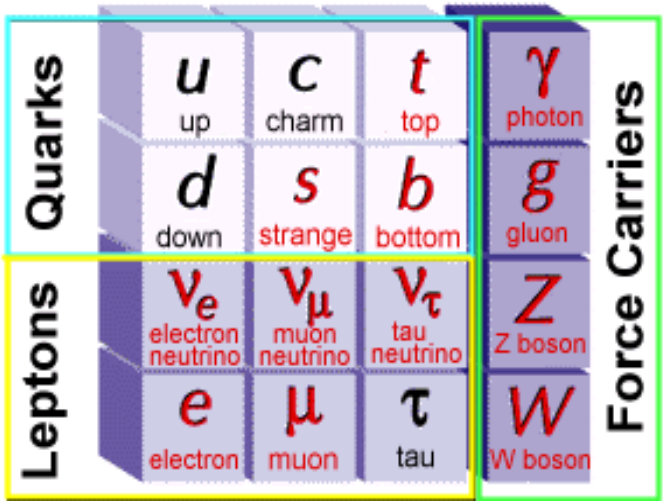
5th Croatian Teachers Programme
CERN, 3-5.4.2023

Uvod u Fiziku elementarnih čestica



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

Što znamo o temeljnoj gradnji svemira

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

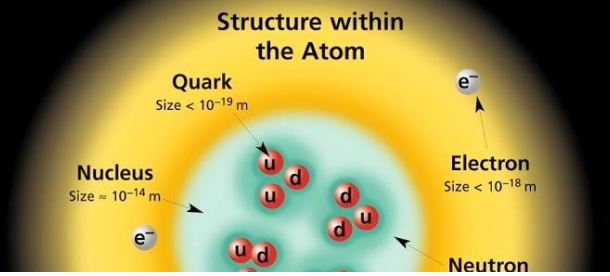
matter constituents
spin = 1/2, 3/2, 5/2, ...

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 ur

Electric ch the proton

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

lled ong the rt, the ener- ed into addi- bine into served in

residual esidual elec- so be

Baryo

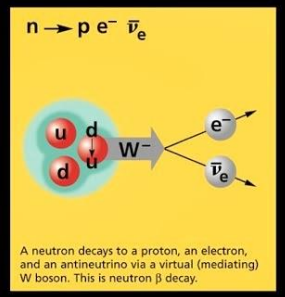
Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	–1	1.672	3/2

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

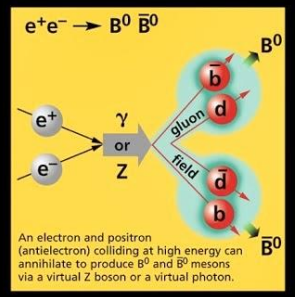
Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2.980	0

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.

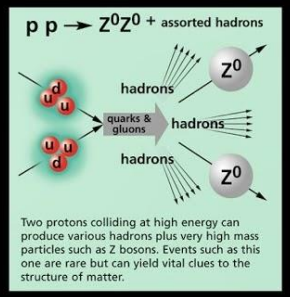
Figures
These diagrams are an artist's conception of physical processes. They are *not* exact and have *no* meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.



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.

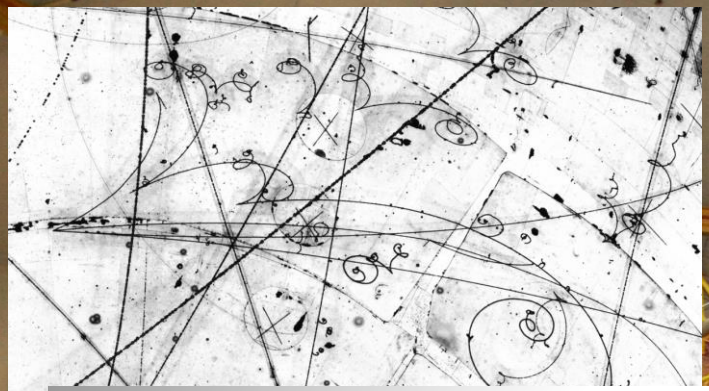


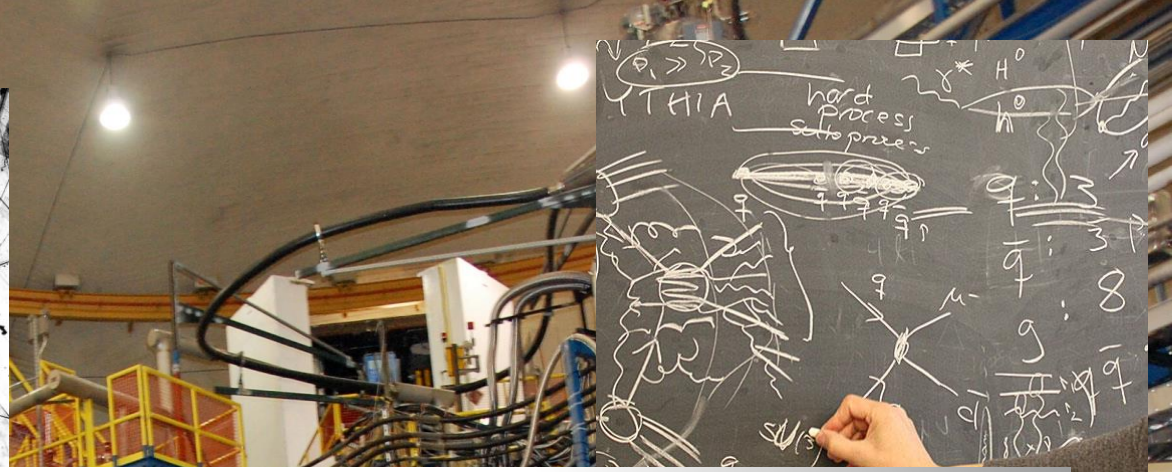
Two protons colliding at high energy can produce various hadrons plus very high mass particles such as Z bosons. Events such as this one are rare but can yield vital clues to the structure of matter.

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

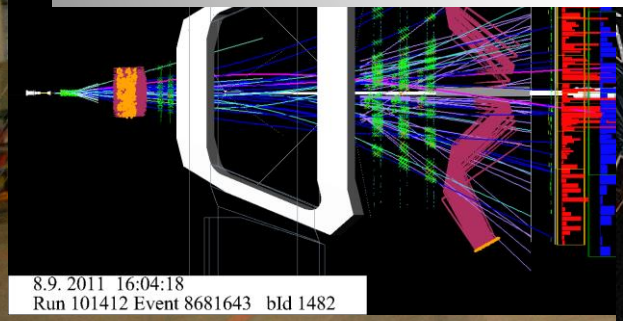
This chart has been made possible by the generous support of:
U.S. Department of Energy
U.S. National Science Foundation
Lawrence Berkeley National Laboratory
Stanford Linear Accelerator Center
American Physical Society, Division of Particles and Fields
BURLE INDUSTRIES, INC.

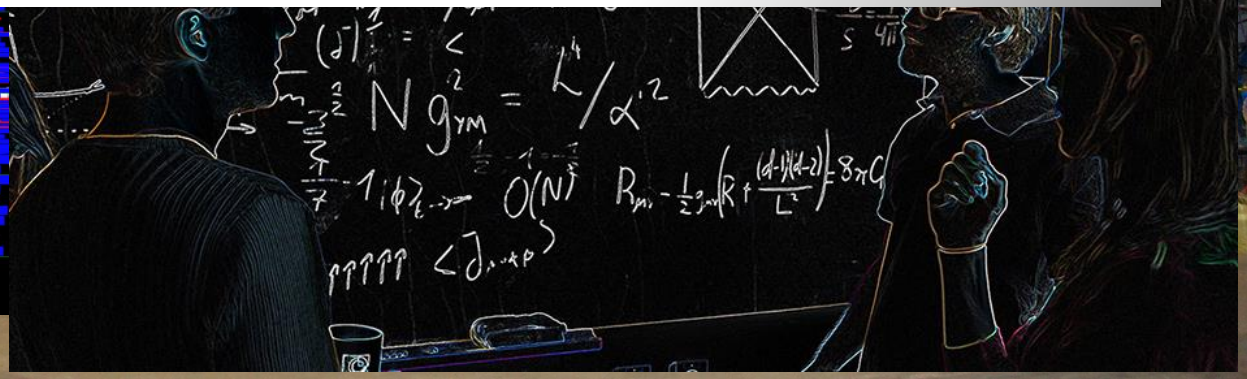
http://CPEPweb.org



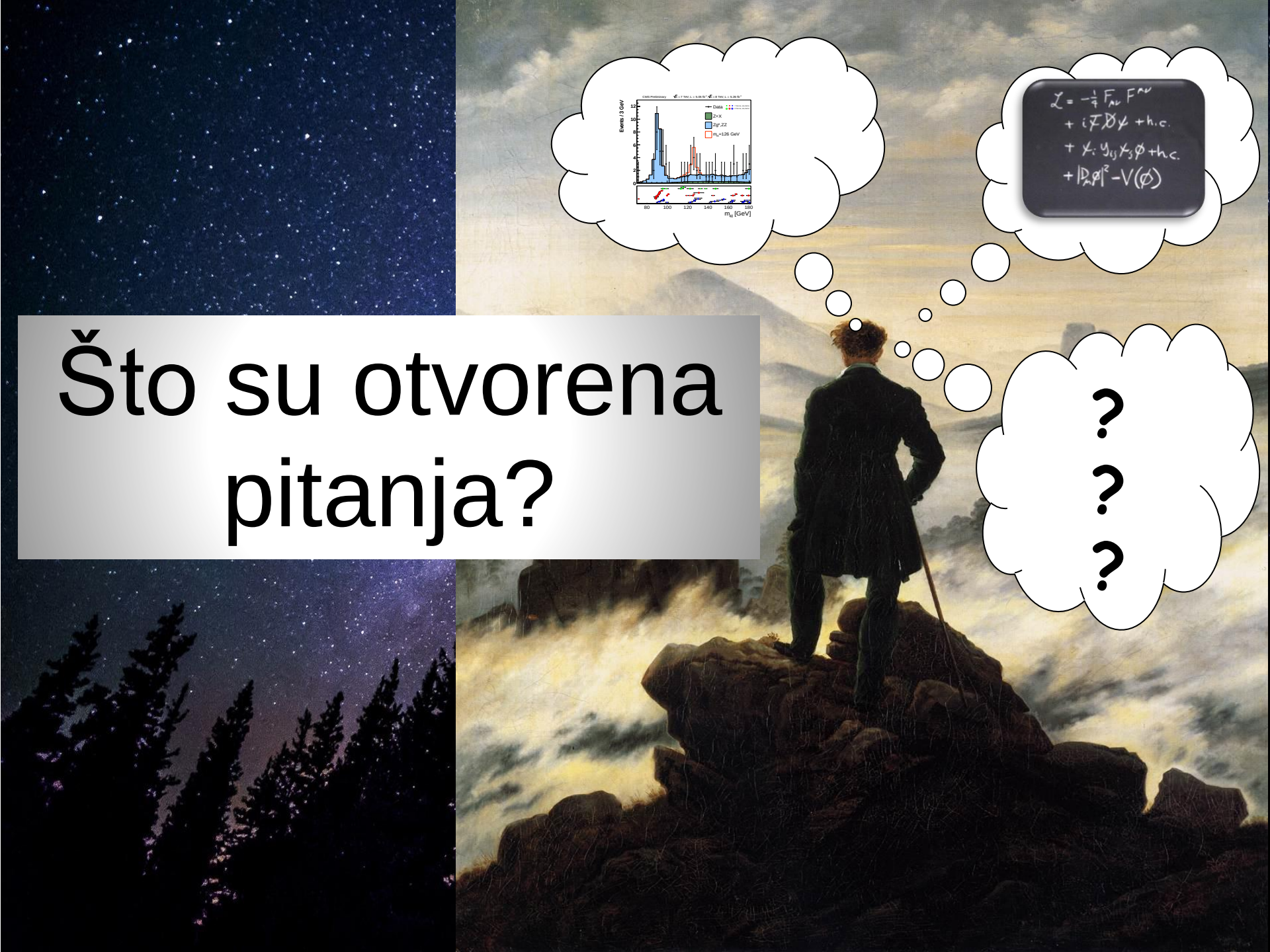


Preko 100 godina plodonosne suradnje Teorije i Eksperimenta





Što su otvorena pitanja?



The Standard Model

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

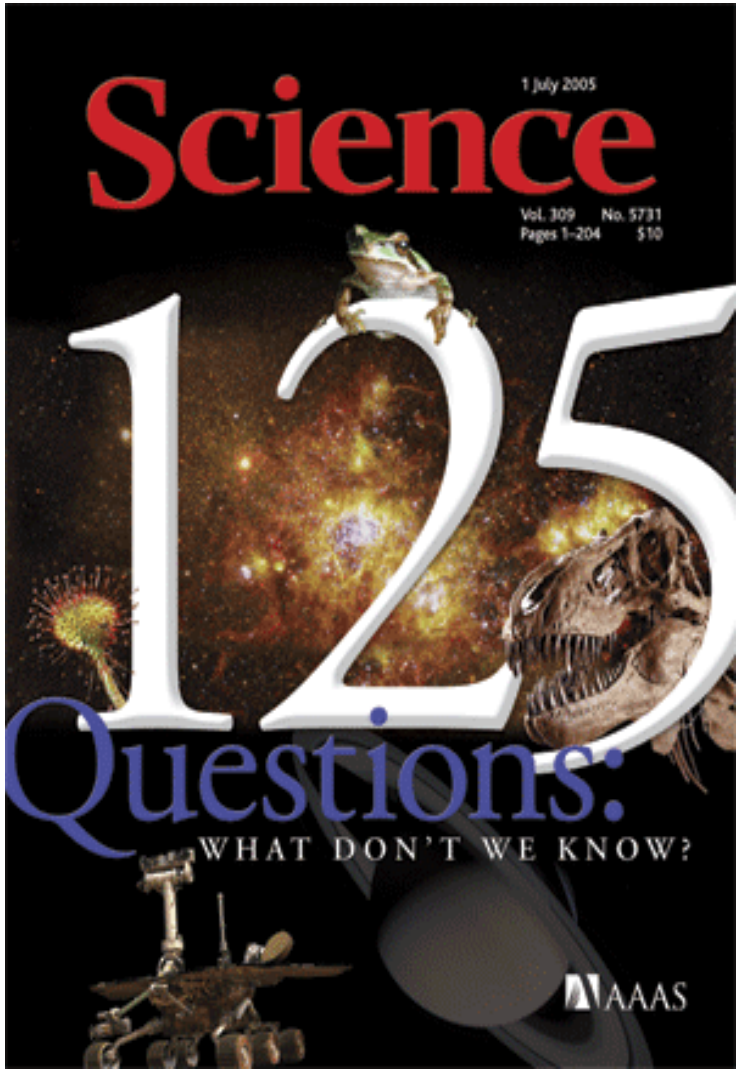
Fizika: eksperimentalna znanost

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"

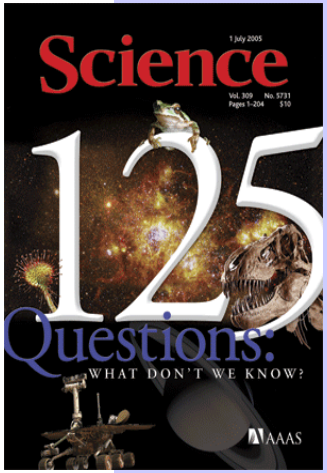
Richard Feynman

Velika pitanja!



- Pitanje broj 1: **Od čega se sastoji svemir?**

In Science



INTRODUCTION AND OPENING ESSAY

What Don't We Know?
D. Kennedy and C. Norman

In Praise of Hard Questions
T. Siegfried

Online Extras

Be sure to check out these online extras related to our 125th Anniversary Issue:

Your Turn

Did we miss your favorite scientific conundrum? Visit our special online forum to comment on our 125 questions or nominate your own choice.

Anniversary Editorial

Science Editor-in-Chief Donald Kennedy celebrates the magazine's

THE QUESTIONS

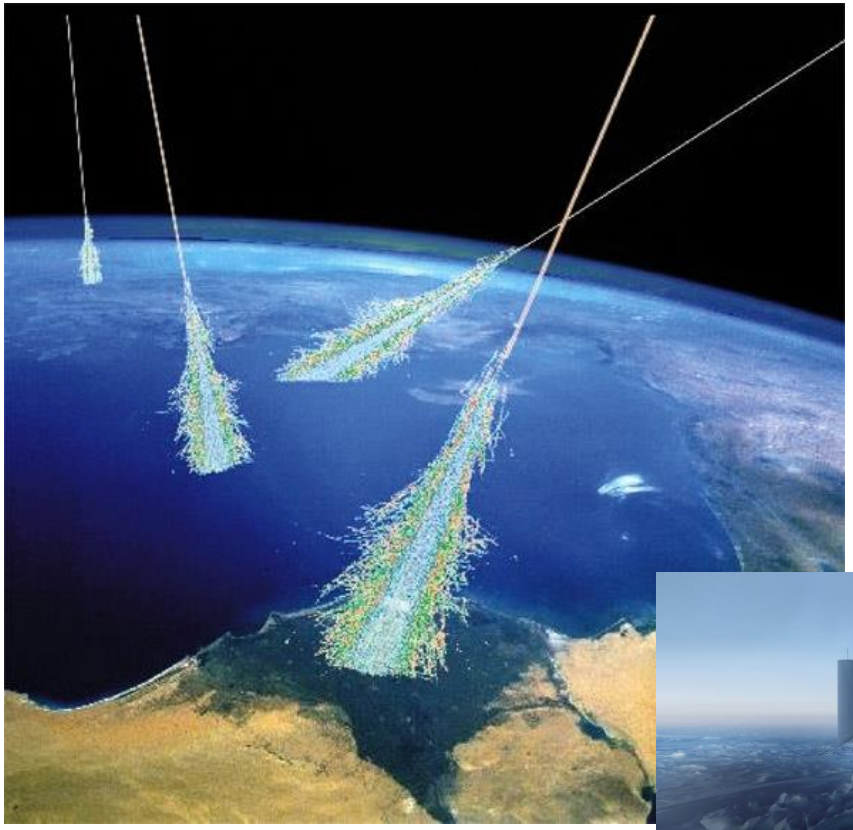
The Top 25
Essays by our news staff on 25 big questions facing science over the next quarter-century.

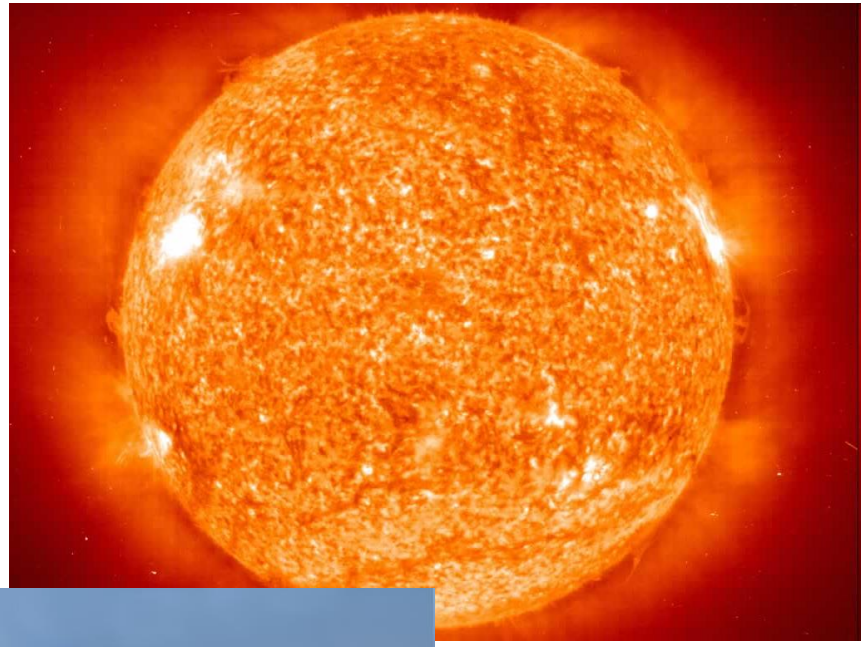
- > What Is the Universe Made Of?
- > What is the Biological Basis of Consciousness?
- > Why Do Humans Have So Few Genes?
- > To What Extent Are Genetic Variation and Personal Health Linked?
- > Can the Laws of Physics Be Unified?
- > How Much Can Human Life Span Be Extended?
- > What Controls Organ Regeneration?
- > How Can a Skin Cell Become a Nerve Cell?
- > How Does a Single Somatic Cell Become a Whole Plant?
- > How Does Earth's Interior Work?
- > Are We Alone in the Universe?
- > How and Where Did Life on Earth Arise?

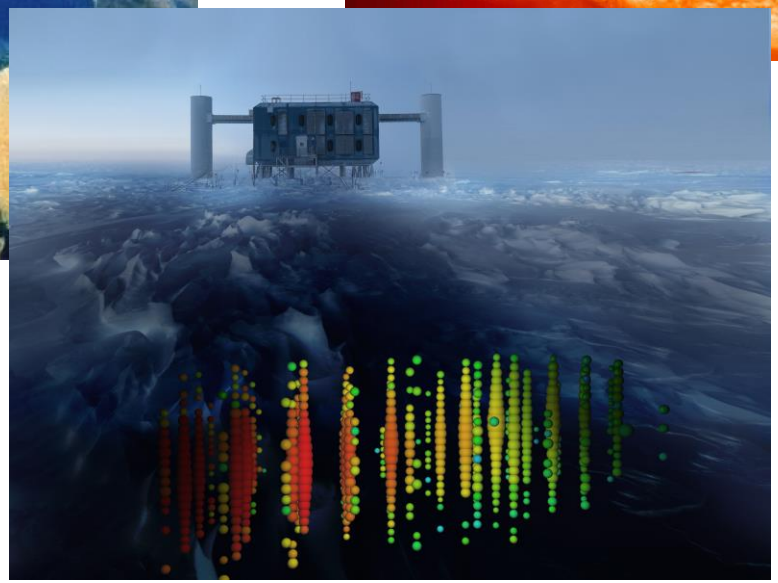
http://www.sciencemag.org/site/feature/misc/webfeat/125th/

fizika elementarnih čestica: Moderno ime za stara pitanja

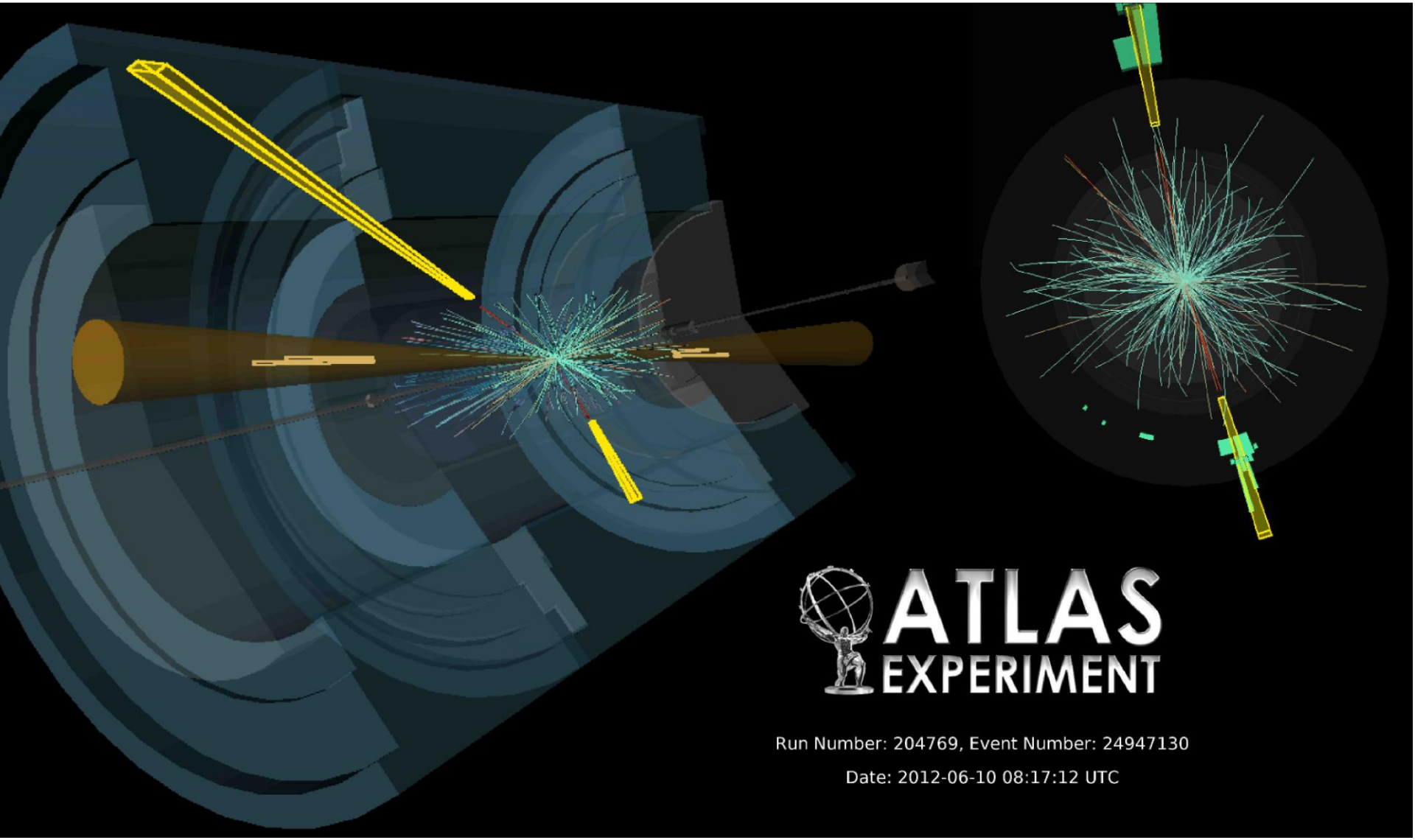
Fenomeni: u prirodi







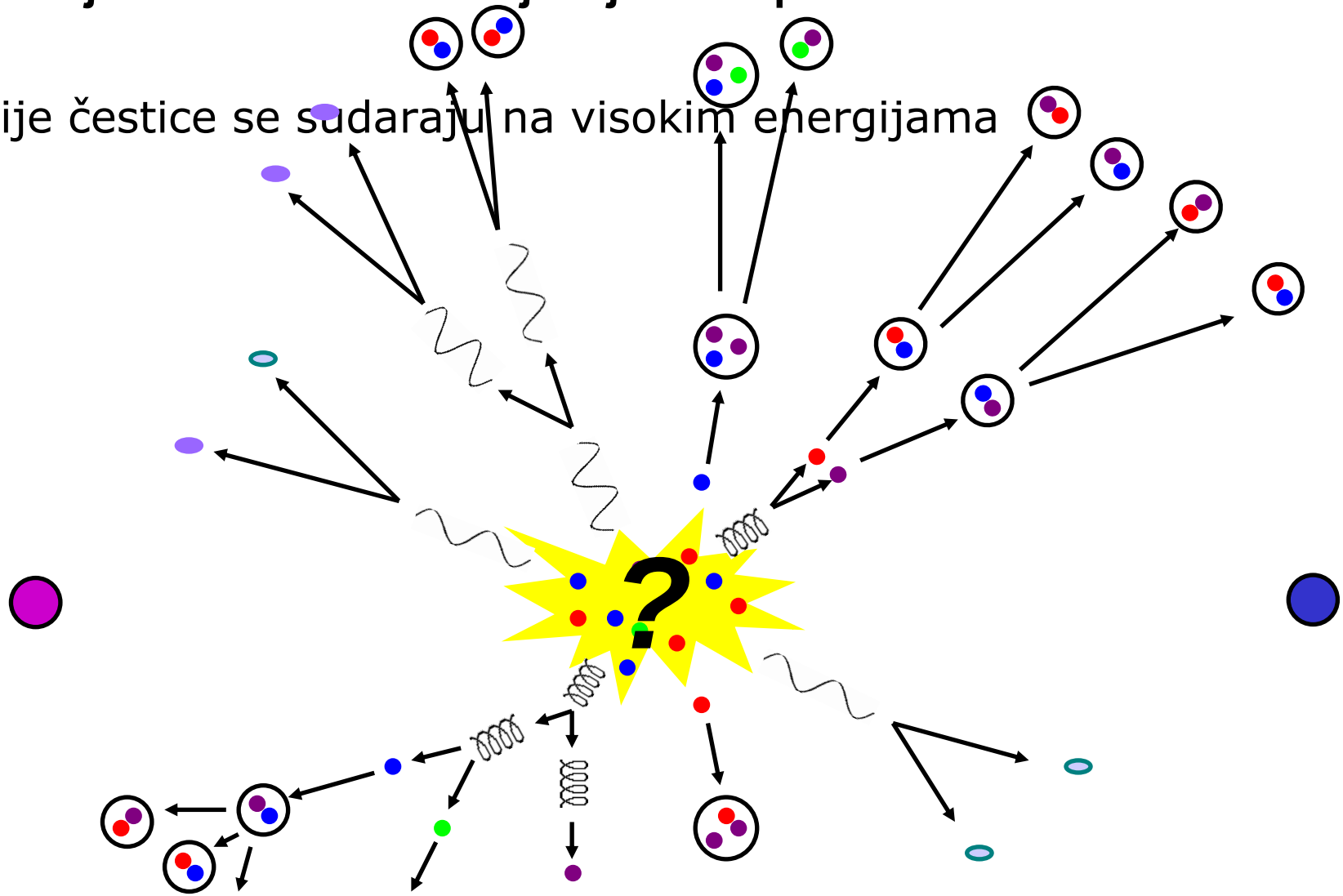
Fenomeni: u laboratoriju



Fenomeni: sudari čestica

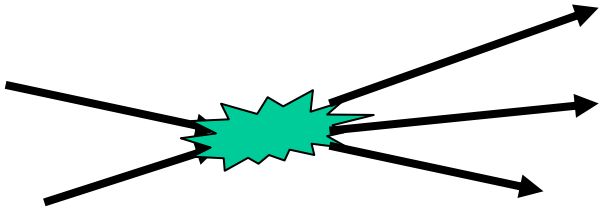
Stvaraju se nove čestice koje mjerimo i proučavamo

Dvije čestice se sudaraju na visokim energijama



Kako eksperimentalno pristupiti EČ

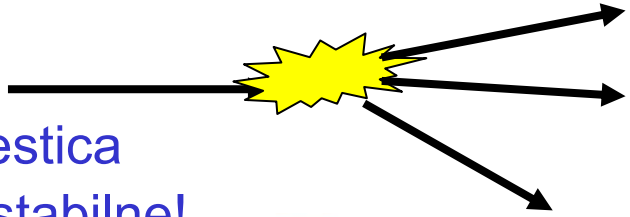
Sve informacije o elementarnim česticama potječu iz triju izvora:



1. <u>Raspršenja</u>

   Čestica na metu ili sudar dviju snopa

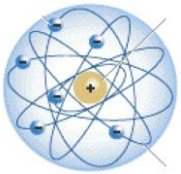
   Informacija o interakciji se dobiva iz mjerenja čestica koje proizlaze iz raspršenja (masa, energija, pravac, impuls, spin, …)



2. <u>Raspadi</u>

   Mjerenje ostataka spontanog raspada čestica

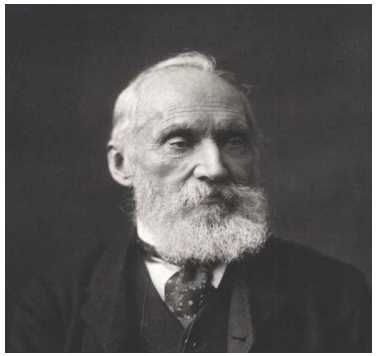
   Od svih poznatih čestica: gotovo sve nestabilne!



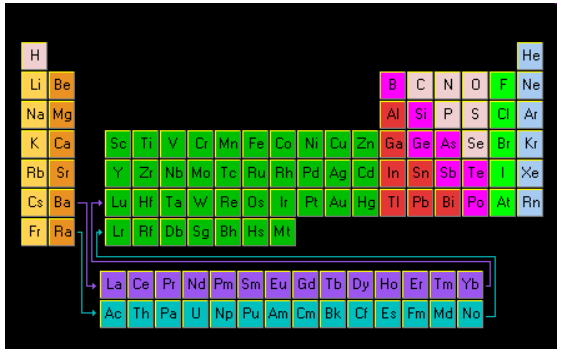
3. <u>Vezana stanja</u>

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

Fizika na kraju 19. stoljeća



William Thomson
(Lord Kelvin)

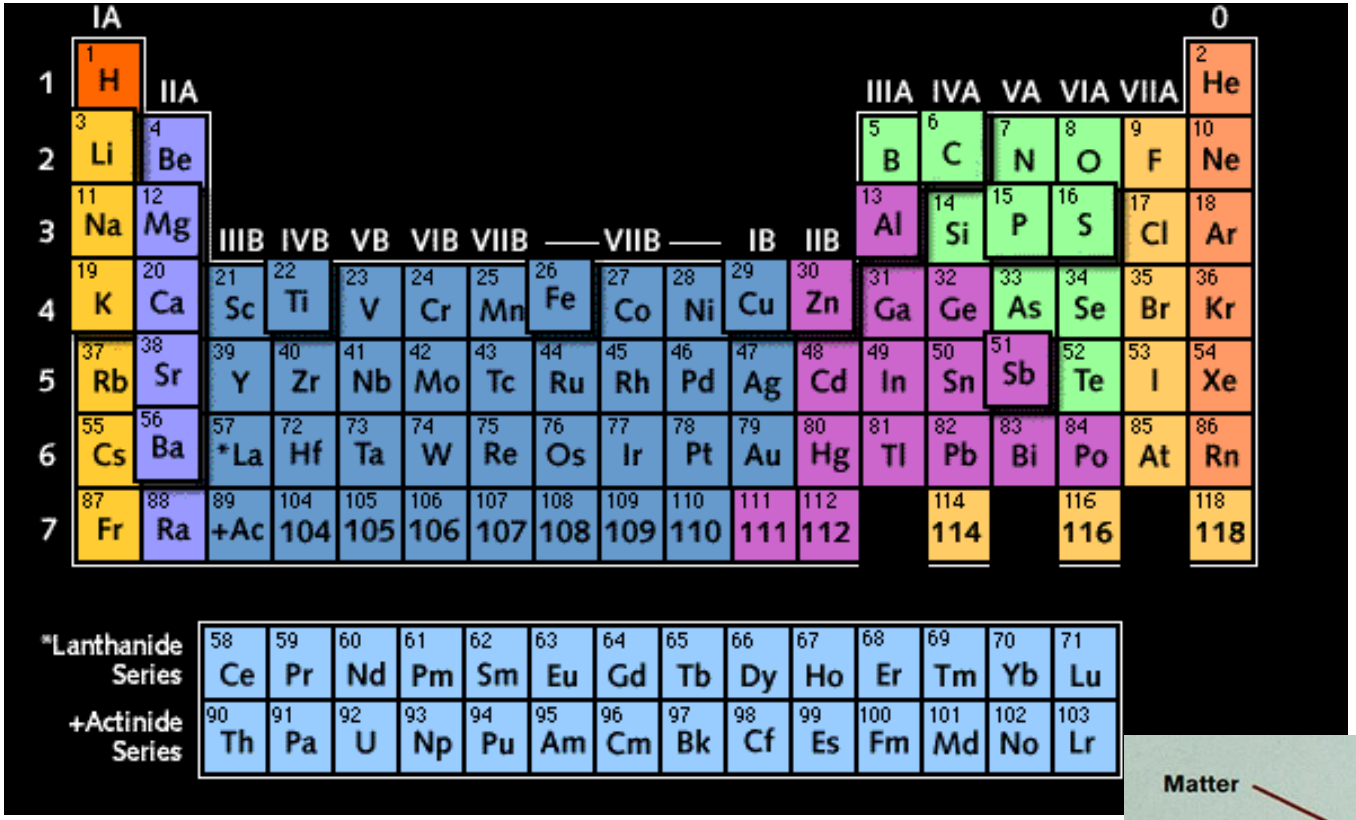


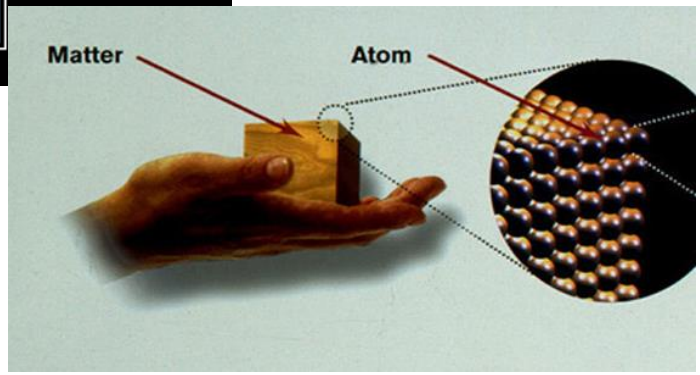
- Cijela fizika opisana kroz:
  - Mehanika (Newton)
  - Termodinamika
  - Elektrodinamika (Maxwell)

"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 inaće vedrom nebu fizike:
  - Materija sastavljena od atoma?
  - Spektar zračenja crnog tijela?
  - Michelson-Morley Eksperiment?

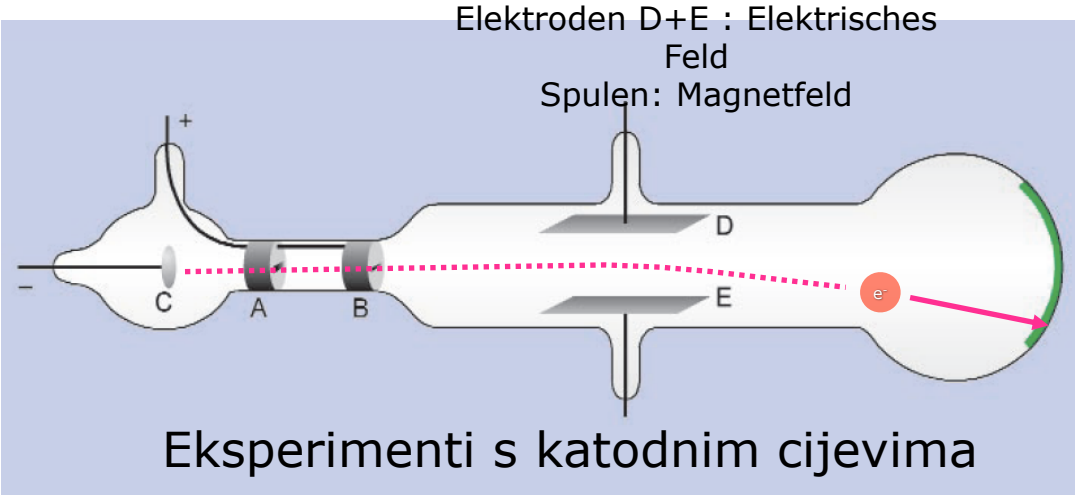
Elementarne čestice: do 1897





1897, prva elementarna čestica: Elektron

J.J. Thomson



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

(Struje u katodnim cijevima se sastoje od čestica)

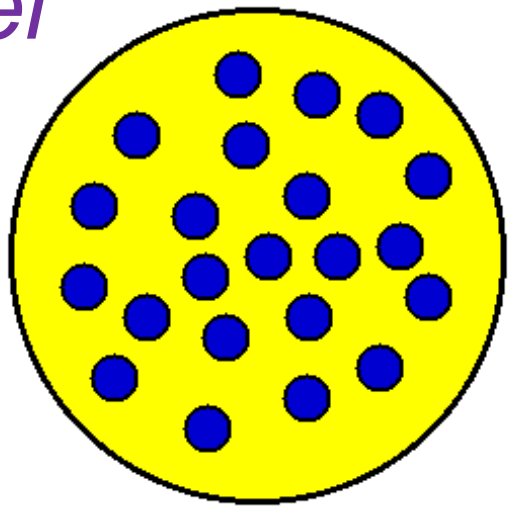
$$m_e \approx M_H/1836$$

"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!

Thomsonov model atoma

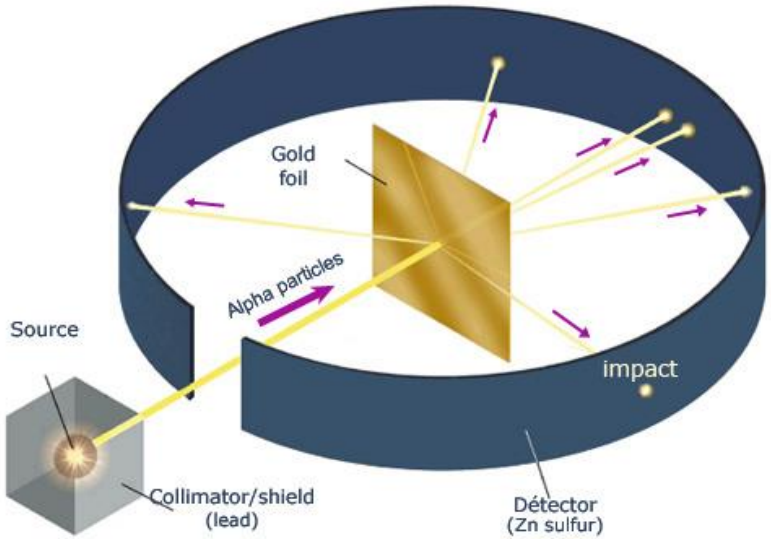
”Plum pudding model”

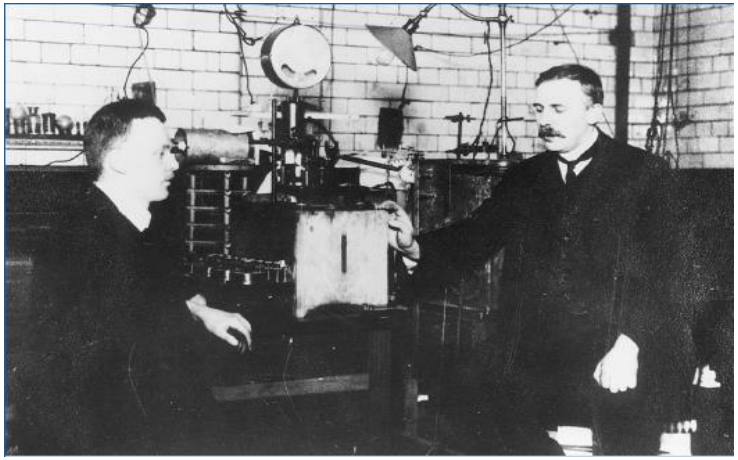


<u>Thomsonov model atoma</u>:

- Električni nabijena kugla
- Radijus ~ 10^{-8} cm
- Pozitivni naboj: homogeno raspodijeljen u cijelom atomu
- Elektroni s negativnim nabojem raspršeni u kugli

Otkriće atomske jezgre: Rutherfordov eksperiment



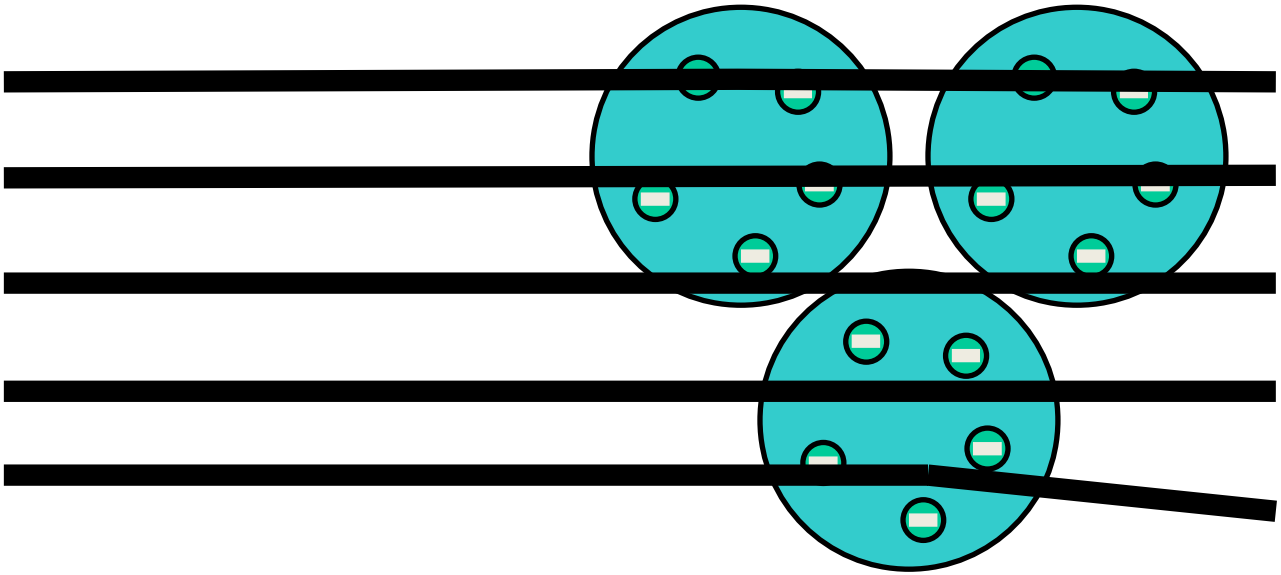


Ernest Rutherford (r) und Hans Geiger (l) in Manchester

<u>Bitni elementni eksperimenta</u>

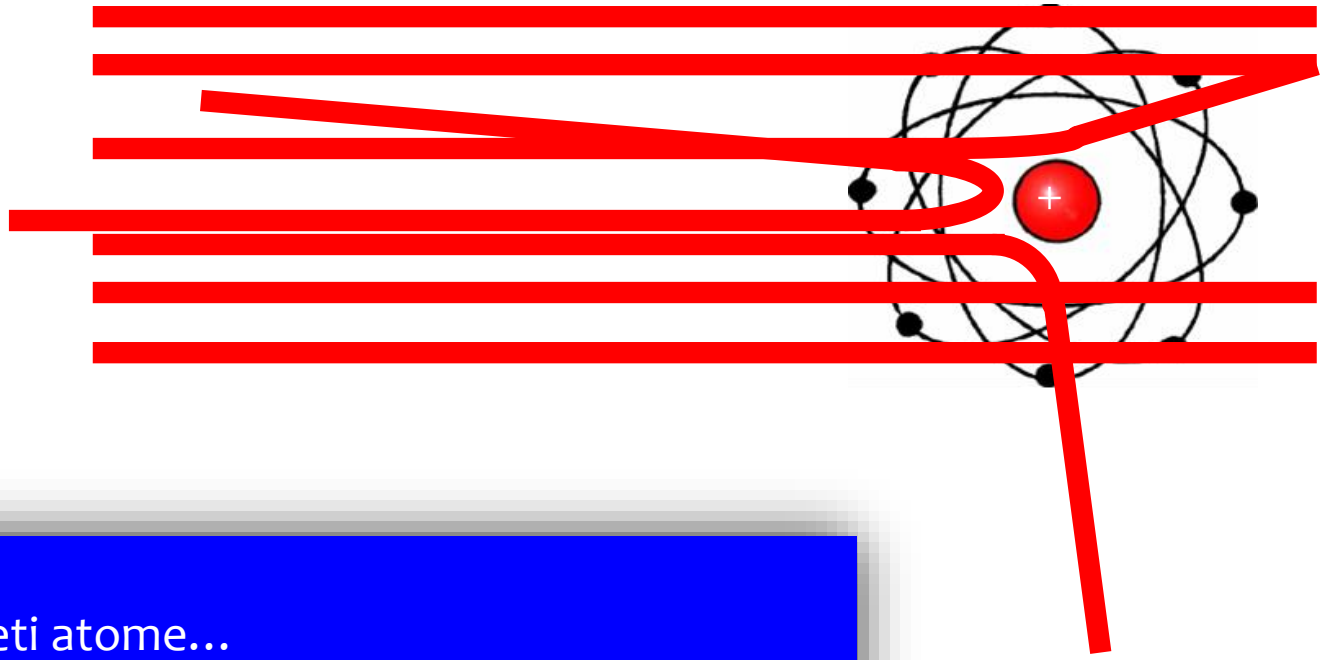
- Snop
- Meta
- Detekcija
- Izbor podataka (u našem žargonu: *triggering*)

Thomsonov model atoma



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

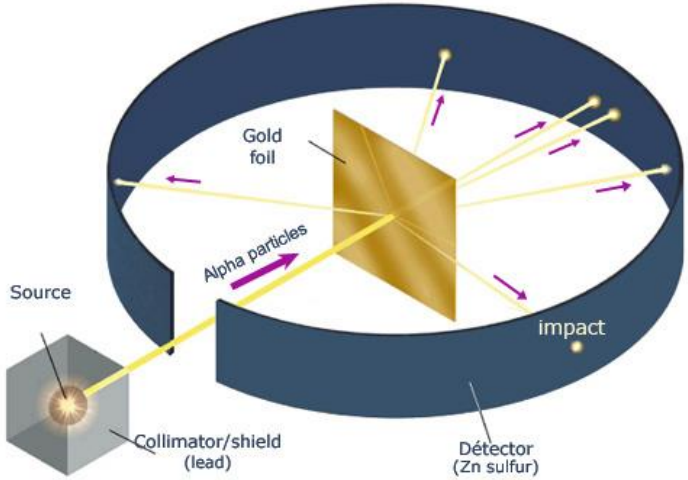
Rutherfordov model atoma

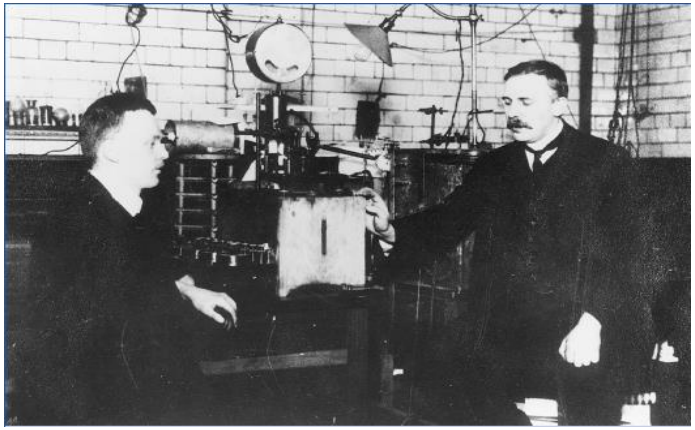


Rutherford model:
I dalje ne možemo vidjeti atome…
Negativni elektroni oko malog, gustog pozitivnog centra
Kakve eksperimentalne rezultate predviđa ovaj model?

