Searches for Tau Sleptons
at the Large Hadron Collider

Alexander Mann
mann@cern.ch
On behalf of the ATLAS and CMS Collaborations

7th Edition of the Large Hadron Collider Physics Conference
Puebla, Mexico, 20th May – 25th May 2019
### Setting the Scene

#### Standard Model with 2 Higgs doublets

- **quarks**: $u$, $c$, $t$, $d$, $s$, $b$
- **gauge bosons**: $\gamma$, $Z^0$, $W^\pm$, $g$
- **Higgs bosons**: $h$, $H^0$, $A$, $H^\pm$
- **leptons**: $e$, $\mu$, $\tau$, $\nu_e$, $\nu_\mu$, $\nu_\tau$

#### (minimal) Supersymmetric Extension

- **higgsinos + gauginos**: $\tilde{\chi}_{01}^0$, $\tilde{\chi}_{02}^0$, $\tilde{\chi}_{03}^0$, $\tilde{\chi}_{04}^0$, $\tilde{\chi}_{\pm1}^\pm$
- **squarks**: $\tilde{u}_{L,R}$, $\tilde{c}_{L,R}$, $\tilde{t}_{L,R}$, $\tilde{d}_{L,R}$, $\tilde{s}_{L,R}$, $\tilde{b}_{L,R}$
- **sleptons**: $\tilde{\nu}_e$, $\tilde{\nu}_\mu$, $\tilde{\nu}_\tau$, $\tilde{\nu}^\pm$, $\tilde{e}_{L,R}$, $\tilde{\mu}_{L,R}$, $\tilde{\tau}_{1,2}$

---

Alexander Mann (LMU München)  
Searches for Tau Sleptons  
7th LHCP Conference — 22.05.2019  
2
Setting the Scene

- **Standard Model with 2 Higgs doublets**
  - quarks: $u$, $c$, $t$, $d$, $s$, $b$
  - gauge bosons: $\gamma$, $Z^0$, $W^\pm$, $g$
  - leptons: $\nu_e$, $\nu_\mu$, $\nu_\tau$, $e$, $\mu$, $\tau$
  - Higgs bosons: $h$, $H^0$

- **(minimal) Supersymmetric Extension**
  - higgsinos + gauginos:
    - $\tilde{\chi}^0_1$, $\tilde{\chi}^0_2$, $\tilde{\chi}^0_3$, $\tilde{\chi}^0_4$
    - $\tilde{\chi}^{\pm}_1$, $\tilde{\chi}^{\pm}_2$
  - squarks:
    - $\tilde{u}_{L,R}$, $\tilde{c}_{L,R}$, $\tilde{t}_{L,R}$
    - $\tilde{d}_{L,R}$, $\tilde{s}_{L,R}$, $\tilde{b}_{L,R}$
  - sleptons:
    - $\tilde{\nu}_e$, $\tilde{\nu}_\mu$, $\tilde{\nu}_\tau$, $\tilde{\tau}_{1,2}$

- **Topic of this talk:** scalar superpartner of tau lepton = “tau slepton” or “stau” ($\tilde{\tau}_1$)
Motivation

- Tau sleptons $\tilde{\tau}$ in decay chains $\Rightarrow$ final states enriched with tau leptons
  - tau lepton: hadronic ($\tau_h$) or leptonic decay ($\tau_\ell$)
- Often $m(\tilde{\tau}) < m(\tilde{e})$, $m(\tilde{\mu})$ — in particular for SUSY scenarios with large $\tan \beta$
  - neutralinos and charginos then decay predominantly via tau sleptons
- Models with low fine-tuning often feature a light tau slepton
- Light $\tilde{\tau}$ almost degenerate with bino LSP enables co-annihilation
  $\Rightarrow$ obtain relic dark-matter density consistent with observations
- Searches with tau leptons complementary to searches with light leptons
  - cover as much of SUSY phenomenology as possible

- Note: will assume R-parity conservation and prompt decays$^\star$
Different Production Modes of SUSY Particles

\[ pp, \sqrt{s} = 13 \text{ TeV}, \text{NLO+NLL - NNLO+NNLL} \]

\[
\begin{align*}
gg & \quad \tilde{\chi}^- \tilde{\chi}^0 \text{ (wino)} \\
\bar{q} \bar{q} & \quad \tilde{\chi}^0 \tilde{\chi}^0 \text{ (wino)} \\
\bar{t} \bar{t} & \quad \tilde{\tau}_1 \tilde{\tau}_1
\end{align*}
\]
Different Production Modes of SUSY Particles

**strong production**
inclusive final states

Example simplified model with **indirect** production of $\tilde{\tau}$:
Different Production Modes of SUSY Particles

Example simplified model with indirect production of $\tilde{\tau}$:

$\tilde{g}\tilde{g}$, $\tilde{q}\tilde{q}$, $\tilde{t}_1\tilde{t}_1$, $\tilde{G}\tilde{G}$, $\tilde{\chi}_0^1\tilde{\chi}_1^\pm$ (wino)

$pp, \sqrt{s} = 13$ TeV, NLO+NLL - NNLO+NNLL

3rd generation final states with $b$-jets
Different Production Modes of SUSY Particles

**Example simplified model with indirect production of $\tilde{\tau}$:**

- $\tilde{g}\tilde{g}$
- $\tilde{q}\tilde{q}$
- $\tilde{t}_{1}\tilde{t}_{L}$
- $\tilde{q}\nu_{\tau}/\tau$
- $\tilde{\chi}_{0}^{1}$
- $\tilde{\chi}_{1}^{0}$
Different Production Modes of SUSY Particles

![Graph showing cross section vs. particle mass for different production modes of SUSY particles.]

**Simplified model of direct production of \( \tilde{\tau} \):**

\[
\begin{align*}
\tilde{g}\tilde{g} & \quad \tilde{\chi}^\pm \tilde{\chi}^0 & \text{(wino)} \\
\tilde{q}\tilde{q} & \quad \tilde{\chi}^\pm \tilde{\chi}^- & \text{(wino)} \\
\tilde{t}\tilde{t} & \quad \tilde{\chi}^0 \tilde{\tau} & \\
\tilde{t}\tilde{\tau} & \quad \tilde{\chi}^0 \tilde{\nu} & \\
\end{align*}
\]

**Legend:**
- Blue: \( \tilde{g}\tilde{g} \)
- Red: \( \tilde{\chi}^\pm \tilde{\chi}^0 \) (wino)
- Orange: \( \tilde{q}\tilde{q} \)
- Purple: \( \tilde{\chi}^\pm \tilde{\chi}^- \) (wino)
- Green: \( \tilde{t}\tilde{t} \)
- Brown: \( \tilde{\tau}\tilde{\tau} \)
Different Production Modes of SUSY Particles

- **Strong Production**: Inclusive final states
  - Particle mass [GeV]
  - Cross section [pb]
  - Diagram showing production of SUSY particles

- **Direct Slepton Production**: Tiny cross section
- **Electroweak Production**: Final states with leptons, no jets
- **3rd Generation**: Final states with b-jets

→ from largest to smallest production cross section →
Gluino pair production with decays via staus:

\[ \tilde{g} \tilde{g} \xrightarrow{\tilde{\chi}^\pm \tilde{\chi}^0} \text{(wino)} \]
\[ \tilde{q} \tilde{q} \xrightarrow{\tilde{\tau} / \tilde{\nu}} \]
\[ \tilde{q} \tilde{q} \xrightarrow{\tilde{\tau} / \tilde{\nu}} \]
\[ \tilde{g} \tilde{g} \xrightarrow{\tilde{\chi}^0_1 \tilde{\chi}^0_1} \text{(wino)} \]
\[ \tilde{q} \tilde{q} \xrightarrow{\tilde{\tau} / \tilde{\nu}} \]
\[ \tilde{g} \tilde{g} \xrightarrow{\tilde{\chi}^0_2 \tilde{\chi}^0_2} \text{(wino)} \]
• Search for production of gluinos\(^*\), 36.1 fb\(^{-1}\) @ \(\sqrt{s} = 13\) TeV
• Targets final states with \(\geq 2\) jets, hadronic tau decays, and \(E_T^{\text{miss}}\)

\[\begin{align*}
\tilde{g}, \tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0 / q\bar{q}\tilde{\tau}/ q\bar{q}\nu\tilde{\tau}
\tilde{\chi}_1^\pm / \tilde{\chi}_1^0
\tilde{\tau}/ \tilde{\nu}\tau
\end{align*}\]

• Observed data in agreement with expected SM background
• \(\Rightarrow\) limits at 95 % CL from combination of 1\(\tau\) and 2\(\tau\) channels

\(^*\) and squarks
Top-Squark Production

Stop pair production with decays via staus:

\[ pp, \sqrt{s} = 13 \text{ TeV, NLO+NLL - NNLO+NNLL} \]

\[ \tilde{t}_1 \tilde{t}_1 \quad \tilde{\tau}_1 \tilde{\tau}_1 \]

3rd generation final states with b-jets
• Model assumes these three SUSY particles within reach:
  \( \tilde{t} \) \( \tilde{\tau} \) \( \sim \) massless \( \tilde{G} \)
• Interesting model with intriguing detector signature:
  \( b \)-jets \( \tau \) leptons \( E_T^{\text{miss}} \)

\( \tilde{t}, \tilde{\tau} \) production, with branching ratios \( B(\tilde{t} \rightarrow \tilde{\tau}b\nu) = 1, B(\tilde{\tau} \rightarrow \tau \tilde{G}) = 1 \)

**ATLAS**

\( \sqrt{s} = 13 \text{ TeV}, 36.1 \text{ fb}^{-1} \)

- Observed limit (\( \pm 1 \sigma_{\text{SUSY theory}} \))
- Expected limit (\( \pm 1 \sigma_{\exp} \))

All limits at 95% CL

- 36.1 \( \text{ fb}^{-1} \) @ \( \sqrt{s} = 13 \text{ TeV} \)
- Variables used to discriminate signal vs bg: \( m_{T2} \) and \( E_T^{\text{miss}} \)
- No significant excess observed
- Limits from **combination** of lep-had and had-had channel
- Exclusion of \( m(\tilde{\tau}_1) \) up to 1.0 TeV
  - and of \( m(\tilde{t}_1) \) up to 1.16 TeV
- CMS result: talk by J. Pastika
Electroweak Production

$pp, \sqrt{s} = 13$ TeV, NLO+NLL - NNLO+NNLL

Electroweakino pair production with decays via staus:

$\tilde{\chi}_1^{\pm}$, $\tilde{\chi}_1^0$, $\tilde{\tau}/\tilde{\nu}_\tau$

Alexander Mann (LMU München)
Searches for Tau Sleptons
7th LHCP Conference — 22.05.2019
Goal

- Search for electroweak production of $\tilde{\chi}_1^{\pm} \tilde{\chi}_1^{\mp}$ or $\tilde{\chi}_1^{\pm} \tilde{\chi}_2^0$
- Final states with tau leptons and $E_T^{\text{miss}}$ but no high-$p_T$ jets
- $36 \text{ fb}^{-1} @ \sqrt{s} = 13 \text{ TeV}$ from (2015 and) 2016

CMS

(JHEP 11 (2018) 151)

- Covers all tau-decay modes
  - channels: $e\mu$, $e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$
- 3 SRs in $\tau_h\tau_h$ channel, 44 in $\ell\tau_h$, 44 in $e\mu$
- Data-driven estimates for multi-jet and $W + \text{jets}$ backgrounds (fake tau leptons)

ATLAS


- Only hadronic decays of tau leptons
- 2 SRs, optimized for low and high mass
- Data-driven multi-jet estimate and normalization of $W + \text{jets}$
• No significant deviations from expected SM background observed
• Exp. exclusion driven by $\tau h\tau h$ channel, 20 – 30 GeV improvement from leptonic channels
• Also no significant excess observed
• Excluded mass range similar to CMS result
Impact of Stau-Mass Assumption (e.g. $\tilde{\chi}^{\pm}_1, \tilde{\chi}^{\mp}_1$ Limits)

- **CL$_s$ significance as function of mass parameter $x$** (nominal analysis: $x = 0.5$)
  - $< 1.64 \iff$ exclusion at 95% confidence level
- **compressed scenario** (left):
  - small & large $x \Rightarrow m_{T2}$ distribution broader
- **large mass splitting** (right):
  - large $x \Rightarrow p_T(\tau)$ too soft
Direct Production of Tau-Slepton Pairs

Combined LEP Result (from 2004)
- Strong result from search for $\tilde{\tau} \rightarrow \tau \tilde{\chi}_1^0$
- Lower limit on $m(\tilde{\tau}_R)$: around 90 GeV
  - for almost all $m(\tilde{\chi}_1^0)$
  - LEP result still prevails

- Very small cross section
  - for $\tilde{\tau}_R \tilde{\tau}_R$ yet $\sim$ factor 3 smaller

- $\tilde{\tau}$ production in $pp$ collisions at $\sqrt{s} = 13$ TeV, NLO+NLL - NNLO+NNLL

- $gg$, $qq$, $tt$, $\tilde{t}\tilde{t}$, $\tilde{\tau}_L \tilde{\tau}_L$

- ADLO
  - Excluded at 95% CL ($\mu = -200$ GeV, $\tan\beta = 1.5$)

Observed
Expected
$\tilde{\tau}_R \tilde{\tau}_R$

($\tilde{\tau}_L \tilde{\tau}_L$)

$(\mu = -200$ GeV, $\tan\beta = 1.5$)

Excluded at 95% CL

(*): $B(\tilde{\chi}_1^0 \tau) = 1$
Search for Direct Production of Staus (CMS)

