

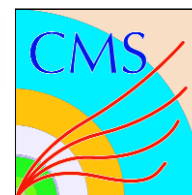


Croatian Teachers Programme
CERN, 26-28.3.2018

Uvod u Fiziku elementarnih čestica

Leptons	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	Force Carriers
	e electron	μ muon	τ tau	
Quarks	u up	c charm	t top	γ photon
	d down	s strange	b bottom	g gluon
				Z Z boson
				W W boson

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CMS Kolaboracija (CERN)*



Standard Model of FUNDAMENTAL PARTICLES AND INTERACTIONS

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

FERMIONS

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

Leptons spin = 1/2		
Flavor	Mass GeV/c ²	Electric charge
ν_e electron neutrino	$<1 \times 10^{-8}$	0
e electron	0.000511	-1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	-1
ν_τ tau neutrino		
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

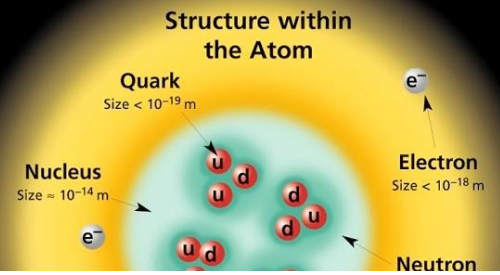
BOSONS

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 particles interact by exchanging gluons.



Što znamo o temeljnoj gradnji svemira

Spin is the quantum number of the proton.
The energy of a proton in cross-section is $E = mc^2$, where $m = 1.67 \times 10^{-27}$ kg.

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^{-41}	0.8	1	25	Not applicable to quarks
for two u quarks at:	10^{-41}	10^{-4}	1	60	Not applicable to hadrons
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

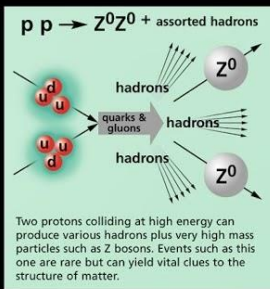
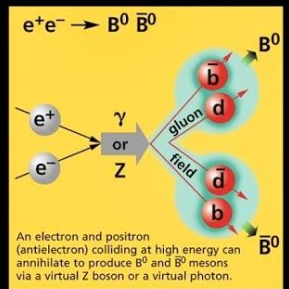
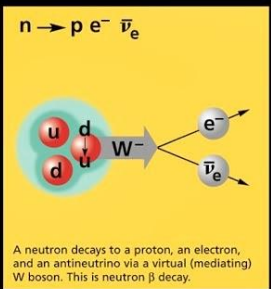
Symbol	Name	Quark content	Electric charge	Mass GeV/c ²	Spin
π^+	pion	u \bar{d}	+1	0.140	0
K ⁻	kaon	s \bar{u}	-1	0.494	0
ρ^+	rho	u \bar{d}	+1	0.770	1
B ⁰	B-zero	d \bar{b}	0	5.279	0
η_c	eta-c	c \bar{c}	0	2.980	0

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., Z⁰, γ , and $\eta_c = c\bar{c}$, but not K⁰ = 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.



The Particle Adventure

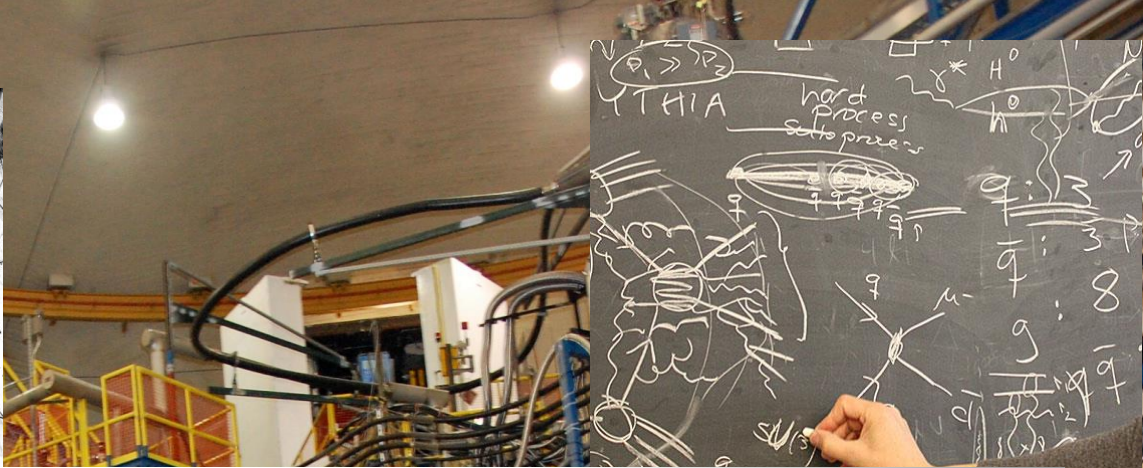
Visit the award-winning web feature *The Particle Adventure* at <http://ParticleAdventure.org>

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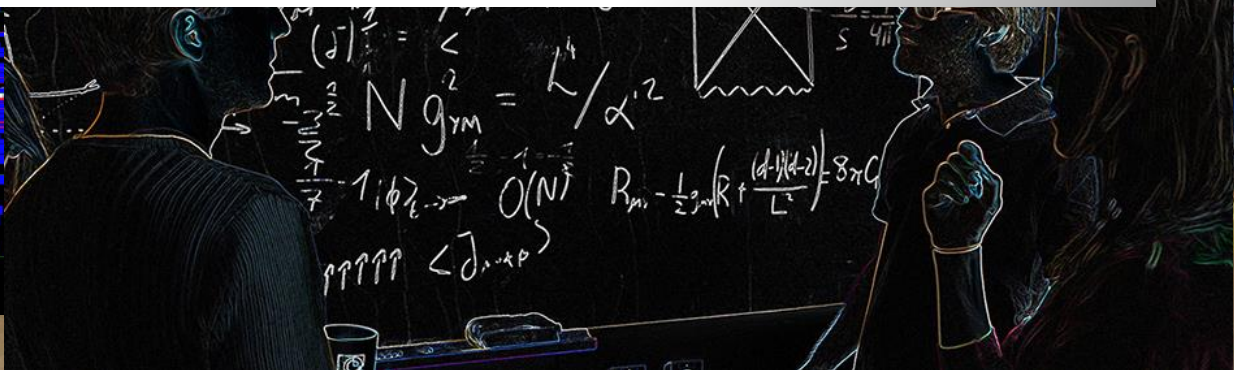
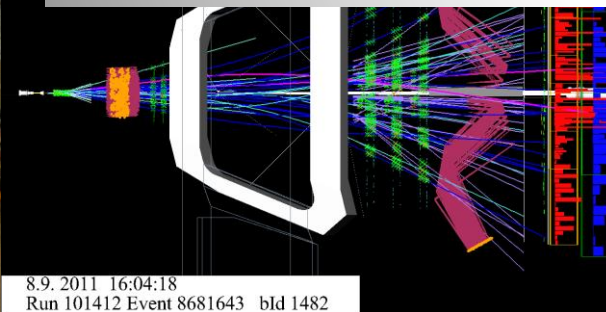
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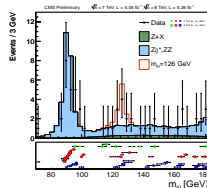
<http://CPEPweb.org>



Preko 100 godina plodonosne suradnje Teorije i Eksperimenta



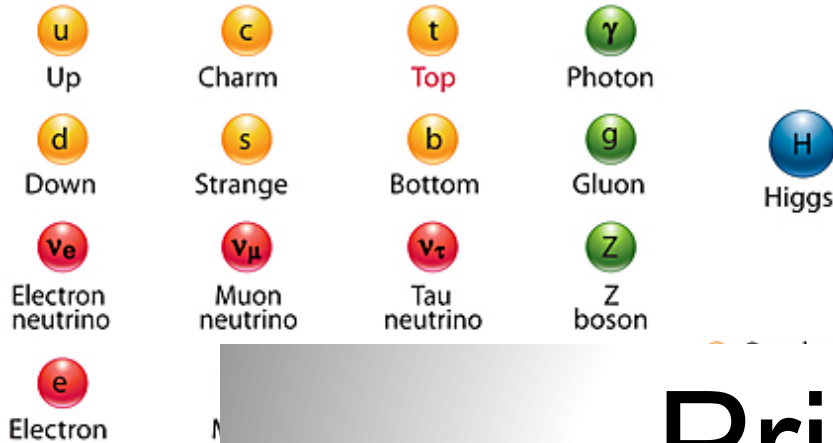
Što su otvorena
pitanja?



$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\psi}\not{\partial}\psi + \text{h.c.} + \chi_i y_{ij} \chi_j \phi + \text{h.c.} + \frac{1}{2} \partial_\mu \phi^2 - V(\phi)$$

?
?
?

The Standard Model



Pričam
Profesorima fizike

$$\begin{aligned}
 & -ie(W_\mu^+ A_\nu - W_\nu^+ A_\mu) + ig'c_w(W_\mu^+ Z_\nu - W_\nu^+ Z_\mu)^2 + \\
 & -\frac{1}{4}|\partial_\mu Z_\nu - \partial_\nu Z_\mu + ig'c_w(W_\mu^- W_\nu^+ - W_\mu^+ W_\nu^-)|^2 + \\
 & -\frac{1}{2}M_\eta^2\eta^2 - \frac{gM_\eta^2}{8M_W}\eta^3 - \frac{g'^2M_\eta^2}{32M_W}\eta^4 + |M_W W_\mu^+ + \frac{g}{2}\eta W_\mu^+|^2 + \\
 & + \frac{1}{2}|\partial_\mu\eta + iM_Z Z_\mu + \frac{ig}{2c_w}\eta Z_\mu|^2 - \sum_f \frac{g}{2} \frac{m_f}{M_W} \bar{\Psi}_f \Psi_f \eta
 \end{aligned}$$

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

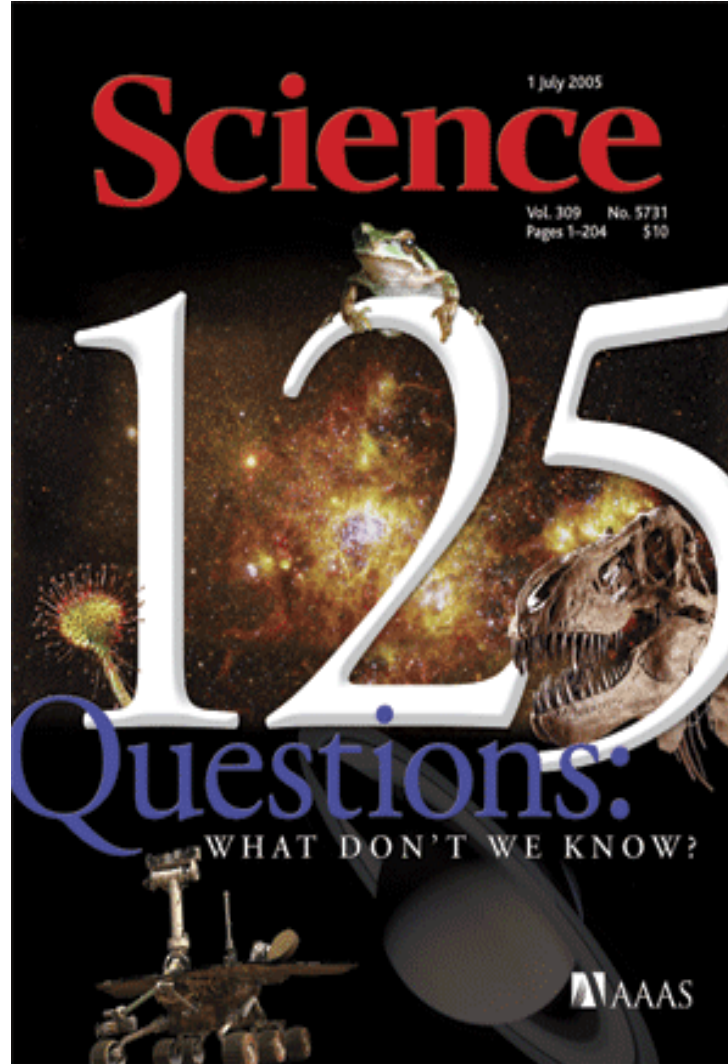
“Physicists learned to realize that whether they like a theory or they don’t like a theory is not the essential question. Rather, it’s whether or not the theory gives predictions that agree with experiments”

Richard Feynman

“ I think, however, that there isn ’ t any solution to this problem of education other than to realize that the best teaching can be done only when there is a direct individual relationship between a student and a good teacher – a situation in which the student discusses the ideas, thinks about the things, talks about the things”

Richard Feynman

Velika pitanja!



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



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

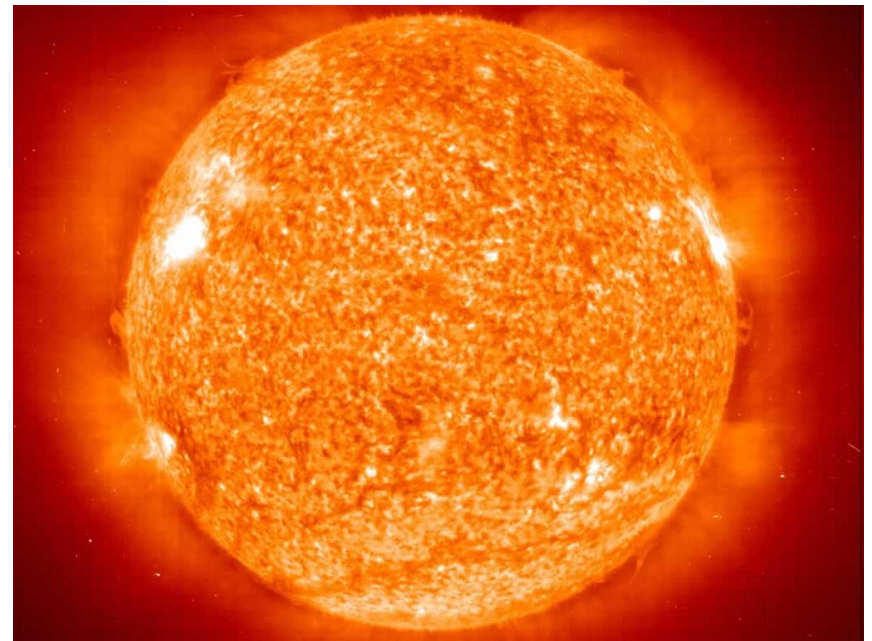
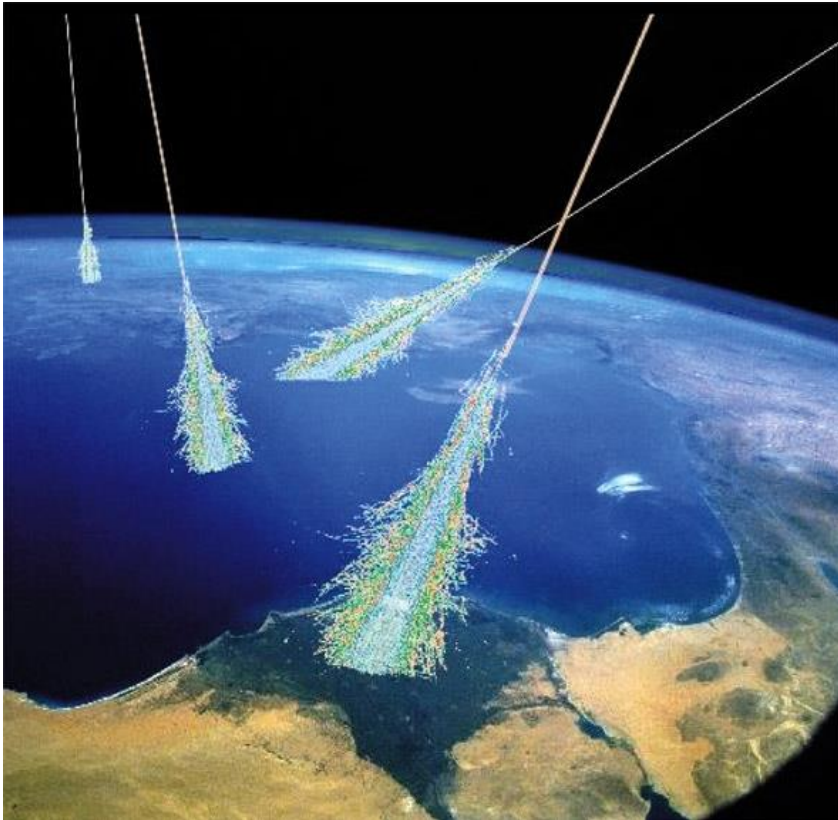
THE QUESTIONS

The Top 25

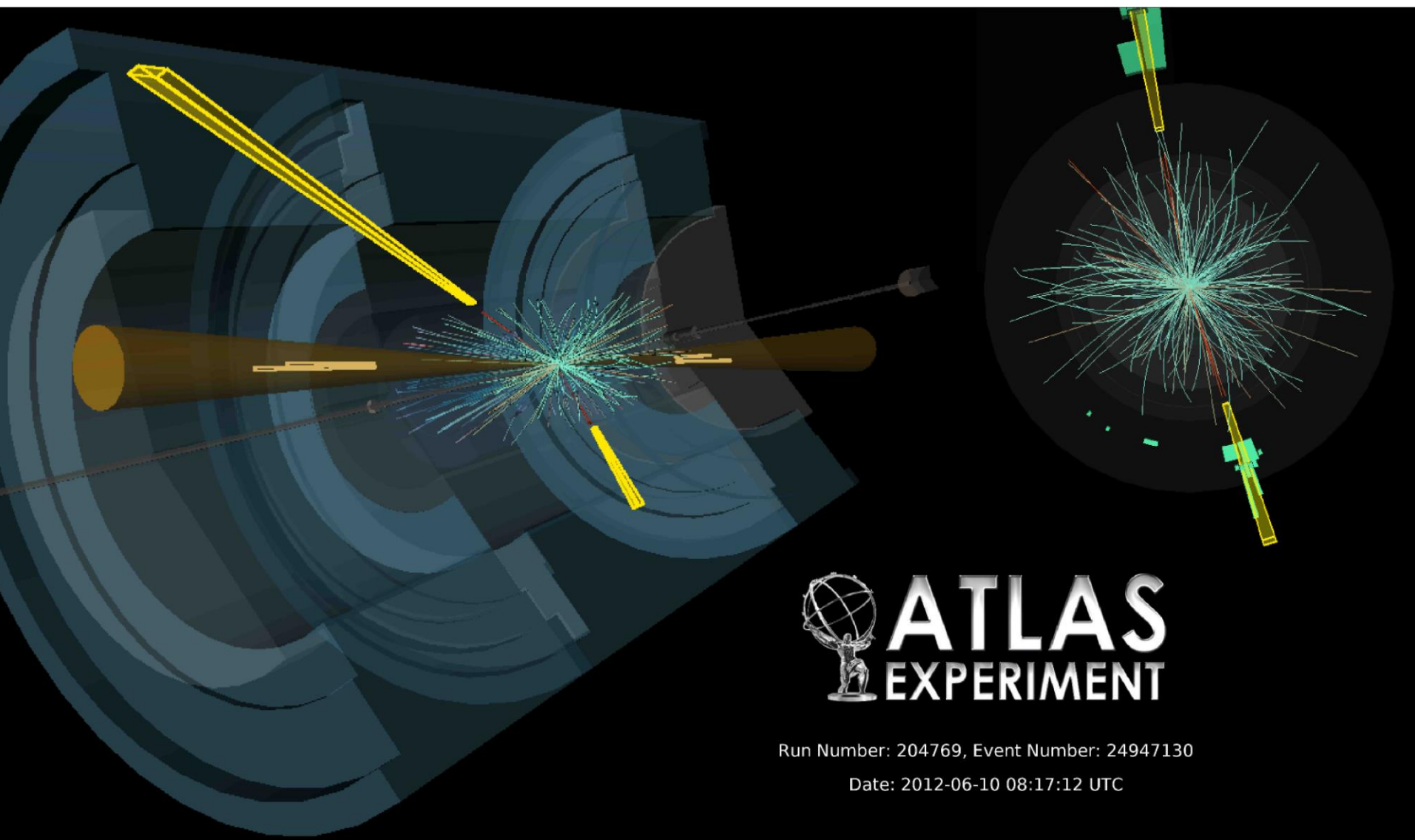
Essays by our news staff on 25 big questions facing science over the next quarter-century.

- > 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?

Fenomeni: u prirodi



Fenomeni: u laboratoriju



 **ATLAS**
EXPERIMENT

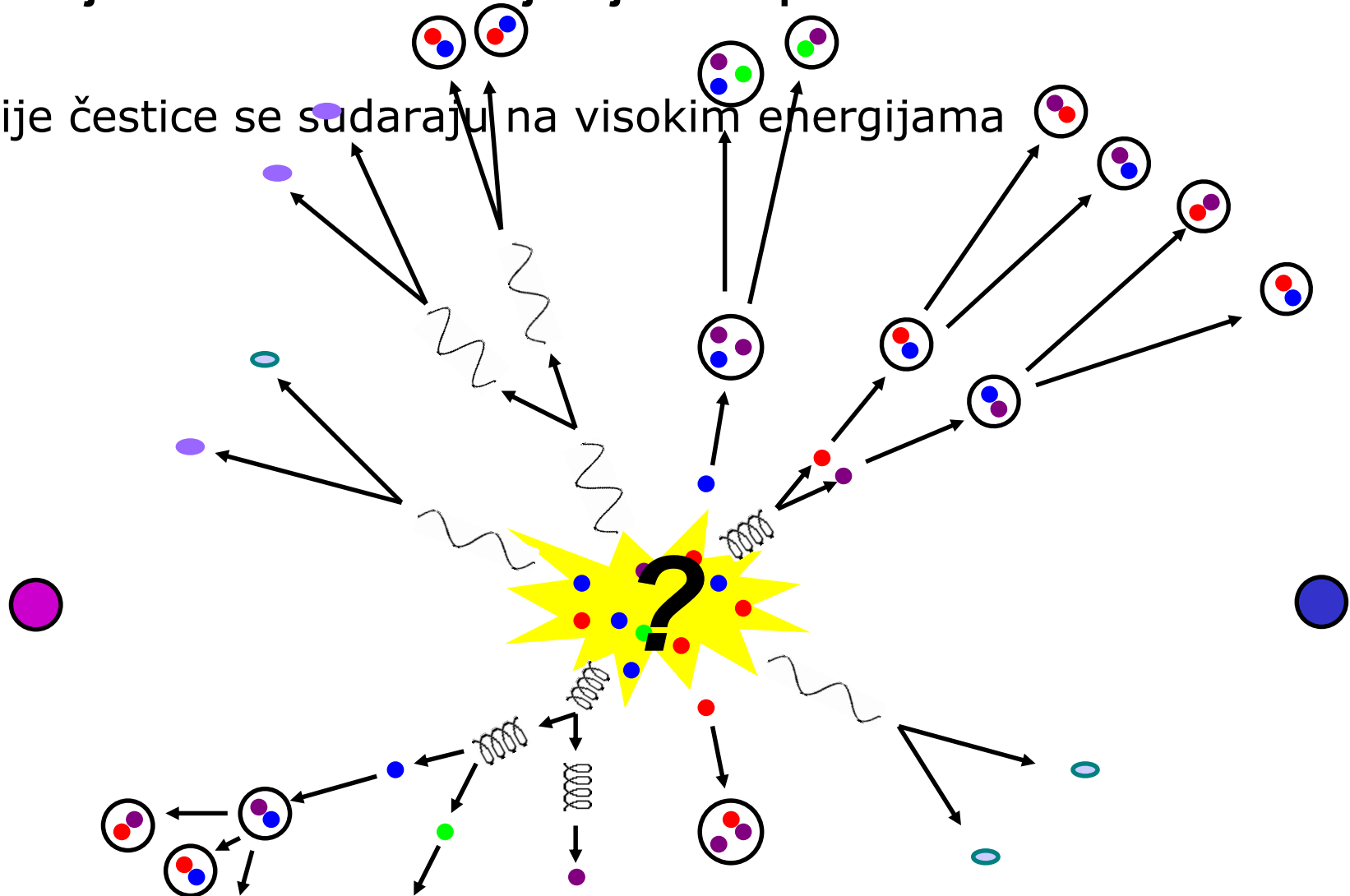
Run Number: 204769, Event Number: 24947130

Date: 2012-06-10 08:17:12 UTC

Fenomeni: sudari čestica

Stvaraju se nove čestice koje mjerimo i proučavamo

Dvije čestice se sudaraju na visokim energijama



fizika elementarnih čestica: Moderno ime za stara pitanja

**Koji su gradivni
elementi svijeta?**

**Kako se
ponašaju?**

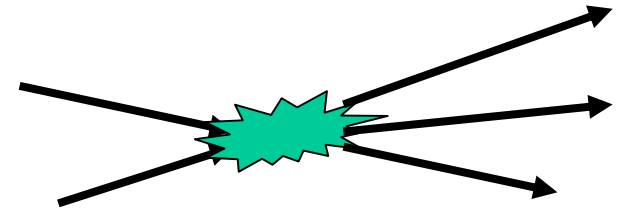
Kako eksperimentalno pristupiti EČ

Sve informacije o elementarnim česticama potječu iz triju izvora:

1. Raspršenja

Čestica na metu ili sudar dviju snopa

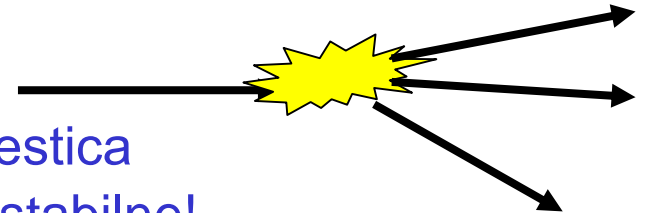
Informacija o interakciji se dobiva iz mjerenja čestica koje proizlaze iz raspršenja (masa, energija, pravac, impuls, spin, ...)



2. Raspadi

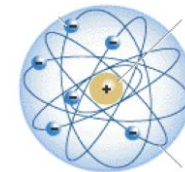
Mjerenje ostataka spontanog raspada čestica

Od svih poznatih čestica: gotovo sve nestabilne!

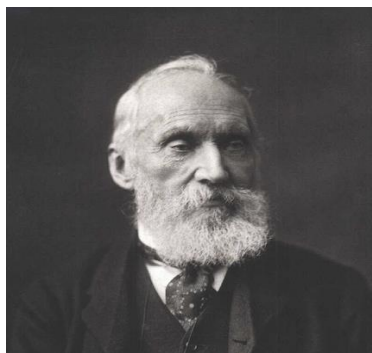


3. Vezana stanja

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



Fizika na kraju 19. stoljeća



William Thomson
(Lord Kelvin)

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

“There is nothing new to be discovered in Physics now. All that remains is more and more precise measurements.”

(Lord Kelvin, 1900)

A periodic table of elements with a color-coded layout. The elements are arranged in rows and columns, with colors ranging from yellow to blue. The table includes elements from Hydrogen (H) to Oganesson (Og).

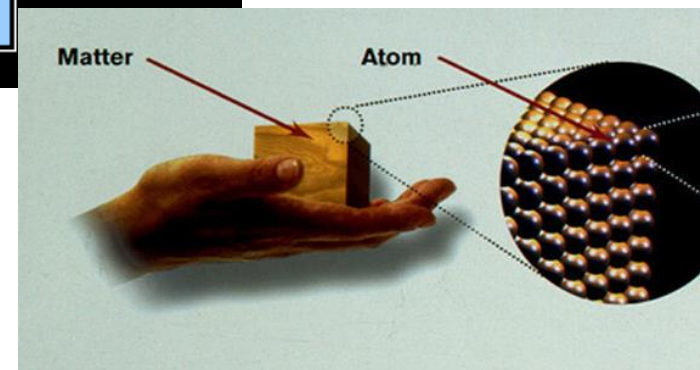
H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	Lu	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	Lr	Rf	Db	Sg	Bh	Hs	Mt									
		La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb		
		Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No		

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

Elementarne čestice: do 1897

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

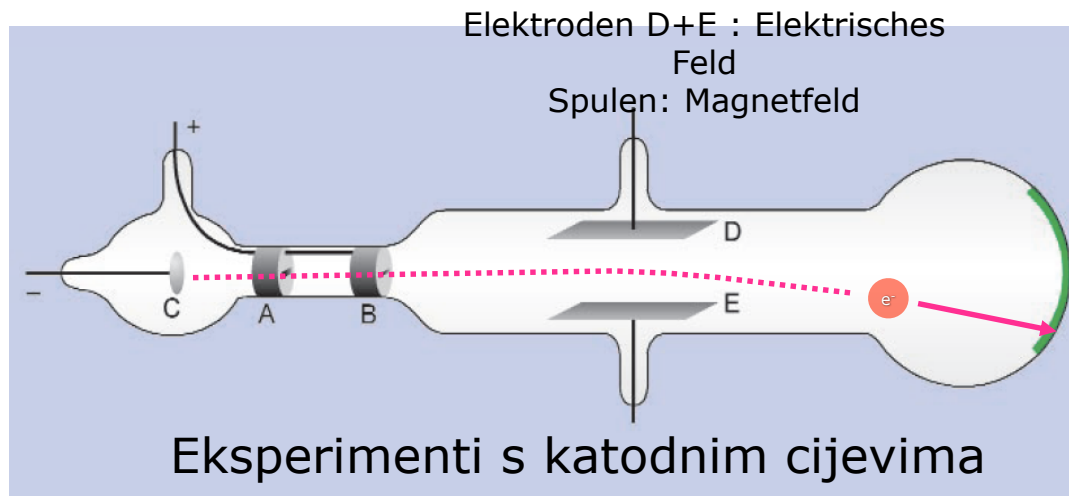
*Lanthanide Series	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
+Actinide Series	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr



1897, prva elementarna čestica: Elektron



J.J. Thomson



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

(Struje u katodnim cijevima se sastoje od čestica)

$$m_e \approx M_H/1836$$

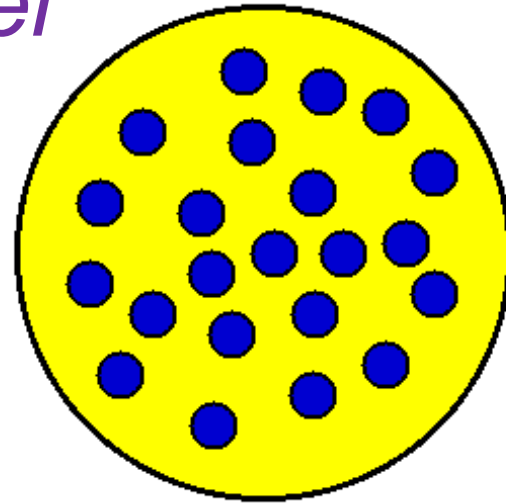
“Could anything at first sight seem more impractical than a body which is so small that its mass is an insignificant fraction of the mass of an atom of hydrogen?” (J.J. Thomson)



ATOMI NISU ELEMENTARNI!

Thomsonov model atoma

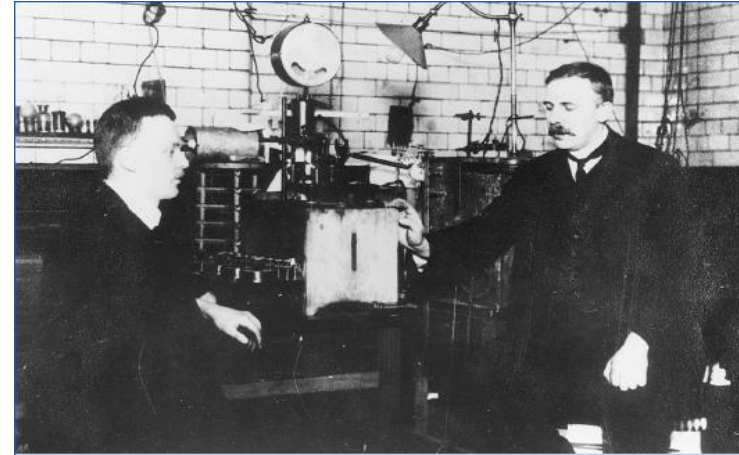
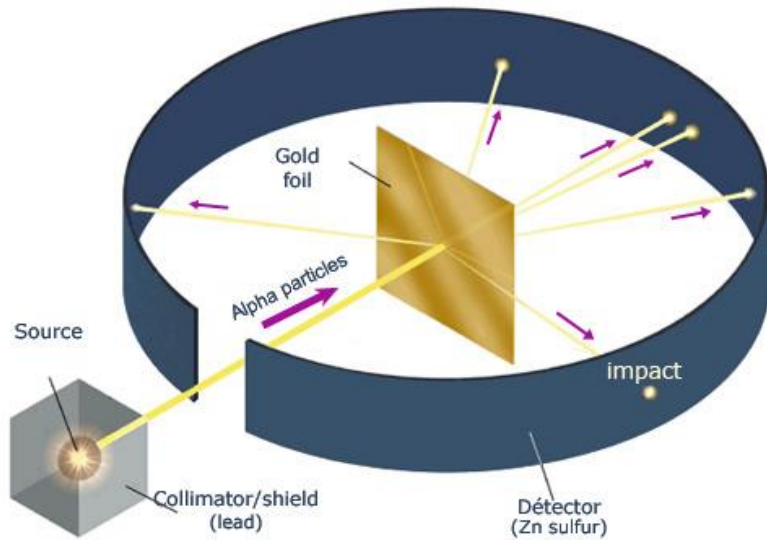
”Plum pudding model”



Thomsonov model atoma:

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

Otkriće atomske jezgre: Rutherfordov eksperiment

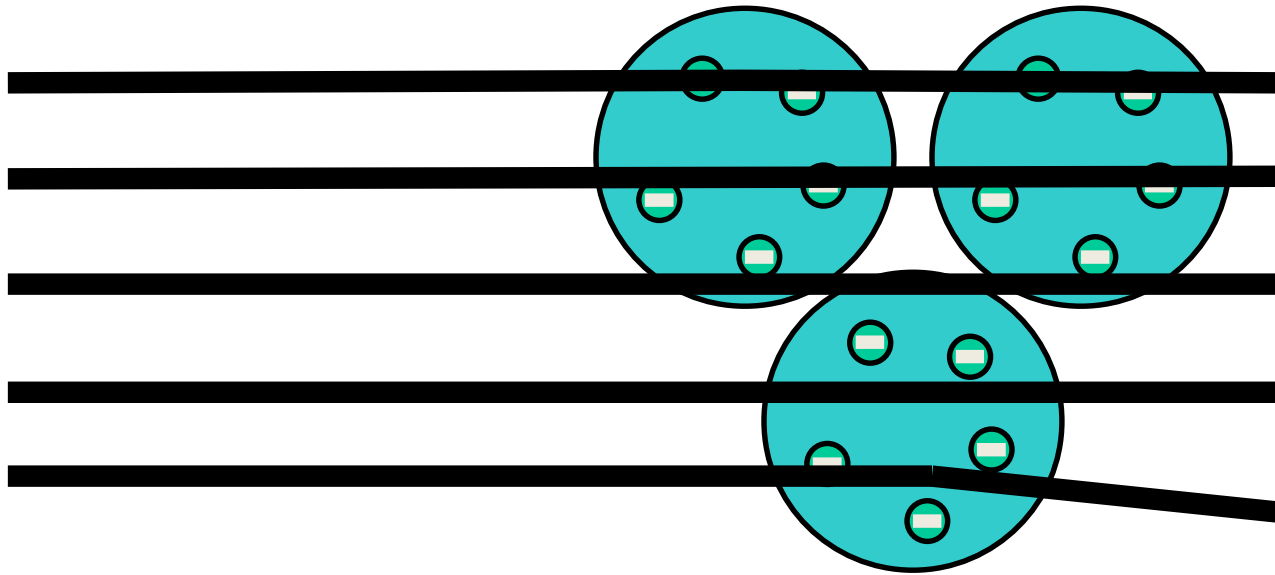


Ernest Rutherford (r) und Hans Geiger (l)
in Manchester

Bitni elementni eksperimenta

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

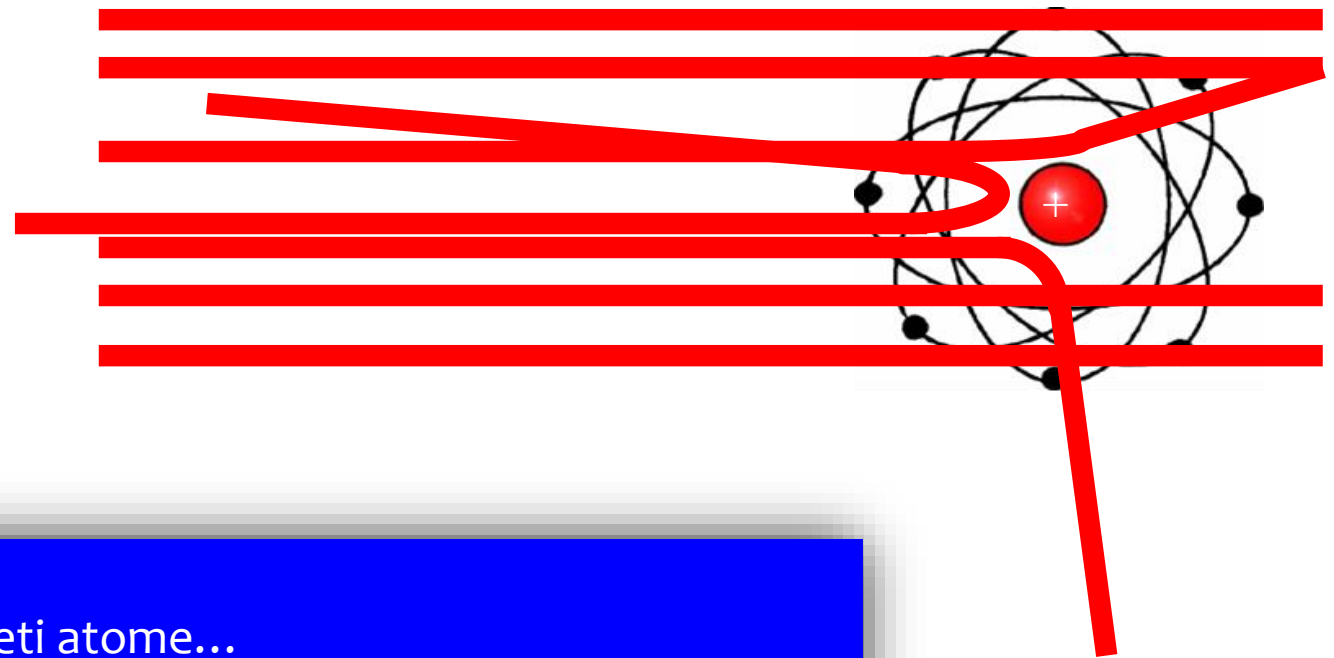
Thomsonov model atoma



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:

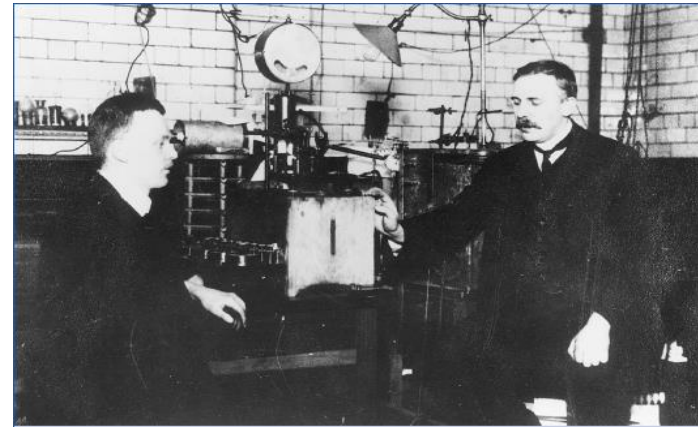
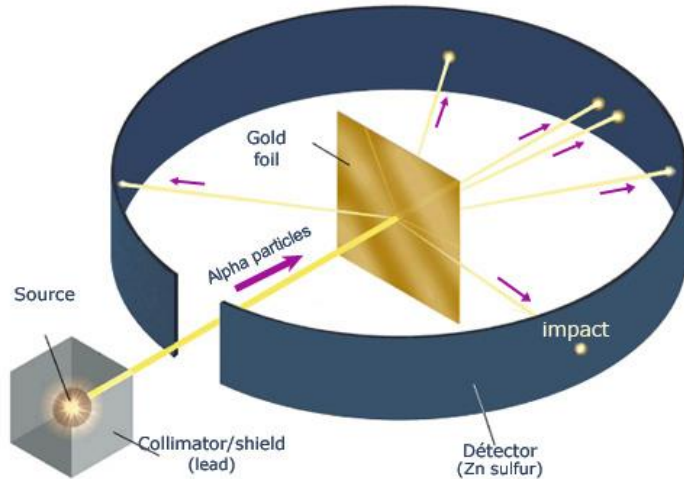
I dalje ne možemo vidjeti atome...

Negativni elektroni oko malog, gustog pozitivnog centra

Kakve eksperimentalne rezultate predviđa ovaj model?

Jezgra atoma je 100 000 puta manja od promjera atom!

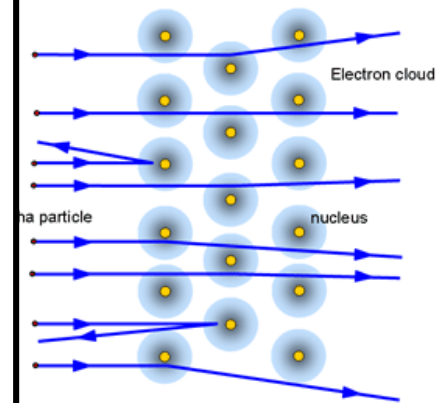
Otkriće atomske jezgre



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 $\sim c$



Einstein
(1905)

Masa / Energija

$$E = M c^2$$

Stvaranje
Novih čestica

KVANTNA FIZIKA

Fizika najmanjih dimenzija



Bohr
(1913)

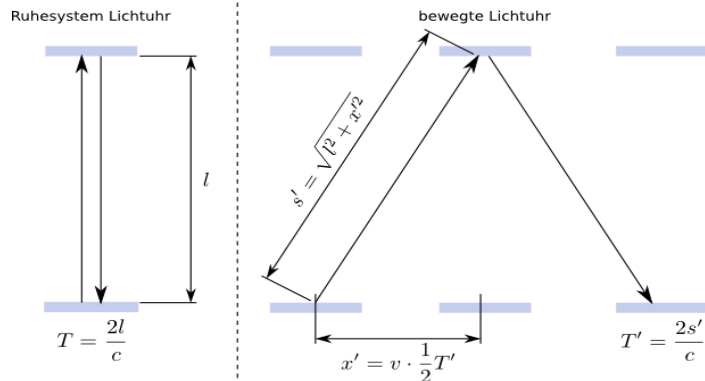
Val / Čestica

$$p = h / \lambda$$

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 promatrače



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



- Nema apsolutnog vremena ni prostora
- Dilatacija vremena - duljine

Masa i Energija

- Masa:

- Spremište energije čestica

- Ne ovisi o brzini

- “definirana”

$$M^2 c^4 = E^2 - p^2 c^2$$

- U miru: **$E = M c^2$**

- M je **Lorentz invarijanta**: ista u svim sustavima (E i p općenito nisu)

- c velik: mala masa = velika količina energije

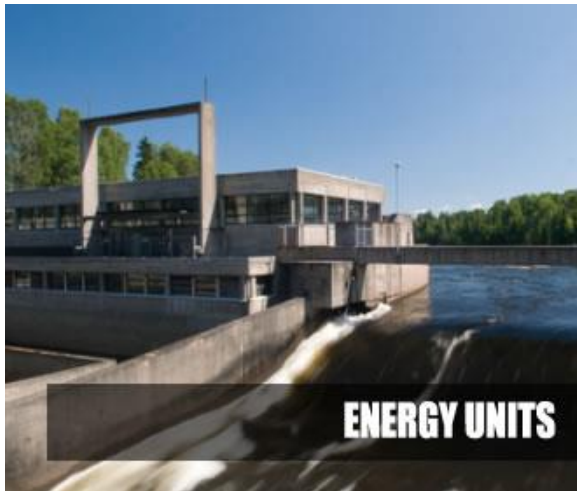


Jedinica za masu (SI): kg

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

masa čovjeka ≈ 100 kg

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



Jedinica za energiju (SI): J

Često se koristi u fizici:

eV (elektron volt)

$1 \text{ eV} = 1.6 \times 10^{-19} \text{ J}$

$1 \text{ GeV} = 10^9 \text{ eV}$

$$E = m$$

$$E = mc^2$$

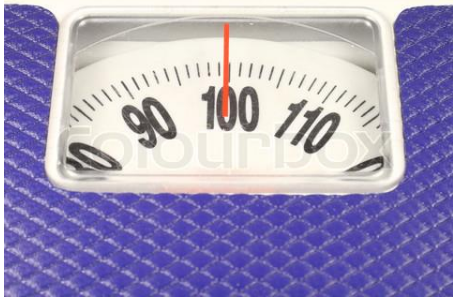
$E = mc^2$

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

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

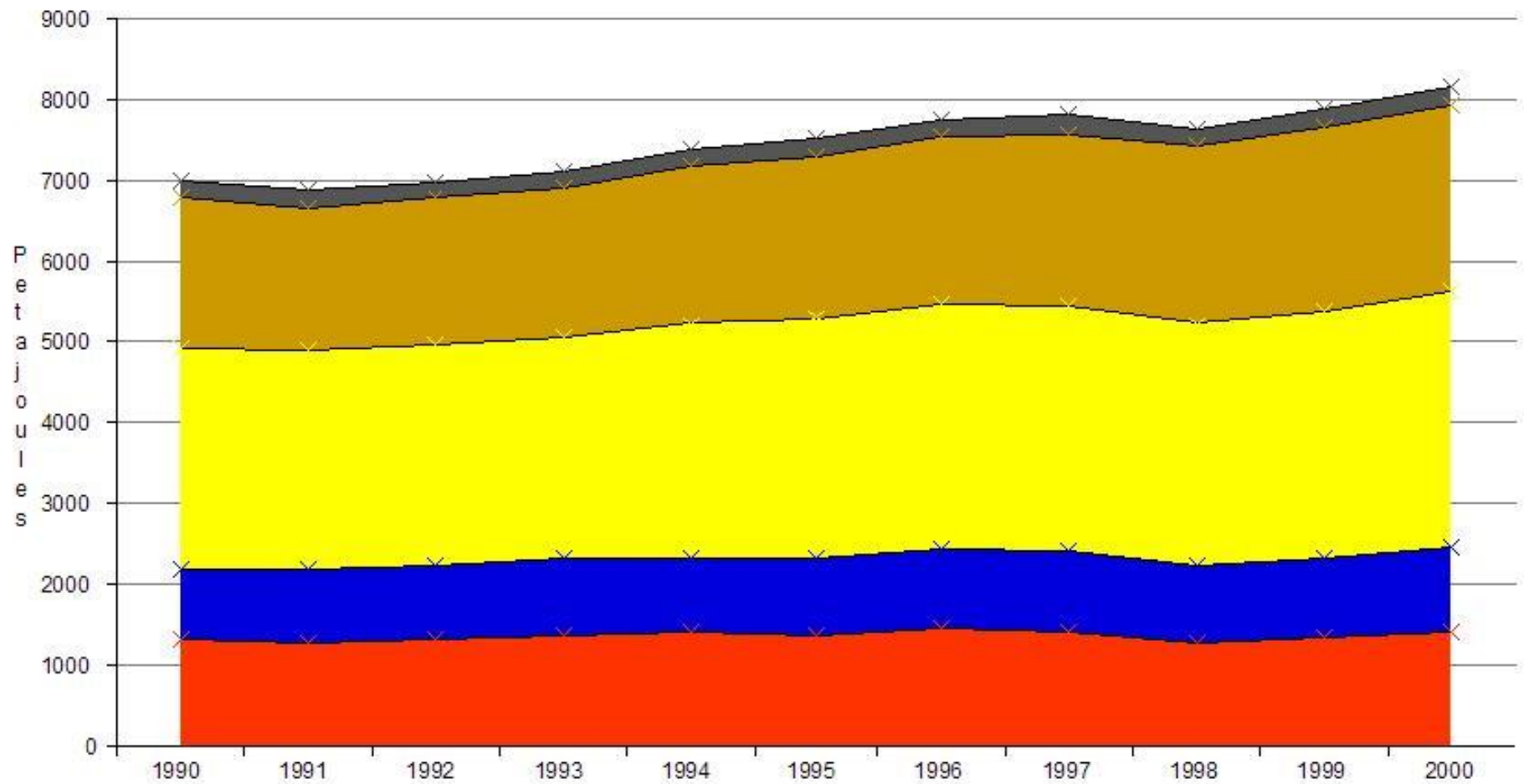
$$m = 100 \text{ kg}$$

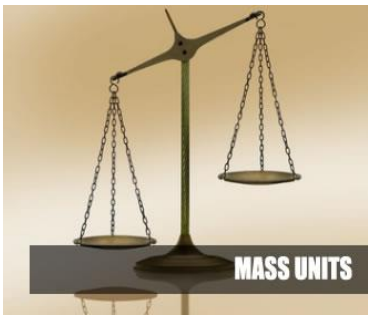
$$E = mc^2 \approx 10^{19} \text{ J}$$



TOTAL ENERGY CONSUMPTION IN CANADA (Petajoules)

Residential Commercial Industrial Transportation Agriculture





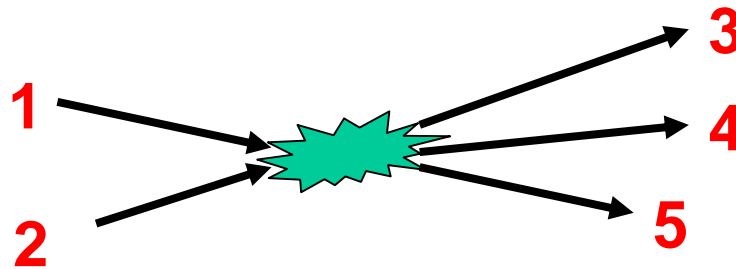
U fizici visokih energija

$$E = mc^2 \quad \longrightarrow \quad [m] = \text{GeV}/c^2$$

$$c = 1 \quad \longrightarrow \quad E = m \quad \longrightarrow \quad [m] = \text{GeV}$$

Očuvane veličine

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



– 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!

