Soft SUSY Searches at ATLAS and CMS

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on behalf of
ATLAS and CMS

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Status Quo

- Wide regions of the SUSY parameter space have been excluded with recent LHC Run II results → putting natural SUSY under extreme pressure!

**Chargino-Neutralino Production**

- There are several ‘crevasses’ of parameter space which are still uncovered
  - This talk focuses on soft SUSY searches with very compressed mass spectra ($\Delta m = \text{small}$)
  - There is a significant effort at ATLAS and CMS focusing on these regions

3G Searches covered in M. Hodgkinson's talk

EWK Searches covered in C. Cid's talk
Why Soft SUSY?

- Natural SUSY requires relatively light stops, higgsinos and gluinos

- Small mass splittings $\Delta m$ can reproduce the correct cosmological dark matter abundance (e.g. Phys. Rev. D 56, 1879)
  - co-annihilation of neutralinos and light stops/charginos

- Access to compressed EWK SUSY models:
  - lower cross-sections for EWKino production wrt. strong production
  - light higgsinos in EWK models
    = window to natural SUSY
  - more details in Carlos’ EWK SUSY talk!

General motivations for SUSY:
- Solution to Hierarchy/Naturalness problem in Standard Model (SM)
- Unification of electroweak (EWK) and strong gauge couplings at GUT scale
- Lightest supersymmetric particle (LSP) = dark matter candidate

- e.g. The Light Stop Window (arXiv:1212.6847)
Initial State Radiation

- **Mass splitting** $\Delta m$ dictates possible decay modes and kinematics
- Small $\Delta m \Rightarrow$ little available energy $\Rightarrow$ soft final states and low $E_T^{\text{miss}}$
  $\rightarrow$ missed by ‘classical’ searches (high $E_T^{\text{miss}}$ and lepton $p_T$s)
- Loss in efficiency for object reconstruction at very low $p_T$s
- Visible decay products do **not** pass acceptance thresholds
  $\Rightarrow$ low threshold triggers and accurate reconstruction essential
- Difficulties with soft products can be mitigated by **initial state radiation** (ISR) = a (quark/gluon) jet originating from partons:
  $\Rightarrow$ signal vertex is boosted and visible decay products detectable

Signature: hard recoil **ISR jet** (high $H_T$) and moderate $E_T^{\text{miss}}$ + soft **leptons/jets**
- leptons down to several GeVs + many analyses veto b-tagged jets
- ISR tagging: “large R” jets capturing ISR gluon jets undergone splitting (**CMS-SUS-16-049**)
Soft Multileptons

Soft Dileptons

**ATLAS-SUSY-2018-16**

Searches for *electroweak* production of supersymmetric particles with *compressed* mass spectra

**CMS-SUS-16-048**

Search for new physics in events with *two soft oppositely charged leptons* and missing transverse momentum

**Trileptons**

**ATLAS-CONF-2020-015**

Search for *chargino-neutralino* pair production in final states with *three leptons* and missing transverse momentum
Soft SUSY Searches at ATLAS and CMS

Soft Dileptons

Two soft opposite-sign (OS) leptons

- same-flavor leptons \((e^±e^± \text{ or } \mu^±\mu^±)\) in two channels:
  - \(2\ell \ (p_T > 5 \text{ GeV})\) and \(1\ell + \geq 1\) track \((1\ell 1\text{T})\)
    - b-jet veto for \(2\ell\)
  - kinematic: \(E_T^{\text{miss}} > 120 \text{ GeV} \) (\(E_T^{\text{miss}}\) trigger)
- muons > 3 GeV (lowPt ID) and electrons > 4.5 GeV
- 3 signal regions targeting EWKinos (SR-E), sleptons (SR-S) and VBF (SR-VBF)

- same or different flavour \((e^±e^±, \mu^±\mu^±, e^±\mu^±)\)
- muons > 3.5 GeV and electrons > 5 GeV
- EWKino and stop selections
- SR binning in: \(m_{\ell\ell}\)
- dedicated dimuon + \(E_T^{\text{miss}}\) trigger \(\rightarrow\) low \(E_T^{\text{miss}}\) SR

Full Run 2

2016

125 GeV (\(\mu\mu\))

Efficiency

Simulation
Data

PF MET (\(\mu\) subtracted) [GeV]

CMS Preliminary

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

Preliminary CMS (13 TeV)

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Soft Dileptons

- **Recursive Jigsaw Reconstruction** (RJR) variables:
  - **ISR recoil**: $R_{\text{ISR}} = \text{ratio of } E_{T}^{\text{miss}} \text{ and } p_{T} \text{ of the ISR system}
  - $m_{T}^{S} = \text{transverse mass of } S \text{ (SUSY) system}

- The **invariant mass** $m_{\ell\ell}$ between two leptons ("off-Z")
- **Transverse mass** of leading lepton $m_{T}\ell^{1}$
- $E_{T}^{\text{miss}}/H_{T}\text{lep}$ where $H_{T}\text{lep} = \text{scalar sum of the lepton } p_{T}$

**SR-E**
- 4 $E_{T}^{\text{miss}}$ regions
- Binning
  - $E_{T}^{\text{miss}}$
  - $m_{T}\ell^{1}$ and $m_{\ell\ell}$
  - $R_{\text{ISR}}$
  - $E_{T}^{\text{miss}}/H_{T}\text{lep}$
Soft SUSY Searches at ATLAS and CMS

**Chargino-Neutralino Production**

**Soft Dileptons**

**Higgsino pMSSM**

**Wino/Bino**

**Higgsino**

**ATLAS-SUSY-2018-16**

**CMS-SUS-16-048**

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(S)Transverse Mass

- The **transverse mass** $m_T$ constructed from lepton $p_T$ and $E_T^{\text{miss}}$ used to calculate the mass of particles decaying to a visible + invisible particle:
  - kinematic edge around the mass of the $W$ boson
  - effective in separating single-leptonic SM processes ($W$+jets, $t\bar{t}$-bar)

$$M_T = \sqrt{2 p_T^\ell p_T^{\text{miss}} \left[1 - \cos (\phi_\ell - \phi_{p_T^{\text{miss}}})\right]}$$

- **Stransverse mass** ($m_{T2}^{mx}$) → transverse mass adapted to dileptons:
  - $m_\chi = $ hypothesised mass of LSP
  - set to 100 GeV $m_{T2}^{100} \rightarrow$ kinematic edge

Used in a number of leptonic searches!
Soft Dileptons

**Slepton Production**

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

**ee/μμ, m_{12}^{100} shape fit**
All limits at 95% CL

**Process:**
\[ pp \rightarrow \tilde{\ell}_{L,R} \tilde{\chi}_1^0 \rightarrow \ell \tilde{\chi}_1^0, \ell \in [e, \mu] \]

**Expected limit (±1σ_{exp})**
**Observed limit (±1σ_{theory})**
**ATLAS 8 TeV \tilde{\ell}_{L,R} excluded**
**ATLAS 13 TeV 36 fb^{-1} \tilde{\ell}_{L,R} excluded**
**LEP \tilde{\ell}_R excluded**

**Diagram:**
- Particles: \( p \), \( j \), \( \tilde{\ell} \), \( \ell \), \( \tilde{\chi}_1^0 \)
- Diagram shows production of sleptons and their decay into dileptons.