- Latest CMS result, made public for Moriond 2019
- Dataset of 77.2 fb⁻¹ @ √s = 13 TeV from 2016 + 2017
- Combines τhτh and ℓτh channels
- Background estimate: as in \( \tilde{\chi}_1^± \tilde{\chi}_1^± \) search

**τhτh channel**
- Di-tau trigger (plus \( E_T^{\text{miss}} \) trigger at \( E_T^{\text{miss}} > 200 \) GeV)
- Select \( \tau_h^+\tau_h^- \) with \( p_T(\tau_h) > 40 \) (45) GeV for 2016 (2017) data
- Veto additional leptons and b-jets
- 6 SRs in \( m_{\tau_2} \) and \( \sum m_\tau \) à two jet categories (\( N_j = 0, \geq 1 \))

**ℓτh channel**
- \( \tau_h + e \) or \( \mu \), single-lepton triggers
- Train BDTs for 3 different stau-mass hypotheses on high-level variables
• Data well described by predicted SM background
  • right: SR yields in $\tau_h \tau_h$ channel, 2017 dataset →
• Cross-section limits from statistical combination of all SRs and full BDT distributions
• Degenerate scenario (left): $m(\tilde{\tau}_{L,R}) > 150 \text{ GeV}$
• Left-handed scenario (bottom right): close but no exclusion observed
• Made public for this conference
• First stau search to use full 139 fb$^{-1}$ of Run-2 dataset
• Based on $\tau_h \tau_h$ channel
• Background estimated as in $\tilde{\chi}_1^+ \tilde{\chi}_1^- / \tilde{\chi}_1^0 \tilde{\chi}_2^0$ search with new developments:
  • “tau promotion”: simulation-based fake-factor method (on 2nd $\tau$) to reduce statistical uncertainty in $W + \text{jets}$ background
  • fake-factor method to cross check estimate for multi-jet background from ABCD method

$\tau_h \tau_h$ channel
• 2 non-overlapping SRs, optimized for low and high stau masses
  • select $\tau_h^+ \tau_h^-$, veto on 3rd lepton, on $b$-jet, and on $Z$ and $h$ boson
• low-mass SR
  • asymmetric di-tau trigger
  • $75 \text{ GeV} < E_T^{\text{miss}} < 150 \text{ GeV}$
  • $70 \text{ GeV} < m_{\tau_2}$
• high-mass SR
  • di-tau + $E_T^{\text{miss}}$ trigger
  • $150 \text{ GeV} < E_T^{\text{miss}}$
  • $70 \text{ GeV} < m_{\tau_2}$
Search for Direct Production of Staus (ATLAS)

ATLAS Preliminary
\( \bar{t} \bar{s} = 13 \text{ TeV}, 139 \text{ fb}^{-1} \)

Multi-jet VR-lowMass
post-fit

Events / 5 GeV

Validation regions confirm
good modelling of SM backgrounds

SRs: also good agreement of data
with expected SM background

top / Z / VV VRs (low-mass + high-mass)
Model-dependent exclusion limits @ 95 % CL:
- $120 \text{ GeV} < m(\tilde{\tau}_{L,R}) < 390 \text{ GeV}$
- $160 \text{ GeV} < m(\tilde{\tau}_L) < 300 \text{ GeV}$

First exclusion of non-degenerate staus at LHC!
- for $m(\tilde{\chi}_1^0)$ up to 60 GeV

No sensitivity to $\tilde{\tau}_R$ production due to slight excess in the more sensitive SR-lowMass

<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+jets</td>
<td>$1.5 \pm 0.7$</td>
<td>$2.5 \pm 1.9$</td>
</tr>
<tr>
<td>Top quark</td>
<td>$0.04^{+0.80}_{-0.40}$</td>
<td>$2.0 \pm 0.5$</td>
</tr>
<tr>
<td>Z+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>$0.00 \pm 0.00$</td>
</tr>
<tr>
<td>Multi-jet</td>
<td>$2.6 \pm 0.7$</td>
<td>$3.1 \pm 1.5$</td>
</tr>
</tbody>
</table>

SM total: $6.0 \pm 1.7$ to $10.2 \pm 3.3$

Observed: 10 to 7

$m(\tilde{\tau}, \tilde{\chi}_1^0) = (120, 1) \text{ GeV}$: $9.8 \pm 3.1$ to $7.2 \pm 2.7$

$m(\tilde{\tau}, \tilde{\chi}_1^0) = (200, 1) \text{ GeV}$: $14 \pm 4$ to $20 \pm 5$

$m(\tilde{\tau}, \tilde{\chi}_1^0) = (280, 1) \text{ GeV}$: $5.9 \pm 2.4$ to $14 \pm 4$
Heavy Charged Long-Lived Particles

- All other searches assume SUSY particles to decay promptly
- Here: search for long-lived staus
  - GMSB model with $\tilde{G}$ LSP and long-lived $\tilde{\tau}$ NLSP
- Charged ⇒ track: measure momentum $p$ in ID and MS
- Heavy ⇒ $\beta \ll 1$: measure ToF in Tile Calorimeter and MS
- Mass hypothesis $m_{\text{ToF}} = p / \beta \gamma$ for candidate tracks

\[ m(\tilde{\tau}_R) < 430 \text{ GeV} \] (420 exp.)

- Custom timing calibration
- Fully data-driven background estimate
- No significant excess observed
Heavy Charged Long-Lived Particles

- All other searches assume SUSY particles to decay promptly
- Here: search for *long-lived* staus
  - GMSB model with $\tilde{G}$ LSP and long-lived $\tilde{\tau}$ NLSP
- Charged $\Rightarrow$ track: measure momentum $p$ in ID and MS
- Heavy $\Rightarrow$ $\beta \ll 1$: measure ToF in Tile Calorimeter and MS
- Mass hypothesis $m_{\text{ToF}} = p/\beta\gamma$ for candidate tracks

More in talk by Sascha on Thursday

exclude $m(\tilde{\tau}_R) < 430$ GeV (420 exp.)
- High-luminosity upgrade of the LHC: expect $3000 \text{ fb}^{-1}$ at $\sqrt{s} = 14 \text{ TeV}$, $\langle \mu \rangle \sim 200$
- Parametrized simulations of performance of upgraded ATLAS or CMS detector
- Assume trigger thresholds similar to current despite higher pile-up
- Selections based mainly on $m_{T2}$, $\sum m_T$, $E_T^{\text{miss}}$
- Dominant backgrounds: $t\bar{t}$, $W + \text{jets}$

- Predicted sensitivity for ATLAS and CMS rather similar

---

**ATLAS Simulation Preliminary**

$\mathcal{L} = 14 \text{ TeV}$, $L = 3000 \text{ fb}^{-1}$, $\langle \mu \rangle = 200$

- combined, $5 \sigma$ discovery
- combined, 95% excl
- $\tilde{\tau}_L$, $5 \sigma$ discovery
- $\tilde{\tau}_L$, 95% excl
- $\tilde{\chi}^0_1$, $5 \sigma$ discovery
- $\tilde{\chi}^0_1$, 95% excl

**CMS Phase-2 Simulation**

$3 \text{ ab}^{-1}$ (14 TeV)

---

**ATLAS:**
- exp. exclusion: $m(\tilde{\tau}_{L,R}) > 710 \text{ GeV}$
- $m(\tilde{\tau}_L) > 650 \text{ GeV}$, $m(\tilde{\tau}_R) > 540 \text{ GeV}$
- exp. discovery ($5 \sigma$): $m(\tilde{\tau}_{L,R}) < 500 \text{ GeV}$

**CMS:**
- exp. exclusion: $m(\tilde{\tau}_{L,R}) > 650 \text{ GeV}$
- exp. discovery ($5 \sigma$): $m(\tilde{\tau}_{L,R}) < 470 \text{ GeV}$
Summary & Outlook

Searches for Tau Sleptons

- \tilde{\tau} appears in many searches for SUSY at the LHC
- Presented latest public ATLAS and CMS results
- Highlights: two recent analyses with first-time sensitivity for direct production of tau sleptons at the LHC!

\[
\begin{align*}
\tilde{\tau} & \to \tau^\pm \to \ell^\pm \nu \ell^\mp \nu \\text{(CMS)} \\
\tilde{\tau} & \to \tau^\pm \to \ell^\pm \nu \ell^\mp \nu \\text{(ATLAS)}
\end{align*}
\]

What’s next?

- Obvious opportunities for improvements in stau searches:
  - ATLAS: add \ell_T\tau channel (like CMS does)
  - CMS: add 2018 data (like ATLAS has already)
  - likely modest gains, but CMS probably able to exclude \tilde{\tau}_L, plus first LHC exclusion of \tilde{\tau}_R? (if “luckier” than ATLAS)
- Need to close gaps in “compressed” and light-\tilde{\tau} scenarios:
  - employ multi-variate analysis techniques and shape fits
  - improve tau-reconstruction and identification techniques
  - ATLAS + CMS combination?
    - not attempted for searches yet but useful for \tilde{\tau}_R?
  - think about Run-3 tau triggers
Searches for Tau Sleptons

• \( \tilde{\tau} \) appears in many searches for SUSY at the LHC
• Presented latest public ATLAS and CMS results
• Highlights: two recent analyses with first-time sensitivity for direct production of tau sleptons at the LHC!

What’s next?

• Obvious opportunities for improvements in stau searches:
  • ATLAS: add \( \ell T_H \) channel (like CMS does)
  • CMS: add 2018 data (like ATLAS has already)
  • likely modest gains, but CMS probably able to exclude \( \tilde{\tau}_L \), plus first LHC exclusion of \( \tilde{\tau}_R \)? (if “luckier” than ATLAS)

• Need to close gaps in “compressed” and light-\( \tilde{\tau} \) scenarios:
  • employ multi-variate analysis techniques and shape fits
  • improve tau-reconstruction and identification techniques
  • ATLAS + CMS combination?
    • not attempted for searches yet but useful for \( \tilde{\tau}_R \)?
  • think about Run-3 tau triggers
Extra Material
ATLAS Electroweak SUSY Summary Plot (March 2019)

March 2019  ATLAS Preliminary  \( \sqrt{s} = 8.13 \text{ TeV}, 20.3-139 \text{ fb}^{-1} \)

Observed limits at 95% CL

\( \tilde{\chi}_1^+ \tilde{\chi}_1^- \) via
- \( \tilde{l}^- / \tilde{\nu}^+ \) 2\( l \)
  - arXiv:1509.07152
  - ATLAS-CONF-2019-008
- \( \tilde{\tau}_L / \tilde{\nu}_\tau \) 2\( \tau \)
  - arXiv:1407.0350
  - arXiv:1708.07875
- WW 2\( l \)
  - arXiv:1403.5294
  - ATLAS-CONF-2019-008

\( \tilde{\chi}_1^\pm \tilde{\chi}_2^0 \) via
- \( \tilde{l}^- / \tilde{\nu}^+ \) 2\( l + 3l \)
  - arXiv:1509.07152
  - arXiv:1803.02762
- WZ 2\( l + 3l \)
  - arXiv:1403.5294
  - arXiv:1712.08119
  - arXiv:1803.02762
  - arXiv:1806.02293
- \( \text{Wh} \) 1bb+2jbb+1\( \gamma \gamma + t\bar{t} \)
  - arXiv:1812.09432

\( \tilde{\chi}_1^+ \tilde{\chi}_1^- / \tilde{\chi}_1^\pm \tilde{\chi}_2^0 \) via
- \( \tilde{\tau}_L / \tilde{\nu}_\tau \) 2\( \tau \)
  - arXiv:1708.07875

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

\( m(\tilde{l}^- / \tilde{\nu}^+ / \tilde{\nu}) = \frac{1}{2} \left[ m(\tilde{\chi}_1^0) + m(\tilde{\chi}_2^0) \right] \)
CMS Electroweak SUSY Summary Plot (July 2018)

\[ pp \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_1^\pm, \quad pp \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0, \quad pp \rightarrow \tilde{\tau}_1 \tilde{\tau}_1 \quad \text{July 2018} \]

CMS

35.9 fb\(^{-1}\) (13 TeV)

- 1709.05406, 3l (\(\tilde{\chi}_2^{0} \rightarrow \tilde{\tau}_L \tilde{\tau}_L\), BF(\(\tau\))=0.5, \(x_{\tau}=0.5\))
- 1709.05406, 3l (\(\tilde{\chi}_2^{0} \rightarrow \tilde{\tau}_R \tilde{\tau}_R\), \(x_{\tau}=0.5\))
- 1807.02048, 2\(\tau\) comb. (\(\tilde{\chi}_2^{0} \rightarrow \tilde{\tau}_L \tau \tau\)), \(x_{\tau}=0.5\)
- 1807.07799, 2l OS (\(\tilde{\chi}_1^0 \rightarrow \tilde{\tau}_L \tilde{\tau}_L\), \(x_{\tau}=0.5\))
- 1807.02048, 2\(\tau\) comb. (\(\tilde{\chi}_1^0 \rightarrow \tilde{\tau}_R \tau \tau\)), \(x_{\tau}=0.5\)
- 1801.03957, comb. (\(\tilde{\chi}_2^{0} \rightarrow W \tilde{\chi}_1^0\))
- 1801.03957, comb. (\(\tilde{\chi}_2^{0} \rightarrow W \tilde{\chi}_1^0\))
- 1806.05264, 2l OS (\(\tilde{e}_{LR}^L \tilde{e}_{LR}^L, \tilde{\mu}_{LR}^L \tilde{\mu}_{LR}^L\))

Expected

Observed

\[ m_{\chi_1^0} [\text{GeV}] \]

\[ m_{\tilde{\chi}_2^0} = m_{\tilde{\chi}_1^0} \] or \[ m_{\tilde{e}_{L/R}} = m_{\tilde{\mu}_{L/R}} \] [GeV]

\[ \text{July 2018} \]
# Summary of Exclusion Ranges from ATLAS SUSY Searches (March 2019)

