The status of HH searches at the LHC

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on behalf of the ATLAS and CMS Collaborations

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SM Higgs Boson Pair Production

- After discovering the Higgs boson, the ultimate probe of the Standard Model is to fully measure the Higgs potential

- Higgs self-coupling fundamental parameter of the Standard Model

\[
V(\Phi) = \frac{1}{2} \mu^2 \Phi^2 + \frac{1}{4} \lambda \Phi^4 = \lambda \nu^2 h^2 + \lambda \nu h^3 + \frac{1}{4} \lambda h^4
\]

- Rare process of the Standard Model
  - Destructive interference
  - \( \sigma_{SM}(gg \rightarrow HH) = 33.5 \text{ fb} \approx 1\% \cdot \sigma_{SM}(gg \rightarrow H) \) at 13 TeV
BSM Higgs Boson Pair Production

- Non-resonant HH production
  - BSM contribution can modify the Higgs boson coupling parameters and enhance the HH cross section

- Resonant HH production
  - Various models expect a new particle decaying into a Higgs boson pair
  - Randall-Sundrum graviton (spin-2): $G \rightarrow hh$
  - 2HDM heavy Higgs boson (spin-0): $H \rightarrow hh$
Higgs Boson Pair Decays

- Many final states to explore
  - $bbbb$: largest branching fraction
  - $bb\gamma\gamma$ and $WW\gamma\gamma$: clean diphoton signature
- Searches in marked final states will be presented using:
  - ATLAS: 2015-2016 dataset, 36.1 fb$^{-1}$
  - CMS: 2016 dataset, 35.9 fb$^{-1}$
- Also, see Agni Bethani’s talk on ATLAS searches for $VH/HH$ resonances

<table>
<thead>
<tr>
<th></th>
<th>$bb$</th>
<th>$WW$</th>
<th>$\tau\tau$</th>
<th>$ZZ$</th>
<th>$\gamma\gamma$</th>
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<tr>
<td>$bb$</td>
<td>33%</td>
<td></td>
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<td></td>
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<tr>
<td>$WW$</td>
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<td>25%</td>
<td></td>
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<td>$\tau\tau$</td>
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<td>7.4%</td>
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<td>$ZZ$</td>
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<td>1.2%</td>
<td>0.34%</td>
<td>0.076%</td>
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<tr>
<td>$\gamma\gamma$</td>
<td>0.26%</td>
<td>0.10%</td>
<td>0.029%</td>
<td>0.013%</td>
<td>0.0053%</td>
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# Searches for Higgs Boson Pair Production

## Searches for Higgs Boson Pair Production in ATLAS

<table>
<thead>
<tr>
<th>Process</th>
<th>Reference</th>
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<tbody>
<tr>
<td>$H H \rightarrow bbbb$</td>
<td>JHEP 01 (2019) 030</td>
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<tr>
<td>$H H \rightarrow bbWW \rightarrow bbqq\ell\nu$</td>
<td>JHEP 04 (2019) 092</td>
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<tr>
<td>$H H \rightarrow bb\tau\tau$</td>
<td>Phys. Rev. Lett. 121, 191801 (2018)</td>
</tr>
<tr>
<td>$H H \rightarrow WWWW$</td>
<td>arXiv:1811.11028</td>
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<tr>
<td>$H H \rightarrow bb\gamma\gamma$</td>
<td>JHEP 11 (2018) 040</td>
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<tr>
<td>$H H \rightarrow WW\gamma\gamma$</td>
<td>Eur. Phys. J. C 78 (2018) 1007</td>
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<tr>
<td>Combination</td>
<td>New results paper in preparation</td>
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## Searches for Higgs Boson Pair Production in CMS