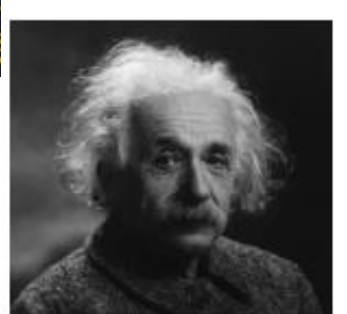
Masa nije očuvana

proton proton sudar na LHC-u



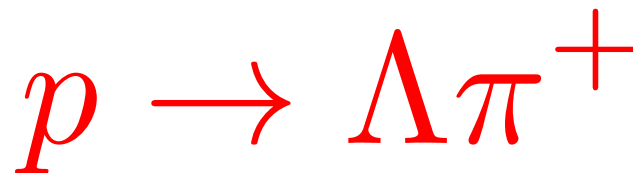
$$\sum_{i \in \text{final}} m_i \gg 2m_p$$

$$E = mc^2$$



Relativnost i raspad: Test

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

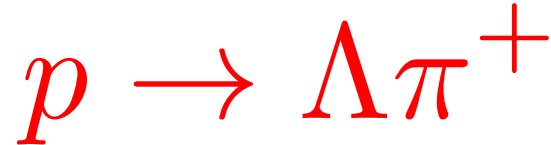


a) DA

b) NE

Relativnost i raspadi: Test

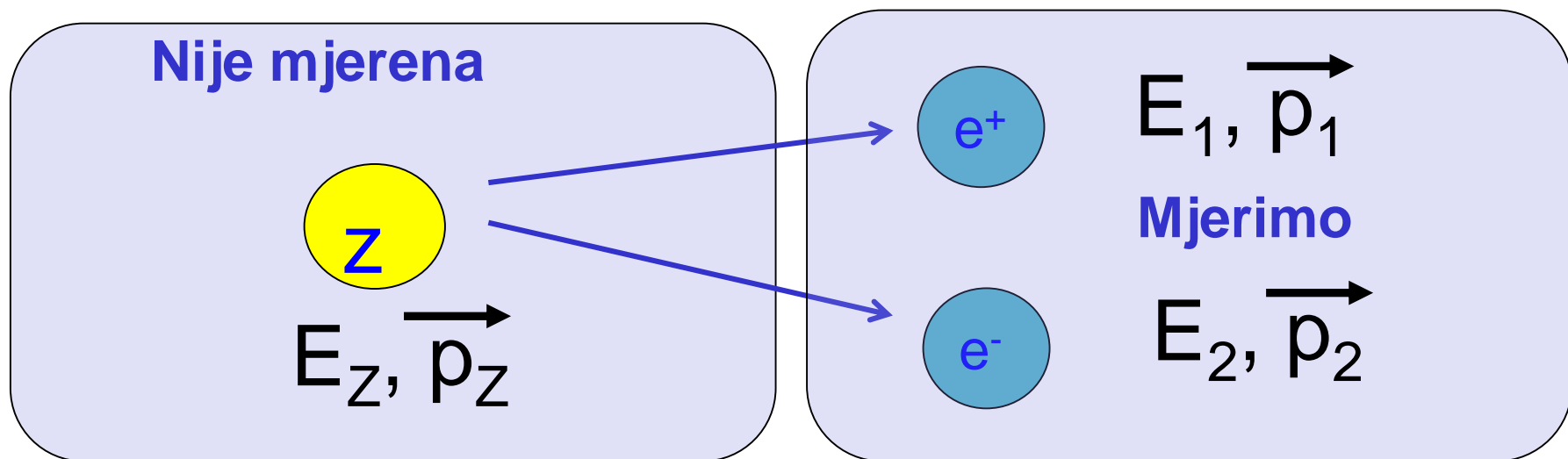
- Zbog očuvanja energije se proton u miru ne može raspasti na način



– $M(p)$ 938 MeV, $M(\Lambda)$: 1116 MeV, $M(\pi^+)$: 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 impulsa

$$E_Z = E_1 + E_2$$
$$\vec{p}_Z = \vec{p}_1 + \vec{p}_2$$

Invarijantna masa

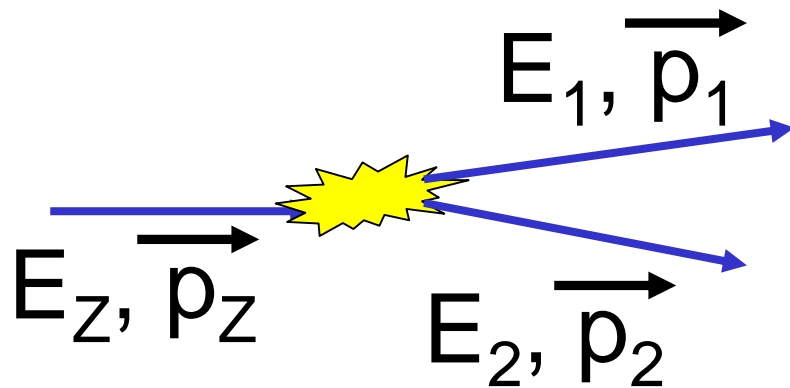
$$M_Z^2 = E_Z^2 - p_Z^2 = (E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2$$

Vježba: dodajte nedostajuće c faktore
(dimenzionalna analiza!)

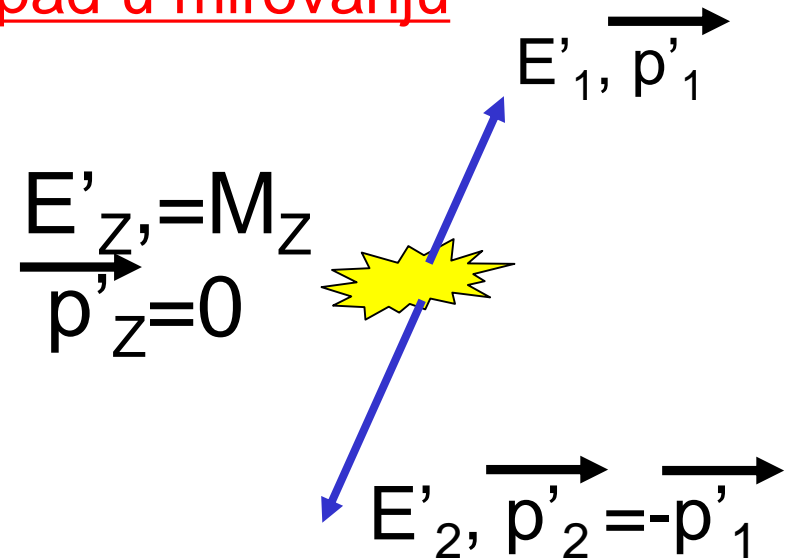
Izbor sustava

Možemo promatrati raspad u više mogućih sustava

Raspad u letu



Raspad u mirovanju

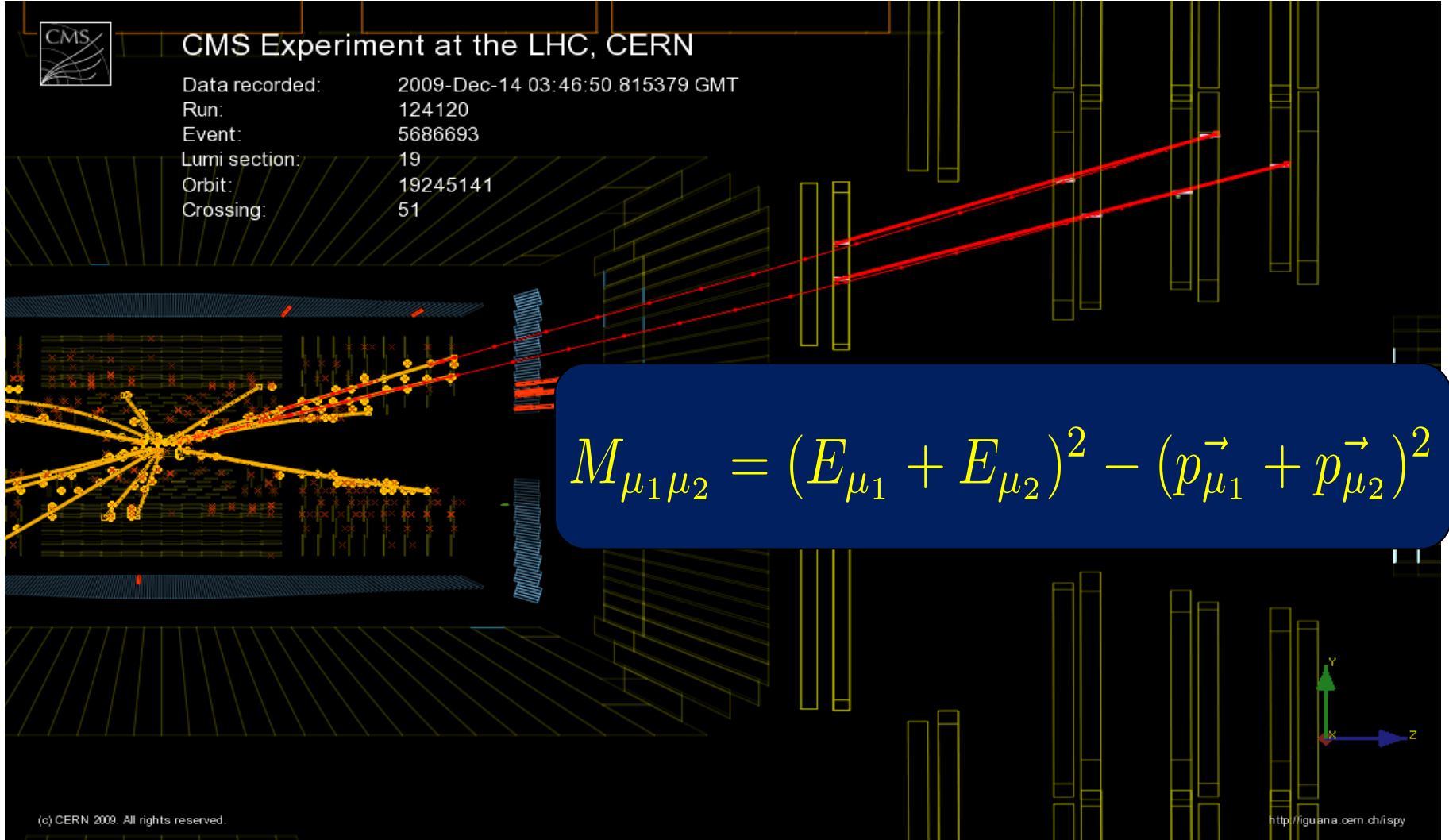


Općenito: E_i i E'_i nisu jednaki
U kojem sustavu računati inv. Masu?

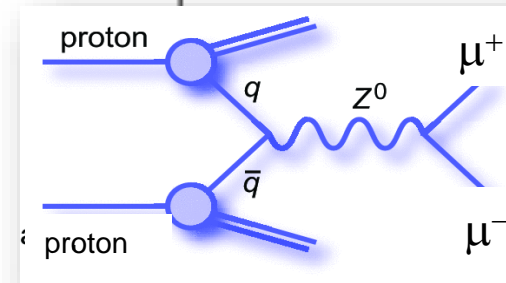
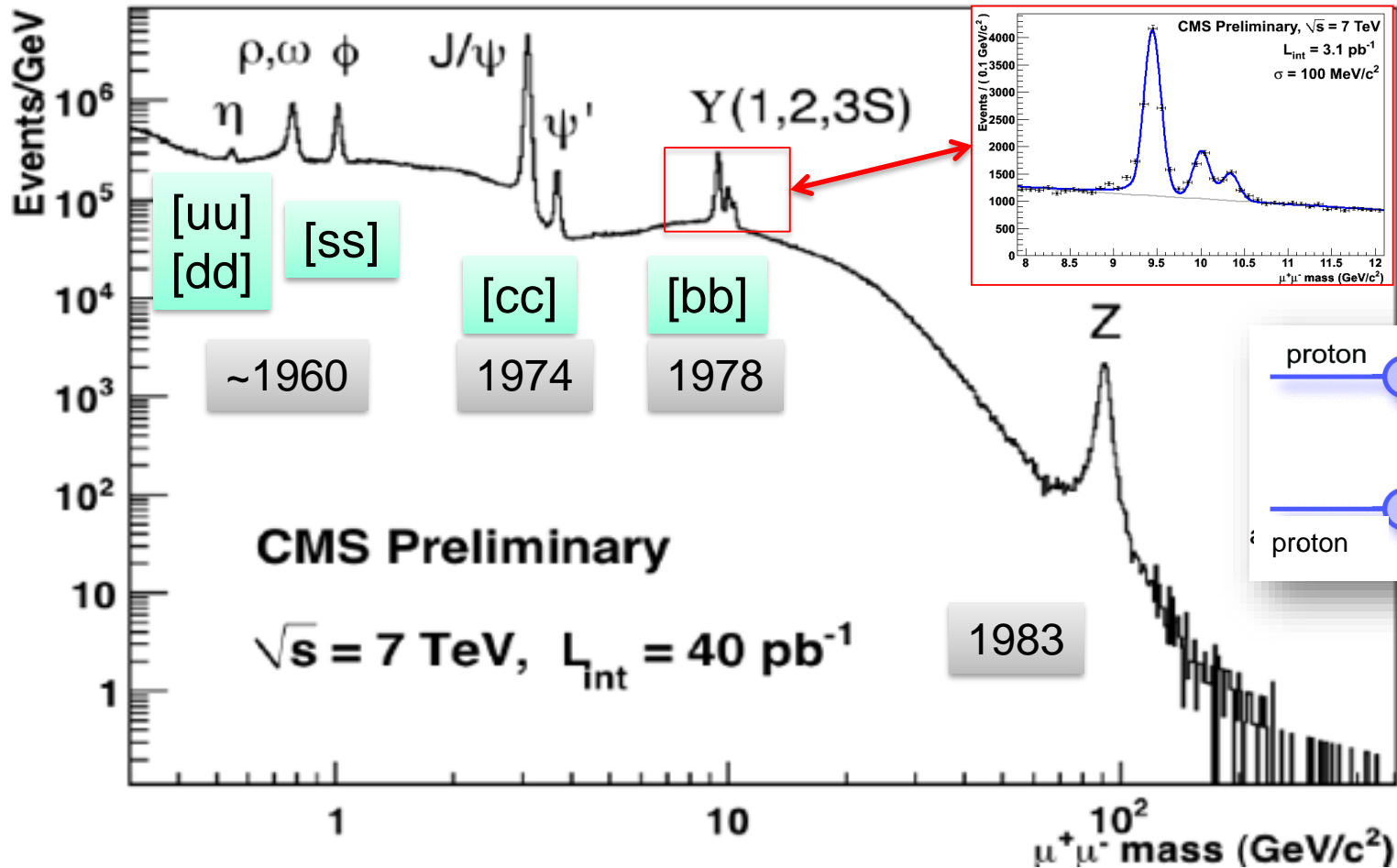
$$\text{Einstein : } (E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2 = (E'_1 + E'_2)^2 - (\vec{p}'_1 + \vec{p}'_2)^2$$

NIJE BITNO: INVARIJANTNA MASA NE OVISI O PROMATRAČU

Događaji sa 2 miona

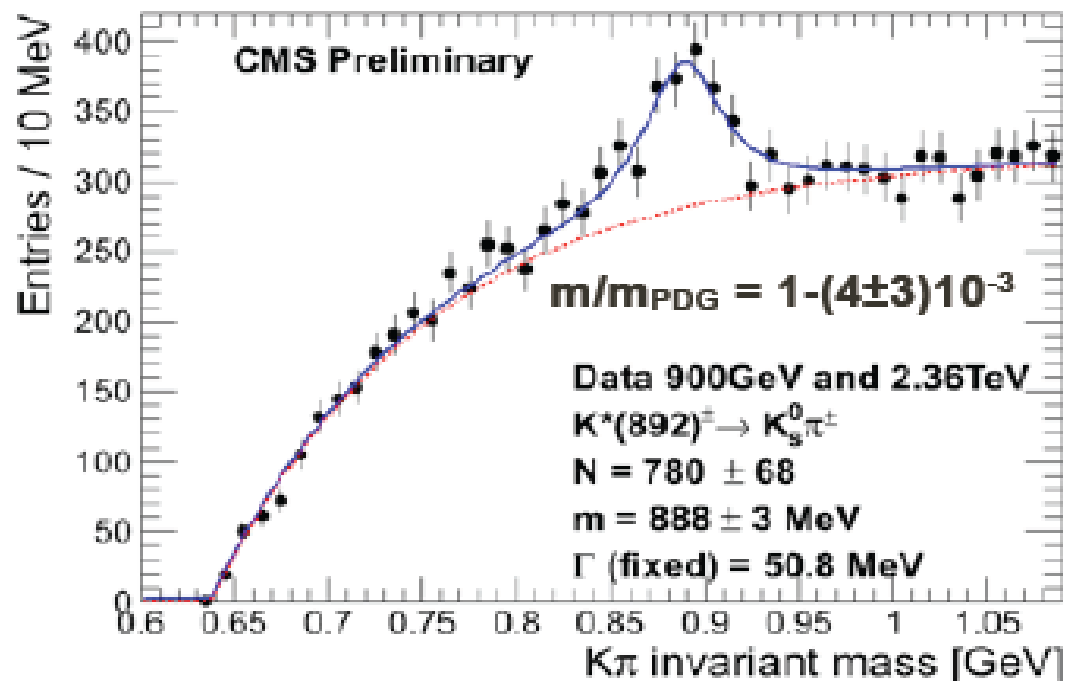
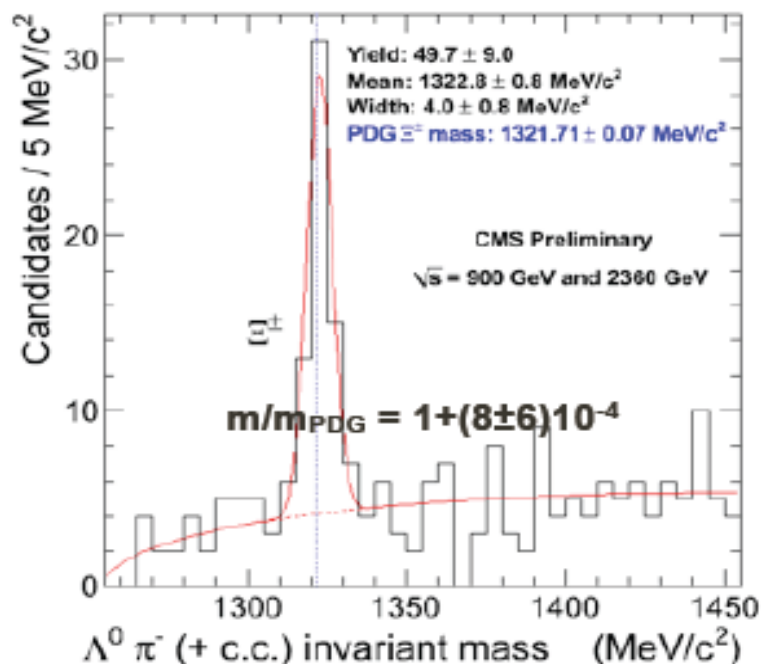


Ponovno otkriće SM na LHC-u



40 pb⁻¹ collected in 2010

Signal i pozadina – Primjeri iz prvih LHC podataka



Elementarne čestice: kvantni objekti

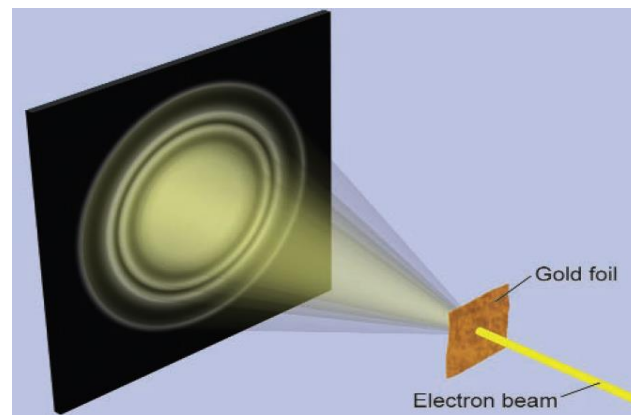
- Svim česticama pripadaju svojstva čestica:

- 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 mjereni:

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

- Isto vrijedi za energiju i vrijeme:

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

Kvantna jednačba gibanja

- Schroedinger: ponašanje čestica opisano kroz valnu jednačbu

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

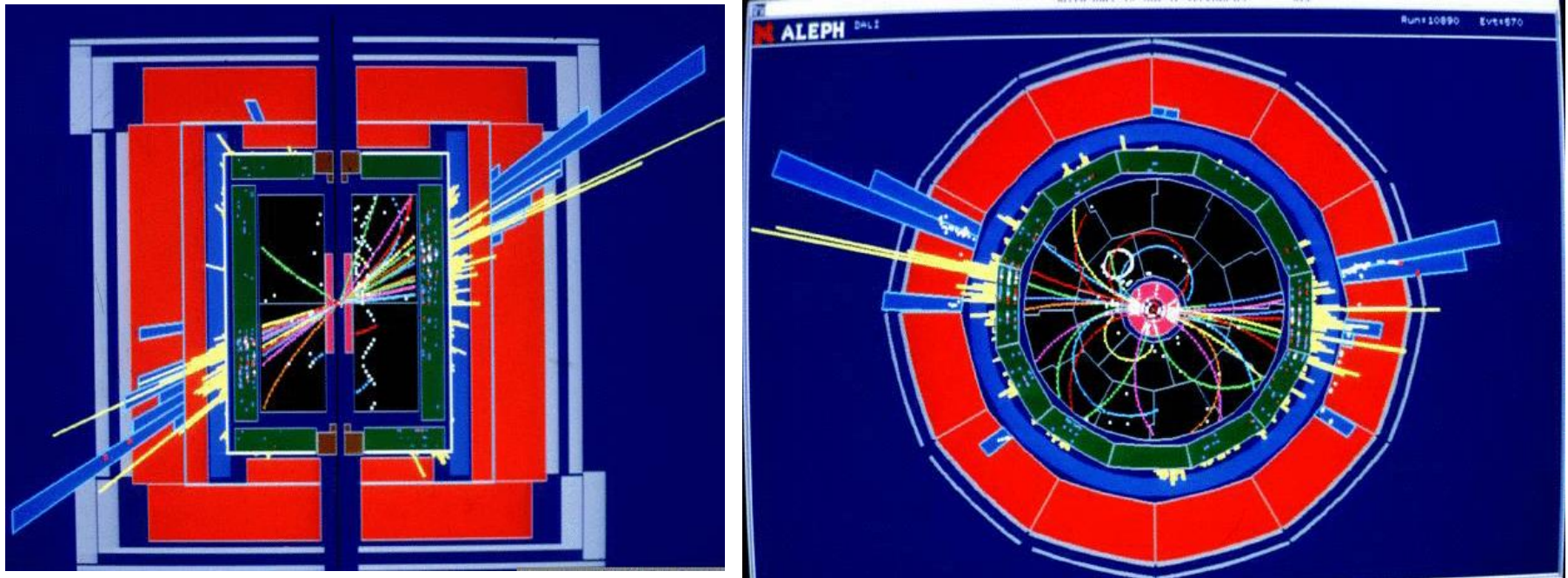
- Novost: valna funkcija nije više direktno mjerljiva nego predstavlja vjerojatnost!
- Nigdje tako dobro vidljivo kao kod elementarnih čestica

Schrödinger
1926

Primjer slučajnosti: Z raspad

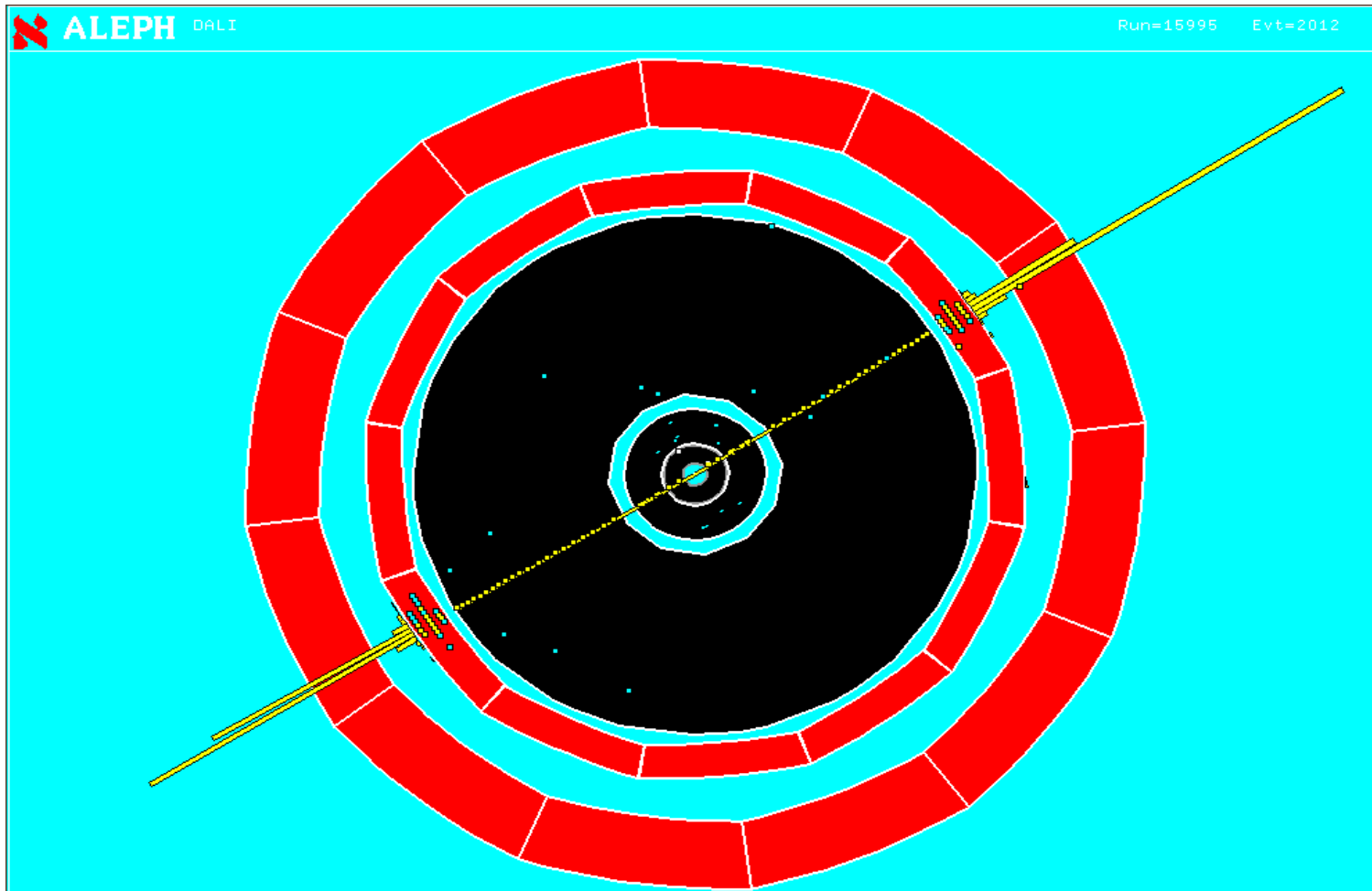
Eksperiment

Sudaramo snopove elektrona i pozitrona na energiji od 91 GeV
Produciramo Z bozone i proučavamo njihove raspade...

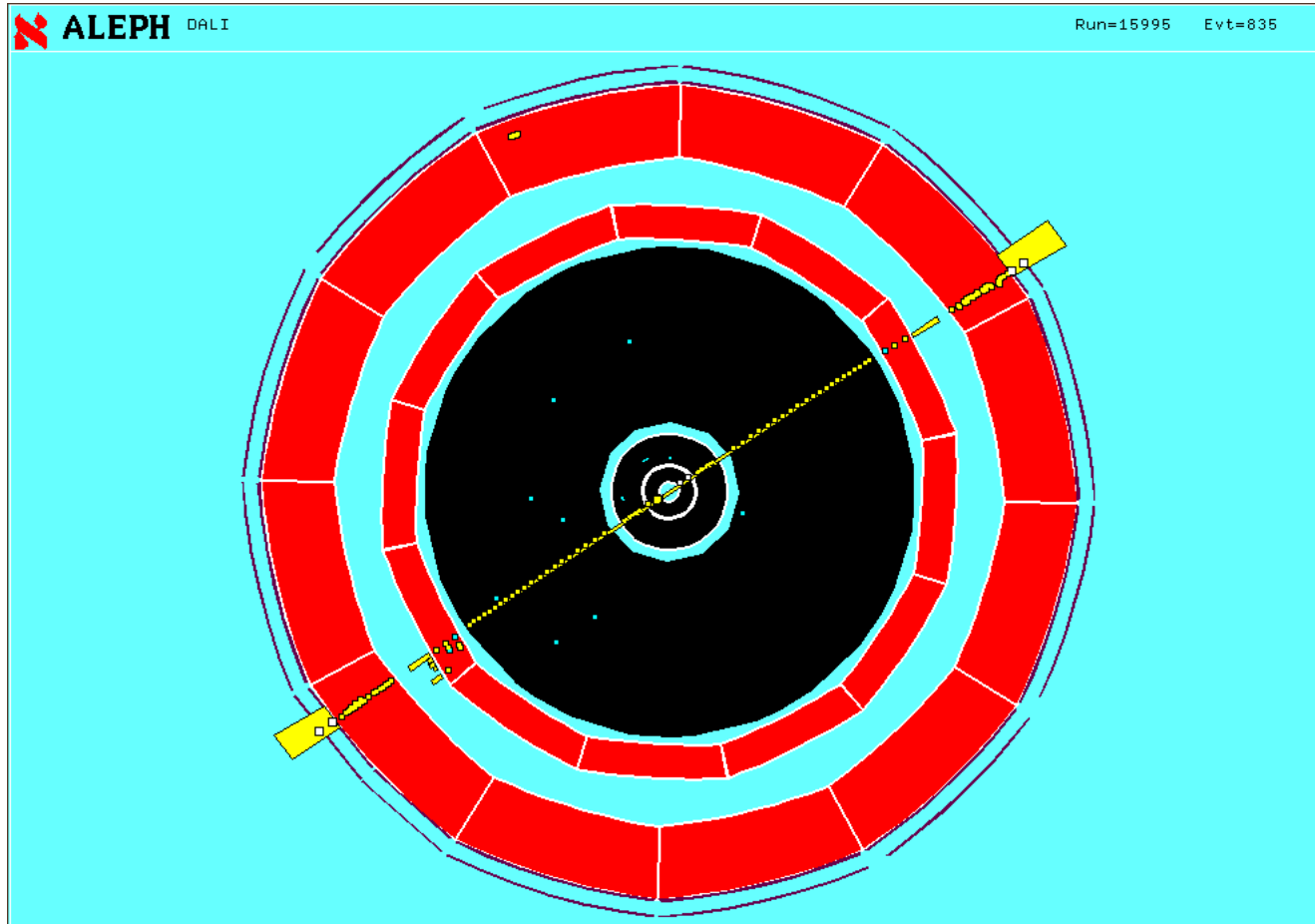


Ajmo to ponoviti...

Još jedan raspad Z bozona

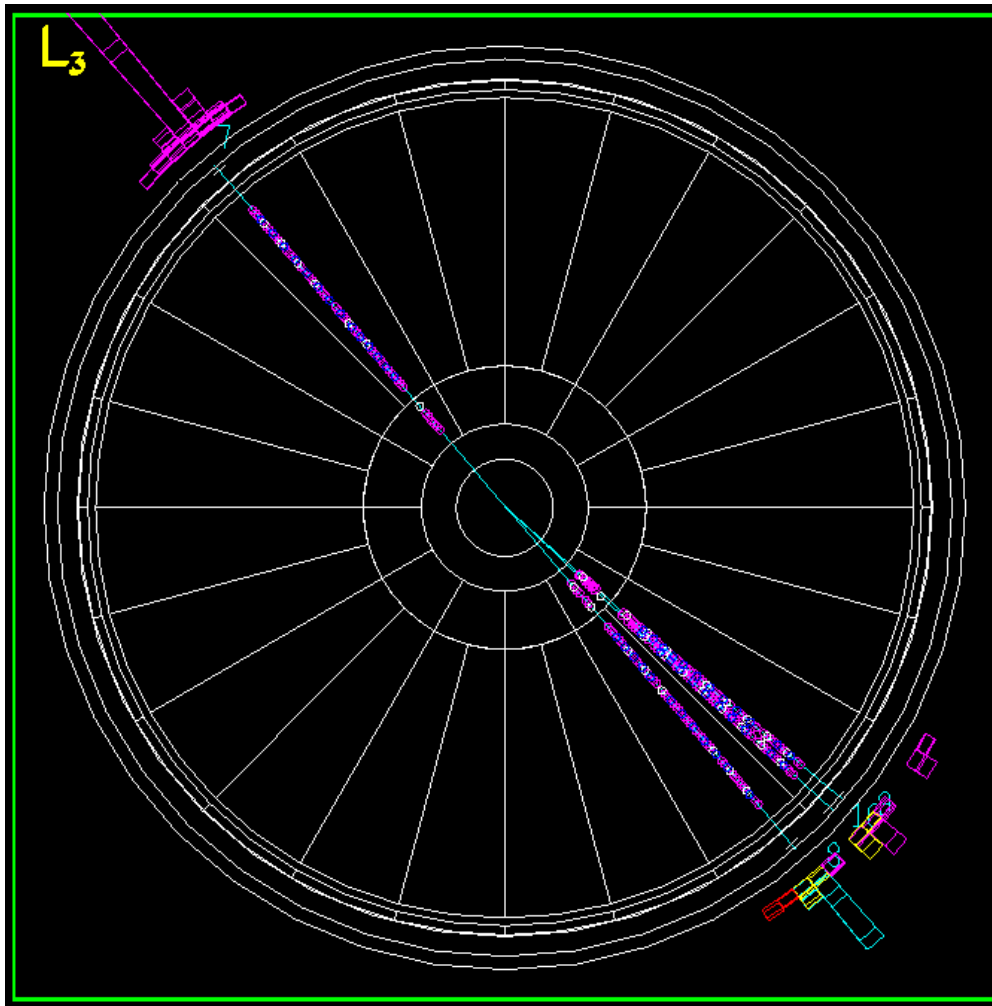


I još jednom



Stvarno se radi o ISTOM eksperimentu...

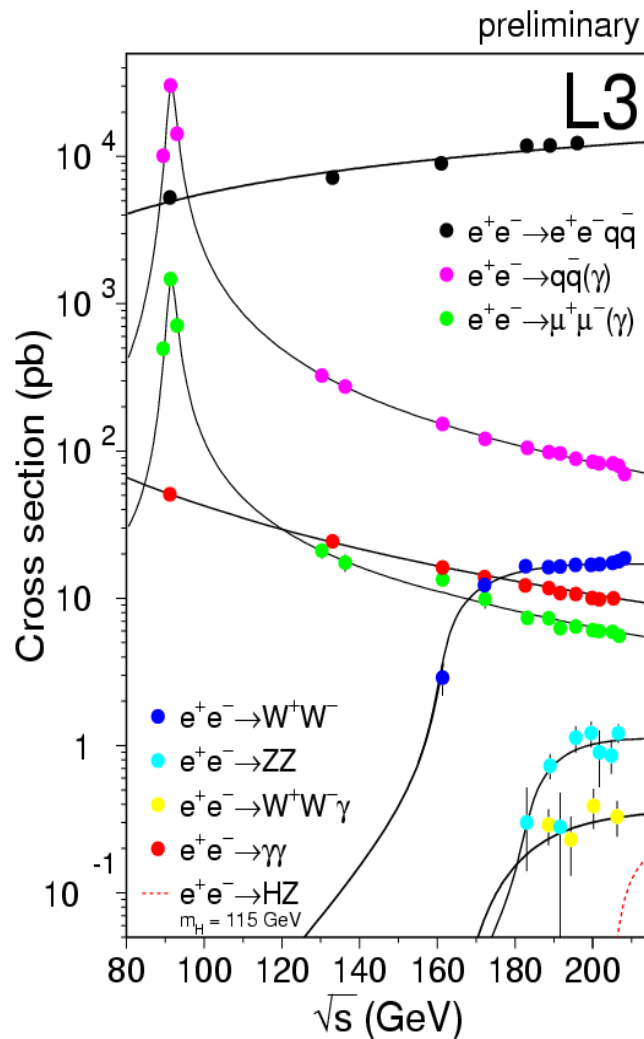
I još jedan

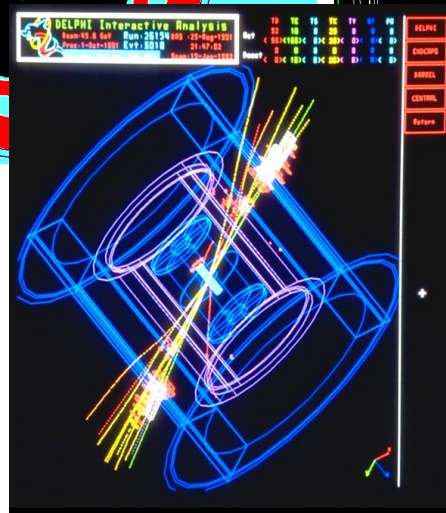
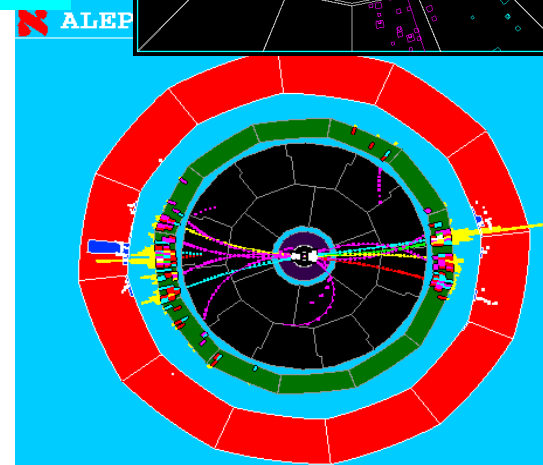
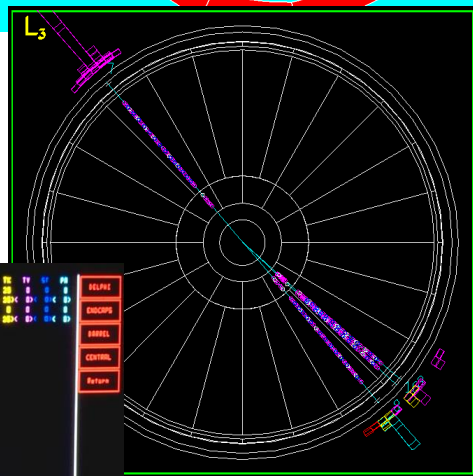
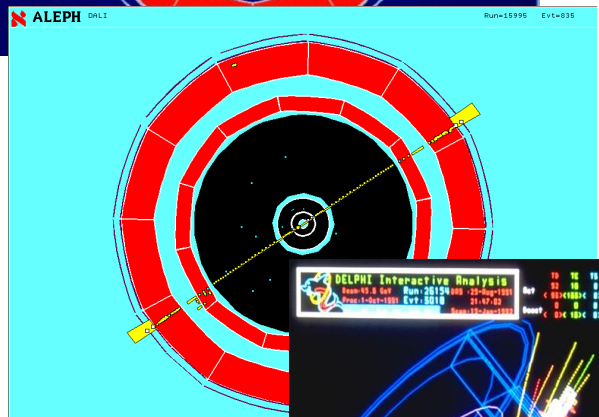
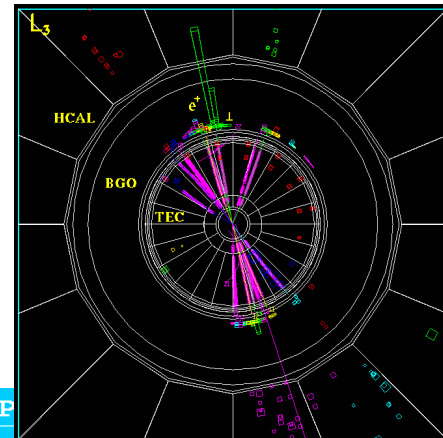
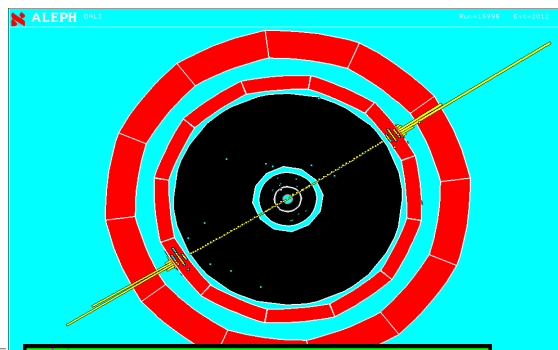
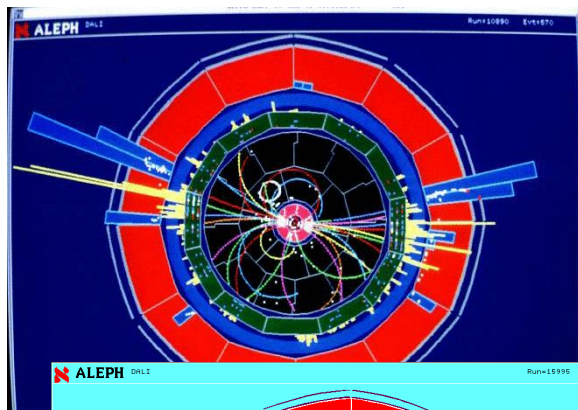


Što nam teorija kaže o Z raspadima

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

Ali ne kaže
nam apsolutno
ništa o ...



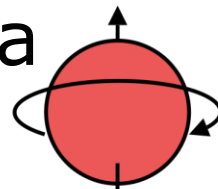


... A što će biti sljedeći?

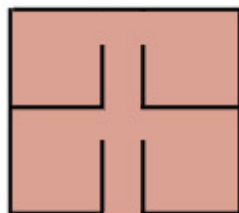
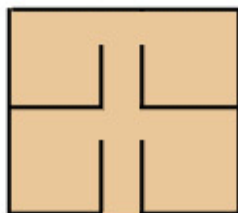
Ako kvantna teorija vrijedi to nije određeno fizikalnim zakonima, čisto je slučajno!

Kvantno svojstvo: Spin

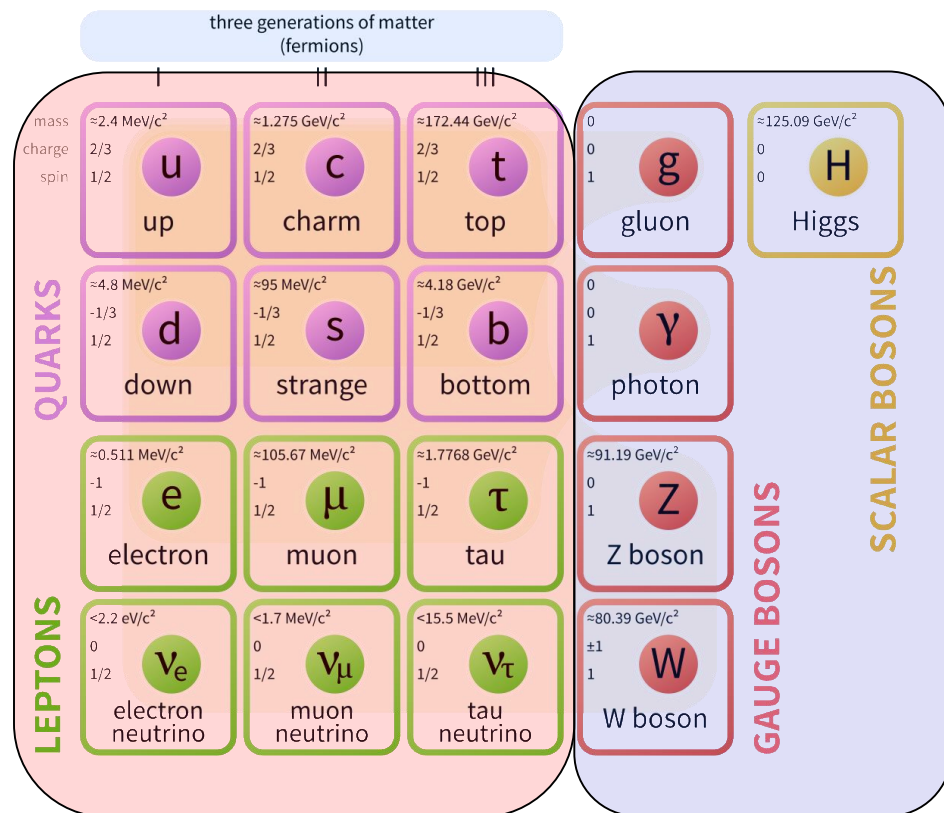
- Čisto kvantna pojava: intrinzična kutna količina gibanja, SPIN
- Kutna količina gibanja je očuvana veličina
- Kutna količina gibanja može imati samo vrijednosti, u jedinici Planckove konstante:
 - $0, 1, 2, 3, \dots$: Bozoni
 - $\frac{1}{2}, \frac{3}{2}, \frac{5}{2}, \dots$: Fermioni
- Važno svojstvo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



Bozoni i Fermioni



Standard Model of Elementary Particles



Fermioni

Bozoni

SPIN

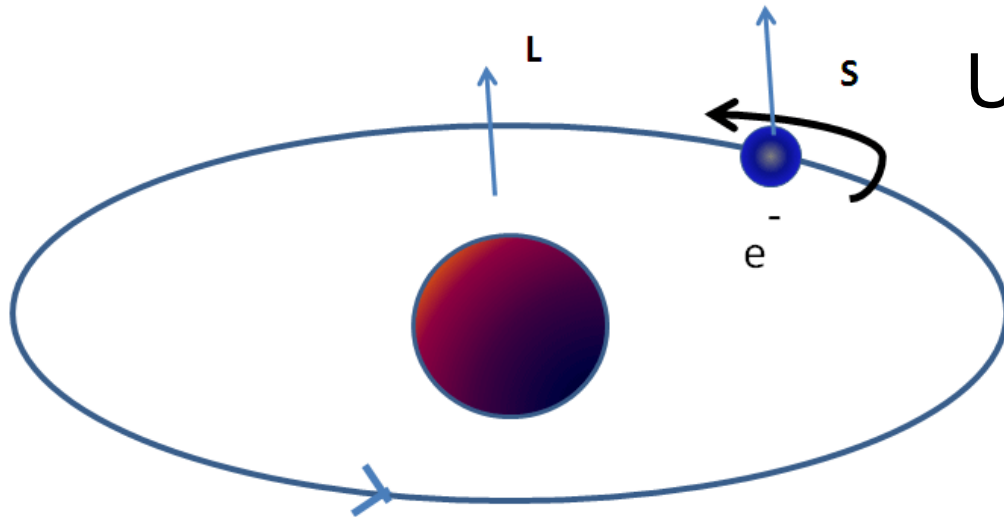
1/2

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 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



BBC FOUR

$$V = \sum P^a V_{p^a}$$

$$V = V_0 - \sum V_{r_A} \left\{ 1 - \sigma_A \right\}$$

PAUL DIRAC

PHYSICIST

antisym

Čestice i ... **Antičestice!**



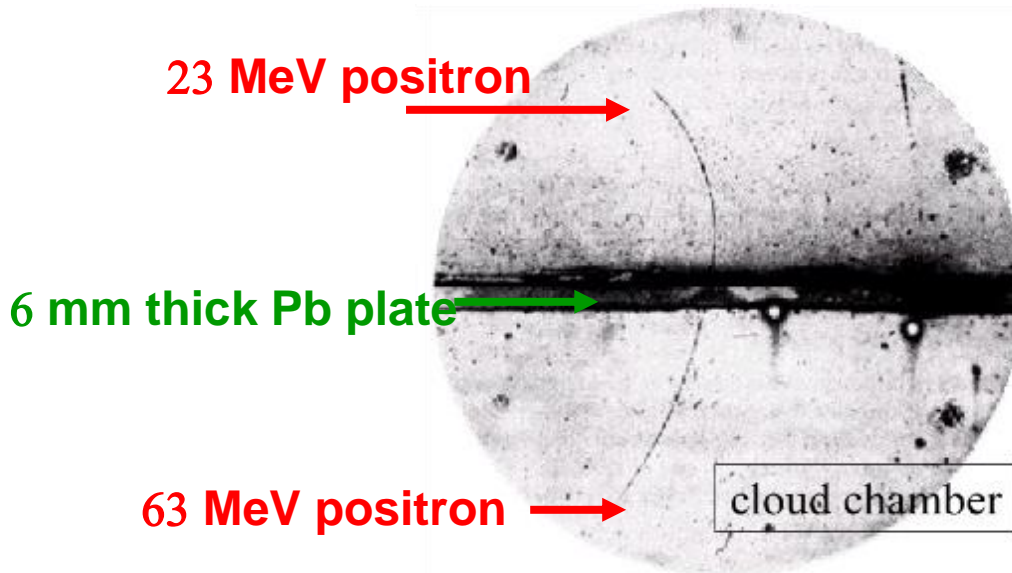
P.A.M. Dirac

Relativnost i kvantna fizika zahtjevaju

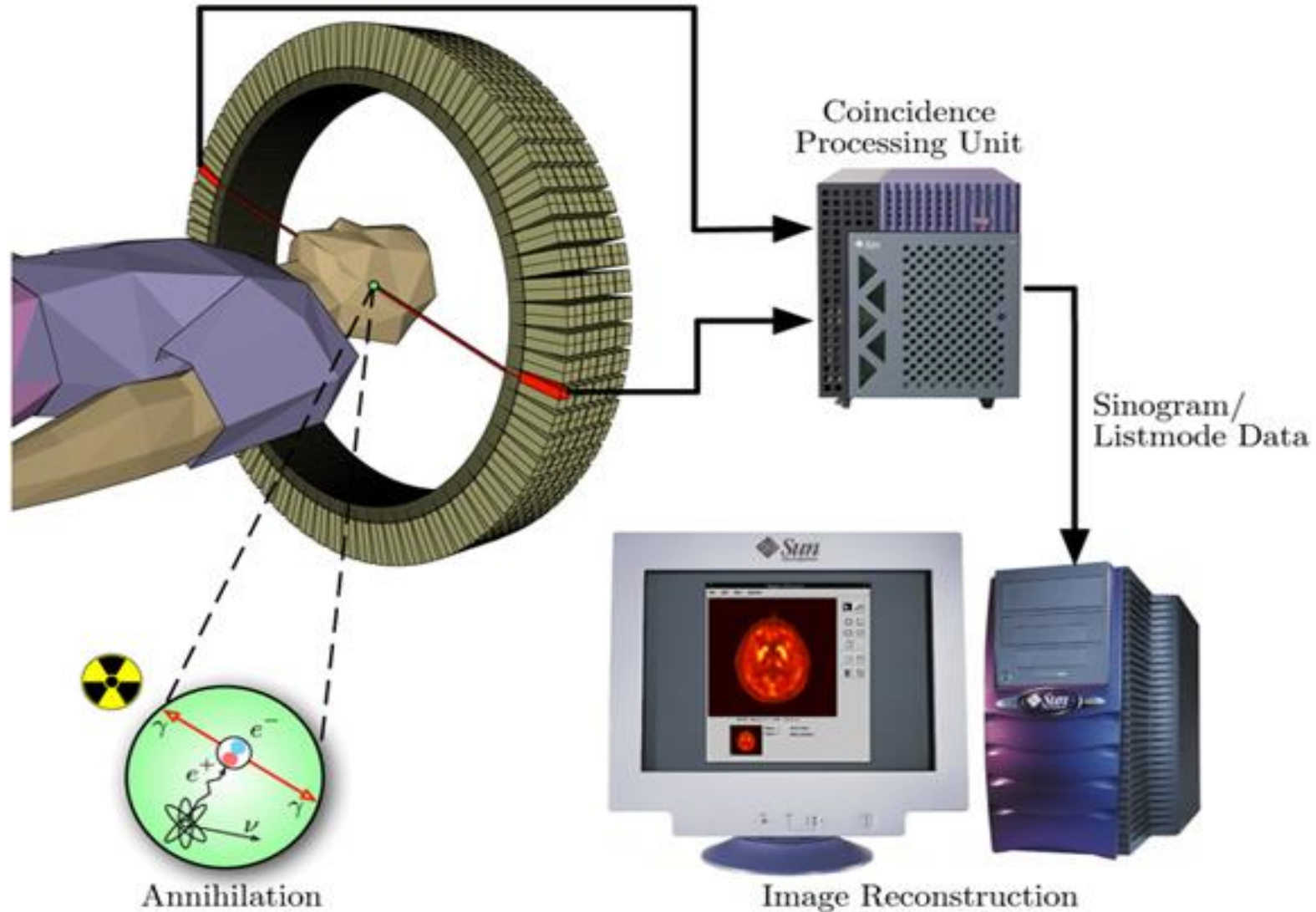
Za svaku česticu postoji i antičestica sa istom masom i suprotnim kvantnim brojevima