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

March 2019

<table>
<thead>
<tr>
<th>Model</th>
<th>Signature</th>
<th>( \int L , dt , (\text{fb}^{-1}) )</th>
<th>Mass limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weak #2</td>
<td>( \tilde{b}_1 \tilde{b}_1 \rightarrow b \tilde{W}^0 \tilde{Z}, \tilde{Z} \rightarrow b \tilde{b} )</td>
<td>Multiple</td>
<td>36.1</td>
</tr>
<tr>
<td>EW direct</td>
<td>( \tilde{t}^\pm \rightarrow t \tilde{W}^\mp ) via ( WW )</td>
<td>( 3 , \text{c}, \mu )</td>
<td>36.1</td>
</tr>
<tr>
<td></td>
<td>( \tilde{t}^\pm \rightarrow t \tilde{W}^\mp ) via ( WW )</td>
<td>( 2 , \text{c}, \nu )</td>
<td>36.1</td>
</tr>
<tr>
<td>Reference</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.
**Overview of SUSY results: electroweak production**

**36 fb$^{-1}$ (13 TeV)**

<table>
<thead>
<tr>
<th>Process</th>
<th>CMS</th>
<th>July 2018</th>
</tr>
</thead>
<tbody>
<tr>
<td>$pp \rightarrow \tilde{\chi}^0 \tilde{\chi}^0 \rightarrow \ell\nu\ell\nu\tilde{\chi}^0\tilde{\chi}^0$</td>
<td>[arXiv:1706.09055]</td>
<td>[arXiv:1706.09055]</td>
</tr>
<tr>
<td>$pp \rightarrow \tilde{\ell} \ell \rightarrow \ell\nu\ell\nu\tilde{\chi}^0\tilde{\chi}^0$</td>
<td>[arXiv:1706.09055]</td>
<td>[arXiv:1706.09055]</td>
</tr>
<tr>
<td>$pp \rightarrow \tilde{\chi}^\pm \rightarrow \tau\nu\tilde{\chi}^0\tilde{\chi}^0$</td>
<td>[arXiv:1706.09055]</td>
<td>[arXiv:1706.09055]</td>
</tr>
<tr>
<td>$pp \rightarrow \tilde{\chi}^\pm \rightarrow \tau\nu\tilde{\chi}^0\tilde{\chi}^0$</td>
<td>[arXiv:1706.09055]</td>
<td>[arXiv:1706.09055]</td>
</tr>
<tr>
<td>$pp \rightarrow \tilde{\chi}^\pm \rightarrow \tau\nu\tilde{\chi}^0\tilde{\chi}^0$</td>
<td>[arXiv:1706.09055]</td>
<td>[arXiv:1706.09055]</td>
</tr>
<tr>
<td>$pp \rightarrow \tilde{\chi}^\pm \rightarrow \tau\nu\tilde{\chi}^0\tilde{\chi}^0$</td>
<td>[arXiv:1706.09055]</td>
<td>[arXiv:1706.09055]</td>
</tr>
<tr>
<td>$pp \rightarrow \tilde{\chi}^\pm \rightarrow \tau\nu\tilde{\chi}^0\tilde{\chi}^0$</td>
<td>[arXiv:1706.09055]</td>
<td>[arXiv:1706.09055]</td>
</tr>
<tr>
<td>$pp \rightarrow \tilde{\chi}^\pm \rightarrow \tau\nu\tilde{\chi}^0\tilde{\chi}^0$</td>
<td>[arXiv:1706.09055]</td>
<td>[arXiv:1706.09055]</td>
</tr>
<tr>
<td>$pp \rightarrow \tilde{\chi}^\pm \rightarrow \tau\nu\tilde{\chi}^0\tilde{\chi}^0$</td>
<td>[arXiv:1706.09055]</td>
<td>[arXiv:1706.09055]</td>
</tr>
<tr>
<td>$pp \rightarrow \tilde{\chi}^\pm \rightarrow \tau\nu\tilde{\chi}^0\tilde{\chi}^0$</td>
<td>[arXiv:1706.09055]</td>
<td>[arXiv:1706.09055]</td>
</tr>
</tbody>
</table>

Selection of observed limits at 95% C.L. (theory uncertainties are not included). Probe up to the quoted mass limit for light LSPs unless stated otherwise. The quantities $\Delta M$ and $x$ represent the absolute mass difference between the primary sparticle and the LSP, and the difference between the intermediate sparticle and the LSP relative to $\Delta M$, respectively, unless indicated otherwise.
Particle content of the **Minimal Supersymmetric Standard Model (MSSM)**

- **Quarks**: $u$, $c$, $t$, $d$, $s$, $b$
- **Gauge Bosons**: $\gamma$, $Z^0$, $A$, $W^\pm$, $H^\pm$, $g$
- **Higgs Bosons**: $h$, $H^0$
- **Higgsinos**: $\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$
- **Gauginos**: $\tilde{\chi}_1^\pm$, $\tilde{\chi}_2^\pm$
- **Squarks**: $\tilde{u}_{L,R}$, $\tilde{c}_{L,R}$, $\tilde{t}_{L,R}$, $\tilde{d}_{L,R}$, $\tilde{s}_{L,R}$, $\tilde{b}_{L,R}$
- **Sleptons**: $\tilde{\nu}_e$, $\tilde{\nu}_\mu$, $\tilde{\nu}_\tau$, $\tilde{e}_{L,R}$, $\tilde{\mu}_{L,R}$, $\tilde{\tau}_{L,R}$

- **Exception**: Higgs sector — need two complex Higgs doublets ($2 \times $ SM) $\Rightarrow$ 5 Higgs bosons.

- “For every fermion there is a boson and v.v.”
- “Electroweakinos” ($\tilde{B}$, $\tilde{W}_{1,2,3}$) and higgsinos ($\tilde{H}_u^0$, $\tilde{H}_d^0$, $\tilde{H}_u^+$, $\tilde{H}_d^-$) mix to neutralinos $\tilde{\chi}_{1,2,3,4}^0$ and charginos $\tilde{\chi}_{1,2}^\pm$. 

---

Alexander Mann (LMU München)  
Searches for Tau Sleptons  
7th LHCP Conference — 22.05.2019 29
**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 $\Rightarrow$ 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 $\Rightarrow$ light stop and light gluino as only light (relevant) coloured sparticle
- some additional mechanism needed (as in GMSB) to produce “correct” Higgs mass
• 44 m × 25 m × 25 m, 7000 tonnes
• Subdetectors = concentrical cylinders surrounding nominal IP
• Tracking detectors — solenoid magnet — calorimeters — muon spectrometer
ATLAS and CMS

- Two big, independent, multi-purpose detectors: ATLAS and CMS
- Situated at Interaction Points 1 and 5 of the LHC
- Different concepts, but same basic structure
  - almost $4\pi$ coverage, forward-backward symmetric cylindrical geometry:
    - tracking detectors, electromagnetic and hadronic calorimeters, muon system (+ magnets)
- Sophisticated trigger system to select collision events to be recorded (online filter)
# Di-Tau Triggers Thresholds

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Trigger</th>
<th>Year</th>
<th>Online [GeV]</th>
<th>Offline [GeV]</th>
<th>Efficiency [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS</td>
<td>di-tau + $E_T^{\text{miss}}$</td>
<td>2015–2016</td>
<td>35,25,50</td>
<td>50,40,150</td>
<td>80</td>
</tr>
<tr>
<td>ATLAS</td>
<td>di-tau</td>
<td>2015–2016</td>
<td>85,50</td>
<td>95,65</td>
<td>80</td>
</tr>
<tr>
<td>ATLAS</td>
<td>di-tau + $E_T^{\text{miss}}$</td>
<td>2015–2018</td>
<td>50–75,40,150</td>
<td>75–80</td>
<td></td>
</tr>
<tr>
<td>ATLAS</td>
<td>di-tau</td>
<td>2015–2018</td>
<td>95,60–75</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CMS</td>
<td>di-tau</td>
<td>2016</td>
<td>35,35</td>
<td>40,40</td>
<td>60–95</td>
</tr>
<tr>
<td>CMS</td>
<td>di-tau</td>
<td>2017</td>
<td>40,40</td>
<td>45,45</td>
<td></td>
</tr>
</tbody>
</table>

Di-Tau Trigger Efficiencies

MC and data16

Simulation 2018

HLT_DoubleMediumIsoPFTau35_-
Trk1_eta2p1_Reg seeded by
L1_DoubleIsoTau28er

combination of Medium/
TightChargedIsoPFTau35/40

\( \tau_h(35) \tau_h(35) \) trigger at \( \langle \mu \rangle = 50 \)
Tau Leptons: Properties

- Tau lepton: heaviest known lepton, $m(\tau) = 1777$ MeV
  - heavier than lightest mesons → can decay both to leptons or to hadrons
- Tau lepton: short lifetime, $c\tau = 0.087$ mm
  - decay before reaching active detector regions

\[ \text{BR}(\tau^- \rightarrow \ell^- \bar{\nu}_\ell \nu_\tau) \sim \frac{1}{6} \]
\[ \text{BR}(\tau^- \rightarrow \text{hadrons} + \nu_\tau) \sim \frac{4}{6} \]

- Leptonic decays: leptons ($e, \mu$) from tau decay register as “prompt” light leptons
- Hadronic decays: can be reconstructed from detector signature of decay
- Part of momentum / energy detector-invisible due to neutrinos
Tau Leptons: Reconstruction & Identification

ATLAS
- seeded by jets
- tracks assigned to core and isolation cone
- BRT for energy calibration combines
  - measured energy of calorimeter clusters
  - momentum measurement from tracker
  - using “Tau Particle Flow”
- BDT-based discriminant against $q/g$ jets
- overlap-based $e$ veto

CMS
- Particle Flow algorithm
  - $\Rightarrow$ charged + neutral hadrons, $e, \mu, \gamma$
- Hadrons-plus-strips algorithm $\Rightarrow \tau$
  - seeded by jets
  - cluster $e + \gamma$ constituents of jet in “strips”
    $\Rightarrow \pi^0$ candidates
  - combine charged hadrons and $\pi^0$ cand’s
    $\Rightarrow \tau$ decay candidates
  - BDT-based discriminant against $q/g$ jets
  - plus BDT against $e$
    and tracks in MS against $\mu$

hadronically decaying tau lepton

jet arising from a quark
• Search for production of squarks and gluinos, 36.1 fb$^{-1}$ @ $\sqrt{s} = 13$ TeV
• Targets final states with $\geq 2$ jets (strong production), hadronic tau decays, and $E_T^{\text{miss}}$
• Interpretation: simplified model and gauge-mediated supersymmetry breaking (GMSB)

![Diagram showing the typical decay chain in GMSB model](image)

- Two mutually exclusive channels:
  - $= 1 \tau_{\text{had}}$: 2 SRs (1 for low-$p_T$ taus in compressed scenarios)
  - $\geq 2 \tau_{\text{had}}$: 4 SRs (1 for GMSB model)
Inclusive Search for Tau Final States

Interpretations: model-dependent exclusion contours

- No relevant deviation from SM prediction in any SR
  - two (correlated) $< 2\sigma$ excesses at high $H_T$ in $2\tau$
- Improved analysis w.r.t. $3.2$ fb$^{-1}$ results, $1\tau$ and $2\tau$ channel combined in global fit
- GMSB: production of $\tilde{q}\tilde{q}$ dominates at large $\Lambda$

\[ \sum m_T \text{ in } 2\tau \text{ multibin SR} \]
### Inclusive Search for Tau Final States

#### Region Definitions

<table>
<thead>
<tr>
<th>Subject of selection</th>
<th>1τ channel</th>
<th>2τ channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trigger</td>
<td>$E_T^{\text{miss}} &gt; 180 \text{ GeV}$, $p_T^{\text{jet}_1} &gt; 120 \text{ GeV}$</td>
<td></td>
</tr>
<tr>
<td>Jets</td>
<td>$N_{\text{jet}} \geq 2$, $p_T^{\text{jet}_2} &gt; 25 \text{ GeV}$</td>
<td></td>
</tr>
<tr>
<td>Multijet events</td>
<td>$\Delta \phi(p_T^{\text{jet}_{1,2}}, p_T^{\text{miss}}) &gt; 0.4$</td>
<td></td>
</tr>
<tr>
<td>τ-leptons</td>
<td>$N_\tau = 1$</td>
<td>$N_\tau \geq 2$</td>
</tr>
</tbody>
</table>

Table 5: Summary of the $W$ and top control regions. These requirements are applied in addition to the trigger, jet, and multijet requirements of the preselection. The variables $N_\tau$, $N_{\text{jet}}$, $N_{\mu}$, and $N_{\text{b-jet}}$ are the number of τ-leptons, jets, muons, and $b$-tagged jet, respectively; other variables are defined in the text.

<table>
<thead>
<tr>
<th>Subject of selection</th>
<th>1τ SRs</th>
<th>Medium-mass SRs</th>
</tr>
</thead>
<tbody>
<tr>
<td>τ-leptons</td>
<td>$20 &lt; p_T^\tau &lt; 45 \text{ GeV}$</td>
<td>$p_T^\tau &gt; 45 \text{ GeV}$</td>
</tr>
<tr>
<td>Event kinematics</td>
<td>$E_T^{\text{miss}} &gt; 400 \text{ GeV}$</td>
<td>$\sum m_T^{\tau} &gt; 80 \text{ GeV}$</td>
</tr>
<tr>
<td></td>
<td>$m_T^{\tau} &gt; 250 \text{ GeV}$</td>
<td>$H_T &gt; 1000 \text{ GeV}$</td>
</tr>
</tbody>
</table>

Table 6: Summary of the $Z(\nu\nu)$, $Z(\tau\tau)$ and multijet control regions. These requirements are applied in addition to the trigger, and jet requirements of the preselection. The variables $N_\tau$ and $N_\mu$ are the number of τ-leptons, and muons, respectively; $q_\tau$ is the charge of τ-lepton $i$; other variables are defined in the text.

