

# Higgs@PDG

## STATUS OF HIGGS BOSON PHYSICS

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# HEP with a Higgs boson

*“If you don't have the ball, you cannot score”*

Now the PDG has the ball



In ~~football~~ as in watchmaking, talent and elegance mean nothing without rigor and precision.  
Higgs Physics

$H^0$

$J = 0$

In the following  $H^0$  refers to the signal that has been discovered in the Higgs searches. Whereas the observed signal is labeled as a spin 0 particle and is called a Higgs Boson, the detailed properties of  $H^0$  and its role in the context of electroweak symmetry breaking need to be further clarified. These issues are addressed by the measurements listed below.

Concerning mass limits and cross section limits that have been obtained in the searches for neutral and charged Higgs bosons, see the sections “Searches for Neutral Higgs Bosons” and “Searches for Charged Higgs Bosons ( $H^\pm$  and  $H^{\pm\pm}$ )”, respectively.

## $H^0$ MASS

A combination of the results from ATLAS and CMS, where a recent unpublished result from CMS is used, yields an average value of  $125.6 \pm 0.3$  GeV, see the review on “Status of Higgs Boson Physics.”

<u>VALUE (GeV)</u>	<u>DOCUMENT ID</u>	<u>TECN</u>	<u>COMMENT</u>
<b>125.7 ± 0.4 OUR AVERAGE</b>			
125.5 ± 0.2 <sup>+0.5</sup> <sub>-0.6</sub>	1,2 AAD	13AK ATLS	pp, 7 and 8 TeV
125.8 ± 0.4 ± 0.4	1,3 CHATRCHYAN13J	CMS	pp, 7 and 8 TeV

Lionel Messi, 2014

## 11. STATUS OF HIGGS BOSON PHYSICS

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I. Introduction	161
II. The Standard Model and the Mechanism of Electroweak Symmetry Breaking	162
II.1. The SM Higgs boson mass, couplings and quantum numbers	163
II.2. The SM custodial symmetry	163
II.3. Stability of the Higgs potential	164
II.4. Higgs production and decay mechanisms	164
II.4.1. Production mechanisms at hadron colliders	164
II.4.2. Production mechanisms at $e^+e^-$ colliders	166
II.4.3. SM Higgs branching ratios and total width	166
III. The discovery of a Higgs boson	167
III.1. The discovery channels	167
III.1.1. $H \rightarrow \gamma\gamma$	168
III.1.2. $H \rightarrow ZZ^{(*)} \rightarrow \ell^+\ell^-\ell'^+\ell'^-$ , ( $\ell, \ell' = e, \mu$ )	168
III.2. Mass and width measurements	169
III.3. $H \rightarrow W^+W^- \rightarrow \ell^+\nu\ell^-\bar{\nu}$	169
III.4. Decays to fermions	170
III.4.1. $H \rightarrow \tau^+\tau^-$	171
III.4.2. $H \rightarrow b\bar{b}$	171
III.5. Observed signal strengths	173
III.6. Higgs Production in association with top quarks	173
III.7. Searches for rare decays of the Higgs boson	174
III.7.1. $H \rightarrow Z\gamma$	174
III.7.2. $H \rightarrow \mu^+\mu^-$	174
III.7.3. Rare modes outlook	174
III.8. Non-standard decay channels	174
III.8.1. Invisible Higgs boson decays	174
III.8.2. Exotic Higgs boson decays	174
IV. Properties and nature of the new bosonic resonance	175
IV.1. Theoretical framework	175
IV.1.1. Effective Lagrangian formalism	175
IV.1.2. Constraints on Higgs physics from other measurements	176
IV.2. Experimental results	176
IV.2.1. Introduction	176
IV.2.2. Measuring the signal in categories	177
IV.2.3. Characterization of the main production modes	177
IV.2.4. Evidence for VBF production	177
IV.2.5. Measurement of the coupling properties of $H$	178
IV.2.6. Differential cross sections	181
IV.3. Main quantum numbers $J^{PC}$	181
IV.3.1. Charge conjugation $C$	181
IV.3.2. General framework	181
IV.3.3. Statistical procedure	182
IV.3.4. $J^P$ determination	182

