

“Status of Higgs Physics” : PDG Review

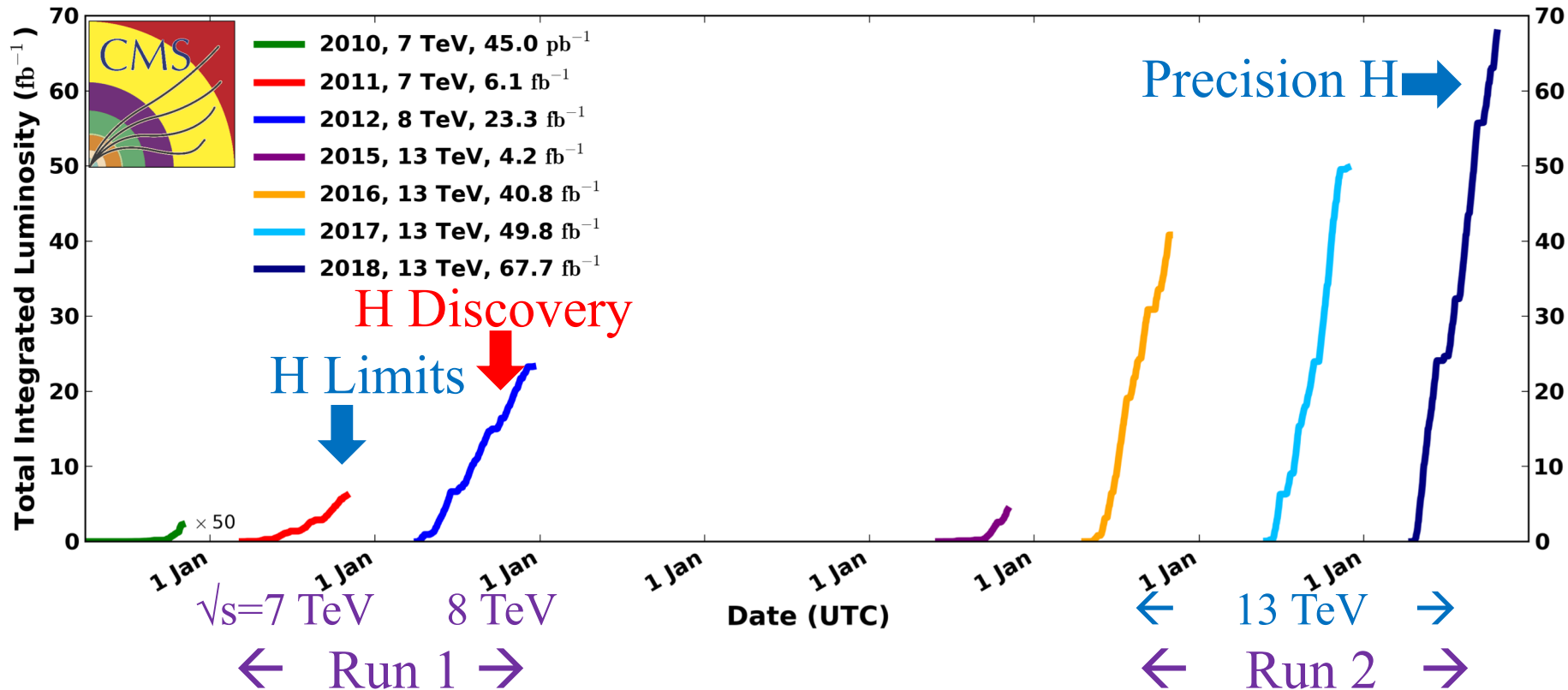
Marcela Carena, Christophe Grojean,
Marumi Kado & Vivek Sharma

