Compressed Electroweak Searches at the LHC

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Compressed SUSY has spectra with very small mass differences ($\Delta m$) between sparticles.
→ challenging to observe at experiments.
In this talk: EWK production with small $\Delta m$(NLSP, LSP).
No sign of SUSY at the LHC may imply compressed spectra or other difficult corners of the SUSY parameter space.

Motivated scenarios with compressed EWK sector:
• Higgsino-like N1, N2, C1: Motivated by Naturalness: $|\mu| \sim O(100\text{GeV}) \ll |M_1| \ll |M_2|$.
  • Pure Higgsinos: Mass splittings generated by radiative corrections $\rightarrow O(100\text{MeV})$
  • Mixed Higgsino-wino: larger mass splittings of $O(1-10\text{GeV})$.
• Compressed wino-like LSP and bino-like NLSP: motivated by consistency with experimental dark matter constraints on relic density and direct detection.
• Anomaly mediated SUSY breaking models predict pure wino LSP.
Compressed SUSY is difficult to observe at the LHC due to

- Lower production cross sections, especially for Higgsinos.
- Soft decay products from compressed decays.

Strategies for improving sensitivity:

- Increase acceptance by improving reconstruction and identification of “softer” (lower $p_T$) objects.
- Design dedicated triggers for compressed spectra, e.g. trigger soft lepton pairs.
- Look inside events with hard initial state radiation (ISR), which can boost the rest of the system.
- Explore long lifetimes in pure wino or Higgsino cases with very small $\Delta m$ using long-lived signatures, like disappearing tracks.
Exploring the soft dileptons final state

Main target process: \( \text{N2C1 production with } \Delta m(\text{N2/C1, N1}) \sim 1-50 \text{ GeV} \), with decay through virtual W or Z bosons.

- Small \( \Delta m \) gives rise to very soft leptons challenging to detect. Small dilepton invariant masses \( m_{ll} \).
- Moderate \( E_T^{\text{miss}} \) from N2 / C1 decays.
- The recoil against the ISR jet will boost the N2C1 system in the opposite direction and
  - increase chances that leptons will pass \( p_T \) thresholds,
  - increase chances that “invisible” objects will give rise to larger \( E_T^{\text{miss}} \).

Further interpretations for compressed stop (CMS) and compressed slepton (ATLAS) models.
Explore soft leptons:

Reliable soft lepton ID is crucial

→ ATLAS uses a reoptimized lepton selection in low $p_T$ to improve signal efficiency.

Combined reconstruction, ID, isolation and vertex association efficiencies within detector acceptance for a mix of EWkino and slepton samples (lepton $p_T$ close to $\Delta m/3$ for EWkinos or $\Delta m/2$ for sleptons):

$e, \mu$ efficiency $\sim 0.3, 0.7$ for $p_T = 5$ GeV.

Explore dilepton invariant mass edge:

- For $N2 \rightarrow ZN1$, $Z \rightarrow ll$, kinematic endpoint of the dilepton invariant mass distribution is $m_{ll}^{\text{max}} = \Delta m(N2, N1)$.
- Simulated $m_{ll}$ distribution agrees with analytic calculation of the expected lineshape (shape depends on the product of signed N2 and N1 mass parameters).
Final state: 2 oppositely charged leptons + moderate $E_T^{\text{miss}} + \geq 1$ jet (for ISR)

Trigger:

- CMS $\mu\mu$ channel:
  Dedicated soft dimuon trigger: $p_T(\mu) > 3$ GeV, $p_T(\mu\mu) > 3$ GeV.
  $\rightarrow$ offline $E_T^{\text{miss}}$ cut lowered to $>125$ GeV

- Soft dielectron trigger challenging. Using inclusive $E_T^{\text{miss}}$ triggers.
  $\rightarrow$ offline $E_T^{\text{miss}}$ cut $>200$ GeV

- ATLAS: inclusive $E_T^{\text{miss}}$ triggers, online threshold between 70-110 GeV.
  $\rightarrow$ offline $E_T^{\text{miss}}$ cut $>120$ GeV. Reweights MC with efficiency.

