New data on the Higgs boson by CMS

FFK-2014, Dubna, Russia, 1-5 Dec. 2014

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on behalf of the CMS Collaboration

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Outline

- Higgs boson of the Standard Model
- LHC and CMS at CERN
- Methods of the Search
- Observation at LHC
- Is it the SM Higgs?
- What else?

With the support of half the world

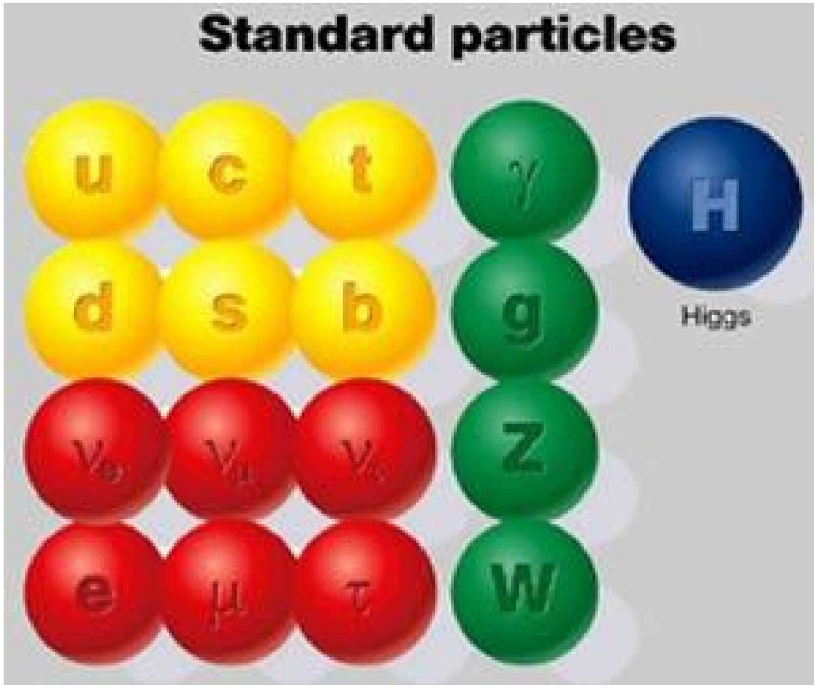
including the Hungarian OTKA Grants K-103917 and K-109703

References

- The CMS Collaboration: *Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC*, Phys. Lett. B 716 (2012) 30-61. Long version: JHEP 1306 (2013) 081
- The CMS Collaboration: *Measurement of the properties of a Higgs boson in the four-lepton final state*, Phys. Rev. D **89** (2014) 092007.
- The CMS Collaboration: *Observation of the diphoton decay of the Higgs boson and measurement of its properties*, Eur. Phys. J. C **74** (2014) 3076.
- The CMS Collaboration: *Evidence for the direct decay of the 125 GeV Higgs boson to fermions*, Nature Phys. **10** (2014) 557.
- The CMS Collaboration: *Precise determination of the mass of the Higgs boson and studies of the compatibility of its couplings with the standard model*, CMS Physics Analysis Summary, HIG-14-009, 2014.
- The CMS Collaboration: *Constraints on the spin-parity and anomalous HVV couplings of the Higgs boson in proton collisions at 7 and 8 TeV*, arXiv:1411.3441 [hep-ex], submitted to Phys. Rev. D (14 Nov. 2014)

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 ⇒ *colorless* **composite hadrons** of 2 kinds
hadrons = mesons ($q\bar{q}$) + baryons (qqq)

The Standard Model

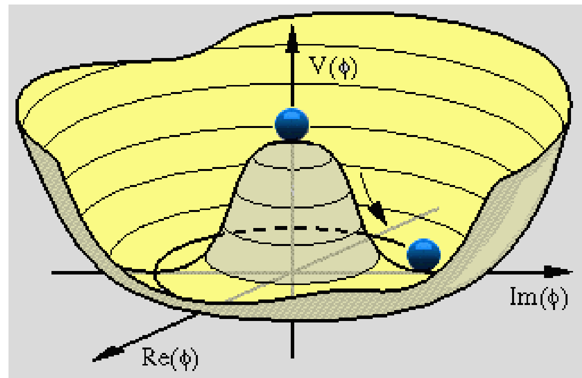
Derive 3 interactions of local $U(1)$, $SU(2)$ and $SU(3)$ symmetries

Unify and separate e-m $U(1)$ and weak $SU(2)$ interactions using spontaneous symmetry breaking:
Anderson-Brout-Englert- Higgs-Guralnik-Hagen-Kibble (BEH) mechanism, 1963-64

Add a 4-component, symmetry breaking BEH-field to vacuum.
From the ruined $U(1) \otimes SU(2)$ separate a good $U(1)$ local symmetry

⇓

electromagnetism + zero-mass photon, OK!



Turn 3 d.f. of BEH-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.

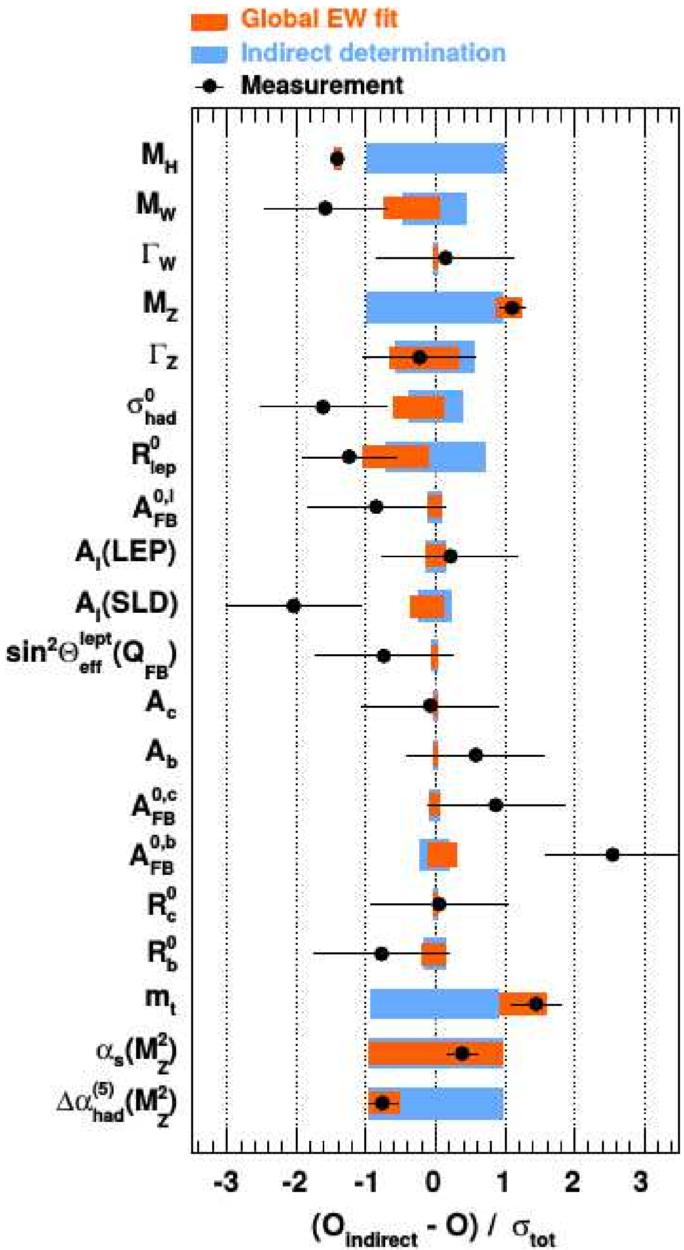
Standard Model fitting, 2014

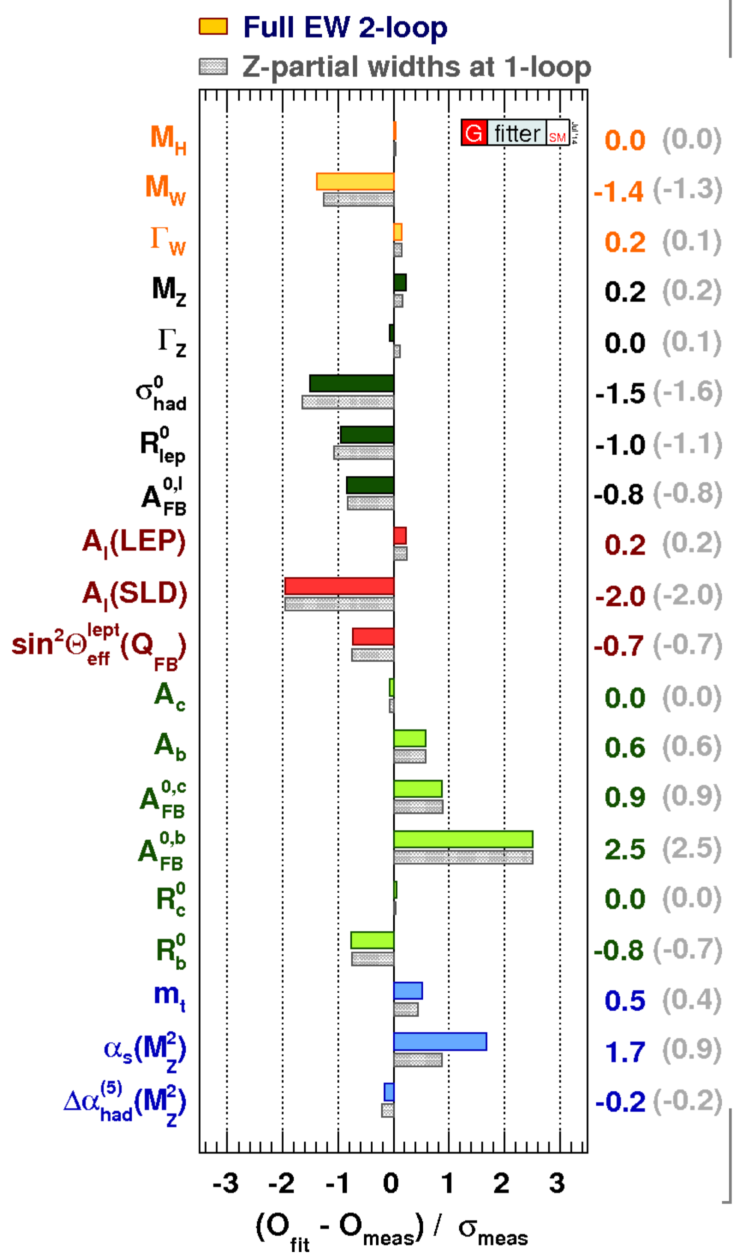
Includes hundreds of measurements of all experiments

$$\frac{|\text{Expt} - \text{theory}|}{\text{expt. uncertainty}}$$

Slightly deviating quantity: forward-backward asymmetry of $e^+e^- \to Z \to b\bar{b}$

The Gfitter Group: arxiv.org:1407.3792





The Higgs boson of the Standard Model

Spinless, neutral, heavy particle

The scalar particle needed for renormalisation

SM: it must exist!

Many jokes were of the Higgs boson before the discovery

- The Higgs boson walks into a bar. The bartender says "Watch out, there were some guys looking for you."
- I'm trying to find a good Higgs joke. It may take years, but I'm sure it exists.
- 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?" (*Mass:* Inertia, people, ceremony)
- The Higgs boson walks into a bar. The bartender does not understand...

Luminosity: collision rate

Luminosity: $L = fn\frac{N_1 N_2}{A}$

$[L] = \mathrm{s}^{-1}\mathrm{cm}^{-2}$ (∼ 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 σ at efficiency ϵ

$$R = \epsilon\sigma L$$

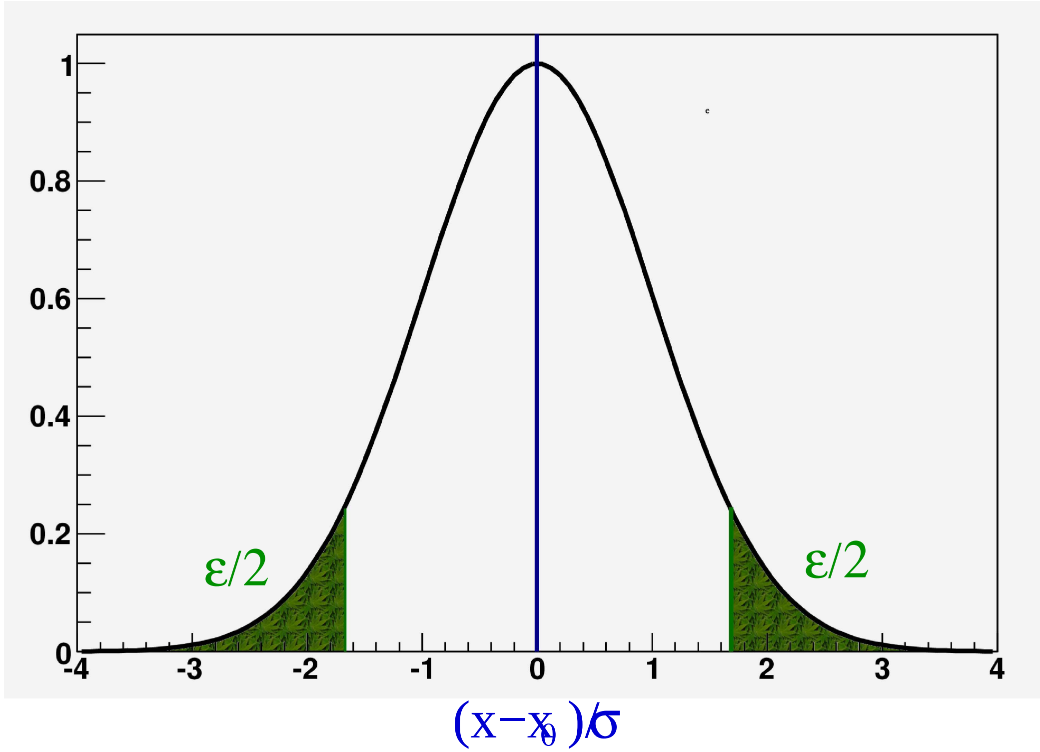
Integrated luminosity: $\int_{t_1}^{t_2} L dt$
measured in units of inverse cross-section:
$[\mathrm{pb}^{-1},\ \mathrm{fb}^{-1}]$

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
$X_{obs} - X_0 > 1.64\sigma$

And what is σ?