**Analysis:**
- The diagram illustrates the search for soft SUSY signatures in ATLAS and CMS experiments.
- The plot displays constraints on the mass difference \( \Delta m(\tilde{\ell}_L, \tilde{\chi}_1^0) \) and the slepton mass \( m(\tilde{\ell}_{L,R}) \).
Soft SUSY Searches at ATLAS and CMS

Trileptons

- EWK production with a 3L final state (WZ-mediated)
  - “On-shell” selections covered in Carlos’ EWK Talk
  - “Off-shell” WZ selection → compressed EWK scenarios

- SR binning in $E_T^{\text{miss}}$ and jet multiplicity
  - SRs targeting moderate mass splittings ($\Delta m = 40 - 90$ GeV)
  - Higher $E_T^{\text{miss}}$ SR → highly compressed mass spectra ($\Delta m < 40$ GeV)

- Primary discriminants:
  - kinematic edge at $m_{\ell\ell}^{\text{min}} = \Delta m$
  - kinematic edge in transverse mass $m_T^{100}$
  - transverse mass $m_T^{m_{\ell\ell}^{\text{min}}}$ using $m_{\ell\ell}^{\text{min}}$ assignment

- complementary with soft 2L (ATLAS-SUSY-2018-16)

- constraints are calculated in the bino-wino coannihilation dark-matter scenario where $\Omega_{\text{DM}}h^2 \leq$ the observed value
Compressed VBF

ATLAS-SUSY-2018-16

Searches for electroweak production of supersymmetric particles with compressed mass spectra

CMS-SUS-17-007

Search for supersymmetry with a compressed mass spectrum in the vector boson fusion topology with 1-lepton and 0-lepton final states
Compressed VBF

**VBF** topology: forward jets in opposite hemispheres and large dijet invariant mass

**ATLAS-SUSY-2018-16**

- SR of Soft 2L search: SR-VBF
- **VBF recoil**: $R_{VBF} = RJR$ with ISR replaced by 2 leading jets
- Large separation: low and high regions
- Binning in $R_{VBF}$ and $m_{ll}$

**CMS-SUS-17-007**

- 1st search of VBF + soft 1L + EWK SUSY search in 0ljj
- low-$p_T$ $\rightarrow$ difficult to reconstruct and identify leptons:
  - one lepton (e, m, $\tau_h$) ($1\ell jj$) binned in $m_T$
  - zero ($0\ell jj$) leptons binned in $m_{jj}$
- Transverse mass $m_T > 110$ GeV (beyond $m_W$ peak)
Compressed VBF

VBF (Off Shell W*/Z*)

Wino/Bino

$\Delta m$ down to 1 GeV!
Soft Tau

CMS-SUS-19-002

Search for supersymmetry with a compressed mass spectrum in events with a soft \( \tau \) lepton, a highly energetic jet, and large missing transverse momentum
Soft Tau

- First search of a soft hadronically-decaying tau:
  - stau decaying to tau and neutralino + ISR
    - $\Delta m(\text{stau}, \chi_1^0) \leq 50 \text{ GeV}$
  - $20 < p_T(\tau_H) < 40 \text{ GeV}$
  - SR binning in terms of transverse mass of $\tau_H$:
    $$m_T(p^\text{miss}, \tau_h) = \sqrt{2p_T^\text{miss} p_T(\tau_h) (1 - \cos \Delta \phi(p^\text{miss}, \tau_h))},$$

SSM1: chargino-neutralino + stau production

- First limits to surpass LEP bound of 103.5 GeV for $m(\chi_1^{\pm})$ in compressed scenarios
Compressed Stop

ATLAS-SUSY-2018-12
ATLAS-CONF-2020-003

CMS-SUS-19-009
CMS-SUS-18-003
CMS-SUS-17-005
CMS-SUS-16-048
CMS-SUS-16-049
CMS-SUS-16-032
Compressed Stop

- $\Delta m \equiv m_{\text{stop}} - m_{\text{LSP}}$ dictates decay modes and kinematics:
  - Final states classified according to $W$ decay-modes: hadronic, single- and di-leptonic
- **Very compressed** scenario when: $\Delta m < m_W \rightarrow$ decay via an off-shell $t^*$ and $W^*$

Decay modes:
1. Charm decay (FCNC)
2. Chargino-mediated
3. Four-body

‘Classical’ searches (also targeting compressed):
- All-hadronic:
  - ATLAS-SUSY-2018-12
  - CMS-SUS-16-049
- Single leptonic:
  - ATLAS-CONF-2020-003
  - CMS-SUS-19-009
- Top corridor ($\Delta m \sim m_t$):
  - CMS-SUS-18-003
Soft B-Tagging

Stop decays → top decays → final states with $b$-jets
- tagging $b$-jets with $p_T > 1$ GeV
- sensitivity to compressed models
  - signal efficiency and background rejection

**Soft b-tagging** algorithms:
  - used in all-hadronic ([CMS-SUS-16-049](https://cds.cern.ch/record/2247484))
  - used in stop 1L ([CMS-SUS-19-009](https://cds.cern.ch/record/2481085)) for $\Delta m \sim m_W$
- **Track-based Low-$p_T$ Vertex Tagger (T-LVT)** ([ATLAS-CONF-2019-027](https://cds.cern.ch/record/2640142))
  - used in all-hadronic ([ATLAS-CONF-2020-003](https://cds.cern.ch/record/2749300))
  - used in stop 1L ([ATLAS SUSY-2018-12](https://cds.cern.ch/record/2636450))
- **DeepJet/DeepCSV**
  - used in 1L ([CMS-SUS-19-009](https://cds.cern.ch/record/2481085)) for $\Delta m \sim m_t$

- jets reconstructed from tracks
- identifying SVs without the presence of a jet
Soft SUSY Searches at ATLAS and CMS

Single Leptonic

- Stop pair-production in **single lepton** channel
- Analysis strategy and non-compressed scenarios covered in Mark’s 3G talk
  - dedicated signal regions for compressed scenarios: **ISR**
  - dedicated **soft b-tagging** techniques for very small Δm’s

**ATLAS-CONF-2020-003**

**CMS-SUS-19-009**

Four-body decay
All Hadronic

- Stop pair-production in **all-hadronic** channel
- Analysis strategy and non-compressed scenarios covered in Mark’s 3G talk
  - dedicated signal regions for compressed scenarios: ISR
  - dedicated **soft b-tagging** + $R_{ISR}$ for very small $\Delta m$’s

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**ATLAS SUSY-2018-12**

**CMS-SUS-16-049**

Four-body decay

![Diagram of four-body decay](image)

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Soft SUSY Searches at ATLAS and CMS

Other Searches

- There are a number of other searches covering compressed phase-spaces:

CMS-SUS-17-005

CMS-SUS-16-048

CMS-SUS-16-049

CMS-SUS-16-032

CMS-SUS-17-005

CMS-SUS-16-032

CMS-SUS-16-048

Four-body decay

Charm decay (FCNC)

Chargino-mediated decay
Improvements

- Solely increased integrated luminosity is not expected to bring large gains in sensitivity ⇒ improve techniques:
  - **Soft lepton** reconstruction and identification:
    - MVA/DeepNN discriminators for low $p_T$ leptons
  - **Soft b-tagging** techniques
  - **Soft tracks** (eg. $1\ell + 1T$ EWKino SR in Soft 2L)
  - **ISR tagging**:
    - recoil: Recursive Jigsaw (RJR) or $H_T$/MET
    - “large-R” jets → used in CMS-SUS-16-049
    - quark-gluon likelihood QGL-discriminator
- Dedicated **cross-triggers** to lower MET and lepton thresholds
  - soft object(s) + ISR + MET (CMS-DP 2020/004)
  - VBF + soft lepton (CMS-DP 2020/014)
- Shift to more sophisticated **signal models** eg. extensions to long-lived particles (for very small $\Delta m$, particles are displaced)
Summary & Outlook

• Soft SUSY = small $\Delta m \rightarrow$ soft visible decay products (leptons/jets/$E_T^{miss}$)
  – characteristic: ISR boost of signal vertex

• Significant effort at ATLAS and CMS focusing on these regions to ensure phase-space is well covered
  – brand new full Run 2 results with strongest limits in a number of compressed models
  – many dedicated analyses are currently in the works
    • stay tuned for more incoming results!
  – all analyses use specialized methods to target these regions (soft lepton ID, RJR, soft b-tagging, soft tracks, ISR tagging, triggers, new signal models, …)

We need to take advantage of these innovative methods to really push to the limits detection, analysis and theory!
Backup
Soft SUSY Searches at ATLAS and CMS