PDG Workshop*
25-27 Oct, 2018, LBNL

* Our prior presentation to PDG was in Fall' 2014@LBL

Evolution of Higgs Physics: From Limits to Precision

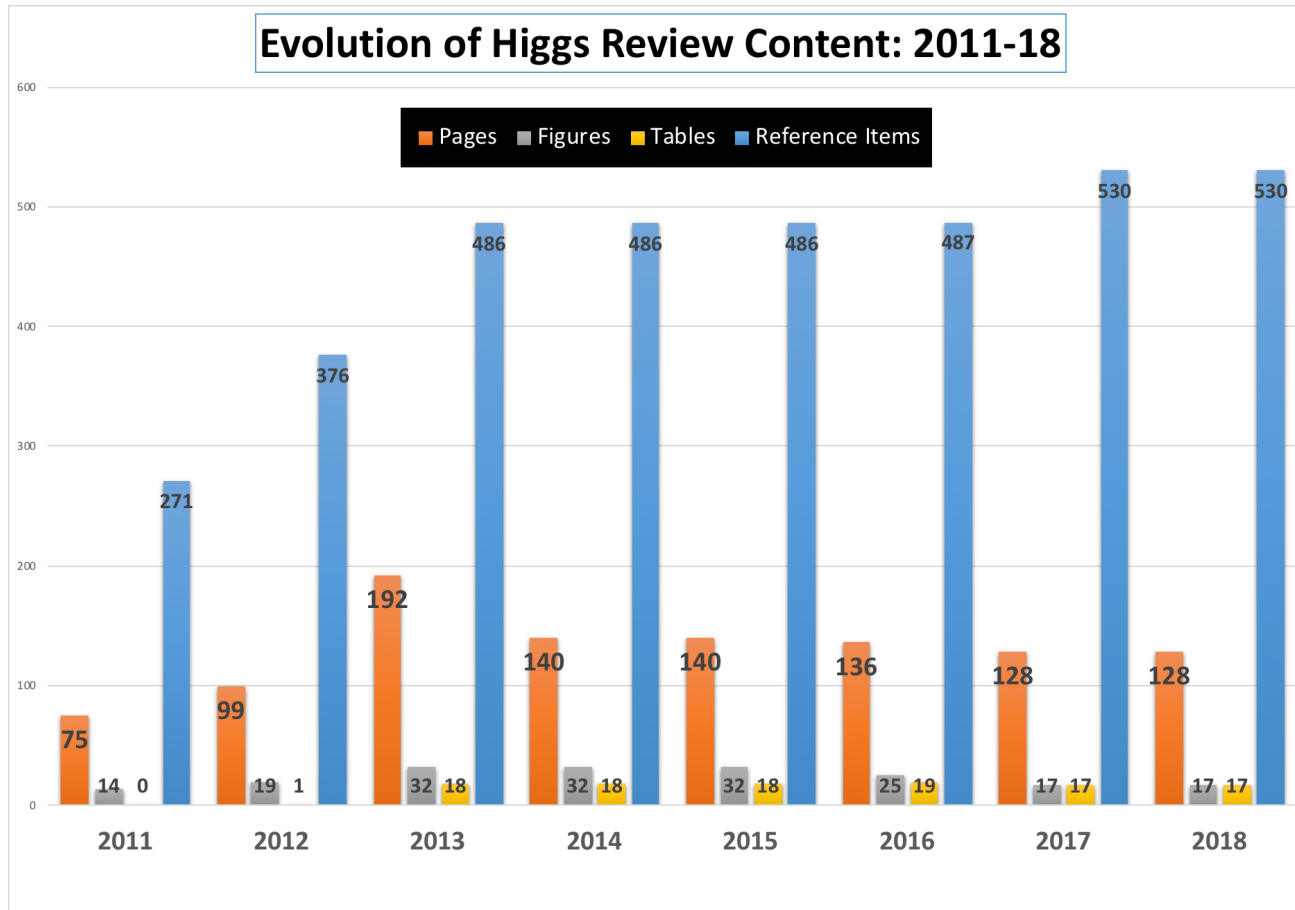
Data included from 2010-03-30 11:22 to 2018-10-23 11:15 UTC



The field of Higgs physics has very rapidly expanded

Run 2 now over ⇒ ≥ 160 fb⁻¹ for ATLAS & CMS each !

