Search for the Higgs Boson:  
A Numerical Adventure of Exclusion and Discovery  

*CCP-2013, Moscow, 21-24 August 2013*  

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on behalf of the CMS Collaboration  
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Outline

- The Higgs boson of the Standard Model
- Statistical Methods of the Search
- Exclusion at LEP
- Observation at LHC
- What next?

With the support of the Hungarian OTKA Grant NK-81447
References


The CMS Collaboration: Measurements of the properties of the new boson with a mass near 125 GeV
CMS Physics Analysis Summary HIG-13-005, 14 March 2013


The ATLAS Collaboration: Combined coupling measurements of the Higgs-like boson with the ATLAS detector using up to 25 fb\(^{-1}\) of proton-proton collision data
ATLAS NOTE, ATLAS-CONF-2013-034
The Zoo of the Standard Model

The elementary particles

3 fermion families:
1 pair of quarks and
1 pair of leptons in each

3 kinds of gauge bosons:
the force carriers

All identified and studied!

+ the Higgs boson (?)

Color: the charge of the strong interaction
colored quarks $\Rightarrow$ colorless composite hadrons of 2 kinds
hadrons = mesons ($q\bar{q}$) + baryons ($qqq$)
Derive 3 interactions of local $U(1)$, $SU(2)$ and $SU(3)$ symmetries

Unify and separate e-m $U(1)$ and weak $SU(2)$ interactions using spontaneous symmetry breaking:

(Anderson-Englert-Brout-Higgs-Guralnik-Hagen-Kibble mechanism, 1963-64)

Add a 4-component, symmetry breaking field to vacuum.

Separate a good $U(1)$ local symmetry from the ruined $U(1) \otimes SU(2)$

\[ \downarrow \]

electromagnetism + zero-mass photon, OK!

Turn 3 d.f. of Higgs-field to create masses for $Z$, $W^+$, $W^-$, get a correct weak interaction with 3 heavy gauge bosons.

4th degree of freedom: heavy scalar boson.
Status in 2013

Includes hundreds of measurements of all experiments

| Expt – theory | expt. uncertainty |
Slightly deviating quantity used to change

Now it is forward-backward asymmetry of

$e^+ e^- \rightarrow Z \rightarrow b\bar{b}$

LEP Electroweak Working Group:

http://lepewwg.web.cern.ch/

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta \alpha_{\text{had}}^{(5)}(m_Z)$</td>
<td>0.02750 ± 0.00033</td>
</tr>
<tr>
<td>$m_Z$ [GeV]</td>
<td>91.1875 ± 0.0021</td>
</tr>
<tr>
<td>$\Gamma_Z$ [GeV]</td>
<td>2.4952 ± 0.0023</td>
</tr>
<tr>
<td>$\sigma_{\text{had}}$ [nb]</td>
<td>41.540 ± 0.037</td>
</tr>
<tr>
<td>$R_l$</td>
<td>20.767 ± 0.025</td>
</tr>
<tr>
<td>$A_{\text{fb}}^{0,l}$</td>
<td>0.01714 ± 0.00095</td>
</tr>
<tr>
<td>$A_l(P_\tau)$</td>
<td>0.1465 ± 0.0032</td>
</tr>
<tr>
<td>$R_b$</td>
<td>0.21629 ± 0.00066</td>
</tr>
<tr>
<td>$R_c$</td>
<td>0.1721 ± 0.0030</td>
</tr>
<tr>
<td>$A_{\text{fb}}^{0,b}$</td>
<td>0.0992 ± 0.0016</td>
</tr>
<tr>
<td>$A_{\text{fb}}^{0,c}$</td>
<td>0.0707 ± 0.0035</td>
</tr>
<tr>
<td>$A_b$</td>
<td>0.923 ± 0.020</td>
</tr>
<tr>
<td>$A_c$</td>
<td>0.670 ± 0.027</td>
</tr>
<tr>
<td>$A_l(SLD)$</td>
<td>0.1513 ± 0.0021</td>
</tr>
<tr>
<td>$\sin^2 \theta_{\text{eff}}(Q_{\text{fb}})$</td>
<td>0.2324 ± 0.0012</td>
</tr>
<tr>
<td>$m_W$ [GeV]</td>
<td>80.385 ± 0.015</td>
</tr>
<tr>
<td>$\Gamma_W$ [GeV]</td>
<td>2.085 ± 0.042</td>
</tr>
<tr>
<td>$m_t$ [GeV]</td>
<td>173.20 ± 0.90</td>
</tr>
</tbody>
</table>