The total uncertainty of the physics parameters $\underline{P}$ 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 $\underline{\Theta}$) could be added up with correlations accounted for with a final uncertainty roughly: $\sigma = \sqrt{\sigma^2_{\mathrm{stat}} + \sigma^2_{\mathrm{syst}}}$

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

$$\mathcal{L}(P;x) = \mathcal{W}(x|P) = \int \mathcal{W}(x|P,\Theta)\mathcal{W}(\Theta|P)d\Theta$$

What is observed: resonance

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

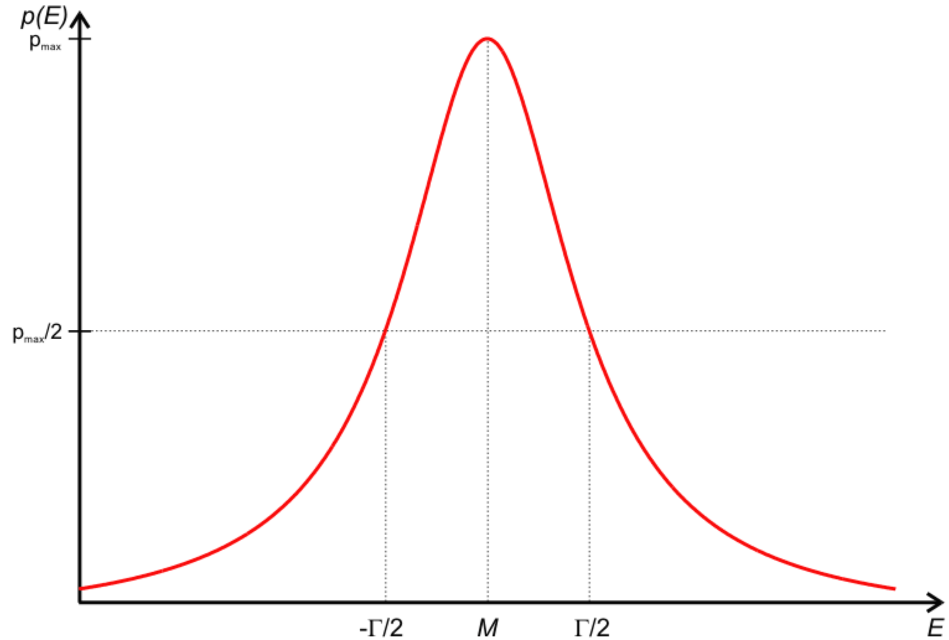
Probability distribution:

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

Breit-Wigner equation

$$\left.\begin{matrix} M \\ \Gamma \end{matrix}\right\} \text{resonance} \left\{\begin{matrix} \text{centre} \\ \text{width} \end{matrix}\right.$$

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



Lorentz curve

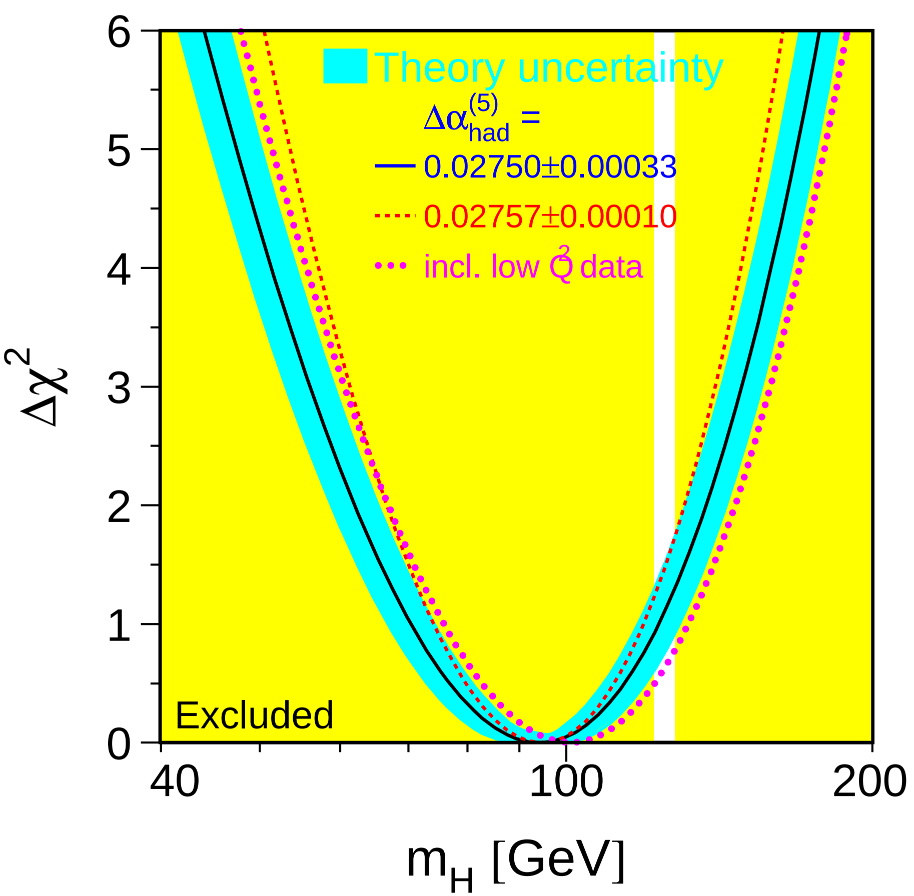
New particle discovery: resonance at decay energy corresponding to the same particle mass in all possible decay channels

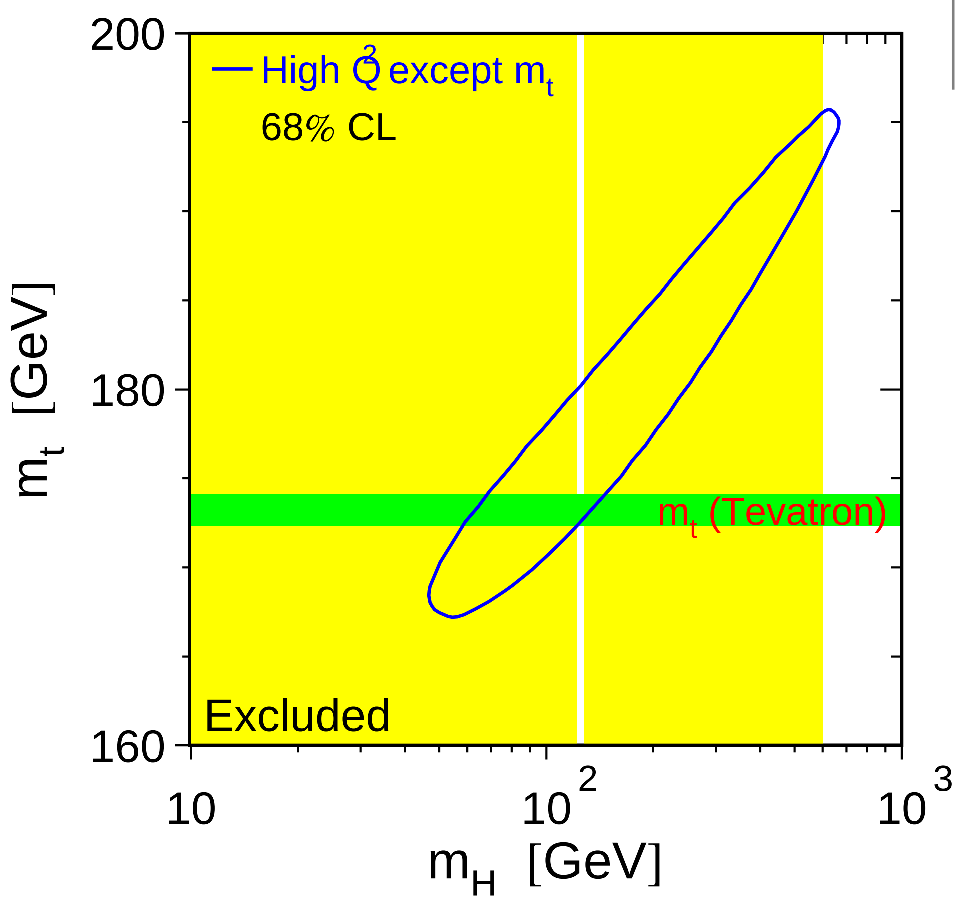
Hunting the Higgs boson

- 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 B background, enhance S signal via maximizing e.g.
  $N_S/\sqrt{N_B}$ or $N_S/\sqrt{N_S+N_B}$ or $2\cdot(\sqrt{N_S+N_B}-\sqrt{N_B})^{\dagger}$
- Calculate at experimental luminosity expected nr. of events for signal and background at various conditions.
- SM background $\sim$ experiment? (**YES** $\Downarrow$ / **NO** $\Uparrow$).

† Bityukov and Krasnikov, 1999

LEP & LHC (2011): exclusion





The LEP Collaborations: Electroweak Measurements in Electron-Positron Collisions at W-Boson-Pair Energies at LEP, Physics Reports **532** (2013) 119-244.

LHC exclusion (2011 data) included

Blind Analysis

"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."

A. Roodman: *Blind Analysis in Particle Physics,* http://arxiv.org/abs/physics/0312102, SLAC, 2003

Originally coming from medicine

Basic analysis method of searches at LEP and LHC:

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

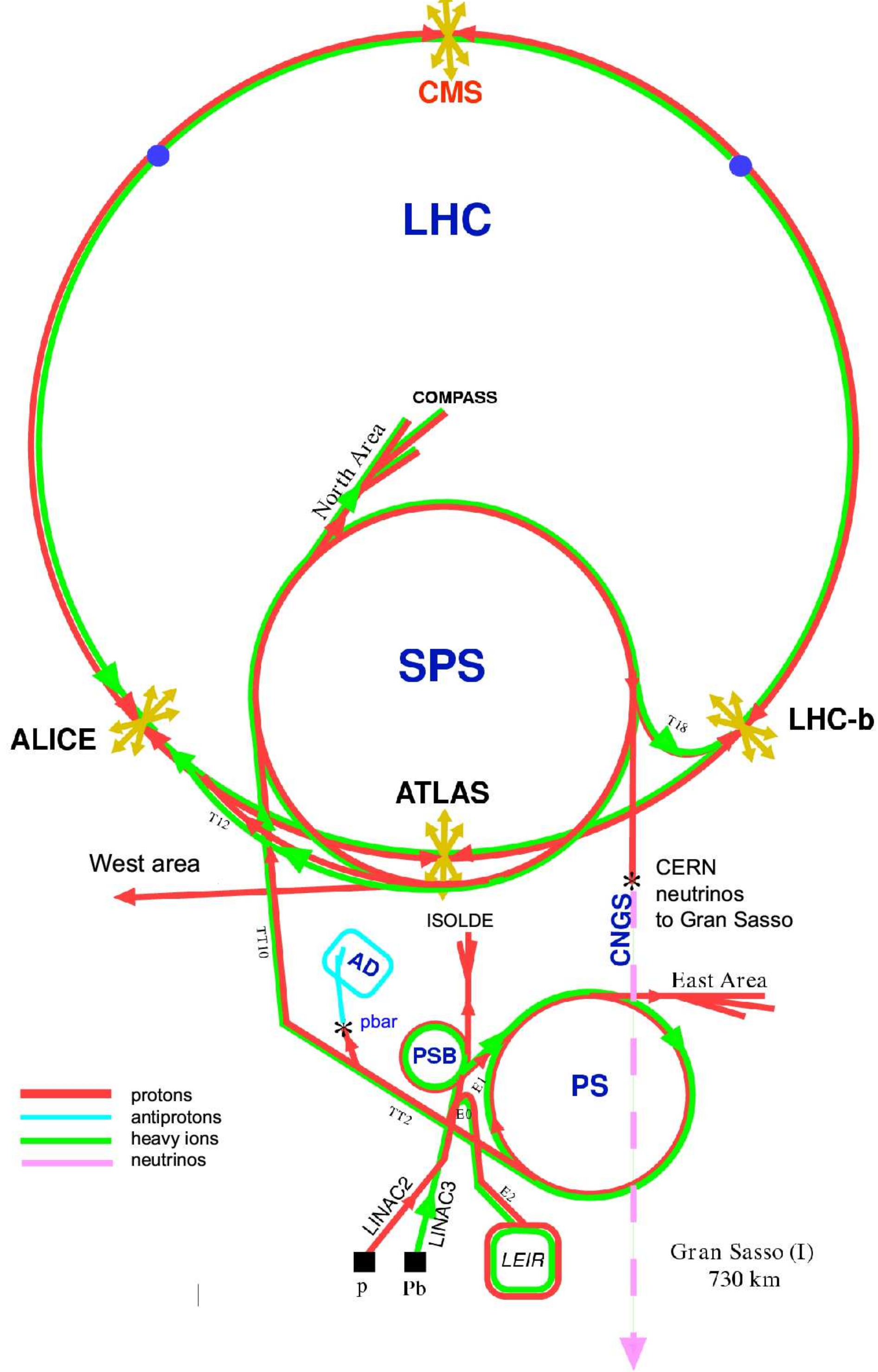
CMS, 2012: $110 < M_H < 140$ GeV blinded