Evolution of PDG Higgs Review 2011-2018



← 21 pages of
859
references

There has been a significant effort to reduce the length especially in the 2016 & 2018 editions by decreasing the number of figures and increased use of summary “tables”

Evolution of the Higgs Review: 2014 → 2016 → 2018

- **2014** involved a reduction of ~ 28% in length with respect to the 2013 online version, first edition after the Higgs Discovery edition to follow PDG Editors guidance (2012 has an addendum after the Higgs discovery)
[2013 was a Complete Rewrite, as noted by the 2014 Advisory Board comments]

Evolution of the Higgs Review: 2014 → 2016 → 2018

- **2016** involved important changes in the balance between Experimental results and BSM theory, following **most** of the 2014 advisory board recommendations
 - Update on state of the art discussion of **SM Higgs production and decay rates**.
 - **First results on main production channels at 13 TeV**
 - Expanded on **Higgs production with top quarks or in top decays**
 - Added **Higgs boson pair production**
 - Added **rare decays channels** ($H \rightarrow ee$, LFV, probing charm & light quark couplings)
 - Created sections on **Combination of search channels** and **EFT analysis for probing Higgs coupling properties**, combining a theoretical framework and fits to experimental data
 - Extended discussion on constraints on **Higgs width**
 - **Shortened by 50% the introduction to BSM and by 35% the SUSY theory subsection**
 - Kept at similar levels the Non-SUSY weak dynamics, Composite Higgs and BSM searches subsections
 - **Expanded section on experimental searches for extended Higgs sectors**

Evolution of the Higgs Review: 2014 → 2016 → 2018

- **2018** involved an additional reduction of ~10% in length and a significant reshape of the presentation
 - Sharpen the text in ALL sections to make place for new information
 - New results/updates on SM theory calculations of production and decay rates.
 - Added new strategy for learning about the Higgs width from on-shell rate in diphoton channel
 - **Important rewrite and reduction by 35% of the SUSY BSM theory section, maximally optimized to interface with SUSY section of the report and to support the additional Higgs searches interpretations**
 - Update on 2HDM theory
 - Update on BSM Searches

Comments:

2015 online version essentially the same as 2014 (long shutdown between 2013-15)
2017 online version quite similar to 2018 (took time to update results in 2017)

Status of Higgs Physics : Current Landscape

Precision

- Mass and width
- Coupling properties
- Quantum numbers (Spin, CP)
- Differential cross sections
- Off Shell couplings and width
- Interferometry

Rare decays

- $Z\gamma, \gamma\gamma^*$
- $\mu\mu$
- LFV $\mu\tau, e\tau$
- $J/\Psi\gamma, \Upsilon\gamma, \phi\gamma, \rho\gamma$

Rare Production

- tH, ttH
- FCNC top decays
- Di-Higgs production (trilinear couplings and interference effects)

Preamble

The Higgs boson

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	
VALUE (GeV)	DOCUMENT ID TECN COMMENT
125.18 ± 0.16 OUR AVERAGE	
125.26 ± 0.20 ± 0.08	¹ SIRUNYAN 17AV CMS pp, 13 TeV, ZZ* → 4ℓ
125.09 ± 0.21 ± 0.11	2,3 AAD 15B LHC pp, 7, 8 TeV

PDG Listing entry for the Higgs boson

Is the SM minimal?

Extended scalar sectors:

- Singlet SM extensions
- 2HDM searches
- CP violation in extended Higgs sectors
- MSSM, NMSSM searches
- Higgs triplets and doubly charged Higgs bosons
- Composite Higgs frameworks

