ATLAS + CMS Searches for EWK SUSY in hadronic and semi-leptonic final states

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(CERN)
On behalf of the ATLAS + CMS Collaborations

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Electroweak SUSY at the LHC

- **SM processes being measured with exceptional precision**
  - Including new measurements of rare SM processes
- **Stringent limits on strong-production of SUSY particles**
  - Lower mass limits: gluinos (2 TeV) and stops (1 TeV)

- With the full Run-2 dataset:
  - Can probe direct electroweak production of charginos/neutralinos and sleptons

- Naturalness favours light higgsinos, begin probing with full Run-2 dataset

- Access to rare processes which require a lot of data for discovery potential
- Using the now well established Higgs boson as a portal to new physics
- Connections to recent anomalies
Fully hadronic boosted

- Interpretations based on various models:
  - Baseline MSSM scenario with bino, wino and higgsino
  - Light higgsinos and gravitino LSP
  - Light higgsinos and axino LSP assuming the SM extension with a QCD axion

- Mass hierarchy in the bino/wino/higgsino LSP scenario

- Boosted boson identification
  - Large-R jet tagging (R = 1.0)
  - Events contain two large-R jets: Boson tagging

- SRs categorized based on: 2B2Q or 4Q
- Variable radius track jets for b-jet ID inside jet

- Backgrounds:
  - Irreducible: VVV, tt+X, estimated from MC
  - Reducible: Z+jets, W+jets, tt estimated from CR
Fully hadronic boosted

- No significant excess above SM prediction
- Higgsino production decaying into a massless gravitino LSP: 940 GeV (100 % Br)

Exclusion limits on simplified wino/bino models
- Chargino-neutralino pair production limits:
  - 960 GeV in WZ and 1060 GeV in Wh
Chargino/Neutralino: Wh, h->bb

- Single lepton + bb + $p_T^{miss}$ final state

- Both small-R ($\Delta R = 0.4$) and large-R ($\Delta R = 0.8$) jet collections
  - Large-R jets $p_T > 250$ GeV

- Charginos / neutralinos excluded with masses up to 820 GeV
- LSPs with mass up to 350 GeV are excluded when the mass of the chargino / neutralino is ~ 700 GeV
Chargino/Neutralino: Wh, h->bb

- Search for charginos and neutralinos decaying to Higgs boson and W boson
  - W boson —> leptonic decays (single lepton)
  - Higgs decays to bb

- Large MET, tagging of h and W decays

- No significant excess found < 2 sigma local
- Exclusion limits: up to 740 GeV
Chargino/Neutralino: $h \rightarrow \gamma\gamma$

- **Higgs boson decay to diphotons** (narrow peak in $\gamma\gamma$)
- Main backgrounds from $\gamma\gamma$ and $\gamma+\text{jets}$
- Parametrised likelihood fits in each category-based SRs
  - $W$-boson decay, MET significance, $N$ ($b$-)jets, razor

- **ATLAS**: Limits up to 310 GeV for electroweakino production (Wh decays)

- **CMS Higgsino-like**: Excluded neutralino decays exclusively to a $h$ and a gravitino for neutralino masses below 290 GeV

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![ATLAS Higgs boson decay](https://example.com/atlas-higgs-decay.png)

**ATLAS**

- Data, SM Higgs boson, $\gamma\gamma$, $\gamma+\text{jets}$
- Limits at 95% CL

**CMS**

- EWP analysis bin 2
- Data, Signal plus background, Total background, Signal

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![Higgsino-like neutralino](https://example.com/higgsino-neutralino.png)

**Higgsino-like neutralino**

- ATLAS: Limits up to 310 GeV for electroweakino production (Wh decays)
- CMS Higgsino-like: Excluded neutralino decays exclusively to a $h$ and a gravitino for neutralino masses below 290 GeV
RPV SUSY

- EWKino production, higgsino LSP type
- RPV: LSP unstable and decays in SM particles
- $\geq 1l/2SS$, and many (b-)jets final states

- SRs up to 15 (10) jets for the $\geq 1l$ (2SSI) with 0, 1, 2, 3 and $\geq 4$ b-jets
- Data driven approach to estimate backgrounds in each N jet slice

