Measurements of the Higgs boson by ATLAS and CMS

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Content

- Introduction: LHC, ATLAS and CMS experiments

- The SM-like Higgs boson h: measurements and searches
  - expected production cross sections and branching ratios for SM h
  - measurements of bosonic decay modes: \( ZZ^* \rightarrow 4l, \gamma\gamma, WW^* \rightarrow l\nu l\nu \)
  - measurements of fermionic decay modes: \( \tau\tau \) and \( Vh, h \rightarrow bb \)
  - measurement of \( tth \) production
  - searches for non-resonant \( hh \)-production

- Searches for beyond SM (BSM) Higgs boson (H)
  - searches for BSM double Higgs boson production
  - charged BSM Higgs boson searches
  - searches for MSSM A/H boson

- Conclusion
The Large Hadron Collider (LHC)

- LHC operated with proton-proton (pp)-collisions at $\sqrt{s} = 7$ TeV in 2010-2011 and at 8 TeV in 2012. 50 ns between collisions, 1380 bunches

- After shutdown in 2013-2014 it resumed operation at 13 TeV (25 ns bunch spacing, 2556 bunches)

- Multi-purpose experiments: **ATLAS and CMS**
  Another big experiments: LHCb, ALICE

- Delivered data:
  2011: 5.5 fb$^{-1}$ per ATLAS and CMS
  2012: 23 fb$^{-1}$  2015: 4 fb$^{-1}$
  2016: 40 fb$^{-1}$  2017: 50 fb$^{-1}$  2018: 60 fb$^{-1}$

Luminosity of $2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ is reached in 2017 and 2018 which exceeds the design value by a factor of two

**LHC operated and operates perfectly!**
The ATLAS experiment (JINST 3 (2008) S08003)

>3,000 physicists from 182 institutions representing 38 countries
Main goals: Higgs boson and other SM studies, searches for new physics
The CMS experiment

(JINST 3 (2008) S08004)

>3,000 physicists from about 200 institutions in 42 countries
Main goals: Higgs boson and other SM studies, searches for new physics

Total weight 12500 t, Overall diameter 15 m, Overall length 21.6 m, Magnetic field 4 Tesla
Higgs boson in the Standard Model (SM)

- Higgs boson (h) provides fundamental particles with masses
- Higgs boson mass is the only free parameter in the theory. From theoretical considerations (perturbative unitarity): $m_h < 1$ TeV
- h is expected to have vacuum quantum numbers, i.e. $J^P = 0^+$

What we knew about h boson about ten years ago?

- $m_h > 114.4$ GeV at 95% CL, smaller masses excluded at higher level
  Combined results from four LEP experiments, PL B565 (2003) 61

- $m_h < 152$ GeV at 95% CL, predicted value: $m_h = 94^{+29}_{-24}$ GeV
  from theoretical analysis of EW precision data, http://lepewwg.web.cern.ch

- Discovered by both ATLAS and CMS experiments, $m_h \approx 125$ GeV
  Note. FNAL CDF + D0 experiments found $\approx 3\sigma$ evidence for h boson
Expected SM Higgs boson production cross sections at LHC vs $\sqrt{s}$ vs at $m_h=125$ GeV

$\sigma(pp \to H + X)$ [pb]

- $pp \to H$ (N3LO QCD + NLO EW)
- $pp \to qgH$ (NNLO QCD + NLO EW)
- $pp \to WH$ (NNLO QCD + NLO EW)
- $pp \to ZH$ (NNLO QCD + NLO EW)
- $pp \to bbH$ (NNLO QCD in 5FS; NLO QCD in 4FS)
- $pp \to t\bar{t}H$ (NLO QCD + NLO EW)
- $pp \to tH$ (NLO QCD, t-ch + s-ch)

**Run 1 vs Run 2**

- $ggF$: O(10) pb
- VBF: O(1) pb
- $Vh$: O(1) pb
- $t\bar{t}h$: <1 pb
- $th$: <0.1 pb

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWG#SM_Higgs
CERN Yellow report 4

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10/17/2018
I. Tsukerman, ICPPA2018
### Expected $h$ branching ratios at $m_h=125.09$ GeV

Numbers for the BR are taken from [https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CERNYellowReportPageAt13TeV](https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CERNYellowReportPageAt13TeV)

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>BR, %</th>
<th>Observability in the experiment</th>
<th>Event rates*</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h\rightarrow bb$</td>
<td>57.5 ± 1.9</td>
<td>Mainly in $Vh$ and $tth$ production</td>
<td>&gt;24000/36 fb$^{-1}$</td>
</tr>
<tr>
<td>$h\rightarrow WW^*$</td>
<td>21.6 ± 0.9</td>
<td>Leptonic decays of both $W$</td>
<td>≈17000/36 fb$^{-1}$</td>
</tr>
<tr>
<td>$h\rightarrow gg$</td>
<td>8.56 ± 0.86</td>
<td>no good experimental signature</td>
<td></td>
</tr>
<tr>
<td>$h\rightarrow \tau\tau$</td>
<td>6.30 ± 0.36</td>
<td>Mainly in $VBF$ production</td>
<td>≈10000/36 fb$^{-1}$</td>
</tr>
<tr>
<td>$h\rightarrow cc$</td>
<td>2.90 ± 0.35</td>
<td>Very big continuum background</td>
<td></td>
</tr>
<tr>
<td>$h\rightarrow ZZ^*$</td>
<td>2.67 ± 0.11</td>
<td>Leptonic decays of both $Z$</td>
<td>≈250/36 fb$^{-1}$</td>
</tr>
<tr>
<td>$h\rightarrow \gamma\gamma$</td>
<td>0.228 ± 0.011</td>
<td>Excellent photon resolution</td>
<td>≈5000/36 fb$^{-1}$</td>
</tr>
<tr>
<td>$h\rightarrow Z\gamma$</td>
<td>0.155 ± 0.014</td>
<td>Leptonic decay of $Z$</td>
<td>≈250/36 fb$^{-1}$</td>
</tr>
<tr>
<td>$h\rightarrow \mu\mu$</td>
<td>0.022 ± 0.001</td>
<td>Excellent muon resolution</td>
<td>≈500/36 fb$^{-1}$</td>
</tr>
</tbody>
</table>

*estimated number of events, collected at 13 TeV pp collisions (for 36 fb$^{-1}$ data sample taken in 2015-16) assuming 100% detection efficiency*
"h→ZZ^*→4l" invariant mass spectra at 13 TeV