“Otkrio” kao teorijski zahtjev Dirac (1928)

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

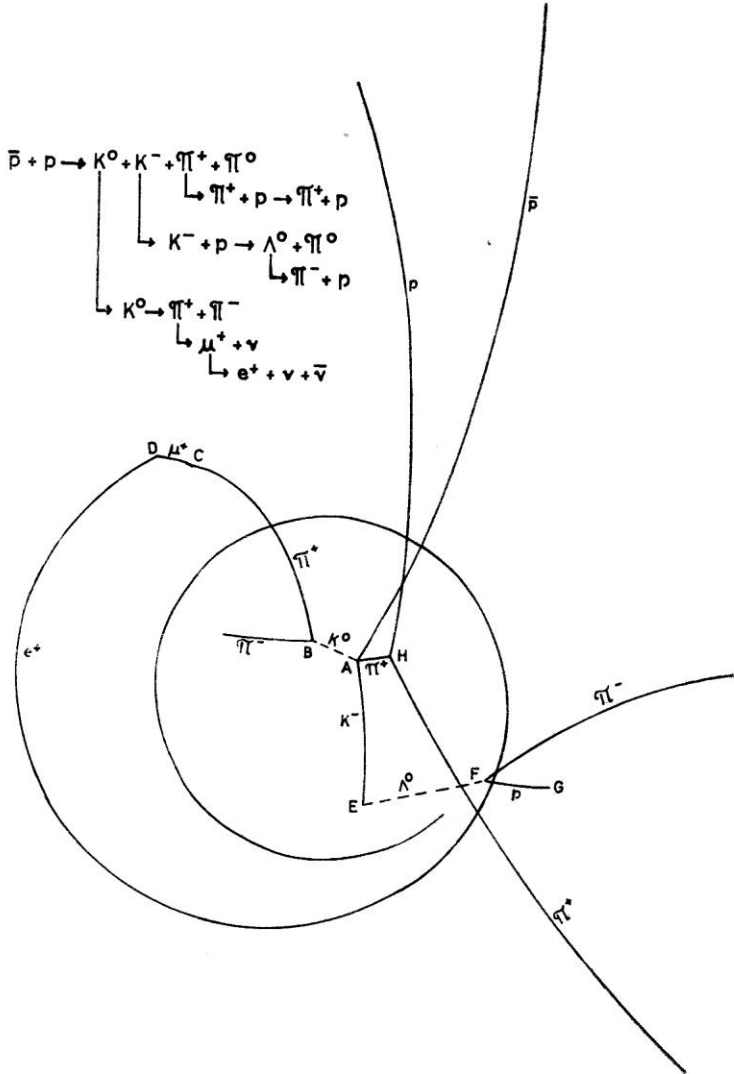


Antimaterija u medicini: PET Tomografija





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



1932: Svijet je jednostavan

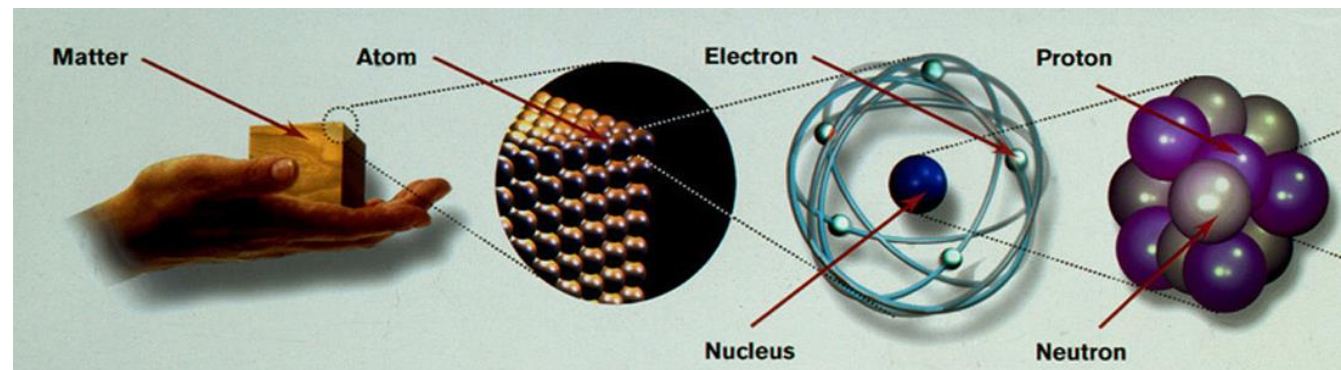
Otkriće neutrona (Chadwick, 1932)

Neutron: Neutralna čestica sa masom kao proton



Elementarne čestice 1932 g.:

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

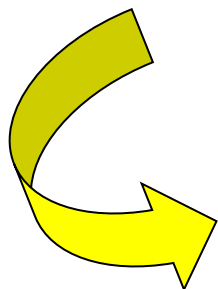
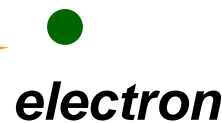
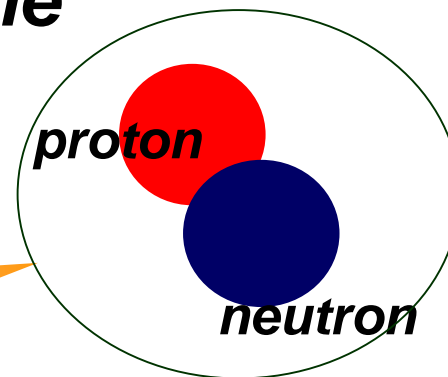
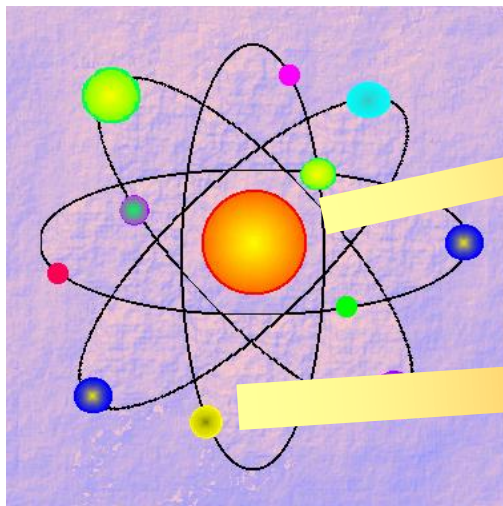


H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	Lu	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	Lr	Rf	Db	Sg	Bh	Hs	Mt									
		La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb		
		Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No		



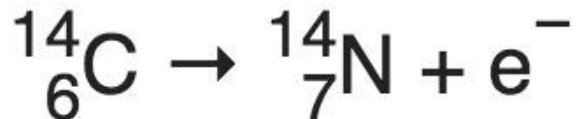
Periodic Table

Atom



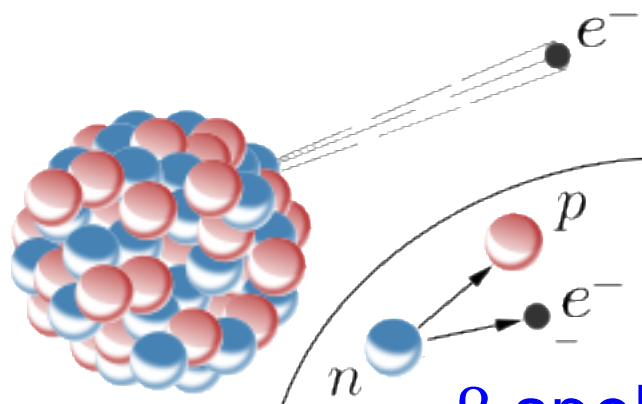
Enigma β raspada

Neke jezgre se raspadaju putem β raspada, npr.

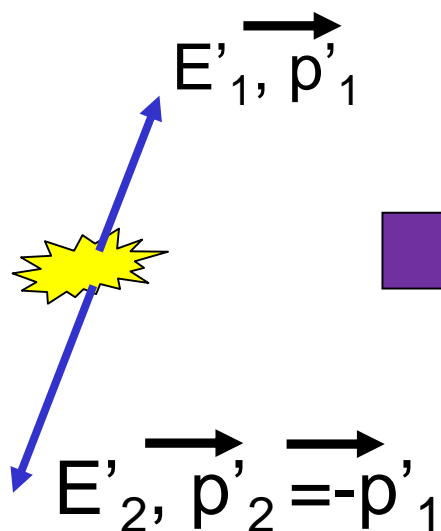


SPIN: 0 1 1/2

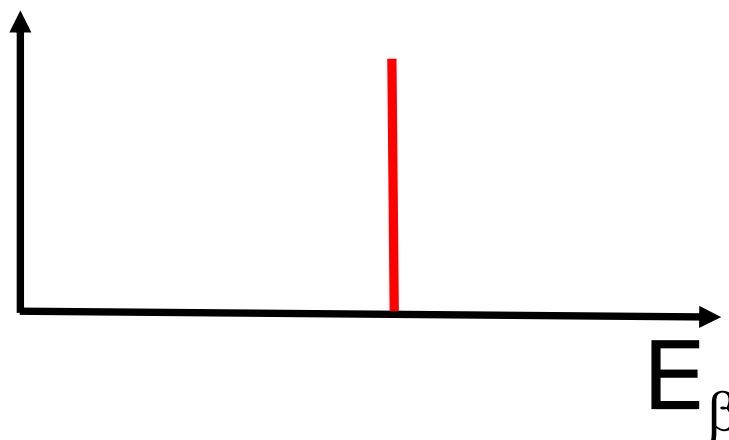
**Očuvanje kutne
Količine gibanja????**



β spektrum ?



Očekujemo monokromatični spektar

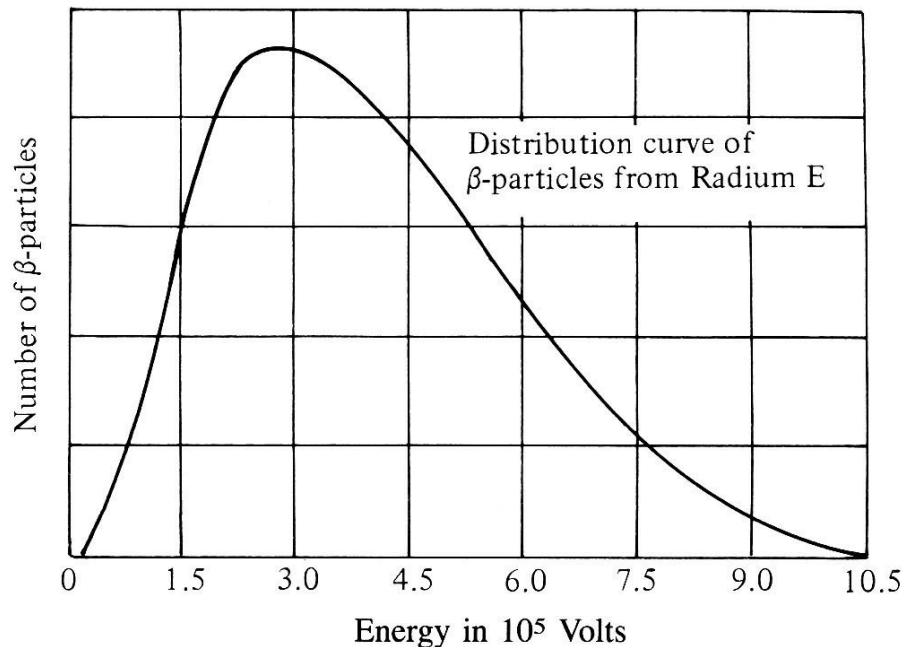


Problem β raspada: kontinuirani spektar

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: $^{210}\text{Bi}_{83}$
(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 ${}^6\text{Li}$ 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 $\frac{1}{2}$ 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

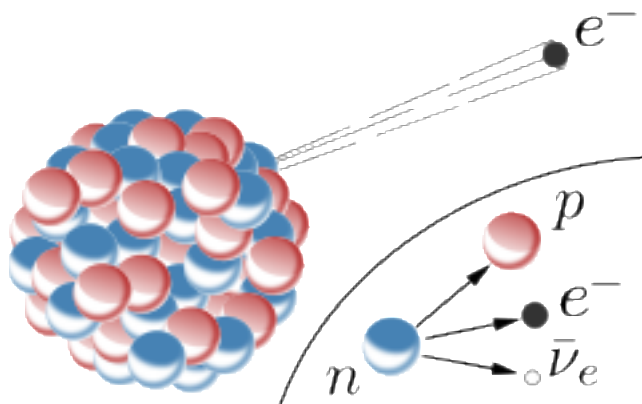
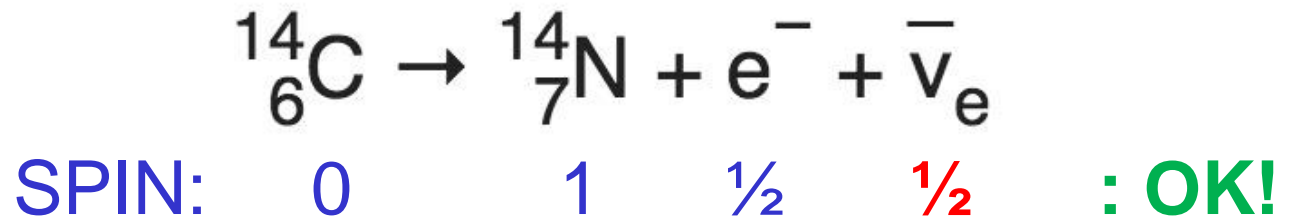
So, dear Radioactives, examine and judge it. Unfortunately I cannot appear in Tübingen personally, since I am indispensable here in Zürich because of a ball on the night of 6/7 December.

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

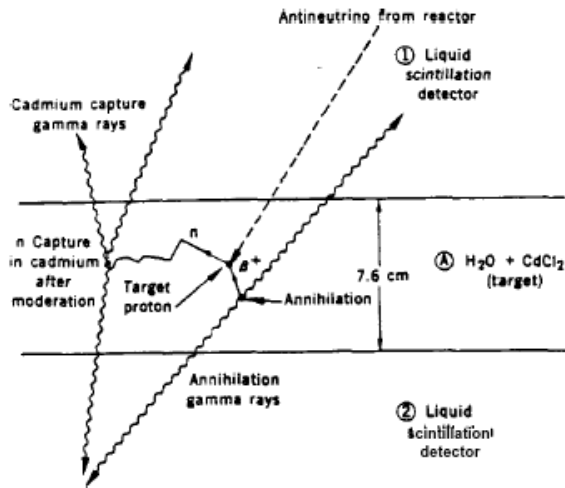


Otkrili smo
nevidljivu česticu
koristeći isključivo
Zakone očuvanja

Neutrini postoje!

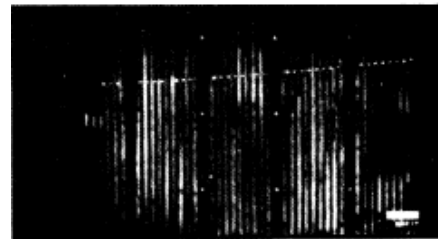
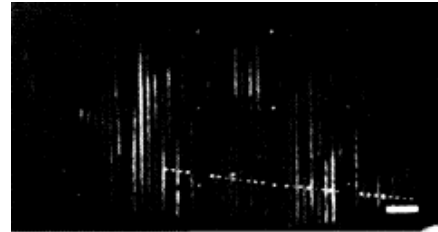
ν_e

(Reines, Cowan 1953)



ν_μ

(1962)



ν_τ

(2000)

Three typical single-track events in the BNL neutrino experiment

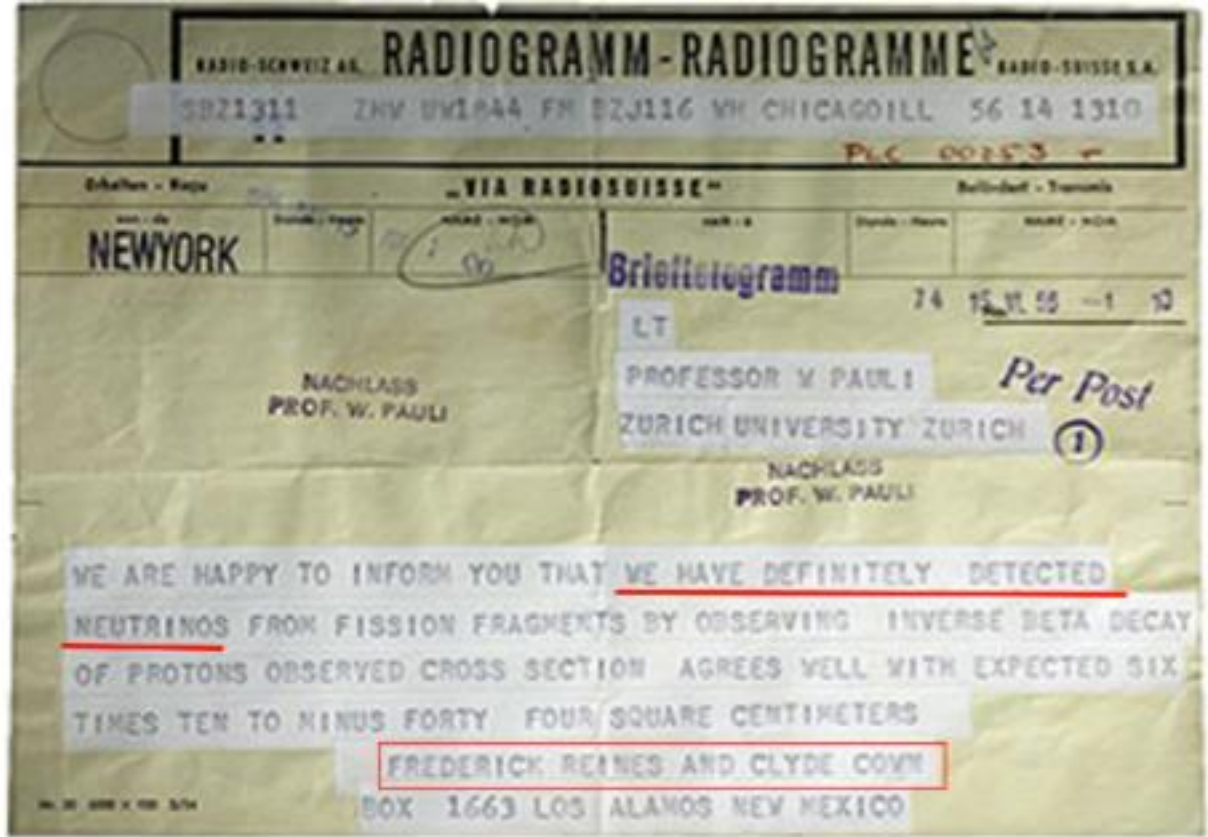
Pauli: "I have done a terrible thing. I have proposed a particle that cannot be detected. It is something no theorist should ever do."



Réacteur de Savannah River (USA)



Reines et Cowan à Pauli (1956)



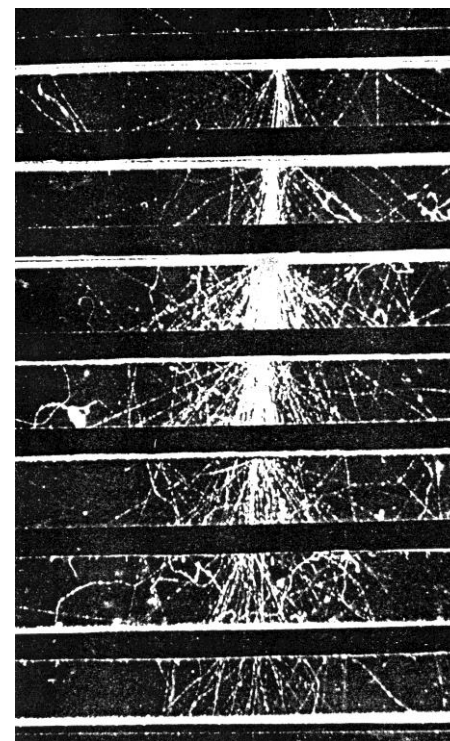
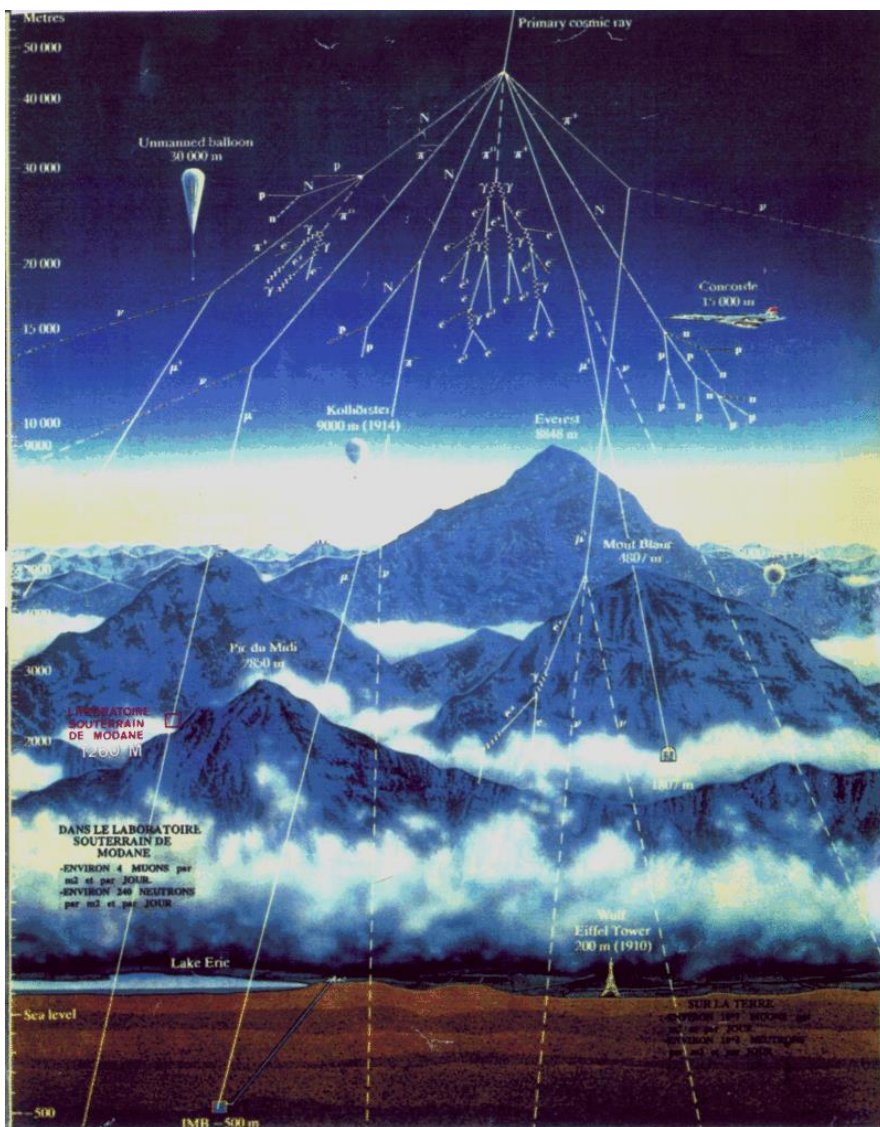
Frederick REINES and Clyde COWAN
 Box 1663, LOS ALAMOS, New Mexico
 Thanks for message. Everything comes to
 him who know how to wait.
 Pauli

Pauli :

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?”)

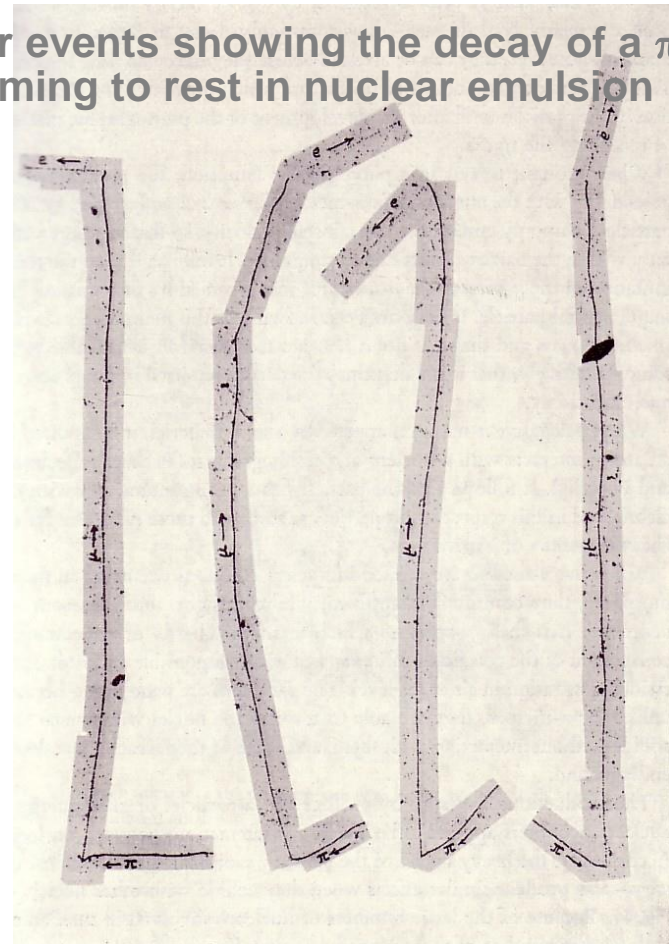
– Teški elektron

π

– Iz sudara zračenja sa
jezgrama

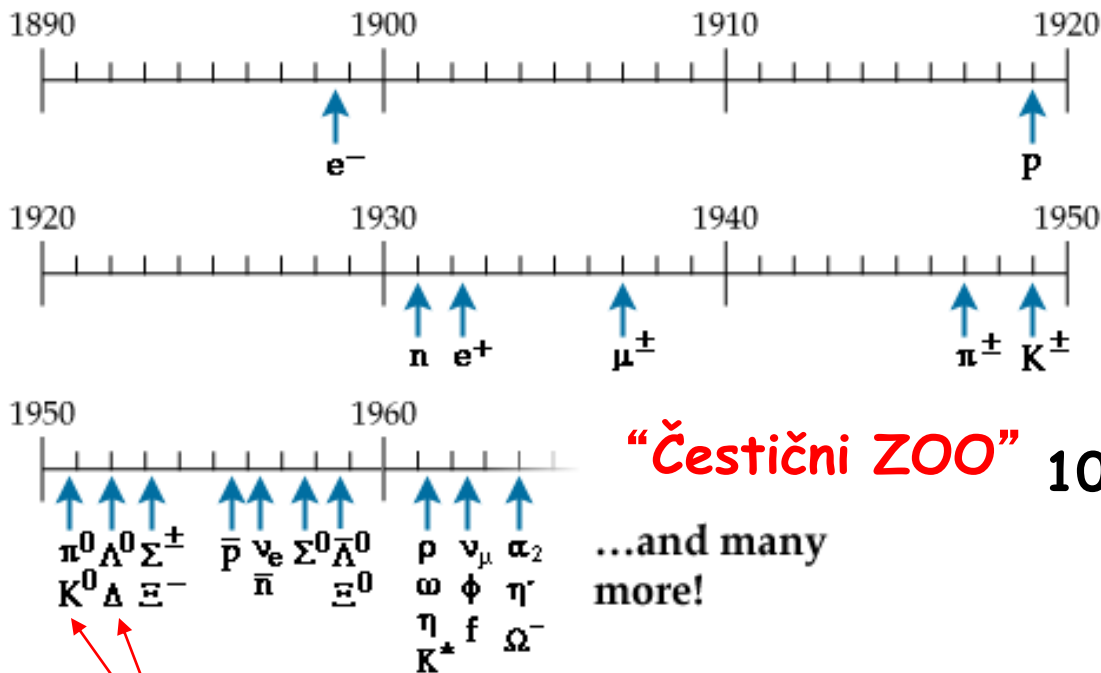


Four events showing the decay of a π^+
coming to rest in nuclear emulsion



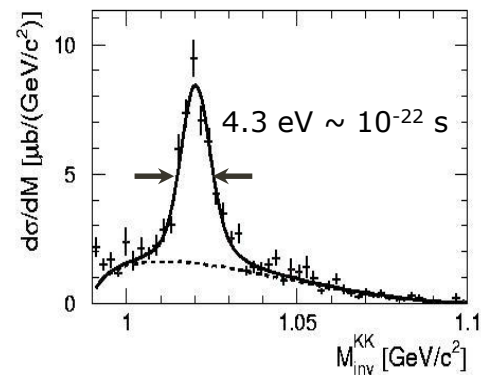
... sve više i više

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



“Čestični ZOO”

...and many more!



Ponovo više od 100 elementarnih čestica!

ali Jesu li stvarno?

“Strange particles” (Murray Gell-Mann)

Kvarkovi?

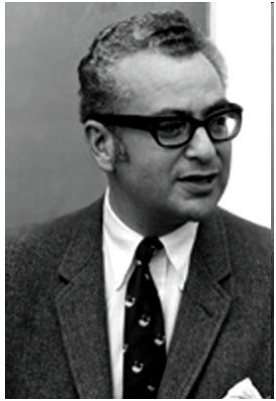
1964 (Gell-Mann, Zweig): Hadroni bi mogli biti građeni od 3 elementarnih čestica:
Gell-Mann ih krsti "quarks"

	<i>u</i>	<i>d</i>	<i>s</i>
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

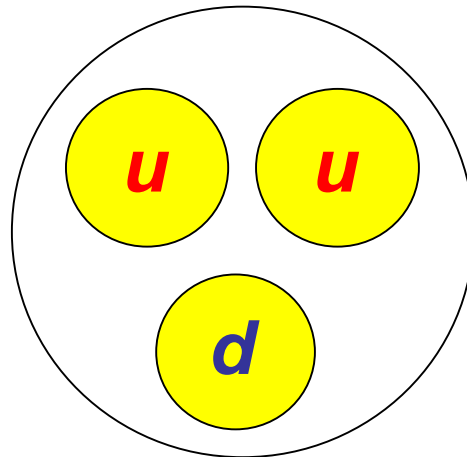
kvarkova



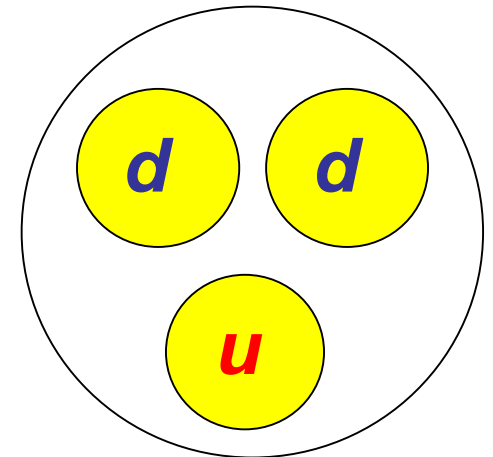
Elementarne čestice s nabojom manjim od elementarnog naboja (elektrona) koje se pojavljuju u više vrsta ili **okusa**

Zweig

Gell-Mann

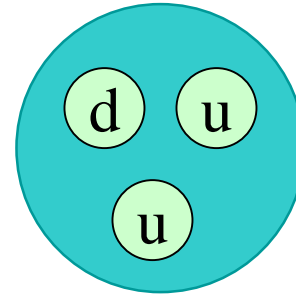


proton



neutron

Od čega se sastoji proton?

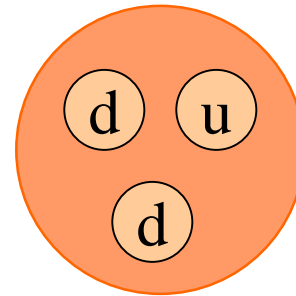


$$q(u) = +2/3$$

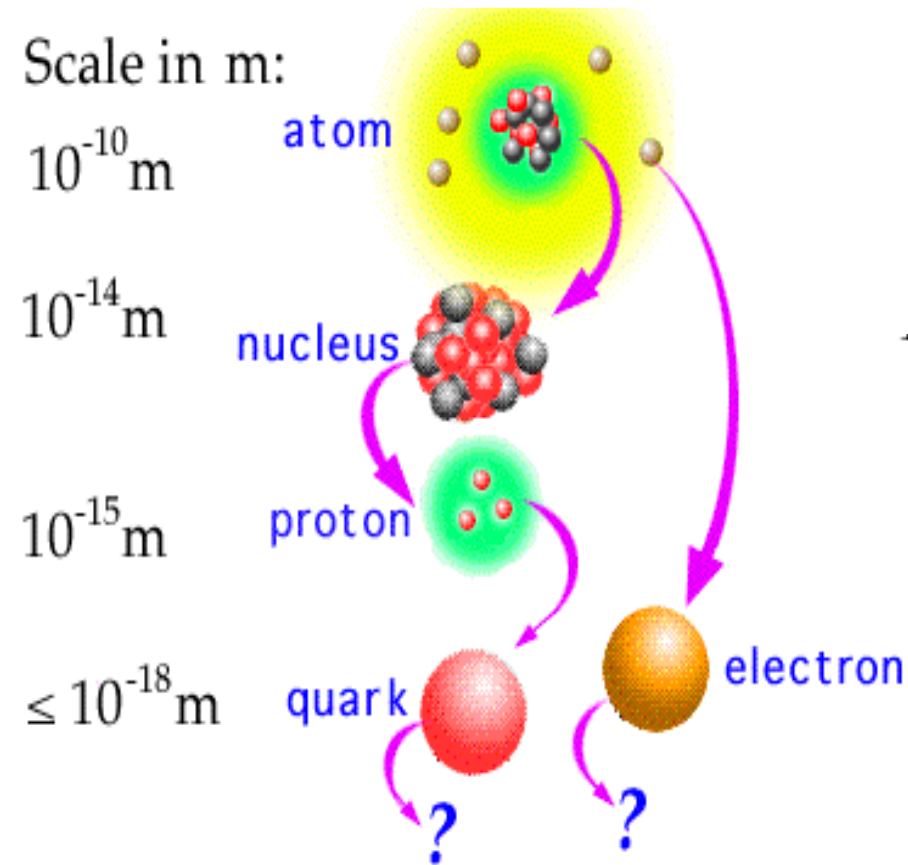
$$q(d) = -1/3$$

$$q(p) = +1$$

... i neutron?



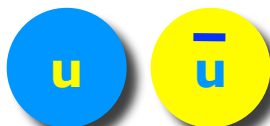
$$q(n) = -1/3 - 1/3 + 2/3 = 0$$



Kvarkovi – Moguće kombinacije

Mezoni

= Kvark-Antikvark



+2/3 e -2/3 e

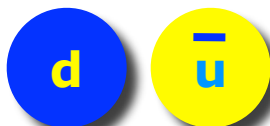
π^0

Nekoliko poznatih mezona



+2/3 e +1/3 e

π^+



-1/3 e -2/3 e

π^-



+2/3 e +1/3 e

K^+

Barioni:

3 kvarka ili
3 antikvarka



+2/3 e -1/3 e -1/3 e

Λ



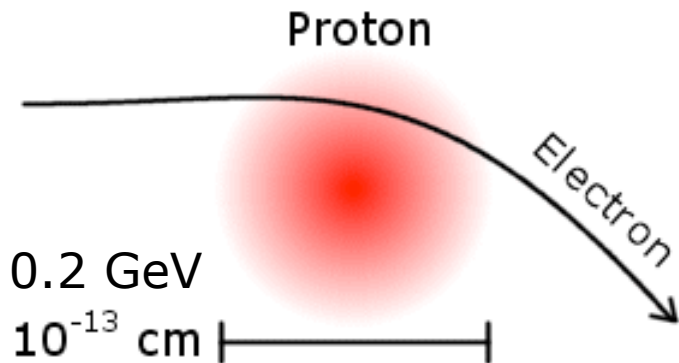
-2/3 e +1/3 e +1/3 e

$\bar{\Lambda}$

Kvarkovi postoje!

Otkriće kvarkova

Raspršenje elektrona na protone

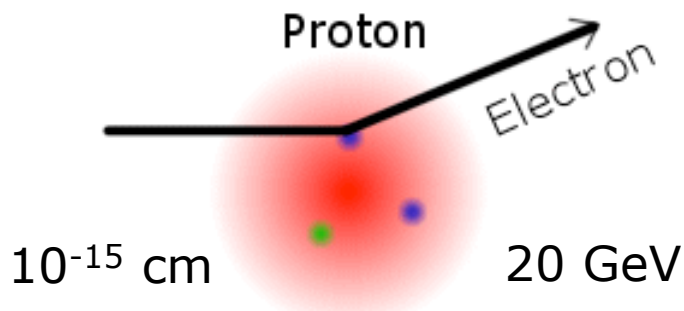


1956 Hofstadter: Mjerenje radiusa protona



Stanford Linear Accelerator Centre

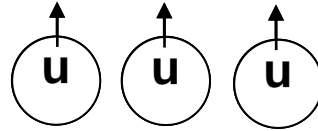
1967 Friedmann, Kendall, Taylor (SLAC): ~ Rutherford eksperiment s elektronima
--> u protonu se nalaze 3 'tvrda' (točkasta) centra raspršenja



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

Jaka sila vidi... BOJU!

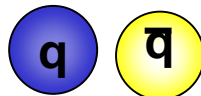
$\Delta^{++}(u^{\uparrow}u^{\uparrow}u^{\uparrow})$



A moj princip
isključenja?



Slaganje boja u nešto bezbojno



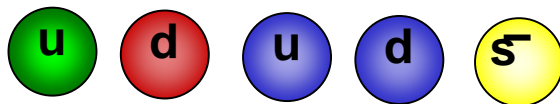
Mezoni



Barioni

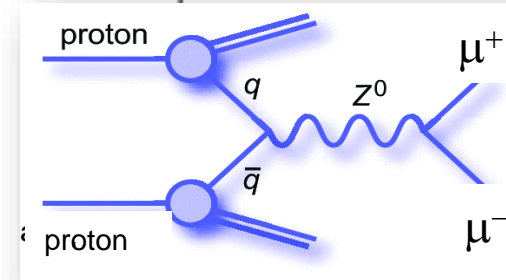
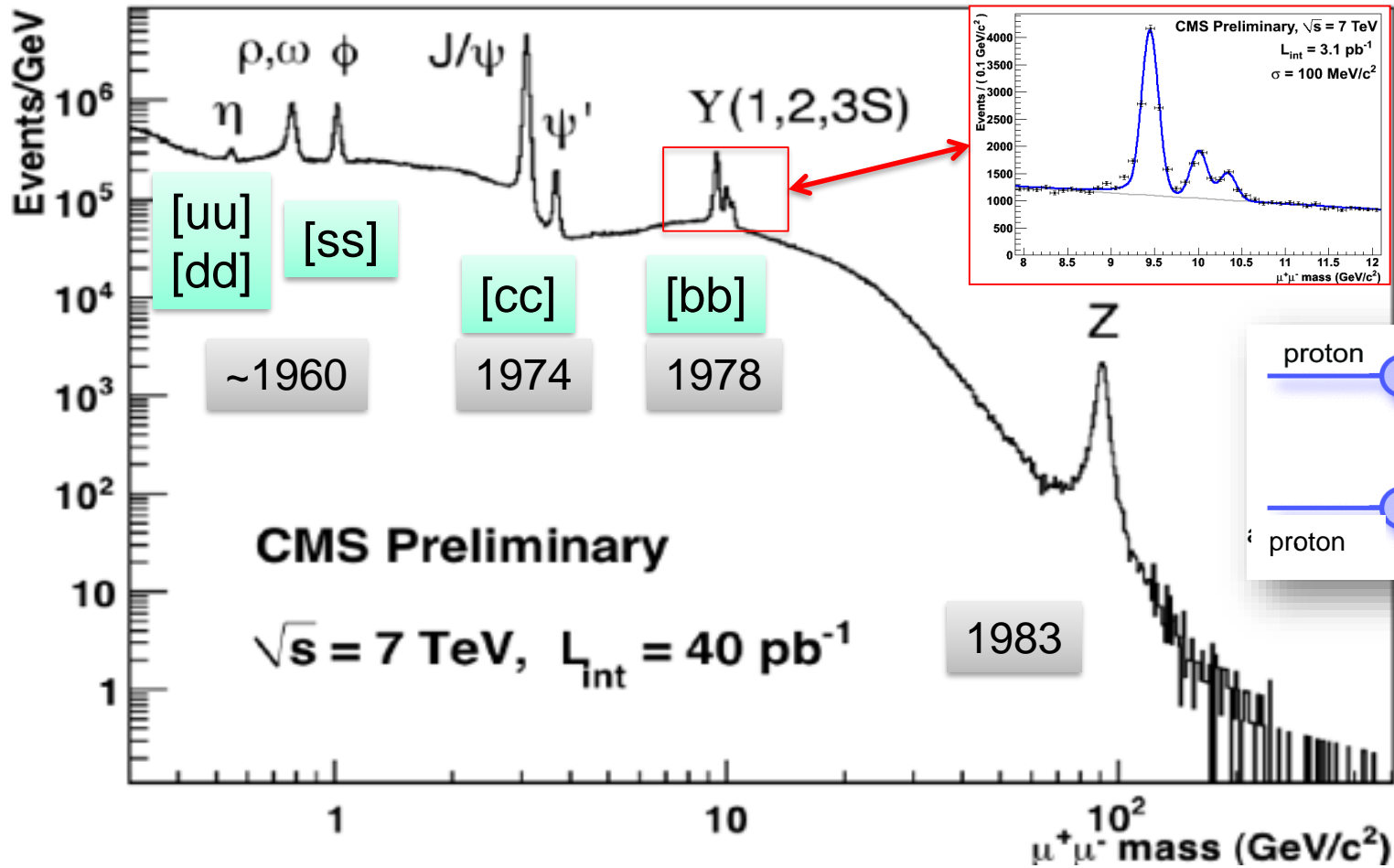


Anti-barioni



Egzotični barion

Nove rezonancije: novi kvarkovi!

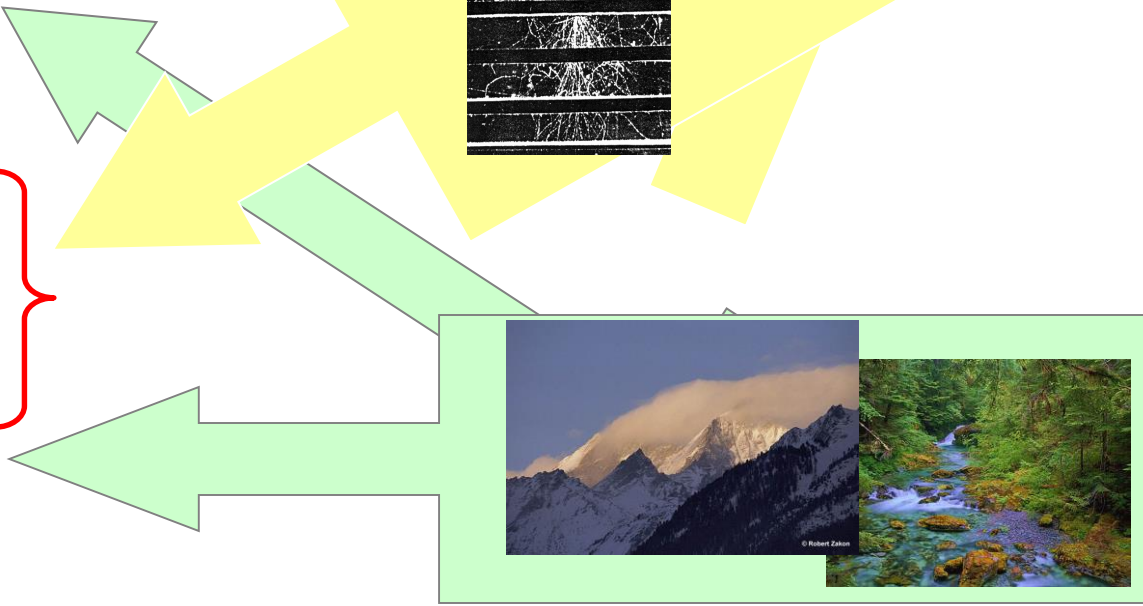
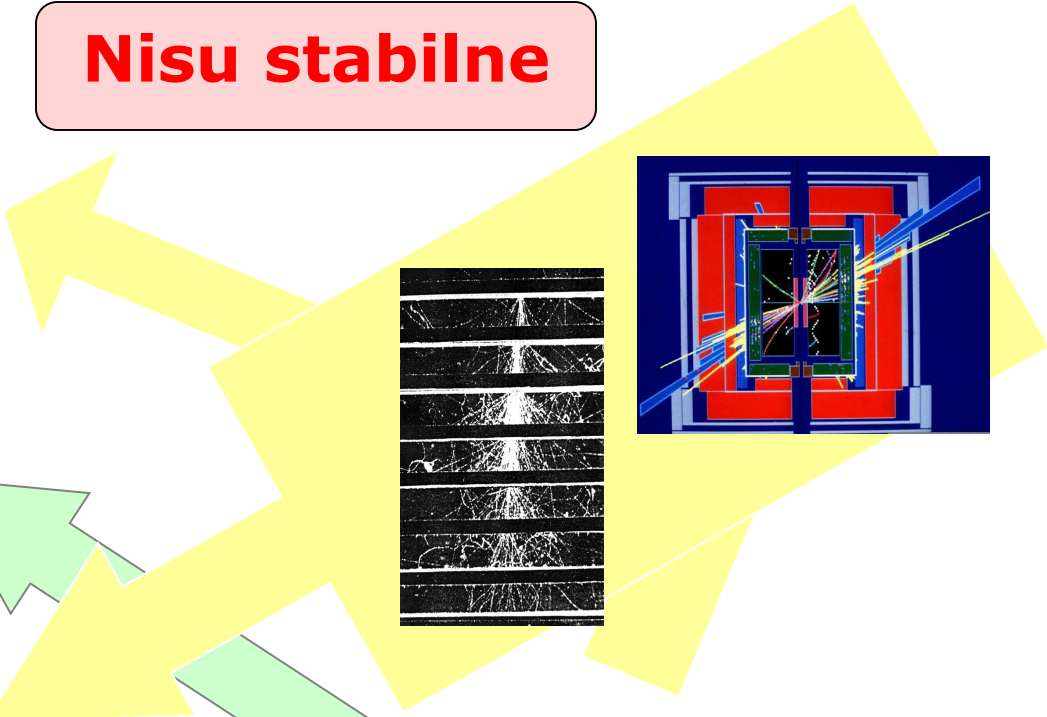


40 pb⁻¹ collected in 2010

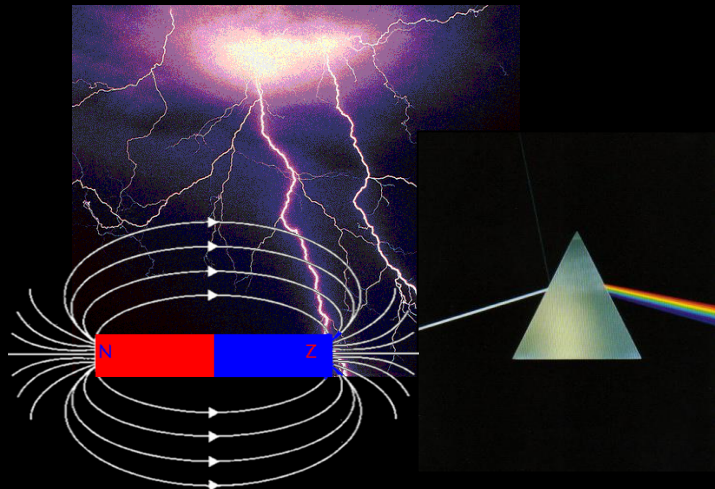
Elementarne čestice, 2017

Leptons			
Electric Charge			
Tau	-1	0	Tau Neutrino
Muon	-1	0	Muon Neutrino
Electron	-1	0	Electron Neutrino
Quarks			
Electric Charge			
Bottom	-1/3	2/3	Top
Strange	-1/3	2/3	Charm
Down	-1/3	2/3	Up
each quark: <i>R</i> , <i>B</i> , <i>G</i> 3 colors			

Nisu stabilne



4 temeljne sile



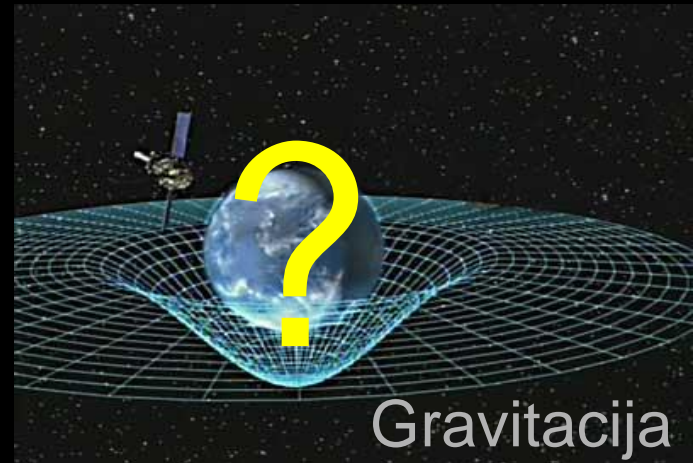
Elektromagnetska sila



Jaka sila



Slaba sila

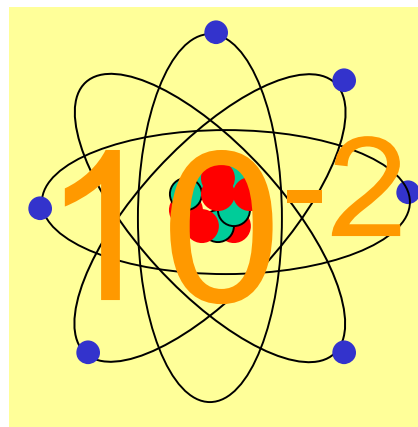


Gravitacija

Jačine sile

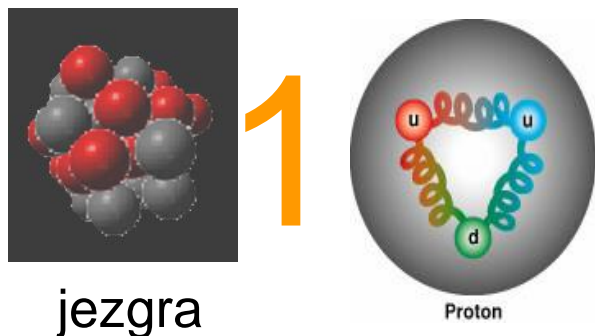


Gravitacijska sila



atom

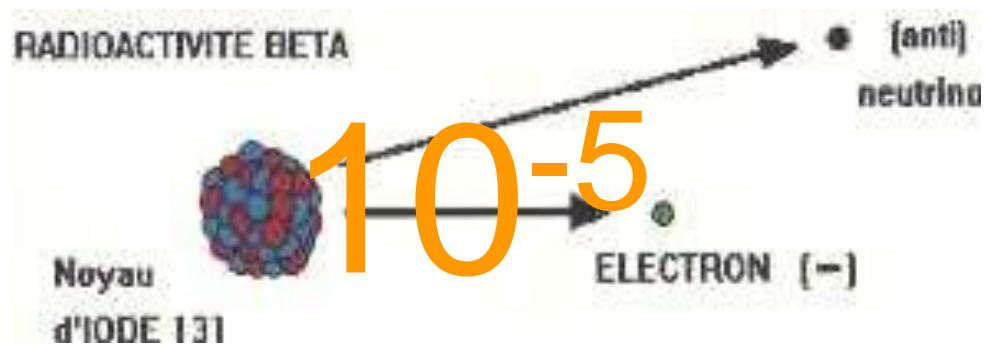
Elektromagnetska sila



jezgra

Proton

Jaka nuklearna sila



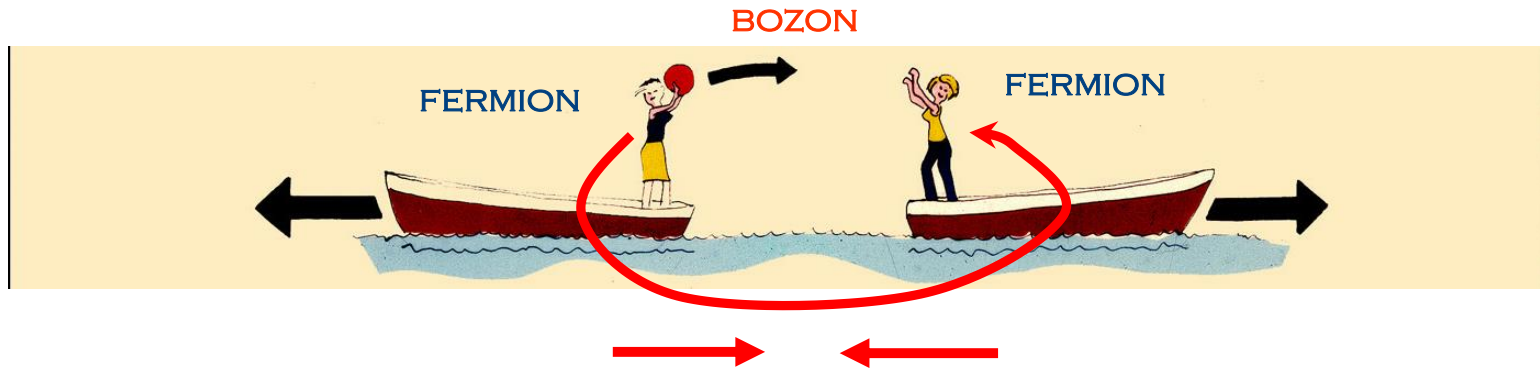
Slaba sila

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

$$d \rightarrow u + e^- + \bar{\nu}_e$$

Sile: Izmjena čestica

Relativnost: nema djelovanja na daljinu!