IV.3.5. Probing $CP$ mixing	183
V. New physics models of EWSB in the light of the Higgs boson discovery	184
V.1. Higgs bosons in the Minimal Supersymmetric Standard Model (MSSM)	185
V.1.1. The MSSM Higgs boson masses	185
V.1.2. MSSM Higgs boson couplings	187
V.1.3. Decay properties of MSSM Higgs bosons	188
V.1.4. Production mechanisms of MSSM Higgs bosons	188
V.1.5. Benchmark scenarios in the MSSM for a 125 GeV light Higgs	189
V.2. Indirect constraints on additional states	190
V.3. Higgs Bosons in singlet extensions of the MSSM	190
V.3.1. The xMSSM Higgs boson masses and phenomenology	191
V.4. Supersymmetry with extended gauge sectors	192
V.5. Effects of $CP$ violation	193
V.5.1. Effects of $CP$ violation on the MSSM Higgs spectrum	193
V.6. Non-supersymmetric extensions of the Higgs sector	193
V.6.1. Two-Higgs-doublet models	194
V.6.2. Higgs Triplets	195
V.7. Composite Higgs models	196
V.7.1. Little Higgs models	196
V.7.2. Models of partial compositeness	196
V.7.3. Minimal composite Higgs models	198
V.8. The Higgs boson as a dilaton	198
V.9. Searches for signatures of extended Higgs sectors	199
V.9.1. Standard decays for non-standard processes	203
V.9.2. Outlook of searches for additional states	203
VI. Summary and Outlook	203

## I. Introduction

The observation by ATLAS [1] and CMS [2] of a new boson with a mass of approximately 125 GeV decaying into  $\gamma\gamma$ ,  $WW$  and  $ZZ$  bosons and the subsequent studies of the properties of this particle is a milestone in the understanding of the mechanism that breaks electroweak symmetry and generates the masses of the known elementary particles<sup>1</sup>, one of the most fundamental problems in particle physics.

In the Standard Model, the mechanism of electroweak symmetry breaking (EWSB) [3] provides a general framework to keep untouched the structure of the gauge interactions at high energy and still generate the observed masses of the  $W$  and  $Z$  gauge bosons by means of charged and neutral Goldstone bosons that manifest themselves as the longitudinal components of the gauge bosons. The discovery of ATLAS and CMS now strongly suggests that these three Goldstone bosons combine with an extra (elementary) scalar boson to form a weak doublet.

This picture matches very well with the Standard Model (SM) [4] which describes the electroweak interactions by a gauge field theory invariant under the  $SU(2)_L \times U(1)_Y$  symmetry group. In the SM, the EWSB mechanism posits a self-interacting complex doublet of scalar fields, and the renormalizable interactions are arranged such

<sup>1</sup> In the case of neutrinos, it is possible that the EWSB mechanism plays only a partial role in generating the observed neutrino masses, with additional contributions at a higher scale via the so called see-saw mechanism.

## Higgs @ PDG 2014

- 53 double-column printed pages
- 32 figures
- 18 tables
- 500 References
- > 50'000 downloads

- ◆ SM Higgs: sections II, III, IV
- ◆ New Physics models with a light Higgs boson: section V