**ATLAS:** ATLAS-CONF-2018-018

- 195 events observed with $m_{4l}$ 115-130 GeV
- Expected background: 59±4 events
- Expected signal at 125 GeV: 112±5 events

**CMS:** CMS-PAS-HIG-2018-001

- 126 events observed with $m_{4l}$ 117-130 GeV
- Expected background: 39±3 events
- Expected signal at 125.1 GeV: 69±6 events

Very clear maximum around 125 GeV is seen by both experiments.
**h→4l fiducial cross section and signal strength**

**ATLAS:** ATLAS-CONF-2018-018

2015-2017 years:

\[ \frac{\sigma_{\text{meas}}}{\sigma_{\text{SM}}} = \mu = 1.19^{+0.16}_{-0.15} \text{ at 125 GeV} \]

- Measured fid. cross section: 4.0 ±0.5 fb
- Expected fid. cross section: 3.35 ±0.15 fb

**CMS:** CMS-PAS-HIG-2018-001

\[ \mu = 1.06^{+0.15}_{-0.13} \text{ at 125.1 GeV (2016-2017)} \]

- 2015-16 data only, JHEP 1711 (2017) 047:
  - Measured fid. cross section: 2.9 ±0.6 fb
  - Expected fid. cross section: 2.76 ±0.14 fb

- \( h \to ZZ^* \) significance is \( O(10 \sigma) \) in both experiments
- No significant deviation from the SM is observed

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h → γγ invariant mass at 13 TeV

**ATLAS:** ATLAS-CONF-2018-028
Many categories; 733K events selected
Average signal/background ratio ≈0.02
M_{γγ} resolution is ≈1.9 GeV at 125 GeV

**CMS:** arXiv:1804.02716
Many categories
Expected: ≈1800 h → γγ events near 125 GeV
M_{γγ} resolution is about 1.7 GeV at 125 GeV

Clear excess around 125 GeV is seen by both experiments
**h → γγ** signal strength at 13 TeV

**ATLAS:** ATLAS-CONF-2018-028

\[ \mu = 1.06 \pm 0.13 \text{ at } 125.09 \text{ GeV} \]

Measured fid. cross section: \( 60.4 \pm 8.5 \text{ fb} \)

Expected fid. cross section: \( 63.5 \pm 3.3 \text{ fb} \)

**CMS:** arXiv:1804.02716, 1807.03825

\[ \mu = 1.18^{+0.17}_{-0.14} \text{ at } 125.09 \text{ GeV} \]

Measured fid. cross section: \( 84 \pm 13 \text{ fb} \)

Expected fid. cross section: \( 73 \pm 4 \text{ fb} \)

**h → γγ** significance exceeds 5 \( \sigma \) in both experiments

No significant deviation from the SM is observed
h→WW(*) →ℓνν transverse mass at 13 TeV

- Only transverse mass $m_T$ can be reconstructed
- Categories: 0 jets: mainly ggF, 1 jets: ggF+VBF, 2 jets: mainly VBF

**ATLAS:** arXiv:1808.09054

Vh channel not yet included
Same flavours not included

**CMS:** arXiv:1806.05246

Vh channel included
Same flavours included

Big and wide bump around 100-120 GeV is seen by both experiments
h → WW(*) → lνlν signal strength at 13 TeV

**ATLAS:** arXiv:1808.09054

- Observed significance: 6.3 σ
- Expected significance: 5.2 σ

\[ \mu_{ggF} = 1.21^{+0.22}_{-0.21}, \mu_{VBF} = 0.62^{+0.37}_{-0.36} \]

**CMS:** arXiv:1806.05246

- Observed significance: 9.1 σ
- Expected significance: 7.1 σ
- Fiducial cross sections measured

\[ \mu_{ggF} = 1.38^{+0.21}_{-0.24}, \mu_{VBF} = 0.29^{+0.66}_{-0.29} \]

**Graphs:**
- ATLAS: \( \sqrt{s} = 13 \text{ TeV}, 36.1 \text{ fb}^{-1} \)
  - 68% CL
  - 95% CL
  - Best fit
  - SM

- CMS: \( 35.9 \text{ fb}^{-1} \) (13 TeV)
  - h → WW* significance exceeds 5 σ in each experiment
  - No significant deviation from the SM is observed
$h \to \tau\tau$ invariant mass at 13 TeV

- Many event categories to improve signal significance
- Signature: two reconstructed taus in $ll$, $l\ell h$ and $hh$ decay modes
- Major role of VBF and “boosted $h \to \tau\tau$” categories

**ATLAS:** ATLAS-CONF-2018-021

**CMS:** PL B779 (2018) 283

Big and wide bump around 125 GeV is seen by both experiments
h→ττ signal strength at 13 TeV

**ATLAS:** ATLAS-CONF-2018-021

\[ \mu = 1.09 \pm 0.26 \text{ at } 125 \text{ GeV} \]

Observed significance: 4.9 \( \sigma \), 5.9\( \sigma \) with Run1

Expected significance: 4.7 \( \sigma \), 5.9\( \sigma \) with Run1

\[ \mu = 1.09 \pm 0.36 \text{ at } 125.1 \text{ GeV} \]

Observed significance: 4.4 \( \sigma \), 6.4\( \sigma \) with Run1

Expected significance: 4.1 \( \sigma \), 5.4\( \sigma \) with Run1

**CMS:** PL B779 (2018) 283

h→ττ significance exceeds 5 \( \sigma \) in both experiments

No significant deviation from the SM is observed
(W+Z)h, h→bb invariant mass at 13 TeV

- Separate final states with 0 (Z→vv), 1 (W→ν) and 2 (Z→ll) leptons
- Signatures: two b-jets and tight lepton(s) or large $E_T^{\text{miss}}$
- Many variables in multivariate analysis to separate signal from background
- Successful validation of the analysis procedure on (W/Z)Z with Z→bb

**ATLAS:** PL B786 (2018) 59

**CMS:** arXiv:1808.08242, PRL accepted

Wide bump around 125 GeV is seen by both experiments
\((W+Z)h, \, h\rightarrow bb\) signal strength at 13 TeV

**ATLAS:** PL B786 (2018) 59

\[ \mu = 1.01 \pm 0.20 \text{ at 125 GeV for VH only} \]

Obs. significance: 4.9 \(\sigma\), 5.4 \(\sigma\) with Run1

Exp. significance: 4.4 \(\sigma\), 5.5 \(\sigma\) with Run1

**CMS:** arXiv:1808.08242, PRL accepted

\[ \mu = 1.04 \pm 0.20 \text{ at 125 GeV including non-Vh} \]

