređenost

Heisenberg (1925)

- Količina gibanja i pozicija ne mogu biti istovremeno precizno mjerene:

$$\Delta x \Delta p \geq \frac{\hbar}{2}$$

- Isto vrijedi za energiju i vrijeme:

$$\Delta E \Delta t \geq \hbar$$

Kvantna jednadžba gibanja

Schrödinger
1926

- Schroedinger:ponašanje čestica opisano kroz valnu jednadžbu

$$i\hbar \frac{\partial}{\partial t}\psi = -\frac{\hbar^2 \nabla^2}{2m}\psi + V(r)\psi$$

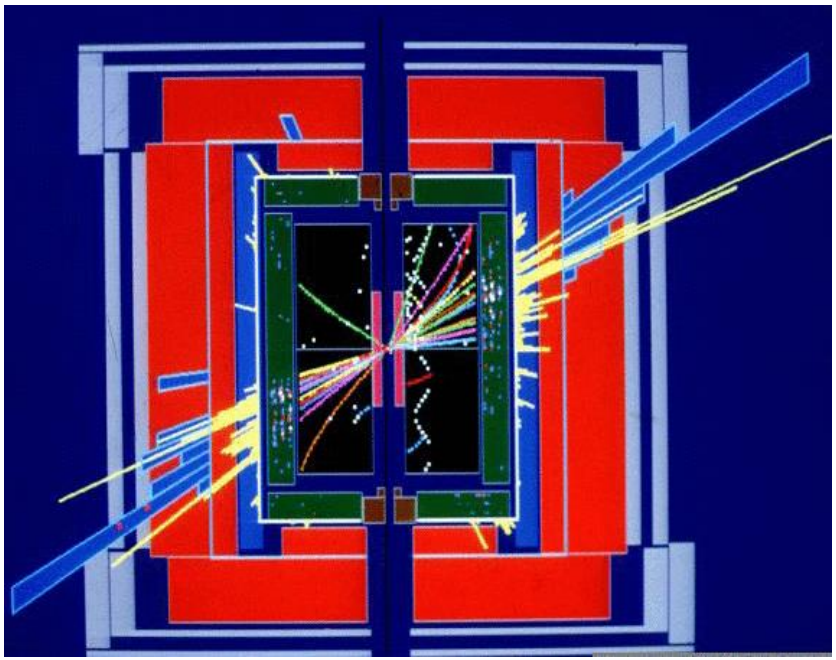
- Novost: valna funkcija nije više direktno mjerljiva nego predstavlja vjerojatnost!
- Nigdje tako dobro vidljivo kao kod elementarnih čestica

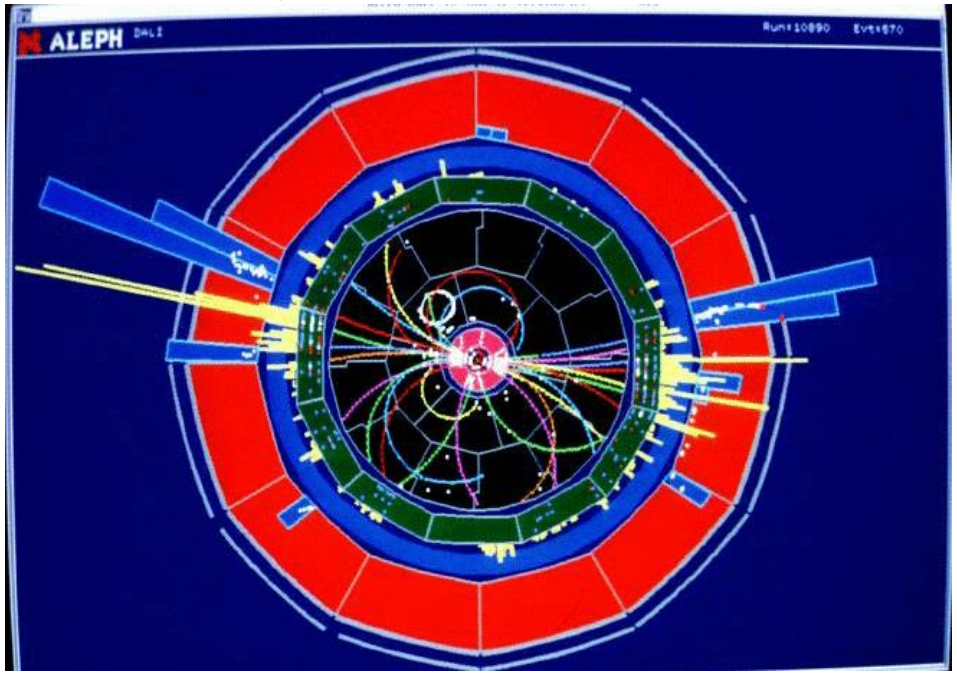
Primjer slučajnosti: Z raspad

Eksperiment

Sudaramo snopove elektrona i pozitrona na energiji od 91 GeV

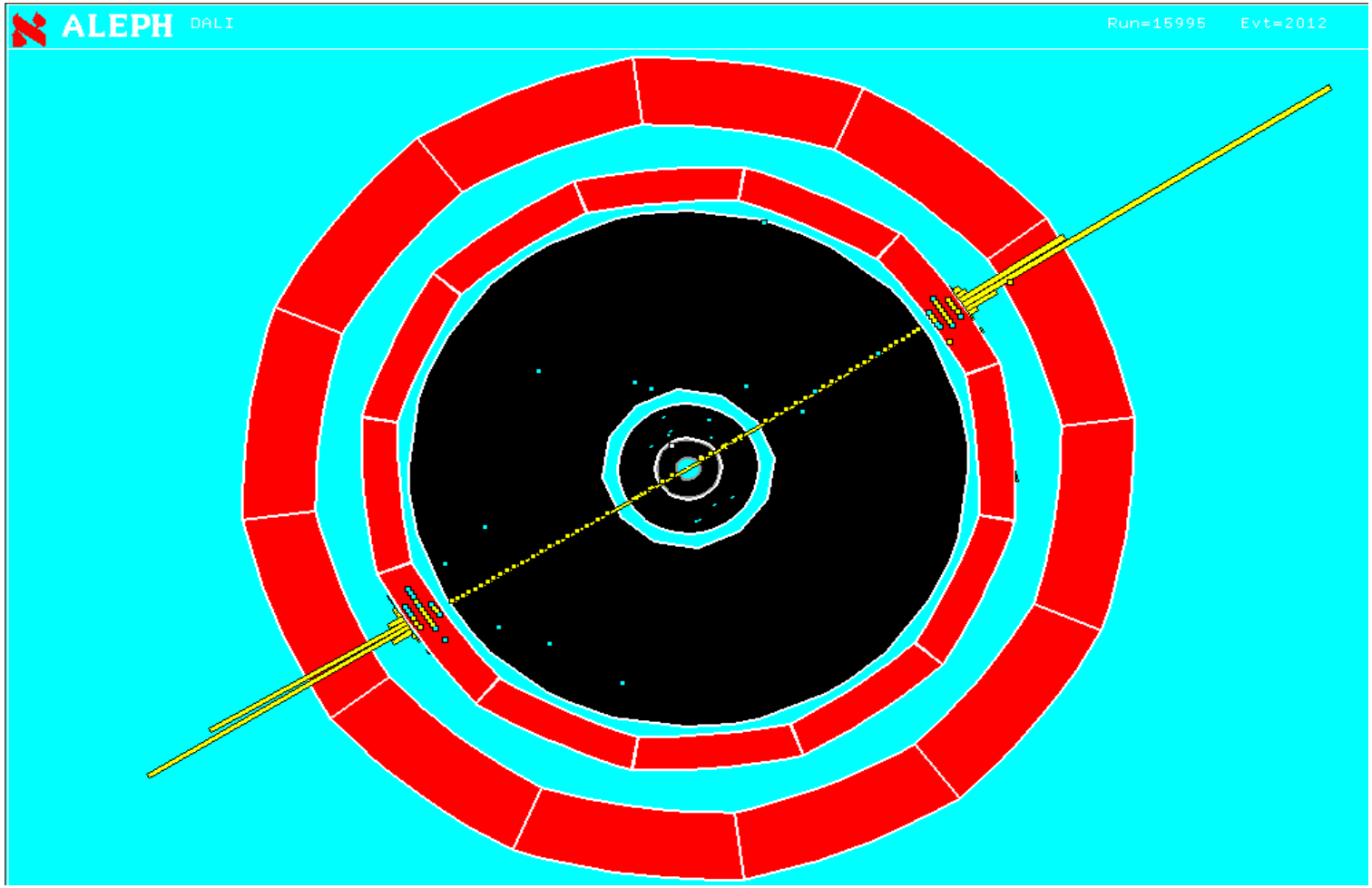
Produciramo Z bozone i proučavamo njihove raspade…





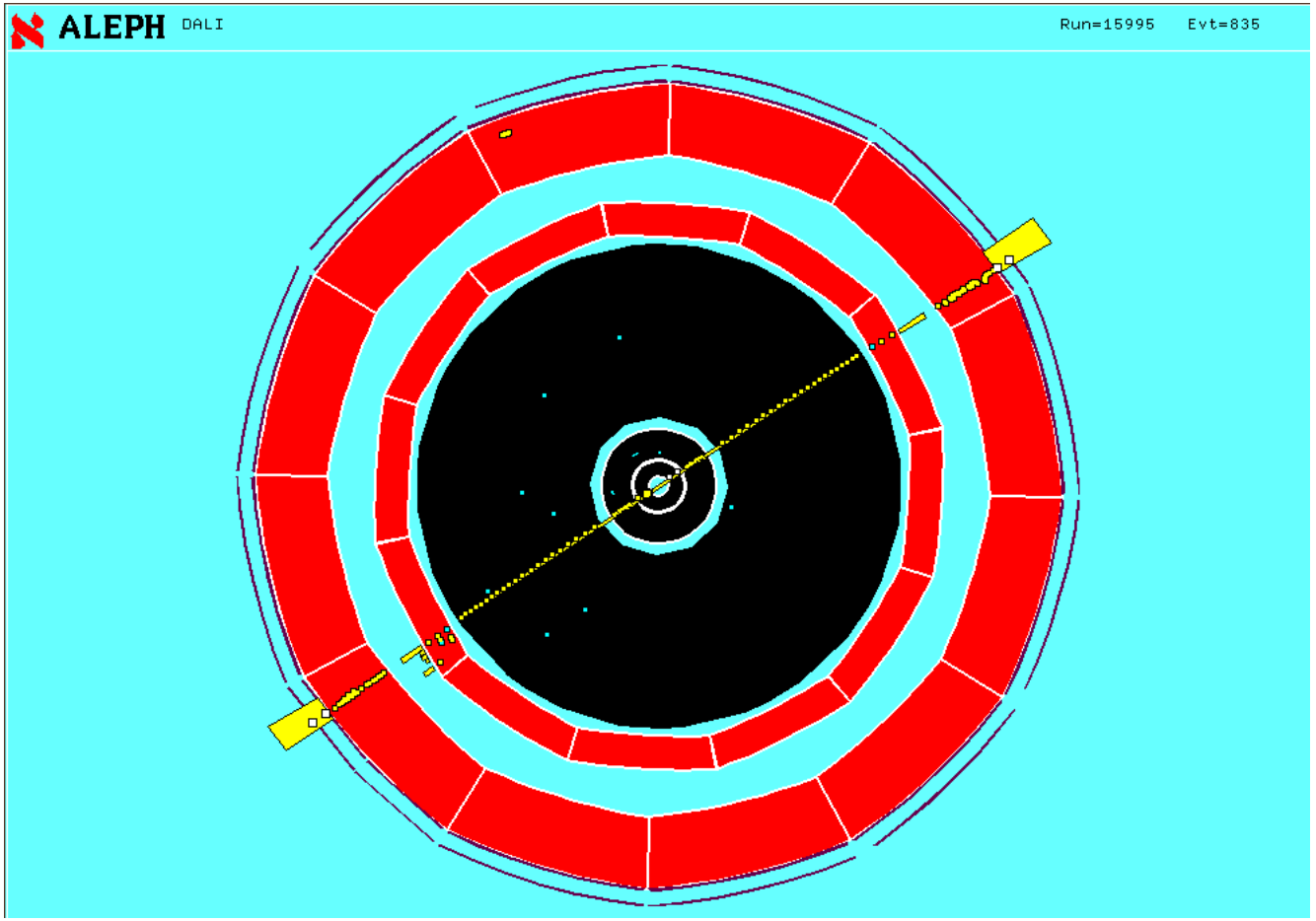
Ajmo to ponoviti...

Još jedan raspad Z bozona



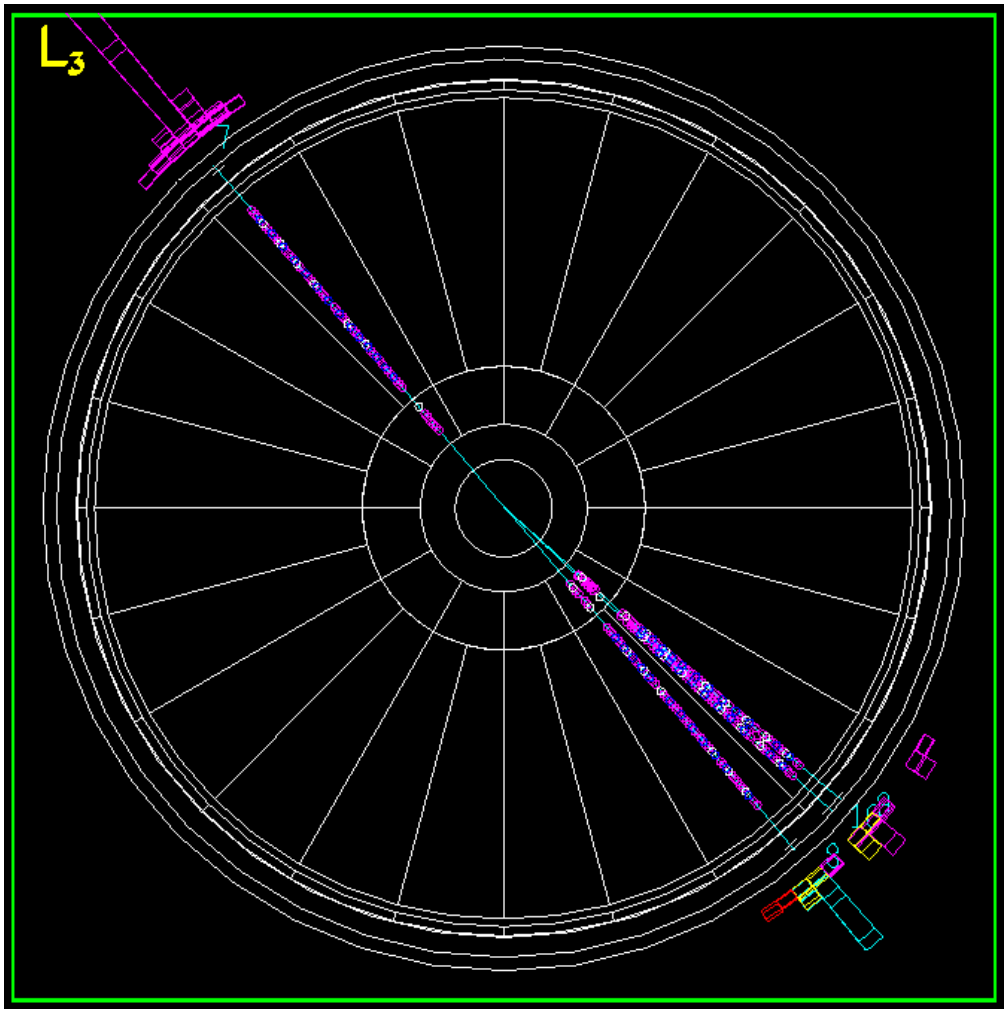
Prilično različito!

I još jednom



Stvarno se radi o ISTOM eksperimentu…

I još jedan

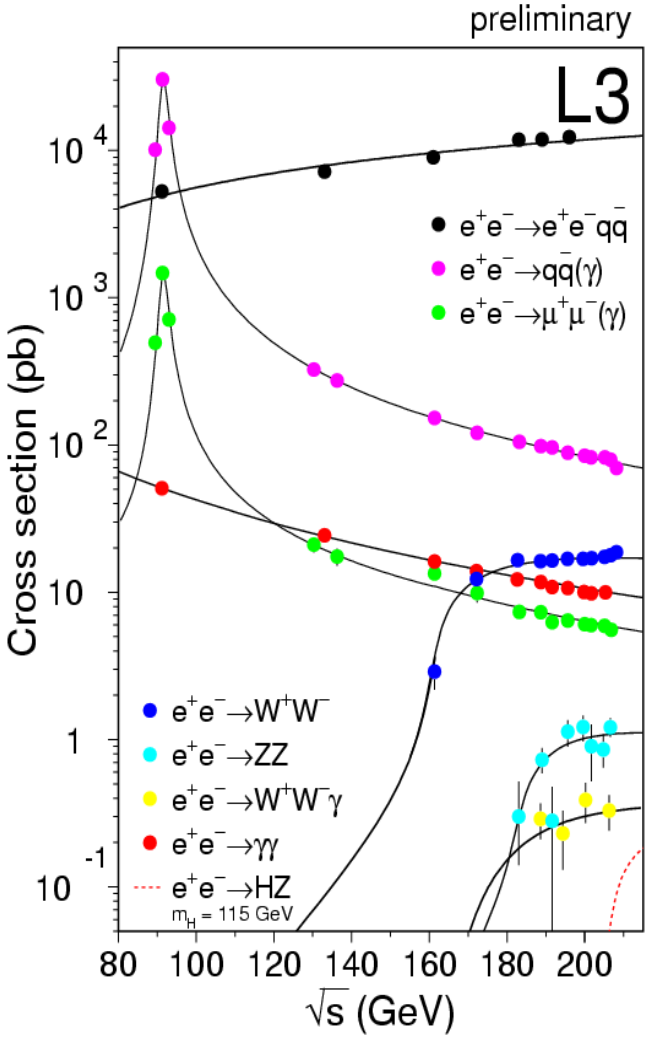


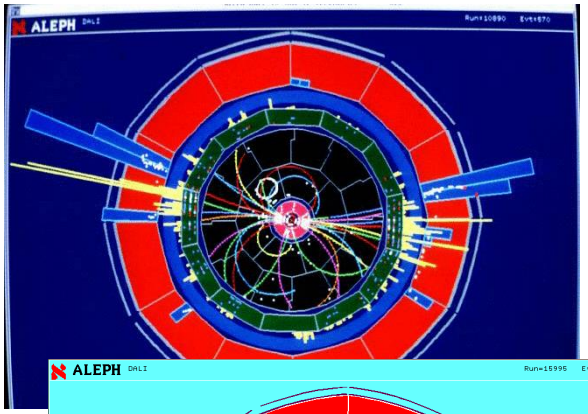
Što nam teorija kaže o Z raspadima

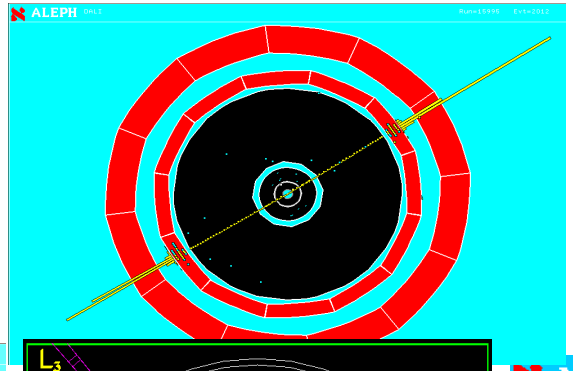
- Predviđa koje su vrste raspada moguće
- Predviđa koliko često (%) će se raspasti u svaki

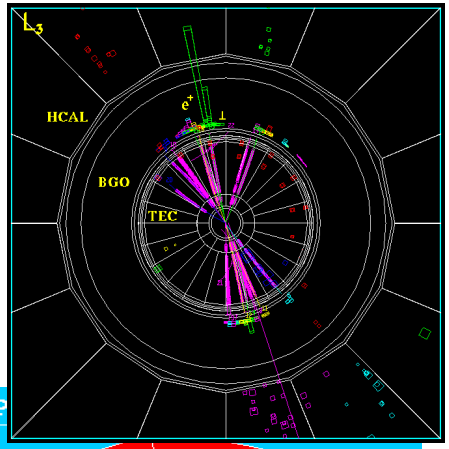
I jako točno!

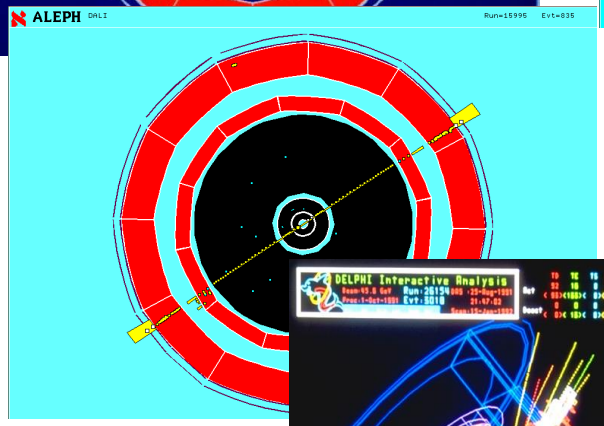
Ali ne kaže nam apsolutno ništa o …

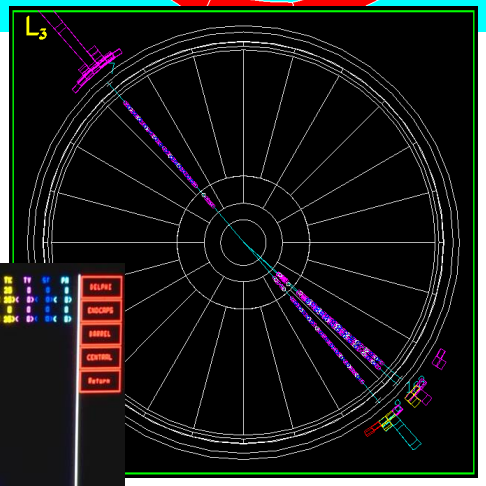


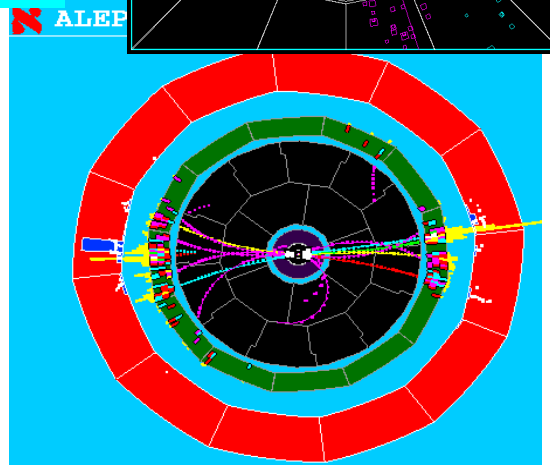








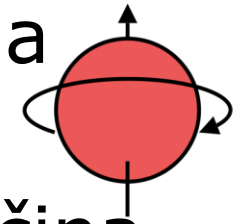




… A što će biti sljedeći?

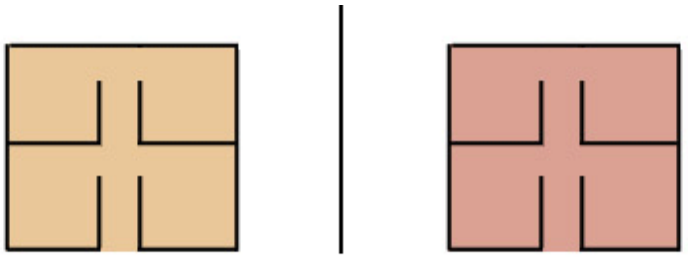
Ako kvantna teorija vrijedi to nije određeno fizikalnim zakonima, čisto je slučajno!

