Search for “Electroweakinos” with the ATLAS Detector at the LHC

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On behalf of the ATLAS Collaboration

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Introduction

Search for Electroweakinos

- Electroweakinos = charginos $\tilde{\chi}^{\pm}_{1,2}$ + neutralinos $\tilde{\chi}^{0}_{1,2,3,4}$ (mixtures of bino, winos, higgsinos)
- Superpartners of $U(1)_Y$ and $SU(2)_L$ gauge bosons and Higgs doublets

Motivation

- Complementarity: EWK production may dominate at LHC if squarks and gluinos heavy
- Naturalness: masses of lightest charginos and neutralinos accessible at LHC

Superpartners:
squarks, sleptons, gauginos and higgsinos

$\sigma_{tot}[pb]$: pp $\rightarrow$ SUSY
$\sqrt{S} = 8$ TeV
Run-2 of LHC has begun, past months: push to finalize remaining Run-1 SUSY analyses
Not enough Run-2 data yet to produce competitive new results for EWK production

Here: recent EWK results from ATLAS, 20 fb$^{-1}$ at $\sqrt{s} = 8$ TeV (2012 dataset from Run-1)

Searches produced null results (no significant excess beyond SM expectation observed)

$\Rightarrow$ limits on masses of supersymmetric particles
Introduction

Recent Results from the ATLAS Electroweak Searches

- \( h \rightarrow \gamma(\gamma) + \not{E}_T \) via \( \tilde{\chi}^0_{1/2} \):
  “Search for exotic Higgs-boson decays in events with at least one photon, missing transverse momentum, and two forward jets produced in \( \sqrt{s} = 8 \text{ TeV} \) pp collisions with the ATLAS detector”

- \( \tilde{\chi}^{\pm}_1 \tilde{\chi}^0_2 \) via \( Wh \):
  “Search for direct pair production of a chargino and a neutralino decaying to the 125 GeV Higgs boson in \( \sqrt{s} = 8 \text{ TeV} \) pp collisions with the ATLAS detector”

- **EWK Summary Paper:**
  “Search for the electroweak production of supersymmetric particles in \( \sqrt{s} = 8 \text{ TeV} \) pp collisions with the ATLAS detector”
  (ATLAS-SUSY-2014-05, to appear)
Scope

- Goal: summarize and extend search for electroweak supersymmetry
- Focus: improvements for compressed scenarios and models with low cross sections

New Analyses

- 2 OS $\tau$ (MVA)
- 2 SS $\ell$ (VBF)
- 2 OS $\ell$ (ISR)
- 2 SS $\ell$ (MVA)
- 3$\ell$ incl. 1 SFOS $\ell$ pair (ISR)
- Extend reach through lower lepton-$p_T$ thresholds, exploit ISR & VBF, use MVA techniques

New Aspects

- Statistical combinations of new and existing searches
- Impact of mass of intermediate slepton in simplified models on exclusion reach is tested
Interpretations

- Simplified models: (specific production mode, fixed decay chain, BR = 100 %)

- Phenomenological models:
  - “Electroweak” pMSSM (phenomenological Minimal Supersymmetric Standard Model)
    - → only direct production of $\tilde{\chi}^\pm$ and $\tilde{\chi}^0$, relevant parameters: $\tan \beta$, $M_1$, $M_2$, $\mu$
  - NUHM2 (two-parameter Non-Universal Higgs Masses model):
    - → CMSSM with 2 additional parameters
  - GMSB (Gauge-Mediated Supersymmetry Breaking)
    - → LSP is $\tilde{G}$, electroweak production dominates for large $\Lambda$

- $R$-parity assumed to be conserved
2 OS $\tau$ (MVA) — Overview

Analysis


Event Preselection

• Exactly two opposite-sign taus (light lepton veto)
• Veto on $b$-tagged jets and $Z$ boson decays

MVA

• Train boosted decision trees on 12 input variables with good discriminatory power:
  $E_T$, $m_{\text{eff}}$, $m_{T\tau}$, $m_{\tau\tau}$, $\Delta \phi(\tau, \tau)$, $\Delta \eta(\tau, \tau)$, $p_T^{\tau_1}$, $p_T^{\tau_2}$, $m_{T\tau_1}$, $m_{T\tau_2}$, $\Delta \phi(E_T, \tau_1)$ and $\Delta \phi(E_T, \tau_2)$.
• One SR based on BDT output
95% CL upper limits on cross-section for combined production of $\tilde{\tau}_L\tilde{\tau}_L$ and $\tilde{\tau}_R\tilde{\tau}_R$, $m(\tilde{\chi}_1^0)$ ranging from 0 GeV to 100 GeV

- No excess beyond SM expectation $\Rightarrow$ set limits in simplified model
- MVA improves upon previous expected limits
- Best observed upper limit for $m(\tilde{\tau}) = 109$ GeV and massless $\tilde{\chi}_1^0$
Benefits VBF (lower cross-section):