Izmjena bozona je izvor sila između fermiona

sil	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 sile

Stvaranje i izmjena čestice nosioca sile

-> **Energija nije očuvana...**
za kratko vrijeme!

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

U vremenu Δt čestica može proći $R = c \Delta t$

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

Npr.:

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

Kvantna elektrodinamika

Kvantizirana
elektromagnetska polja:
Foton

Brzina c : masa = 0

Elektromagnetske
interakcije

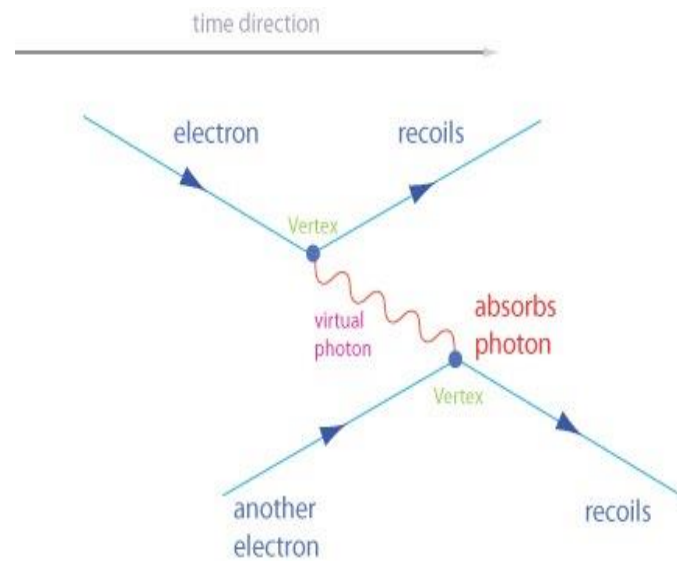
=

Emisija i apsorpcija fotona

Električni naboj očuvan!



R. P. Feynman



Feynmanovi diagrami

Jaka sila: QCD

Teorija jake interakcije:

Kvantna kromodinamika (QCD)

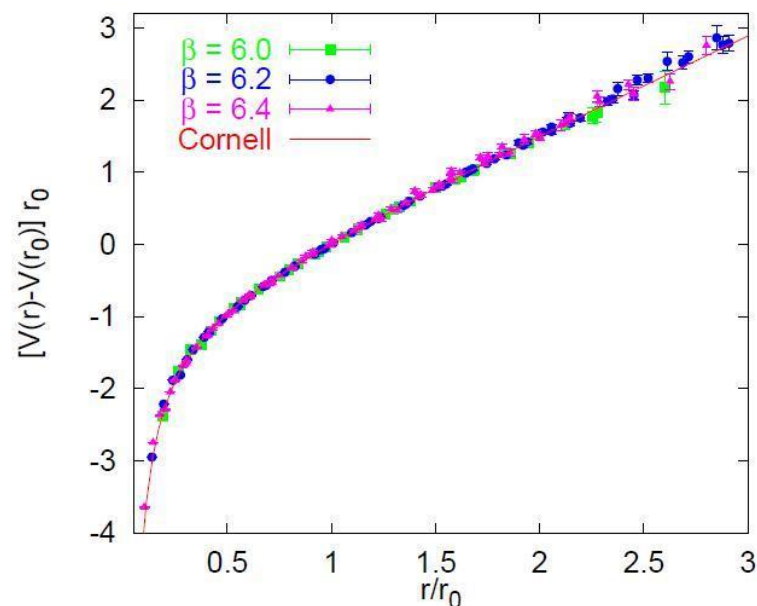
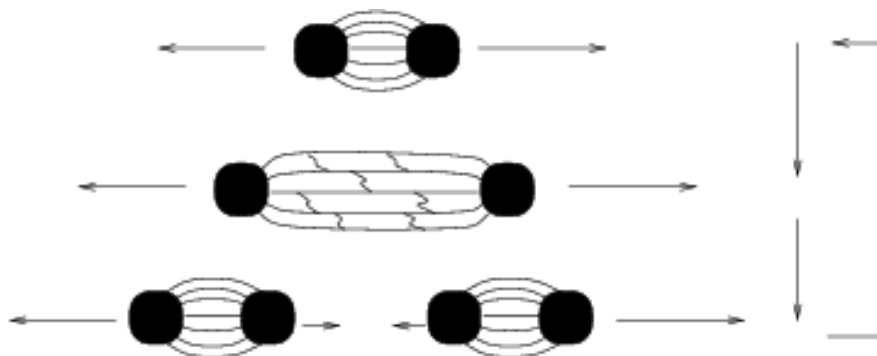
- 3 različita naboja: boje (crveno, zeleno, plavo)
- Nosioци jake sile (8 gluona)

SAMO bezbojna stanja mogu postojati: nema slobodnog kvarka



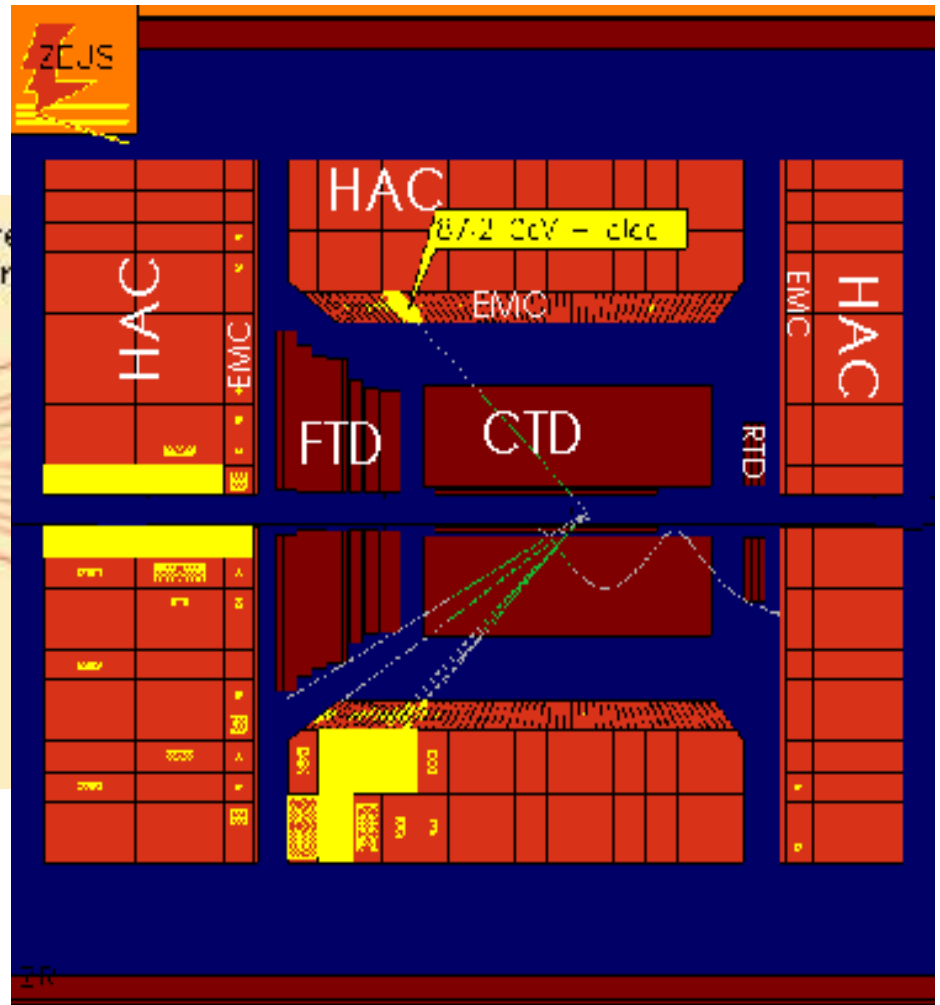
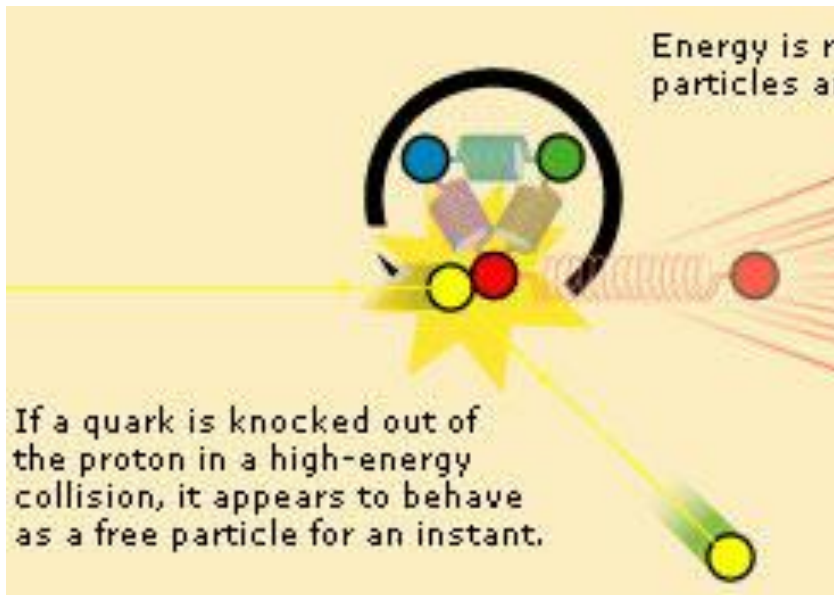
Nema slobodnog kvarka: "Confinement"

Zbog QCD potencijala:
isplativije energički
izvući iz vakuuma
par kvark-antikvark
za stovirati bezbojne
hadrone

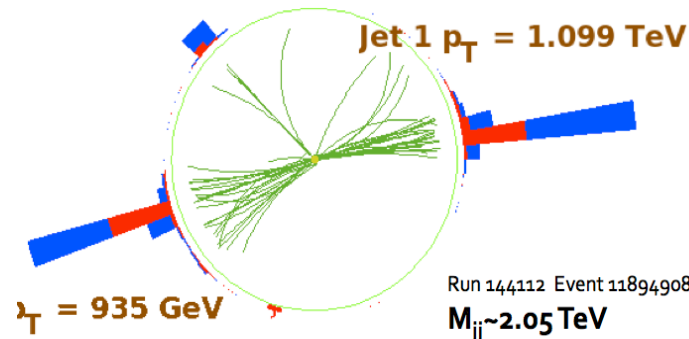
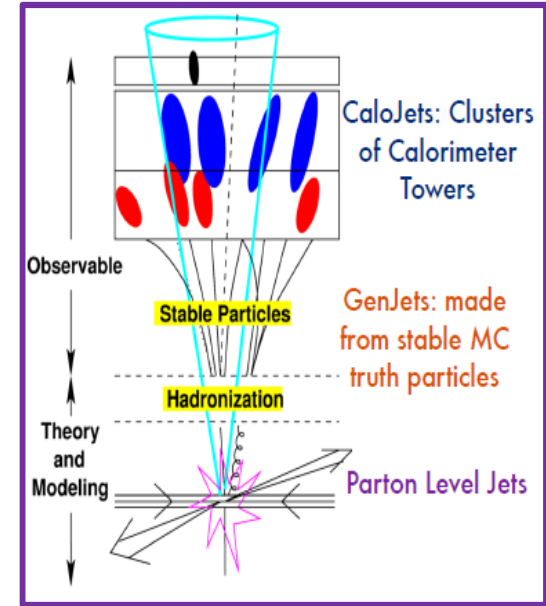
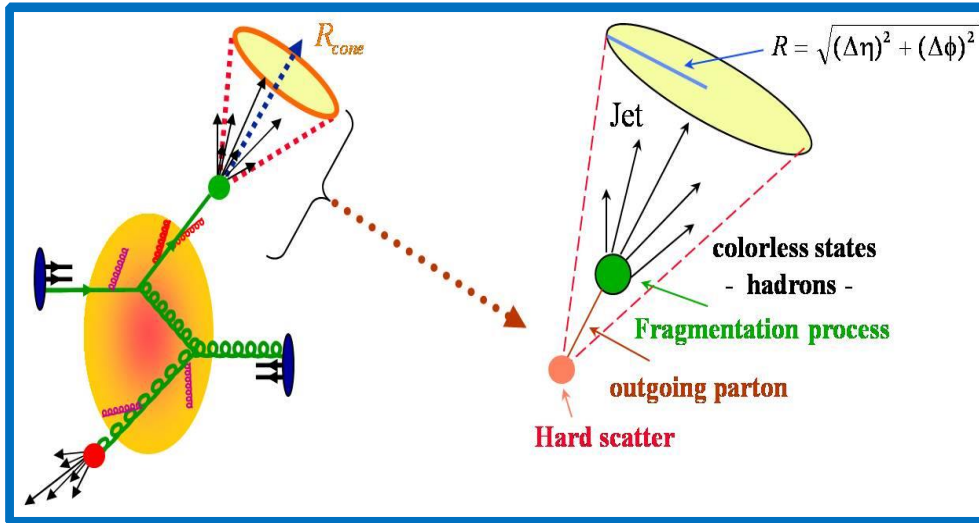


Posljedica:
Hadronski mlaz
"Jet"

Jets (hadronski mlazovi)



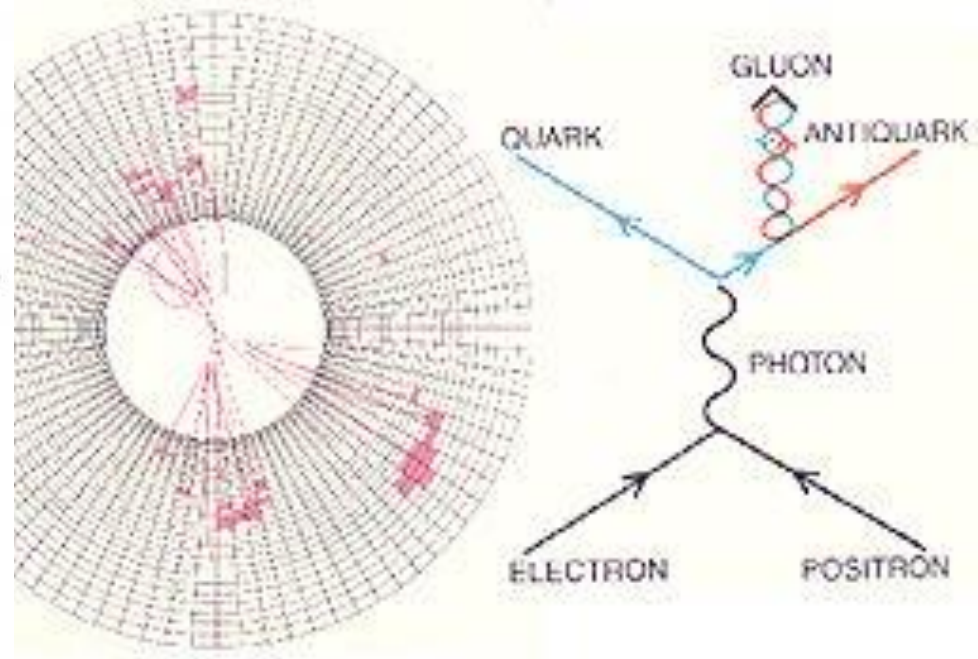
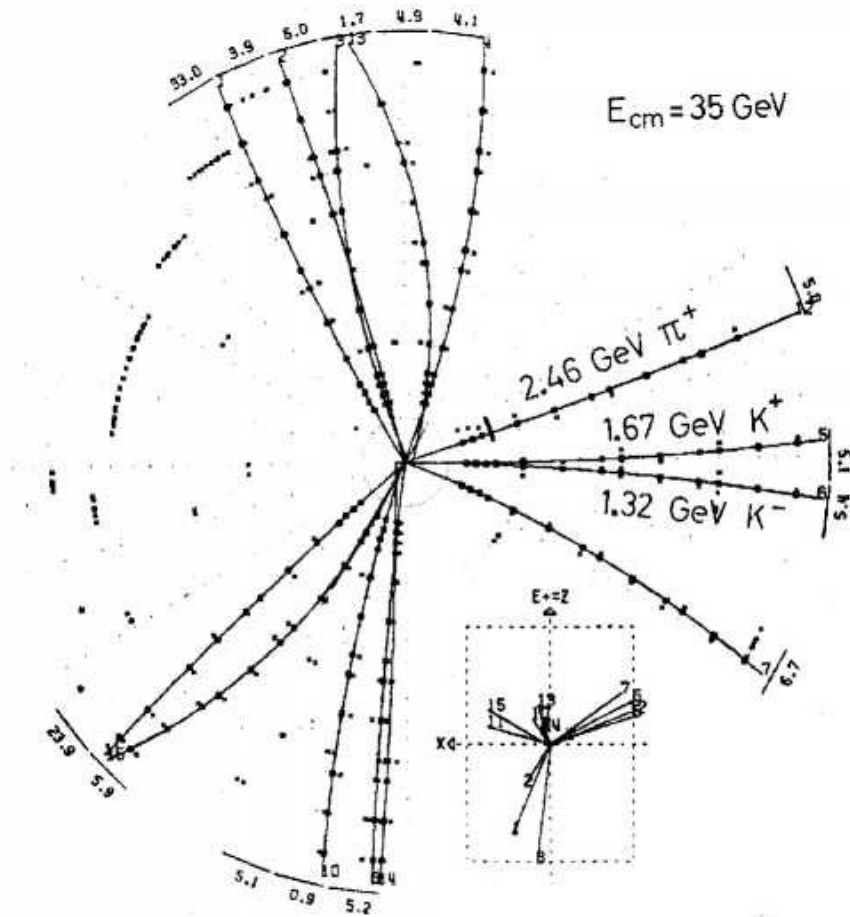
Kvarkovi - Jets



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

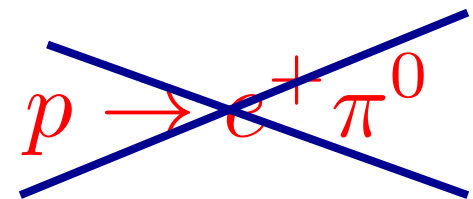
Antibarion: -1

Mezon: 0

Činjenica: barionski broj je očuvan u svim poznatim reakcijama

= Zbroj kvarkova i antikvarkova je konstantan

Npr. zabranjuje: Raspad protona



Očuvano (?) svojstvo: "Okus"

- Svakoj vrsti čestica se pripisuje okus:

- "u,c,t,d,s,b" okus
- Antičestica: suprotno

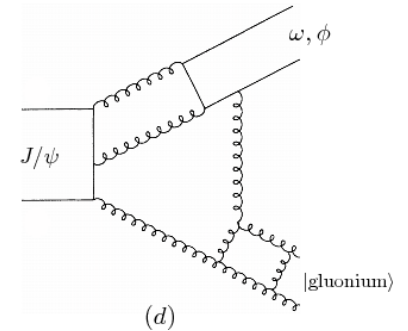
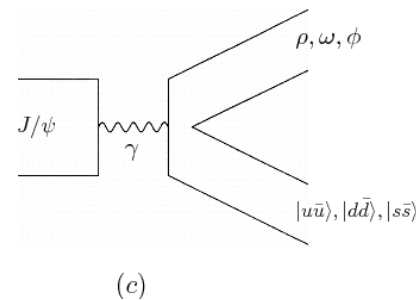
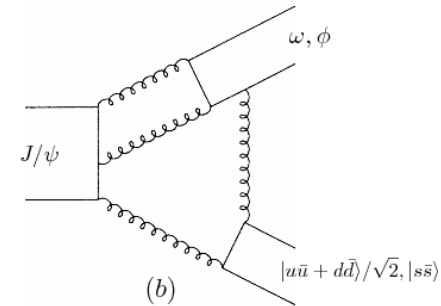
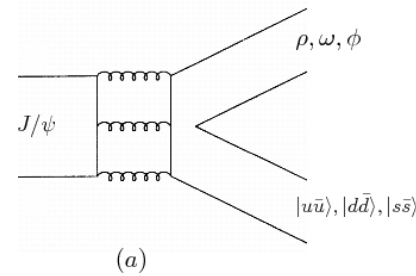
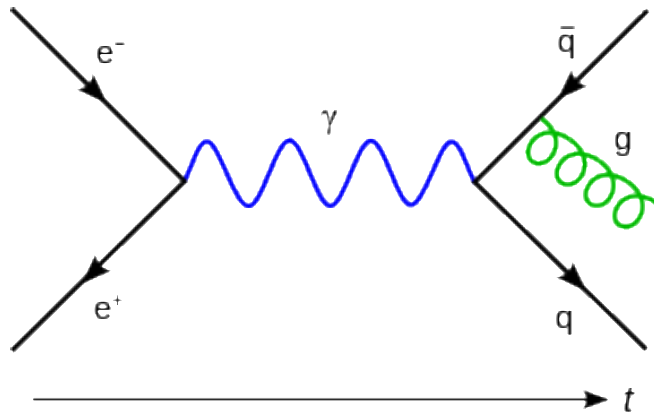
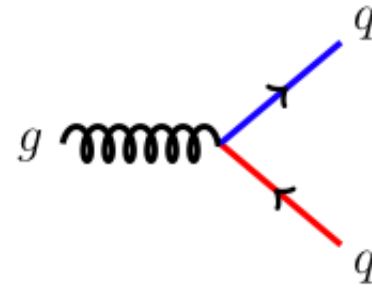
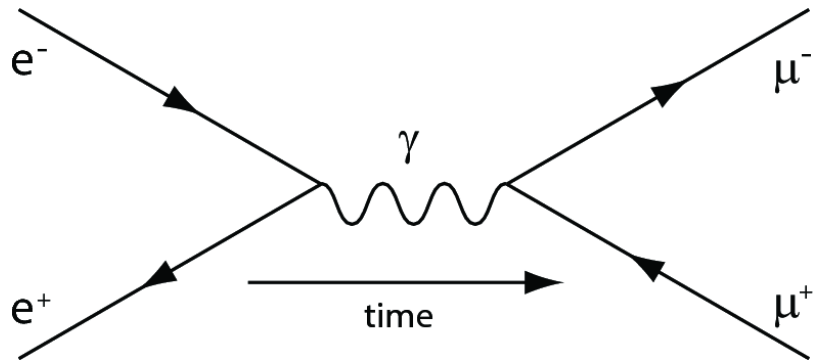
Quarks	u up	c charm	t top
	d down	s strange	b bottom
Leptons	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino
	e electron	μ muon	τ tau

γ photon
g gluon
Z Z boson
W W boson

Force Carriers

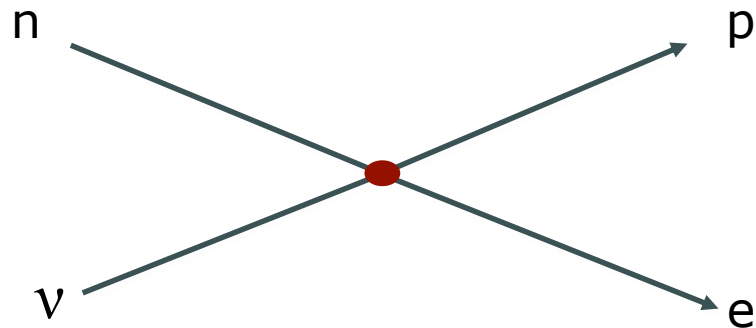
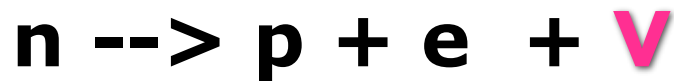
- Okus je očuvan u svim jakim i elektromagnetskim reakcijama:
 - Ako se stvara u-kvark, mora i anti-u

Očuvanje okusa u e.m. i jakim interakcijama



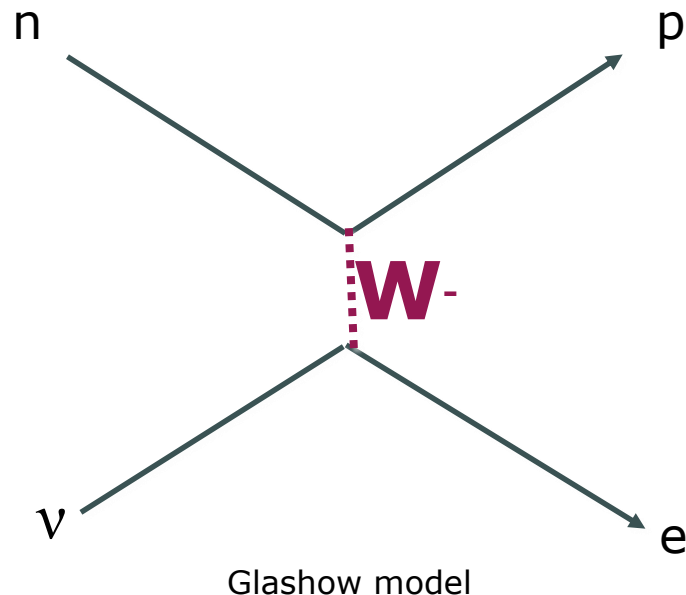
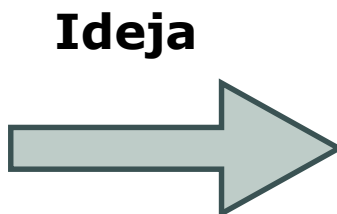
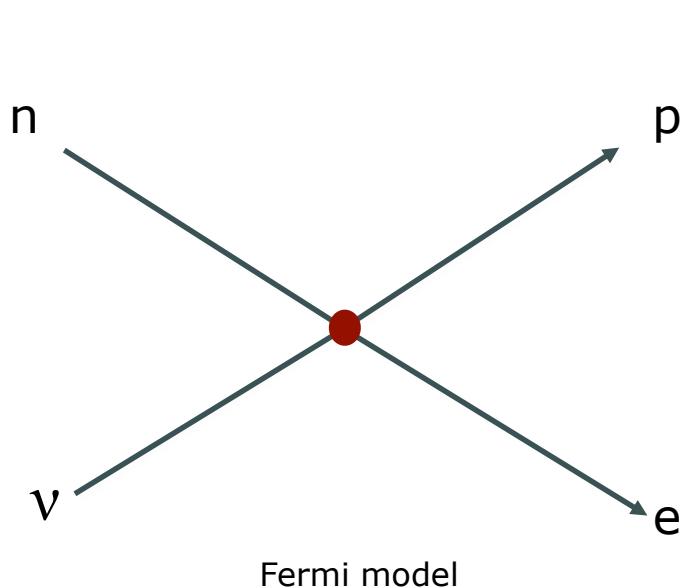
Slaba sila

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



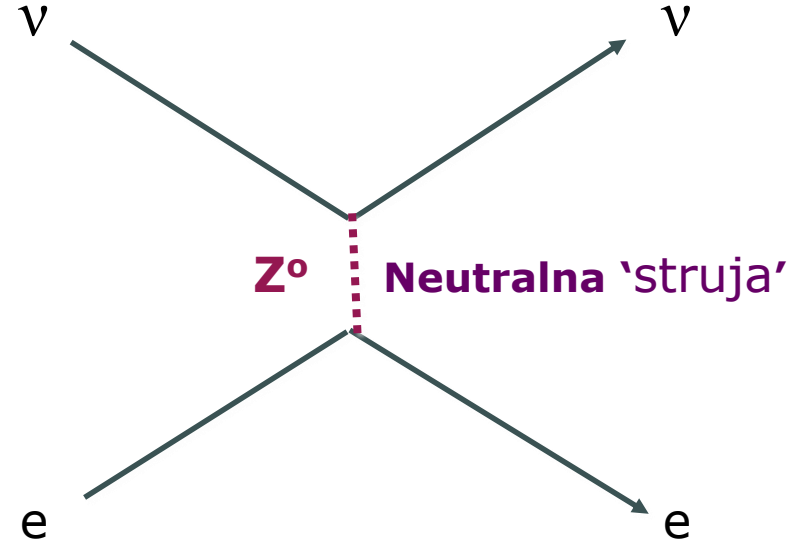
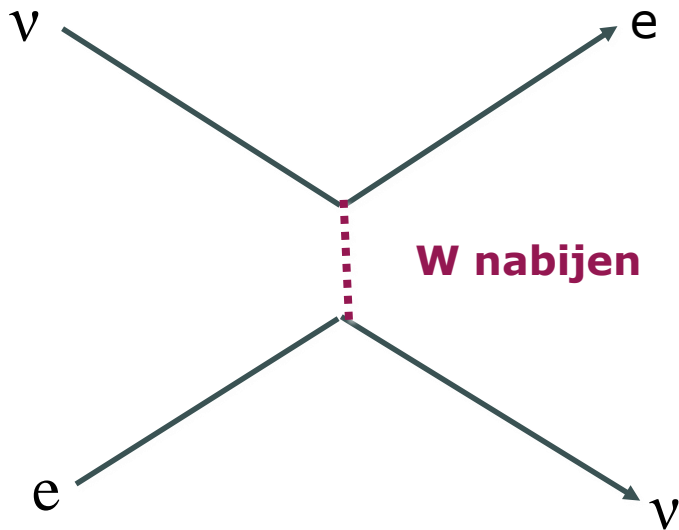
Nosioci slabe sile

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

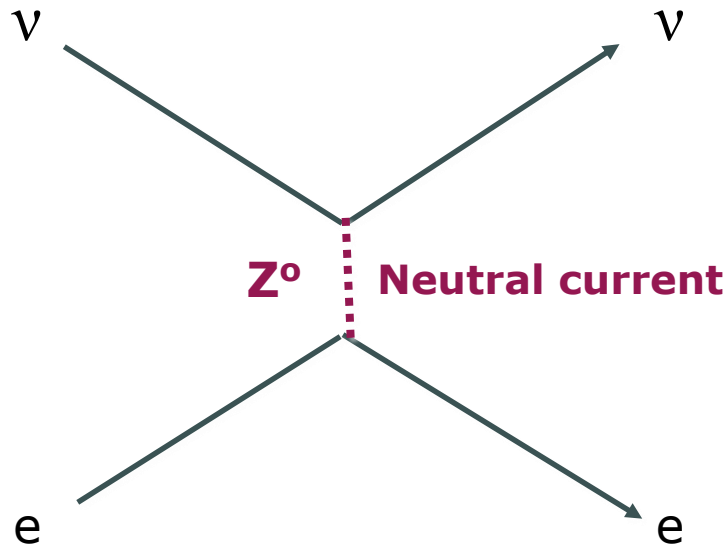
- e.m. i slaba sila su Aspekti iste "elektroslabe sile"
- I kvarkovi i leptoni imaju naboj slabe sile.
- **W i Z Bozoni dobivaju svoju masu od Higgsovog polja (1964)**

Opažanje elektroslabih interakcija

1973

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

Otkriće “neutralnih Struja”, CERN (1973)



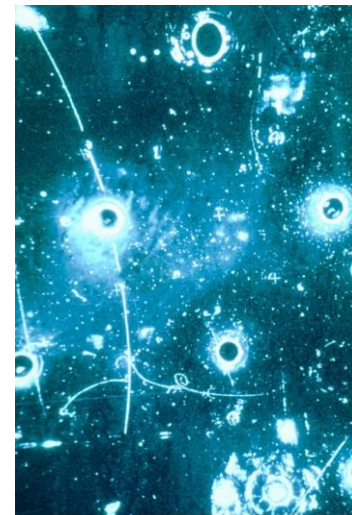
OBSERVATION OF NEUTRINO-LIKE INTERACTIONS WITHOUT MUON OR ELECTRON IN THE GARGAMELLE NEUTRINO EXPERIMENT

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

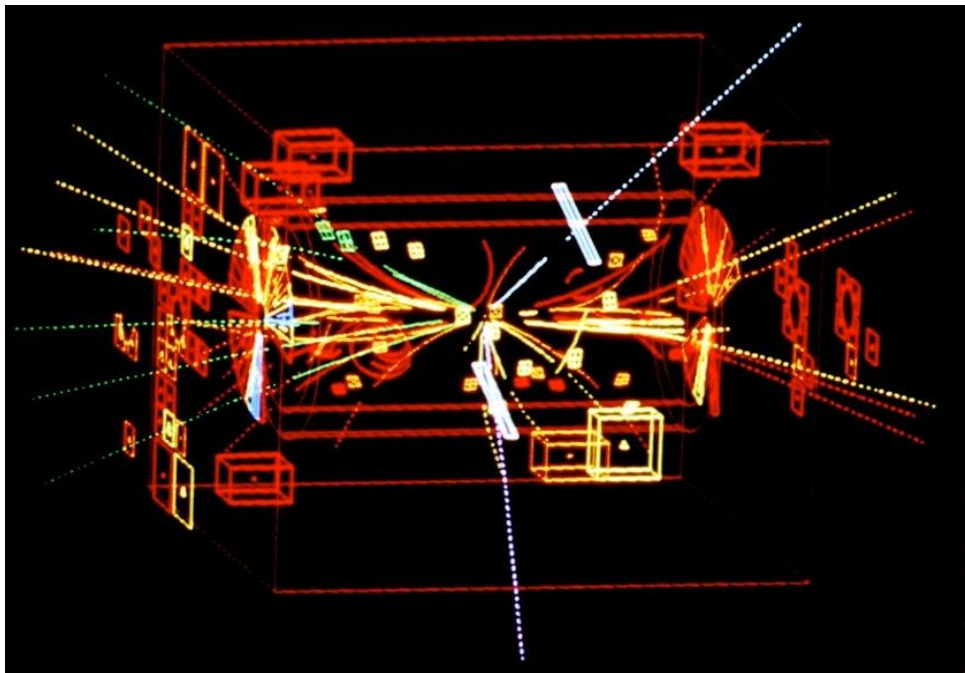
R. BALDI, U. CAMERINI**, D.C. CUNDY, I. DANILCHENKO***, W.F. FRY**
D. HAIDT, S. NATALI[†], P. MUSSET, B. OSCULATI, R. PALMER^{††},
J.B.M. PATTISON, D.H. PERKINS⁺, A. PULLIA, A. ROUSSET,
W. VENUS^{**} and H. WACHSMUTH
CERN, Geneva, Switzerland

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

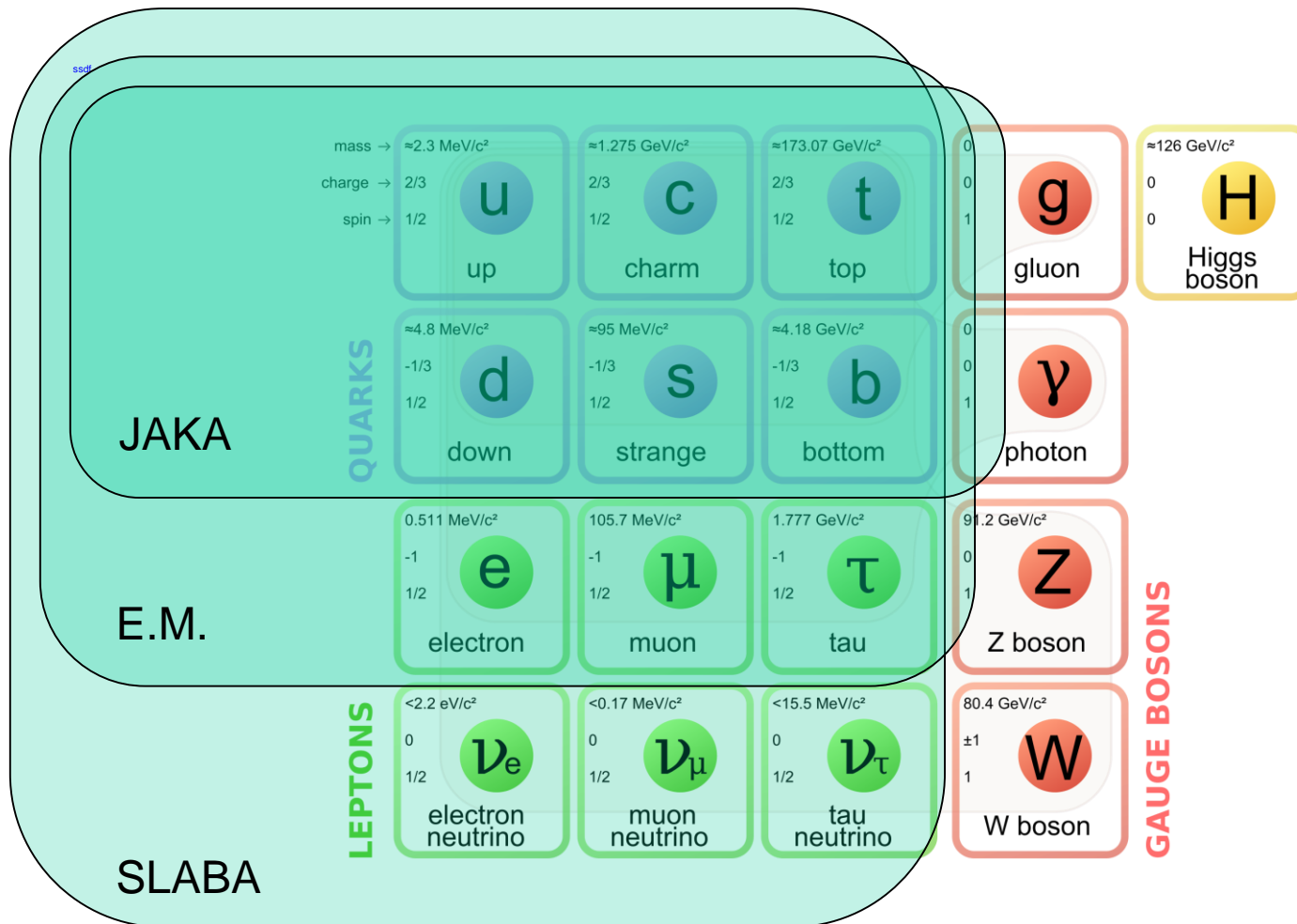
CERN (1983)



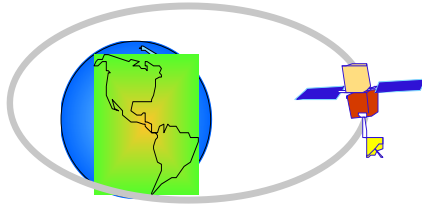
Carlo Rubbia, Simon van der Meer

W kandidat u detektoru UA-1

Čestice Standardnog modela i njihove interakcije



Ujedinjenje sila

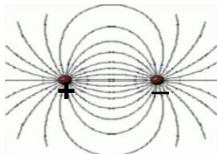


Zemaljska mehanika

Univerzalna gravitacija

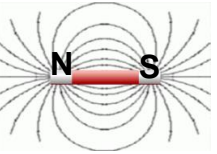
Nebeska mehanika

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



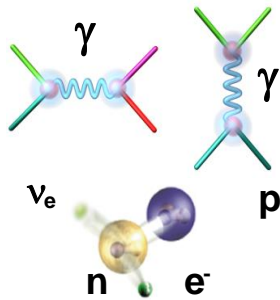
Elektricitet

Elektromagnetizam



Magnetizam

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



Elektromagnetizam

Elektroslaba

Slaba sila

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

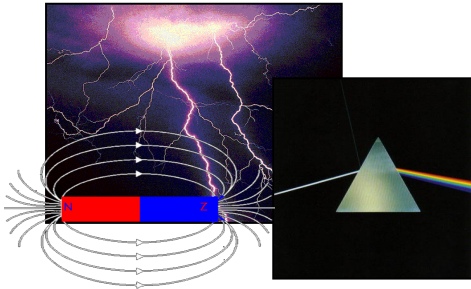


Ispitivanje sve manjih dimeznija
otkriva
dublje pravilnosti

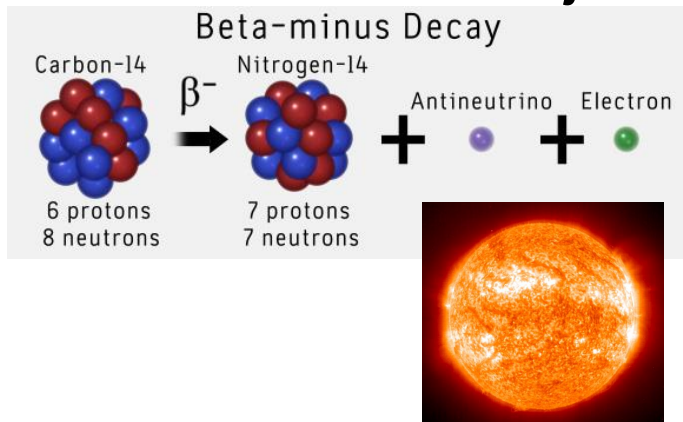
UJEDINJENI OPIS

Elektroslabo ujedinjenje

Elektromagnetizam

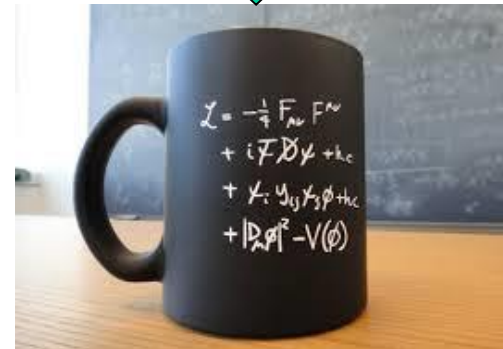


Slabe interakcije



Elektroslaba teorija

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



Gradnja elektroslabe teorije

- Kreće se od 2 abstraktne sile

- **W sila**: 3 bezmasena nosioca



SU(2)

- **B sila**: 1 bezmaseni nosioc



U(1)

- **Fizikalni neutralni nosioci sile:**
mješana stanja

- Foton



77% B^0 , 23% W^0

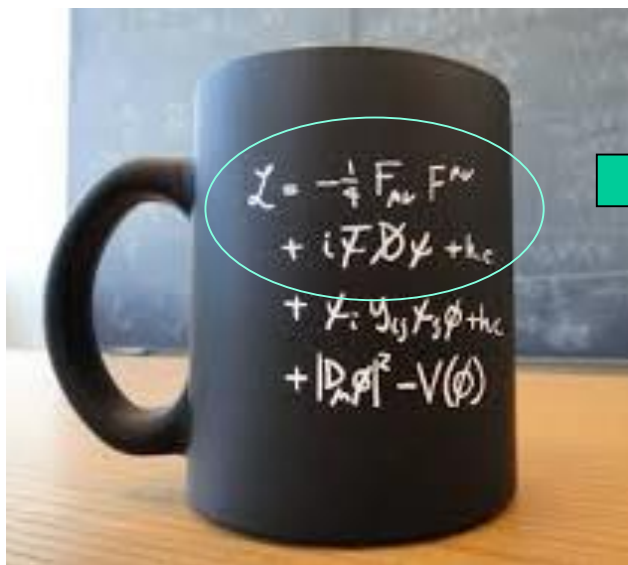
- Z^0



77% W^0 , 23% B^0

Elektroslabi bozoni

- Nosioci elektroslabe sile



Elektroslaba teorija

- svi bozoni bezmaseni
- Sile \sim jednake

Opažanja

e.m. Sila

Foton $m=0$

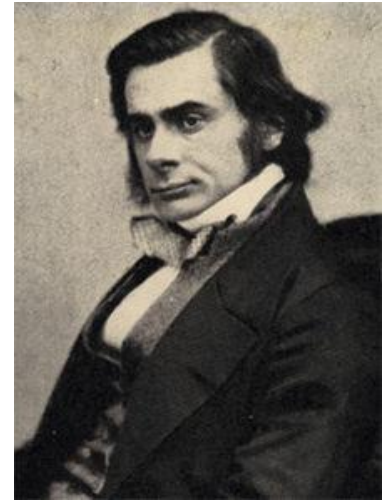
Slaba sila

W & Z bozoni: $m \sim 80-90$ GeV

Slaba sila \ll 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

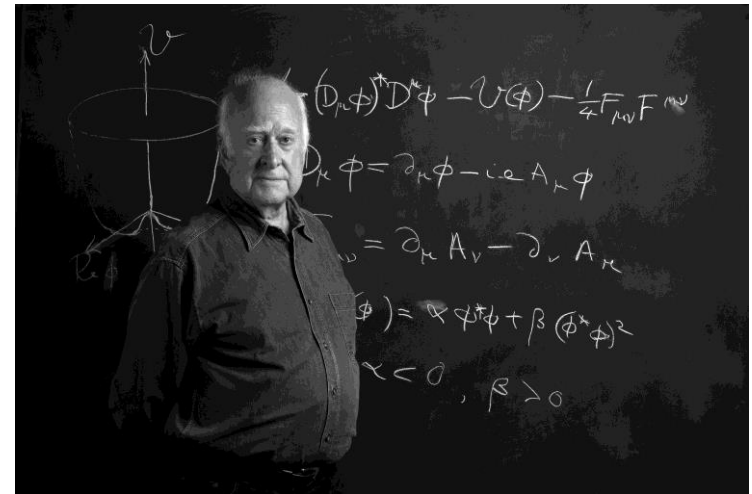
Ideja za spasiti SM

- 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!

