

CMS Experiment at the LHC, CERN
Data recorded: 2012-May-27 22:36:47.271633 GMT
RunNumber: 126089 / 131440354

Vjerojatnost i statistika u otkriću Higgsovog bozona

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CMS kolaboracija - CERN

Zadar, 8. siječnja 2015.

FUNDAMENTAL PARTICLES AND INTERACTIONS

Standard Model of

FERMIONS

Leptons	Quarks
Electron	Up
Muon	Down
Tau	Strange
Neutrinos	Charm
	Bottom
	Top

Structure within the Atom

Properties of the Interactions

Particle Processes

Unsolved Mysteries

Lagrangian standardnog modela

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

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

$$- \frac{1}{4} |\partial_\mu A_\nu - \partial_\nu A_\mu - ie(W_\mu^- W_\nu^+ - W_\mu^+ W_\nu^-)|^2 - \frac{1}{2} |\partial_\mu W_\nu^+ - \partial_\nu W_\mu^+ +$$

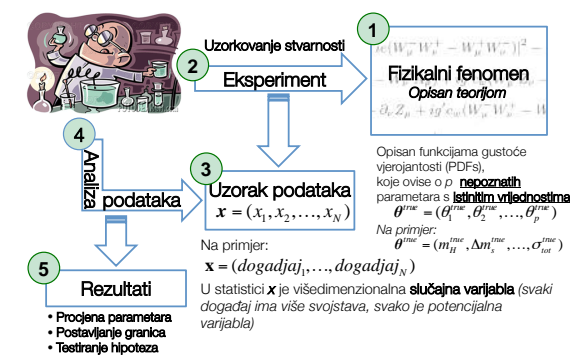
$$- ie(W_\mu^+ A_\nu - W_\nu^+ A_\mu) + ig' c_w (W_\mu^+ Z_\nu - W_\nu^+ Z_\mu)|^2 +$$

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

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

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

Kako istražujemo prirodu?



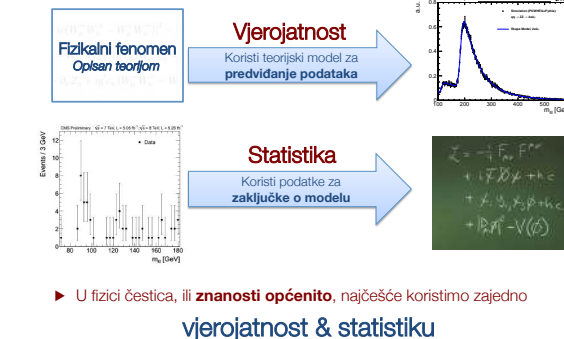
Naša glavna nada

► Pronaći nešto novo



- Ali:
- Nove stvari su rijetke
 - Inače bi ih već netko drugi pronašao ☹

Vjerojatnost i statistika



Analiza podataka

- Analiza podataka je proces pretvaranja izvornih podataka u korisnu informaciju



- Analiza podataka koristi **statistiku** za prezentaciju i interpretaciju (objašnjenje) podataka
- **Opisna statistika**
 - Opisuje osnovna svojstva podataka u kvantitativnom obliku
 - **Induktivna statistika**
 - Izvlači zaključke o slučajnom procesu kroz činjenicu da podaci predstavljaju taj proces u nekom konačnom vremenskom periodu
- Zbog svega ovoga analiza podataka se često naziva i **"Statistička analiza podataka"**

Teorija vjerojatnosti

► Matematička vjerojatnost

- Vjerojatnost je osnovni i apstraktni koncept
 - Kolmogorov 1933.
 - Vjerojatnost P da će se neki događaj x_i dogoditi slijedi Kolmogorove aksiome
- $$(a) P(x_i) \geq 0 \quad \text{for all } i$$
- $$(b) P(x_i \text{ or } x_j) = P(x_i) + P(x_j)$$
- $$(c) \sum_i P(x_i) = 1$$

► Frekventistička vjerojatnost

- Koristi samo izmjerene frekvencije događaja
- U eksperimentu koji mjeri ukupno N događaja, n od njih je tipa x
- Vjerojatnost da će bilo koji događaj biti tipa x iznosi: $P(x) = \lim_{N \rightarrow \infty} \frac{n}{N}$

► Bayesova vjerojatnost

- Zasniva se na *određenom stupnju povjerenja*
- Operativna definicija zasnovana na "Finettievoj koherentnoj opkladi"
- Koliko novaca biste uložili s obzirom na vaše procjenu vjerojatnosti (vjerovanje) u ishod budućeg mjerenja
- Bayesova formula: $P(H|D) = \frac{P(D|H)P(H)}{P(D)}$

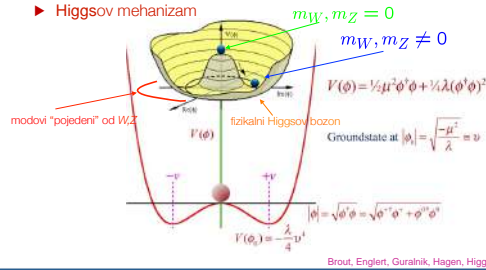
Odakle masa česticama?