- additional jets ⇒ means to separate signal from background
- chargino often boosted ⇒ energetic decay products even in compressed spectra

Event Selection

- Exactly 2 SS light leptons + 2 jets + $E_T > 120$ GeV ($E_T$ trigger)
- One cut-based SR
  - exploit VBF topology (large $m_{jj}$, $|\Delta \eta_{jj}|$, $\eta_{j1} \cdot \eta_{j2}$)
  - + cuts to suppress SM backgrounds (mainly diboson + top quark)

$\leftarrow$ VR-Fakes:

- test prediction of dominant backgrounds from $W +$ jets and $t\bar{t}$ production with fake and non-prompt leptons (fake factor method)

$\rightarrow$ SR
2 SS $\ell$ (VBF) — Results

95% CL upper limits on cross-section for VBF $\tilde{\chi}^\pm_1$ $\tilde{\chi}^\pm_1$ production as function of mass splitting 

$(m(\tilde{\chi}^\pm_1) = 110$ and $120 \text{ GeV})$

- Best observed upper limit for $m(\tilde{\chi}^\pm_1) = 120 \text{ GeV}$ and $m(\tilde{\chi}^\pm_1) - m(\tilde{\chi}^0_1) = 25 \text{ GeV}$: excluded cross-section $10.9 \text{ fb}$, theoretical LO cross-section $4.33 \text{ fb}$
Analysis

- Extends previous analysis to small mass splittings $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)$ by exploiting ISR jets

Event Selection

- Exactly 2 OS light leptons, require high-$p_T$ ISR jet
- Veto on $b$-tagged / forward jets and $Z$ boson decays
- 2 SR based on "super-razor variables" and $R_2$

\[ R_2 = \frac{E^\ell_f}{E^\ell_f + p^\ell_1 + p^\ell_2} \]

in SR "a"
Analysis

- Extends previous analysis to small mass splittings $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$
- New: includes $3\ell$ triggers with low-$p_T$ thresholds and also defines SR with ISR jets

Event Selection

- Exactly 3 light leptons, incl. $\geq 1$ SFOS $\ell$ pair
- Veto on $b$-tagged jets and $\Upsilon$ meson decays
- $2 \times 2$ SR: veto or require jet $> 50$ GeV, $m_{\text{min \ SFOS}}$ between 5 – 15 GeV or 15 – 25 GeV

$E_T$ and $m_{\ell\ell\ell\ell}$ in $3\ell$ SR before cut
Analysis

- Complements $3\ell$ search in case one lepton not reconstructed
- Extends reach for small mass splittings

Event Selection

- Exactly 2 SS light leptons
- Veto on $b$-tagged jets and $m_{SFOS} < 12$ GeV
- Train 8 BDT $\rightarrow$ 8 SR: optimized for four mass-splitting scenarios $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$, each with and w/o ISR jet

Scalar sum of leptons and jet $H_T$

in the non-ISR VR $\rightarrow$

(VR defined based on BDT output)
Results — $\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$ Production

**Left:** complementarity of the new 2 SS $\ell$ (MVA) and the $3\ell$ analysis (for sleptons close to $\tilde{\chi}_2^0$ in mass)

**Middle:** improved sensitivity in compressed scenarios from new $3\ell$ analysis (for sleptons halfway between $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^0$ in mass)

**Right:** new combination of $2\tau$ and $3\ell$ analyses, improves limits in stau-mediated decays

\[ m(\tilde{\ell}) = 0.95m(\tilde{\chi}_2^0) + 0.05m(\tilde{\chi}_1^0) \]

\[ m(\tilde{l}) = \frac{1}{2}(m(\tilde{\chi}_2^0) + m(\tilde{\chi}_1^0)) \]

\[ m(\tilde{\tau}) = \frac{1}{2}(m(\tilde{\chi}_2^0) + m(\tilde{\chi}_1^0)) \]
Results — $\tilde{\chi}_1^{\pm} \tilde{\chi}_1^{0}$ / $\tilde{\chi}_2^{0} \tilde{\chi}_3^{0}$ Production

ATLAS-SUSY-2014-05

Simplified Model: $\tilde{\chi}_1^{\pm} \tilde{\chi}_1^{0} \rightarrow 2 \times \tilde{\nu} (\tilde{\nu}) \rightarrow 2 \times \nu \chi_0$

ATLAS Preliminary

$\sqrt{s} = 8$ TeV, 20.3 fb$^{-1}$

$m_{\tilde{\chi}_1} = (m_{\tilde{\nu}}, m_{\chi_0})/2$

SR2I-1

ATLAS Preliminary

$\sqrt{s} = 8$ TeV, 20.3 fb$^{-1}$

$\tilde{\chi}_1^{0} \tilde{\chi}_1^{0}$ production with slepton-mediated decays

Simplified Model: $\tilde{\chi}_2^{0} \tilde{\chi}_3^{0} \rightarrow 2 \times \nu \chi_0 \rightarrow 2 \times \nu \chi_0$