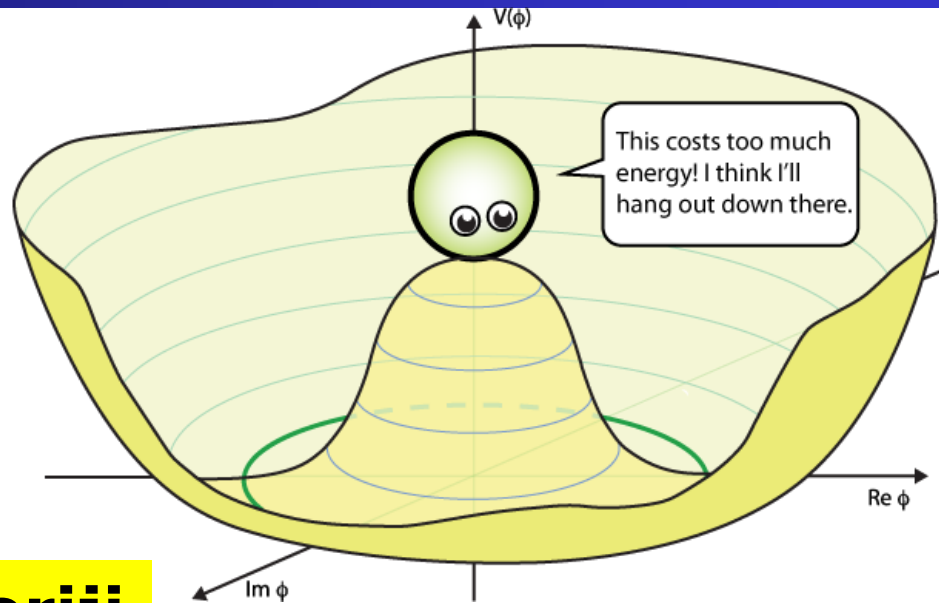
Osnovni postulat
“Higgsovog mehanizma”:

**Postoji novo polje, higgsovo
polje, koje ispunjava cijeli
svemir**

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

Higgsov mehanizam

Spontani lom simetrije

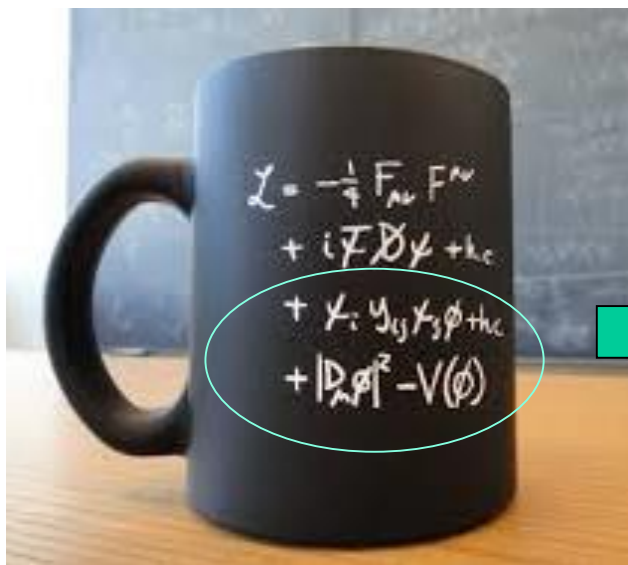


Higgsovo polje u teoriji

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

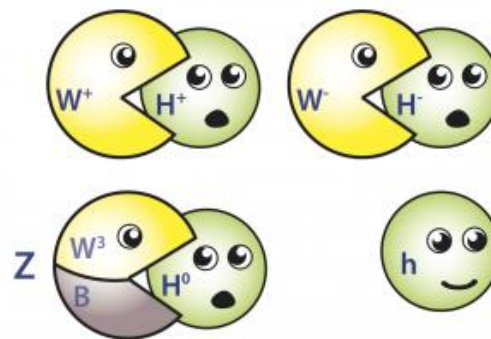
Glashow-Salam-Weinberg Model

Elektroslabе 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 tekućini



Higgsov mehanizam

Interakcija s
Higgsovim poljem

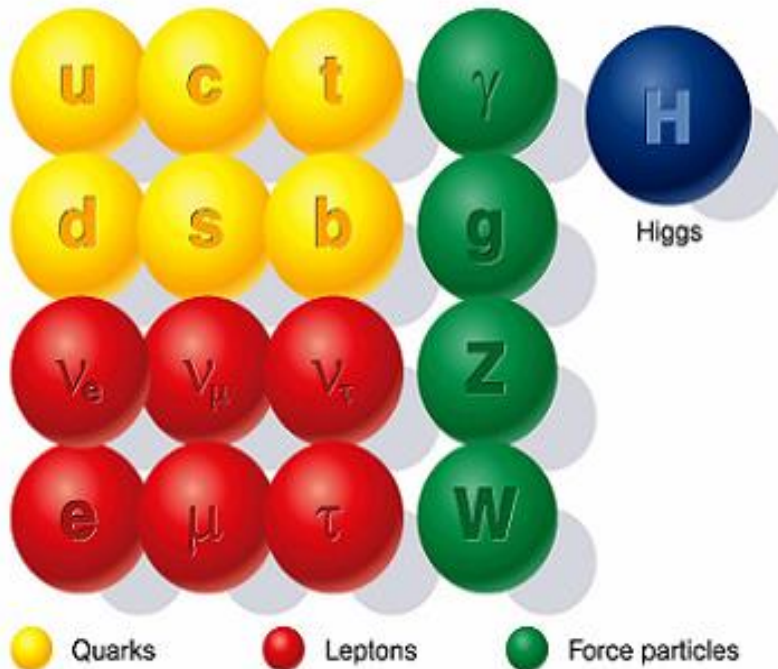


Trenje u viskoznoj
tekućini



Standard Model of Elementary Particles

Standard particles



$$\begin{aligned}
 \mathcal{L}_{GWS} = & \sum_f (\bar{\Psi}_f (i\gamma^\mu \partial_\mu - m_f) \Psi_f - e Q_f \bar{\Psi}_f \gamma^\mu \Psi_f A_\mu) + \\
 & \left[(\bar{a}_L^i \gamma^\mu b_L^i W_\mu^+ + \bar{b}_L^i \gamma^\mu a_L^i W_\mu^-) + \frac{g}{2c_w} \sum_f \bar{\Psi}_f \gamma^\mu (I_f^3 - 2s_w^2 Q_f - I_f^3 \gamma_5) \Psi_f Z \right. \\
 & \left. + \lambda_\mu A_\nu - \partial_\nu A_\mu - ie (W_\mu^- W_\nu^+ - W_\mu^+ W_\nu^-) \right]^2 - \frac{1}{2} |\partial_\mu W_\nu^+ - \partial_\nu W_\mu^+ + \\
 & -ie (W_\mu^+ A_\nu - W_\nu^+ A_\mu) + ig' c_w (W_\mu^+ Z_\nu - W_\nu^+ Z_\mu)|^2 + \\
 & -\frac{1}{4} |\partial_\mu Z_\nu - \partial_\nu Z_\mu + ig' c_w (W_\mu^- W_\nu^+ - W_\mu^+ W_\nu^-)|^2 + \\
 & -\frac{1}{2} M_\eta^2 \eta^2 - \frac{g M_\eta^2}{8 M_W} \eta^3 - \frac{g'^2 M_\eta^2}{32 M_W} \eta^4 + |M_W W_\mu^+ + \frac{g}{2} \eta W_\mu^+|^2 + \\
 & + \frac{1}{2} |\partial_\mu \eta + i M_Z Z_\mu + \frac{ig}{2c_w} \eta Z_\mu|^2 - \sum_f \frac{g}{2} \frac{m_f}{M_W} \bar{\Psi}_f \Psi_f \eta
 \end{aligned}$$



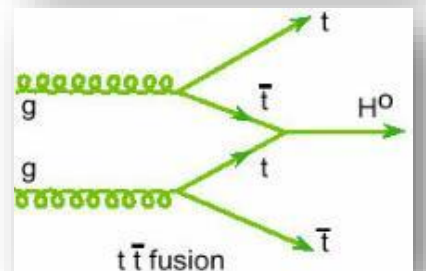
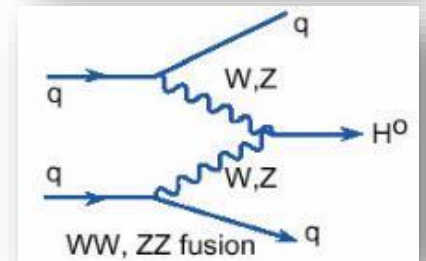
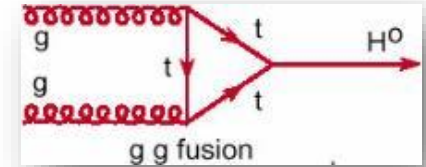
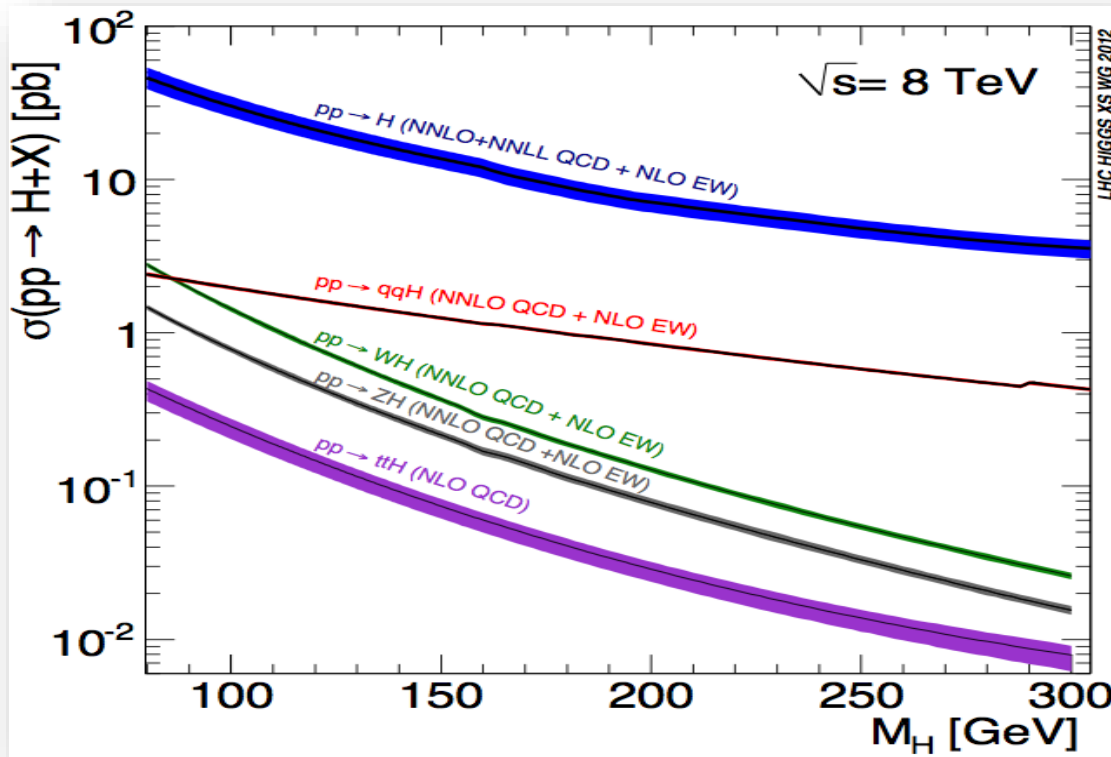
Jedini sigurno opaženi
Higgs u CMS
eksperimentu do 2012.

Dr. Peter Higgs



Potruga za Higgsovim bozonom

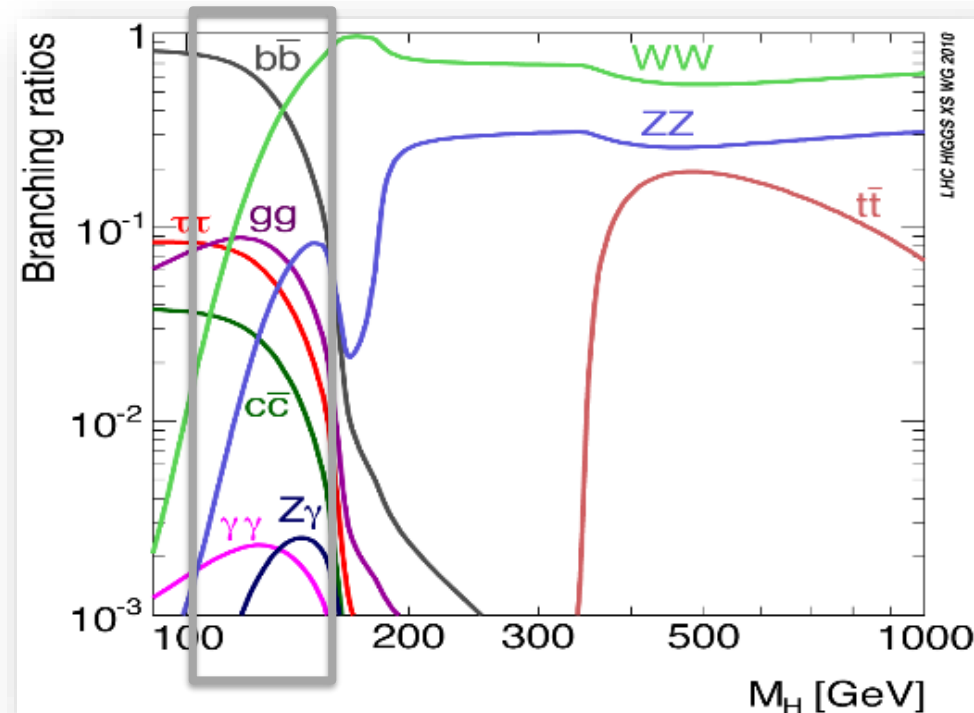
Kako se producira Higgsov bozon?



Kako se raspada Higgsov bozon?

Promatrani kanali raspada

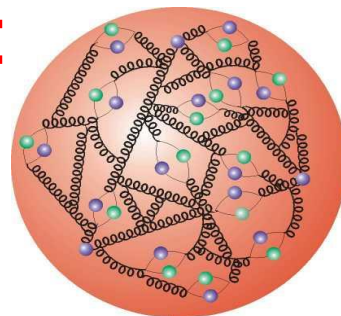
- Visoke mase: WW , ZZ
- Niske mase: bb , $\tau\tau$, WW , ZZ , $\gamma\gamma$
- Područje niskih masa je jako bogato, ali i teško:
Teško identificirati glavne kanale raspada (bb , $\tau\tau$) zbog velike pozadine
- Najprecizniji kanali: $H \rightarrow \gamma\gamma$ & $H \rightarrow ZZ \rightarrow 4l$



Analiza sudara: komplicirana!

Hadronski sudarivač
(sudar ~50 točkastih čestica)

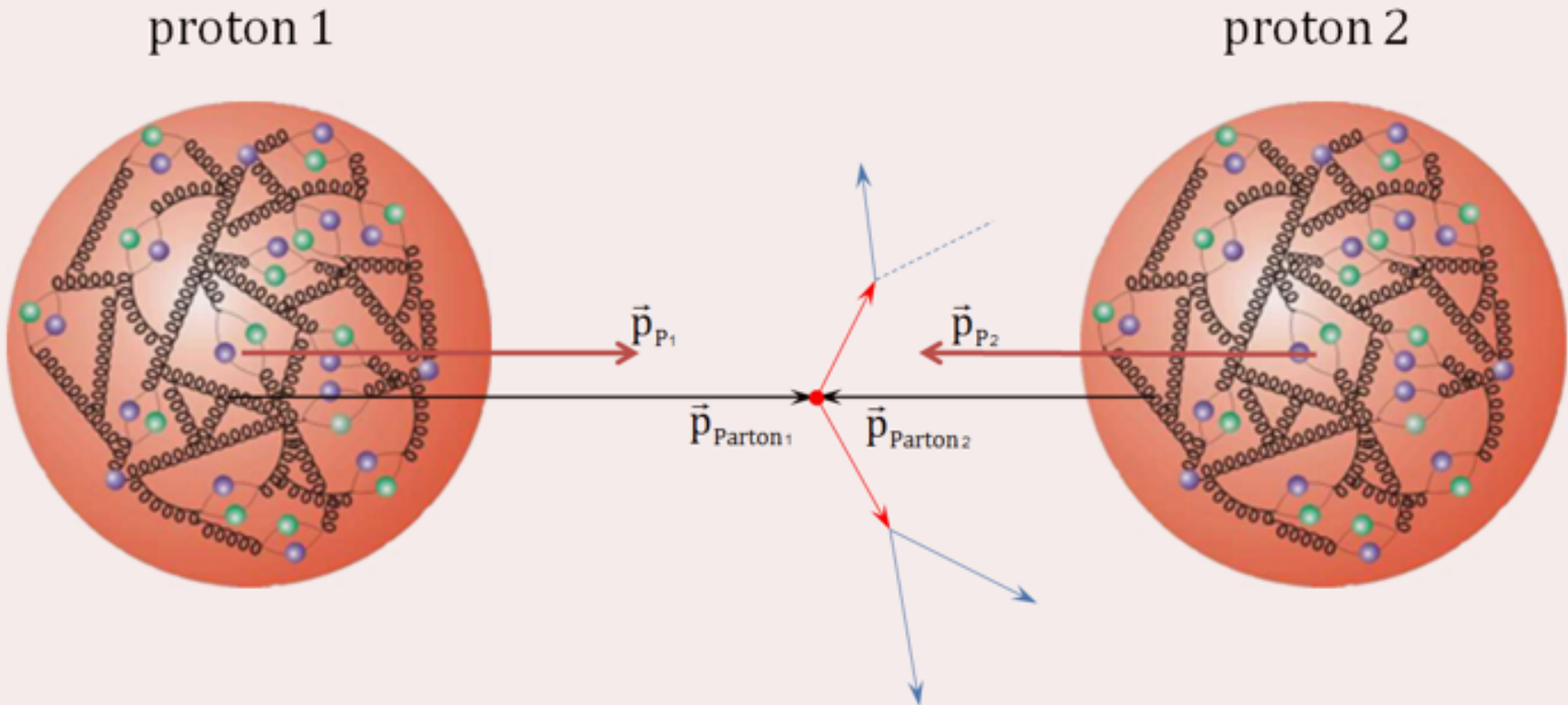
Proton:



Gdje je Asterix?



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



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

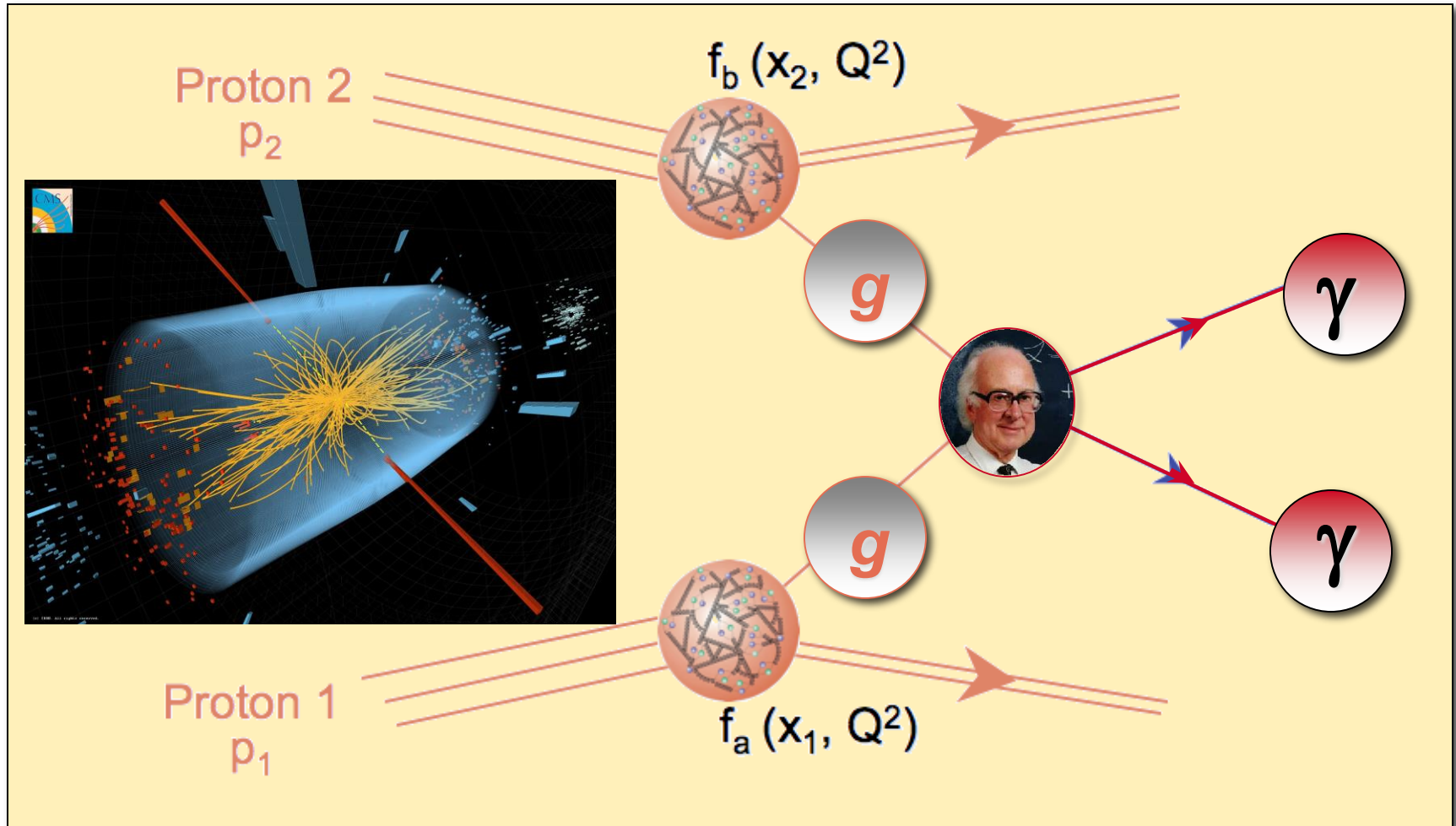
\vec{p}_{P_2} ... momentum proton 2

• interaction vertex

$\vec{p}_{\text{Parton 1}}$... momentum parton 1

$\vec{p}_{\text{Parton 2}}$... momentum parton 2

Osnovni procesi na LHC-u

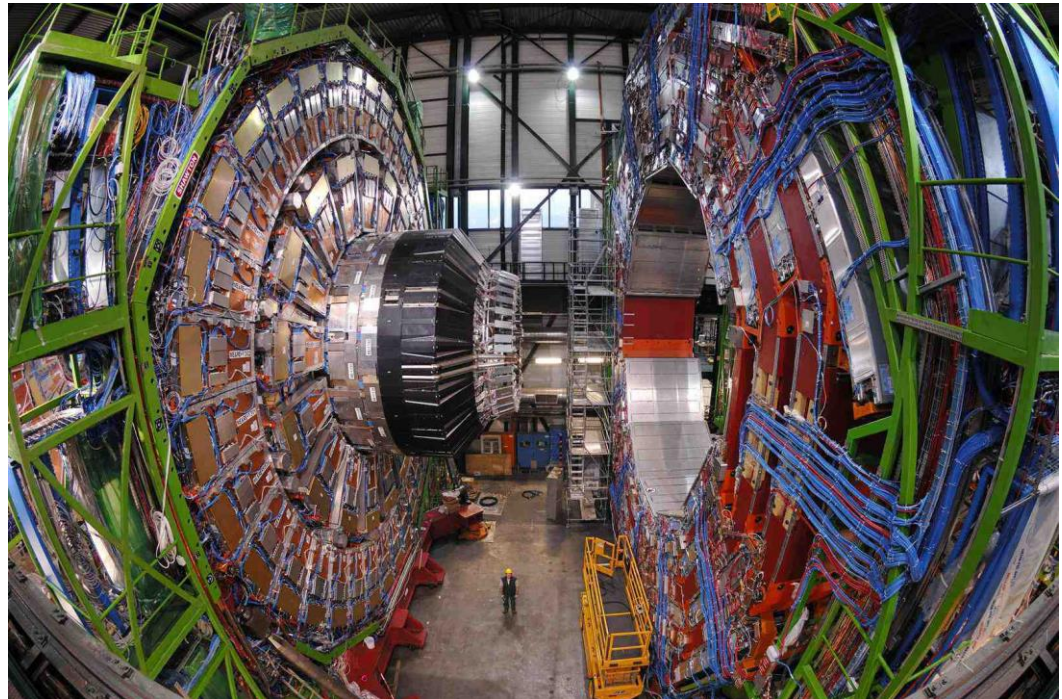


Kako vidimo

STANDARD MODEL OF ELEMENTARY PARTICLES

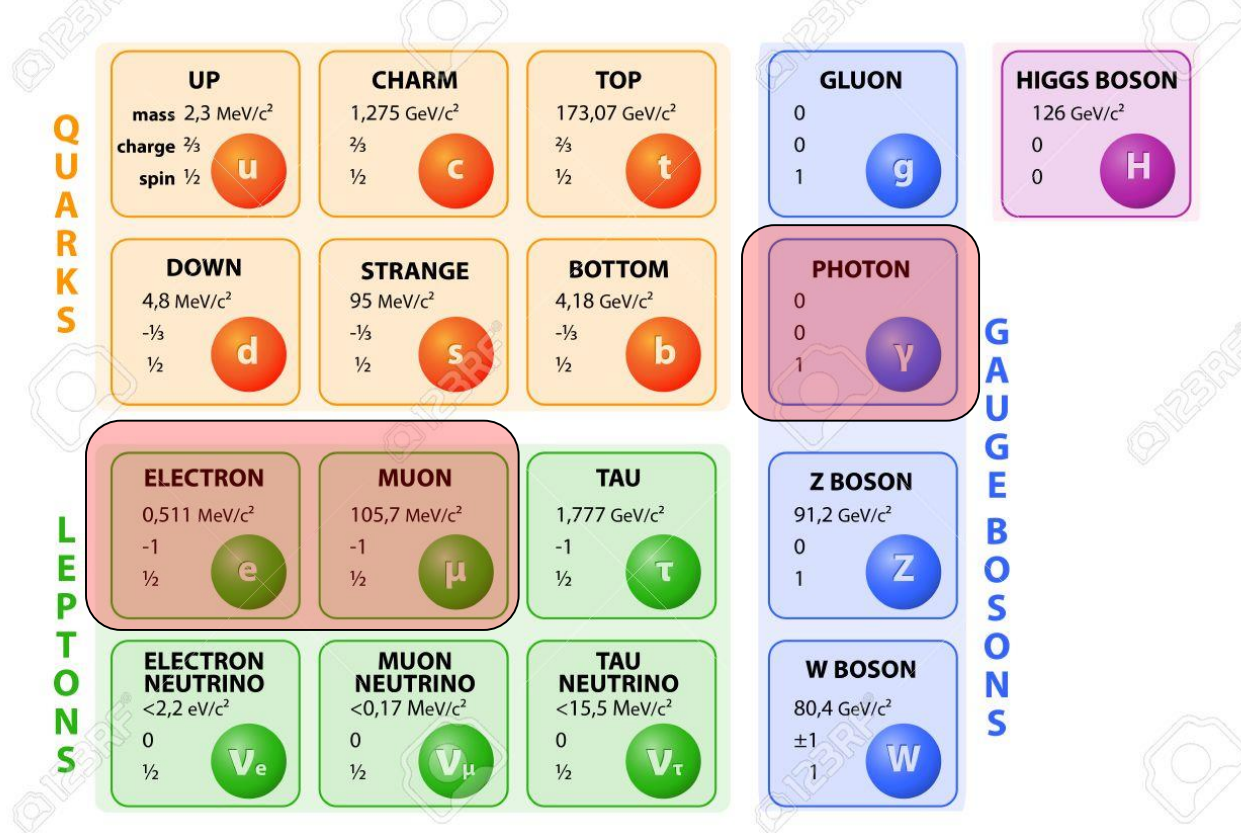
Q U A R K S	UP mass 2,3 MeV/c ² charge 2/3 spin 1/2 u	CHARM 1,275 GeV/c ² 2/3 1/2 c	TOP 173,07 GeV/c ² 2/3 1/2 t	GLUON 0 0 0 1 g	HIGGS BOSON 126 GeV/c ² 0 0 0 H
	DOWN 4,8 MeV/c ² -1/3 1/2 d	STRANGE 95 MeV/c ² -1/3 1/2 s	BOTTOM 4,18 GeV/c ² -1/3 1/2 b	PHOTON 0 0 0 1 γ	G A U G E B O S O N S
	ELECTRON 0,511 MeV/c ² -1 1/2 e	MUON 105,7 MeV/c ² -1 1/2 μ	TAU 1,777 GeV/c ² -1 1/2 τ	Z BOSON 91,2 GeV/c ² 0 0 1 Z	
	ELECTRON NEUTRINO <2,2 eV/c ² 0 1/2 ν_e	MUON NEUTRINO <0,17 MeV/c ² 0 1/2 ν_μ	TAU NEUTRINO <15,5 MeV/c ² 0 1/2 ν_τ	W BOSON 80,4 GeV/c ² ±1 1 W	

u



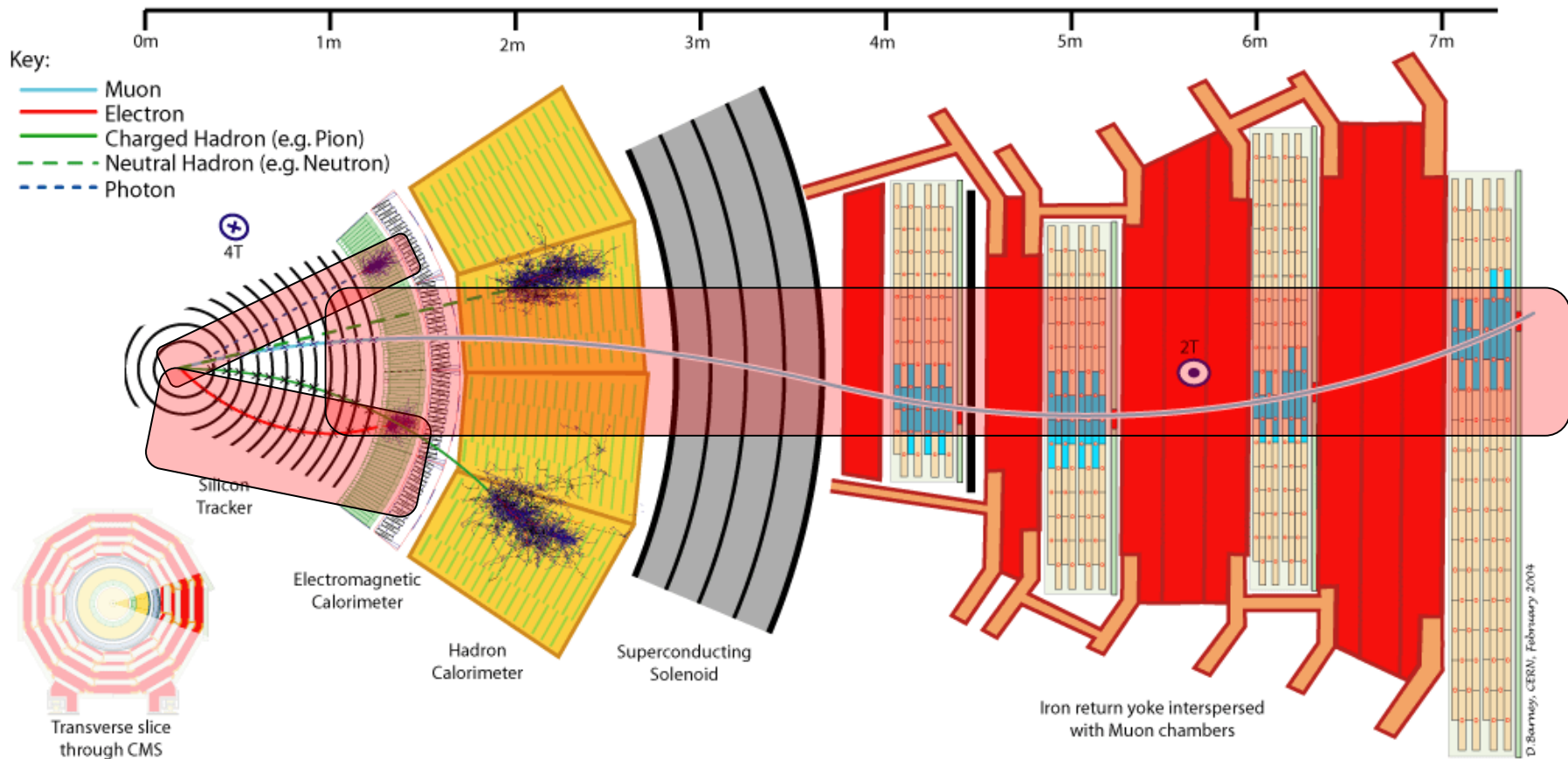
Čestice Standardnog modela

STANDARD MODEL OF ELEMENTARY PARTICLES



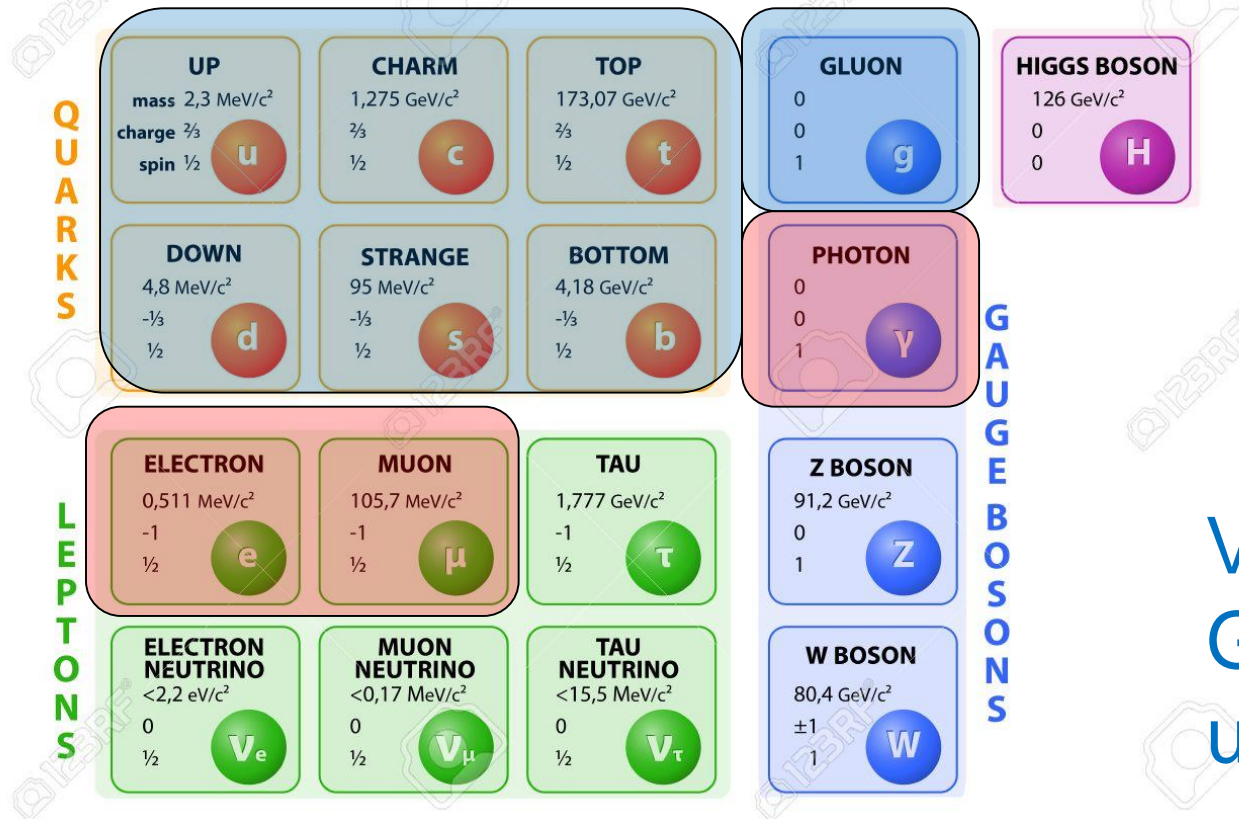
Vidimo ih
u detektoru

Elektron, foton i mion u CMS detektoru



Čestice Standardnog modela

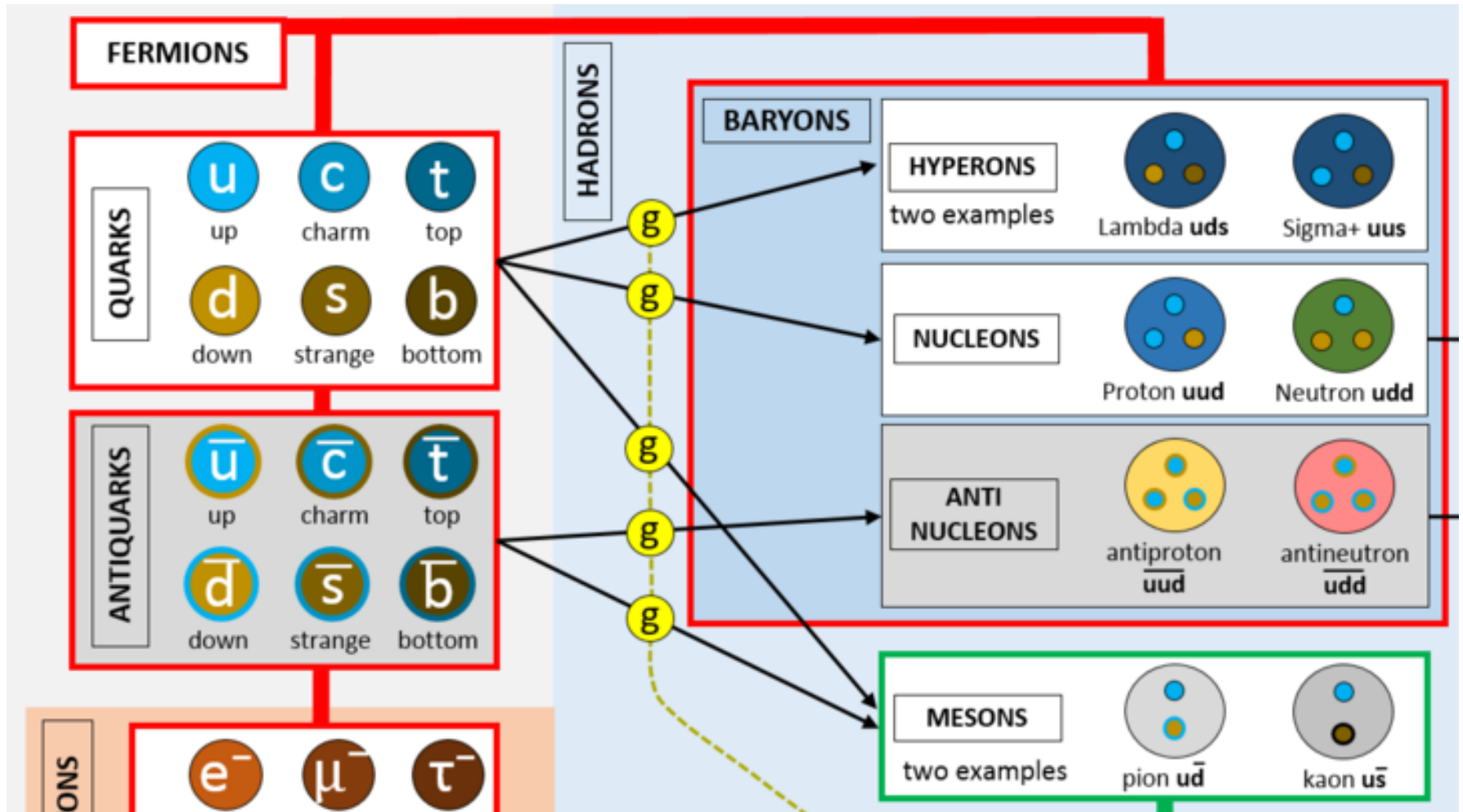
STANDARD MODEL OF ELEMENTARY PARTICLES



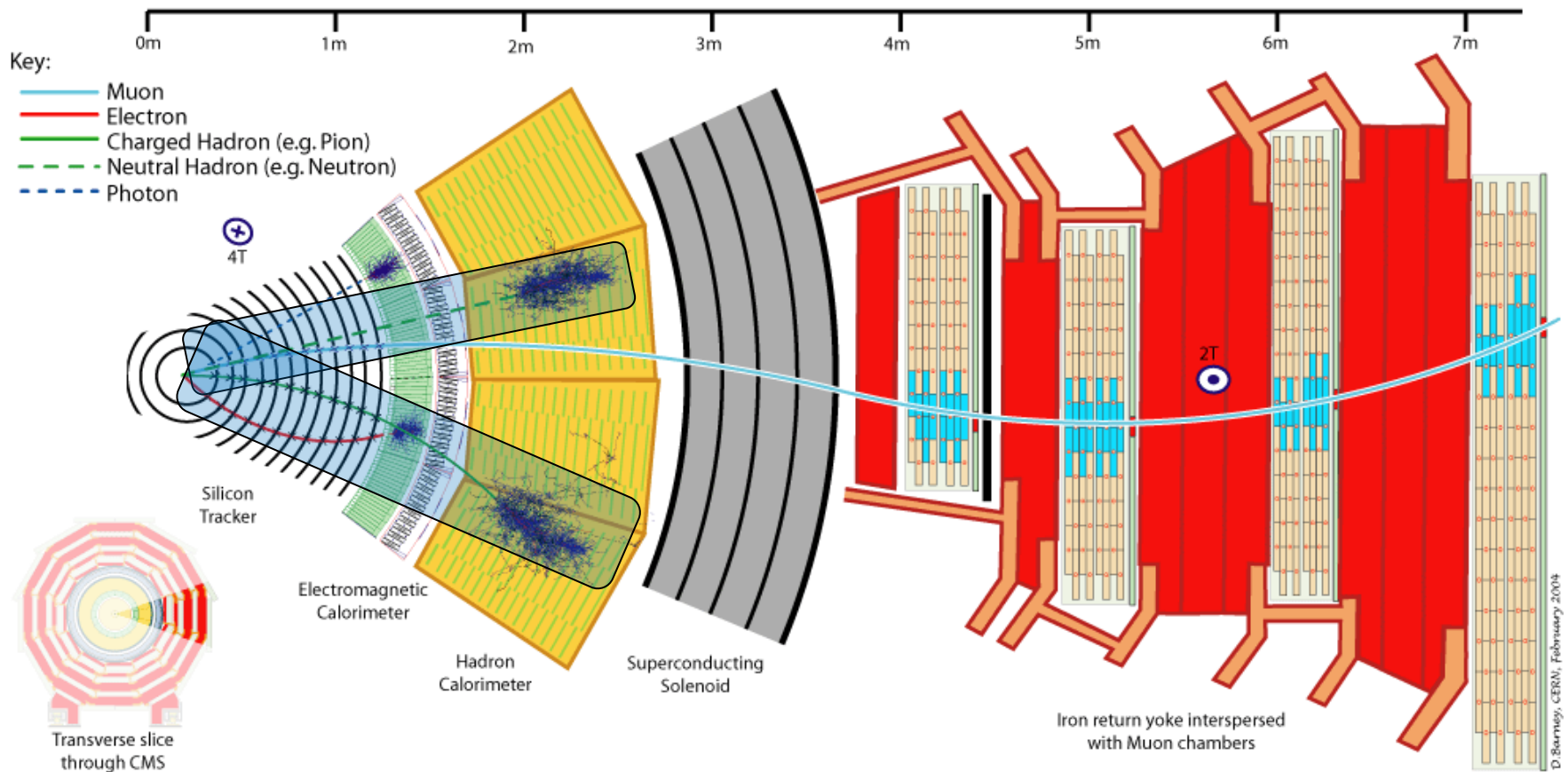
Vidimo ih
u detektoru

Vidimo ih
Grupirane
u hadronima

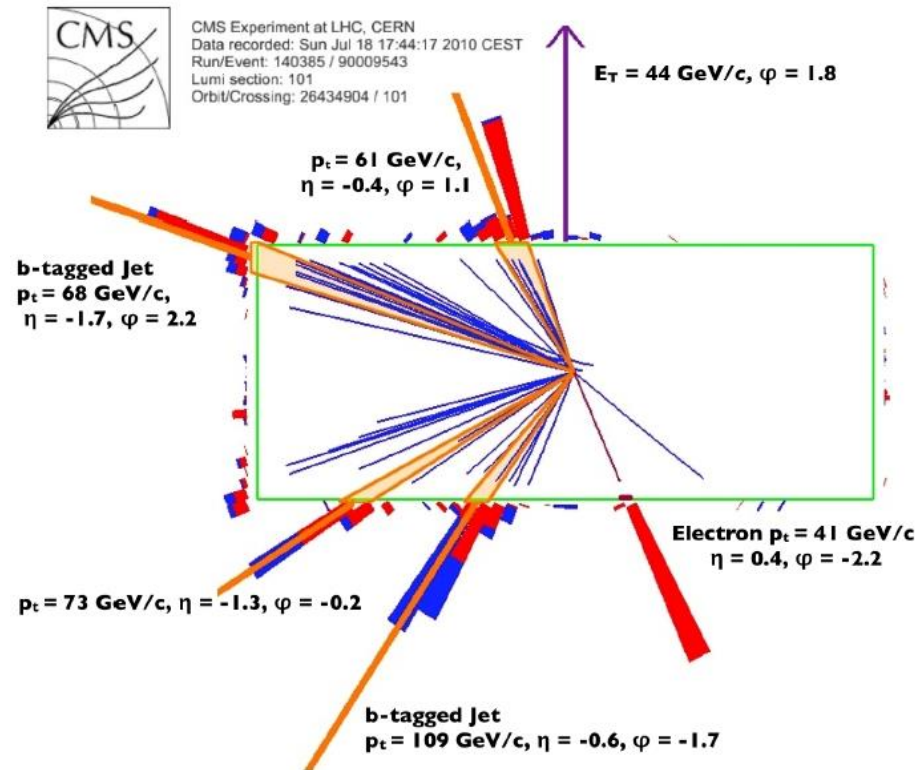
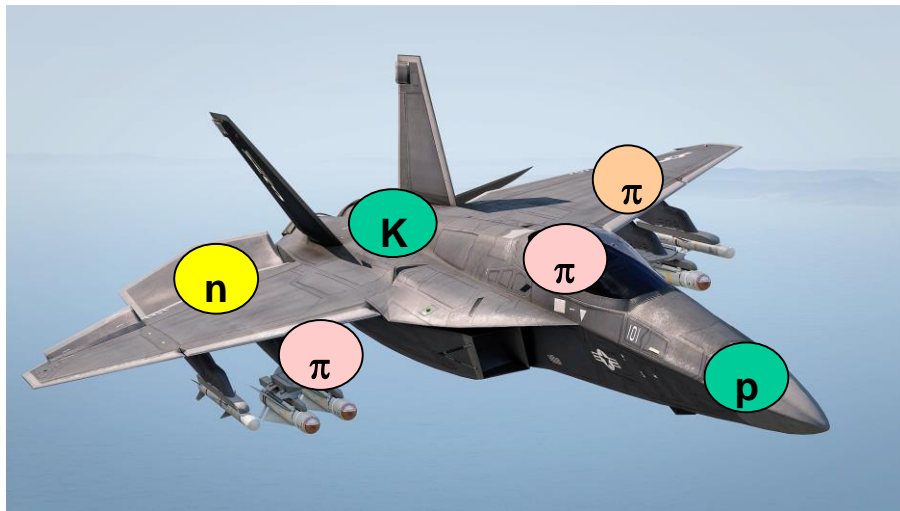
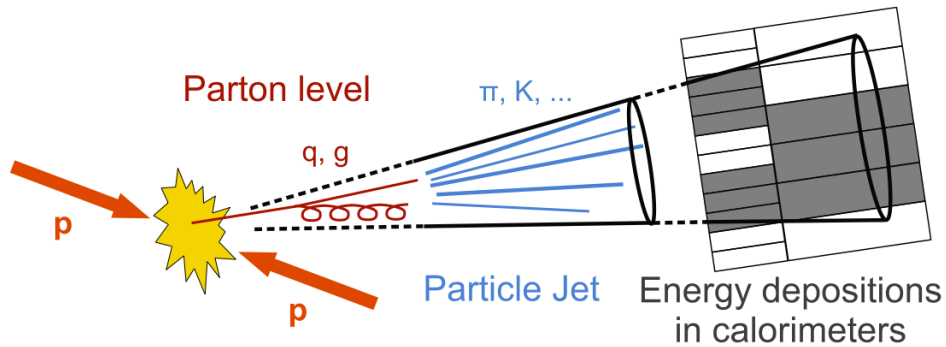
Hadroni



Hadroni u CMS detektoru



Hadroni obično dolaze u grupama: Mlazovi ("Jets")



Čestice Standardnog modela

STANDARD MODEL OF ELEMENTARY PARTICLES

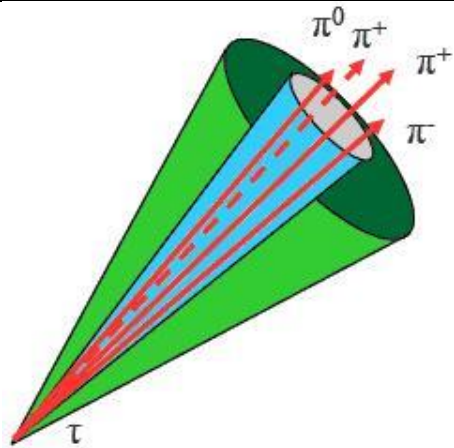
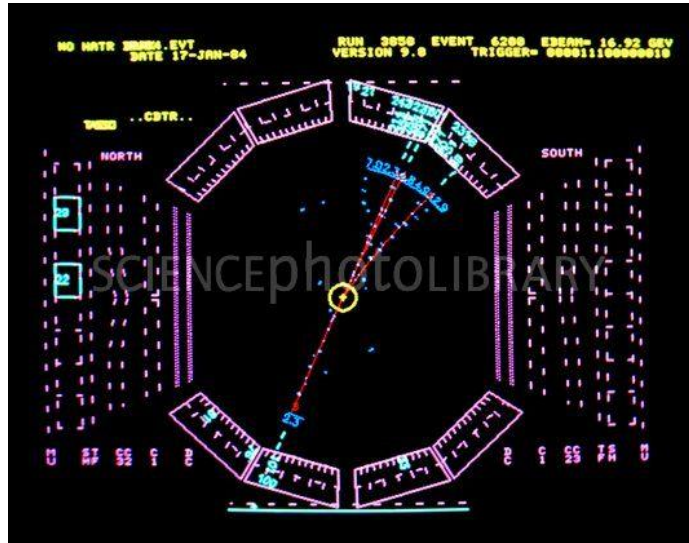
Q U A R K S	UP mass $2,3 \text{ MeV}/c^2$ charge $\frac{2}{3}$ spin $\frac{1}{2}$ u	CHARM mass $1,275 \text{ GeV}/c^2$ charge $\frac{2}{3}$ spin $\frac{1}{2}$ c	TOP mass $173,07 \text{ GeV}/c^2$ charge $\frac{2}{3}$ spin $\frac{1}{2}$ t	GLUON 0 0 1 g	H I G G S B O S O N	
	DOWN mass $4,8 \text{ MeV}/c^2$ charge $-\frac{1}{3}$ spin $\frac{1}{2}$ d	STRANGE mass $95 \text{ MeV}/c^2$ charge $-\frac{1}{3}$ spin $\frac{1}{2}$ s	BOTTOM mass $4,18 \text{ GeV}/c^2$ charge $-\frac{1}{3}$ spin $\frac{1}{2}$ b	PHOTON 0 0 1 γ		
	ELECTRON mass $0,511 \text{ MeV}/c^2$ charge -1 spin $\frac{1}{2}$ e	MUON mass $105,7 \text{ MeV}/c^2$ charge -1 spin $\frac{1}{2}$ μ	TAU mass $1,777 \text{ GeV}/c^2$ charge -1 spin $\frac{1}{2}$ τ			Z BOSON mass $91,2 \text{ GeV}/c^2$ 0 1 Z
	ELECTRON NEUTRINO mass $<2,2 \text{ eV}/c^2$ 0 spin $\frac{1}{2}$ ν_e	MUON NEUTRINO mass $<0,17 \text{ MeV}/c^2$ 0 spin $\frac{1}{2}$ ν_μ	TAU NEUTRINO mass $<15,5 \text{ MeV}/c^2$ 0 spin $\frac{1}{2}$ ν_τ	W BOSON mass $80,4 \text{ GeV}/c^2$ ± 1 1 W		