Jezgra atoma je 100 000 puta manja od promjera atom!

Otkriće atomske jezgre

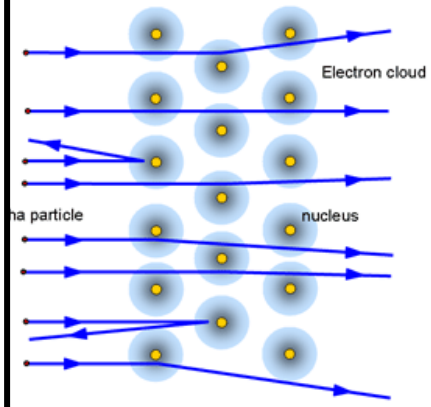




Ernest Rutherford (r) und Hans Geiger (l)
in Manchester

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

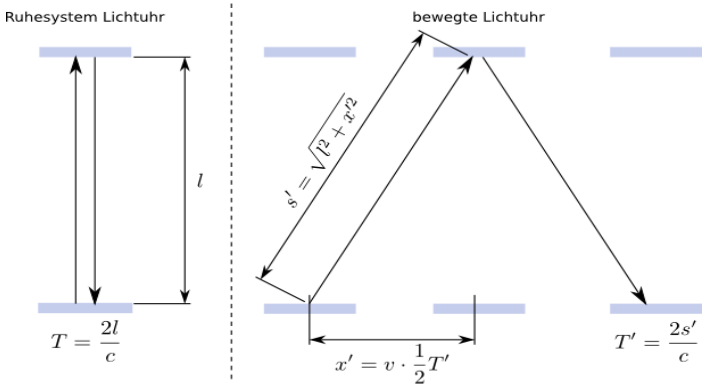
$p = h / \lambda$

Bohr
(1913)

Ispitivanje strukture
materije

Relativnost: principi

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



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

- Nema apsolutnog vremena ni prostora
- Dilatacija vremena - duljine

Masa i Energija

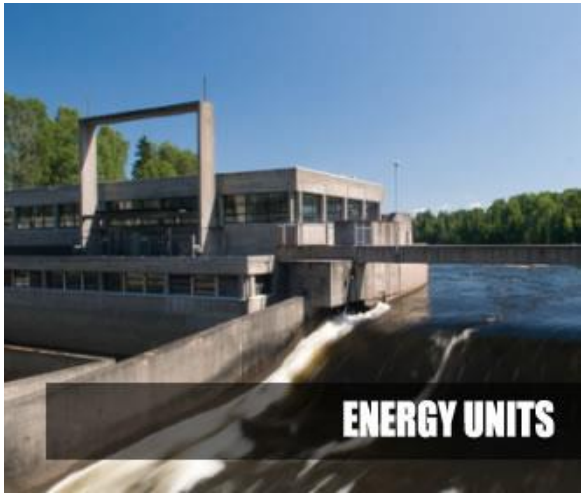
- Masa:
  - Spremište energije čestica
  - Ne ovisi o brzini
  - "definirana" $$M^2c^4 = E^2 - p^2c^2$$
  - U miru: **E = M c²**
  - M je **Lorentz invarianta**: ista u svim sustavima (E i p općenito nisu)
  - c velik: mala masa= velika količina energije

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

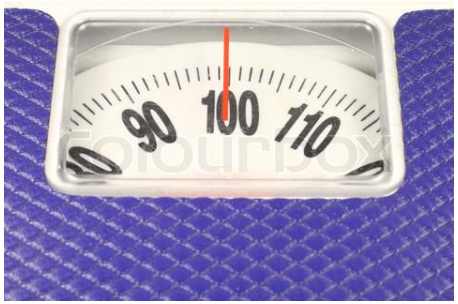
$$E = m$$

$$E = mc^2$$

$E = mc^2$

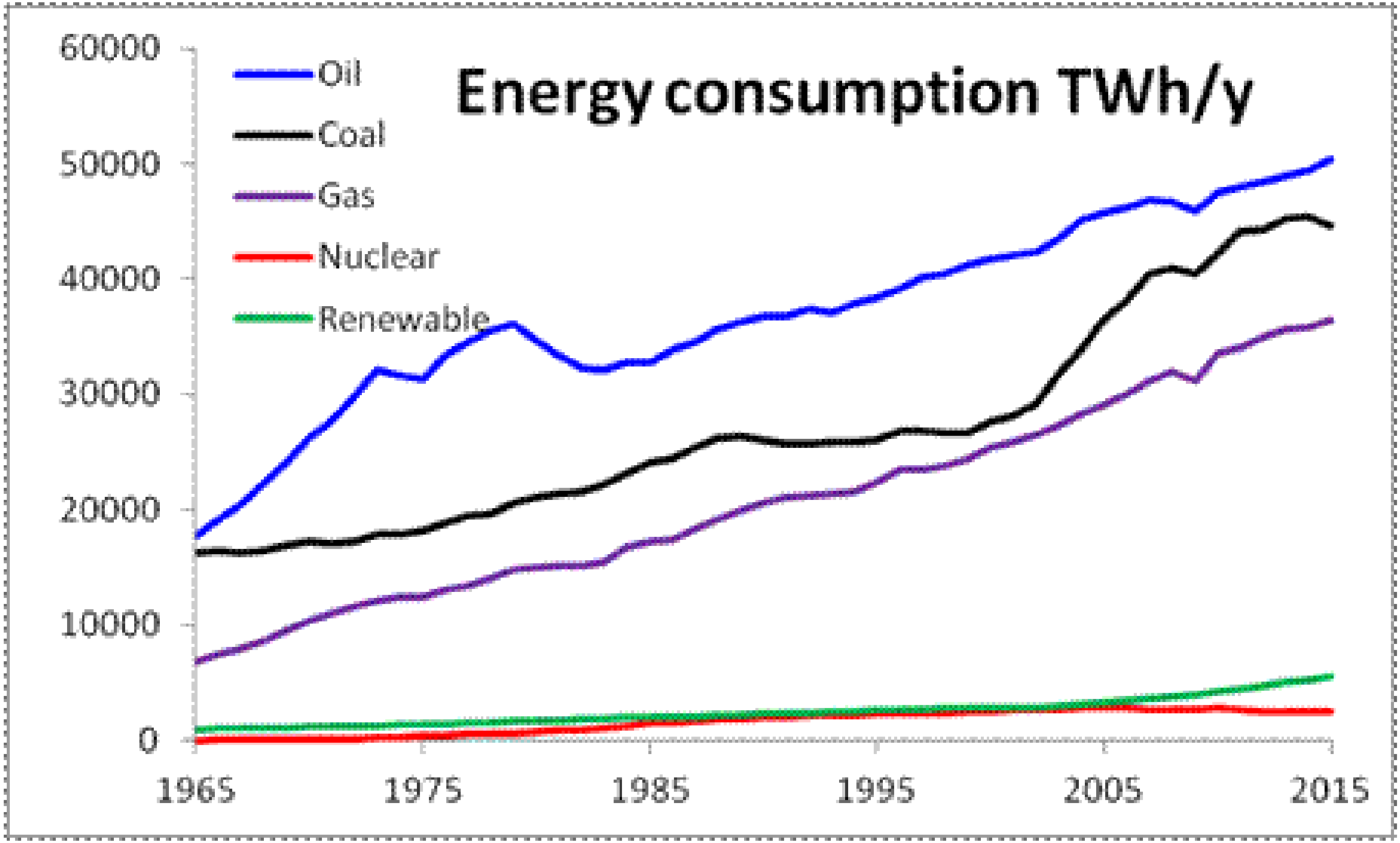
$c = 300\ 000\ \text{km/h} = 10^8\ \text{m/s}$

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

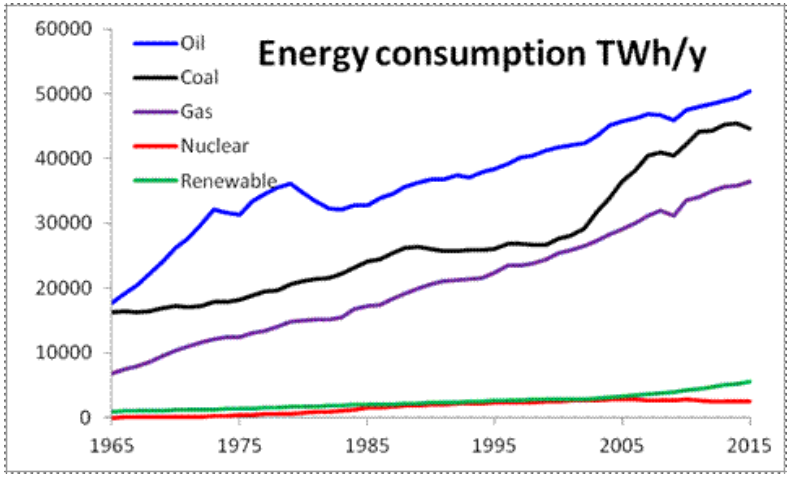


$m = 100\ \text{kg}$

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



$$2015 : 109136\,\mathrm{TWh} = 3.93 \cdot 10^{20}\,\mathrm{J} =\sim 4400\,\mathrm{kg} \cdot c^2$$


Energy consumption TWh/y
Oil
Coal
Gas
Nuclear
Renewable
60000
50000
40000
30000
20000
10000
0
1965
1975
1985
1995
2005
2015

=

~2 *

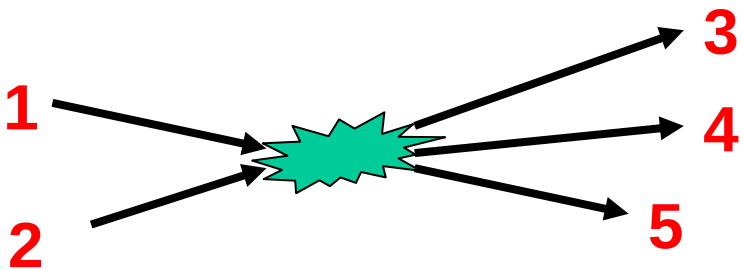
U fizici visokih energija

$E = mc^2$ → $[m] = GeV/c^2$

$c = 1$ → $E = m$ → $[m] = GeV$

Očuvane veličine

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



  - Vrijedi

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

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

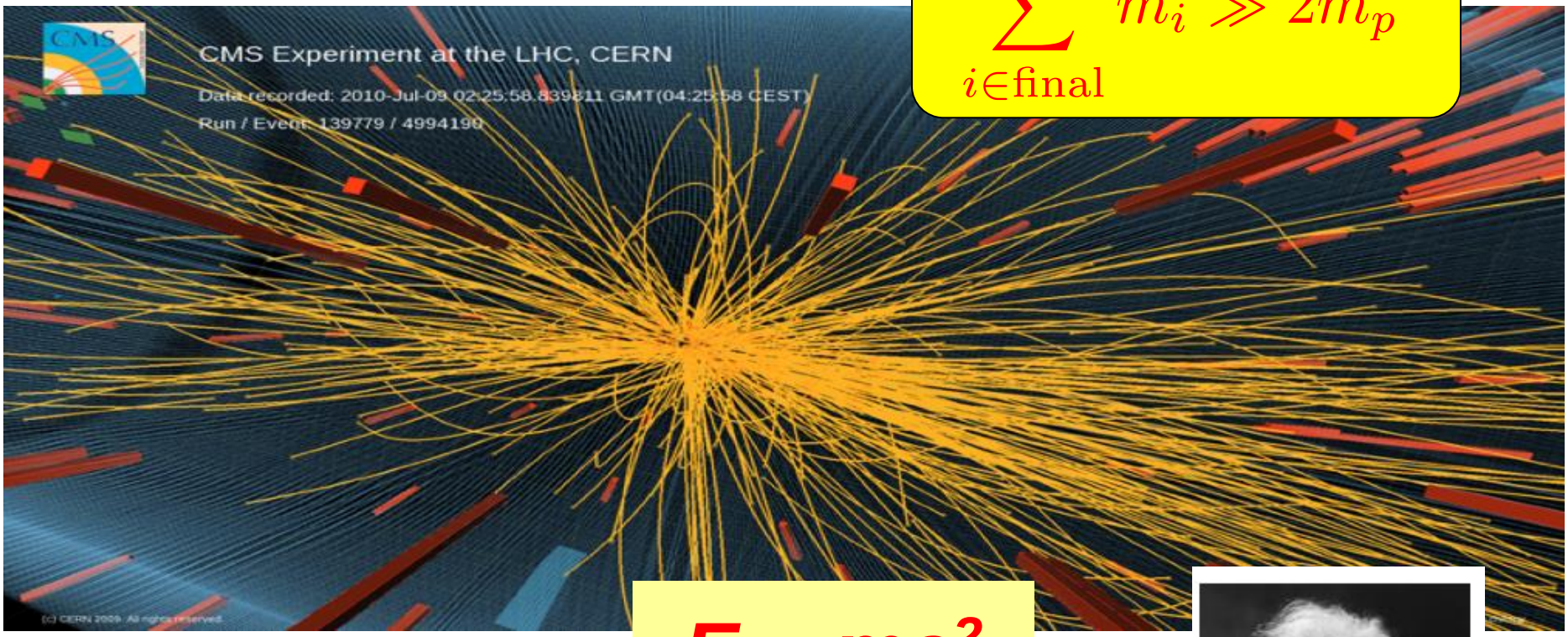
  - Ali općenito: $M_1 + M_2 \neq M_3 + M_4 + M_5$

Masa nije očuvana veličina!

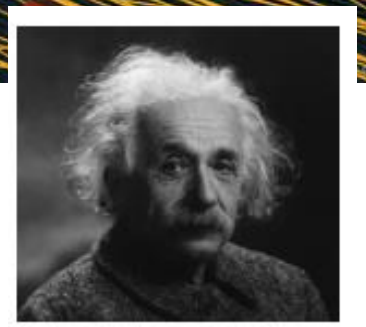
Masa nije očuvana

proton proton sudar na LHC-u

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



$$E = mc^2$$



Relativnost i raspadi: Test

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

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

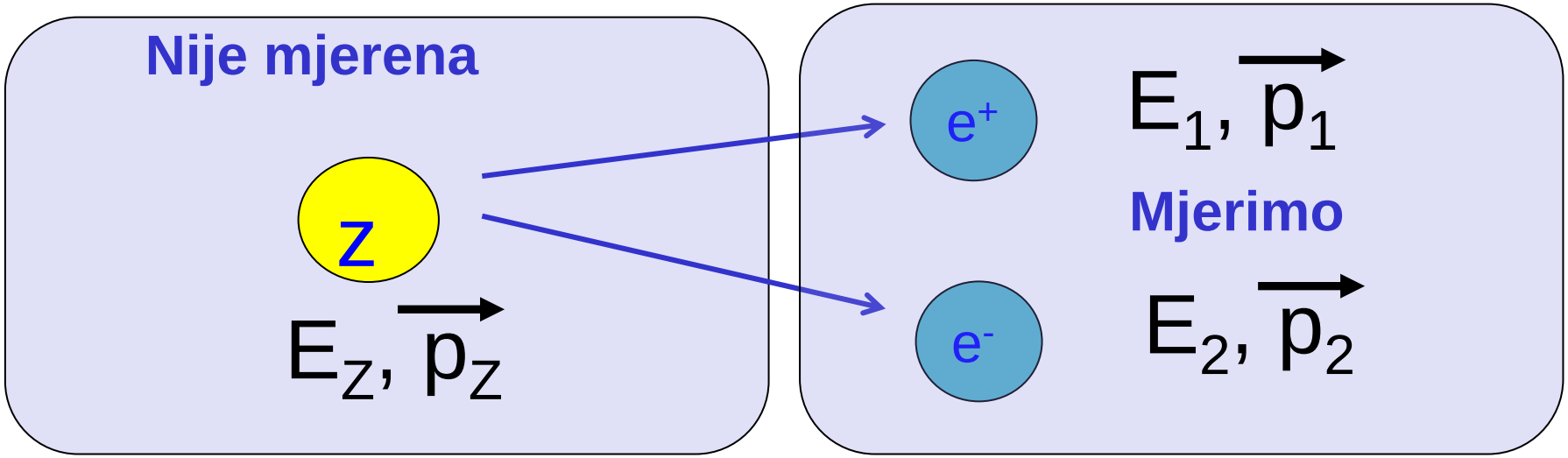
a) DA

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

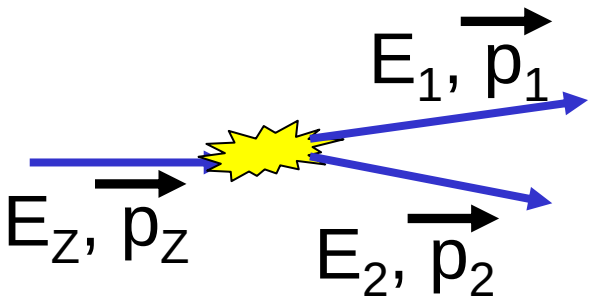
$$M_Z^2 = E_Z^2 - p_Z^2 = (E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2$$

Vježba: dodajte nedostajuće c faktore (dimenzionalna analiza!)

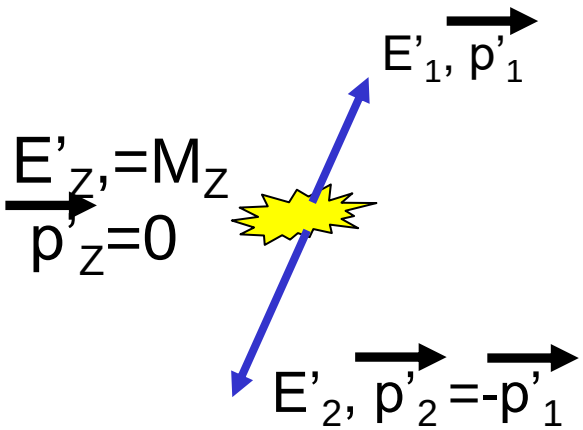
Izbor sustava

Možemo promatrati raspad u više mogućih sustava

Raspad u letu



Raspad u mirovanju



Općenito: E_i i E'_i nisu jednaki

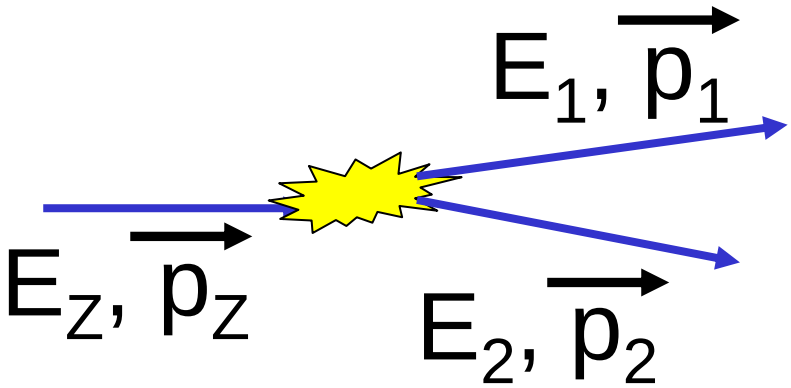
U kojem sustavu računati inv. Masu za dobiti pravu masu čestice?

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

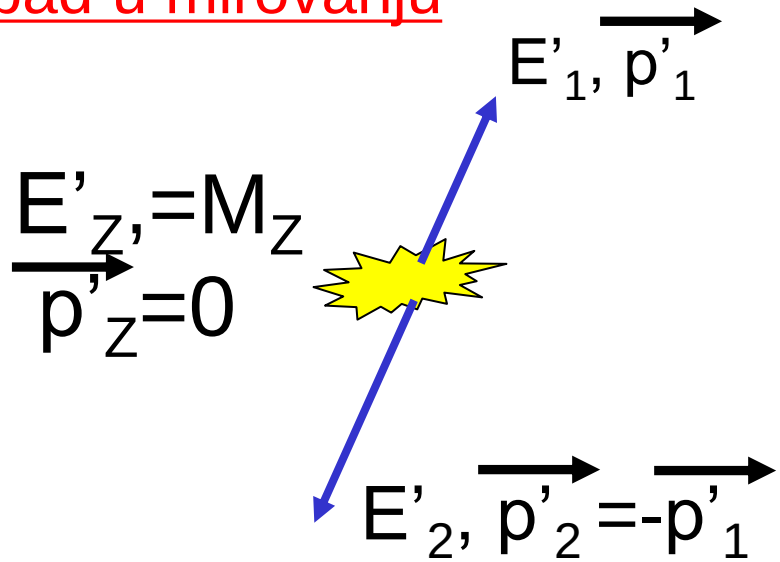
Izbor sustava

Možemo promatrati raspad u više mogućih sustava

Raspad u letu



Raspad u mirovanju



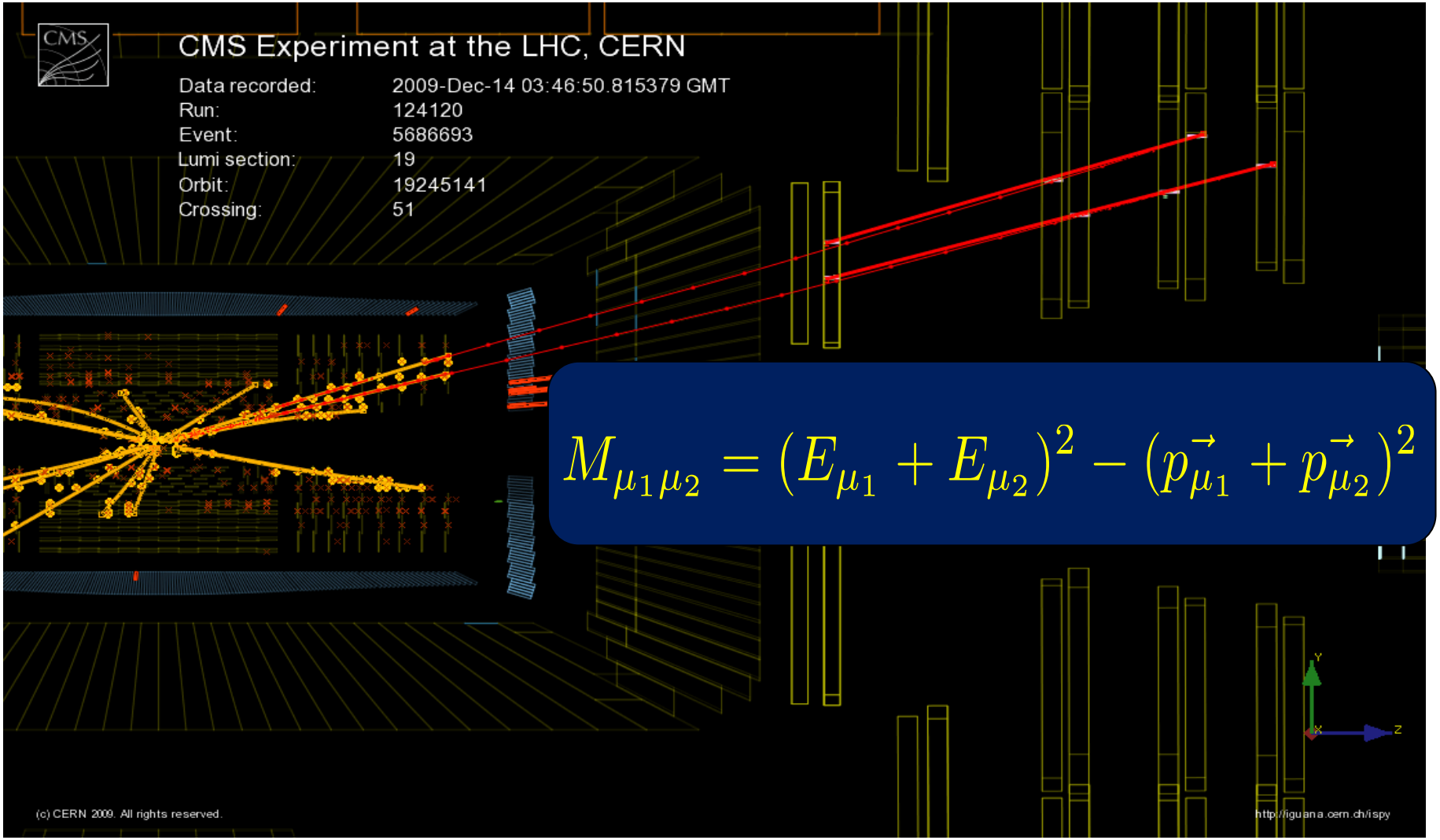
Općenito: E_i i E'_i nisu jednaki

U kojem sustavu računati inv. Masu?

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

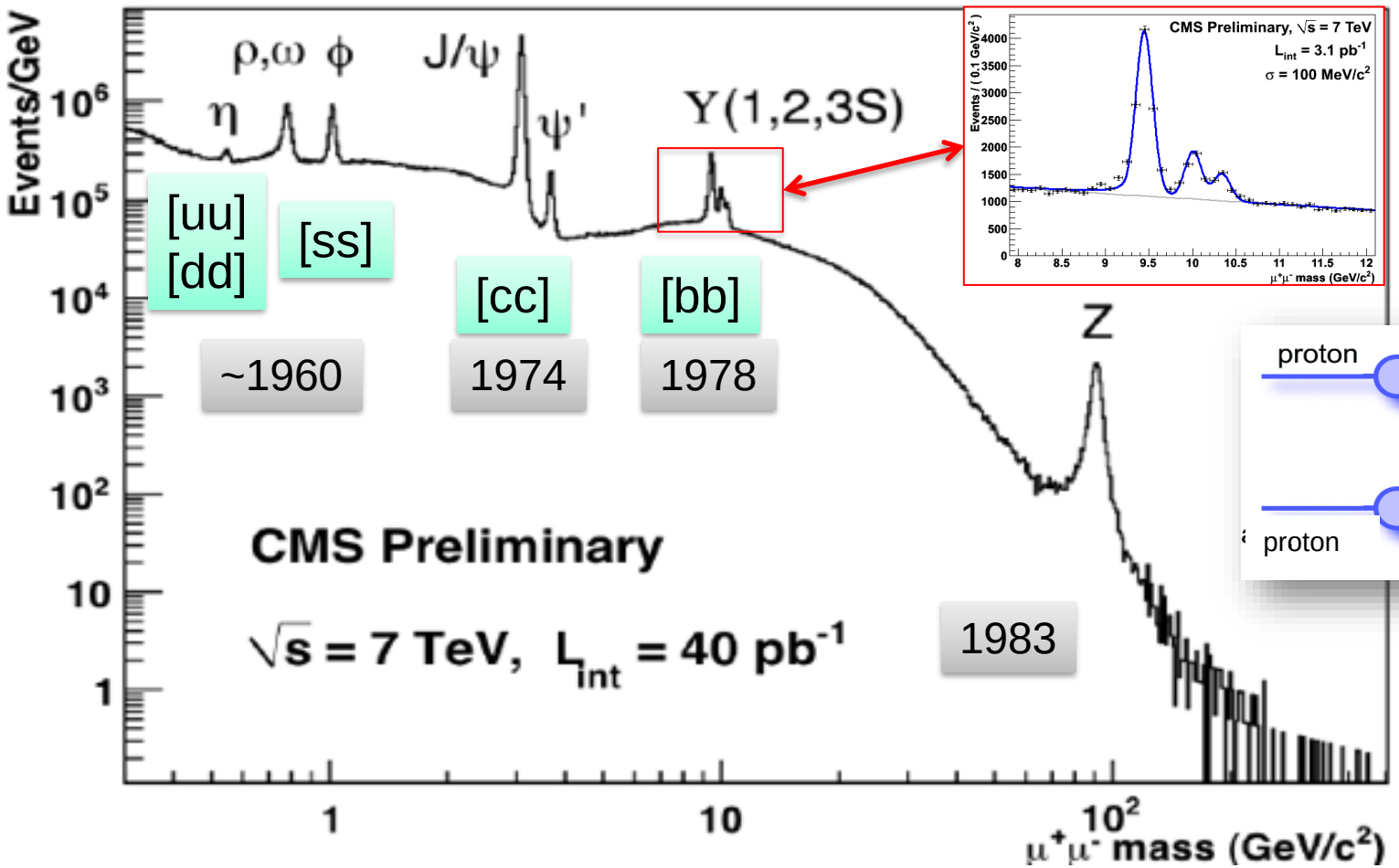
NIJE BITNO: INVARIJANTNA MASA NE OVISI O PROMATRAĆU

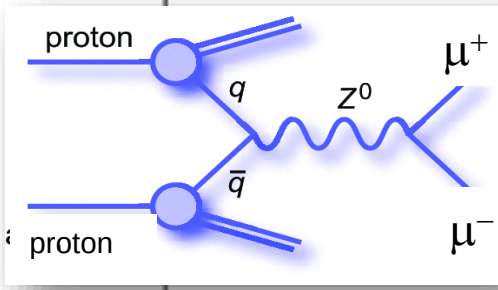
Događaji sa 2 miona



$$M_{\mu_1\mu_2} = (E_{\mu_1} + E_{\mu_2})^2 - (\vec{p_{\mu_1}} + \vec{p_{\mu_2}})^2$$

Ponovno otkriće SM na LHC-u

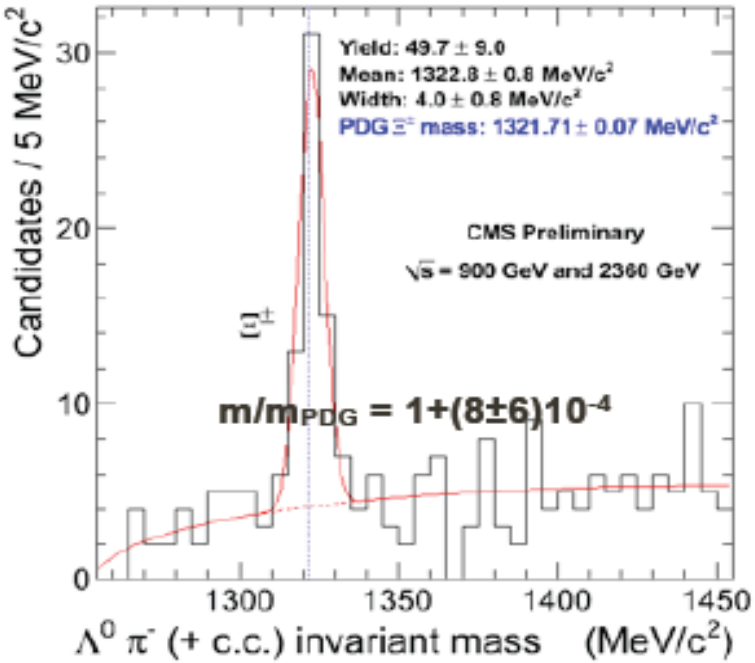


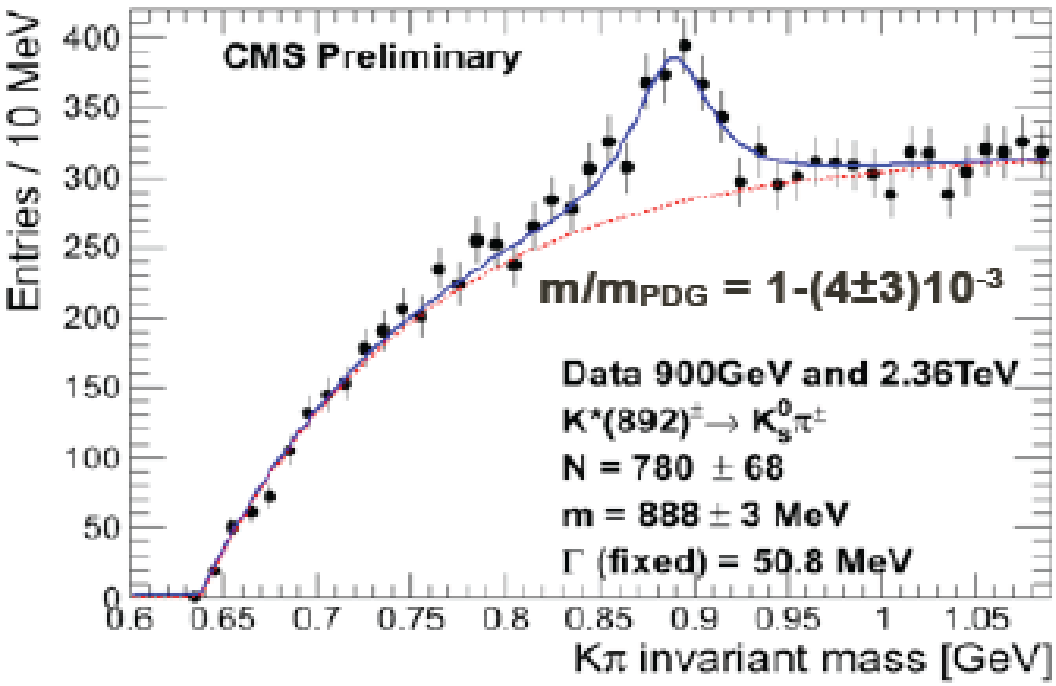


40 pb^{-1} collected in 2010

V. Brigljević

Signal i pozadina – Primjeri iz prvih LHC podataka

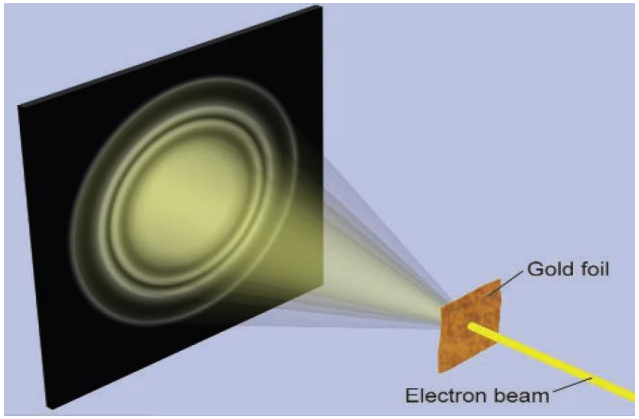




Elementarne čestice: kvantni objekti

- 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:

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

- Isto vrijedi za energiju i vrijeme:

$$\boxed{\Delta E \Delta t \geq \hbar}$$

Kvantna jednadžba gibanja

Schrödinger
1926

- Schroedinger:ponašanje čestica opisano kroz valnu jednadžbu

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

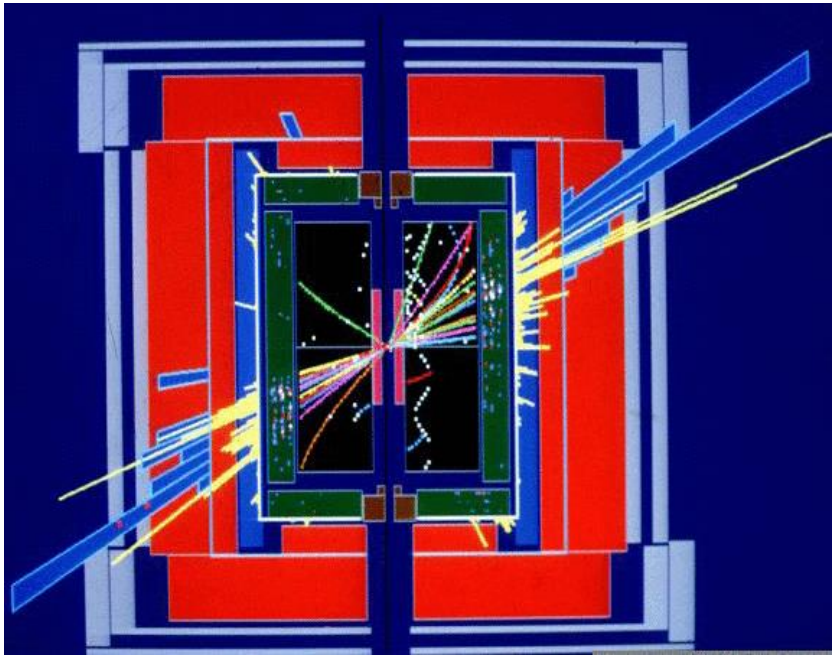
- Novost: valna funkcija nije više direktno mjerljiva nego predstavlja vjerojatnost!
- Nigdje tako dobro vidljivo kao kod elementarnih čestica

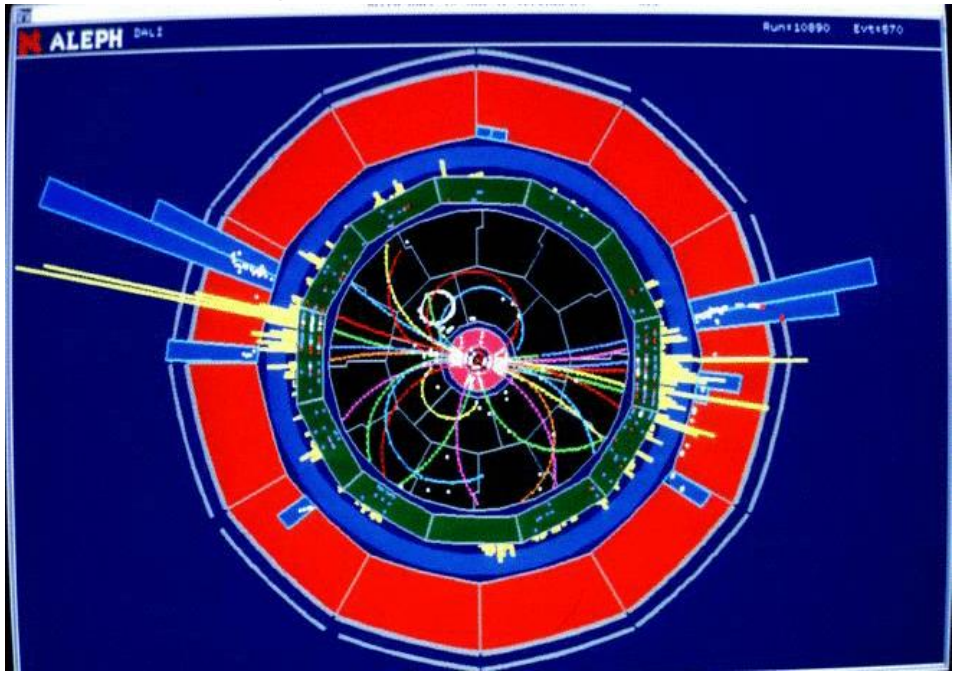
Primjer slučajnosti: Z raspad

Eksperiment

Sudaramo snopove elektrona i pozitrona na energiji od 91 GeV

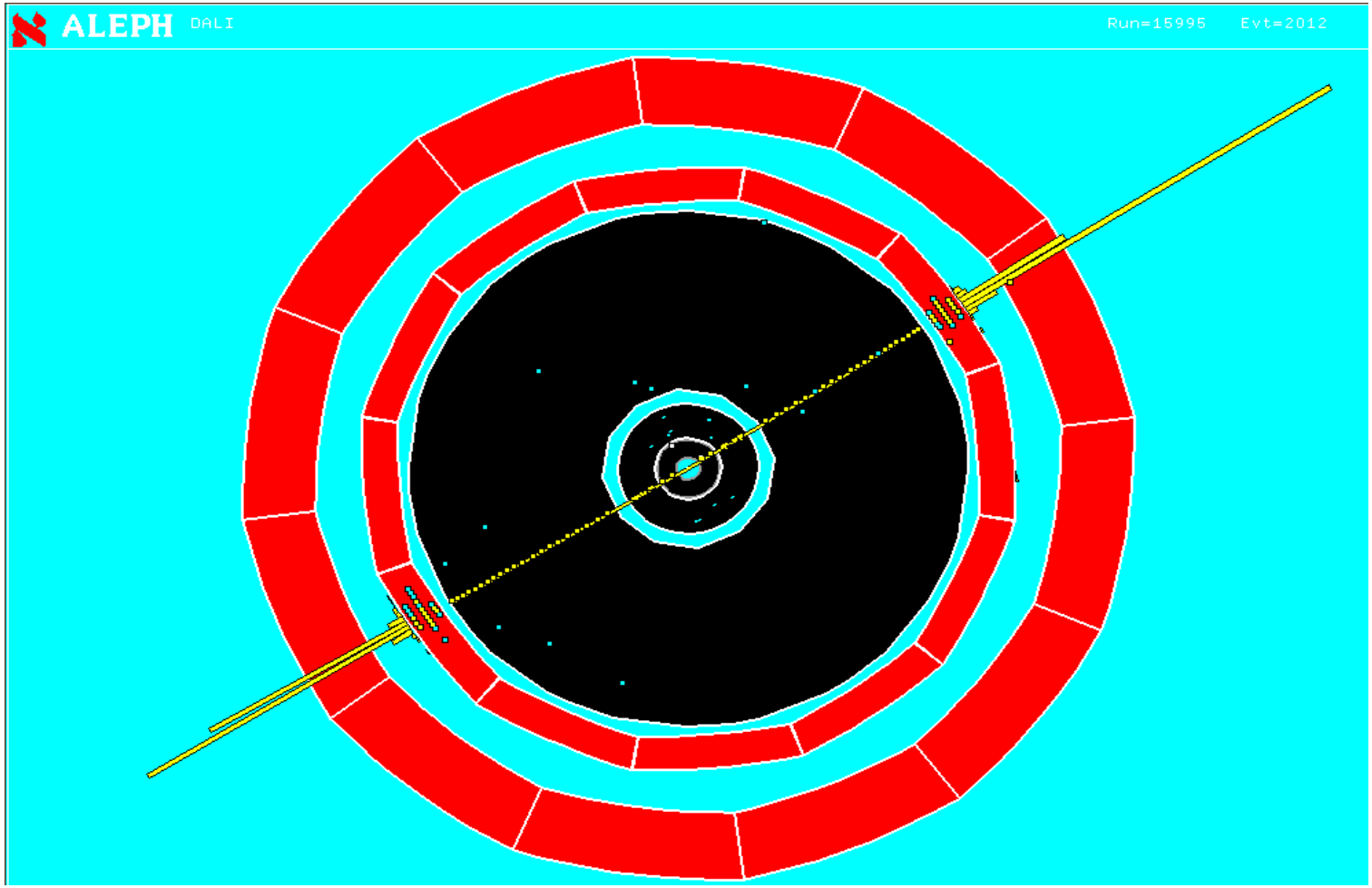
Produciramo Z bozone i proučavamo njihove raspade…





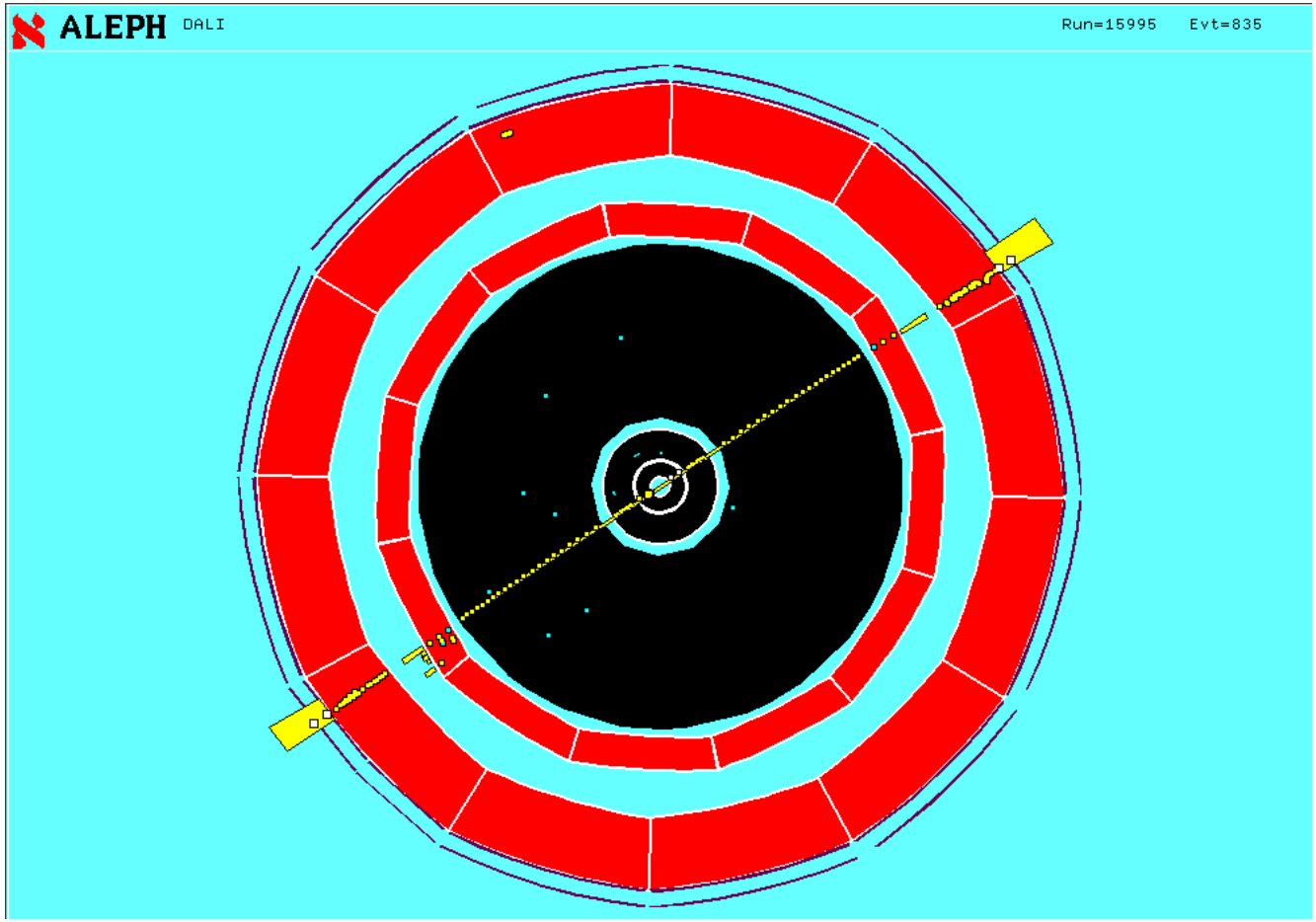
Ajmo to ponoviti...