March 2012
The Higgs boson of the Standard Model

Spontaneous symmetry breaking:
Spinless, neutral, heavy particle
The scalar particle needed for renormalisation
Does it really exist? SM: it must!

Many jokes of the Higgs boson on internet...
The Higgs boson walks into a bar. The bartender says "Watch out, there were some guys looking for you."
The Higgs boson walks into a church. The priest says „Your kind is not welcome here”. The boson replies: „But without me how can you have mass?”
Where is the Higgs boson?

By-product of spontaneous symmetry breaking of the SM
Most wanted particle of physics as
the only missing piece of the Standard Model.

Experimentally not observed before 2012

„It was in 1972 ...
that my life as a boson really began”

Peter Higgs:
My Life as a Boson: The Story of „The Higgs”,
Statistical Concepts of Particle Physicists

are far from those of official math statistics!

*LHC Statistics for Pedestrians* by Eilam Gross
in PHYSTAT-LHC Workshop on Statistical Issues for LHC Physics, CERN-2008-001, p. 205:

*A pedestrians guide . . . to help the confused physicist to understand the jargon and methods used by HEP Phystatisticians.*

A Phystatistician is a Physicist who knows his way in Statistics and knows how Kendalls advanced theory of statistics book looks like....

Every collaboration has phystatistician experts and they all have quite different ideas how to analyse data...
Last 2 PHYSTAT-LHC Workshops

CERN, Geneva, Switzerland, 27–29 June 2007

Proceedings
Editors: H. B. Prosper
L. Lyons
A. De Roeck

Dezső Horváth: Search for the Higgs Boson
CERN-2008-001
7 March 2008

Proceedings of the
PHYSTAT 2011 Workshop
on
Statistical Issues Related to Discovery
Claims in Search Experiments
and
Unfolding
CERN, Geneva, Switzerland
17–20 January 2011

Editors: Harrison B. Prosper (Florida State University)
Louis Lyons (Imperial College and Oxford)
Welcome to the CMS Statistics Committee

Contents:

- Who we are and how to reach us
- News
- Committee meetings and other regular activities:
- Recommendations from the Committee
- Questions and Answers
- Software tools
- Talks and Notes on Statistics
- The Combined Statistics Forum of ATLAS and CMS
- Workshops on Statistics for Physicists
- Publications
- Other Links
Likelihood

Poisson distribution \((n_i \text{ events in bin } i)\):

\[
P(n_i | \mu_i) = \frac{\mu_i^{n_i} e^{-\mu_i}}{n_i!}
\]

Poisson likelihood: \(\mathcal{L} = \prod_i P(n_i | \mu_i)\)

Expected \(<n_i>\):

\[
\mu_i = \sum_j L \sigma_j \epsilon_{ji}
\]

\(L\): luminosity (\(\sim\) collision rate),
\(\sigma_j\): cross section of source \(j\),
\(\epsilon_{ji}\): efficiency (Monte Carlo) of source \(j\) in bin \(i\).
Luminosity: collision rate

Luminosity: 

\[ L = fn \frac{N_1 N_2}{A} \]

\([L] = \text{s}^{-1}\text{cm}^{-2} \quad (\sim \text{flux})\]

\(f\): circulation frequency; \(n\): nr. of bunches in ring; \(N_1, N_2\) particles/bunch; \(A\): spatial overlap

Rate of reaction with cross section \(\sigma\) at \(\epsilon\) efficiency

\[ R = \epsilon \sigma L \]

Integrated luminosity: \(\int_{t_1}^{t_2} L dt\)

measured in units of inverse cross-section:

\([\text{pb}^{-1}, \text{fb}^{-1}]\)
Exclusion and Discovery

General convention in accelerator experiments:

Exclusion of a given phenomenon at $\geq 95\%$ confidence level.