- First limits on EWK production with prompt RPV decay to quarks since LEP
- Higgsino (wino) masses between 200 (197) GeV and 320 (365) GeV excluded

- Jet multiplicity predicted by parametrization of the jet scaling up to 10 or more jets
- b-jet multiplicity extracted at low number of jets
- NN discriminant to reach sensitivity to Higgsino production
- Background invariance under N b-jets

ATLAS-CONF-2021-007
Stau pair production

- Two hadronic tau and light lepton + hadronic tau final states
  \((77.2 \text{ fb}^{-1}) = 2016+2017\)
- Backgrounds from fake tau estimates —> transfer factor

- **Hadronic**: \(m_{T2}\) (stransverse mass), Sum \(m_T\) and \(N_j\)
  \[m_{T2} = \min_{p_T^{\ell X(1)}+p_T^{X(2)}=p_T^{\text{miss}}} \left[ \max \left(m_T^{(1)}, m_T^{(2)}\right) \right]\]

- **Semi-leptonic**: BDT of kinematic variables (e.g. contransverse mass)
  \[m_{CT} = \sqrt{2p_T^\ell p_T^{\tau_h}[1 + \cos \Delta \phi(\ell, \tau_h)]}\]

- No significant excess found

- Limits set between 90 and 200 GeV and neutralino masses of 1, 10, and 20 GeV

- Combination of both channels
Stefan Guindon (CERN)

LHCP 2021

Stau pair production

- **Two hadronic tau** final state
- Final state divided into low and high $E_T^{miss}$ regions
- **Two SRs: highMass and lowMass SR**
  - Trigger dependent
  - $E_T^{miss}$ cut to split SRs (150 GeV)
  - $m_{T2} > 70$ GeV

- Both SRs are shown binned in $m_{T2}$

- No excess is found in either of the signal regions
  - Exclude $120$ GeV < $m$(stau) < $390$ GeV
  - 2-SR single bin combined fit only

- Large contribution from $W+$jets and multi-jet events (1 or 2 fake taus)

- **ABCD Method to model multi-jet**
Long Lived Charginos

**Search for long-lived chargino production**
- Using disappearing track signature in ID
- Tracks which have hits in the inner-most pixels

**Charginos that are pure wino or higgsino**

- **Details in talk by:** E. Sian Kuwertz

![Graphs showing search for long-lived charginos](image)

- **Lifetime dependent limits**
- **Chargino masses up to 474 (175) GeV are excluded in scenarios where the chargino is a pure wino (higgsino)**
- **Chargino masses up to 660 (210) GeV are excluded in scenarios where the chargino is a pure wino (higgsino)**
Summary Figures

- Still no indication for SUSY yet in the LHC
- Summary figures of chargino/neutralino exclusion limits (CMS and ATLAS)

Not all of the production and decay modes are fully analysed using the full Run-2 dataset
  - Small production modes, difficult multi-object final states

More results to come from the full Run-2 dataset
Summary and Outlook

• **New searches for electroweak SUSY at CMS and ATLAS**
  • Using the large, high-quality Run 2 dataset
  • *Thanks to the excellent performance of the LHC and experiments!*

• **Exploring new signals**
  • First sensitivity to direct stau searches, additional final states with Higgs
  • Probing very difficult final state signatures in compressed scenarios

• **For now the data remains compatible with SM predictions**
  • Though we know the SM cannot explain everything we observe in the Universe

• **New searches for SUSY are still to come with the full Run-2 dataset**
  • Preparing optimal searches for the upcoming larger Run-3 dataset in order to explore new regions of phase space

• **Still only a fraction of data-taking at the full lifetime of LHC and HL-LHC**
Additional Slides
LHC has given us the opportunity to test fundamental parameters of the SM.

