ATLAS searches for resonances decaying to boson pairs

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on behalf of the ATLAS collaboration
Analyses covered in this talk:

- $Z' \to H$ with $H \to bb$: *Phys. Rev. Lett. 125, 251802*
- $H^{\pm\pm}$ and $H^\pm$ into $2l^{\text{SC}}, 3l, 4l$: *CERN-EP-2020-240*
- Heavy diphoton resonances: *CERN-EP-2020-248*
- $HH \to \gamma\gamma bb$: *ATLAS-CONF-2021-016*

Data:

- 2015-2018
- 139 fb$^{-1}$ @ 13 TeV
- Pileup = O(30-40) close to average for full dataset
- Different trigger settings
Z’ → Hy with H → bb
Novel b-jet identification technique

Photon $p_T > 200$ GeV

250 GeV < $p_{T,\text{jet}}$ < 400 GeV

800 GeV < $p_{T,\text{jet}}$ < 1000 GeV

1500 GeV < $p_{T,\text{jet}}$ < 2000 GeV

The CoM algorithm

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MC studies show that the two b-tagging efficiencies are **uncorrelated** → Can use ttbar events for calibration

- MC studies show that the b-tagging efficiency is almost identical in top vs H → bb decays
- Estimated MC-to-data scale factor is consistent with 1 (within 5% syst)
Z' → Hy with H → bb

New mass range:

0.7-4 TeV

Old mass range:

0.72-3.25 TeV

Photon $p_T > 200$ GeV

$$B(m_{J\gamma}) = (1 - x)^{p_1} x^{p_2 + p_3 \log(x)} \quad x = m_{J\gamma}/\sqrt{s}, \quad \sqrt{s} = 13\text{ TeV}$$

Data are compatible with background-only hypothesis

Previous results:

**H^{±±} and H^{±} into 2l^{SC}, 3l, 4l**

Framework

Type-II seesaw model (J. Schechter and J. W. F. Valle, 1980)
Considering an additional Y=2 scalar triplet acquiring vev=100MeV at EWSB

**Scenario #1:**

\[ m_{H^{±}} > 100 \text{ GeV} + m_{H^{±±}} \]

**Scenario #2 (new):**

\[ m_{H^{±}} < 5 \text{ GeV} + m_{H^{±±}} \]

BR = 40-60%
Other contributions are negligible after 2l^{SC} or 3l selection

Considering only \( m_{H^{±±}} > 200 \text{ GeV} \)

BR = 100%
H$^{±±}$ and H$^{±}$ into 2l$^{SC}$, 3l, 4l

Lepton fake factors

Increased statistics allowed for improvement in lepton fake factors (non-prompt lepton background) and their uncertainties

<table>
<thead>
<tr>
<th></th>
<th>electron</th>
<th>muon</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>fake factor</td>
<td></td>
</tr>
<tr>
<td></td>
<td>stat. Uncertainty</td>
<td>total uncertainty</td>
</tr>
<tr>
<td>2lSC</td>
<td>0.03 @ pT=40 GeV</td>
<td>30% @ 20 GeV &lt; pT &lt; 60 GeV</td>
</tr>
<tr>
<td></td>
<td>0.16 @ pT&gt;60 GeV (was 0.48)</td>
<td>55% @ pT &gt; 60 GeV (was 35%)</td>
</tr>
<tr>
<td>3l</td>
<td>0.021 @ pT=40 GeV</td>
<td>60% @ pT &gt; 60 GeV</td>
</tr>
<tr>
<td></td>
<td>0.009 @ pT&gt;60 GeV (was 0.39)</td>
<td>(was 55%)</td>
</tr>
<tr>
<td>4l</td>
<td>insufficient statistics</td>
<td></td>
</tr>
</tbody>
</table>

H$^{\pm\pm}$ and H$^\pm$ into 2$\ell$\textsuperscript{sc}, 3$\ell$, 4$\ell$

Systematic uncertainties

ATLAS
\[ \sqrt{s} = 13 \text{ TeV} \ 139 \text{ fb}^{-1} \]

<table>
<thead>
<tr>
<th>Relative uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total uncertainty</td>
</tr>
<tr>
<td>Charge-flip stat</td>
</tr>
<tr>
<td>Non-prompt lepton stat</td>
</tr>
<tr>
<td>MC statistical unct.</td>
</tr>
<tr>
<td>Charge-flip syst</td>
</tr>
<tr>
<td>Background normalisation unct.</td>
</tr>
<tr>
<td>Experimental unct.</td>
</tr>
</tbody>
</table>

