"Status of Higgs Physics" : PDG Review

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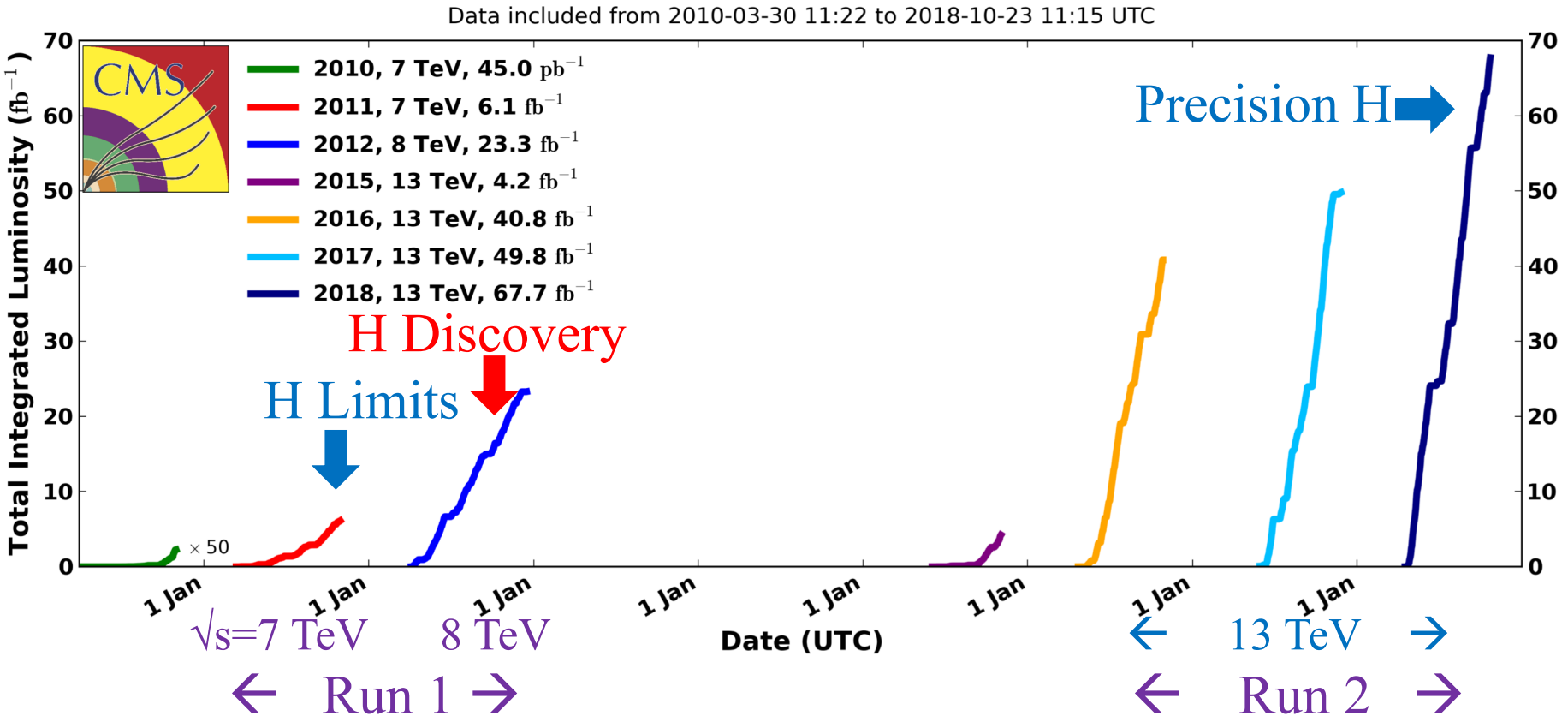
* Our prior presentation to PDG was in Fall' 2014@LBL

