Recent Higgs Highlights

Jan Steggemann
PSI Colloquium
16 November 2023
Or: We are close to LHC halftime (in terms of discovery potential). Is there hope to make another major finding in the Higgs sector?

1. What do we know about the observed Higgs boson?
2. A look at the Higgs couplings to vector bosons and fermions
3. A brief story of recent searches for additional Higgs bosons

Jan Steggemann
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What do we know about the Higgs boson?

Note: As member of the CMS Collaboration, I will mostly show CMS results, in particular whenever ATLAS and CMS results are equivalent
Does it exist? Let’s go back in time

In 2011, Peter Mättig and Michael Stöltzer surveyed all HEP experimentalists and theorists [1806.09201]
2012 observation!

Driven by decays to bosons: $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ$
(and to a smaller extent $H \rightarrow WW$)

![Graph of CMS data showing $S/(S+B)$ weighted events vs. $m_{\gamma\gamma}$ and $m_{4\ell}$ distributions.](image-url)
2012 observation!

Driven by decays to bosons: $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ$

(and to a smaller extent $H \rightarrow WW$)


2012 observation!

Driven by decays to bosons: $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ$
What is its mass?

The sole free parameter in the Standard Model (SM) Higgs sector

1-2% mass resolution

2012: $m = 125.3 \pm 0.4 \text{ (stat.)} \pm 0.5 \text{ (syst.) GeV (CMS)}$

126.0 $\pm 0.4 \text{ (stat.)} \pm 0.4 \text{ (syst.) GeV (ATLAS)}$
2023 Mass Update - 125 GeV it is

< 1% mass resolution in best event category

2023: \( m = 125.08 \pm 0.12 \text{ (stat.)} \pm 0.05 \text{ (syst.)} \text{ GeV} \) (CMS HZZ)

125.11 \( \pm 0.09 \) (stat.) \( \pm 0.06 \) (syst.) GeV (ATLAS combined)

Reaching below per-mil level precision

0.09 GeV syst. uncertainty

CMS-PAS-HIG-21-019
Does it couple/decay to fermions?

Main discovery channels:
Can only show consistency with ggH production
(SM: top-dominated loop)
Does it couple/decay to fermions?

$\sigma = \kappa^2 \sigma_{\text{SM}}$  \hspace{1cm} \text{coupling modifiers} \hspace{1cm} \Gamma = \kappa^2 \Gamma_{\text{SM}}$

Essential to probe Higgs decays to fermions as well as $tt$-associated production ($ttH$)
Established Yukawa couplings

Much more challenging than \( H \rightarrow \gamma \gamma \) and \( H \rightarrow ZZ \):

- 10-20% mass resolution (compared to 1-2%)
- Harder-to-control, partially irreducible backgrounds

End of 2013: Evidence of \( H \rightarrow \tau \tau \) decays, by CMS & ATLAS → combined observation.

In run 2, observation of \( H \rightarrow bb \), \( ttH \) production, and evidence for \( H \rightarrow \mu \mu \)

Gavin Salam:

*Is this any less important than the discovery of the Higgs boson itself?*

*My opinion: no, because fundamental interactions are as important as fundamental particles*
2022: Towards high-precision $H \rightarrow \tau \tau$

Reaching 10% expected uncertainties thanks to refined analysis strategies and improved tau identification
Spin and CP?

Quickly excluded alternative spin and parity hypotheses in $H\rightarrow ZZ$

Run 2 added detailed studies of CP admixtures also in Higgs-fermion couplings: Pure CP-odd Higgs-tau and Higgs-top couplings excluded

CMS public results on CP/Spin
ATLAS public results
Measuring the Higgs width: Off-shell

Proposed by Kaola/Melnikov and Campbell et al

For SM width (4.1 MeV):
Interference dominates w.r.t. pure H signal
→ deficit w.r.t. SM continuum ZZ production
(which would also correspond to zero width)

For larger width values, H signal term starts
to dominate
(SM width value fairly close to giving
maximal negative interference)
Evidence for offshell production & measurement of width

First measurement: $\Gamma_H = 3.2^{+2.4}_{-1.7}$ MeV

$\Gamma_H = 4.5^{+3.3}_{-2.5}$ MeV
The observed Higgs boson

- $m_H = 125.1 \pm 0.1$ GeV (my approx.)
- Spin 0
- CP-even (no large CP-admixture)
- Production and decay into vector bosons consistent with SM $\rightarrow$ Major source of EWSB
- Yukawa couplings $\sim$ mass (3rd gen., 2nd gen.)
- Width consistent with SM

Not discussed today but very important as well:
- Production dynamics: so far consistent with SM
- No sign of invisible or undetected decays
- Higgs self-coupling/potential: lots of analyses but need more data; $\kappa_{2V} > 0$ ($>5\sigma$)
New physics in the Higgs sector?