Observation of something new: $> 5\sigma$ above background.

One-sided exclusion: $X > X_0$ at 95\% CL if $X_{\text{obs}} - X_0 > 1.64\sigma$
And what is $\sigma$?

The total uncertainty of the physics parameters $P$ according to the best honest guess of the experimentalist.

It has a statistical component (from the number of observed events) and systematic ones from various sources:

Monte Carlo statistics and inputs, calibration factors, efficiencies, etc. (nuisance parameters $\Theta$) could be added up with correlations accounted for with a final uncertainty roughly:

$$\sigma = \sqrt{\sigma_{\text{stat}}^2 + \sigma_{\text{syst}}^2}$$

However, we derive the final uncertainty via marginalizing (integrating out) the nuisance parameters in likelihood $\mathcal{L}$ using the related probability distributions $\mathcal{W}$:

$$\mathcal{L}(P; x) = \mathcal{W}(x|P) = \int \mathcal{W}(x|P, \Theta)\mathcal{W}(\Theta|P)d\Theta$$
A blind analysis is a measurement which is performed without looking at the answer. Blind analyses are the optimal way to reduce or eliminate experimenter’s bias, the unintended biasing of a result in a particular direction.”


Originally coming from medicine

Basic analysis method of Higgs search at LHC:

Optimize, prove and publish your analysis technique using simulations and earlier data only before touching new data in the critical region

CMS, 2012: \(110 < M_H < 140\) GeV blinded because of \(3\sigma\) excess observed in 2011

Simultaneous *unblinding* for all analysis channels
The Large Electron Positron collider
Accelerators at CERN, LEP era
# The LEP Collider

<table>
<thead>
<tr>
<th>Year</th>
<th>$E(e^+e^-)$, GeV</th>
<th>$\int Ldt/4$, pb$^{-1}$</th>
<th>main goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>1989–94</td>
<td>$\sim 91$</td>
<td>140</td>
<td>$Z^0$</td>
</tr>
<tr>
<td>1995</td>
<td>130–136</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>1996</td>
<td>161–172</td>
<td>20</td>
<td>$W^+W^-$</td>
</tr>
<tr>
<td>1997</td>
<td>184</td>
<td>60</td>
<td>WW, ZZ</td>
</tr>
<tr>
<td>1998</td>
<td>189</td>
<td>190</td>
<td>WW, ZZ</td>
</tr>
<tr>
<td>1999</td>
<td>192–202</td>
<td>220</td>
<td>Higgs</td>
</tr>
<tr>
<td>2000</td>
<td>204–209</td>
<td>220</td>
<td>Higgs</td>
</tr>
</tbody>
</table>
Search for the SM Higgs boson at LEP

Dominant formation:

Higgs-strahlung
\( e^- e^+ \rightarrow Z H \)

Dominant decay:

\( H \rightarrow b\bar{b} \)

Various analyses for different Z decays
What is observed: resonance

\[ \tau = \Gamma^{-1} \text{ lifetime } \Rightarrow \text{exp. decay: } N(t) = N_0 e^{-\Gamma t} \]

Probability distribution:

\[ |\chi(E)|^2 = \frac{1}{(E-M)^2 + \Gamma^2/4} \]

Breit-Wigner equation

\[
\begin{align*}
M & \text{ resonance} \\
\Gamma & \text{ centre width}
\end{align*}
\]

\((\hbar = 1, c = 1)\)

Lorentz curve

New particle discovery: resonance at decay energy corresponding to the particle mass
Hunting the Higgs boson