ATLAS Preliminary

$\sqrt{s} = 8$ TeV, 20.3 fb$^{-1}$

Combined 3$\ell$, 4$\ell$

arXiv:1405.5086

All limits at 95% CL

• Left: nice complementarity of new 2 OS $\ell$ (ISR) analysis at small mass splittings
• Right: new combination of 3$\ell$ and 4$\ell$ analyses shows 30 GeV improvement in limits
Impact of Variable Slepton Mass

- Comparison of exclusion limits for several different $m(\tilde{\ell}) = x \cdot m(\text{ISP})$  ($m(\tilde{\chi}_1^0) = 0$ GeV)

- $\Rightarrow$ Impact of intermediate slepton mass on limit small

- Same picture for the other models ($\tilde{\chi}_1^\pm, \tilde{\chi}_1^\mp, \tilde{\chi}_2^0, \tilde{\chi}_3^0$)
New Summary Plots with Interpretations in Simplified Models

**ATLAS Preliminary**
20.3 fb⁻¹, √s=8 TeV

**W/Z/h-boson mediated decays**
- \( \tilde{\chi}_1^\pm \tilde{\chi}_1^\mp \) via WW,
- \( \tilde{\chi}_1^\pm \tilde{\chi}_2^0 \) via WZ/Wh
- Small sensitivity from new analyses (→ no combination)

**\( \tilde{\ell} \)-mediated decays**
- \( \tilde{\chi}_1^\pm \tilde{\chi}_1^\mp \), \( \tilde{\chi}_1^\pm \tilde{\chi}_2^0 \), \( \tilde{\chi}_2^0 \tilde{\chi}_3^0 \) production with slepton-mediated decays
- light blue: new analysis
- red: combination with new analyses
- green, orange: new combinations

- \( m_{\tilde{\chi}_1^\pm} = m_{\tilde{\chi}_2} + m_{\tilde{\chi}_3} \)
- \( m_{\tilde{\chi}_1^\mp} = m_{\tilde{\chi}_2^0} + m_{\tilde{\chi}_3^0} \)
- \( m_{\tilde{\chi}_1^\pm} = 2m_{\tilde{\chi}_2^0} \)
- pMSSM ($\mu$-$M_2$ plane): new combination of $2\ell$, $3\ell$, and $Wh$ (added)
- NUHM2 ($\mu$-$m_{1/2}$ plane): new interpretation of $2\ell$, $3\ell$ (drives exclusion limit), and $4\ell$
- GMSB ($\Lambda$-$\tan \beta$ plane): new reinterpretation of $4\ell$ analysis, yields improvement by 15 – 20 TeV w.r.t. earlier combination of 2 SS / 3$\ell$ analyses
### End of Run-1

- No strong signs for physics beyond the Standard Model found in Run-1 data
- Large number of SUSY analyses have been made public
- Presented the new EWK summary paper
  - with final $\sqrt{s} = 8$ TeV ATLAS limits for EWK production
  - not only a summary, but also new analyses and new combinations

### Onto Run-2

- Run-2 is on-going, new data already flowing in
- First months certainly belong to strong searches
  - stronger benefit from higher center-of-mass energy, quick re-not-discovery of SUSY
- Electroweak searches need more data to become competitive with Run-1 results
  - will be able to build upon lots of experience from Run-1
  - profit on long term from higher integrated luminosity in Run-2

### Web Page

- Overview of public results on searches for supersymmetry using ATLAS:
  
  https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults
VBF $H \rightarrow \gamma(\gamma) + \not{E}_T$ in GMSB / NMSSM

- Search for exotic Higgs decays, photon + $\not{E}_T$ final state
- Motivation: $\text{BR}(h \rightarrow \text{BSM}) \sim \mathcal{O}(50\%)$ possible
- VBF Higgs production, $m_h = 125 \text{ GeV}$
- Interpretation:
  - GMSB: $h \rightarrow \tilde{G}\tilde{\chi}^0_1$ (or $\tilde{\chi}^0_1\tilde{\chi}^0_1$), $\tilde{\chi}^0_1 \rightarrow \tilde{G}\gamma$
  - NMSSM: $h \rightarrow \tilde{\chi}^0_2\tilde{\chi}^0_1$ (or $\tilde{\chi}^0_2\tilde{\chi}^0_2$), $\tilde{\chi}^0_2 \rightarrow \tilde{\chi}^0_1\gamma$
  - Diphoton final states also considered

- Event selection:
  - 1 isolated photon, $\not{E}_T > 50 \text{ GeV}$
  - $\geq 2$ separated jets with high inv. mass
  - lepton veto, non-VBF jet veto
- Signal region yields:
  - expected: $38.0 \pm 2.2 \pm 4.5$
    (dominant background: $\gamma$+jets, multijet)
  - observed in data: 50