<table>
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<tr>
<th>Process</th>
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<tbody>
<tr>
<td>$H H \rightarrow bbbb$ non-resonant</td>
<td>JHEP 04 (2019) 112</td>
</tr>
<tr>
<td>$H H \rightarrow bbbb$ resonant</td>
<td>JHEP 08 (2018) 152</td>
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<tr>
<td>$H H \rightarrow bbqq\ell\nu$</td>
<td>arXiv:1904.04193</td>
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<tr>
<td>$H H \rightarrow bbl\nu\ell\nu$</td>
<td>JHEP 01 (2018) 054</td>
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<tr>
<td>$H H \rightarrow bb\tau\tau$</td>
<td>Phys. Lett. B 778 (2018) 101</td>
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<tr>
<td>$H H \rightarrow bb\gamma\gamma$</td>
<td>Phys. Lett. B 788 (2018) 7</td>
</tr>
</tbody>
</table>
**HH → bbbb Analyses**

- Largest branching ratio
- Resolved and boosted topologies considered
- **ATLAS**
  - Resolved: $b$-jet triggers, 4 $b$-tagged jets
  - Boosted: large-$R$ jet trigger, 2 large-$R$ jets, with 2/3/4 small-$R$ $b$-tagged track-jets
  - Signal region: both Higgs candidate masses consistent with expected $m_h$ within resolution
  - Discriminating variable: $m_{hh}$ invariant mass
- **CMS**
  - Resolved: jet (including $b$-jet) triggers, 4 $b$-tagged jets
  - Boosted: jet (including $b$-jet) triggers, 2 large-$R$ jets, dedicated MVA “double-$b$-tagger” used to identify Higgs candidates
  - Discriminating variable: BDT score (resolved) and $m_{hh}$ invariant mass (boosted)
- Main backgrounds: multi-jet and $t\bar{t}$
**HH → bbbb Results**

- **Non-resonant hh production:** observed (expected) 95% CL upper limit on $\sigma(hh) \times BR(bbbb)$:
  - ATLAS: 147 fb $= 12.9 \cdot \sigma_{SM}$ (20.7 $\cdot \sigma_{SM}$)
  - CMS: 847 fb (419 fb)

- **Resonant hh production:** 2HDM interpretation:
  - No significant excess observed
  - ATLAS: largest deviation at 280 GeV, 3.6$\sigma$ local (2.3$\sigma$ global) significance
  - CMS: largest deviation at 460 GeV, 2.6$\sigma$ local significance
$HH \rightarrow bbWW$ Analyses

- **ATLAS ($bbqq\ell\nu$)**
  - Resolved: 1 $\ell$, $E_T^{\text{miss}}$, 4 small-$R$ jets (2 $b$-jets)
  - Boosted: 1 $\ell$, $E_T^{\text{miss}}$, 1 large-$R$ $b$-jet, 2 small-$R$ jets
  - Discriminating variable: $m_{HH}$ invariant mass

- **CMS**
  - $bbqq\ell\nu$:
    - 1 $\ell$, $E_T^{\text{miss}}$, 1 large-$R$ $b$-jet, 1 large-$R$ jet
    - Likelihood fit in 2D plane of $m_{bb}$ and $m_{HH}$
  - $bb\ell\nu\ell\nu$:
    - 2 OS leptons ($e$ or $\mu$), 2 $b$-tagged jets
    - Discriminating variable: DNN output

- Dominant backgrounds: $tt$, $W$+jets, multi-jet
$HH \rightarrow bbWW$ Results

- **Non-resonant $hh$ production:** observed limits
  - ATLAS $\sigma(hh) \times BR(bbWW) = 2.5$ pb ($300\sigma_{SM}$)
  - CMS $\sigma(hh) \times BR(bbl\nu\ell\nu) = 72$ fb ($79\cdot\sigma_{SM}$)

- **Resonant $hh$ production:** 2HDM interpretation:
  - ATLAS ($bbqq\ell\nu$): set limits between 5.6 pb ($m_X = 500$ GeV) and 0.2 pb ($m_X = 3$ TeV)
  - CMS ($bbqq\ell\nu$): set limits between 123 fb ($m_X = 800$ GeV) and 8.3 fb ($m_X = 3.5$ TeV)
  - CMS ($bbl\nu\ell\nu$): set limits between 430 fb ($m_X = 260$ GeV) and 17 fb ($m_X = 900$ GeV)
**HH → bbττ Analyses**