Razlog za ovo bi mogao biti u postojanju nove čestice, tzv. **"Higgsovog bozona"**

Standard model and Higgs boson

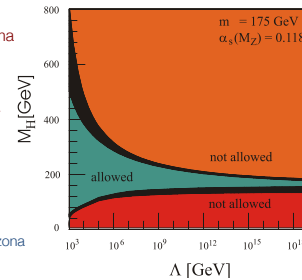
- Standardni Model $SU(3) \times SU(2) \times U(1)$ elektroslabih i jakih interakcija izuzetno dobro potvrđeni i izmjereni tijekom proteklih ~ 30 godina
 - Ali i dalje nekompletni i ne potpuno zadovoljavajući ...
- Sve čestice dobijaju masu kroz međudjelovanje sa skalarnom česticom → Higgsovom bozonom
- Higgsov mehanizam



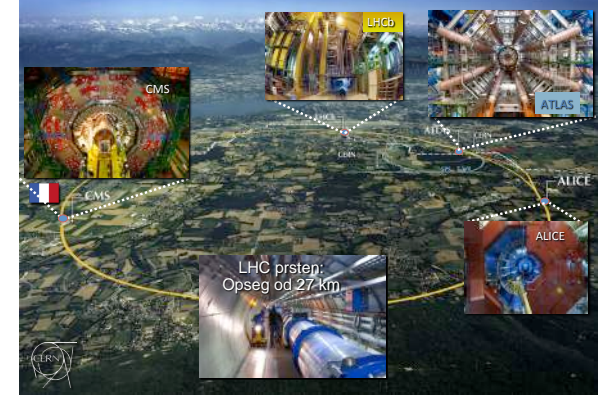
Brout, Englert, Gurahnik, Hagen, Higgs, Kibble (1964)

Higgsov bozon: osnovna svojstva

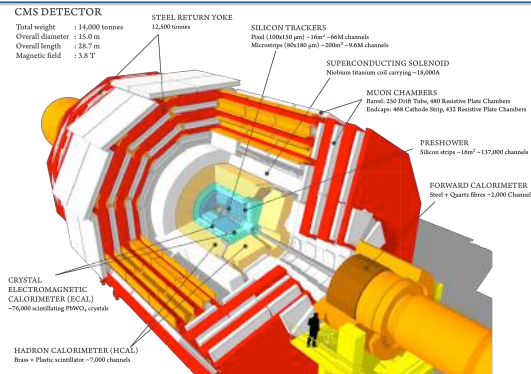
- Čestica spina = 0
- Vežanje proporcionalno masama čestica
- Problem: masa Higgsovog bozona je slobodan parametar
- Teorijska ograničenja
 - Unitarnost** (nema vjerojatnosti > 1)
 - Trivijalnost** (samo-vežanje Higgsovog bozona ostaje konačno)
 - Stabilnost** (vakuma)



Veliki sudarač hadrona - LHC



Kompaktni mionski solenoid - CMS



CMS kolaboracija

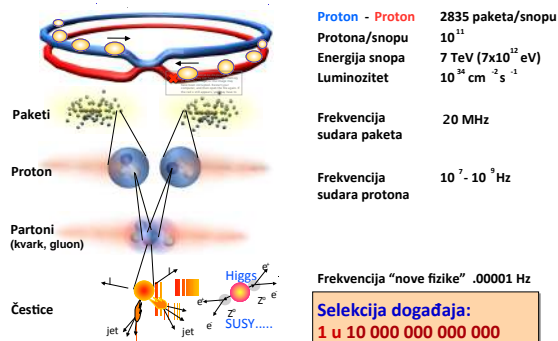


41 zemalja, 179 institucija
~3400 znanstvenika, od kojih ~800 doktoranada

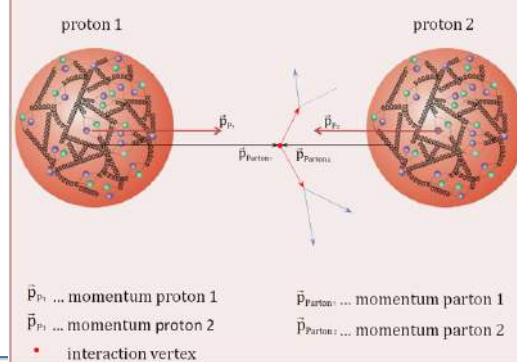
Neki bitni pojmovi u fizici čestica

- Udarni presjek (σ)**
 - Mjera "učestalosti" fizikalnog procesa
 - Jedinica: barn (10^{-28} cm^2)
 - Tipične vrijednosti: femtobarn (fb), pikobarn (pb)
- Luminozitet (L)**
 - Ili trenutni luminozitet
 - Mjera "učestalosti" sudara
 - Tipično: $L = 10^{33} \text{ cm}^{-2}\text{s}^{-1}$
- Integrirani luminozitet ($\mathcal{L} = \int L dt$)**
 - Mjera broja sudara prikupljenih u nekom vremenskom intervalu
 - Jedinica: (udarni presjek) $^{-1}$ Npr. $1 \text{ fb}^{-1} = 1000 \text{ pb}^{-1}$
 - Tipično (na LHC-u): few fb^{-1}
- Broj događaja (N)**
 - Broj (očekivanih) događaja (N) u nekom vremenskom intervalu
 - $N = \sigma \cdot \mathcal{L}$