because of 3σ excess observed in 2011

Simultaneous *unblinding* for all pre-approved analysis channels

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



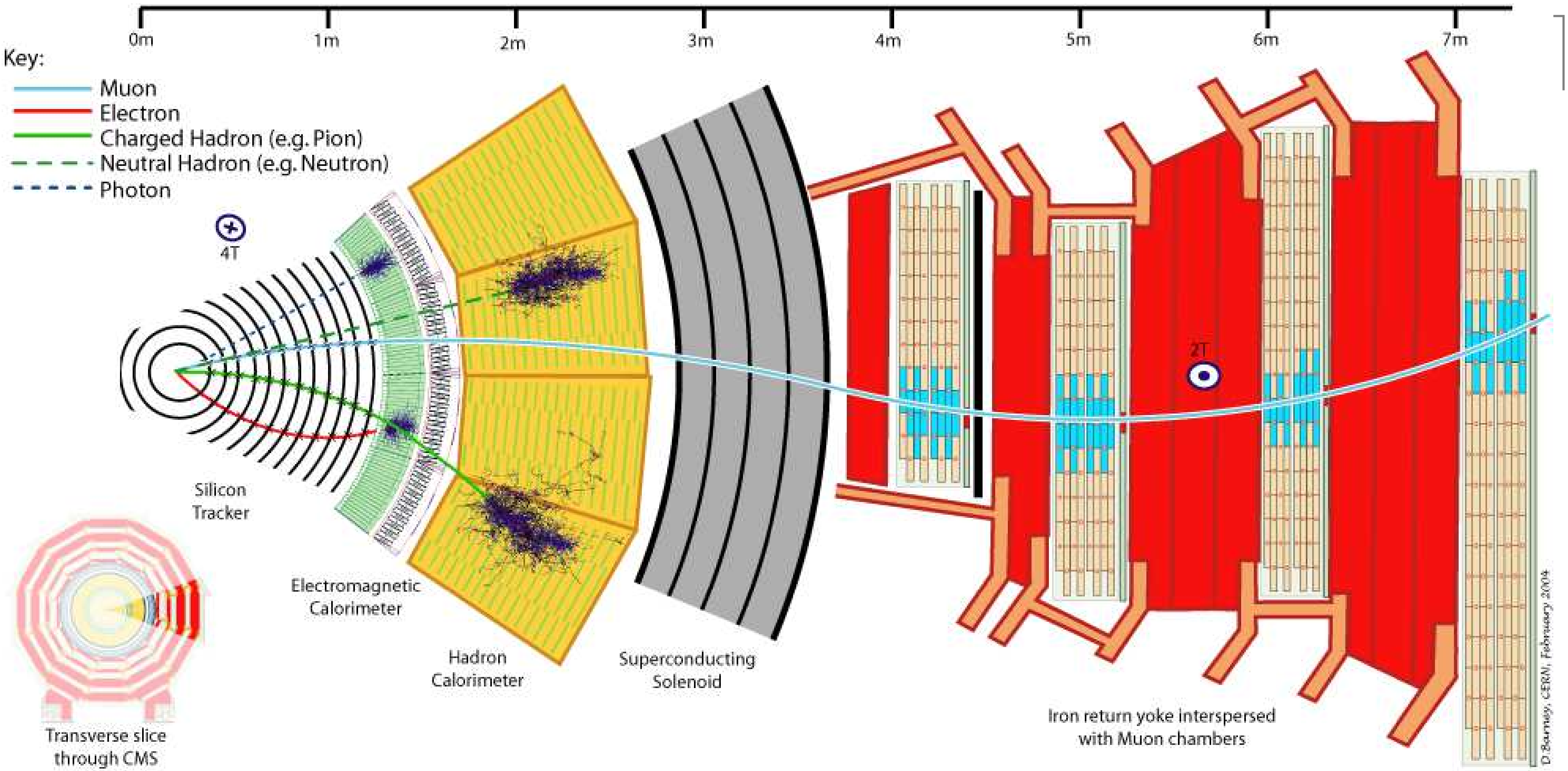
Steering magnets of LHC

1232 superconducting magnets (before installation)
($L = 15$ m, $M = 35$ t, $T = 1.9$ K, $B = 8.3$ T)

Dipole magnets of LHC in the tunnel

Higgs Search at LHC

CMS: Compact Muon Solenoid

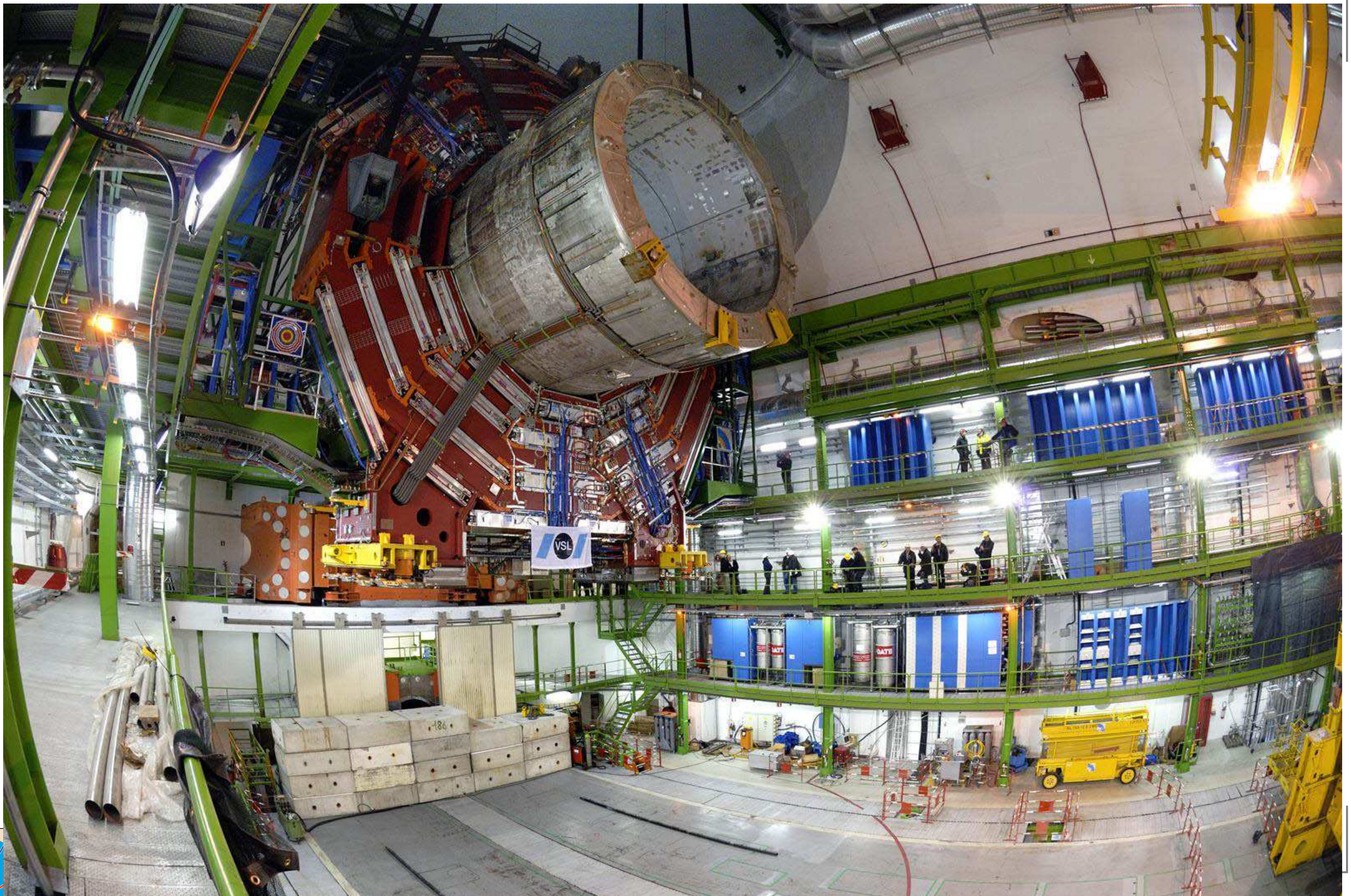


14000 ton digital camera:

100 M pixel, 20 M pictures/sec, 1000 GB/sec data

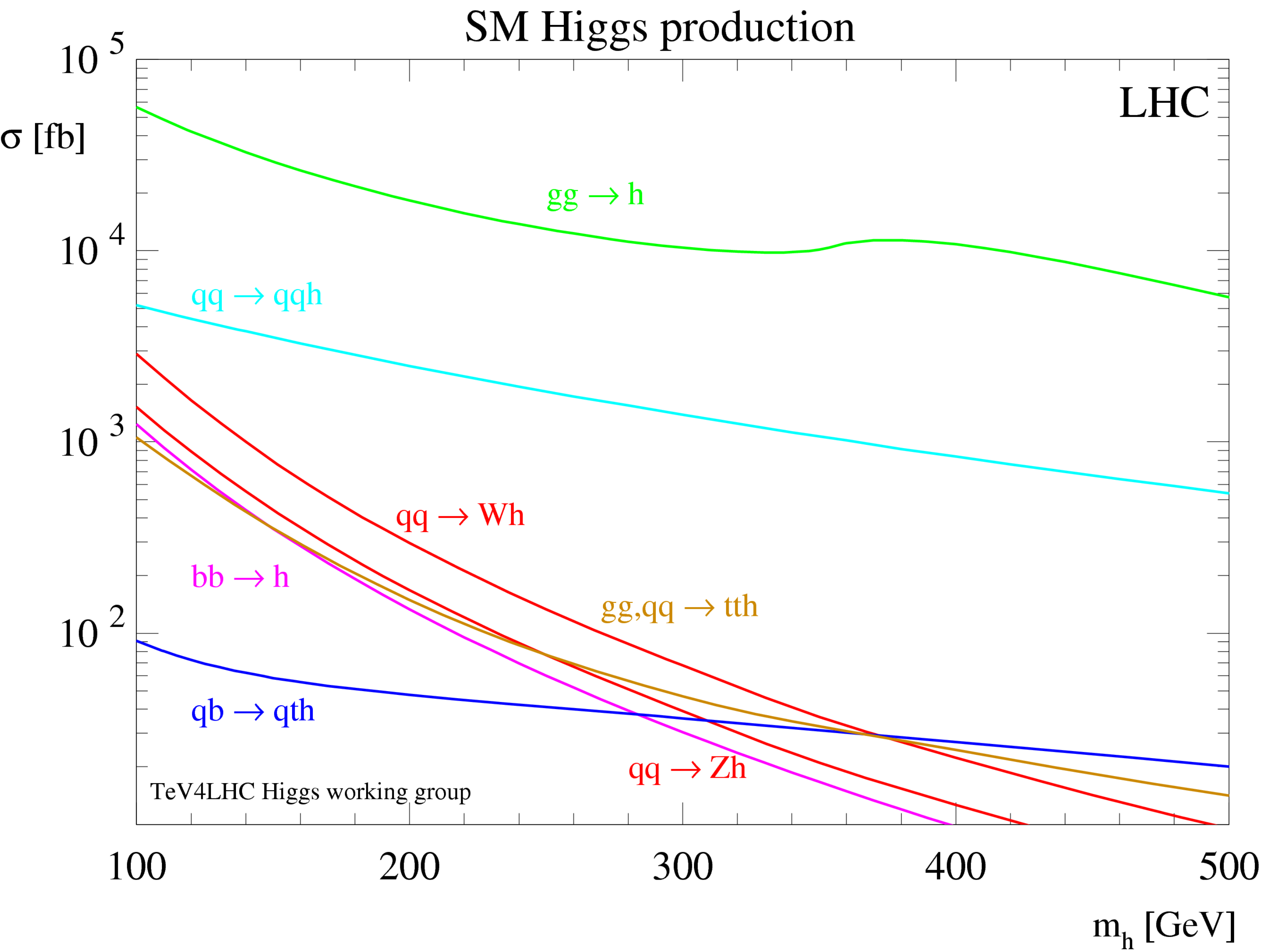
Max 1000 pictures/sec processed ⇒ intelligent filter!!