Exclusion limits in mono-photon channel
Search for \( pp \rightarrow \tilde{\chi}_1^{\pm} \tilde{\chi}_2^0 \) decaying via \( Wh \)

Focus on scenarios where \( \tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 h \) dominant:
- \( \tilde{\chi}_1^{\pm} \) and \( \tilde{\chi}_2^0 \) wino-like, \( m(\tilde{\chi}_1^{\pm}) \approx m(\tilde{\chi}_2^0) \)
- Always: \( W \rightarrow 1\ell + \not{E}_T \)
- Combination of 3 signatures: SM-like \( h \rightarrow bb / \gamma\gamma / \ell\nu qq' \)

- \( bb \):
  - 2 SR based on transverse mass \( m_T^W \), cotransv. mass \( m_{CT} \)
  - dominant bg.: \( W \) and top-quark production

- \( \gamma\gamma \):
  - 2 SR based on \( m_T^{W_{\gamma1,2}} \), \( W \) and \( h \) roughly back-to-back
  - dominant bg.: multijets + \( Z\gamma \) (misid. \( \gamma \) from leptons or jets)

- \( WW \):
  - 2 SR for each \( ee, e\mu, \mu\mu \) based on \( \Delta\eta_{ll}, m_{\text{eff}}, m_T^{\text{max}} \)
  - dominant bg.: dibosons (irr.), non-prompt leptons (red.)

- common: Higgs-mass window / sidebands
• Event yields: consistent with SM expectations in all signal regions
• Interpretation: upper limits on visible cross section and in simplified models
• Limits: in individual channels and as combination (incl. 3$\ell$ analysis)
• $bb$ channel: strongest limits for massless LSP overall, but actual exclusion from $\gamma\gamma$ stronger at low gaugino masses

Limits on signal strength for massless $\tilde{\chi}^0_1$

Exclusion limits in mass plane
ATLAS Preliminary: 20.3 fb⁻¹, √s = 8 TeV

Status: Feb 2015

Expected limits:
- \( \tilde{\chi}_{1} \tilde{\chi}_{2} \) via \( L_\ell/\tilde{\nu}_\ell \), 3L, arXiv:1402.7029
- \( \tilde{\chi}_{1} \tilde{\chi}_{1} \) via \( L_\ell/\tilde{\nu}_\ell \), 2L, arXiv:1403.5294
- \( \tilde{\chi}_{1} \tilde{\chi}_{2} \) via \( \tau_\ell/\tilde{\nu}_\ell \), 3L, arXiv:1402.7029
- \( \tilde{\chi}_{1} \tilde{\chi}_{2} \) via \( \tilde{\tau}_\ell/\tilde{\nu}_\ell \), \( \geq 2\tau \), arXiv:1407.0350
- \( \tilde{\chi}_{1} \tilde{\chi}_{2} \) via \( \tilde{\nu}_\ell \), \( \geq 2\tilde{\tau} \), arXiv:1407.0350
- \( \tilde{\chi}_{1} \tilde{\chi}_{2} \) via \( WZ \), 2L, arXiv:1403.5294
- \( \tilde{\chi}_{1} \tilde{\chi}_{2} \) via \( Wh \), \( lbb+\ell\gamma\ell\ell \), 3L, arXiv:1501.07110
- \( \tilde{\chi}_{1} \tilde{\chi}_{2} \) via \( WW \), 2L, arXiv:1403.5294

All limits at 95% CL

Observations:
- \( m_{\tilde{\chi}_{1}/\tilde{\tau}_{\ell}} = 0.5(m_{\tilde{\chi}_{1}^0} + m_{\tilde{\chi}_{2}^0}) \)
- \( L = e/\mu/\tau \)
- \( l = e/\mu \)
- \( m_{\tilde{\chi}_{1}} = m_{\tilde{\chi}_{1}^0} + m_{\tilde{\chi}_{2}^0} \)
- \( m_{\tilde{\chi}_{2}} = m_{\tilde{\chi}_{2}^0} + m_{\tilde{\chi}_{1}^0} \)
- \( m_{\tilde{\chi}_{1}} = 2m_{\tilde{\chi}_{2}^0} \)
### Summary of Exclusion Ranges from ATLAS SUSY Searches in Run-1