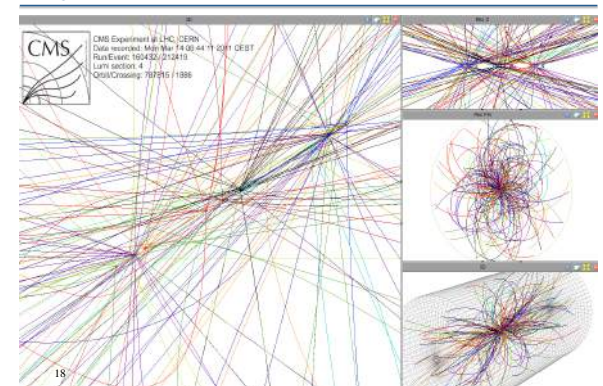
Sudari na LHC-u



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



Visoki luminozitet: višestruke interakcije PILE-UP



Pitanje broj 1

Kako Higgsov bozon izgleda u detektoru?

- Podpitanje: Kako često očekujemo da se pojavi u detektoru?

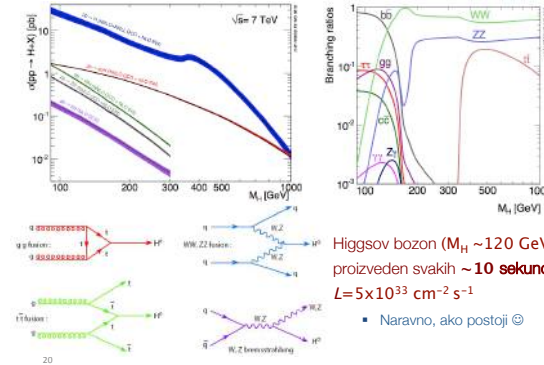
Odgovor nam daje

Teorija

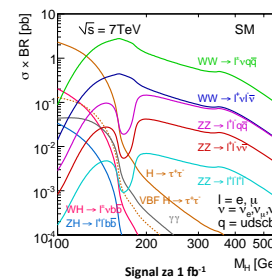
Fizikalna teorija → teorija vjerojatnosti

+ elektronika + mehanika + Monte Carlo simulacije + računarstvo + razni matematički modeli + programiranje + teorija informacija + čvrsto stanje + tehnologija lasera

Higgsov bozon na LHC-u



Higgsov bozon: kanali raspada



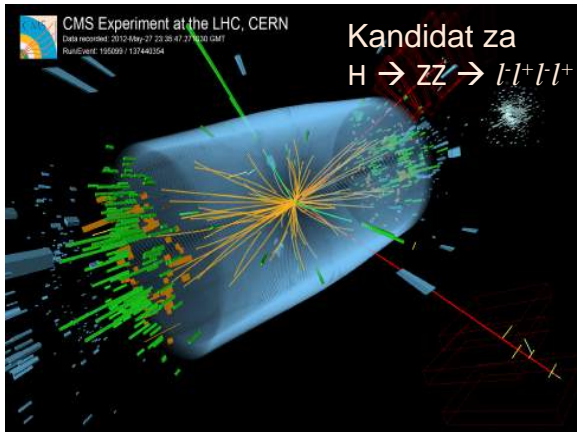
Kanal raspada	Maseno područje
$H \rightarrow \gamma\gamma$	110–150
$H \rightarrow b\bar{b}$	110–135
$H \rightarrow \tau\tau$	110–140
$H \rightarrow WW \rightarrow 2l 2\nu$	110–1000
$H \rightarrow ZZ \rightarrow 4l$	110–1000
$H \rightarrow ZZ \rightarrow 2l 2\tau$	180–1000
$H \rightarrow ZZ \rightarrow 2l 2Z$	226–1000
$H \rightarrow ZZ \rightarrow 2l 2\nu$	250–1000

Najosjetljiviji kanali za lagani Higgs:

$$H \rightarrow \gamma\gamma$$

$$H \rightarrow WW \rightarrow l \nu l \nu$$

$$H \rightarrow ZZ \rightarrow l l l l$$



Pitanje broj 2

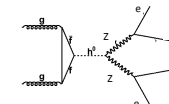
Kako od oko 20 000 000 000 000 000 događaja koje smo uspjeli snimiti odabrati baš one koje imaju Higgsov bozon?

Odgovor je takozvana

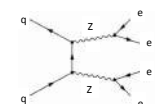
Selekcija događaja

Signal vs pozadina

- Signal:** događaj dolazi od procesa kojeg studiramo
– Primjer: $H \rightarrow ZZ \rightarrow e^+e^-e^+e^-$
- Pozadina:** bilo koji drugi događaj
 - “Trivijalna” pozadina: lako je odbacimo
 - Na primjer, zahtjevamo 4 elektrona u konačnom stanju
 - “Opasna” pozadina: bilo koji proces s 4 elektrona u konačnom stanju

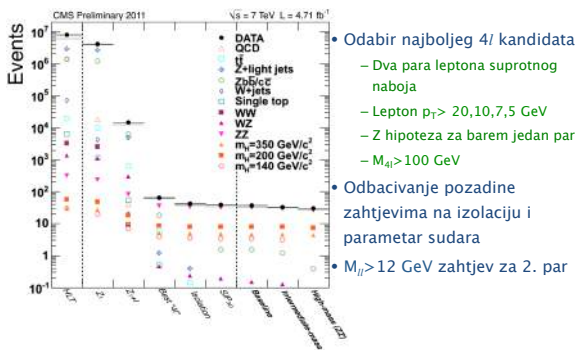


Signal: $pp \rightarrow H \rightarrow ZZ \rightarrow 4e$



‘Opasna’ pozadina: $pp \rightarrow ZZ \rightarrow 4e$

$H \rightarrow ZZ \rightarrow l+l+l+l+$ selekcija događaja



Pitanje broj 3

Kako ćemo uopće znati da smo otkrili nešto novo?