**Simplified SUSY Models**

- We can categorise SUSY signals in terms of **production** and **decay** modes:

  **SUSY Production:**
  - Typically pair-produced (R-parity conservation)
  - Production modes → choice guided by cross-sections

  **Production modes:**
  - **Strong:** gluinos, squarks
  - **EWK:** charginos, neutralinos, sleptons

  **SUSY Decay:**
  - Decay into SUSY and detectable SM particles → final states
  - **Mass splitting** $\Delta m$ dictates possible decay modes and kinematics

  **Final states:**
  - Hadronic $(0\ell) =$ **jets**
  - Single-leptonic $(1\ell)$
  - Multi-leptonic $(2\ell+)$
  - **MET** in the form of LSPs (R-parity conserving)
  - **b-jets** from top decays
**ATLAS Summary**

**Soft SUSY Searches at ATLAS and CMS**

**ATLAS Preliminary**

**\( \sqrt{s} = 8,13 \) TeV, 20.3-139 fb\(^{-1} \)**

May 2020

**ATLAS Preliminary**

\( \tilde{t}, \tilde{\tau} \) production

Limits at 95% CL

**Observed limits**

**Expected limits**

Data 15-16, \( \sqrt{s} = 13 \) TeV, 36.1 fb\(^{-1} \)

\( \tilde{t} \rightarrow \tilde{\chi}_1^0/t \rightarrow \nu b \tilde{\chi}_1^0 \rightarrow b \tilde{\chi}_1^0 \)


[1709.04183, 1711.11520, 1708.03301, 1903.07570]

Higgsino LSP

1712.08119

Wino LSP, \( \mu < 0 \)

1708.04183, 1711.11520

Higgsino LSP

1708.04183, 1711.11520

**Bino LSP**

1711.11520

Higgsino LSP

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Wino EWK

1806.02093

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ATLAS-CONF-2020-003

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Soft SUSY Searches at ATLAS and CMS

CMS Summary

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LHCP 2020
# CMS Summary

## Overview of SUSY results: squark pair production

### \( \sqrt{s} = 13 \text{ TeV} \)

<table>
<thead>
<tr>
<th>Process</th>
<th>Mass Constraints</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>( pp \to \tilde{t} \tilde{t} )</td>
<td>( \alpha = 0.5 )</td>
<td>( \Delta M_{\tilde{t}} = 5 \text{ GeV, BF} \sim 50% )</td>
</tr>
<tr>
<td>( \tilde{t} \to t \tilde{\chi}_1^\pm \to bW^+ + \tilde{\chi}_1^\pm )</td>
<td>( \Delta M_{\tilde{t}} &lt; 80 \text{ GeV (max. exclusion)} )</td>
<td></td>
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<tr>
<td>( \tilde{t} \to b \tilde{\chi}_1^\pm \to bW^\pm + \tilde{\chi}_1^\pm )</td>
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<tr>
<td>( \tilde{q} \to q \tilde{\chi}_1^\pm )</td>
<td>( \alpha = 0.5 )</td>
<td>( \Delta M_{\tilde{q}} = M_{\tilde{q}} - M_{\tilde{\chi}_1^\pm} = 300 \text{ GeV} )</td>
</tr>
</tbody>
</table>

Selection of observed limits at 95% CL (theory uncertainties are not included). Probes up to the quoted mass limit for light LSFs unless stated otherwise. The quantities \( \Delta M \) and \( \alpha \) represent the absolute mass difference between the primary sparticle and the LSP, and the difference between the intermediate sparticle and the LSP relative to \( \Delta M_{\tilde{t}} \), respectively, unless indicated otherwise.
### Overview of SUSY results: electroweak production

- \( \mathcal{P}P \rightarrow \tilde{\chi}_2^{0+} \rightarrow \ell \bar{\nu} \ell \rightarrow \ell \nu \ell \ell \)
  - arXiv:1709.05406
  - flavour democratic, \( x = 0.5 \)

- \( \mathcal{P}P \rightarrow \tilde{\chi}_2^{0-} \rightarrow \tau \bar{\nu} \ell \rightarrow \tau \nu \ell \ell \)
  - \( \geq 3 \ell + 2 \ell \) same-sign: arXiv:1709.05406
  - flavour democratic, \( x = 0.5 \)

- \( \mathcal{P}P \rightarrow \tilde{\chi}_2^{0-} \rightarrow \tau \nu \tau \rightarrow \tau \nu \ell \ell \)
  - \( \geq 3 \ell / \tau \) arXiv:1709.05406
  - \( \tau \) enriched, \( x = 0.5 \)

- \( \mathcal{P}P \rightarrow \tilde{\chi}_2^{0-} \rightarrow \tau \nu \ell \rightarrow \tau \nu \ell \ell \)
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  - \( \tau \) enriched, \( x = 0.95 \)

- \( \mathcal{P}P \rightarrow \tilde{\chi}_2^{0+} \rightarrow W Z \chi_1^{00} \)
  - \( \geq 3 \ell / h \) arXiv:1709.05406
  - combined: arXiv:1801.00345, 1706.09933
  - opposite-sign: arXiv:1709.08908

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- \( \mathcal{P}P \rightarrow \tilde{\chi}_2^{0+} \rightarrow \ell \ell \)

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.
Event Topologies

- We can draw similarities in the **event topologies** that are targeted:
  - Expect large **hadronic activity** in the event:
    - high $H_T$ (scalar sum of jets $p_T$s)
    - larger **jet multiplicity** ($N_{jets}$)
      - **b-jets** ($N_b$) from top quark decays
        » arise in many models eg. T1tttt or T5tttt
        » no b-jets for eg. T5qqqqVV or T5qqqqWW
    - Significant **missing transverse energy** $p_T^{miss}$ from LSPs which are undetected
      - Standard signature of R-parity conserving models
  - **Final states** typically consist of:
    - lepton(s) + jets (b-jets) + $p_T^{miss}$
Toolbox

- We can draw similarities in the **tools** that are used \(\rightarrow\) observables:
  - Kinematic variables – calculation of energy sums: \(H_T, p_T^{\text{miss}}\)
    - distinguishing compressed vs. uncompressed mass spectra
  - Jet multiplicities: \(N_{\text{jets}}\) and \(N_b\):
    - all presented analyses require at least 2 jets
    - \(N_b\) categorisation can provide sensitivity to different models
  - The **transverse mass** \(m_T\) constructed from lepton \(p_T\) and MET used to calculate the mass of particles decaying to a visible + invisible particle:
    \[
    M_T = \sqrt{2p_T^\ell p_T^{\text{miss}} \left[1 - \cos \left(\phi_\ell - \phi_{p_T^{\text{miss}}}\right)\right]}
    \]
    - sharp decline around the mass of the W boson
    - effective in separating single-leptonic SM processes (W+jets, tt-bar)
  - The **invariant mass** \(m_{\ell\ell}\) between two leptons targeting dileptonic signatures:
    - "on-Z" signature: decays involving an on-shell Z boson produce peak in \(m_{\ell\ell}\)
Soft SUSY Searches at ATLAS and CMS

<table>
<thead>
<tr>
<th>Lep.</th>
<th>EWK</th>
<th>Strong</th>
<th>VBF</th>
</tr>
</thead>
<tbody>
<tr>
<td>3+</td>
<td>ATLAS CONF-2020-015 (3L)</td>
<td></td>
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<tr>
<td></td>
<td>CMS-SUS-16-048 (Soft 2L)</td>
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<tr>
<td>1</td>
<td>ATLAS-CONF-2020-003 (Stop 1L) CMS-SUS-19-009 (Stop 1L)</td>
<td>CMS-SUS-17-005 (Soft 1L)</td>
<td>CMS-SUS-17-007 (Soft VBF 1/0L)</td>
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<tr>
<td>0</td>
<td>ATLAS-SUSY-2018-12 (All had.) CMS-SUS-16-049 (All had.)</td>
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</table>
# Compressed @ ATLAS