Obs. signific.: 4.8 \(\sigma\), 5.6 \(\sigma\) including non-Vh

Exp. signific.: 4.9 \(\sigma\), 5.5 \(\sigma\) including non-Vh

\[ \leq 5.1 \text{ fb}^{-1} (7 \text{ TeV}) + \leq 19.8 \text{ fb}^{-1} (8 \text{ TeV}) + \leq 77.2 \text{ fb}^{-1} (13 \text{ TeV}) \]

\(H\rightarrow bb\)

- **ATLAS**
  - VH, \(H\rightarrow bb\)
  - Total
  - Stat.
  - \(\mu = 1.08 \pm 0.35\)

- **CMS**
  - Observed
  - \(\pm 1\sigma\) (stat \(\oplus\) syst)
  - \(\pm 1\sigma\) (syst)

- **Comb.**
  - \(\mu = 0.98 \pm 0.21\)

\(h\rightarrow bb\) significance exceeds 5 \(\sigma\) in both experiments

No significant deviation from the SM is observed
Observation of tth production

- Yukawa coupling of h to top can be directly constrained using \( pp \rightarrow tth + X \) process
- Final states with \( h \rightarrow ZZ^*, WW^*, \tau\tau \) (multi-leptons), bb, \( \gamma\gamma \)

**ATLAS:** PL B784 (2018) 173

**CMS:** PRL120 (2018) 231801
Observation of $tth$ production at 13 TeV

**ATLAS:** PL B784 (2018) 173

$\mu = 1.32^{+0.28}_{-0.26}$ at 125.1 GeV

Observed significance: $5.8 \sigma$, $6.3 \sigma$ with Run1
Exp. significance: $4.9 \sigma$, $5.1 \sigma$ with Run1

**CMS:** PRL120 (2018) 231801

$\mu = 1.26^{+0.31}_{-0.26}$ at 125.1 GeV

Observed significance: $5.2 \sigma$
Expected significance: $4.2 \sigma$

$tth$ significance exceeds $5 \sigma$ in both experiments
No significant deviation from the SM is observed
Higgs boson combination at 13 TeV: production

\[ \mu = 1.13^{+0.09}_{-0.08} \text{ at } 125.09 \text{ GeV} \]

\[ \mu = 1.17^{+0.10}_{-0.10} \text{ at } 125.09 \text{ GeV} \]

All four main production modes are observed by each experiment.
No significant deviation from the SM is found assuming SM branching ratios.
Higgs boson combination at 13 TeV: decays

**ATLAS:** CONF-2018-031

**CMS:** HIG-17-031

**July 2018**

**September 2018**

For $bb$, only $36 \, fb^{-1}$ result included

All five main decay modes are observed by each experiment

No significant deviation from the SM is found assuming SM production modes
Limits on non-resonant hh production at 13 TeV

**ATLAS**: ATLAS-CONF-2018-043

Three decay combinations of two h-bosons are joined to put a limit on non-resonant hh-production

**CMS**: PAS-HIG-17-030

Four decay combinations of two h-bosons are joined to put a limit on non-resonant hh-production

Aiming for observation of the SM hh-production with 3000 fb⁻¹
Non-SM Higgs bosons

- SM-like Higgs boson (h) with $m_h=125$ GeV was discovered six years ago. Great success of the SM, however it does not explain many things.

- Many extensions of the SM proposed by theorists were rejected after this discovery, but some of them have not been excluded.

- BSM models with additional Higgs bosons
  - Electroweak singlet (EWS) models which includes extra heavy scalar higgs boson
  - Another models include additional Higgs doublet (2HDM):
    - 5 Higgs bosons
      
      Parameters: Higgs boson masses, ratio of VEV for two doublets ($\tan \beta$), mixing angle between H and h ($\alpha$), potential parameter mixing the two doublets ($m_{12}^2$)

Minimal supersymmetric models (MSSM) are subset of 2HDM
Similar combinations of hh-decays are used to search for H→hh resonance

ATLAS: ATLAS-CONF-2018-043

CMS: PAS-HIG-17-030

95% CL limits vary from 1pb at 300 GeV to 20 fb at 1 TeV

95% CL limits vary from O(1 pb) at 300 GeV to 3.5 fb at 3 TeV

ATLAS Preliminary

$\sqrt{s} = 13$ TeV, 27.5 - 36.1 fb$^{-1}$ spin-0

$95\%$ CL limits vary from 1pb at 300 GeV to 20 fb at 1 TeV
Charged Higgs boson searches

- $H^\pm$ in MSSM. Relation between $m_{top}$ and $M_{H^\pm}$ dictates both production mode and decay channels

- Charged Higgs boson in 2HDM cascade

  - Low mass $H^\pm$:
    - $H^\pm bWb$ final state
    - $H^\pm \rightarrow cs$ at $\tan \beta < 1$
    - $H^\pm \rightarrow \tau \nu_\tau$ at $\tan \beta > 1$

  - High mass $H^\pm$:
    - $tH^\pm$ final state
    - $H^\pm \rightarrow \tau \nu_\tau$ is OK

- Charged Higgs boson in 2HDM cascade

  - $A^0$ is assumed to be too heavy
  - $h^0$ is 125 GeV Higgs boson
  - Final state is $WWbb$ as for $tt$-background
H$^+ \rightarrow \tau\nu$ at 13 TeV

- Search mass range: 90-2000 GeV for ATLAS, 80-3000 GeV for CMS, production mode $pp \rightarrow tbH^+$ ($m_{H^+} > m_{\text{top}}$)
- Final states with one $\tau$-lepton and $W \rightarrow$ hadrons
- Interpretation in hMSSM benchmark scenario

![Diagrams for tbH$^+$ production](image)

**ATLAS**

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

- Observed (95% CL)
- $\pm 1\sigma$
- $\pm 2\sigma$
- Expected (95% CL)
- 2015 result

![Graph](image)

Limits on $\sigma(pp \rightarrow tbH^+) \times BR(H^+ \rightarrow \tau\nu)$:

- 4.2 (0.0025) pb at 90 (2000) GeV

**CMS**

PAS-HIG-18-014

![Graph](image)

Limits on $\sigma(pp \rightarrow tbH^+) \times BR(H^+ \rightarrow \tau\nu)$:

- 6 (0.005) pb at 80 (3000) GeV
A/H^0 \to \tau\tau at 13 TeV

- Search mass range: 200-2250 GeV
- Production via gluon fusion or b-associated
- hh and hh final states of two taus
- Interpretation in MSSM benchmark scenarios

Limits on $\sigma \times BR(H/A \to \tau\tau)$ for ggF:
- 780 (5.8) fb at 200 (2250) GeV
Limits on $\sigma \times BR(H/A \to \tau\tau)$ for bbH/A:
- 700 (3.7) fb at 200 (2250) GeV

Limits on $\sigma \times BR(H/A \to \tau\tau)$ for ggF:
- 18 pb (3.5 fb) at 90 (3200) GeV
Limits on $\sigma \times BR(H/A \to \tau\tau)$ for bbH/A:
- 15 pb (2.5) fb at 90 (3200) GeV
Conclusion

With 7-13 TeV LHC data, the ATLAS and CMS collaborations observed four main production mechanisms and five main decays of the Higgs boson. Their cross sections / branching ratios were measured. They all agree with the SM predictions.

With the same datasets, ATLAS and CMS measured some differential cross sections for the SM-like Higgs boson and compared them with the most recent theoretical calculations.

ATLAS and CMS also performed searches for non-standard Higgs bosons in many final states. Nothing was found yet. Strict limits on production cross sections of new scalars were put.

ATLAS and CMS continues to improve existing measurements and to search for deviations from the SM with new 13 TeV data and, in the future, will use 14 TeV data.
Backup slides

- Combined $h$ differential cross sections at 13 TeV
- Searches for $h/H \rightarrow \text{invisible}$ at 13 TeV
- Brief summary of $h$ results at 7 and 8 TeV
- Perspectives of $h/H$ searches and measurements at HL-LHC
- Off-shell $h \rightarrow 4\ell$ at 13 TeV in CMS
- Measurement of Higgs boson mass at 13 TeV
- Simplified template $h$ cross sections in ATLAS at 13 TeV
- Low mass spin-0 diphoton resonances at 13 TeV
- Searches for $H^+ \rightarrow t\bar{b}$ at 13 TeV in ATLAS
- Fiducial volume definitions for $h \rightarrow 4\ell$ and $\gamma\gamma$ cross sections
- $H \rightarrow \gamma\gamma$ and $H \rightarrow Z\gamma$ exclusion at 13 TeV
- FCNC $t \rightarrow hc(u)$ in ATLAS and $th$-production in CMS

ATLAS public results: https://twiki.cern.ch/twiki/bin/view/AtlasPublic

Combined $h \rightarrow 4l$, $\gamma \gamma$ diff. cross sections in ATLAS

ATLAS-CONF-2018-002

No significant difference with recent theoretical calculations is observed
No significant difference with recent theoretical calculations is observed
H → invisible

- In the SM, $B(h → \text{inv.}) = B(h → ZZ^{(*)} → 4\nu) = O(10^{-3})$, but it can be larger in BSM.
- Such a decay is a good WIMP and/or Dark Matter candidate.
- The best way to search is to use VBF mechanism; signature is large $E_T^{\text{miss}}$.

ATLAS

- $13$ TeV, $36$ fb$^{-1}$
- $90\%$ CL results
- Higgs portals:
  - Scalar WIMP
  - Fermion WIMP
- Other expts:
  - LUX
  - PandaX-II
  - Xenon1T

CMS

- $90\%$ CL limits $B(H → \text{inv}) < 0.22$
- $35.9$ fb$^{-1}$ (13 TeV)
- Direct detection:
  - LUX
  - CDMSLite
  - XENON-1T
  - CRESST-II
  - PandaX-II
Brief summary of $h$ results at 7-8 TeV

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Reference</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>125.36±0.41 GeV</td>
<td>PR D90 (2014) 052004</td>
<td>125.09±0.24 GeV with CMS</td>
</tr>
<tr>
<td>Signal strength vs SM</td>
<td>1.18±0.15</td>
<td>EPJC76 (2016) 6</td>
<td>1.09±0.10 with CMS</td>
</tr>
<tr>
<td>in $h \rightarrow \gamma \gamma$ mode</td>
<td>1.17±0.28</td>
<td>EPJC76 (2016) 6</td>
<td>5.2σ (discovery)</td>
</tr>
<tr>
<td>in $h \rightarrow 4l$ mode</td>
<td>1.46±0.40</td>
<td>EPJC76 (2016) 6</td>
<td>8.1σ (discovery)</td>
</tr>
<tr>
<td>in $h \rightarrow WW' \rightarrow l\nu\nu$</td>
<td>1.18±0.24</td>
<td>EPJC76 (2016) 6</td>
<td>6.5σ (discovery)</td>
</tr>
<tr>
<td>in $h \rightarrow \tau\tau$ mode</td>
<td>1.44±0.42</td>
<td>EPJC76 (2016) 6</td>
<td>4.5σ (evidence)</td>
</tr>
<tr>
<td>in $h \rightarrow bb$ mode</td>
<td>0.63±0.39</td>
<td>EPJC76 (2016) 6</td>
<td>1.4σ</td>
</tr>
<tr>
<td>in ggF production</td>
<td>1.23±0.23</td>
<td>EPJC76 (2016) 6</td>
<td>1.03±0.17 with CMS</td>
</tr>
<tr>
<td>in VBF production</td>
<td>1.23±0.32</td>
<td>EPJC76 (2016) 6</td>
<td>1.18±0.25 with CMS</td>
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<tr>
<td>in Vh production</td>
<td>0.80±0.36</td>
<td>EPJC76 (2016) 6</td>
<td>0.84±0.40 with CMS</td>
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<tr>
<td>in tth production</td>
<td>1.81±0.80</td>
<td>EPJC76 (2016) 6</td>
<td>2.3±0.7 with CMS</td>
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<tr>
<td>Spin/parity</td>
<td>0+</td>
<td>EPJC 75 (2015) 476</td>
<td>4l, $NN$, $\gamma\gamma$ modes</td>
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<tr>
<td>Width</td>
<td>&lt;22.7 MeV (95% CL)</td>
<td>EPJC 75 (2015) 335</td>
<td>Off-shell $h \rightarrow WW/ZZ$</td>
</tr>
<tr>
<td>BR($h \rightarrow$ invisible)</td>
<td>&lt;0.28 (95% CL)</td>
<td>JHEP 01 (2016) 172</td>
<td>WIMP searches</td>
</tr>
</tbody>
</table>