#### ATLAS SUSY Searches* - 95% CL Lower Limits

<table>
<thead>
<tr>
<th>Model</th>
<th>$\ell, \mu, \tau, \gamma$</th>
<th>Jets</th>
<th>$E_T^{miss}$ (GeV)</th>
<th>$\ell, \tau, H_T$ (GeV)</th>
<th>Mass limit</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSUGRA/CMSMSS</td>
<td>0-3 e, $\mu$, $\tau$, $\gamma$</td>
<td>0-3 jets</td>
<td>20.3</td>
<td>$E_T^{miss}$ = 850 GeV</td>
<td>$\tau = 600$</td>
<td>1507.05525</td>
</tr>
<tr>
<td>$\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0$</td>
<td>0</td>
<td>2-6 jets</td>
<td>20.3</td>
<td>$E_T^{miss}$ = 780 GeV</td>
<td>$\tau = 800$</td>
<td>1405.7975</td>
</tr>
<tr>
<td>$\tilde{\chi}_1^+ = \tilde{\chi}<em>2^0 + m</em>{\chi}$</td>
<td>0</td>
<td>2-6 jets</td>
<td>20.3</td>
<td>$E_T^{miss}$ = 1330 GeV</td>
<td>$\tau = 1000$</td>
<td>1507.05525</td>
</tr>
<tr>
<td>$\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0$</td>
<td>0-1 e, $\mu$, $\tau$, $\gamma$</td>
<td>2-6 jets</td>
<td>20.3</td>
<td>$E_T^{miss}$ = 1260 GeV</td>
<td>$\tau = 800$</td>
<td>1405.7975</td>
</tr>
<tr>
<td>$\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0$</td>
<td>0-1 e, $\mu$, $\tau$, $\gamma$</td>
<td>2-6 jets</td>
<td>20.3</td>
<td>$E_T^{miss}$ = 1320 GeV</td>
<td>$\tau = 1000$</td>
<td>1507.05525</td>
</tr>
<tr>
<td>$\tilde{\chi}_1^0$</td>
<td>$\tilde{\chi}_2^0$</td>
<td>1-2 $\tau$ + 0.1 (fNLSP)</td>
<td>20.3</td>
<td>$E_T^{miss}$ = 1290 GeV</td>
<td>$\tau = 800$</td>
<td>1405.7975</td>
</tr>
<tr>
<td>GGM (bino NLSP)</td>
<td>0</td>
<td>mono-jet</td>
<td>20.3</td>
<td>$E_T^{miss}$ = 1300 GeV</td>
<td>$\tau = 800$</td>
<td>1405.7975</td>
</tr>
<tr>
<td>GGM (higgsino-bino NLSP)</td>
<td>0</td>
<td>mono-jet</td>
<td>20.3</td>
<td>$E_T^{miss}$ = 1300 GeV</td>
<td>$\tau = 800$</td>
<td>1405.7975</td>
</tr>
<tr>
<td>GGM (higgsino-bino NLSP)</td>
<td>0</td>
<td>mono-jet</td>
<td>20.3</td>
<td>$E_T^{miss}$ = 1300 GeV</td>
<td>$\tau = 800$</td>
<td>1405.7975</td>
</tr>
<tr>
<td>Gravitino LSP</td>
<td>0</td>
<td>mono-jet</td>
<td>20.3</td>
<td>$E_T^{miss}$ = 1300 GeV</td>
<td>$\tau = 800$</td>
<td>1405.7975</td>
</tr>
</tbody>
</table>

#### ATLAS Preliminary

$\sqrt{s} = 7, 8$ TeV

*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1-$\sigma$ theoretical signal cross section uncertainty.*

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**Search for EWKinos with ATLAS**

LHCP — 02.09.2015

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Alexander Mann (LMU München)
Comparison of 95% exclusion limits for $m(\tilde{\chi}_1^0) = 0 \text{ GeV}$ and $m(\tilde{\ell}) = x \cdot m(\text{ISP})$

Impact of intermediate slepton mass very small for all three models (exception: $x = 0.95$)
Interpretations

- **Simplified models**: (specific production mode, fixed decay chain, BR = 100 %)
  - $\tilde{\tau} \tilde{\tau}$
  - $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$ in VBF

- **Phenomenological models**:  
  - "Electroweak" pMSSM (phenomenological Minimal Supersymmetric Standard Model)
    - only direct production of $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_1^0$ (sfermions and others decoupled)
    - reduced set of parameters: $\tan \beta, M_1, M_2, \mu$ (instead of 19)
  - NUHM2 (two-parameter Non-Universal Higgs Masses model):
    - CMSSM + 2 additional parameters, $\mu$ and $m_A$
    - little fine-tuning, Higgs mass 125 GeV, squark masses of few TeV
    - electroweak production dominates for heavy gluino masses
  - GMSB (Gauge-Mediated Supersymmetry Breaking)
    - LSP is $\tilde{G}$, electroweakino decays yield final states with many leptons
    - electroweak production dominates for large $\Lambda$

- $R$-parity assumed to be conserved
Production cross sections for the simplified models of the direct production of \( \tilde{\chi}_1^\pm \tilde{\chi}_1^\mp \), \( \tilde{\chi}_1^\pm \tilde{\chi}_2 \), \( \tilde{\chi}_2 \tilde{\chi}_3 \), and \( \tilde{\tau}^+ \tilde{\tau}^- \).
Table 2: The triggers used in the analyses and the offline $p_T$ threshold used, ensuring that the lepton(s) or $E_T^{miss}$ triggering the event are in the plateau region of the trigger efficiency. Where multiple triggers are listed for an analysis, events are used if any of the triggers is passed. Muons are triggered within a restricted range of $|\eta| < 2.4$.