$2\ell^{\text{sc}}$, 3$\ell$, 4$\ell$

$m_{H^{\pm\pm}} = 200 \text{ GeV}$

$m_{H^{\pm\pm}} = 300 \text{ GeV}$

$m_{H^{\pm\pm}} = 400 \text{ GeV}$

$m_{H^{\pm\pm}} = 500 \text{ GeV}$
**Results**

Data agree with background-only hypothesis.
Heavy diphoton resonances

Framework

- Two benchmark models:
  - Spin 0 (generic resonance $X$) with $m_X = 200 – 3000$ GeV and $\Gamma_X$ either 4 MeV (Narrow Width Approximation) or $\Gamma_X = 0\text{–}10\% m_X$
  - Spin 2 (lowest KK graviton in RS1 model) with $m_{G^*} > 500$GeV and $k/M_{Pl} = 0.01 – 0.1$
- Novelties of the analysis:
  - Common event selection for the two searches
  - **Functional decomposition** method (*arXiv:1805.04536*) to assess spurious signal uncertainty
  - Updated photon reconstruction, identification, isolation and energy calibration
Heavy diphoton resonances

Functional decomposition

Smallest (= fewest dof) function which maintains the flexibility to model all variations of background template:

\[ f(x; b, a_0, a_1) = N \left( 1 - x^{1/3} \right)^b x^{a_0 + a_1 \log(x)} \]

\[ x = m_{\gamma\gamma} / \sqrt{s} \]

Fitted signal yields are considered spurious signals

Functional decomposition:

1) Fit the background template with orthonormal exponentials
2) Bin the smoothed template
3) Use it to determine the spurious signal via a sig+bkg model

Sensitivity improves by 2-28 %

Repeated experiments: the bias is the same between unsmoothed and smoothed templates, and both are much smaller than the spurious signal uncertainty

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Heavy diphoton resonances

Result

The RS1 model is excluded for $m_{G^*} < 2.2, 3.9, 4.5$ TeV
and $k/M_{Pl} = 0.01, 0.05, 0.1$

Most significant excess ($m_\chi \sim 684$ GeV NWA and $k/M_{Pl} = 0.01$) has 3.29σ significance
Global significance is 1.30 (1.36) σ for spin-0 (spin-2) interpretations

Previous results:
\[ \sigma_{HH}(ggF) = 31.02^{+2.2\%}_{-5.0\%} \text{ (Scale)} \pm 3.0\% (\alpha_s + \text{PDF}) \pm 2.6\% (m_{top}) \text{ fb} \]

\[ \sigma_{HH}(VBF) = 1.72^{+0.03\%}_{-0.04\%} \text{ (Scale)} \pm 2.1\% (\alpha_s + \text{PDF}) \text{ fb} \]

- Non-resonant enhancements, e.g. loop corrections, non-SM couplings, \( k_\lambda = \lambda_{HHH}/\lambda_{HHH}^{SM} \)

- Resonant enhancements, e.g.:

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**HH → γγbb**

Common event preselection

- Diphoton trigger with $E_T > 25,35$ GeV
- Photon identification: loose (2015-16) + medium (2017-18)
- At least two photons passing the object selection criteria
- $105 \text{ GeV} < m_{\gamma\gamma} < 160 \text{ GeV}$
- (sub)leading $p_T > (25\%) 35\% m_{\gamma\gamma}$
- Exactly two b-tagged jets (orthogonality wrt $H \to bbbb$)
- No electrons, no electrons
- $N_j < 6 @ |\eta|<2.5$ (reject ttbarH events decaying hadronically)
- Object selection = tight ID, isolated photons
- **New categorization** based on $m^*_{bb\gamma\gamma} = m_{bb\gamma\gamma} - m_{bb} - m_{\gamma\gamma} + 250$ GeV
HH → γγbb

Results

Tighter constraint on $k_\lambda$

Old was $k_\lambda = [-8.1, 13.1]$ (CERN-EP-2019-099)