No significant deviation from the SM is observed
Higgs boson perspectives at HL-LHC: recent notes

**ATLAS:**
- $Vh, \, h \rightarrow cc \quad$ PUB-2018-016
- $h \rightarrow \mu \mu \quad$ PUB-2018-006
- EFT $H \rightarrow 4l \, , \gamma \gamma \quad$ PUB-2017-018
- Theory uncertainty \quad PUB-2018-010
- $hh \rightarrow bb \gamma \gamma \quad$ PUB-2017-001
- $hh \rightarrow bbbb \quad$ PUB-2016-024
- $tthh \quad$ PUB-2016-023
- $VBF \, H \rightarrow WW \quad$ PUB-2016-018

...and more results at:

**CMS:**

- $h \rightarrow ZZ, \, \gamma \gamma \, ; \, BSM \, H \rightarrow \tau \tau, \, \text{invisible and} \, hh \, : \quad$
  - CMS-PAS-FTR-16-002 (ECFA 2016)
- $hh \rightarrow bb \gamma \gamma, \, bb \tau \tau, \, bbWW: \quad$ CMS-PAS-FTR-15-002
  ...and more results at:

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsFP

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/PUBnotes
Higgs boson perspectives: ATLAS and CMS

ATLAS-PHYS-PUB-2014-016

**ATLAS** Simulation Preliminary
\( \sqrt{s} = 14 \text{ TeV}: \int L dt = 300 \text{ fb}^{-1} ; \int L dt = 3000 \text{ fb}^{-1} \)

- \( H \rightarrow \gamma \gamma \) (comb.)
- \( H \rightarrow ZZ \) (comb.)
- \( H \rightarrow WW \) (comb.)
- \( H \rightarrow Z\gamma \) (incl.)
- \( H \rightarrow b\bar{b} \) (comb.)
- \( H \rightarrow \tau \tau \) (VBF-like)
- \( H \rightarrow \mu \mu \) (comb.)

\[ \Delta \mu/\mu \]

<table>
<thead>
<tr>
<th>( H \rightarrow \gamma \gamma )</th>
<th>( H \rightarrow WW )</th>
<th>( H \rightarrow ZZ )</th>
<th>( H \rightarrow b\bar{b} )</th>
<th>( H \rightarrow \tau \tau )</th>
<th>( H \rightarrow \mu \mu )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>0.05</td>
<td>0.10</td>
<td>0.00</td>
<td>0.10</td>
<td>0.00</td>
</tr>
</tbody>
</table>

CMS Projection

Expected uncertainties on Higgs boson signal strength

- \( 300 \text{ fb}^{-1} \) at \( \sqrt{s} = 14 \text{ TeV} \) Scenario 1
- \( 3000 \text{ fb}^{-1} \) at \( \sqrt{s} = 14 \text{ TeV} \) Scenario 2

\[ \Delta \mu/\mu \]

<table>
<thead>
<tr>
<th>( H \rightarrow \gamma \gamma )</th>
<th>( H \rightarrow WW )</th>
<th>( H \rightarrow ZZ )</th>
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</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>0.05</td>
<td>0.10</td>
<td>0.00</td>
<td>0.10</td>
</tr>
</tbody>
</table>

17.10.2018

И. Цукерман, ОФН РАН 2014
Off-shell $h \to 4l$ at 13 TeV in CMS

The measured value is compatible with the SM prediction.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Observed</th>
<th>Expected</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Gamma_H$ (MeV)</td>
<td>$3.2^{+2.8}_{-2.2}$ [0.08, 9.16]</td>
<td>$4.1^{+5.0}_{-4.0}$ [0.0, 13.7]</td>
</tr>
</tbody>
</table>
Higgs boson combination: mass at 13 TeV

**ATLAS:** PL B784 (2018) 345

**CMS:** JHEP 11 (2017) 047

4/ mass $125.26 \pm 0.21$ GeV
Simplified template x-sections for $h \rightarrow 4l$ at 13 TeV

**Stage 0**
- Particle level production bins
  - $= 0$-jet
    - $p_T^{l} < 60$ GeV
    - $60 < p_T^{l} < 120$ GeV
    - $p_T^{l} > 120$ GeV
  - $= 1$-jet
    - $60 < p_T^{l} < 120$ GeV
    - $p_T^{l} > 120$ GeV
  - $\geq 2$-jets
- $p_T^{l} < 200$ GeV
- $p_T^{l} > 200$ GeV

**Reduced Stage 1**
- $ggF-0j$
- $ggF-1j; p_T^{l} < 60$ GeV
- $ggF-1j; p_T^{l} = 60 < p_T^{l} < 120$ GeV
- $ggF-1j; p_T^{l} > 120$ GeV
- $ggF-2j$

**Reconstructed event categories**
- $N_{jet} = 0, p_T^{l} < 100$ GeV
  - $0j; p_T^{l} < 60$ GeV
  - $1j; p_T^{l} < 60$ GeV
  - $1j; 60 < p_T^{l} < 120$ GeV
  - $1j; p_T^{l} = 120$ GeV
- $N_{jet} = 1$
  - $1j; p_T^{l} > 120$ GeV
- $N_{jet} \geq 2$
  - $m_{bb} > 120$ GeV
  - $m_{bb} \leq 120$ GeV
- $N_{lep} = 0, p_T^{l} > 100$ GeV
  - $0j; p_T^{l} > 120$ GeV
  - $VH-Lep$
  - $ttH-Lep$
  - $ttH-Had$

**ATLAS Preliminary**
- 13 TeV, 79.8 fb$^{-1}$
Simplified template x-sections for $h \rightarrow \gamma \gamma$ at 13 TeV