Još jedan raspad Z bozona



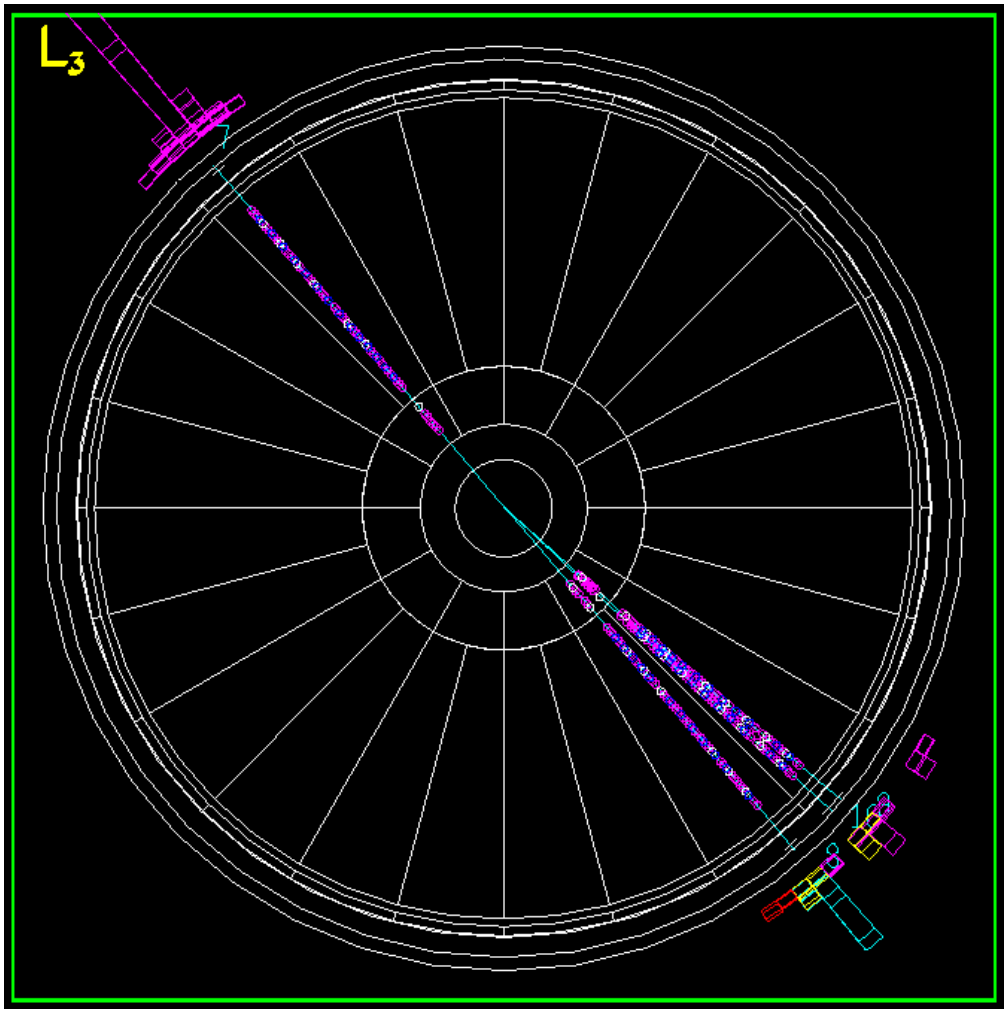
Prilično različito!

I još jednom



Stvarno se radi o ISTOM eksperimentu…

I još jedan

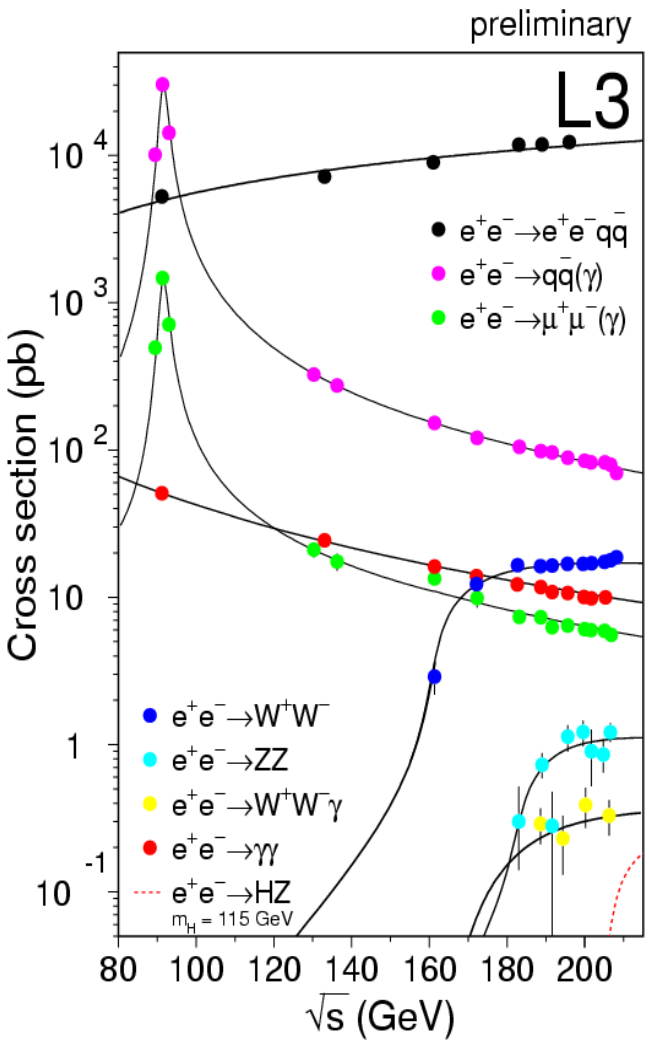


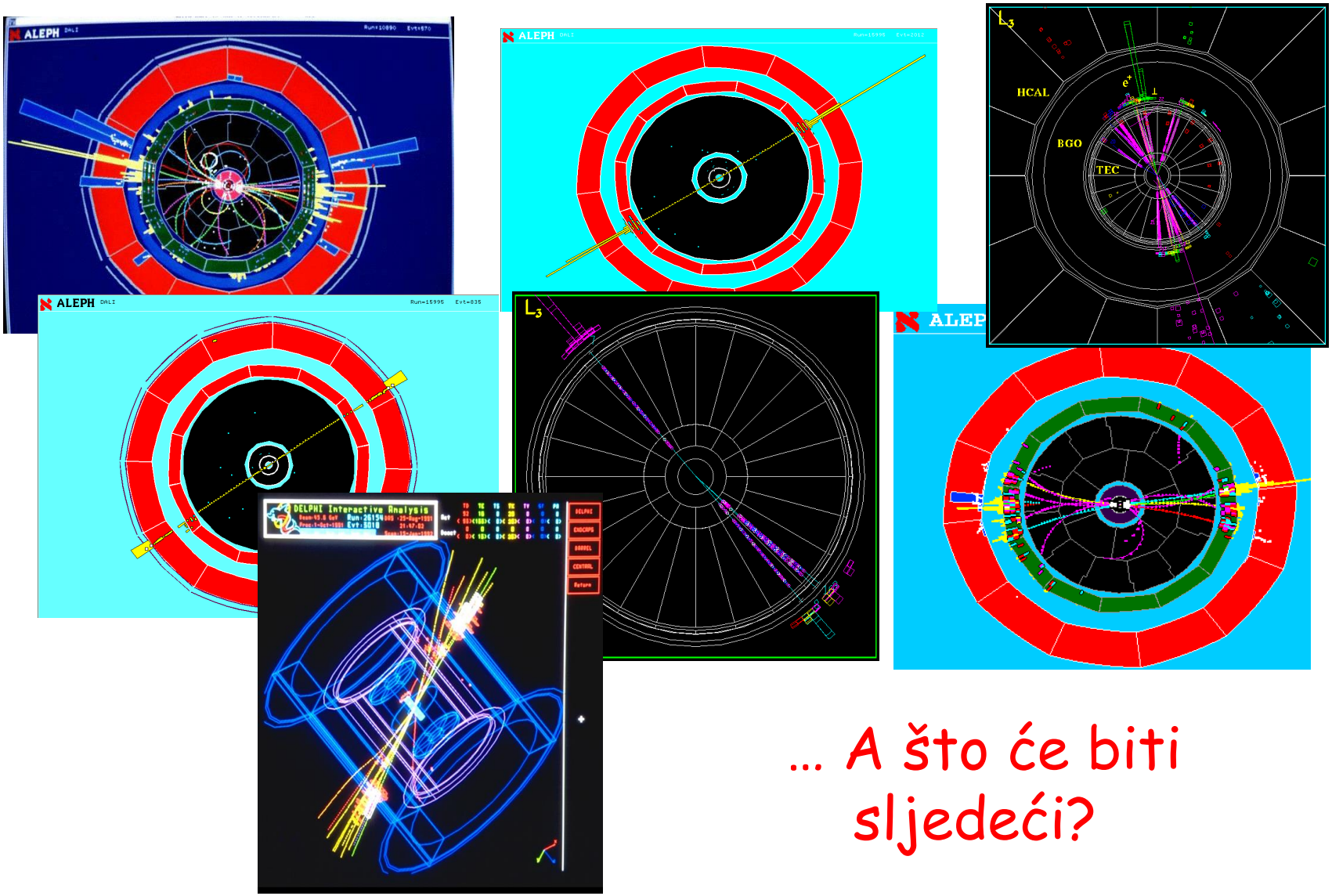
Što nam teorija kaže o Z raspadima

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

I jako točno!

Ali ne kaže nam apsolutno ništa o ...

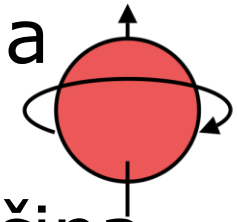




… A što će biti sljedeći?

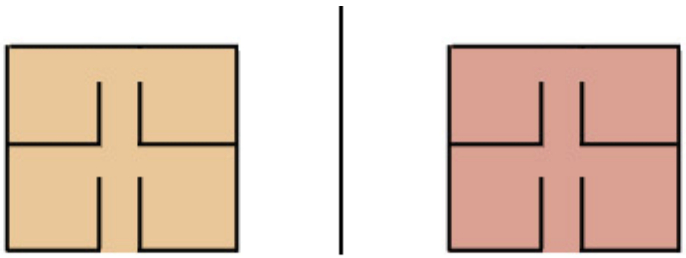
Ako kvantna teorija vrijedi to nije određeno fizikalnim zakonima, čisto je slučajno!

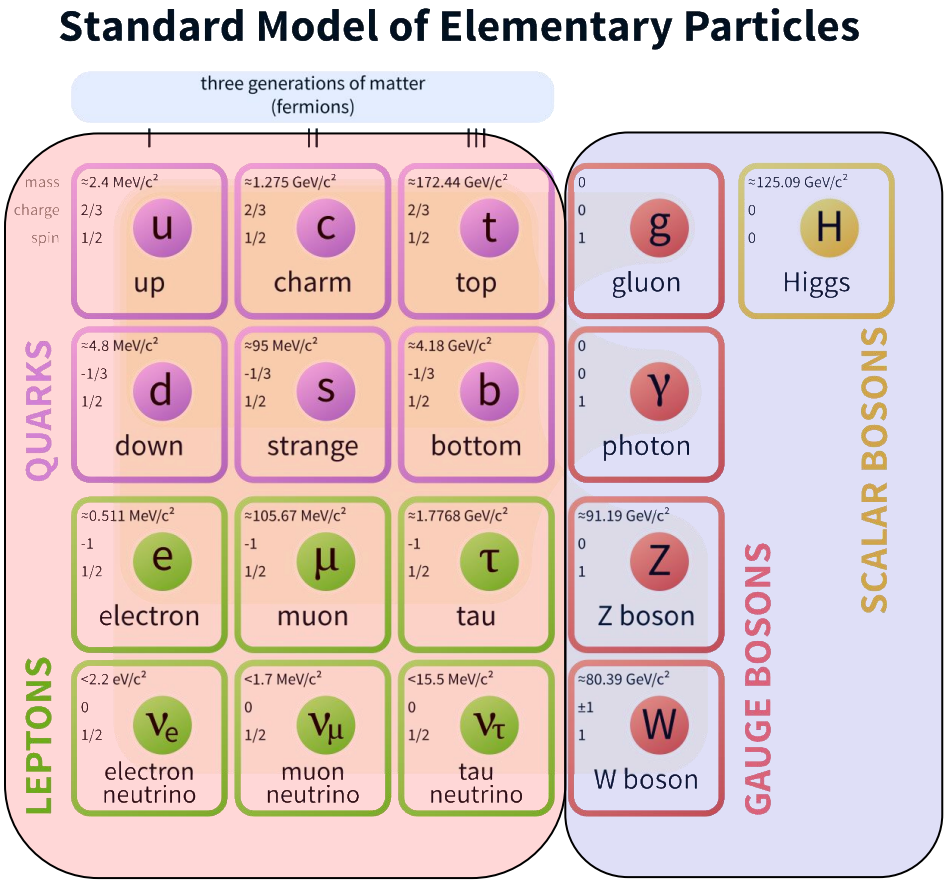
Kvantno svojstvo: Spin



- 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





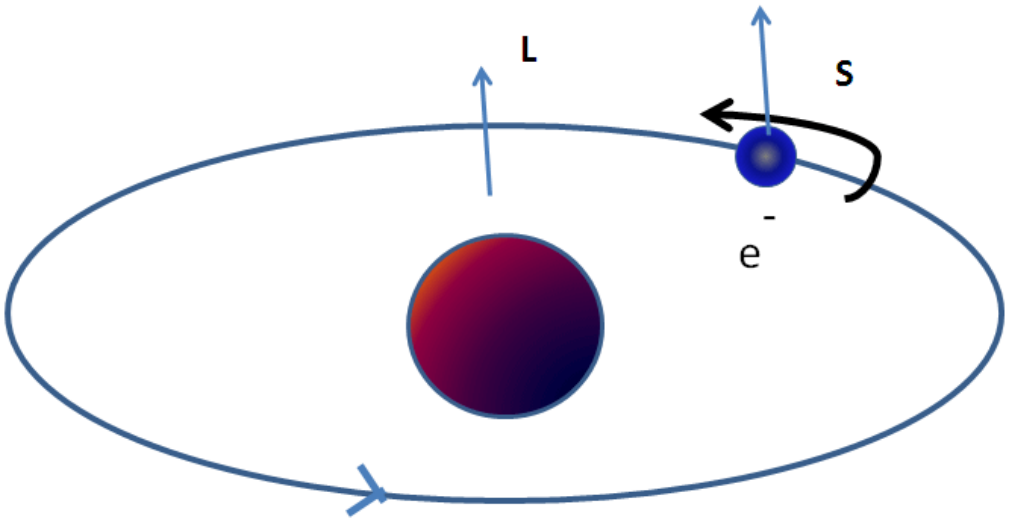
Fermioni **Bozoni**

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, …

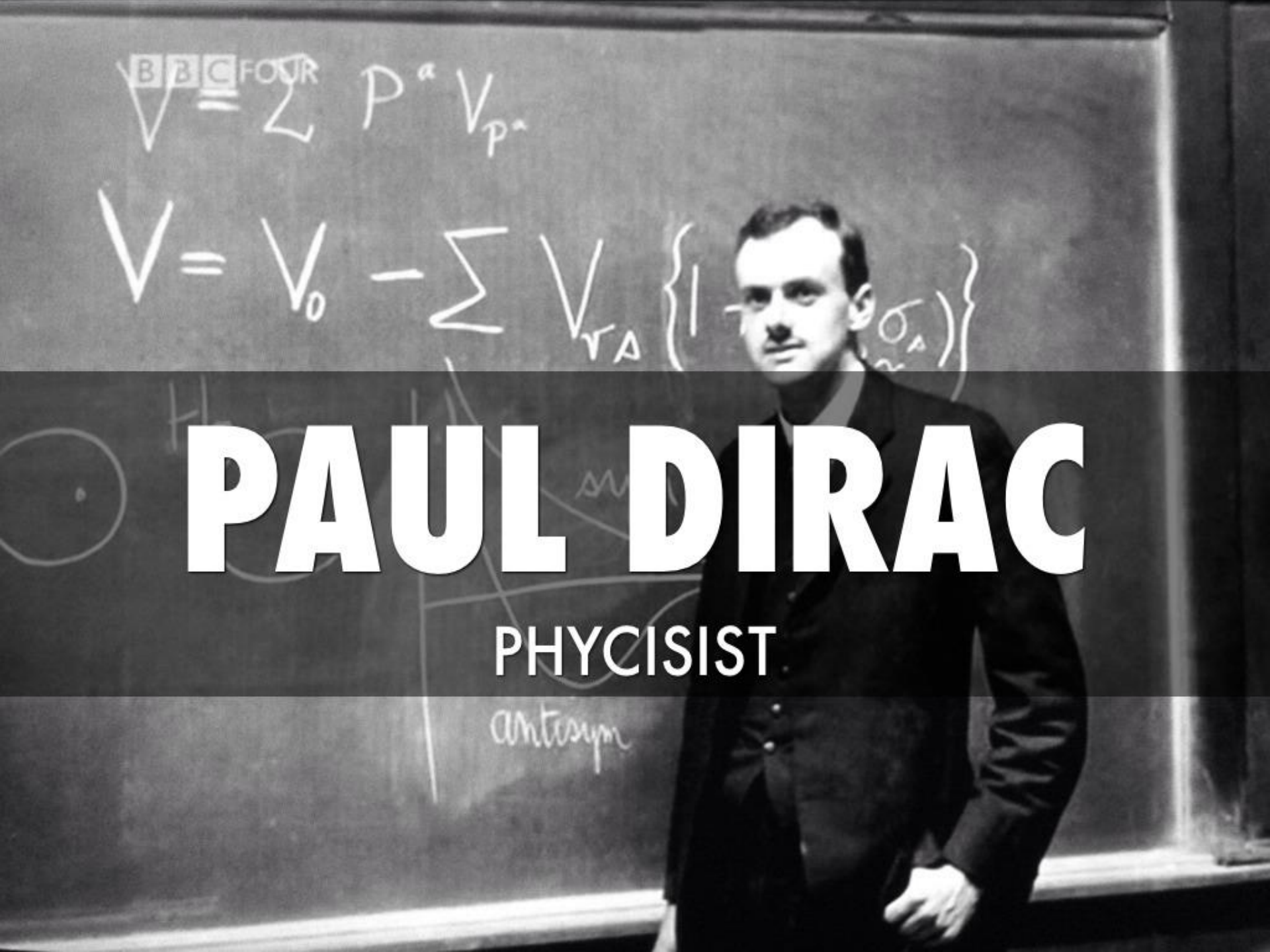
Ukupna kutna količina gibanja



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

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!

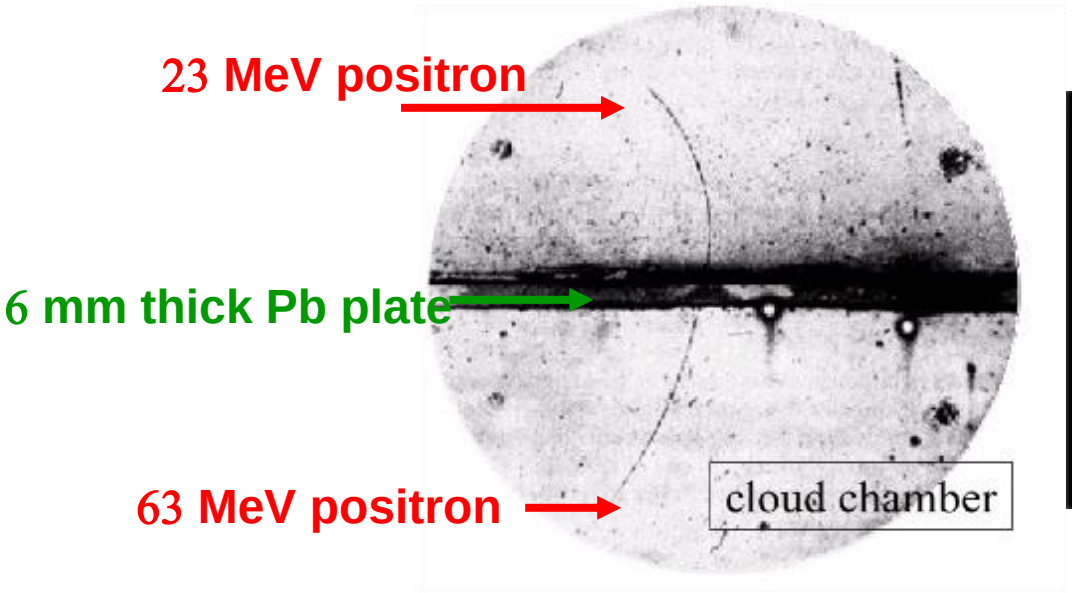
P.A.M. Dirac

Relativnost i kvantna fizika zahtjevaju

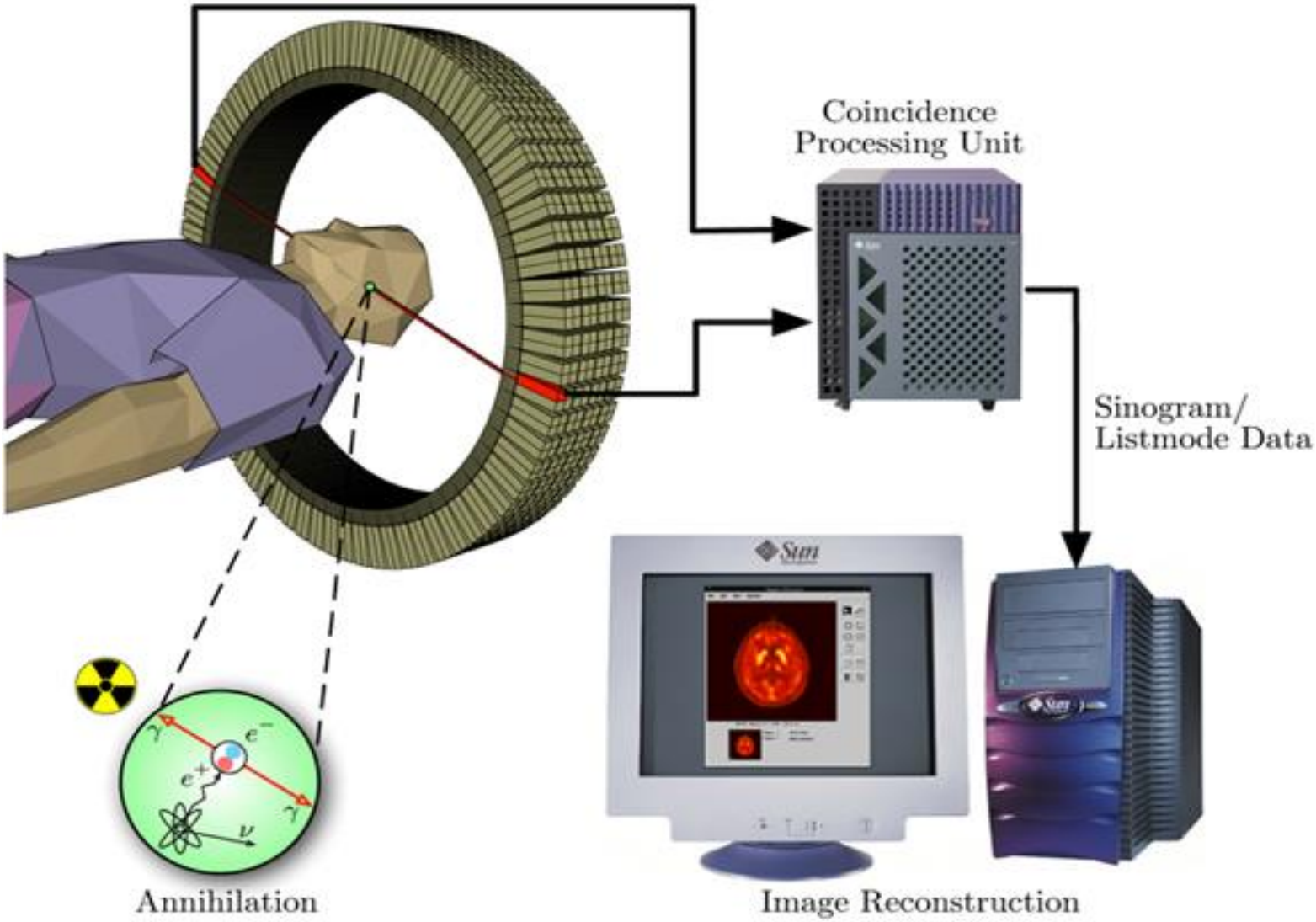
Za svaku česticu postoji i antičestica sa istom masom i suprotnim kvantnim brojevima

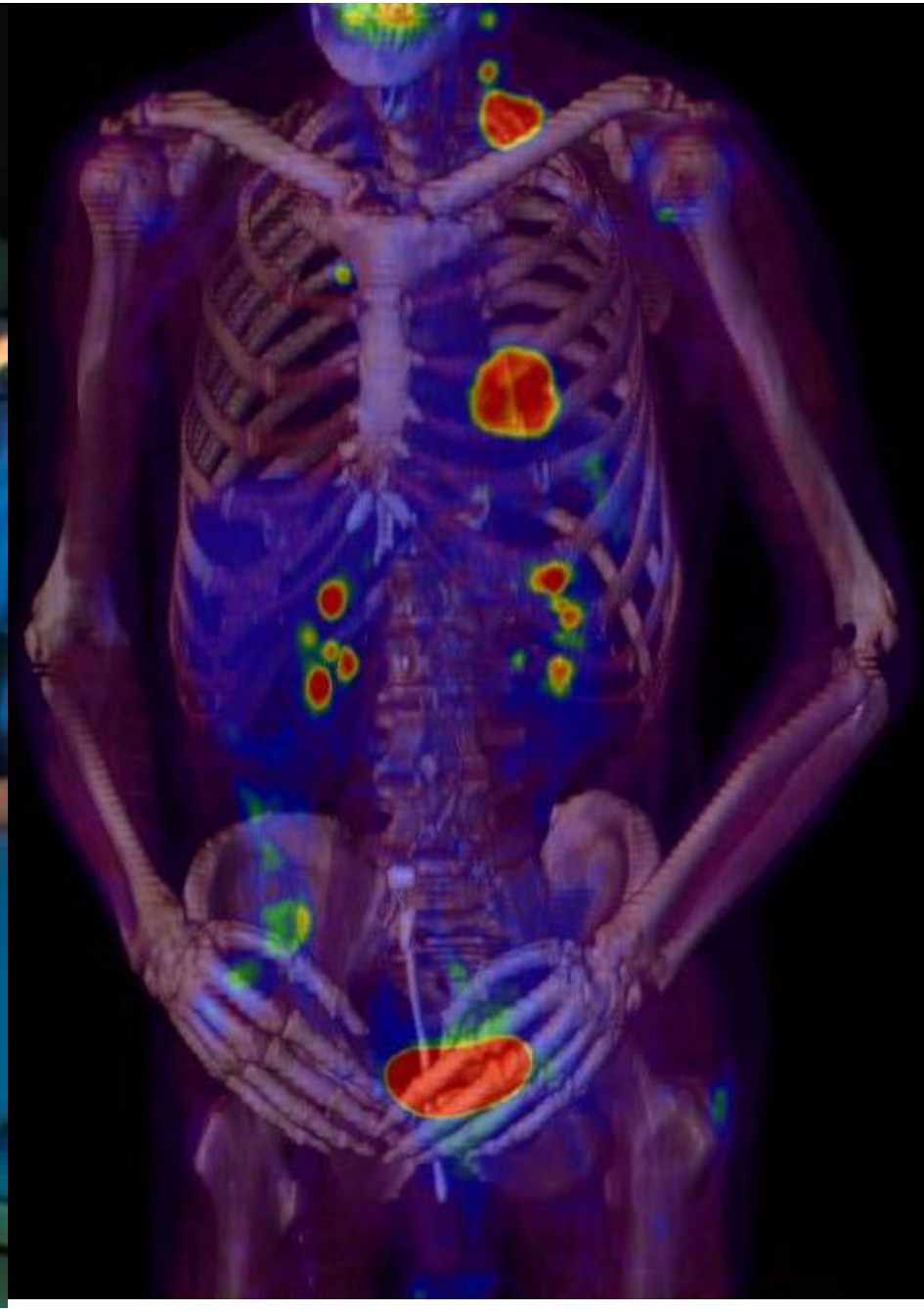
"Otkrio" kao teorijski zahtjev Dirac (1928)

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

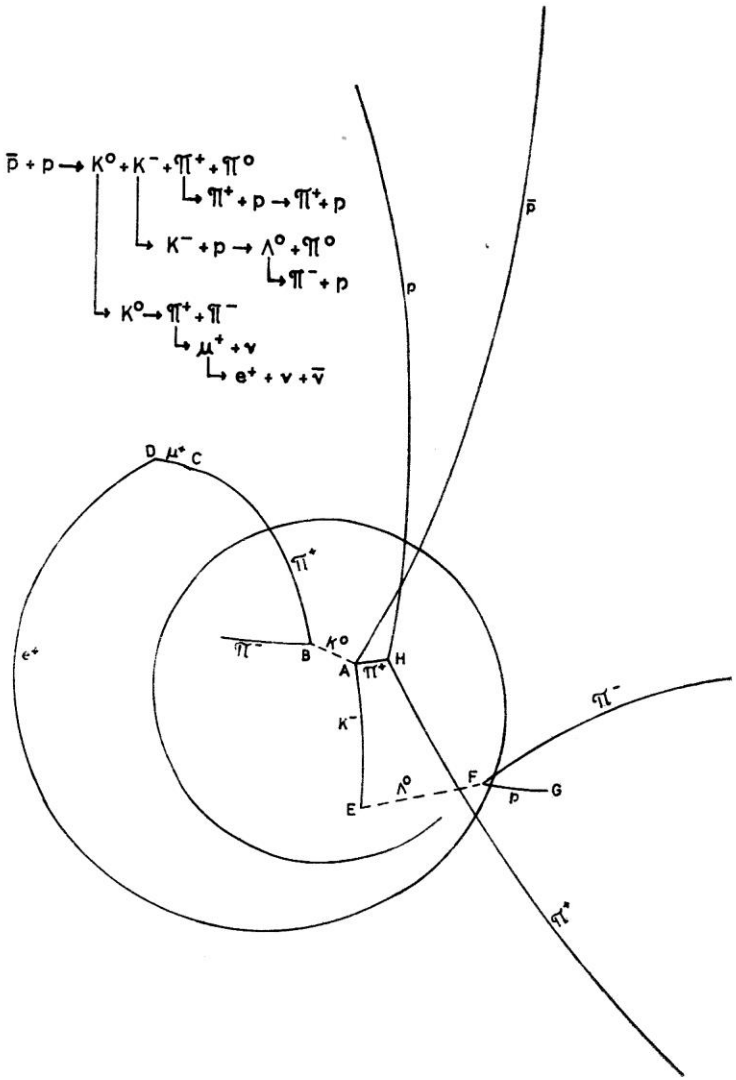


Antimaterija u medicini: PET Tomografija





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



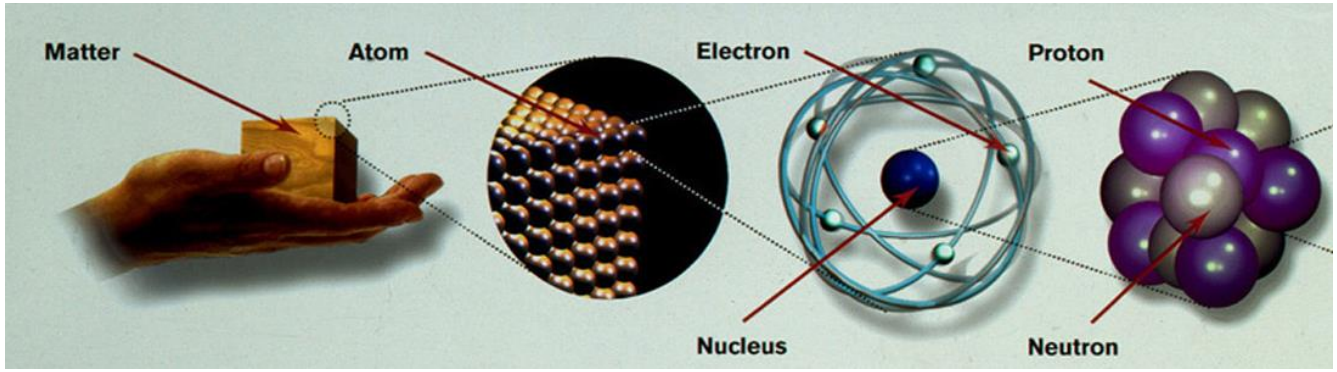
1932: Svijet je jednostavan

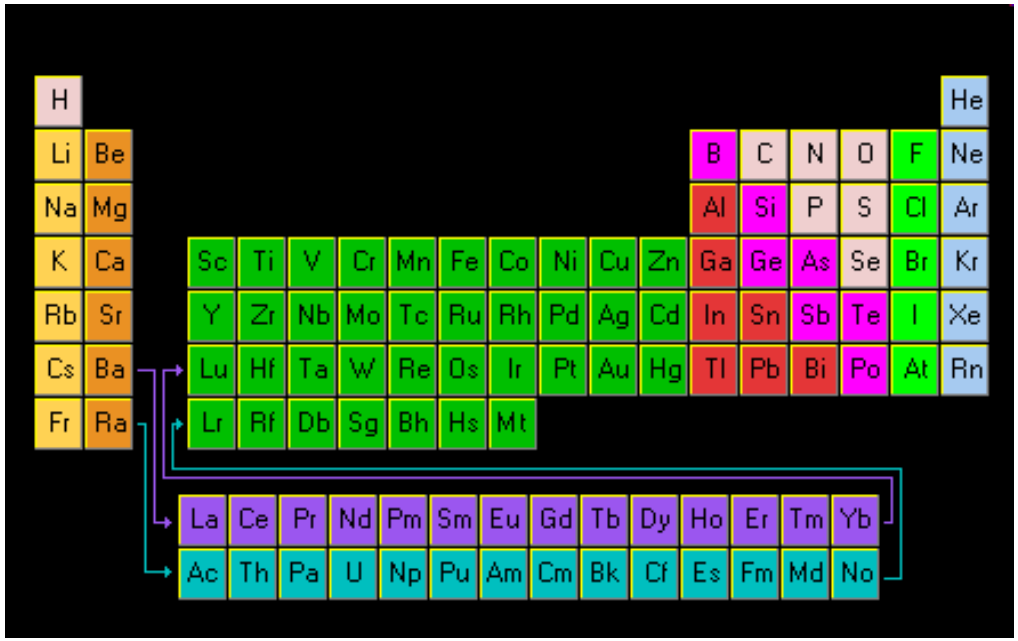
Otkriće neutrona (Chadwick, 1932)

Neutron: Neutralna čestica sa masom kao proton

Elementarne čestice 1932 g.:

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

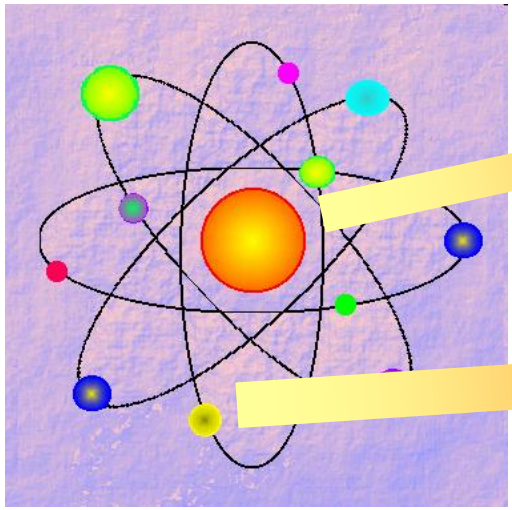


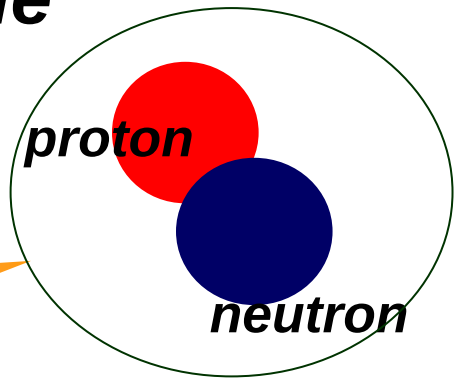


?

Periodic Table

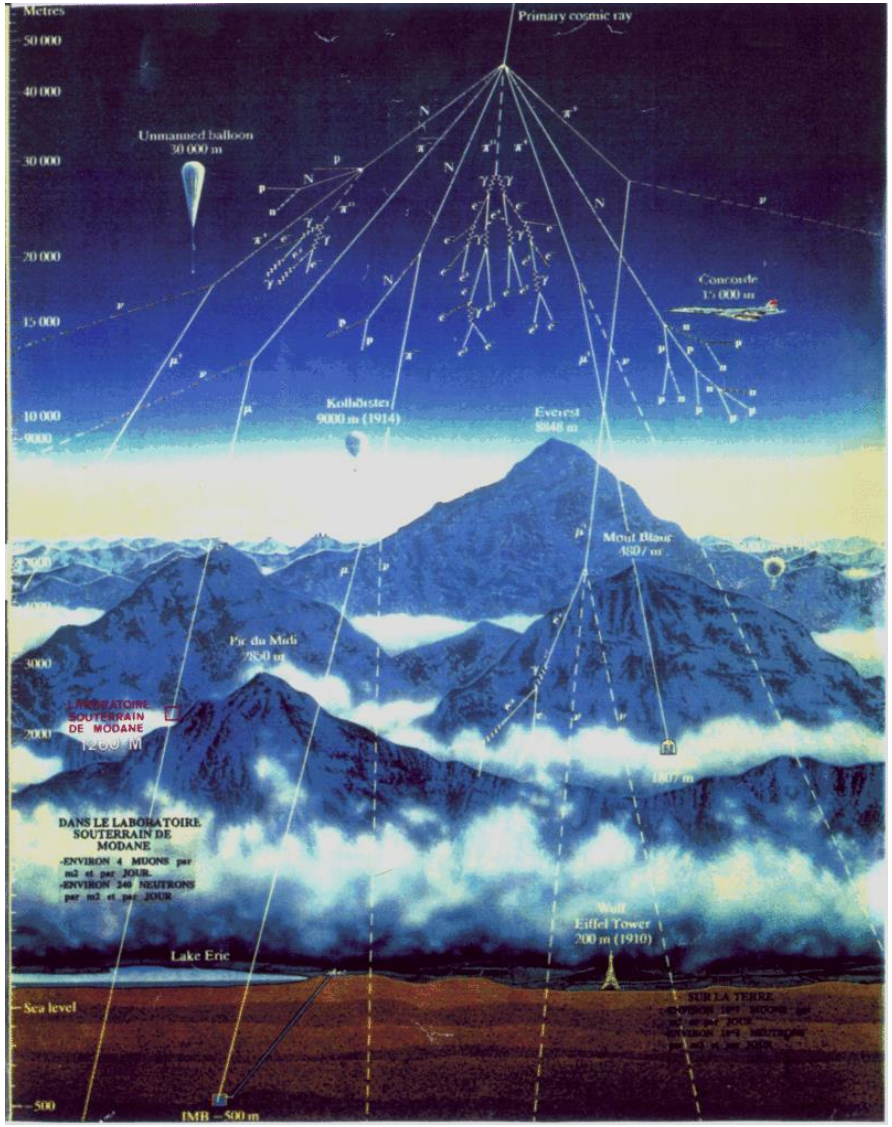
Atom





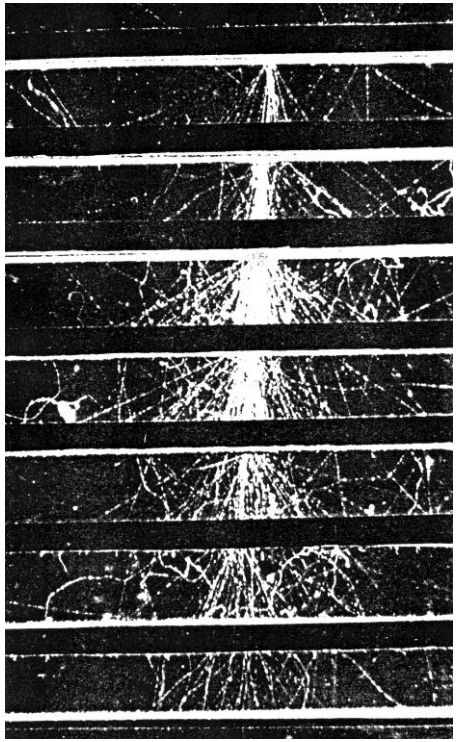
electron

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?”)

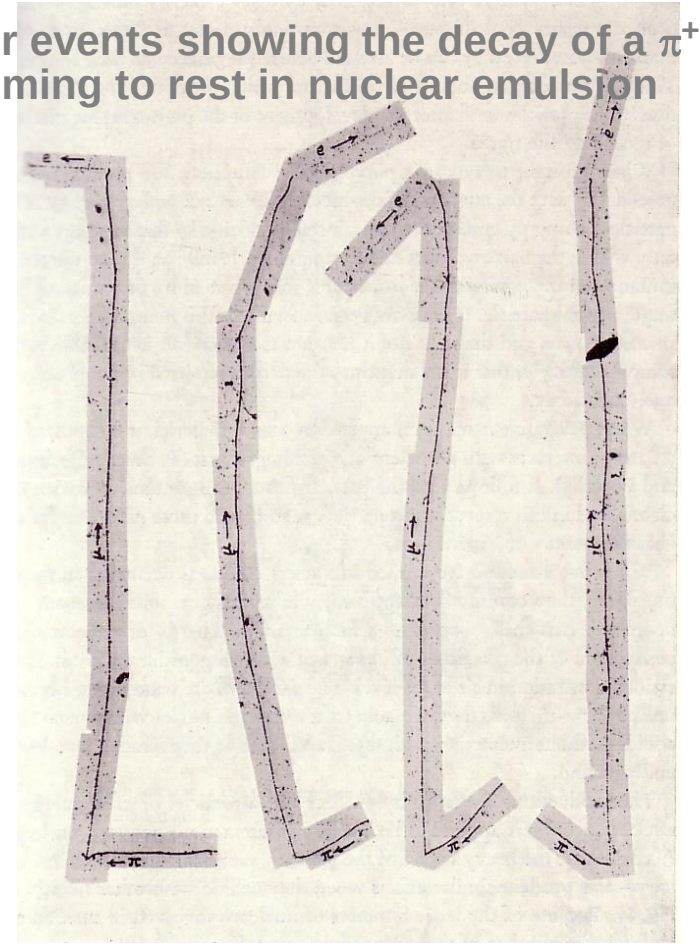
– Teški elektron

π

– Iz sudara zračenja sa jezgrama

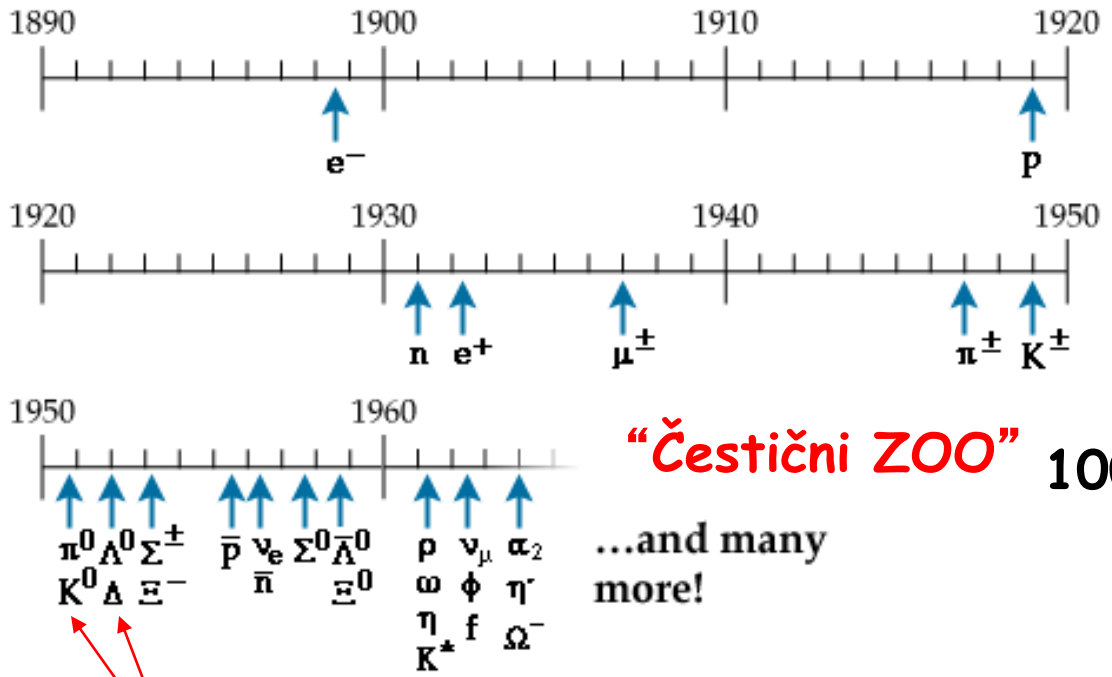
$\pi^+ \rightarrow \mu^+ \nu_\mu$; $\pi^- \rightarrow \mu^- \nu_\mu$

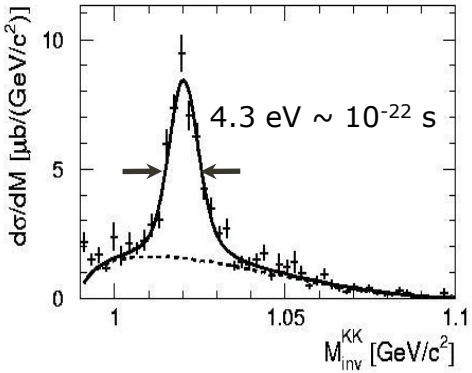
Four events showing the decay of a π^+ coming to rest in nuclear emulsion



… sve više i više

~ 1950-1960: puno novih čestica otkrivene u kosmičkom 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?