**ATLAS**
- Two channels:
  - two hadronically decaying taus
  - one hadronically and one leptonically decaying tau
- 2 taus (at least one hadronically decaying), 2 small-$R$ or 1 large-$R$ b-jets
- BDT trained to discriminate signal from backgrounds, separate BDT for each mass hypothesis
- Discriminating variable: BDT score

**CMS**
- Two channels:
  - two hadronically decaying taus
  - one hadronically and one leptonically decaying tau
- $e/\mu/\tau_h + \tau_h$, 2 small-$R$ or 1 large-$R$ b-jets
- Discriminating variable: $m_{HH}^{K_{in}F}$ (resonant), $m_{T2}$ (non-resonant)
- Dominant backgrounds: $t\bar{t}$, multi-jet, $Z+\text{jets}$
**HH → bbττ** Results

- **Non-resonant hh production**: observed (expected) 95% CL upper limits on $\sigma(hh) \times BR(bb\tau\tau)$:
  - **ATLAS**: $30.9 \text{ fb} = 12.7 \cdot \sigma_{SM} \ (36.0 \text{ fb})$
  - **CMS**: $75.4 \text{ fb} = 30 \cdot \sigma_{SM} \ (61.0 \text{ fb})$

- **Resonant hh production**: hMSSM interpretation:
  - No significant excess observed
  - **ATLAS**: masses between $305 \text{ GeV}$ and $402 \text{ GeV}$ excluded for $\tan \beta = 2$
  - **CMS**: masses between $230 \text{ GeV}$ and $360 \text{ GeV}$ excluded for $\tan \beta = 1$

- The $\tan \beta$ is the ratio of the vacuum expectation values of the two Higgs doublets
**HH → WWWW Analyses**

- Cut and count analysis
- Three channels defined by number of leptons
  - Two (same sign) leptons: $ee$, $e\mu$, $\mu\mu$, $E_T^{\text{miss}}$, at least two jets, $b$-jet veto
  - Three leptons: total charge $\pm 1$, $E_T^{\text{miss}}$, at least two jets, $b$-jet veto
  - Four leptons: total charge 0, $b$-jet veto
- Dominant backgrounds: Diboson, $tV$, $ttV/H$ and $VVV$, $W+\text{jets}$, $tt\bar{t}$
**$HH \rightarrow WWWW$ Results**

- **Non-resonant $hh$ production:** observed (expected) 95% CL upper limits on $\sigma(hh)$:
  - ATLAS: $5.3 \text{ pb} = 160 \cdot \sigma_{\text{SM}} (3.8 \text{ pb})$

- **Resonant $hh$ production:** 2HDM interpretation:
  - No significant excess observed
  - ATLAS: set limits between $9.3 \text{ pb}$ ($m_X = 260 \text{ GeV}$) and $2.8 \text{ pb}$ ($m_X = 500 \text{ GeV}$)
**HH → bbγγ Analyses**

- **ATLAS**
  - 2 photons, 2 jets (1 or 2 b-tags)
  - $m_{jj}$ invariant mass compatible with the mass of the Higgs boson
  - Discriminating variables: $m_{\gamma\gamma}$ (non-resonant) and $m_{\gamma\gamma jj}$ (resonant)
  - Particularly sensitive at low masses

- **CMS**
  - 2 photons, 2 jets
  - $m_{\gamma\gamma}$ and $m_{jj}$ in Higgs mass window
  - BDT classifier, including b-tagging information to select signal-like events
  - Discriminating variable: $m_{\gamma\gamma}$ and $m_{jj}$

- Dominant backgrounds:
  - $\gamma\gamma$-continuum, single Higgs
**HH → bbγγ Results**