**Extended Higgs sectors**
Additional singlets, doublets, triplets, …

- *Modified couplings* of the Higgs boson
- *Additional Higgs bosons*

**Why attractive:**
- No guarantee of minimality of Higgs sector (cf. other aspects of SM)
- Specific models can address specific issues of SM
- SUSY (MSSM, NMSSM) naturally has a light SM-like Higgs boson

**BSM that couples only or preferentially to the Higgs sector**
*Can manifest itself in various ways*
- While it can also affect the effective observed Higgs boson couplings, more direct impact generally on production dynamics (if any)
- Otherwise direct production of BSM with Higgs involvement, e.g. a dark sector, or heavy states that decay to Higgs + X
It really does look like the SM Higgs boson!

F. Gianotti (Higgs@10)
Or doesn’t it? Going back to 2021…

**ATLAS** Preliminary

$\sqrt{s} = 13$ TeV, 36.1-139 fb$^{-1}$

$m_H = 125.09$ GeV, $|y_H| < 2.5$

$p_{SM} = 2.8\%$

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**ATLAS-CONF-2021-053**
2022: CMS obtains quite similar results

Nature 607 (2022) 60-68
2022: At the same time, ATLAS moves a bit in SM direction
Few things to note

1. Sum rule for extended Higgs sectors with only singlets and doublets:
   \[ \sum_i (\kappa_{V}^{H_i})^2 = 1 \]
   (where i runs over all scalars)
   Seeing \( \kappa_{V} > 1 \) would therefore point to triplets (or sth. completely different)

2. Sensitivity to \( \kappa_f \) equally comes from top and tau

3. Two of the CMS results not based on full run 2 data: VH(bb) and ttH(bb)
Measurement of $ttH$ production with $H\rightarrow bb$

CMS Preliminary

59.7 fb$^{-1}$ (13 TeV)

2018 discriminant bins

Events/bkg

CMS-PAS-HIG-19-011
ttH with H→bb: Signature and Strategy

In each of the three lepton final states:

**Categories** based on n(jets) and n(b-tags)

**Multi-class ANNs:**
- Events are assigned to most probable category

**In joint ttH & ttB category: Fit to Likelihood ratio of ANN outputs**

**ttH(bb):** 4b + 0, 1, or 2 leptons + jets

**Essential:** b-tagging!
Fitted distributions (2018)

CMS Preliminary

FH

≥4 b-tags
7 jets
≥9 jets
8 jets
≥4 b-tags
5 jets
≥6 jets
7 jets
≥9 jets
ttLF, ttC, tt2b cats.
tHQ cat.
tHq cat.
ttH cat.
ttH+ttB cat.

SL

≥3 b-tags
3 jets
≥4 jets
ttLF, ttC cats.
ttH+ttB cat.

DL

≥4 b-tags
≥5 jets
≥6 jets
≥7 jets
≥8 jets
≥9 jets
≥5 jets
≥6 jets
≥7 jets
≥8 jets
≥9 jets
ttLF, ttC, tt2b cats.
ttH+ttB cat.

Postfit

36.7 fb⁻¹ (13 TeV)

59.7 fb⁻¹ (13 TeV)

other years in backup
Results

Deficit of a bit more than 2 standard deviations w.r.t. the SM prediction, with syst. unc. > stat. unc. 