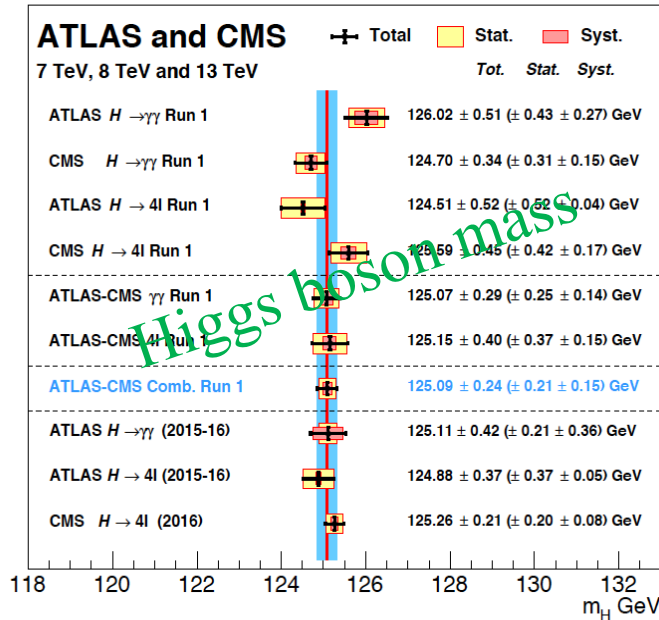
Tool for discovery

- Portal to DM (invisible Higgs)
- Portal to hidden sectors
- Portal to BSM physics with H^0 in the final state (ZH^0, WH^0, H^0H^0)

Towards a Global Interpretation

- Towards Fiducial Measurements
- Towards a consensus for an EFT Framework

Some Summaries in Tabular Form



Channel	ATLAS	CMS
$b\bar{b}\gamma\gamma$	117 (161)** [187]	19 (17) [188]
$b\bar{b}b\bar{b}$	29 (38)* [189]	342 (308)** [190]
$b\bar{b}\tau^+\tau^-$	—	30 (25) [191]
$b\bar{b}W^+W^-$	—	79 (89) [192]
$W^+W^-\gamma\gamma$	747 (386)* [193]	—

Decay mode	ggH	VBF	VH	ttH
$\gamma\gamma$ (A)	0.81 ± 0.16 $^{+0.10}_{-0.08}$	2.0 ± 0.5 $^{+0.4}_{-0.3}$	0.7 ± 0.8 ± 0.3	1.4 ± 0.4 ± 0.2
$\gamma\gamma$ (C)	1.10 $^{0.20}_{-0.18}$	0.8 $^{0.6}_{-0.5}$	2.4 $^{1.1}_{-1.0}$	2.3 ± 0.8 $^{0.3}_{-0.2}$
4 l (A)	1.04 ± 0.14 $^{+0.10}_{-0.10}$	2.8 ± 0.9 ± 0.3	0.9 ± 1.0 ± 0.1	< 1.8 68% CL
4 l (C)	1.20 $^{+0.22}_{-0.21}$	0.05 $^{+0.03}_{-0.05}$	0.0 $^{+2.0}_{-1.1}$	< 1.3 68% CL
WW* (A)	1.21 ± 0.12 ± 0.18	0.62 $^{+0.30}_{-0.28}$ ± 0.22	1.3 ± 1.4 ± 0.4	1.50 $^{+0.45}_{-0.44}$ $^{+0.44}_{-0.40}$
WW* (C)	1.38 $^{+0.21}_{-0.24}$	0.29 $^{+0.68}_{-0.23}$	3.27 $^{+1.88}_{-1.70}$ $^{+0.56}_{-0.48}$	1.97 $^{+0.42}_{-0.41}$ $^{+0.56}_{-0.48}$
$\tau^+\tau^-$ (A)	1.14 $^{+0.23}_{-0.22}$ $^{+0.41}_{-0.34}$	0.98 $^{+0.16}_{-0.25}$ $^{+0.41}_{-0.35}$	2.3 ± 1.6	1.36 $^{+0.89}_{-0.81}$ $^{+0.79}_{-0.63}$
$\tau^+\tau^-$ (C)	1.2 $^{+0.5}_{-0.4}$	1.11 $^{+0.34}_{-0.35}$	-0.33 ± 1.02	0.28 $^{+0.86}_{-0.77}$ $^{+0.68}_{-0.57}$
$b\bar{b}$ (A)	—	-3.9 ± 2.8	0.9 ± 0.18 $^{+0.21}_{-0.19}$	0.83 ± 0.30 ± 0.55
$b\bar{b}$ (C)	2.3 ± 1.5 $^{+1.0}_{-0.4}$	2.8 $^{+1.6}_{-1.4}$	1.2 ± 0.4	0.82 ± 0.23 $^{+0.37}_{-0.36}$
$\mu^+\mu^-$ (A)	< 3.0 (3.1)	Incl.	—	—
$\mu^+\mu^-$ (C)	< 2.6 (1.9)	—	—	—
Z γ (A)	< 6.6 (5.2)	Incl.	—	—
Z $\gamma, \gamma^*\gamma$ (C)	< 3.9 (2.9)	Incl.	Incl.	—
Inv. (A)	—	<28% (31%)	<67% (39%)	—
Inv. (C)	Incl.	<24% (23%)	—	—

