SUSY at CMS

Koushik Mandal

Eötvös Loránd University, Budapest

On behalf of CMS Collaboration
Supersymmetry

- One of the most studied BSM theories
  - Could solve hierarchy problem
  - Could unify fundamental forces of nature

- New particles from SUSY
- Search for SUSY particles (sparticles) in LHC

- Lightest Supersymmetric Particle (LSP) could be DM candidate in R-parity conserving scenario

$R$-parity = $(-1)^{3(B-L)+2s}$
Production of SUSY particles in TeV energy scale

Strong Production: gluinos, stops, sbottoms, squarks (1st & 2nd generation)
- Large cross section, jetty environment

Electroweak: charginos, neutralinos and sleptons
- Smaller cross section, clean signature with leptons

SUSY models contain many parameters

In LHC, **Simplified models** are considered
- Masses and the decay modes of the target particles are only the free parameters
- The rest of the SUSY particles are set to the masses beyond LHC reach
- Easier for event generation, optimization studies and result interpretation
Dedicated searches for different SUSY production mechanism

Extensive coverage of various signal topologies

Variety of final state signature

<table>
<thead>
<tr>
<th>CMS Searches</th>
<th>SUSY Production</th>
<th>Additional Searches</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>R-parity Conserving</td>
<td>R-parity Violating</td>
</tr>
<tr>
<td></td>
<td>Strong SUSY</td>
<td>Electroweak SUSY</td>
</tr>
<tr>
<td>0 lepton or Hadronic</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 lepton</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Multi-leptons</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
General Search Strategy

Select data using the trigger depending on the final state of targeted signals

Identify the SM processes having same final state as of the signals

Build search variables sensitive to signal hypothesis

Estimation of SM backgrounds

Selection on the search variables to design the search region (SR)

Full Run2 data corresponding to 137 fm⁻¹ luminosity

SM backgrounds: ttbar, W/Z+jets, QCD, DY, VV..

Cut and count analysis in inclusive SRs

Exclusive SR based on the shape of a chosen variable

Machine learning with MVA approach

Comparison between estimated backgrounds and observed data including all the uncertainties

Jet multiplicity: $N_{\text{jets}}$

MET or $p_T^{\text{miss}}$:

$$\sum_{\text{Reconstructed Particles}} -p_T$$

HT:

$$\sum_{\text{jets}} |P_T^j|$$

MHT or $H_T^{\text{miss}}$:

$$\sum_{\text{Jets}} -p_T$$

Transverse mass:

$$m_T^2 = m^2 + p_T^2 + p_T^2$$

MT2:

$$\min_{\vec{p}_T^{X(1)} + \vec{p}_T^{X(2)} = \vec{p}_T^{\text{miss}}} \left[ \max \left( M_T^{(1)}, M_T^{(2)} \right) \right]$$

Tagged heavy objects like b, top, W, Z and H

Koushik Mandal  SUSY(CMS)  5
Strong SUSY with Jet & MET

- Targets gluino and squarks in hadronic final state
- 4D SR with $N_{\text{jets}}$, $N_{\text{bjets}}$, HT and MHT
- Data driven estimation for major backgrounds
  - *Lost Lepton* (Missing leptons (e and $\mu$) or hadronically decaying $\tau$): Single lepton CR is used
  - $Z(\rightarrow \nu\nu)+$jets: Combination of $Z(\rightarrow l^+l^-)+$jets and $\gamma+$jets CRs
  - QCD multijets: Inverted $\Delta\phi$ CR
Strong SUSY with MT2

Similar search as inclusive jets+MET search

Sensitive search variables: $N_{\text{jets}}$, $N_{\text{bjets}}$, HT and MT2

- Complementing MT2 search in compressed region with **disappearing track** analysis
- Gluino and squarks decays to neutralino via a chargino
- For chargino-neutralino mass splitting ~100 MeV, chargino decays inside tracker: chargino track disappear
- Requirement of disappearing track (short track) suppress SM background to a large extend

Exclusion improved by hundreds of GeV
Gluino search with one high $p_T$ lepton, multiples jets including b-jets and large MET

- Lepton transverse mass ($m_T$) and large jet mass ($M_J$) are the key search variables

$$m_T = \sqrt{2p_T\ell\cdot p_T^{\text{miss}}[1 - \cos(\Delta\phi_{\ell,p_T^{\text{miss}}})]} \quad M_J = \sum_{J_i=\text{large-R jets}} m(J_i)$$

Backgrounds are estimated using ABCD method in the 2D phase space of $m_T$ and $M_J$
Large mass difference between $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^0$ results in highly energetic Z