Vidimo ih
u detektoru

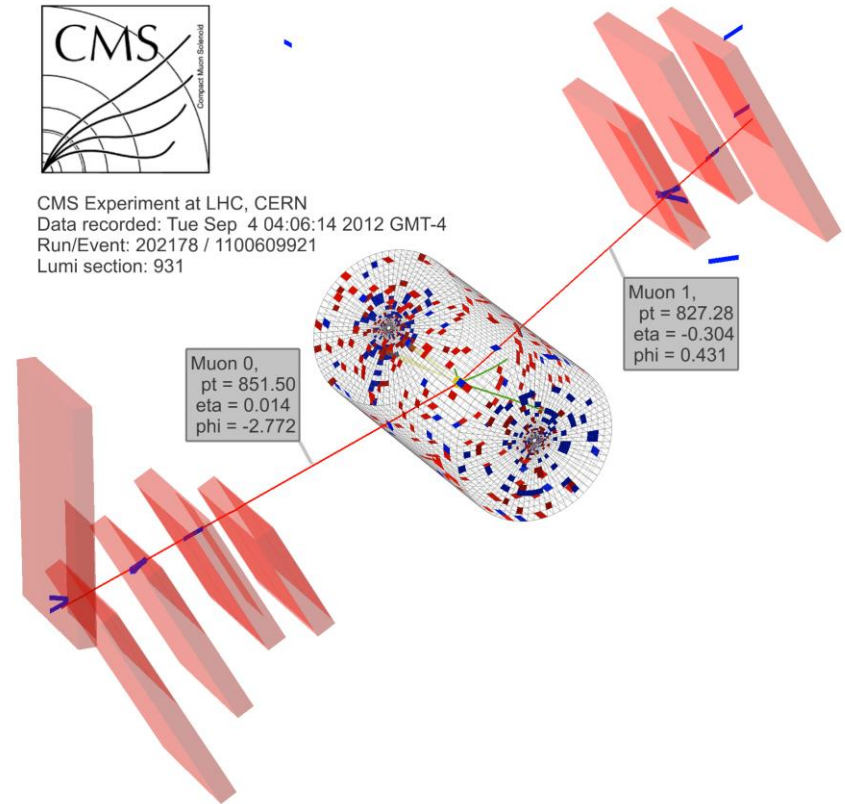
Vidimo ih
Grupirane
u hadronima

Vidimo produkte
Njihovog raspada

Raspadi čestica u detektoru



CMS Experiment at LHC, CERN
Data recorded: Tue Sep 4 04:06:14 2012 GMT-4
Run/Event: 202178 / 1100609921
Lumi section: 931



Čestice Standardnog modela

STANDARD MODEL OF ELEMENTARY PARTICLES

Q U A R K S	UP mass $2,3 \text{ MeV}/c^2$ charge $\frac{2}{3}$ spin $\frac{1}{2}$ u	CHARM mass $1,275 \text{ GeV}/c^2$ charge $\frac{2}{3}$ spin $\frac{1}{2}$ c	TOP mass $173,07 \text{ GeV}/c^2$ charge $\frac{2}{3}$ spin $\frac{1}{2}$ t	GLUON 0 0 1 g	H I G G S B O S O N	
	DOWN mass $4,8 \text{ MeV}/c^2$ charge $-\frac{1}{3}$ spin $\frac{1}{2}$ d	STRANGE mass $95 \text{ MeV}/c^2$ charge $-\frac{1}{3}$ spin $\frac{1}{2}$ s	BOTTOM mass $4,18 \text{ GeV}/c^2$ charge $-\frac{1}{3}$ spin $\frac{1}{2}$ b	PHOTON 0 0 1 γ		
	ELECTRON mass $0,511 \text{ MeV}/c^2$ charge -1 spin $\frac{1}{2}$ e	MUON mass $105,7 \text{ MeV}/c^2$ charge -1 spin $\frac{1}{2}$ μ	TAU mass $1,777 \text{ GeV}/c^2$ charge -1 spin $\frac{1}{2}$ τ			Z BOSON mass $91,2 \text{ GeV}/c^2$ 0 1 Z
	ELECTRON NEUTRINO mass $<2,2 \text{ eV}/c^2$ 0 spin $\frac{1}{2}$ ν_e	MUON NEUTRINO mass $<0,17 \text{ MeV}/c^2$ 0 spin $\frac{1}{2}$ ν_μ	TAU NEUTRINO mass $<15,5 \text{ MeV}/c^2$ 0 spin $\frac{1}{2}$ ν_τ	W BOSON mass $80,4 \text{ GeV}/c^2$ ± 1 1 W		
	L E P T O N S					G A U G E B O S O N S

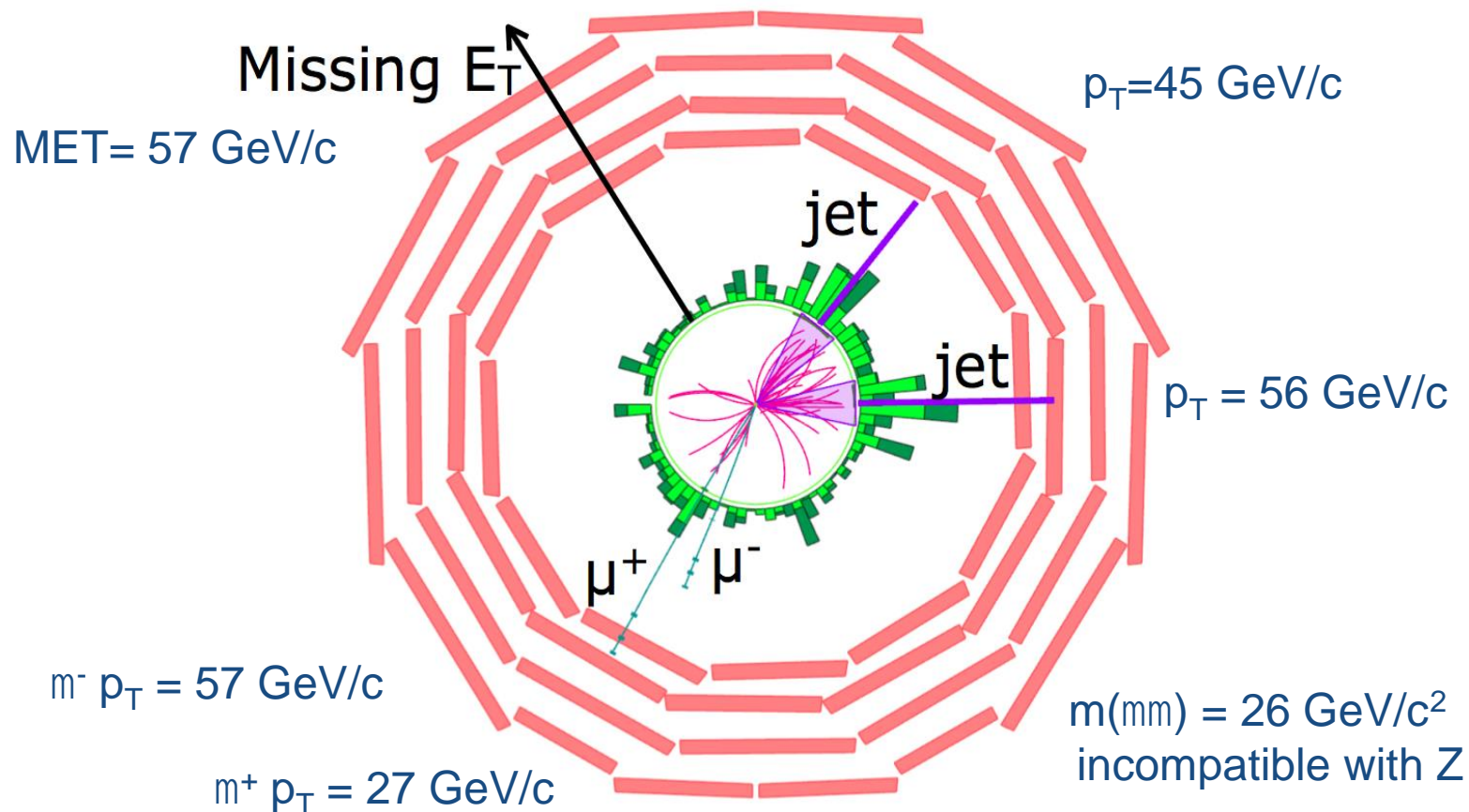
Vidimo ih
u detektoru

Vidimo ih
Grupirane
u hadronima

Vidimo produkte
Njihovog raspada

Ne vidimo ih

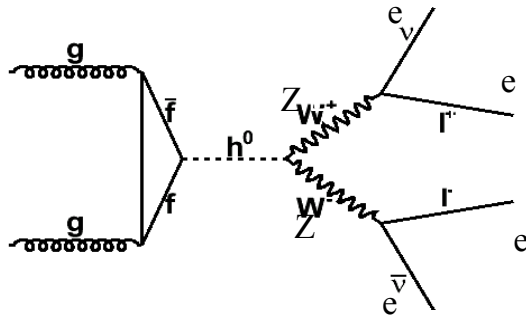
Fizikalni objekti u CMS detektoru



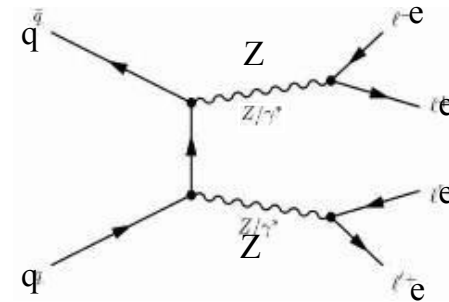
Top Di-Muon Candidate Event

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



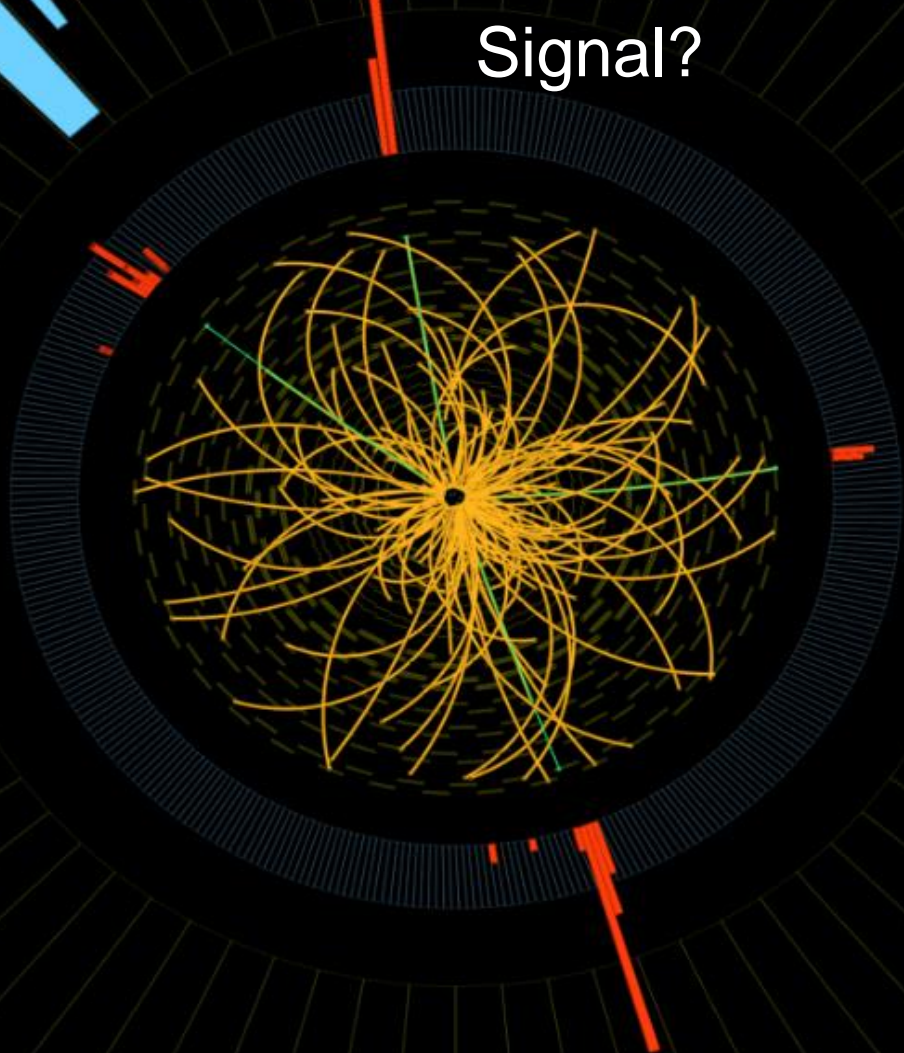
Signal: $pp \rightarrow H \rightarrow ZZ \rightarrow 4e$



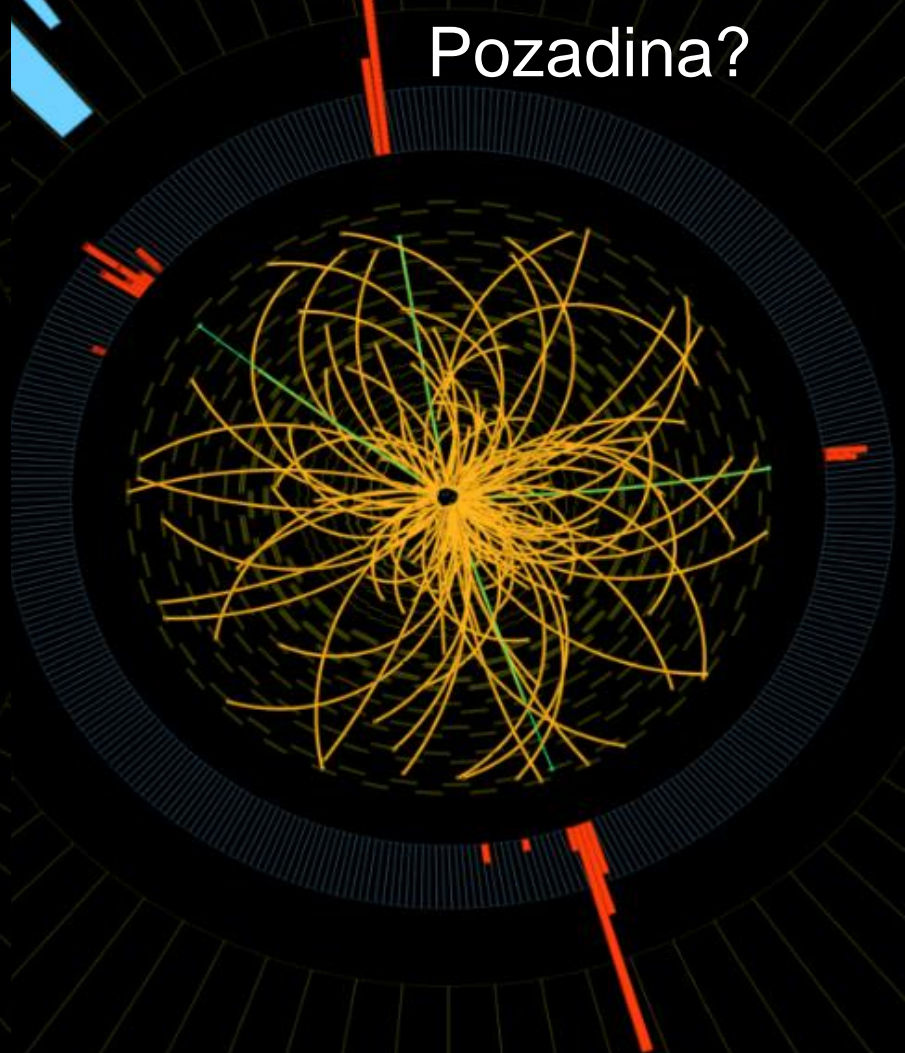
'Opasna' pozadina: $pp \rightarrow ZZ \rightarrow 4e$



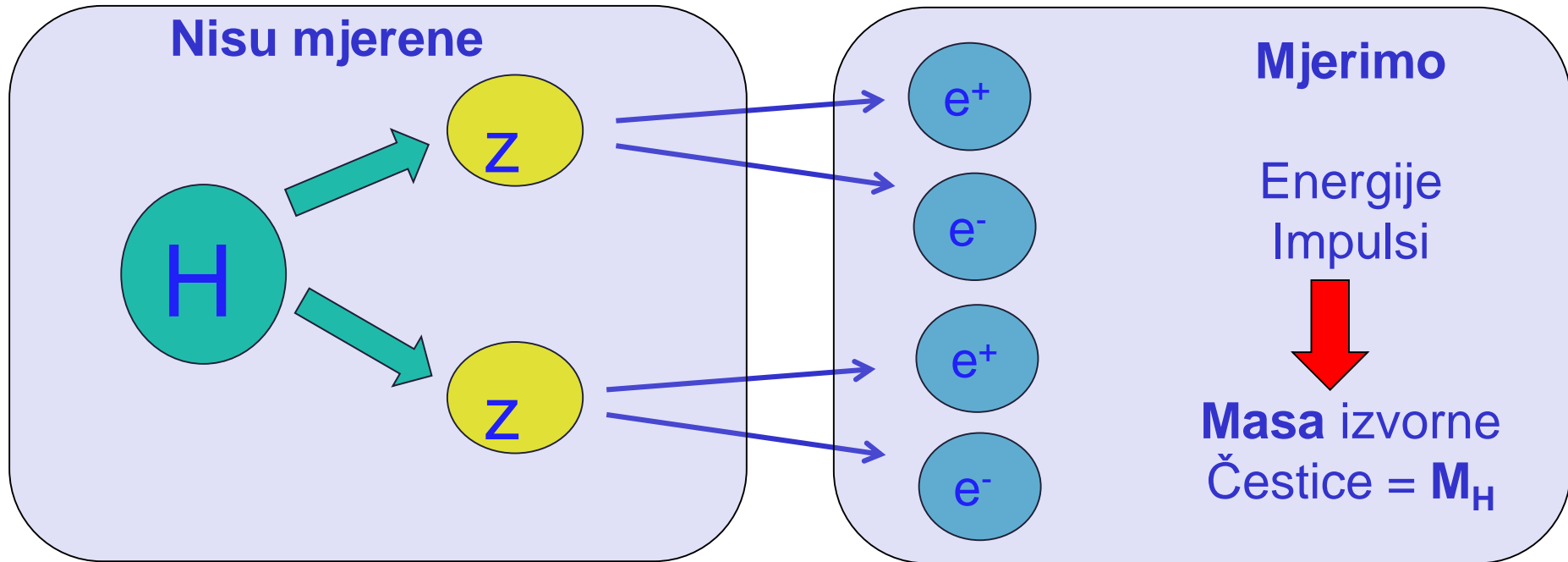
Signal?



Pozadina?



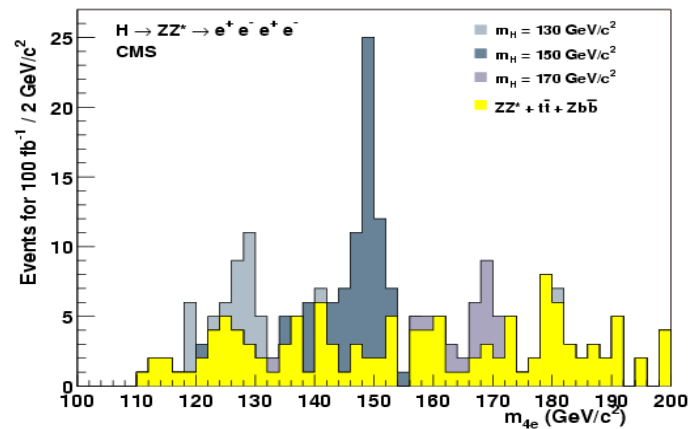
Kako identificirati signal



- “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”



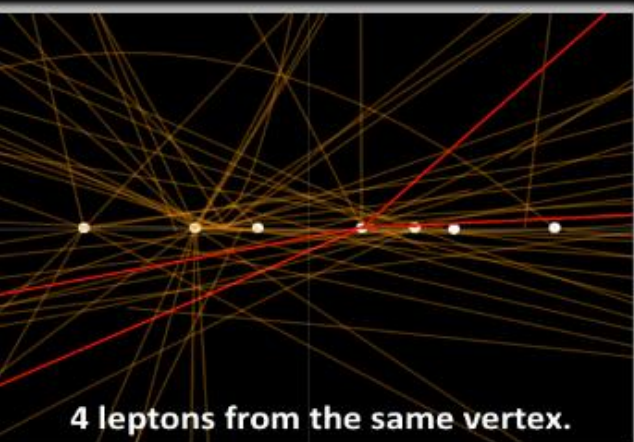
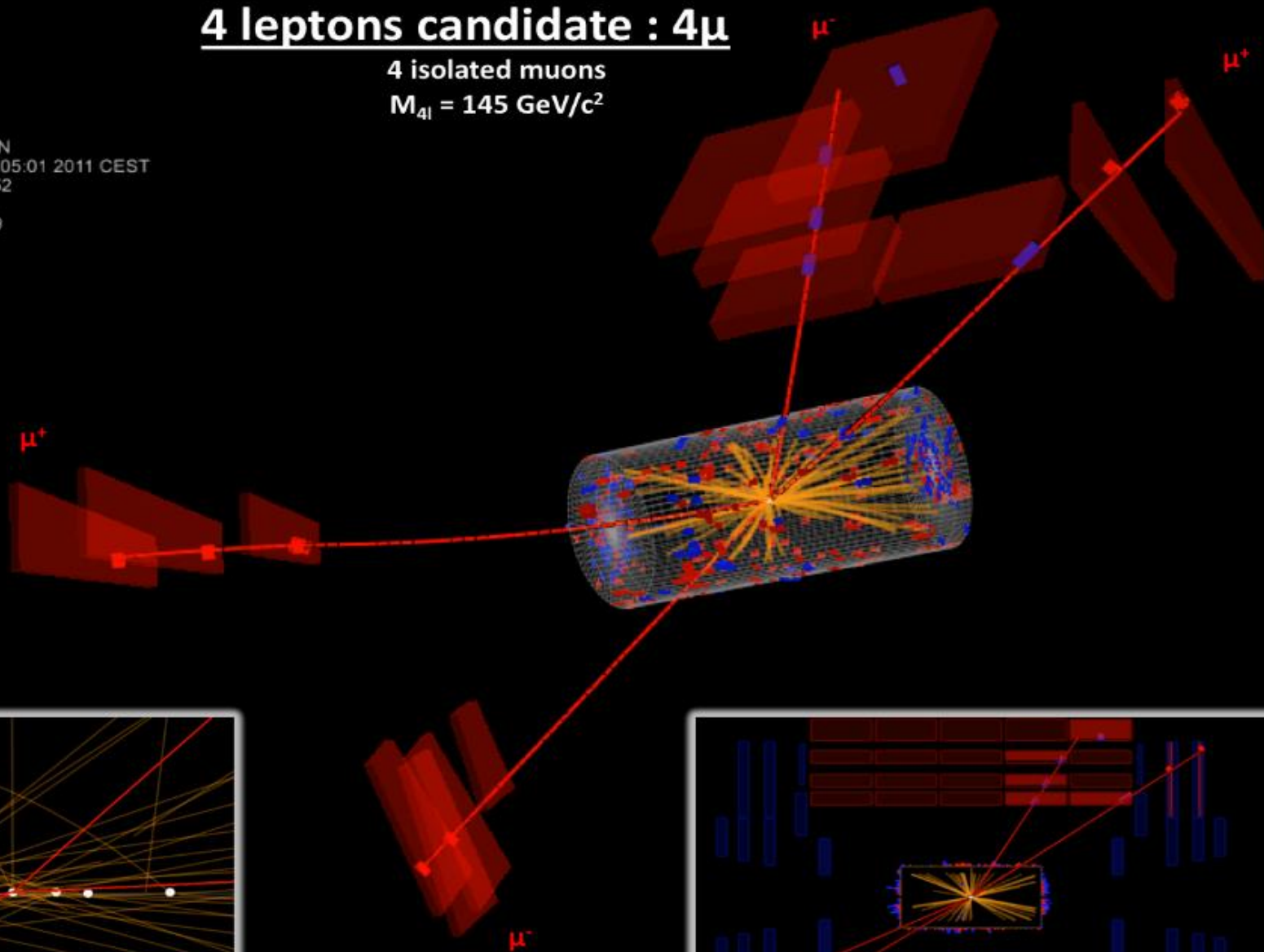


4 leptons candidate : 4μ

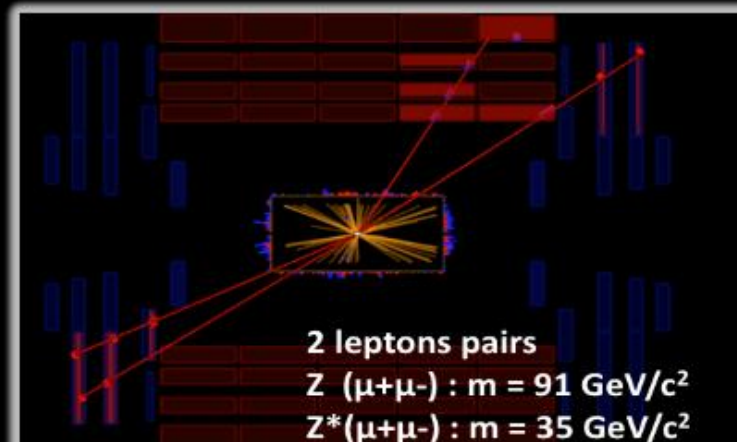
4 isolated muons

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

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



4 leptons from the same vertex.



2 leptons pairs
 $Z (\mu+\mu-) : m = 91 \text{ GeV}/c^2$
 $Z^*(\mu+\mu-) : m = 35 \text{ GeV}/c^2$

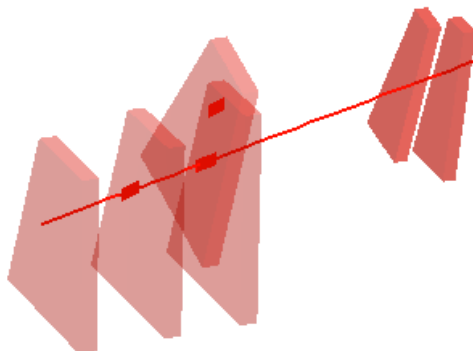


$\mu^+(Z_1) p_T : 43 \text{ GeV}$

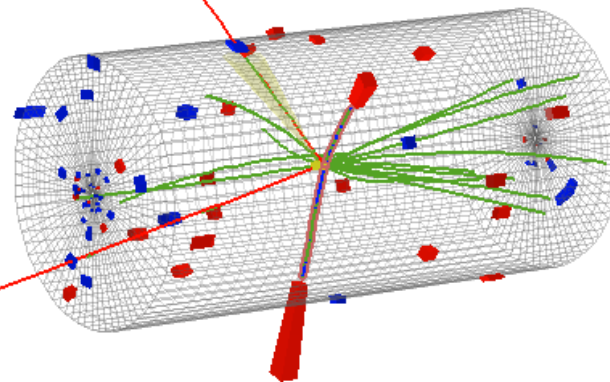
8 TeV DATA

4-lepton Mass : 126.9 GeV

$\mu^-(Z_1) p_T : 24 \text{ GeV}$



$e^-(Z_2) p_T : 10 \text{ GeV}$



$e^+(Z_2) p_T : 21 \text{ GeV}$

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



$\gamma(Z_1) E_T : 8 \text{ GeV}$

$\mu^-(Z_1) p_T : 28 \text{ GeV}$

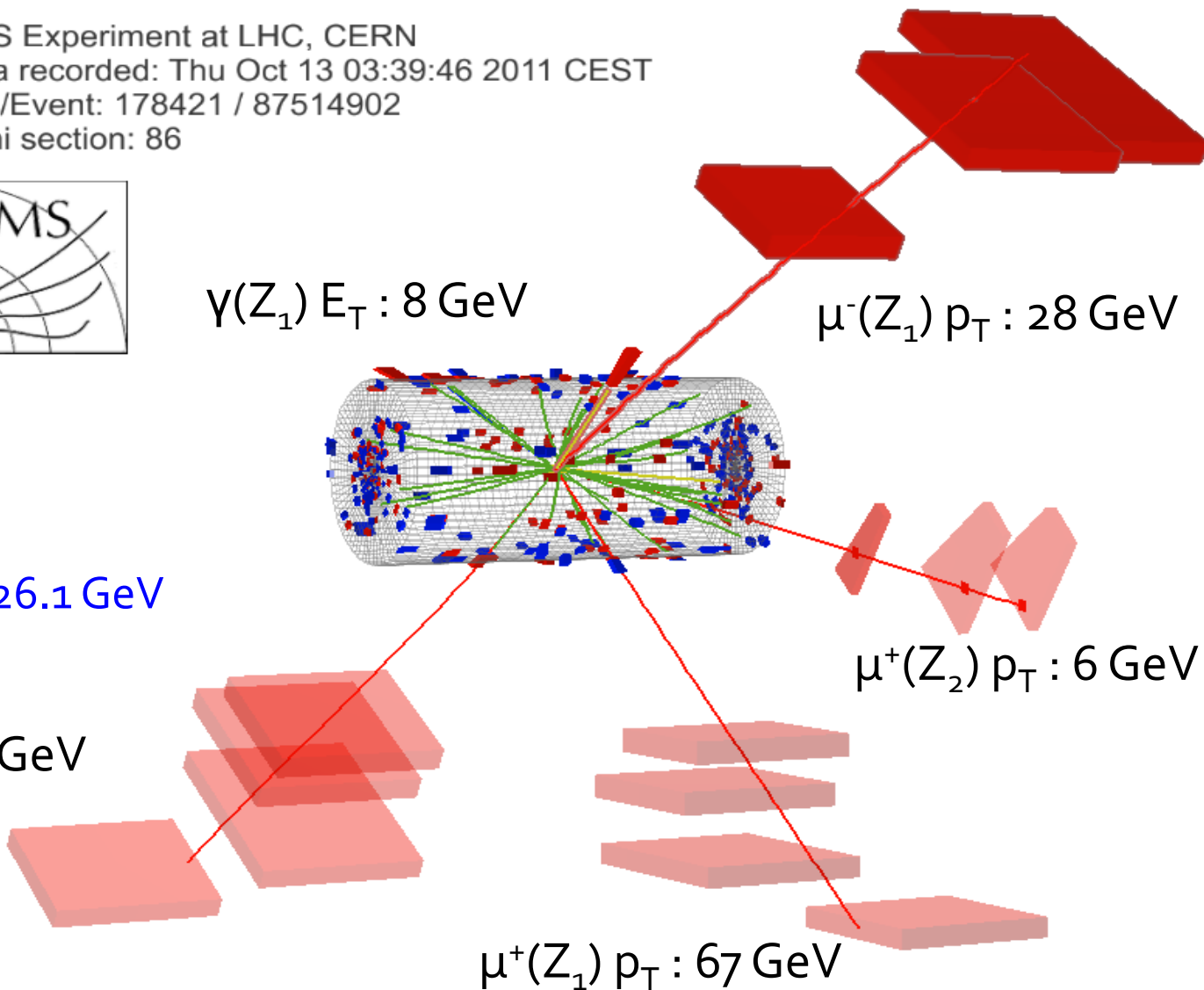
7 TeV DATA

$4\mu+\gamma$ Mass : 126.1 GeV

$\mu^-(Z_2) p_T : 14 \text{ GeV}$

$\mu^+(Z_2) p_T : 6 \text{ GeV}$

$\mu^+(Z_1) p_T : 67 \text{ GeV}$



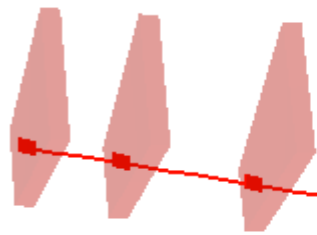


CMS Experiment at LHC, CERN
Data recorded: Tue Oct 4 00:10:13 2011 CEST
Run/Event: 177782 / 72158025
Lumi section: 99

$\mu^-(Z_2) p_T : 15 \text{ GeV}$

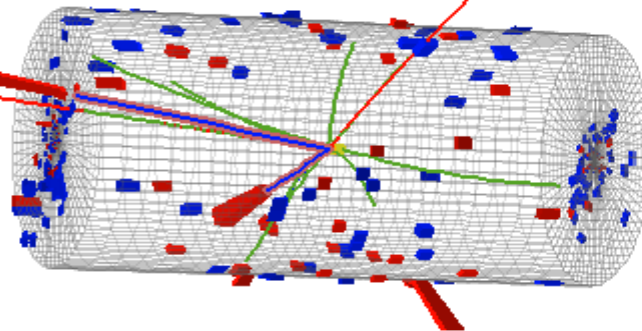
7 TeV DATA

4-lepton Mass : 125.8 GeV

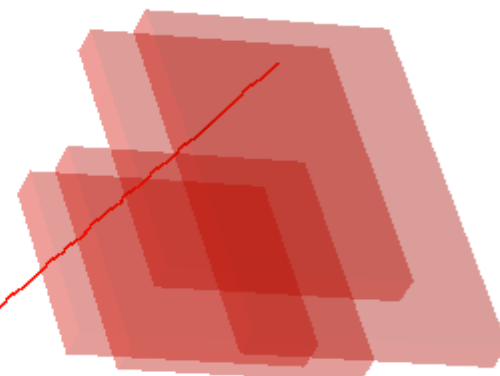


$e^+(Z_1) p_T : 28 \text{ GeV}$

$\mu^+(Z_2) p_T : 12 \text{ GeV}$

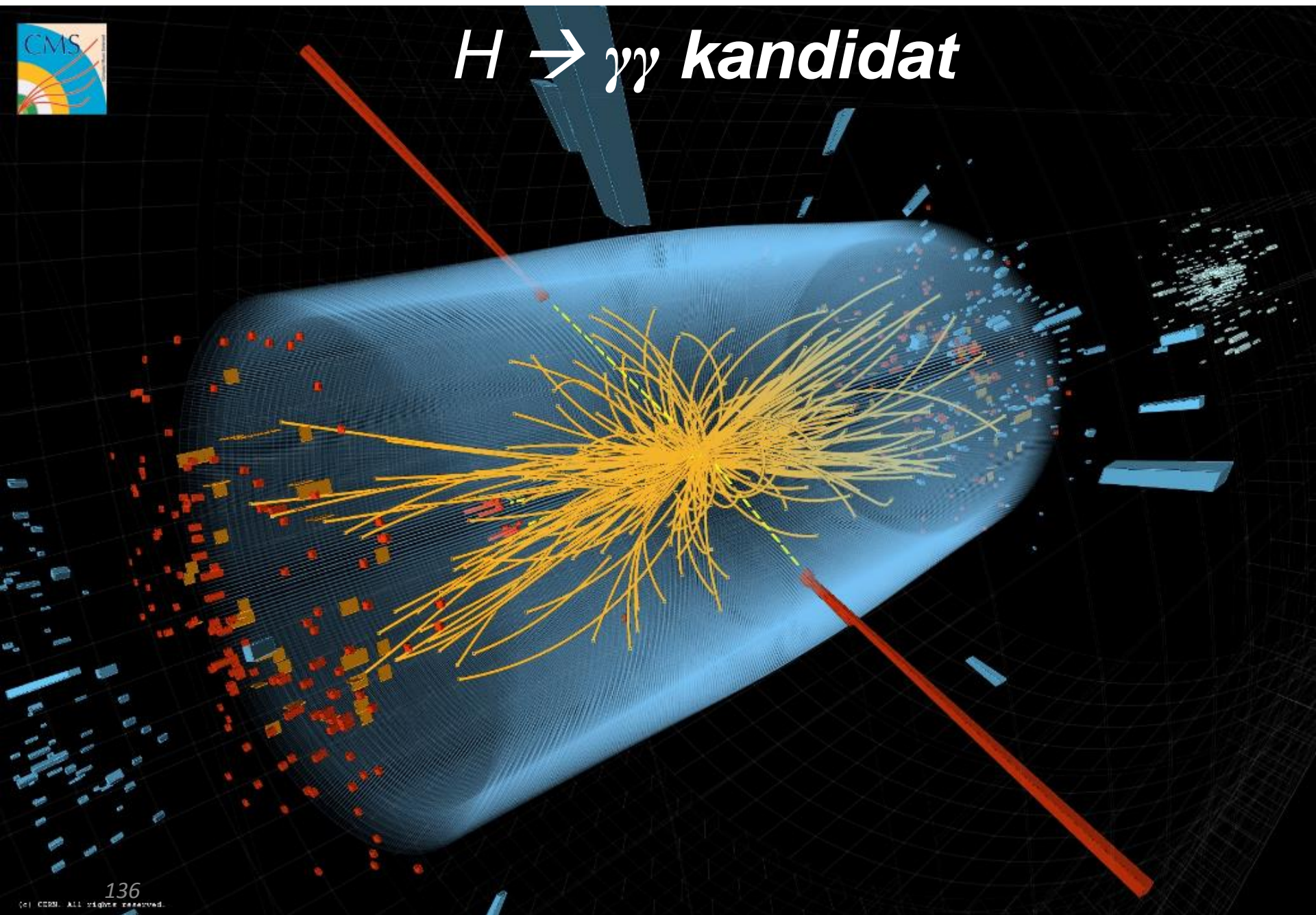


$e^-(Z_1) p_T : 14 \text{ GeV}$

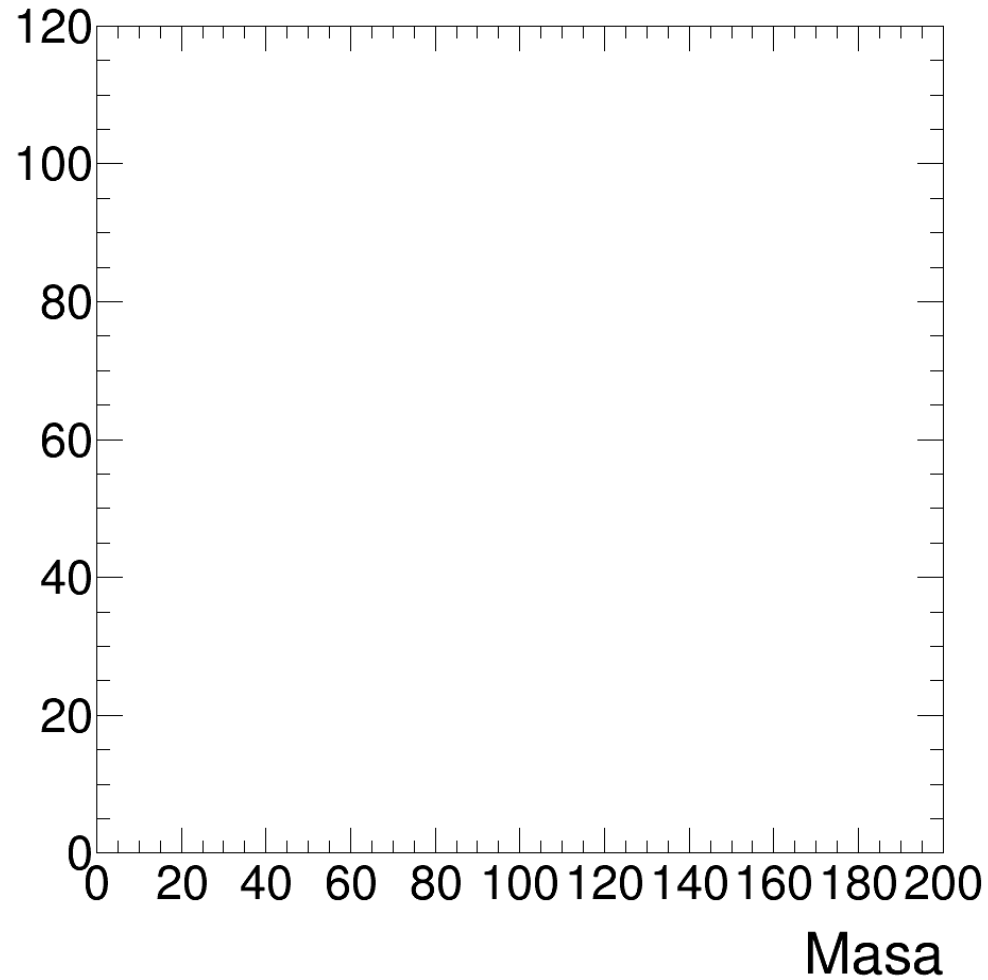




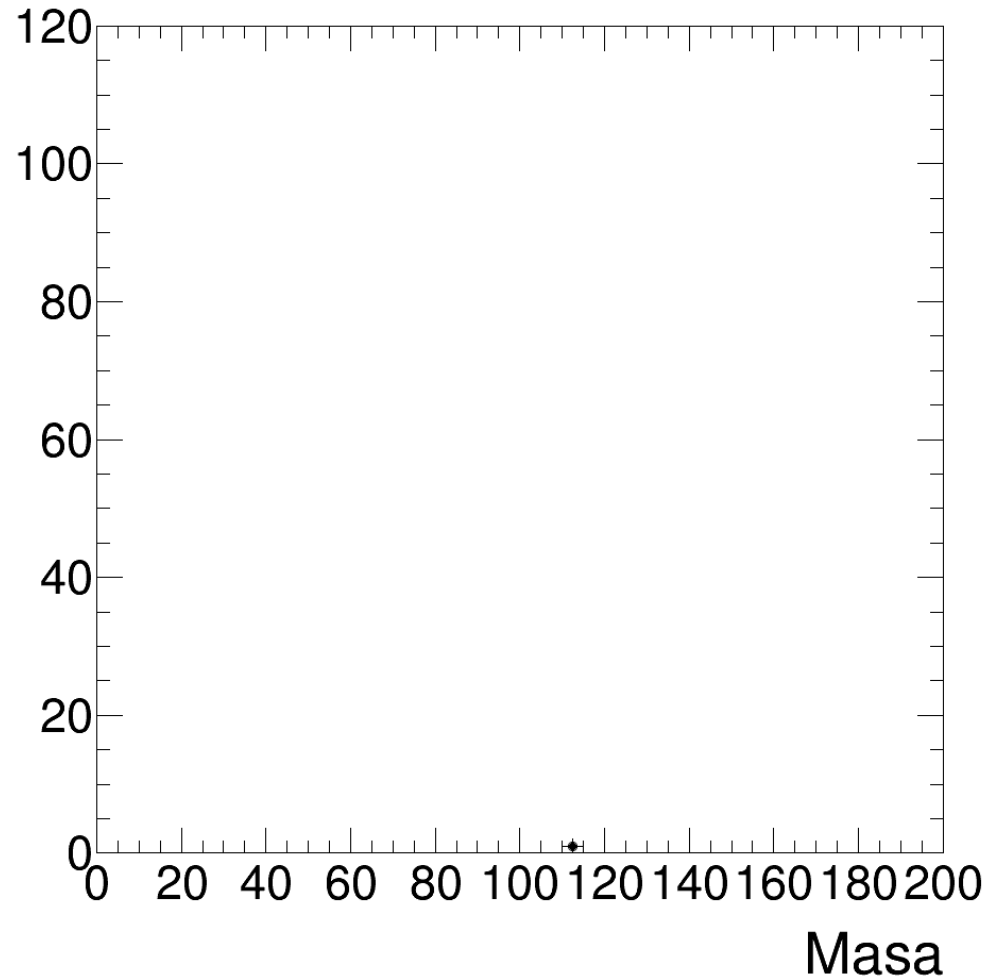
$H \rightarrow \gamma\gamma$ kandidat



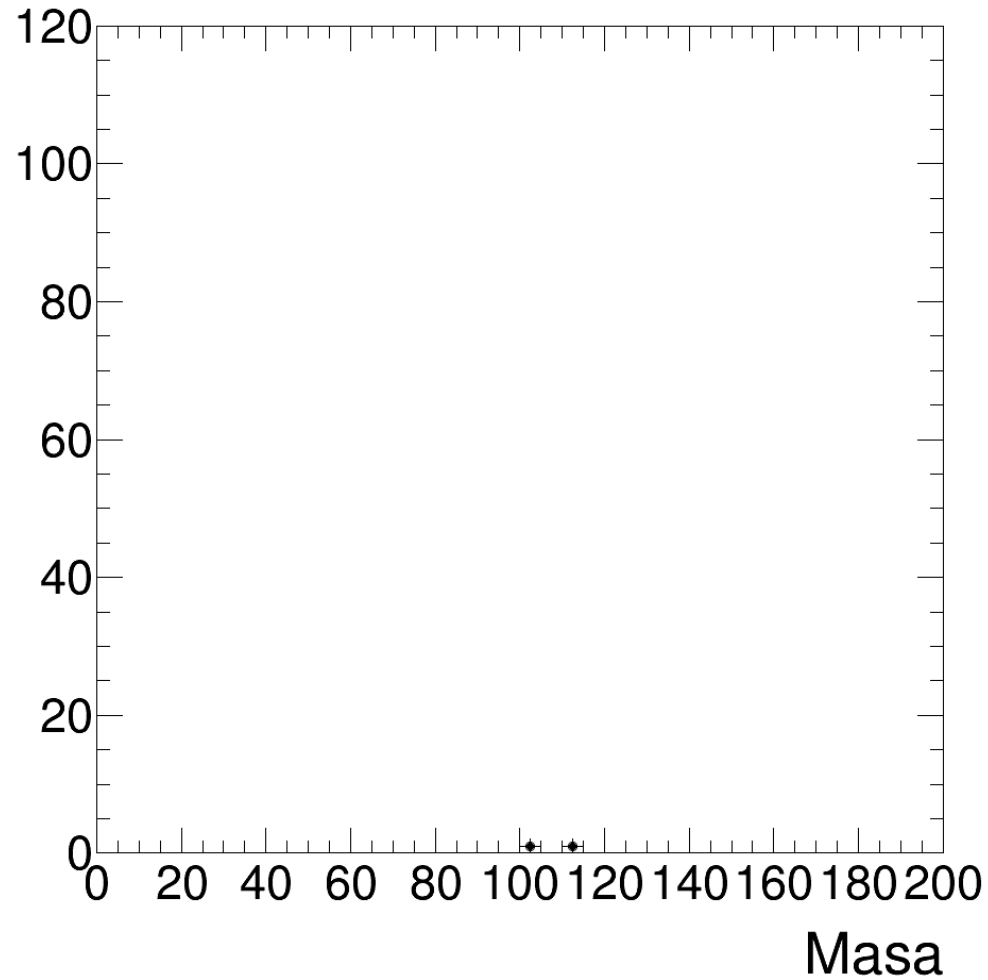
Čekamo, mjerimo i brojimo događaje...



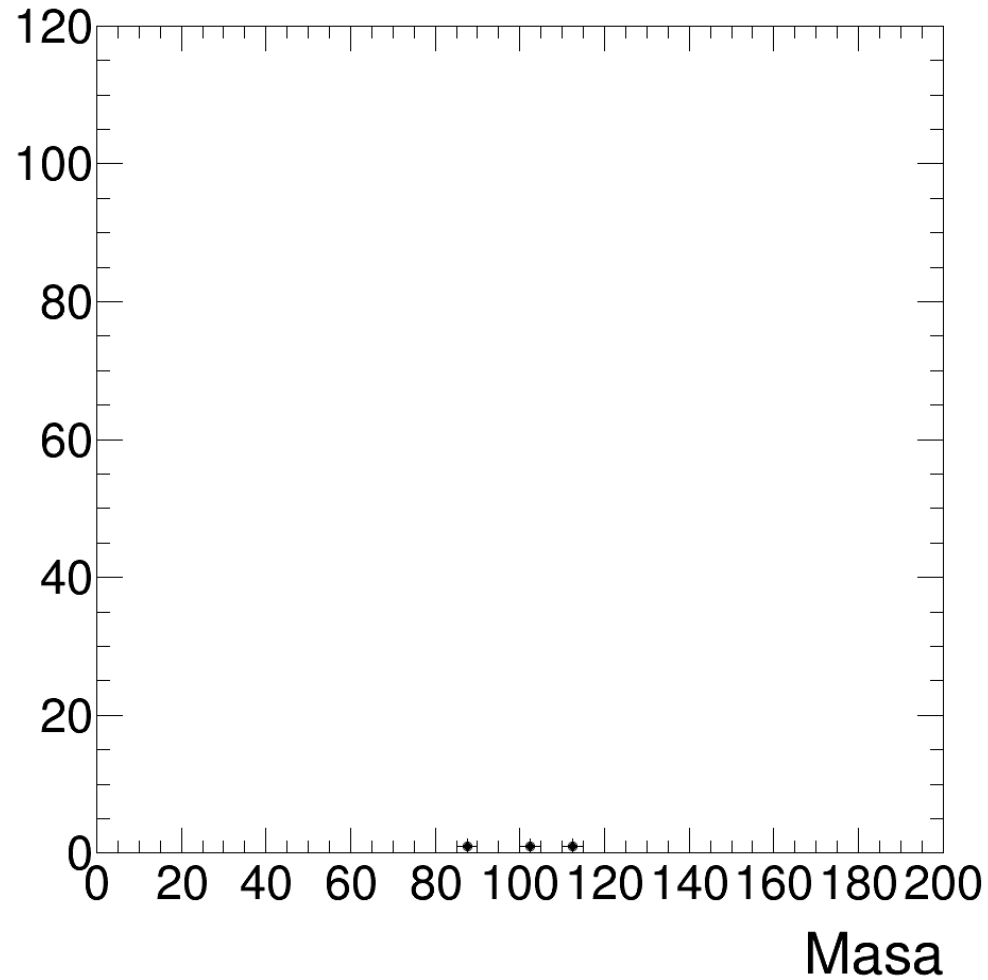
Čekamo, mjerimo i brojimo događaje...



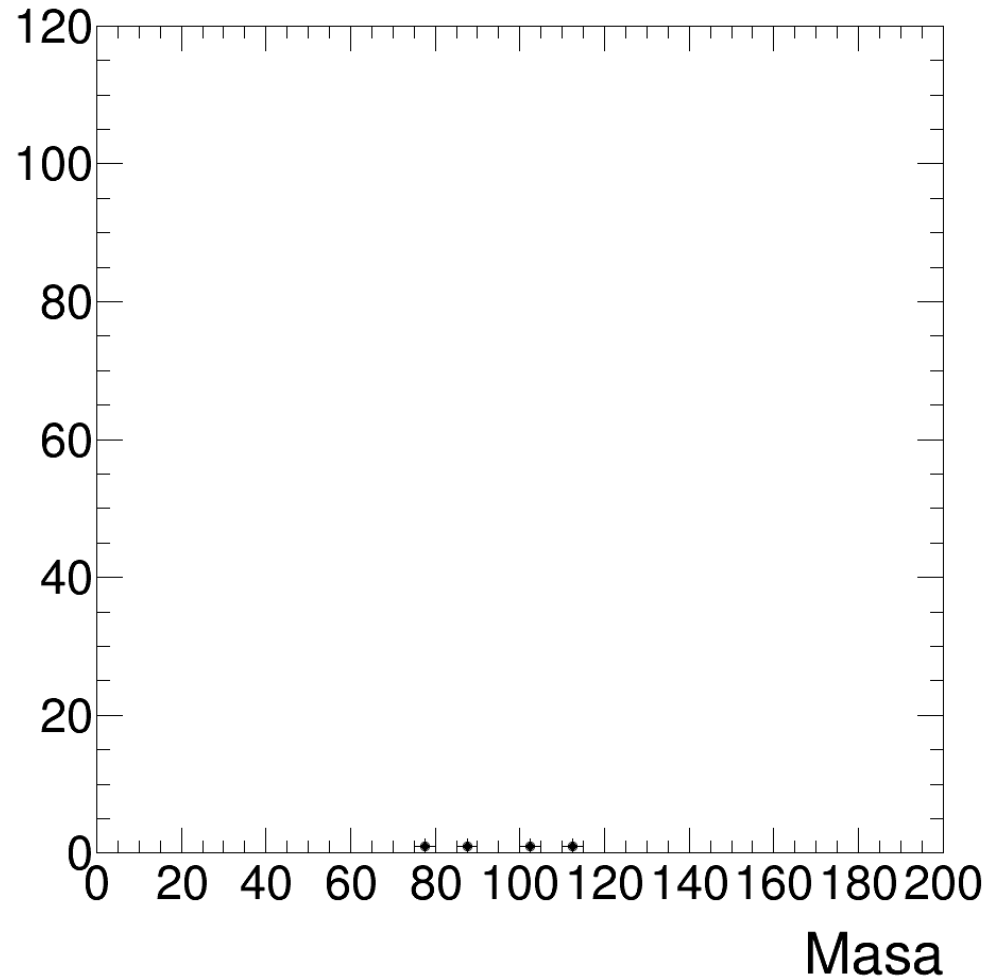
Čekamo, mjerimo i brojimo događaje...



