Standard Model Higgs Boson Measurements at the LHC

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SUSY2019
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Outline

• Standard Model Higgs Boson cross sections and branching fractions at the LHC
• The Higgs boson we have discovered
• Current status:
  • Mass, spin, width
  • Couplings to fermions observed
  • Couplings to the top quark observed
• Current Focus: ‘Simplified Template’ and differential cross section measurements
• Recent highlights from CMS and from ATLAS
• Summary and conclusions
• Acknowledgements
Significant increase in production rate due to higher center-of-mass energy from LHC Run-1 to Run-2!
"This result constitutes evidence for the existence of a new massive state that decays into two photons."

"Clear evidence for the production of a neutral boson ... is presented."

Goal for Runs 1-3 of the LHC and beyond:
- Measure its mass and other properties including couplings
- Is it alone? (see talk by A-M Magnan)
Current status: Mass

**ATLAS**
- Run 1: $\sqrt{s} = 7-8$ TeV, 25 fb$^{-1}$; Run 2: $\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$

- **Run 1**
  - $H \rightarrow 4\ell$: $m_H = 124.51 \pm 0.52$ (stat) GeV
  - $H \rightarrow \gamma\gamma$: $m_H = 126.02 \pm 0.51$ (stat) GeV

- **Run 2**
  - $H \rightarrow 4\ell$: $m_H = 124.79 \pm 0.37$ (stat) GeV
  - $H \rightarrow \gamma\gamma$: $m_H = 124.93 \pm 0.40$ (stat) GeV

- **Run 1+2**
  - $H \rightarrow 4\ell$: $m_H = 124.71 \pm 0.30$ (stat) GeV
  - $H \rightarrow \gamma\gamma$: $m_H = 125.32 \pm 0.35$ (stat) GeV

- **Combined**
  - Run 1: $m_H = 125.38 \pm 0.41$ (stat) GeV
  - Run 2: $m_H = 124.86 \pm 0.27$ (stat) GeV
  - Run 1+2: $m_H = 124.97 \pm 0.24$ (stat) GeV

**ATLAS + CMS Run 1**
- $m_H = 125.09 \pm 0.21$ GeV


**JHEP 11 (2017) 047**

**Current status**

$m_H = 124.97 \pm 0.24$ (stat) GeV

Compare to Run 1 ATLAS + CMS combined: $m_H = 125.09 \pm 0.21$ (stat) $\pm 0.11$ (scale) $\pm 0.02$ (other) $\pm 0.01$ (theory) GeV

→ Single experiments now better, still statistics-dominated
Current status: Spin and width

Run 1 results: compatible with Spin-0 and CP-even, CP-even/odd mix not ruled out

Width: Exploit coupling ratio between off- and on-shell production

$\Gamma < 14.4 \text{ MeV (15.2 exp.) @ 95% C.L.}$

Run 2, $H \rightarrow ZZ^* \rightarrow 4\ell + 2\ell2\nu$

$\Gamma < 9.16 \text{ MeV (13.7 exp.) @ 95% C.L.}$

Run 1 + Run2, $H \rightarrow ZZ^* \rightarrow 4\ell$

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Current status: Decays to fermions observed

H → ττ Single-experiment observations (Run1 + 2016 data)

VH, H → bb Single-experiment observations (Run1 + 2016/17 data)


Current status: Coupling to top quark observed

**ttH: Single-experiment observations w/combined channels:**
- CMS (Run1 + 2016 data)
- ATLAS (2016/2017 data)

**ttH, H → γγ Single-channel 4.1σ evidence:**
- CMS (2016/2017 data)

**ATLAS: Single-channel 4.9σ observation:**
- Full Run 2

**References:**
- Phys. Rev. Lett. 120 (2018) 231801

**Note:**
- CMS-PAS-HIG-18-018
- ATLAS-CONF-2019-004
- S. Gascon-Shotkin SUSY2019 20 May 2019
• Measure cross sections for the different production modes, split more finely into kinematic regions

• Results less model-dependent, more adapted for kinematically-dependent interpretations (EFT...)

• Also continue to target traditional differential cross section measurements
Recent CMS Results: \( ttH, H \rightarrow \gamma\gamma \)

- **BDT used in all classes**

- **2016-2017 combined \( \mu \)**
Recent CMS Results: ttH, multilepton ($\tau_h$) final states

- 7 event classes including **1 new**: $2\ell + 2\tau_h$
- Signal extracted by fit to BDT discriminants
- Main systematic uncertainty from fake background yield estimate
- Observed (expected) combined (2016+2017) signal rate: $0.96^{+0.34}_{-0.31} (1.00^{+0.30}_{-0.27})$ times SM $\Rightarrow$ observed (expected) significance: $3.2\sigma (4.0\sigma)$
Recent CMS Results: ttH, H→bb