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### Preliminary event selection (main cuts)

<table>
<thead>
<tr>
<th></th>
<th>CMS</th>
<th>ATLAS 2 leptons</th>
<th>ATLAS 1 lep + 1 track</th>
<th>Motivation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e_1\mu$ $p_T$</td>
<td>[5 - 30]</td>
<td>$l_1$: &gt;5</td>
<td>&gt;5, &lt;10 for lepton, track</td>
<td>soft leptons</td>
</tr>
<tr>
<td>(2nd $\mu$ $p_T$)</td>
<td>[3.5 - 30]</td>
<td>$e_2$, $\mu_2$ &gt; 4.5, 3</td>
<td></td>
<td>boosted $E_T^{\text{miss}}$</td>
</tr>
<tr>
<td>$E_T^{\text{miss}}$</td>
<td>&gt;125,200 for $\mu\mu$, ee</td>
<td>&gt;120</td>
<td>&gt;200</td>
<td></td>
</tr>
<tr>
<td>$n_{\text{jets}}$</td>
<td>$\geq 1$</td>
<td>$\geq 1$</td>
<td>$\geq 1$</td>
<td>ISR activity</td>
</tr>
<tr>
<td>$H_T$</td>
<td>$\geq 100$</td>
<td>jet1 $p_T &gt; 100$</td>
<td>jet1 $p_T &gt; 100$</td>
<td>Hard ISR</td>
</tr>
<tr>
<td>$n_{\text{bjets}}$</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>reject ttjets</td>
</tr>
<tr>
<td>$m_T$</td>
<td>&lt; 70</td>
<td>[10, 60]</td>
<td>&lt; 60</td>
<td>reject ttjets</td>
</tr>
<tr>
<td>$m_{\tau\tau}$</td>
<td>veto [0, 160]</td>
<td>veto [0, 160]</td>
<td>-</td>
<td>reject $Z\rightarrow\tau\tau$</td>
</tr>
<tr>
<td>$m_{ll}$</td>
<td>[4, 9] or [10.5, 50]</td>
<td>[3,60] (ee) [1,60] ($\mu\mu$)</td>
<td>[0.5, 5]</td>
<td>reject J/psi, Z</td>
</tr>
</tbody>
</table>

+ several other cuts

low $E_T^{\text{miss}}$ - low $\Delta m$, low $E_T^{\text{miss}}$ - high $\Delta m$, high $E_T^{\text{miss}}$ dedicated regions
Recursive jigsaw reconstruction: Divides event into two hemispheres perpendicular to thrust axis (maximum back-to-back $p_T$, approximates the recoil direction)
- **S**: contains EWKino / slepton decay products
- **ISR**: contains adronic ISR activity.

Builds kinematic variables to isolate the EWKino / slepton + ISR signal:
- $R_{\text{ISR}}$: $E_T^{\text{miss}} / p_T($ISR system$)$
- $M_T^S$: Transverse mass of the $S$ system.

Signal region binning:
- **ATLAS**: $m_\ll$ and $R_{\text{ISR}}$ for EWKinos ($m_{T2}$ and $E_T^{\text{miss}}$ for sleptons)
- **CMS**: $m_\ll$ and $E_T^{\text{miss}}$ for EWKinos (lepton $p_T$ and $E_T^{\text{miss}}$ for stops).
Mainly data-driven background estimation methods (similar in CMS and ATLAS):

- **tt / tW, WW/WZ, Z*(γ*)+jets**
  BG estimate using data events in control regions and MC transfer factors.

- **Fake / non-prompt lepton**
  BG (from jet misidentified as leptons, γ conversions semileptonic heavy flavor decays) by
  - loosening the tight lepton ID in one of the leptons in the SRs
  - reweighting the events by a non-prompt lepton misidentification efficiency obtained from a multijet-enriched measurement sample.

Data are consistent with the SM.
Soft dileptons: BG estimation, results

ATLAS-CONF-2019-014

Compare to SM predictions by a profile likelihood method (similar in ATLAS and CMS):

- BG-only fit to control regions to constrain BG normalization parameters.
- Compare with data in validation regions to verify accuracy of BG modelling.
- BG + signal fit to data in signal regions.

Data are consistent with the SM.
Soft dileptons: Bino LSP - wino NLSP limits

CMS SUS-16-048
N2/C1 excluded up to 230 GeV for $\Delta m = 20$ GeV.
Uniquely complements the other EWKino searches.