Impressive agreement of SM theory predictions to ATLAS data.
Supersymmetry

• A new symmetry to protect masses of particles at the Planck scale
• Symmetry between fermions and bosons
  • Includes an extended Higgs sector

• Can offer a DM candidate $\rightarrow$ also a WIMP
• Solves the fine-tuning problem of the Higgs mass

**Image credit:** M. Rimoldi

**Broken symmetry:** mass (SUSY) $\neq$ mass (SM)
Analysis Strategy

- Build **signal regions (SRs)** based on requirements on signal / background discriminating variables to target specific SUSY event topologies
  - Optimised for discovery & exclusion

- Determine Standard Model background in **control regions (CRs)** and test background estimates in the **validation regions (VRs)**

- **Fit in CR:**
  - Simultaneous fit of all components in CR

- **Check modelling in VR (post-fit):**
  - SM backgrounds (with MC)
  - Fake objects (MC and/or data-driven)

- **Combined fit of CR and SR:**
  - Fit for discovery or exclusion
Fully hadronic production modes

<table>
<thead>
<tr>
<th>Model</th>
<th>Production</th>
<th>Final states</th>
<th>SRs simultaneously fitted</th>
<th>Branching ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>$(\tilde{W}, \tilde{B})$</td>
<td>$\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp, \tilde{\chi}_2^0$</td>
<td>WW, WZ, Wh</td>
<td>4Q-VV, 2B2Q-WZ, 2B2Q-Wh</td>
<td>$\mathcal{B}(\tilde{\chi}_1^\pm \rightarrow W\tilde{\chi}_1^0) = 1$, $\mathcal{B}(\tilde{\chi}_2^0 \rightarrow Z\tilde{\chi}_1^0)$ scanned.</td>
</tr>
<tr>
<td>$(\tilde{H}, \tilde{B})$</td>
<td>$\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp, \tilde{\chi}_2^0$, $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp, \tilde{\chi}_2^0$</td>
<td>WW, WZ, Wh, ZZ, Zh, hh</td>
<td>4Q-VV, 2B2Q-VZ, 2B2Q-Vh</td>
<td>$\mathcal{B}(\tilde{\chi}_1^\pm \rightarrow W\tilde{\chi}_1^0) = 1$, $\mathcal{B}(\tilde{\chi}_2^0 \rightarrow Z\tilde{\chi}_1^0)$ scanned, $\mathcal{B}(\tilde{\chi}_1^\pm \rightarrow h\tilde{\chi}_1^0) = 1 - \mathcal{B}(\tilde{\chi}_2^0 \rightarrow Z\tilde{\chi}_1^0)$</td>
</tr>
</tbody>
</table>
| $(\tilde{W}, \tilde{H})$ | $\tilde{\chi}_2^\pm \tilde{\chi}_2^\mp, \tilde{\chi}_3^0$ | WW, WZ, Wh, ZZ, Zh, hh | 4Q-VV, 2B2Q-VZ, 2B2Q-Vh | Determined from $(M_2, \mu, \tan \beta)$.
| $(\tilde{H}, \tilde{W})$ | $\tilde{\chi}_2^\pm \tilde{\chi}_2^\mp, \tilde{\chi}_3^0$, $\tilde{\chi}_3^\pm \tilde{\chi}_3^\mp, \tilde{\chi}_2^0$ | WW, WZ, Wh, ZZ, Zh, hh | 4Q-VV, 2B2Q-VZ, 2B2Q-Vh | Determined from $(M_2, \mu, \tan \beta)$.
| $(\tilde{H}, \tilde{G})$ | $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp, \tilde{\chi}_1^\pm \tilde{\chi}_1^\mp, \tilde{\chi}_1^0$, $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp, \tilde{\chi}_2^0$ | ZZ, Zh, hh | 4Q-ZZ, 2B2Q-ZZ, 2B2Q-Zh | $\mathcal{B}(\tilde{\chi}_1^0 \rightarrow h\tilde{G})$ scanned. |
| $(\tilde{H}, \tilde{a})$ | $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp, \tilde{\chi}_1^\pm \tilde{\chi}_1^\mp, \tilde{\chi}_2^0$, $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp, \tilde{\chi}_2^0$ | ZZ, Zh, hh | 4Q-ZZ, 2B2Q-ZZ, 2B2Q-Zh | $\mathcal{B}(\tilde{\chi}_1^0 \rightarrow h\tilde{a})$ scanned. |