<table>
<thead>
<tr>
<th>Prod.</th>
<th>Analysis</th>
<th>Number</th>
<th>Description</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>EWK</td>
<td>3L</td>
<td>ATLAS-CONF-2020-015</td>
<td>Search for chargino-neutralino pair production in final states with three leptons and missing transverse momentum</td>
<td>ATLAS-CONF-2020-015</td>
</tr>
<tr>
<td>Stop</td>
<td>Stop 1L</td>
<td>ATLAS-CONF-2020-003</td>
<td>Search for new phenomena with top quark pairs in final states with one lepton, jets, and missing transverse momentum</td>
<td>ATLAS-CONF-2020-003</td>
</tr>
<tr>
<td>Stop</td>
<td>All Hadronic</td>
<td>ATLAS SUSY-2018-12</td>
<td>Search for a scalar partner of the top quark in the all-hadronic $tt$ plus missing transverse momentum final state</td>
<td>Submitted to EPJC</td>
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## Compressed @ CMS

<table>
<thead>
<tr>
<th>Prod.</th>
<th>Analysis</th>
<th>Number</th>
<th>Description</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>EWK</td>
<td>Soft Tau + ISR + MET</td>
<td><strong>CMS-SUS-19-002</strong></td>
<td>Search for supersymmetry with a compressed mass spectrum in events with a soft $\tau\tau$ lepton, a highly energetic jet, and large missing transverse momentum</td>
<td><strong>Phys. Rev. Lett.</strong> 124 (2020) 041803</td>
</tr>
<tr>
<td>VBF</td>
<td>VBF + SUSY</td>
<td><strong>CMS-SUS-17-007</strong></td>
<td>Search for supersymmetry with a compressed mass spectrum in the vector boson fusion topology with 1-lepton and 0-lepton final states</td>
<td><strong>JHEP 08 (2019)150</strong></td>
</tr>
<tr>
<td>Stop</td>
<td>Soft 1L</td>
<td><strong>CMS-SUS-17-005</strong></td>
<td>Search for top squarks decaying via four-body or chargino-mediated modes in single-lepton final states</td>
<td><strong>JHEP 09 (2018) 065</strong></td>
</tr>
<tr>
<td>Stop</td>
<td>All hadronic</td>
<td><strong>CMS-SUS-16-049</strong></td>
<td>Search for direct production of supersymmetric partners of the top quark in the all-jets final state</td>
<td><strong>J. High Energy Phys. 10 (2017) 005</strong></td>
</tr>
<tr>
<td>Stop</td>
<td>Stop 1L</td>
<td><strong>CMS-SUS-19-009</strong></td>
<td>Search for direct top squark pair production in events with one lepton, jets, and missing transverse momentum</td>
<td><strong>JHEP 05 (2020) 032</strong></td>
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<tr>
<td>Stop</td>
<td>Compressed charm</td>
<td><strong>CMS-SUS-16-032</strong></td>
<td>Search for the pair production of third-generation squarks with two-body decays to a bottom or charm quark and a neutralino</td>
<td><strong>Phys. Lett. B 778 (2018) 263</strong></td>
</tr>
</tbody>
</table>
Soft 2L

• Baseline selection:
  – 2 OS same-flavor leptons (e±e∓ or μ±μ∓) as two channels:
    • 2ℓ (p_T > 5 GeV) and 1ℓ + ≥1 track (1ℓ1T)
      – b-jet veto for 2ℓ
    – Kinematic: $E_T^{\text{miss}} > 120$ GeV ($E_T^{\text{miss}}$ trigger) + ISR: leading jet $p_T \geq 100$ GeV
    – Muons > 3 GeV and $|\eta| < 2.5$ (lowPt identification criterion)
    – Electrons > 4.5 GeV and $|\eta| < 2.47$
    – Jets > 30 GeV and $|\eta| < 2.8$ (VBF $|\eta| < 4.5$)
    – B-tagged jets: jets within $|\eta| < 2.5$ (MV2c1 algorithm)

• Main backgrounds:
  – reducible backgrounds: fake/nonprompt leptons
    • fake factor method
  – irreducible backgrounds: tt/tW, WW/WZ, and $Z^*/\gamma (\rightarrow \tau\tau)$ + jets
    • estimated using MC simulations normalized to data in dedicated CRs
Soft 2L

- Signal regions split into three categories each targeting different models:

**Chargino-Neutralino Production**

- **SR-E**
  - 4 $E_T^{\text{miss}}$ regions (different $\Delta m$)
  - Binning:
    - $E_T^{\text{miss}}$
    - $m_T^\ell$ and $m_\parallel$
    - $R_{\text{ISR}}$
    - $E_T^{\text{miss}}/H_T^{\text{lep}}$

**Slepton Production**

- **SR-S**
  - Binning:
    - $E_T^{\text{miss}}$
    - $R_{\text{ISR}}$
    - $m_{T2}^{100}$

**VBF Production**

- **SR-VBF**
  - Large dijet invariant mass
  - Large separation: low and high regions
  - Binning in $R_{\text{VBF}}$ and $m_\parallel$
### Soft 2L

- **Preselection:**

<table>
<thead>
<tr>
<th>Variable</th>
<th>2(\ell)</th>
<th>1(\ell) T</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of leptons (tracks)</td>
<td>= 2 leptons</td>
<td>= 1 lepton and ≥ 1 track</td>
</tr>
<tr>
<td>Lepton (p_T) [GeV]</td>
<td>(p_T^{\ell} &gt; 5)</td>
<td>(p_T^{\ell} &lt; 10)</td>
</tr>
<tr>
<td>(\Delta R_{\ell\ell})</td>
<td>(\Delta R_{ee} &gt; 0.30, \Delta R_{\mu\mu} &gt; 0.05, \Delta R_{e\mu} &gt; 0.2)</td>
<td>(0.05 &lt; \Delta R_{\ell\text{track}} &lt; 1.5)</td>
</tr>
<tr>
<td>Lepton (track) charge and flavor</td>
<td>(e^{\pm} e^{\mp}) or (\mu^{\pm} \mu^{\mp})</td>
<td>(e^{\pm} e^{\mp}) or (\mu^{\pm} \mu^{\mp})</td>
</tr>
<tr>
<td>Lepton (track) invariant mass [GeV]</td>
<td>(3 &lt; m_{ee} &lt; 60, 1 &lt; m_{\mu\mu} &lt; 60)</td>
<td>(0.5 &lt; m_{\ell\text{track}} &lt; 5)</td>
</tr>
<tr>
<td>(J/\psi) invariant mass [GeV]</td>
<td>veto (3 &lt; m_{\ell\ell} &lt; 3.2)</td>
<td>veto (3 &lt; m_{\ell\text{track}} &lt; 3.2)</td>
</tr>
<tr>
<td>(m_{\tau\tau}) [GeV]</td>
<td>&lt; 0 or &gt; 160</td>
<td>&gt; 120</td>
</tr>
<tr>
<td>(E_T^{\text{miss}}) [GeV]</td>
<td>&gt; 120</td>
<td>&gt; 120</td>
</tr>
<tr>
<td>Number of jets</td>
<td>≥ 1</td>
<td>≥ 1</td>
</tr>
<tr>
<td>Number of (b)-tagged jets</td>
<td>= 0</td>
<td>no requirement</td>
</tr>
<tr>
<td>Leading jet (p_T) [GeV]</td>
<td>≥ 100</td>
<td>≥ 100</td>
</tr>
<tr>
<td>(\min(\Delta \phi(\text{any jet}, p_T^{\text{miss}})))</td>
<td>&gt; 0.4</td>
<td>&gt; 0.4</td>
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<tr>
<td>(\Delta \phi(j_1, p_T^{\text{miss}})^\dagger)</td>
<td>≥ 2.0</td>
<td>≥ 2.0</td>
</tr>
</tbody>
</table>
Soft SUSY Searches at ATLAS and CMS