Consistent with ATLAS (*) result: $\mu = 0.35^{+0.36}_{-0.34}$

As in previous ttH(bb) analyses, larger ttB rate than expected

(*) JHEP 06 (2022) 97
Systematic uncertainties

<table>
<thead>
<tr>
<th>Uncertainty source</th>
<th>$\Delta\mu_{t\bar{t}J}$ (observed)</th>
<th>$\Delta\mu_{t\bar{t}J}$ (expected)</th>
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<tr>
<td>Total</td>
<td>$+0.26/-0.26$</td>
<td>$+0.28/-0.25$</td>
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</table>

- **$t\bar{t} +$ jets uncertainties** most important

Also given the interesting results, extensively validated robustness of $t\bar{t} +$B model, e.g. using inclusive $t\bar{t} +$jets MC, $t\bar{t} +$B scaled by factor of 1.2
What to say about it

+ Will be interesting to see the fully combined CMS results (also including updated VH(bb))
+ … and subsequently the ATLAS-CMS combination of the couplings (one can guess the outcome though correlations aren’t trivial)

- Cherry-picking… (the one discrepant result out of many)
- Specific parametrisation not easily mappable to most well-known extended Higgs models
- H→bb measurements (and to some extent H→ττ) have significant, difficult-to-model backgrounds

More data will tell!
How to look for additional Higgs bosons

“Heavy” neutral scalars (<~ 100 GeV to ~ TeV):

**Produced** like $h_{125}$:

- **gluon fusion**, vector boson fusion, or $t$- or $b$-associated
  - Need the **LHC** (or future high-energy collider) and multi-purpose experiment (currently **ATLAS** or **CMS**)
  - Cross sections typically smaller than $h_{125}$: Searches $L_{int}$-limited

**Decays:**

Either into SM like $h_{125}$ ($ZZ$, $WW$, $γγ$; $ττ$, $bb$, ...) or heavier ($tt$)

Or into boson pairs $H→h_{125}h_{125}/hh/h_{125}h/aa/ZA/…$

$A→Zh_{125}/ZH/ha/…$

$N$
How to look for additional Higgs bosons

“Heavy” neutral scalars (~ 100 GeV to ~ TeV):

- Produced like $h_{125}$:
  - gluon fusion, vector boson fusion,
  - $t$- or $b$-associated

- Need the LHC (or future high-energy collider)
  - multi-purpose experiment (currently ATLAS or CMS)

- Cross sections typically smaller than $h_{125}$: Searches $L$-limited

Decays:
- Either into SM like $h_{125}$: $ZZ, WW, \gamma\gamma; \tau\tau, bb, ...$
  - Or into boson pairs $H\rightarrow h_{125}h_{125}/hh/h_{125}h/aa/ZA/...$
  - $A\rightarrow Zh_{125}/ZH/ha/...$

A plethora of interesting final states and searches, experimentally very rich!

Nowadays, most of the searches aren’t “simple” bump hunts anymore, but increase the sensitivity by using multiple event categories or multivariate classifiers (BDTs, DNNs)
Run 1/early run 2: 95 GeV $H \rightarrow \gamma \gamma$

Fit $m(\gamma \gamma)$ spectrum in three categories defined by BDT that separates photon pairs from Higgs decays from those from the continuum.

Excess has spurred some interest in theory community, though accounting for look-elsewhere-effect leads to significance of only 1.5$\sigma$.
Jumping ahead to 2022: $H \rightarrow WW$ at 650 GeV

Broad excess for VBF production
Largest local (global) significance: 3.8 (2.6) $\sigma$ at 650 GeV
Summer 2022: $H \rightarrow h_{125}h \rightarrow \gamma\gamma b\bar{b}$

Largest local (global) significance: $3.8 \ (2.8) \ \sigma$

at 650 GeV and 90 GeV

(similar excess at 100 GeV, consistent with 95 GeV)
March 2023: CMS update 95 GeV H→γγ

Additional VBF category and improved Z rejection.
Similar significance as before (but more expected when scaling 2016 excess)
Local (global) significance: 2.9 (1.3) σ at 95.4 GeV
June 2023: ATLAS update 95 GeV H→γγ

Similar sensitivity as CMS search. No production-mode categories.
No significant local excess, but largest one near 95 GeV…

Data distribution in one of 4 categories
2023: ATLAS $A \rightarrow ZH \rightarrow lltt$

Largest local significance at 650 GeV and 450 GeV

For all previous $A \rightarrow ZH$ searches, $A \rightarrow ZH$ and $H \rightarrow ZA$ are indistinguishable.
A few more related searches