$(\tilde{W}, \tilde{B})$ simplified models: $(\tilde{W}, \tilde{B})$-SIM

<table>
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<th>Branching ratio</th>
</tr>
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<tr>
<td>C1C1-WW</td>
<td>$\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$</td>
<td>WW</td>
<td>4Q-WW</td>
<td>$\mathcal{B}(\tilde{\chi}_1^\pm \rightarrow W\tilde{\chi}_1^0) = 1$.</td>
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<td>C1N2-WZ</td>
<td>$\tilde{\chi}_1^\pm \tilde{\chi}_2^0$</td>
<td>WZ</td>
<td>4Q-WZ, 2B2Q-WZ</td>
<td>$\mathcal{B}(\tilde{\chi}_1^\pm \rightarrow W\tilde{\chi}_1^0) = \mathcal{B}(\tilde{\chi}_2^0 \rightarrow Z\tilde{\chi}_1^0) = 1$.</td>
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<tr>
<td>C1N2-Wh</td>
<td>$\tilde{\chi}_1^\pm \tilde{\chi}_2^0$</td>
<td>Wh</td>
<td>2B2Q-Wh</td>
<td>$\mathcal{B}(\tilde{\chi}_1^\pm \rightarrow W\tilde{\chi}_1^0) = \mathcal{B}(\tilde{\chi}_2^0 \rightarrow h\tilde{\chi}_1^0) = 1$.</td>
</tr>
</tbody>
</table>
Fully hadronic SR definitions

\[ V_{qq}-\text{tagging} \ (J_2) \]

- Pass: CR
- Fail: SR/VR

\[ V_{qq}-\text{tagging} \ (J_1) \]

Pass: 70
Fail: 135

\[ m(J_{bb}) \ [\text{GeV}] \]
## Fully hadronic boosted regions

<table>
<thead>
<tr>
<th></th>
<th>SR(CR0L) 4Q</th>
<th>SR(CR0L) 2B2Q</th>
<th>VR(CR)1L 4Q</th>
<th>VR(CR)1L 2B2Q</th>
<th>VR(CR)1Y 4Q</th>
<th>VR(CR)1Y 2B2Q</th>
<th>VRTTX</th>
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<td>$n_{\text{Large-}R\text{ jets}}$</td>
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<td>$\geq 2$</td>
<td>$\geq 2$</td>
<td>$\geq 2$</td>
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<td>$p_T(\ell_1)$ [GeV]</td>
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<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>$&gt; 30$</td>
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<tr>
<td>$n_{\text{photon}}$</td>
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<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<td>-</td>
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<tr>
<td>$n(V_{qq})$</td>
<td>$2 (= 1)$</td>
<td>$1 (= 0)$</td>
<td>$2 (= 1)$</td>
<td>$1 (= 0)$</td>
<td>$2 (= 1)$</td>
<td>$1 (= 0)$</td>
<td>-</td>
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<tr>
<td>$n(!V_{qq})$</td>
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<td>$0 (= 1)$</td>
<td>$0 (= 1)$</td>
<td>$0 (= 1)$</td>
<td>$0 (= 1)$</td>
<td>$0 (= 1)$</td>
<td>-</td>
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<tr>
<td>$n(J_{bb})$</td>
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<td>$= 1$</td>
<td>$= 0$</td>
<td>$= 1$</td>
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<tr>
<td>$m(J_{bb})$ [GeV]</td>
<td>$\in [70, 135 (150)]$</td>
<td>$\in [70, 150]$</td>
<td>$\in [70, 150]$</td>
<td>$\in [70, 150]$</td>
<td>$\in [70, 150]$</td>
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<td>$E_T^{\text{miss}}$ [GeV]</td>
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<td>$&gt; 200$</td>
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<td>-</td>
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<tr>
<td>$m_{\text{eff}}$ [GeV]</td>
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<td>$&gt; 1000 (&gt; 900)$</td>
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<td>-</td>
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<td>$\text{min} \Delta \phi (V, j)$</td>
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<td>$m_{T2}$ [GeV]</td>
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## EWP yy analysis categories