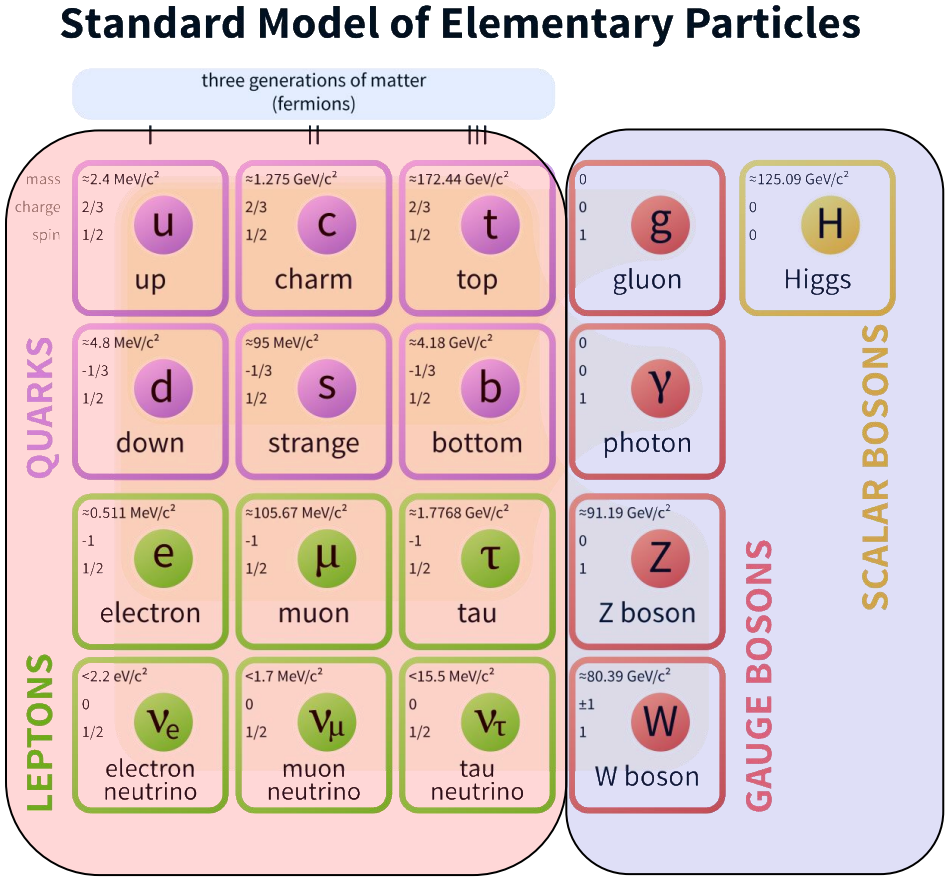
Kvantno svojstvo: Spin



- Čisto kvantna pojava: intrinzična kutna količina gibanja, SPIN
- Kutna količina gibanja je očuvana veličina
- Kutna količina gibanja može imati samo vrijednosti, u jedinici Planckove konstante:
  - 0,1,2,3,...: Bozoni
  - ½,3/2, 5/2, …: Fermioni
- Važno svojstvo kvantne teorije:
  - 2 fermiona NE MOGU biti u istom stanju
  - 2 ili više bozona mogu biti u istom stanju

Bozoni i Fermioni





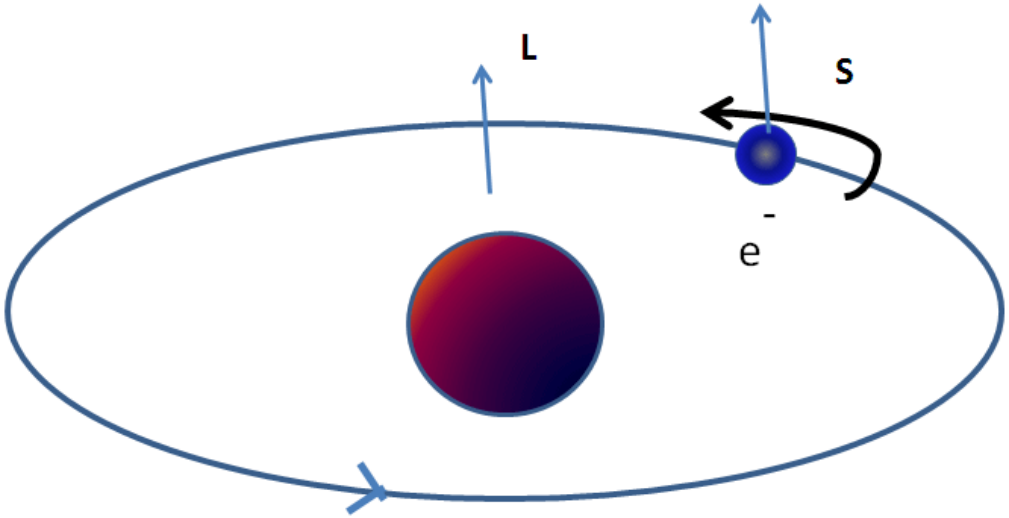
Fermioni **Bozoni**

SPIN **1/2** **1** **0**

Kutna količina gibanja

Vrsta kutne količine gibanja	Simbol	Dopuštene vrijednosti
Orbitalni	L	0,1,2,...
Spin (intrizični)	S	0,1/2, 1, 3/2, 2, …

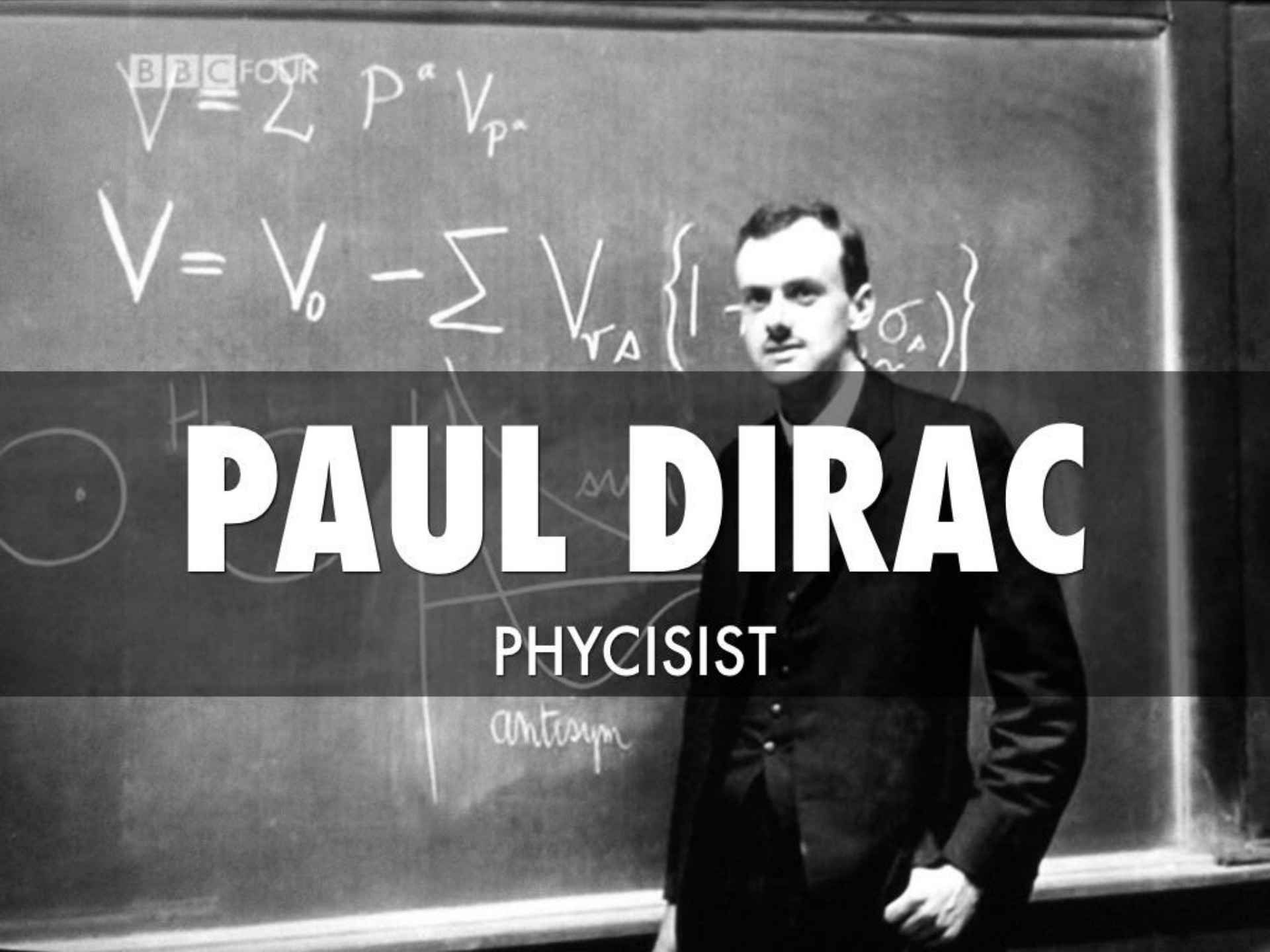
Ukupna kutna količina gibanja



$$\vec{J} = \vec{L} + \vec{S}$$

Kvantna teorija + Teorija relativnosti

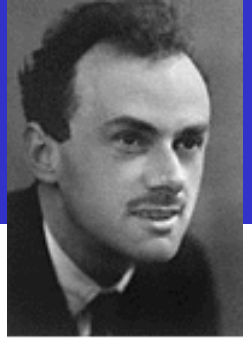
- Schroedingerova jednažba nije relativistička
- Spajanjem dvije teorije dobivamo važne nove pojave:
  - Za svaku česticu postoji i **antičestica**
  - Čestice se mogu stvarati i poništiti: Broj čestica nije očuvan



PAUL DIRAC

PHYCISIST

Čestice i ... Antičestice!



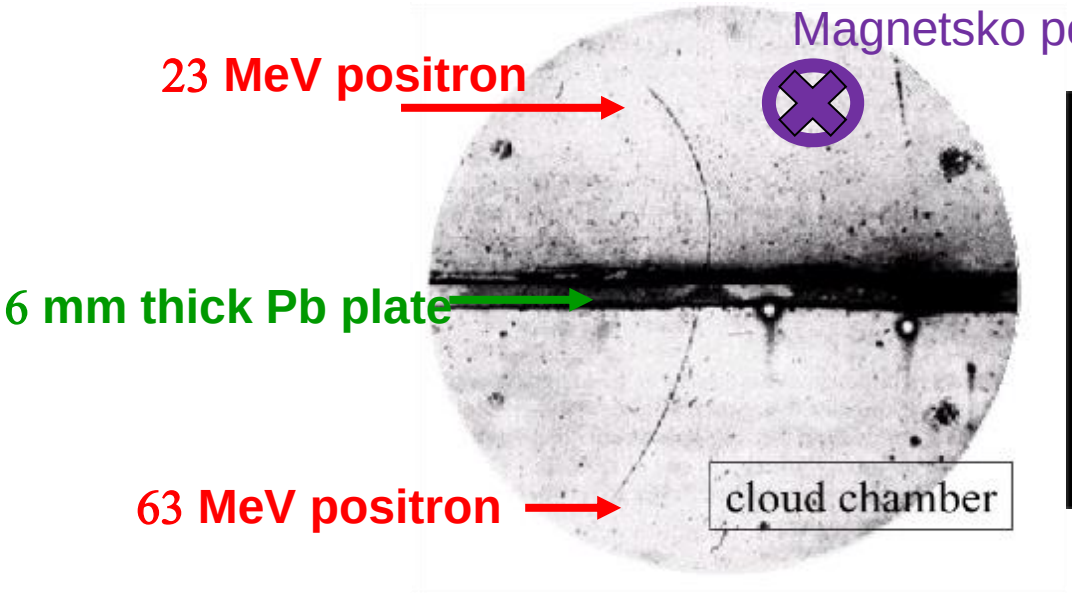
P.A.M. Dirac

Relativnost i kvantna fizika zahtjevaju

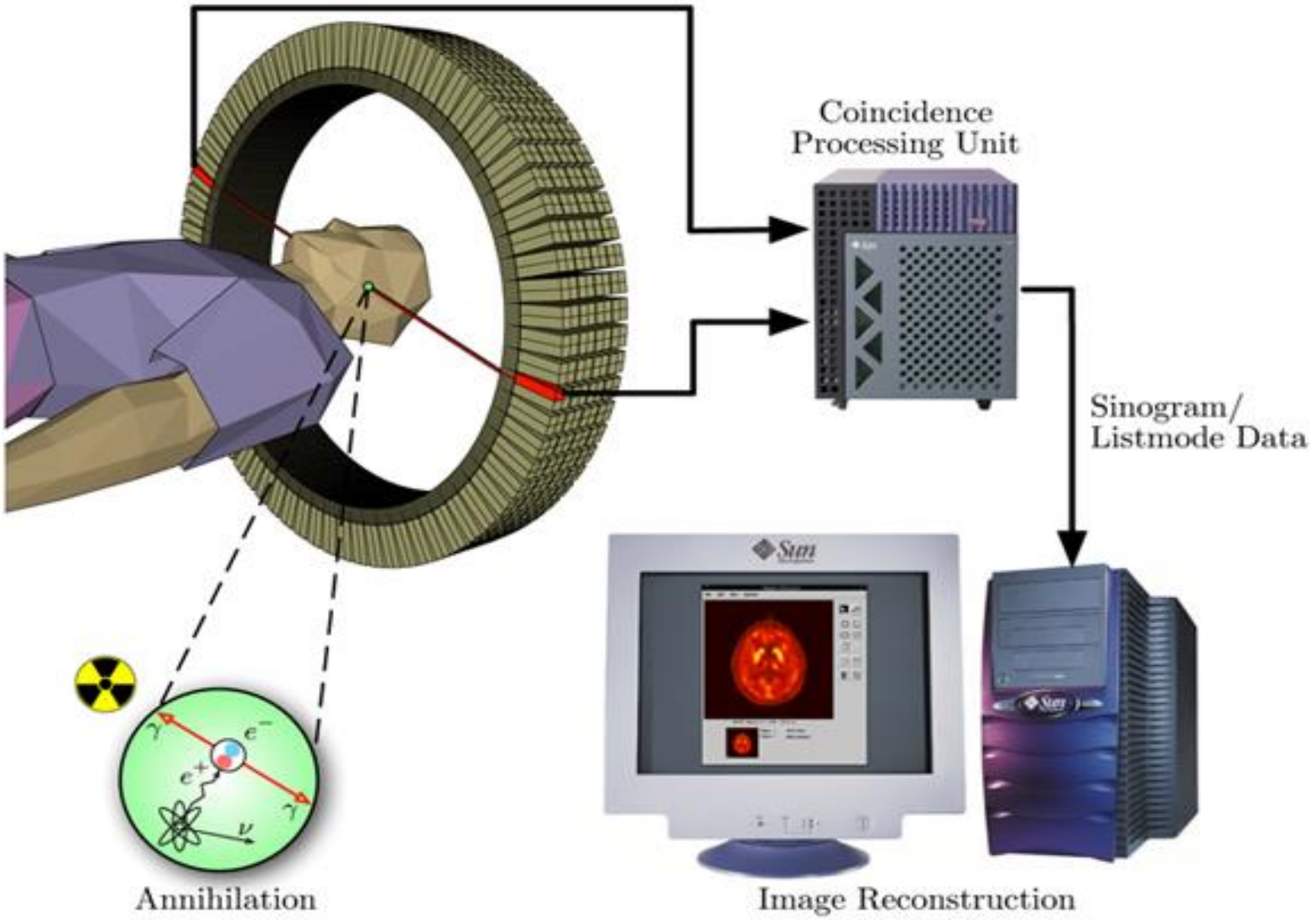
Za svaku česticu postoji i antičestica sa istom masom i suprotnim kvantnim brojevima

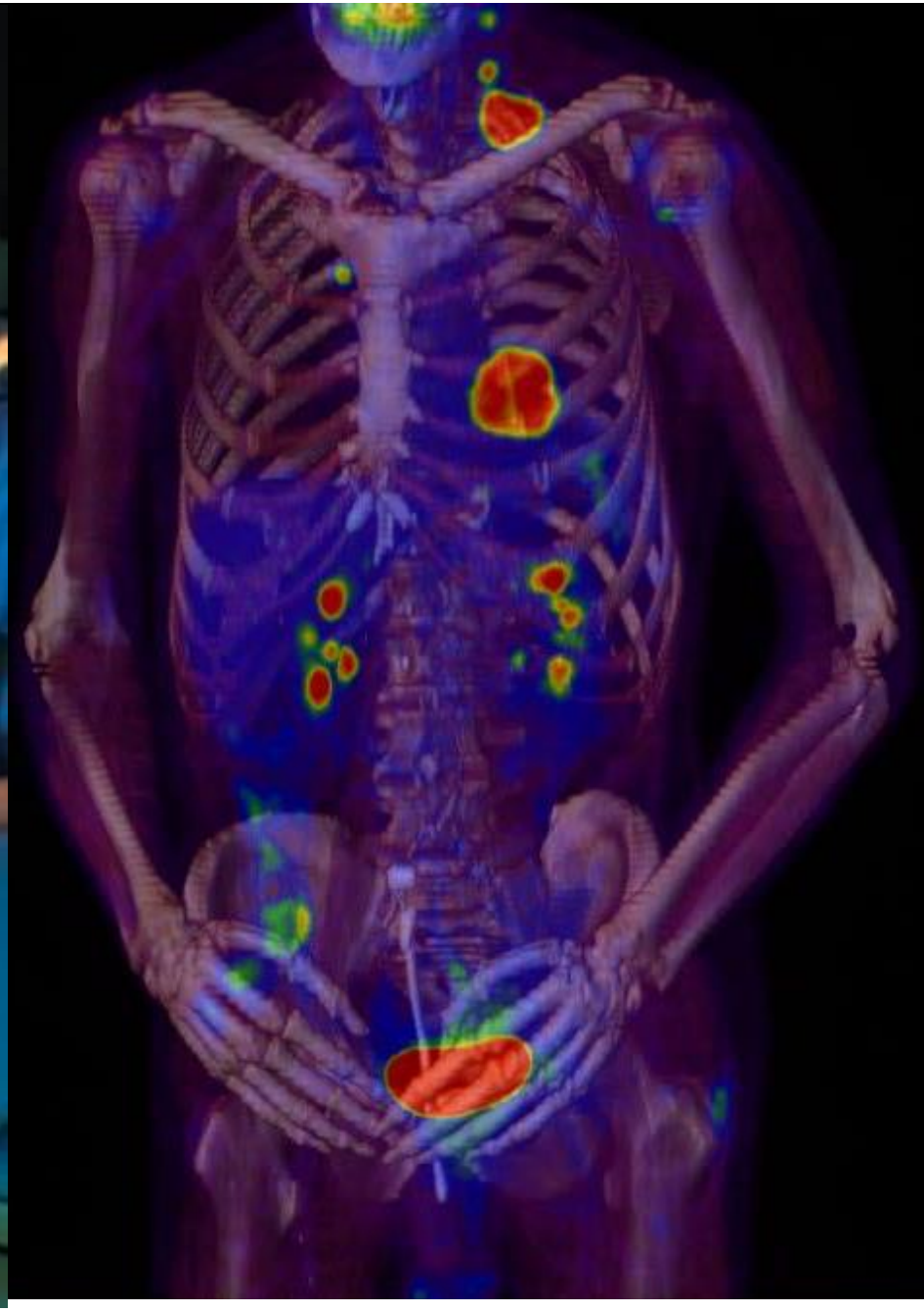
"Otkrio" kao teorijski zahtjev Dirac (1928.)

Potvrda: Otkriće pozitrona (anti-elektron): C.D.Anderson (1932)

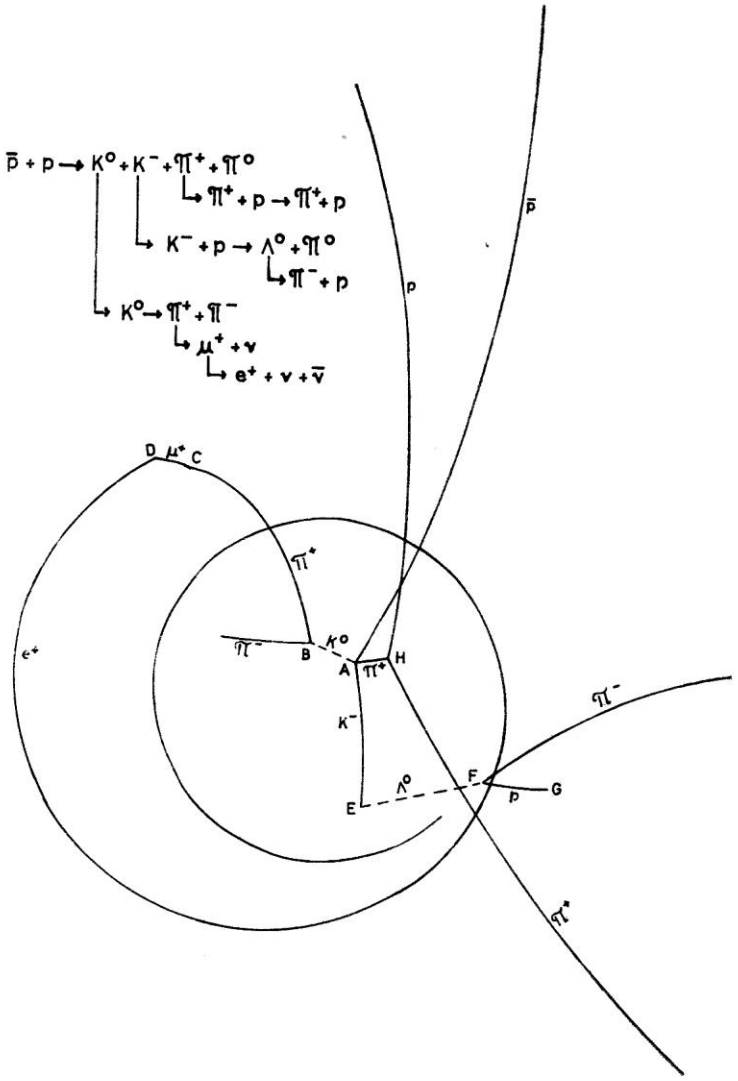


Antimaterija u medicini: PET Tomografija





Example of antiproton annihilation at rest in a liquid hydrogen bubble chamber



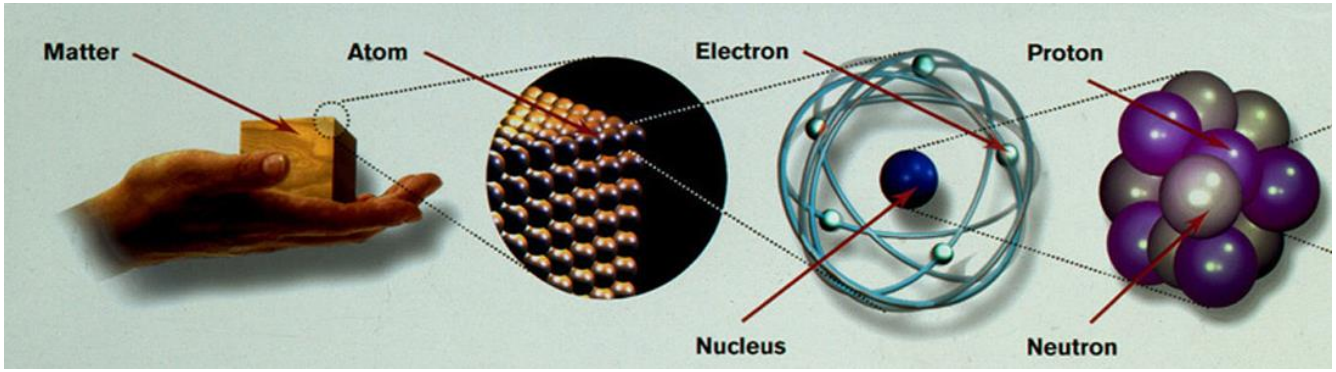
1932.: Svijet je jednostavan

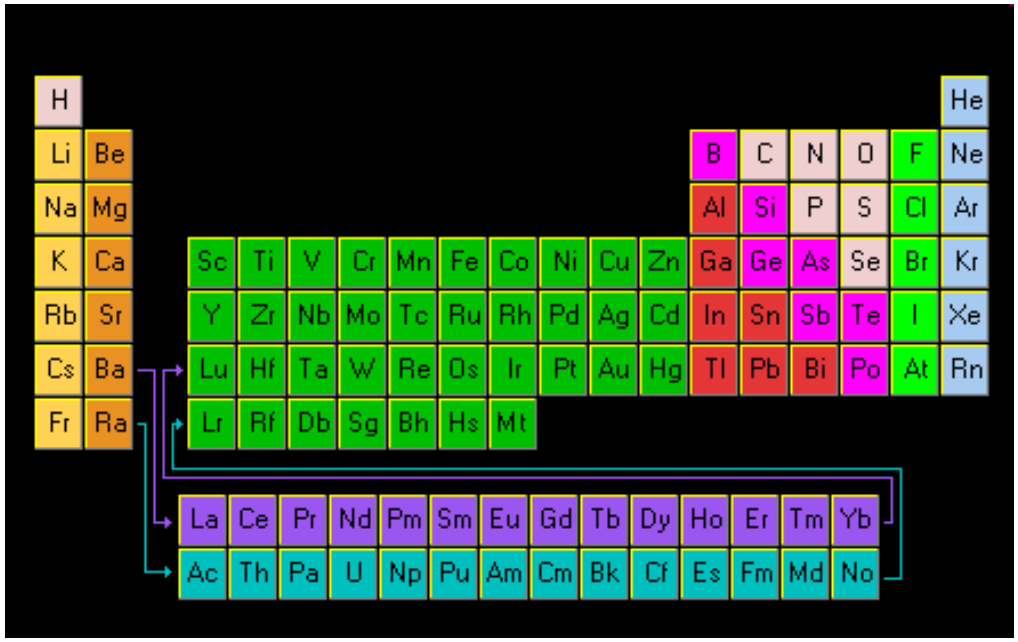
Otkriće neutrona (Chadwick, 1932.)

Neutron: Neutralna čestica sa masom kao proton

Elementarne čestice 1932. g.:

- proton: Q = + 1 e
- Neutron: Q = 0
- Elektron: Q = - 1 e

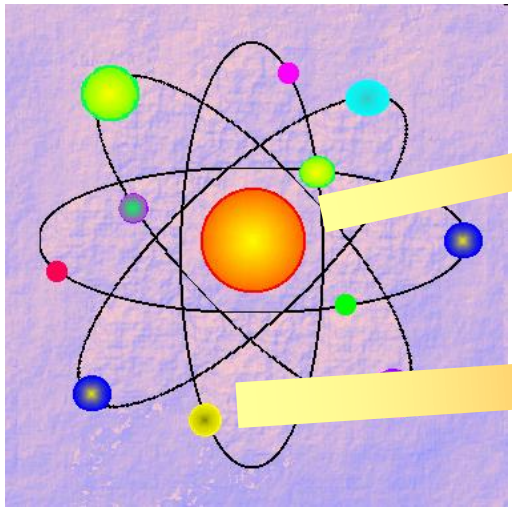


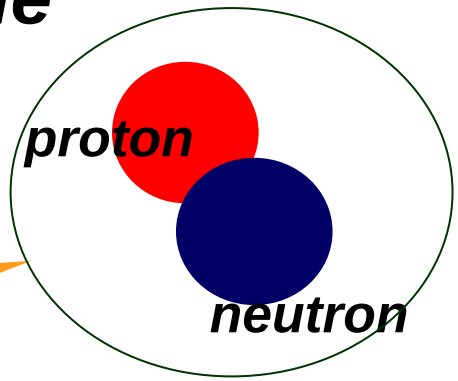


?

