Search for Physics Beyond the Standard Model in Final States with Two or Three Soft Leptons and Missing Transverse Momentum in p-p Collisions at $\sqrt{s} = 13$ TeV

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SUSY Searches in a Nutshell

- Minimal Supersymmetric Standard Model (MSSM) → Simplified models with most particles decoupled → Phenomenology based on couple of particles @ TeV scale

- Usual signatures:
  - Large amounts of $p_T^{miss}$
  - Visible, high-$p_T$ particles

  ⇒ No sign of SUSY particles

- Attention turns to less explored signatures:
  - Experimentally challenging
  - Highly theoretically motivated
Compressed SUSY: Experiment

- SUSY with compressed mass spectrum: $\Delta m(\text{particles}) \lesssim \mathcal{O}(10\%)$ of their masses

- Final state with
  - Small to moderate amounts of $p_T^{\text{miss}}$
  - Visible, low-$p_T$ particles

- At the limit of
  - Detection,
  - Reconstruction and
  - Identification

\[ \Delta m [\text{GeV}] \sim \mathcal{O}(1 - \mathcal{O}(100)) \]

\[ \text{Decoupled from LHC accessible Physics} \]

\[ \text{CMS} \]

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

\[ \text{Expected} \quad \text{Observed} \]

\[ m_{\tilde{\chi}_2^0} = m_{\tilde{\chi}_1^0} [\text{GeV}] \]

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Compressed SUSY: Theory

- EWK production:
  - **Wino/bino** compressed scenario ($M_1, M_2 \ll \mu$):
    - Theoretically motivated by the observed DM density
    - Not constrained by direct DM detection experiments
  - Direct **higgsino** production ($\mu < M_1, M_2$):
    - Naturalness arguments ⇒
      Higgsino triplet with similar mass near the EW scale
Compressed SUSY: Theory

- Top squark (stop) production:
  - Light stop ~mass degenerate with EWK LSP
  - Large Yukawa coupling + Mixing ⇒
    - Stops expected light
  - Co-annihilation region ⇒ LSP as source for DM
SUSY in Soft 2ℓOS & 3ℓ Final States

• New CMS result on compressed signatures: **CMS-SUS-PAS-18-004**

• Full Run 2 result: 137 fb⁻¹ → Trigger on \( p_T^{\text{miss}} \) (+leptons)

• Electroweak production → Small cross section

• Request initial state radiation (ISR) jet to induce \( p_T^{\text{miss}} \):
  
  - \( H_T > 100 \text{ GeV} \)
  
  - \( p_T^{\text{miss}} > 125 \text{ GeV} \)

• 2 SFOS (+1) leptons (\( e^+e^-/\mu^+\mu^- + e^\pm/\mu^\pm \))
  
  - Prompt & Isolated
  
  - Soft: \( 3.5 < p_T < 30 \text{ GeV} \)
Dilepton Mass $M(\ell\ell)$

- $M(\ell\ell)$ distribution sensitive to SUSY particles mass difference:
  $M(\ell\ell) \sim M_{Z^*} \sim \Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$

- Compressed model $\Rightarrow 1 < M(\ell\ell) < 50$ GeV

- Signal modeling refinements affect $M(\ell\ell)$
  $(\Gamma_{\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \ell\bar{\ell}}, W/Z$ branching fraction)
2ℓOS-EWK Search Regions

- $p_T^{\text{miss}}$ (GeV)
  - 125
  - 200
  - 240
  - 290

$M_{\ell\ell}$ (GeV) $\sim$ $\Delta m(\tilde{\chi}_1^0, \tilde{\chi}_2^0)$

- $\mu\mu$
- ee

Another handle to separate signal from bkg: Bin in $p_T^{\text{miss}}$

CMS Preliminary

137.1 fb$^{-1}$ (13 TeV)

Events

Data

Non-prompt bkg
- $\ttbar(2\ell)$
- Diboson
- $\text{DY}(\to \tau\tau)$
- $\text{WZ}$

Data/pred.

Total unc.

Non-prompt e/µ

VV

TChi275/10

TChi150/3

TChi175/5

DY

Rares

TChi200/40

WZ

Non-prompt e/µ

V (13 TeV)

137.1 fb$^{-1}$ (13 TeV)
3ℓ-EWK Search Regions

- Extra lepton ⇒ SM depleted, signal-rich
- To enhance statistics:
  - No ISR jet requirement
  - Slightly different binning
2ℓOS-Stop Signal Regions

- Include different flavour pairs
- Slightly different binning

CMS Preliminary

137.1 fb⁻¹ (13 TeV)
Nonprompt $\ell$

Nonprompt leptons:
- MisID'ed jets or $\ell$ from heavy quark decays
- Estimated with **Tight-to-Loose** method

**Tight ID** (tight Iso and IP$_{3D}$ cuts)
**Loose ID** (non isolated and/or non prompt)

- **Measurement Region (MR)**
  Measure Fake Rate (FR) in QCD-enriched data
  FR: Probability of Loose ID $\ell$ to pass the Tight ID

  \[
  FR(p_T, \eta) = \frac{\text{Tight ID } \ell}{\text{Loose ID } \ell}
  \]