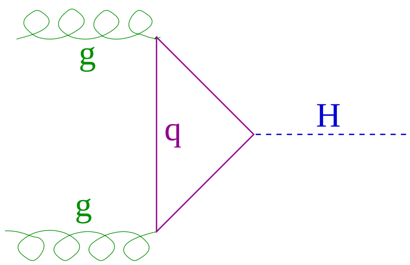
The (Compact Muon) Solenoid itself



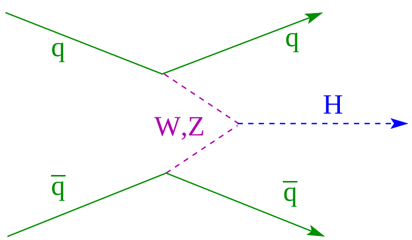
Formation of the SM Higgs boson

in p-p collisions at LHC





gluon fusion



vector boson fusion

Decay of the SM Higgs boson

March 2012

Not excluded by 2011 CMS data:

$114 < M_{\mathrm{H}} < 127$ GeV

(at 95% CL)

(where many decay processes contest)

Best identified:

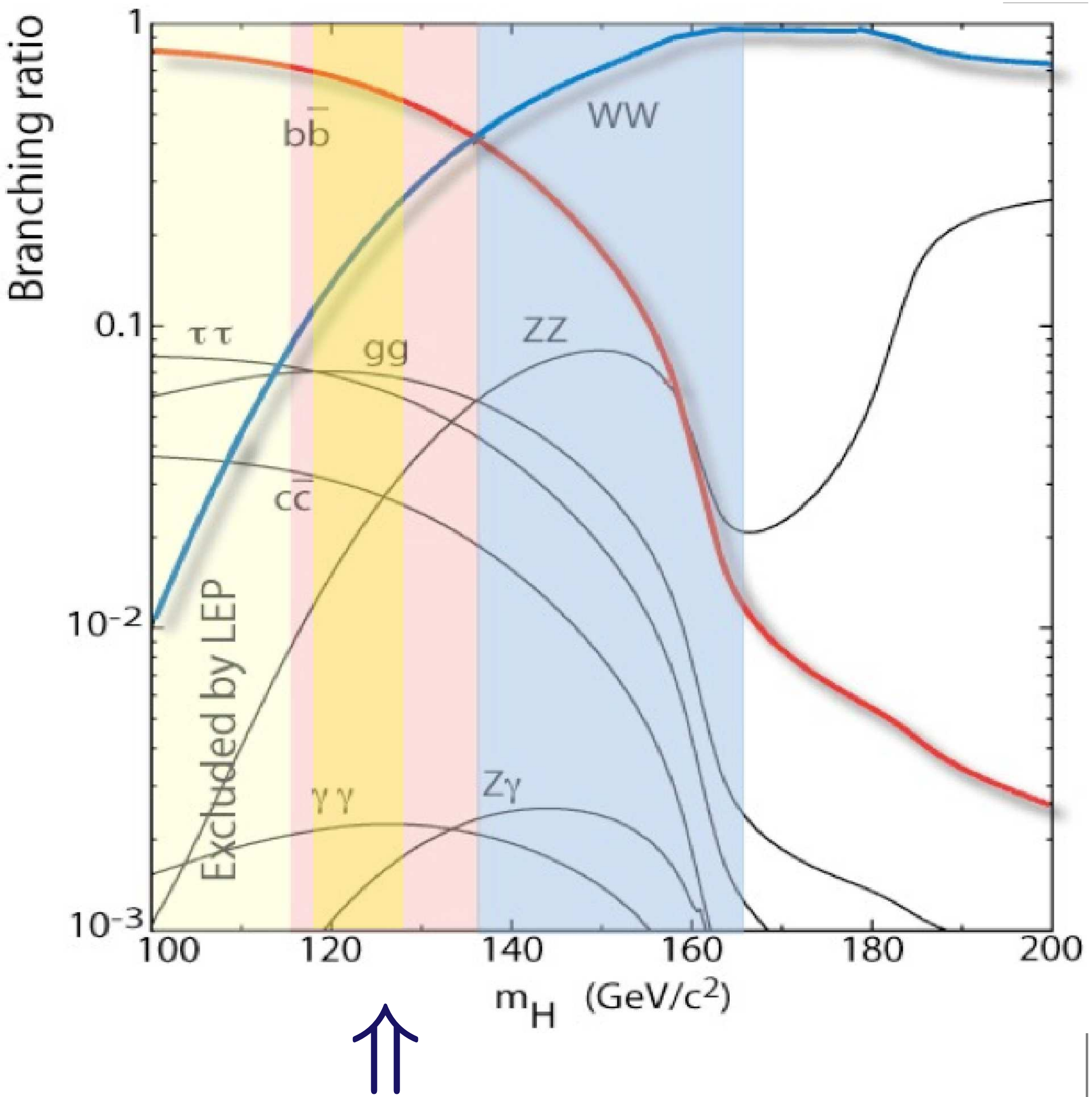
$\mathrm{H} \to \gamma\gamma$;

$\mathrm{H} \to \mathrm{ZZ}^* \to \ell^+\ell^-\ell^+\ell^-$

$(\ell^\pm = \mathrm{e}^\pm, \mu^\pm)$

Excess observed

$2 - 3\sigma$ at $\sim$125 GeV!

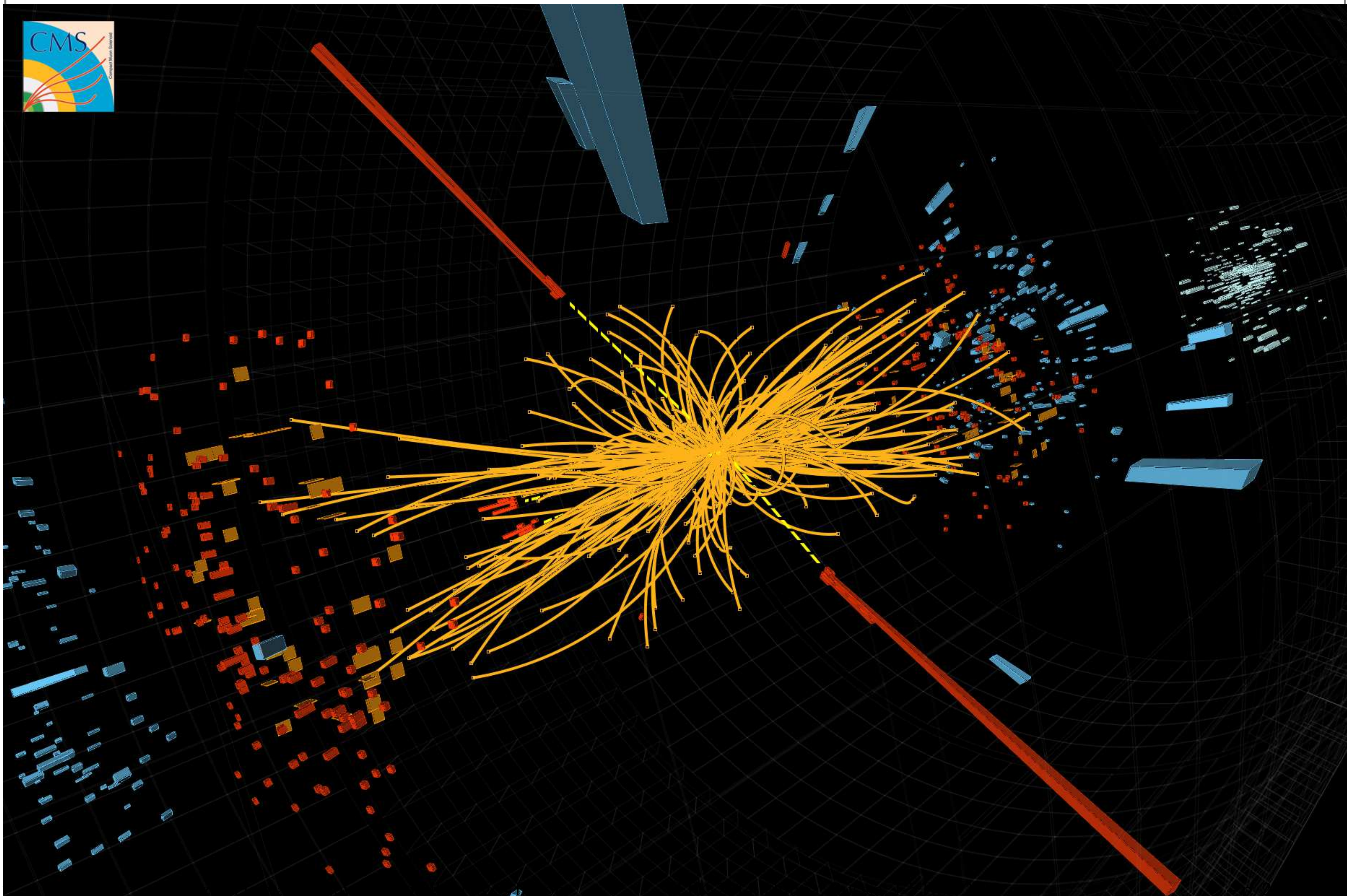


CMS: elektromagnetic calorimeter

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 $\to \gamma\gamma$ and H $\to$ ZZ $\to \ell^+\ell^-\ell^+\ell^-$, at the same invariant mass of $m \approx 126$ GeV see a new boson at a convincing statistical significance of 5σ conf. level each with properties corresponding to those of the SM Higgs boson.

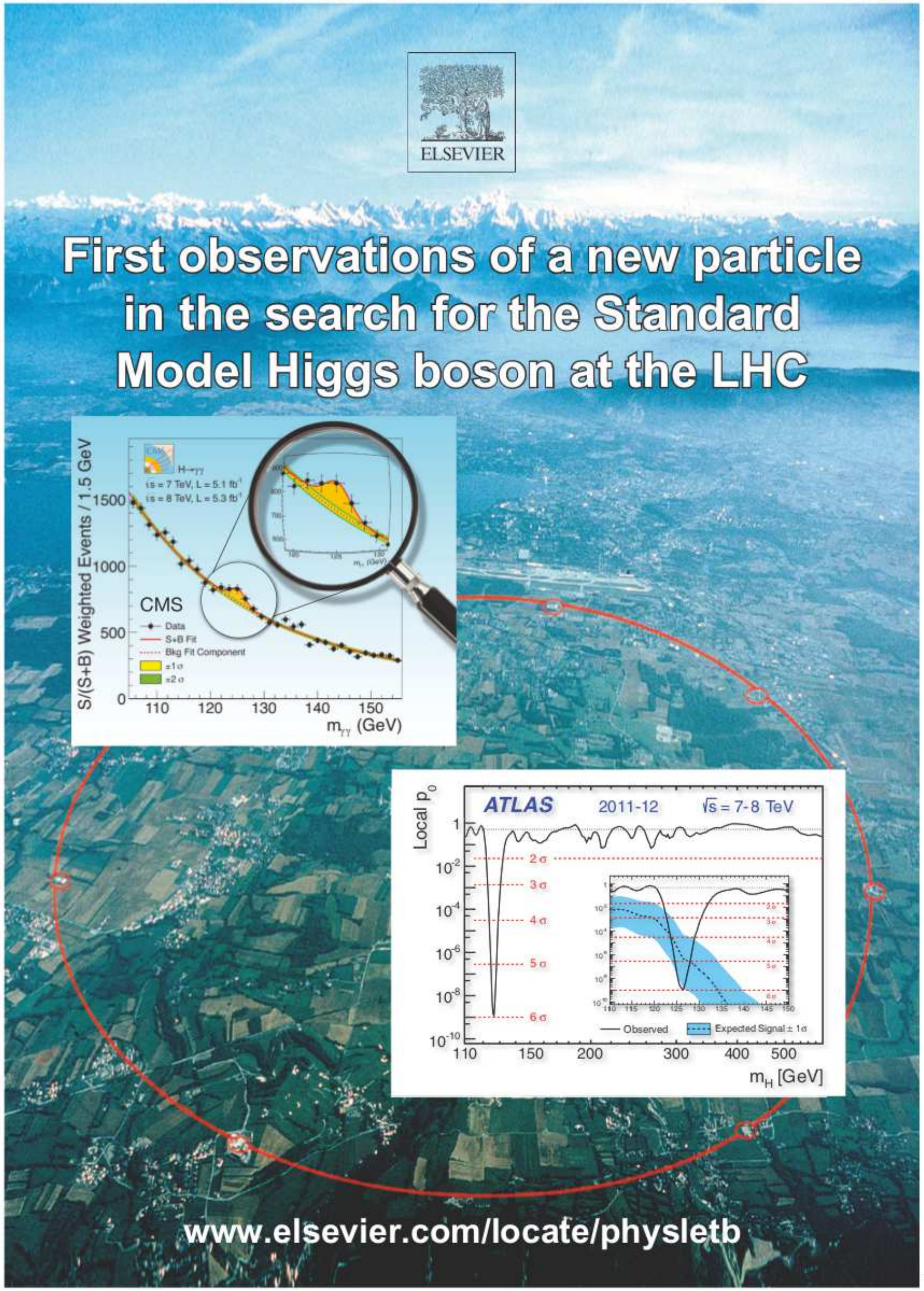
Matthew Chalmers: Nature on-line, 2 July 2012!

"Physicists Find New Particle, but is it the Higgs?"

The basic question!

François Englert and Peter Higgs

CMS and ATLAS: A new boson



Physics Letters B 716 (2012) 1–29

Contents lists available at SciVerse ScienceDirect

Physics Letters B

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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.