Matteusz Zarucki

Soft 2L

- EWKino SR:

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_T^{\text{miss}}$ [GeV]</td>
<td>[120, 200]</td>
<td>[120, 200]</td>
<td>&gt; 200</td>
<td>&gt; 200</td>
</tr>
<tr>
<td>$E_T^{\text{miss}}/H_T^{\text{lep}}$</td>
<td>&lt; 10</td>
<td>&gt; 10</td>
<td>-</td>
<td>&gt; 30</td>
</tr>
<tr>
<td>$\Delta \phi(\text{lep}, p_T^{\text{miss}})$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>&lt; 1.0</td>
</tr>
<tr>
<td>Lepton or track $p_T$ [GeV]</td>
<td>$p_T^{\ell_2} &gt; 5 + m_{\ell\ell}/4$</td>
<td>-</td>
<td>$p_T^{\ell_2} &gt; \min(10, 2 + m_{\ell\ell}/3)$</td>
<td>$p_T^{\text{track}} &lt; 5$</td>
</tr>
<tr>
<td>$M_T^S$ [GeV]</td>
<td>-</td>
<td>&lt; 50</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$m_T^{\ell_i}$ [GeV]</td>
<td>[10, 60]</td>
<td>-</td>
<td>&lt; 60</td>
<td>-</td>
</tr>
<tr>
<td>$R_{\text{ISR}}$ [GeV]</td>
<td>[0.8, 1.0]</td>
<td>-</td>
<td>[max(0.85, 0.98 − 0.02 × m_{\ell\ell}), 1.0]</td>
<td>-</td>
</tr>
</tbody>
</table>
Soft 2L

- VBF and Slepton SRs:

<table>
<thead>
<tr>
<th>Variable</th>
<th>VBF SR Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_{\ell\ell}$ [GeV]</td>
<td>$&lt; 40$</td>
</tr>
<tr>
<td>Number of jets</td>
<td>$\geq 2$</td>
</tr>
<tr>
<td>$p_T^{j2}$ [GeV]</td>
<td>$&gt; 40$</td>
</tr>
<tr>
<td>$E_T^{\text{miss}}$ [GeV]</td>
<td>$&gt; 150$</td>
</tr>
<tr>
<td>$E_T^{\text{miss}}/H_T^{\text{lep}}$</td>
<td>$&gt; 2$</td>
</tr>
<tr>
<td>$p_T^{\ell2}$ [GeV]</td>
<td>$&gt; \min(10, 2 + m_{\ell\ell}/3)$</td>
</tr>
<tr>
<td>$m_{\ell1}$ [GeV]</td>
<td>$&lt; 60$</td>
</tr>
<tr>
<td>$R_{\text{VBF}}$</td>
<td>$[\max(0.6, 0.92 - m_{\ell\ell}/60), 1.0]$</td>
</tr>
<tr>
<td>$\eta_{j1} \cdot \eta_{j2}$</td>
<td>$&lt; 0$</td>
</tr>
<tr>
<td>$m_{jj}$ [GeV]</td>
<td>$&gt; 400$</td>
</tr>
<tr>
<td>$\Delta\eta_{jj}$</td>
<td>$&gt; 2$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Variable</th>
<th>SR–S–low</th>
<th>SR–S–high</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_T^{\text{miss}}$ [GeV]</td>
<td>[150, 200]</td>
<td>&gt; 200</td>
</tr>
<tr>
<td>$m_{T2}^{100}$ [GeV]</td>
<td>&lt; 140</td>
<td>&lt; 140</td>
</tr>
<tr>
<td>$p_T^{\ell2}$ [GeV]</td>
<td>$&gt; \min(15, 7.5 + 0.75 \times (m_{T2} - 100))$</td>
<td>$&gt; \min(20, 2.5 + 2.5 \times (m_{T2} - 100))$</td>
</tr>
<tr>
<td>$R_{\text{ISR}}$</td>
<td>[0.8, 1.0]</td>
<td>$[\max(0.85, 0.98 - 0.02 \times (m_{T2} - 100)), 1.0]$</td>
</tr>
</tbody>
</table>
Soft 2L

**ATLAS-SUSY-2018-16**
Soft 2L

- Efficiencies:

![Efficiency Plot](image)
Soft SUSY Searches at ATLAS and CMS

ATLAS-SUSY-2018-16

Soft 2L

• Uncertainties:
### Soft 2L

#### Results:

<table>
<thead>
<tr>
<th>Signal Region</th>
<th>$N_{\text{obs}}$</th>
<th>$N_{\text{exp}}$</th>
<th>$(e\sigma)^{\text{obs}}_{\text{exp}}$ [fb]</th>
<th>$S^{\text{obs}}_{\text{exp}}$</th>
<th>$S^{\text{exp}}_{\text{exp}}$</th>
<th>$p(s = 0)$</th>
</tr>
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<tr>
<td><strong>SR-E</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>$m_{\ell\ell} &lt; 1$</td>
<td>0</td>
<td>1.0 ± 1.0</td>
<td>0.022</td>
<td>3.0</td>
<td>3.0</td>
<td>0.50</td>
</tr>
<tr>
<td>$m_{\ell\ell} &lt; 2$</td>
<td>46</td>
<td>44 ± 6.8</td>
<td>0.15</td>
<td>21</td>
<td>19</td>
<td>0.38</td>
</tr>
<tr>
<td>$m_{\ell\ell} &lt; 3$</td>
<td>90</td>
<td>77 ± 12</td>
<td>0.29</td>
<td>41</td>
<td>31</td>
<td>0.18</td>
</tr>
<tr>
<td>$m_{\ell\ell} &lt; 5$</td>
<td>151</td>
<td>138 ± 18</td>
<td>0.38</td>
<td>52</td>
<td>43</td>
<td>0.24</td>
</tr>
<tr>
<td>$m_{\ell\ell} &lt; 10$</td>
<td>244</td>
<td>200 ± 19</td>
<td>0.62</td>
<td>86</td>
<td>49</td>
<td>0.034</td>
</tr>
<tr>
<td>$m_{\ell\ell} &lt; 20$</td>
<td>383</td>
<td>301 ± 23</td>
<td>0.95</td>
<td>132</td>
<td>61</td>
<td>0.0034</td>
</tr>
<tr>
<td>$m_{\ell\ell} &lt; 30$</td>
<td>453</td>
<td>366 ± 27</td>
<td>1.04</td>
<td>144</td>
<td>70</td>
<td>0.0065</td>
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<tr>
<td>$m_{\ell\ell} &lt; 40$</td>
<td>492</td>
<td>420 ± 30</td>
<td>0.96</td>
<td>134</td>
<td>74</td>
<td>0.027</td>
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<tr>
<td>$m_{\ell\ell} &lt; 60$</td>
<td>583</td>
<td>520 ± 35</td>
<td>0.97</td>
<td>135</td>
<td>84</td>
<td>0.063</td>
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<tr>
<td><strong>SR-VBF</strong></td>
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<tr>
<td>$m_{\ell\ell} &lt; 2$</td>
<td>0</td>
<td>2.8 ± 1.6</td>
<td>0.022</td>
<td>3.0</td>
<td>3.9 ± 1.6</td>
<td>0.50</td>
</tr>
<tr>
<td>$m_{\ell\ell} &lt; 3$</td>
<td>1</td>
<td>3.1 ± 1.7</td>
<td>0.030</td>
<td>3.6</td>
<td>4.4 ± 2.0</td>
<td>0.50</td>
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<tr>
<td>$m_{\ell\ell} &lt; 5$</td>
<td>2</td>
<td>3.3 ± 1.7</td>
<td>0.035</td>
<td>4.8</td>
<td>5.2 ± 2.1</td>
<td>0.50</td>
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<tr>
<td>$m_{\ell\ell} &lt; 10$</td>
<td>9</td>
<td>8.4 ± 2.7</td>
<td>0.068</td>
<td>9.5</td>
<td>8.8 ± 2.3</td>
<td>0.43</td>
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<tr>
<td>$m_{\ell\ell} &lt; 20$</td>
<td>36</td>
<td>32 ± 5</td>
<td>0.14</td>
<td>20</td>
<td>16 ± 6</td>
<td>0.27</td>
</tr>
<tr>
<td>$m_{\ell\ell} &lt; 30$</td>
<td>58</td>
<td>52 ± 7</td>
<td>0.19</td>
<td>26</td>
<td>21 ± 8</td>
<td>0.28</td>
</tr>
<tr>
<td>$m_{\ell\ell} &lt; 40$</td>
<td>82</td>
<td>74 ± 10</td>
<td>0.24</td>
<td>33</td>
<td>27 ± 10</td>
<td>0.27</td>
</tr>
<tr>
<td><strong>SR-VBF-high</strong></td>
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</tr>
<tr>
<td>$m_{\ell\ell} &lt; 2$</td>
<td>0</td>
<td>2.4 ± 1.1</td>
<td>0.022</td>
<td>3.0</td>
<td>4.0 ± 1.6</td>
<td>0.50</td>
</tr>
<tr>
<td>$m_{\ell\ell} &lt; 3$</td>
<td>1</td>
<td>3.0 ± 1.4</td>
<td>0.025</td>
<td>3.5</td>
<td>4.6 ± 1.8</td>
<td>0.50</td>
</tr>
<tr>
<td>$m_{\ell\ell} &lt; 5$</td>
<td>2</td>
<td>3.0 ± 1.4</td>
<td>0.034</td>
<td>4.7</td>
<td>5.1 ± 2.0</td>
<td>0.50</td>
</tr>
<tr>
<td>$m_{\ell\ell} &lt; 10$</td>
<td>3</td>
<td>3.8 ± 1.7</td>
<td>0.041</td>
<td>5.6</td>
<td>5.8 ± 2.1</td>
<td>0.50</td>
</tr>
<tr>
<td>$m_{\ell\ell} &lt; 20$</td>
<td>9</td>
<td>11.7 ± 2.8</td>
<td>0.055</td>
<td>8</td>
<td>9 ± 4</td>
<td>0.50</td>
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<tr>
<td>$m_{\ell\ell} &lt; 30$</td>
<td>17</td>
<td>20 ± 5</td>
<td>0.079</td>
<td>11</td>
<td>13 ± 5</td>
<td>0.50</td>
</tr>
<tr>
<td>$m_{\ell\ell} &lt; 40$</td>
<td>26</td>
<td>28 ± 6</td>
<td>0.10</td>
<td>14</td>
<td>15 ± 6</td>
<td>0.50</td>
</tr>
<tr>
<td><strong>SR-S</strong></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$m_{\ell\ell}^{2L} &lt; 100.5$</td>
<td>24</td>
<td>27 ± 4.8</td>
<td>0.09</td>
<td>13</td>
<td>14 ± 5</td>
<td>0.50</td>
</tr>
<tr>
<td>$m_{\ell\ell}^{2L} &lt; 101$</td>
<td>41</td>
<td>46 ± 6.5</td>
<td>0.11</td>
<td>16</td>
<td>18 ± 7</td>
<td>0.50</td>
</tr>
<tr>
<td>$m_{\ell\ell}^{2L} &lt; 102$</td>
<td>91</td>
<td>82 ± 10</td>
<td>0.25</td>
<td>35</td>
<td>28 ± 10</td>
<td>0.25</td>
</tr>
<tr>
<td>$m_{\ell\ell}^{2L} &lt; 105$</td>
<td>158</td>
<td>158 ± 17</td>
<td>0.30</td>
<td>41</td>
<td>41 ± 16</td>
<td>0.50</td>
</tr>
<tr>
<td>$m_{\ell\ell}^{2L} &lt; 110$</td>
<td>243</td>
<td>242 ± 21</td>
<td>0.38</td>
<td>52</td>
<td>52 ± 19</td>
<td>0.36</td>
</tr>
<tr>
<td>$m_{\ell\ell}^{2L} &lt; 120$</td>
<td>328</td>
<td>312 ± 24</td>
<td>0.51</td>
<td>71</td>
<td>60 ± 22</td>
<td>0.26</td>
</tr>
<tr>
<td>$m_{\ell\ell}^{2L} &lt; 130$</td>
<td>419</td>
<td>388 ± 28</td>
<td>0.66</td>
<td>92</td>
<td>68 ± 27</td>
<td>0.17</td>
</tr>
<tr>
<td>$m_{\ell\ell}^{2L} &lt; 140$</td>
<td>472</td>
<td>443 ± 31</td>
<td>0.69</td>
<td>95</td>
<td>74 ± 28</td>
<td>0.19</td>
</tr>
</tbody>
</table>
Soft 2L

- Limits on EWKino:

\[ \Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^\pm) \text{ [GeV]} \]

**ATLAS**
\[ \sqrt{s} = 13 \text{ TeV, 139 fb}^{-1} \]
- ee/\mu\mu, m_t shape fit
- All limits at 95% CL
- \( pp \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^\pm \) (Wino)
- \( \tilde{\chi}_2^0 \rightarrow Z^* \tilde{\chi}_1^0 \tilde{\chi}_1^\pm \rightarrow W^* \tilde{\chi}_1^0 \)
- \( m(\tilde{\chi}_2^0) \times m(\tilde{\chi}_1^0) < 0 \)
Soft 2L

- Limits on VBF:

![Graph showing limits on VBF](image-url)
Soft SUSY Searches at ATLAS and CMS

Soft 2L

• Limits on sleptons (no mass degeneracy assumed):

ATLAS

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

ee/\mu\mu, m_{\tilde{\chi}}^{3/2} shape fit
All limits at 95% CL

\[ pp \rightarrow \tilde{\ell}_L/R_{L/R}, \tilde{\ell} \rightarrow \ell \tilde{\chi}_1^0, \ell \in [e, \mu] \]
Compressed VBF

- Models:

  - Light slepton models
  - Off-shell $W^*/Z^*$
Compressed VBF

CMS-SUS-17-007

Soft SUSY Searches at ATLAS and CMS

• Results:

Light slepton model

Off-shell W*/Z*

m(\tilde{\chi}_1^\pm) [GeV]

Cross section UL at 95% CL [fb]

Cross section UL at 95% CL [fb]
Compressed VBF

• Comparison to SOS (CMS-SUS-16-048):
  – Competitive also for EWK models
## Compressed VBF

<table>
<thead>
<tr>
<th>Process</th>
<th>$\mu jj$</th>
<th>$ejj$</th>
<th>$\tau_hjj$</th>
<th>$0\ell jj$</th>
</tr>
</thead>
<tbody>
<tr>
<td>DY+jets</td>
<td>0.20 ± 0.07</td>
<td>0.10 ± 0.04</td>
<td>0.10 ± 0.04</td>
<td>3714 ± 760</td>
</tr>
<tr>
<td>W+jets</td>
<td>13 ± 3</td>
<td>6 ± 1</td>
<td>7 ± 2</td>
<td>2999 ± 620</td>
</tr>
<tr>
<td>VV</td>
<td>1.7 ± 0.7</td>
<td>1.5 ± 0.6</td>
<td>0.9 ± 0.9</td>
<td>77 ± 18</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>13 ± 4</td>
<td>11 ± 4</td>
<td>5 ± 3</td>
<td>577 ± 128</td>
</tr>
<tr>
<td>Single top quark</td>
<td>2.2 ± 0.9</td>
<td>0.2 ± 0.1</td>
<td>0.6 ± 0.3</td>
<td>104 ± 10</td>
</tr>
<tr>
<td>QCD</td>
<td>$0^{+0.2}_{-0}$</td>
<td>$0^{+1.2}_{-0}$</td>
<td>23 ± 5</td>
<td>546 ± 69</td>
</tr>
<tr>
<td>Total BG</td>
<td>31 ± 5</td>
<td>19 ± 5</td>
<td>37 ± 6</td>
<td>8017 ± 992</td>
</tr>
<tr>
<td>Data</td>
<td>36</td>
<td>29</td>
<td>38</td>
<td>8408</td>
</tr>
</tbody>
</table>
Soft Tau