- Podpitanje: Ili je to možda samo slučajna pojava?

Pitanje broj 4

Kad zaključimo da je to ipak nešto novo, kako ćemo onda znati da je to Higgsov bozon?

- Podpitanje: Ili je to možda nešto drugo?

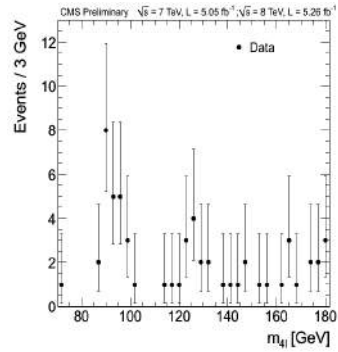
Odgovor na oba pitanja nam daje
Statistička analiza podataka

Kad vidimo nešto zanimljivo ...

- Je li to nešto novo?
- Ili možemo objasniti s onim što već znamo?
- Koristimo princip tzv. **Occamove oštrice**

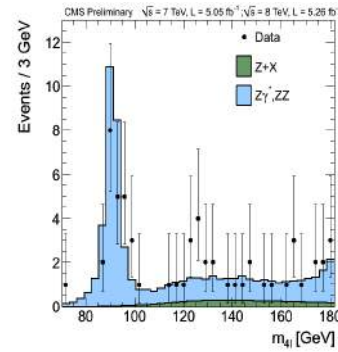


Izmjereno



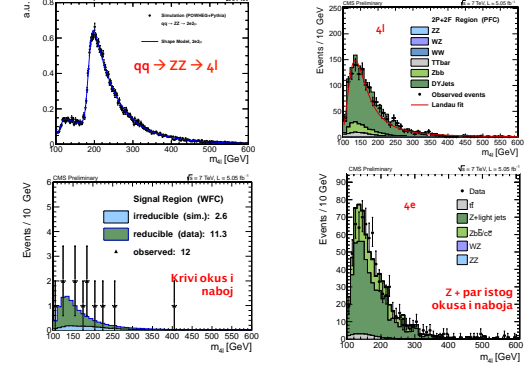
28

Izmjereno + predviđeno/očekivano



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Modeli za pozadinu

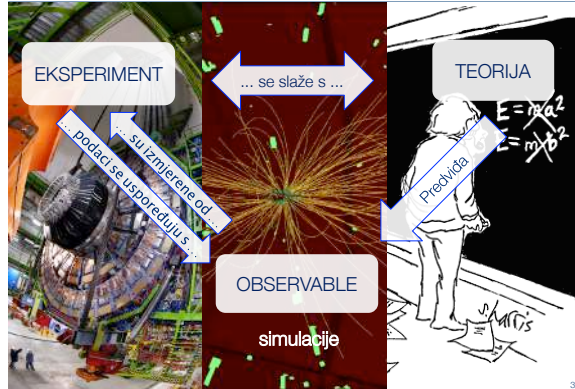


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Monte Carlo

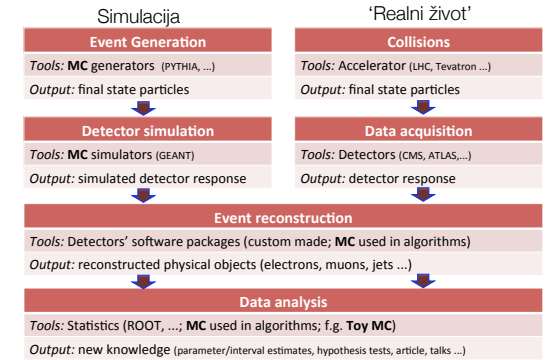


Zašto simulacije?



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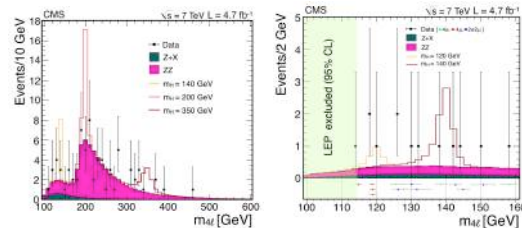
Monte Carlo metode u fizici čestica



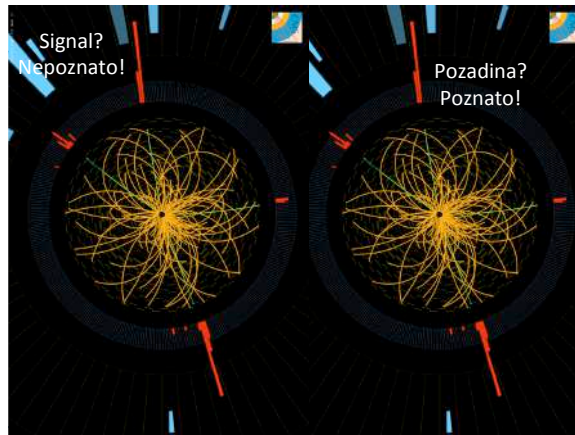
Adapted from T. Sjöstrand, CERN Academic Training Lectures 2005