# Status in 2014 → 2015 Updates

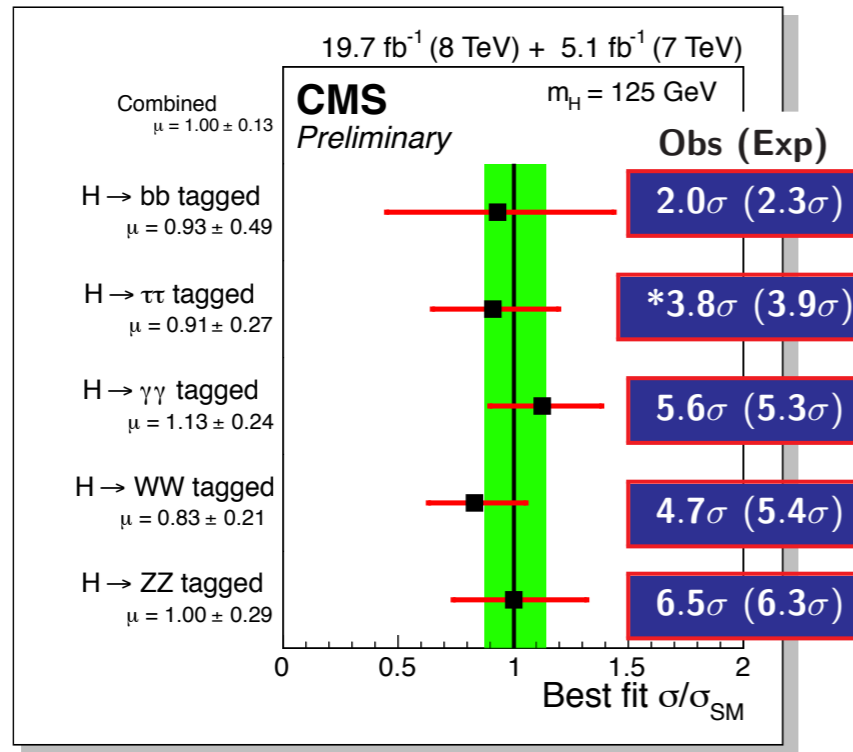
## PDG 2014 edition

	$\gamma\gamma$	ZZ (4 $l$ )	WW ( $l\nu l\nu$ )	$\tau\tau$	W/Z(bb)	Combination
<b>ATLAS</b>						
$\mu$ (at 125.5 GeV)	$1.55^{+0.33}_{-0.28}$	$1.43^{+0.40}_{-0.35}$	$0.99^{+0.31}_{-0.28}$	$1.4^{+0.5}_{-0.4}$	$0.2 \pm 0.7$	$1.3 \pm 0.2$
Z Exp.	4.1	4.4	3.8	4.1	1.4	-
Z Obs.	7.4	6.6	3.8	3.2	0.3	-
Mass (GeV)	$126.8 \pm 0.2 \pm 0.7$	$124.3 \pm 0.5 \pm 0.5$	-	-	-	$125.5 \pm 0.2 \pm 0.6$
Reference	[119]	[119]	[119]	[133]	[138]	[119]
<b>CMS</b>						
$\mu$ (at 125.7 GeV)	$0.77 \pm 0.27$	$0.92 \pm 0.28$	$0.68 \pm 0.20$	$1.10 \pm 0.41$ $0.87 \pm 0.29^*$	$1.15 \pm 0.62$	$0.80 \pm 0.14$
Z Exp.	3.9	7.1	5.3	2.6 (3.6*)	2.2	-
Z Obs.	3.2	6.7	3.9	2.8 (3.4*)	2.0	-
Mass (GeV)	$125.4 \pm 0.5 \pm 0.6$	$125.8 \pm 0.5 \pm 0.2$	-	-	-	$125.7 \pm 0.3 \pm 0.3$
Reference	[120]	[121]	[127]	[131,132]	[137]	[124]
<b>Tevatron</b>						
$\mu$ (at 125 GeV)	$6.0^{+3.4}_{-3.1}$	-	$0.9 \pm 0.8$	$1.7^{+2.3}_{-1.7}$	$1.6 \pm 0.7$	$1.4 \pm 0.6$
Reference	[108]	-	[108]	[108]	[108]	[108]