- Improved QCD rejection in fully-hadronic channel: $\Delta \eta_{jets}$
- Dilepton channel: MEM→input to BDT

- Improved ‘deep learning’ b-tag→up to 18% improvement in per-class significance
- 3.9σ evidence (3.5σ expected) achieved combining 2016/17
Recent CMS Results: $H \rightarrow \tau\tau$

CMS-PAS-HIG-18-032

- Probes $\mu$, $e\tau$, $\mu\tau$ and $\tau_1\tau_2$ final states with 2016/17 data
- Signal extracted with fit to neural network output dist’n

- Inclusive and per-process $\mu$ and $\sigma$, $\sigma$ also in STXS bins

<table>
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<tr>
<th>Variable</th>
<th>$e\mu$</th>
<th>$e\tau$</th>
<th>$\mu\tau$</th>
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</table>

- $\mu$ of quark- vs gluon-initiated processes, $K_F$ vs $K_V$

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Recent CMS Results: $H \rightarrow \gamma\gamma$ STXS

- 2016/17 data combined permits cross section measurements in STXS ‘stage 1’ with some bins merged: 7- and 13-bin variants
- All measurements in agreement with SM predictions
Recent CMS Results: $H \rightarrow ZZ^* \rightarrow 4\ell$ Full Run 2

CMS-PAS-HIG-19-001

- Fiducial cross section $\sigma_{fid} = 2.73^{+0.23}_{-0.22}$(stat.)$^{+0.24}_{-0.19}$(syst.) fb
- $\sigma_{SM} = 2.76 \pm 0.14$ fb
- As well as at the other 2 $\sqrt{s}$

Cross-section measurements in many STXS bins (‘Stage 1.1’) and differential measurements in several variables possible, all compatible with SM predictions.

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Recent ATLAS Results: VH, $H \rightarrow bb$

- Target leptonic $V$ decays, dedicated BDT
- Differential measurements in STXS Stage 1 bins
- Constraints set on coefficients of the five $OW$, $OB$, $OHW$, $OHB$ and $Od$ operators in the ‘Higgs Effective Lagrangian’ (HEL) implementation
Recent ATLAS Results: Combined Cross Section Measurements

**ATLAS Preliminary**

*ATLAS* 

$\sqrt{s} = 13$ TeV, 24.5 - 79.8 fb$^{-1}$

$m_{\ell\ell} = 125.09$ GeV, $|y_{\ell\ell}| < 2.5$

$P_{\text{SM}} = 76\%$

**Cross-section normalized to SM value**

- $\mu = 1.11^{+0.09}_{-0.08} = 1.11 \pm 0.05(\text{stat.})^{+0.05}_{-0.04}(\text{exp.})^{+0.05}_{-0.04}(\text{sig. th.}) \pm 0.03(\text{bkg. th.})$
- Overall signal strength: Improved wrt ATLAS+CMS Run 1 except for bkg.
- theory uncertainty, no longer statistics-dominated

<table>
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<tr>
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<th>Total</th>
<th>Stat</th>
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<th>SM</th>
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<td>VBF</td>
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<td>1.21</td>
<td>±0.24</td>
<td>±0.17</td>
<td>±0.15</td>
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</table>

**ATLAS CONF-2019-005**

- Overall $\mu$ agree with SM prediction

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**Best fit $\mu$**

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<th>Thbgd</th>
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<td>1.09</td>
<td>+0.11</td>
<td>+0.07</td>
<td>+0.04</td>
<td>+0.03</td>
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<tr>
<td>ATLAS + CMS (expected)</td>
<td>1.09</td>
<td>-0.10</td>
<td>-0.07</td>
<td>-0.04</td>
<td>-0.03</td>
</tr>
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</table>
Recent ATLAS Results: STXS Cross Section Measurements

ATLAS Preliminary

\( \tilde{t}\tilde{t} = 13 \text{ TeV}, 36.1 - 79.8 \text{ fb}^{-1} \)

\( m_H = 125.09 \text{ GeV}, |y_H| < 2.5 \)

\( \rho_{\text{SM}} = 81\% \)

<table>
<thead>
<tr>
<th>( gg \rightarrow H \rightarrow H \rightarrow )</th>
<th>Total</th>
<th>Stat.</th>
<th>Syst.</th>
<th>SM</th>
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<tbody>
<tr>
<td>0-jet</td>
<td>1.18</td>
<td>±0.13 (±0.10, ±0.09)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1-jet, ( p_T^J &lt; 60 \text{ GeV} )</td>
<td>0.53</td>
<td>±0.39 (±0.32, ±0.22)</td>
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<td>1-jet, ( 60 \leq p_T^J &lt; 120 \text{ GeV} )</td>
<td>0.82</td>
<td>±0.30 (±0.28, ±0.17)</td>
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<td>1-jet, ( 120 \leq p_T^J &lt; 200 \text{ GeV} )</td>
<td>1.18</td>
<td>±0.68 (±0.58, ±0.36)</td>
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<td>( H \rightarrow W^+W^- \rightarrow JJJ )</td>
<td>1.79</td>
<td>±0.62 (±0.53, ±0.32)</td>
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<tr>
<td>( H \rightarrow bb \rightarrow JJJ )</td>
<td>1.02</td>
<td>±0.48 (±0.39, ±0.29)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Ratios of BR set to SM values, generally good agreement with SM predictions

- ‘Stage 1’ scheme with some bins merged

- Ratios of BR set to SM values, generally good agreement with SM predictions

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Recent ATLAS Results: Constraints on H self-coupling

...with a single Higgs boson!