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Situacija u 2011. godini



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

$$+ \frac{g}{\sqrt{2}} \sum_i (\bar{u}_L \gamma^\mu b_L W_\mu^+ + \bar{b}_L \gamma^\mu u_L W_\mu^-) + \frac{g}{2c_w} \sum_f \bar{\Psi}_f \gamma^\mu (I_f^3 - 2s_w^2 Q_f - I_f^3 \gamma_5) \Psi_f Z_\mu +$$

$$- \frac{1}{4} |\partial_\mu A_\nu - \partial_\nu A_\mu - ie(W_\mu^- W_\nu^+ - W_\mu^+ W_\nu^-)|^2 - \frac{1}{2} |\partial_\mu W_\nu^+ - \partial_\nu W_\mu^+ +$$

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

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

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

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

Dvije mogućnosti za 2012. godinu



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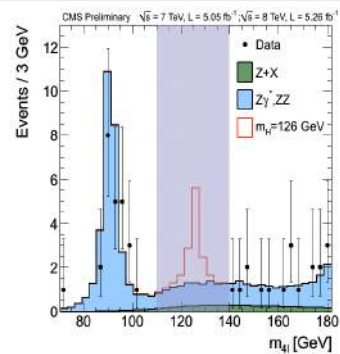
"Mi smo sebi najveći neprijatelji ..."



"Slijepa analiza"



$H \rightarrow ZZ \rightarrow l^+l^-l^+l^-$ raspodjela događaja



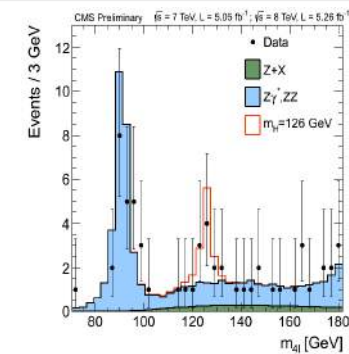
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Dan kad smo pogledali u područje signala 14 lipnja 2012 @ 18h00



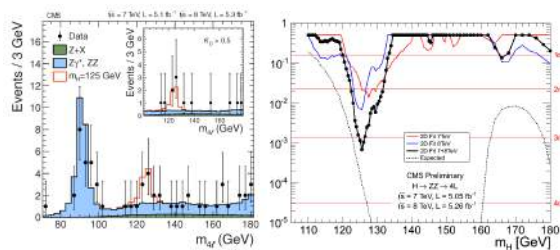
50

$H \rightarrow ZZ \rightarrow l^+l^-l^+l^-$ raspodjela događaja

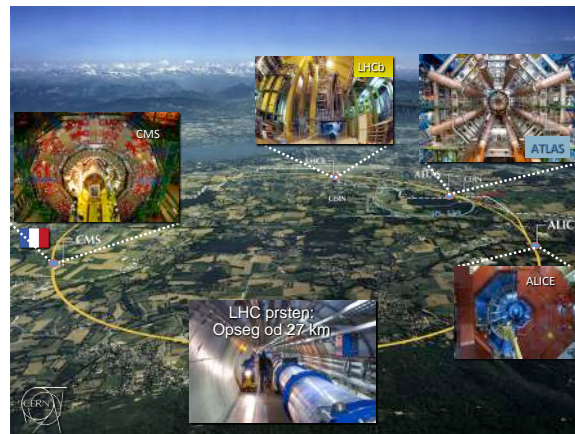


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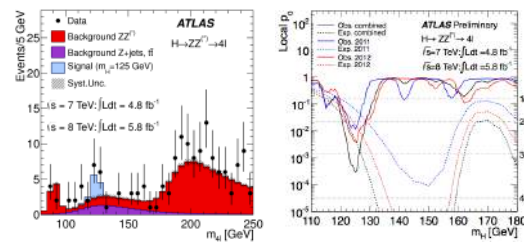
$H \rightarrow ZZ \rightarrow l^+l^-l^+l^-$ rezultati



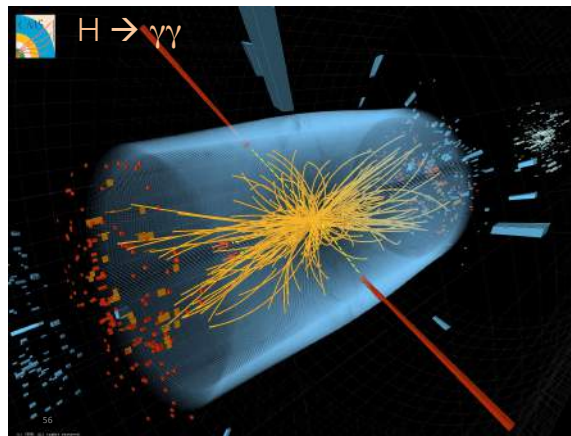
52



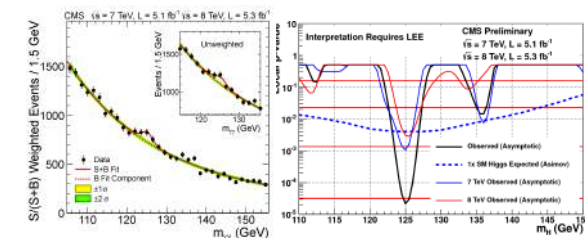
ATLAS $H \rightarrow ZZ \rightarrow l-l^+l-l^+$ rezultati