ATLAS-CONF-2019-014
N2/C1 excluded up to 205 GeV for $\Delta m = 5$ GeV.
Achieve LEP C1 limit 103.5 GeV for $\Delta m = 2.6$ GeV

Extended sensitivity in the ATLAS search in low $\Delta m$. 
Soft dileptons: Higgsino LSP limits

**CMS SUS-16-048**

**SMS model:**

N2 excluded up to 167 GeV for $\Delta m = 15$ GeV.

**ATLAS-CONF-2019-014**

**SMS model:**

N2 excluded up to 162 GeV for $\Delta m = 10$ GeV.

**phenomenological MSSM:**

$\mu$ excluded up to 160 GeV for $M_1, M_2 = 300, 600$ GeV.

$\mu$ excluded up to 100 GeV for $M_1, M_2 = 700, 1400$ GeV.

Larger $M_1 \rightarrow$ smaller $\Delta m \rightarrow$ less sensitivity.
Compressed stop limits: EWK mediated decays

CMS SUS-16-048

Soft dilepton search:

Leptonic stop decays

C1 mediated stops excluded up to 450 GeV for $\Delta m = 40$ GeV.

CMS SUS-17-005, CMS SUS-16-049

Combination of two dedicated stop searches:

- Soft single lepton + high $E_T^{\text{miss}}$ + hight $p_T$ ISR jet.
- Multijets + high $E_T^{\text{miss}}$.

Hadronic stop decays

C1 mediated stops excluded up to 670 GeV.
Soft dilepton: compressed slepton limits

- Direct light flavor slepton pair production.
- Limits derived by a fit to $m_{T2}$ distribution.

Sleptons excluded up to 238 GeV for $\Delta m = 10$ GeV.
Achieve LEP smuon limit 94.6 GeV ($\Delta m = 2$ GeV) for $\Delta m = 670$ MeV - 29 GeV.
Same sign dilepton channel in a generic multilepton EWKino search.

- Relevant for compressed EWKinos.
  - In N2C1 production, one of the leptons in N2 decay chain **may not fulfil selection criteria**, and be **lost**. Recover these events.

**Event selection:**

- SS dilepton pair with
  - \( p_T^{1,2}(e) > 25,15 \text{ GeV} \), or
  - \( p_T^{1,2}(\mu) > 20,10 \text{ GeV} \)
- \( E_T^{\text{miss}} > 60 \text{ GeV} \).
- Veto opposite sign leptons
- 0 and 1 ISR jet categories
- Binning done in \( E_T^{\text{miss}}, \min(m_T(l_1), m_T(l_2)) \) and \( p_T(\ell\ell) \).

**Data are consistent with the SM.**
Same sign dileptons: Limits

N2C1 production, 2-body decays through left or right sleptons.

\[ m_{\tilde{\ell}} = m_{\tilde{\nu}} = m_{\tilde{\chi}_0^0} + x \left( m_{\tilde{\chi}_0^0} - m_{\tilde{\chi}_1^0} \right) \]

\( x = 0.05, 0.95 \) give compressed scenarios.

Combination of the SS channel and a trilepton channel.

SS channel exclusively makes the low \( \Delta m \) region accessible.
• When $\Delta m(C1, N1) \sim O(100 \text{ MeV})$, $C1$ is long lived.

• Decays in the tracker to a soft pion + $E_T^{\text{miss}} \rightarrow$ disappearing track signature.

• Final state for EWKino production: disappearing track + $E_T^{\text{miss}}$ + hard ISR jet.

• Find tracklets with hits in pixel layers ($R = [12,30]$ cm), but no hits in silicon strip layers ($R > 30$ cm).
For pure wino C1 with lifetime $c\tau = 0.2\text{ns}$, C1 excluded up to 460 GeV.

For pure higgsino C1, C1 excluded up to 152 GeV.

AMS B C1 excluded up to 505 GeV for $c\tau = 0.5-60\text{ns}$. 
Summary

• Non-existence of new physics signals requires exploring more challenging scenarios, such as compressed SUSY.

• Theory motivations for compressed EWKino scenarios: include Naturalness and compatibility with DM-related observations.

• Compressed EWKinos lead to soft decay products.
  • Employed improved soft object identification methods, soft object triggers, ISR objects, same sign dileptons or long-lived signatures in searches.

• Larger datasets and further advancements in search methods will improve the sensitivity.