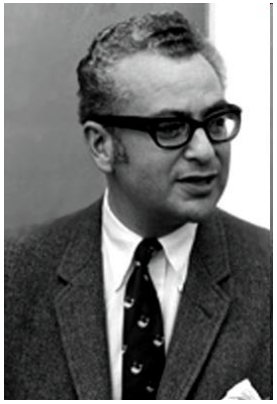
1964 (Gell-Mann, Zweig): Hadroni bi mogli biti građeni od 3 elementarnih čestica:

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

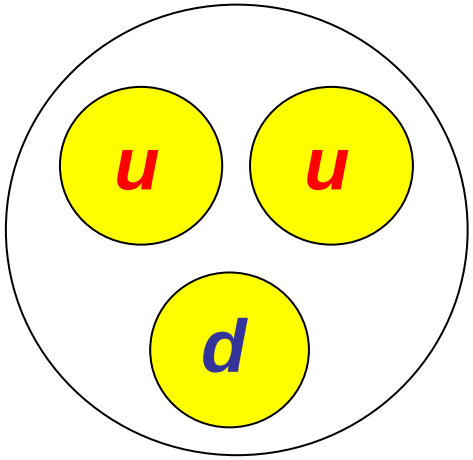
1964 se predlaže ideja **kvarkova**



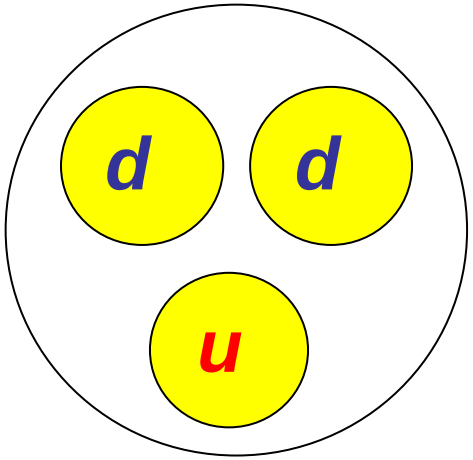
Gell-Mann

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

Nekoliko poznatih mezona

u $\bar{u}$ — +2/3 e, -2/3 e — π^0

u $\bar{d}$ — +2/3 e, +1/3 e — π^+

d $\bar{u}$ — -1/3 e, -2/3 e — π^-

u $\bar{s}$ — +2/3 e, +1/3 e — K^+

Barioni:

3 kvarka ili

3 antikvarka

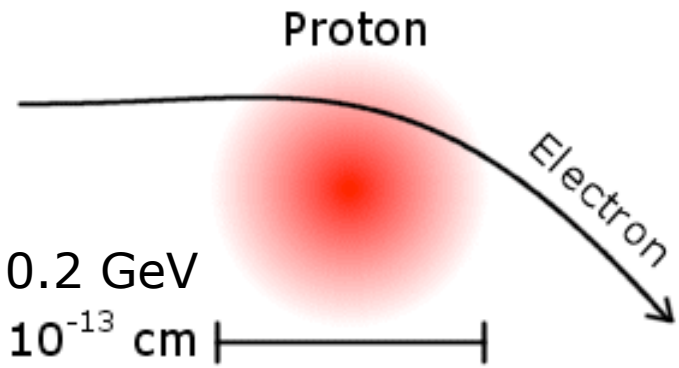
u d s — +2/3 e, -1/3 e, -1/3 e — Λ

$\bar{u}$ $\bar{d}$ $\bar{s}$ — -2/3 e, +1/3 e, +1/3 e — $\bar{\Lambda}$

Kvarkovi postoje!

Otkriće kvarkova

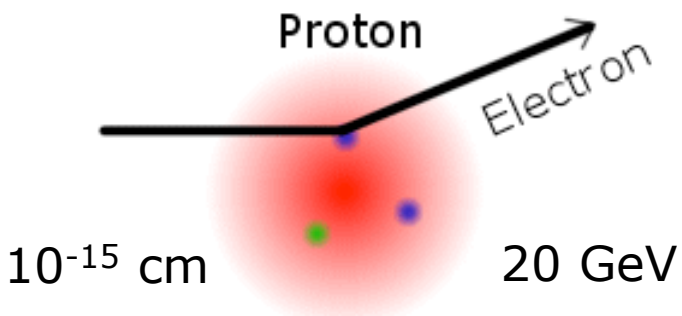
Raspršenje elektrona na protone



1956 Hofstadter: Mjerenje radiusa protona

Stanford Linear Accelerator Centre

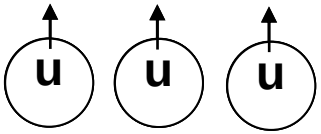
1967 Friedmann, Kendall, Taylor (SLAC): ~ Rutherford eksperiment s elektronima --> u protonu se nalaze 3 'tvrda' (točkasta) centra raspršenja

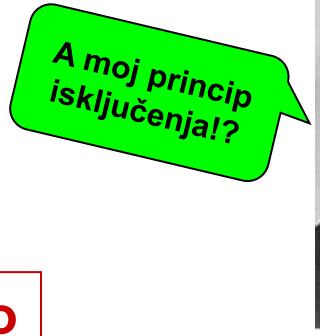


Mjerenja u skladu s prisutnošću 2 up- 1 down-Kvarka u protonu

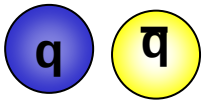
Jaka sila vidi... BOJU!

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





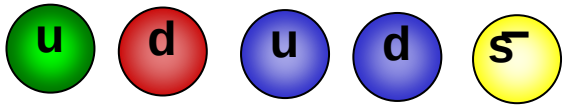
Slaganje boja u nešto bezbojno



→ **Mezoni**

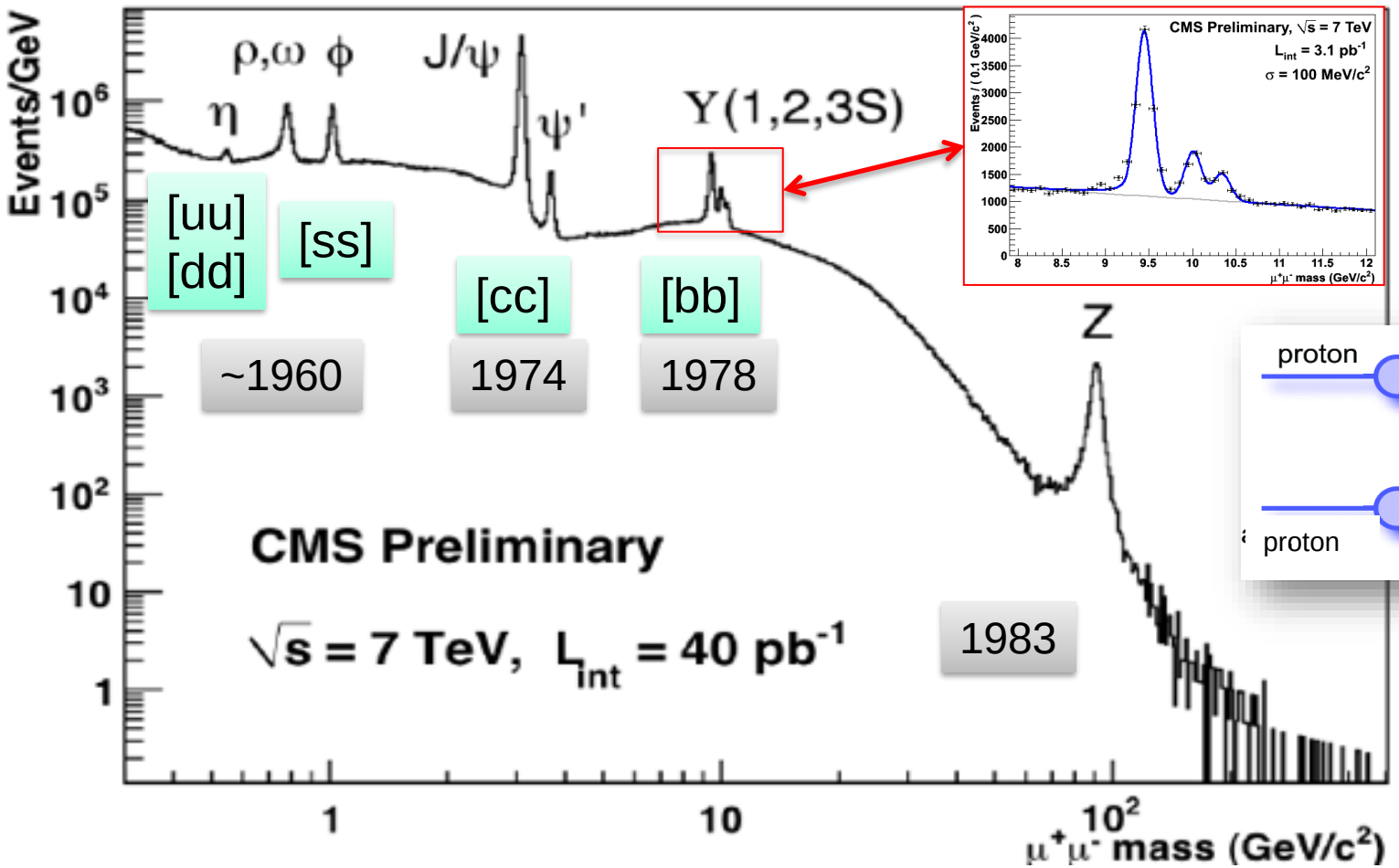
→ **Barioni**

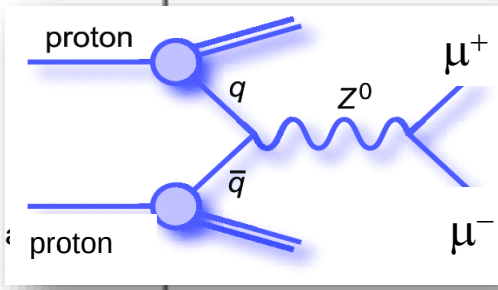
→ **Anti-barioni**



→ **Egzotični barion**

Nove rezonancije: novi kvarkovi!





40 pb^{-1} collected in 2010

V. Brigljević

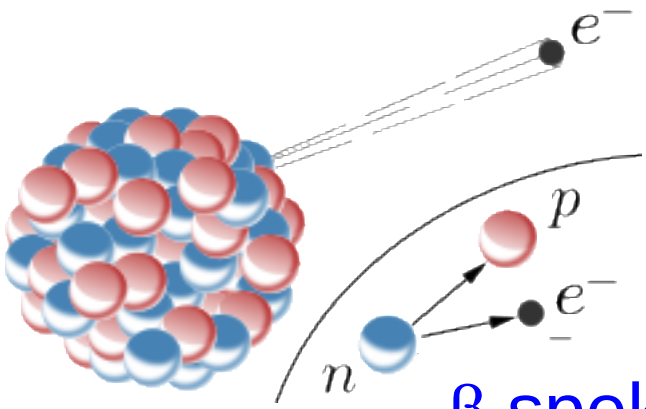
Enigma β raspada

Neke jezgre se raspadaju putem β raspada, npr.

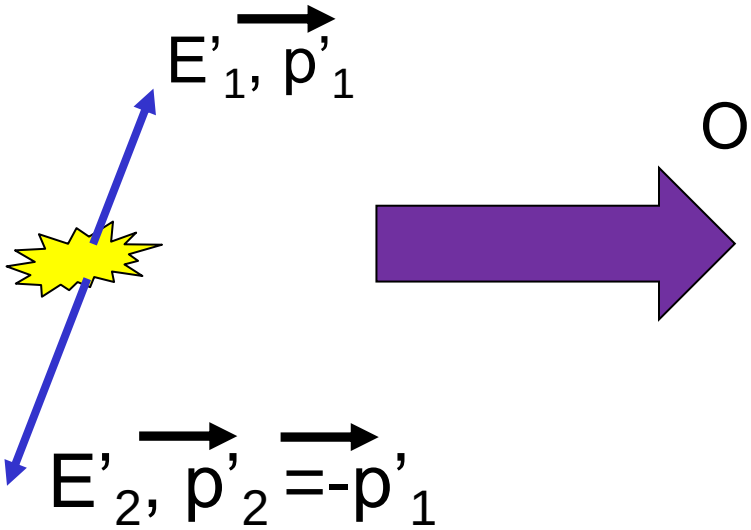
$$^{14}_{6}C \rightarrow ^{14}_{7}N + e^{-}$$

SPIN: 0 1 1/2

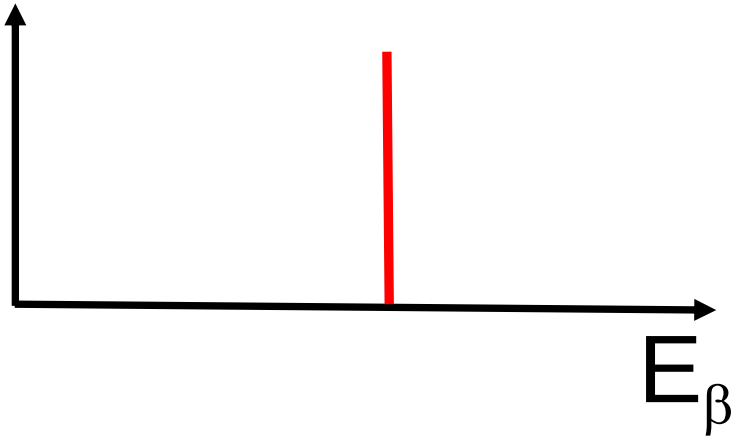
Očuvanje kutne Količine gibanja????



β spektrum ?



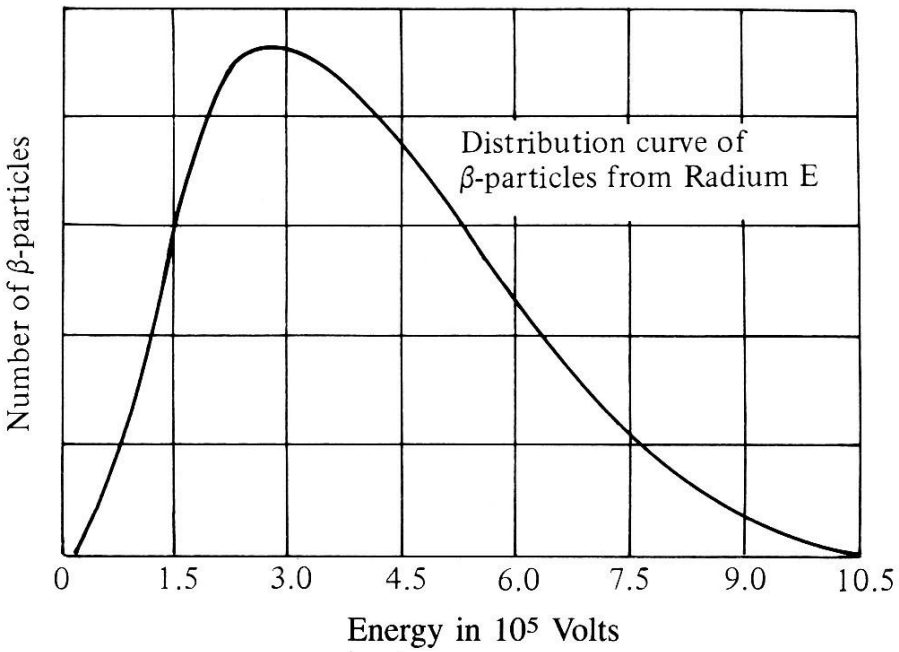
Očekujemo monokromatični spektar



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

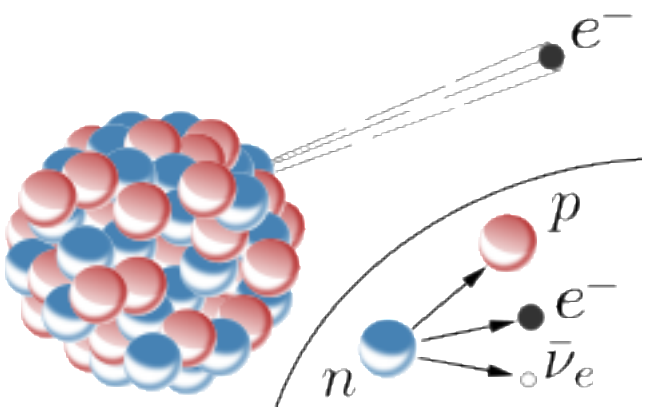
Rješenje problema β raspada: Nova čestica = Neutrino!

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

Neutrini postoje!

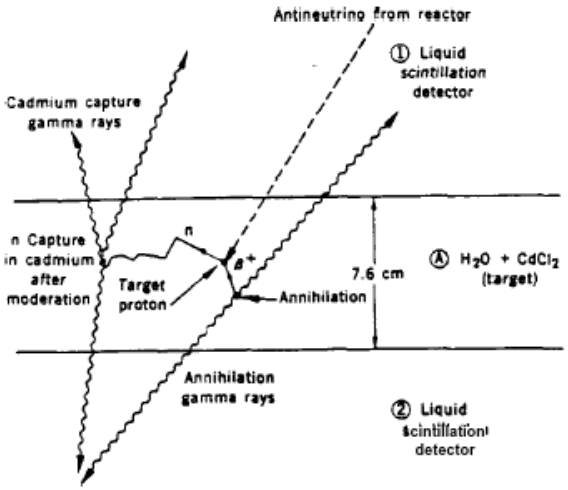
ν_e

ν_μ

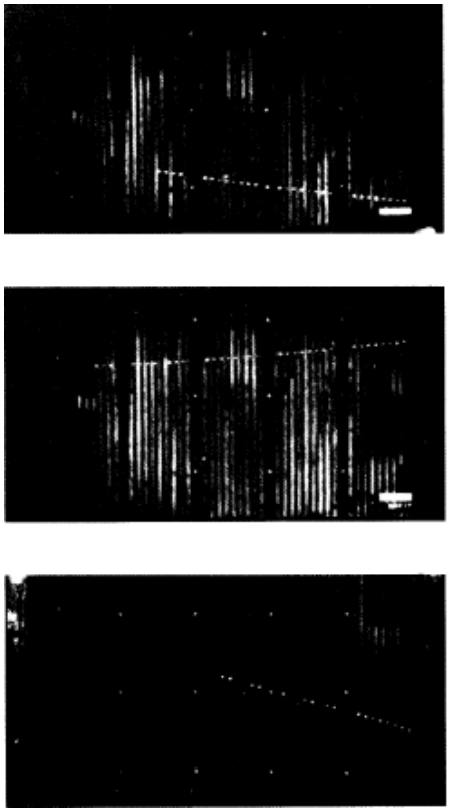
ν_τ

(Reines, Cowan 1953)

$\bar{\nu} + p \rightarrow e^+ + n$



(1962)

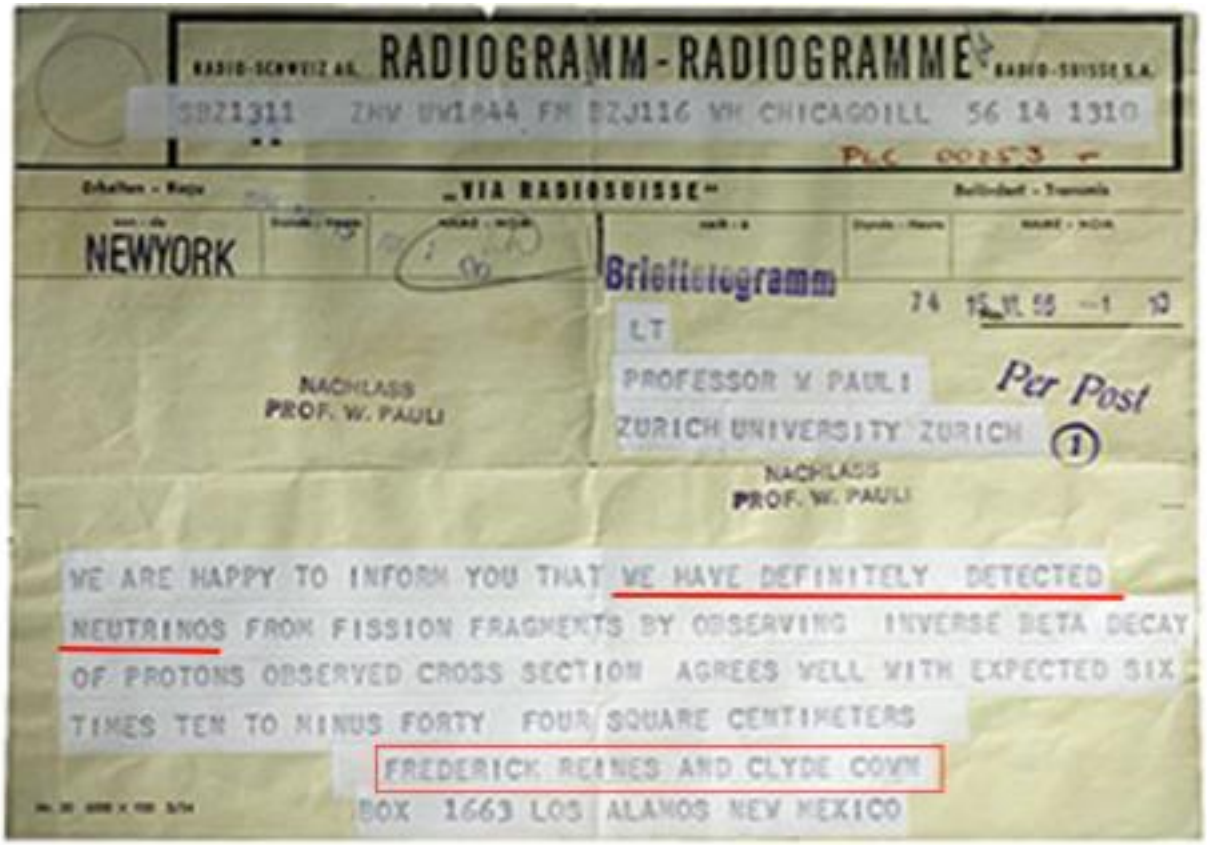


(2000)

Three typical single-track events in the BNL neutrino experiment

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)



RADIO-SCHWEIZ AG. RADIOGRAMM-RADIOGRAMME RADIO-SUISSE S.A.

SBZ1311 ZKV UW1P44 FM BZJ116 WH CHICAGOILL 56 14 1310

PLC 00153

„VIA RADIOSUISSE"

NEWYORK

Brieftelegramm

74 15.11.56 -1 10

LT

PROFESSOR W PAULI

ZURICH UNIVERSITY ZURICH

Per Post

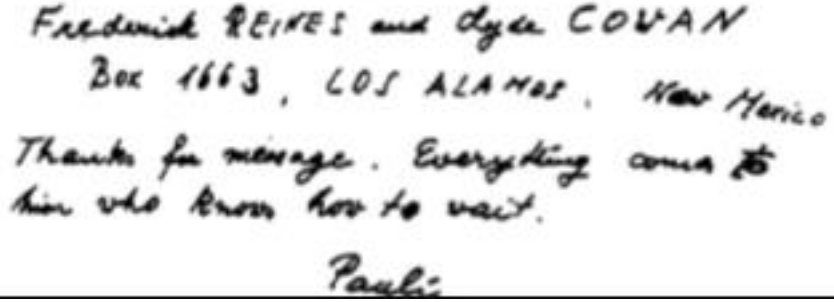
NACHLASS PROF. W. PAULI

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 COWAN

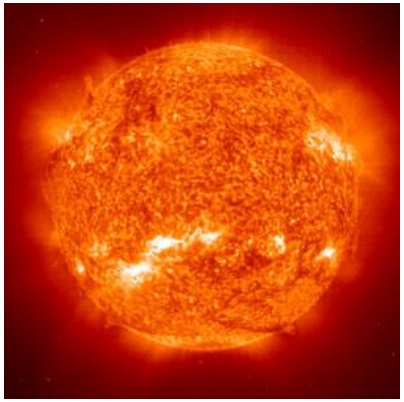
BOX 1663 LOS ALAMOS NEW MEXICO

Pauli :

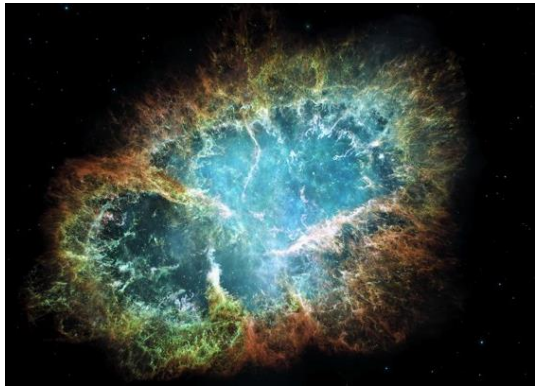


Frederick REINES and Clyde COWAN
Box 1663, LOS ALAMOS, New Mexico
Thanks for message. Everything comes to him who knows how to wait.
Pauli

Neutrini pluštaju sa svih strana



Sunce: 64 milijardi po cm^2 po sekundi



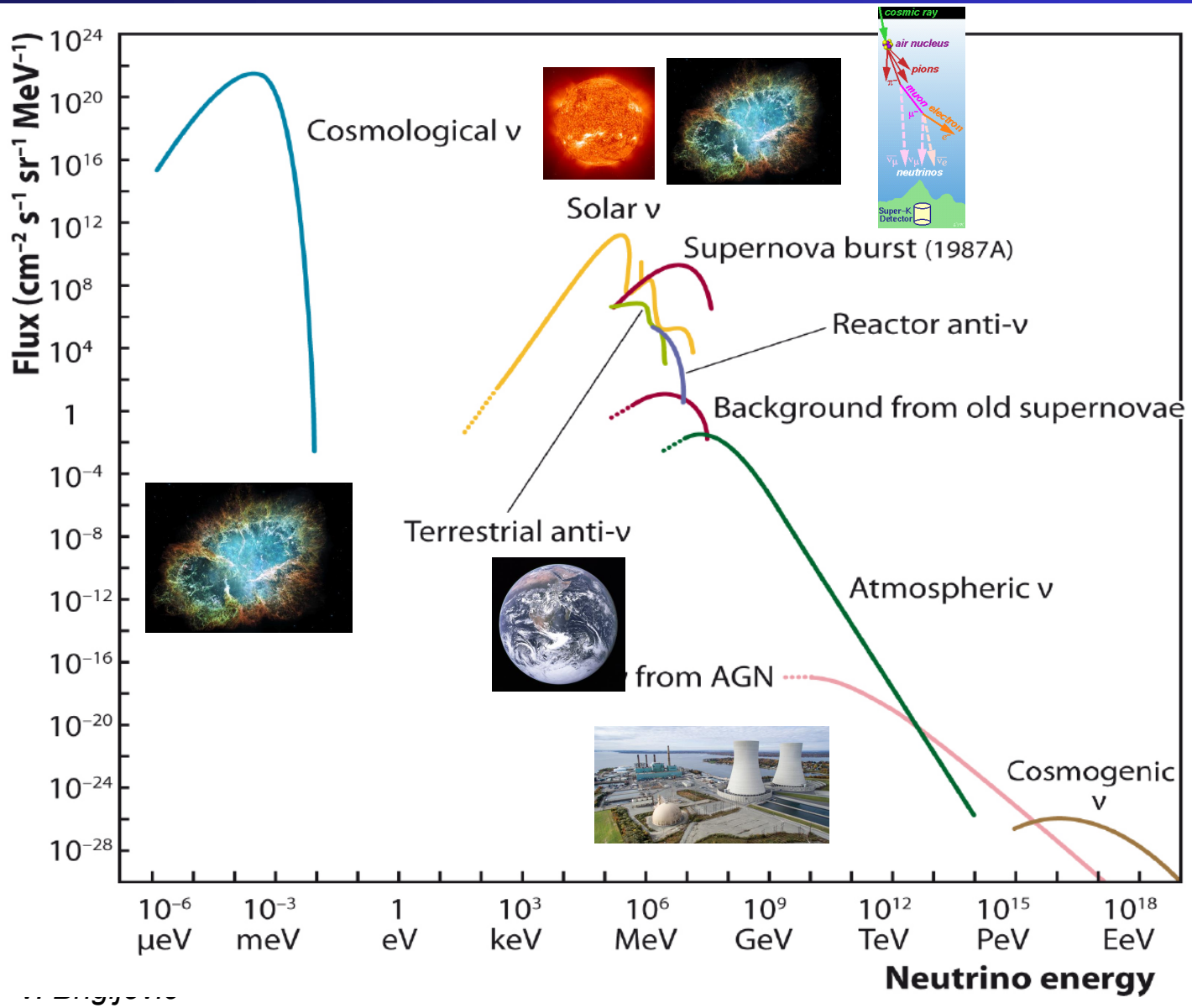
Supernova iz naše galaksije: 5 milijardi po cm^2 svake sekunde kroz 10 sekundi

Veliki prasak:
U svakom cm^3 oko 300 neutrina

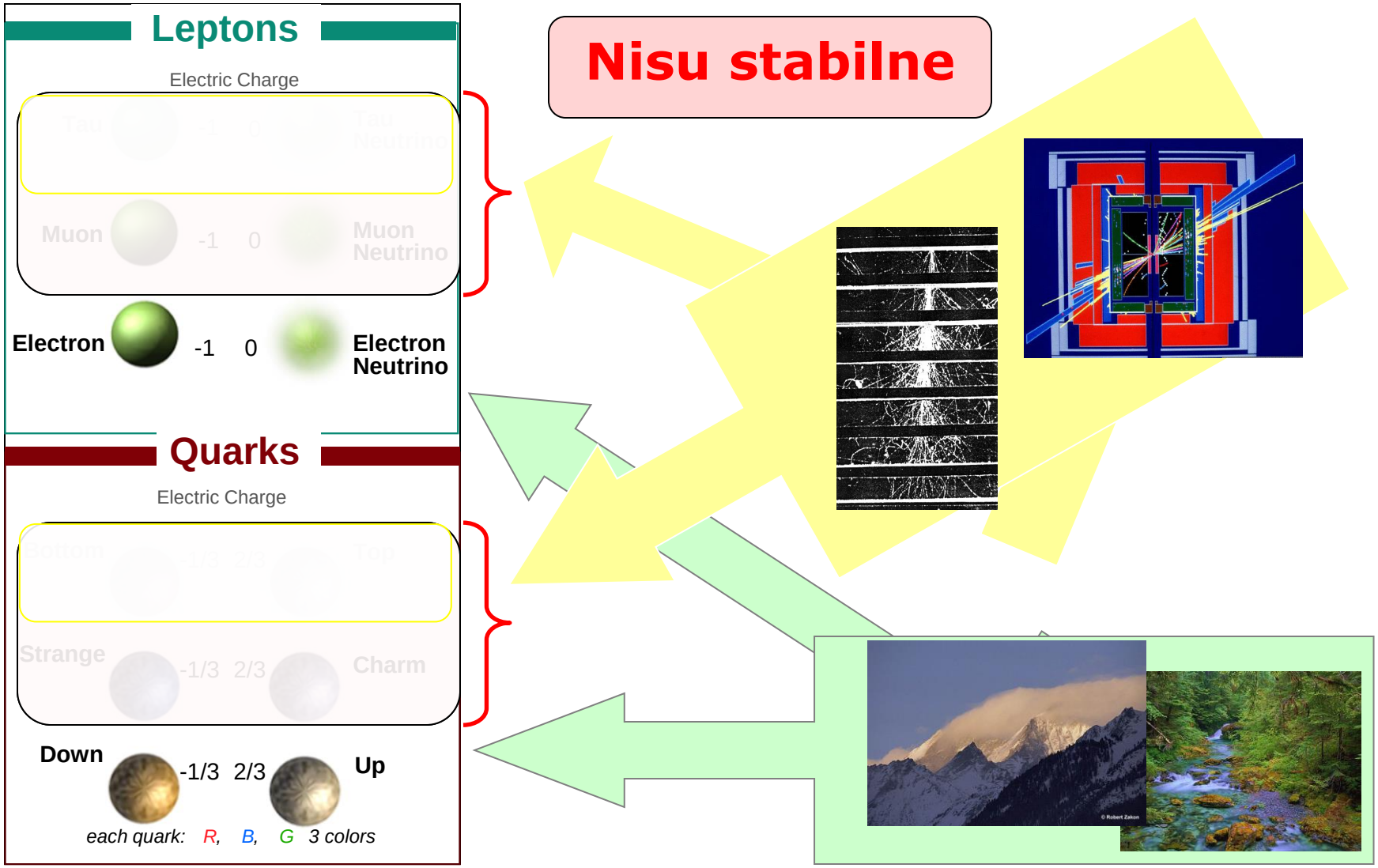
Nuklearke:
Oko 100,000 po cm^2 svake sekunde na 200km od centrale

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

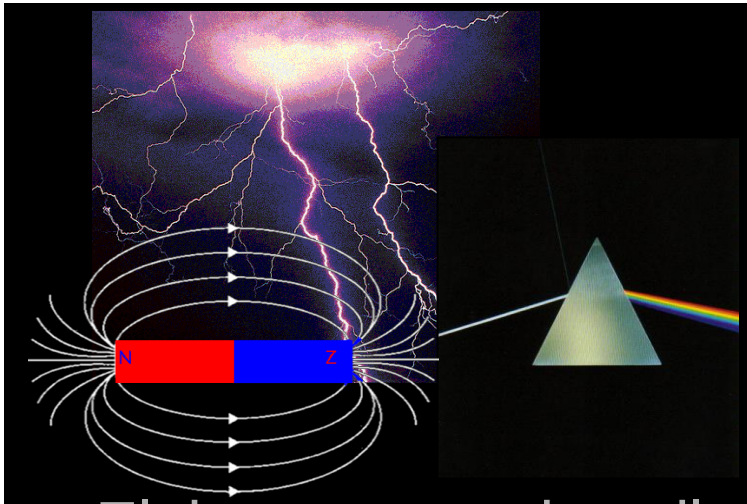
Spektar neutrina



Elementarne čestice, 2019

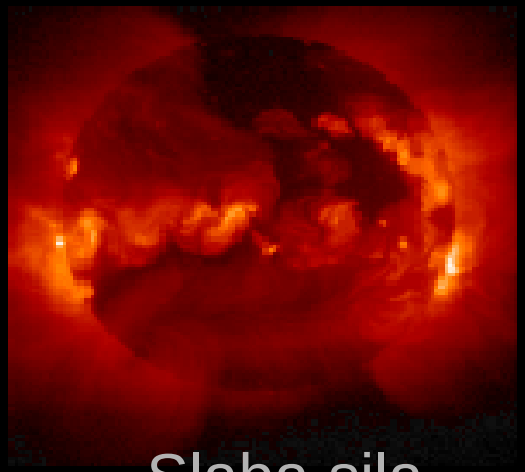


4 temeljne sile

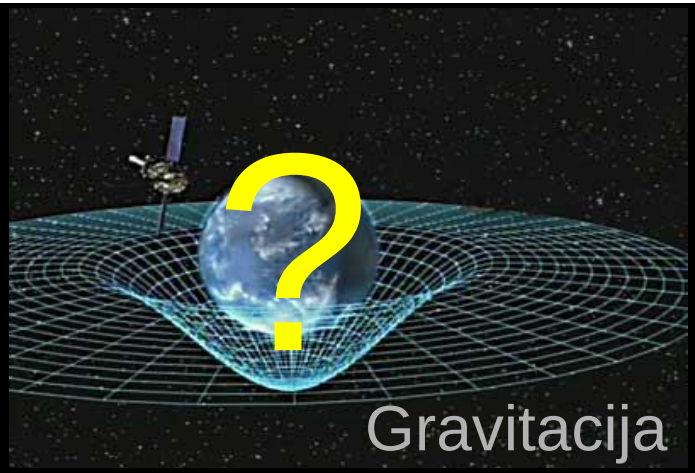


Elektromagnetska sila

Jaka sila

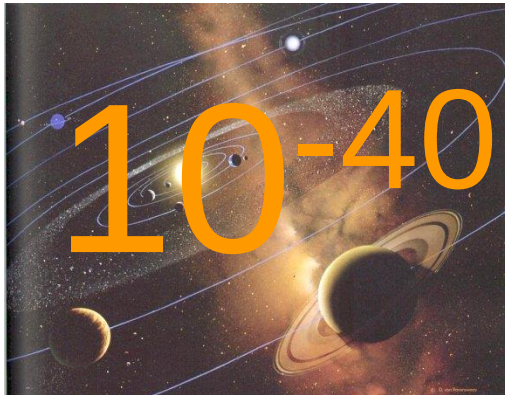


Slaba sila

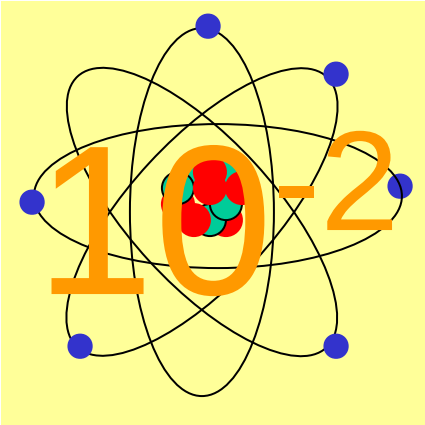


Gravitacija

Jačine sila

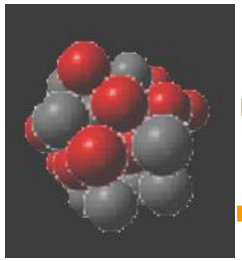


Gravitacijska sila

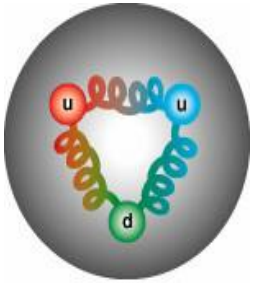


atom

Elektromagnetska sila

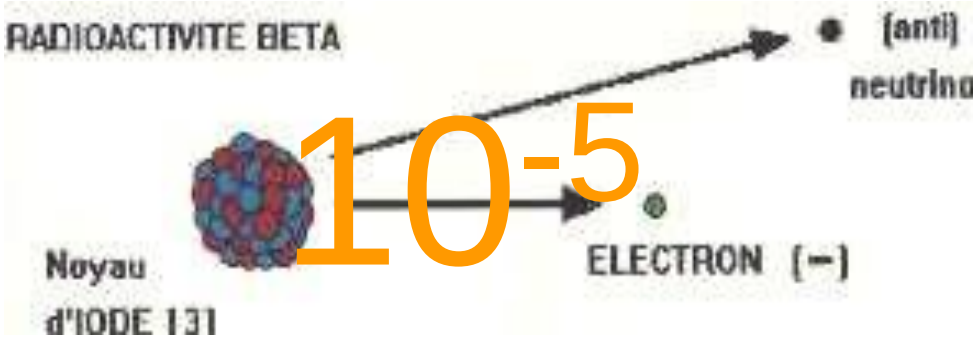


1



jezgra

Jaka nuklearna sila



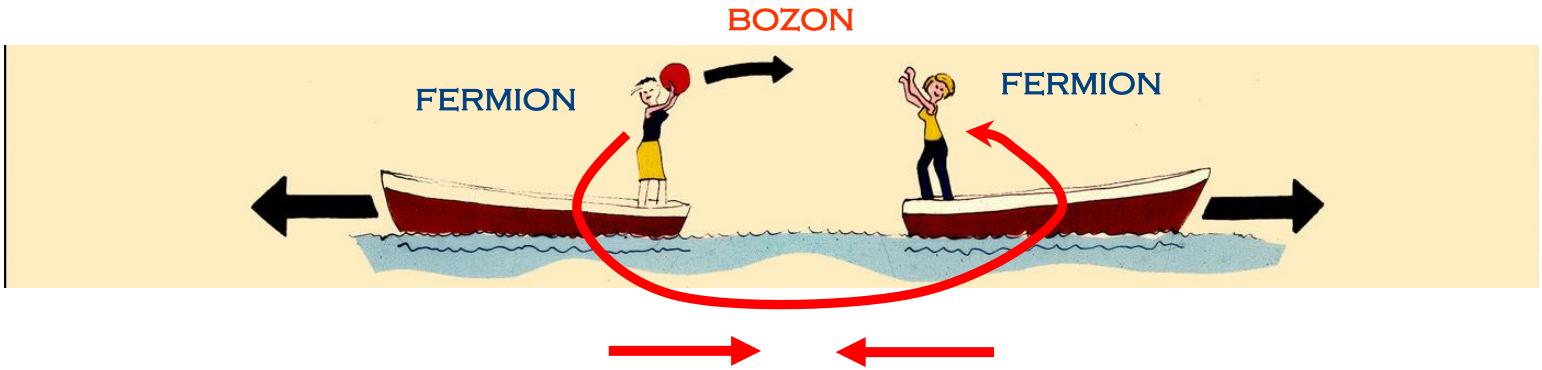
$n \rightarrow p + e^- + \nu_e$

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

Slaba sila

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

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 ćestica može proći R = c Δt

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

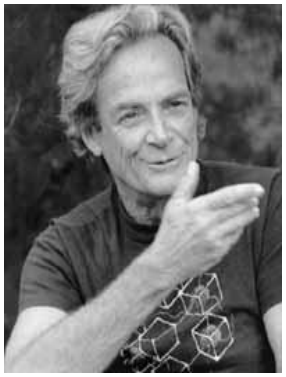
Npr.:

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

Kvantna elektrodinamika

Kvantizirana elektromagnetska polja: Foton

Brzina c: masa = 0



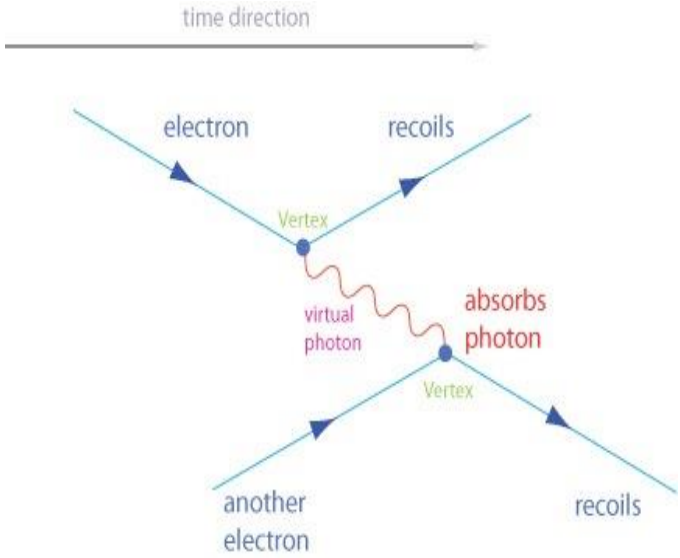
R. P. Feynman

Elektromagnetske interakcije

=

Emisija i apsorpcija fotona

Električni naboj očuvan!