	Expected	Observed
$\gamma\gamma$	4.6 σ (ATLAS) 5.3 σ (CMS)	5.2 σ (ATLAS) 4.6 σ (CMS)
ZZ	6.2 σ (ATLAS) 6.3 σ (CMS)	8.1 σ (ATLAS) 6.5 σ (CMS)
WW	5.9 σ (ATLAS) 5.4 σ (CMS)	6.5 σ (ATLAS) 4.7 σ (CMS)
$\tau^+\tau^-$	3.4 σ (ATLAS) 3.9 σ (CMS)	4.5 σ (ATLAS) 3.8 σ (CMS)
$b\bar{b}$	2.6 σ (ATLAS) 2.5 σ (CMS)	1.4 σ (ATLAS) 2.1 σ (CMS)
$\tau^+\tau^-$ (Combined)	5.0 σ	5.5 σ
$b\bar{b}$ (Combined)	3.7 σ	2.6 σ

	ATLAS (Run 1)	CMS (Run 1)	CMS (Run 2)
BR($H \rightarrow \tau\mu$)	(0.53 ± 0.51)%	0.81 $^{+0.39}_{-0.17}$ %	(0.00 ± 0.12)%
95% CL Obs. (Exp.)	1.43% (1.04%)	1.51% (0.75%)	0.25% (0.25%)
$H \rightarrow \tau e$ 95% CL Obs. (Exp.)	1.02% (1.21%)	0.69%*	0.61% (0.37%)

	ATLAS (Run 1)	CMS (Run 1)	CMS (13 TeV, 2015)
ggF (monojet); $H \rightarrow$ inv.	—	67 (71) % [*]	—
VBF; $H \rightarrow$ inv.	28 (31) %	37 (40) % [*]	69 (62) %
$Z \rightarrow \ell^+\ell^-$; $H \rightarrow$ inv.	75 (62) %	75 (91) %	125 (125)%
$Z \rightarrow b\bar{b}$; $H \rightarrow$ inv.	—	182 (189) % [*]	—
$Z \rightarrow jj$; $H \rightarrow$ inv.	78 (86)%	—	—
Combination of all direct searches	25 (27)%	36 (30) %	—

Thoughts On Next Editions of Higgs Review

A flood of defining precision measurements coming in the next 3 years

Additions/Updates: Wish list

- **Highlight 2018 observations of $t\bar{t}H$, $H \rightarrow \tau\tau$ and $H \rightarrow b\bar{b}$**
- Run 2 Higgs Mass & Coupling measurements & their combination (Run 1 + 2)
- Expand on **Higgs differential production cross section**
- Expand on **di-Higgs** discussion, in particular in relation to self couplings and interference effects in the presence of new scalars/new physics
- Expand on the **Higgs portals and exotic Higgs decays** (with connection to long-lived particles)
- Update/Expand on searches for **extended Higgs sectors and their connections with BSM scenarios**
- Re-shape the EFT presentation: integrated w/ Higgs coupling measurements
 - reach out to the relevant community → **achieve consensus**
- Briefly discuss connections between **Higgs and cosmology**, in particular on **inflation & electroweak baryogenesis** and the **dynamics of the EW phase transition**

Thoughts On Next Editions of Higgs Review

Subtractions:

- Reduce **present narrative, figures** in several places to make way for newer material like Differential XS, ttH, and Di-Higgs searches/studies
 - **Not much “fat” text left to remove from review to remain self-contained**
- More summary tables to convey the information (finally with Latex 😊)
- Try to reduce # of references
 - **Reduce refs by pointing to past PDG versions (?)**
 - **tried already: received sharp blowback from some theorists**

Responses to 2016 Advisory Board on Higgs Review

- “We recommend keeping the integration of theoretical and experimental aspects of a topic together in one review”

– **Thank You !**

“The Higgs review is highly successful and will grow in importance. We recommend that in the future it be divided into two reviews: one on the Higgs in the Standard Model, listed under the “Standard Model” category, and one on Higgs in Beyond the Standard Model theories, to be listed under the “Hypothetical” category. This second review would include material on Composite Higgs Bosons and Dynamical Electroweak Symmetry Breaking”...”This will lead to a better balance between theoretical and experimental contents in reviews of the Higgs within the Standard Model section.”

– **While we understand this viewpoint, after fair bit of thinking and discussion, we respectfully disagree.**

Why keep SM and BSM Narratives Together ?

1. Currently SM and BSM **intertwined** in every section: **a split will imply a major rewriting**
2. While the Higgs is very much SM-like, it is at the **heart of most BSM scenarios** (because of the question of naturalness).
3. Measuring any **property of the Higgs** is primarily a quest of BSM physics, often in a complementary way to direct searches (e.g. in MSSM or MCHM). The Higgs boson is a **tool for exploration** as much as a standalone topic of investigation.
4. All BSM theory text is oriented and focused on the Higgs, in a way that is **complementary to other BSM reviews** (e.g. SUSY or Dynamic SB) and relevant both to the measurements of the Higgs couplings and to the search for additional states.
The links between reviews have been inserted in the current version.
5. The scope of the searches reported in our review is only the searches for **additional Higgs bosons** and not additional top-partners or other resonances usually present in any BSM models.

Breakdown of Narrative: Th Vs Ex , SM Vs BSM

Topic	Theory [pages]	Expt [pages]	$\frac{Th}{Th + expt}$
SM	≈ 16.5	≈ 24	41%
BSM	≈ 30	≈ 30	50%
All	46.5	54	46%

Summary & Outlook

- In 8 years, the Higgs Landscape evolved from:
Limits → Discovery → Precision measurements
- The PDG Higgs reviews have evolved in these years to reflect this rapid transformations
- The reviews are integrated with community activities:
 - LHC Higgs XS Working Group
 - LHC Higgs Combination Group
- With the end of Run 2, flood of precision measurements and sensitive searches are expected in the near future
- We prefer to keep the SM and BSM Higgs narrative altogether

We welcome your suggestions to further improve this review !