- **Non-resonant hh production:** observed (expected) 95% CL upper limits on $\sigma(hh)$:
  - ATLAS: $0.73 \text{ pb} = 22 \cdot \sigma_{SM} (0.93 \text{ pb})$
  - CMS: $0.79 \text{ pb} = 24 \cdot \sigma_{SM} (0.63 \text{ pb})$

- **Resonant hh production:** 2HDM interpretation:
  - No significant excess observed
  - ATLAS: set limits between $1.14 \text{ pb}$ ($m_X = 260 \text{ GeV}$) and $0.12 \text{ pb}$ ($m_X = 1 \text{ TeV}$)
  - CMS: set limits between $0.23 \text{ fb}$ ($m_X = 250 \text{ GeV}$) and $4.2 \text{ fb}$ ($m_X = 750 \text{ GeV}$)
**HH → WWγγ Analyses**

- 2 photons, 1 e or μ, 2 jets ($WW → ℓνqq$)

- Parameterized fit to $m_{γγ}$

- Dominant backgrounds: $γγ$-continuum, single Higgs
**HH → WWγγ Results**

- **Non-resonant hh production:** observed (expected) 95% CL upper limit on $\sigma(hh) \times BR(WWγγ)$
  - ATLAS: 7.5 fb = $230 \cdot \sigma_{SM}$ (5.3 fb)

- **Resonant hh production:** 2HDM interpretation:
  - No significant excess observed
  - ATLAS: set limits between 40 pb ($m_X = 260$ GeV) and 6.1 pb ($m_X = 500$ GeV)
Combinations

Non-resonant $HH$ production

- Statistical combination of the most sensitive individual channels

ATLAS new results:

- $HH \rightarrow bbbb$
- $HH \rightarrow bbWW$
- $HH \rightarrow bb\tau\tau$
- $HH \rightarrow WWWW$
- $HH \rightarrow bb\gamma\gamma$
- $HH \rightarrow WW\gamma\gamma$

- Observed: $6.9 \cdot \sigma_{SM}$
- Expected: $10.0 \cdot \sigma_{SM}$

CMS:

- $HH \rightarrow bbbb$
- $HH \rightarrow bb\tau\tau$
- $HH \rightarrow bb\gamma\gamma$
- $HH \rightarrow bbVV \ (V = W \ or \ Z)$

- Observed: $22.2 \cdot \sigma_{SM}$
- Expected: $12.8 \cdot \sigma_{SM}$
Combinations

Limits on $\kappa \lambda$

- Combined limits on $\kappa \lambda = \lambda_{HHH}/\lambda_{SM}$
- All couplings except the Higgs boson self-coupling $\lambda_{HHH}$ set to their SM values

- ATLAS allowed range:
  - Observed: $-5.0 < \kappa \lambda < 12.0$
  - Expected: $-5.8 < \kappa \lambda < 12.0$

- CMS allowed range:
  - Observed: $-11.8 < \kappa \lambda < 18.8$
  - Expected: $-7.1 < \kappa \lambda < 13.6$
Combinations
Resonant $HH$ production

- Combined limits on scalar resonance corresponding to CP-even heavy Higgs in hMSSM (2HDM) model
- No significant excess observed
- ATLAS: set upper limits between 4 fb and 1 pb
- CMS: set upper limits between 4 fb and 2 pb
Conclusions & Summary

- ATLAS and CMS are highly active in searching for Higgs boson pair production. Effort to cover maximum final states.

- Shown recent searches based on $36.1 \text{ fb}^{-1}$ (ATLAS) and $35.9 \text{ fb}^{-1}$ (CMS) of LHC Run-2 data

- Improved sensitivity using boosted techniques and machine learning

- No excess in non-resonant production, limits $6.9 - 22.2 \cdot \sigma_{\text{SM}}$

- No significant excess observed in resonance search

- Analyzing full Run-2 dataset, $140 \text{ fb}^{-1}$