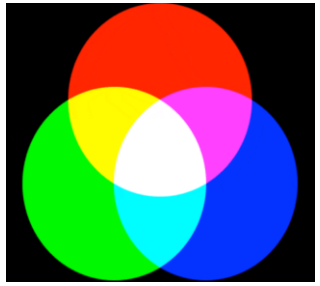
Feynmanovi diagrami

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

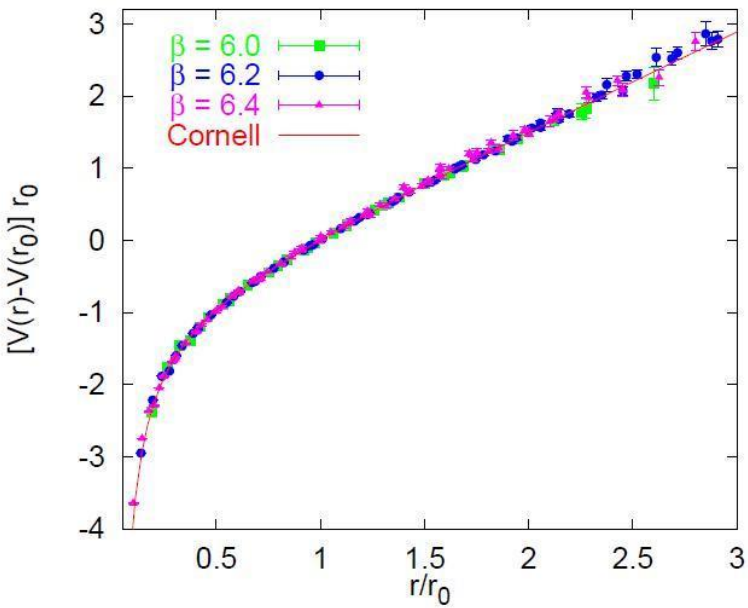
Nema slobodnog kvarka: "Confinement"

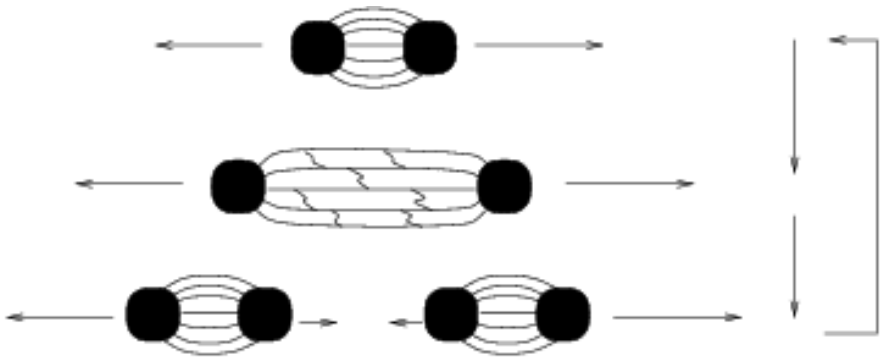
Zbog QCD potencijala:

isplativije energički izvući iz vakuuma

par kvark-antikvark

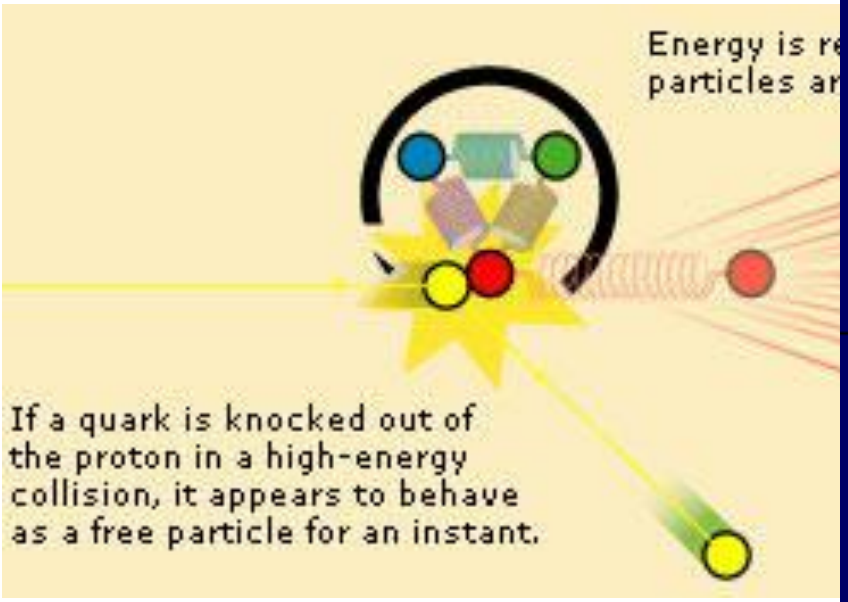
za stoviriti bezbojne hadrone

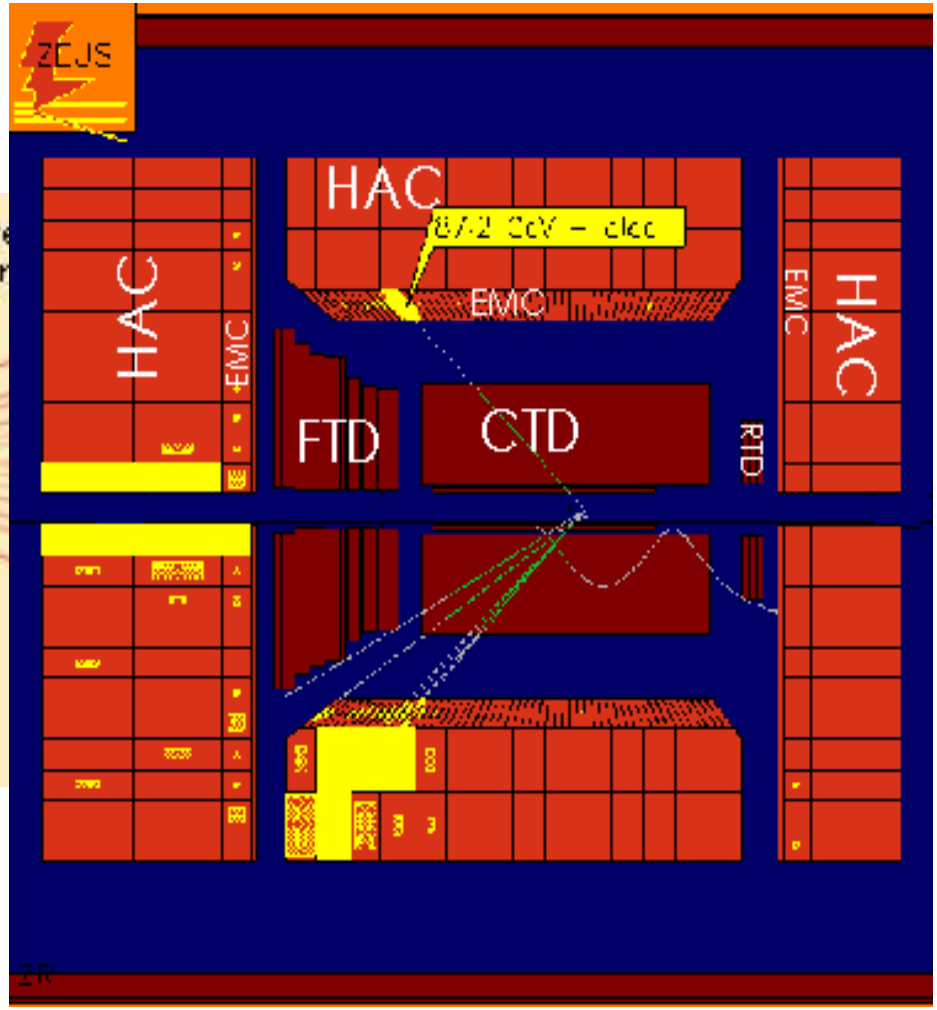




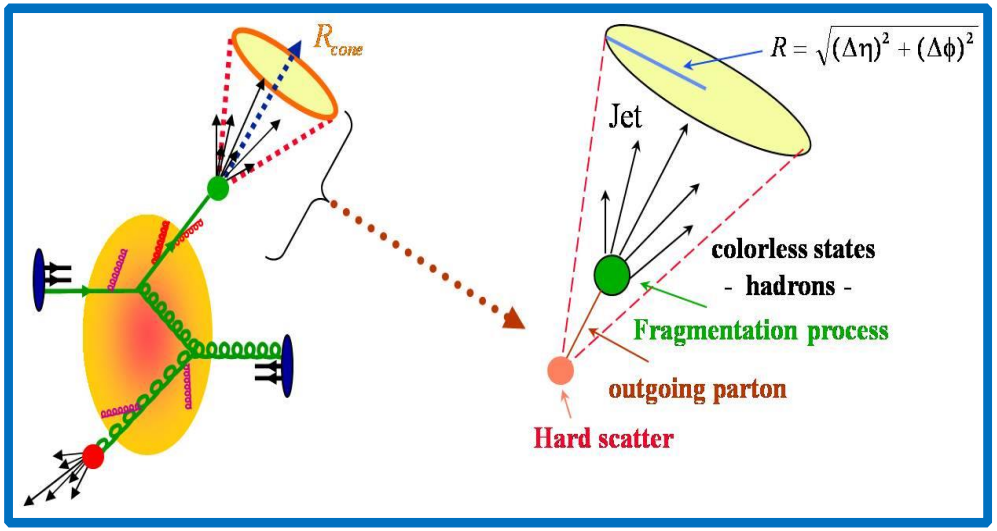
Posljedica:
Hadronski mlaz
"Jet"

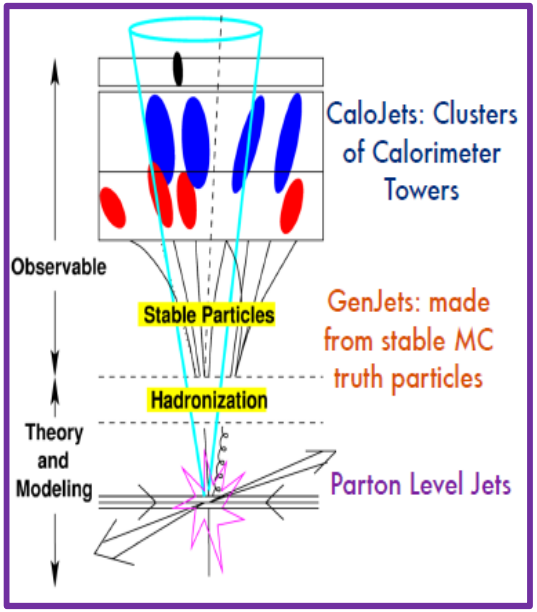
Jets (hadronski mlazovi)

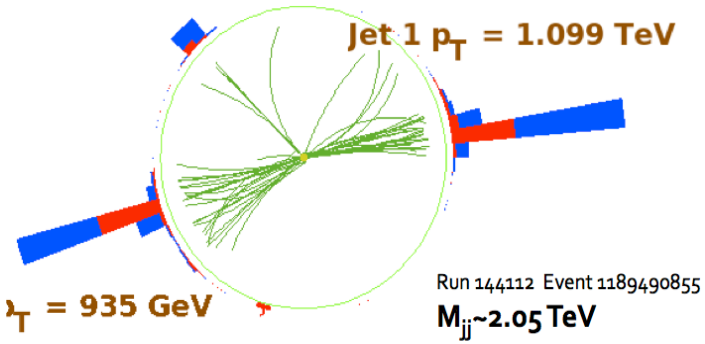




Kvarkovi - Jets

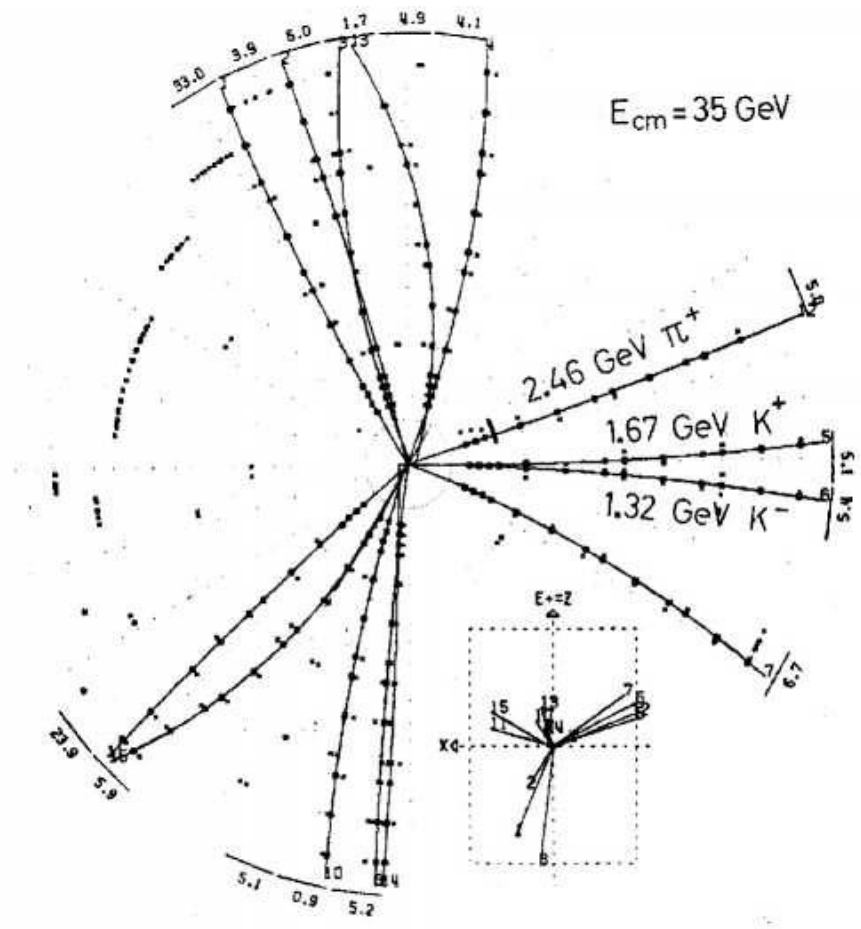


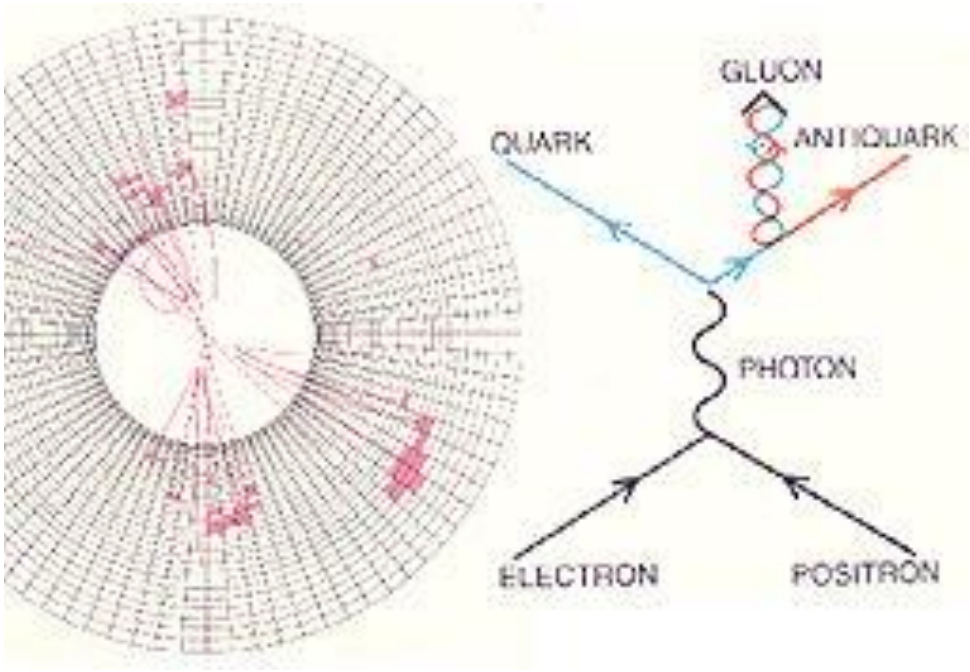




QCD: Gluoni

Otkriće gluona **(DESY, 1979)**





PETRA Storage Ring, 1979, DESY (Hamburg)

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

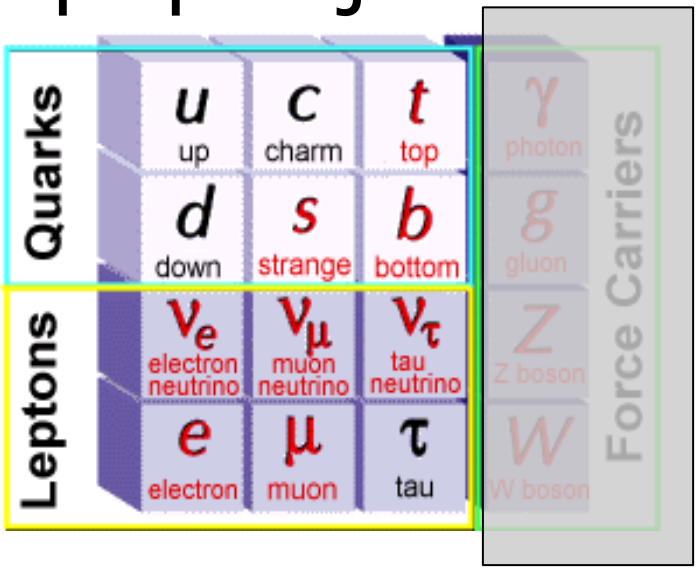
Činjenica: barionski broj je očuvan u svim poznatim reakcijama

= Zbroj kvarkova i antikvarkova je konstantan

Npr. zabranjuje: Raspad protona $\cancel{p \rightarrow e^{+} \pi^{0}}$

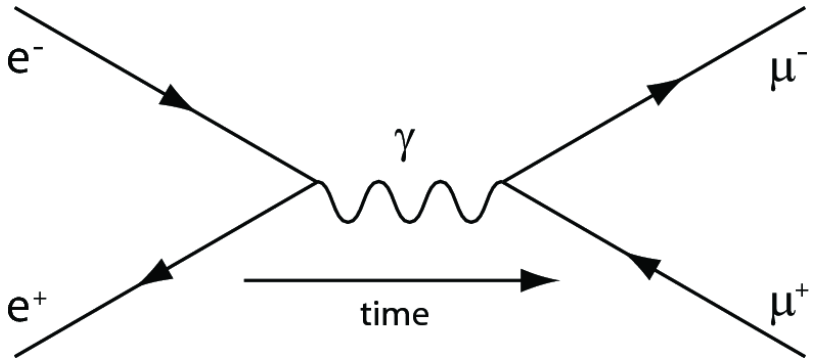
Očuvano (?) svojstvo: "Okus"

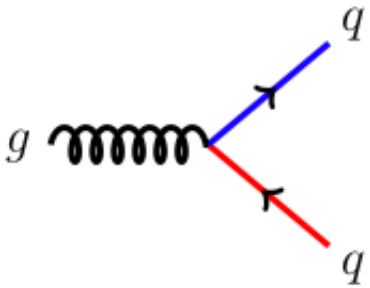
- Svakoj vrsti čestica se pripisuje okus:
  - "u,c,t,d,s,b" okus
  - Antičestica: suprotno

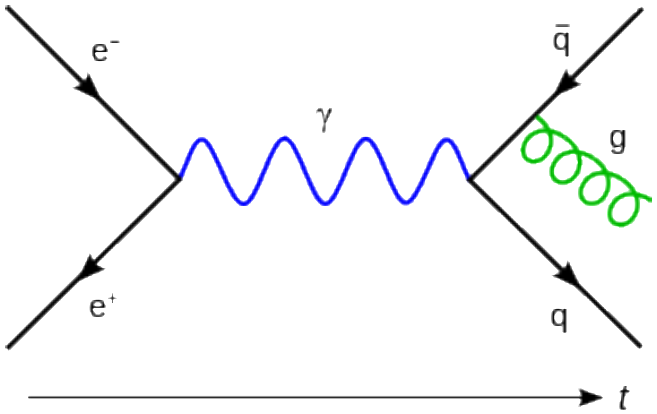


- Okus je očuvan u svim jakim i elektromagnetskim reakcijama:
  - Ako se stvara u-kvark, mora i anti-u

Očuvanje okusa u e.m. i jakim interakcijama



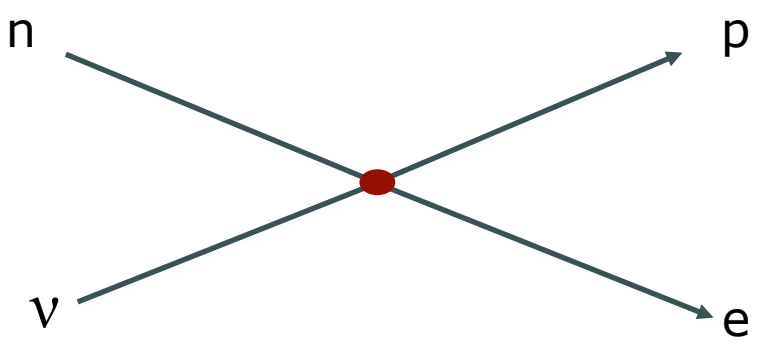




Slaba sila

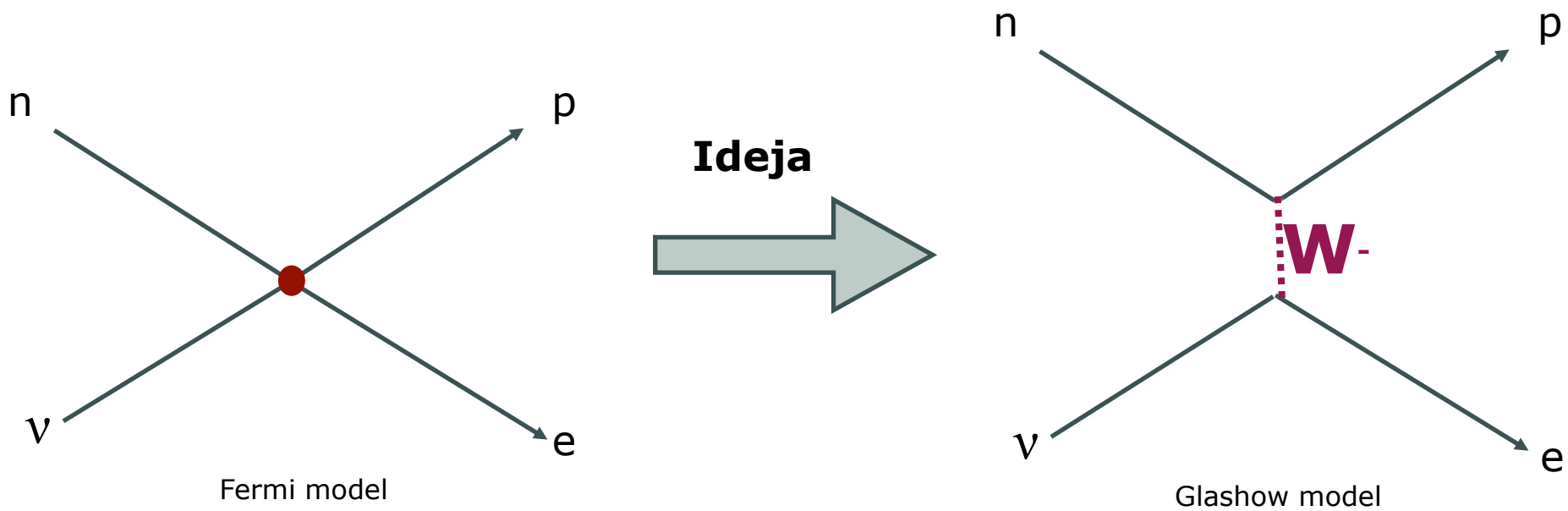
- Druga vrsta sporijih procesa opažena:
  - Radioaktivni raspadi (β raspadi)
  - Interakcija neutrina
  - "Okus" (vrsta) kvarkova nije očuvan

n --> p + e + ν



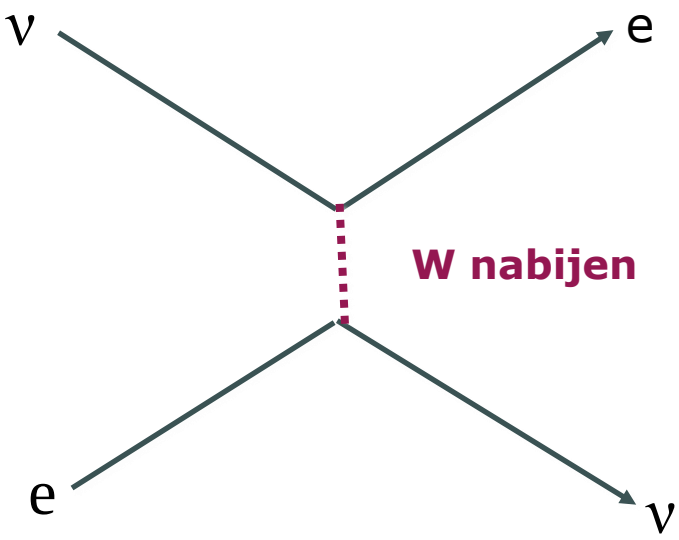
Nosioci slabe sile

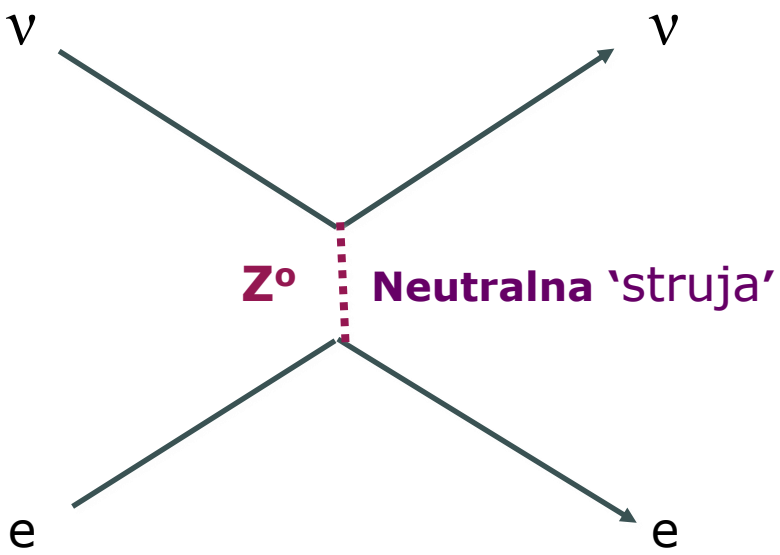
Slabe interakcije se odvijaju putem izmjene teškog bozona



Velika masa (80 GeV) obašnajva krati doseg i malu vjerojatnost Interakcije za slabu silu

Elektroslaba sila





Glashow, Salam, Weinberg (1968)

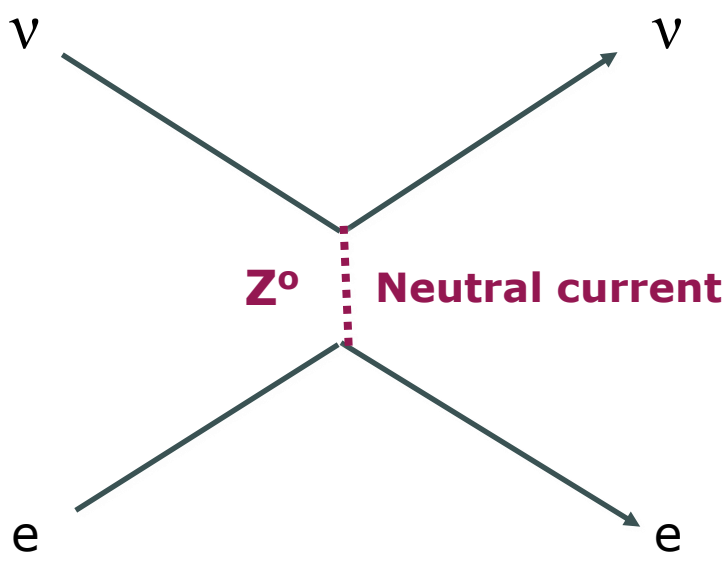
Ujedinjenje elektromagnetse i slabe sile

- e.m. i slaba aila su Aspekti iste "elektroslabe sile"
- I kvarkovi i leptoni imaju naboj salbe sile.
- **W i Z Bozoni dobivaju svoju masu od Higgsovog polja (1964)**

Opažanje elektroslabih interakcija

1973

Otkriće **"neutralnih Struja", CERN (1973)**



Nuclear Physics B73 (1974) 1–22 North-Holland Publishing Company

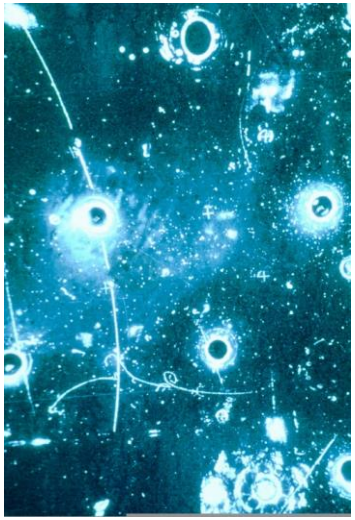
OBSERVATION OF NEUTRINO-LIKE INTERACTIONS WITHOUT MUON OR ELECTRON IN THE GARGAMELLE NEUTRINO EXPERIMENT

F.J. HASERT, S. KABE, W. KRENZ, J. VON KROGH, D. LANSKE, J. MORFIN, K. SCHULTZE and H. WEERTS
III. Physikalisches Institut der Technischen Hochschule, Aachen, Germany

G. BERTRAND-COREMANS, J. SACTON, W. VAN DONINCK and P. VILAIN*
Interuniversity Institute for High Energies, U.L.B., V.U.B., Brussels, Belgium

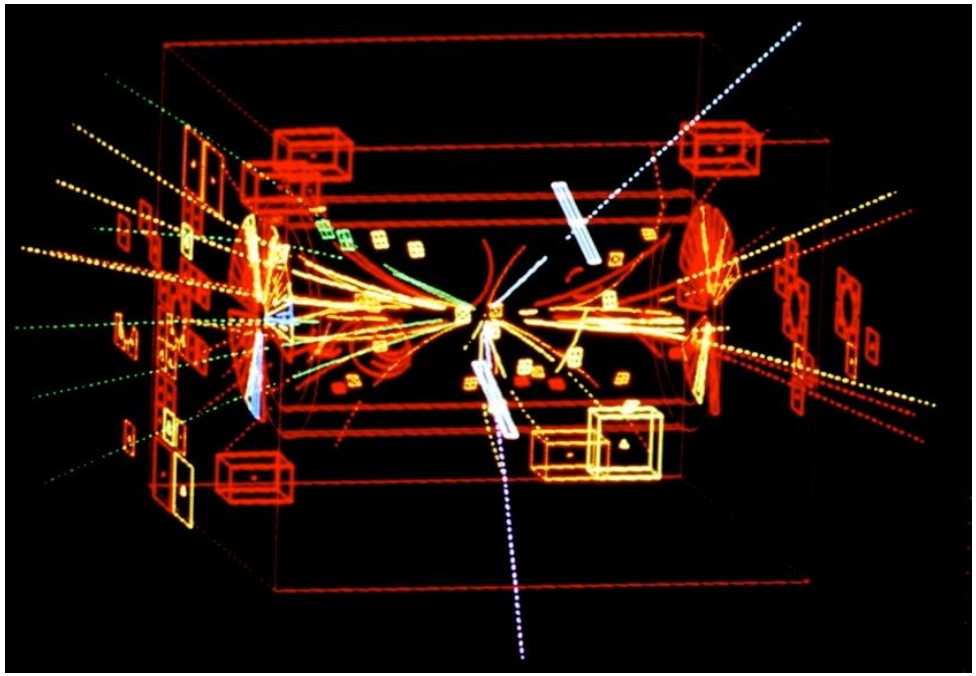
R. BALDI, U. CAMERINI**, D.C. CUNDY, I. DANILCHENKO***, W.F. FRY**, D. HAIDT, S. NATALI‡, P. MUSSET, B. OSCULATI, R. PALMER‡‡, J.B.M. PATTISON, D.H. PERKINS+, A. PULLIA, A. ROUSSET, W. VENUS++ and H. WACHSMUTH
CERN, Geneva, Switzerland

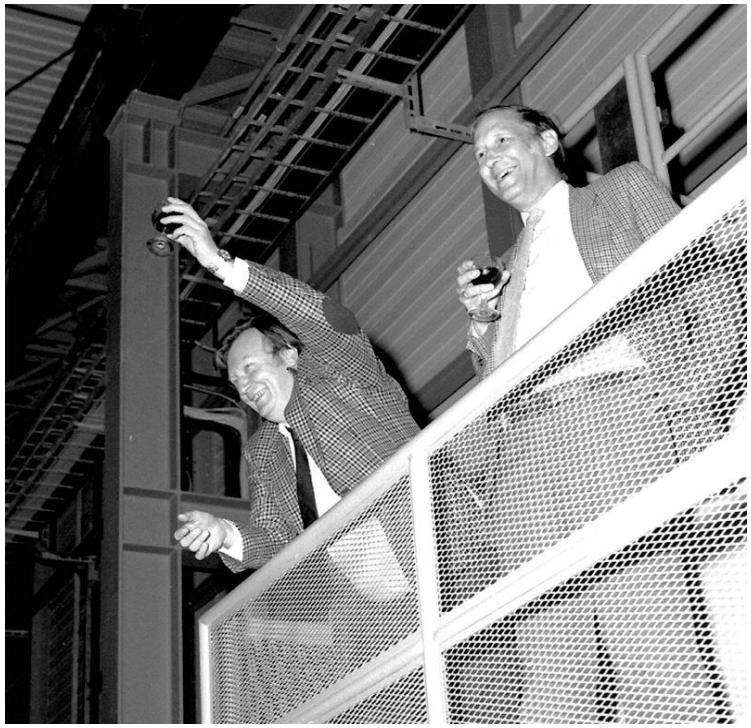
V. BRISSON, B. DEGRANGE, M. HAGUENAUER, L. KLUBERG, U. Nguyen-KHAC and P. PETIAU
Laboratoire de Physique Nucleaire des Hautes Energies, Ecole Polytechnique, Paris France



Otkriće W i Z bozona

CERN (1983)

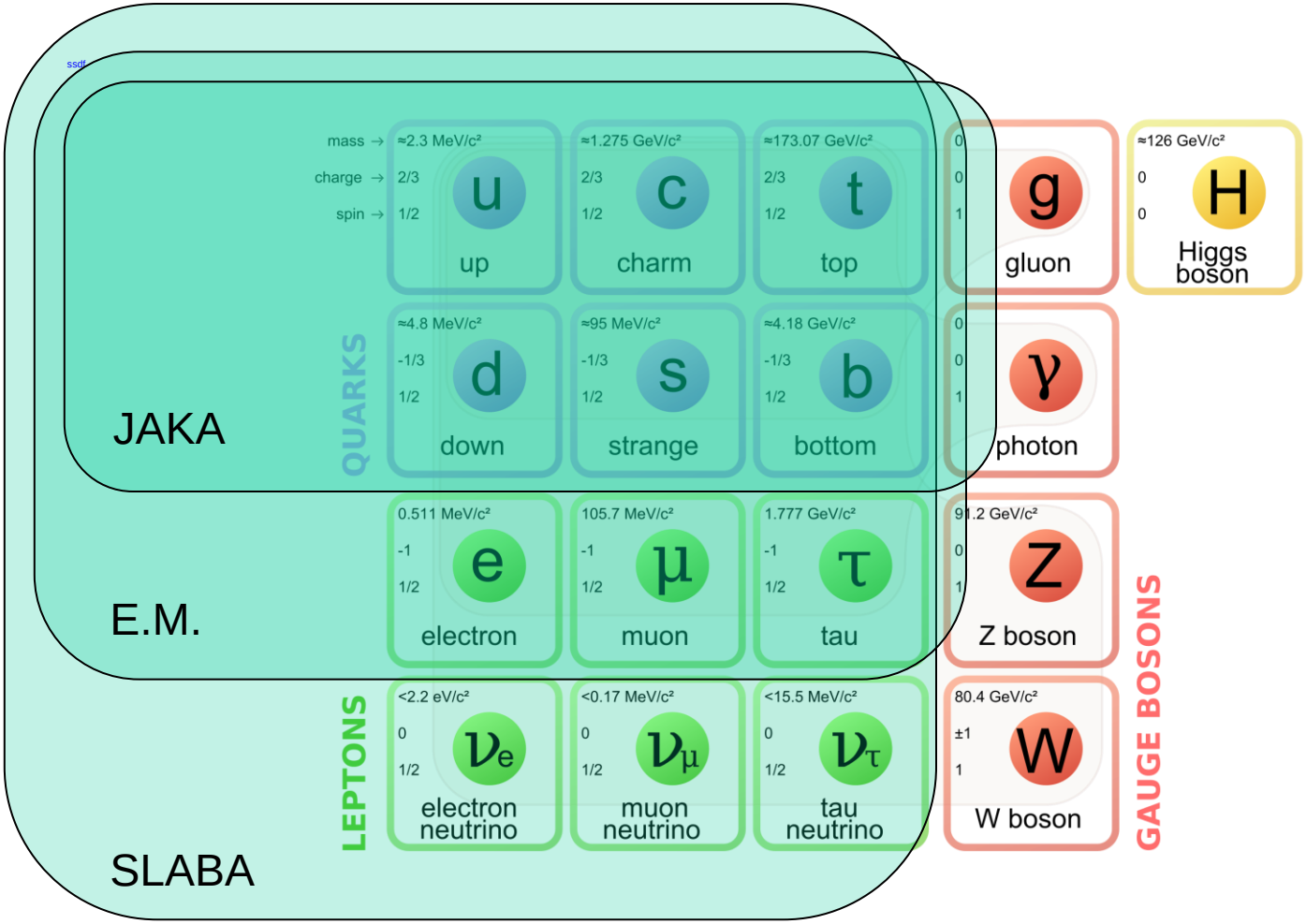




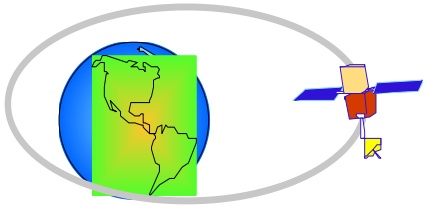
Carlo Rubbia, Simon van der Meer

W kandidat u detektoru UA-1

Čestice Standardnog modela i njihove interakcije



Ujedinjenje sila

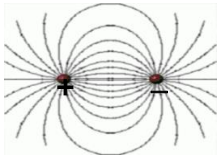


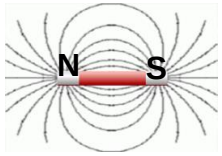
Zemaljska mehanika

Univerzalna gravitacija

Nebeska mehanika

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



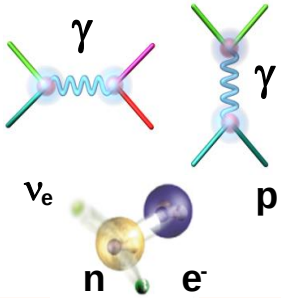


Elektricitet

Elektromagnetizam

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

Magnetizam



Elektromagnetizam

Elektroslaba

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

Slaba sila

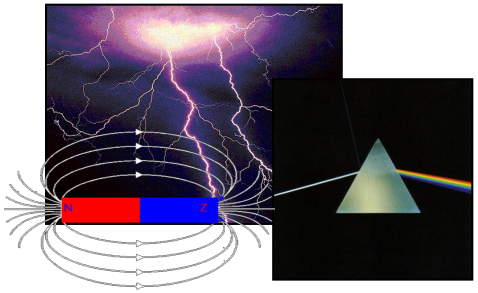
Ispitivanje sve manjih dimeznija
otkriva
dublje pravilnosti

?

UJEDINJENI OPIS

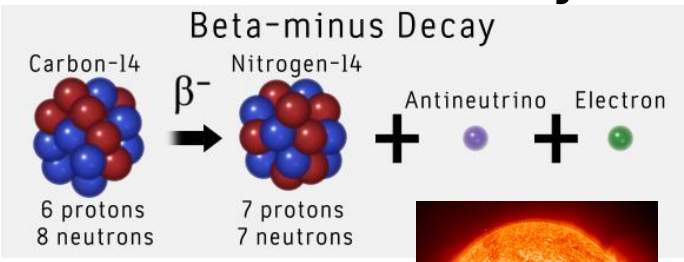
Elektroslabo ujedinjenje

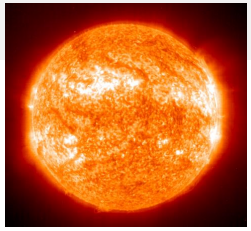
Elektromagnetizam



+

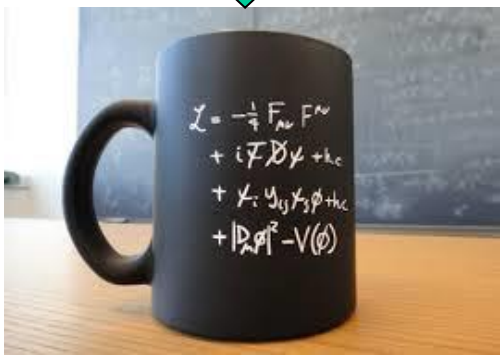
Slabe interakcije





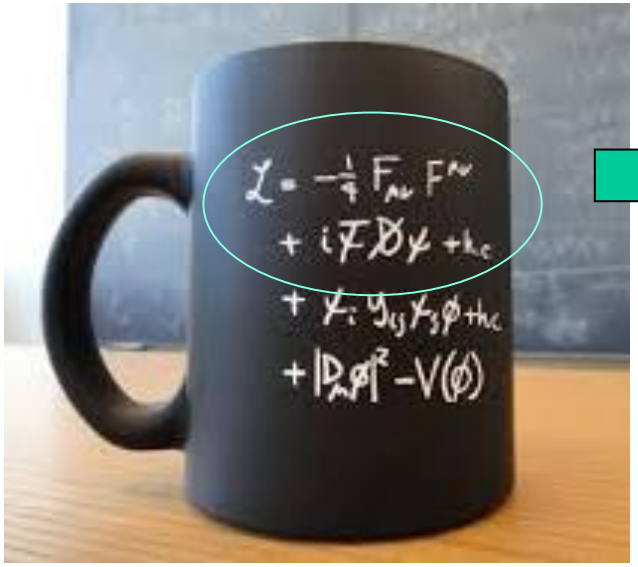
Elektroslaba teorija

- 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

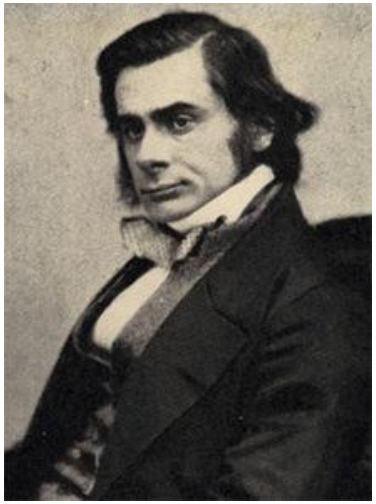
Slaba sila

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."



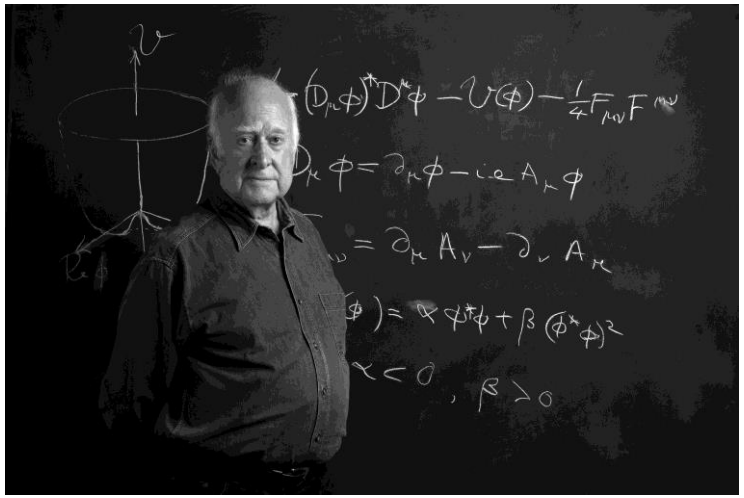
Thomas Henry Huxley

Ideja za spasiti SM

- Inovativne ideje za uvesti mase bozona u SM, tzv. “Higgsov mehanizam” dolaze sa više strana u 60im

  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!

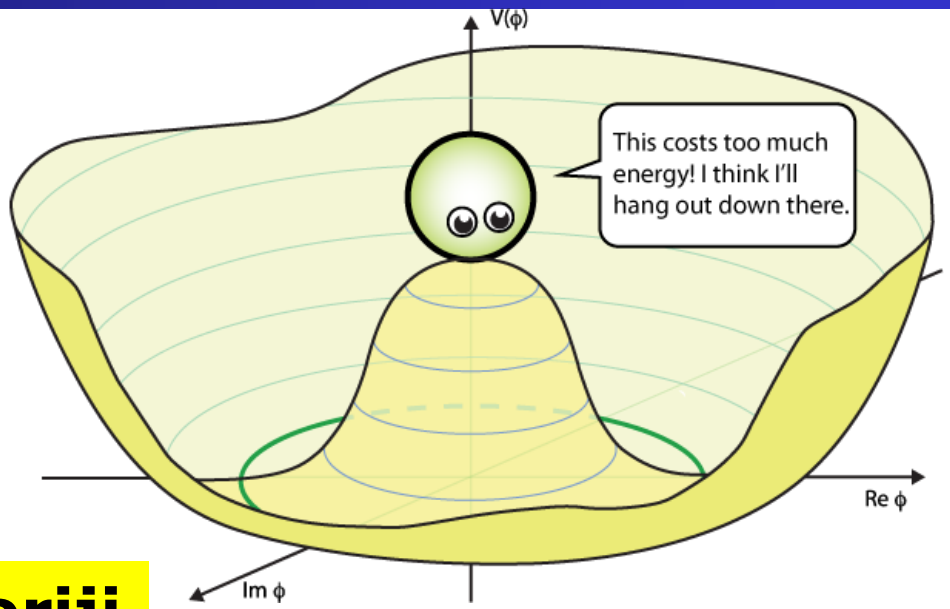
Osnovni postulat
“Higgsovog mehanizma”:

Postoji novo polje, higgsovo polje, koje ispunjava cijeli svemir

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

Higgsov mehanizam

Spontani
lom simetrije

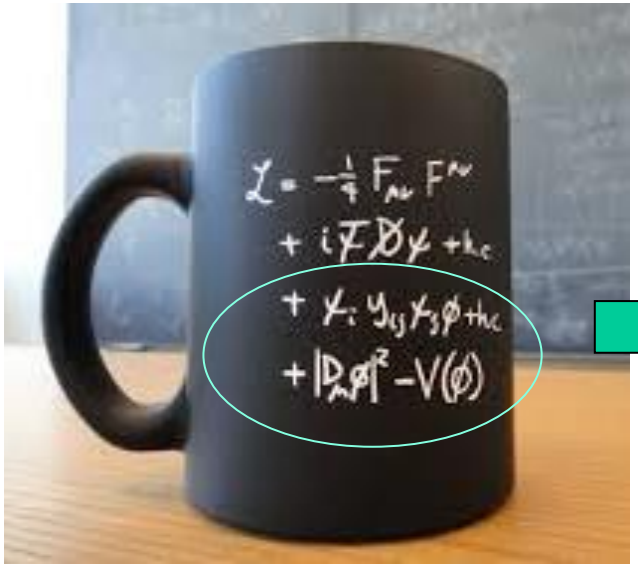


Higgsovo polje u teoriji

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

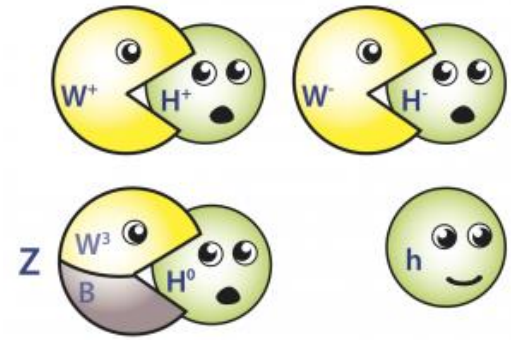
Glashow-Salam-Weinberg Model

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

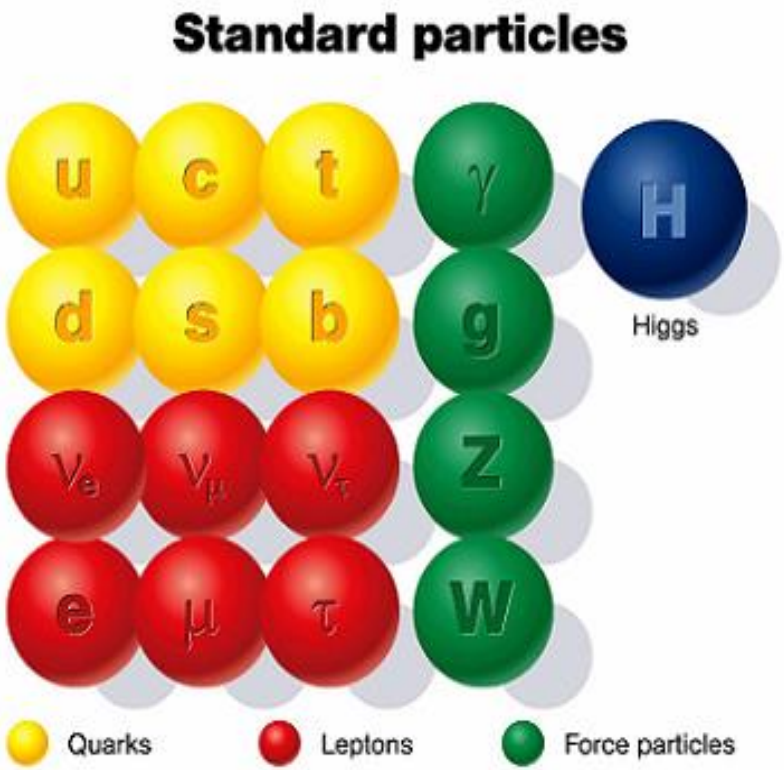
Higgsov mehanizam

Interakcija s Higgsovim poljem ≡ Frikcija u viskoznoj tekučini

Higgsov mehanizam

Interakcija s Higgsovim poljem ≡ Trenje u viskoznoj tekućini

Standard Model of Elementary Particles



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

$$(\bar{a}^i_L \gamma^\mu b^i_L W^+_\mu + \bar{b}^i_L \gamma^\mu a^i_L W^-_\mu) + \frac{g}{2c_w} \sum_f \bar{\Psi}_f \gamma^\mu (I^3_f - 2s^2_w Q_f - I^3_f \gamma_5) \Psi_f Z$$

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

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

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

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

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

Jedini sigurno opaženi Higgs u CMS eksperimentu do 2012.

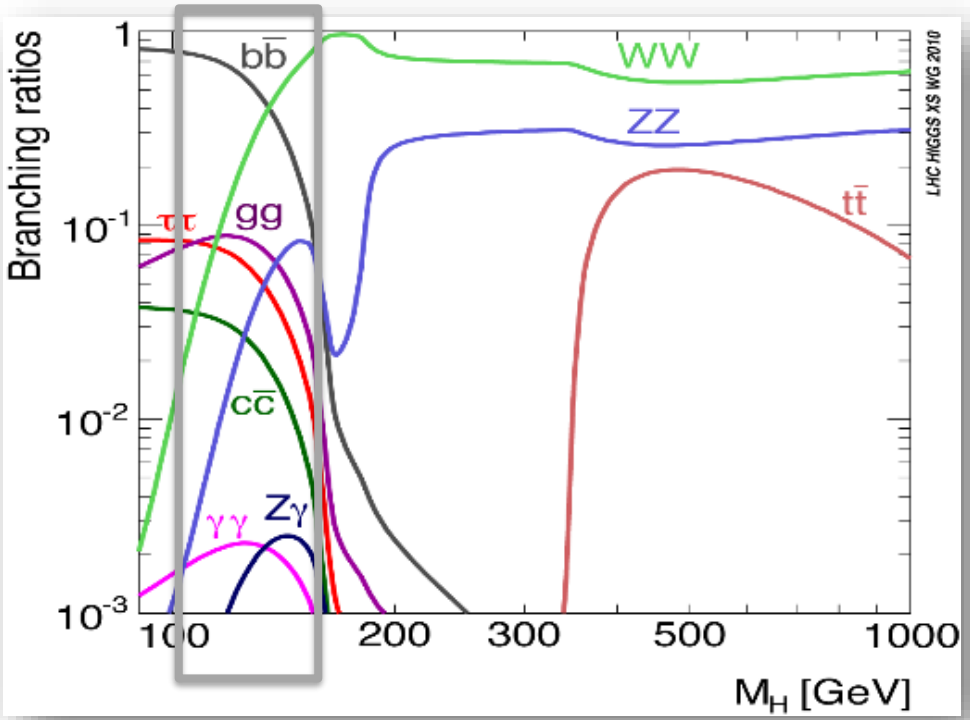
Dr. Peter Higgs

Potraga za Higgsovim bozonom

Kako se raspada Higgsov bozon?