Extrapolated HL-LHC (15 TeV 3 ab$^{-1}$): $k_\lambda = 1$ with 3 (4.5) $\sigma$ (stat + sys) per experiment (ATL-PHYS-PUB-2018-053, CMS PAS FTR-18-019)
Conclusions

Analysis updates on resonances decaying into boson pairs using 139 fb$^{-1}$ at 13 TeV collected in 2015-2018

$Z' \to H_y$ with $H \to bb$

- Enhanced sensitivity due to novel algorithm to identify b-jets in the large-R jet CoM frame

$H^{\pm\pm}$ and $H^\pm$ into $2l^{\text{sc}}, 3l, 4l$

- New channel: $H^{\pm\pm}H^\pm$ associated production
- Improved measurement of lepton fake factor and their uncertainties

Heavy diphoton resonances

- Common event selection for spin-0 and spin-2
- Spurious signal uncertainty assessed by Functional decomposition

$HH \to yybb$

- New categorization based on $m_b^*\bar{b}\gamma\gamma$ improves HH mass resolution

All searches are compatible with background-only hypotheses
Z' → Hy with H → bb

Selection

Single photon trigger
\( p_T > 200 \text{ GeV} \)
\( \eta < 1.37 \) (calo barrel)

Mass window optimization
\( m_H - \Delta m_D < m_j < m_H - \Delta m_U \)

- Calculated by maximizing search sensitivity
- \( m_{Z'} \) dependent

- Large-R jet (R=1)
- Removed subjets (R=0.2) with <5%\( p_T \)
- \( m_j \) from calo+track
- 50 GeV < \( m_j < 200 \) GeV
- \( p_T > 200 \) GeV
- \(|\eta| < 2.00\)

\[ \Delta R_{\gamma J} > 1.0 \]
- At least 1\( \gamma \)+1J
Selection

- Candidates are divided into single and double b-tagged
- Optimization of the $p_T$ cuts:
  \[
  p_{T}^{\gamma_j} > p_T^0 + a \times m_{J_y} \\
  p_{T}^{J_j} > 0.8 \left( p_T^0 + a \times m_{J_y} \right)
  \]
  → signal efficiency 10-20%

Fit

- Signal PDF:
  - Crystal ball + Gaussian
  - Parameters extracted from MC and interpolated in $m_{Z'}$ with polynomials
- Background PDF:
  - $B(x) = (1 - x)^{p_1} x^{p_2 + p_3 \log(x)}$
  - validated in control regions
- Systematics as Gaussian nuisance parameters
H$^{±±}$ and H$^±$ into 2l$^{SC}$, 3l, 4l

**Backgrounds**

**Type 1: WZ production (2l$^{SC}$, 3l)**
- Jet multiplicity distribution corrected by normalisation factor from WZ CR (orthogonal to 3l CR)

**Type 2: electron charge flip (2l$^{SC}$)**
- Due to electron interaction in the ID
- Misidentification rate estimated from Z → ee (JINST 14 (2019) P12006)

**Type 3: non-prompt leptons (all)**
- Main sources: b- and c-hadron decays
- Scale factors measured in data for 4l

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### H$^{±±}$ and H$^±$ into 2l$^{SC}$, 3l, 4l

<table>
<thead>
<tr>
<th>$m_{H^{±±}}$ [GeV]</th>
<th>200</th>
<th>300</th>
<th>350</th>
<th>400</th>
<th>500</th>
<th>600</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_{H^±}$ [GeV]</td>
<td>400</td>
<td>400</td>
<td>700</td>
<td>700</td>
<td>700</td>
<td>700</td>
</tr>
<tr>
<td>$\mathcal{B}(H^{±±} \rightarrow W^±W^±)$ [%]</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Cross section [fb] (H$^{±±}$ pair production)</td>
<td>81.0</td>
<td>16.5</td>
<td>8.7</td>
<td>4.9</td>
<td>1.8</td>
<td>0.7</td>
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### QCD NLO cross sections for signal