Hadronically decaying boosted Z is tagged using high $p_T$, wide-cone (radius of 0.8) jet

Requirement of two energetic Z-tagged jets and high MET greatly suppresses the SM backgrounds

MET and soft drop masses of the leading and sub-leading jets are two search variables

Background estimated from jet mass sideband using mass shape variable

Then modelled in MET bins using MET shape
0L Stop Search with Top Tagger

- Targets stop and gluino

- Two SRs sensitive to the different signals corresponding to the high and low $\Delta m(\text{stop, neutralino})$ values

- Identification of top quark in wide $p_T$ range
  - Merged tagging algorithm for boosted tops
  - Deep Neural Network based Resolved tagger for low $p_T$ tops

- Use of W tagger and soft b tagger

arXiv
Leptonic (1L & 2L) Stop search

- Stop search in one lepton final state
- $M_T$ to suppress ttbar/$W+$jets
- Modified topness ($t_{\text{mod}}$) to discriminate leptonic ttbar
  
  \[ t_{\text{mod}} = \ln(\text{min} S), \quad S = \frac{(m_W^2 - (p_T + p_E)^2)^2}{2m_W^2} + \frac{(m_T^2 - (p_T + p_W)^2)^2}{2m_T^2} \]
- Hadronic top tagger categories
- Use of $W$ and soft $b$ tagger

- Stop search in di lepton final state
- MET significance ($S$) to suppress Drell-Yan
- $m_{T2}(ll)$ and $m_{T2}(blbl)$ to suppress ttbar
- Categorize in same and different flavor dilepton region

---

Koushik Mandal  

SUSY(CMS)
Stop Search in Top Corridor

- Probe the stop in the top corridor $m(\text{stop}) - m(\text{LSP}) \sim m(\text{top})$
- Challenging due to the similarity between signal and ttbar background
- Search in dilepton final state with MET and at least two jets
- Utilize DNN to distinguish signal from ttbar background

Exclusion limit combined from 0, 1, 2L and corridor stop searches
Strong SUSY results

Gluino excluded up to 2.3 TeV

Stop excluded up to 1.3 TeV

Sbottom excluded up to 1.25 TeV

Single (degenerate) squark is excluded up to 1.3 (1.8) GeV
Electroweak SUSY in 2L(SS) & Multileptons

- Search for pair produced chargino/neutralino
- Final state with same sign di leptons or 3/4 lepton (up to 2 $\tau_h$)
- Consider three decay topologies
- Parametric NN with $\delta m($chargino,LSP$)$ to increase search sensitivity

Gauge Mediated decay with gravitino as LSP

Direct decay

Mediated by light sleptons

Exclude EWkino up to 1.4 TeV

CMS Preliminary

SUSY(CMS)
- Signature with leptonic $W$ and $H \rightarrow bb$
- Boosted $H$ tagging with AK8 jets targets high mass-splitting (between chargino/neutralino and LSP) models
- Requirement of two $b$ jets
- $m_T$ and $m_{CT}$ to suppress SM backgrounds

Estimated backgrounds and observed data in SR

Exclude EWkino up to 800 GeV

Koushik Mandal

SUSY(CMS)
Target signal decay modes with two opposite sign same flavor leptons

Consider direct slepton pair production

Discrepancy in the last bin:
Local significance of 1.6 s.d.
Overall no significance excess

Exclude slepton up to 700 GeV
Search for Stau in Hadronic Final State

- Search for pair produced stau
  - pure LH, pure RH, and degenerate production (LH+RH)

- Also consider GMSB scenario where stau is long lived
  - $c\tau(\text{stau})$ 0.01 - 10 mm

- Final state: two hadronic taus + missing energy from LSP

- SR binned in $N_{\text{jets}}$, $MT_2$, $p_T(\tau_1)$, $\sum MT = MT(\tau_1) + MT(\tau_2)$

- Selection on tau IP for displaced stau signal

Exclude stau up to 400 GeV
Other Searches

Strong and electroweak SUSY search in two SS or three charged lepton final state

**SUS-19-008**

Strong and electroweak SUSY search With Higgs and MET

**SUS-20-004**

Electroweak SUSY search in WW, WZ and WH hadronic final state

**SUS-21-002**

Stealth/RPV stop search

**SUS-20-004, PRD**
Summary

- A highlight of SUSY searches in CMS with full Run2 data
  - A wide range of signal models
  - Advanced and improved techniques compared to the previous round of analyses
  - Brand new analyses
- So far no sign of SUSY
- Extend the exclusion limits up to several hundred of GeV
- *Stay tuned* for SUSY search in the unexplored parameter space with Run3 & HL data at LHC

Thank You!
Back Up