1) ATLAS $H \rightarrow WW$ doesn’t confirm CMS result but less sensitive

2) CMS $A/H \rightarrow \tau\tau$ sees a local (global) excess of 2.6 (2.3) $\sigma$ at 95 GeV

3) CMS $A/H \rightarrow tt$ finds a local (global) excess of 3.5 (1.9) $\sigma$ at 400 GeV
Few things to say…

1. The **look-elsewhere-effect is important** and global significances need to be taken seriously
2. While finding excesses at consistent mass values is intriguing, one **cannot simply multiply p-values**
3. With that said, all of these results are bump hunts and experimentally fairly robust, in particular the ones involving $H \rightarrow \gamma \gamma$

We luckily don’t need to conclude, but can wait for
• ATLAS results on $H \rightarrow h_{125} h \rightarrow \gamma \gamma b b$, $A/H \rightarrow t t$, $A/H \rightarrow \tau \tau$
• CMS results on $A \rightarrow Z H \rightarrow l l t t$, full run 2 results on $A/H \rightarrow t t$
• ATLAS and CMS results on $H \rightarrow h_{125} h \rightarrow b b \gamma \gamma$ (with $h \rightarrow \gamma \gamma$), $H \rightarrow h_{125} h \rightarrow 4 b$ (+ more channels); and on $H \rightarrow Z Z$ (!) and $H \rightarrow W W$ in more channels.

➔ **All of these should come!**

*(Some people drew even more connections, e.g. Yaouanc/Richard, but I stop here)*
Conclusion

In the last 11 years, we *characterised the 125 GeV Higgs boson extremely well*: quantum numbers, mass at the sub-per-mil level, couplings to W, Z and 3rd generation quarks and leptons at the few to 10% level, width, and more!

At the same time, we look for deviations from the SM predictions in many places: The combined *couplings to fermions and vector bosons* show some deviations from the SM predictions that are worth keeping an eye one with more data

In parallel, we are looking for additional Higgs bosons: There are *potentially intriguing excesses at masses of 650 GeV and 95 GeV* (and maybe more). Upcoming results will tell us more, hopefully soon!
Additional information
Vacuum stability

Via CERN courier, based on Particle Data Group/JHEP 12 089

The results presented in this talk will tighten the constraints
Comparison with other ttH measurements

Similar sensitivity as multilepton measurement
Off-shell Higgs width: Most recent result

Extracted width: $\Gamma_H = 2.9^{+2.3}_{-1.7}$ MeV
Consistent with SM and confirms previous results

Signal strengths for off-shell VBF/VH production ($\mu_V$) and for ggF ($\mu_F$) consistent with SM expectation
Validation plots

**pre-fit**
QCD dominant background
(here from MC)

Scaled to the outcome of the final fit to data
Good modelling of observables sensitive to relative ratio of different tt+B components (e.g. gluon splitting)
Categories based on n(jets) and n(b-tags)

- Three signal regions, requiring $60(72) \text{ GeV} < m_{qq} < 100(90) \text{ GeV}$
- For each signal region two loose b-tag control regions:
  - One to estimate the QCD background; the other to train the ANNs
- Three further validation regions with $m_{qq}$ outside of the signal window

Train artificial neural network (ANN) against all backgrounds, using various inputs:

- kinematic variables
- matrix element discriminant

Fit ANN discriminant output
Strategy: Lepton+jets channel (LJ)

Two categories based on n(jets) and n(b-tags)

Compared to DL channel:
- More fine-grained background categories
- Likelihood ratio only with respect to $tt+b(b)$ events
- Dedicated $tHq$ and $tHW$ nodes
- Additional ANN inputs:
  - $H\rightarrow bb$ candidate identified with dedicated BDT
  - Fine-grained b-tag information

$tt+2b$: 2 $b$ hadrons close enough to be in a single jet
Backgrounds are crucial

In particular the irreducible tt+bb background:
Lots of work on the theory side, coordinated by the LHC Higgs WG, in the past years

Based on these recommendations, **new setup for ttbb simulation:**
- NLO accuracy simulation using Powheg-Box-Res (*Jezo et al*) with OpenLoops (*Buccioni et al*) in the 4FS
- 4FS preferred since additional b jets are simulated at the ME level
- $\mu_R$ and $\mu_F$ chosen based on several phenomenological studies (*YR4 Jezo et al Cascioli et al Buccioni et al*)

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