Search for R-Parity Violating Decays of Supersymmetric Top Quarks With the CMS Experiment

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The Standard Model

- Classifies known fundamental particles.
- Describes how the electromagnetic, weak, and strong interactions mediate the dynamics of these particles.
- Does not describe gravity
- Predictions have mostly excellent agreement with experimental results
Super-Symmetry

- Proposes a symmetry between fermions and bosons.
  - Each fermion has a bosonic “super partner”.
  - Broken/Unbroken Symmetry

- SUSY Advantages:
  - Can provide dark matter candidate (LSP)
  - Can stabilize the Higgs mass against large quantum corrections

**Diagram:**

- Quarks: u, c, t, d, s, b
- Higgs bosons: H_u, H_d, W^0
- Leptons: e, μ, τ
- Gauge bosons: W^±
- Squarks: ě, ě, ď, ď
- Higgsinos:  g, B, H_u, H_d, W^0, W^±

Mixing patterns:
- 2 charginos: \( \tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm \)
- 4 neutralinos: \( \tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0 \)
SUSY and Naturalness

- SM prediction needs cancellation to about one part in $1,000,000,000,000,000,000,000,000,000,000,000,000,000,000$
- Higgs mass receives a nearly equal and opposite correction from the top and stop quarks.
- This provides a natural cancellation of mass terms
Feynman Diagrams

- Represents interaction between particles
- Time goes left to right
- Particles are represented by forward arrows, antiparticles by backwards arrows
Our SUSY Signal

$$\tilde{t}\tilde{t}^* \rightarrow \mu^+ \mu^- b\bar{b}$$

- We are looking for the hypothetical decay of a stop quark to a muon and a bottom quark

- Our goal is to look for evidence of this process by comparing the expected number of background events from standard model processes to the observed data from CERN

- Our search strategy is to define multiple signal regions to be sensitive to a wide range of stop masses
**R-Parity Violation**

\[ \tilde{t}\tilde{t}^* \rightarrow \mu^+ \mu^- b\bar{b} \]

- **R Parity - SUSY comes in even pairs**
- **Our signal violates R parity conservation, i.e. the stop decays to only standard model particles**
  - No Stable LSP $\rightarrow$ no natural dark matter candidate
- **Why this Process?**
  - Final state is easy to detect
  - R parity violating models have not been searched for extensively
Data

- Data is produced from 8 TeV proton proton collisions at the LHC
- Collision data is produced and analyzed with the CMS detector (compact muon solenoid)
Detector

- Protons in the LHC reach speeds of 0.9999999922 c, going around the 27km ring over 11,000x a second

- Combined strands of superconducting cable produced for the LHC would go around the equator 6.8 times

- 2 billion collisions per second

- New collision every 50 ns

- Has cost ~6.4 billion dollars
Personal Experimental Apparatus

- Used for analyzing large quantities of CERN data
- Only research group in the world using this device
Plan of Attack

- Investigate relevant backgrounds, i.e. processes with similar final states to our signal
- Set selection criteria on kinematical quantities based on their ability to:
  - Isolate signal from background
  - Confirm validity of samples
- Use event yields to see if we found SUSY
  - If not, set limit on what the stop mass can be
  - Because the higher the stop mass, the more rare the process
Major Backgrounds

\[ Z \rightarrow \mu^- \mu^+ b \bar{b} \]

- Suppress by requiring that the invariant mass of the two muons is not consistent with the Z.

\[ t \bar{t} \rightarrow \mu^- \mu^+ b \bar{b} \nu_\mu \bar{\nu}_\mu \]

- Background contains neutrinos, not present in signal → background characterized by momentum imbalance in transverse plane.
Example Cut

- One piece of information we place restrictions on is the missing energy in the transverse direction (MET)

- Conservation of Momentum indicates missing momentum
  - This is called “missing energy” for historical reasons

  - This occurs because of:
    - Missed/Mismeasured Particles
    - New physics
    - Neutrinos

  - Prevalent in tt backgrounds, but not in signal
Missing Transverse Energy

- Dominant Backgrounds: TT, DY

- Cutting at 60 GeV will remove a substantial amount of TT, with little loss of signal
Money Plot

Delta Vs. Average Mass

- Average and delta mass is computed by measuring the energy of the final state pair.
Average and delta mass is computed by measuring the energy of the final state pair.

- Control region used in analysis
- Signal region for the 600 GeV mass point
- We make a corresponding signal region for each mass point
Control Regions

● Why do we use these?
  ○ Validate samples
    ■ Samples could be completely wrong
    ■ Test sample/data agreement without signal contamination
  ○ Data Driven Predictions
    ■ We predict the amount of background we expect in our signal regions by using data in our control region
    ■ We expect a 2:1 ratio between electron-muon and di-muon final states for some backgrounds
    ■ Predictions are then based on what we see in data rather than what we generate with simulations
### Signal Region Yields

<table>
<thead>
<tr>
<th>Signal Region by mass (GeV)</th>
<th>SM only Hypothesis</th>
<th>SM + SUSY Hypothesis</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>SR 200</td>
<td>2109</td>
<td>57200</td>
<td></td>
</tr>
<tr>
<td>SR 400</td>
<td>41.7</td>
<td>384.1</td>
<td></td>
</tr>
<tr>
<td>SR 600</td>
<td>2.8</td>
<td>37.1</td>
<td></td>
</tr>
<tr>
<td>SR 800</td>
<td>0</td>
<td>2.6</td>
<td></td>
</tr>
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- Difference in predictions between Standard Model and Susy.
  - We can use this to get an idea for which is more accurate
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<tr>
<td>SR 200</td>
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<td>2250</td>
</tr>
<tr>
<td>SR 400</td>
<td>41.7</td>
<td>384.1</td>
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</tr>
<tr>
<td>SR 600</td>
<td>2.8</td>
<td>37.1</td>
<td>3</td>
</tr>
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- Data is consistent with SM only
- Clearly low mass susy is eliminated
- We lose sensitivity at higher mass points
- We must now set a limit on where SUSY could exist
Cross section upper limit

- Since we know what the stop production cross-section is (if the stop were to exist), our upper limit on the cross section can be translated into a lower limit on the mass of the stop.
- We exclude at 95% CL that the stop quark exists with mass < 780 GeV, if it decays 100% of the times into $b\mu$.
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Backups
2:1 Ratio

**Decay**

\[ t\bar{t} \rightarrow W^+W^-b\bar{b} \]
\[ \rightarrow W^+ \rightarrow l^+\nu \]
\[ \rightarrow W^- \rightarrow l^-\bar{\nu} \]

\[ Z \rightarrow l^+l^-b\bar{b} \]

**Lepton Final States**

- \( e^+e^- \)
- \( e^+\mu^- \)
- \( e^-\mu^+ \)
- \( \mu^+\mu^- \)

- We expect 2x as many events as \( e\mu \) events
- We do not expect a 2:1 correspondance
Selection

- Opposite Sign
- ignoring electron-electron events
- eta < 2.4
- ID/Isolation
- Jet pt > 30
- Jet eta < 2.5
- hyp pt > 20
- nJets >= 2
- z veto
- Invariant mass > 20
- |deltaMass| < 100
- Control Region:
  - Average Mass < 250
  - met >= 60
  - b-tagged jets ≥ 2

- SR 1 (mass >= 700 GeV)
  - |avgMass - stopMass| < 50
  - met ≤ 60
  - b-tagged jets ≥ 2

- Signal Region (mass <= 650 GeV)
  - |avgMass - stopMass| < 50
  - met ≤ 60
  - b-tagged jets ≥ 1