ATLAS: 2931 authors

ARTICLE INFO

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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 datasets used correspond to integrated luminosities of approximately 4.8 fb^{-1} collected at $\sqrt{s} = 7$ TeV in 2011 and 5.8 fb^{-1} at $\sqrt{s} = 8$ TeV in 2012. Individual searches in the channels $H \to ZZ^{(*)} \to 4\ell$, $H \to \gamma\gamma$ and $H \to WW^{(*)} \to e\nu\mu\nu$ in the 8 TeV data are combined with previously published results of searches for $H \to ZZ^{(*)}$, $WW^{(*)}$, $b\bar{b}$ and $\tau^+\tau^-$ in the 7 TeV data and results from improved analyses of the $H \to ZZ^{(*)} \to 4\ell$ and $H \to \gamma\gamma$ channels in the 7 TeV data. Clear evidence for the production of a neutral boson with a measured mass of 126.0 ± 0.4 (stat) ± 0.4 (sys) GeV is presented. 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 Higgs boson.

Physics Letters B 716 (2012) 30–61

Contents lists available at SciVerse ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

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

CMS Collaboration *

CERN, Switzerland

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 achievement of this observation.

CMS: 2899 authors

ARTICLE INFO

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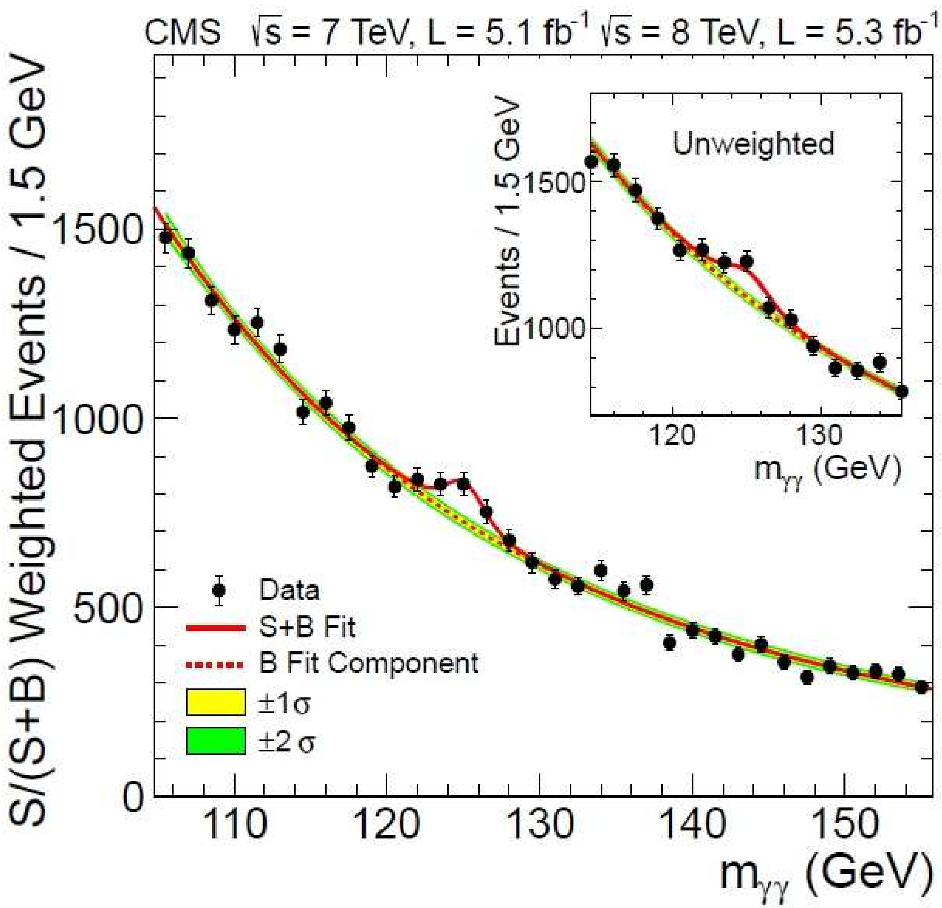
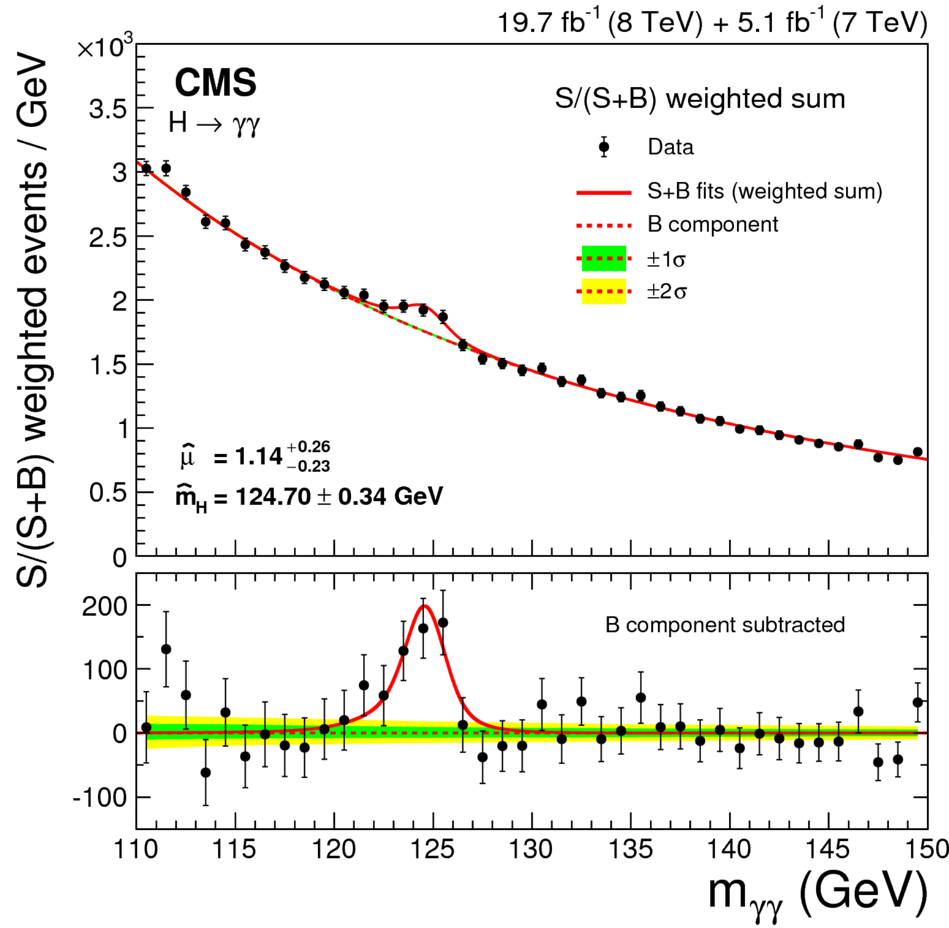
ABSTRACT

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 5.3 fb^{-1} at 8 TeV. The search is performed in five 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 $125.3 \pm 0.4(\text{stat.}) \pm 0.5(\text{syst.})$ GeV. The decay to two photons indicates that the new particle is a boson with spin different from one.

CMS: H → γγ mass distribution



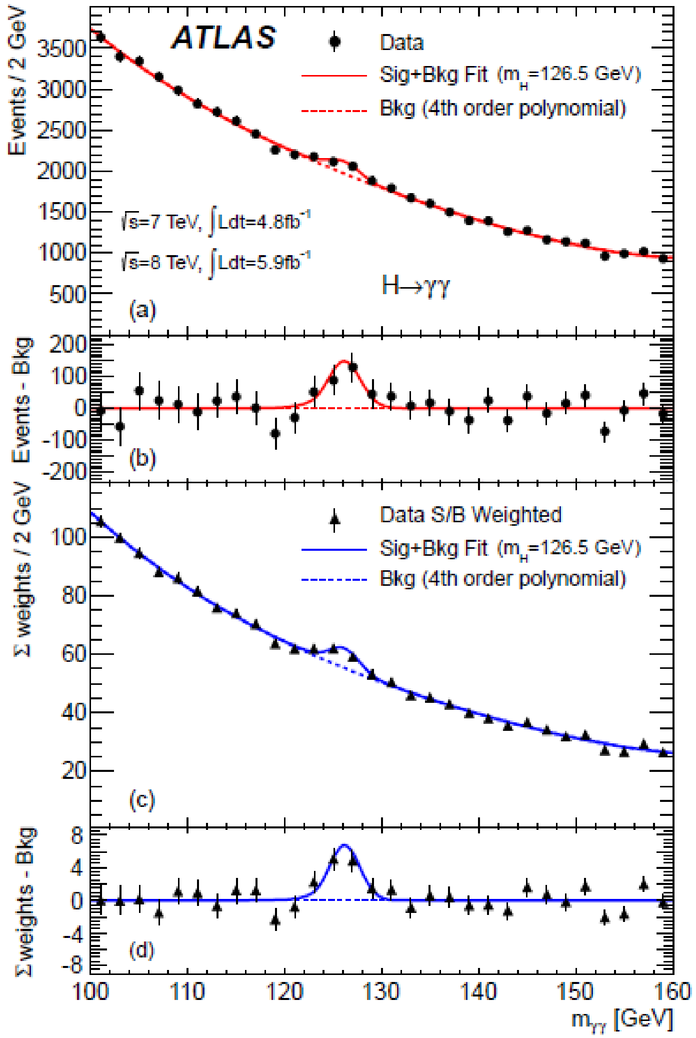


2012 (2011 + 25% of 2012 data) 2014 (2011 + all 2012 data)

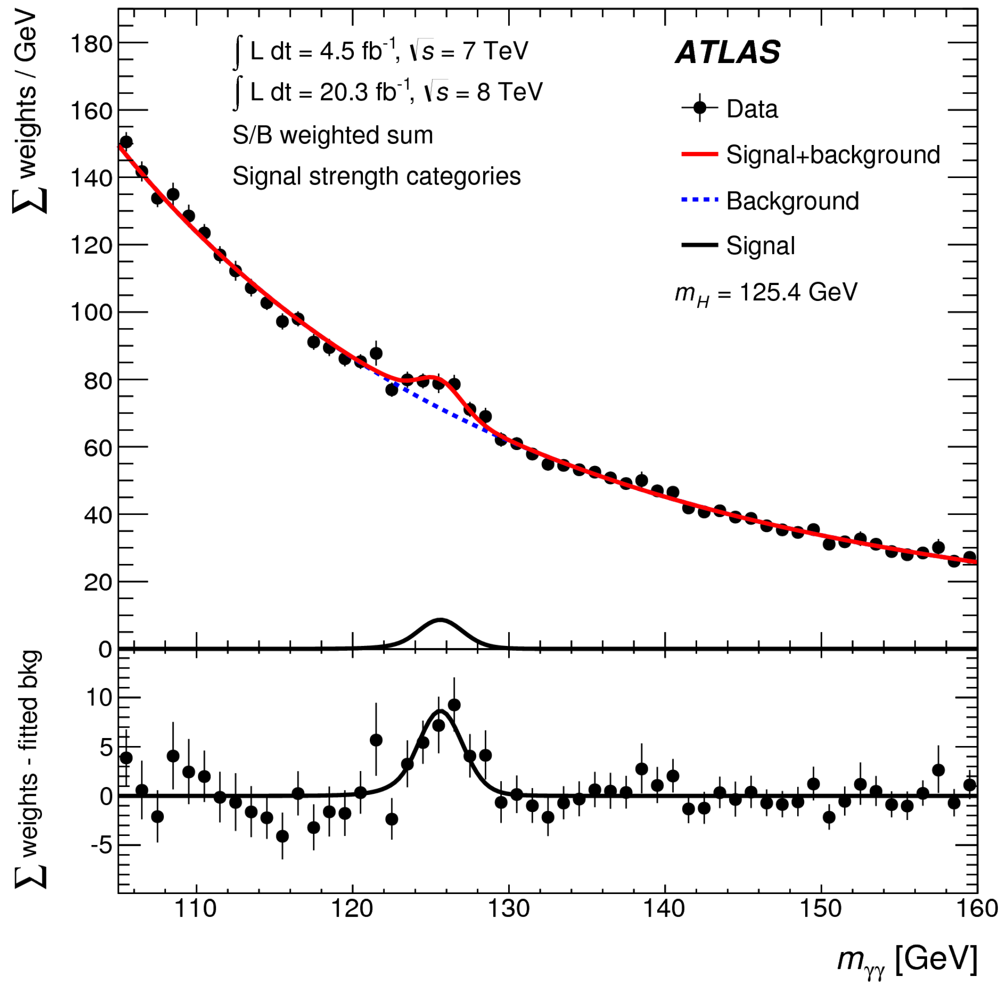
$$\sigma_{\mathrm{expt}}/\sigma_{\mathrm{SM}} = 1.14 \pm 0.21(\mathrm{stat}) {}^{+0.09}_{-0.05}(\mathrm{syst}) {}^{+0.13}_{-0.09}(\mathrm{theo})$$