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$H \rightarrow \gamma\gamma$ p-vrijednost

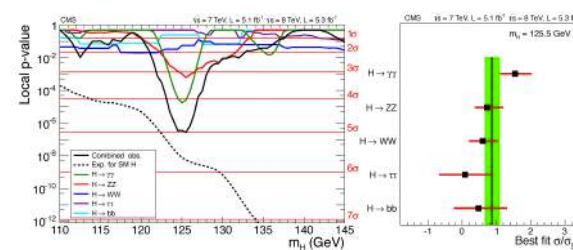


Kombinacija i interpretacija



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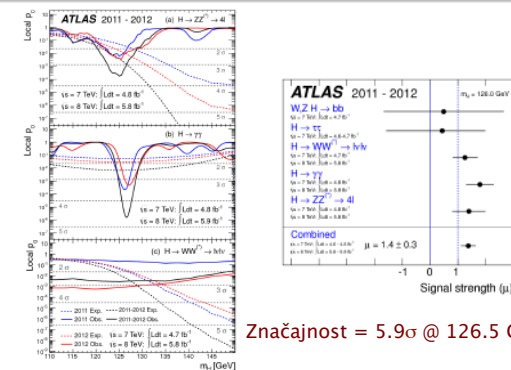
Novi bozon: CMS



Značajnost = 5σ @ 125.5 GeV

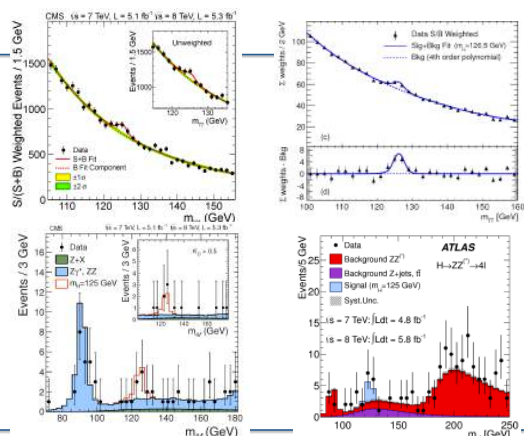
1

Novi bozon: ATLAS



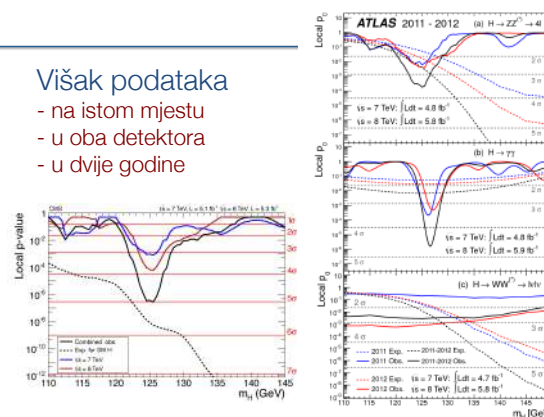
Značajnost = 5.9σ @ 126.5 GeV

6



Višak podataka

- na istom mjestu
- u oba detektora
- u dvije godine



Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC [☆]

This paper is dedicated to the memory of our ATLAS colleagues who did not live to see the full impact and significance of their contributions to the experiment.

ATLAS Collaboration*

I. Adamczak³⁶, D.J. Adams³⁵, T.N. Aditya³⁷, J. Adelman¹¹⁶, S. Adhikari¹⁰², P. Adhikari⁷⁵, T. Ador¹²⁸, S.

Aefsky²¹, J.A. Aguilar-Saavedra^{12b, 2}, M. Agasisti¹⁷, M. Ahmoucha²¹, S.P. Ahier²², F. Aides¹⁸, A. Ahmed^{12a}, M. Anwar²¹, G. Alesi^{12b, 12c}, T. Aldajani^{16a},

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doi:10.1371/journal.pone.0020120.g002

Abstract

A search for the Standard Model Higgs boson in proton–proton collisions with the ATLAS detector at the LHC is presented. The datasets used correspond to integrated luminosities of approximately 4.8 fb^{-1} collected

$H \rightarrow ZZ^{(*)} \rightarrow 4\ell$, $H \rightarrow \gamma\gamma$ and $H \rightarrow WW^{(*)} \rightarrow e\mu\nu$ in the 8 TeV data are combined with previous

improved analyses of the $H \rightarrow ZZ^{*} \rightarrow 4\ell$ and $H \rightarrow \gamma\gamma$ channels in the 7 TeV data. Clear evidence for production of a neutral higgs with a measured mass of 126.0 ± 0.4 (stat) ± 0.4 (sys) GeV is observed.

This observation, which has a significance of 5.9 standard deviations, corresponding to a background fluctuation probability of 1.7×10^{-9} , is compatible with the production and decay of the Standard Model

**Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC**

This paper is dedicated to the memory of our colleague who worked on CMS but has since passed away. In recognition of their many contributions to the advancement of this observation.