Periodic Table

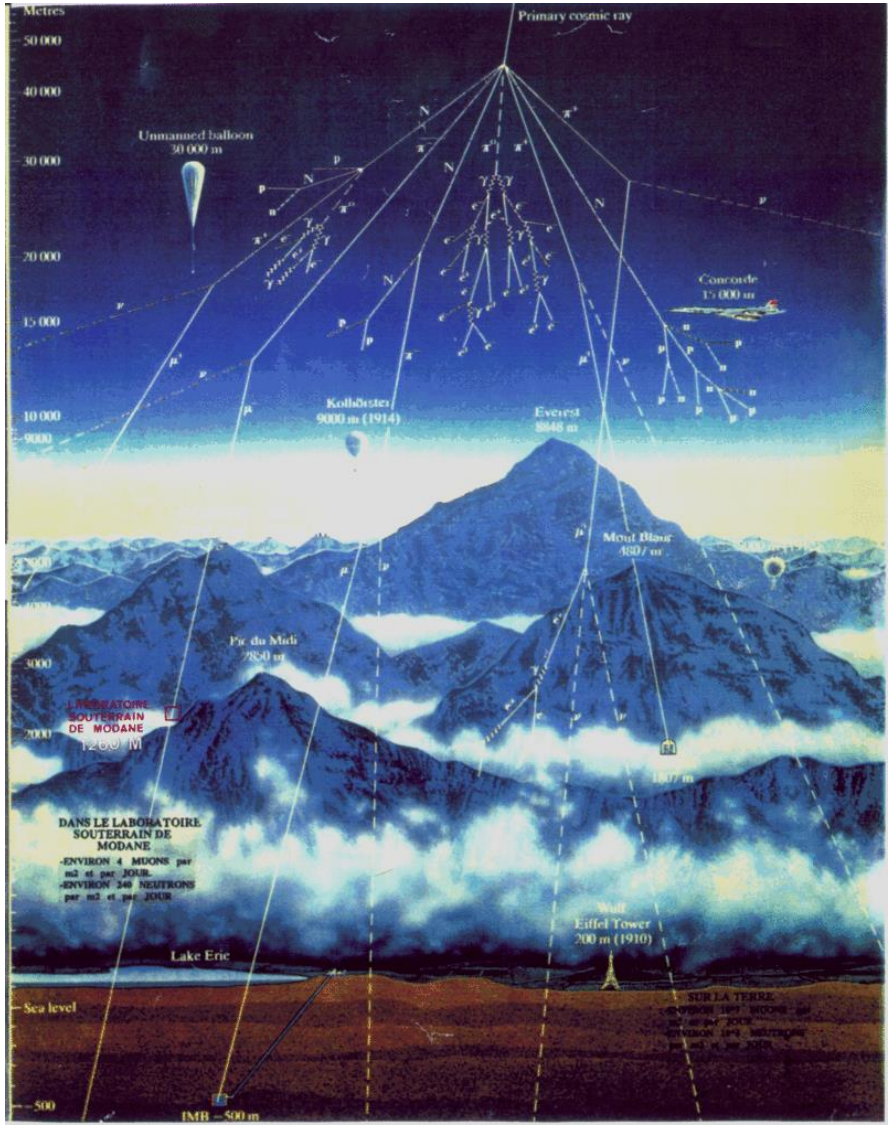
Atom





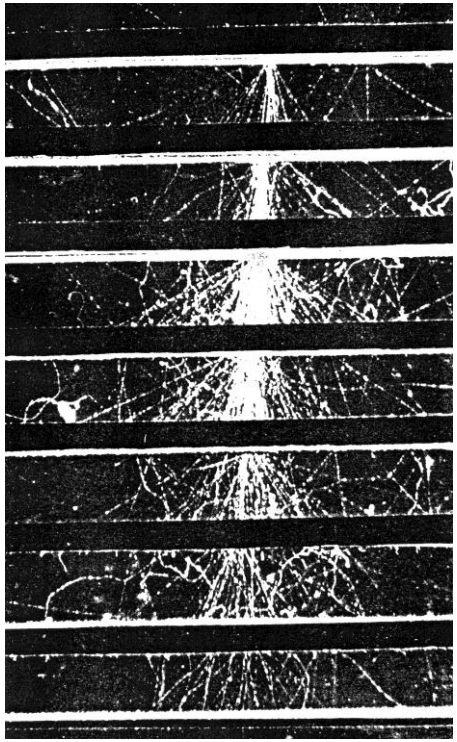
electron

Prvi snopovi: padaju s neba



[Kozmičko zračenje]

Jedini izvor visoko energetskih čestica do ~1950.



Cloud chamber image of an electromagnetic shower. Pb plates, each 1. 27 cm thick

Svijet se zakomplicira...

U kozmičkom zračenju otkriveni

μ

potpuno neočekivan

(Rabbi: “Who ordered that?”)

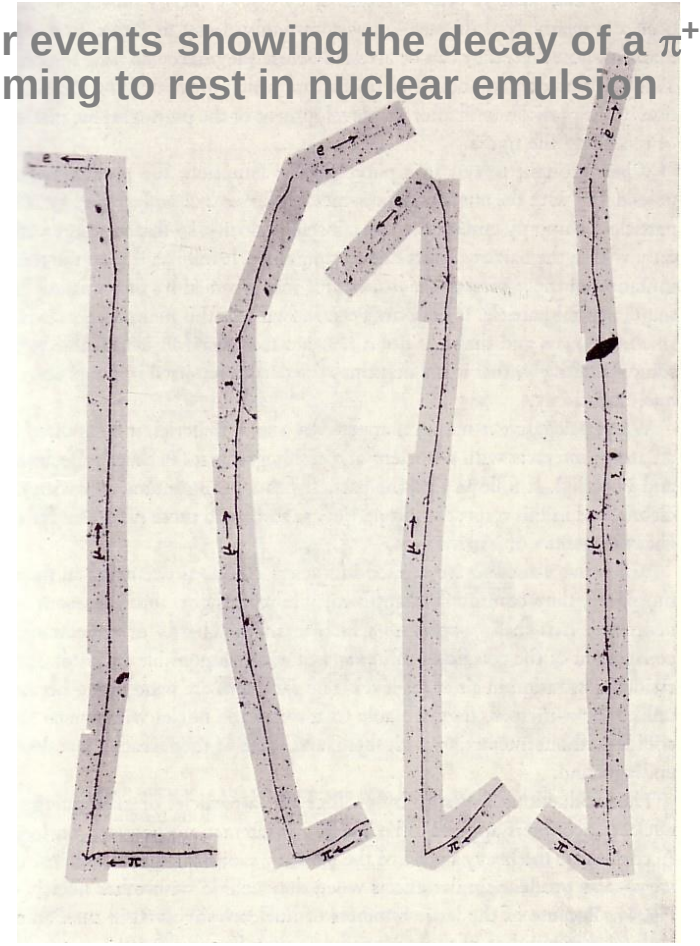
– Teški elektron

π

– Iz sudara zračenja sa jezgrama

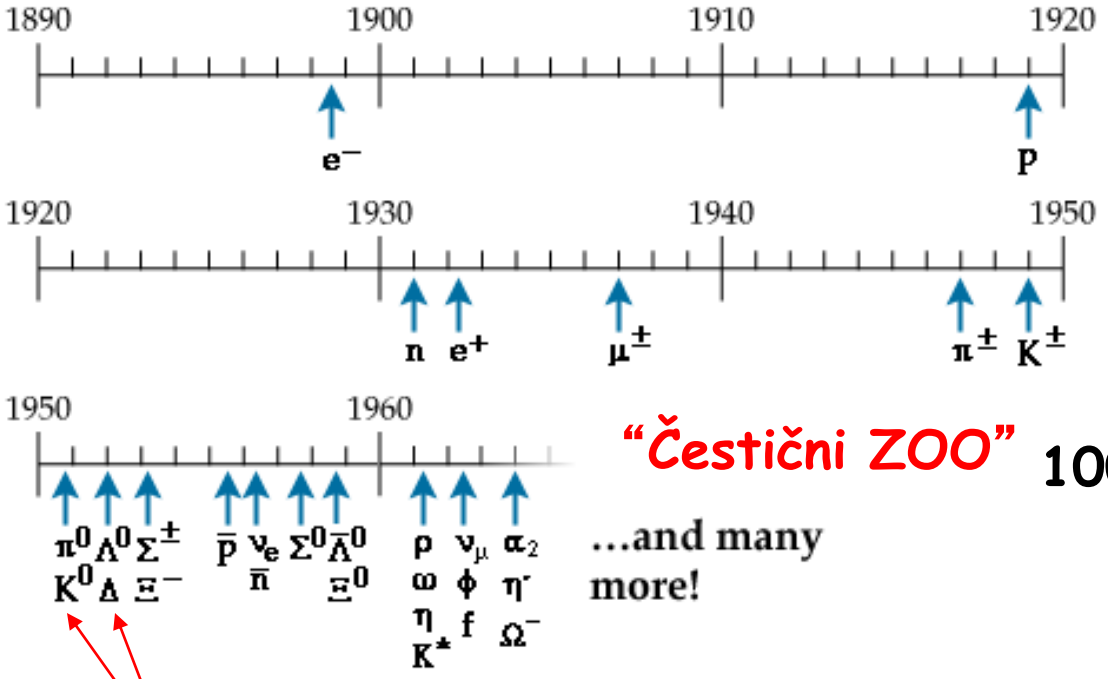
$\pi^+ \rightarrow \mu^+ \nu_\mu$; $\pi^- \rightarrow \mu^- \nu_\mu$

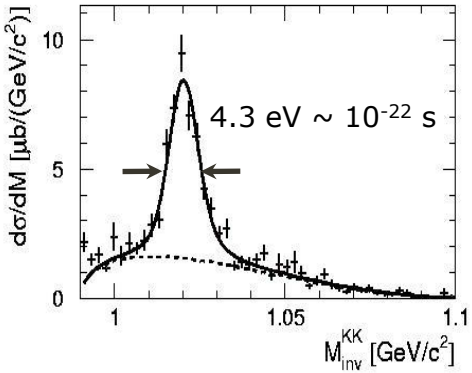
Four events showing the decay of a π^+ coming to rest in nuclear emulsion



… sve više i više

~ 1950.-1960.: puno novih čestica otkriveno u kozmičkom zračenju i na prvim akceleratorima (CERN, BNL, …)





"Čestični ZOO"

Ponovo više od 100 elementarnih čestica!

ali
Jesu li stvarno?

"Strange particles" (Murray Gell-Mann)

Kvarkovi?

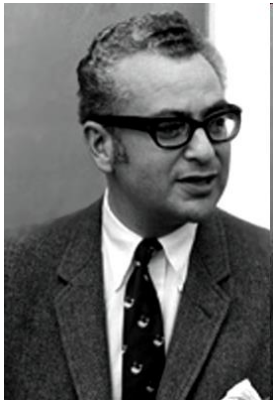
1964 (Gell-Mann, Zweig): Hadroni bi mogli biti građeni od 3 elementarnih čestica:

Gell-Mann ih krsti ”quarks”

	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

i 3 antikvarka ($\bar{u}$, $\bar{d}$, $\bar{s}$) sa suprotnim kvantnim brojevima

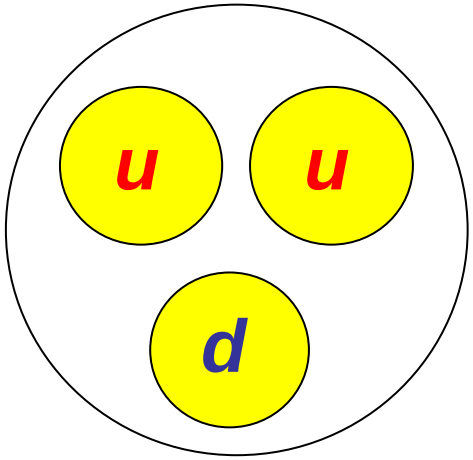
1964. se predlaže ideja **kvarkova**



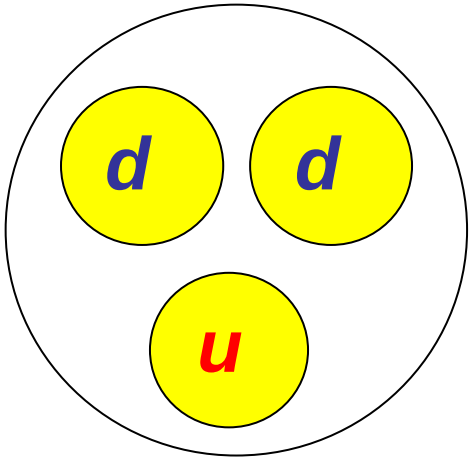
Gell-Mann

Zweig

Elementarne čestica s nabojom manjim od elementarnog naboja (elektrona) koje se pojavljuju u više vrsta ili okusa



proton

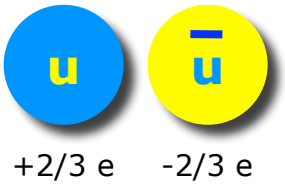


neutron

Kvarkovi – moguće kombinacije

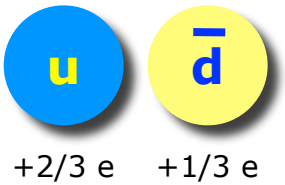
Mezoni

= Kvark-Antikvark

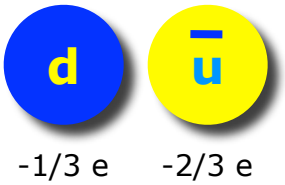


π^0

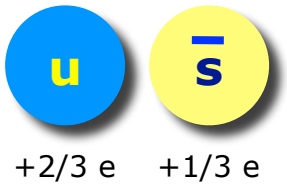
Nekoliko poznatih mezona



π^+



π^-

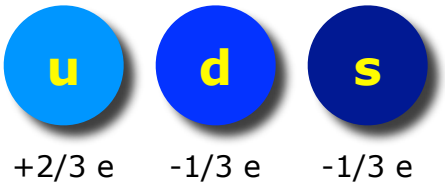


K^+

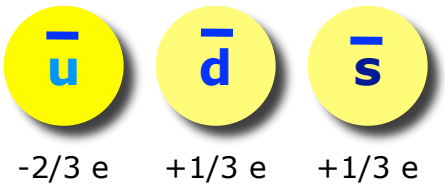
Barioni:

3 kvarka ili

3 antikvarka



Λ

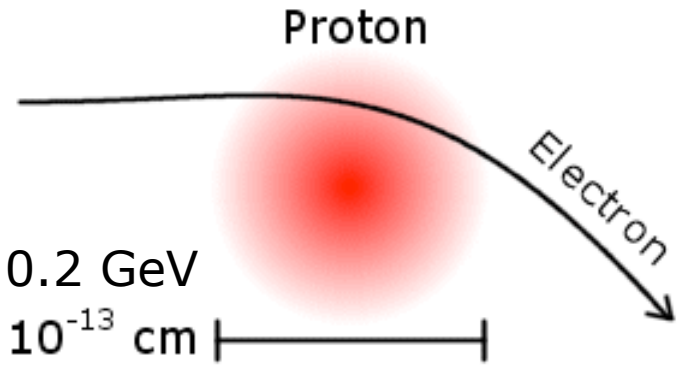


$\overline{\Lambda}$

Kvarkovi postoje!

Otkriće kvarkova

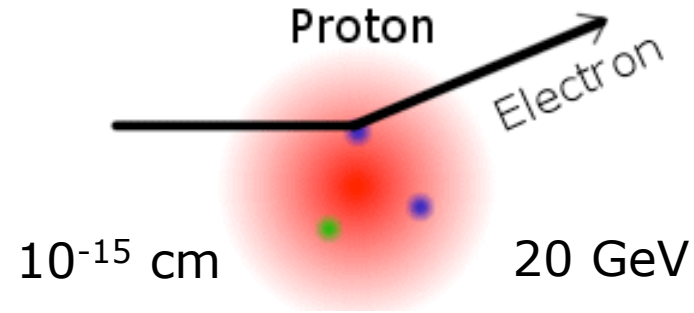
Raspršenje elektrona na protone



1956. Hofstadter: Mjerenje radiusa protona

Stanford Linear Accelerator Centre

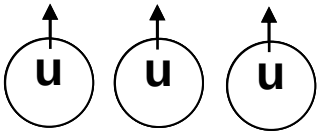
1967. Friedmann, Kendall, Taylor (SLAC): ~ Rutherford eksperiment s elektronima --> u protonu se nalaze 3 'tvrda' (točkasta) centra raspršenja

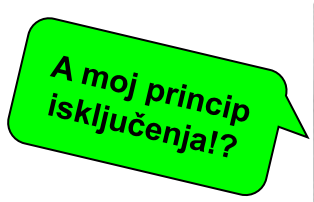


Mjerenja u skladu s prisutnošću 2 up- 1 down-Kvarka u protonu

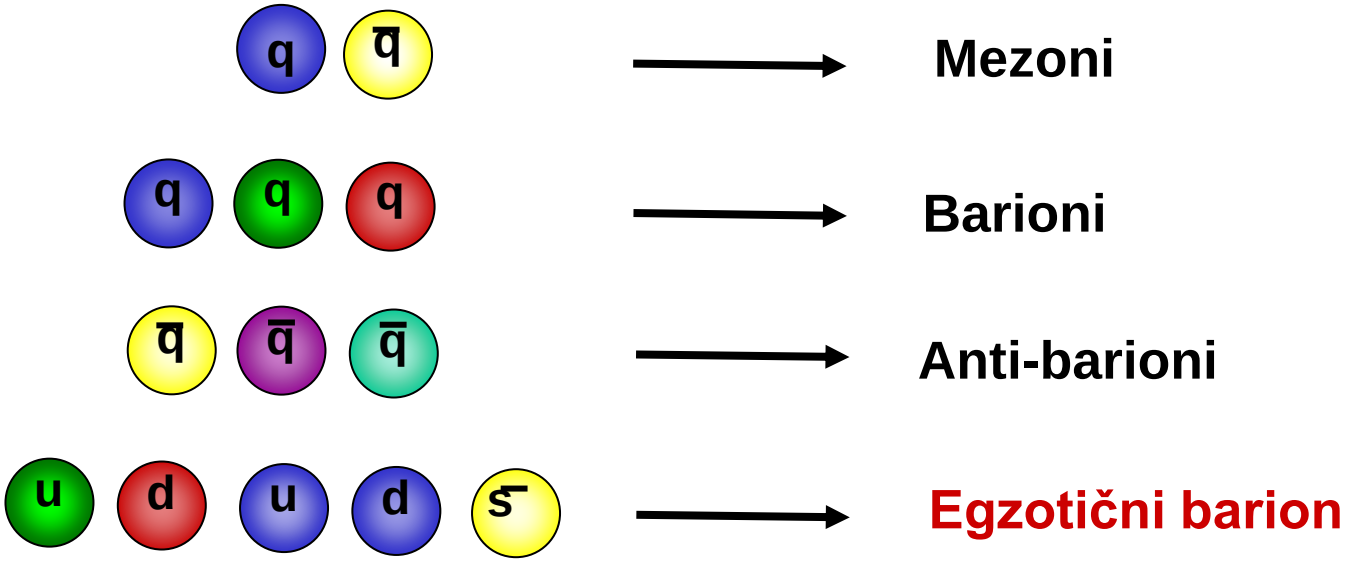
Jaka sila vidi... BOJU!

$\Delta^{++}(u^{\uparrow}u^{\uparrow}u^{\uparrow})$

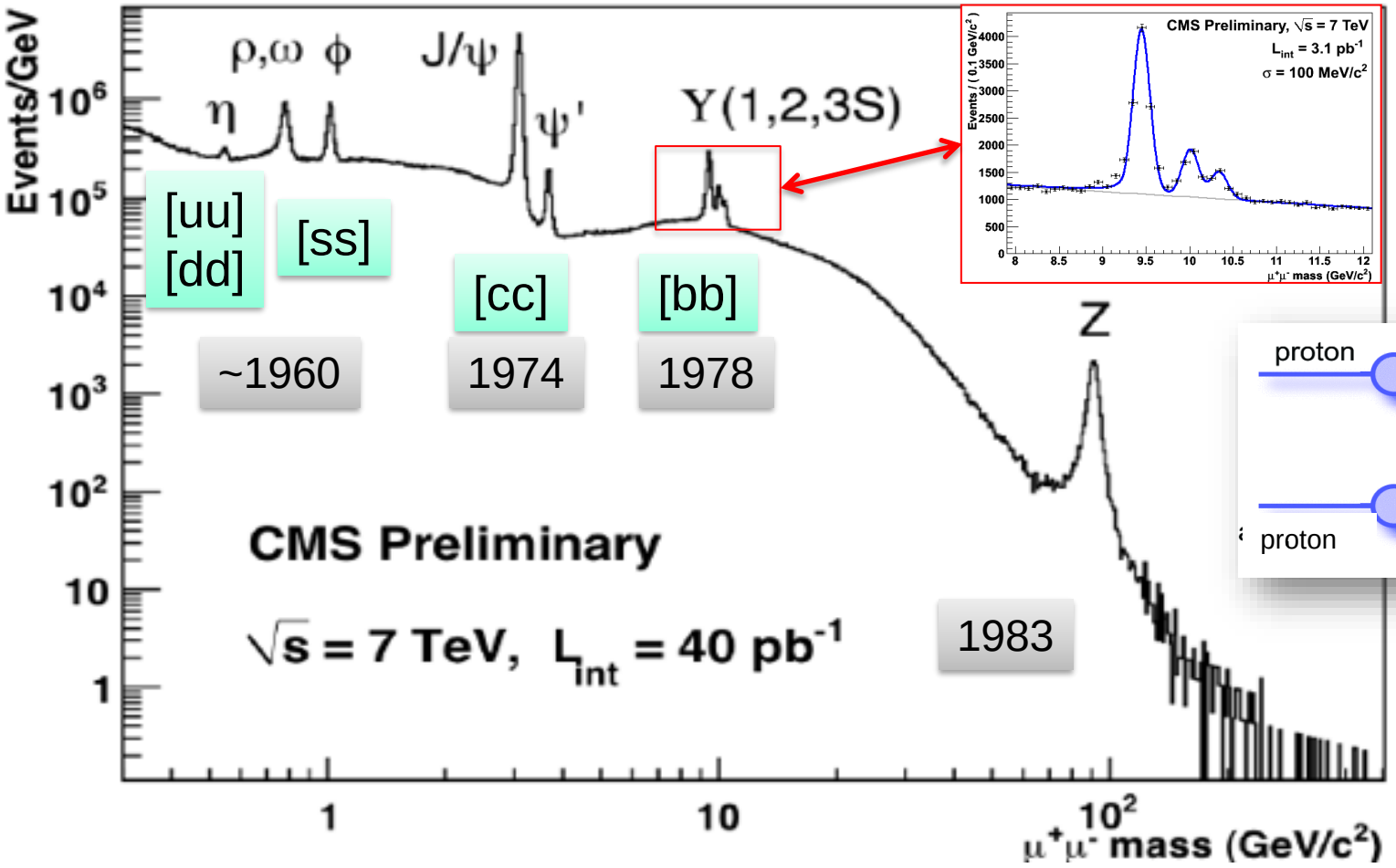


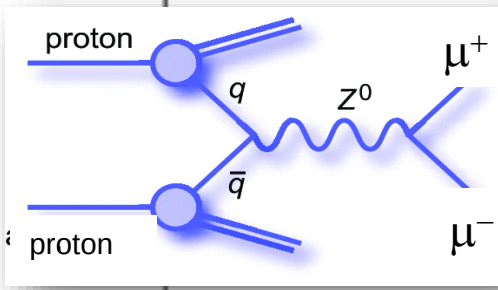


Slaganje boja u nešto bezbojno



Nove rezonancije: novi kvarkovi!





40 pb^{-1} collected in 2010

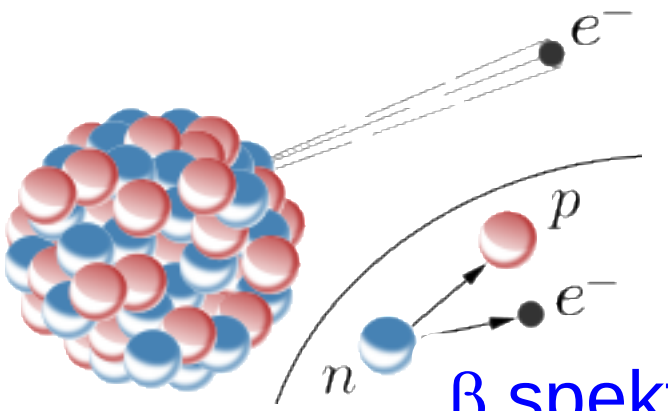
Enigma β raspada

Neke jezgre se raspadaju putem β raspada, npr.