<table>
<thead>
<tr>
<th>Subject of selection</th>
<th>Z(νν) CR</th>
<th>Z(ττ) CR</th>
<th>Multijet CR</th>
</tr>
</thead>
<tbody>
<tr>
<td>τ-leptons</td>
<td>$N_\tau = 1$</td>
<td>$N_\tau \geq 2$, $q_\tau = -q_\tau$</td>
<td>$N_\tau = 1$</td>
</tr>
<tr>
<td>Multijet events</td>
<td>$\Delta \phi(p_T^{\text{jet}_{1,2}}, p_T^{\text{miss}}) &gt; 0.4$</td>
<td>$\Delta \phi(p_T^{\text{jet}_{1,2}}, p_T^{\text{miss}}) &lt; 0.3$</td>
<td></td>
</tr>
<tr>
<td>Muons</td>
<td>$N_\mu = 0$</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Top suppression</td>
<td>$N_{\text{b-jet}} = 0$</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Event kinematics</td>
<td>$H_T &lt; 800 \text{ GeV}$</td>
<td>$100 &lt; m_T^{\tau} &lt; 200 \text{ GeV}$</td>
<td>$100 &lt; m_T^{\tau} &lt; 200 \text{ GeV}$</td>
</tr>
<tr>
<td></td>
<td>$E_T^{\text{miss}} &lt; 300 \text{ GeV}$</td>
<td>$m_T^{\tau} + m_T^{\text{miss}} &gt; 0.3$</td>
<td>$E_T^{\text{miss}}/m_{\text{eff}} &lt; 0.2$</td>
</tr>
<tr>
<td></td>
<td>$\Delta \phi(p_T^{\text{jet}_1}, p_T^{\text{miss}}) &gt; 2.0$</td>
<td>$\Delta \phi(p_T^{\text{jet}_1}, p_T^{\text{miss}}) &gt; 1.0$</td>
<td>—</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Subject of selection</th>
<th>Compressed</th>
<th>High-mass</th>
<th>2τ SRs</th>
<th>Multibin</th>
<th>GMSB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jets</td>
<td>$m_T^{\tau\tau} &gt; 70 \text{ GeV}$</td>
<td>$m_T^{\tau \mu} &gt; 150 \text{ GeV}$</td>
<td>$m_T^{\tau \mu} &gt; 150 \text{ GeV}$</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>event kinematics</td>
<td>$H_T &lt; 1100 \text{ GeV}$</td>
<td>$H_T &gt; 1100 \text{ GeV}$</td>
<td>$H_T &gt; 800 \text{ GeV}$</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>$m_T^\tau + m_T^\mu &gt; 350 \text{ GeV}$</td>
<td>—</td>
<td>$N_{\text{jet}} \geq 3$</td>
<td>7 bins in $m_T^{\tau \mu}$</td>
<td>—</td>
</tr>
</tbody>
</table>
Inclusive Search for Tau Final States

- NF for $Z \rightarrow \nu \nu$, $Z \rightarrow \tau \tau$ and multijet from 3 CRs
- $W$ / top: 3 NFs from 2 · 3 CRs
  - kinematic (modelling of bg kinematics and acceptance, measured in single-muon events)
  - true-tau (tau reco+ID efficiencies, measured in single-tau events)
  - fake-tau (mismodelling in simulation, measured in tau-muon channel)
- multijet from jet smearing (very small contribution)
Inclusive Search for Tau Final States

- 5 VRs for $1\tau$
  - validate $H_T$, $E_T^{\text{miss}}$, $m_T^{\tau}$ modelling
- 3 VRs for $2\tau$
  - validate $W$/top and $Z \rightarrow \tau\tau$

Table 7: Validation regions for the $1\tau$ channel. These requirements are applied in addition to the preselection. The variables are defined in the text.

<table>
<thead>
<tr>
<th>Subject of selection</th>
<th>$1\tau$ medium-mass VRs</th>
<th>$1\tau$ compressed VRs</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau$-leptons</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$p_T^{\tau} &gt; 45$ GeV</td>
<td></td>
<td>$20 &lt; p_T^{\tau} &lt; 45$ GeV</td>
</tr>
<tr>
<td>Event kinematics</td>
<td>$m_T^{\tau} &lt; 250$ GeV</td>
<td>$m_T^{\tau} &gt; 250$ GeV</td>
</tr>
<tr>
<td></td>
<td>$E_T^{\text{miss}} &lt; 400$ GeV</td>
<td>$E_T^{\text{miss}} &gt; 400$ GeV</td>
</tr>
<tr>
<td></td>
<td>$H_T &gt; 1000$ GeV</td>
<td>$H_T &lt; 1000$ GeV</td>
</tr>
<tr>
<td></td>
<td>$E_T^{\text{miss}} &lt; 80$ GeV</td>
<td>$E_T^{\text{miss}} &gt; 80$ GeV</td>
</tr>
<tr>
<td></td>
<td>$E_T^{\text{miss}} &lt; 400$ GeV</td>
<td>$E_T^{\text{miss}} &gt; 400$ GeV</td>
</tr>
</tbody>
</table>

Table 8: Validation regions for the $2\tau$ channel. These requirements are applied in addition to the preselection. The variables are defined in the text.

<table>
<thead>
<tr>
<th>Subject of selection</th>
<th>$2\tau$ W/Top VR</th>
<th>$Z(\tau\tau)$ VR</th>
</tr>
</thead>
<tbody>
<tr>
<td>W/top separation</td>
<td>$N_{b\text{-jet}} = 0/\geq 1$</td>
<td>—</td>
</tr>
<tr>
<td>Event kinematics</td>
<td>$H_T &lt; 800$ GeV</td>
<td>$H_T &gt; 800$ GeV</td>
</tr>
<tr>
<td></td>
<td>$m_T^{\tau_1} + m_T^{\tau_2} &gt; 150$ GeV</td>
<td>$m_T^{\tau_1} + m_T^{\tau_2} &lt; 150$ GeV</td>
</tr>
<tr>
<td></td>
<td>$m_T^{\tau_1} &lt; 60$ GeV</td>
<td>—</td>
</tr>
</tbody>
</table>

Number of events

- Data
- SM ± 1 $\sigma^{\text{tot}}$
- Top Quarks
- $W \rightarrow \tau\nu$
- $Z \rightarrow \nu\nu$
- $Z \rightarrow \tau\tau$
- VV
- $W \rightarrow l\nu$
- Other
Model assumes these three SUSY particles within reach: \( \tilde{t}, \tilde{\tau}, \sim \) massless \( \tilde{G} \)

Interesting model with intriguing detector signature:
- \( b \)-jets
- tau leptons
- \( E_T^{\text{miss}} \)

Data / SM

ATLAS
\( \sqrt{s} = 13 \text{ TeV}, 36.1 \text{ fb}^{-1} \)
SR HH

Events / 40 GeV

\( m_{\tilde{\tau}_1, \tilde{\tau}_2} \) [GeV]

36.1 fb\(^{-1} \) @ \( \sqrt{s} = 13 \text{ TeV} \)

Analysis selections:
- “lep-had” \( (\tau_\ell \tau_h) \) and “had-had” \( (\tau_h \tau_h) \) channels

Dominant background:
- top-quark pair production \( (t\bar{t}) \)
Using Taus in Searches for Top Squarks

Results & Interpretation

- Observed event yields in signal selections in good agreement with SM expectation
- Limits derived from statistical combination of lep-had and had-had channel
- Exclusion of $m(\tilde{\tau}_1)$ up to 1.0 TeV at 95 % confidence level
  - and of $m(\tilde{t}_1)$ up to 1.16 TeV

\begin{align*}
\tilde{t}\tilde{t} \text{ production, with branching ratios } B(\tilde{t}_1 \to \tilde{\tau}_1 b) = 1, B(\tilde{\tau}_1 \to \tau \tilde{G}) = 1
\end{align*}

\begin{align*}
\sqrt{s} = 13 \text{ TeV, 36.1 fb}^{-1}
\end{align*}

\begin{align*}
\begin{array}{l}
\text{Observed limit (} \pm 1 \sigma_{\text{SUSY}} \text{)} \\
\text{Expected limit (} \pm 1 \sigma_{\text{exp}} \text{)}
\end{array}
\end{align*}

\begin{align*}
\begin{array}{l}
\text{SR LH} \quad \text{SR HH}
\end{array}
\end{align*}

\begin{align*}
\begin{array}{l}
\text{Observed events} \\
\text{Total background} \\
\text{Fake } \tau_{\text{had}} + e/\mu \\
\text{tt} (\text{fake } \tau_{\text{had}}) \\
\text{tt} (\text{real } \tau_{\text{had}}) \\
\text{tt} + V \\
\text{Diboson} \\
\text{Single-top} \\
\text{V + jets} \\
\text{Others} \\
\text{Signal}
\end{array}
\begin{array}{l}
3 \\
2.2 \pm 0.6 \\
1.4 \pm 0.5 \\
0.6 \pm 0.7 \\
0.22 \pm 0.12 \\
0.28 \pm 0.30 \\
0.25 \pm 0.14 \\
0.26 \pm 0.12 \\
0.15 \pm 0.11 \\
0.28 \pm 0.13 \\
0.10 \pm 0.24 \\
0.13 \pm 0.11 \\
0.032 \pm 0.014 \\
0.26 \pm 0.09 \\
0.082 \pm 0.022 \\
0.09 \pm 0.04 \\
3.3 \pm 0.7
\end{array}
\end{align*}

\begin{align*}
(m(\tilde{t}_1) = 1100 \text{ GeV}, m(\tilde{\tau}_1) = 590 \text{ GeV})
\end{align*}
## Preselection

**lep-had**: single-electron or single-muon trigger

**had-had**: $E_T^\text{miss}$ or di-tau trigger

**Leptons**
- exactly one $\tau_{\text{had}}$ + one signal electron or muon
- exactly two $\tau_{\text{had}}$

**Trigger-related requirements**
- $p_T(e, \mu) > 27$ GeV
- $E_T^\text{miss} > 180$ GeV or $p_T(\tau_1, \tau_2, \text{jet}_1) > 50, 40, 80$ GeV
- $p_T(\text{jet}_2) > 26$ GeV
- $p_T(\tau_{\text{had}}) > 70$ GeV
- $n_b$-jet $\geq 1$

### Variable CR LH $t\bar{t}$-real

**Charge($\ell, \tau_{\text{had}}$)** opposite

**$m_{T2}(\ell, \tau_{\text{had}})$** $< 60$ GeV [60, 100] GeV

**$E_T^\text{miss}$** $> 210$ GeV $> 210$ GeV

**$m_T(\ell)$** $> 100$ GeV $> 100$ GeV

**$m(\ell, \tau_{\text{had}})$** — — $> 60$ GeV

### Variable CR RH $t\bar{t}$-fake (OS)

**Charge($\ell, \tau_{\text{had}}$)** opposite

**$m_{T2}(\ell, \tau_{\text{had}})$** $< 60$ GeV [60, 100] GeV

**$E_T^\text{miss}$** $> 210$ GeV $> 210$ GeV

**$m_T(\ell)$** $> 100$ GeV $> 100$ GeV

**$m(\ell, \tau_{\text{had}})$** — — $> 60$ GeV

### Variable SR LH

**Charge($\ell, \tau_{\text{had}}$)** opposite

**$m_{T2}(\ell, \tau_{\text{had}})$** $< 60$ GeV [60, 100] GeV

**$E_T^\text{miss}$** $> 210$ GeV $> 210$ GeV

**$m_T(\ell)$** $> 100$ GeV $> 100$ GeV

**$m(\ell, \tau_{\text{had}})$** — — $> 60$ GeV

### Variable CR HH $t\bar{t}$-fake

**Charge($\tau_1, \tau_2$)** — opposite

**$m_{T2}(\tau_1, \tau_2)$** $< 30$ GeV $< 30$ GeV

**$E_T^\text{miss}$** $> 120$ GeV $> 120$ GeV

**$m_T(\tau_1)$** $< 70$ GeV $> 70$ GeV

**$m(\tau_1, \tau_2)$** $> 70$ GeV $> 70$ GeV

### Variable CR HH $t\bar{t}$-real

**Charge($\tau_1, \tau_2$)** opposite

**$m_{T2}(\tau_1, \tau_2)$** $< 30$ GeV $< 30$ GeV

**$E_T^\text{miss}$** $> 120$ GeV $> 120$ GeV

**$m_T(\tau_1)$** $< 70$ GeV $> 70$ GeV

**$m(\tau_1, \tau_2)$** $> 70$ GeV $> 70$ GeV

### Variable SR HH

**Charge($\tau_1, \tau_2$)** opposite

**$m_{T2}(\tau_1, \tau_2)$** $< 30$ GeV $< 30$ GeV

**$E_T^\text{miss}$** $> 120$ GeV $> 120$ GeV

**$m_T(\tau_1)$** $< 70$ GeV $> 70$ GeV

**$m(\tau_1, \tau_2)$** $> 70$ GeV $> 70$ GeV
Using Taus in Searches for Top Squarks

Total systematic uncertainty
- SR LH: ±29%
- SR HH: ±53%

Fake-factor method
- ±23%

Jet-related
- ±9.4%
- ±36%

Tau-related
- ±7.2%
- ±32%

Other experimental
- ±6.2%
- ±12%

Theory modelling
- ±8.4%
- ±20%

MC statistics
- ±7.5%
- ±17%

Normalization factors
- ±4.8%
- ±14%

Luminosity
- ±0.3%
- ±0.8%

### Signal channel

<table>
<thead>
<tr>
<th>Signal channel</th>
<th>$\langle A\epsilon\sigma \rangle^{95\text{obs}}$ [fb]</th>
<th>$\delta^{95\text{obs}}$</th>
<th>$\delta^{95\text{exp}}$</th>
<th>$\text{CL}_b$</th>
<th>$p(s = 0)$</th>
<th>$Z$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SR LH</td>
<td>0.15</td>
<td>5.4</td>
<td>$4.5^{+2.6}_{-1.5}$</td>
<td>0.65</td>
<td>0.32 (0.47)</td>
<td></td>
</tr>
<tr>
<td>SR HH</td>
<td>0.13</td>
<td>4.7</td>
<td>$4.6^{+1.5}_{-1.5}$</td>
<td>0.52</td>
<td>0.48 (0.05)</td>
<td></td>
</tr>
</tbody>
</table>