<table>
<thead>
<tr>
<th>STXS Regions</th>
<th>Reconstruction Categories</th>
</tr>
</thead>
<tbody>
<tr>
<td>[0-jet]</td>
<td>ggF 0J Fwd, Cen (28, 29)</td>
</tr>
<tr>
<td>$p_T^H &lt; 60\text{ GeV}$</td>
<td>ggF 1J Low (27)</td>
</tr>
<tr>
<td>$60 \leq p_T^H &lt; 120\text{ GeV}$</td>
<td>ggF 1J Med (26)</td>
</tr>
<tr>
<td>$120 \leq p_T^H &lt; 200\text{ GeV}$</td>
<td>ggF 1J High (25)</td>
</tr>
<tr>
<td>$p_T^H &gt; 200\text{ GeV}$</td>
<td>ggF 1J BSM (24)</td>
</tr>
<tr>
<td>not VBF-like,</td>
<td>ggF 2J Low (23)</td>
</tr>
<tr>
<td>$p_T^H &lt; 60\text{ GeV}$</td>
<td>ggF 2J Med (22)</td>
</tr>
<tr>
<td>$60 \leq p_T^H &lt; 120\text{ GeV}$</td>
<td>ggF 2J High (21)</td>
</tr>
<tr>
<td>$120 \leq p_T^H &lt; 200\text{ GeV}$</td>
<td>VBF low-$p_T^{Hjj}$ BDT tight, loose (18, 19)</td>
</tr>
<tr>
<td>$p_T^{Hjj} &lt; 25\text{ GeV}$</td>
<td>VBF high-$p_T^{Hjj}$ BDT tight, loose (16, 17)</td>
</tr>
<tr>
<td>$p_T^{Hjj} \geq 25\text{ GeV}$</td>
<td>VH had BDT tight, loose (14, 15)</td>
</tr>
<tr>
<td>not VBF-like, $ \geq 2$-jet</td>
<td>qqH BSM (13)</td>
</tr>
<tr>
<td>$p_T^H &lt; 200\text{ GeV}$</td>
<td>VH lep High, Low (9, 10)</td>
</tr>
<tr>
<td>$p_T^H \geq 25\text{ GeV}$</td>
<td>(Z$\rightarrow \nu\nu$) VH MET High, Low (11, 12)</td>
</tr>
<tr>
<td>$p_T^{Hjj} &lt; 25\text{ GeV}$</td>
<td>(Z$\rightarrow \ell\ell$) VH dilep (8)</td>
</tr>
<tr>
<td>$p_T^{Hjj} \geq 25\text{ GeV}$</td>
<td>(had decays) ttH had BDT1-4 (4-7)</td>
</tr>
<tr>
<td>VH-like $\geq 2$-jet</td>
<td>(lep decays) ttH lep BDT1-3 (1-3)</td>
</tr>
<tr>
<td>VH-like $\geq 2$-jet</td>
<td>Rest</td>
</tr>
<tr>
<td>VH-like $\geq 2$-jet</td>
<td>VH</td>
</tr>
<tr>
<td>VH-like $\geq 2$-jet</td>
<td>qq $\rightarrow WH$</td>
</tr>
<tr>
<td>VH-like $\geq 2$-jet</td>
<td>qq $\rightarrow ZH$, $gg \rightarrow ZH$</td>
</tr>
</tbody>
</table>

*VBF-like: $m_{jj} > 400\text{ GeV}$, $|\Delta y_{jj}| > 2.8$

**VH-like: $60 < m_{jj} < 120\text{ GeV}$

---

ATLAS preliminary

10/17/2018

I. Tsukerman, ICPPA2018
Low mass scalar $X \rightarrow \gamma \gamma$ at 13 TeV

- **ATLAS**: ATLAS-CONF-2018-025
- **CMS**: PAS-HIG-17-013

No significant deviation from the SM is observed
H$^+ \rightarrowtb$ at 13 TeV in ATLAS

- Search mass range: 300-1000 GeV
- Production mode $pp \rightarrow tbH^+$ ($m_{H^+} > m_{top}$)
- Multi-jet final states with one lepton from top
- Multivariate analysis, interpretation within benchmark scenarios of MSSM models

Limits on $\sigma(pp \rightarrow tbH^+) \times BR(H^+ \rightarrow tb)$:
2.9 (0.070) pb at 200 (2000) GeV
Short-term LHC and ATLAS (CMS) perspectives

- **2018**: collection of $\approx 55$-$60$ fb$^{-1}$ of pp collision data at 13 TeV
  Complete ATLAS and CMS data samples will correspond to about 150 fb$^{-1}$
  A lot of papers is planned based on these ("Run 2") data samples

- **2019-2020**: LHC/ATLAS + CMS Upgrade Phase-I
  They should be upgraded to operate at luminosity up to $3 \times 10^{34}$ cm$^{-2}$ s$^{-1}$

- **2021-2023**: Run 3 at 14 TeV energy aimed to collect 300 fb$^{-1}$
  More precise measurements of $h(125)$ couplings, and its main decay channels
  Discovery of new physics or set of strict upper limits on cross sections
  Rare $b$-meson decays, investigation of QGP in PbPb-collisions

- **2024-2026**: LHC/experiments Phase-II Upgrade
  High Luminosity (HL)-LHC, the project is under development
  ATLAS and CMS should work at up to $7 \times 10^{34}$ cm$^{-2}$ s$^{-1}$ luminosities
  For the LHCb experiment Phase-II upgrade will be in 2030.
**ATLAS and CMS perspectives for Higgs boson**

- Precise measurement of five main decay modes
  - 10-20% with 300 fb$^{-1}$, 5-10% with 3000 fb$^{-1}$
  - This precision depends on theory uncertainty to be reached in the future

- Measurement of rare $h$ boson decay modes
  - 40-50% (15-30%) for $\mu\mu$ and $Z\gamma$ for 300 (3000) fb$^{-1}$
  - Also attempt to observe $h \rightarrow cc$, $h \rightarrow J/\psi\gamma$, $Y\gamma$ decay modes with 3000 fb$^{-1}$

- Measurement of the SM $hh$ production ($hhh$ coupling)
  - Might be possible only for 3000 fb$^{-1}$ provided many decay combinations of both higgs bosons will be performed

- Discovery / evidence for BSM Higgs boson(s)?
  - If not, strict limits on their production cross sections using different production mechanisms and decay modes as much as possible
Long-term LHC plans and FCC-hh

- **2026-2037** – HL-LHC stage
  - Full data sample 14 TeV – 3000-4000 fb\(^{-1}\)
  - Precision measurements of h(125) coupling, its rare decays
  - Further search of new physics, very rare decays of heavy flavours

- **After 2037**: new (hadron) supercolliders?
  - FCC-hh at CERN (pp: 28-100 TeV) or SppC in China (71 TeV)
  - Another options at CERN: FCC-eh, FCC-ee…