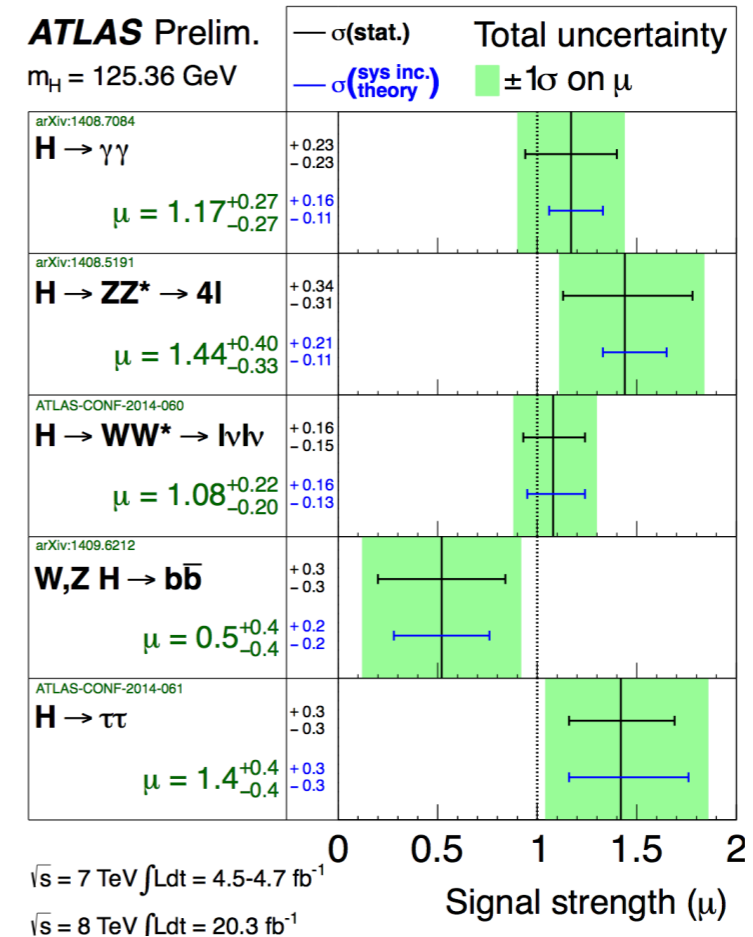
## ICHEP'14

★ "seen" ★ "tried"	H → bb	H → $\tau\tau$	H → WW	H → ZZ	H → $\gamma\gamma$	H → Z(*) $\gamma$	H → inv.	H → $\mu\mu$	H → cc H → HH
ggH		★	★	★	★	☆		☆	
VBF	☆	★	★	☆	★	☆	☆	☆	
VH	★	☆	☆	☆	☆		☆		
ttH	☆	☆	☆		☆				

CMS updates



ATLAS updates





# “What will be new and different in the 2015 edition?”

## □ LHC Run I Legacy Results

No new 13 TeV results but CMS/ATLAS final legacy results on full Run-1 data

Finalization of all ttH channels (including multi-lepton channels)

Constraints on Spin/Parity

	ATLAS limits	CMS limits	CMS sig. strengths
$t\bar{t}(H \rightarrow \gamma\gamma)$	<5.3 (6.4)	<5.4 (5.5)	$\mu = -0.2^{+2.4}_{-1.9}$
$t\bar{t}(H \rightarrow b\bar{b})$	<13.1 (10.5) <sup>‡</sup>	<4.5 (3.7)*	$\mu = 1.0^{+1.9}_{-2.0}$
$t\bar{t}(H \rightarrow 4\ell)$	–	<6.8 (8.8)	$\mu = -4.8^{+5.0}_{-1.2}$
$t\bar{t}(H \rightarrow 3\ell)$	–	<6.7 (3.8)	$\mu = 2.7^{+2.2}_{-1.8}$
$t\bar{t}(H \rightarrow SS2\ell)$	–	<9.1 (3.4)	$\mu = 5.3^{+2.2}_{-1.8}$
$t\bar{t}(H \rightarrow \tau^+\tau^-)$	–	<12.9 (14.2)	$\mu = -1.4^{+6.3}_{-5.5}$
Combination	–	<4.3 (1.8)	$\mu = 2.5^{+1.1}_{-1.0}$

## □ Combination

Published combination of Higgs properties

ATLAS+CMS combination of Higgs properties (mass, signal strengths, couplings...)