<table>
<thead>
<tr>
<th>Trigger</th>
<th>$p_T$ threshold [ GeV]</th>
<th>Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single $\tau$</td>
<td>150</td>
<td>Direct stau production</td>
</tr>
<tr>
<td>Double $\tau$</td>
<td>40,25</td>
<td></td>
</tr>
<tr>
<td>Single Isolated $e$</td>
<td>25</td>
<td>Compressed spectra $\ell^+\ell^-, 3\ell$</td>
</tr>
<tr>
<td>Single Isolated $\mu$</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td>Double $e$</td>
<td>14,14</td>
<td>Compressed spectra $\ell^+\ell^-, \ell^+\ell^\pm, 3\ell$</td>
</tr>
<tr>
<td></td>
<td>25,10</td>
<td></td>
</tr>
<tr>
<td>Double $\mu$</td>
<td>14,14</td>
<td>Compressed spectra $\ell^+\ell^-, \ell^+\ell^\pm, 3\ell$</td>
</tr>
<tr>
<td></td>
<td>18,10</td>
<td></td>
</tr>
<tr>
<td>Triple $e$</td>
<td>20,9,9</td>
<td>Compressed spectra $3\ell$</td>
</tr>
<tr>
<td>Triple $\mu$</td>
<td>7,7,7</td>
<td>Compressed spectra $3\ell$</td>
</tr>
<tr>
<td></td>
<td>19,5,5</td>
<td></td>
</tr>
<tr>
<td>Combined $e\mu$</td>
<td>14(e),10(\mu)</td>
<td>Compressed spectra $3\ell$</td>
</tr>
<tr>
<td></td>
<td>18(\mu),10(e)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>9(e),9(e),7(\mu)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>9(e),7(\mu),7(\mu)</td>
<td></td>
</tr>
</tbody>
</table>

$E_T^{miss}$ 120 Chargino production via VBF

Compressed Spectra

- For small mass splittings between sparticles and LSP $\Rightarrow$ low-momentum decay products $\Rightarrow$ experimentally challenging
- Motivation: naturalness $\Rightarrow$ light higgsino $\Rightarrow$ $\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$, $\tilde{\chi}_1^\pm$ usually higgsino-dominated $\Rightarrow$ small $m(\tilde{\chi}_1^0) \lesssim m(\tilde{\chi}_2^0), m(\tilde{\chi}_1^\pm)$
Exclusion limits are calculated by statistically combining results from disjoint SRs.
Where SRs overlap, the best expected SR is used for each grid point.

Table 23: Searches used to probe each of the models described in Section 2.

<table>
<thead>
<tr>
<th>Model</th>
<th>( Wh ) [23]</th>
<th>( 2\ell^\dagger ) [19]</th>
<th>( 2\tau^* ) [22]</th>
<th>( 3\ell^\diamond ) [20]</th>
<th>( 4\ell ) [21]</th>
<th>2( \tau ) MVA*</th>
<th>SR2( \ell^\dagger )</th>
<th>SS MVA$</th>
<th>SR3( \ell^\diamond/1 )</th>
<th>SR2( \ell^\dagger )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \tilde{\tau} \tilde{\tau} ) via ( \ell_L ) with ( x = 0.5 )</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
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\( \dagger \) The opposite-sign, two-lepton signal regions in Ref. [19] and Section 8.1 overlap.

\( \ast \) The two-tau signal regions in Ref. [22] and Section 7 overlap.

\( \diamond \) The three-lepton signal regions in Ref. [20] and Section 8.3 overlap.

\( \$ \) The same-sign, two-lepton signal regions in Section 8.2 and Section 9 overlap.
EWK Summary Paper

Definition of Super-Razor Variables ($R_2$, $M^R_\Delta$, $\Delta \phi^\beta_R$)

$m_{T2}$ The “stransverse mass” is calculated as

$$m_{T2} = \min_{\vec{q}_T} \left[ \max \left( m_T(p_T^{\ell_1/\tau_1}, \vec{q}_T), m_T(p_T^{\ell_2/\tau_2}, E_T^{\text{miss}} - \vec{q}_T) \right) \right],$$

where $\ell_1/\tau_1$ and $\ell_2/\tau_2$ denote the highest- and second-highest-$p_T$ leptons or taus in the event, respectively, and $\vec{q}_T$ is a test transverse vector that minimizes the larger of the two transverse masses $m_T$. The $m_{T2}$ distribution has a kinematic endpoint for events where two massive pair-produced particles each decay to two objects, one of which is detected and the other escapes undetected [108, 109].

$m_{\text{eff}}$ The scalar sum of the transverse momenta of the signal leptons, taus, jets and $E_T^{\text{miss}}$ in the event:

$$m_{\text{eff}} = E_T^{\text{miss}} + \Sigma p_T^{\text{leptons}} + \Sigma p_T^{\text{taus}} + \Sigma p_T^{\text{jets}}.$$  

In the case of the two-tau analysis, only the sum of the $E_T^{\text{miss}}$ and two taus is used.