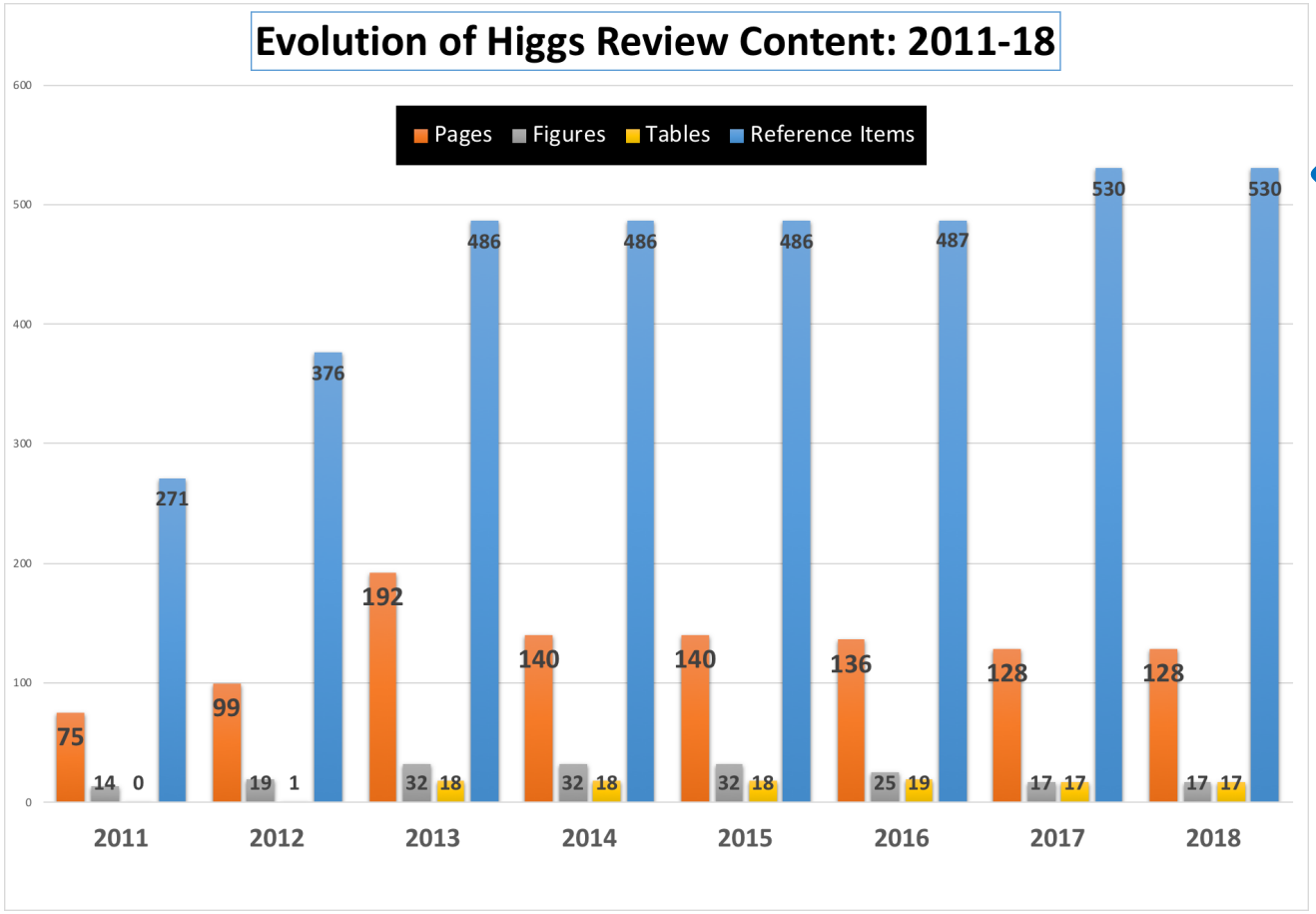
Evolution of Higgs Physics: From Limits to Precision



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→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