## □ Rare Decay Channels

$\gamma\gamma^*$ , invisible

$h \rightarrow J/\Psi + \gamma$  as a measurement of the charm Yukawa coupling

## □ Flavor violating channels

$h \rightarrow \tau\mu$

$t \rightarrow hc$

# *“What will be new and different in the 2015 edition?”*

- **Rare production channels**

  - th**

  - h+boosted jet**

- **Double-Higgs production**

  - gg  $\rightarrow$  hh**

  - WW  $\rightarrow$  hh**

- **Kinematical distributions**

  - Differential cross sections in ZZ and  $\gamma\gamma$  channels**

  - off-shell couplings and EFT interpretation** (rather than bound on width)

  - interferometry in  $\gamma\gamma$  channel**

- **BSM Higgs Searches**

# *How did we handle the previous recommendations?*

“ The Higgs review should be **rewritten in a very substantial way** as soon as possible, and no later than the 2013 update following the publication of final results from ATLAS and CMS on the full 7 and 8 TeV datasets. The focus should be on the SM Higgs and its properties.”

- ◆ **All New: We rewrote the review completely**

- ◆ **SM Higgs: We devoted 1/2 of the review: Sections II, III and IV to the SM-like Higgs Properties, production mechanisms and decay rates.**

**Description of SM Higgs boson analysis channels**

**General theoretical framework to analyze deviations of Higgs properties from SM predictions**

- ◆ **New Physics models with a light Higgs boson: Section V**

**SUSY extensions (incl. new sources of CP violation),**

**Non-SUSY extensions with an elementary Higgs,**

**Composite Higgs models**

**Searches for additional Higgs bosons**

## *How did we handle the previous recommendations?*

“On the experimental side, we suggest reorganizing the review to include first a summary of the status before July 4 (a condensation of the present section), and then detailing the data that has subsequently been collected.”

- **We have ~ a page of the status prior to July 4th, 2012, the rest is on new analyses**
- **We are considering to shorten the details of the discovery analyses in the 2015 edition (refer to 2014 edition)**

“On the theory side, the focus should be changed to reflect the transition to a precision measurement era. The data should be interpreted in a model-independent manner (with analogy to the  $S$  and  $T$  variables of electroweak precision tests, which would parameterize both the tree-level structure of the theory and the loop-induced effects). This would provide a guide to future measurements.”

- **We show the interpretation of data in terms of the EFT approach (Section IV).**  
This allows to evaluate deviations of the Higgs couplings from its SM values (SM coupling modifiers) in an as much as possible model independent manner
- **We present likelihood contours of global fits in terms of pairs of SM coupling modifiers under some assumptions for the rest of them.**
- **We present a general framework to study the spin and parity quantum numbers of the newly discovered particle. The most general tensor structure is used for the three possible spin hypotheses of spin 0, spin 1 and spin 2, as well as for probing CP mixture.**



# *Can we make it shorter?*

- ◆ **Need to cover new exp. results**

- ◆ **TH vs EXP**

  - separated or kept together?

  - We all agree is better to keep them together.

  - More useful, coherent. More work, but the hardest part already done

- ◆ **What could be removed:**

  - large description of the analyses part? Refer to the 2014 edition for details?

  - narrative about the discovery? Already quite succinct!

  - pre-LHC bounds? Already quite succinct too, but could refer to the 2014 edition

- ◆ **What could be improved:**

  - expand the EFT part?

  - balance susy and compositeness parts while keeping them concise