### Observed events

<table>
<thead>
<tr>
<th>Signal channel</th>
<th>SR LH</th>
<th>SR HH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed events</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Total background</td>
<td>2.2 ± 0.6</td>
<td>1.9 ± 1.0</td>
</tr>
<tr>
<td>Fake $\tau_{\text{had}} + e/\mu$</td>
<td>1.4 ± 0.5</td>
<td>—</td>
</tr>
<tr>
<td>$t\bar{t}$ (fake $\tau_{\text{had}}$)</td>
<td>—</td>
<td>0.6 ± 0.7</td>
</tr>
<tr>
<td>$t\bar{t}$ (real $\tau_{\text{had}}$)</td>
<td>0.22 ± 0.12</td>
<td>0.28 ± 0.30</td>
</tr>
<tr>
<td>$t\bar{t} + V$</td>
<td>0.25 ± 0.14</td>
<td>0.26 ± 0.12</td>
</tr>
<tr>
<td>Diboson</td>
<td>0.15 ± 0.11</td>
<td>0.28 ± 0.13</td>
</tr>
<tr>
<td>Single-top</td>
<td>0.10 ± 0.14</td>
<td>0.13 ± 0.11</td>
</tr>
<tr>
<td>$V + \text{jets}$</td>
<td>0.032 ± 0.014</td>
<td>0.26 ± 0.09</td>
</tr>
<tr>
<td>Others</td>
<td>0.082 ± 0.022</td>
<td>0.09 ± 0.04</td>
</tr>
<tr>
<td>Signal</td>
<td>3.3 ± 0.7</td>
<td>4.7 ± 1.2</td>
</tr>
</tbody>
</table>

$(m(\tilde{t}_1) = 1100\text{ GeV}, m(\tilde{\tau}_1) = 590\text{ GeV})$
SRs for $\ell\tau_h$ channels

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0j − 1</td>
<td>&lt;40</td>
<td>&lt;40</td>
<td>&lt; −100</td>
</tr>
<tr>
<td>0j − 2</td>
<td>&gt;40</td>
<td>&gt; −500</td>
<td>&gt; 0</td>
</tr>
<tr>
<td>0j − 3</td>
<td>[40,80]</td>
<td>&lt;40</td>
<td>&lt; −100</td>
</tr>
<tr>
<td>0j − 4</td>
<td>&gt;50</td>
<td>&lt;100</td>
<td>&gt; 0</td>
</tr>
<tr>
<td>0j − 5</td>
<td>[40,80]</td>
<td>&lt; −100</td>
<td>&gt; 0</td>
</tr>
<tr>
<td>0j − 6</td>
<td>&gt;100</td>
<td>&gt; 0</td>
<td>&gt; 0</td>
</tr>
<tr>
<td>0j − 7</td>
<td>&gt;80</td>
<td>&gt; −500</td>
<td>&gt; 0</td>
</tr>
<tr>
<td>0j − 8</td>
<td>[80,120]</td>
<td>&lt; −100</td>
<td>&gt; 0</td>
</tr>
<tr>
<td>0j − 9</td>
<td>&gt;100</td>
<td>&gt; 0</td>
<td>&gt; 0</td>
</tr>
<tr>
<td>0j − 10</td>
<td>[40,80]</td>
<td>&lt; −150</td>
<td>&gt; 0</td>
</tr>
<tr>
<td>0j − 11</td>
<td>&gt;150</td>
<td>&gt; 0</td>
<td>&gt; 0</td>
</tr>
<tr>
<td>0j − 12</td>
<td>&gt;80</td>
<td>&gt; −500</td>
<td>&gt; 0</td>
</tr>
<tr>
<td>0j − 13</td>
<td>[120,250]</td>
<td>&lt; −100</td>
<td>&gt; 0</td>
</tr>
<tr>
<td>0j − 14</td>
<td>&gt;100</td>
<td>&gt; 0</td>
<td>&gt; 0</td>
</tr>
<tr>
<td>0j − 15</td>
<td>[40,80]</td>
<td>&lt; −150</td>
<td>&gt; 0</td>
</tr>
<tr>
<td>0j − 16</td>
<td>[−150, −100]</td>
<td>[40,80]</td>
<td>&lt; −150</td>
</tr>
<tr>
<td>0j − 17</td>
<td>&gt;100</td>
<td>&gt; 0</td>
<td>&gt; 0</td>
</tr>
<tr>
<td>0j − 18</td>
<td>[80,100]</td>
<td>&gt; −500</td>
<td>&gt; 0</td>
</tr>
<tr>
<td>0j − 19</td>
<td>[100,120]</td>
<td>&gt; −500</td>
<td>&gt; 0</td>
</tr>
<tr>
<td>0j − 20</td>
<td>&gt;120</td>
<td>&gt; −500</td>
<td>&gt; 0</td>
</tr>
<tr>
<td>0j − 21</td>
<td>&gt;250</td>
<td>&gt;0</td>
<td>&gt; −500</td>
</tr>
</tbody>
</table>

- $D_\zeta = P_{\zeta,miss} = 0.85P_{\zeta,vis}$ with
  - $P_{\zeta,vis} = \vec{p}_T^{miss} \cdot \vec{\zeta}$
  - $P_{\zeta,vis} = (\vec{p}_T(\ell_1) + \vec{p}_T(\ell_2)) \cdot \vec{\zeta}$
  - $\vec{\zeta}$ = bisector between directions of leptons
- helps to discriminate other processes from events in which $E_T^{miss}$ originates from decay of 2 $\tau$ leptons
**Searches for Tau Sleptons**

**SRs for $e\mu$ channel**

<table>
<thead>
<tr>
<th>Bin name</th>
<th>$p_T^{miss}$ [GeV]</th>
<th>$m_T2$ [GeV]</th>
<th>$D_T$ [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0j-1$</td>
<td>&lt;40</td>
<td>&lt;40</td>
<td>&lt; -100</td>
</tr>
<tr>
<td>$0j-2$</td>
<td>&gt;40</td>
<td>&lt;0</td>
<td>&gt; -500</td>
</tr>
<tr>
<td>$0j-3$</td>
<td>[40,80]</td>
<td>&lt;40</td>
<td>&lt; -100</td>
</tr>
<tr>
<td>$0j-4$</td>
<td>[40,80]</td>
<td>&gt;50</td>
<td>&gt; -100</td>
</tr>
<tr>
<td>$0j-5$</td>
<td>&gt;80</td>
<td>&gt;100</td>
<td>&gt; -500</td>
</tr>
<tr>
<td>$0j-6$</td>
<td>[80,120]</td>
<td>&lt;40</td>
<td>&lt; -100</td>
</tr>
<tr>
<td>$0j-7$</td>
<td>&gt;120</td>
<td>&gt;100</td>
<td>&gt; -100</td>
</tr>
<tr>
<td>$0j-8$</td>
<td>&gt;150</td>
<td>&gt;100</td>
<td>&gt; -100</td>
</tr>
<tr>
<td>$0j-9$</td>
<td>[120,250]</td>
<td>&lt;150</td>
<td>&lt; -100</td>
</tr>
<tr>
<td>$0j-10$</td>
<td>&gt;150</td>
<td>&gt;100</td>
<td>&gt; -100</td>
</tr>
<tr>
<td>$0j-11$</td>
<td>[80,120]</td>
<td>&gt;120</td>
<td>&gt; -100</td>
</tr>
<tr>
<td>$0j-12$</td>
<td>&gt;80</td>
<td>&gt;120</td>
<td>&gt; -100</td>
</tr>
<tr>
<td>$0j-13$</td>
<td>[120,250]</td>
<td>&gt;40</td>
<td>&lt; -100</td>
</tr>
<tr>
<td>$0j-14$</td>
<td>[120,250]</td>
<td>&gt;150</td>
<td>&gt; -100</td>
</tr>
<tr>
<td>$0j-15$</td>
<td>[100,120]</td>
<td>&gt;150</td>
<td>&gt; -100</td>
</tr>
<tr>
<td>$0j-16$</td>
<td>[80,100]</td>
<td>&gt;150</td>
<td>&gt; -100</td>
</tr>
<tr>
<td>$0j-17$</td>
<td>&gt;120</td>
<td>&gt;150</td>
<td>&gt; -100</td>
</tr>
<tr>
<td>$0j-18$</td>
<td>&gt;500</td>
<td>&gt;150</td>
<td>&gt; -100</td>
</tr>
<tr>
<td>$0j-19$</td>
<td>&gt;500</td>
<td>&gt;100</td>
<td>&gt; -100</td>
</tr>
<tr>
<td>$0j-20$</td>
<td>&gt;500</td>
<td>&gt;100</td>
<td>&gt; -100</td>
</tr>
<tr>
<td>$0j-21$</td>
<td>&gt;100</td>
<td>&gt;100</td>
<td>&gt; -100</td>
</tr>
<tr>
<td>$0j-22$</td>
<td>&gt;250</td>
<td>&gt;0</td>
<td>&gt; -500</td>
</tr>
</tbody>
</table>

**Direct stau interpretations:**

- Left-handed scenario
- Maximally-mixed scenario
- Right-handed scenario
<table>
<thead>
<tr>
<th>W-CR</th>
<th>W-VR</th>
</tr>
</thead>
<tbody>
<tr>
<td>One isolated muon and one medium tau lepton with opposite sign</td>
<td></td>
</tr>
<tr>
<td>b-jet veto</td>
<td></td>
</tr>
<tr>
<td>$m(\mu, \tau) &gt; 70$ GeV</td>
<td></td>
</tr>
<tr>
<td>$E_T^{\text{miss}} &gt; 60$ GeV</td>
<td></td>
</tr>
<tr>
<td>$50 &lt; m_{T,\mu} &lt; 150$ GeV</td>
<td></td>
</tr>
<tr>
<td>$m_{T,\mu} + m_{T,\tau} &gt; 80$ GeV</td>
<td></td>
</tr>
<tr>
<td>$0.5 &lt; \Delta R(\mu, \tau) &lt; 3.5$</td>
<td></td>
</tr>
<tr>
<td>$10 &lt; m_{T_2} &lt; 60$ GeV</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Z-VR</th>
<th>Top-VR</th>
</tr>
</thead>
<tbody>
<tr>
<td>At least one opposite-sign tau lepton pair</td>
<td></td>
</tr>
<tr>
<td>Tau $p_T &gt; 50, 40$ GeV</td>
<td></td>
</tr>
<tr>
<td>$E_T^{\text{miss}} &gt; 60$ GeV</td>
<td></td>
</tr>
<tr>
<td>At least two medium tau leptons</td>
<td></td>
</tr>
<tr>
<td>b-jet veto</td>
<td></td>
</tr>
<tr>
<td>at least one medium and one loose tau lepton</td>
<td></td>
</tr>
<tr>
<td>$m_{T_2} &lt; 10$ GeV</td>
<td></td>
</tr>
<tr>
<td>$m_{T_2} &gt; 10$ GeV</td>
<td></td>
</tr>
<tr>
<td>$m_{CT}$ top-tagged</td>
<td></td>
</tr>
</tbody>
</table>

Source of systematic uncertainty

<table>
<thead>
<tr>
<th>SR-lowMass</th>
<th>SR-highMass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normalisation uncertainties of the multi-jet background</td>
<td>32</td>
</tr>
<tr>
<td>Statistical uncertainty of MC samples</td>
<td>18</td>
</tr>
<tr>
<td>Multi-jet estimation</td>
<td>14</td>
</tr>
<tr>
<td>Pile-up reweighting</td>
<td>8</td>
</tr>
<tr>
<td>Jet energy scale and resolution</td>
<td>11</td>
</tr>
<tr>
<td>Tau identification and energy scale</td>
<td>6</td>
</tr>
<tr>
<td>$E_T^{\text{miss}}$ soft-term resolution and scale</td>
<td>2</td>
</tr>
<tr>
<td>Total</td>
<td>40</td>
</tr>
</tbody>
</table>
### Table