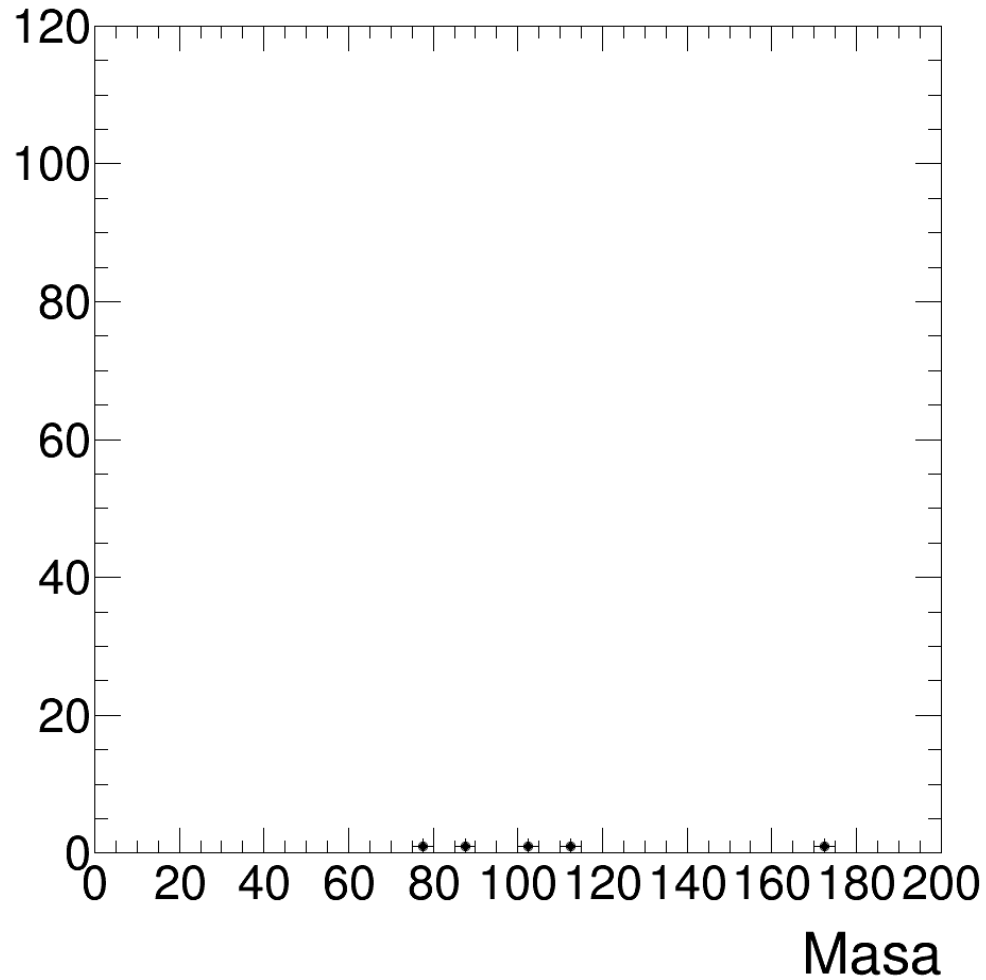
Čekamo, mjerimo i brojimo događaje...



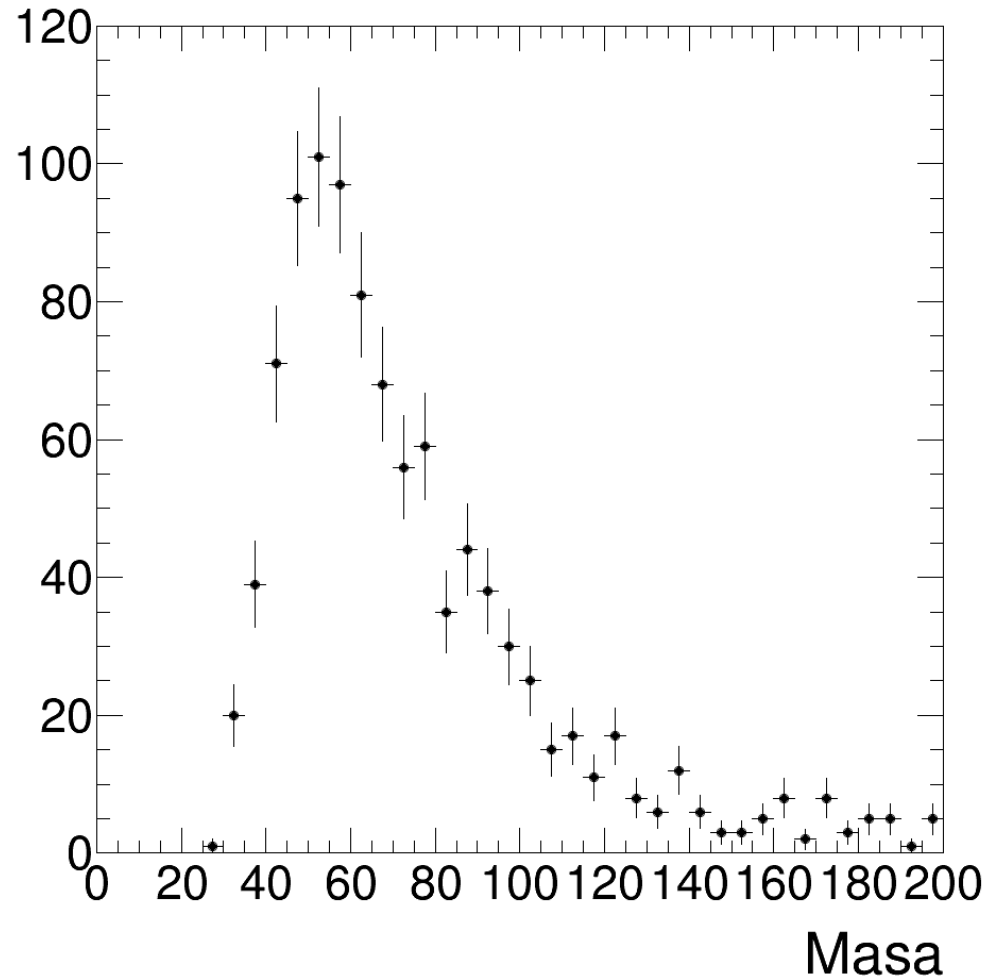
Čekamo, mjerimo i brojimo događaje...



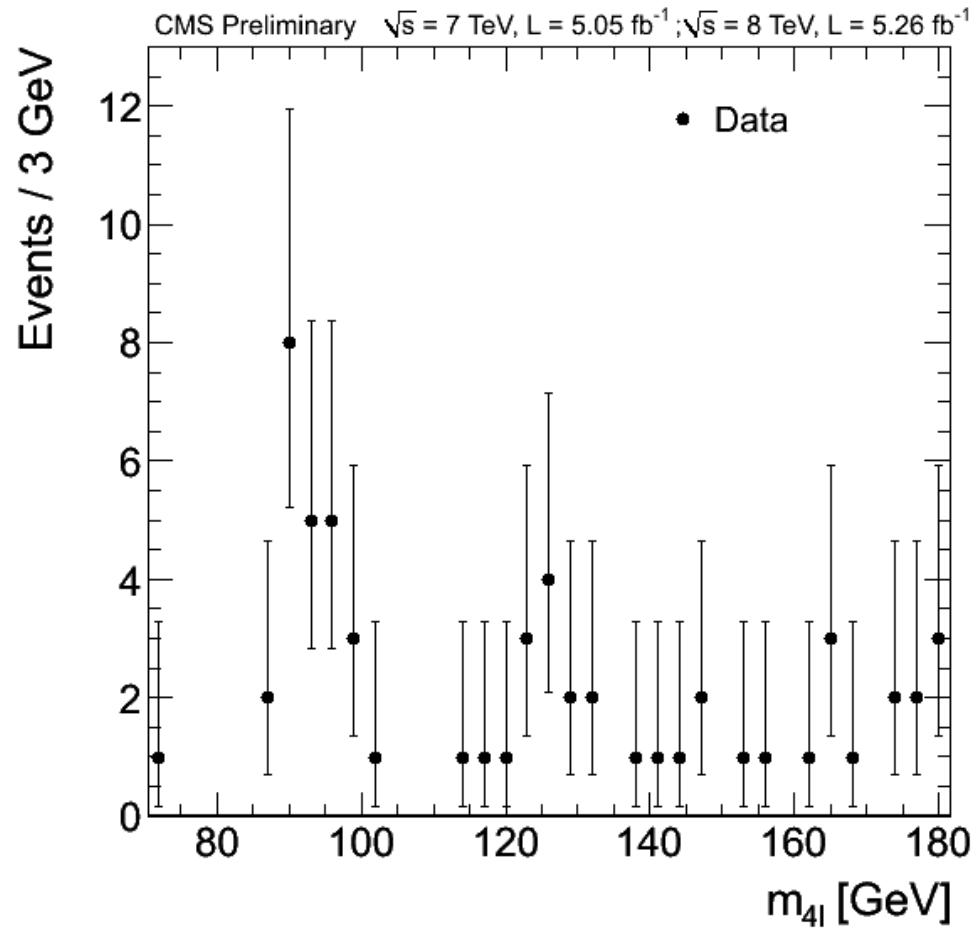
Čekamo, mjerimo i brojimo događaje...



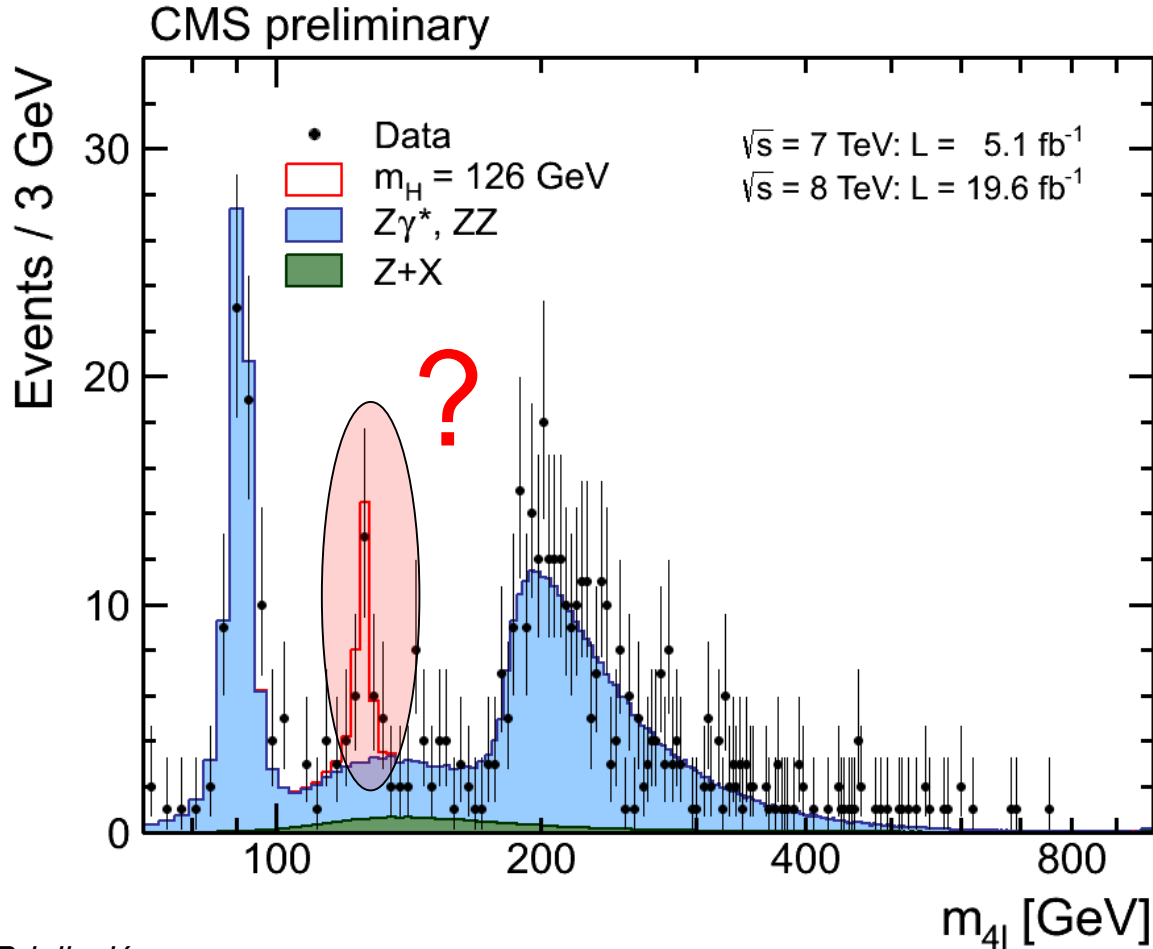
Čekamo, mjerimo i brojimo događaje...



Mjereno



Zaključak: otkriće ili fluktuacija?



**Pronašli novu
česticu?**

ili

**Pozadina se igra
s nama?**

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 najjaviti 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)

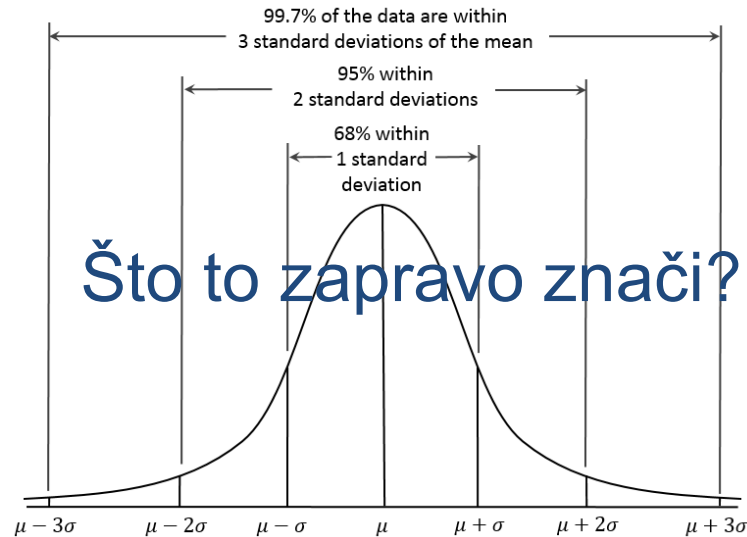
Kada najaviti otkriće?

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



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: $(1/6)^9=1/10077696$

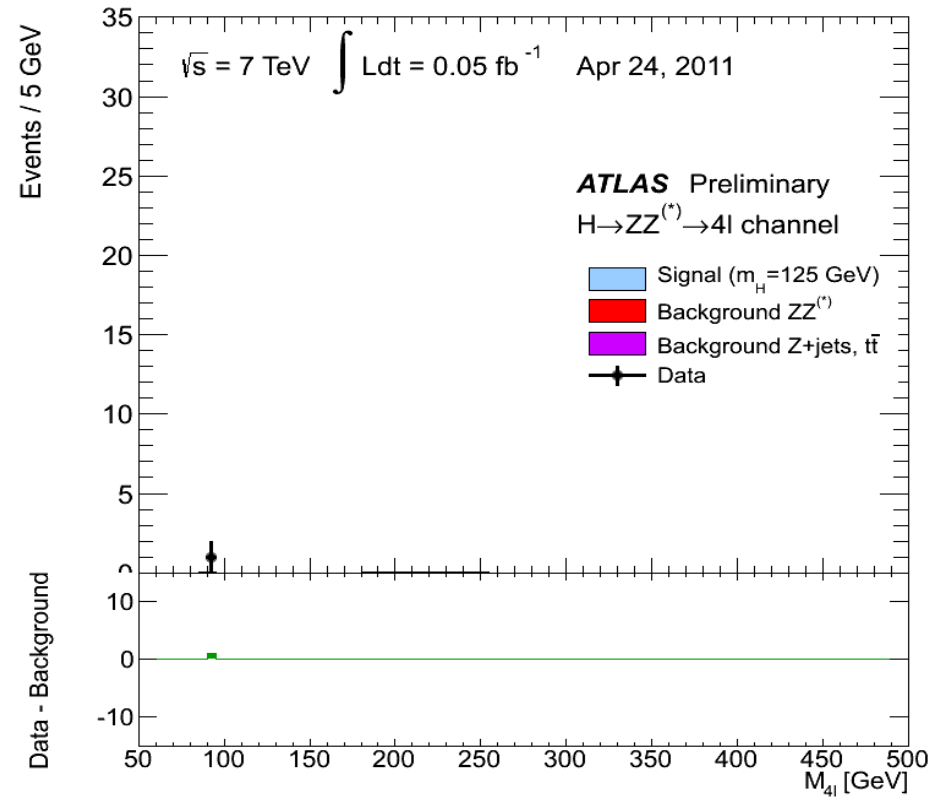
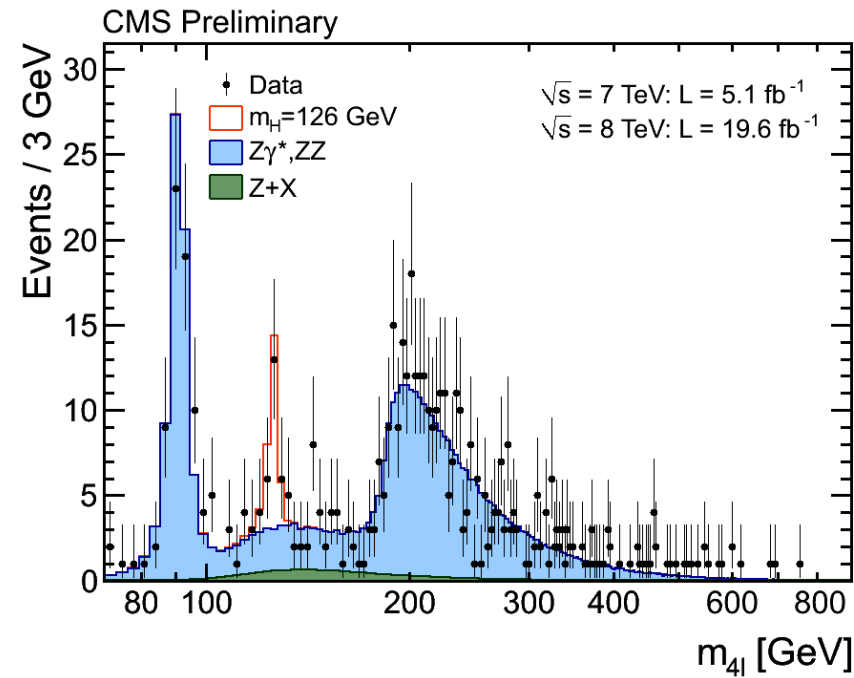
Veća od 5σ

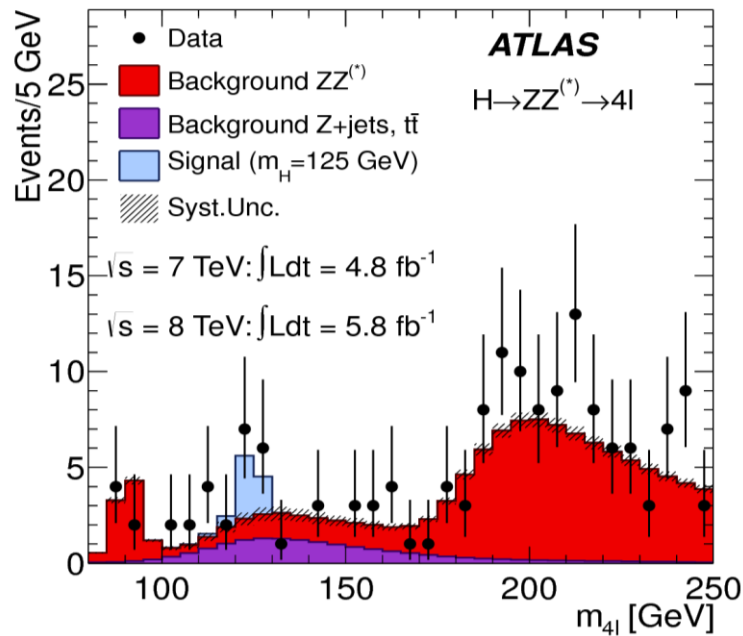
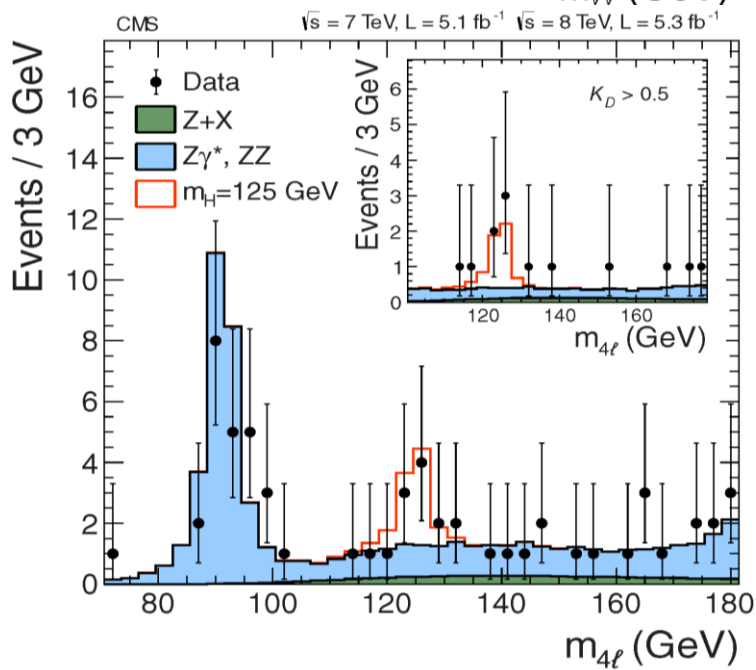
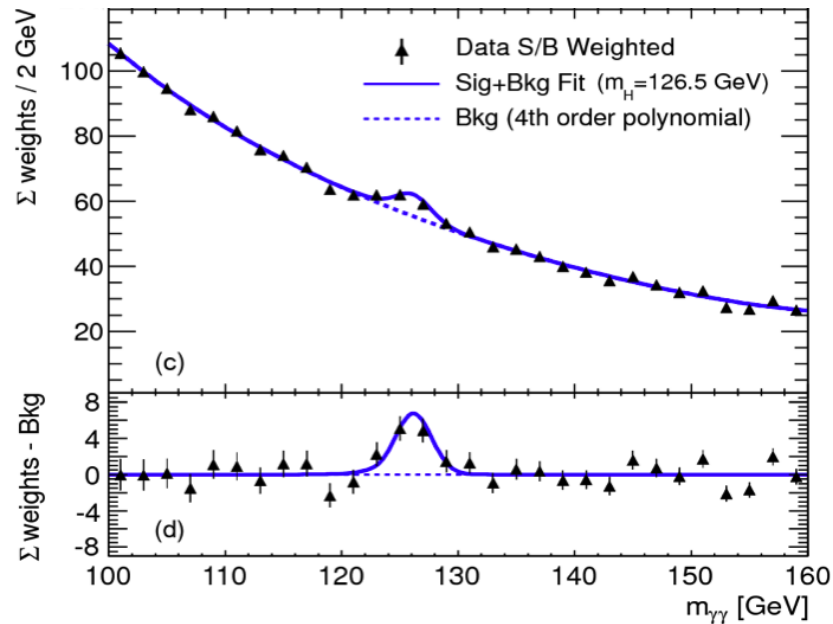
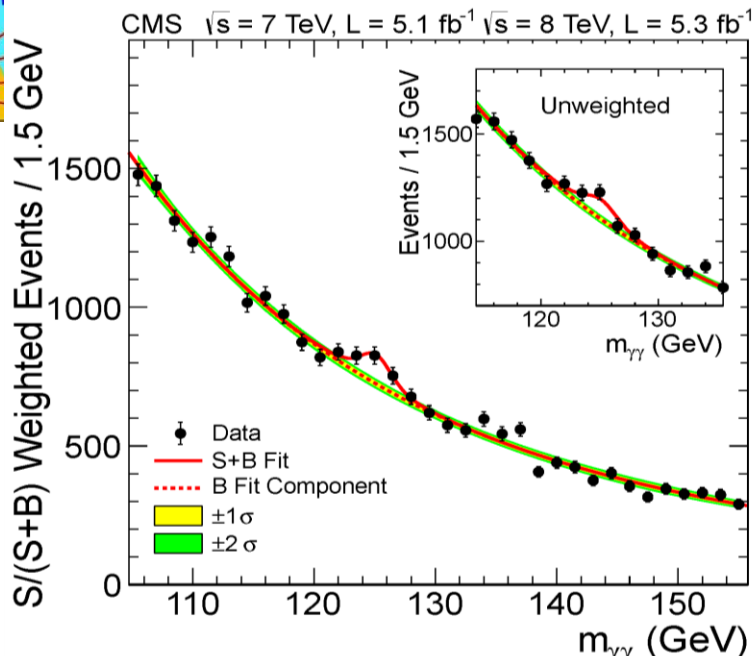
Pa još kad se takva situacija dogodi dvaput!
(npr. Higgsov bozon u ATLAS-u i CMS-u)

Kombinacija i interpretacija

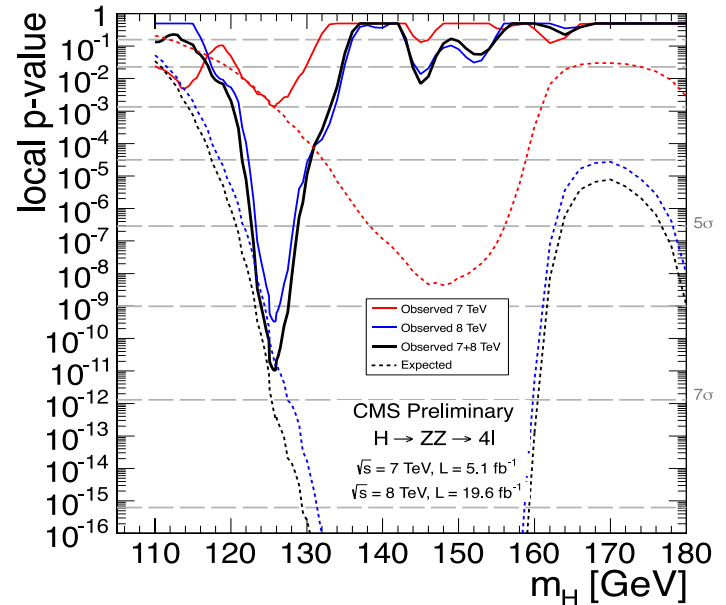
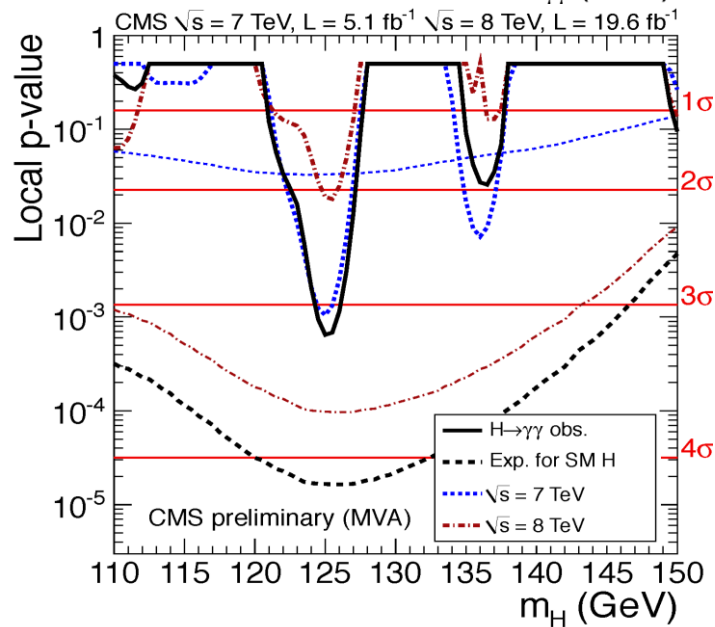
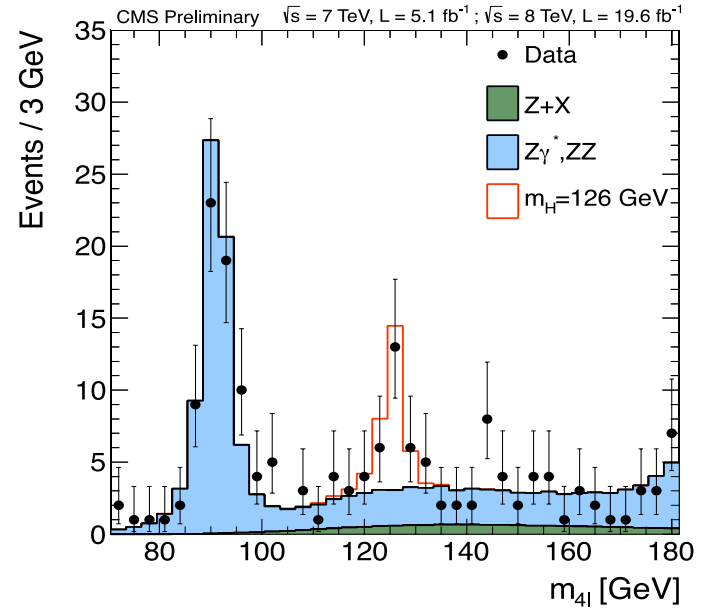
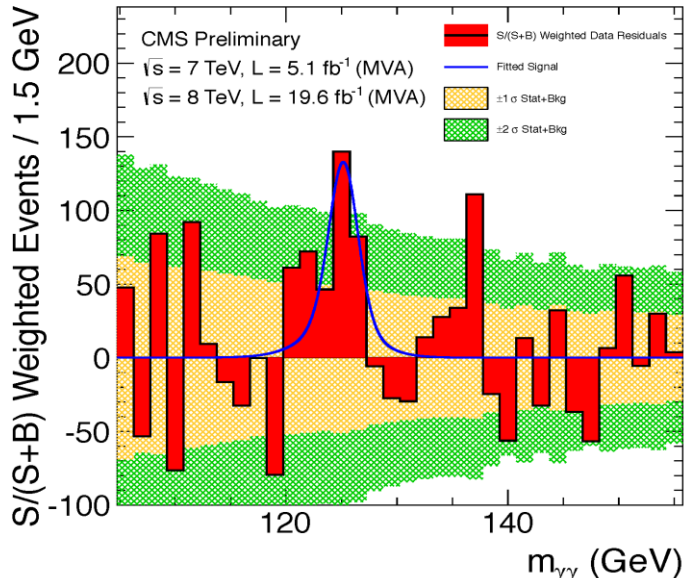


Čekamo, mjerimo i brojimo...

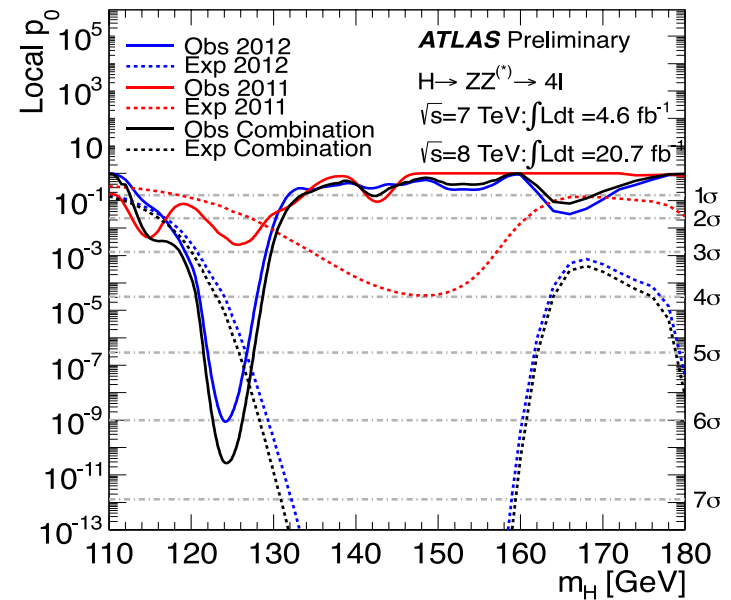
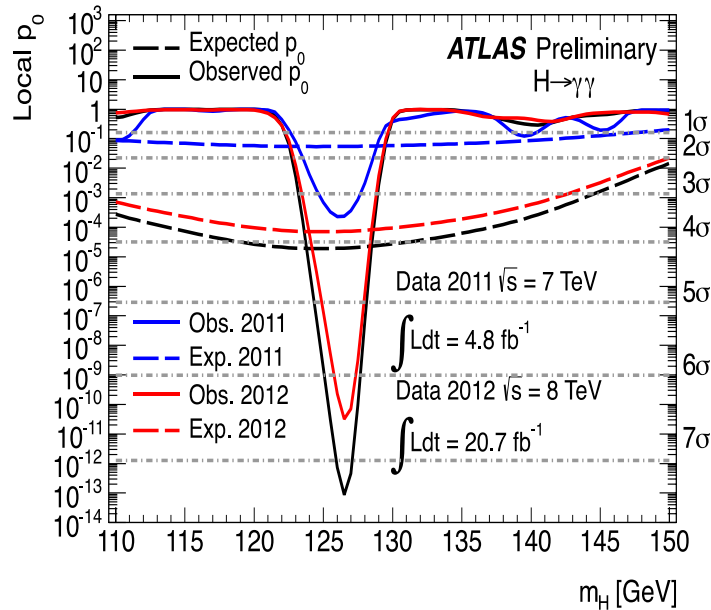
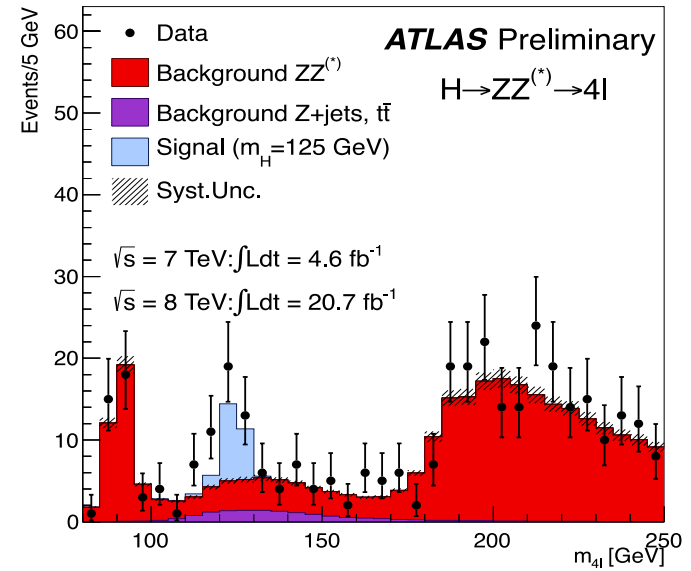
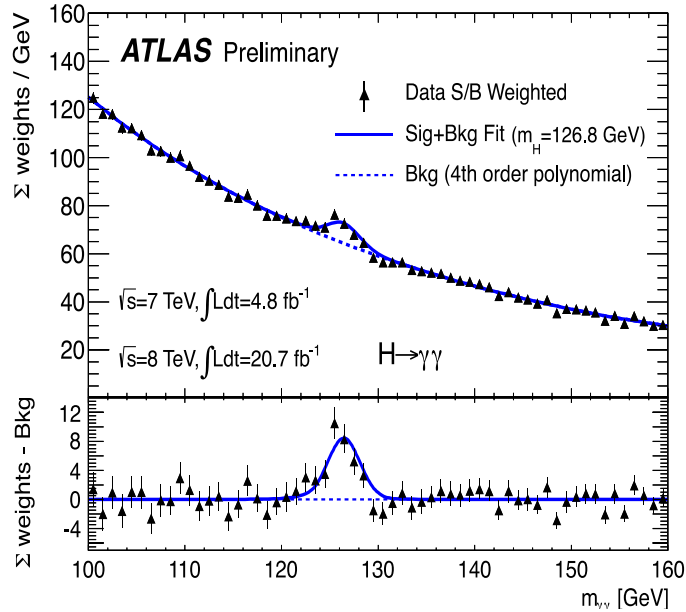




CMS – Najnoviji rezultati



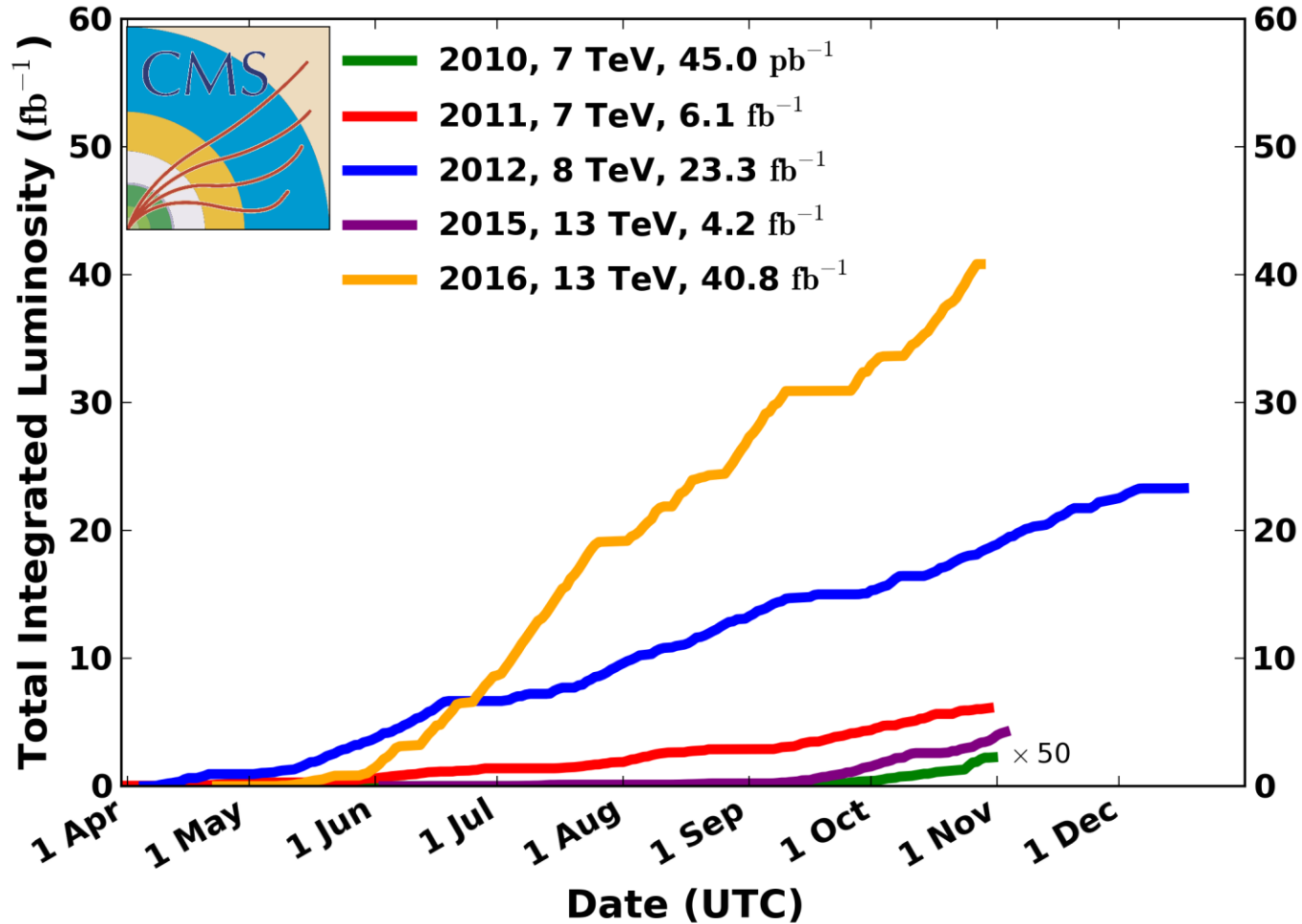
ATLAS – Najnoviji rezultati



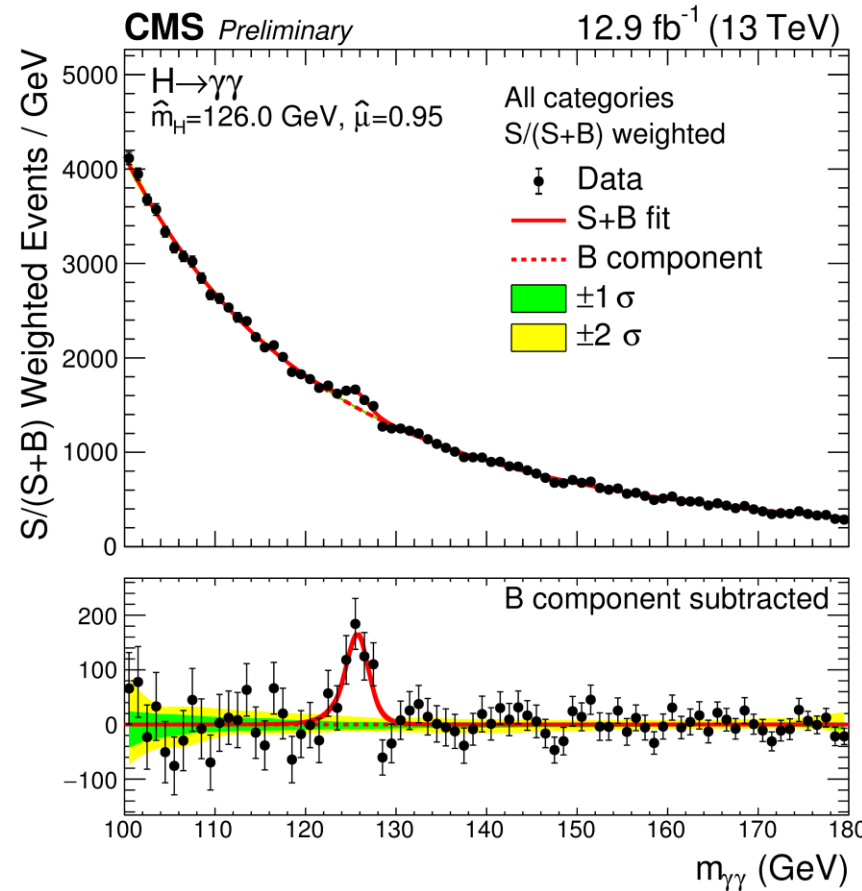
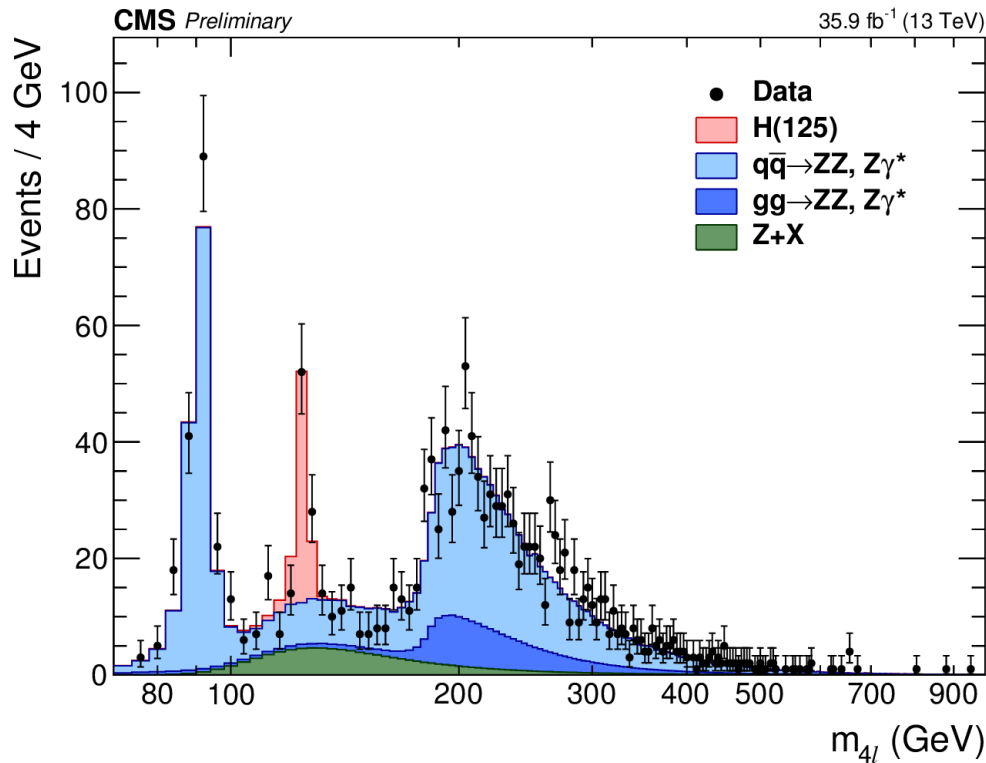
OD 2015. LHC RADI PONOVO

CMS Integrated Luminosity, pp

Data included from 2010-03-30 11:22 to 2016-10-27 14:12 UTC



Higgsov bozon je još uvijek s nama!



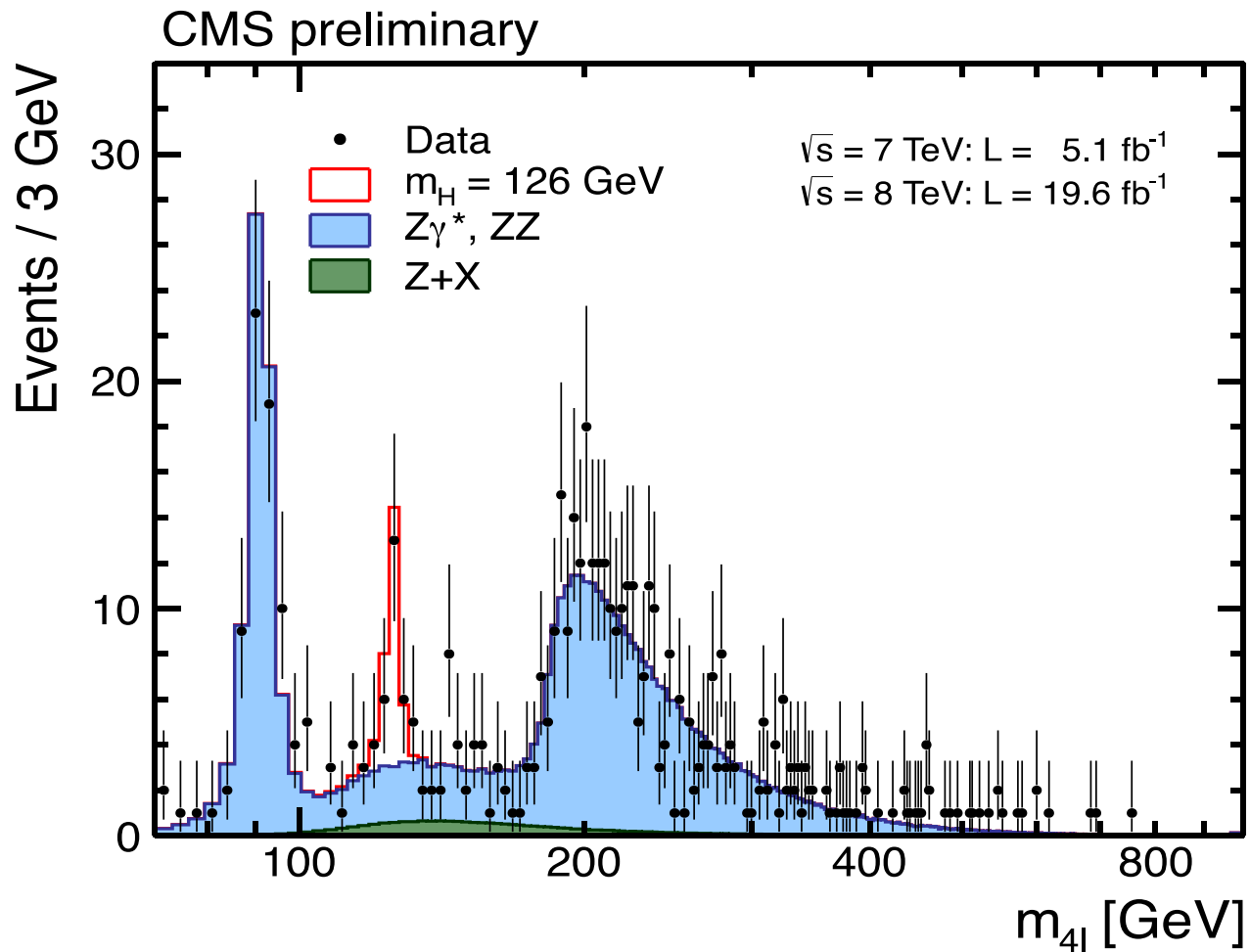


Zaključak

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

~ 125 GeV

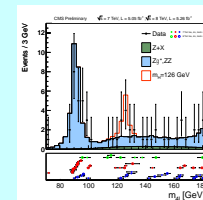
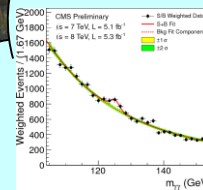
Ovo je bilo Kako smo ga otkrili?



Pitanje se promijenilo

Postoji li Higgsov bozon?