<table>
<thead>
<tr>
<th>$m_{H^{±±}}$ [GeV]</th>
<th>200</th>
<th>220</th>
<th>300</th>
<th>400</th>
<th>450</th>
<th>500</th>
<th>550</th>
<th>600</th>
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</thead>
<tbody>
<tr>
<td>$m_{H^±}$ [GeV]</td>
<td>196</td>
<td>215</td>
<td>295</td>
<td>395</td>
<td>445</td>
<td>496</td>
<td>545</td>
<td>602</td>
</tr>
<tr>
<td>$\mathcal{B}(H^{±±} \rightarrow W^±W^±)$ [%]</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>$\mathcal{B}(H^± \rightarrow W^±Z)$ [%]</td>
<td>58.8</td>
<td>44.3</td>
<td>37.3</td>
<td>44.7</td>
<td>45.9</td>
<td>45.7</td>
<td>48.4</td>
<td>50.8</td>
</tr>
<tr>
<td>Cross section [fb] (H$^{±±}$H$^±$ associated production)</td>
<td>88.7</td>
<td>44.5</td>
<td>9.5</td>
<td>3.0</td>
<td>1.9</td>
<td>1.2</td>
<td>0.8</td>
<td>0.5</td>
</tr>
</tbody>
</table>

### Backgrounds

<table>
<thead>
<tr>
<th>Process</th>
<th>Generator</th>
<th>ME accuracy</th>
<th>PDF</th>
<th>Parton shower and hadronisation</th>
<th>Parameter set</th>
</tr>
</thead>
<tbody>
<tr>
<td>VV, VY</td>
<td>SHERPA</td>
<td>NLO (0-1j) + LO (2-3j)</td>
<td>NNPDF3.0nlnlo</td>
<td>SHERPA</td>
<td>default</td>
</tr>
<tr>
<td>VV- EW jj</td>
<td>SHERPA</td>
<td>LO</td>
<td>NNPDF3.0nlnlo</td>
<td>SHERPA</td>
<td>default</td>
</tr>
<tr>
<td>VV V</td>
<td>SHERPA</td>
<td>NLO(6j) + LO (1-2j)</td>
<td>NNPDF3.0nlnlo</td>
<td>SHERPA</td>
<td>default</td>
</tr>
<tr>
<td>V + jets</td>
<td>SHERPA</td>
<td>NLO (0-2j) + LO (3-4j)</td>
<td>NNPDF3.0nlnlo</td>
<td>SHERPA</td>
<td>default</td>
</tr>
<tr>
<td>VH</td>
<td>PYTHIA 8</td>
<td>LO</td>
<td>NNPDF2.3lo</td>
<td>PYTHIA 8</td>
<td>A14</td>
</tr>
<tr>
<td>t$t$H</td>
<td>PowHEP-Box v2</td>
<td>NLO</td>
<td>NNPDF3.0nlnlo</td>
<td>PYTHIA 8</td>
<td>A14</td>
</tr>
<tr>
<td>t$\bar{t}$V, tW Z, tZ</td>
<td>MadGraph5_aMC@NLO</td>
<td>NLO</td>
<td>NNPDF3.0nlnlo</td>
<td>PYTHIA 8</td>
<td>A14</td>
</tr>
<tr>
<td>t$\bar{t}$, tW</td>
<td>PowHEP-Box v2</td>
<td>NLO</td>
<td>NNPDF3.0nlnlo</td>
<td>PYTHIA 8</td>
<td>A14</td>
</tr>
<tr>
<td>t$t$tt, t$tW$, t$\bar{t}W$</td>
<td>MadGraph5_aMC@NLO</td>
<td>NLO</td>
<td>NNPDF3.1nlo</td>
<td>PYTHIA 8</td>
<td>A14</td>
</tr>
</tbody>
</table>
**H^{±±} and H^{±} into 2l^{SC}, 3l, 4l**

Event reconstruction

**Primary vertices:**
- From ID tracks with $p_T > 500$ MeV

**Jets:**
- Particle flow, anti-$k_t$ (R=0.4) with $p_T > 20$ GeV and $|\eta| < 2$
- Removed calo noise and non-collision background
- Jet-vertex tagging discriminant to remove pile-up

**b-tagging**
- RNN-based algorithm at $|\eta| < 2.5$
- 70% efficiency measured on ttbar

**Electrons**
- ID tracks matched to EM-cal clusters at $|\eta| < 2.47$ (excluding barrel-endcap transition)
- $p_T > 10$ GeV
- Loose identification for candidates (85-95% efficiency), tight identification for signal (65-88% efficiency)
- Reduced photon conversion background + Non-prompt-lepton veto
- Isolation requirements
- Suppressing charge flip using a BDT discriminant

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**H^{±±} and H^{±} into 2l^{SC}, 3l, 4l**