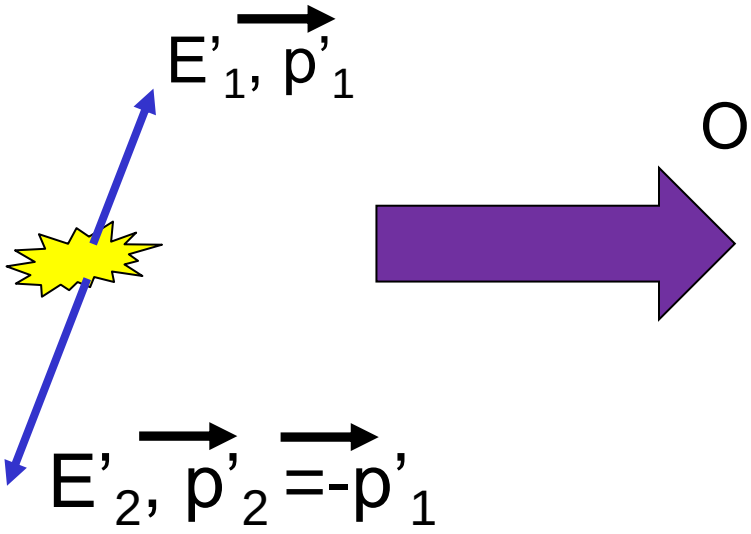
$$^{14}_{6}C \rightarrow {}^{14}_{7}N + e^{-}$$

SPIN: 0 1 1/2

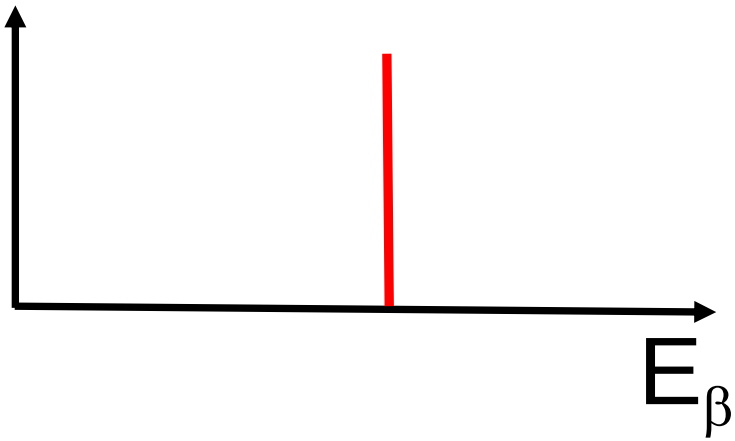
Očuvanje kutne količine gibanja????



β spektrum ?



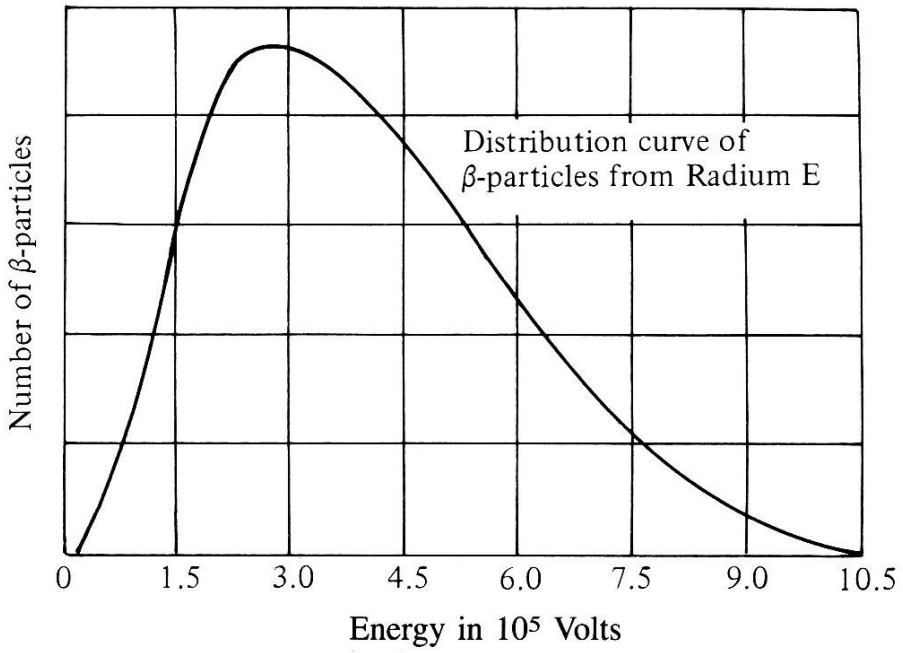
Očekujemo monokromatični spektar



Problem β raspada: kontinuirani spektar

Problem sa β spektrom
(trebao bi biti monokromatičan)

First measurement by Chadwick (1914)



Kako se onda zamišljao β^- raspad: $n \rightarrow p + e^-$

Radium E: $^{210}Bi_{83}$
(a radioactive isotope produced in the decay chain of ^{238}U)

Očuvanje energije?

Pauliovo pismo

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

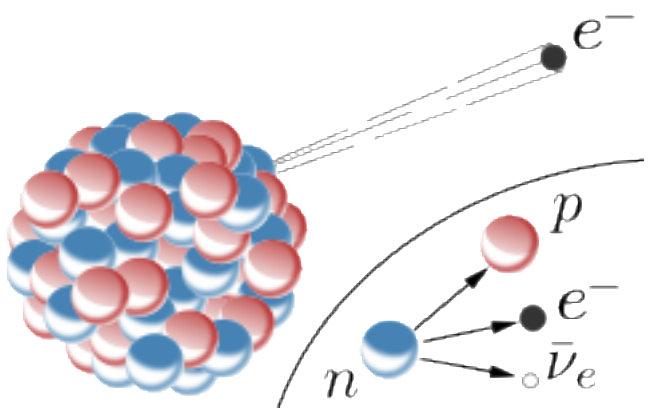
Rješenje problema β raspada: Nova čestica = Neutrino!

Pauli: u β raspadu se emitira još jedna čestica:

- Neutralna
- Nevidljiva (jako slabo međudjeluje)
- Polucijelog spina

$$^{14}_{6}C \rightarrow {}^{14}_{7}N + e^{-} + \bar{\nu}_e$$

SPIN: 0 1 ½ ½ : OK!



Otkrili smo
nevidljivu česticu
koristeći isključivo
Zakone očuvanja

Pauli: "I have done a terrible thing. I have proposed a particle that cannot be detected. It is something no theorist should ever do."

Reines et Cowan à Pauli (1956)

RADIOGRAMM-RADIOGRAMME

"VIA RADIOSUISSE"

NEWYORK

Brieftelegramm

NACHLASS PROF. W. PAULI

PROFESSOR W PAULI

ZURICH UNIVERSITY ZURICH

Per Post

NACHLASS PROF. W. PAULI

WE ARE HAPPY TO INFORM YOU THAT WE HAVE DEFINITELY DETECTED NEUTRINOS FROM FISSION FRAGMENTS BY OBSERVING INVERSE BETA DECAY OF PROTONS OBSERVED CROSS SECTION AGREES WELL WITH EXPECTED SIX TIMES TEN TO MINUS FORTY FOUR SQUARE CENTIMETERS

FREDERICK REINES AND CLYDE COWN

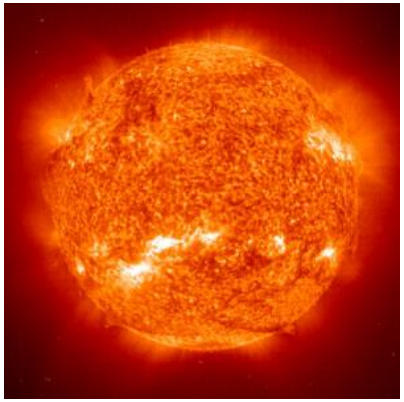
BOX 1663 LOS ALAMOS NEW MEXICO

Pauli :

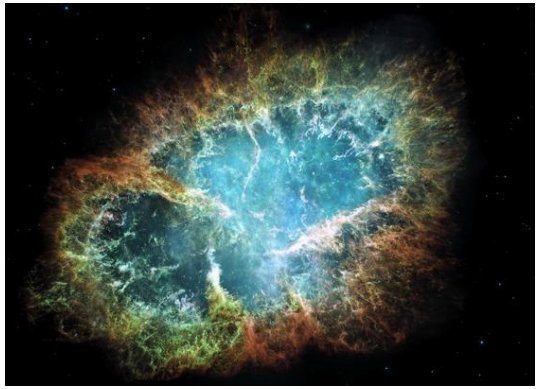
Frederick REINES and Clyde COWAN
Box 1663, LOS ALAMOS, New Mexico
Thanks for message. Everything comes to him who knows how to wait.

Pauli

Neutrini pljušte sa svih strana



Sunce: 64 milijardi po cm^2 po sekundi



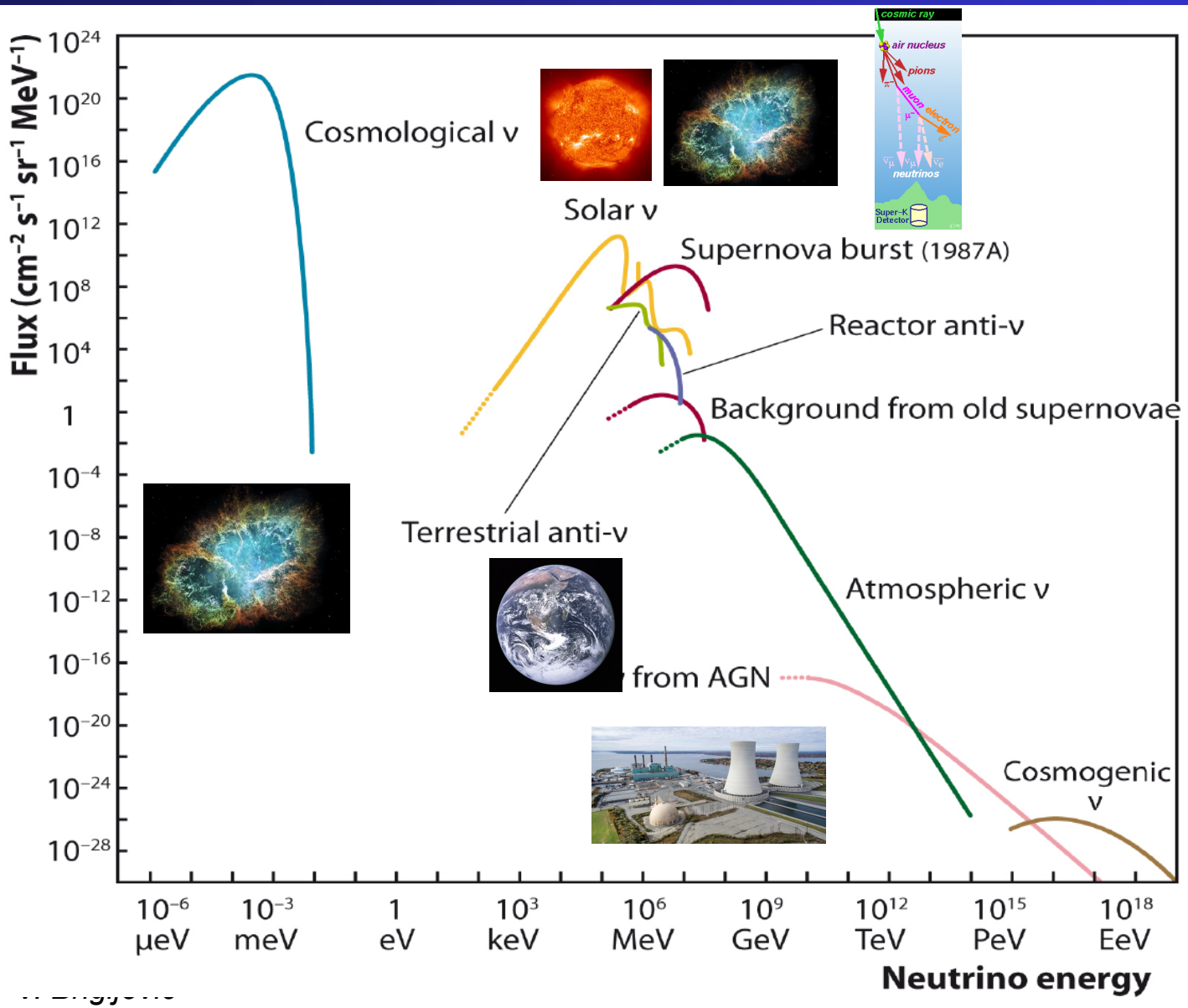
Supernova iz naše galaksije: 5 milijardi po cm^2 svake sekunde kroz 10 sekundi

Veliki prasak:
U svakom cm^3 oko 300 neutrina

Nuklearke:
Oko 100,000 po cm^2 svake sekunde na 200km od centrale

Geofizički i atmosferski neutrini:
6 milijuna po cm^2 svake sekunde

Spektar neutrina



Elementarne čestice, 2024.

Leptons

Electric Charge

Tau -1 0 Tau Neutrino

Muon -1 0 Muon Neutrino

Electron -1 0 Electron Neutrino

Quarks

Electric Charge

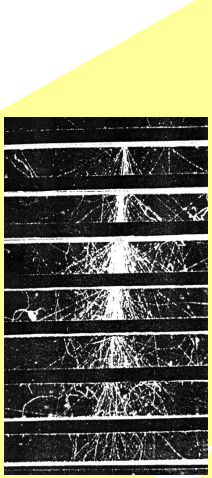
Bottom -1/3 2/3 Top

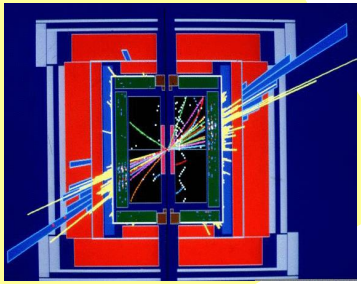
Strange -1/3 2/3 Charm

Down -1/3 2/3 Up

each quark: R, B, G 3 colors

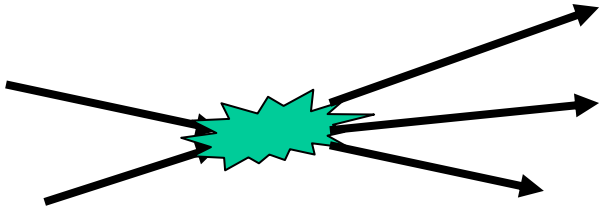
Nisu stabilne

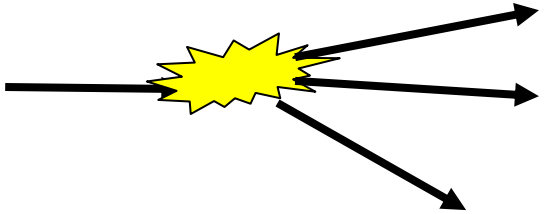


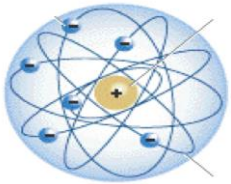



Koji su gradivni elementi svijeta?
Kako se ponašaju?

Pitanje sila / interakcije

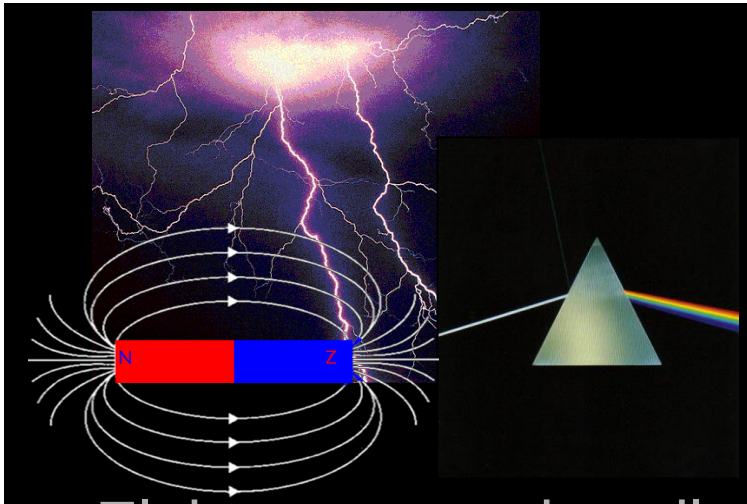






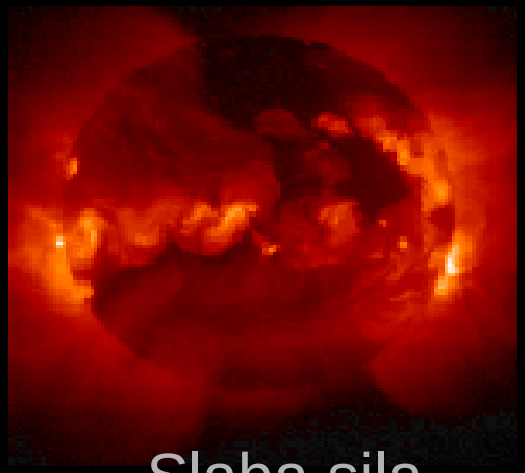
- Čestice ne žive same: reakcije, struktura, …
- U reakcijama, raspadima, vezanim stanjima:
  - Koliko različitih vrsta interakcija / sila?
  - Koje čestice osjetljive na koje sile?
  - Očuvane veličine, naboji, …?

4 temeljne sile

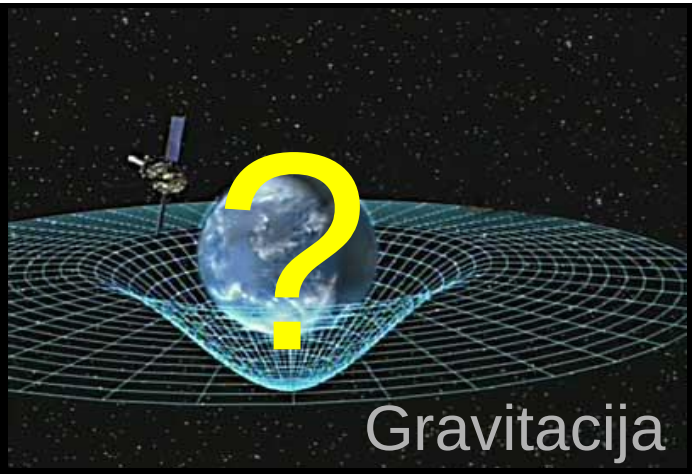


Elektromagnetska sila

Jaka sila



Slaba sila



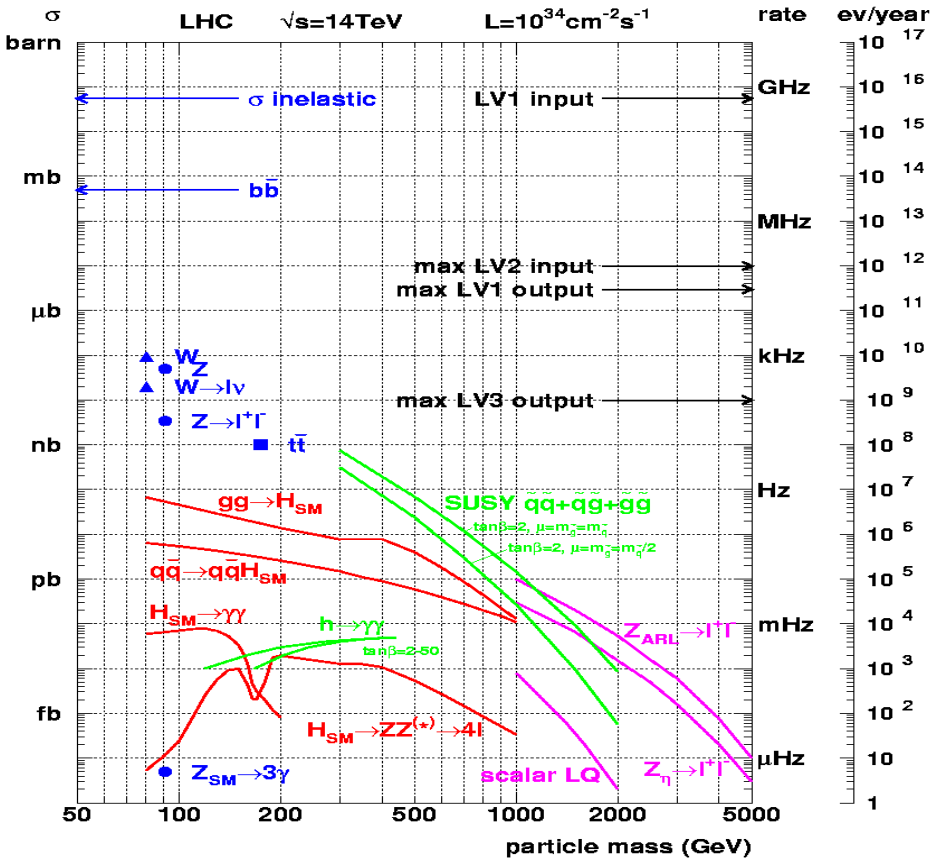
Gravitacija

Jačine sila: udarni presjeci, vremena života

Vremena života nekoliko čestica

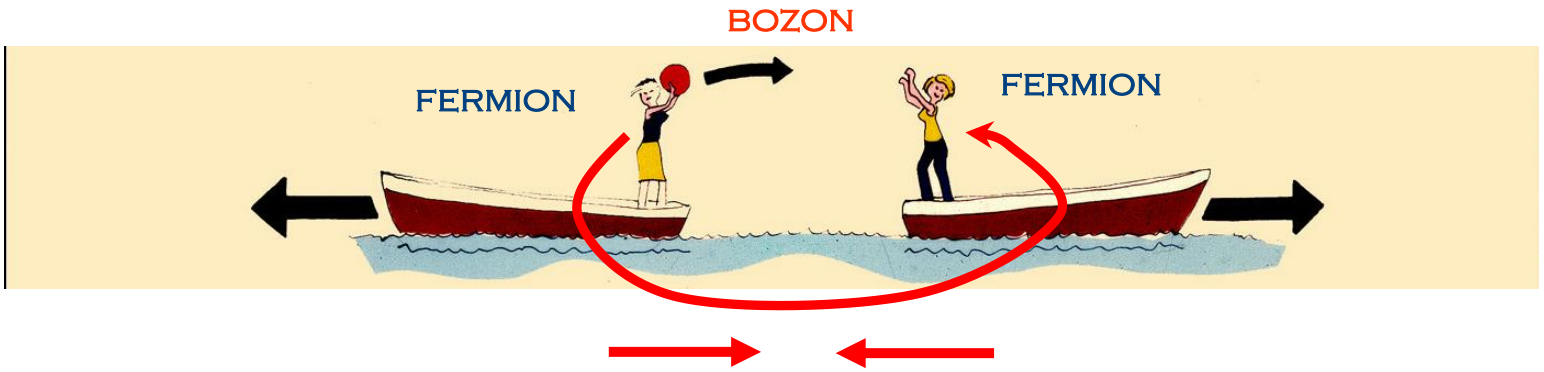
Čestica	Vrijeme života
ρ mezon	$4.5\ 10^{-24}$ s
Δ^{++} barion	$5.6\ 10^{-24}$ s
π^0 mezon	$8.5\ 10^{-17}$ s
π^+ mezon	$2.6\ 10^{-8}$ s
μ	$2.2\ 10^{-6}$ s
Neutron	878 s (~14min)
Higgsov bozon	$1.6\ 10^{-22}$ s

Udarni presjeci na LHC-u



Sile: Izmjena čestica

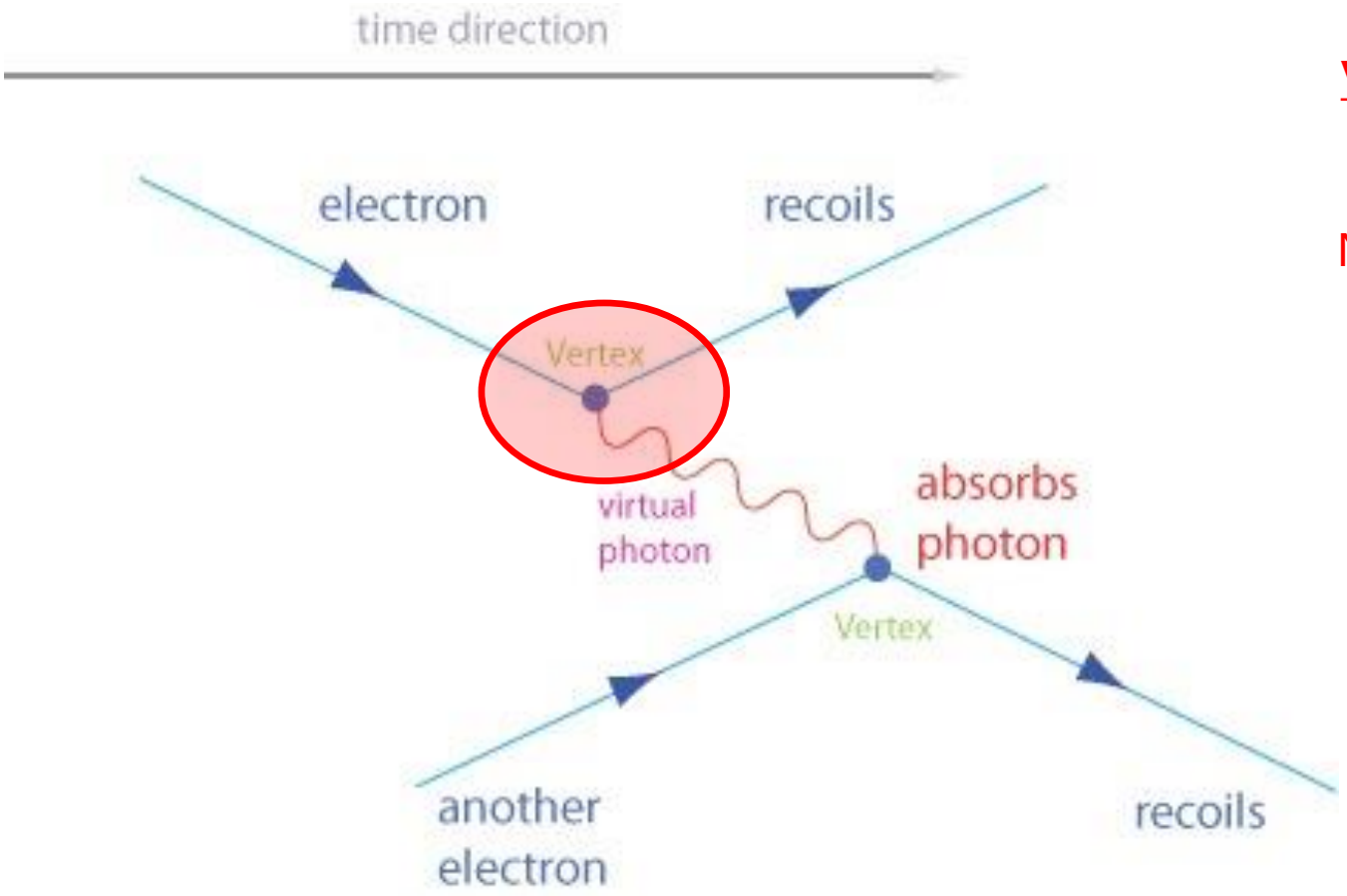
Relativnost: nema djelovanja na daljinu!