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<tr>
<th>Bin number</th>
<th>Category</th>
<th>$p_T^{\gamma\gamma}$ (GeV)</th>
<th>$M_R$ (GeV)</th>
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<td>EWP 24</td>
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<td>0.225–0.285</td>
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<td>EWP 26</td>
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<td>$\geq 150$</td>
<td>0.000–0.185</td>
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<td>EWP 27</td>
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<td>150–200</td>
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<td>EWP 28</td>
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<td>$\geq 200$</td>
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<tr>
<td>EWP 29</td>
<td>Low-Res</td>
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<td>$\geq 150$</td>
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<tr>
<td>EWP 30</td>
<td>Low-Res</td>
<td>0–110</td>
<td>$\geq 150$</td>
<td>0.285–0.325</td>
</tr>
<tr>
<td>EWP 31</td>
<td>Low-Res</td>
<td>0–110</td>
<td>$\geq 150$</td>
<td>0.225–0.285</td>
</tr>
<tr>
<td>EWP 32</td>
<td>Low-Res</td>
<td>0–110</td>
<td>$\geq 150$</td>
<td>0.000–0.185</td>
</tr>
<tr>
<td>EWP 33</td>
<td>Low-Res</td>
<td>0–110</td>
<td>150–200</td>
<td>0.185–0.225</td>
</tr>
<tr>
<td>EWP 34</td>
<td>Low-Res</td>
<td>0–110</td>
<td>$\geq 200$</td>
<td>0.185–0.225</td>
</tr>
</tbody>
</table>
Chargino/Neutralino: Wh, h->γγ

- Higgs boson decay to diphotons
- Categories based on pT of the diphoton h, and additional Z, W, or H → bb candidates
- SR bins: N (b-)jets and razor variables

\[ \text{Wino-like model NLSP} \]
\[ \text{Higgsino-like neutralino PP} \]

- Parametrised likelihood fits in each SR
- **Wino-like**: Excluded chargino and neutralino masses below 235 GeV with a gravitino mass of 1 GeV

**Higgsino-like**: Excluded neutralino decays exclusively to a h and a gravitino for neutralino masses below 290 GeV
Modelling the Higgs as background

- **Dominant backgrounds:**
  - Resonant Higgs
  - Non-resonant $\gamma\gamma$, $\gamma$+jet

- Higgs modelled as double-sided crystal ball functions

- Non-resonant background fitted in sideband regions
  - *Different analytic functions per region*

- SM Higgs predictions across categories

- **Excess fitted as signal**

- Combined un-binned likelihood fit
General Limits

- No significant excess was found in any individual category

- No significant excess observed in combined fit to data

- First observed sensitivity to Wh(γγ) at ATLAS

  - Large gain when compared to 36 fb\(^{-1}\)
    - Use of all W boson decay channels

\[\chi_1^\pm \chi_2^0 \rightarrow \chi_1^0 W^\pm \chi_1^0 h, \quad \text{BR}(\chi_1^\pm \rightarrow W^\pm \chi_1^0) = \text{BR}(\chi_2^0 \rightarrow h\chi_1^0) = 100\%\]

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

Limits at 95\% CL

\[\sigma_{\text{BSM}} = \sigma \times A \times \varepsilon \ [\text{fb}]
\]

Model-independent upper limits on the visible cross section
### WH(γγ) Categories

<table>
<thead>
<tr>
<th>Channels</th>
<th>Names</th>
<th>Selection</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>Leptonic</strong></td>
<td></td>
</tr>
<tr>
<td>Category 1</td>
<td>0 &lt; $S_{E_T^\text{miss}} \leq 2$, $N_\ell \geq 1$</td>
<td></td>
</tr>
<tr>
<td>Category 2</td>
<td>2 &lt; $S_{E_T^\text{miss}} \leq 4$, $N_\ell \geq 1$</td>
<td></td>
</tr>
<tr>
<td>Category 3</td>
<td>4 &lt; $S_{E_T^\text{miss}} \leq 6$, $N_\ell \geq 1$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$S_{E_T^\text{miss}} &gt; 6$, $N_\ell \geq 1$</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Hadronic</strong></td>
<td></td>
</tr>
<tr>
<td>Category 5</td>
<td>5 &lt; $S_{E_T^\text{miss}} \leq 6$, $N_\ell = 0$, $N_j \geq 2$, $M_{jj} \in [40, 120]$ GeV</td>
<td></td>
</tr>
<tr>
<td>Category 6</td>
<td>6 &lt; $S_{E_T^\text{miss}} \leq 7$, $N_\ell = 0$, $N_j \geq 2$, $M_{jj} \in [40, 120]$ GeV</td>
<td></td>
</tr>
<tr>
<td>Category 7</td>
<td>7 &lt; $S_{E_T^\text{miss}} \leq 8$, $N_\ell = 0$, $N_j \geq 2$, $M_{jj} \in [40, 120]$ GeV</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$S_{E_T^\text{miss}} &gt; 8$, $N_\ell = 0$, $N_j \geq 2$, $M_{jj} \in [40, 120]$ GeV</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Rest</strong></td>
<td></td>
</tr>
<tr>
<td>Category 9</td>
<td>6 &lt; $S_{E_T^\text{miss}} \leq 7$, $N_\ell = 0$, $N_j &lt; 2$ or ( $N_j \geq 2$, $M_{jj} \notin [40, 120]$ GeV)</td>
<td></td>
</tr>
<tr>
<td>Category 10</td>
<td>7 &lt; $S_{E_T^\text{miss}} \leq 8$, $N_\ell = 0$, $N_j &lt; 2$ or ( $N_j \geq 2$, $M_{jj} \notin [40, 120]$ GeV)</td>
<td></td>
</tr>
<tr>
<td>Category 11</td>
<td>8 &lt; $S_{E_T^\text{miss}} \leq 9$, $N_\ell = 0$, $N_j &lt; 2$ or ( $N_j \geq 2$, $M_{jj} \notin [40, 120]$ GeV)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$S_{E_T^\text{miss}} &gt; 9$, $N_\ell = 0$, $N_j &lt; 2$ or ( $N_j \geq 2$, $M_{jj} \notin [40, 120]$ GeV)</td>
<td></td>
</tr>
</tbody>
</table>
### WH(γγ): Analytic function