---

### Parameter Comparison

<table>
<thead>
<tr>
<th>Parameter</th>
<th>FCC-hh</th>
<th>SppC</th>
<th>LHC</th>
<th>HL LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>collision energy cms [TeV]</td>
<td>100</td>
<td>71.2</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>dipole field [T]</td>
<td>16</td>
<td>20</td>
<td>8.3</td>
<td></td>
</tr>
<tr>
<td># IP</td>
<td>2 main + 2</td>
<td>2</td>
<td>2 main + 2</td>
<td></td>
</tr>
<tr>
<td>bunch intensity ([10^{11}])</td>
<td>1</td>
<td>1 (0.2)</td>
<td>2</td>
<td>1.1</td>
</tr>
<tr>
<td>bunch spacing [ns]</td>
<td>25</td>
<td>25 (5)</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>luminosity/(lp) ([10^{34} \text{ cm}^{-2}\text{s}^{-1}])</td>
<td>5</td>
<td>~25</td>
<td>12</td>
<td>1</td>
</tr>
<tr>
<td>events/bunch crossing</td>
<td>170</td>
<td>~850 (170)</td>
<td>400</td>
<td>27</td>
</tr>
<tr>
<td>stored energy/beam [GJ]</td>
<td>8.4</td>
<td>6.6</td>
<td>0.36</td>
<td>0.7</td>
</tr>
<tr>
<td>E-loss/turn synchrotron radiation/beam</td>
<td>5 MeV</td>
<td>2 MeV</td>
<td>7 keV</td>
<td>7 keV</td>
</tr>
<tr>
<td></td>
<td>3 MW</td>
<td>5.8 MW</td>
<td>5.4 kW</td>
<td>9.5 kW</td>
</tr>
</tbody>
</table>
Fiducial volume definition for $h \to 4\ell$

<table>
<thead>
<tr>
<th>Leptons and jets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leptons: $p_T &gt; 5$ GeV, $</td>
</tr>
<tr>
<td>Jets: $p_T &gt; 30$ GeV, $</td>
</tr>
<tr>
<td>remove jets with: $\Delta R(\text{jet}, \ell) &lt; 0.1$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Lepton kinematics and isolation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leading lepton $p_T$: $p_T &gt; 20 \text{ GeV}$</td>
</tr>
<tr>
<td>Subleading lepton $p_T$: $p_T &gt; 10 \text{ GeV}$</td>
</tr>
<tr>
<td>Additional electrons (muons) $p_T$: $p_T &gt; 7 \text{ (5) GeV}$</td>
</tr>
<tr>
<td>Pseudorapidity of electrons (muons): $</td>
</tr>
<tr>
<td>Sum $p_T$ of all stable particles within $\Delta R &lt; 0.3$ from lepton: $&lt; 0.35 p_T$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Lepton selection and pairing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lepton kinematics: $p_T &gt; 20, 15, 10 \text{ GeV}$</td>
</tr>
<tr>
<td>Leading pair ($m_{12}$): SFOS lepton pair with smallest $</td>
</tr>
<tr>
<td>Subleading pair ($m_{34}$): remaining SFOS lepton pair with smallest $</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Event selection (at most one quadruplet per event)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass requirements: $50 \text{ GeV} &lt; m_{12} &lt; 106 \text{ GeV}$ and $12 \text{ GeV} &lt; m_{34} &lt; 115 \text{ GeV}$</td>
</tr>
<tr>
<td>Lepton separation: $\Delta R(\ell_i, \ell_j) &gt; 0.1$</td>
</tr>
<tr>
<td>$J/\psi$ veto: $m(\ell_i, \ell_j) &gt; 5 \text{ GeV}$ for all SFOS lepton pairs</td>
</tr>
<tr>
<td>Mass window: $115 \text{ GeV} &lt; m_{4\ell} &lt; 130 \text{ GeV}$</td>
</tr>
<tr>
<td>If extra leptons with $p_T &gt; 12 \text{ GeV}$: Quadruplet with the largest ME</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Event topology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existence of at least two same-flavor OS lepton pairs, where leptons satisfy criteria above</td>
</tr>
<tr>
<td>Invariant mass of the $Z_1$ candidate: $40 &lt; m_{Z_1} &lt; 120 \text{ GeV}$</td>
</tr>
<tr>
<td>Invariant mass of the $Z_2$ candidate: $12 &lt; m_{Z_2} &lt; 120 \text{ GeV}$</td>
</tr>
<tr>
<td>Distance between selected four leptons: $\Delta R(\ell_i, \ell_j) &gt; 0.02$ for any $i \neq j$</td>
</tr>
<tr>
<td>Invariant mass of any opposite-sign lepton pair: $m_{\ell^+\ell^-} &gt; 4 \text{ GeV}$</td>
</tr>
<tr>
<td>Invariant mass of the selected four leptons: $105 &lt; m_{4\ell} &lt; 140 \text{ GeV}$</td>
</tr>
</tbody>
</table>
Fiducial volume definition for $h \rightarrow \gamma \gamma$

### Objects Definition

<table>
<thead>
<tr>
<th>Sources</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photons</td>
<td>$</td>
</tr>
<tr>
<td>Jets</td>
<td>$</td>
</tr>
<tr>
<td>- Central jets</td>
<td>$</td>
</tr>
<tr>
<td>- $b$-jets</td>
<td>$</td>
</tr>
<tr>
<td>Leptons, $\ell = e$ or $\mu$</td>
<td>$p_T &gt; 10$ GeV, $</td>
</tr>
<tr>
<td></td>
<td>$p_T &gt; 10$ GeV, $</td>
</tr>
</tbody>
</table>