<table>
<thead>
<tr>
<th>SR</th>
<th>Sample</th>
<th>CR-B</th>
<th>CR-C</th>
<th>CR-A</th>
<th>T = C/B</th>
<th>Multi-jet in SR-D</th>
</tr>
</thead>
<tbody>
<tr>
<td>lowMass</td>
<td>Data</td>
<td>556</td>
<td>674</td>
<td>8</td>
<td>1.16</td>
<td>4.3 ± 4.0</td>
</tr>
<tr>
<td></td>
<td>Z+jets</td>
<td>3.4 ± 2.1</td>
<td>19 ± 5</td>
<td>0.8 ± 0.4</td>
<td>0.01 ± 0.01</td>
<td></td>
</tr>
<tr>
<td></td>
<td>W+jets</td>
<td>8.9 ± 1.8</td>
<td>20 ± 5</td>
<td>1.8 ± 1.0</td>
<td>0.30 ± 0.12</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Diboson</td>
<td>0.94 ± 0.12</td>
<td>3.3 ± 0.2</td>
<td>0.29 ± 0.07</td>
<td>0.01 ± 0.01</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Top</td>
<td>1.61 ± 0.30</td>
<td>4.1 ± 0.5</td>
<td>1.4 ± 1.1</td>
<td>0.01 ± 0.01</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Multi-jet</td>
<td>541 ± 24</td>
<td>627 ± 27</td>
<td>3.7 ± 1.6</td>
<td>0.01 ± 0.01</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Reference point 2</td>
<td>0.06 ± 0.01</td>
<td>0.16 ± 0.02</td>
<td>1.68 ± 0.16</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Reference point 1</td>
<td>0.63 ± 0.08</td>
<td>2.37 ± 0.21</td>
<td>1.92 ± 0.16</td>
<td></td>
<td></td>
</tr>
<tr>
<td>highMass</td>
<td>Data</td>
<td>1565</td>
<td>836</td>
<td>5</td>
<td>0.43</td>
<td>1.3 ± 1.1</td>
</tr>
<tr>
<td></td>
<td>Z+jets</td>
<td>56 ± 31</td>
<td>93 ± 42</td>
<td>0.02 ± 0.29</td>
<td>1.8 ± 1.9</td>
<td></td>
</tr>
<tr>
<td></td>
<td>W+jets</td>
<td>151 ± 22</td>
<td>125 ± 17</td>
<td>1.1 ± 0.4</td>
<td>2.0 ± 2.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Diboson</td>
<td>9.6 ± 1.1</td>
<td>20.5 ± 2.0</td>
<td>0.8 ± 0.4</td>
<td>0.01 ± 0.01</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Top</td>
<td>9.2 ± 1.5</td>
<td>25.4 ± 3.4</td>
<td>0.01 ± 0.01</td>
<td>1.8 ± 1.9</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Multi-jet</td>
<td>13.9 ± 50</td>
<td>570 ± 50</td>
<td>3.1 ± 0.6</td>
<td>1.8 ± 1.9</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Reference point 2</td>
<td>0.53 ± 0.08</td>
<td>2.37 ± 0.21</td>
<td>1.92 ± 0.16</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Reference point 1</td>
<td>0.63 ± 0.08</td>
<td>2.37 ± 0.21</td>
<td>1.92 ± 0.16</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Diagrams

- **VR-F (lowMass)**
- **VR-F (highMass)**
- **ATLAS**
Search for Electroweak SUSY Production

More sensitive signal region, “H” corresponds to SR-highMass and “L” to SR-lowMass
$\sum m_T$ and $m_{T^2}$ distributions after baseline selection in $\tau_h \tau_h$ channel

$E_T^{\text{miss}}$ and $m_T^{\text{tot}} = \sqrt{m_T^2(l, \bar{p}_T^{\text{miss}}) + m_T^2(\tau_h, \bar{p}_T^{\text{miss}})}$ distributions after baseline selection in $\mu \tau_h$ channel
visible mass spectrum of $\tau$ lepton pair system in $\tau_h\tau_h$ DY+jets validation sample (left, after 2-D correction of $Z$ mass and $p_T$ from $Z \to \mu\mu$ control sample) and $\ell \tau_h$ DY+jets validation sample (right, after normalization SF + correction of $Z$ $p_T$ from from $Z \to \mu\mu$ control sample)
observed event counts and predicted background yields
($\sum m_T, \tau_T\tau_T$, prefit)
(2016 and 2017)

observed event counts and predicted background yields
($\sum m_T, \tau_T\tau_T$, postfit)
(2016 and 2017)
observed event counts and predicted background yields (BDT100, $\mu\tau_h$, prefit) (2016 and 2017)

observed event counts and predicted background yields (BDT100, $\mu\tau_h$, postfit) (2016 and 2017)
Search for Direct Production of Staus (CMS)

Alexander Mann (LMU München)

Searches for Tau Sleptons

CMS-PAS-SUS-18-006

7th LHCP Conference — 22.05.2019

\[ m(\tilde{\chi}_1^0) = 1 \text{ GeV} \quad m(\tilde{\chi}_1^0) = 10 \text{ GeV} \quad m(\tilde{\chi}_1^0) = 20 \text{ GeV} \]

- Top: left-handed scenario
- Bottom: degenerate scenario

- Left-handed scenario (bottom right): exclude 1.14 \( \sigma \) (132 fb) at 125 GeV
### Region definitions

<table>
<thead>
<tr>
<th>Selections</th>
<th>TVR-lowMass</th>
<th>ZVR-lowMass</th>
<th>VVVR-lowMass</th>
<th>TVR-highMass</th>
<th>ZVR-highMass</th>
<th>VVVR-highMass</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>≥ 2 medium (\tau) (OS), (p_T(\tau) &gt; 60\ \text{GeV}), (E_T^{\text{miss}} &gt; 150\ \text{GeV})</td>
<td>(E_T^{\text{miss}} &gt; 150\ \text{GeV})</td>
<td>(E_T^{\text{miss}} &gt; 150\ \text{GeV})</td>
<td>(E_T^{\text{miss}} &gt; 150\ \text{GeV})</td>
<td>(E_T^{\text{miss}} &gt; 150\ \text{GeV})</td>
<td>(E_T^{\text{miss}} &gt; 150\ \text{GeV})</td>
</tr>
<tr>
<td></td>
<td>(\Delta R(\tau_1, \tau_2) &gt; 1.2)</td>
<td>(&lt; 70\ \text{GeV})</td>
<td>(&lt; 110\ \text{GeV})</td>
<td>(&lt; 110\ \text{GeV})</td>
<td>(&lt; 1\ \text{GeV})</td>
<td>(&lt; 200\ \text{GeV})</td>
</tr>
<tr>
<td></td>
<td>(m(\tau_1, \tau_2) &gt; 70\ \text{GeV})</td>
<td>(60\ \text{GeV} &lt; m_T,\tau \leq 150\ \text{GeV})</td>
<td>(60\ \text{GeV} &lt; m_T,\tau \leq 250\ \text{GeV})</td>
<td>(60\ \text{GeV} &lt; m_T,\tau \leq 250\ \text{GeV})</td>
<td>(60\ \text{GeV} &lt; m_T,\tau \leq 250\ \text{GeV})</td>
<td>(60\ \text{GeV} &lt; m_T,\tau \leq 250\ \text{GeV})</td>
</tr>
</tbody>
</table>

**W-CR**

- 1 medium \(\tau\) and 1 isolated \(\mu\) (OS)
- \(p_T(\tau) > 60\ \text{GeV}, \ p_T(\mu) > 50\ \text{GeV}\)
- \(E_T^{\text{miss}} > 60\ \text{GeV}\)
- \(b\)-jet veto and top-tagged events veto
- \(m(\mu, \tau) > 70\ \text{GeV}\)
- \(1 < \Delta R(\mu, \tau) < 3.5\)
- \(50 < m_T,\mu < 150\ \text{GeV}\)
- \(m_T,\mu + m_T,\tau > 250\ \text{GeV}\)
- \(30 < m_T^2 < 70\ \text{GeV}\)

**W-VR**

- 2 medium \(\tau\) (OS), \(\geq 1\) tight \(\tau\)
- \(\Delta R(\tau_1, \tau_2) < 3.2\)
- \(|\Delta \phi(\tau_1, \tau_2)| > 0.8\)
- \(m_T^2 > 70\ \text{GeV}\)

---

**SR – lowMass**

- 2 tight \(\tau\) (OS)
- \(p_T(\tau) > 60\ \text{GeV}, \ p_T(\mu) > 50\ \text{GeV}\)
- \(E_T^{\text{miss}} > 60\ \text{GeV}\)
- \(b\)-jet veto and top-tagged events veto
- \(m(\mu, \tau) > 70\ \text{GeV}\)
- \(1 < \Delta R(\mu, \tau) < 3.5\)
- \(50 < m_T,\mu < 150\ \text{GeV}\)
- \(m_T,\mu + m_T,\tau > 250\ \text{GeV}\)
- \(30 < m_T^2 < 70\ \text{GeV}\)

**CR – lowMass**

- \(m_T(\tau_1, \tau_2) > 70\ \text{GeV}\)
Search for Direct Production of Staus (ATLAS)

ABCD method for low-mass SR (left) and high-mass SR (right)
\( m_{T2} \) and ...

\[ \ldots E_{T}^{\text{miss}} \text{ in multi-jet low-mass and high-mass VR-F} \]
### Search for Direct Production of Staus (ATLAS)

#### ATLAS Preliminary

$\sqrt{s} = 13$ TeV, 139 fb$^{-1}$

**Events**

<table>
<thead>
<tr>
<th>Process</th>
<th>Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>10^5</td>
</tr>
<tr>
<td>SM Total</td>
<td>10^4</td>
</tr>
<tr>
<td>Multi-jet</td>
<td>10^3</td>
</tr>
<tr>
<td>Top quark</td>
<td>10^2</td>
</tr>
<tr>
<td>Z+jets</td>
<td>10^1</td>
</tr>
<tr>
<td>Multi-boson</td>
<td>10</td>
</tr>
<tr>
<td>Higgs</td>
<td>1</td>
</tr>
<tr>
<td>W+jets</td>
<td>1</td>
</tr>
</tbody>
</table>

**Data/SM**

<table>
<thead>
<tr>
<th>VR</th>
<th>Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>TVR-lowMass</td>
<td>1</td>
</tr>
<tr>
<td>ZVR-lowMass</td>
<td>1</td>
</tr>
<tr>
<td>VVR-lowMass</td>
<td>1</td>
</tr>
<tr>
<td>TVR-highMass</td>
<td>1</td>
</tr>
<tr>
<td>ZVR-highMass</td>
<td>1</td>
</tr>
<tr>
<td>VVR-highMass</td>
<td>1</td>
</tr>
</tbody>
</table>

**Top / Z / VV VRs**

- low-mass
- high-mass

---

#### ATLAS Preliminary

$\sqrt{s} = 13$ TeV, 139 fb$^{-1}$

**$m_{T2}$, W CR, pre-fit**

<table>
<thead>
<tr>
<th>$m_{T2}$ (GeV)</th>
<th>Events / 5 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>600</td>
</tr>
<tr>
<td>35</td>
<td>500</td>
</tr>
<tr>
<td>40</td>
<td>400</td>
</tr>
<tr>
<td>45</td>
<td>300</td>
</tr>
<tr>
<td>50</td>
<td>200</td>
</tr>
<tr>
<td>55</td>
<td>100</td>
</tr>
<tr>
<td>60</td>
<td>100</td>
</tr>
<tr>
<td>65</td>
<td>100</td>
</tr>
<tr>
<td>70</td>
<td>100</td>
</tr>
</tbody>
</table>

**$m_{T2}$, W VR, post-fit**

<table>
<thead>
<tr>
<th>$m_{T2}$ (GeV)</th>
<th>Events / 5 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>350</td>
</tr>
<tr>
<td>35</td>
<td>300</td>
</tr>
<tr>
<td>40</td>
<td>250</td>
</tr>
<tr>
<td>45</td>
<td>200</td>
</tr>
<tr>
<td>50</td>
<td>150</td>
</tr>
<tr>
<td>55</td>
<td>100</td>
</tr>
<tr>
<td>60</td>
<td>100</td>
</tr>
<tr>
<td>65</td>
<td>100</td>
</tr>
<tr>
<td>70</td>
<td>100</td>
</tr>
</tbody>
</table>

---

Alexander Mann (LMU München)
### Search for Direct Production of Staus (ATLAS)

#### Source of systematic uncertainty

<table>
<thead>
<tr>
<th>Source of systematic uncertainty</th>
<th>SR-lowMass (%)</th>
<th>SR-highMass (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistical uncertainty of MC samples</td>
<td>11</td>
<td>21</td>
</tr>
<tr>
<td>Tau identification and energy scale</td>
<td>19</td>
<td>10</td>
</tr>
<tr>
<td>Normalisation uncertainties of the multi-jet background</td>
<td>13</td>
<td>9</td>
</tr>
<tr>
<td>Multi-jet estimation</td>
<td>6</td>
<td>11</td>
</tr>
<tr>
<td>W+jets theory uncertainty</td>
<td>5</td>
<td>8</td>
</tr>
<tr>
<td>Diboson theory uncertainty</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>Jet energy scale and resolution</td>
<td>5</td>
<td>8</td>
</tr>
<tr>
<td>( E_{T}^{\text{miss}} ) soft-term resolution and scale</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>28</strong></td>
<td><strong>33</strong></td>
</tr>
</tbody>
</table>

### Source of systematic uncertainty

<table>
<thead>
<tr>
<th>m (~( \tilde{\tau}, \tilde{\chi}_1 )) GeV</th>
<th>SR-lowMass (%)</th>
<th>SR-highMass (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(120, 1)</td>
<td>(280, 1)</td>
</tr>
<tr>
<td>Tau identification and energy scale</td>
<td>29</td>
<td>14</td>
</tr>
<tr>
<td>Statistical uncertainty of MC samples</td>
<td>6</td>
<td>10</td>
</tr>
<tr>
<td>Signal cross section uncertainty</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>Jet energy scale and resolution</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>( E_{T}^{\text{miss}} ) soft-term resolution and scale</td>
<td>3&lt;1</td>
<td>&lt;1</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>31</strong></td>
<td><strong>18</strong></td>
</tr>
</tbody>
</table>