Event reconstruction

**Muons:**
- MS tracks matching ID tracks at $|\eta| < 2.5$
- $p_T > 10$ GeV and "Medium quality" requirement
- 98% efficiency in $Z \rightarrow \mu\mu$
- Constraints on impact parameters and isolation
- Non-prompt-lepton veto

**Overlap removal**
- To remove cases in which the detector response to a single physical object produces two final state objects
### Event reconstruction

**H^{±±} and H^± into 2l^{SC}, 3l, 4l**

<table>
<thead>
<tr>
<th></th>
<th>Electrons</th>
<th>Muons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Candidate</td>
<td>L</td>
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</tr>
<tr>
<td></td>
<td>L^{+}</td>
<td>L^{+}</td>
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<tr>
<td></td>
<td>T</td>
<td>T</td>
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</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Electrons</th>
<th>Muons</th>
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<tbody>
<tr>
<td>$</td>
<td>z_0 \sin \theta</td>
<td>\ $</td>
</tr>
<tr>
<td>$</td>
<td>d_0</td>
<td>/\sigma(d_0)\ $</td>
</tr>
<tr>
<td>Identification</td>
<td>Loose</td>
<td>Tight</td>
</tr>
<tr>
<td></td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Non-prompt-lepton veto</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Electron charge-flip veto</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Loose and minimal isolated

<table>
<thead>
<tr>
<th>Test</th>
<th>Value</th>
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<tbody>
<tr>
<td>Loose</td>
<td>Yes</td>
</tr>
<tr>
<td>Loose and minimal isolated</td>
<td>Yes</td>
</tr>
<tr>
<td>Tight</td>
<td>Yes</td>
</tr>
</tbody>
</table>

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**H^{±±} and H^{±} into 2l^{SC}, 3l, 4l**

**Signal regions**

<table>
<thead>
<tr>
<th>Charged Higgs boson mass</th>
<th>m_{H^{±±}} = 200 GeV</th>
<th>m_{H^{±±}} = 300 GeV</th>
<th>m_{H^{±±}} = 400 GeV</th>
<th>m_{H^{±±}} = 500 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Selection criteria</td>
<td>2l^{SC} channel</td>
<td>2l^{SC} channel</td>
<td>2l^{SC} channel</td>
<td>2l^{SC} channel</td>
</tr>
<tr>
<td>m_{jets} [GeV]</td>
<td>100, 450</td>
<td>100, 500</td>
<td>300, 700</td>
<td>400, 1000</td>
</tr>
<tr>
<td>S</td>
<td>&lt;0.3</td>
<td>&lt;0.6</td>
<td>&lt;0.6</td>
<td>&lt;0.9</td>
</tr>
<tr>
<td>ΔR_{ℓ±,ℓ±}</td>
<td>&lt;1.9</td>
<td>&lt;2.1</td>
<td>&lt;2.2</td>
<td>&lt;2.4</td>
</tr>
<tr>
<td>Δφ_{ℓ±,ℓ±,E_{T}^{miss}}</td>
<td>&lt;0.7</td>
<td>&lt;0.9</td>
<td>&lt;1.0</td>
<td>&lt;1.0</td>
</tr>
<tr>
<td>m_{ℓℓ} [GeV]</td>
<td>40, 150</td>
<td>90, 240</td>
<td>130, 340</td>
<td>130, 400</td>
</tr>
<tr>
<td>E_{T}^{miss} [GeV]</td>
<td>&gt;100</td>
<td>&gt;130</td>
<td>&gt;170</td>
<td>&gt;200</td>
</tr>
</tbody>
</table>

| Selection criteria     | 3ℓ channel           | 3ℓ channel           | 3ℓ channel           | 3ℓ channel           |
| ΔR_{ℓ±,ℓ±}             | [0.2, 1.7]           | [0.0, 2.1]           | [0.2, 2.5]           | [0.3, 2.8]           |
| m_{ℓℓ} [GeV]           | >160                 | >190                 | >240                 | >310                 |
| E_{T}^{miss} [GeV]     | >30                  | >55                  | >80                  | >90                  |
| ΔR_{jet}               | [0.1, 1.5]           | [0.1, 2.0]           | [0.1, 2.3]           | [0.5, 2.3]           |
| p_{T}^{leading jet} [GeV] | >40                 | >70                  | >100                 | >95                  |