CMS Collaboration, Eur. Phys. J. C (2014) 74:3076

ATLAS: H $\to \gamma\gamma$ mass distribution



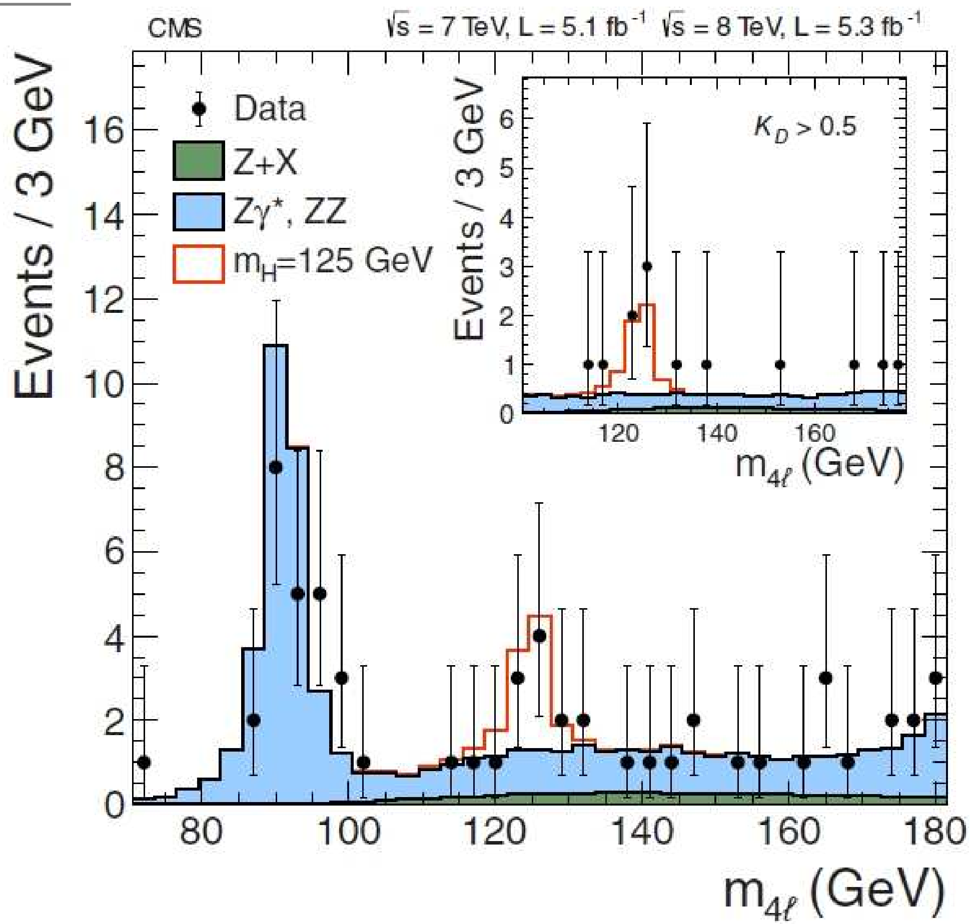
2012 (2011 + 25% of 2012 data)



2014 (2011 + all 2012 data)

ATLAS Collaboration,
arXiv.org:1408.7084, 2014

CMS: $H \to ZZ^* \to \ell^+\ell^-\ell^+\ell^-$



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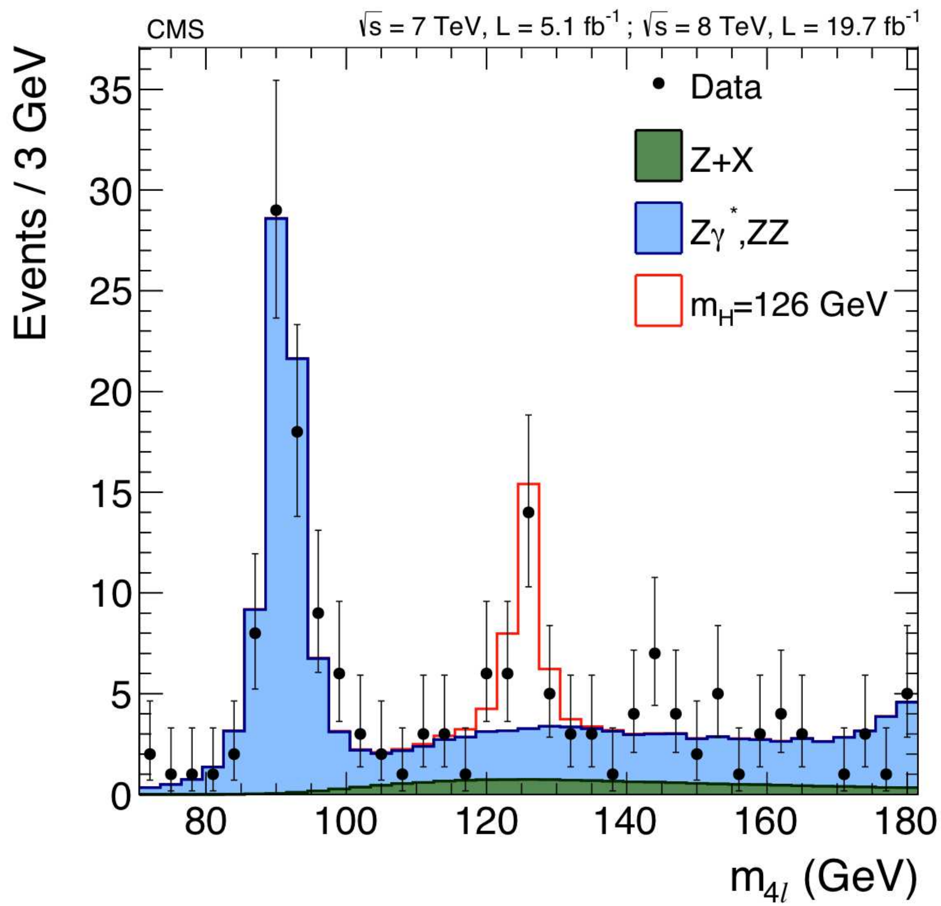


2014 (2011 + all 2012 data)

$$\sigma/\sigma_{SM} = 0.93 \left\{ \begin{matrix} +0.26 \\ -0.23 \end{matrix} \right\} (\text{stat}) \left\{ \begin{matrix} +0.13 \\ -0.09 \end{matrix} \right\} (\text{syst})$$

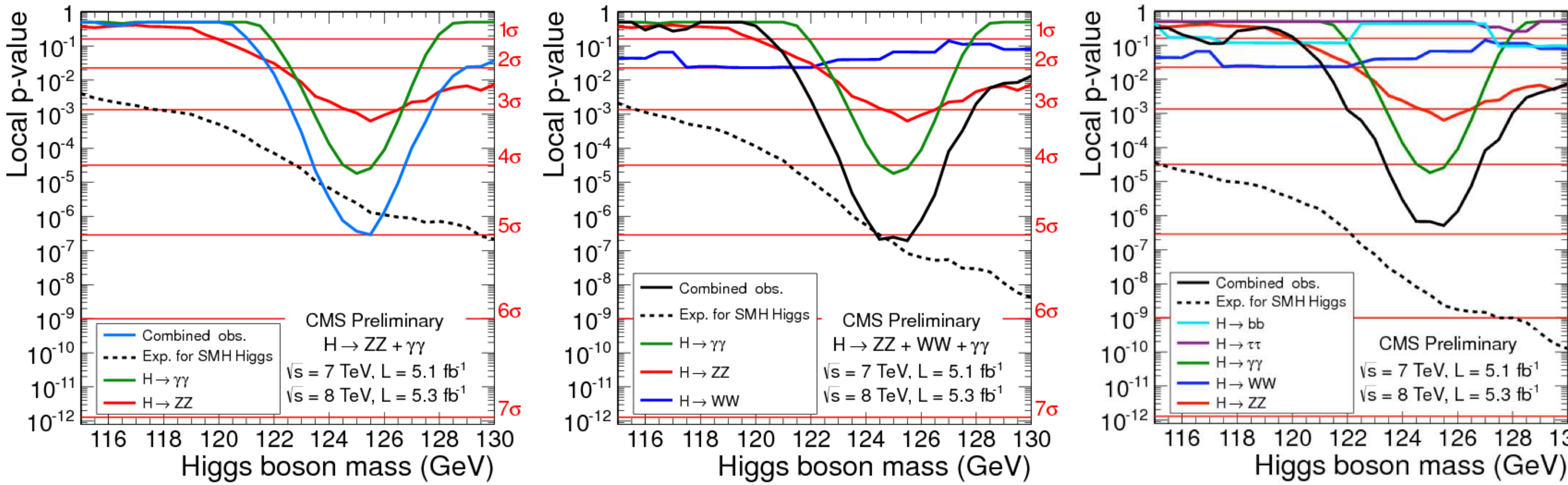
CMS Collaboration, Physical Review D 89, 092007 (2014)

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

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

CMS: $p-$distributions (4 July 2012)

The probability that random fluctuation of the measured background could give the observed excess.



$\gamma\gamma$ and ZZ: $\mathbf{5.0\sigma}$ $\gamma\gamma$, ZZ and WW: $\mathbf{5.1\sigma}$ All together: $\mathbf{4.9\sigma}$

ATLAS got the same: $\gamma\gamma$ and ZZ: $\mathbf{5.0\sigma}$

Adding WW increased the ATLAS excess to $\mathbf{6.0\sigma}$

Higgs Jokes after the Discovery

- The Higgs discovery unleashed a Big Bang of bad jokes.
- The Higgs discovery makes me feel heavier already. What we need instead is the anti-Higgs. A particle that takes mass away.
- Physicists *massively* celebrated the Higgs discovery.
- Are you there God Particle? It's me, Average Person that doesn't understand you.
- Better double check. I thought I discovered a Higgs boson under my couch last year but turned out to be an old marble.
- If we can control the Higgs field then we can really build Weapons of Mass Destruction.
- A top quark and a Higgs had a public break up on the weekend. The quark stormed off, complaining that the Higgs kept telling it how heavy it was and had nothing else to say.

We have a/the Higgs boson, what next?

All results (ATLAS & CMS, properties of various production and decay channels) for the Higgs boson agree within uncertainties.

We have found a Higgs boson, very probably that predicted by the Standard Model, and thus proved the validity of the SM. What next?

We must study its properties, especially to measure its coupling strengths to other particles as those are fundamental physical constants.

CMS, H→$\gamma\gamma$: mass and cross section

Mass (CMS, $\gamma\gamma$):

$$m_{\gamma\gamma} = 124.70 \pm 0.31(\text{stat}) \pm 0.15(\text{syst})\text{GeV}$$
$$= 124.70 \pm 0.34 \text{ GeV}$$

Signal strength as compared with SM prediction:

$$\sigma_{\text{expt}}/\sigma_{\text{SM}} =$$
$$1.14 \pm 0.21(\text{stat}) \left\{ \begin{matrix} +0.09 \\ -0.05 \end{matrix} \right\} (\text{syst}) \left\{ \begin{matrix} +0.13 \\ -0.09 \end{matrix} \right\} (\text{theo})$$
$$= 1.14 \left\{ \begin{matrix} +0.26 \\ -0.23 \end{matrix} \right\}$$

CMS Collaboration, Eur. Phys. J. C (2014) 74:3076

CMS, H→ZZ: mass and cross section

$$\mathrm{H}\to\mathrm{ZZ}\to\ell^+\ell^-\ell^+\ell^- \quad (\ell = \mathrm{e},\ \mu)$$

$$m_{4\mathrm{e}} = 126.2 \left\{ \begin{matrix} +1.5 \\ -1.8 \end{matrix} \right\} \quad m_{2\mathrm{e}2\mu} = 126.3 \left\{ \begin{matrix} +0.9 \\ -0.7 \end{matrix} \right\}$$

$$m_{4\mu} = 125.1 \left\{ \begin{matrix} +0.6 \\ -0.9 \end{matrix} \right\}.$$

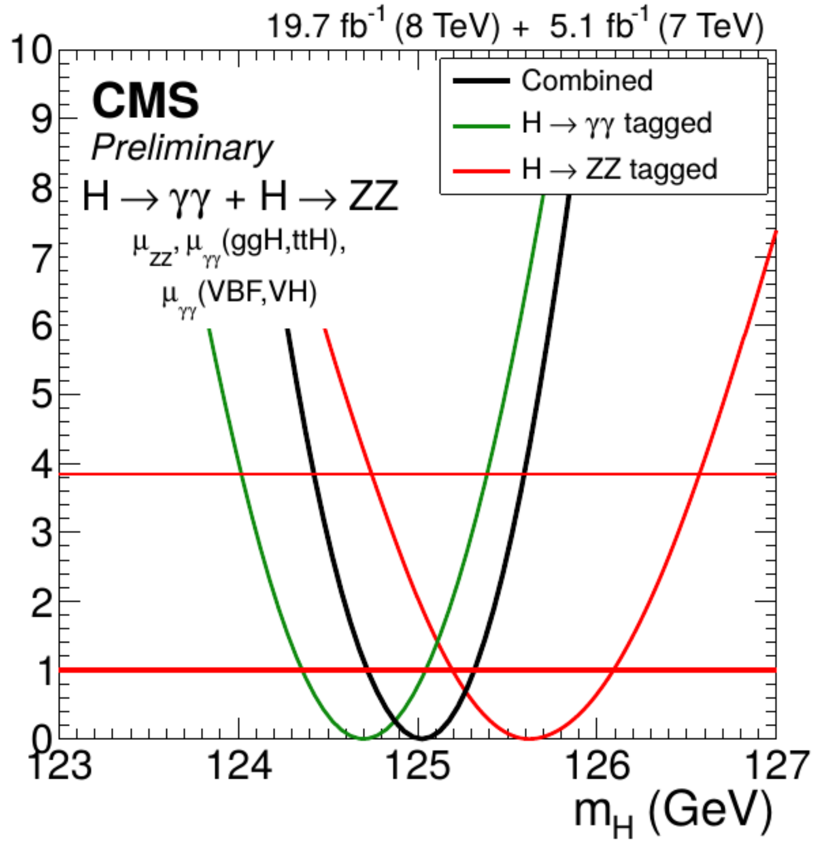
Mass average: $m_{\mathrm{ZZ}} = 125.6 \pm 0.4(\mathrm{stat}) \pm 0.2(\mathrm{syst})$ GeV

