Searches for SUSY with the CMS experiment

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The CMS detector
Why Supersymmetry?

Fine Tuning problem

\[(125\text{GeV})^2 = m_H^2 = m_{H,0}^2 + \Delta m_H^2\]

\[\propto \sum_f -g_f \Lambda_{UV} \quad \text{can be as large as } \Lambda_{Planck}\]

SUSY Solution:

For each fermion add a diagram with a scalar to cancel \(\Delta m_H^2\)

\[\rightarrow \text{introduce for each fermion a scalar}\]

(and vice versa)
What is SUSY?

\[ Q |\text{Boson}\rangle = |\text{Fermion}\rangle, \quad Q |\text{Fermion}\rangle = |\text{Boson}\rangle \]

- Broken symmetry: heavier masses
Bonus I: Gauge unification

- Gauge unification of the strong, EM and weak force
Bonus II: Dark Matter Candidate

- Baryon (B) and lepton (L) quantum numbers seem intrinsically fermionic, but not nec. in SUSY
  \[ Q |\text{Boson}\rangle = |\text{Fermion}\rangle, \quad Q |\text{Fermion}\rangle = |\text{Boson}\rangle \]

- need to forbid direct exchanges of squarks and sleptons between ordinary quarks and leptons
  \[ \rightarrow \text{introduce a } B\&L \text{ for bosonic superpartners} \]

- R parity = \((-1)^R = (-1)^{2S}(-1)^{3B+L} = \{ \]
  - 1 for SM particle
  - -1 for SUSY partner

- R-parity conserved:
  - SUSY particles produced in pairs
  - Lightest SUSY particle (LSP) stable = WIMP candidate
How does SUSY compare to the SM?

Largest cross sections for strong production = gluinos & squarks → discovery channel at energy frontier

Electroweak and slepton production lower cross sections, but generally cleaner signatures with leptons
Simplified models of SUSY

- Not possible to scan the whole MSSM space
  - Huge phase space
  - many cascade decays

- Consider only simple decay chains
- Generally on only 2 parameters:
  - heavy mother particle
  - lightest supersymmetric particle (LSP) that is not directly detectable

- 100% branching ratio (unless otherwise indicated)
Diverse final states allow to target various production and decay channels

Focus of today's talk are the latest results with the Run2 dataset

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Inclusive hadronic searches: Sensitivity to a large phase space

- Cover various strong production models
- Sensitivity though binning in jet & b-jet, $H_T$, $M_{E_T}$ etc..

$H_T = \sum jets \mid \vec{p}_T \mid$

$H_{miss} = \mid - \sum jets \vec{p}_T \mid$

$M_{T2}(m_c) = \min_{\vec{p}_T^{c(1)} + \vec{p}_T^{c(2)} = \vec{p}_{miss}} \max(M_T^{(1)}, M_T^{(2)})$

SUS-19-006 & SUS-19-005
Main backgrounds

- **QCD multi-jet:**
  - Mis-measurement of a jet leads to imbalanced event
  - Estimated with rebalance & smear technique

- **W+jets & ttbar (Lost lepton):**
  - $\mathrm{ME}_T$ from neutrino from leptonic $W$ decay
  - Charged lepton not caught by veto
  - Estimated from 1lepton data control region

- **$Z_{\nu\nu}$+jets:**
  - $\mathrm{ME}_T$ from the two neutrinos
  - Estimated from $\gamma$+jets or $Z\rightarrow ll$
Interpretation in gluino & squark production

- Full Run2 dataset analyzed
- Reach masses of over 2 TeV
Single lepton search

- 1 lepton $p_T^{\text{miss}}, S_T, N_j, N_b, M_J$

$$M_J = \sum_{J_i=\text{large-}R\text{ jets}} m(J_i)$$

$$m_T = \sqrt{2p_T^{\ell}p_T^{\text{miss}}} [1 - \cos(\Delta\phi_\ell, p_T^{\text{miss}})]$$

- Main background from leptonic decays of $t\bar{t}$ estimated with ABCD in $M_J$ and $m_T$ plane
2 same sign leptons & multilepton search

- Signal regions by number of leptons and their $p_T$, $H_T$, $p_T^{\text{miss}}$, $m_T$, $N_j$, $N_b$

- Main backgrounds:
  - Non-prompt leptons from W+jets & QCD
  - Rare SM: ttV, WW, WZ

- Low thresholds for the leptons (15/10 for $e/\mu$) give sensitivity to small mass splittings

SUS-19-008
Interpretation in gluino & squark production

Sensitivity to leptonic decays of EW bosons produced in the decay chains
Interpretation in R-parity violating models