Izmjena bozona je izvor sila između fermiona

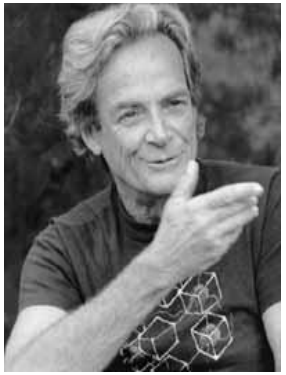
sila	bozon	primjer
jaka	gluon (bez mase)	atomska jezgra
elektromagnetska	foton (bez mase)	atomske orbite
Slaba	Z^0 W^+ W^- (teške)	radiaktivnost
gravitacija	graviton (bez mase) ??	nebeska tijela

Interakcije



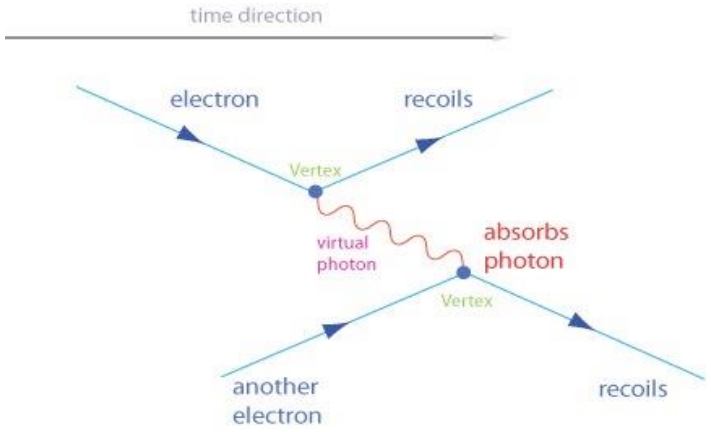
Vrh interakcije
Fermion
Nositelj
Naboj (vezanje)

R. P. Feynman

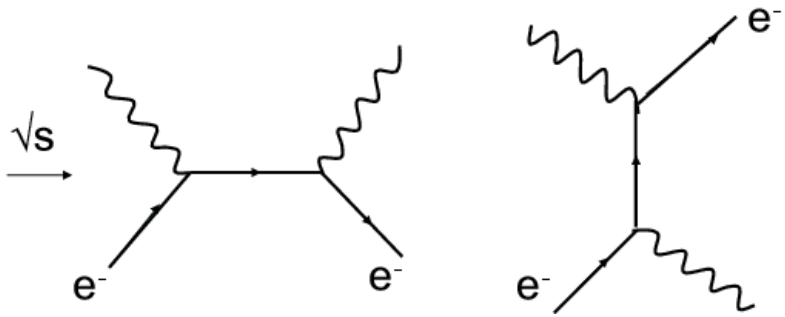


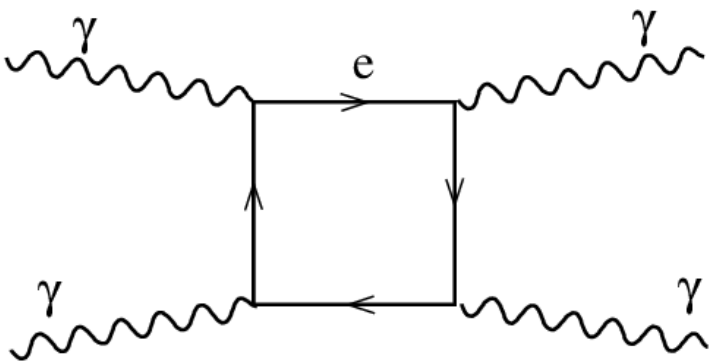
Feynmanovi diagrami

Elektromagnetska sila



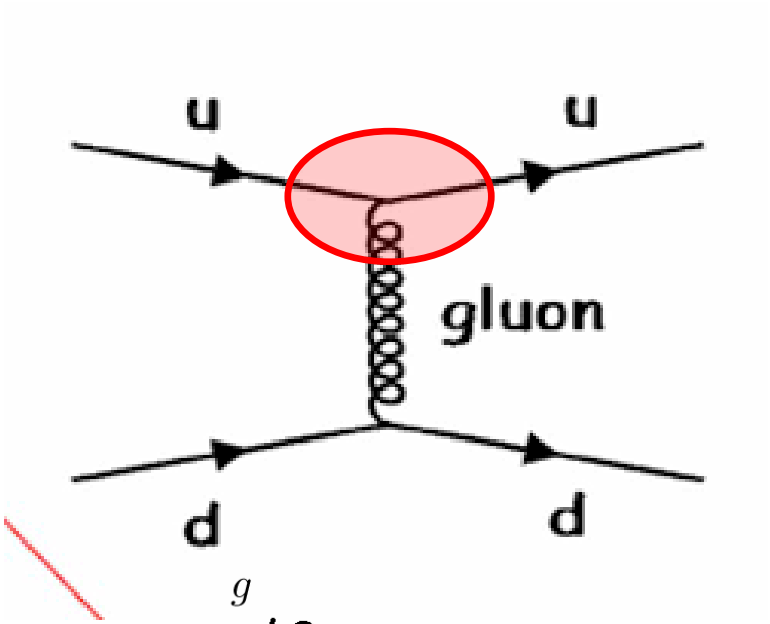
b) Compton scattering:

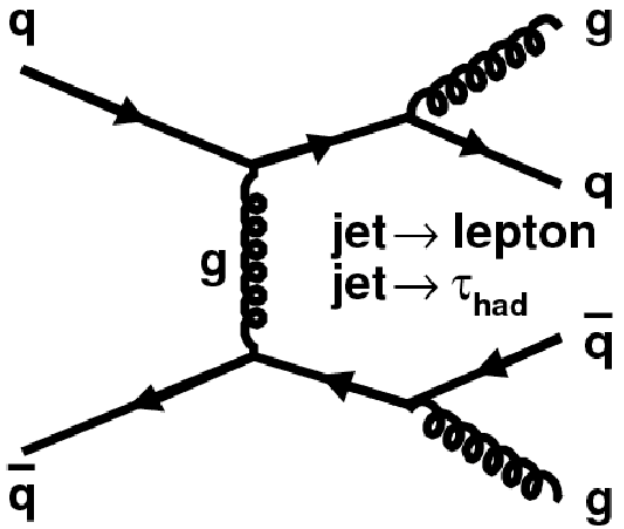


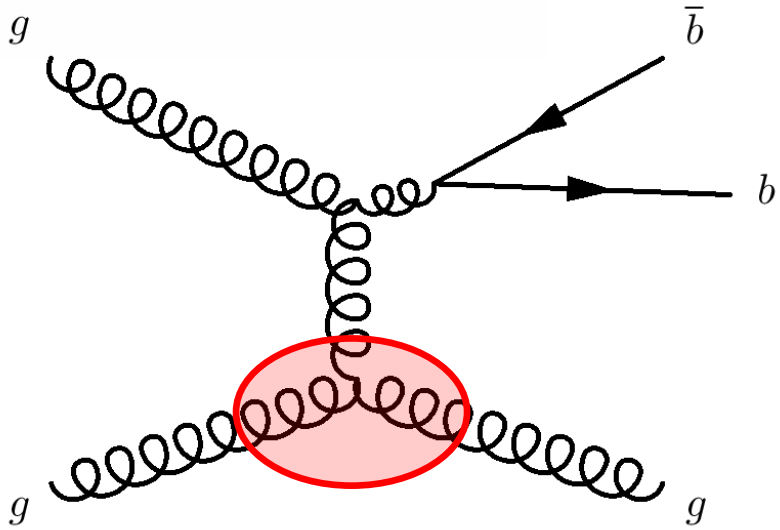


+ crossed

Jake interakcije



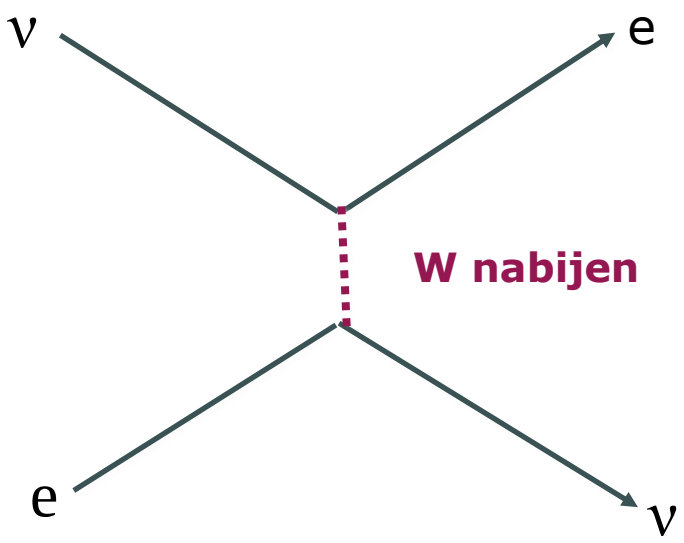


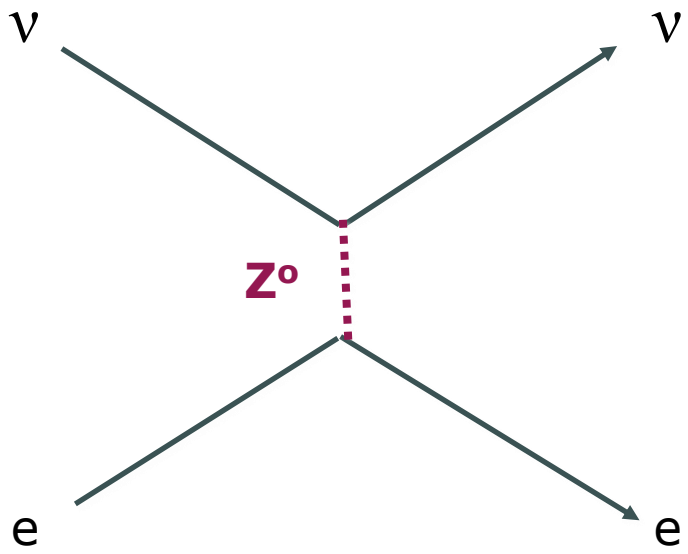


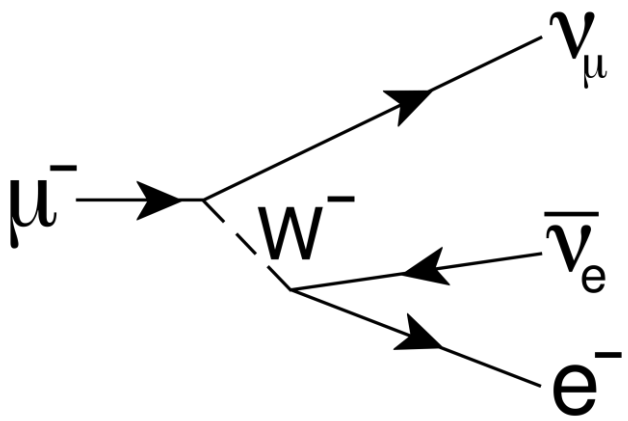
Naboj: boja

Gluon nosi boji!

Slabe interakcije





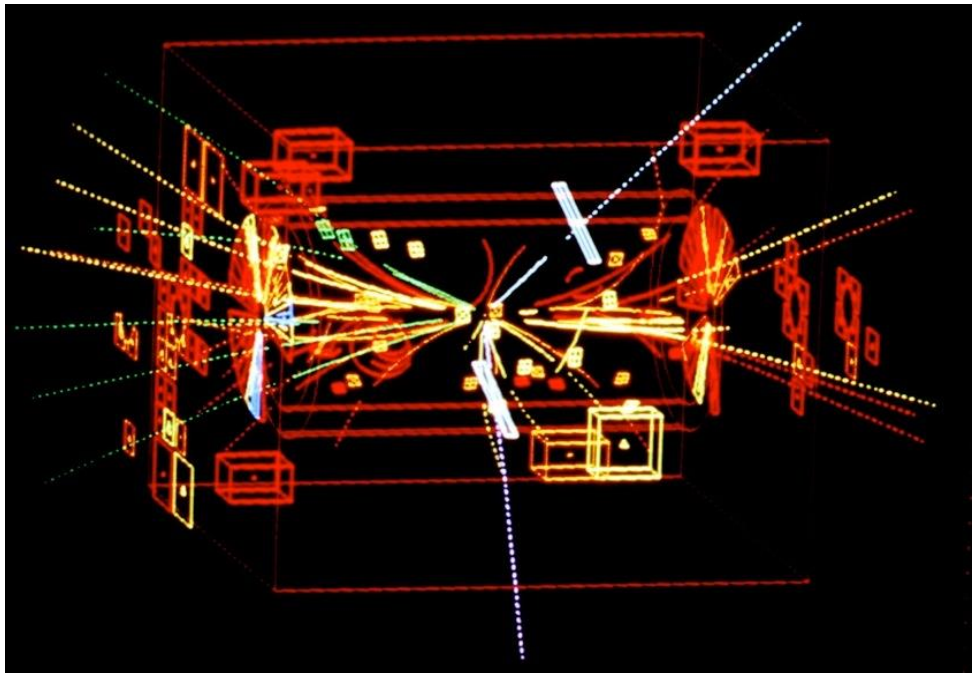


Nositelji sile: W i Z bozoni

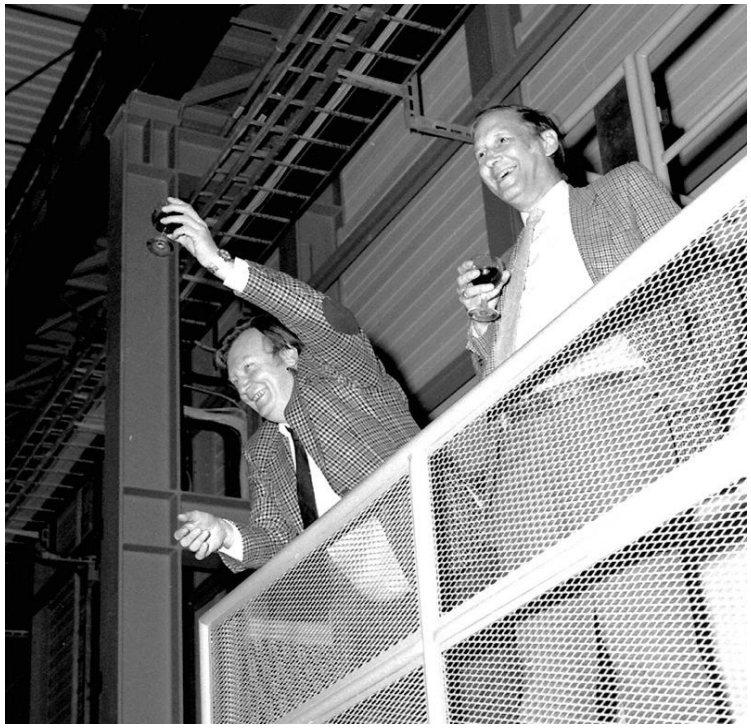
Imaju veliku masu!
W+/-: ~80 GeV, Z: ~91 GeV

Otkriće W i Z bozona

CERN (1983.)



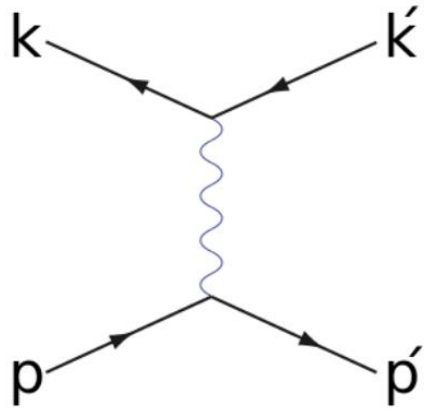
W kandidat u detektoru UA-1



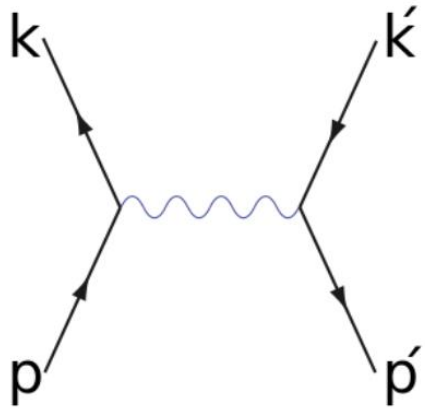
Carlo Rubbia, Simon van der Meer

Feynmanovi diagram nisu samo igra

Koristeći **Feynmanova pravila**, pretvaramo diagrame direktno u amplitude



(scattering)



(annihilation)

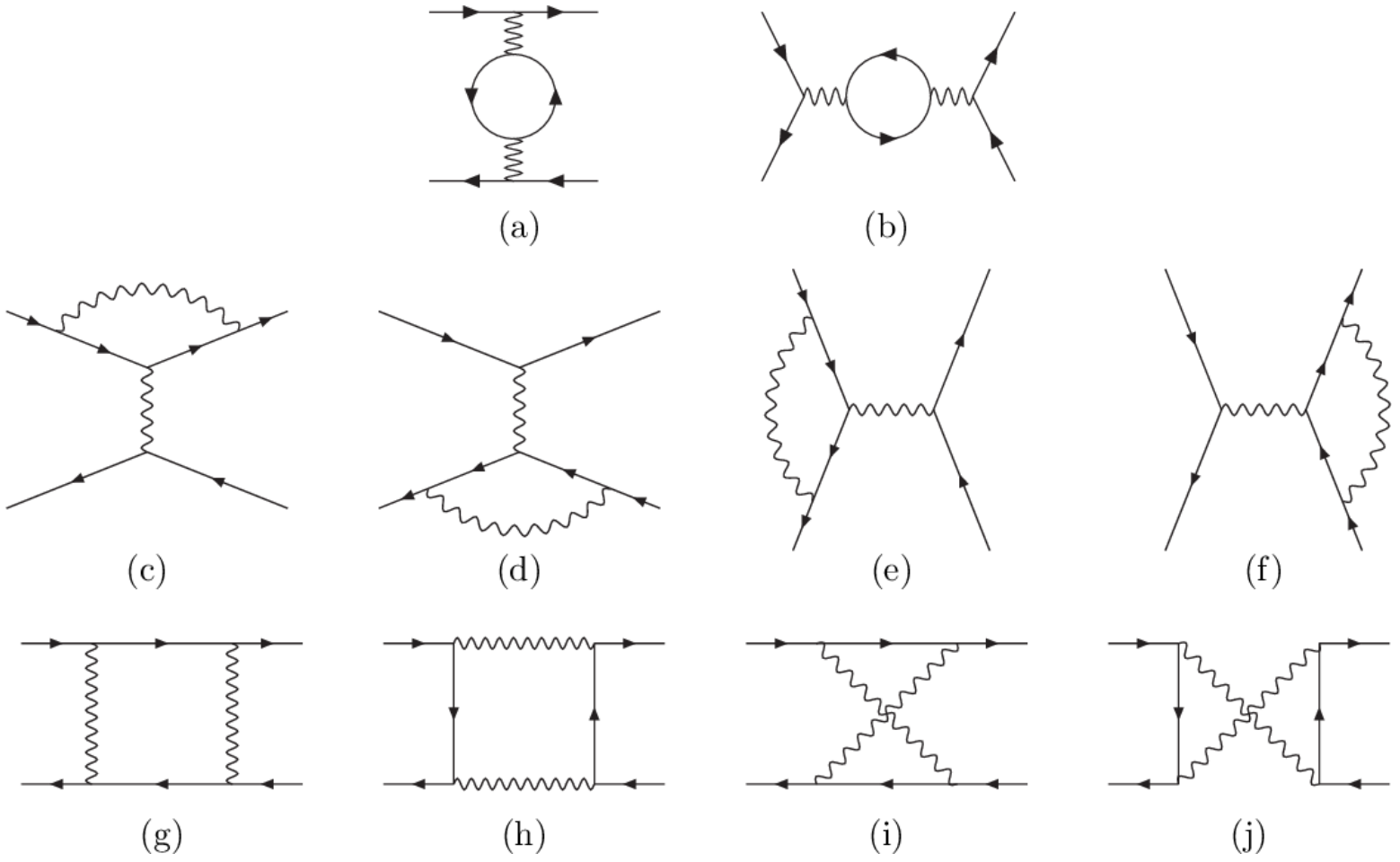
$$\mathcal{M} = -e^2 \left(\bar{v}_k \gamma^\mu v_{k'}\right) \frac{1}{(k-k')^2} \left(\bar{u}_{p'} \gamma_\mu u_p\right) + e^2 \left(\bar{v}_k \gamma^\nu u_p\right) \frac{1}{(k+p)^2} \left(\bar{u}_{p'} \gamma_\nu v_{k'}\right)$$

Iz (kvadrirane) amplitude dobivamo vjerojatnost interakcije

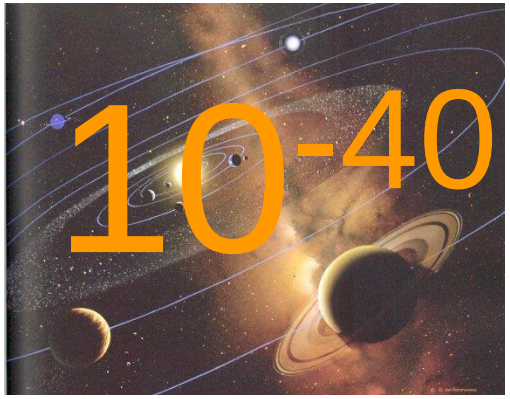
Ali ovo nije cijela prića…

Procesi višeg reda

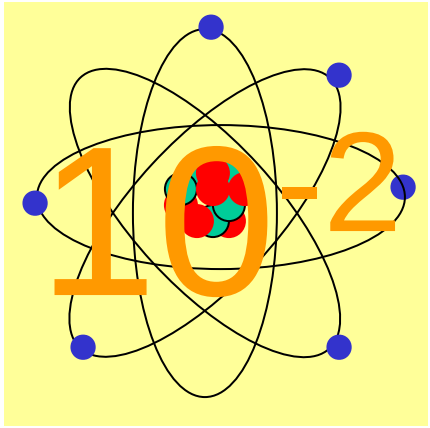
Puni račun treba uzeti u obzir SVE što bi se moglo dogoditi



Jačine sila

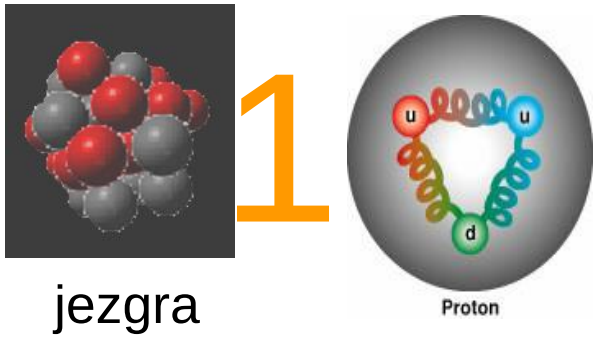


Gravitacijska sila



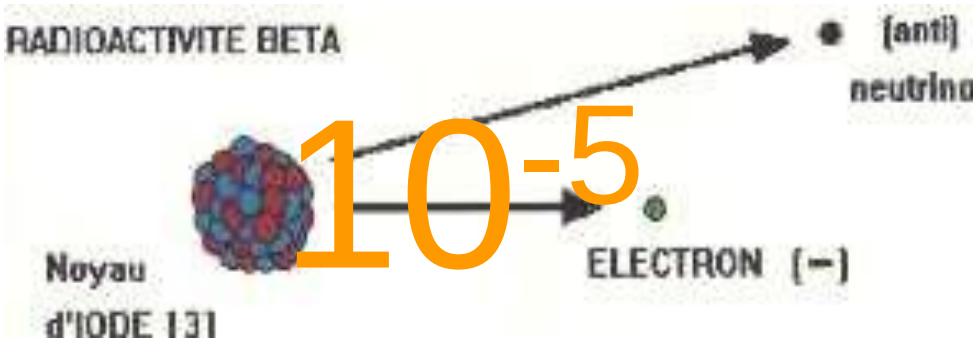
atom

Elektromagnetska sila



jezgra

Jaka nuklearna sila



Slaba sila

$n \rightarrow p + e^- + \nu_e$

$d \rightarrow u + e^- + \nu_e$

Doseg sila

Stvaranje i izmjena čestice nosioca sile

-> Energija nije očuvana...

za kratko vrijeme!

$$\Delta t \approx \frac{\hbar}{\Delta E} = \frac{\hbar}{mc^2}$$

U vremenu Δt čestica može proći R = c Δt

$$R \approx \frac{\hbar c}{mc^2}$$

Npr.:

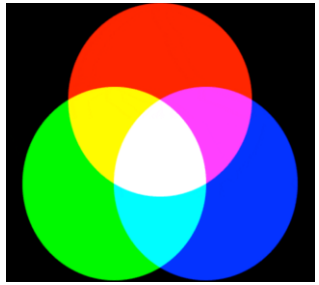
- Nositelj sile nema mase (m=0): R = ∞
- Nositelj sile mase m=80 GeV: R = 10^{-3} fm

Jaka sila: QCD

Teorija jake interakcije:

Kvantna kromodinamika (QCD)

- 3 različita naboja: boje (crveno, zeleno plavo)
- Nosioci jake sile (8 gluona)



SAMO bezbojna stanja mogu postojati: nema slobodnog kvarka

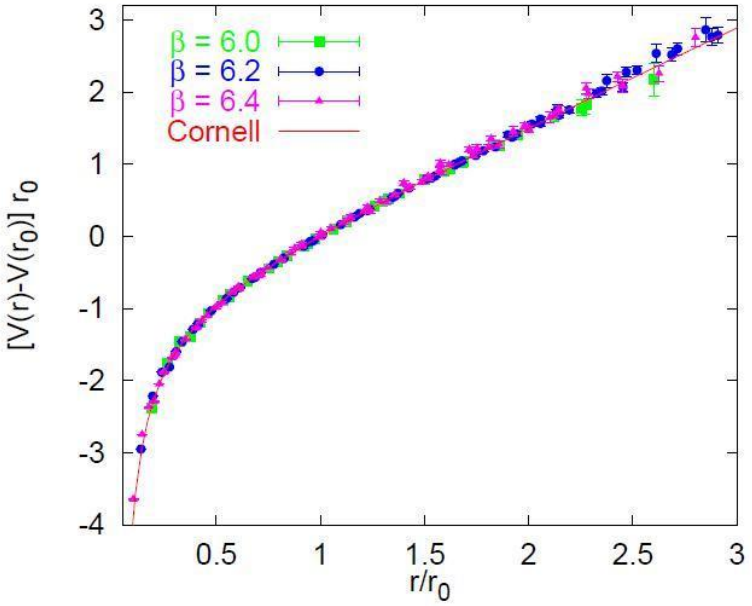
Nema slobodnog kvarka: "Confinement"

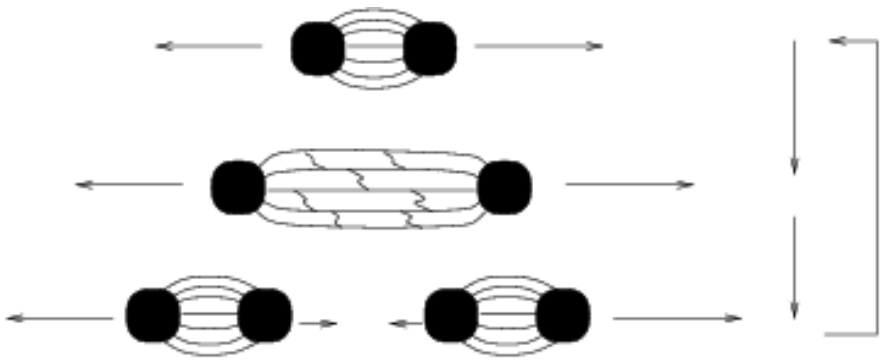
Zbog QCD potencijala:

isplativije energetski izvući iz vakuuma

par kvark-antikvark

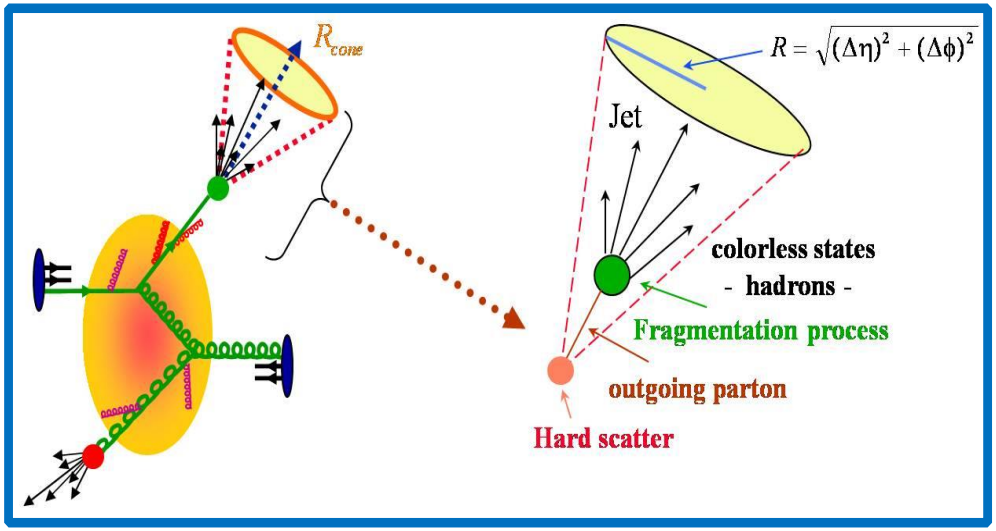
za stvoriti bezbojne hadrone

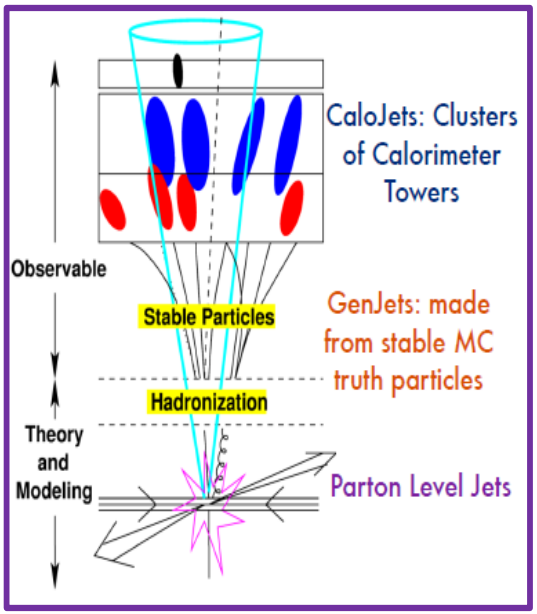


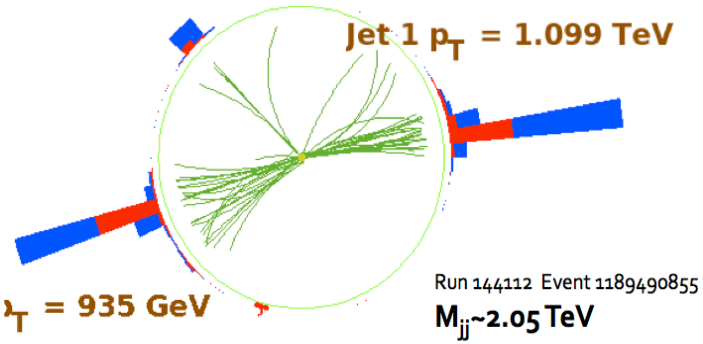


Posljedica:
Hadronski mlaz
"Jet"

Kvarkovi - Jets







Očuvano: broj bariona

Svakoj čestici se pripisuje barionski broj:

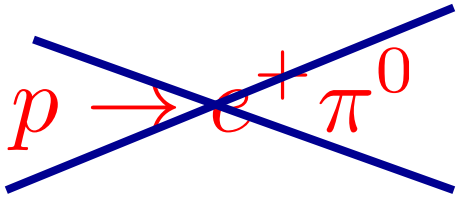
Čestica	e,μ,τ	Neutrino	Kvark	antikvark
B	0	0	+1/3	-1/3

Barion: +1 Antibarion: -1 Mezon: 0

Činjenica: barionski broj je očuvan u svim poznatim reakcijama

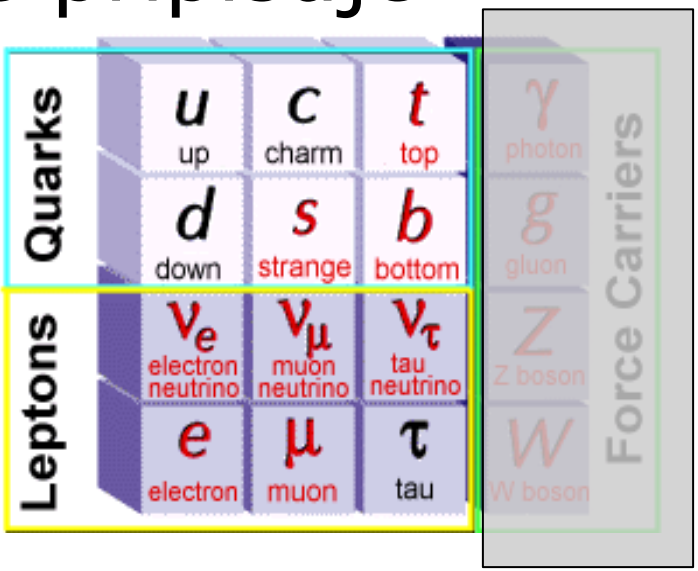
= Zbroj kvarkova i antikvarkova je konstantan

Npr. zabranjuje: raspad protona



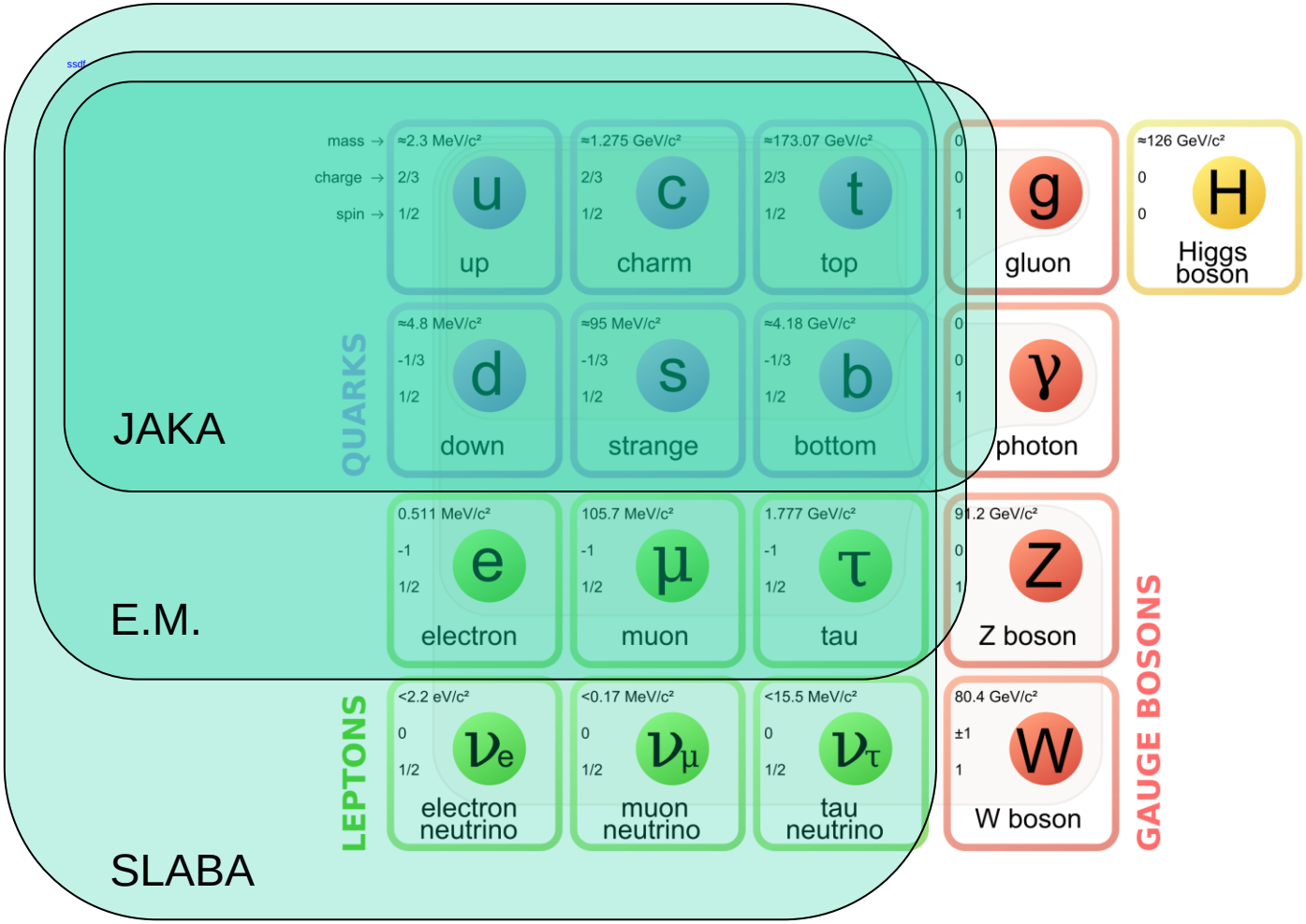
Očuvano (?) svojstvo: "Okus"

- Svakoj vrsti čestica se pripisuje okus:
  - "u,c,t,d,s,b" okus
  - Antičestica: suprotno

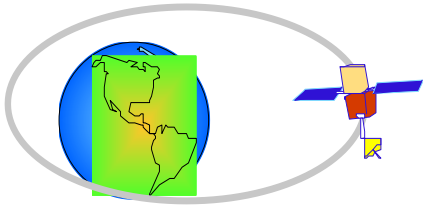


- Okus je očuvan u svim jakim i elektromagnetskim reakcijama:
  - Ako se stvara u-kvark, mora i anti-u

Čestice Standardnog modela i njihove interakcije



Ujedinjenje sila

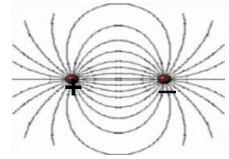


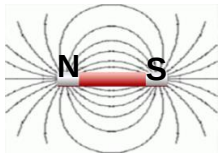
Zemaljska mehanika

Nebeska mehanika

Univerzalna gravitacija

Inercijalna vs. Gravitacijska masa
(I. Newton, 1687.)



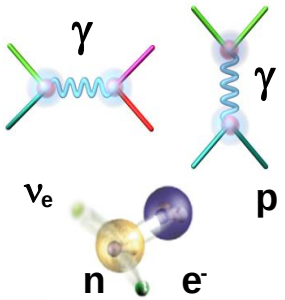


Elektricitet

Magnetizam

Elektromagnetizam

Elektromagnetski valovi (foton)
(J.C. Maxwell, 1860.)



Elektromagnetizam

Slaba sila

Elektroslaba

Intermedijalni bozoni W, Z
(1970.-83.)

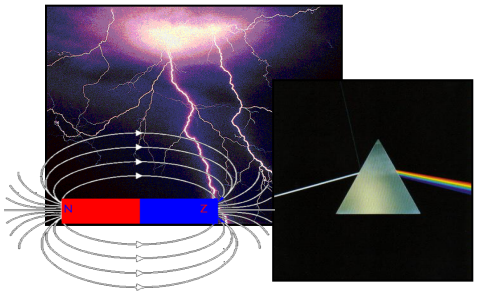
?

Ispitivanje sve manjih dimeznija otkriva dublje pravilnosti

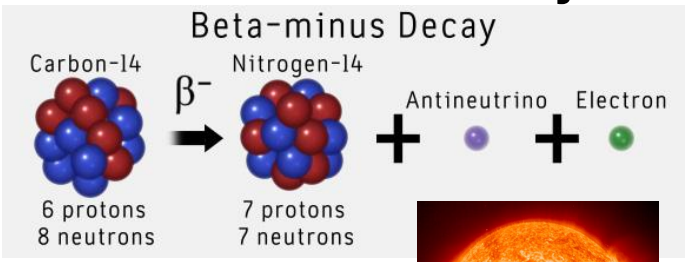
UJEDINJENI OPIS

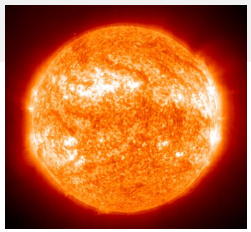
Elektroslabo ujedinjenje

Elektromagnetizam



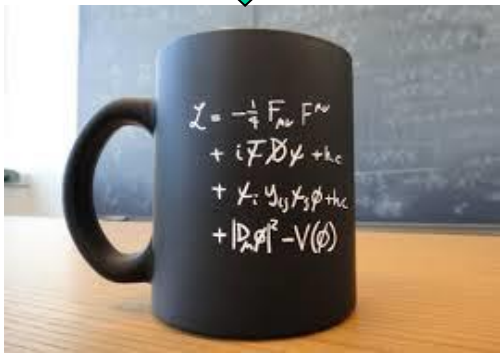
Slabe interakcije





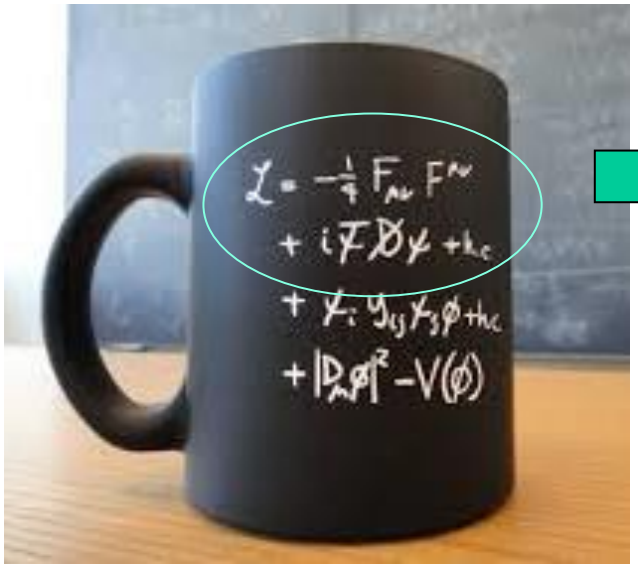
Elektroslaba teorija

- Zajednički izvor za elektromagnetsku i slabu silu
- Elektroslaba teorija temeljena na principu simetrije između 2 sile



Elektroslabi bozoni

- Nosioci elektroslabe sile



Elektroslaba teorija

- svi bozoni bezmaseni
- Sile ~ jednake

Opažanja

e.m. Sila

Foton m=0

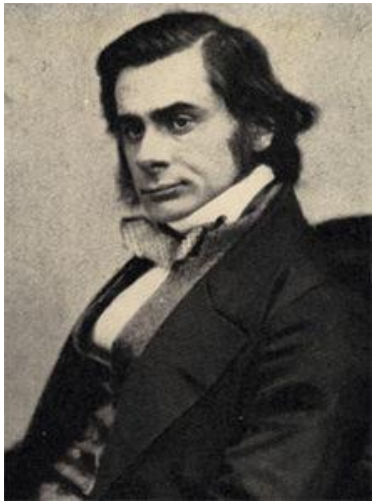
Slaba sila

W & Z bozoni: m~80-90 GeV

Slaba sila << e.m sila

Različite mase za fotona, W i Z:
lome simetriju i time i SM!

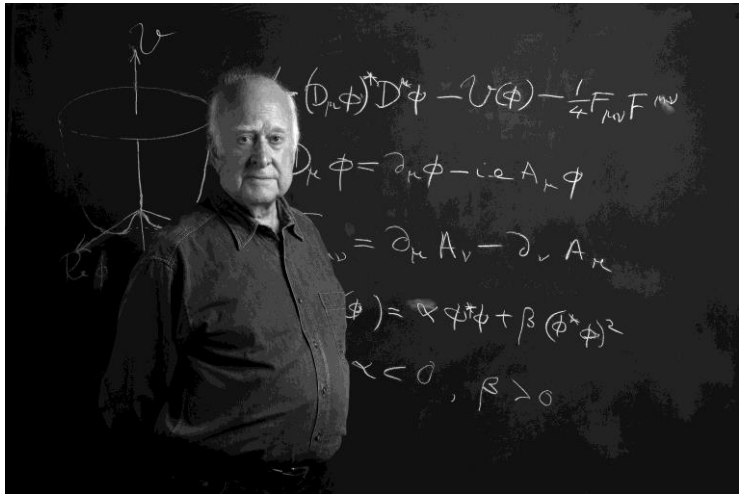
"The great tragedy of science - the slaying of a beautiful hypothesis by an ugly fact."



Thomas Henry Huxley

Ideja za spasiti SM

- Inovativne ideje za uvesti mase bozona u SM, tzv. "Higgsov mehanizam" dolaze s više strana u 60-im godinama
  - Brout-Englert, Higgs
  - Guralnik-Hagen-Kibble



- Koristimo "Higgs" kao ime za cijelu skupinu (uključuje i Petera Higgsa)

- Polazimo od ničega: **Vakuum!**
  - Klasična fizika: Vakuum postoji u volumenu iz kojega se odstranila sva materija

U Vakuumu: Higgs!

Osnovni postulat

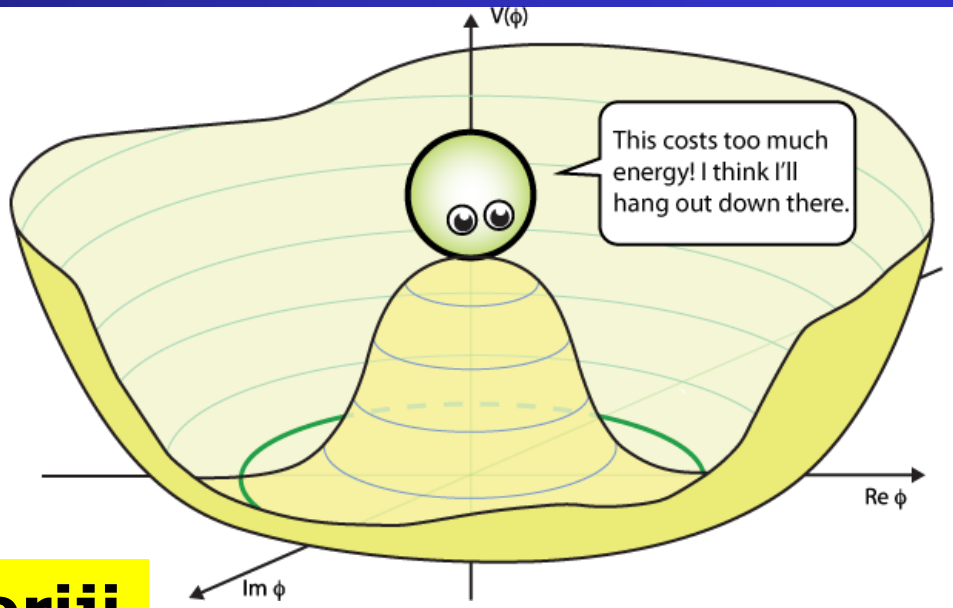
"Higgsovog mehanizma":

Postoji novo polje, Higgsovo polje, koje ispunjava cijeli svemir

Njegova je prosječna vrijednost postala različita od nule kad se rani svemir ohladio

Higgsov mehanizam

Spontani
lom simetrije

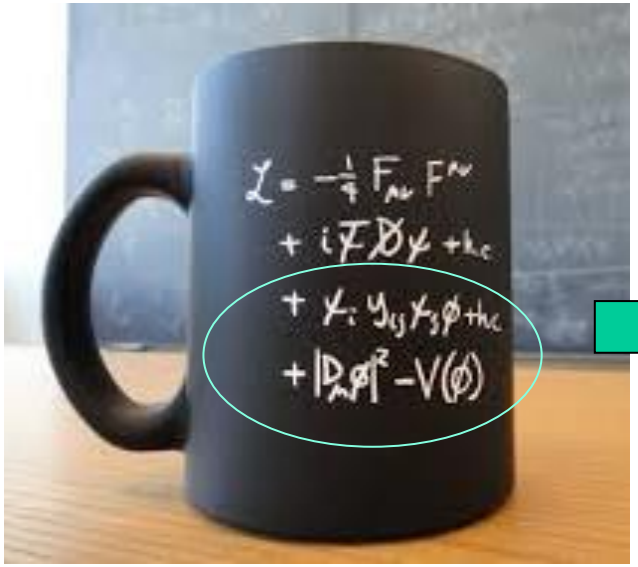


Higgsovo polje u teoriji

- Ispunjava cijeli prostor
- Nije 0 na minimumu energije
- Lomi simetriju u minimumu
- W i Z bozoni poprimaju masu kroz međudjelovanje s Higgsovim poljem

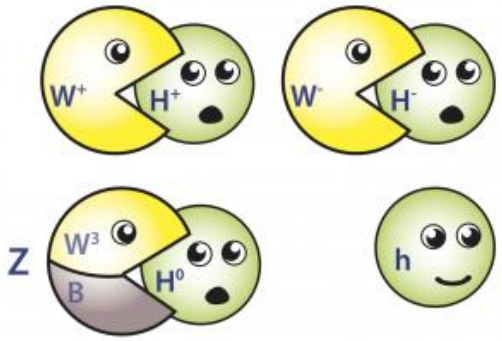
Glashow-Salam-Weinberg Model

Elektroslabe interakcije
+
Higgsov mehanizam



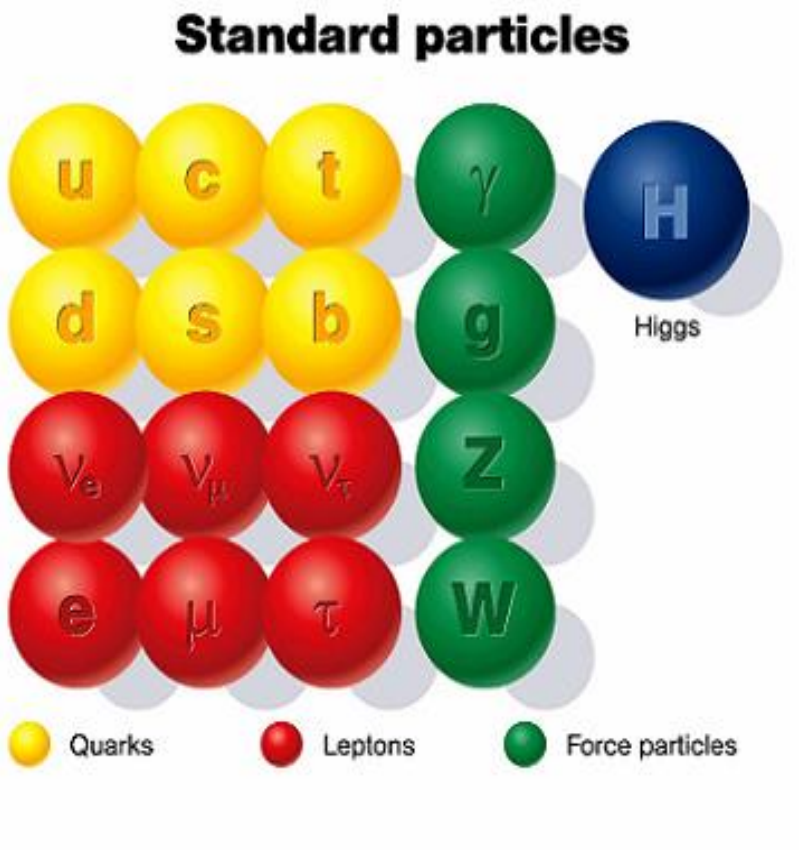
+
Teorija jake interakcije
(QCD)
= **Standardni Model**