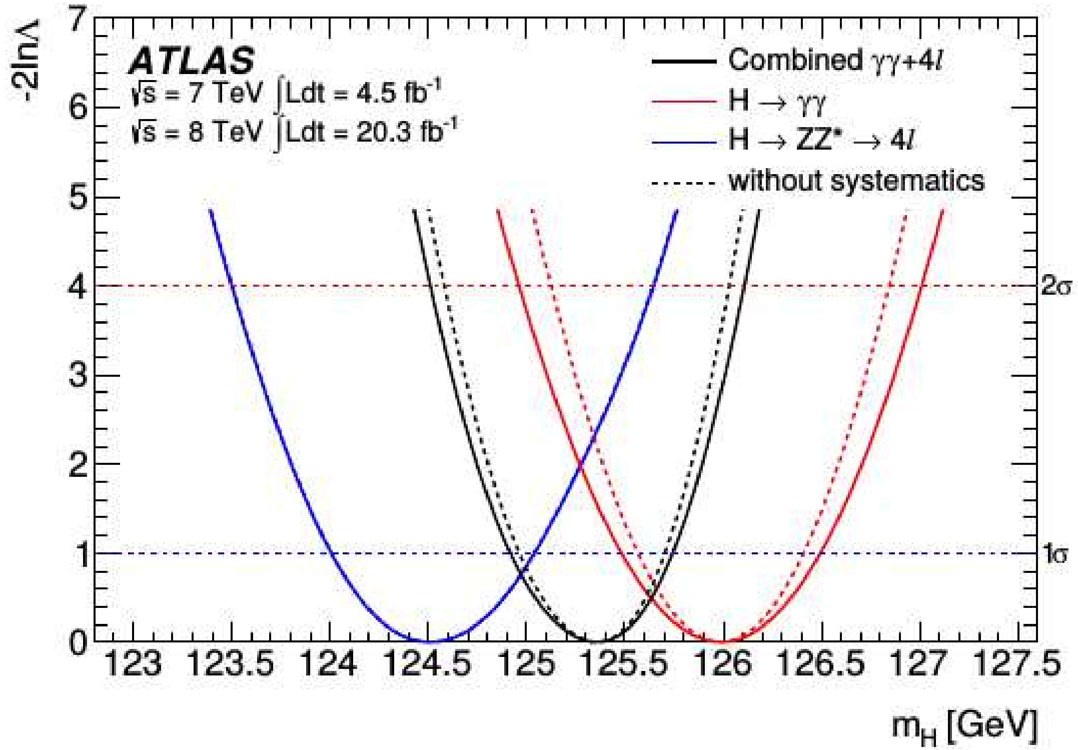
Signal strength as compared with SM prediction:

$$\sigma/\sigma_{\mathrm{SM}} = 0.93 \left\{ \begin{matrix} +0.26 \\ -0.23 \end{matrix} \right\} (\mathrm{stat}) \quad \left\{ \begin{matrix} +0.13 \\ -0.09 \end{matrix} \right\} (\mathrm{syst})$$

CMS Collaboration, Physical Review D 89, 092007 (2014)

CMS vs. ATLAS: masses





CMS, 2014: mass and cross section

Combination of all channels:

$H \to \gamma\gamma$, $H \to ZZ \to \ell^+\ell^-\ell^+\ell^-$, $H \to WW \to \ell\nu\ell\nu$, $H \to \tau\tau$,
WH, ZH; $H \to \bar{b}b$, $\bar{t}tH$, H→hadrons, leptons.

(CMS Physics Analysis Summary HIG-14-009, 2014)

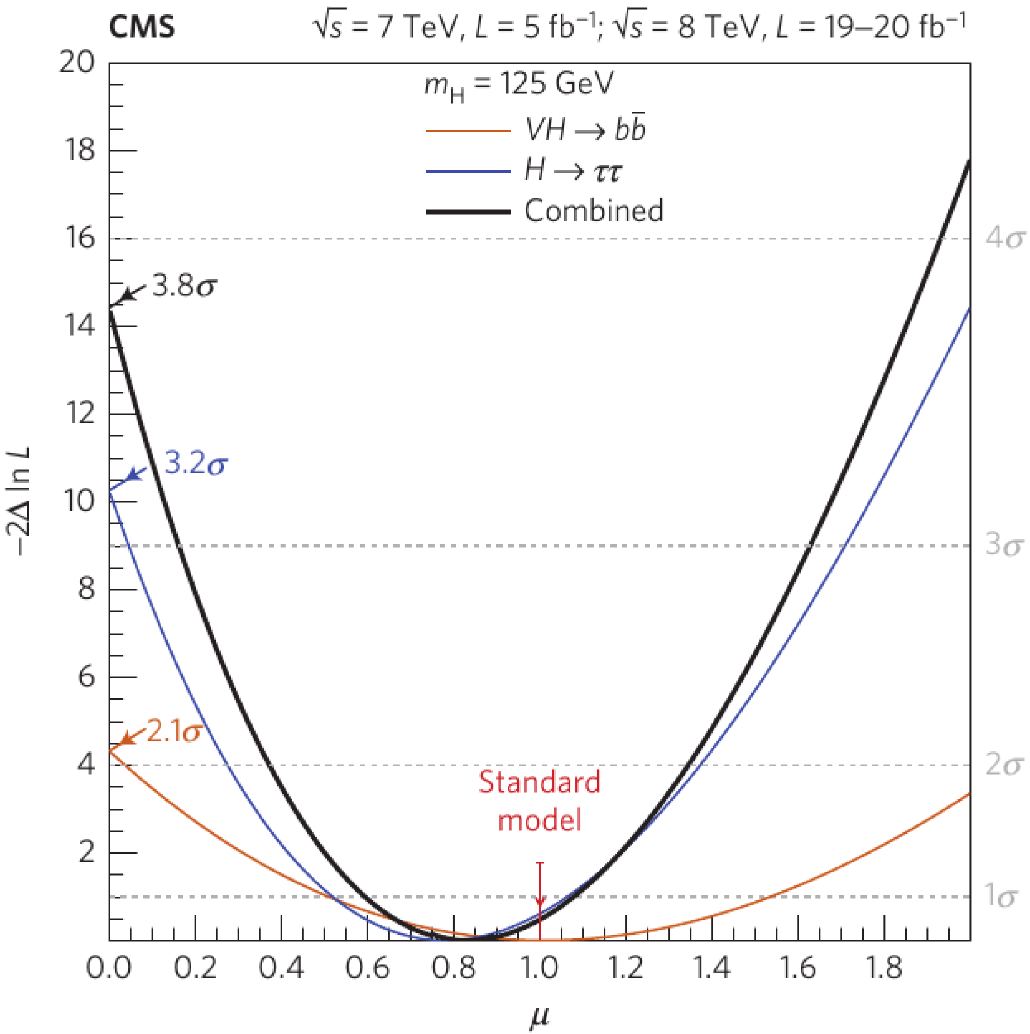
Measured mass:

$$m_H = 125.03 \left\{ \begin{array}{c} +0.26 \\ -0.27 \end{array} \right\} (\mathrm{stat}) \left\{ \begin{array}{c} +0.13 \\ -0.15 \end{array} \right\} (\mathrm{syst})\ \mathrm{GeV}$$

Signal strength as compared to SM prediction at the measured mass:

$$\sigma/\sigma_{SM} = 1.00\ \pm 0.09(\mathrm{stat})\ \pm 0.07(\mathrm{syst}) \left\{ \begin{array}{c} +0.08 \\ -0.07 \end{array} \right\} (\mathrm{theo})$$

CMS, Dec. 2012: coupling to fermions?



Channel (m_H = 125 GeV)	Significance (σ) Expected	Significance (σ) Observed	Best-fit μ
$VH \to b\bar{b}$	2.3	2.1	1.0 ± 0.5
$H \to \tau\tau$	3.7	3.2	0.78 ± 0.27
Combined	4.4	3.8	0.83 ± 0.24

The CMS Collaboration: *Evidence for the direct decay of the 125 GeV Higgs boson to fermions*, Nature Phys. **10** (2014) 557.

CMS, Nov 2014: spin, parity

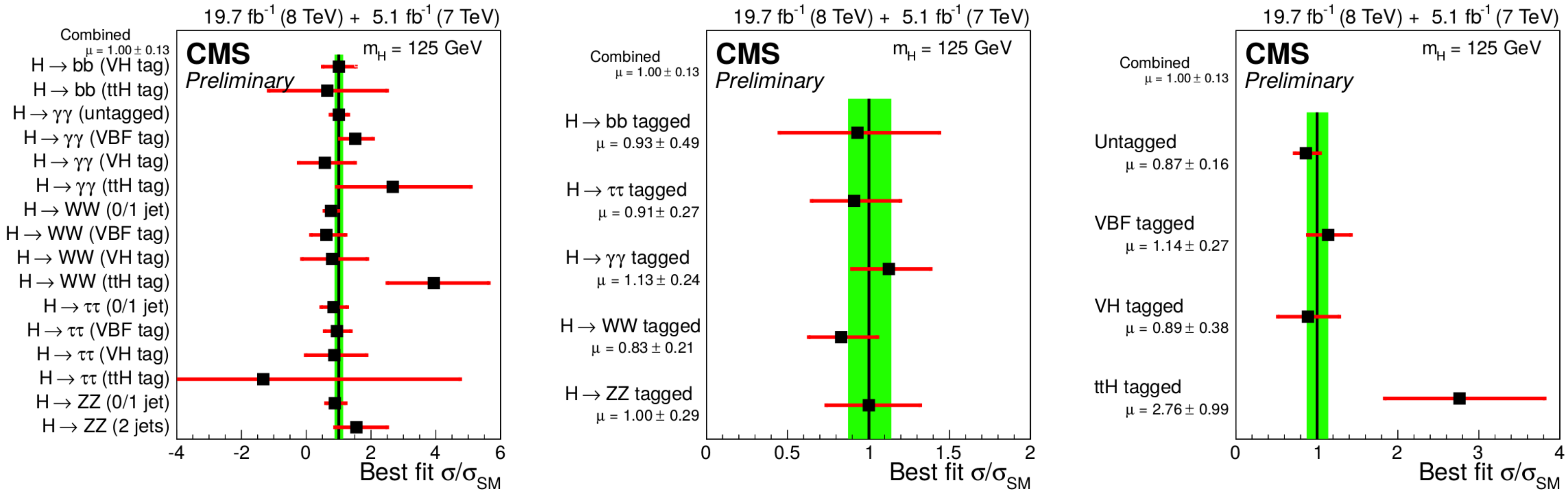
CMS data ($\gamma\gamma$, ZZ and WW modes collected in 2011 and 2012) favour $J^{PC} = 0^{++}$ parity for the 125 GeV Higgs boson assuming the conservation of C- and CP-parity for its interactions.

- $S = 1$ mixed parity states excluded to 99.999% CL
- $S = 2$ excluded to 99% CL
- $P = +$:
  - H $\to$ ZZ, Zγ^*, $\gamma^*\gamma^* \to 4\ell$
  - H $\to$ WW $\to \ell\nu\ell\nu$
- $C = +$: H $\to \gamma\gamma$.

Everything points toward a scalar, SM-like Higgs boson.

The CMS Collaboration: *Constraints on the spin-parity and anomalous HVV couplings of the Higgs boson in proton collisions at 7 and 8 TeV*, arXiv:1411.3441 [hep-ex], submitted to Phys. Rev. D (14 Nov. 2014)

CMS: is it the SM Higgs boson?