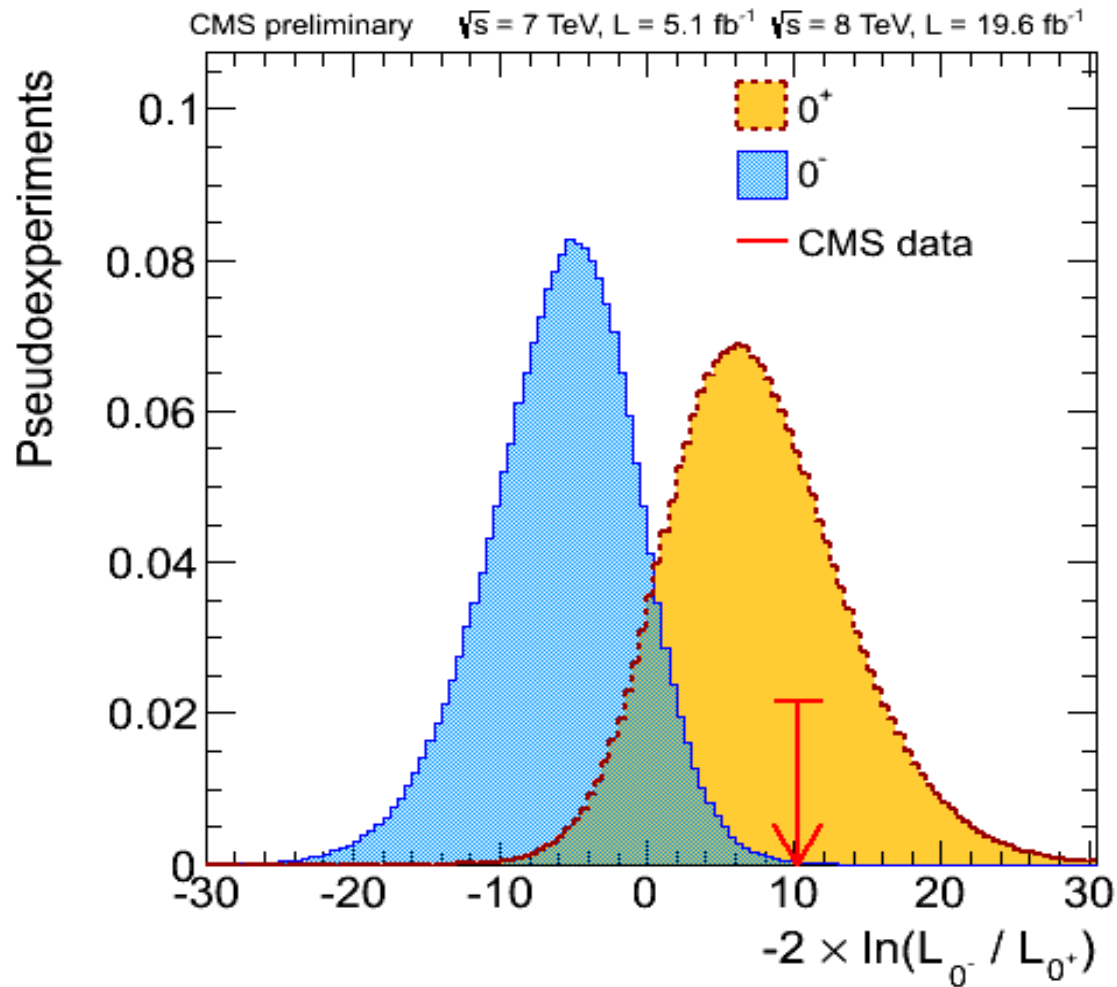
Je li



Higgsov bozon?

A sada ... Što smo u biti otkrili?

I kako to znamo ...



Mjerenje svojstava

- Koji tip objekta smo otkrili?
 - Je li ovo Higgsov bozon Standardnog modela?
 - Ili nešto drugo ...
- Za sada ovaj objekt zovemo “čestica **X**”
- Testiramo:
 - Kolika je masa od **X**?
 - Je li **X** proizveden u skladu s očekivanjima za Higgsov bozon?
 - Raspada li se **X** u skladu s očekivanjima za Higgsov bozon?
 - Veže li se **X** s ostalim česticama u skladu s očekivanjima za Higgsov bozon?
 - Jesu li spin i parnost od **X** u skladu s očekivanjima za Higgsov bozon?

Sažetak

- Kolika je masa od **X**?
 - **Oko 125 GeV**
- Je li **X** proizveden u skladu s očekivanjima za Higgsov bozon?
 - **Da**
- Raspada li se **X** u skladu s očekivanjima za Higgsov bozon?
 - **Da**
- Veže li se **X** na ostale čestice u skladu s očekivanjima za Higgsov bozon?
 - **Da**
- Jesu su spin i parnost od **X** u skladu s očekivanjima za Higgsov bozon?
 - **Da**
- Stoga, što je **X**?
 - **Vrlo vjerojatno se radi o Higgsovom bozonu Standardnog modela**

Evolucija jezika

- **Veljača 2012.**

- Combined results of **searches for the standard model Higgs boson** in pp collisions at $\sqrt{s} = 7$ TeV
- By CMS Collaboration, **Phys. Lett. B710 (2012) 26-48**

- **Srpanj 2012.**

- **Observation** of a **new boson** with a mass of 125 GeV with the CMS experiment at the LHC
- By CMS Collaboration, **Phys. Lett. B716 (2012) 30-61**

- **Prosinac 2012.**

- Study of the Mass and Spin-Parity of the **Higgs Boson Candidate** Via Its Decays to Z Boson Pairs
- By CMS Collaboration, **Phys. Rev. Lett. 110 (2013) 081803**

- **Srpanj 2013.**

- Measurements of **Higgs boson** production and couplings in diboson final states with the ATLAS detector at the LHC
- By ATLAS Collaboration, **Phys. Lett. B 726 (2013) 88**

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



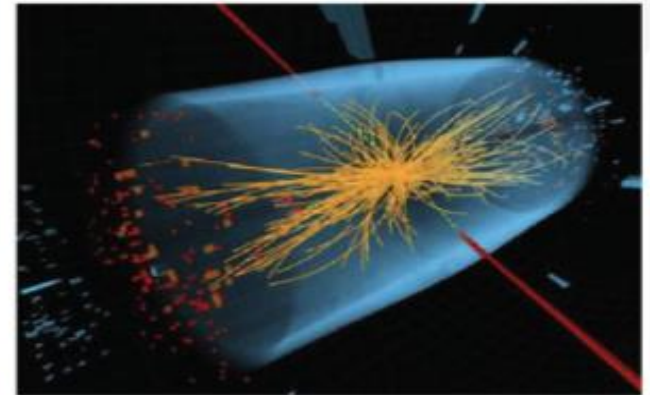
Fabrice Coffrini/Agence France-Presse — Getty Images

CERN officials held a press conference near Geneva on Wednesday.

LA NEWS DEL GIORNO | CERNEL POLITICA | 10:21 | Roma, 4 lug 2012

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



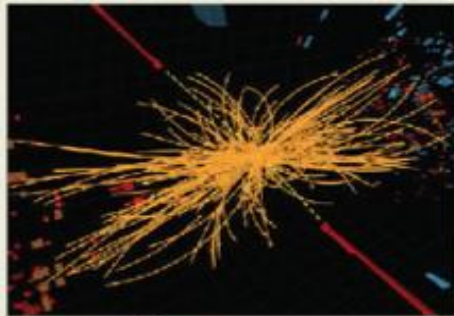
Roma, 4 lug. (TMNews) - L'enigma relativo all'esistenza del "bosone di Higgs", il "Santo Graal" della fisica delle particelle elementari, potrebbe essere ormai vicino alla soluzione: la conferenza stampa in programma oggi al Cern potrebbe dissipare gli ultimi dubbi.



LENTA.RU вторник, **Прогресс**
издание Rambler Media Group

04.07.2012, 12:13:02

Воскресия для **прогресс** | 2012

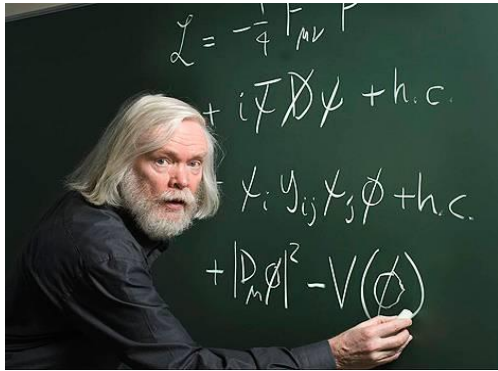


Изображение с сайта CERN

Physicists discover a candidate for the boson Higgs

Физики обнаружили претендента на роль **бозона Хиггса**





John Ellis^{1,2} and Tevong You¹

*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

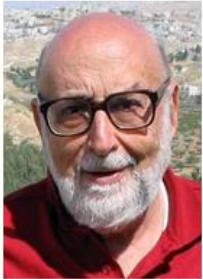


Photo: Pnicolet via Wikimedia Commons

François Englert

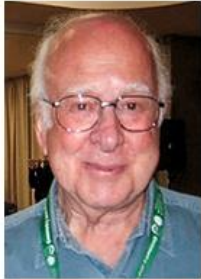


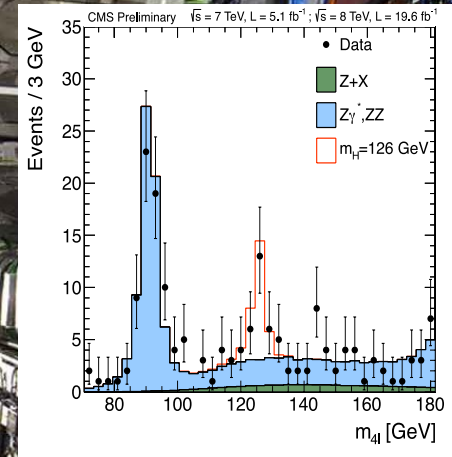
Photo: G-M Greuel via Wikimedia Commons

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"

Jedini sigurno opaženi
Higgs u CMS
eksperimentu do 2012.

Dr. Peter Higgs



Više nije!

2013 NOBEL PRIZE IN PHYSICS

François Englert Peter W. Higgs



© The Nobel Foundation, Photo: Lovisa Engblom.



The Nobel Prize in Physics 2013
François Englert, Peter Higgs

The Nobel Prize in Physics 2013

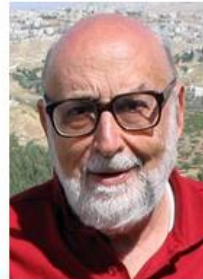


Photo: Pricolet via
Wikimedia Commons
François Englert

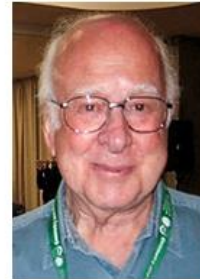
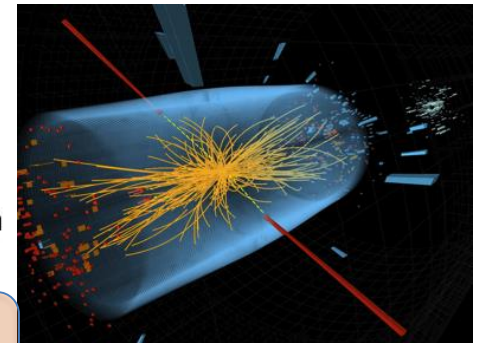
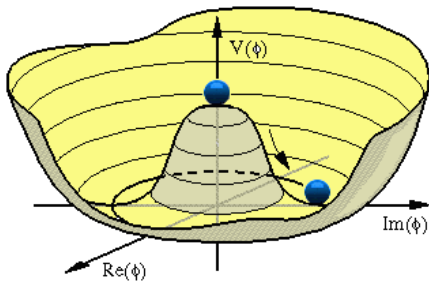


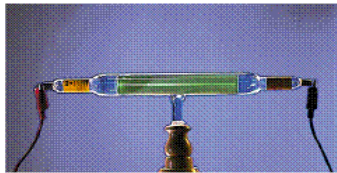
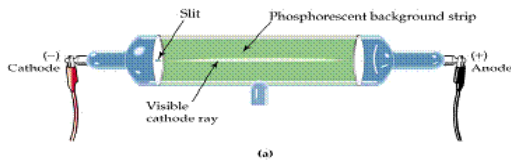
Photo: G-M Greuel via
Wikimedia Commons
Peter W. Higgs



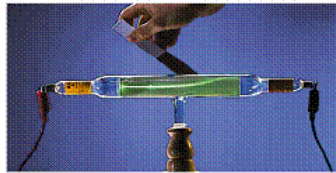
The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs "for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental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

STANDARDNI MODEL JE KOMPLETAN I POTVRĐEN

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



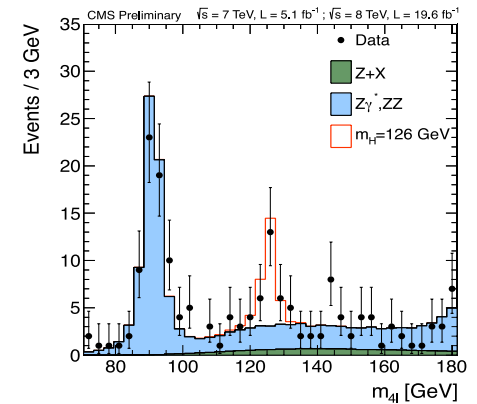
(b)



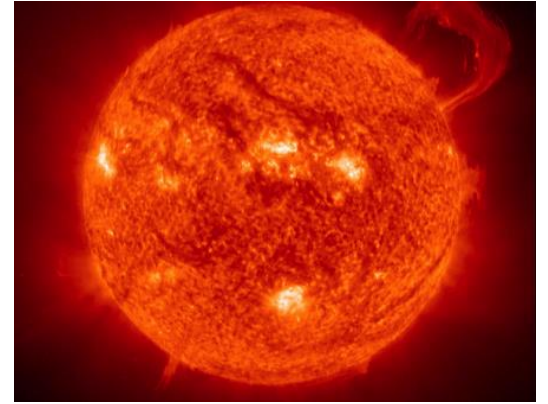
(c)

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

Discovery of the Higgs boson
LHC (2012)



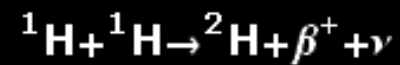
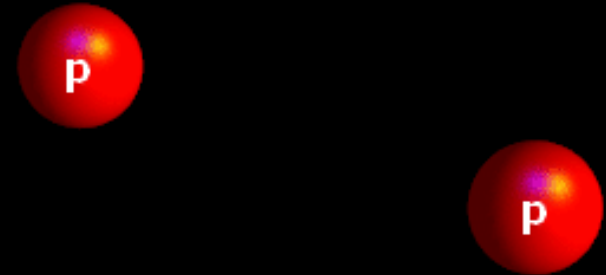
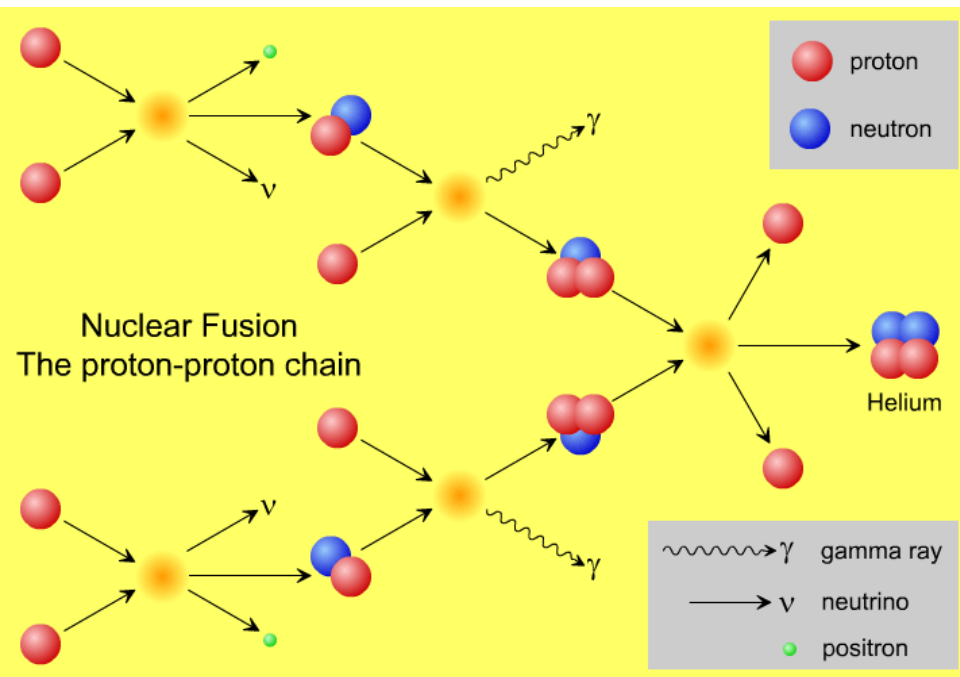
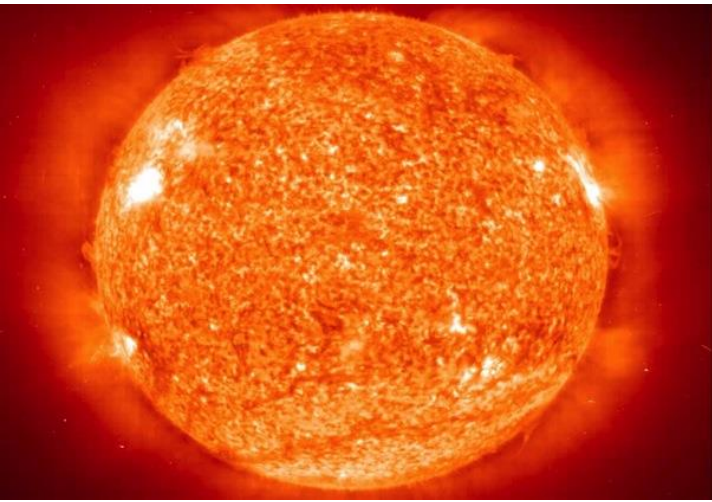
I objašnjava mnogo toga



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

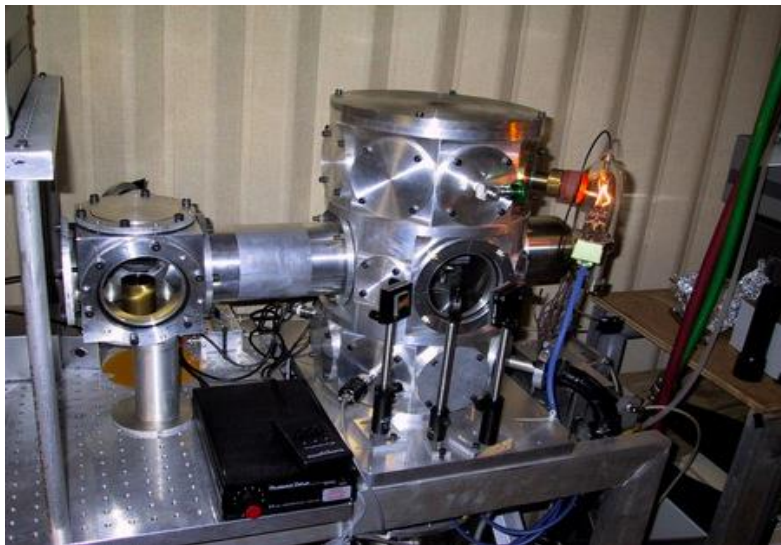


Primjer: fuzija u suncu

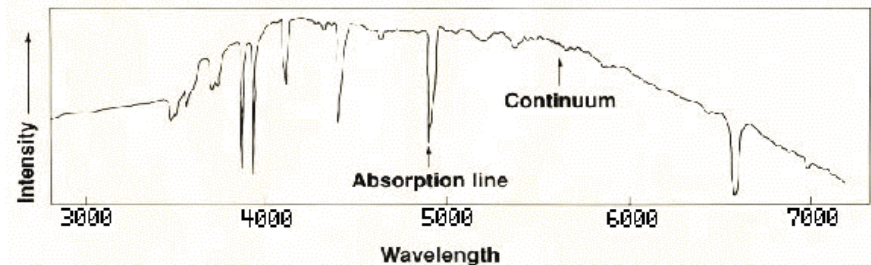


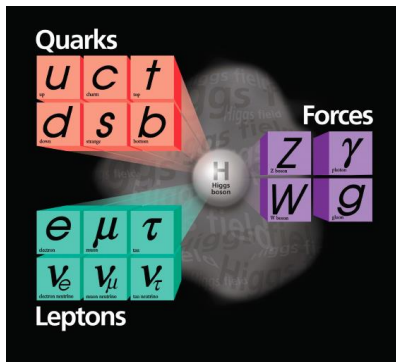
Na zemlji i u cijelom svemiru

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



H δ H γ H β H α



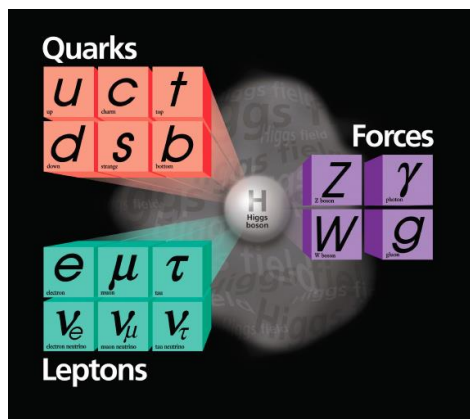


Zašto većina nas mislimo da SM ne može biti kraj priče

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

SM NE objašnjava

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



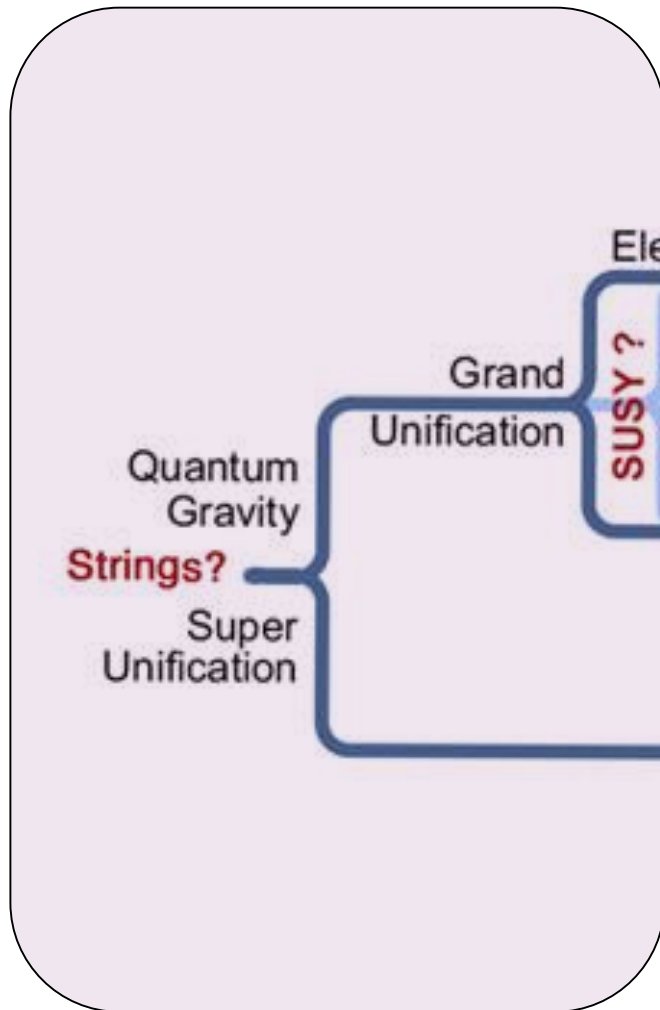
And most importantly:

- **WHAT ABOUT GRAVITY?**

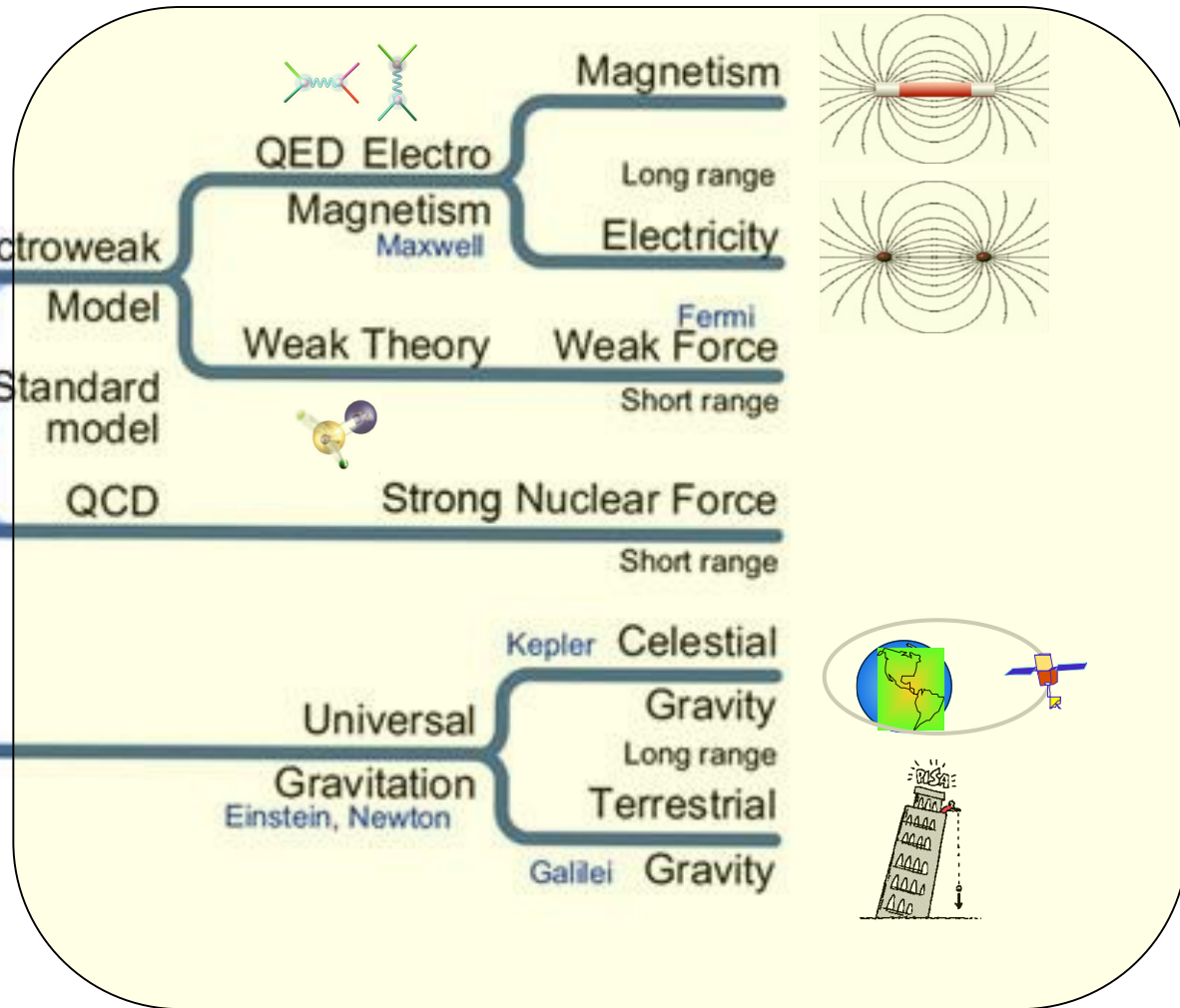
Fizika voli UJEDINITI

Ide li to dalje?

SPEKULACIJA



ČINJENICE

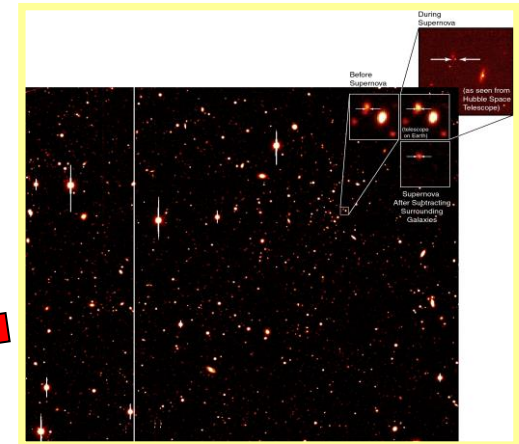
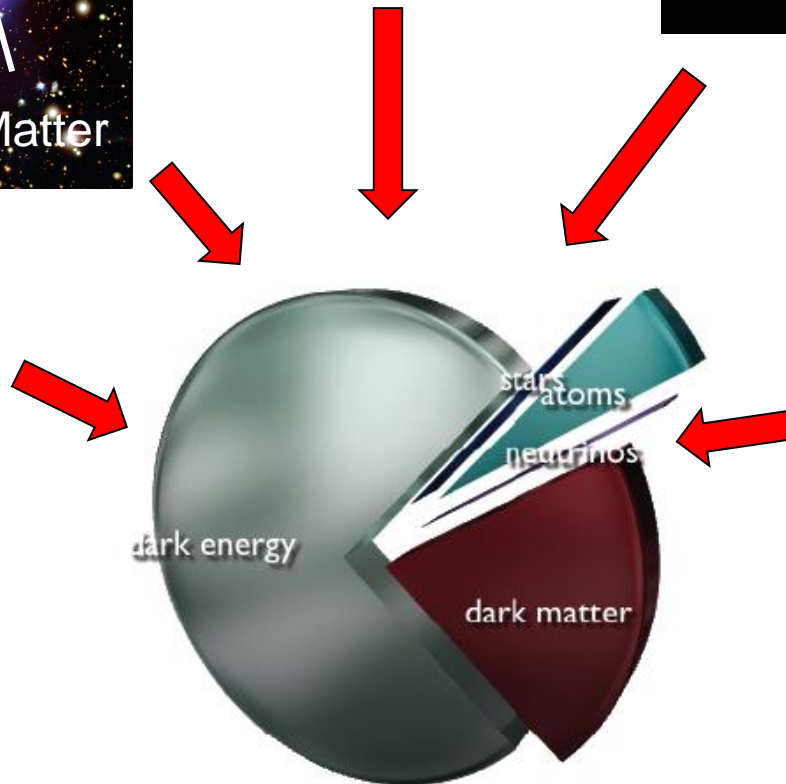
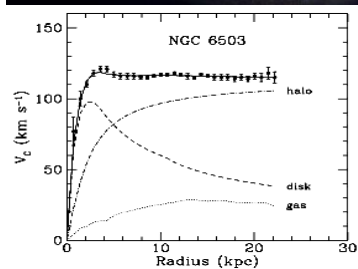
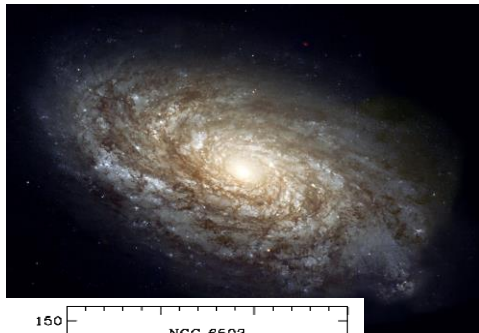
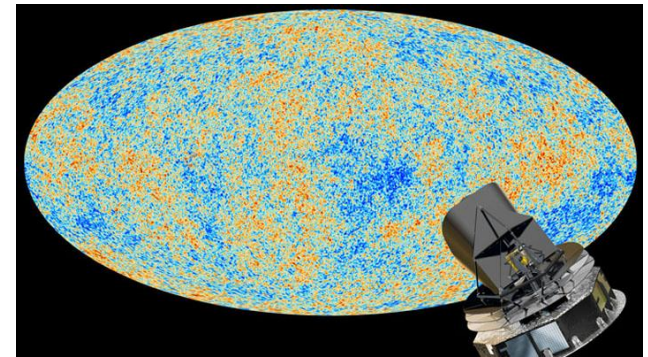
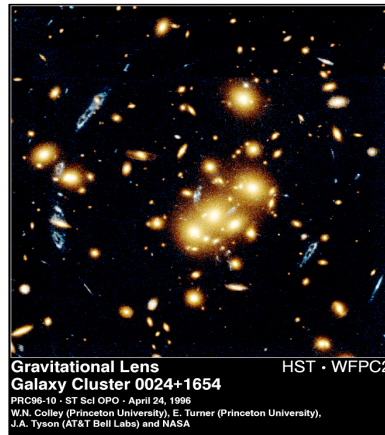
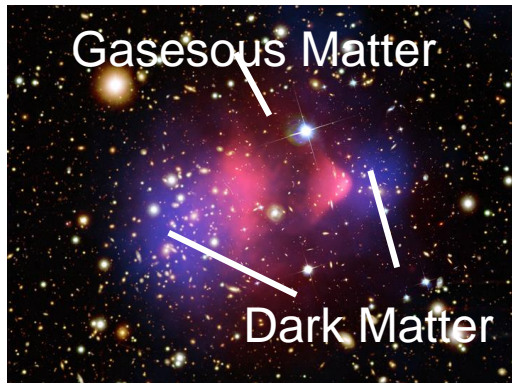


Zašto ZNAMO da SM nikako ne može biti kraj priče

Postoje opažanja u vidljivom svemiru koje SM nikako ne može objasniti

Huge amounts of invisible matter:

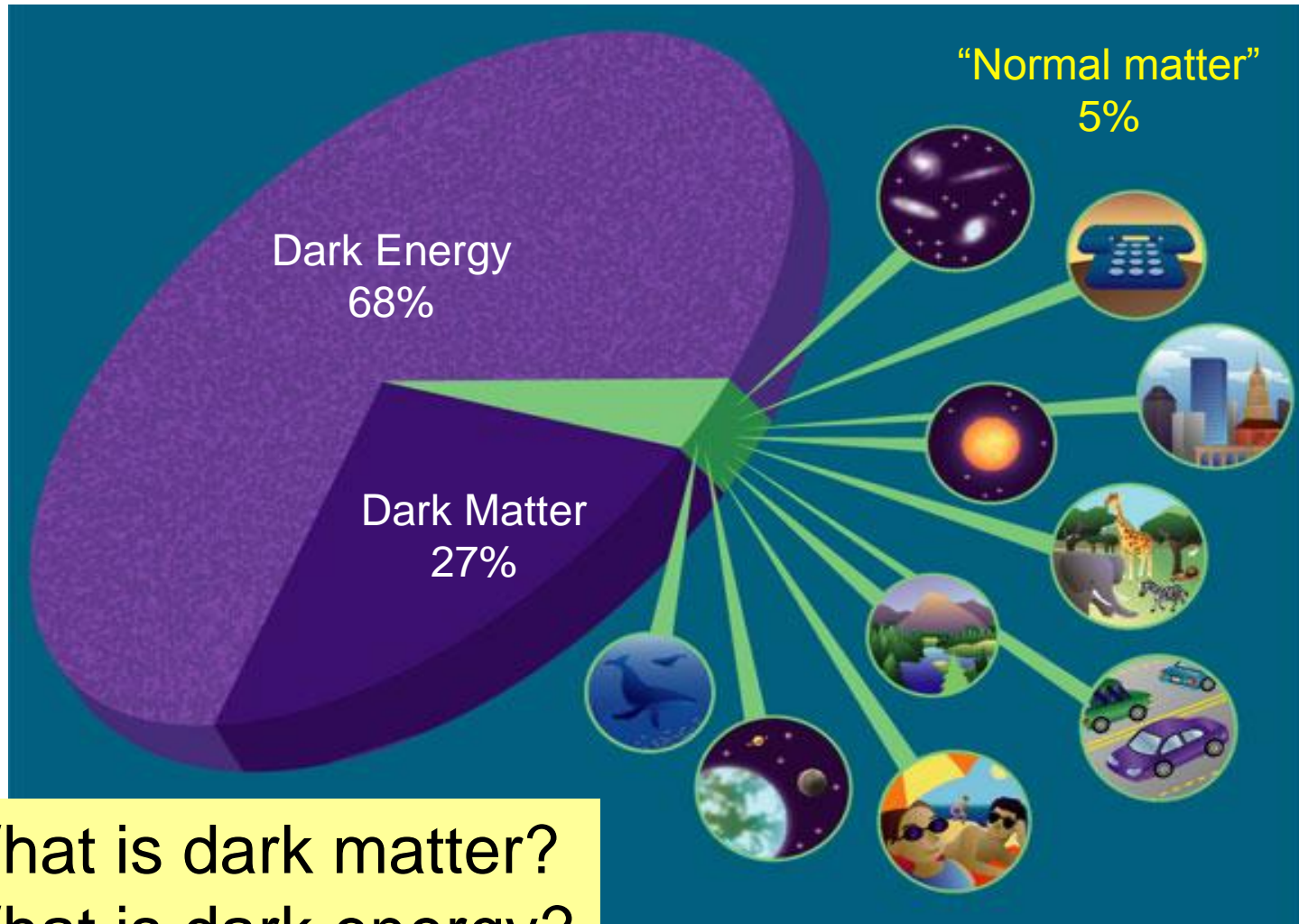
“DARK MATTER”



The expansion of the universe is accelerating:

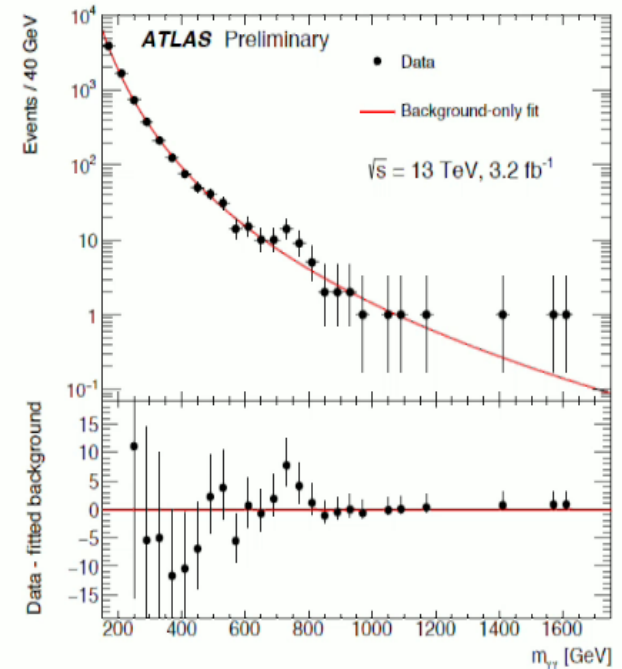
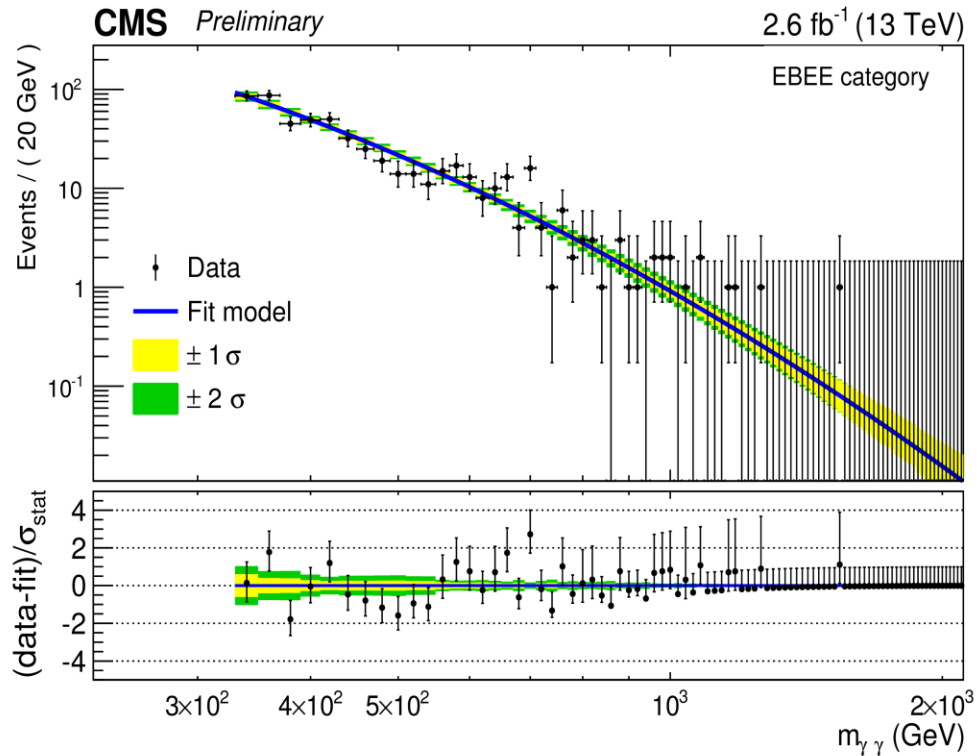
“DARK ENERGY”

What is the Universe made of?



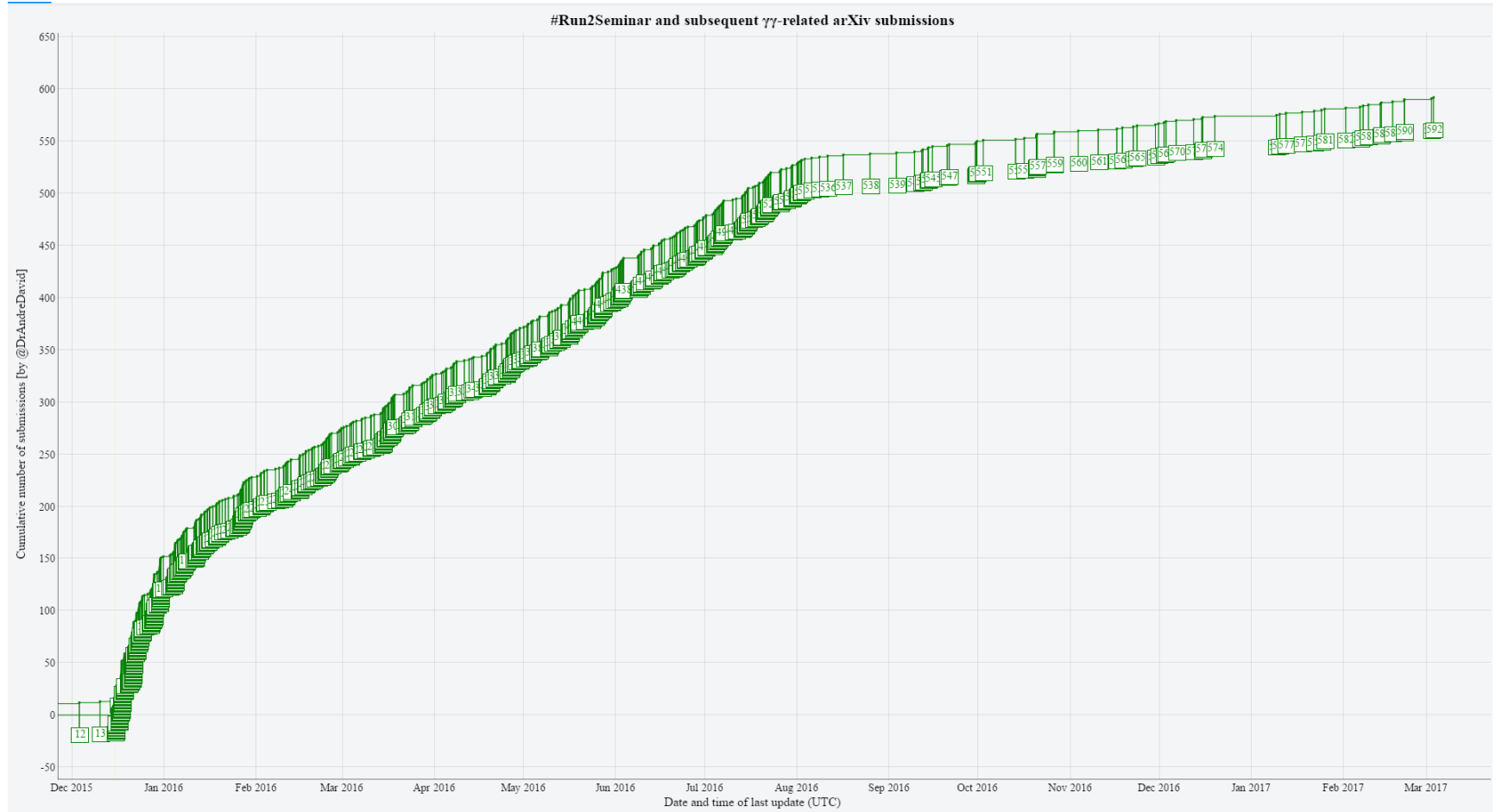
What is dark matter?
What is dark energy?

2015: Naznake nove čestice?

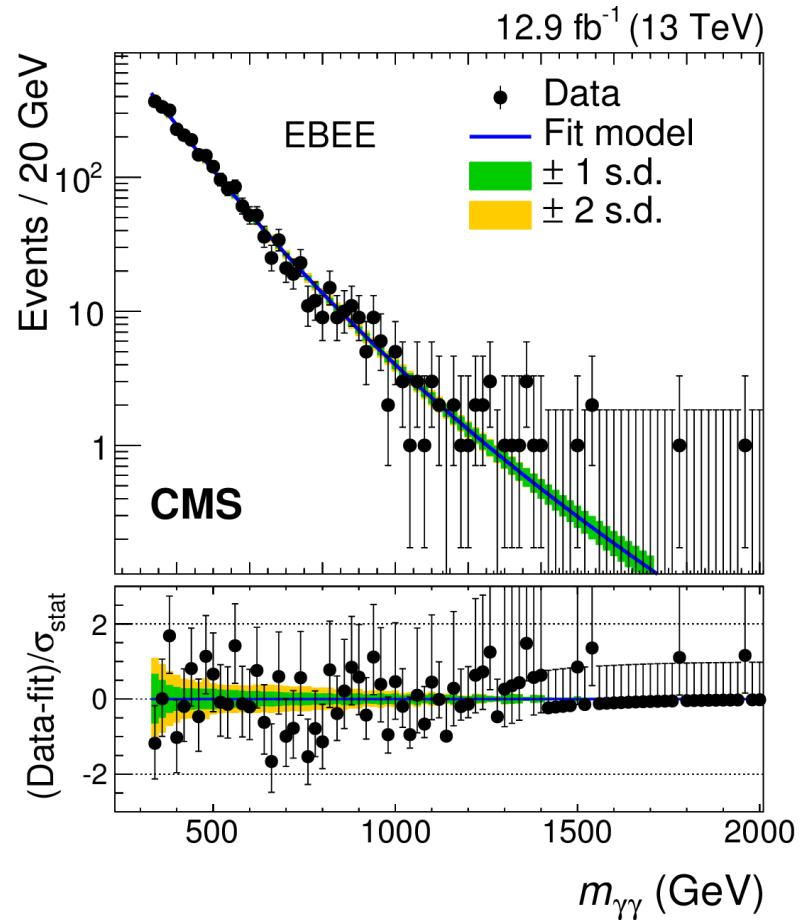
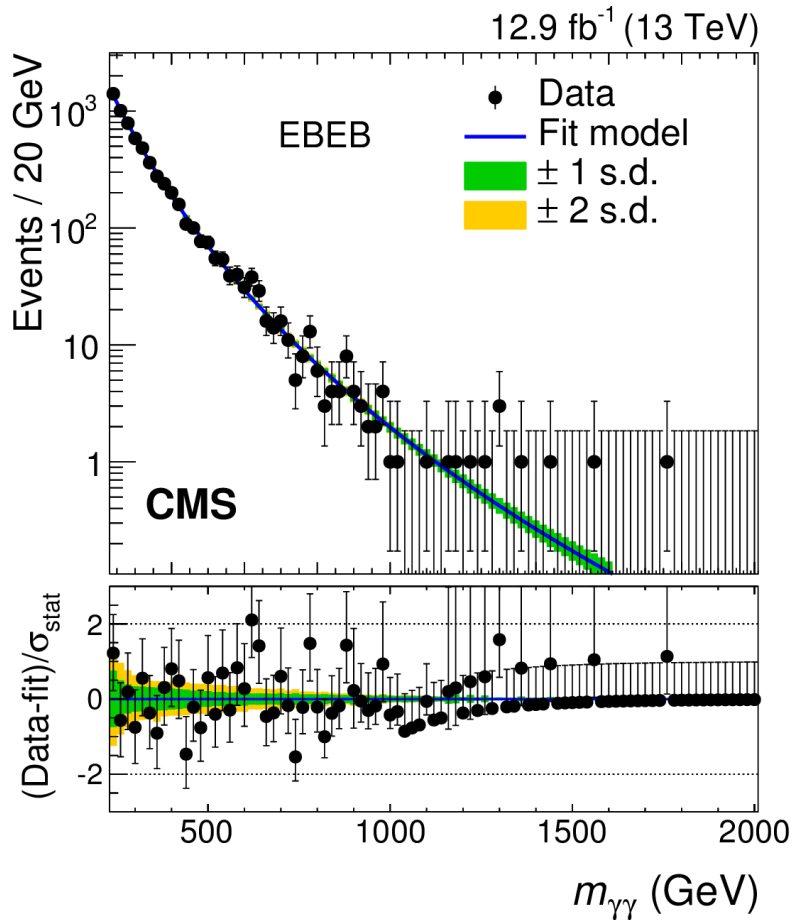


Signifikantnost viška događaja između 3 i 4 σ u oba eksperimenta

2015: Naznake nove čestice?



...ipak se statistika poigrala s nama

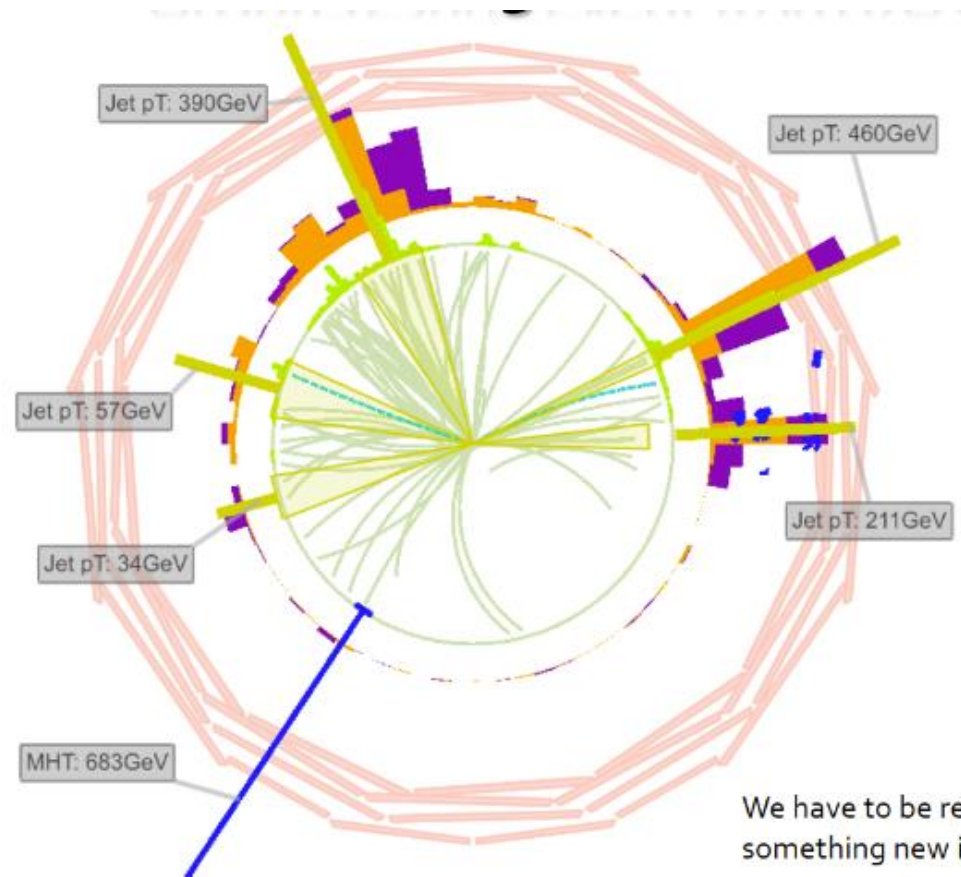


Može li nam LHC nešto reći o
prirodi tamne materije?

Može

Tamna tvar na LHC-u?

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



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!