Promatrani kanali raspada

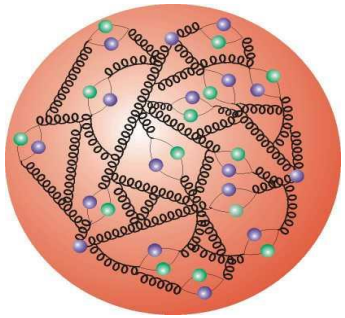
- Visoke mase: WW, ZZ
- Niske mase: bb, ττ, WW, ZZ, γγ
- Područje niskih masa je jako bogato, ali i teško:
  Teško identificirati glavne kanale raspada (bb, ττ) zbog velike pozadine
- Najprecizniji kanali: H→γγ & H→ZZ→4l



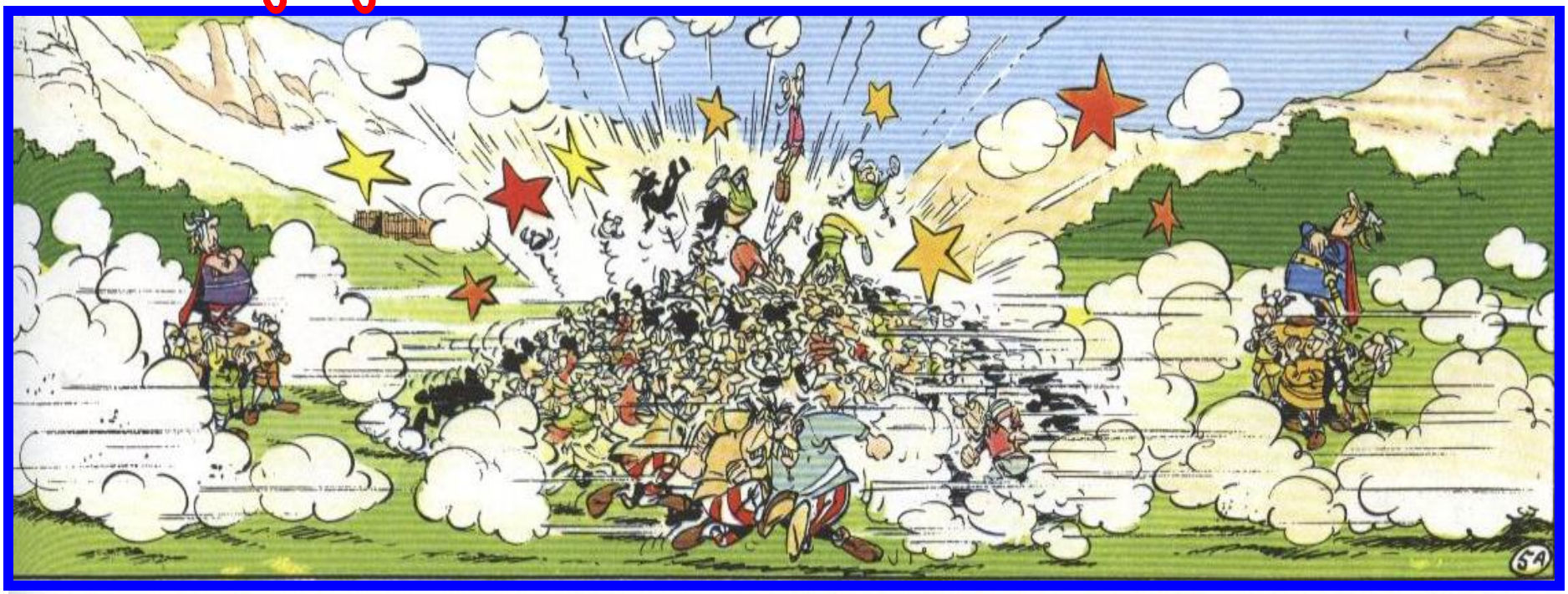
Analiza sudara: komplicirana!

Hadronski sudarivač
(sudar ~50 točkastih čestica)

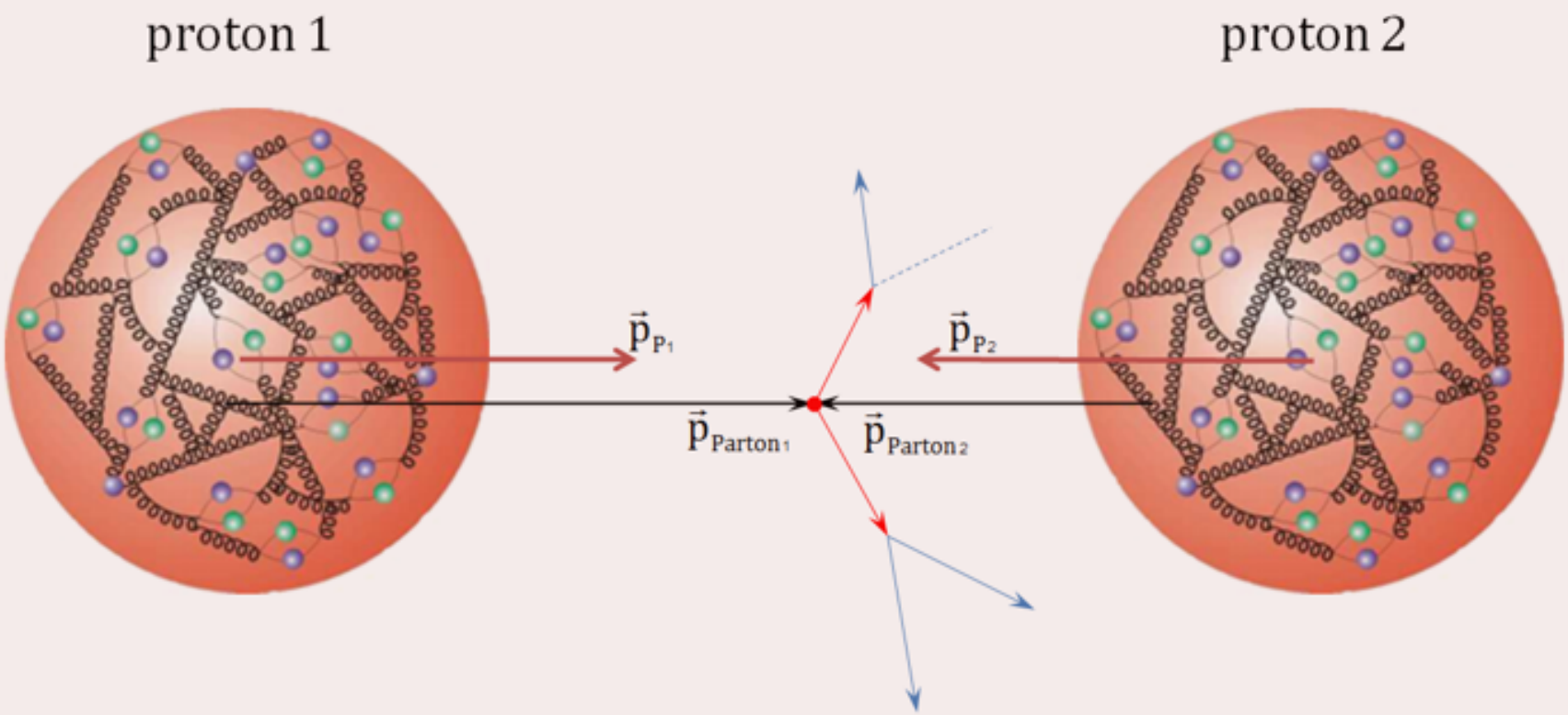
Proton:



Gdje je Asterix?



Interactions of constituents of the colliding protons, the so called partons (quarks, gluons)



$\vec{p}_{P_1}$ ... momentum proton 1

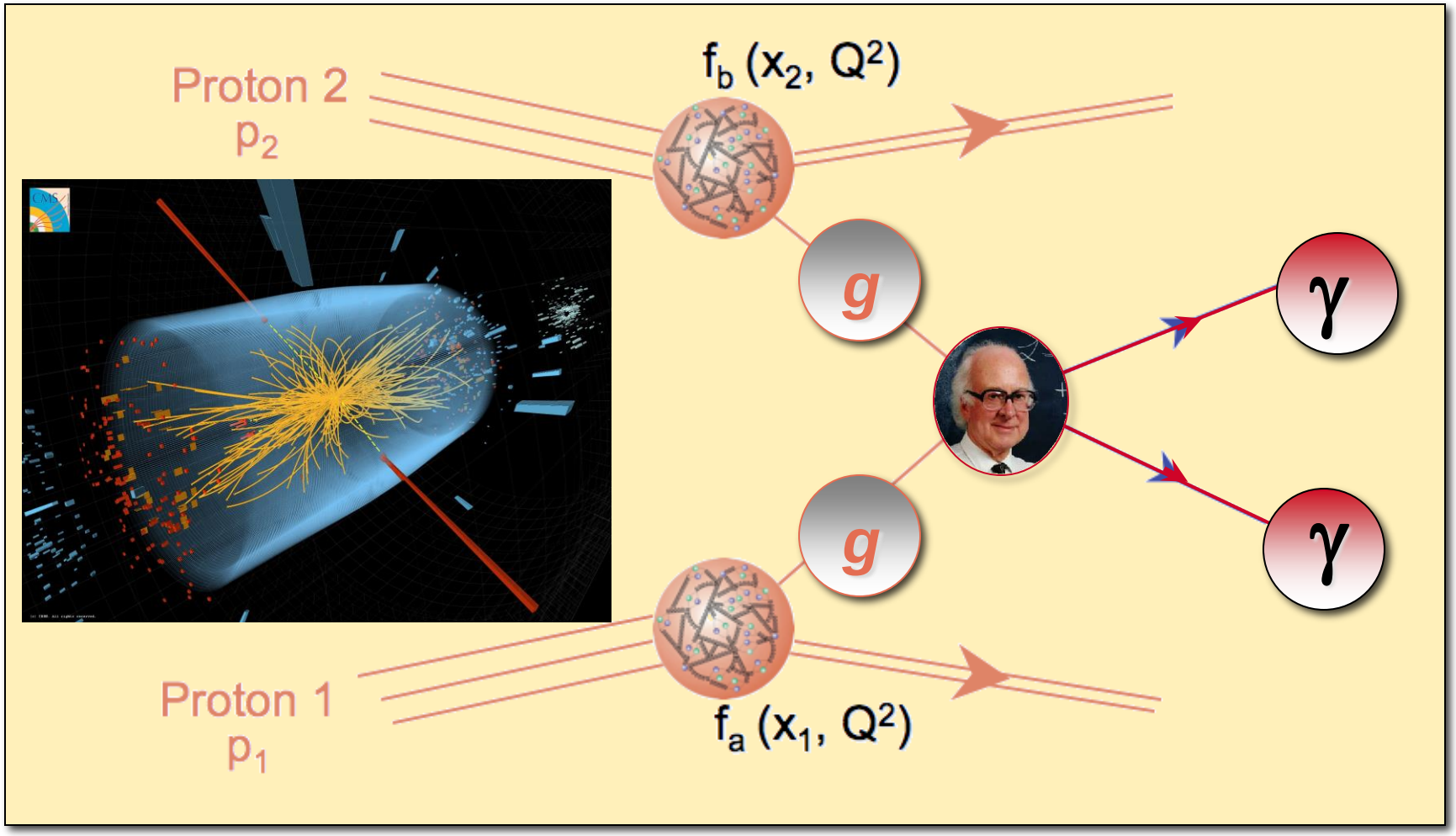
$\vec{p}_{P_1}$ ... momentum proton 2

• interaction vertex

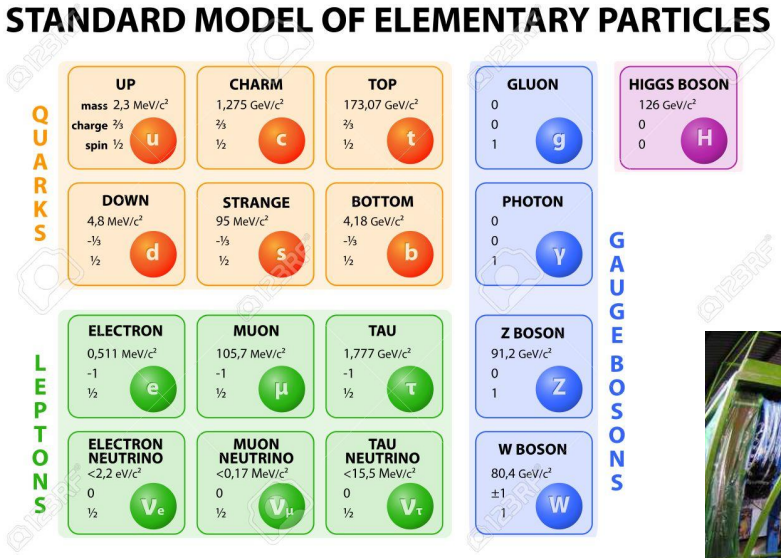
$\vec{p}_{Parton_1}$ ... momentum parton 1

$\vec{p}_{Parton_2}$ ... momentum parton 2

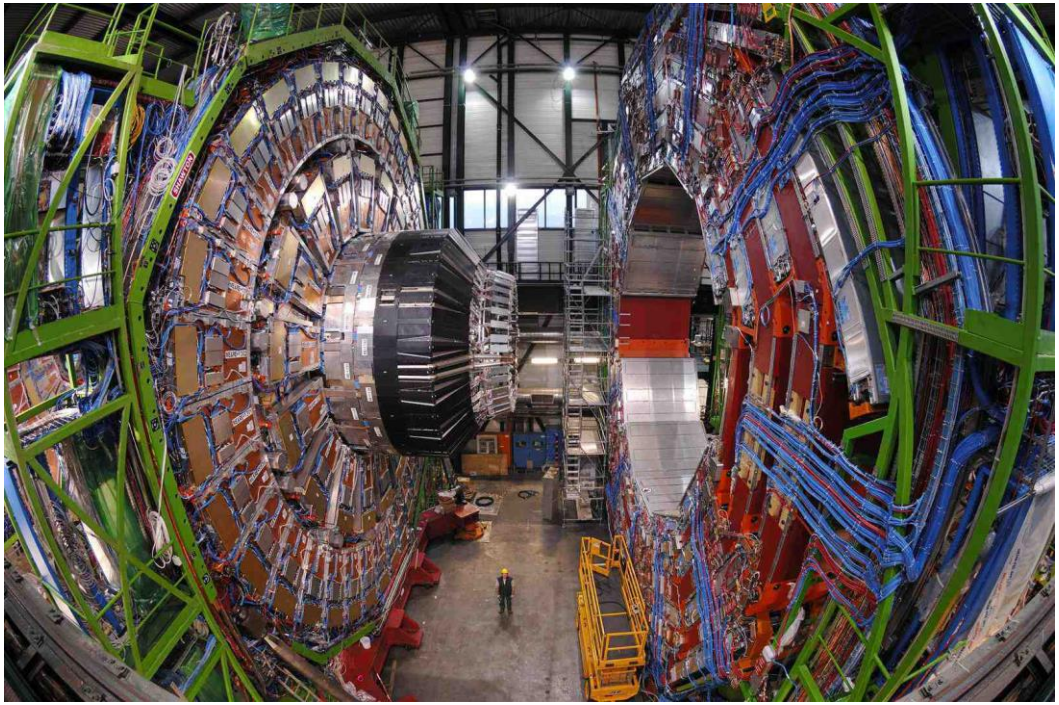
Osnovni procesi na LHC-u



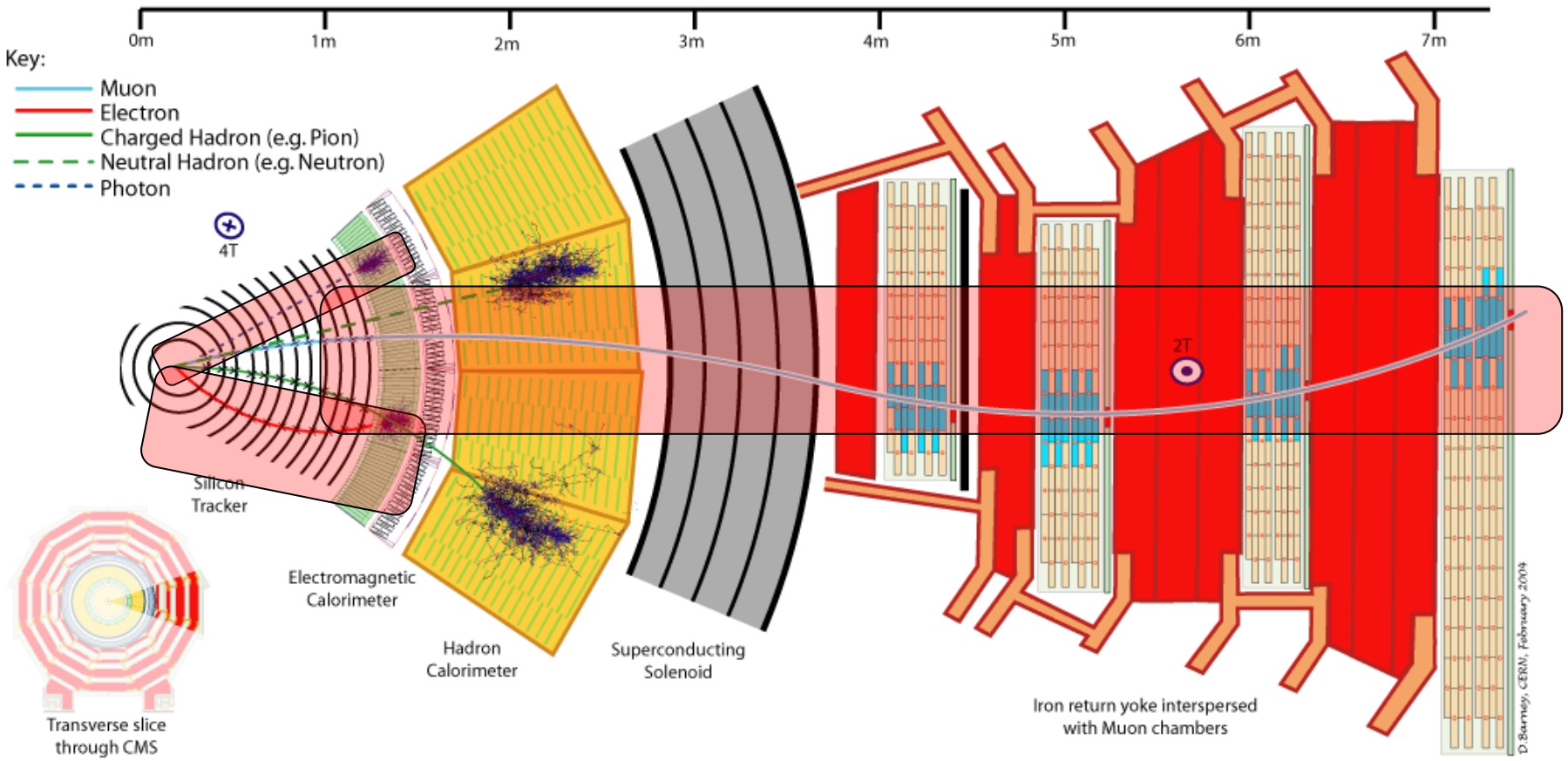
Kako vidimo



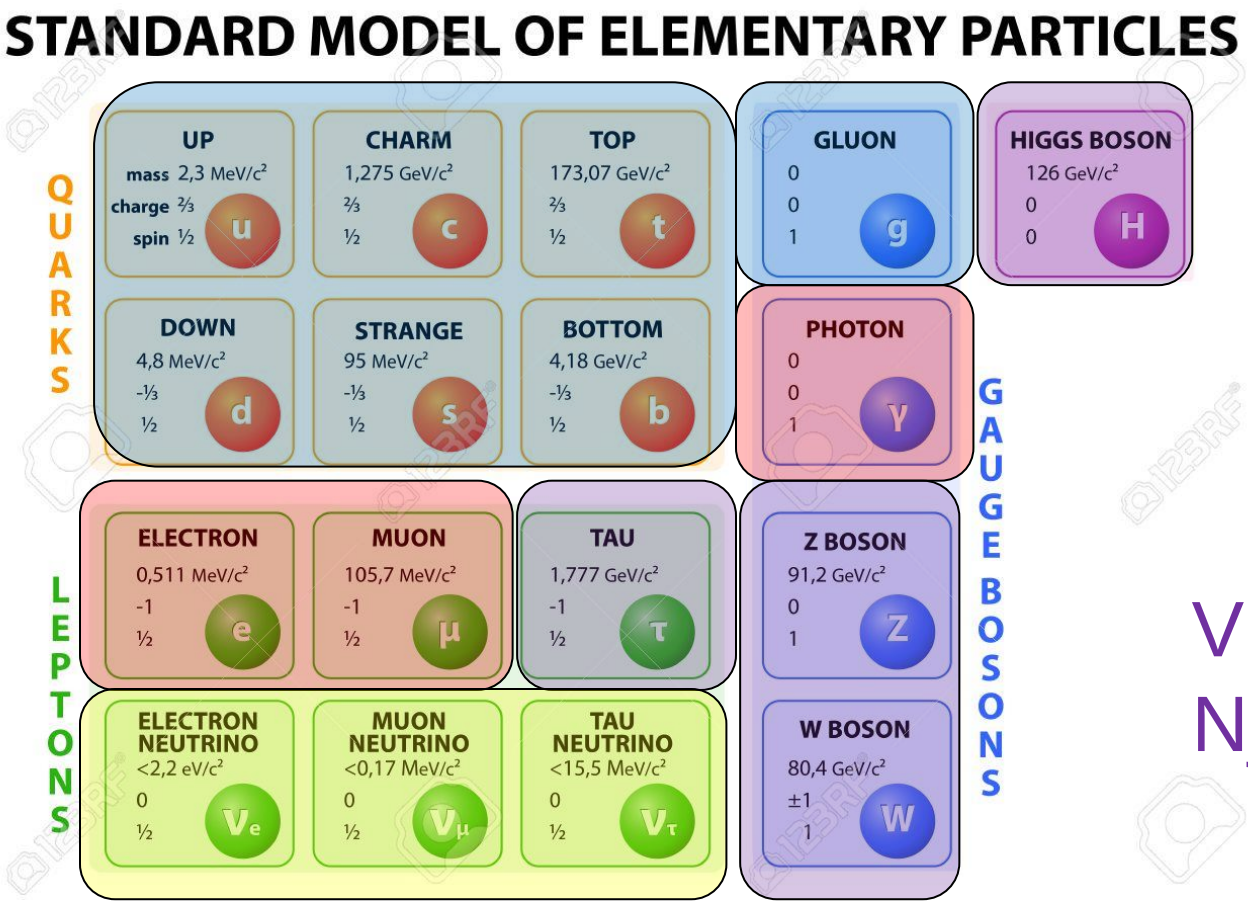
u



Elektron, foton i mion u CMS detektoru



Čestice Standardnog modela



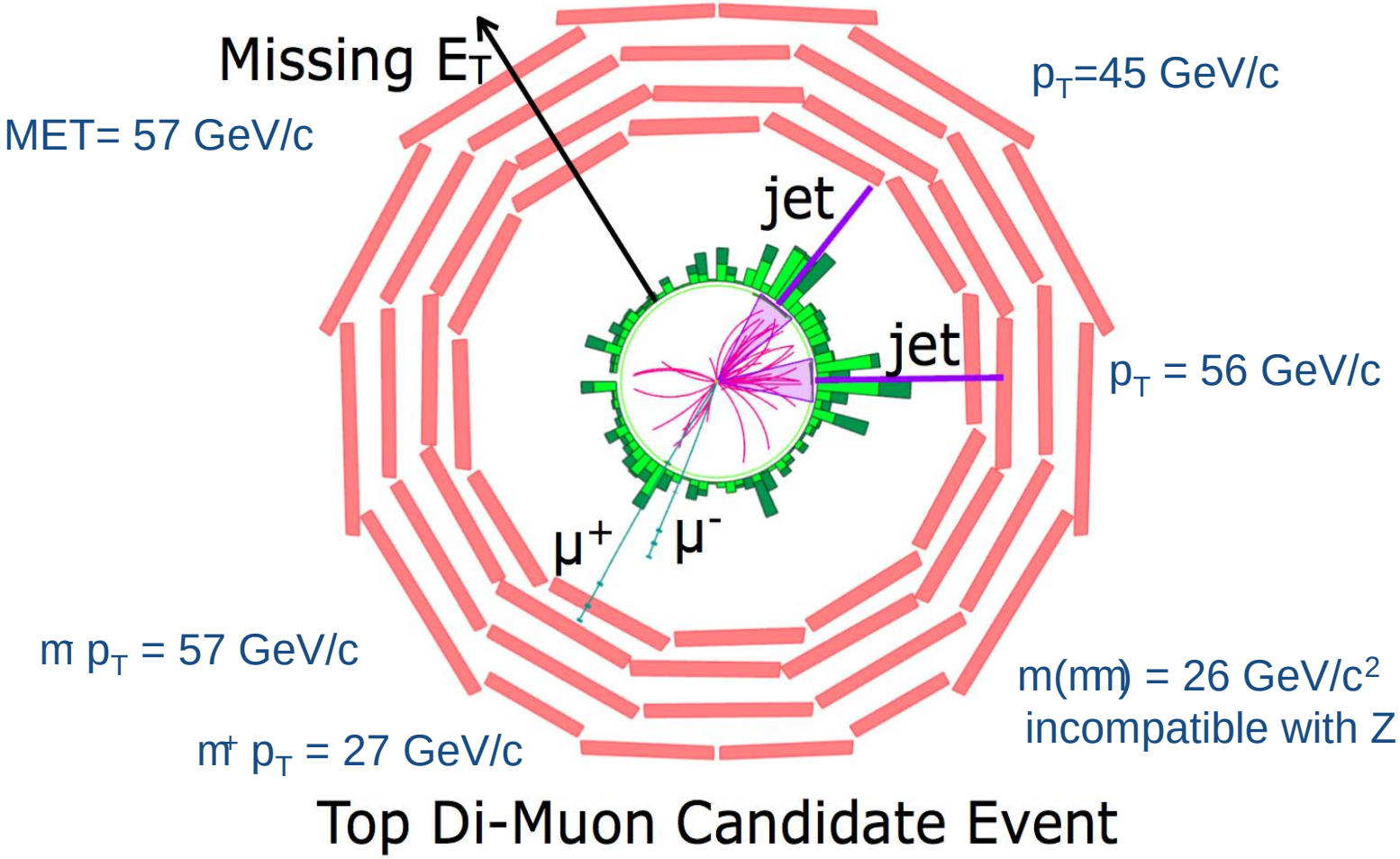
Vidimo ih u detektoru

Vidimo ih Grupirane u hadronima

Vidimo produkte Njihovog raspada

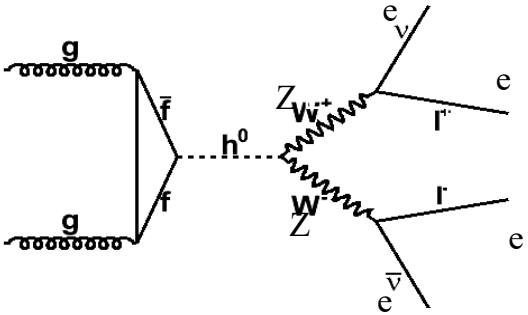
Ne vidimo ih

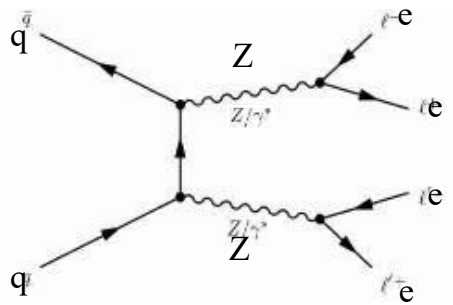
Fizikalni objekti u CMS detektoru



Signal i pozadina

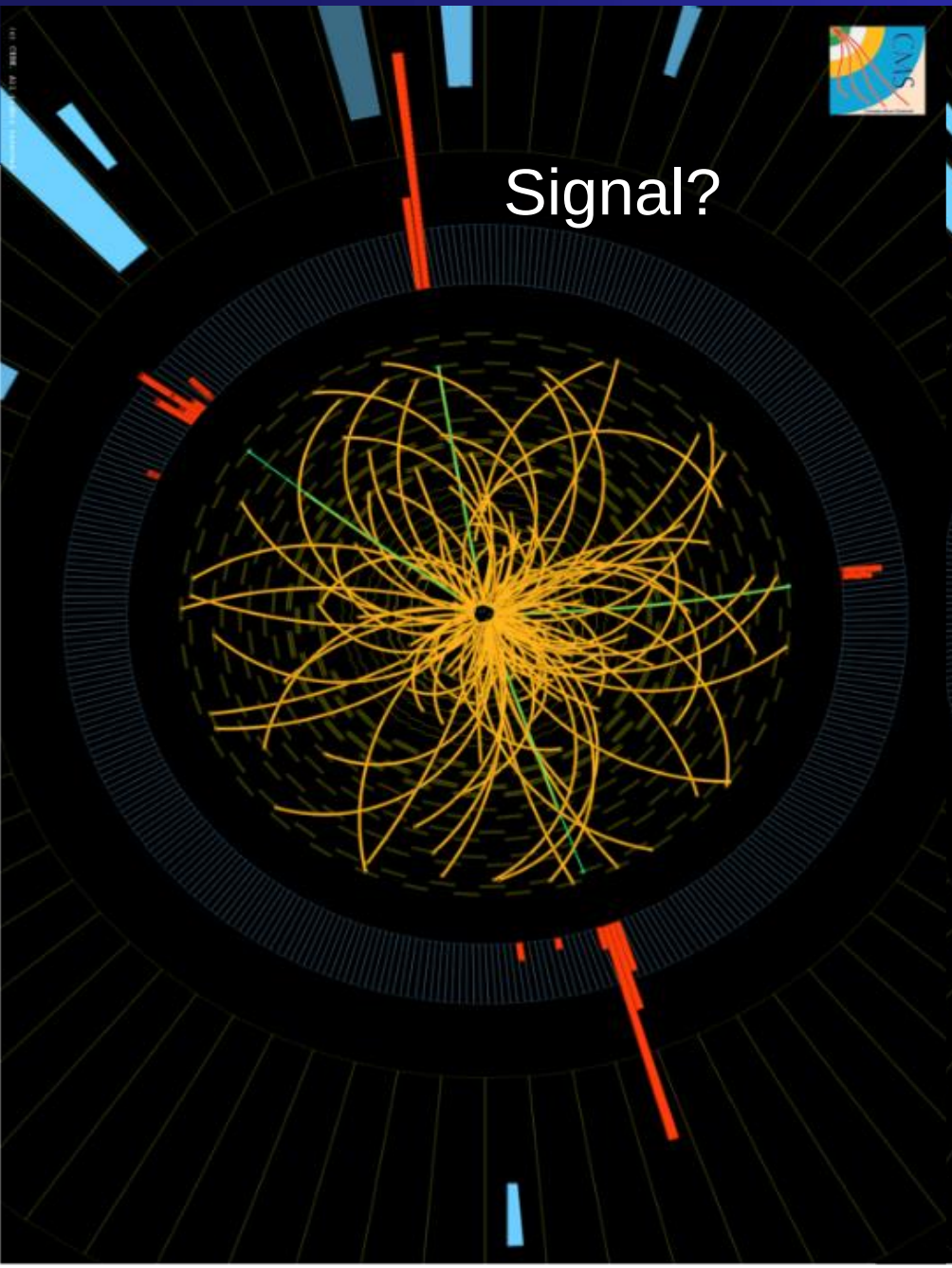
- **Signal**: Događaj koji dolazi iz traženog procesa
  - Example: $H \rightarrow ZZ \rightarrow e^+e^-e^+e^-$
- **Pozadina:** sve ostalo
  - Opasno: može izgledati upravo kao signal

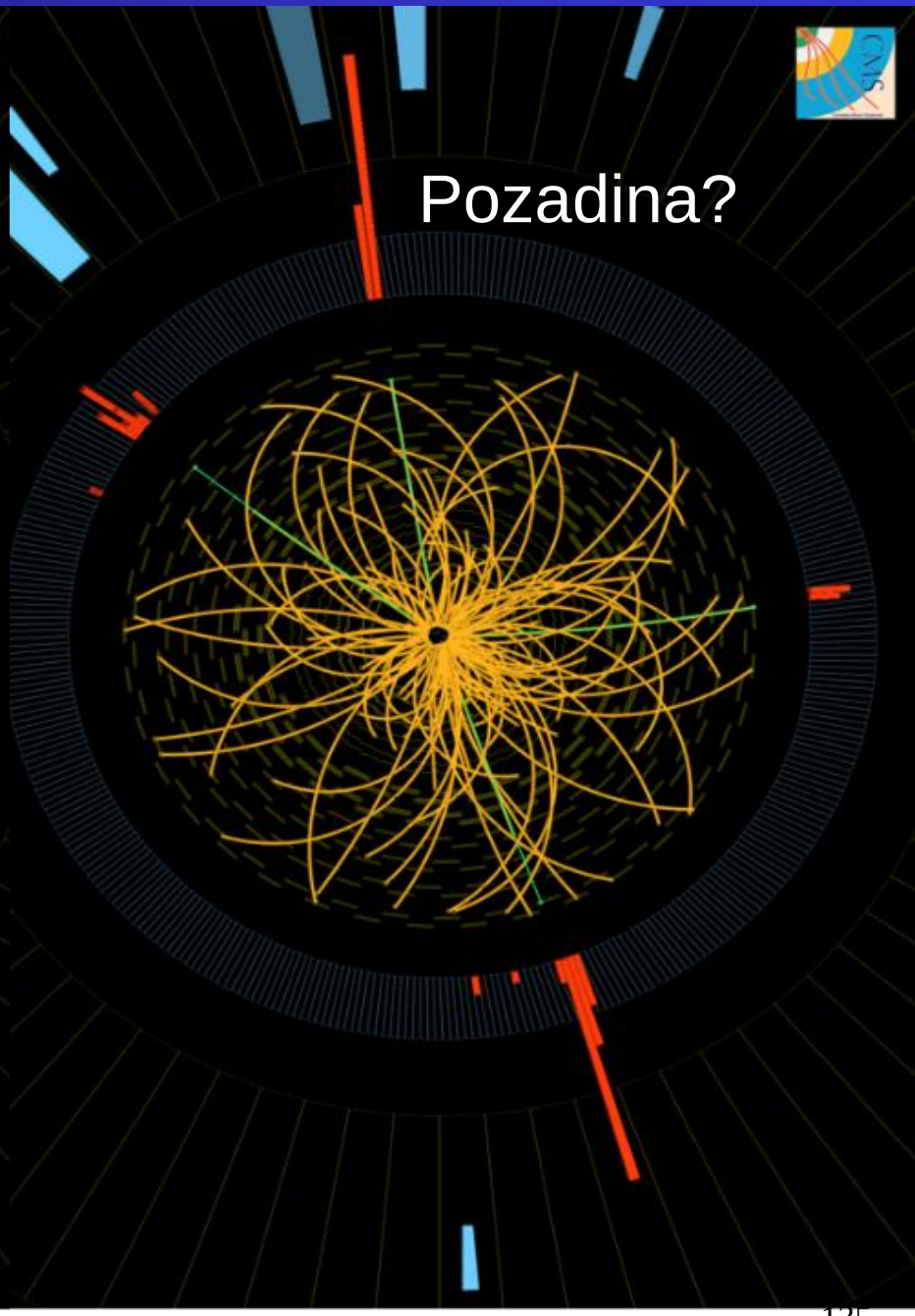




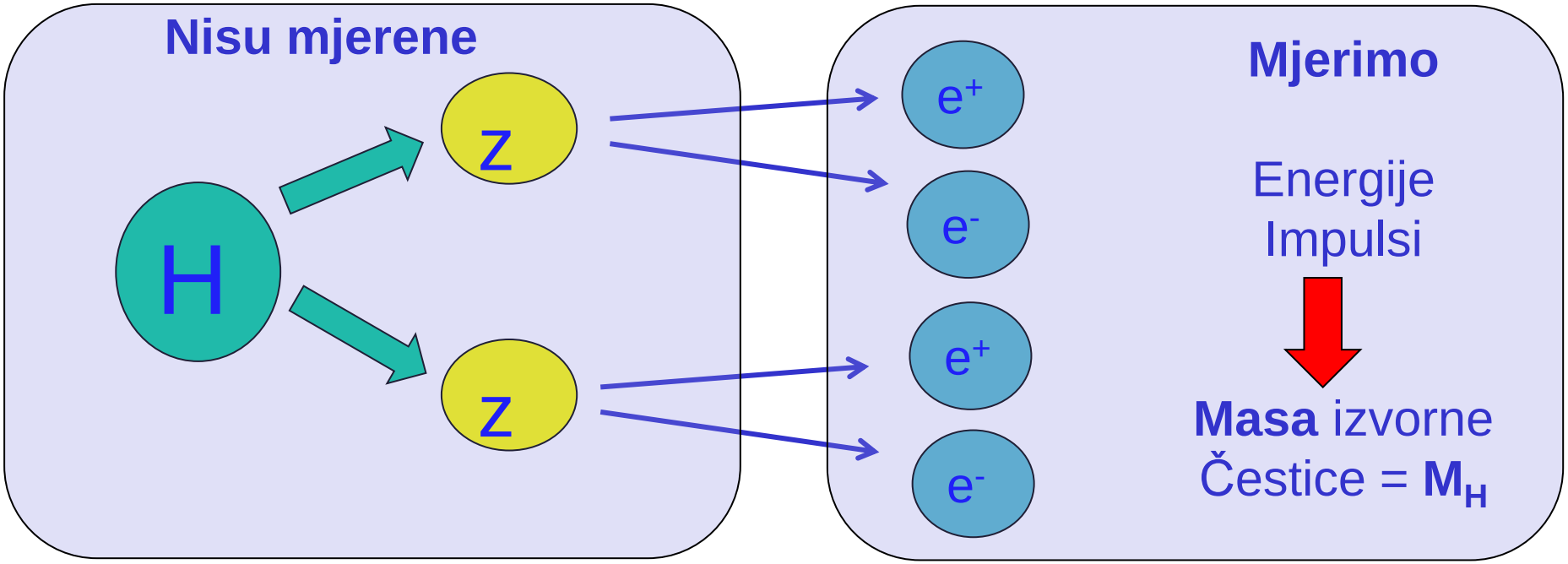
Signal: pp→H→ZZ→4e

'Opasna' pozadina: pp→ZZ→4e


Signal?


Pozadina?

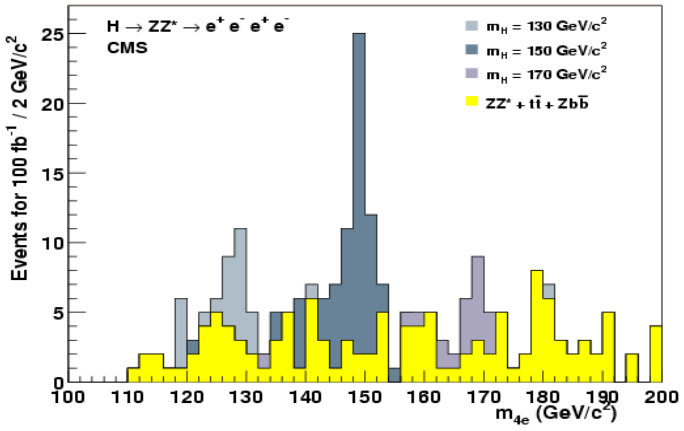
Kako identificirati signal



- "Invarijantna masa" produkta raspada:
  - Masa Higgsovog bozona za signal
  - Proizvoljna vrijednost za pozadinu

Potraga za raspadom $H \rightarrow ZZ^* \rightarrow 4l$ ($l=e,\mu$)

"Zlatni kanal"

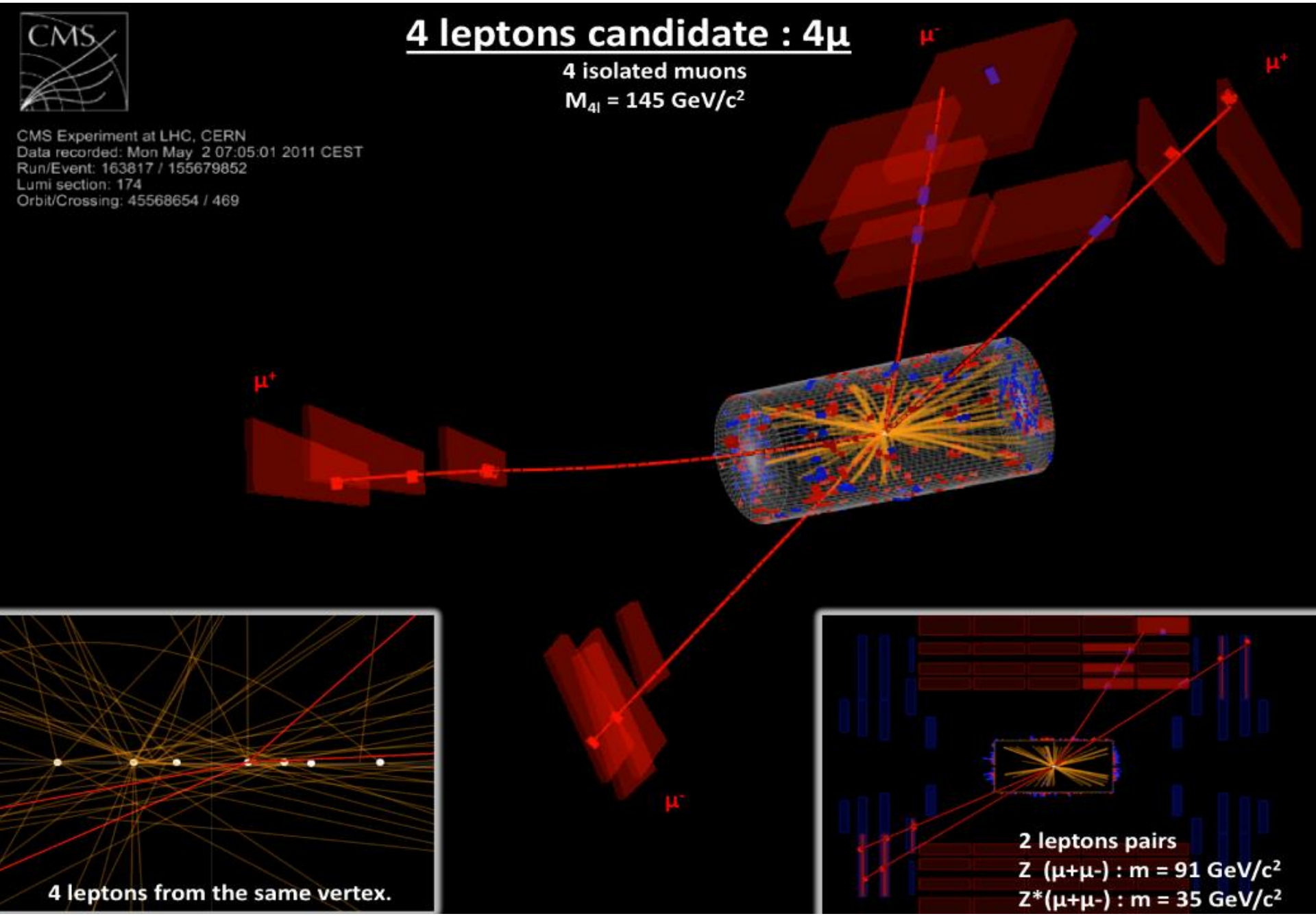


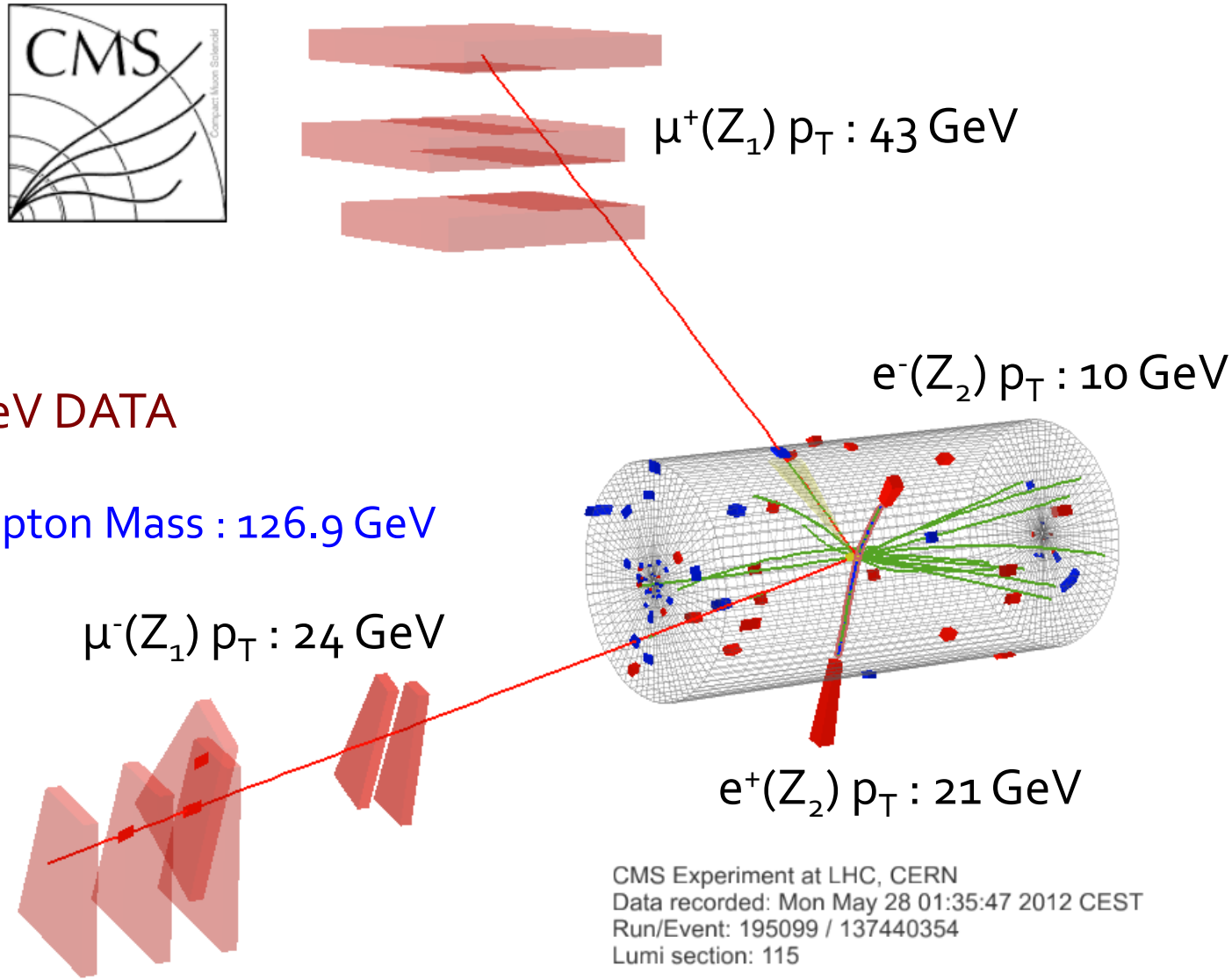
4 leptons candidate : 4μ

4 isolated muons

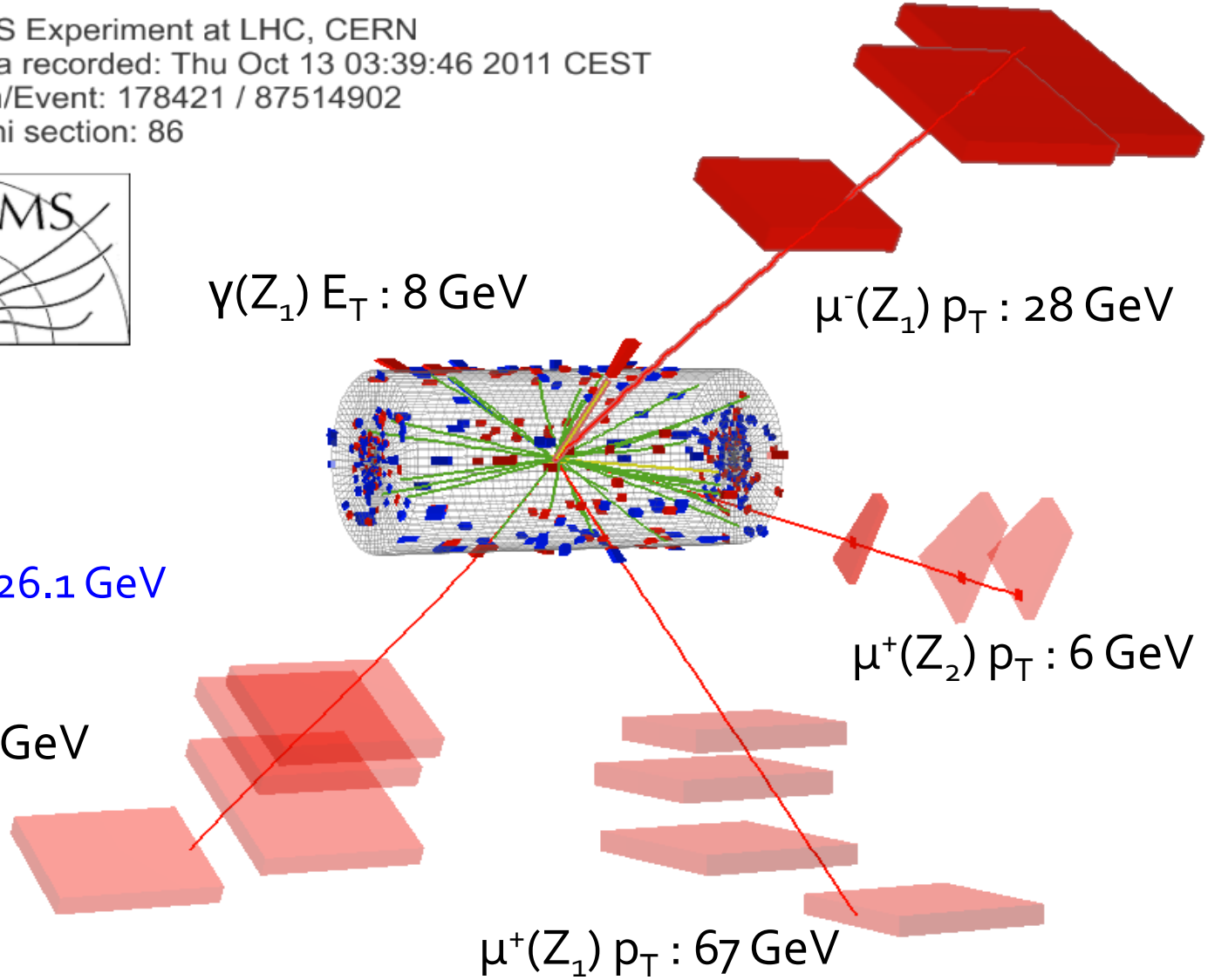
M_{4l} = 145 GeV/c^2

CMS Experiment at LHC, CERN
Data recorded: Mon May 2 07:05:01 2011 CEST
Run/Event: 163817 / 155679852
Lumi section: 174
Orbit/Crossing: 45568654 / 469