Spares

Status of Higgs Physics, 2018 Edition

Table of Contents

I. Introduction	180	V.1.2. Spin and parity	196
II. The standard model and the mechanism of electroweak symmetry breaking	181	V.1.3. Probing fixed J^P scenarios	197
II.1. The SM Higgs boson mass, couplings and quantum numbers	182	V.1.4. Probing CP-mixing and anomalous HVV couplings	197
II.2. The SM custodial symmetry	182	V.2. Off-shell couplings of the Higgs boson	198
II.3. Stability of the Higgs potential	182	V.3. The Higgs boson width	198
II.4. Higgs production and decay mechanisms	183	V.3.1. Direct constraints	198
II.4.1. Production mechanisms at hadron colliders	183	V.3.2. Indirect constraints from mass shift in the diphoton channel	199
II.4.2. Production mechanisms at e^+e^- colliders	185	V.3.3. Indirect constraints from on-shell rate in the diphoton channel	199
II.4.3. SM Higgs branching ratios and total width	185	V.3.4. Indirect constraints from off-shell couplings	199
III. The experimental profile of the Higgs boson	186	VI. Probing the coupling properties of the Higgs boson	200
III.1. The principal decay channels to vector bosons	186	VI.1. Effective Lagrangian framework	200
III.1.1. $H \rightarrow \gamma\gamma$	186	VI.2. Probing coupling properties	201
III.1.2. $H \rightarrow ZZ^* \rightarrow \ell^+\ell^-\ell^+\ell^-$	187	VI.2.1. Combined measurements of the coupling properties of H	201
III.1.3. Measurement of the Higgs boson mass	187	VI.2.2. Differential cross sections	203
III.1.4. $H \rightarrow W^+W^- \rightarrow \ell^+\nu\ell^-\bar{\nu}$	187	VI.2.3. Constraints on non-SM Higgs boson interactions in an effective Lagrangian	204
III.2. Decays to fermions	188	VI.2.4. Simplified Template Cross Sections	204
III.2.1. $H \rightarrow \tau^+\tau^-$	188	VII. New physics models of EWSB in the light of the Higgs boson discovery	204
III.2.2. $H \rightarrow b\bar{b}$	189	VII.1. Higgs bosons in the minimal supersymmetric standard model (MSSM)	205
III.3. Higgs production in association with top quarks or in top decays	190	VII.1.1. MSSM Higgs boson phenomenology	206
III.3.1. The associated production with top quark pairs	190	VII.2. Supersymmetry with singlet extensions	207
III.3.2. The associated production with a single top quark	190	VII.3. Supersymmetry with extended gauge sectors	208
III.3.3. Flavor changing neutral current decays of the top quark	191	VII.4. Effects of CP violation	209
III.4. Higgs boson pair production	191	VII.5. Non-supersymmetric extensions of the Higgs sector	209
III.4.1. Searches for Higgs boson pair production	191	VII.5.1. Two-Higgs-doublet models	210
III.4.2. The Higgs self coupling	191	VII.5.2. Higgs triplets	211
III.5. Searches for rare decays of the Higgs boson	192	VII.6. Composite Higgs models	211
III.5.1. $H \rightarrow Z\gamma$	192	VII.6.1. Little Higgs models	211
III.5.2. $H \rightarrow \mu^+\mu^-$	192	VII.6.2. Models of partial compositeness	212
III.5.3. $H \rightarrow e^+e^-$	192	VII.6.3. Minimal composite Higgs models	214
III.5.4. Lepton flavor violating (LFV) Higgs boson decays	192	VII.6.4. Twin Higgs models	214
III.5.5. Probing charm- and light-quark Yukawa couplings	193	VII.7. Searches for signatures of extended Higgs sectors	214
III.5.6. Rare decays outlook	193	VII.7.1. Searches for non-standard production processes of the Higgs boson	219
III.6. Searches for non-standard model decay channels	193	VII.7.2. Outlook of searches for additional states	219
III.6.1. Invisible decays of the Higgs boson	193	VIII. Summary and outlook	219
III.6.2. Exotic Higgs boson decays	194		
IV. Combining the main channels	194		
IV.1. Principles of the combination	194		
IV.2. Main decay modes and observation of Higgs decays to taus	195		
IV.3. Main production modes and evidence for VBF production	195		
V. Main quantum numbers and width of the Higgs boson	196		
V.1. Main quantum numbers J^{PC}	196		
V.1.1. Charge conjugation	196		

Comparison of # of Reference Items (2018 Ed)

Review Topic	# of Reference items
SUSY	423
Higgs	530
Neutrino Mass/Mix/Oscillation	315

Prognostication On Future Higgs Results

- **2018:**
 - ATLAS & CMS continue publishing results from partial Run 2 data, e.g. ttH , $H \rightarrow \tau\tau$ and $H \rightarrow bb$ Observation
- **2019:**
 - ATLAS & CMS continue to publish results from **full Run 2** prompt Reco data
 - **& Combine with Run 1 ?**
 - prepare for “**Legacy**” Run 2 results with final reconstruction
- **≥ 2020 :**
 - First **Legacy** publications + combinations of results from within each collaboration
 - Prelim. (Run 1 +) Run 2 **LHC** combination of results?
 - Publish Run1 + Run 2 LHC SM combination results in 2021 ??