- Limits set on two models:
  - **SSM1**: sum of chargino-neutralino production with stau production
  - **SSM2**: direct production of left-handed stau pairs

- **SSM1**: First limits to surpass LEP bound of 103.5 GeV for $m(\chi_1^{\pm})$ in compressed scenarios
- **SSM2**: 4x improvement wrt. previous non-ISR searches
Stop 0L + 1L

- Analysis strategy and non-compressed scenarios covered in Mark’s 3G Talk
  - Compressed: require an ISR is used to improve sensitivity to the targeted decays
  - Take advantage of new, dedicated soft b-tagging techniques to target the compressed states (ATLAS-CONF-2019-027): track-jet b-tagging
### Stop 1L

**Compressed spectra with $\Delta m (t, \tilde{t}) \sim m_t$**

**Label I**
- Selection criteria: $N_j \geq 5$, leading-$p_T$ jet not b-tagged, $N_{b,\text{med}} \geq 1$,
- $p_T^\ell < \max (50, 250 - 100 \times \Delta \phi (p_T^{\text{miss}}, p_T^\ell))$ GeV,
- $p_T^{\text{miss}}$ bins [GeV] [250, 350, 450, 550, 750, $+\infty$]

**Label J**
- Selection criteria: $N_j \geq 3$, leading-$p_T$ jet not b-tagged, $N_{b,\text{soft}} \geq 1$,
- $p_T^\ell < \max (50, 250 - 100 \times \Delta \phi (p_T^{\text{miss}}, p_T^\ell))$ GeV,
- $p_T^{\text{miss}}$ bins [GeV] [250, 350, 450, 550, 750, $+\infty$]

<table>
<thead>
<tr>
<th>Label</th>
<th>$N_j$</th>
<th>$N_{b,\text{med}}$</th>
<th>$N_{b,\text{soft}}$</th>
<th>$p_T^{\text{miss}}$ [GeV]</th>
<th>Lost lepton</th>
<th>$1\ell$ (not from t)</th>
<th>$1\ell$ (from t)</th>
<th>$Z \to \nu\bar{\nu}$ Total expected</th>
<th>Total observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>$\geq 5$</td>
<td>$\geq 1$</td>
<td>$\geq 0$</td>
<td>250–350</td>
<td>403 ± 40</td>
<td>21 ± 8</td>
<td>71 ± 71</td>
<td>17 ± 4</td>
<td>511 ± 81</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>350–450</td>
<td>108 ± 15</td>
<td>6.8 ± 2.5</td>
<td>12 ± 12</td>
<td>7.8 ± 1.6</td>
<td>134 ± 19</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>450–550</td>
<td>31 ± 8</td>
<td>2.5 ± 1.0</td>
<td>2.0 ± 2.0</td>
<td>2.9 ± 0.8</td>
<td>39 ± 8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>550–750</td>
<td>11 ± 5</td>
<td>1.4 ± 0.6</td>
<td>0.27 ± 0.27</td>
<td>1.8 ± 0.5</td>
<td>14 ± 5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>750–$+\infty$</td>
<td>1.8 ± 1.1</td>
<td>$1.9^{+2.5}_{-1.9}$</td>
<td>0.16 ± 0.16</td>
<td>0.28 ± 0.10</td>
<td>4.1 ± 2.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>250–350</td>
<td>201 ± 21</td>
<td>37 ± 7</td>
<td>27 ± 27</td>
<td>10.4 ± 1.5</td>
<td>276 ± 35</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>350–450</td>
<td>38 ± 7</td>
<td>11.6 ± 2.2</td>
<td>3.4 ± 3.4</td>
<td>4.3 ± 0.9</td>
<td>58 ± 8</td>
</tr>
<tr>
<td>J</td>
<td>$\geq 3$</td>
<td>$\geq 0$</td>
<td>$\geq 1$</td>
<td>450–550</td>
<td>11.5 ± 3.5</td>
<td>3.3 ± 0.6</td>
<td>0.7 ± 0.7</td>
<td>1.7 ± 0.6</td>
<td>17 ± 4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>550–750</td>
<td>3.5 ± 2.3</td>
<td>2.1 ± 0.5</td>
<td>—</td>
<td>1.1 ± 0.8</td>
<td>6.6 ± 2.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>750–$+\infty$</td>
<td>0.4 ± 0.4</td>
<td>0.44 ± 0.16</td>
<td>0.02 ± 0.02</td>
<td>0.2 ± 0.4</td>
<td>1.0 ± 0.6</td>
</tr>
</tbody>
</table>
Compressed Analyses

Will take look at three examples of compressed analyses in more detail:

1. Fully-hadronic: (CMS-SUS-16-049)
2. Soft single-lepton (CMS-SUS-17-005)

Common aspects of these searches:

- Moderate MET (incl. triggers): dominant QCD-multijet events in p-p colliders significantly reduced (as with the majority of SUSY searches)
- Presence of ISR:
  - Decay products typically aligned with boost direction of LSP
  - high hadronic energy $H_T$
- Backgrounds:
  - $W+$jets and $tt$-bar dominate:
    • Suppressed/isolated using transverse mass $M_T(l, \text{MET})$ [or $M_T(b, \text{MET})$ for fully-hadronic (if there are any b-tagged jets)]
    • Estimation: Data/simulation scale factors dedicated sideband Control Regions (CRs) and extrapolating to the Signal Regions (SRs) using MC
Soft SUSY Searches at ATLAS and CMS

Fully-Hadronic

- Search for direct **stop pair-production** in events with **jets** and large MET

- More ‘inclusive’ search: target both un-compressed and compressed models:
  - T2tt-4bd: Four-body decay
  - T2bW: Chargino-mediated
  - T2cc: Flavour-violating: (FCNC)

- Additional baseline selection:
  - **Lepton veto** reducing leptonic tt-bar and W+jets events
  - Minimum 2 jets
  - Veto top or W objects (using special tagging methods)
  - Low m$_T$(b, MET), if there are any b-tagged jets

- Main backgrounds: **tt-bar** and **W+Jets**
  - decaying **leptonically** where lepton is lost = ‘lost lepton’ (LL) background
Interpretations

• Signal models for stop pair-production followed by decays:

T2tt-4bd: **four-body** stop decay via t*/W*

T2bW: **chargino-mediated** stop decay via W*

• chargino mass halfway in between stop and LSP
• Provides solution for small width issue (long lifetime) for very small Δm
Fully-Hadronic

- Background estimations:
  - Lost lepton (LL) from single-lepton control samples (TF = 0l/1l)
  - $Z(\rightarrow \nu\nu)$+jets decays (to neutrinos) estimated from decays to dilepton pairs $Z\rightarrow ll$
  - QCD (< 10%) estimated from data control sample

- SRs defined using: Njets, Nbjets, $N_{SV}$, $p_T$(ISR), MET

- **ISR-tagging:**
  - ‘fat’ definition for jets (large cone size $R = 0.8$)
    - to catch ISR gluon undergoing large splitting
  - fail ‘Loose’ b-tag working point

- **Soft b-tagging** via reconstructing secondary vertices (SVs) not associated to a jet
  [using the IVF (inclusive vertex finder) algorithm]
Fully-Hadronic Limits

• Results of the analysis targeting the fully-hadronic models:

**T2tt-4bd:** four-body stop decay via $t^*/W^*$

**T2bW:** chargino-mediated stop decay via $W^*$
Soft Single Lepton

- Search for direct stop pair-production in events with at least one soft lepton, low jet multiplicity and moderate MET

- Compressed models:
  - T2tt-4bd: Four-body decay
  - T2bW: Chargino-mediated

- Two sets of SRs, defined by lepton $p_T < 30$ GeV:
  - SR1 (very low $\Delta m$): veto b-jets
  - SR2 (higher $\Delta m$): allow soft b-jet ($< 60$ GeV)