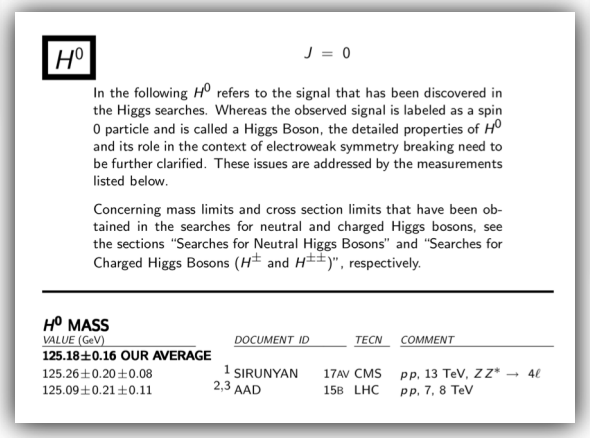
Precision
- Mass and width
- Coupling properties
- Quantum numbers (Spin, CP)
- Differential cross sections
- Off Shell couplings and width
- Interferometry

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, $ZZ^* \to 4\ell$
125.09±0.21±0.11	[2,3] AAD	15B	LHC	pp, 7, 8 TeV

PDG Listing entry for the Higgs boson

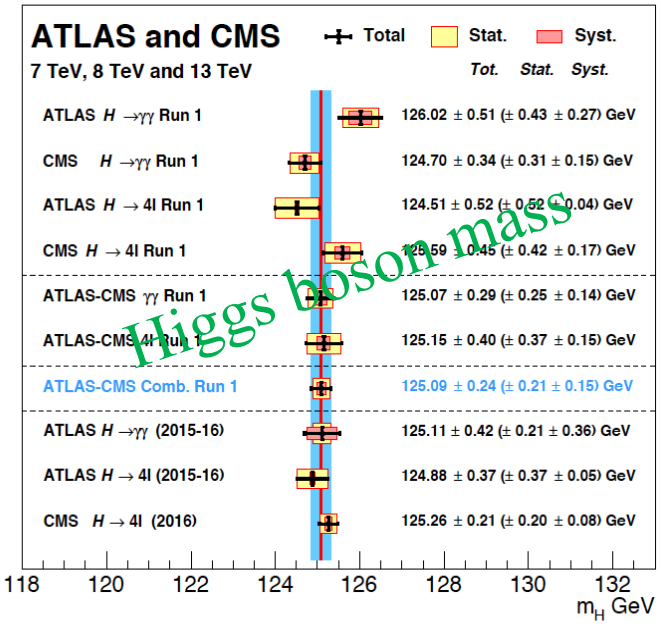
Is the SM minimal?