$R_2$ The quantity $R_2$ is defined as

$$R_2 = \frac{E_T^{\text{miss}}}{E_T^{\text{miss}} + p_T^{\ell_1} + p_T^{\ell_2}}.$$  

The $R_2$ distribution is shifted towards unity for signal events compared to the background, due to the existence of the LSPs that results in a larger $E_T^{\text{miss}}$ fraction.

$M^R_\Delta$, $\Delta \phi^\beta_R$ The super-razor quantities $M^R_\Delta$ and $\Delta \phi^\beta_R$ are defined in Ref. [110]. These variables are motivated by the generic process of the pair production of two massive particles, each decaying into a set of visible and invisible particles (i.e. $\tilde{\chi}^\pm_1 \rightarrow \ell \nu_\ell \tilde{\chi}^0_1$). Similar to $m_{T2}$, $M^R_\Delta$ is sensitive to the squared mass difference of the pair-produced massive particle and the invisible particle, via a kinematic endpoint. These two variables are expected to have a similar performance. For systems where the invisible particle has mass that is comparable to the pair-produced massive particle (i.e. compressed spectra), the variable $\Delta \phi^\beta_R$ has a pronounced peak near $\pi$. The effect is magnified as the spectrum becomes more and more compressed, making this variable a good discriminator for compressed spectra searches.
Signal MC

- $\tilde{\tau}\tilde{\tau}$, $\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp$, $\tilde{\chi}_1^\pm\tilde{\chi}_2^0$: Herwig++ (2.5.2)
- $\tilde{\chi}_2^0\tilde{\chi}_3^0$, VBF $\tilde{\chi}_1^\pm\tilde{\chi}_1^\pm$: MadGraph5 (-1.5.12 / _aMC@NLO-2.1.1) + Pythia (6.426)

Signal Grids: EWKino Composition

- $\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp$, $\tilde{\chi}_1^\pm\tilde{\chi}_2^0$: both $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ pure wino and mass-degenerate, $\tilde{\chi}_1^0$ pure bino, slepton-mediated decays: BR = 1/6 for all 3 $\tilde{\ell}_L$ / $\tilde{\nu}$, stau-mediated: BR = 1/2 for $\tilde{\tau}_L$ / $\tilde{\nu}_\tau$
- $\tilde{\chi}_2\tilde{\chi}_3$: $\tilde{\chi}_2^0$ and $\tilde{\chi}_3^0$ pure higgsino and mass-degenerate, $\tilde{\chi}_1^0$ pure bino, BR = 1/2 for $\tilde{e}_R$, $\tilde{\mu}_R$
- SS $\tilde{\chi}_1^\pm$-pair production in VBF: $\tilde{\chi}_1^\pm$ pure wino, $\tilde{\chi}_1^0$ pure bino, BR = 1/6 for all 3 $\tilde{\ell}_L$ / $\tilde{\nu}$

Interpretation: GMSB Bump

- For most of the parameter space: co-NLSP (stau and slepton)
- Low $\tan\beta$: just slepton as NLSP → BR to light leptons larger
- Since light-lepton analyses usually better reach → better sensitivity there
Dominating Backgrounds

- **2 OS \( \tau \) (MVA):**
  - reducible (\( \geq 1 \) fake taus): \( W + \text{jets} \) (multi-jet)
  - irreducible (2 prompt taus): diboson (\( tt, Z + \text{jets} \))

- **2 OS \( \ell \) (ISR)**
  - irreducible (2 prompt leptons): \( WW, \top, (ZV, \text{Higgs}, Z + \text{jets}) \)
  - reducible (\( \geq 1 \) fake leptons, e.g. \( e \) conversions): small

- **2 SS \( \ell \) (MVA)**
  - irreducible (2 prompt SS leptons): diboson (triboson, \( ttV, tZ, \text{higgs} \))
  - reducible (\( \geq 1 \) fake leptons): \( W\gamma \)
  - charge flip (\( \geq 1 \) lepton with mismeasured charge)

- **3\( \ell \) incl. 1 SFOS \( \ell \) pair (ISR)**
  - reducible (\( \geq 1 \) fake leptons): \( tt, Z + \text{jets} (W + \text{jets}, WW, \top) \)
  - irreducible (3 prompt leptons): \( WZ/ZZ \) (triboson, \( ttV, tZ, \text{higgs} \))

- **2 SS \( \ell \) (VBF)**
  - reducible (\( \geq 1 \) fake leptons): \( W + \text{jets} (tt, W\gamma) \)
  - irreducible (2 prompt leptons): \( WZ, WW \)
  - charge flip (\( \geq 1 \) lepton with mismeasured charge)
Dominating Systematic Uncertainties