- Compose a complete SM background using Monte Carlo simulation taking all types of possible events normalized to their cross-sections.
- Higgs signal: simulation of all possible production and decay processes with all possible Higgs-boson masses
- Put all these through the detector simulation to get events analogous to the measured ones.
- Optimize the event selection: reduce background, enhance signal via e.g.
  \[ \frac{\text{sig}}{\sqrt{\text{bgr}}} = \max \] or \[ 2 \cdot (\sqrt{\text{sig}} + \sqrt{\text{bgr}} - \sqrt{\text{bgr}}) = \max. \]
- Calculate at experimental luminosity expected nr. of events for signal and background at various conditions.
- SM background \( \sim \) experiment? (YES \( \downarrow \) / NO \( \uparrow \)).
Hypothesis Testing: Test Statistic

Likelihood ratio: signal+background/background \( Q = \mathcal{L}_{s+b}/\mathcal{L}_b \)

Usually analysed and plotted:

\[
-2 \ln Q(m_H) = 2 \sum_{k=1}^{N_{\text{ch}}} \left[ s_k(m_H) - \sum_{j=1}^{n_k} \ln \left( 1 + \frac{s_k(m_H)S_k(x_{jk};m_H)}{b_kB_k(x_{jk})} \right) \right]
\]

- \( n_k \): events observed in channel \( k \), \( k = 1 \ldots N_{\text{ch}} \)
- \( s_k(m_H) \) and \( b_k \): signal and background events in channel \( k \) for Higgs mass \( m_H \)
- \( S_k(x_{jk};m_H) \) and \( B_k(x_{jk}) \): probability distributions for events for Higgs mass \( m_H \) at test point \( x_{jk} \)
- \( x_{jk} \): position of event \( j \) of channel \( k \) on the plane of its reconstructed Higgs mass and cumulative testing variable constructed of various features of the event like b-tagging, signal likelihood, neural network output, etc.
No Higgs at LEP: $M_H > 114.4$ GeV

Expected and observed signal confidence level assuming background only


Excess in ALEPH’s 4-jet events at 115 GeV:

$E_{\text{LEP2000}} = 206$ GeV \quad m_H(115) + m_Z(91) = 206$ GeV !!
LEP: exclusion by experiment

ALEPH

-2\ln(Q) vs. m_H (GeV/c^2)

DELPHI

-2\ln(Q) vs. m_H (GeV/c^2)

L3

-2\ln(Q) vs. m_H (GeV/c^2)

OPAL

-2\ln(Q) vs. m_H (GeV/c^2)
LEP: exclusion by channel

LEP Hqq

-2 ln(Q)

m_H (GeV/c^2)

LEP Hvv

-2 ln(Q)

m_H (GeV/c^2)

LEP Hee + Hmumu

-2 ln(Q)

m_H (GeV/c^2)

LEP Htt + ttZ

-2 ln(Q)

m_H (GeV/c^2)
ALEPH event \((e^+e^- \rightarrow bbqq)\)

b quark: long lifetime \(\Rightarrow\) secondary vertex
Event weights vs. Higgs mass for 17 selected LEP events

Accelerators of CERN now

LHC: Large Hadron Collider
SPS: Super Proton Synchrotron
AD: Antiproton Decelerator
ISOLDE: Isotope Separator On Line DEvice
PSB: Proton Synchrotron Booster
PS: Proton Synchrotron
LINAC: LINear ACcelerator
LEIR: Low Energy Ion Ring
CNGS: Cern Neutrinos to Gran Sasso
Steering magnets of LHC

1232 superconducting magnets (before installation)

\( L = 15 \text{ m}, \ M = 35 \text{ t}, \ T = 1.9 \text{ K}, \ B = 8.3 \text{ T} \)
Dipole magnets of LHC in the tunnel
CMS: Compact Muon Solenoid

Key:
- Blue: Muon
- Red: Electron
- Green: Charged Hadron (e.g. Pion)
- Dashed Green: Neutral Hadron (e.g. Neutron)
- Dash-Dot Green: Photon

14000 ton digital camera:
- 100 M pixel, 20 M pictures/sec, 1000 GB/sec data
- Processes max 400 pictures/sec ⇒ intelligent filter!!