<table>
<thead>
<tr>
<th>Category</th>
<th>Function</th>
<th>$\Delta N_{\text{bkg}}^{\text{non-res}}$</th>
<th>$\Delta N_{\text{bkg}}^{\text{non-res}} / N_{\text{bkg}}^{\text{non-res.}}$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$(1 - x^{1/3})^b \cdot x^a$</td>
<td>5.5</td>
<td>2.4</td>
</tr>
<tr>
<td>2</td>
<td>$\sum_{j=0}^{3} C^j_3 x^j (1 - x)^{3-j} b_{j,3}$</td>
<td>1.8</td>
<td>2.4</td>
</tr>
<tr>
<td>3</td>
<td>$\exp(a \cdot x)$</td>
<td>0.6</td>
<td>3.6</td>
</tr>
<tr>
<td>4</td>
<td>$\exp(a \cdot x)$</td>
<td>0.3</td>
<td>3.7</td>
</tr>
<tr>
<td>5</td>
<td>$\exp(a \cdot x)$</td>
<td>1.6</td>
<td>2.8</td>
</tr>
<tr>
<td>6</td>
<td>$\exp(a \cdot x)$</td>
<td>0.5</td>
<td>3.3</td>
</tr>
<tr>
<td>7</td>
<td>$\exp(a \cdot x)$</td>
<td>0.3</td>
<td>5.1</td>
</tr>
<tr>
<td>8</td>
<td>$\exp(a \cdot x)$</td>
<td>0.2</td>
<td>4.6</td>
</tr>
<tr>
<td>9</td>
<td>$\exp(a \cdot x)$</td>
<td>1.5</td>
<td>2.3</td>
</tr>
<tr>
<td>10</td>
<td>$\exp(a \cdot x)$</td>
<td>0.6</td>
<td>2.5</td>
</tr>
<tr>
<td>11</td>
<td>$\exp(a \cdot x)$</td>
<td>0.4</td>
<td>5.6</td>
</tr>
<tr>
<td>12</td>
<td>$\exp(a \cdot x)$</td>
<td>0.4</td>
<td>3.0</td>
</tr>
</tbody>
</table>
# WH(\gamma\gamma): Systematic uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>Signals [%]</th>
<th>Backgrounds [%]</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>SM Higgs boson</td>
<td>Non-resonant background</td>
</tr>
<tr>
<td><strong>Experimental</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Luminosity</td>
<td>1.7</td>
<td></td>
<td>–</td>
</tr>
<tr>
<td>Jets (Scale, Resolution, JVT)</td>
<td>0.2–3.3</td>
<td>0.9–30.7</td>
<td>–</td>
</tr>
<tr>
<td>Electron/Photon (Scale, Resolution)</td>
<td>0.3–1.5</td>
<td>0.6–2.7</td>
<td>–</td>
</tr>
<tr>
<td>Photon (identification, isolation, trigger)</td>
<td>2.2–2.6</td>
<td>2.8–4.3</td>
<td>–</td>
</tr>
<tr>
<td>Electron (identification isolation)</td>
<td>0.0–0.5</td>
<td>0.0–0.6</td>
<td>–</td>
</tr>
<tr>
<td>Muon (identification, isolation, Scale, Resolution)</td>
<td>&lt; 0.6</td>
<td>&lt; 0.3</td>
<td>–</td>
</tr>
<tr>
<td>$E_T^{\text{miss}}$ reconstruction (jets, soft term)</td>
<td>&lt; 0.7</td>
<td>0.4–13.9</td>
<td>–</td>
</tr>
<tr>
<td>Pileup reweighting</td>
<td>0.3–1.8</td>
<td>1.3–15</td>
<td>–</td>
</tr>
<tr>
<td>Non-resonant background modelling</td>
<td>–</td>
<td>2–6</td>
<td></td>
</tr>
<tr>
<td><strong>Theoretical</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Factorization and renormalization scale</td>
<td>&lt; 1</td>
<td>3.7–5.9</td>
<td>–</td>
</tr>
<tr>
<td>PDF+$\alpha_S$</td>
<td>&lt; 6.6</td>
<td>2.1–2.9</td>
<td>–</td>
</tr>
<tr>
<td>Multiple parton-parton interactions</td>
<td>&lt; 1</td>
<td></td>
<td>–</td>
</tr>
<tr>
<td>$\text{BR}(H \rightarrow \gamma\gamma)$</td>
<td>1.73</td>
<td></td>
<td>–</td>
</tr>
</tbody>
</table>
**Chargino/Neutralino: Wh, h->\gamma\gamma**