- Use VBF and VH cross section measurements in Stage 1 STXS bins, parametrized as function of $\kappa_\lambda = \lambda_3 / \lambda_{3}^{\text{SM}}$

- Crucial assumption: All Higgs boson couplings are SM-like

- Exclude $\kappa_\lambda = [-3.2, 11.9] \ @ \ 95\% \ CL$ (compare to $[-5.0, 12.1]$ for di-Higgs with 36.1fb-1)
The «κ» framework: Definitions and Methodology

- Relationship between signal strengths $\mu$ and coupling modifiers $\kappa$

\[
\sigma_i = \kappa_i^2 \ast \sigma_i(SM), \quad \Gamma_f = \kappa_f^2 \ast \Gamma_f(SM) \Rightarrow \\
\mu^f_i = \kappa_i^2 \ast \kappa_f^2 / (\Gamma_H/\Gamma_H(SM))
\]

- Effective coupling modifiers $\kappa_g$, $\kappa_\gamma$ for loops (describing $ggF$ production and $H \rightarrow \gamma\gamma$ decay)

- Coupling modifier ratios $\lambda_{ij} = \kappa_i / \kappa_j$

- All measurements assume the combined mass measurement exact value: $m_H = 125.09 \text{ GeV}$

- Production processes: $ggF$, VBF, WH, ZH, ttH

- Decay channels: $H \rightarrow ZZ, WW, \gamma\gamma, \tau\tau, bb, \mu\mu$

- Parameter estimation via profile lh ratio test statistic $\Lambda$ and estimator $q = -2\ln\Lambda$ assumed $X^2$
ATLAS & CMS: Generic Parametrization

\[ J. \text{High Energy Phys. } 08 \text{ (2016) 045} \]

\[ \text{arXiv:1809.10733, accepted by Eur.Phys J.C} \]

- **ATLAS+CMS Run 1**: \( \text{BR}_{\text{BSM}} < 0.34 @95\%\text{CL} \)

- **CMS 2016**: \( B_{\text{inv}} < 0.22, B_{\text{undet}} < 0.38 \)

- **ATLAS 2016/17**: \( B_{\text{inv}} < 0.30, B_{\text{undet}} < 0.38, \quad \text{BR}_{\text{BSM}} = B_{\text{inv}} + B_{\text{undet}} < 0.47 \) (\( H \rightarrow ZZ^* \) offshell included)

- **Allow BSM loop contributions + either BSM contributions to \( \Gamma_H (\kappa_v \leq 1) \)** or not (\( \text{BR}_{\text{BSM}} = 0 \))

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ATLAS & CMS: $\kappa$ framework constrained scenarios

- Assume no BSM loop contributions and $\text{BR}_{\text{BSM}} = 0$: Coupling modifiers to fermions vs. to vector bosons

- Assume BSM contributions from loops only ($\text{BR}_{\text{BSM}} = 0$), other $\kappa$ fixed to SM values: Effective coupling modifiers $\kappa_g$, $\kappa_\gamma$ for loops describing ggF production and $H \rightarrow \gamma\gamma$ decay

J. High Energy Phys. 08 (2016) 045
ATLAS-CONF-2019-005

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ATLAS & CMS: Mass-scaled $\kappa$ vs. Mass

- Assume no BSM loop contributions and $\text{BR}_{\text{BSM}} = 0$

\[ \text{J. High Energy Phys. 08 (2016) 045} \]

\[ \text{arXiv:1809.10733, accepted by Eur.Phys J.C} \]

\[ \text{ATLAS-CONF-2019-005} \]
Conclusions and Perspectives

• Most Run 2 full-statistics results are still to come (~140fb⁻¹)

• Perspectives for Run 3 (2021-2023): Hope for >150fb⁻¹ at \( \sqrt{s} = 14 \text{ TeV} \)

• HL-LHC: Starts 2026, expect 3ab⁻¹, hope for ~2-4% precision for most couplings
Acknowledgements


- The Organizers and staff at Texas A&M University Corpus Christi
Backup
## Recent CMS Results: $ttH \rightarrow \text{multilepton}$

**CMS-PAS-HIG-18-019**

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