- R parity not conserved: lightest SUSY particle **not** stable
  - no LSP in the final state
Dedicated stop search in 1 lepton final state

- Signal regions: $H_T$, $H_T^{\text{miss}}$, $N_j$, $N_b$ and top-tagging (resolved and boosted)

- Main backgrounds:
  - 2-lepton events where 1-lepton is lost (ttbar+single top): estimated from 2 lepton control region in data
  - $W$+jets: estimated from 0b data control region
Stop → tau decays

- Signal regions: $H_T$, $p_T^{miss}$, $M_{T2}$

- Main backgrounds:
  - Taus from ttbar decays
  - Misidentified jet as a tau

- Sensitive to $\tan\beta$ and higgsino-like scenarios

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

\[ x = [0.25, 0.5, 0.75] \]

SUS-19-003

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**Tau slepton search**

- Signal regions: $\tau_h \tau_h$ & $l\tau_h$ ($l=e,\mu$)

- Machine learning used to improve previous results
  - DNN for $\tau_h \tau_h$
  - Boosted decision tree for $l\tau_h$

\[\chi^0_1 \text{ mass}\]
Search with $H \rightarrow \gamma\gamma$ in the cascade

- Search for excess on Higgs peak
- **Non resonant background** from fit to data
- **SM Higgs** and **Signal** shapes from simulation
- Simultaneous fit of signal & background

SUS-18-007
Target Signals

One boson per cascade produced
- At least one $H \rightarrow \gamma \gamma$
- Use other boson as additional discriminant against SM: $H \rightarrow bb$, $Z \rightarrow bb$, $Z \rightarrow ll$, $W \rightarrow ev$, $W \rightarrow \mu\nu$
- Additional $b$ jets for sbottom quark model
Search with $H \rightarrow \gamma\gamma$ in the cascade

- Two approaches targeting strong (SP) and electroweak (EWP) production models
Long-lived SUSY particles

- Displaced vertices: 0.1-1mm
- Disappearing tracks: ~10cm
- Stable: 1-10m
Long-lived particles: Disappearing tacks

- Extension of the fully hadronic $M_{T2}$ analysis
- Categorizing in length of the track:
  Short (pixel only), medium (<7 hits), long (>7 hits)
  & track $p_T$

Main backgrounds from:
- charged pions & leptons that
  - significantly interact with tracker
    or
  - poorly reconstructed
- Fake tracks
Long-lived particles: Disappearing tacks

- gluino branching fraction is 1/3 each for $\tilde{\chi}_1^0$, $\tilde{\chi}_1^+$ and $\tilde{\chi}_1^-$
- Mass of $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_1^0$ assumed to differ by only a few hundred MeV
- momentum of pion only a few hundred MeV

$\tau = 10\text{ cm}$, $\tau = 50\text{ cm}$, $\tau = 2\text{ m}$

CMS Preliminary 137 fb$^{-1}$ (13 TeV)
Conclusions

- Showed the latest results of SUSY searches at the CMS experiment with the Run2 dataset
  - More results to come with the full Run2 dataset!

- No significant excess over background predictions were found
  → set exclusion limits on various simplified models of SUSY

- Factor of 20 in integrated luminosity still to come with the HL-LHC

- We're at about 60% of the mass reach with the LHC
BACK UP
Electroweak composition

- Cross section depends on the bino/wino/higgsino composition

<table>
<thead>
<tr>
<th>Bino</th>
<th>Wino</th>
<th>Higgsino</th>
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<tbody>
<tr>
<td>$\tilde{q}_{L,R}$</td>
<td>$\tilde{q}_{L,R}$</td>
<td>$\tilde{q}_{L,R}$</td>
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<tr>
<td>$\tilde{H}_{u,d}$</td>
<td>$\tilde{L}_{3,4}/\tilde{\chi}_2^\pm$</td>
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<tr>
<td>$\tilde{W}$</td>
<td>$\tilde{L}_{2}/\tilde{\chi}_1^\pm$</td>
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<tr>
<td>$\tilde{B}$</td>
<td>$\tilde{\chi}_1^0$</td>
<td>$\tilde{B}$</td>
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arxiv 1902.11267
QCD Estimate: Rebalance and Smear

**Rebalance** jets to true hard scatter event with \( ME_T \approx 0 \)

**Smear** jets according to response

QCD multi-jet events have no intrinsic \( ME_T \), only instrumental \( ME_T \) due to detector response that depends on \( \eta \) & \( p_T \) of jets

Good agreement with out of the box simulation

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