- **2 OS $\tau$ (MVA):** stat. unc. on MC samples (20 %), $E_T$ soft-term resolution (20 %); total: 35 %
- **2 OS $\ell$ (ISR):** theory & modeling (generator modeling, parton shower, . . . , 22 – 24 %); total: 23 – 28 %
- **2 SS $\ell$ (MVA):** stat. unc. on MC samples (7 – 74 %), real lepton subtraction 8 – 33 %), jet-energy resolution (1 – 35 %); total: 18 – 81 %
- **3$\ell$ incl. 1 SFOS $\ell$ pair (ISR):** stat. unc. on reducible bg. estimate (11 – 34 %), muon misidentification probability (red. bg. est., < 1 – 27 %), total: 25 – 59 %
- **2 SS $\ell$ (VBF):** fake-factor closure test (13 %), stat. unc. on the red. bg. (11 %), total: 21 %
VBF $H \rightarrow \gamma(\gamma) + E_T$ in GMSB / NMSSM

**Monophoton signals**

**Diphoton signals**

**Observed limits**

$$m_{\text{NLSP}} \ [\text{GeV}]$$

$$m_{\text{LSP}} \ [\text{GeV}]$$

$\sqrt{s} = 8 \text{ TeV}, 20.3 \text{ fb}^{-1}$

**Expected limits**

**Observed limit**

**Preliminary ATLAS**

-1 = 8 TeV, 20.3 fb$^{-1}$

**Observed limits**

$$p$$

$$\chi^0_1/\tilde{\chi}^0_2$$

$$\tilde{G}/\tilde{\chi}^0_1$$

$$\gamma$$

$$j$$

**Diphoton production**

Alexander Mann (LMU München)

Search for EWKinos with ATLAS
Individual limits in 3 channels ($\ell bb$, $\ell \gamma \gamma$, $\ell \ell^+ \ell^-$):
Discriminating Variables

- Cotransverse mass $m_{CT} = \sqrt{(E_{T}^{b_1} + E_{T}^{b_2})^2 - |\vec{p}_{T}^{b_1} - \vec{p}_{T}^{b_2}|^2}$
  $t\bar{t}$: upper endpoint at approximately top mass

- Transverse mass $m_{W} = \sqrt{2E_{T}E_{T}^{\text{miss}} - 2\vec{p}_{T}^{\ell} \cdot \vec{p}_{T}^{\text{miss}}}$
  $W + \text{jets}$: at low values

- $m_{W\gamma}^{1,2} = \sqrt{(m_{W})^2 + 2E_{T}^{W}E_{T}^{\gamma_i} - 2\vec{p}_{T}^{W} \cdot \vec{p}_{T}^{\gamma_i}}$
  including photon in transverse mass allows to identify lept. $W$ decays with photon FSR

- $\Delta \phi (W, h)$: $W \rightarrow \ell \nu$ and $h\gamma\gamma$ back-to-back

- $m_{T}^{\text{max}} = \max \{ m_{T}(\ell_1), m_{T}(\ell_2) \}$ (against $W$)

- $m_{\text{eff}} = \text{sum of } p_{T} \text{ of leptons, jets and } E_{T}$ (against diboson)

- $E_{T}^{\text{miss,rel}} = E_{T}$ reduced by component along direction of nearest lepton or jet (against $Z$, non-prompt leptons, reduced impact from mismeasurements)

- small $\Delta \eta_{ll}$ against $WZ, ZZ$
SUSY Models

### mSUGRA / CMSSM Parameters
- → gravity-mediated SUSY breaking
- $m_0$: mass of scalar particles
- $m_{1/2}$: gaugino masses
- $A_0$: trilinear Higgs-sfermion-sfermion coupling parameter
- $\tan \beta = \nu_u / \nu_d$: ratio of the vacuum expectation values of the two Higgs doublets
- sign of the Higgsino mass parameter $\mu$
- NUHM2: adds $m_{H_u}, m_{H_d}$, trade for $\mu, m_A$

### GMSB Parameters
- → gauge-mediated SUSY breaking
- $\Lambda$: SUSY breaking mass scale felt by the low-energy sector
- $M_{\text{mes}}$: mass scale of the messenger fields
- $N_5$: number of SU(5) messenger fields
- $C_{\text{grav}}$: scale factor of the gravitino coupling
- $\tan \beta = \nu_u / \nu_d$: ratio of the vacuum expectation values of the two Higgs doublets
- sign of the Higgsino mass parameter $\mu$

### NGM
- starts from General Gauge Mediation
- GGM: no specific SUSY mass hierarchy is predicted for colored and uncolored states
  ⇒ gluinos and squarks can be below the TeV scale = within reach of LHC
- NGM: decouple all sparticles not related to fine-tuning of Higgs sector
  ⇒ light stop and light gluino as only light (relevant) coloured sparticle
- some additional mechanism needed (as in GMSB) to produce "correct" Higgs mass