Why “Compressed SUSY”? 

- **theoretically interesting**
  - relic density of compressed models expected to be consistent with cosmological observations [*]
  - natural SUSY expects light and compressed (MeV—GeV) higgsinos [**]

- **experimentally motivated**
  - level of compression determines possible final states
  - thus: same SUSY scenario leads to different final states
  - especially particles with low transverse momentum („soft“) can be produced in decay
  - hard to resolve compressed signatures at the LHC!

- and of course:
  - we haven’t found SUSY yet in noncompressed spectra, maybe it pops up in the compressed?


Compressed SUSY Searches in CMS

… at 13 TeV with the 2016 data set (35.9/fb):

<table>
<thead>
<tr>
<th>Colored SUSY</th>
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<tbody>
<tr>
<td>SUS-16-032</td>
<td>third-generation squark production and FCNC in the cc or bb + $p_T^{miss}$ final states</td>
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<tr>
<td>SUS-16-036</td>
<td>exploring the jets + $p_T^{miss}$ final state with the $M_{T2}$ variable</td>
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<tr>
<td>SUS-16-049</td>
<td>dedicated top squark search in all-hadronic signatures</td>
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<tr>
<td>SUS-16-052</td>
<td>soft single lepton search for compressed top squark spectra</td>
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<tr>
<td>SUS-17-005</td>
<td>soft single lepton search for compressed top squark spectra (MVA update)</td>
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<tr>
<td>SUS-17-010</td>
<td>two opposite-sign lepton search for top squark models</td>
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<th>Electroweak SUSY</th>
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<td>SUS-16-039</td>
<td>probing a multitude of final states with two or more leptons</td>
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<tr>
<td>SUS-16-045</td>
<td>exploring the WH + $p_T^{miss}$ signature with $H \rightarrow \gamma \gamma$ decays using the Razor variables</td>
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<td>SUS-16-048</td>
<td>search for light and compressed higgsinos in events with two soft opposite-sign leptons</td>
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<tr>
<td>SUS-17-004</td>
<td>search for SUSY in WZ + $p_T^{miss}$ events in the trilepton final state</td>
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❖ going to discuss the most recent and most challenging searches highlighted in blue
Search Strategy in the Compressed

- conventional searches designed for large mass splittings
  - thus, large amounts of free energy in the particle decay
  - yields hard final state objects, but also gives Lorentz boost to the LSPs
  - also leads to large values of $p_T^{\text{miss}}$ in signal — shape difference between background and signal
  - can trigger on hard visible objects (electrons, muons, jets) and/or $p_T^{\text{miss}}$

- not so easy in the compressed region
  - LSPs not boosted due to low $\Delta m$ — low values of $p_T^{\text{miss}}$ — no shape difference to SM bkg
  - but: shape difference restored in initial state radiation (ISR) boosts the SUSY particle system
  - cannot trigger on soft visible objects, but on $p_T^{\text{miss}}$
  - look for shape difference in other variables for events with high $p_T^{\text{miss}}$
This paper is organized as follows. A brief description of the CMS detector is presented in Section 2, while Section 3 discusses the simulation of background and signal processes. Event signals.

Nevertheless, such models are particularly interesting because their dark matter relic density is experimentally challenging since the visible decay products are typically very soft (i.e. low-momentum), and therefore often evade identification.

In models with\(^{3}\) the mass lies halfway between the masses of the \(\chi^1\) and \(\tilde{t}_1\). As a result, the \(W\) bosons from chargino decays are produced far off-shell. These will be referred to as the “T2ttC”, “T2bWC”, and “T2cc” models, respectively, where \(C\) denotes the hypothesis of a compressed mass spectrum in the first two cases.

In models with\(^{2}\) the \(m_{\chi^0}\) is only 5 GeV greater than that of the \(\tilde{t}_1\), which is only 5 GeV greater than that of the \(\chi^0\). As a result, the \(W\) bosons fromdecays that we consider are produced off-shell.