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



Higgs boson mass

Decay mode	ggH	VBF	VH	ttH
$\gamma\gamma$ (A)	$0.81 \pm 0.16\ ^{+0.10}_{-0.08}$	$2.0 \pm 0.5\ ^{+0.4}_{-0.3}$	$0.7 \pm 0.8 \pm 0.3$	$1.4 \pm 0.4 \pm 0.2$
$\gamma\gamma$ (C)	$1.10\ ^{0.20}_{-0.18}$	$0.8\ ^{0.6}_{-0.5}$	$2.4\ ^{1.1}_{-1.0}$	$2.3 \pm 0.8\ ^{0.3}_{-0.2}$
4ℓ (A)	$1.04 \pm 0.14\ ^{+0.10}_{-0.10}$	$2.8 \pm 0.9 \pm 0.3$	$0.9 \pm 1.0 \pm 0.1$	< 1.8 68% CL
4ℓ (C)	$1.20\ ^{+0.22}_{-0.21}$	$0.05\ ^{+0.03}_{-0.05}$	$0.0\ ^{+2.0}_{-0.0}$	< 1.3 68% CL
WW^* (A)	$1.21 \pm 0.12 \pm 0.18$	$0.62\ ^{+0.30}_{-0.28} \pm 0.22$	$\ ^{+1.4}_{-4.2}$	$1.50\ ^{+0.45}_{-0.44}\ ^{+0.44}_{-0.40}$
WW^* (C)	$1.38\ ^{+0.21}_{-0.24}$	$0.29\ ^{+0.68}_{-0.29}$	$3.27\ ^{+1.88}_{-1.70}\ ^{+0.56}_{-0.48}$	$1.97\ ^{+0.42}_{-0.41}\ ^{+0.56}_{-0.48}$
$\tau^+\tau^-$ (A)	$1.14\ ^{+0.23}_{-0.22}\ ^{+0.41}_{-0.34}$	$0.98\ ^{+0.46}_{-0.25}\ ^{+0.41}_{-0.35}$	2.3 ± 1.6	$1.36\ ^{+0.89}_{-0.81}\ ^{+0.79}_{-0.63}$
$\tau^+\tau^-$ (C)	$1.2\ ^{+0.6}_{-0.5}$	$1.11\ ^{+0.34}_{-0.35}$	-0.33 ± 1.02	$0.28\ ^{+0.86}_{-0.77}\ ^{+0.68}_{-0.57}$
$b\bar{b}$ (A)	–	-3.9 ± 2.8	$0.9 \pm 0.18\ ^{+0.21}_{-0.19}$	$0.83 \pm 0.30 \pm 0.55$
$b\bar{b}$ (C)	$2.3 \pm 1.5\ ^{+1.0}_{-0.4}$	$2.8\ ^{+1.6}_{-1.4}$	1.2 ± 0.4	$0.82 \pm 0.23\ ^{+0.37}_{-0.36}$
$\mu^+\mu^-$ (A)	$< 3.0\,(3.1)$	Incl.	–	–
$\mu^+\mu^-$ (C)	$< 2.6\,(1.9)$	–	–	–
$Z\gamma$ (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%)	–	

Higgs boson properties

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]	—

Di-Higgs limits

	Expected	Observed
$\gamma\gamma$	4.6σ (ATLAS) 5.3σ (CMS)	5.2σ (ATLAS) 4.6σ (CMS)
ZZ	6.2σ (ATLAS) 6.3σ (CMS)	8.1σ (ATLAS) 8.5σ (CMS)
WW	5.9σ (ATLAS) 5.4σ (CMS)	6.5σ (ATLAS) 4.7σ (CMS)
$\tau^+\tau^-$	3.4σ (ATLAS) 1.9σ (CMS)	4.5σ (ATLAS) 3.8σ (CMS)
$b\bar{b}$	2.6σ (ATLAS) 2.5σ (CMS)	1.4σ (ATLAS) 2.1σ (CMS)
$\tau^+\tau^-$ (Combined)	5.0σ	5.5σ
$b\bar{b}$ (Combined)	3.7σ	2.6σ

Signal Significances

	ATLAS (Run 1)	CMS (Run 1)	CMS (Run 2)
BR($H \to \tau\mu$)	(0.53 ± 0.51)%	$(0.84\ ^{+0.39}_{-0.37})$%	(0.00 ± 0.12)%
95% CL Obs. (Exp.)	1.43% (1.01%)	1.51% (0.75%)	0.25% (0.25%)
$H \to \tau e$ 95% CL Obs. (Exp.)	1.02% (1.21%)	0.69%*	0.61% (0.37%)

Flavor violating H

	ATLAS (Run 1)	CMS (Run 1)	CMS (13 TeV, 2015)
ggF (monojet); $H \to$ inv.	–	67 (71) % [*]	-
VBF; $H \to$ inv.	28 (31) %	57 (50) % [*]	69 (62) %
$Z \to \ell^+\ell^-$; $H \to$ inv.	75 (82)%	75 (91) %	125 (125)%
$Z \to b\bar{b}$; $H \to$ inv.	–	182 (189) % [*]	-
$Z \to jj$; $H \to$ inv.	78 (86)%	–	-
Combination of all direct searches	25 (27)%	36 (30) %	-

Invisible Higgs

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 ttH , H→ $\tau\tau$ and H→bb**
- 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

Comparision 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→ $\tau\tau$ and H→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 ??