- SRs binned in lepton $p_T$, transverse mass $m_T$ and simultaneous selection on MET and $H_T$ (or $p_T$(ISR)) $\equiv C_T$

- Main prompt backgrounds (tt-bar and W+Jets): data/MC scaling is extrapolated from a high $p_T (> 30$ GeV) CRs to the low $p_T$ SRs

- Nonprompt backgrounds (QCD, $Z(\rightarrow vv)+$jets) estimated using TL ‘Fake-Rate’ method

Preselection:

- MET $> 200$ GeV
- $H_T > 300$ GeV
- ISR-jet $p_T > 100$ GeV
- At least one lepton and $2^{nd}$ lep. veto ($p_T > 20$ GeV)
- Tau veto
- $3^{rd}$ hard jet veto
- $\Delta \phi_{(j1,j2)} < 2.5$ rad. [anti-QCD]
Soft Dileptons SOS

• Search for **two low momentum opposite-sign (OS) leptons** and moderate MET

• Requirement of 2 leptons ⇒ cleaner vs hadronic (QCD multijet, $Z(\rightarrow\nu\nu)+\text{jets}$)

• Additional baseline selection:
  – 2 OS leptons (same or different flavour)
  – Moderate MET
  – At least 1 jet
  – B-tagged jets rejected → reduces $t\bar{t}$-bar

• Main backgrounds:
  – $W+\text{jets} + \text{nonprompt lepton}$
  – Fully leptonic $t\bar{t}$-bar decays
  – Drell-Yan and $VV$

• SRs binned in terms of dilepton invariant mass $M(\ell\ell)$ and MET
## Soft Dileptons SOS

<table>
<thead>
<tr>
<th>Variable</th>
<th>SR selection criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_\ell$</td>
<td>2 ($\mu\mu$, $\mu e$, ee)</td>
</tr>
<tr>
<td>$q(\ell_1)q(\ell_2)$</td>
<td>−1</td>
</tr>
<tr>
<td>$p_T(\ell_1), p_T(\ell_2)$</td>
<td>[5, 30] GeV</td>
</tr>
<tr>
<td>$p_T(\mu_2)$ for high-$p_T^{\text{miss}}\tilde{\tau}$-like SR</td>
<td>[3.5, 30] GeV</td>
</tr>
<tr>
<td>$</td>
<td>\eta_\mu</td>
</tr>
<tr>
<td>$</td>
<td>\eta_e</td>
</tr>
<tr>
<td>$IP_{3D}$</td>
<td>&lt;0.01 cm</td>
</tr>
<tr>
<td>$SIP_{3D}$</td>
<td>&lt;2</td>
</tr>
<tr>
<td>$Iso_{\text{rel}}(\ell_{1,2})$</td>
<td>&lt;0.5</td>
</tr>
<tr>
<td>$Iso_{\text{abs}}(\ell_{1,2})$</td>
<td>&lt;5 GeV</td>
</tr>
<tr>
<td>$p_T(\text{jet})$</td>
<td>&gt;25 GeV</td>
</tr>
<tr>
<td>$</td>
<td>\eta</td>
</tr>
<tr>
<td>$N_b$ ($p_T&gt;$25 GeV, CSV)</td>
<td>0</td>
</tr>
<tr>
<td>$M(\ell\ell)$</td>
<td>[4, 9] or [10.5, 50] GeV (for $\mu\mu$ and ee)</td>
</tr>
<tr>
<td>$p_T(\ell\ell)$</td>
<td>&gt;3 GeV</td>
</tr>
<tr>
<td>$p_T^{\text{miss}}$</td>
<td>&gt;125 GeV (for $\mu\mu$)</td>
</tr>
<tr>
<td>$p_T^{\text{miss}}$ (muon corrected)</td>
<td>&gt;200 GeV (for $\mu e$, ee)</td>
</tr>
<tr>
<td>$p_T^{\text{miss}}/H_T$</td>
<td>&gt;125 GeV (for $\mu\mu$)</td>
</tr>
<tr>
<td>$H_T$</td>
<td>&gt;200 GeV (for $\mu e$, ee)</td>
</tr>
<tr>
<td>$M(\tau\tau)$</td>
<td>[0.6, 1.4]</td>
</tr>
<tr>
<td>$M_T(\ell_i, p_T^{\text{miss}})$, $i = 1, 2$</td>
<td>&gt;100 GeV</td>
</tr>
<tr>
<td>$M_T(\ell_i, p_T^{\text{miss}})$, $i = 1, 2$</td>
<td>veto [0, 160] GeV</td>
</tr>
<tr>
<td>$M_T(\ell_i, p_T^{\text{miss}})$, $i = 1, 2$</td>
<td>&lt;70 GeV (electroweakino selection only)</td>
</tr>
</tbody>
</table>
Soft Dileptons SOS

- **Background estimations:**
  - Prompt: CR enriched in tt, DY and VV
  - Nonprompt: TL ‘Fake-Rate’ Method

- **Compressed models:**
  - T2bW: Chargino-mediated decay
  - TChiWZ (EWK): pair-production of neutralinos and charginos (compressed higgsino spectrum):
    - decays via virtual Z* and W*

- EWK limits update LEP results
Compressed Analyses

Summary of interpretations of compressed SUSY signals:

1. **Fully-hadronic** (SUS-16-049) compressed models:
   - T2tt-4bd: Four-body decays
   - T2bW: Chargino-mediated decays
   - T2cc: 2-body decay (FCNC)

2. **Single-lepton (SUS-17-005):**
   - T2tt-4bd: Four-body decays
   - T2bW: Chargino-mediated decays

3. **Soft dileptons SOS (SUS-16-048):**
   - T2bW: Chargino-mediated decays
   - TChiWZ (EWK): pair-production of neutralinos and charginos
EWK Cross-Sections
Higgsino pMSSM

• Higgsino pMSSM model:

  pMSSM:
  • $\mu = \text{higgsino mass parameter}$
  • $M_1 = \text{bino mass parameter}$
  • $M_2 = \text{wino mass parameter}$
  • $M_3 = \text{gluino mass parameter}$

• Grid: $\mu$ and $M_1$ ($M_2 = 2M_1$ for gaugino unification at GUT scale; $M_3$ decoupled)
QG Likelihood

- Motivation: many analyses have signal with jets originating from quarks and backgrounds with gluon-enriched jets
  - In our case, we would like to reduce the W background

- Variables to distinguish between jets originating from quarks vs gluons:
  - Quark-gluon likelihood discriminant $qgl = \text{probability of the jet to originate from a quark parton (1 for light-quark jets and at 0 for gluon jets)}$
  - Jet energy sharing variable: $ptD$ (0 for $\infty$ particles and 1 for 1 particle in jets)
  - Angular spread measured by minor axis $\sigma_2$ in the $\eta$-$\phi$ plane: $\text{axis2}$
  - Multiplicity: total number of PF candidates reconstructed within jet

- Links:
Recoil and Jigsaw

• Motivation: we rely strongly on the recoil of the decay products vs ISR:
  – Visible decay products + MET boosted

• Since ISR ~ opposite MET one can define the recoil of the system wrt. ISR in terms of MET: Recoil $\equiv$ MET/ISR jet $p_T$

• Other proxies:
  – Recoil = MET/leading jet $p_T$
  – Recoil = MET/sqrt($H_T$)
  – Recoil = MET/$W_{lep}$ (where $W_{lep}$ = $lep. \ p_T$ + MET summed vectorially)

• Jigsaw uses an estimator for this quantity:
  – $R_{ISR} = \frac{|p_I \cdot p^\perp_{ISR}|}{|p_{ISR}|}$ (I associated with MET)
  – Reference frame dependent quantities
  – Talk at EPS by P. Jackson
  – Paper 2 and Paper 1

Mateusz Zarucki