Branching ratios of different decay channels
as compared to SM predictions for a 125.03 GeV Higgs boson

CMS Physics Analysis Summary HIG-14-009, 3 July 2014

Signal strengths vs. SM expectations

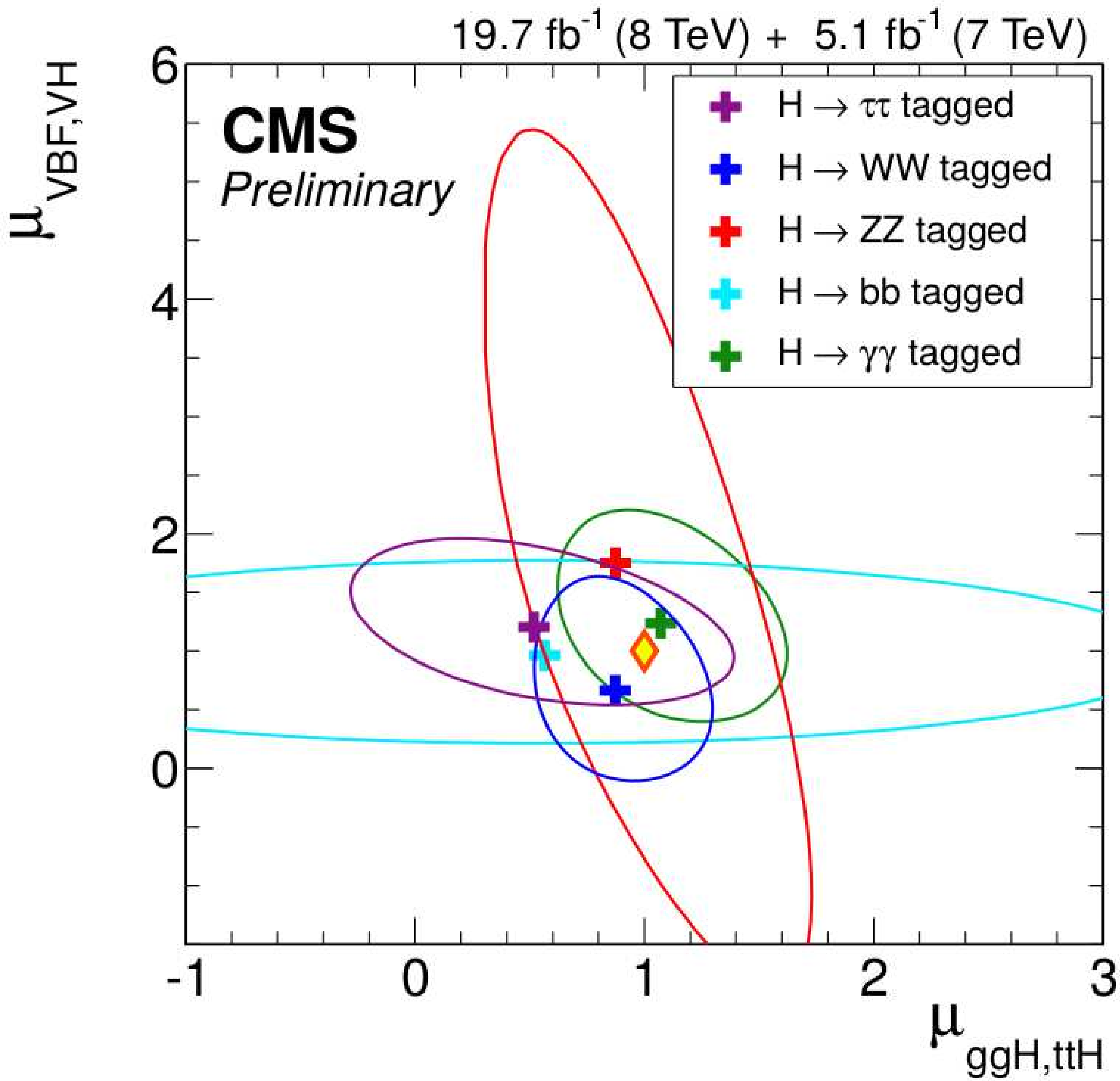
CMS preliminary results

Relative signal strengths for various production and decay channels

68% confidence level contours

All agree with the SM

CMS Physics Analysis Summary HIG-14-009, 3 July 2014



CMS vs. ATLAS: mass

(determined consistently, in various ways)

Mass averaged for both channels and all decay modes

CMS, 2013: $\mathbf{125.7 \pm 0.3(stat) \pm 0.3(syst)}$ GeV/c^2

CMS, 2014: $\mathbf{125.03 \pm \left\{ \begin{array}{c} +0.26 \\ -0.27 \end{array} \right\} (stat) \pm \left\{ \begin{array}{c} +0.13 \\ -0.15 \end{array} \right\} (syst)}$ GeV/c^2

ATLAS, 2013: $\mathbf{125.5 \pm 0.2(stat) \pm \left\{ \begin{array}{c} +0.5 \\ -0.6 \end{array} \right\} (syst)}$ GeV/c^2

ATLAS, 2014: $\mathbf{125.36 \pm 0.37(stat) \pm 0.18(syst)}$
$\mathbf{= 125.36 \pm 0.41}$ GeV/c^2

High gain in systematics with some loss of statistics.

CMS vs. ATLAS: signal strength

Total cross section for all production and decay channels as compared to the SM prediction for $M_H = 125$ GeV ($\mu = \sigma_{\rm obs}/\sigma_{\rm SM}$):

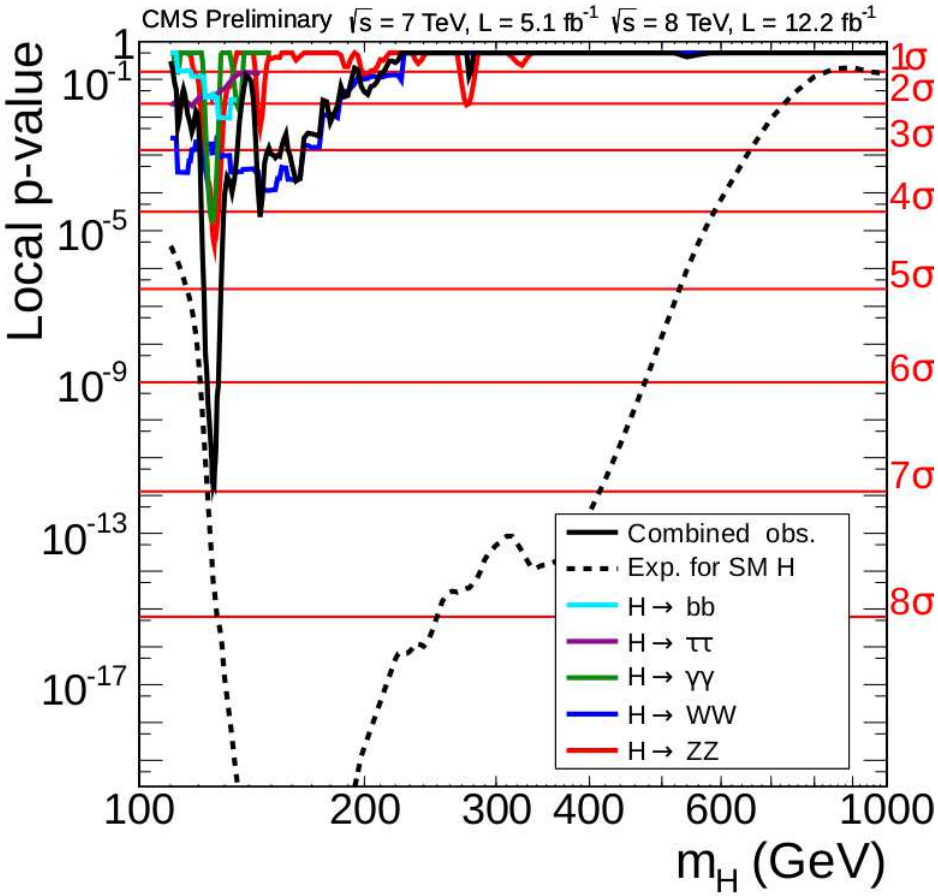
CMS, 2013: $\mathbf{0.80 \pm 0.14}$

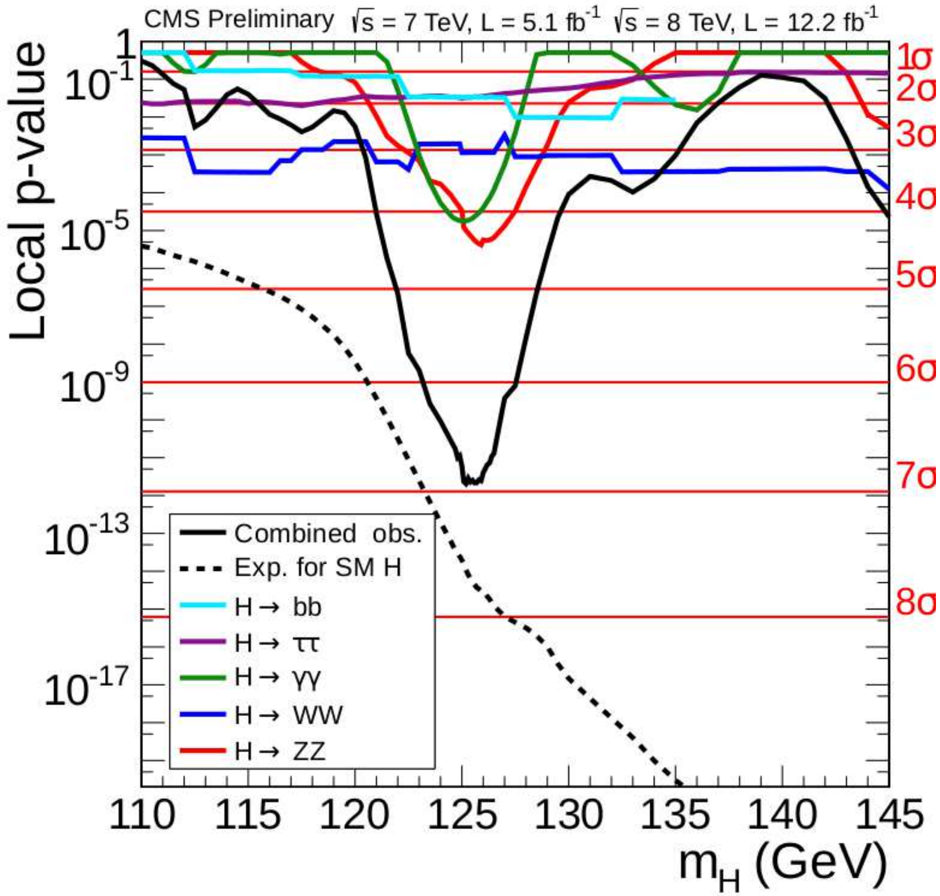
CMS, 2014: $\mathbf{1.00 \pm 0.09(stat) \pm 0.07(syst) \pm \left\{ \begin{array}{c} +0.08 \\ -0.07 \end{array} \right\} (theo)}$

ATLAS, 2013: $\mathbf{1.43 \pm 0.16(stat) \pm 0.14(syst)}$

All agree with the Standard Model (unfortunately)

CMS, Dec. 2012: other Higgs bosons?





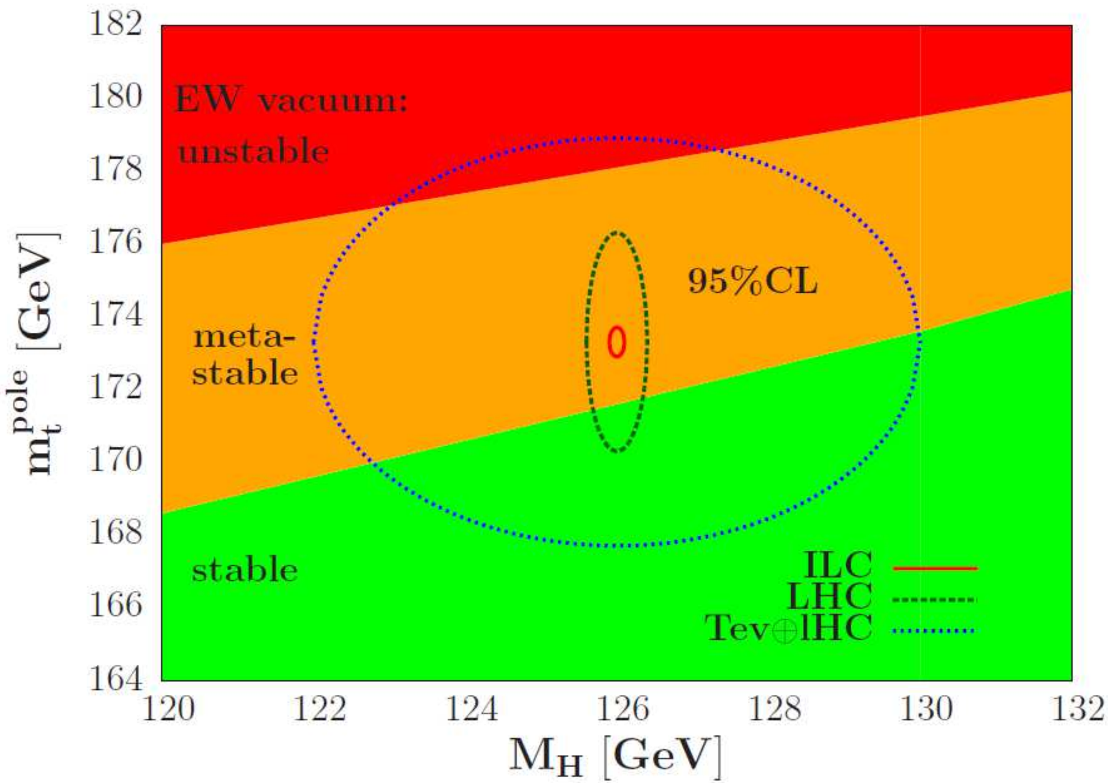
Doubling 8 TeV statistics increased CMS excess to 6.9 σ

Sharp peak, close to SM exp. at 125 GeV, far less elsewhere

What does $M_\mathrm{H} = 125$ GeV mean?

Conference *Why $M_H = 126$ GeV?*, Madrid, 25-27 Sep. 2013

- *M_H vs. M_top is critical, at vacuum stability border*
- Need very precise M_H, M_top and α_s.
- SM may be valid until Planck energy (10^{18} GeV)!
- New physics anywhere??



S. Alekhin et al., arXiv:1207.0980, 2012

OR:

- *Somebody is pulling our leg???*
- *Anthropic principle???*

Conclusion

- We very probably observed the Standard Model Higgs boson or (unfortunately, much less probably) a Higgs boson of a more general model.
- All measured properties are consistent with the predictions for the SM Higgs-boson.
- LHC will restart in 2015 at much higher energy and luminosity.
- Let us hope for some deviation from the Standard Model (although none seen yet).

Thanks for your attention!

Spare slides for questions

Hypothesis Testing: Test Statistic

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

Usually analysed and plotted:

$$-2\ln Q(m_H) =$$

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

- n_k: events observed in channel k, $k = 1 \dots N_{\rm ch}$
- $s_k(m_H)$ 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.