- Simetrija (iako skrivena) spašena
- W i Z bozon dobivaju masu od Higgsovog polja



- Fermioni također dobivaju masu kroz međudjelovanje s Higgsovim poljem

Standard Model of Elementary Particles



$$\mathcal{L}_{GWS} = \sum_f (\bar{\Psi}_f (i\gamma^\mu \partial\mu - m_f)\Psi_f - eQ_f \bar{\Psi}_f \gamma^\mu \Psi_f A_\mu) +$$

$$(\bar{a}_L^i \gamma^\mu b_L^i W_\mu^+ + \bar{b}_L^i \gamma^\mu a_L^i W_\mu^-) + \frac{g}{2c_w} \sum_f \bar{\Psi}_f \gamma^\mu (I_f^3 - 2s_w^2 Q_f - I_f^3 \gamma_5) \Psi_f Z$$

$$)_\mu A_\nu - \partial_\nu A_\mu - ie(W_\mu^- W_\nu^+ - W_\mu^+ W_\nu^-)|^2 - \frac{1}{2}|\partial_\mu W_\nu^+ - \partial_\nu W_\mu^+ +$$

$$-ie(W_\mu^+ A_\nu - W_\nu^+ A_\mu) + ig' c_w (W_\mu^+ Z_\nu - W_\nu^+ Z_\mu|^2 +$$

$$-\frac{1}{4}|\partial_\mu Z_\nu - \partial_\nu Z_\mu + ig' c_w (W_\mu^- W_\nu^+ - W_\mu^+ W_\nu^-)|^2 +$$

$$-\frac{1}{2} M_\eta^2 \eta^2 - \frac{g M_\eta^2}{8 M_W} \eta^3 - \frac{g'^2 M_\eta^2}{32 M_W} \eta^4 + |M_W W_\mu^+ + \frac{g}{2} \eta W_\mu^+|^2 +$$

$$+\frac{1}{2}|\partial_\mu \eta + i M_Z Z_\mu + \frac{ig}{2c_w} \eta Z_\mu|^2 - \sum_f \frac{g}{2} \frac{m_f}{M_W} \bar{\Psi}_f \Psi_f \eta$$

Potraga za Higgsovim bozonom

The Nobel Prize in Physics 2013
François Englert, Peter Higgs

The Nobel Prize in Physics 2013

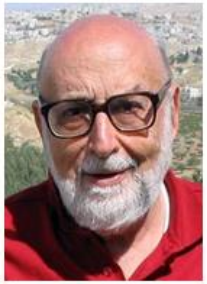


Photo: Pnicolet via Wikimedia Commons

François Englert

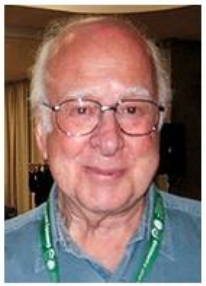
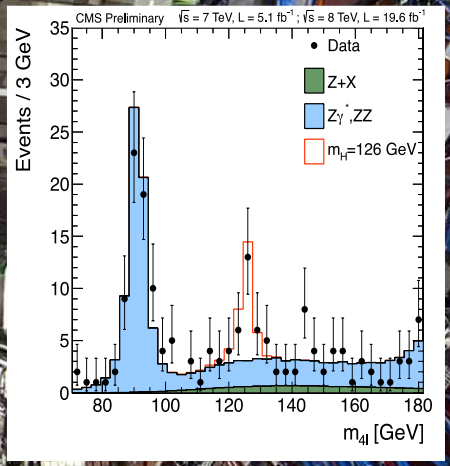


Photo: G-M Greuel via Wikimedia Commons

Peter W. Higgs

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"*



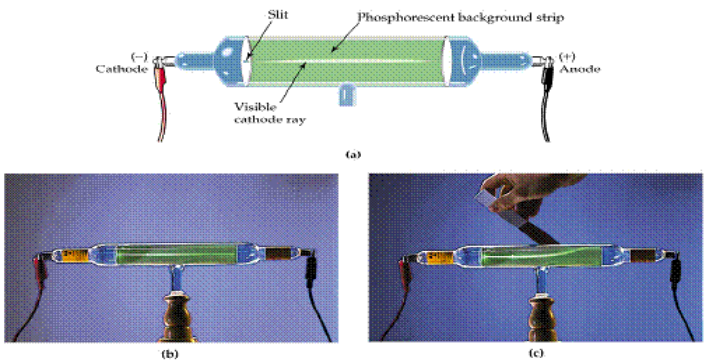
Više nije!

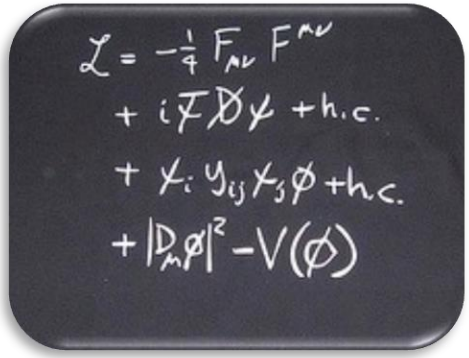
Jedini sigurno opaženi Higgs u CMS eksperimentu do 2012.:

Dr. Peter Higgs

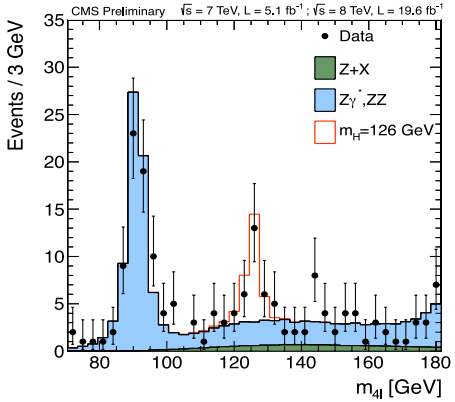
STANDARDNI MODEL
JE KOMPLETAN I POTVRĐEN

Discovery of the electron
J.J. Thomson (1897)

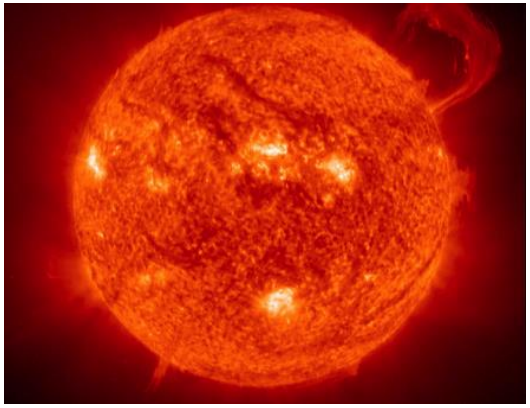




Discovery of the Higgs boson
LHC (2012)

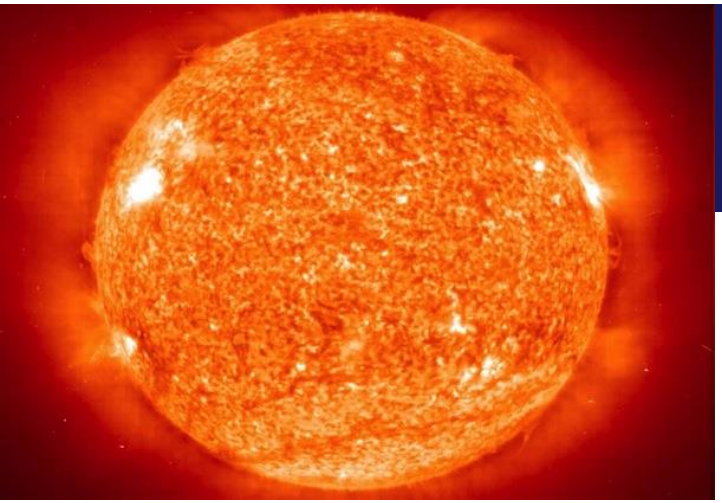


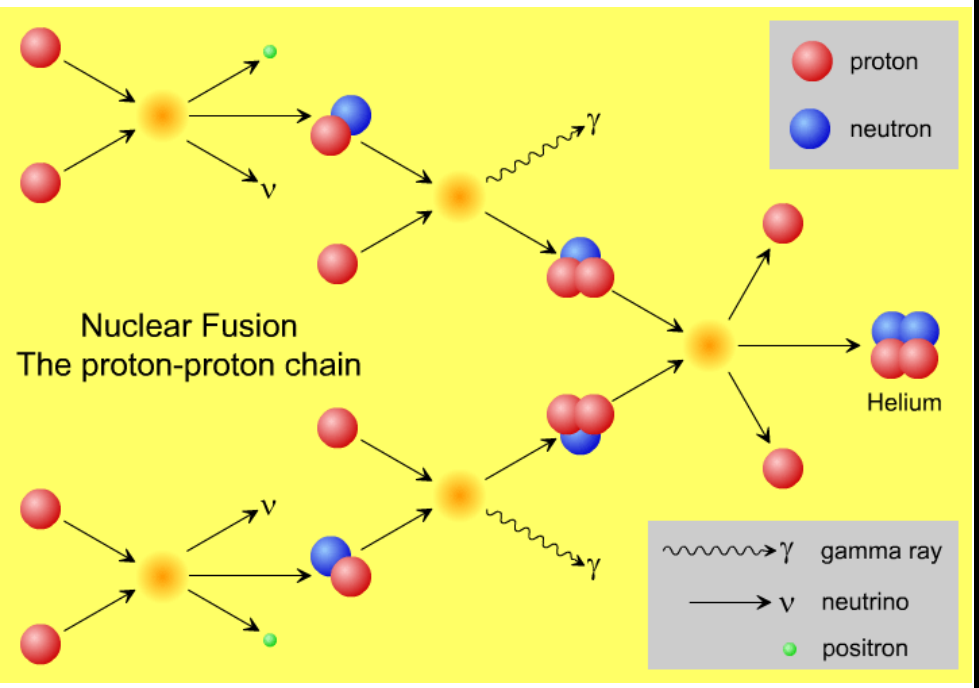
I objašnjava mnogo toga

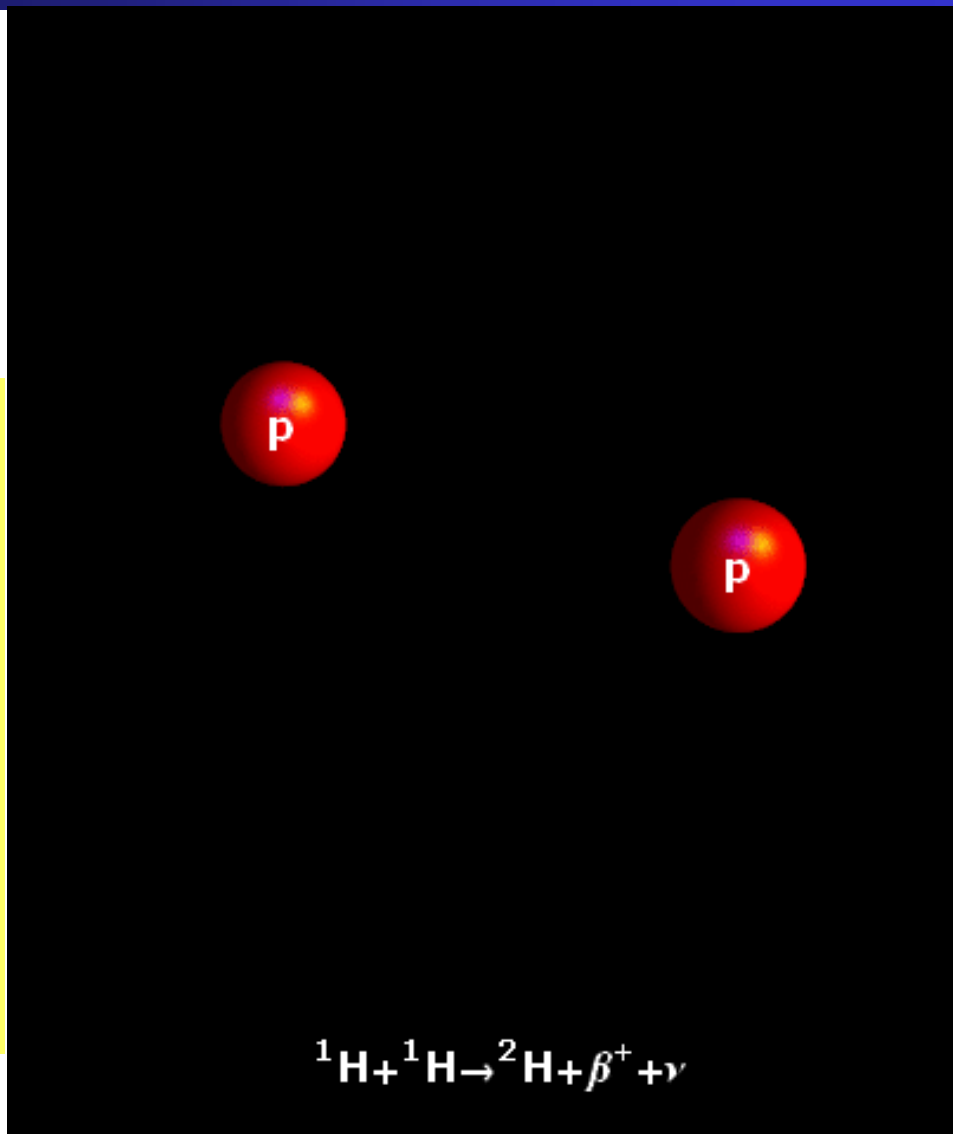


$$\mathcal{L} = -\tfrac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\chi}\not{D}\chi + \text{h.c.} + \chi_i y_{ij} \chi_j \phi + \text{h.c.} + |D_\mu \phi|^2 - V(\phi)$$

Primjer: fuzija u suncu

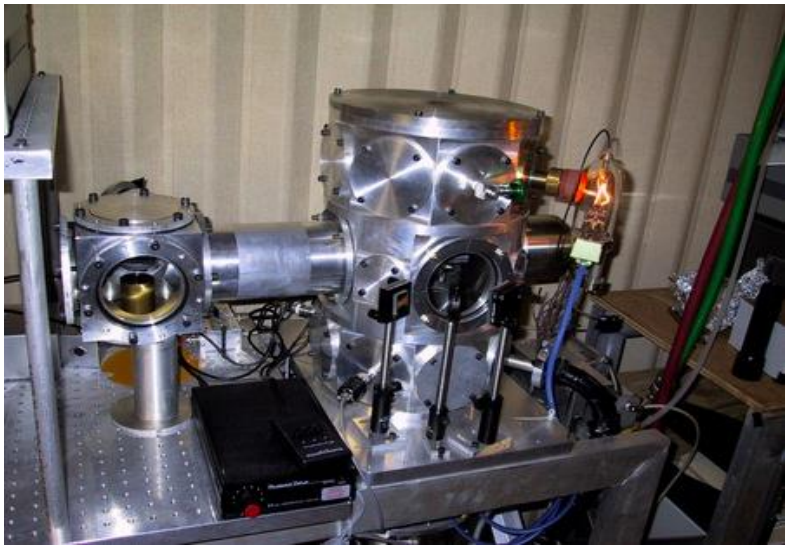


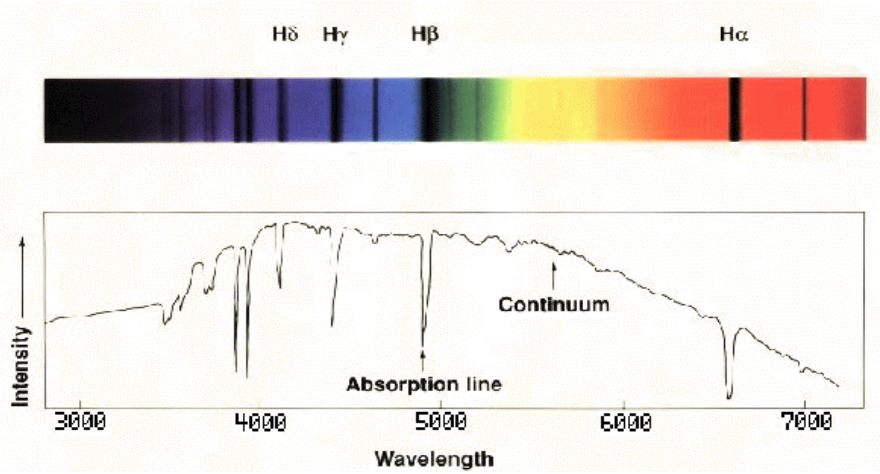


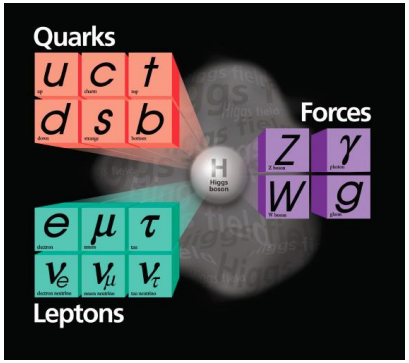


Na Zemlji i u cijelom svemiru

Stella spectra tell us stars are made of the same stuff we can study in an atomic physics lab.



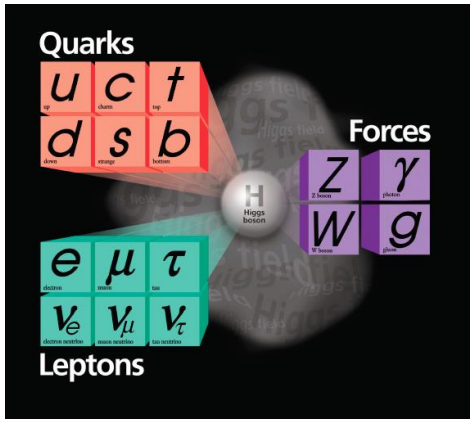




Zašto većina nas misli da SM ne može biti kraj priče

There are things about
the known particles and forces
the SM does not explain
(or at least not satisfactorily)

SM NE objašnjava



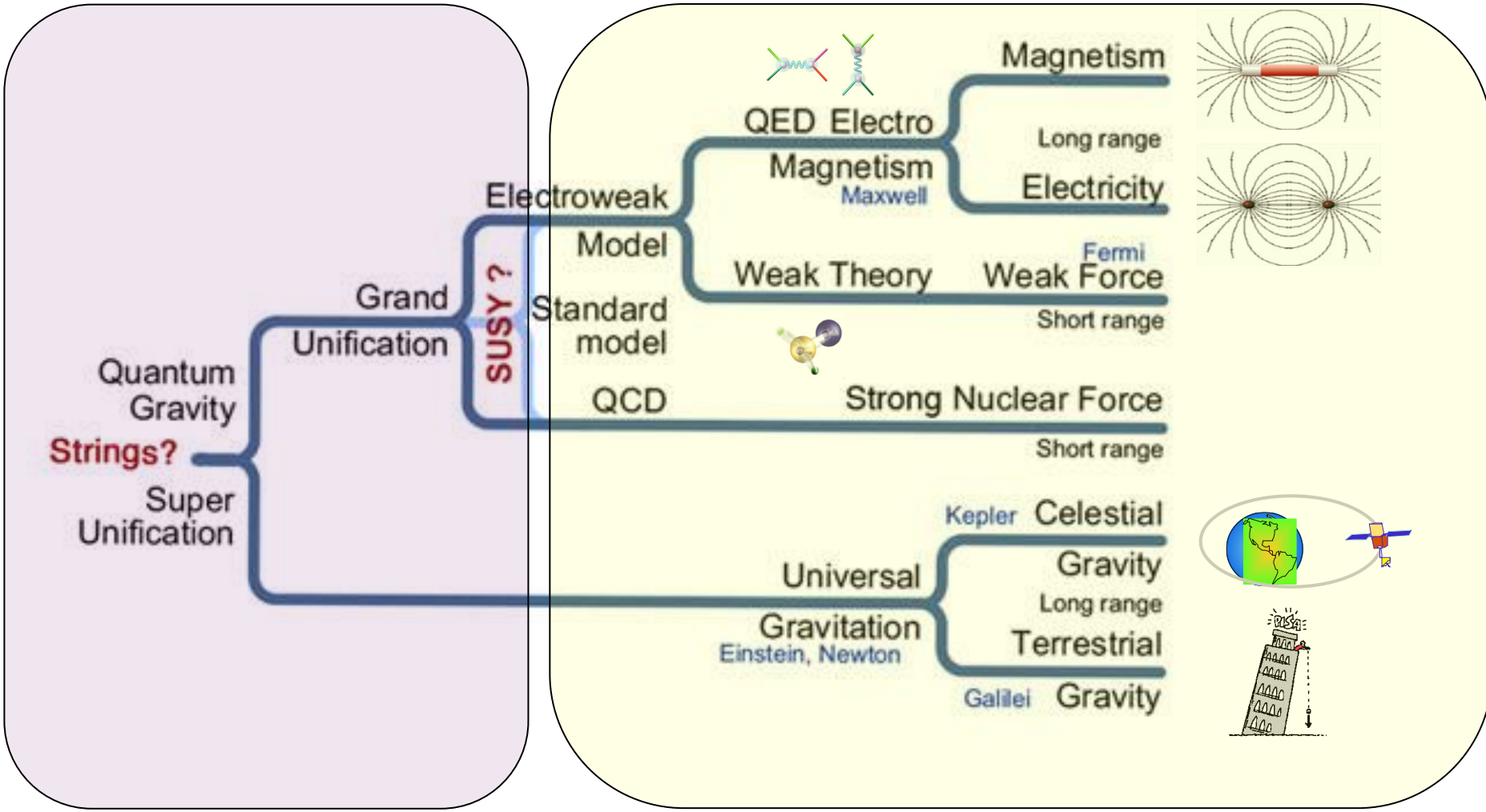
- Zašto 3 generacije?
- Zašto je tako fino podešeno?
- Zašto su mase čestica tako različite
- > 20 free parameters
  - masses, couplings, …
- Where did all the antimatter go?
- Does the Unification go on?

And most importantly:

- WHAT ABOUT GRAVITY?

Fizika voli UJEDINITI
Ide li to dalje?