Dezső Horváth: Search for the Higgs Boson
CCP-2013, Moscow, 21-24 August 2013
The (Compact Muon) Solenoid itself
The CMS Collaboration (2012)

- 179 institutions of 41 countries
- 3275 physicists (incl. 1535 students)
- 790 engineers and technicians
- Participants by countries of institutes:
  USA: 1149, Italy: 439, Germany: 298, Russia: 234

Huge joint effort:
3000 people worked on it for 20 years!
Formation of the SM Higgs boson in p-p collisions at LHC

SM Higgs production

$\sigma$ [fb]

$\mu$ [GeV]

$gg \rightarrow h$

$qq \rightarrow qqh$

$qq \rightarrow Wh$

$bb \rightarrow h$

$qb \rightarrow qth$

$qq \rightarrow Zh$

TeV4LHC Higgs working group

LHC

gluon fusion

vector boson fusion
Decay of the SM Higgs boson

March 2012

Not excluded by 2011 CMS data:

$114 < M_H < 127$ GeV (at 95% CL)

(where many decay processes contest)

Best identified:

$H \rightarrow \gamma \gamma$

Excess observed $2 - 3\sigma$ at $\sim 125$ GeV!
CMS: elektromagnetic calorimeter

optimized for studying $H \rightarrow \gamma\gamma$

75,848 PbWO$_4$ single crystal scintillators
A CMS event: $H \rightarrow \gamma\gamma$ candidate
4 July 2012: we have something!

ATLAS and CMS, at LHC collision energies $7$ and $8$ TeV, in two decay channels $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ \rightarrow \ell^+\ell^-\ell^+\ell^-$, at invariant mass of $m \approx 126$ GeV see a new boson at a convincing statistical significance of $5\sigma$ conf. level each with properties corresponding to those of the SM Higgs boson.

$H \rightarrow \gamma\gamma \Rightarrow J_H = 0$ or $2$

Data analysis was optimized for SM Higgs search...

Nevertheless, it has to be shown to be the SM Higgs, e.g.

- $J_H = 0$: $H \rightarrow ZZ$ and $H \rightarrow WW$ angular distribution of decay products
- $H \rightarrow XY...$ cross sections follow the SM predictions
- There is one Higgs boson only (no charged or more neutral ones)
CMS: $H \rightarrow \gamma\gamma$ (VBF)

Vertex for measuring the $\gamma\gamma$ invariant mass:

two hadron jets from vector boson fusion.

Di-jet event with:
- di-photon mass 121.9 GeV
- di-jet mass 1460 GeV
- jet pT: 288.8 and 189.1 GeV
- jet $\eta$: -2.022 and 1.860
Many p-p collisions can be in the same event (same bunch collision). Record: 78 identified vertices. This increases data taking speed and makes life hard.
First observations of a new particle in the search for the Standard Model Higgs boson at the LHC

Dezső Horváth: Search for the Higgs Boson

CMS and ATLAS: A new boson

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

ATLAS Collaboration*

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.

ARTICLE INFO

Article History
Received 15 July 2012
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ABSTRACT

A search for the Standard Model Higgs boson in proton-proton collisions with the ATLAS detector at the LHC is presented. The searches most correspond to integrated luminosities of approximately 4.8 fb⁻¹ collected at √s = 7 TeV in 2011 and 5.0 fb⁻¹ at √s = 8 TeV in 2012. Individual searches in the channels H → ZZ⁺⁻ → 4ℓ, H → WW⁺⁻ → ℓνℓν and H → WW⁺⁻, ℓντ ± are performed in the 8 TeV data and combined with previously published results of searches for H → ZZ⁺⁻, WW⁺⁻, ℓντ ± and H → τ⁺τ⁻ in the 7 TeV data. Evidence for the production of a new boson with a measured mass of 125 ± 4 GeV and a width of 4 ≤ 3 GeV is presented. The observed mass is consistent with the mass of the Standard Model Higgs boson. The results are interpreted in the context of the Standard Model Higgs boson.