$\mu^+(Z_1)$ p_T : 43 GeV
$e^-(Z_2)$ p_T : 10 GeV
8 TeV DATA
4-lepton Mass : 126.9 GeV
$\mu^-(Z_1)$ p_T : 24 GeV
$e^+(Z_2)$ p_T : 21 GeV
CMS Experiment at LHC, CERN
Data recorded: Mon May 28 01:35:47 2012 CEST
Run/Event: 195099 / 137440354
Lumi section: 115

CMS Experiment at LHC, CERN
Data recorded: Thu Oct 13 03:39:46 2011 CEST
Run/Event: 178421 / 87514902
Lumi section: 86



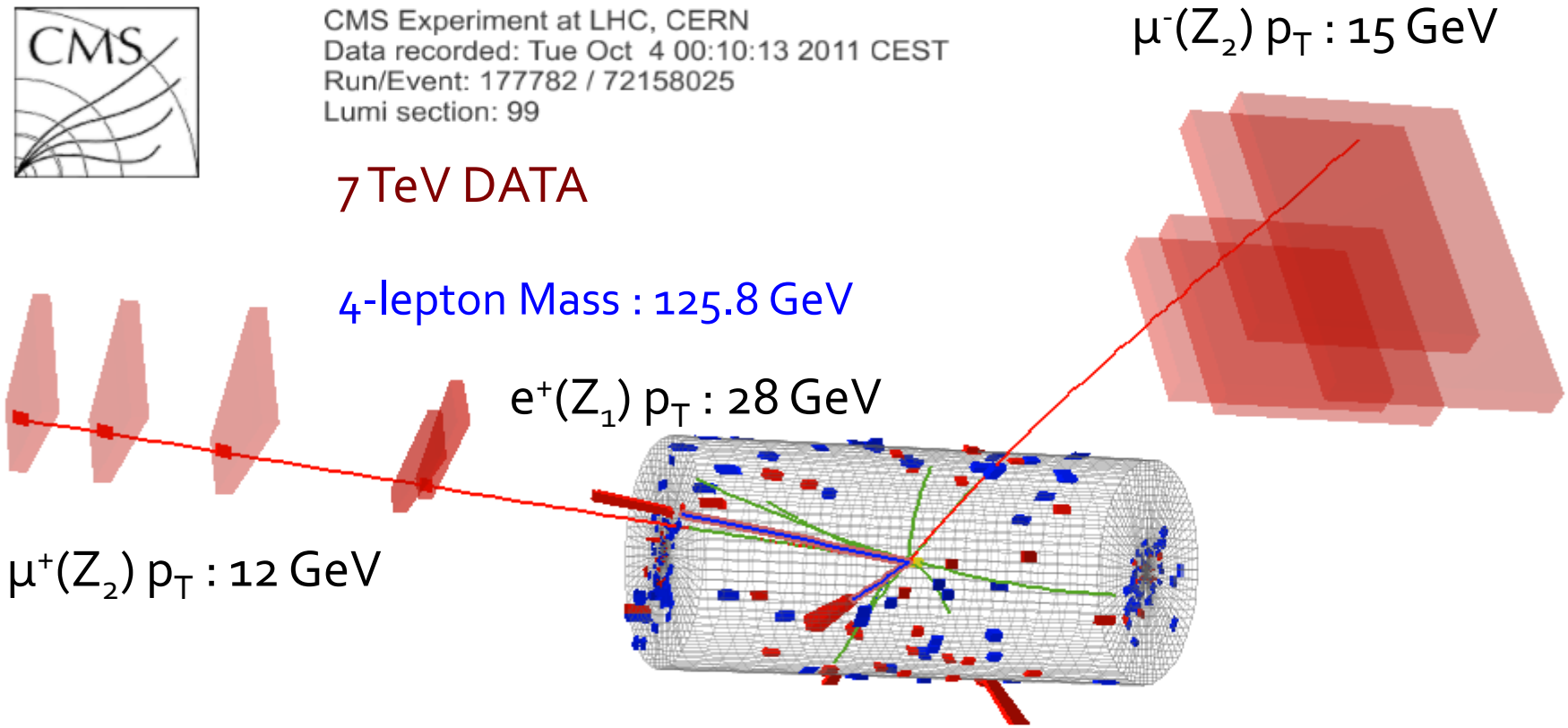
7 TeV DATA

4μ+γ Mass : 126.1 GeV

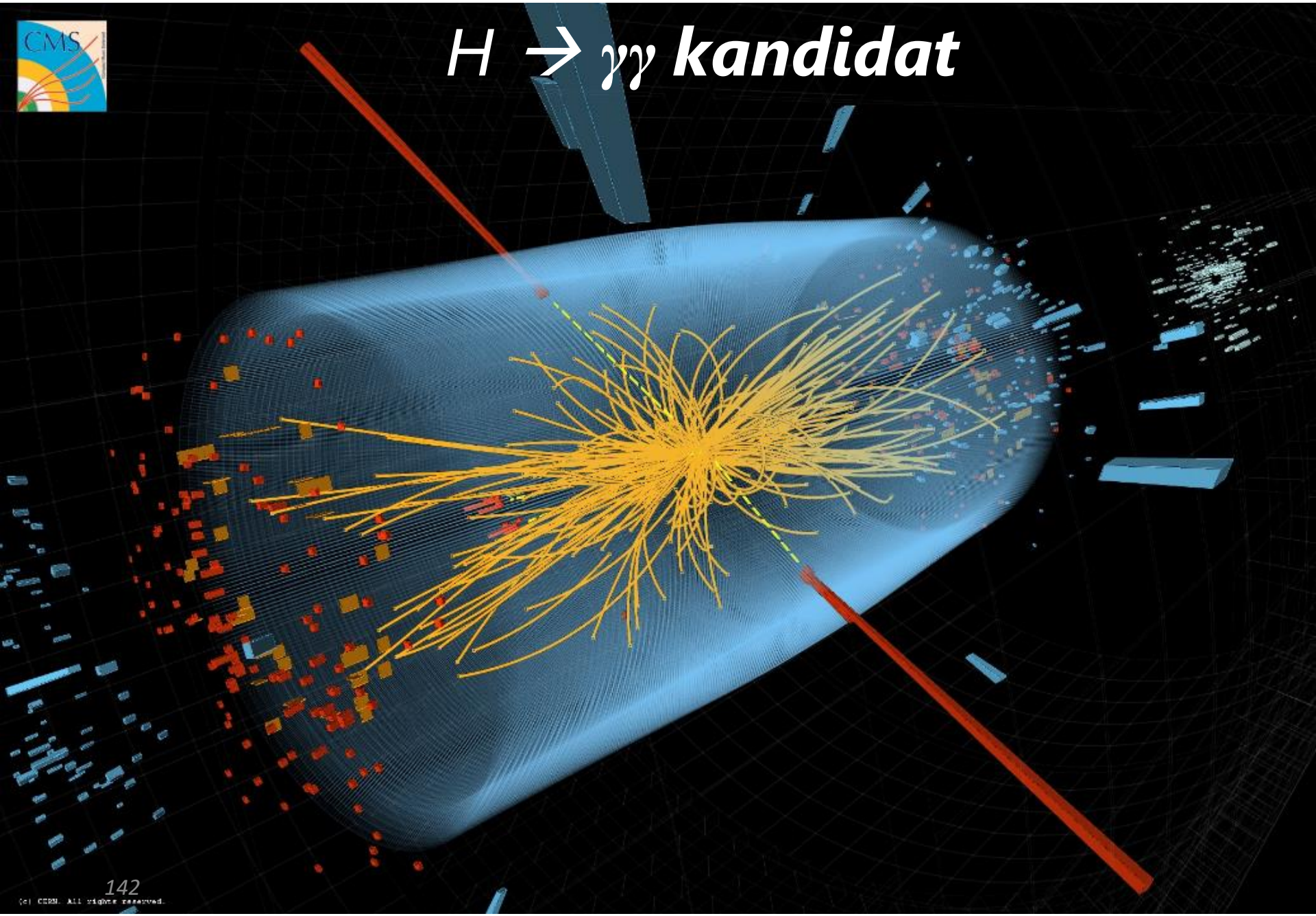
CMS Experiment at LHC, CERN
Data recorded: Tue Oct 4 00:10:13 2011 CEST
Run/Event: 177782 / 72158025
Lumi section: 99

7 TeV DATA

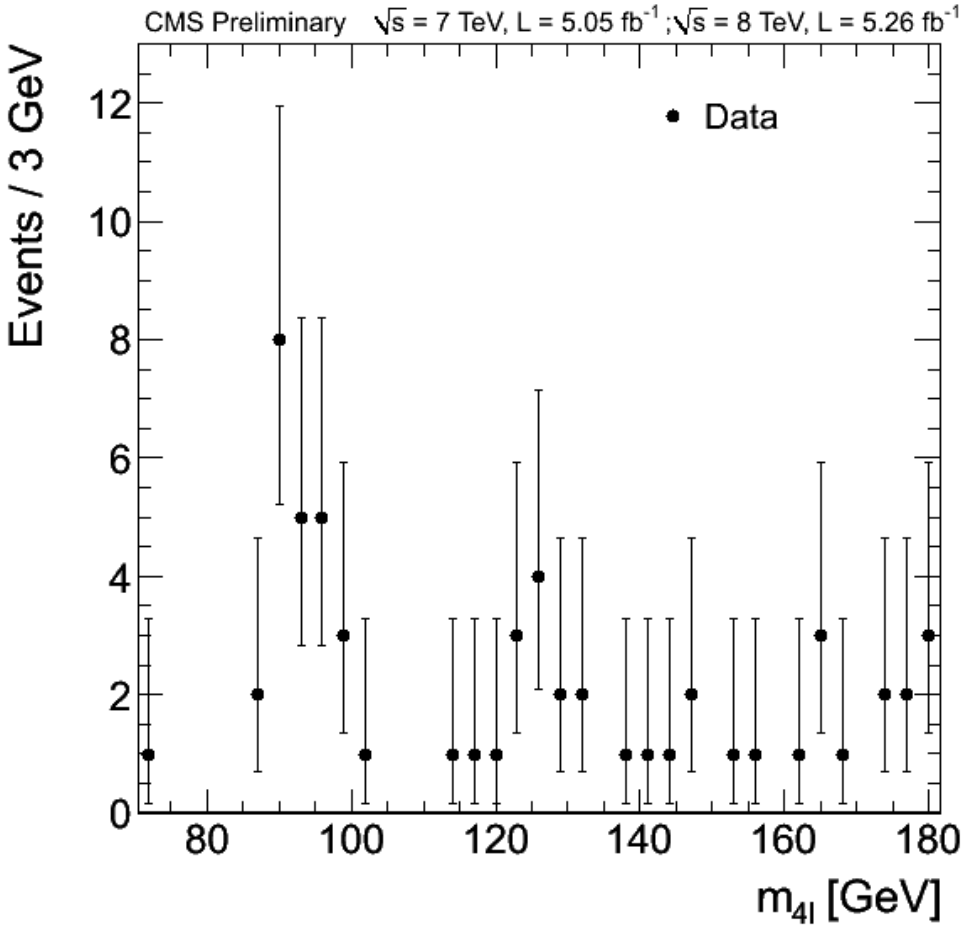
4-lepton Mass : 125.8 GeV



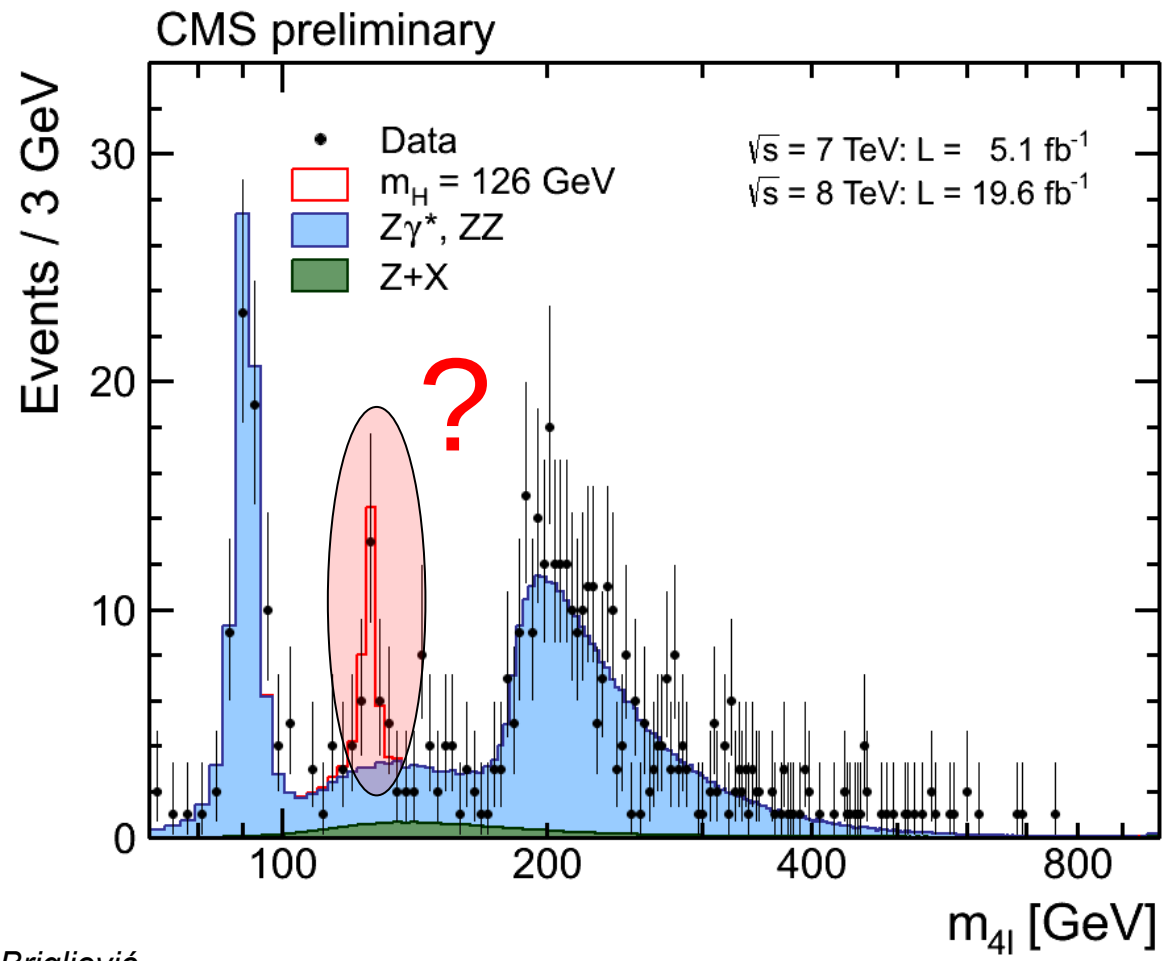
$H \rightarrow \gamma\gamma$ kandidat



Mjereni spektar mase 2 Z bozona (srpanj 2012.)



Zaključak: otkriće ili fluktuacija?



Pronašli novu česticu?

ili

Pozadina se igra s nama?

V. Brigljević

Prihvaćanje ili odbijanje teorija?

- Dobili smo podatke s jednog eksperimenta
  - Teorija 1 se slaže s podacima
  - Teorija 2 se također slaže
  - Teorija 3 također
  - ...
  - Teorija n također
  - Tvrdnja "*Teorija 1 je prihvatljiva*" nema veliku težinu
    - Nije ni pogrešna
- Ali pretpostavimo drugi scenarij
  - Teorija 1 daje precizno predviđanje
  - Eksperiment nije u slaganju s predviđanjem
  - Onda tvrdnja "*Teorija 1* ***nije*** *prihvatljiva*" ima veliku težinu
  - Zaključak: bolje je odbijati nego prihvatiti teorije / hipoteze

Kada najaviti otkriće?

- Tvrditi da ste otkrili nešto je ozbiljna stvar
  - Ostati će dugo s nama (ako ne i zauvijek ☺)
- Dakle, kada tvrdimo da smo nešto otkrili?
  - Kad smo sigurni.
  - Da, ali nismo nikada sigurni!
  - U redu, ali možete biti prilično sigurni ☺
  - 'Prilično' nije znanstvena riječ!?
  - U redu, hajdemo se dakle dogovoriti:
    - Napravite hipotezu da je dobiveni rezultat posljedica fluktuacije pozadine (već poznatih procesa)
    - Izračunajte vjerojatnost za tu hipotezu
    - Odbacite hipotezu ako je < 0.000000287 (significance > 5)

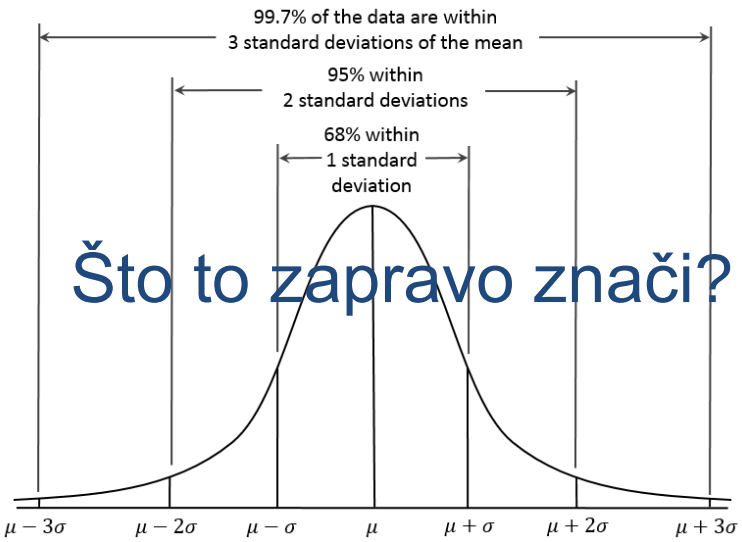
Kada najaviti otkriće?

Konvencija je da se otkriće najavljuje kada je vjerojatnost da je opaženi signal samo fluktuacija pozadine

1 u 3 500 000

(=signifikantnost od 5σ)

ili manja



Što to zapravo znači?

Kada najaviti otkriće?

Vjerojatnost dobivanja jedne 6-ice: 1/6

Vjerojatnost dobivanja osam 6-ica zaredom: $(1/6)^8=1/1679616$

Manja od 5σ

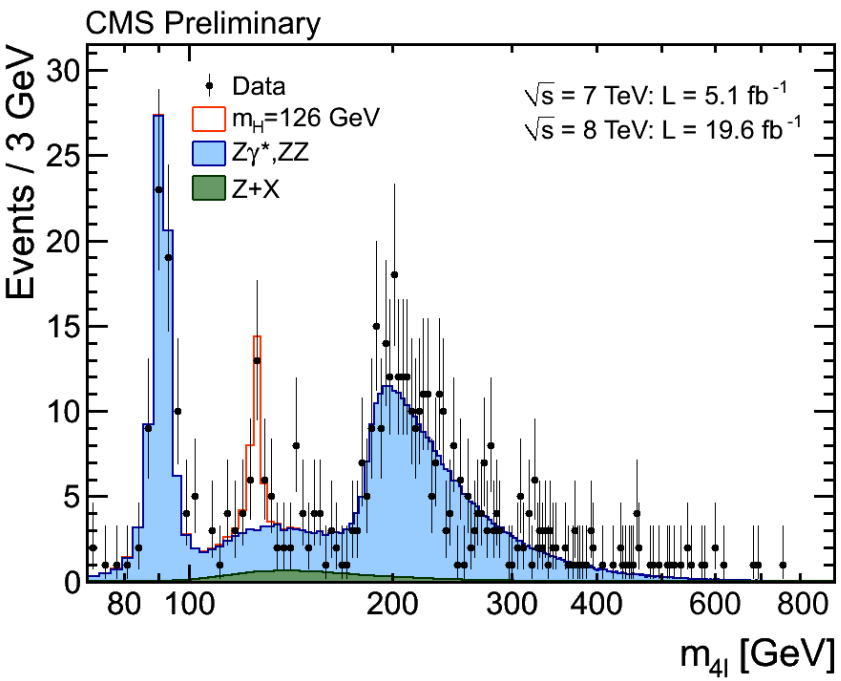
Vjerojatnost dobivanja devet 6-ica zaredom: $(1/6)^9=1/10077696$

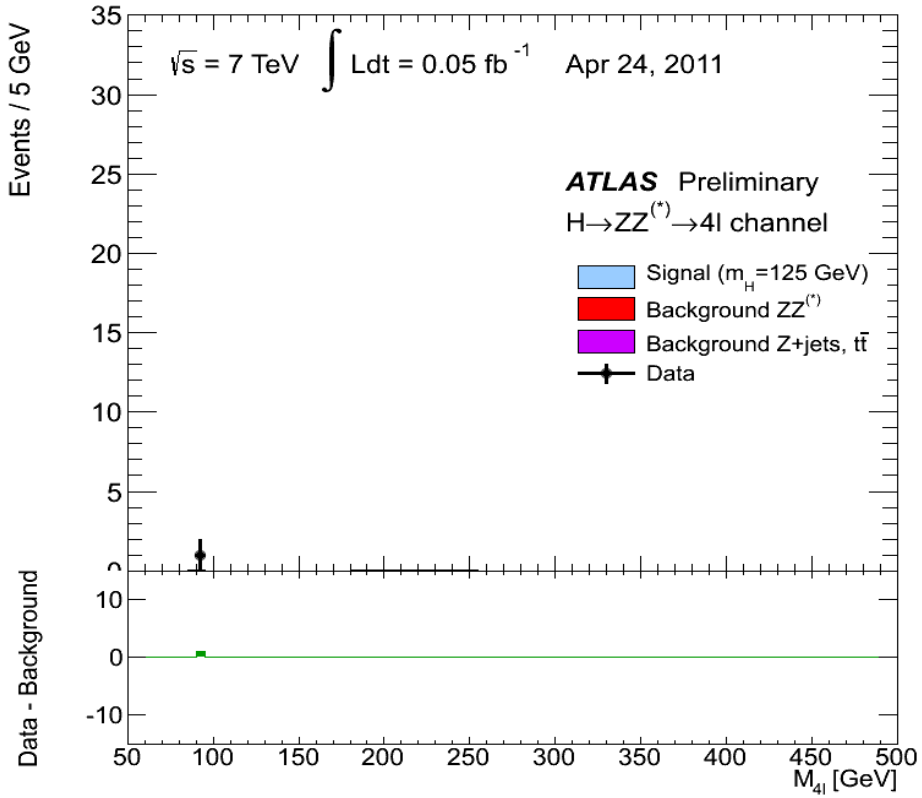
Veća od 5σ

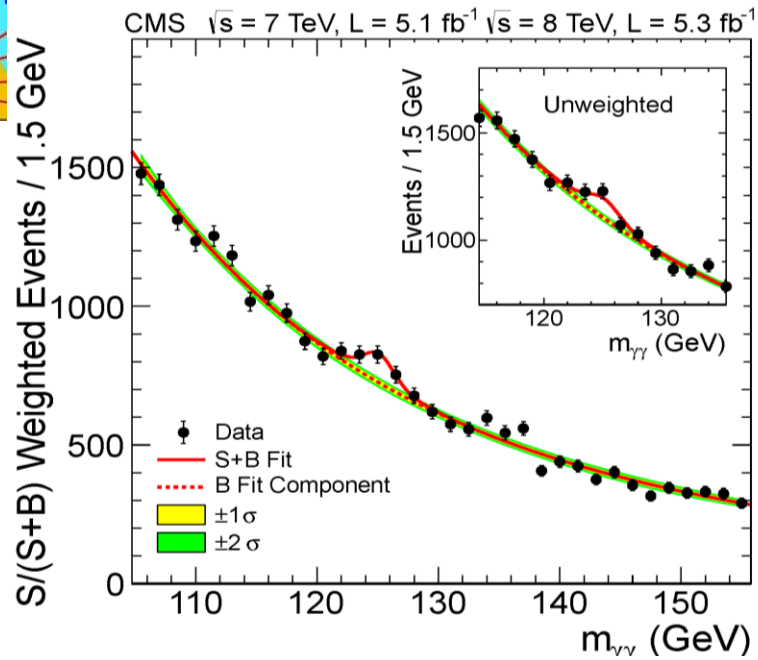
Pa još kad se takva situacija dogodi dvaput!
(npr. Higgsov bozon u ATLAS-u i CMS-u)

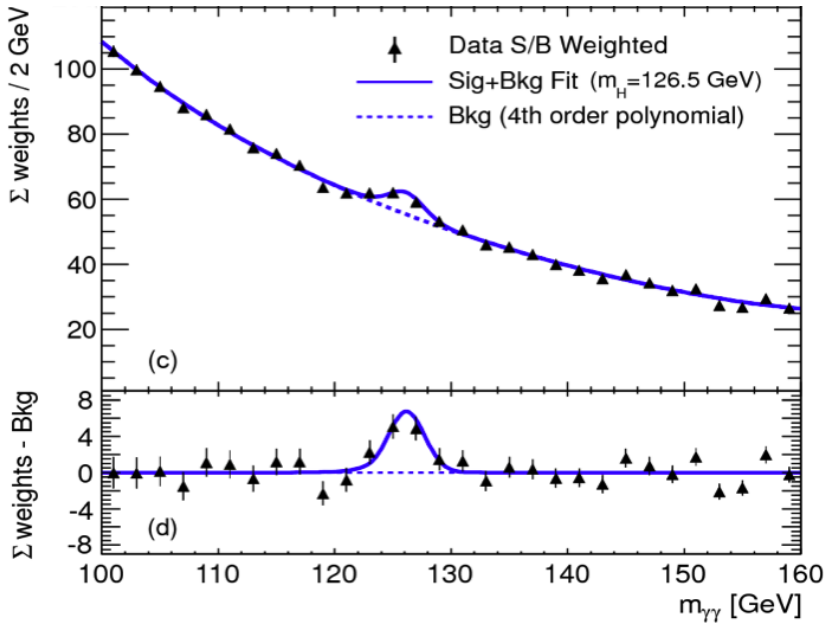
Kombinacija i interpretacija

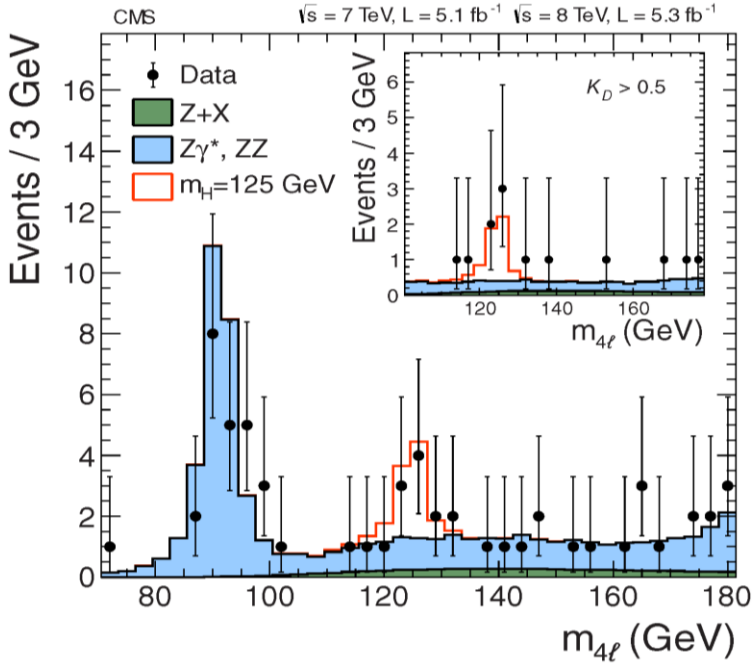
Čekamo, mjerimo i brojimo...

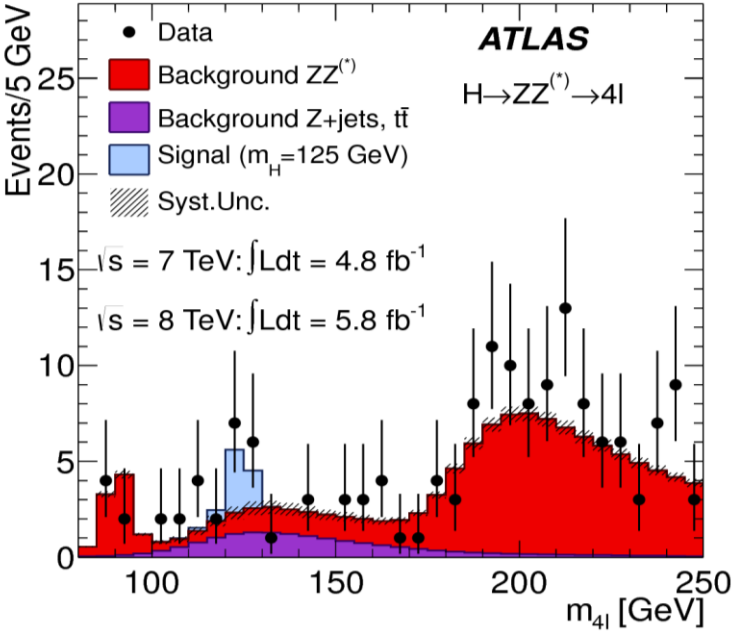




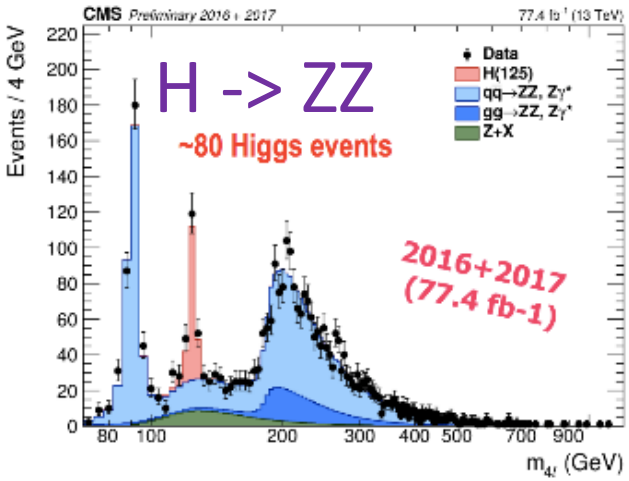

CMS √s = 7 TeV, L = 5.1 fb⁻¹ √s = 8 TeV, L = 5.3 fb⁻¹
S/(S+B) Weighted Events / 1.5 GeV
Unweighted
Events / 1.5 GeV
m_γγ (GeV)
Data
S+B Fit
B Fit Component
±1σ
±2σ
m_γγ (GeV)

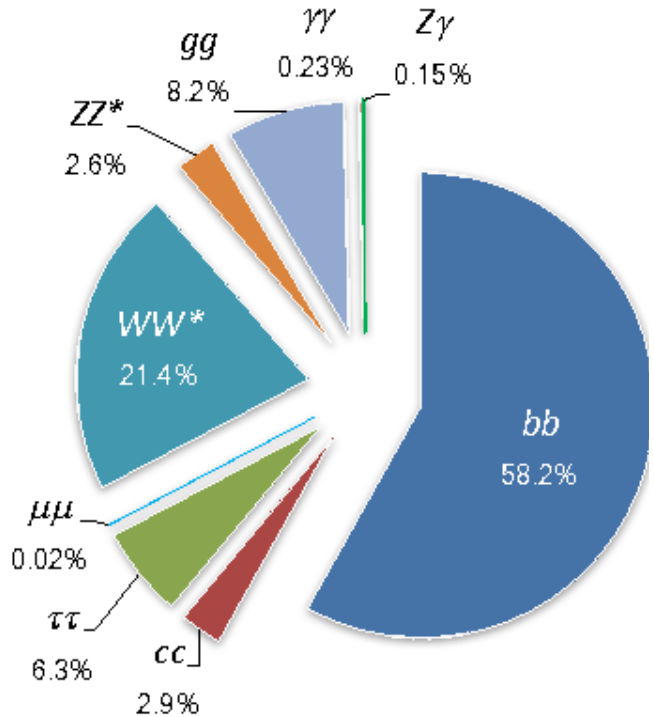

Σ weights / 2 GeV
Data S/B Weighted
Sig+Bkg Fit (m_H=126.5 GeV)
Bkg (4th order polynomial)
(c)
Σ weights - Bkg
(d)
m_γγ [GeV]

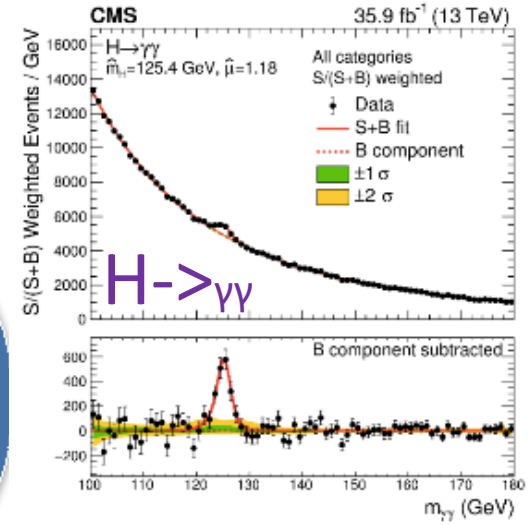

CMS √s = 7 TeV, L = 5.1 fb⁻¹ √s = 8 TeV, L = 5.3 fb⁻¹
Events / 3 GeV
Data
Z+X
Zγ*, ZZ
m_H=125 GeV
K_D > 0.5
m_4ℓ (GeV)

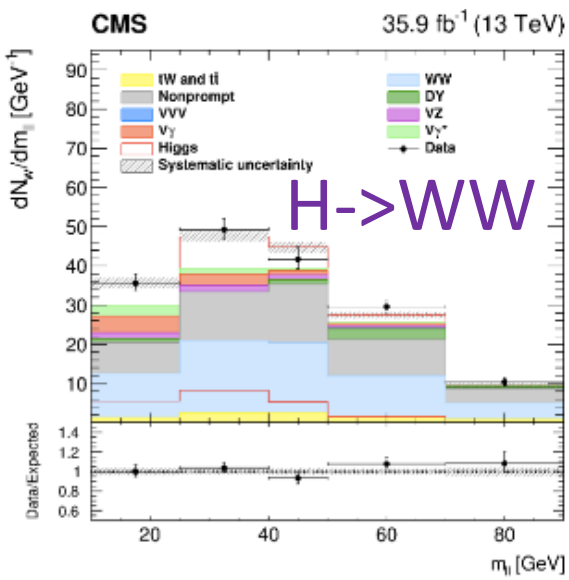

Events/5 GeV
Data
Background ZZ(*)
Background Z+jets, tt̄
Signal (m_H=125 GeV)
Syst.Unc.
ATLAS
H→ZZ(*)→4l
√s = 7 TeV: ∫Ldt = 4.8 fb⁻¹
√s = 8 TeV: ∫Ldt = 5.8 fb⁻¹
m_4l [GeV]

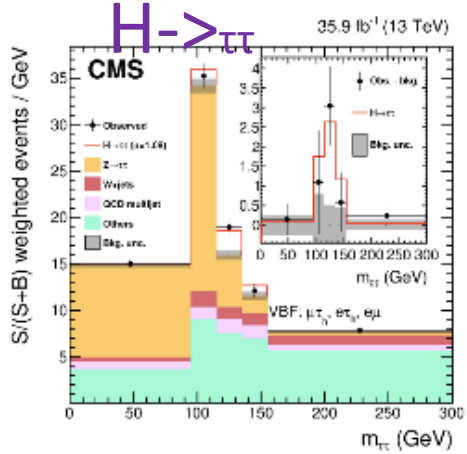
Higgsov bozon 2018.

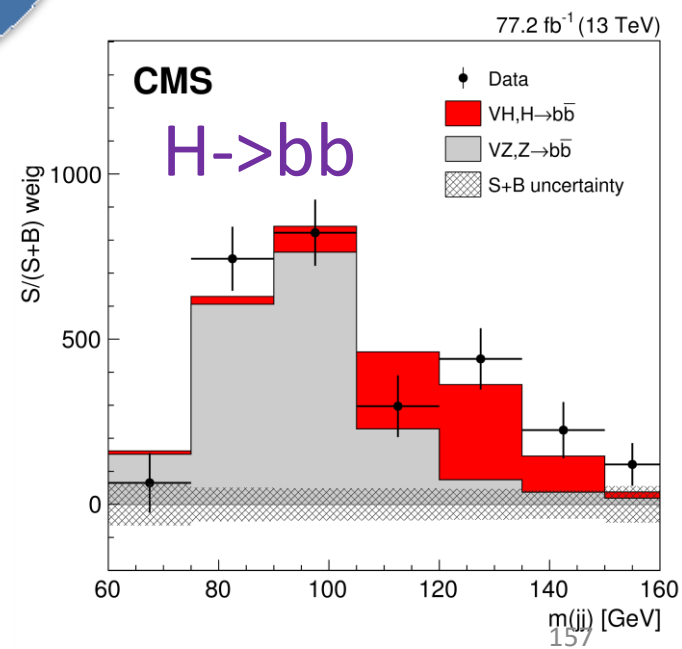




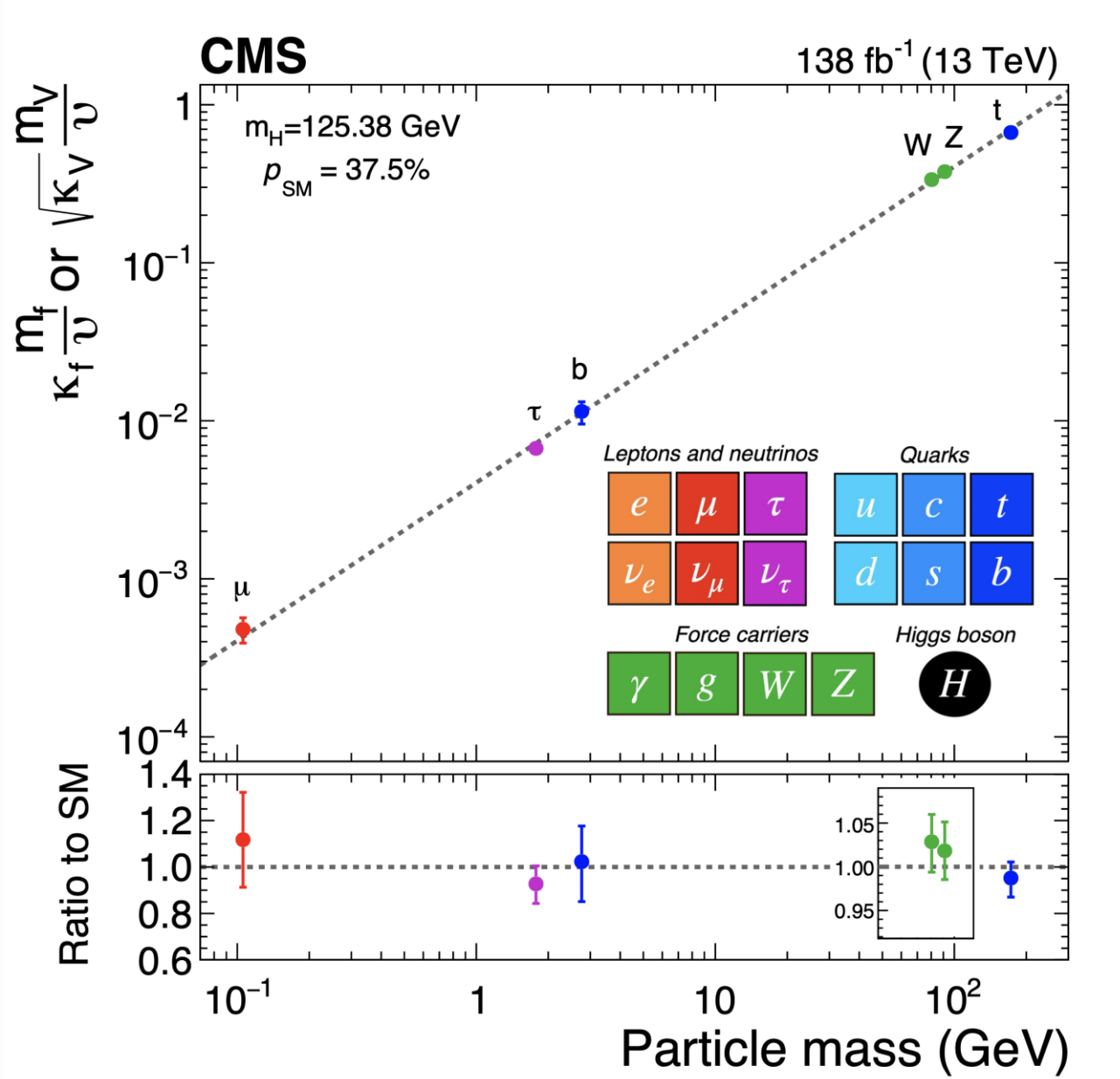








Higgs se stvarno veže za masu

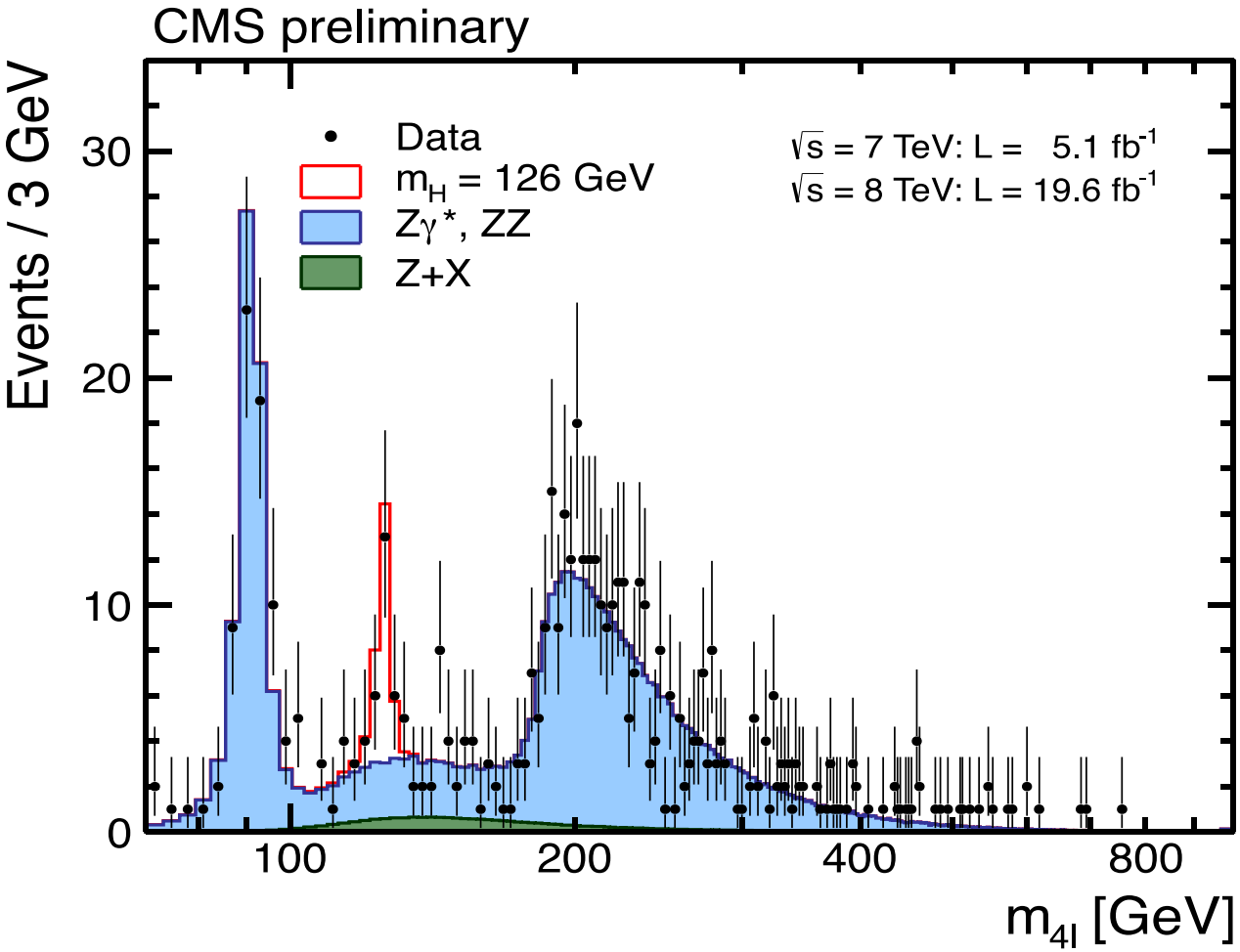


Zaključak

CERN-ovi eksperimenti su uočili novu česticu - bozon, s masom od

~ 125 GeV

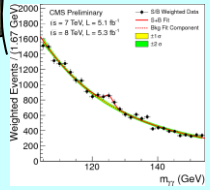
Ovo je bilo …
… Kako smo ga otkrili?