The search regions (SR) are optimized for different models and ranges of \(m_{\tilde{t}_1}\) as the basis for our searches are displayed in Fig. 1. FLAVOR-CHANGING DECAYS (2 BODY) DECAY VIA OFF-SHELL \(W\) (4 BODY) DECAY VIA ON-SHELL \(T\) (2 BODY)
Top Squark Pairs

The ONES I FOCUS ON NEXT
Single Soft Lepton Search

- dedicated search for top squark decay via W and b
  - exactly one electron ($p_T > 5$ GeV) or muon ($p_T > 3.5$ GeV)
  - soft lepton ($p_T < 30$ GeV) and one ISR jet with $p_T > 100$ GeV
- expect $p_T^{miss} > 200$ GeV and $H_T > 300$ GeV
- $\Delta \phi$(jet1, jet2) < 2.5 rad — suppresses dijet and multijet background
  - remaining background is dominated by W+Jets and ttbar
  - estimate from simulation, extract normalization from control regions (lepton-$p_T > 30$ GeV)
- two set of regions: for very low $\Delta m$ and higher $\Delta m$
  - lepton-$p_T$ spectrum depends on $\Delta m$ — use optimized lepton-$p_T$ bins (3.5-5-12-20-30)
  - expect shape difference between signal and background in $M_T(\ell, p_T^{miss})$ and $p_T^{miss}$ (in the bulk of the distributions!)
Single Soft Lepton Search

- alternative search region extraction
  - boosted decision tree (BDT) built on kinematic variables of the lepton and the jets in the event
  - separate training for different SUSY scenarios (\(\Delta m\)); build 8 SR requiring a minimum BDT score
  - largest improvement for mass splittings 40–80 GeV

- combination with all-hadronic analysis (SUS-16-049)
Two OS Leptons

- require leptonic decays from the on-shell W bosons
  - can give two opposite-sign (OS) leptons
- optimized for moderate mass splittings \( m_W < \Delta m < m_t \)
  - leading (trailing) lepton has \( p_T > 25 \) (20) GeV
  - \( m_{\ell\ell} > 20 \) GeV to remove low-mass resonances
  - remove Z resonances by requiring same-flavor pairs \( | m_{\ell\ell} - m_Z | > 15 \) GeV
  - require \( p_T^{\text{miss}} > 140 \) GeV
- remaining backgrounds have W resonances but no LSPs
  - use \( M_{T2} \) to discriminate between SM and SUSY
    \[
    M_{T2}(\ell\ell) = \min_{p_T^{\text{miss1}}+p_T^{\text{miss2}}=p_T^{\text{miss}}} \left( \max \left[ M_T(p_T^{\text{lep1}}, p_T^{\text{miss1}}), M_T(p_T^{\text{lep2}}, p_T^{\text{miss2}}) \right] \right)
    \]
  - discrimination power enhanced by ISR boost of LSPs
Electroweak SUSY: WZ + $p_T^{\text{miss}}$

- Inclusive multilepton search probes chargino-neutralino production with moderate mass splittings
  - Covering broad region of parameter space (small to large $\Delta m$)

- Significant loss in sensitivity at $\Delta m \sim m_Z$ ("WZ corridor")
  - Signal has $m_Z$ available to produce W or Z boson
  - Hence, signal is very similar to SM WZ process

- But signal is a bit different
  - Due to mass constraint from chargino / neutralino signal rarely has $m_{\ell\ell} > 105$ GeV
  - In case of an ISR boost, $p_T^{\text{miss}}$ and $M_T(\ell_3, p_T^{\text{miss}})$ larger for signal than for bkg due to LSPs
Electroweak SUSY: WZ + $p_T^{miss}$