- Higgs boson decay to diphotons
  - Higgs Mass window: \( m(h) \in [105, 160] \) GeV
- Main backgrounds from \( \gamma\gamma \) and \( \gamma + \text{jets} \)
- Parametrised likelihood fits in each SR

**Inclusive W decays:**

- \( W \rightarrow l\nu \) and \( W \rightarrow jj \)

**Wino-like model NLSP**

- Non-resonant background fitted in sideband regions

**12 orthogonal event categories:**

- Lepton / jet number
- \( S_{ETmiss} = E_{Tmiss} / \sqrt{E_T} \)
- Dijet invariant mass in 2jet categories

**First observed sensitivity to Wh(\gamma\gamma) at ATLAS**

- Limits up to 310 GeV for electroweakino production

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WH(γγ): Limits on GMSB model

- GMSB model where two lightest neutralinos and the lightest chargino are Higgsinos
- LSP is the gravitino

\[ \sigma_{\tilde{\chi}_1^0 \tilde{\chi}_2^0} \rightarrow \gamma \gamma \tilde{\chi}_1^{\pm} \tilde{\chi}_2^0, \quad BR(\tilde{\chi}_1^{\pm} \rightarrow W^\pm h) = BR(\tilde{\chi}_2^0 \rightarrow h\tilde{\chi}_1^0) = 100\% \]

\[ m(\tilde{\chi}_1^0) = 0.5 \text{ GeV} \]

\[ h \]

\[ \tilde{\chi}_1^0 \]

\[ \tilde{\chi}_1^0 \]

\[ \tilde{G} \]

\[ \gamma \]

\[ BR(h\tilde{G}) = 100\% \]

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

Limits at 95% CL

\[ m(\tilde{\chi}_1^0) = m(\tilde{\chi}_2^0) + 1 \text{ GeV} \]
Direct stau production

• Search for direct stau production using full Run-2

  • Simplified model assuming two mass-degenerate staus
  • Decay to neutralino (LSP) and tau leptons

**LEP SUSY Summary**

• Lower limits ~ 90 GeV for all neutralino masses (set in 2004)

• Combined LEP limit has prevailed to LHC Run-2
Identifying taus - Triggers

- Improvements in tau triggers in 2018 data-taking

  - For full 2018 - included precision tracking instead of fast tracking pre-selection
    - Reduction in fake track contamination —> increase in 3-prong tau efficiency