| Selection criteria     | 4ℓ channel           | 4ℓ channel           | 4ℓ channel           | 4ℓ channel           |
| m_{ℓℓ} [GeV]           | >230                 | >270                 | >360                 | >440                 |
| E_{T}^{miss} [GeV]     | >60                  | >60                  | >60                  | >60                  |
| p_{T}^{l_{i}} [GeV]    | >65                  | >80                  | >110                 | >130                 |
| ΔR^{min}_{ℓ±,ℓ±}       | [0.2, 1.2]           | [0.2, 2.0]           | [0.5, 2.4]           | [0.6, 2.4]           |
| ΔR^{max}_{ℓ±,ℓ±}       | [0.3, 2.0]           | [0.5, 2.6]           | [0.4, 3.1]           | [0.6, 3.1]           |

\[ S = \frac{\mathcal{R}(\phi_{\ell_1}, \phi_{\ell_2}, \phi_{E_{T}^{miss}}) \cdot \mathcal{R}(\phi_{j_1}, \phi_{j_2}, \cdots)}{\mathcal{R}(\phi_{\ell_1}, \phi_{\ell_2}, \phi_{E_{T}^{miss}}, \phi_{j_1}, \phi_{j_2}, \cdots)} \]

\[ \mathcal{R}(\phi_1, \cdots, \phi_n) = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (\phi_i - \overline{\phi})^2}. \]

- SR’s are optimized to maximize sensitivity for H^{±±} pair production
- Same SR’s used for H^{±±} associated production
- Increased statistics improves lepton fake factors

(10.1140/epjc/s10052-018-6500-y) from previous analysis

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## H^{±±} and H^± into 2*l^{sc}, 3*l, 4*l

Event preselection

<table>
<thead>
<tr>
<th>Selection criteria</th>
<th>2*l^{sc}</th>
<th>3*l</th>
<th>4*l</th>
</tr>
</thead>
<tbody>
<tr>
<td>At least one offline tight lepton with $p_T^\ell &gt; 30$ GeV that triggered the event</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$N_\ell$ (type L)</td>
<td>=2</td>
<td>=3</td>
<td>=4</td>
</tr>
<tr>
<td>$N_\ell$ (type L^+)</td>
<td>=2</td>
<td>=4</td>
<td></td>
</tr>
<tr>
<td>$N_\ell$ (type T)</td>
<td>$\geq 2$ ($\ell_{1,2}$)</td>
<td>=1</td>
<td>$\geq 1$</td>
</tr>
<tr>
<td>$</td>
<td>\sum Q_\ell</td>
<td>$</td>
<td>=2</td>
</tr>
<tr>
<td>Lepton $p_T$</td>
<td>$p_T^{\ell_1,\ell_2} &gt; 30, 20$ GeV</td>
<td>$p_T^{\ell_0,\ell_1,\ell_2} &gt; 10, 20, 20$ GeV</td>
<td>$p_T^{\ell_1,\ell_2,\ell_3,\ell_4} &gt; 10$ GeV</td>
</tr>
<tr>
<td>$E_T^{miss}$</td>
<td>&gt; 70 GeV</td>
<td>&gt; 30 GeV</td>
<td>&gt; 30 GeV</td>
</tr>
<tr>
<td>$N_{jets}$</td>
<td>$\geq 3$</td>
<td>$\geq 2$</td>
<td></td>
</tr>
<tr>
<td>$N_{b-jets}$</td>
<td>=0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low SFOC $m_{\ell\ell}$ veto</td>
<td>=0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Z boson decay veto</td>
<td>$</td>
<td>m^{sc}_{\ell\ell} - m_Z</td>
<td>&gt; 10$ GeV</td>
</tr>
</tbody>
</table>

* SFOC = same flavor opposite charge

Reduce
- Non-prompt lepton
- Electron charge-flip
- VV background
- t-production background

Reduces background from DY and neutral mesons
H^{±±} and H^± into 2l^{SC}, 3l, 4l

Distribution of selected variables used to define the 2l^{SC} SRs
**H^{±±} and H^{±} into 2l^{SC}, 3l, 4l**

Distribution of selected variables used to define the 3l SRs
H^{±±} and H^{±} into 2l^{SC}, 3l, 4l