#### SM process

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Diboson</td>
<td>1.4 ± 0.6</td>
<td>1.9 ± 1.0</td>
<td>63 ± 18</td>
<td>37 ± 11</td>
<td>1.4 ± 0.8</td>
<td>2.6 ± 1.2</td>
</tr>
<tr>
<td>W+jets</td>
<td>13 ± 5</td>
<td>4^{+7}_{-4}</td>
<td>850 ± 70</td>
<td>370 ± 120</td>
<td>1.5 ± 0.7</td>
<td>2.5 ± 1.9</td>
</tr>
<tr>
<td>Top quark</td>
<td>2.7 ± 0.9</td>
<td>3.3 ± 1.6</td>
<td>170 ± 40</td>
<td>114 ± 31</td>
<td>0.04^{+0.80}_{-0.04}</td>
<td>2.0 ± 0.5</td>
</tr>
<tr>
<td>Z+jets</td>
<td>0.3^{+1.4}_{-0.3}</td>
<td>1.5 ± 0.7</td>
<td>13 ± 7</td>
<td>27 ± 20</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^{+0.33}_{-0.01}</td>
<td>0.01 ± 0.01</td>
<td>1.1^{+1.8}_{-1.1}</td>
<td>0.5^{+1.0}_{-0.5}</td>
<td>0.01^{+0.02}_{-0.01}</td>
<td>–</td>
</tr>
<tr>
<td>Multi-jet</td>
<td>55 ± 10</td>
<td>16 ± 7</td>
<td>3.1 ± 3.1</td>
<td>–</td>
<td>2.6 ± 0.7</td>
<td>3.1 ± 1.5</td>
</tr>
<tr>
<td>SM total</td>
<td>72 ± 8</td>
<td>27 ± 5</td>
<td>1099 ± 33</td>
<td>540 ± 130</td>
<td>6.0 ± 1.7</td>
<td>10.2 ± 3.3</td>
</tr>
<tr>
<td>Observed</td>
<td>72</td>
<td>27</td>
<td>1099</td>
<td>552</td>
<td>10</td>
<td>7</td>
</tr>
</tbody>
</table>
Search for Direct Production of Staus (ATLAS)

$m_{T2}$ in low-mass SR (top) and high-mass SR (bottom)

expected event yields for the SUSY reference points, one-sided $p_0$-values (>0.5 truncated at 0.5), obs. and exp. 95% CL upper limits on visible non-SM cross section

<table>
<thead>
<tr>
<th>$m(\tilde{\tau},\tilde{\chi}^0_1)$</th>
<th>SR-lowMass</th>
<th>SR-highMass</th>
</tr>
</thead>
<tbody>
<tr>
<td>(120, 1) GeV</td>
<td>$9.8 \pm 3.1$</td>
<td>$7.2 \pm 2.2$</td>
</tr>
<tr>
<td>(280, 1) GeV</td>
<td>$5.9 \pm 1.5$</td>
<td>$14.0 \pm 2.5$</td>
</tr>
</tbody>
</table>

$p_0$

Expected $\sigma_{vis}^{95}$ [fb]

<table>
<thead>
<tr>
<th></th>
<th>SR-lowMass</th>
<th>SR-highMass</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$0.055^{+0.025}_{-0.014}$</td>
<td>$0.065^{+0.025}_{-0.019}$</td>
</tr>
</tbody>
</table>

Observed $\sigma_{vis}^{95}$ [fb]

<table>
<thead>
<tr>
<th></th>
<th>SR-lowMass</th>
<th>SR-highMass</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.08</td>
<td>0.05</td>
</tr>
</tbody>
</table>

SR definitions

- **SR-lowMass**
  - 2 tight $\tau$s (OS)
  - asymmetric di-tau trigger
  - $75 < E_T^{miss} < 150$ GeV
  - $|\Delta\phi(\tau_1, \tau_2)| > 0.8$
  - $m_{T2} > 70$ GeV

- **SR-highMass**
  - 2 medium $\tau$s (OS), $\geq 1$ tight $\tau$
  - di-tau+$E_T^{miss}$ trigger
  - $E_T^{miss} > 150$ GeV
  - $|\Delta\phi(\tau_1, \tau_2)| > 0.8$
  - $m_{T2} > 70$ GeV
ATLAS Run-1 analysis (MVA)
• BDT trained on 12 input variables ($E_T^{\text{miss}}$, $m_{\text{eff}}$, $m_{T^2}$, $m_{\tau\tau}$, ...)
• (Only) one scenario excluded with $m(\tilde{\tau}) \approx 110$ GeV and massless LSP
• cross sections above 0.115 pb excluded, theoretical cross-section at NLO 0.128 pb
Heavy Charged Long-Lived Particles

- All other searches assume SUSY particles to decay promptly
- Here: search for long-lived staus
  - GMSB model with $\tilde{G}$ LSP and long-lived $\tilde{\tau}$ NLSP
- Charged $\Rightarrow$ track: measure momentum $p$ in ID and MS
- Heavy $\Rightarrow\beta \ll 1$: measure ToF in Tile Calorimeter and MS
- Mass hypothesis $m_{\text{ToF}} = p/\beta\gamma$ for candidate tracks

Analysis of $36.1 \text{ fb}^{-1} @ \sqrt{s} = 13 \text{ TeV}$
- Custom timing calibration
- Fully data-driven background estimate
- Obtained by random sampling from PDFs (momentum, $\beta_{\text{ToF}}$) measured in sidebands
- Remove effect of implicit correlation by binning in $\eta$
- Normalized to data in CR at low mass
- Almost background-free search

Comparison data vs expected background
• Combination of 2 SRs
  • with 2 loose or 1 tight track candidate
• Minimum requirement on track mass $m_{\text{ToF}}^{\text{min}}$
  adapted to signal-mass hypothesis $m_{\text{truth}}$
• No significant excess observed
  • upper limits on production cross section
  • stau result driven by SR-2Cand-FullDet

expected and observed yields in discovery regions

exclude $m(\tilde{\tau}_R) < 430\, \text{GeV}$ (420 exp.)
Table 1: Summary of the five sets of SRs. The trigger as well as the track candidate selection and the number of candidates per event required for the respective SR are given. Also the final selection requirements together with the mass window (one- or two-dimensional) for the final counting are stated. SRs in one block (delimited by horizontal lines) are combined for the statistical interpretation of the results. For SR-Rhad-FullDet, the ID+CALO is used as a fallback only if no loose candidates are found in the event; hence the two SRs are mutually exclusive.

<table>
<thead>
<tr>
<th>Signal region</th>
<th>Trigger</th>
<th>Candidate selection</th>
<th>Candidates per event</th>
<th>Final requirements</th>
<th>Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>SR-Rhad-MSagno</td>
<td>E_T^{miss}</td>
<td>ID+CALO</td>
<td>≥ 1</td>
<td>≤ 1.65 ≥ 200 ≤ 0.75 ≤ 1.0</td>
<td>ToF &amp; dE/dx</td>
</tr>
<tr>
<td>SR-Rhad-FullDet</td>
<td>E_T^{miss}/µ</td>
<td>LOOSE</td>
<td>≥ 1</td>
<td>≤ 1.65 ≥ 200 ≤ 0.75 ≤ 1.3</td>
<td>ToF &amp; dE/dx</td>
</tr>
<tr>
<td>SR-Rhad-FullDet</td>
<td>E_T^{miss}/µ</td>
<td>ID+CALO</td>
<td>≥ 1</td>
<td>≤ 1.65 ≥ 200 ≤ 0.75 ≤ 1.0</td>
<td>ToF &amp; dE/dx</td>
</tr>
<tr>
<td>SR-2Cand-FullDet</td>
<td>E_T^{miss}/µ</td>
<td>LOOSE</td>
<td>= 2</td>
<td>≤ 2.00 ≥ 100 ≤ 0.95</td>
<td>-</td>
</tr>
<tr>
<td>SR-1Cand-FullDet</td>
<td>E_T^{miss}/µ</td>
<td>TIGHT</td>
<td>= 1</td>
<td>≤ 1.65 ≥ 200 ≤ 0.80</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 2: Summary of systematic uncertainties. Ranges indicate a dependence on the mass hypothesis.

<table>
<thead>
<tr>
<th>Source</th>
<th>MS-agnostic</th>
<th>Relative uncertainty [%]</th>
<th>Staus</th>
<th>Charginos</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theoretical inclusive cross section</td>
<td>14–57</td>
<td>14–57</td>
<td>6–10</td>
<td>4–10</td>
</tr>
<tr>
<td>Total uncertainty in signal efficiency</td>
<td>17–19</td>
<td>18–30</td>
<td>7–15</td>
<td>9–18</td>
</tr>
<tr>
<td>Trigger efficiency</td>
<td>1.6</td>
<td>1.9</td>
<td>4.5</td>
<td>3.9</td>
</tr>
<tr>
<td>E_T^{miss}</td>
<td>1.6</td>
<td>1.6</td>
<td>2.0</td>
<td>2.5</td>
</tr>
<tr>
<td>Single-muon</td>
<td></td>
<td>1.0</td>
<td>4.0</td>
<td>3.0</td>
</tr>
<tr>
<td>Theoretical uncertainty (ISR/FSR)</td>
<td>15</td>
<td>15</td>
<td>4</td>
<td>7</td>
</tr>
<tr>
<td>Pileup</td>
<td>0.2–3.8</td>
<td>0.3–5.5</td>
<td>0.1–3.1</td>
<td>0.2–4.4</td>
</tr>
<tr>
<td>Full-detector track reconstruction</td>
<td>-</td>
<td>1.7–14.8</td>
<td>0.2–12.8</td>
<td>0.8–13.0</td>
</tr>
<tr>
<td>Track hit requirements</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Pixel βγ measurement</td>
<td>6.0–11.6</td>
<td>6.0–13.0</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>ToF β measurement</td>
<td>0.5–3.6</td>
<td>9.8–21.9</td>
<td>1.0–3.6</td>
<td>2.0–12.0</td>
</tr>
<tr>
<td>Calorimeter β measurement</td>
<td>0.1–0.5</td>
<td>0.1–1.1</td>
<td>0.1–0.5</td>
<td>0.1–0.5</td>
</tr>
<tr>
<td>Calorimeter OFA correction</td>
<td>0.4–3.6</td>
<td>1.2–3.1</td>
<td>0.1–0.4</td>
<td>0.1–1.3</td>
</tr>
<tr>
<td>MS β measurement</td>
<td>-</td>
<td>9.7–21.7</td>
<td>1.0–3.5</td>
<td>2.0–12.0</td>
</tr>
<tr>
<td>Luminosity</td>
<td>2.1</td>
<td>2.1</td>
<td>2.1</td>
<td>2.1</td>
</tr>
<tr>
<td>Uncertainty in background estimate</td>
<td>33–34</td>
<td>27–33</td>
<td>9–31</td>
<td>9–34</td>
</tr>
</tbody>
</table>

Table 5: p_0-values and model-independent upper limits on cross section (σ) × acceptance (a) × efficiency (ε) for the 16 discovery regions.

<table>
<thead>
<tr>
<th>Selection</th>
<th>m_{min}^{dE/dx} [GeV]</th>
<th>m_{min}^{dE/dx} [GeV]</th>
<th>N_{est.} ±σ_{N_{est.}}</th>
<th>N_{obs.}</th>
<th>p_{0}</th>
<th>Significance [σ]</th>
<th>95% CL upper limit [fb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SR-Rhad-MSagno</td>
<td>550</td>
<td>450</td>
<td>1.8±0.6</td>
<td>4</td>
<td>0.056</td>
<td>1.59</td>
<td>0.2</td>
</tr>
<tr>
<td>SR-Rhad-FullDet</td>
<td>700</td>
<td>600</td>
<td>0.7±0.3</td>
<td>2</td>
<td>0.11</td>
<td>1.24</td>
<td>0.17</td>
</tr>
<tr>
<td>SR-2Cand-FullDet</td>
<td>850</td>
<td>750</td>
<td>0.4±0.1</td>
<td>2</td>
<td>0.028</td>
<td>1.92</td>
<td>0.17</td>
</tr>
<tr>
<td>SR-1Cand-FullDet</td>
<td>550</td>
<td>450</td>
<td>2.8±0.7</td>
<td>6</td>
<td>0.081</td>
<td>1.40</td>
<td>0.25</td>
</tr>
<tr>
<td>SR-1Cand-FullDet</td>
<td>700</td>
<td>600</td>
<td>1.4±0.4</td>
<td>2</td>
<td>0.28</td>
<td>0.57</td>
<td>0.14</td>
</tr>
<tr>
<td>SR-2Cand-FullDet</td>
<td>850</td>
<td>750</td>
<td>0.95±0.2</td>
<td>2</td>
<td>0.18</td>
<td>0.93</td>
<td>0.14</td>
</tr>
<tr>
<td>SR-Rhad-FullDet</td>
<td>175</td>
<td>200±20</td>
<td>227±5</td>
<td>0.5</td>
<td>1.26</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SR-2Cand-FullDet</td>
<td>375</td>
<td>17±2</td>
<td>16±5</td>
<td>0.5</td>
<td>0.24</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SR-1Cand-FullDet</td>
<td>600</td>
<td>2.2±0.2</td>
<td>1±0.5</td>
<td>0.5</td>
<td>0.10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SR-2Cand-FullDet</td>
<td>825</td>
<td>0.48±0.07</td>
<td>0±0.5</td>
<td>0.5</td>
<td>0.08</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SR-1Cand-FullDet</td>
<td>150</td>
<td>1.5±0.3</td>
<td>0±0.5</td>
<td>0.5</td>
<td>0.09</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SR-2Cand-FullDet</td>
<td>350</td>
<td>0.06±0.01</td>
<td>0±0.5</td>
<td>0.5</td>
<td>0.08</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SR-2Cand-FullDet</td>
<td>575</td>
<td>0.007±0.002</td>
<td>0±0.5</td>
<td>0.5</td>
<td>0.08</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SR-2Cand-FullDet</td>
<td>800</td>
<td>0.0017±0.0009</td>
<td>0±0.5</td>
<td>0.5</td>
<td>0.08</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 7: Expected signal yield ($N_{\text{exp.}}$) and acceptance ($a \times \epsilon$) for the full range of simulated masses in the full-detector direct-stau search.