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

CMS Collaboration*

This paper is dedicated to the memory of our colleagues who worked on CMS but have since passed away. In recognition of their many contributions to the advancement of the experiment.

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Received 15 July 2012
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ABSTRACT

Results are presented from searches for the standard model Higgs boson in proton-proton collisions at √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 5.0 fb⁻¹ at 8 TeV. The search is performed in five decay modes: γγ, ZZ(→ℓℓ), WW(→ℓℓνν), τ⁺τ⁻ and ℓ⁺ℓ⁻. 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, exceeding the production of a new particle. The expected significance for a standard model Higgs boson of this mass is 3.8 standard deviations. The excess is most significant in the two decay modes the H → γγ and H → ℓ⁺ℓ⁻. A fit to these signals gives a mass of 125.3 ± 0.4 (stat) ± 0.3 (syst) GeV. The trend of the photon indicates that the new particle is a boson with spin different from one.

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CMS: $H \rightarrow \gamma\gamma$ mass distribution

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

text: 50%, 2899 authors in 16 pp.
ATLAS: $H \rightarrow \gamma\gamma$ mass distribution

ATLAS Collaboration (2931 authors):

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

CMS: $H \rightarrow ZZ^* \rightarrow \ell^+ \ell^- \ell^+ \ell^-$
**p-value**

The probability of obtaining a test statistic at least as extreme as the one that was actually observed, assuming that the null hypothesis is true.

**Higgs search:** The probability that random fluctuation of the measured background could give the observed excess.

**Discovery:** excess above $5\sigma$

**p-value:** how much above
The *Look Elsewhere* effect

Looking for something with threshold $p$ value $p < \alpha$?
If you did not find it you will look elsewhere
(e.g. at different simulated Higgs-masses).

$n_{df}$ (degrees of freedom) *independent* tests should give
$p = 1/n$ possibly leading to false discovery.

Threshold $\alpha$ should be increased to $n_{df} \times \alpha$
(Bonferroni correction)
The probability that random fluctuation of the measured background could give the observed excess.

\( \gamma\gamma \) and ZZ: 5.0\( \sigma \)

\( \gamma\gamma \), ZZ and WW: 5.1\( \sigma \)

All together: 4.9\( \sigma \)

ATLAS got the same: \( \gamma\gamma \) and ZZ: 5.0\( \sigma \)

Adding WW increased the ATLAS excess to 6.0\( \sigma \)
Doubling 8 TeV statistics increased CMS excess to 6.9 $\sigma$

Sharp peak, close to SM exp. at 126 GeV, far less elsewhere
CMS, March 2013: mass vs. x-sec

\[ \langle M_X \rangle = 125.7 \pm 0.3\text{(stat)} \pm 0.3\text{(syst)} \]
CMS data favor $+\, \text{parity}$ for $S_X = 0$

CMS Physics Analysis Summary HIG-13-005
CMS: is it the SM Higgs boson?

Branching ratios of different decay channels as compared to SM predictions for a 126 GeV Higgs boson

\[ \frac{\sigma}{\sigma_{SM}} = 0.80 \pm 0.14 \]

CMS Physics Analysis Summary HIG-13-005

ATLAS result is similar (ATLAS-CONF-2013-034):

\[ \frac{\sigma}{\sigma_{SM}} = 1.3 \pm 0.13 \text{ (stat)} \pm 0.14 \text{ (syst)} \]
Signal strengths vs. SM expectations

CMS preliminary results

Relative signal strengths for various production and decay channels

68% confidence level contours

All agree with the SM

CMS Physics Analysis Summary HIG-13-005, 14 March 2013
Conclusion

- We very probably observed the Standard Model Higgs boson or (unfortunately, less probably) a Higgs boson of a more general model.

- The LHC will restart in 2015 with much higher energy and luminosity.

- Let us hope for some deviation from the Standard Model (although none seen yet).

Thanks for your attention!