### Fiducial region Definition

<table>
<thead>
<tr>
<th>Sources</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diphoton fiducial</td>
<td>$N_\gamma \geq 2$, $p_T^{2\gamma} &gt; 0.35 \cdot m_{\gamma \gamma}$, $p_T^{2\gamma} &gt; 0.25 \cdot m_{\gamma \gamma}$</td>
</tr>
<tr>
<td>$N_{b\text{-jets}}$ measurement</td>
<td>Diphoton fiducial, $N_{\text{jets}} \geq 1$, $N_{\text{leptons}} = 0$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Phase space</th>
<th>Observable</th>
<th>Bin boundaries</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>$N_\text{jet}$</td>
<td>0 15 30 45 80 120 200 350 $\infty$</td>
</tr>
<tr>
<td></td>
<td>$</td>
<td>\cos(\theta^*)</td>
</tr>
<tr>
<td></td>
<td>$p_T^{\gamma\gamma}$ (GeV), $N_\text{jet} = 0$</td>
<td>0 20 60 $\infty$</td>
</tr>
<tr>
<td></td>
<td>$p_T^{\gamma\gamma}$ (GeV), $N_\text{jet} = 1$</td>
<td>0 60 120 $\infty$</td>
</tr>
<tr>
<td></td>
<td>$p_T^{\gamma\gamma}$ (GeV), $N_\text{jet} &gt; 1$</td>
<td>0 150 300 $\infty$</td>
</tr>
<tr>
<td></td>
<td>$N_\text{jet}$</td>
<td>0 1 2 $\infty$</td>
</tr>
<tr>
<td></td>
<td>$N_{\text{leptons}}$</td>
<td>0 1 2 $\infty$</td>
</tr>
<tr>
<td></td>
<td>$p_T^{\text{miss}}$ (GeV)</td>
<td>0 100 200 $\infty$</td>
</tr>
<tr>
<td>1-jet</td>
<td>$p_T^{\gamma\gamma}$ (GeV)</td>
<td>0 45 70 110 200 $\infty$</td>
</tr>
<tr>
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<td>$</td>
<td>\eta</td>
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<tr>
<td></td>
<td>$</td>
<td>\Delta \phi^{\gamma\gamma}$</td>
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<tr>
<td></td>
<td>$</td>
<td>\Delta \phi^{\gamma\gamma}$</td>
</tr>
<tr>
<td>2-jets</td>
<td>$p_T^{\gamma\gamma}$ (GeV)</td>
<td>0 45 90 $\infty$</td>
</tr>
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<td>\eta</td>
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<td></td>
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<td>\Delta \phi^{\gamma\gamma}$</td>
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<td>\Delta \phi^{\gamma\gamma}$</td>
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<tr>
<td>VBF-enriched</td>
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<td></td>
<td>$</td>
<td>\Delta \phi^{\gamma\gamma}$</td>
</tr>
<tr>
<td></td>
<td>$</td>
<td>\Delta \phi^{\gamma\gamma}$</td>
</tr>
<tr>
<td>2-jets +</td>
<td>$</td>
<td>\Delta \eta^{\gamma\gamma}$</td>
</tr>
<tr>
<td>$m^{\gamma\gamma} &gt; 200$ GeV</td>
<td>$</td>
<td>\Delta \phi^{\gamma\gamma}$</td>
</tr>
<tr>
<td></td>
<td>$</td>
<td>\Delta \phi^{\gamma\gamma}$</td>
</tr>
</tbody>
</table>
Higgs boson combination at 13 TeV: couplings

**ATLAS:** CONF-2018-031  
**CMS:** HIG-17-031

ATLAS Preliminary

$\sqrt{s} = 13$ TeV, $36.1 - 79.8$ fb$^{-1}$

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

SM Higgs boson

- $m^F_{FV}$ or $\sqrt{m^V_{FV}}$
- Ratio to SM

CMS

$35.9$ fb$^{-1}$ (13 TeV)

- $m^F_{FV}$ or $\sqrt{m^V_{FV}}$
- (M, $\varepsilon$) fit
- $\pm 1\sigma$
- $\pm 2\sigma$
**h→μμ and h→Zγ exclusion at 13 TeV**

**ATLAS:** CONF-2018-026, 80 fb⁻¹

- At \( m_H = 125 \) GeV for \( μμ \) mode
  - Observed exclusion: \( 2.1 \, \sigma/\sigma_{SM} \)
  - Expected exclusion: \( 2.0 \, \sigma/\sigma_{SM} \)

- Expected \( B(h→Z\gamma→ee/μμ\gamma) = 5 \times 10^{-5} \) only, sizeable background

**CMS:** arXiv:1807.06325, 36 fb⁻¹

- At \( m_H = 125 \) GeV for \( μμ \) mode
  - Obs. exclusion: \( 2.95 \, \sigma/\sigma_{SM} \), 2.92 with Run 1
  - Exp. exclusion: \( 2.45 \, \sigma/\sigma_{SM} \), 2.16 with Run 1
  - Observed \( B(H→μμ) < 0.00064 \)

Expected \( B(h→μμ) = 2.2 \times 10^{-4} \) only, large DY background

**ATLAS:** JHEP10 (2017)112

- At \( m_H = 125 \) GeV for \( Z\gamma \) mode based on 36 fb⁻¹
  - Observed exclusion: \( 6.6 \, \sigma/\sigma_{SM} \)
  - Expected exclusion: \( 5.2 \, \sigma/\sigma_{SM} \)

**CMS:** arxiv:1806.05996

- At \( m_H = 125 \) GeV for combined \( Z(\ast)\gamma + γ^∗γ \) mode based on 36 fb⁻¹
  - Observed exclusion: \( 3.9 \, \sigma/\sigma_{SM} \)
  - Expected exclusion: \( 2.0 \, \sigma/\sigma_{SM} \)

One needs HL-LHC to observe the signal in these modes.
FCNC $t \rightarrow hc(u)$ in ATLAS and $th$-production in CMS

**ATLAS:** PR D98 (2018) 032002, 36 fb$^{-1}$

- Observed exclusion: $B(t \rightarrow hc) < 0.16\%$
- $B(t \rightarrow hu) < 0.19\%$

- Expected exclusion: $B(t \rightarrow hc) < 0.15\%$
- $B(t \rightarrow hu) < 0.15\%$

**CMS:** PAS-HIG-18-009, 36 fb$^{-1}$

- Data favour positive value of the modifier of Higgs-top coupling $\kappa_t$ by $1.5 \sigma$ and exclude regions $[-0.9 - 0.5]$ and $[1.0 - 2.1]$ at 95% CL
Some models with heavy Higgs bosons

- Most studied are two simple extensions to the SM:
  - Electroweak singlet (EWS)
    - New scalar singlet $s$ that mixes with $h$.
  - 2-Higgs-Doublet Model (2HDM)
    - Extra Higgs doublet.
    - Physical particles $h, H, A, H^\pm$.
    - Parameters:
      - Masses: $m_h, m_H, m_A, m_{H^\pm}$.
      - VEV ratio of the two doublets: $\tan \beta$.
      - Mixing angle between $h, H$: $\alpha$.
      - Potential parameter mixing the two doublets: $m_{12}^2$.
    - Different ways to couple doublets with other particles; most studied:
      - Type-I: All quarks couple to only one doublet.
      - Type-II: Up-type quarks couple to one doublet, down-type quarks to the other.
  - MSSM is a subset of 2HDM.
  - Numerous MSSM benchmark models:
    - hMSSM, $m_h^{\text{mod}^+}$, etc.

Denote the 125 GeV resonance as ‘$h$’; $H$ is a heavier resonance.