<table>
<thead>
<tr>
<th>Simulated mass [GeV]</th>
<th>$N_{\text{exp.}} \times \sigma_{N_{\text{exp.}}}$</th>
<th>$a \times \epsilon \times \sigma_{a \times \epsilon}$</th>
<th>$N_{\text{est.}} \times \sigma_{N_{\text{est.}}}$</th>
<th>$N_{\text{obs.}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>287</td>
<td>13 ± 1</td>
<td>0.167 ± 0.005</td>
<td>0.33 ± 0.06</td>
<td>0</td>
</tr>
<tr>
<td>318</td>
<td>9 ± 1</td>
<td>0.179 ± 0.007</td>
<td>0.22 ± 0.04</td>
<td>0</td>
</tr>
<tr>
<td>349</td>
<td>6.1 ± 0.7</td>
<td>0.181 ± 0.005</td>
<td>0.15 ± 0.03</td>
<td>0</td>
</tr>
<tr>
<td>380</td>
<td>4.3 ± 0.6</td>
<td>0.184 ± 0.006</td>
<td>0.11 ± 0.02</td>
<td>0</td>
</tr>
<tr>
<td>411</td>
<td>3.2 ± 0.4</td>
<td>0.196 ± 0.005</td>
<td>0.08 ± 0.02</td>
<td>0</td>
</tr>
<tr>
<td>442</td>
<td>2.4 ± 0.3</td>
<td>0.198 ± 0.007</td>
<td>0.06 ± 0.01</td>
<td>0</td>
</tr>
<tr>
<td>473</td>
<td>1.8 ± 0.3</td>
<td>0.204 ± 0.005</td>
<td>0.045 ± 0.009</td>
<td>0</td>
</tr>
<tr>
<td>504</td>
<td>1.4 ± 0.2</td>
<td>0.210 ± 0.005</td>
<td>0.035 ± 0.007</td>
<td>0</td>
</tr>
<tr>
<td>536</td>
<td>1.0 ± 0.1</td>
<td>0.208 ± 0.005</td>
<td>0.027 ± 0.006</td>
<td>0</td>
</tr>
<tr>
<td>567</td>
<td>0.84 ± 0.10</td>
<td>0.224 ± 0.006</td>
<td>0.027 ± 0.006</td>
<td>0</td>
</tr>
<tr>
<td>598</td>
<td>0.65 ± 0.09</td>
<td>0.227 ± 0.006</td>
<td>0.022 ± 0.005</td>
<td>0</td>
</tr>
<tr>
<td>629</td>
<td>0.50 ± 0.07</td>
<td>0.227 ± 0.006</td>
<td>0.017 ± 0.004</td>
<td>0</td>
</tr>
<tr>
<td>660</td>
<td>0.40 ± 0.05</td>
<td>0.234 ± 0.006</td>
<td>0.014 ± 0.003</td>
<td>0</td>
</tr>
<tr>
<td>692</td>
<td>0.30 ± 0.05</td>
<td>0.234 ± 0.008</td>
<td>0.011 ± 0.003</td>
<td>0</td>
</tr>
<tr>
<td>723</td>
<td>0.24 ± 0.03</td>
<td>0.229 ± 0.007</td>
<td>0.009 ± 0.002</td>
<td>0</td>
</tr>
<tr>
<td>754</td>
<td>0.19 ± 0.02</td>
<td>0.224 ± 0.006</td>
<td>0.008 ± 0.002</td>
<td>0</td>
</tr>
<tr>
<td>785</td>
<td>0.15 ± 0.02</td>
<td>0.222 ± 0.006</td>
<td>0.007 ± 0.002</td>
<td>0</td>
</tr>
<tr>
<td>817</td>
<td>0.12 ± 0.01</td>
<td>0.219 ± 0.006</td>
<td>0.007 ± 0.002</td>
<td>0</td>
</tr>
<tr>
<td>848</td>
<td>0.09 ± 0.01</td>
<td>0.215 ± 0.005</td>
<td>0.006 ± 0.001</td>
<td>0</td>
</tr>
<tr>
<td>879</td>
<td>0.08 ± 0.01</td>
<td>0.212 ± 0.005</td>
<td>0.005 ± 0.001</td>
<td>0</td>
</tr>
<tr>
<td>911</td>
<td>0.065 ± 0.007</td>
<td>0.225 ± 0.006</td>
<td>0.004 ± 0.001</td>
<td>0</td>
</tr>
</tbody>
</table>

**MET Trigger efficiency for a charged LLP**

**Background estimate for the one-tight-candidate SR**

---

**Diagram:**
- A diagram illustrating the MET trigger efficiency for a charged LLP and the background estimate for the one-tight-candidate SR.
- The diagram shows events in 25 GeV bins for $m_{\text{ToF}}$.
- Data points, estimated background, and statistical uncertainties are plotted.
- The background estimate for the full range of simulated masses in the full-detector direct-stau search is also shown.

---

**Observations:**
- The table provides a detailed comparison of expected signal yields, acceptance, estimated backgrounds, and observed data for various simulated masses.
- The data points are accompanied by uncertainties, with a focus on the one-tight-candidate SR.

---

**Summary:**
- The analysis covers a range of simulated masses, from 287 GeV to 911 GeV, with a focus on the efficiency and acceptance for the one-tight-candidate SR.
- The results highlight the precision and detail in the ATLAS simulation, critical for understanding the potential for detecting charged long-lived particles in tau slepton searches.

---

**References:**
- ATLAS Simulation
- Est. bkg + stat. unc.
- Exp. signal ($\tau$ & 442 GeV)
- Data
- SR-1Cand-FullDet (375 GeV)
Direct Stau @ HL-LHC

**Performance Study...**

- High-luminosity upgrade of the LHC (HL-LHC)
  - $3000 \text{ fb}^{-1}$ @ centre-of-mass energy of $\sqrt{s} = 14$ TeV
  - average pile-up of $\langle \mu \rangle \sim 200$ (instantaneous luminosity up to $7 \cdot 10^{34} \text{ Hz/cm}^2$)
- Parametrized simulation of performance of upgraded ATLAS detector
  - in turn based on MC simulations, CERN-LHCC-2015-020
  - describes reconstruction eff’s and resolution and misidentification probabilities for taus and $b$-jets
  - taking into account fake taus in backgrounds

...for Direct Stau

- Consider $\tilde{\tau}_R \tilde{\tau}_R$ and $\tilde{\tau}_L \tilde{\tau}_L$ production
- Select events with $\geq 2 \tau_{\text{had}}$, low jet activity and $E_T^{\text{miss}}$
- Assume di-tau triggers available roughly with current online thresholds despite higher instantaneous luminosity
- Optimized selection for high luminosity
- Dominant backgrounds: $t\bar{t}$, $W + \text{jets}$
Direct Stau @ HL-LHC

SR Definition

≥ 2 OS taus
loose jet-veto
Z-veto
\( \Delta R(\tau_1, \tau_2) < 3.5 \)
\( E_T^{\text{miss}} > 280 \text{ GeV} \)
\( m_{T2} > 40 \text{ GeV} \)
\( m_{T\tau_1} + m_{T\tau_2} > 480 \text{ GeV} \)

- Discovery and exclusion sensitivity: combined up to 710 GeV and 500 GeV
- Depends on systematic uncertainties, here assume 30%
- No discovery sensitivity to pure \( \tilde{\tau}_R \tilde{\tau}_R \) production even at HL-LHC
### Selection requirement

<table>
<thead>
<tr>
<th>Muon (electron) $p_T$</th>
<th>$\ell\tau_h$</th>
<th>$\tau_h\tau_h$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muon (electron) $p_T$</td>
<td>$&gt; 30$ GeV</td>
<td>—</td>
</tr>
<tr>
<td>Muon (electron) $p_T$ (veto)</td>
<td>$&gt; 30$ GeV</td>
<td>$&gt; 20$ GeV</td>
</tr>
<tr>
<td>Muon (electron) $</td>
<td>\eta</td>
<td>$</td>
</tr>
<tr>
<td>Muon (electron) $</td>
<td>\eta</td>
<td>$ (veto)</td>
</tr>
<tr>
<td>$\tau_h p_T$</td>
<td>$&gt; 40$ GeV</td>
<td>$&gt; 50$ GeV</td>
</tr>
<tr>
<td>$\tau_h</td>
<td>\eta</td>
<td>$</td>
</tr>
<tr>
<td>$p_T (\tau_h \tau_h)$</td>
<td>—</td>
<td>$&gt; 50$ GeV</td>
</tr>
<tr>
<td>jet $p_T$ (veto)</td>
<td>$&gt; 30$ GeV</td>
<td>$&gt; 30$ GeV</td>
</tr>
<tr>
<td>jet $</td>
<td>\eta</td>
<td>$ (veto)</td>
</tr>
<tr>
<td>b jet $p_T$ (veto)</td>
<td>$&gt; 20$ GeV</td>
<td>$&gt; 30$ GeV</td>
</tr>
</tbody>
</table>

### $\tau_h\tau_h$:

<table>
<thead>
<tr>
<th>Variable</th>
<th>Bin 0</th>
<th>Bin 1</th>
<th>Bin 2</th>
<th>Bin 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_{T2}$</td>
<td>50 $&lt; M_{T2} &lt; 100$ GeV</td>
<td>100 $&lt; M_{T2} &lt; 150$ GeV</td>
<td>150 $&lt; M_{T2} &lt; 200$ GeV</td>
<td>$M_{T2} &gt; 200$ GeV</td>
</tr>
<tr>
<td>$\Sigma M_T$</td>
<td>400 $&lt; \Sigma M_T &lt; 500$ GeV</td>
<td>500 $&lt; \Sigma M_T &lt; 600$ GeV</td>
<td>$\Sigma M_T &gt; 600$ GeV</td>
<td>—</td>
</tr>
<tr>
<td>$n_{\text{jet}}$</td>
<td>$= 0$</td>
<td>$&gt; 0$</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

(18/24 bins used)

### $\ell\tau_h$:

<table>
<thead>
<tr>
<th>Variable</th>
<th>Bin 0</th>
<th>Bin 1</th>
<th>Bin 2</th>
<th>Bin 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_{T2}$</td>
<td>$M_{T2} &gt; 120$ GeV</td>
<td>$M_{T2} &gt; 120$ GeV</td>
<td>$80 &lt; M_{T2} &lt; 120$ GeV</td>
<td>$80 &lt; M_{T2} &lt; 120$ GeV</td>
</tr>
<tr>
<td>$p_T(\tau_h)$</td>
<td>$&gt; 200$ GeV</td>
<td>$40 &lt; p_T(\tau_h) &lt; 200$ GeV</td>
<td>$&gt; 200$ GeV</td>
<td>$40 &lt; p_T(\tau_h) &lt; 120$ GeV</td>
</tr>
</tbody>
</table>

(4 bins)
\[ \sum M_T \text{ in } \tau_h \tau_h \]

\[ m_{T2} \text{ in } e \tau_h \]

\[ E_{T}^{\text{miss}} \text{ in } \mu \tau_h \]
Impact of intermediate masses

- Study of different assumptions on mass of intermediate particle ($\tilde{\tau}$)

\[ m(\tilde{\tau}) = m(\tilde{\chi}_1^0) + x \cdot (m(\tilde{\chi}_2^0, \tilde{\chi}_1^\pm) - m(\tilde{\chi}_1^0)) \]

- heavy stau ($x = 0.95$)
  \[ \Rightarrow m(\tilde{\chi}_2, \tilde{\chi}_1^\pm) > 510 \text{ GeV} \]

- mass half-way ($x = 0.5$)
  \[ \Rightarrow m(\tilde{\chi}_2, \tilde{\chi}_1^\pm) > 560 \text{ GeV} \]

- light stau ($x = 0.05$)
  \[ \Rightarrow m(\tilde{\chi}_2, \tilde{\chi}_1^\pm) > 480 \text{ GeV} \]
How We Model Backgrounds
The ABCD Method

- Goal: estimate background in signal region D
- Pick 2 uncorrelated variables from selection defining D
- Define 3 additional regions A, B, C enriched in background
- Compute:
  \[ N_D = T \cdot N_A \quad \text{with} \quad T = \frac{N_C}{N_B} \]
- Validate in additional regions E, F
- Caveats:
  - correlations (→ systematic uncertainty)
  - too low statistics
  - purity / background-to-background subtraction (→ simulation dependence)

\[ T = \frac{N_C}{N_B} \]
Observed Limits in SUSY Searches with Tau Leptons

ATLAS, strong, 36 fb$^{-1}$: 2000 GeV ($\tilde{g}\tilde{g}$)

ATLAS, electroweak, 36 fb$^{-1}$: 760 GeV ($\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 + \tilde{\chi}_1^{\pm}\tilde{\chi}_1^\mp$), 630 GeV ($\tilde{\chi}_1^{\pm}\tilde{\chi}_1^\mp$)

ATLAS, stop, 36 fb$^{-1}$: 1160 GeV ($\tilde{t}\tilde{t}$)

CMS, electroweak, 36 fb$^{-1}$: 710 GeV ($\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$), 630 GeV ($\tilde{\chi}_1^{\pm}\tilde{\chi}_1^\mp$)

ATLAS, direct, 139 fb$^{-1}$: 390 GeV