- finer granularity binning in $75 < m_{ll} < 105$ GeV region via additional $H_T$ bins
  - significant limit improvement of about 60 GeV (or 30%) along the WZ corridor
- quite impressive (combined) CMS exclusion in compressed scenarios for EWK model
  - for more details see Mia’s talk (plenary) and Carlos’ talk (parallel)
Soft OS Leptons Pairs

- two soft leptons from off-shell bosons
  - EWK: opposite-sign same-flavor pair from $Z$ (+ hadronic $W$)
  - Top squarks: opposite-sign any-flavor pair from two $W$'s

- $\mu$ ($e$) $p_T$ between 3.5 (5) and 30 GeV
  - dedicated ID and trigger strategy
  - $p_T^{\text{miss}} \geq 125$ GeV possible in $\mu\mu$ final state thanks to specially developed soft $\mu\mu + p_T^{\text{miss}}$ trigger

- strong suppression against important backgrounds
  - boosted Drell-Yan $\rightarrow \tau\tau$ — reconstruct $m_{\tau\tau}$ to remove the bkg
  - dilepton ttbar — reject events with b jets
  - diboson production — suppress events with $M_T(\ell, p_T^{\text{miss}}) > 70$ GeV

- challenge: reject misidentified leptons (e.g. from jets)
Soft OS Leptons Pairs

- top squarks case
  - categorize events in $p_T^{miss}$ and leading lepton $p_T$
  - exclude top squarks up to 450 GeV at $\Delta m \sim 30$ GeV

- electroweak case (WZ-like model)
  - categorize events in $p_T^{miss}$ and invariant mass $m_{\ell\ell}$
  - exclude wino-like charginos / neutralinos up to 230 GeV at $\Delta m \sim 20$ GeV
when it comes to natural SUSY, particular interest lies upon higgsinos!
  
  i.e. charginos and neutralinos with dominant higgsino component

re-interpretation of the WZ-like model with dominant higgsino component (left)
  
  improvement of the LEP limit (~ 100 GeV) for the first time!

also interpretation in pMSSM framework as function of $M_1 = (1/2)M_2$ and $\mu$ (right)
Conclusion

- excellent performance of LHC in 2016 provided CMS with enough data to search for new physics in yet unprobed regions of phase space
- extensive search program performed at CMS covering a huge variety of topologies, both for colored SUSY and EWK SUSY
- development and optimization of key analysis tools allows probing of very compressed regions
  - tackle shape different between SUSY and SM in regimes with ISR
  - novel techniques improve sensitivity to difficult regions of phase space
  - first time sensitivity to higgsino at the LHC, improving the LEP limit!
- larger data sets and improved techniques will allow to probe more unconventional scenarios
  - long-lived higgsinos?
  - disappearing tracks?
- if you want to search for higgsinos (and thus natural SUSY), this is the time!
The End
References


References


[SUS-16-052] CMS Collaboration, *Search for supersymmetry in events with at least one soft lepton, low jet multiplicity, and missing transverse momentum in proton-proton collisions at $\sqrt{s} = 13$ TeV*, CMS-PAS-SUS-16-052, CDS:2273394


References


Appendix
The CMS Detector

- excellent muon system, tracking and EM energy resolution give good particle identification
  - ideally suited for search for new physics in final states with little hadronic activity (as for EWK SUSY)
What is “Compressed SUSY”? 

- **R-parity:**
  - avoids L- or B-number violation
  - common for „mainstream“ SUSY searches
- **consequence:** compressed spectra

![Diagram](image)

**TYPICAL LHC PROCESS:**

- particle acceleration
- hard collision
- particle decay
- SM particle detection

**mass splitting:**

\[ \text{mass splitting} = \Delta m = \text{mass(„INCOMING“ SUSY PARTICLE)} - \text{mass(„OUTGING“ SUSY PARTICLE)} \]

- small \( \Delta m \) \( \leftrightarrow \) „compressed“ parameter space
- translates to the „being close to the diagonal“ in typical exclusion limit plots