  - Post TS1 - included possibility to use RNN ID for taus
SRs and VRs

- **Two SRs: highMass and lowMass SR**
  - Trigger dependent
  - $E_{T}^{\text{miss}}$ cut to split SRs (150 GeV)
  - $m_{T2} > 70$ GeV

- Validation regions confirm good modelling of SM backgrounds (using MC)
Fake tau Modelling

- **ABCD Method to model multi-jet**
  - 2 fake taus in the event

- **Separate lowMass and highMass regions**
  - Multi-jet contributions larger in lowMass regions (75 GeV < $E_T^{\text{miss}}$ < 150 GeV)

- **Good agreement observed in VRs**
Signal Regions

- No excess is found in either of the signal regions
- 2-SR single bin combined fit only
- Both SRs are shown binned in $m_{T2}$

<table>
<thead>
<tr>
<th>SM process</th>
<th>SR-lowMass</th>
<th>SR-highMass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diboson</td>
<td>$1.4 \pm 0.8$</td>
<td>$2.6 \pm 1.2$</td>
</tr>
<tr>
<td>$W+\text{jets}$</td>
<td>$1.5 \pm 0.7$</td>
<td>$2.5 \pm 1.9$</td>
</tr>
<tr>
<td>Top quark</td>
<td>$0.04^{+0.80}_{-0.04}$</td>
<td>$2.0 \pm 0.5$</td>
</tr>
<tr>
<td>$Z+\text{jets}$</td>
<td>$0.4^{+0.5}_{-0.4}$</td>
<td>$0.04^{+0.13}_{-0.04}$</td>
</tr>
<tr>
<td>Higgs</td>
<td>$0.01^{+0.02}_{-0.01}$</td>
<td>-</td>
</tr>
<tr>
<td>Multi-jet</td>
<td>$2.6 \pm 0.7$</td>
<td>$3.1 \pm 1.5$</td>
</tr>
<tr>
<td>SM total</td>
<td>$6.0 \pm 1.7$</td>
<td>$10.2 \pm 3.3$</td>
</tr>
<tr>
<td>Observed</td>
<td>10</td>
<td>7</td>
</tr>
</tbody>
</table>
Model-dependent exclusions

- Limits on mass-degenerate staus (left and right-handed)

- **First direct stau limits from ATLAS:**
  - 95 % CL excluded” $120 \text{ GeV} < m(\text{stau}) < 390 \text{ GeV}$ for massless neutralino
  - 95 % CL excluded” $160 \text{ GeV} < m(\text{stau}) < 300 \text{ GeV}$ for left-handed staus only and a massless neutralino

- No observed sensitivity to right-handed staus
### Long-lived Chargino SR

<table>
<thead>
<tr>
<th>Signal region</th>
<th>Electroweak production</th>
<th>Strong production</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of electrons and muons</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Number of pixel tracklets</td>
<td>≥ 1</td>
<td></td>
</tr>
<tr>
<td>$E_T^{\text{miss}}$ [GeV]</td>
<td>≥ 200</td>
<td>&gt; 250</td>
</tr>
<tr>
<td>Number of jets ($p_T &gt; 20$ GeV)</td>
<td>≥ 1</td>
<td>≥ 3</td>
</tr>
<tr>
<td>Leading jet $p_T$ [GeV]</td>
<td>&gt; 100</td>
<td>&gt; 100</td>
</tr>
<tr>
<td>$\Delta \phi_{\text{jet}} - E_T^{\text{miss}}_{\text{min}}$</td>
<td>&gt; 1.0</td>
<td>&gt; 0.4</td>
</tr>
</tbody>
</table>
Fit to the fake tracklet CR

**ATLAS Preliminary**

\( s = 13 \text{ TeV}, 136 \text{ fb}^{-1} \)

Electroweak production
Fake control region

**ATLAS Preliminary**

\( s = 13 \text{ TeV}, 136 \text{ fb}^{-1} \)

Strong production
Fake control region
Long Lived Charginos

- **Search for long-lived chargino production**
  - Using disappearing track signature in ID
  - At least 4 hits in Pixel, no hits in SCT or further energy deposits

- **Tracklet pT in high $E_T^{\text{miss}}$ SR**

- Chargino masses up to 660 (210) GeV are excluded in scenarios where the chargino is a pure wino (higgsino)