- **Application Region (AR)**
  Nonprompt enriched region with Loose ID $\ell$
  passing SR-like selection $\rightarrow$ weighted by FR $\rightarrow$
  Nonprompt estimate in **Search Region (SR)**

  ❖ Residual non-closure assigned as systematic on non prompt background (up to 40%)
Fake Rate Application

- **Data-Driven (DD)** method: fake rate applied on AR data

- Smooth out stat. fluctuations in low yield regions:
  fake rate applied on norm-to-data AR simulation (semi-DD method)
  - Dedicated shape uncertainties

- **Same Sign (SS) CR**
  - Similar selection to SR but SS requirement
  - Used for evaluation of the nonprompt modeling
  - Strongly constrain the nonprompt bkg uncertainty

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**SS CR post-fit**

![Graph showing CMS Preliminary data and predictions]

- **M(\ell\ell) [GeV]**
  - Axes: X: M(\ell\ell) [GeV], Y: Events
  - Data points and error bars for different categories (e.g., Data, VV, WZ, Nonprompt e/\mu, Total unc.)
  - Ratio data/pred. and total unc.

- **CMS Preliminary**
  - 137.1 fb^{-1} (13 TeV)
Prompt $2\ell$ Bkg

- Prompt $2\ell$ bkg CR split into two MET bins:
  - Low MET (125-200 GeV)
  - High MET (>200 GeV)
- Estimated from simulation and corrected by data driven scale factor

$\ell\ell$ CR

<table>
<thead>
<tr>
<th>Events</th>
<th>CMS Preliminary</th>
<th>137.1 fb$^{-1}$ (13 TeV)</th>
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<tbody>
<tr>
<td>Data</td>
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<td>WZ</td>
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<td>tt(2l)</td>
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<td>Rares</td>
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<tr>
<td>Total unc.</td>
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Data/pred. total unc.

$\ell\ell$ CR

- DY($\tau\tau$) CR
  - Estimate $M_{\tau\tau} \sim M_Z$ from leptons and $p_T^{miss}$
  - $0 < M_{\tau\tau} < 160$ GeV

- TT CR
  - No $M_T(\ell, p_T^{miss})$ cut
  - & Invert b-tag veto
Prompt Multiboson Bkg

- Prompt multiboson bkg enriched regions split into two MET bins:
  - Low MET (125-200 GeV)
  - High MET (>200 GeV)
- Estimated from simulation and corrected by data driven scale factor

**WZ enriched region**
Leptonically decaying WZ most dominant prompt bkg in 3$\ell$ SR
Event selection:
- No $m_{\ell\ell,\text{SFOS}}^{\text{min}}$ bounds
- No Z veto

- **VV (ZZ/WW)** and **Rare bkg**: estimated from simulation
Wino/Bino Interpretation

Acceptance down to low $m_{\ell\ell}$ - sensitivity down to $\Delta m \sim 3$ GeV

Major improvements wrt previous analysis (⭐)

Simplified Wino/Bino model:

- Sensitivity up to $m_{\tilde{\chi}_2^0} \sim 300$ GeV @ $\Delta m \sim 10$ GeV
- $m_{\tilde{\chi}_2^0} \sim 250$ GeV @ $\Delta m \sim 35$ GeV
- Higher $\Delta m$ complementarity from $3\ell$ SR
Higgsino Interpretation

\[ \tilde{\chi}_1^0, \tilde{\chi}_1^\pm \text{ and } \tilde{\chi}_2^0 \text{ mostly higgsinos} \]

**Simplified higgsino**

BR=100% &
cross section pure Higgsino

**pMSSM higgsino**

BR & cross sections varied according to pMSSM model

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**Simplified higgsino model:**

- Exclude up to \( m_{\tilde{\chi}_2^0} \sim 150 \text{ GeV} @ \Delta m \sim 3 \text{ GeV} \)
- \( m_{\tilde{\chi}_2^0} \sim 210 \text{ GeV} @ \Delta m \sim 7 \text{ GeV} \)

**pMSSM Higgsino model:**

- \( \mu \)-M1 parameters
- Small \( \Delta M(\text{NLSP-LSP}) \) mapped to large M1
- Exclude up to \( \mu \sim 185 \text{ GeV} @ M1 \sim 1000 \text{ GeV} \)
Stop Interpretations

Simplified T2bW model:

- Exclude up to \( m_{\tilde{t}} \sim 500 \text{ GeV} \) @ \( \Delta m = 40 \text{ GeV} \)

Major improvements wrt previous analysis (★)

Similar results for T2bff model
Summary

• Compressed SUSY well motivated by a number of interesting scenarios

• New CMS result on compressed SUSY searches in events with 2 or 3 soft leptons and $p_T^{miss}$ with full Run-2 dataset
  • New approaches to overcome experimental challenges
    ➔ Extended acceptance to low $\Delta m$
    ➔ Good control of backgrounds

• Upper limits are set on x-sec of Wino/Bino, Higgsino and Stop models

• Great improvement compared to 2016 results

• Cover challenging corner of phase space ➔ Complementary to other CMS searches