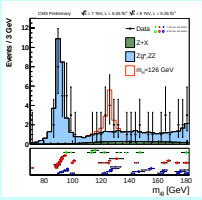


Pitanje se promijenilo

Postoji li Higgsov bozon?

Je li





Higgsov bozon?

The New York Times

Wednesday, July 4, 2012 Last Update: 6:54 AM ET

Discovery of New Particle Could Redefine Physical World

By DENNIS OVERBYE
21 minutes ago

The discovery by physicists at CERN's Large Hadron Collider, if confirmed to be the Higgs boson particle, could lead to a new understanding of how the universe began.

- The Lede Blog: What in the World Is a Higgs Boson? 4:16 AM ET

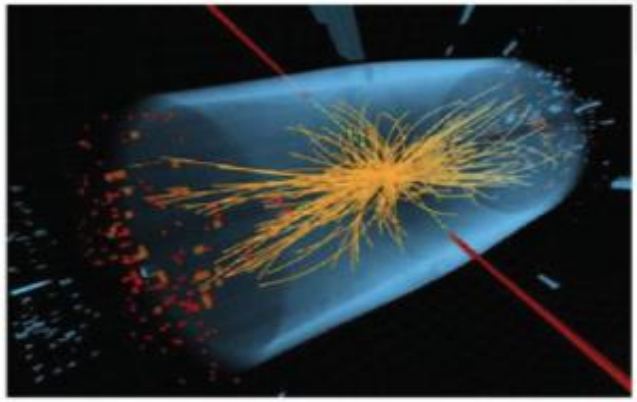
Fabrice Coffrini/Agence France-Presse — Getty Images

CERN officials held a press conference near Geneva on Wednesday.

LA NEWS DEL GIORNO | ORANGE: Politica 10:21

Il Bosone di Higgs esiste, oggi l'annuncio del Cern a Ginevra

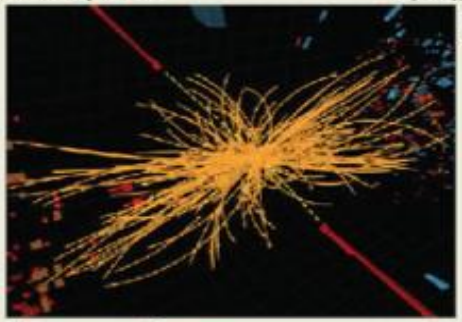
Tanti indizi per il "Santo Graal" della fisica quantistica teorizzato nel 1964. E' l'ultima particella ancora da scoprire



Roma, 4 lug. (TMNews) - L'enigma relativo all'esistenza del "bosone di Higgs", il "Santo Graal" della fisica delle particelle elementari, potrebbe essere oramai vicino alla soluzione: la conferenza stampa in programma oggi al Cern potrebbe dissipare gli ultimi dubbi.

LENTA·RU вторник, Прогресс
издание Rambler Media Group

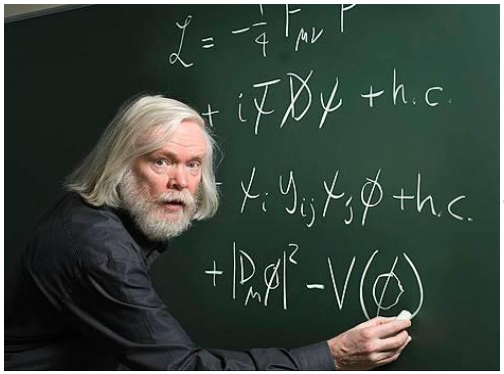
04.07.2012, 12:15:02 Версия для печати | PDF



Изображение с сайта CERN

Физики обнаружили претендента на роль бозона Хиггса

Physicists discover a candidate for the boson Higgs



John Ellis[1,2] and **Tevong You**[1]

Particle Physics and Cosmology Group, Physics Department, King's College London, London WC2R 2LS, UK
Physics Department, CERN, CH-1211 Geneva 23, Switzerland

Abstract

There are many indirect and direct experimental indications that the new particle H discovered by the ATLAS and CMS Collaborations has spin zero and (mostly) positive parity, and that its couplings to other particles are correlated with their masses. Beyond any reasonable doubt, it is a Higgs boson, and here we examine the extent to which its couplings resemble those of the single Higgs boson of the Standard Model. Our global analysis of its couplings to fermions and massive bosons determines that they have the same relative sign as in the Standard Model. We also show directly that these couplings are highly consistent with a dependence on particle masses that is linear to within a few %, and scaled by the conventional electroweak symmetry-breaking scale to within 10%. We also give constraints

The Nobel Prize in Physics 2013
François Englert, Peter Higgs

The Nobel Prize in Physics 2013

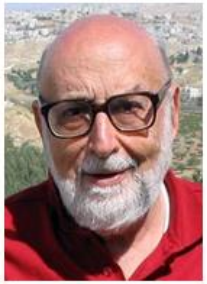


Photo: Pnicolet via Wikimedia Commons
François Englert

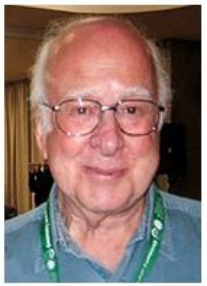
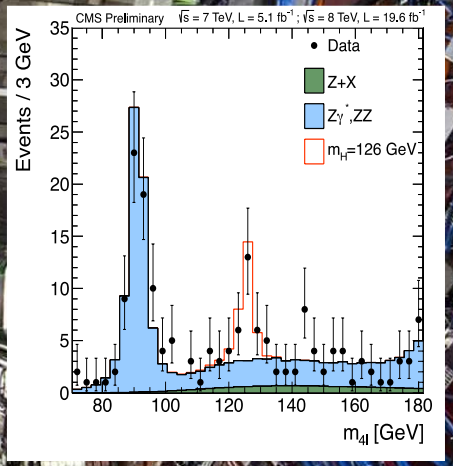


Photo: G-M Greuel via Wikimedia Commons
Peter W. Higgs

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"*



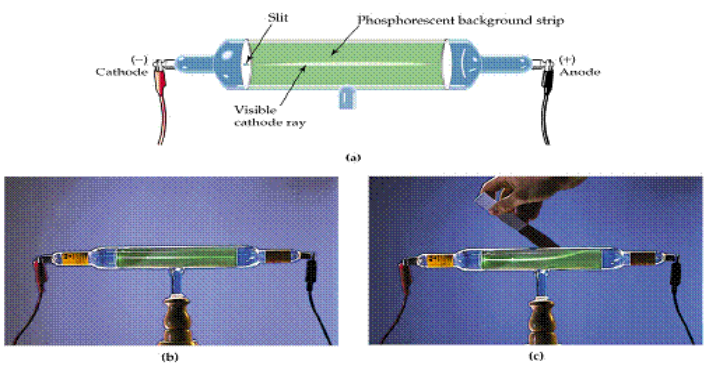
Više nije!

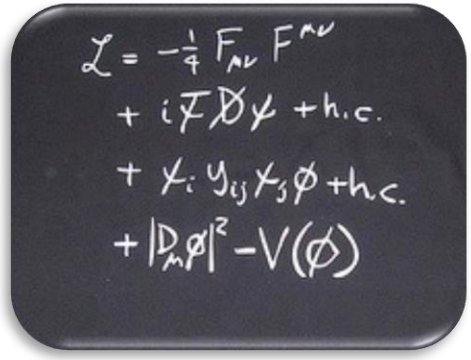
Jedini sigurno opaženi Higgs u CMS eksperimentu do 2012:

Dr. Peter Higgs

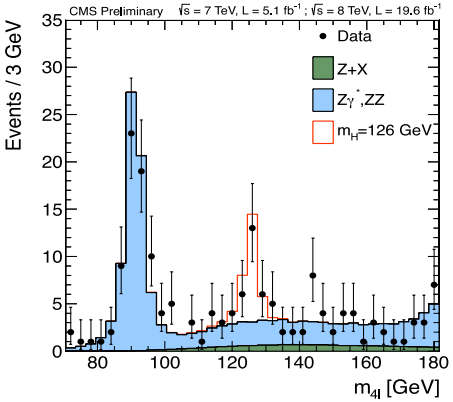
STANDARDNI MODEL
JE KOMPLETAN I POTVRĐEN

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

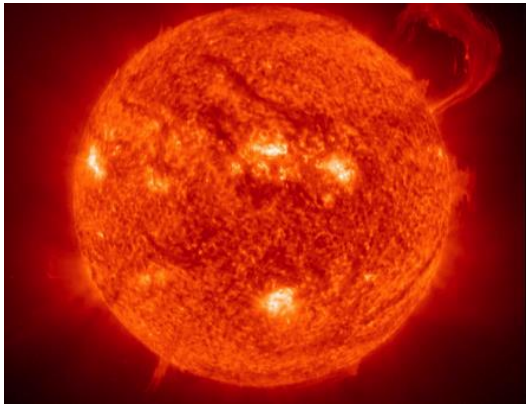




Discovery of the Higgs boson
LHC (2012)

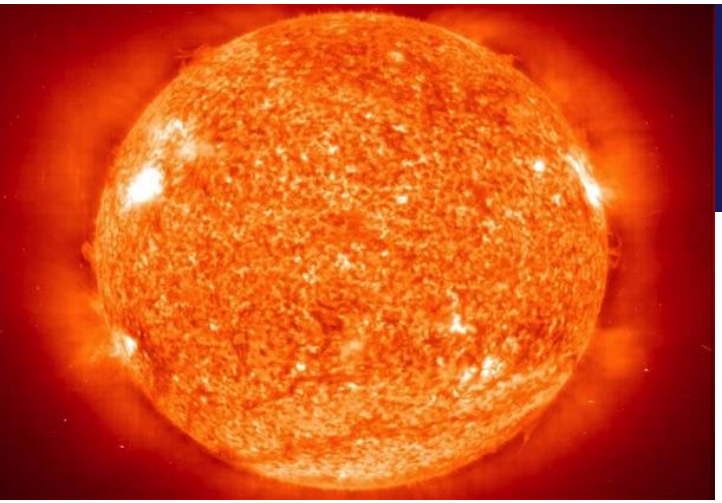


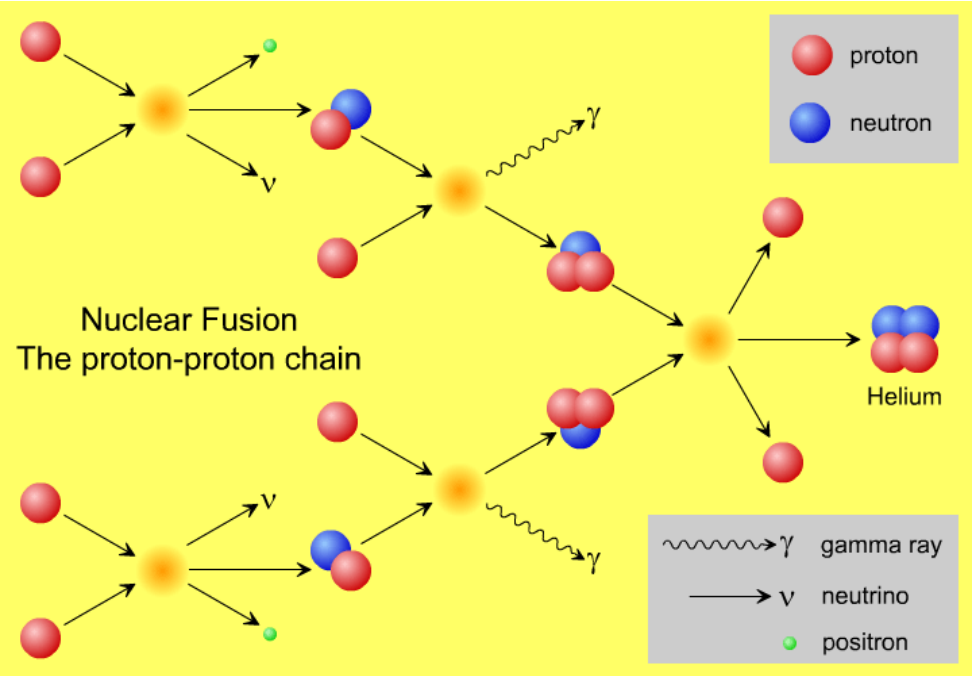
I objašnjava mnogo toga

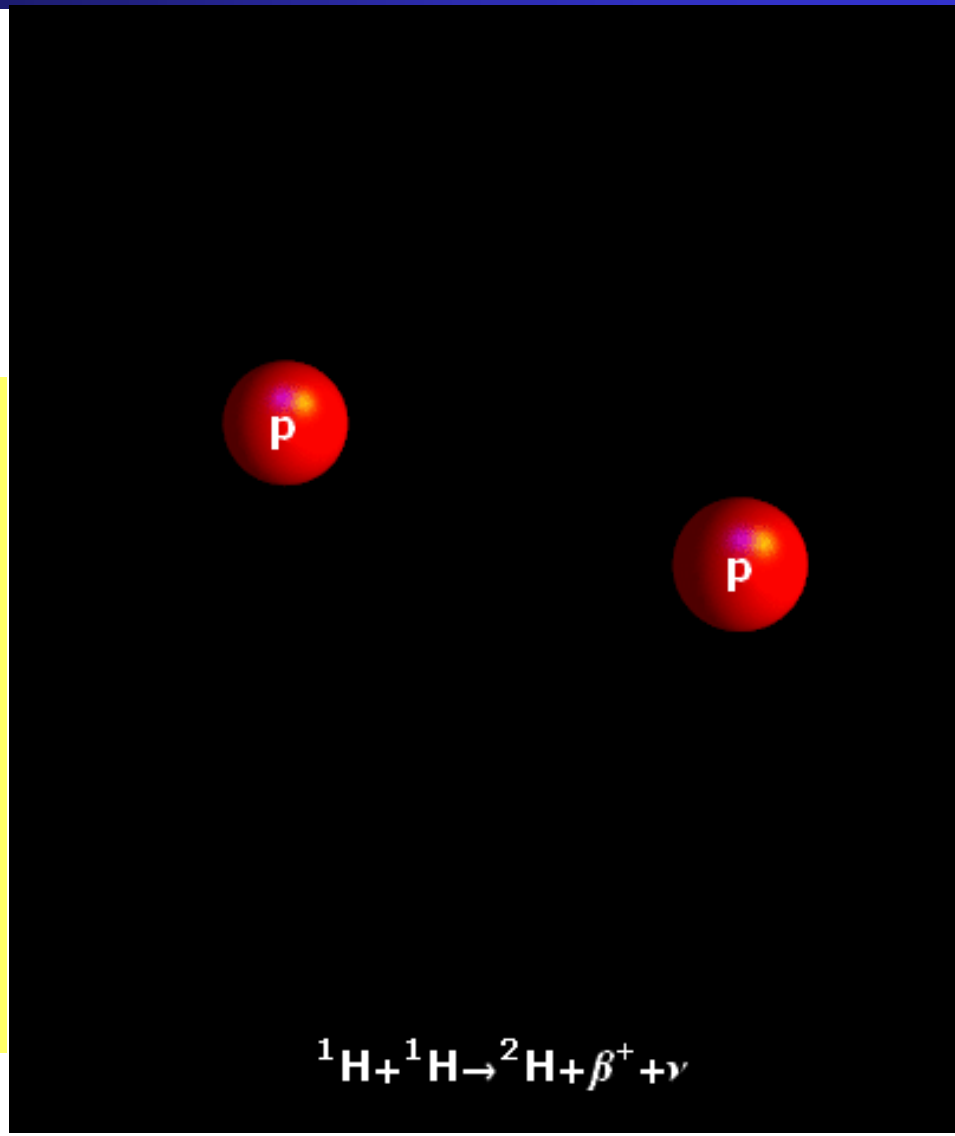


$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\psi} \not{D} \psi + h.c. + \psi_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$

Primjer: fuzija u suncu

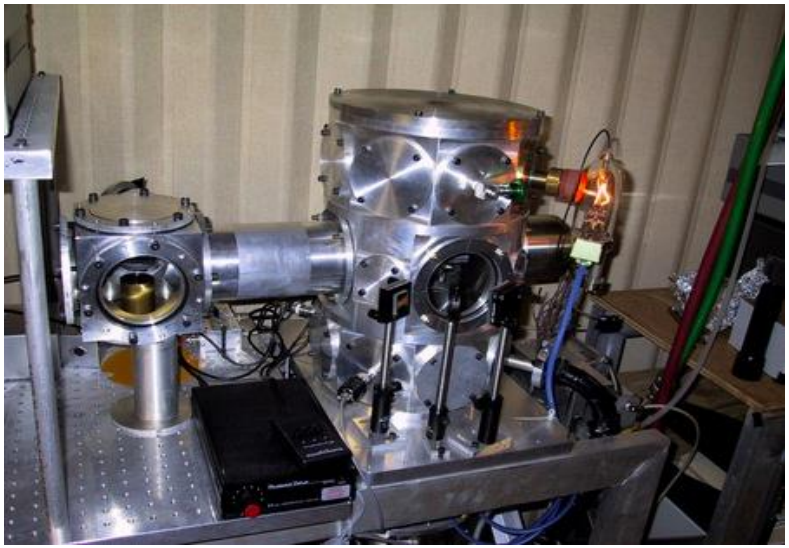


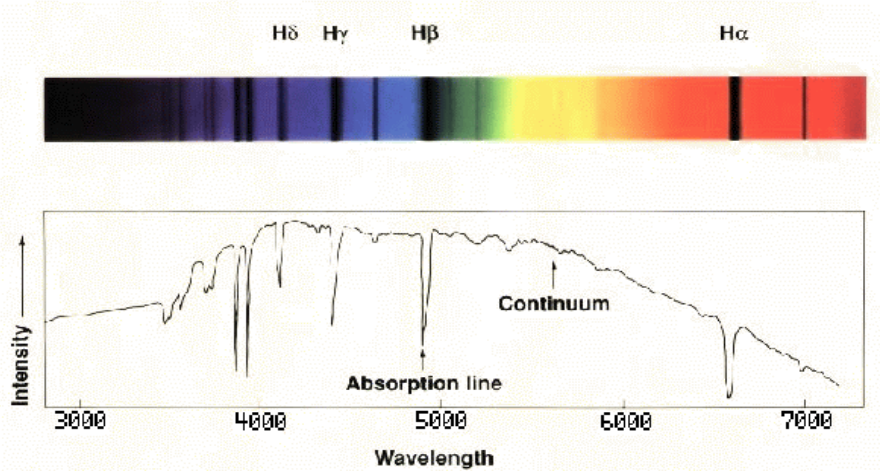


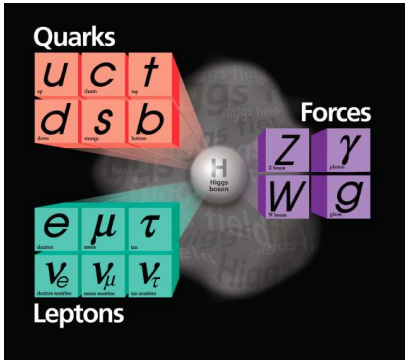


Na zemlji i u cijelom svemiru

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



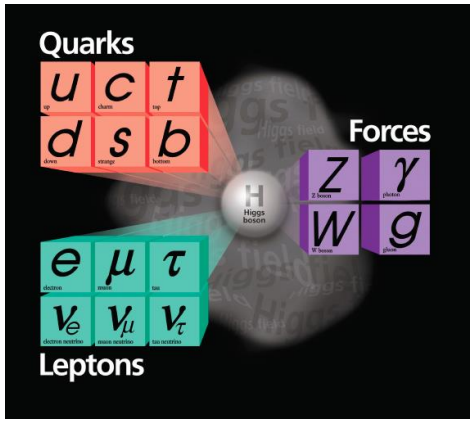




Zašto većina nas mislimo da SM ne može biti kraj priće

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

SM NE objašnjava

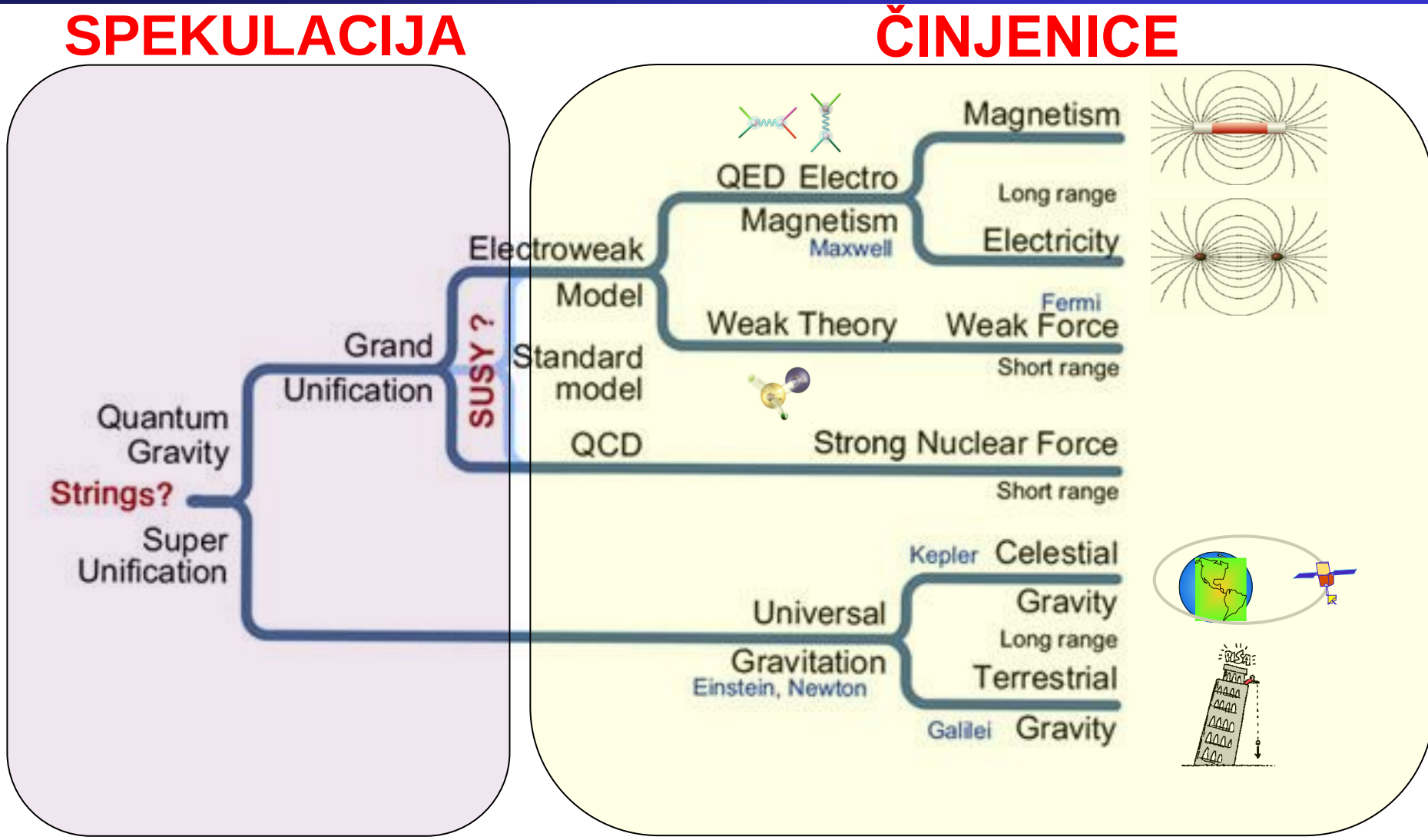


- Zašto 3 generacije?
- Zašto je tako fino podešeno?
- Zašto su mase čestica tako različite
- > 20 free parameters
  - masses, couplings, …
- Where did all the antimatter go?
- Does the Unification go on?

And most importantly:

- WHAT ABOUT GRAVITY?

Fizika voli UJEDINITI
Ide li to dalje?

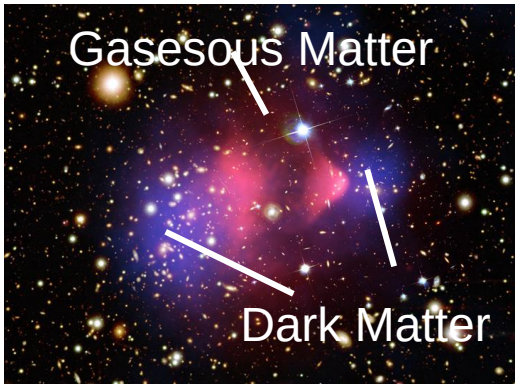


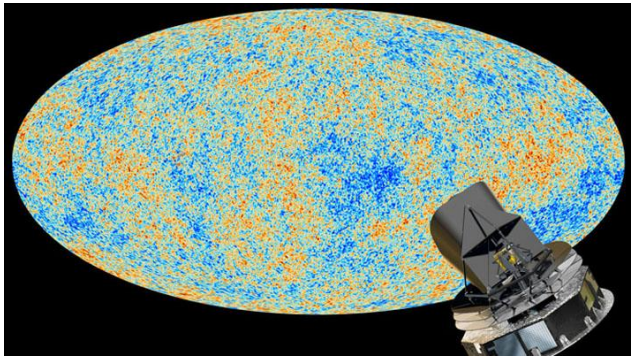
Zašto ZNAMO da SM nikako ne može biti kraj priće

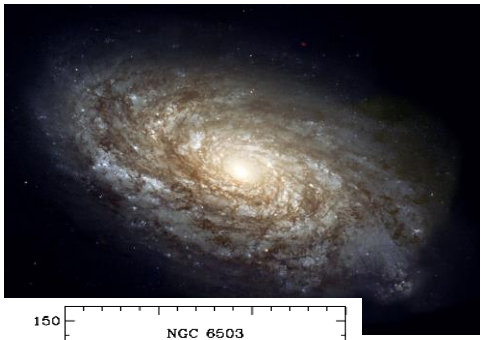
Postoje opažanja u vidljivom svemiru koje SM nikako ne može objasniti

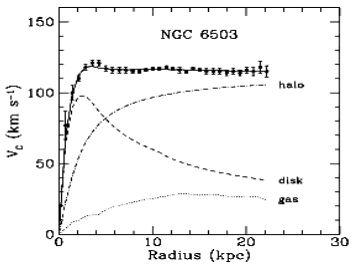
Huge amounts of invisible matter:

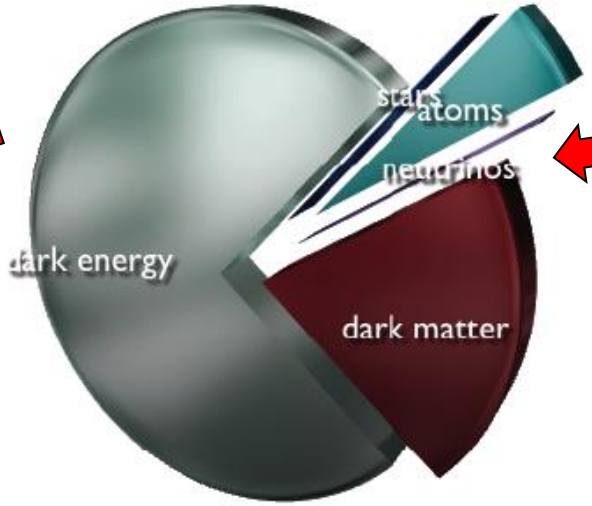
“DARK MATTER”

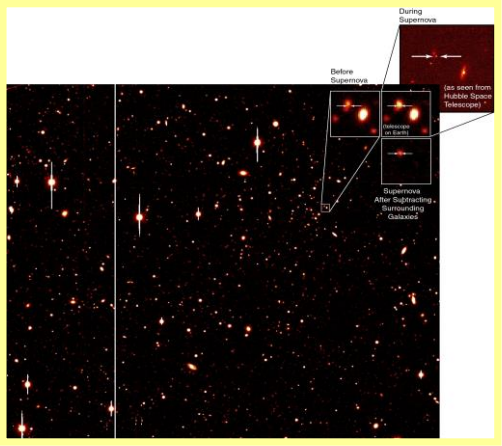








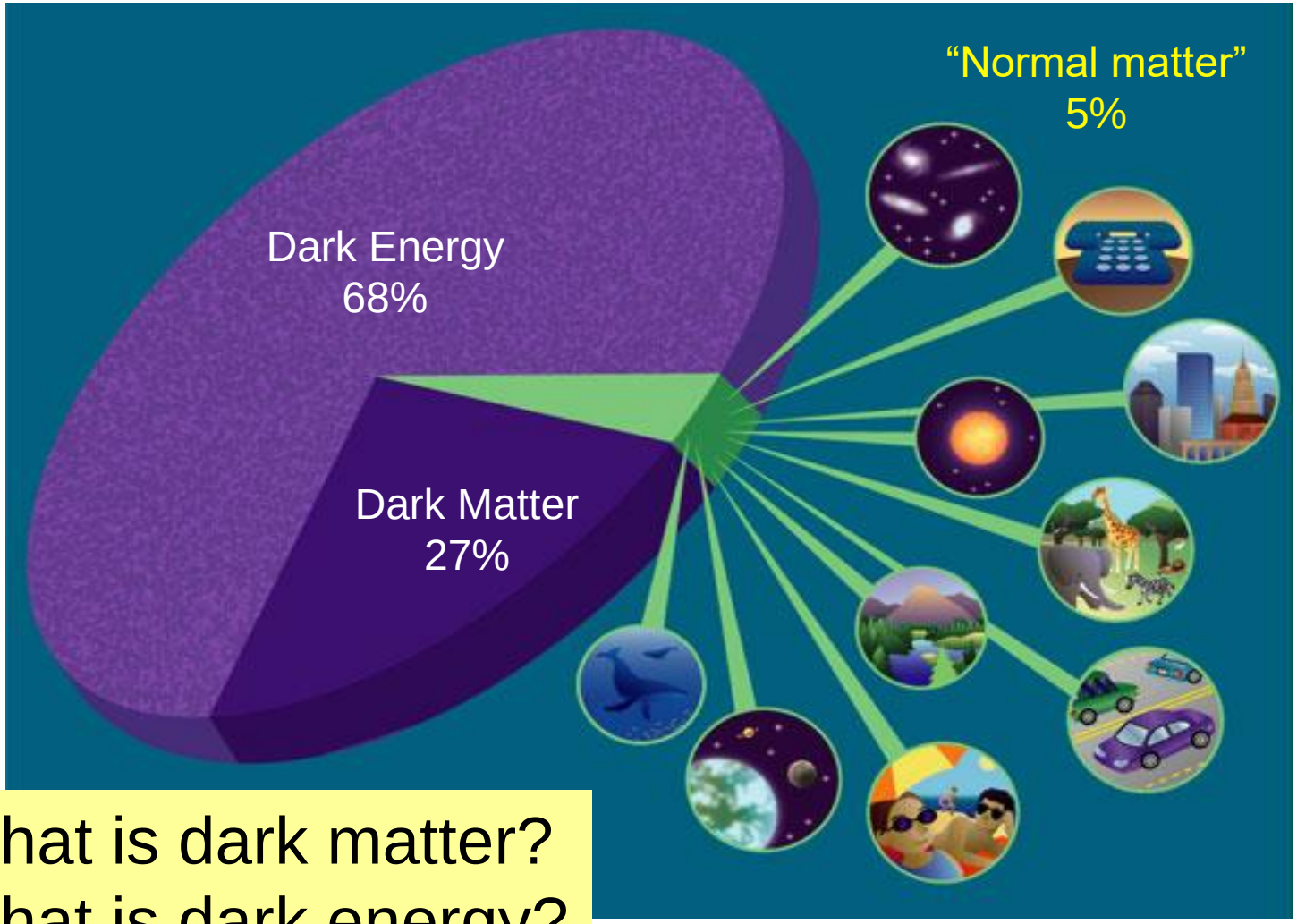




The expansion of the universe is accelerating:

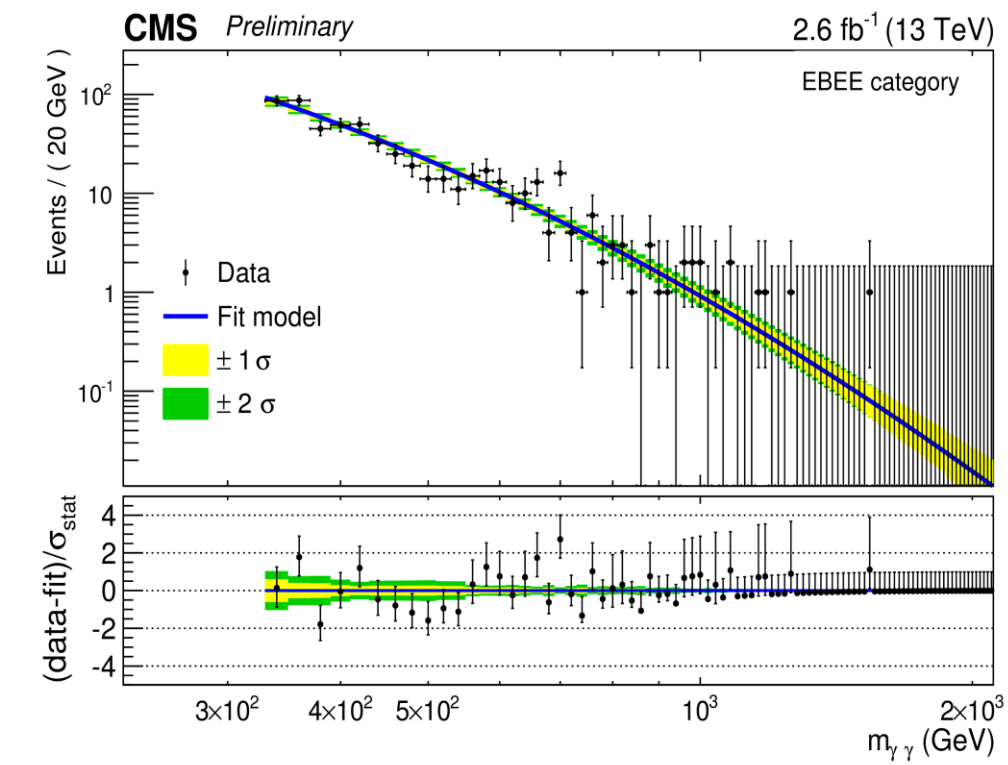
“DARK ENERGY”

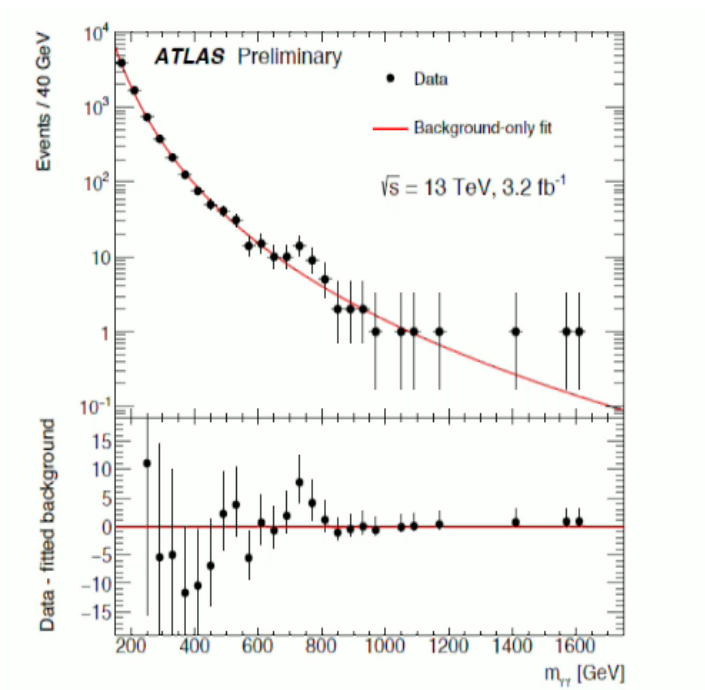
What is the Universe made of?



What is dark matter?
What is dark energy?

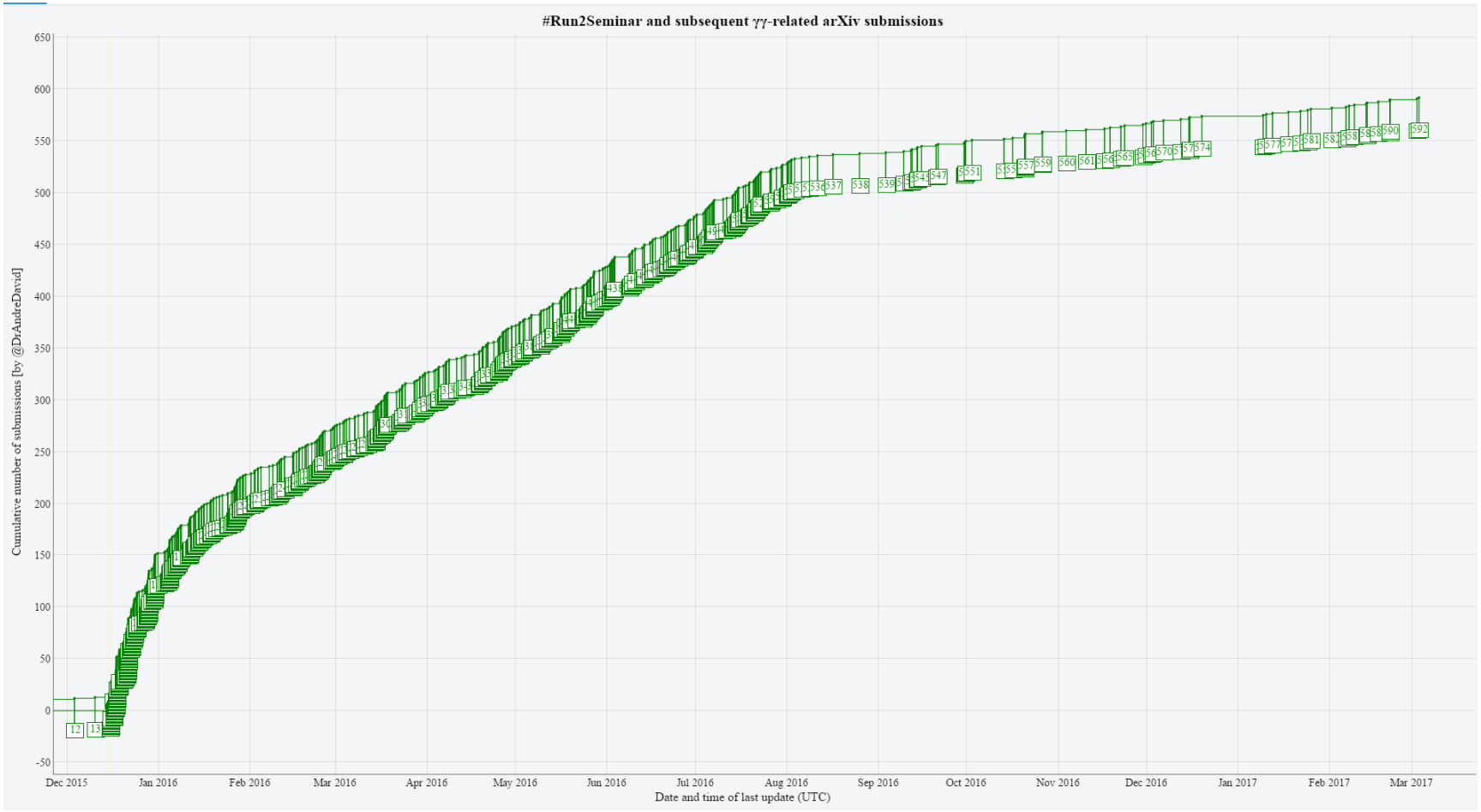
2015: Naznake nove čestice?



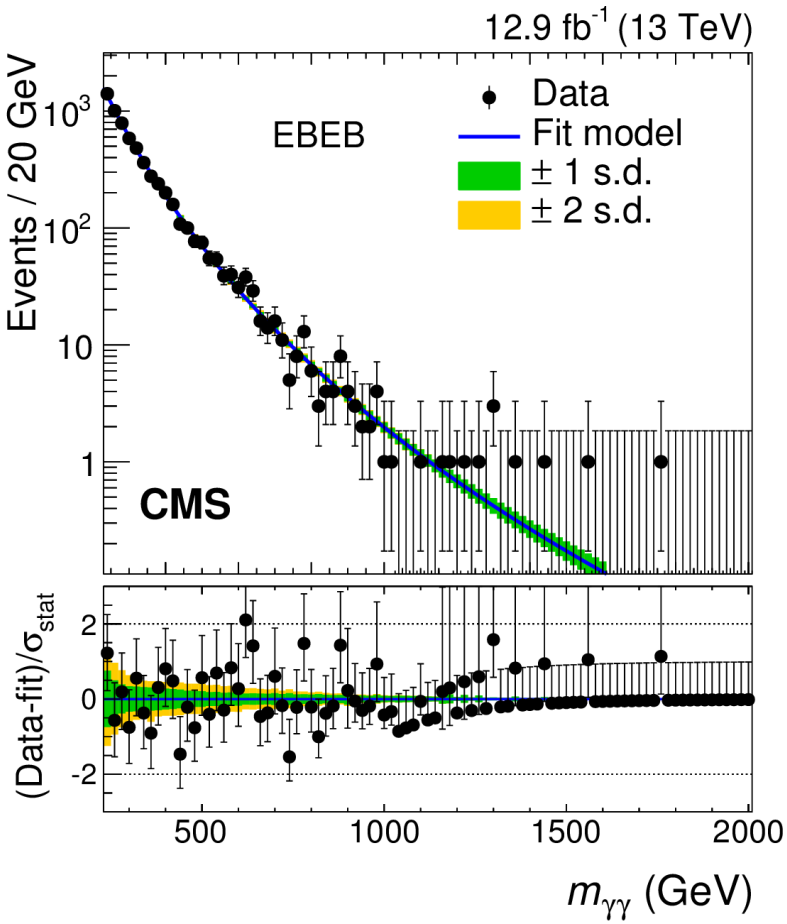


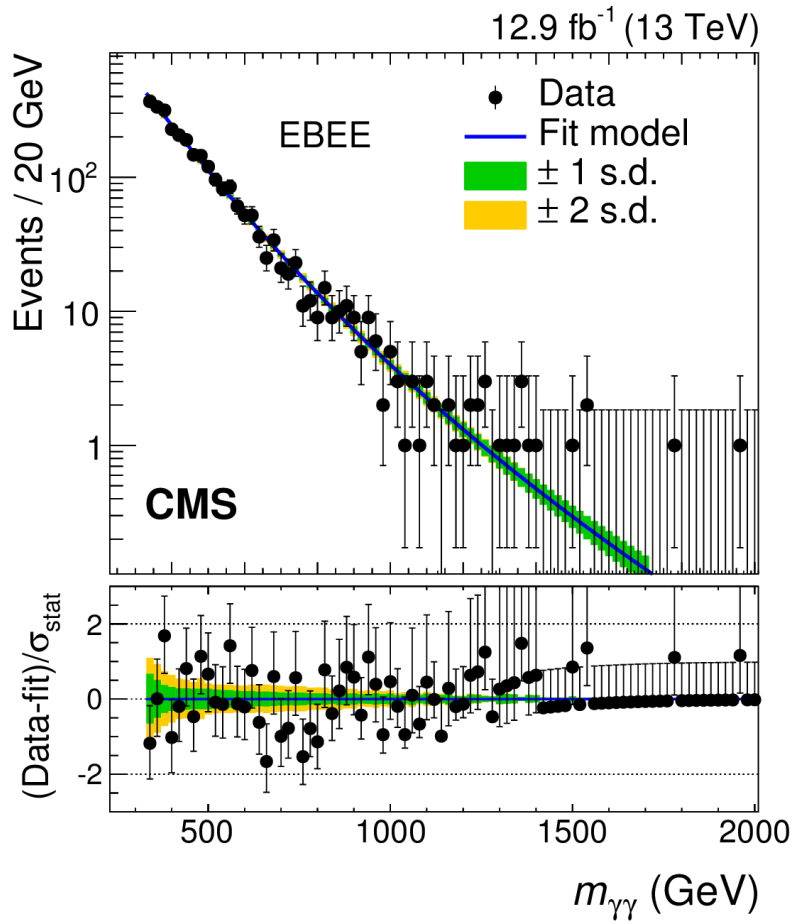
Signifikantnost viška događaja između 3 i 4 σ u oba eksperimenta

2015: Naznake nove čestice?



…ipak se statistika poigrala s nama



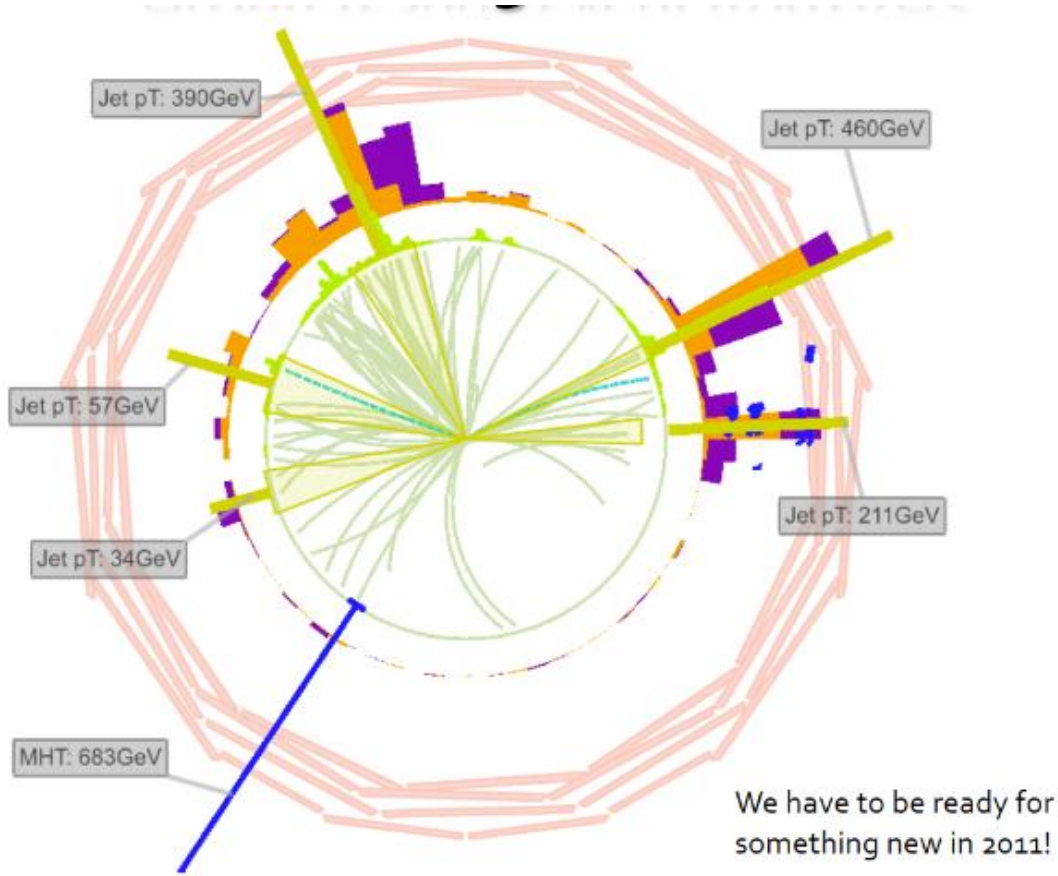


Može li nam LHC nešto reći o prirodi tamne materije?

Može

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!