CMS Collaboration^a

S. Chatrchyan, V. Khachatryan, A.M. Sirunyan, A. Tumasyan

W. Adam, E. Aghe, T. Bergauer, M. Dragicevic, J. Erni, C. Falgarone, M. Friedl, R. Frühwirth, V.M. Ghata, J. Hammer, M. Hahn, N. Harland-Lee, J. Hejblum, W. Kerner, V. Kozlov, M. Krammer, I. Krauss, C. Liko, W. Majumder, L. Malgeri, M. Pernicka, S. Raban, R. Richter, H. Rösner, R. Schöfbeck, J. Strauss,

doi:10.1016/j.physletb.2012.08.021

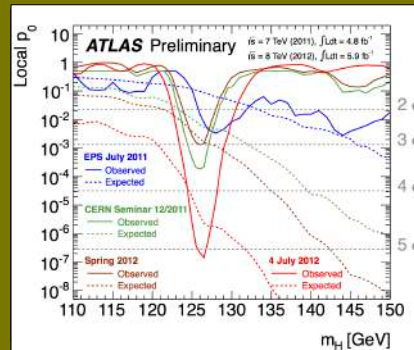
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Abstract

Results are presented from searches for the standard model Higgs boson in proton-proton collisions at $\sqrt{s} = 7$ and 8 TeV in the Compact Muon Solenoid experiment at the LHC, using data samples corresponding to integrated luminosities of up to 5.1 fb^{-1} at 7 TeV and 19.6 fb^{-1} at 8 TeV. The search is performed in the decay modes $\gamma\gamma$, ZZ , W^+W^- , $\tau^+\tau^-$, and $b\bar{b}$. An excess of events is observed above the expected background, with a local significance of 5.0 standard deviations, at a mass near 125 GeV, signalling the production of a new particle. The expected significance for a standard model Higgs boson of that mass is 5.8 standard deviations. The excess is most significant in the two decay modes with the best mass resolution, $\gamma\gamma$ and ZZ ; a fit to these signals gives a mass of $125.3 \pm 0.4 \text{ (stat.)} \pm 0.5 \text{ (syst.)} \pm 0.4 \text{ (theo.) GeV}$. The decay to two photons indicates that the new particle is a boson with spin different from one.

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Evolucija viška događaja tijekom vremena

ATLAS Preliminary

ATLAS Preliminary

ATLAS Preliminary

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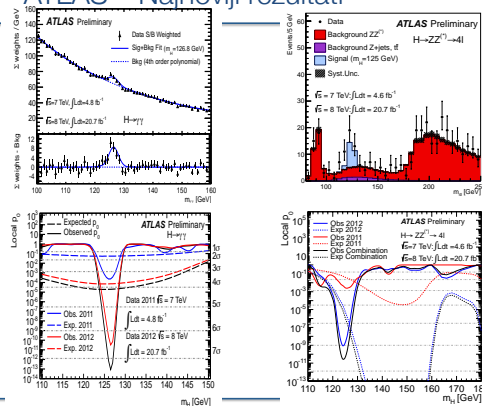
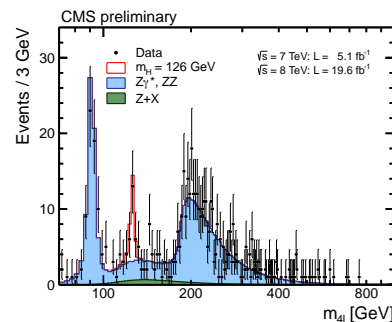
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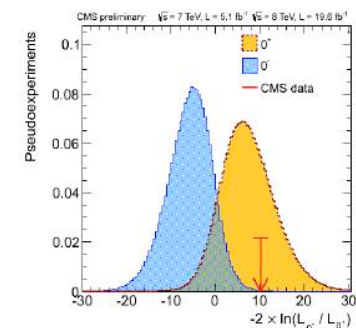
ATLAS Preliminary

ATLAS – Najnoviji rezultati**Ovo je bilo ...****... Kako smo ga otkrili?**

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A sada ... Što smo u biti otkrili?

I kako to znamo ...

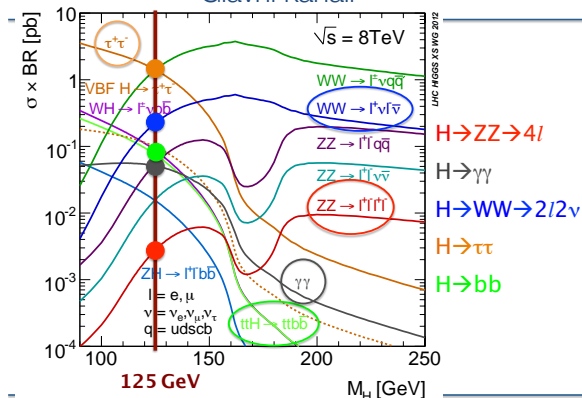


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Mjerenje svojstava

- 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?
 - Koji su spin i parnost od X?