Distribution of selected variables used to define the 4l SRs
## Results

<table>
<thead>
<tr>
<th>SR</th>
<th>(2\ell^{\text{SC}})</th>
<th>(3\ell)</th>
<th>(4\ell)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(ee)</td>
<td>(e\mu)</td>
<td>(\mu\mu)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Prompt lepton</td>
<td>1.66±0.28</td>
<td>4.3±0.5</td>
<td>2.30±0.26</td>
</tr>
<tr>
<td>Charge-flip</td>
<td>0.17±0.07</td>
<td>0.102±0.034</td>
<td>–</td>
</tr>
<tr>
<td>Non-prompt lepton</td>
<td>0.3±0.25</td>
<td>0.65±0.33</td>
<td>0.39±0.19</td>
</tr>
<tr>
<td>Total background Data</td>
<td>2.1±0.4</td>
<td>5.1±0.6</td>
<td>2.69±0.32</td>
</tr>
<tr>
<td>(H^\pm H^\mp) (A_{\text{PP}}\ [%])</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.99±0.24</td>
<td>5.3±0.6</td>
<td>3.03±0.35</td>
</tr>
<tr>
<td>(H^\pm H^\mp) (A_{\text{AP}}\ [%])</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.087</td>
<td>0.233</td>
<td>0.132</td>
</tr>
<tr>
<td>(n_95)</td>
<td>0.57±0.07</td>
<td>1.43±0.16</td>
<td>0.81±0.09</td>
</tr>
<tr>
<td></td>
<td>6.72</td>
<td>9.21</td>
<td>3.24</td>
</tr>
</tbody>
</table>

- The expected background and the observed data event yields in the signal region defined for the \(m_{H^\pm} = 300\) GeV mass hypothesis
- No significant excess over the expected yields is observed in any of the SRs
H^{±±} and H^{±} into 2l^{SC}, 3l, 4l

Results

- The $E_T^{\text{miss}}$ distribution for the SRs of the $m_{H^{±±}} = 300$ GeV signal mass hypothesis

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Heavy diphoton resonances

Framework

Data:
- Diphoton trigger with $E_T > 25,35$ GeV

MC signal:
- Spin-0:
  - $m_X$ in 200-3000 GeV
  - $\Gamma_X = 4$ MeV
- Spin-2:
  - RS1 model
  - $m_{G^*}$ in 500-5000 GeV
  - Coupling $k/M_{Pl}$ in 0.01-0.1

MC background:
- Events with 2 prompt photons
Event selection

- At least two photons with $E_{\text{T}} > 22$ GeV and $|\eta| < 2.37$ (excluding transition between barrel and endcap calo)
- Identification of the diphoton vertex using tracking information
- Tight identification of photons (jet bkg reduction)
- Calculation of $m_{\gamma\gamma}$:
  - Optimized kinematic selection: $E_{\text{T}}/m_{\gamma\gamma} > 0.3, 0.25$
  - Improved significance
  - **Unified selection** for the two spin models
  - In most of the mass range, the expected limits improve
Heavy diphoton resonances

Background estimates

As the search selections for the two models are unified, a **common background modeling** is used.
Heavy diphoton resonances

Fit

**Systematic uncertainties**

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity</td>
<td>±1.7%</td>
</tr>
<tr>
<td>Trigger</td>
<td>±0.5%</td>
</tr>
<tr>
<td>Photon identification</td>
<td>±0.5%</td>
</tr>
<tr>
<td>Photon isolation</td>
<td>±1.5%</td>
</tr>
<tr>
<td>Photon energy scale/resolution</td>
<td>negligible</td>
</tr>
<tr>
<td>Pile-up reweighting</td>
<td>±(2−0.2)%</td>
</tr>
<tr>
<td>Spin-0 production process*</td>
<td>±(7−3)%</td>
</tr>
</tbody>
</table>

**Signal modelling**

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photon energy resolution</td>
<td>+14%</td>
</tr>
<tr>
<td>−9.3%</td>
<td>−29%</td>
</tr>
<tr>
<td>Photon energy scale</td>
<td>±(0.5−0.6)%</td>
</tr>
<tr>
<td>Pile-up reweighting</td>
<td>negligible</td>
</tr>
</tbody>
</table>