SPEKULACIJA **ČINJENICE**

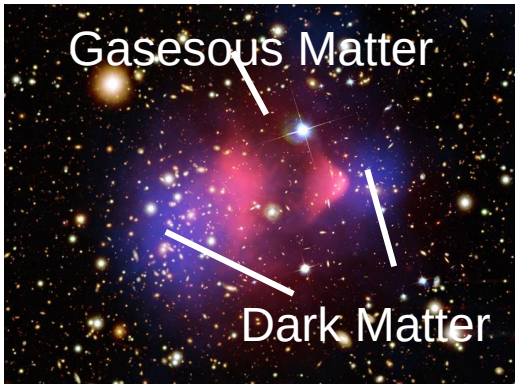


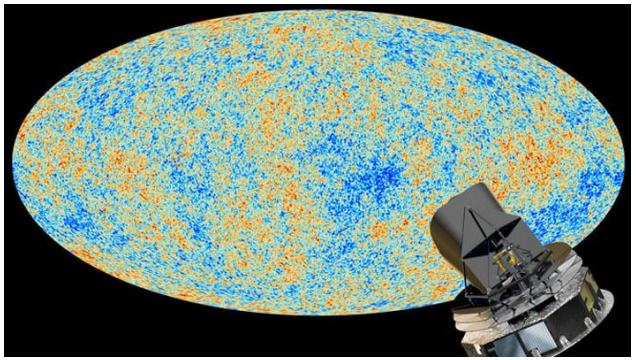
Zašto ZNAMO da SM nikako ne može biti kraj priče

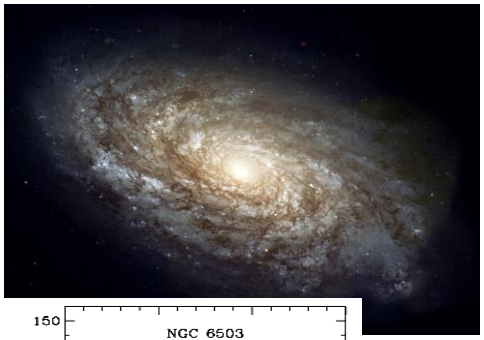
Postoje opažanja u vidljivom svemiru koje SM nikako ne može objasniti

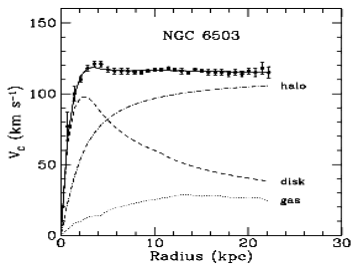
Huge amounts of invisible matter:

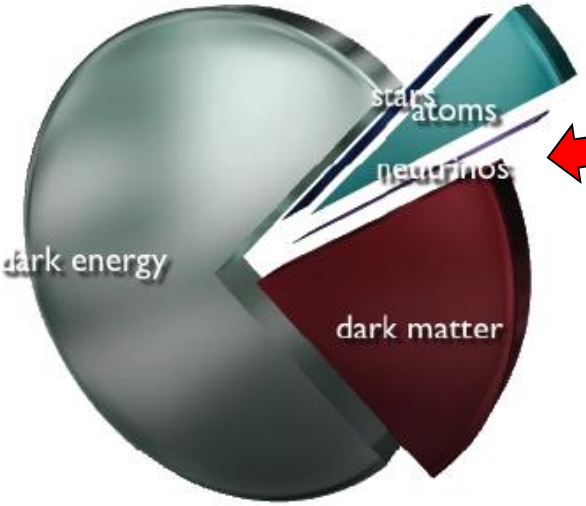
“DARK MATTER”

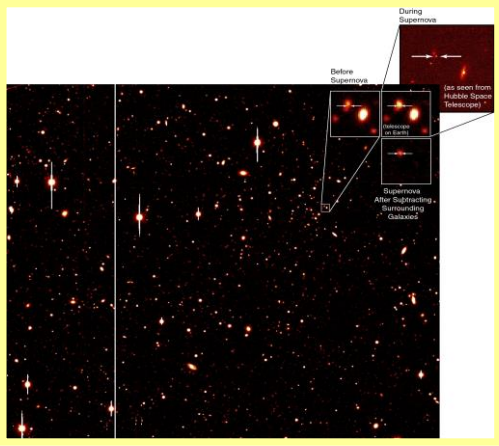








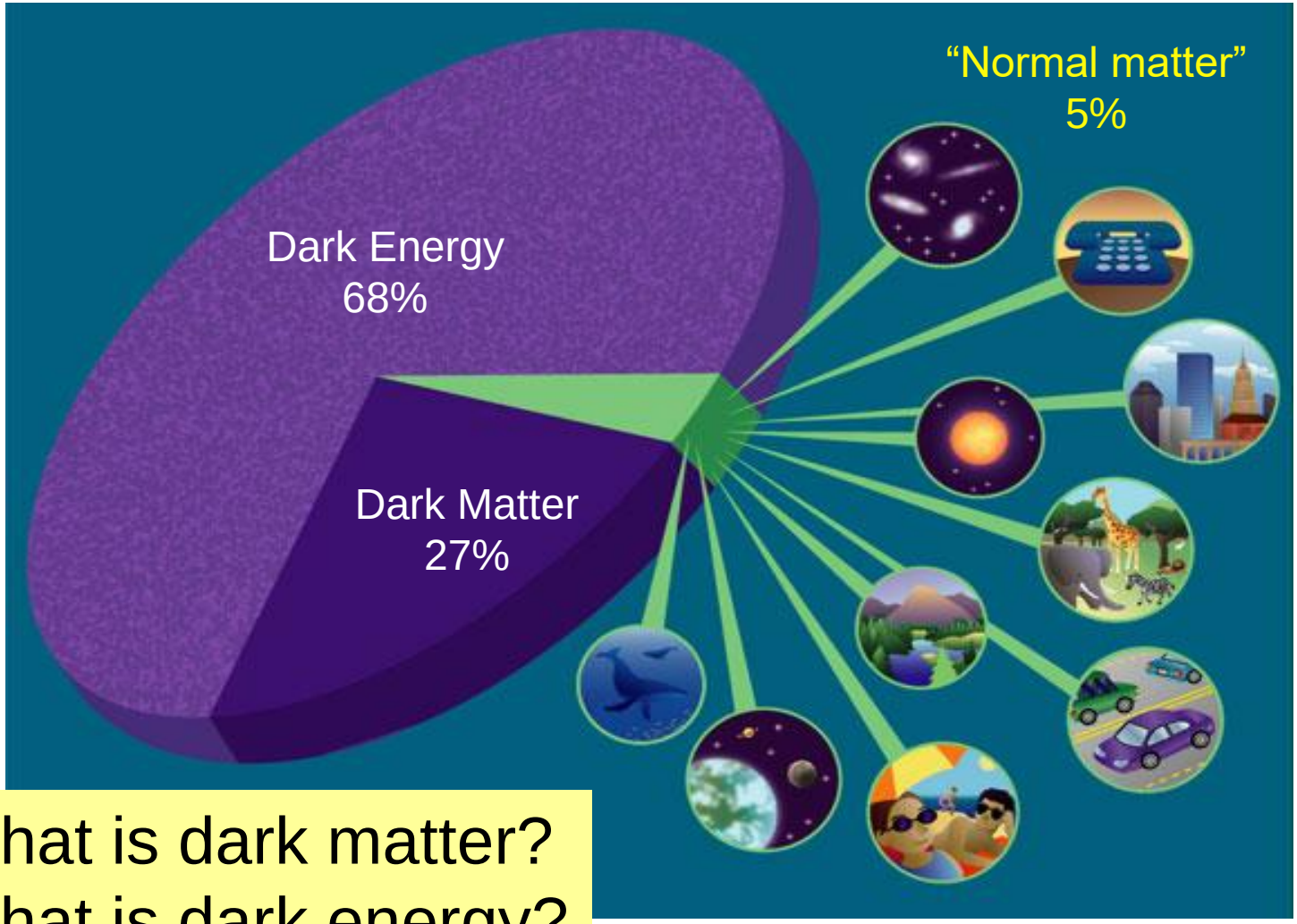




The expansion of the universe is accelerating:

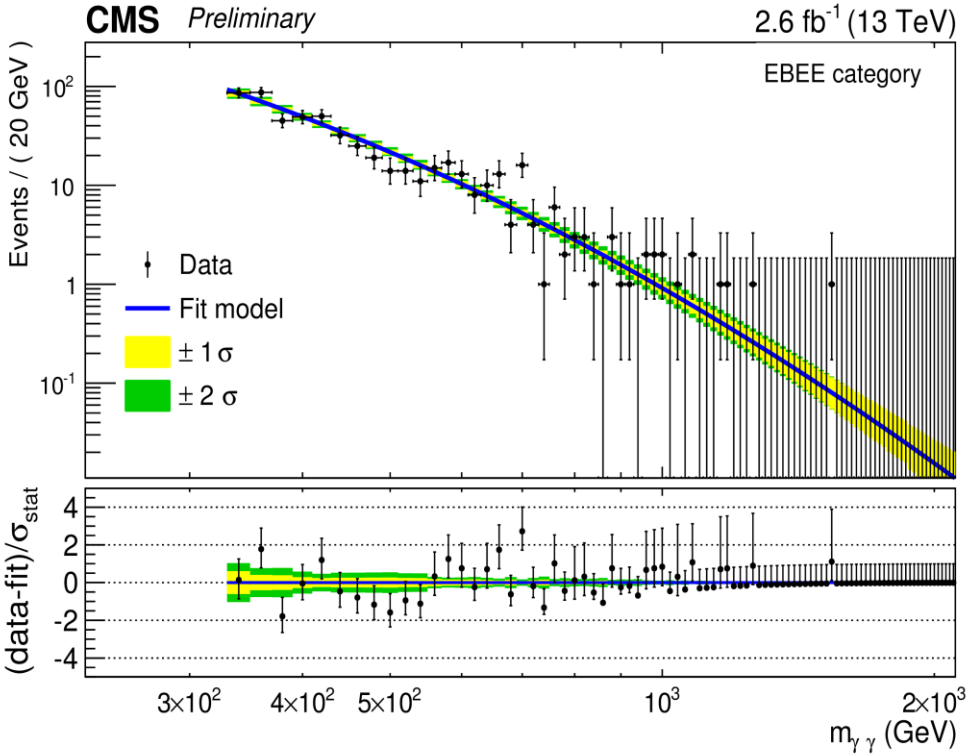
“DARK ENERGY”

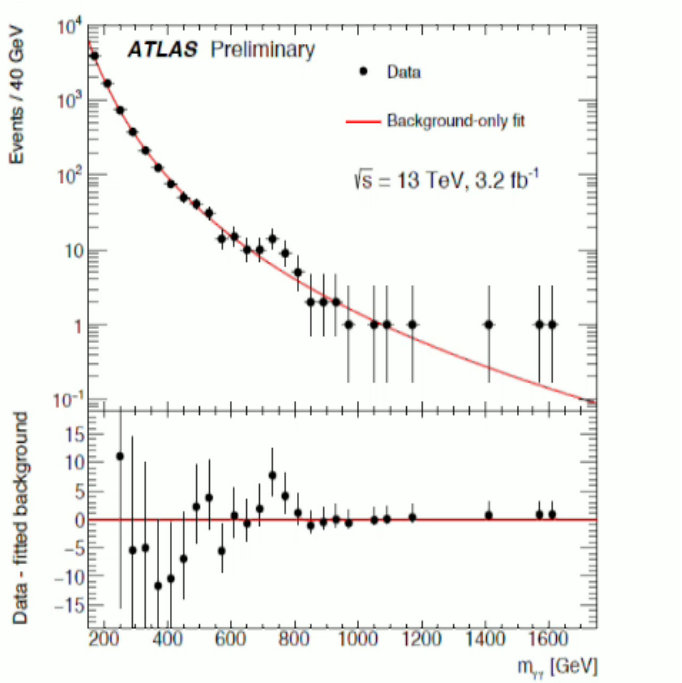
What is the Universe made of?



What is dark matter?
What is dark energy?

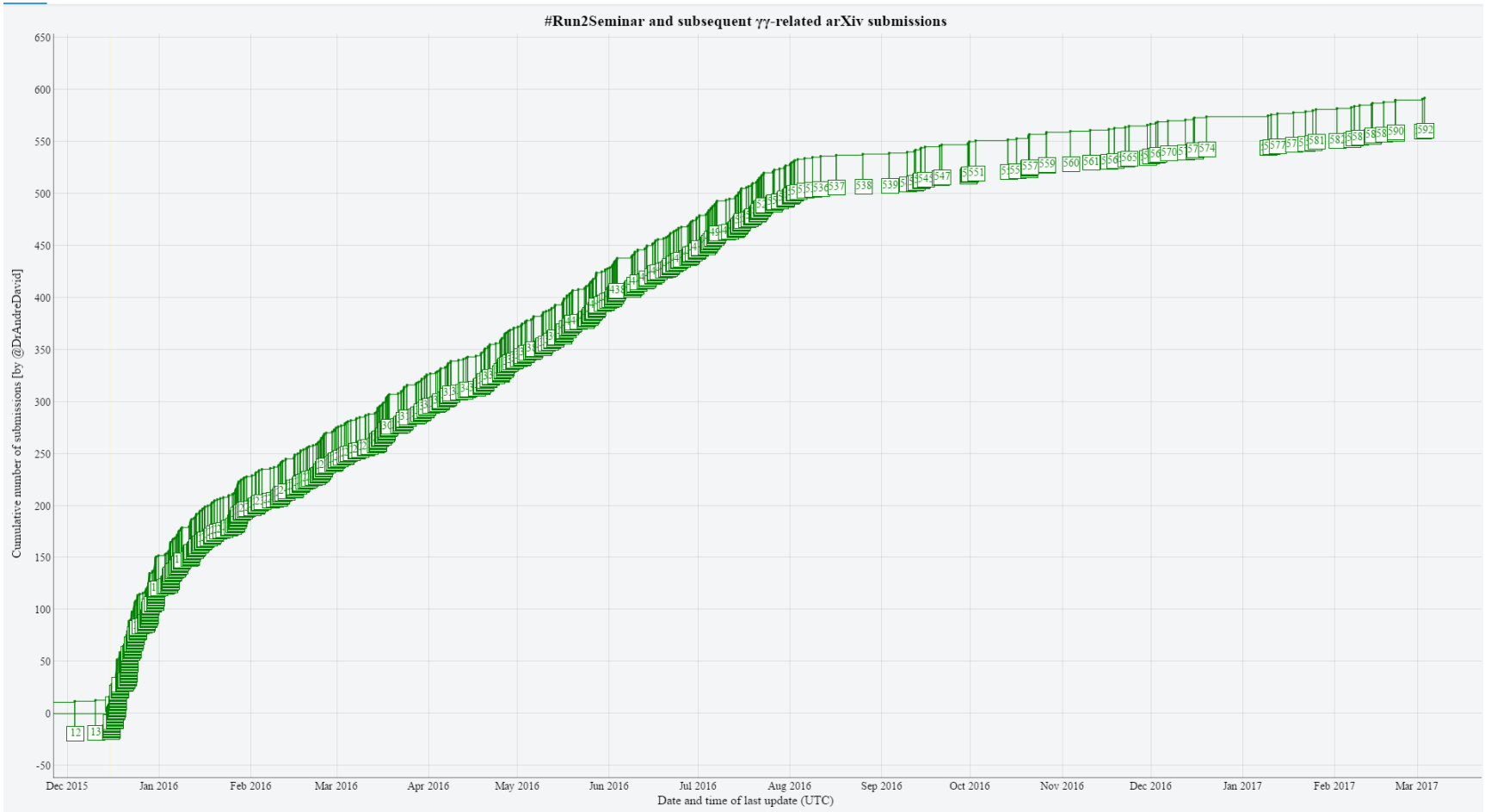
2015: Naznake nove čestice?



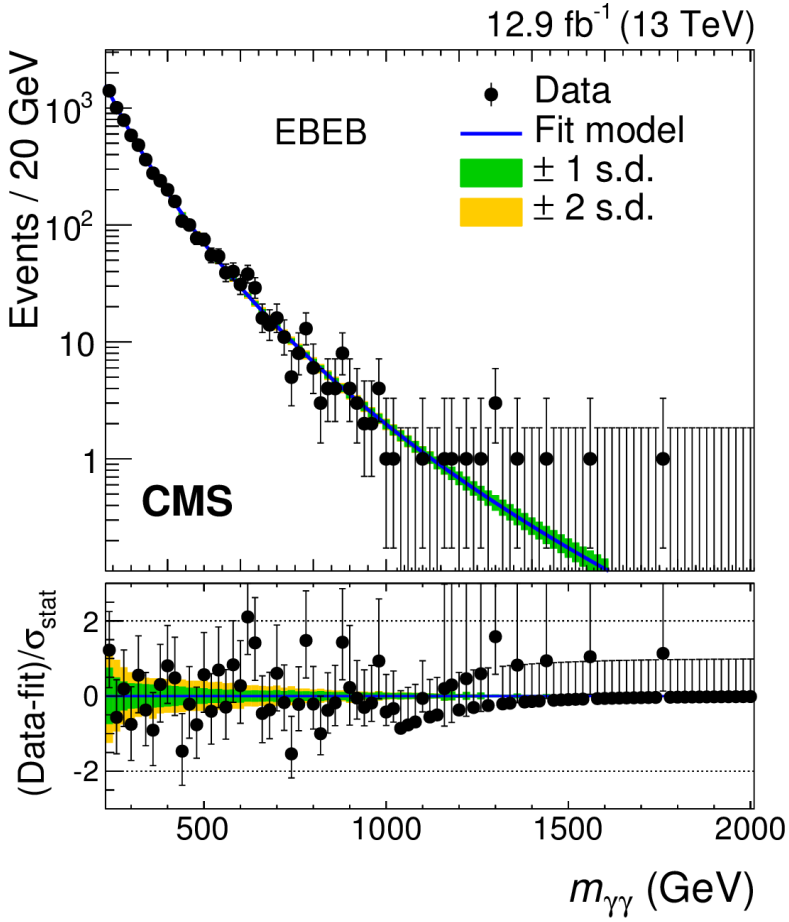


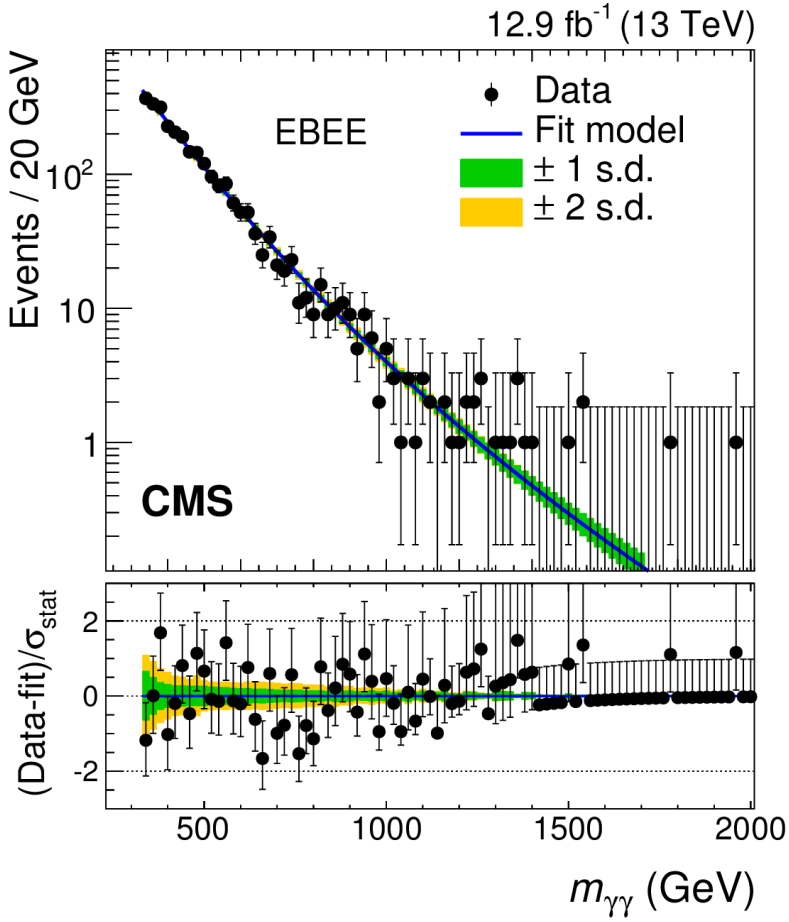
Signifikantnost viška događaja između 3 i 4 σ u oba eksperimenta

2015.: Naznake nove čestice?



…ipak se statistika poigrala s nama





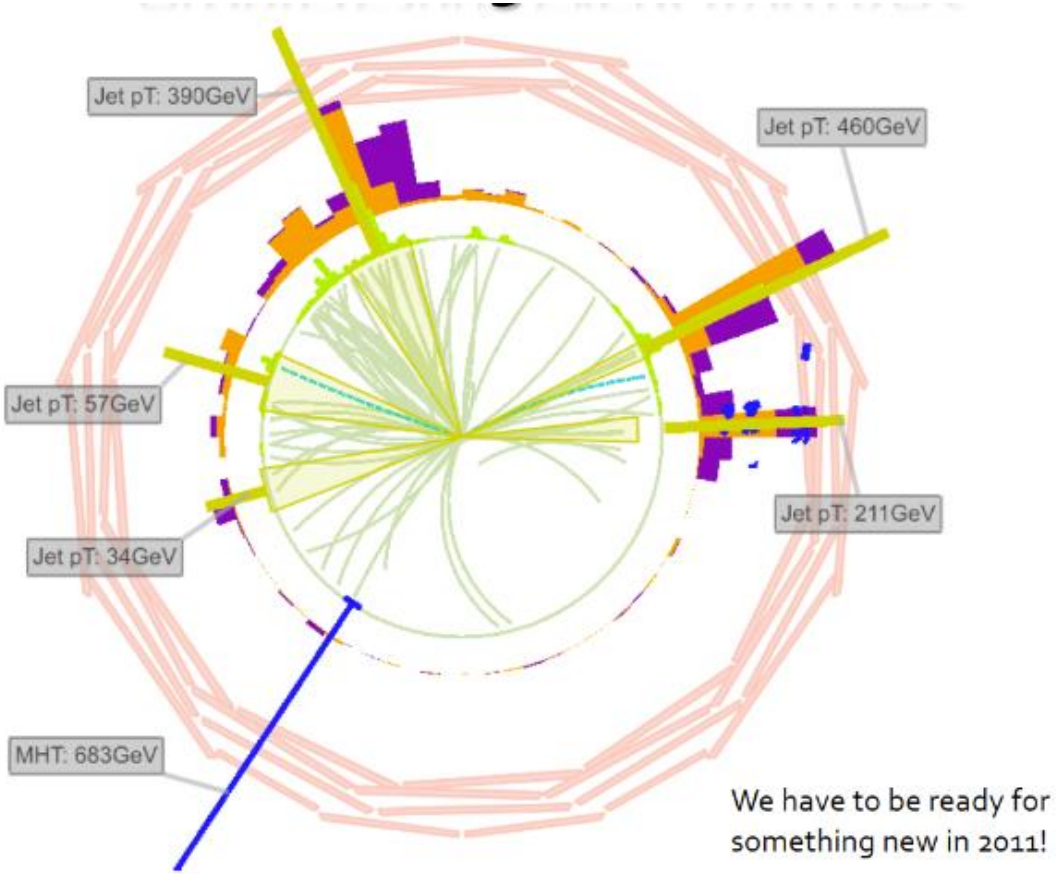
Može li nam LHC nešto reći o prirodi tamne materije?

Možda

(ako su dovoljno lagane)

Tamna tvar na LHC-u?

$$\vec{MET} = -\sum_i \vec{p}_{T,i}$$

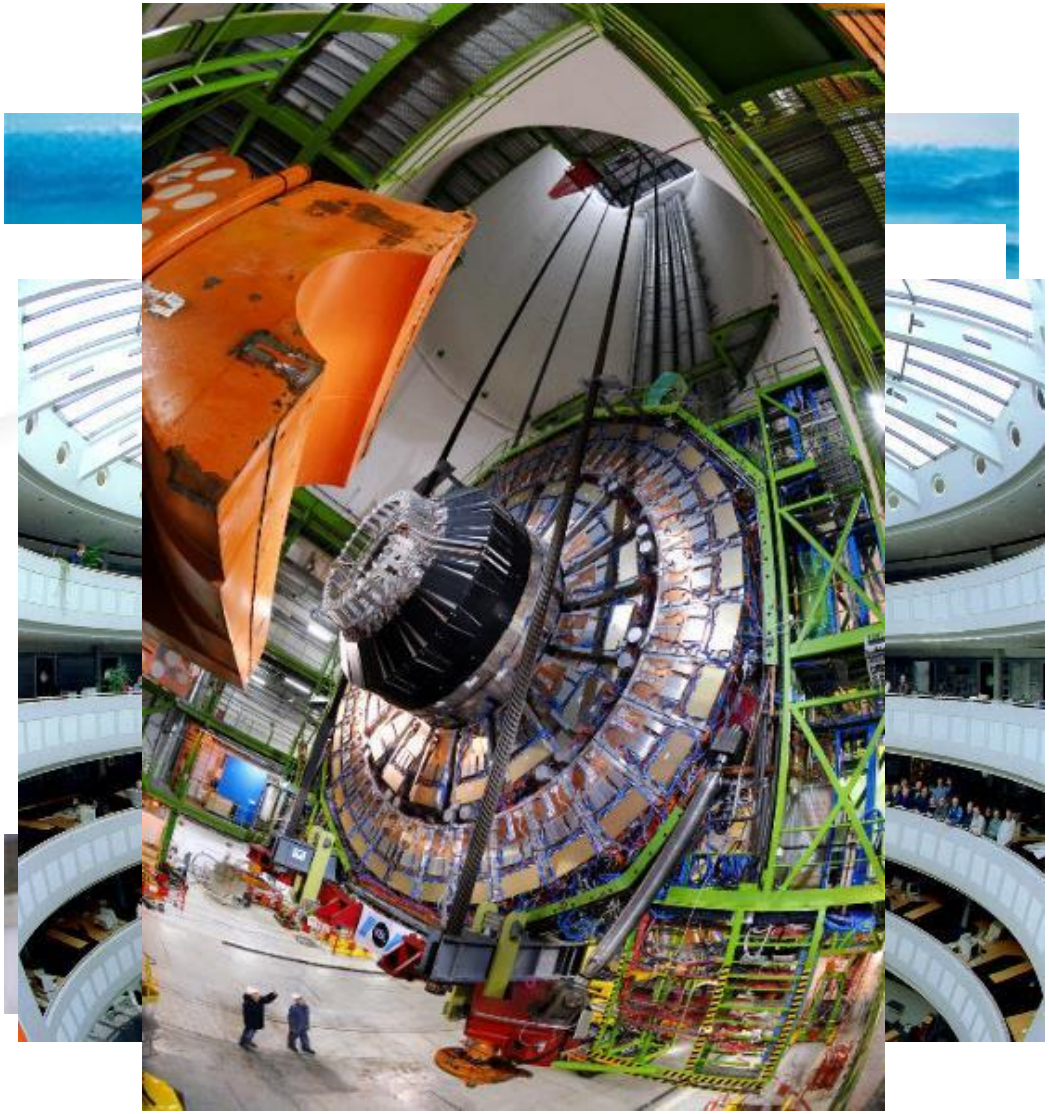


A tamne energije?

???


ALI TRAŽIMO DALJE

Što zahtijevaju nova otkrića …



- **Sudarivače čestica:** Moćne strojeve koji ubrzavaju čestice na ekstremno velike brzine i ‘natjeraju’ da se međusobne sudare
- **Detektore:** Gigantske instrumente za snimanje rezultirajućih čestica koje izlaze iz točke interakcije
- **Računala:** Za prikupljanje, snimanje, distribuciju i analizu ogromnih količina podataka koje proizvode detektori
- **Ljude:** Samo kolaboracije na svjetskoj razini, od po nekoliko tisuća znanstvenika, mogu izvoditi ovakve eksperimente

CMS Collaboration

Hvala na pažnji!