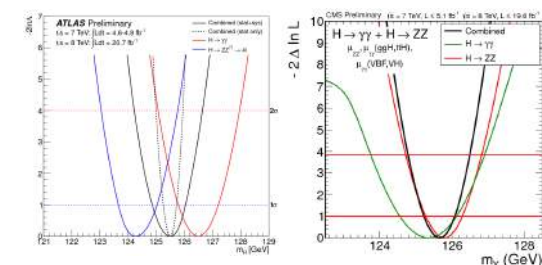
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Glavni kanali

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Kolika je masa od X?

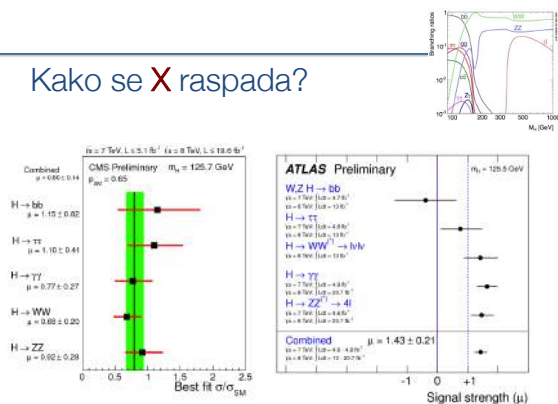
Izmjerena kroz kanale s visokom rezolucijom

H → γγ i H → ZZ → 4l

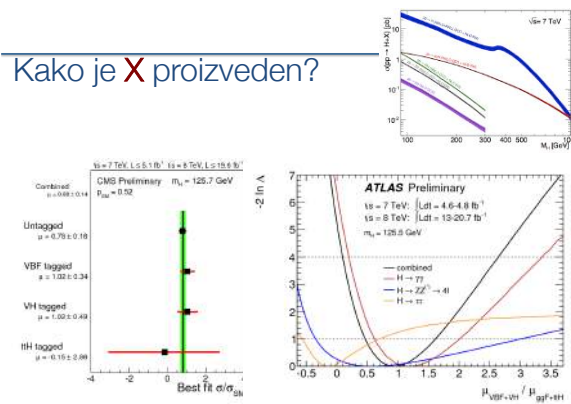
$m_X = 125.5 \pm 0.2 \text{ (stat.)} \pm 0.5 \text{ (sys.) GeV}$ $m_X = 125.7 \pm 0.3 \text{ (stat.)} \pm 0.3 \text{ (syst.) GeV}$

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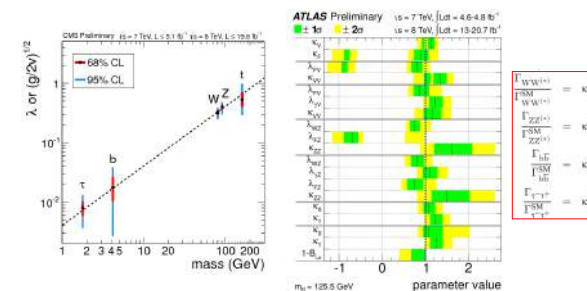
Kako se X raspada?



Kako je X proizveden?

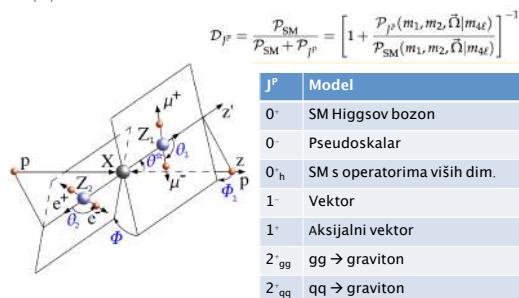


Kako se X veže za ostale čestice?

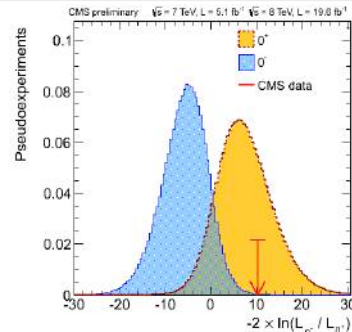


Koji su spin i parnost od X?

- Koristimo kinematičku diskriminantu (KD) za razlikovanje spin-parnost (J^P) modela



Skalar (SM) or pseudoskalar

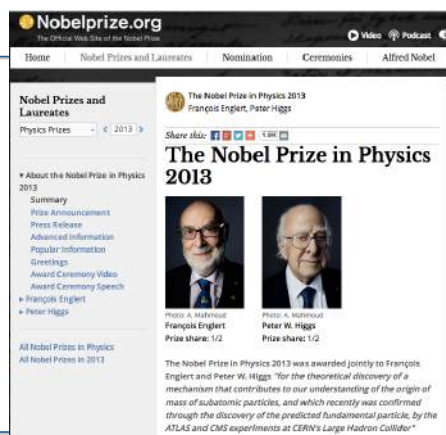


Sažetak

- Kolika je masa od X?
– **Oko 125.5 GeV**
- Je li X proizveden prema očekivanjima za SM Higgsov bozon?
– **Da**
- Raspada li se X prema očekivanjima za SM Higgsov bozon?
– **Da**
- Veže li se X na ostale čestice prema očekivanjima za SM Higgsov bozon?
– **Da**
- Koji su spin i parnost od X?
– **Isključili smo (skoro) sve testirane modele osim SM**
- 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**



CMS i ATLAS kolaboracije