**Spurious signal, Spin-0**

<table>
<thead>
<tr>
<th>Source</th>
<th>Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>NWA</td>
<td>114−0.04</td>
</tr>
<tr>
<td>$\Gamma_X/m_X = 2%$</td>
<td>107−0.14</td>
</tr>
<tr>
<td>$\Gamma_X/m_X = 6%$</td>
<td>223−0.38</td>
</tr>
<tr>
<td>$\Gamma_X/m_X = 10%$</td>
<td>437−0.50</td>
</tr>
</tbody>
</table>

**Spurious signal, Spin-2**

<table>
<thead>
<tr>
<th>Source</th>
<th>Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k/M_{Pl} = 0.01$</td>
<td>4.71−0.04</td>
</tr>
<tr>
<td>$k/M_{Pl} = 0.05$</td>
<td>19.0−0.09</td>
</tr>
<tr>
<td>$k/M_{Pl} = 0.1$</td>
<td>31.2−0.20</td>
</tr>
</tbody>
</table>

The RS1 model is excluded for

$m_{G^*} < 2.2, 3.9, 4.5$ TeV

$k/M_{Pl} = 0.01, 0.05, 0.1$
Main contributions:

- $\gamma\gamma + \text{jets}$
- $H \to \gamma\gamma$
- Reducible: jets wrongly identified as photons
Object selection

**Photons:**
- Connected EM clusters in $|\eta|<2.37$ (excluding endcap-barrel transition)
- Converted-unconverted classification
- Calibrated photon energy with MV regression
- Direction from calo segmentation
- Lateral shower profile + hcal leakage → reduce $\pi^0$ background
- Tight identification + two isolation variables

**Vertex:**
- At least one primary (at least two tracks with $p_T>0.5$ GeV)
- Selection from collision vertices using a NN algorithm

**Electron:**
- EM-cal deposits matched to ID tracks in $|\eta|<2.37$ (excluding endcap-barrel transition)
- $p_T > 10$GeV
- Medium identification criterion: calo + track + TRT
**HH → γγbb**

Object selection

**Muons:**
- High quality MS tracks in $|\eta|<2.7$ ($|\eta|<2.5$ to match ID track)
- $p_T > 10$ GeV
- Medium identification criterion

**Jets:**
- Particle flow reconstruction (calo + track)
- $|y| < 4.4$
- $p_T > 25$ GeV
- If in tracking acceptance ($|\eta|<2.4$) and $p_T < 60$ GeV → tight jet vertex tagger

**Flavor tagging:**
- NN DL1r
- Inputs to DL1r are generated by a RNN (RNNIP)
- Energy corrected for $b$had → $\mu$ and neutrinos
HH → yybb

Non-resonant selection

BDT to discriminate signal from background

<table>
<thead>
<tr>
<th>Category</th>
<th>Selection criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>High mass BDT tight</td>
<td>$m_{bb\gamma\gamma}^* \geq 350 \text{ GeV}$, BDT score ∈ [0.967, 1]</td>
</tr>
<tr>
<td>High mass BDT loose</td>
<td>$m_{bb\gamma\gamma}^* \geq 350 \text{ GeV}$, BDT score ∈ [0.857, 0.967]</td>
</tr>
<tr>
<td>Low mass BDT tight</td>
<td>$m_{bb\gamma\gamma}^* &lt; 350 \text{ GeV}$, BDT score ∈ [0.966, 1]</td>
</tr>
<tr>
<td>Low mass BDT loose</td>
<td>$m_{bb\gamma\gamma}^* &lt; 350 \text{ GeV}$, BDT score ∈ [0.881, 0.966]</td>
</tr>
</tbody>
</table>

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Trained two different BDT’s:
- One for ttbar+γγ background
- One for single-H background

Optimized coefficients to maximize sensitivity

\[ BDT_{\text{tot}} = \frac{1}{\sqrt{C_1^2 + C_2^2}} \sqrt{C_1^2 \left( \frac{BDT_{\gamma\gamma} + 1}{2} \right)^2 + C_2^2 \left( \frac{BDT_{\text{Single}H} + 1}{2} \right)^2} \]
HH → yybb

Fit in non-resonant search

(a) High mass BDT tight

(b) High mass BDT loose

(c) Low mass BDT tight

(d) Low mass BDT loose

Tighter constraint on $k_\lambda$

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HH → yybb
Fit in resonant search

*Narrow Width Approximation (NWA)