Search for Third Generation Leptoquarks and R-Parity Violating Stops with the CMS Experiment at the LHC

Kevin Pedro
(University of Maryland)
for the CMS Collaboration
May 5, 2014
Introduction

• Searches for pair production of scalar leptoquarks and stops in R-parity violating supersymmetry decaying to third generation particles (t, b, τ)
  • Full 8 TeV CMS 2012 dataset, 19.7 fb⁻¹
  • CMS-EXO-12-030: LQ₃ → t + τ search (CDS, twiki)
  • CMS-EXO-12-032: LQ₃ → b + τ & RPV stop search (CDS, twiki)

Outline:
1. Leptoquarks
2. LQ₃ → t + τ results
3. LQ₃ → b + τ results
4. R-parity violation
5. RPV stop results
6. Conclusions
Leptoquarks

- Scalar or vector bosons
- Baryon number (B), lepton number (L), color charge, electric charge (Q)
- SU(5) grand unified theory, SU(4) Pati-Salam, compositeness models, superstrings, technicolor
- Intergenerational decays constrained by limits from low-energy processes and flavor-changing neutral current searches
  ➢ Expected to decay to leptons and quarks of the same generation
- Pair production cross sections have been calculated to NLO in $\alpha_s$
LQ_3 \rightarrow t + \tau \text{ Search}

\text{Required same-sign } \mu\tau_h \text{ pair reduces SM backgrounds}

\text{Major background mainly from jets misidentified as } \tau_h \text{ ("fakes") and also from leptons from heavy flavor decays within jets, estimated from data using Loose-to-Tight Extrapolation Method (LTEM): } (\hat{x} = 1 - x)

\begin{align*}
\begin{pmatrix}
N_{FF} \\
N_{FP} \\
N_{PF} \\
N_{PP}
\end{pmatrix}
&= \frac{1}{(p_\mu - f_\mu)(p_\tau - f_\tau)}
\begin{pmatrix}
p_\mu \cdot p_\tau & -p_\mu \cdot \hat{p}_\tau & -\hat{p}_\mu \cdot p_\tau & \hat{p}_\mu \cdot \hat{p}_\tau \\
-p_\mu \cdot f_\tau & p_\mu \cdot \hat{f}_\tau & \hat{p}_\mu \cdot f_\tau & -\hat{p}_\mu \cdot \hat{f}_\tau \\
-f_\mu \cdot p_\tau & \hat{f}_\mu \cdot \hat{p}_\tau & \hat{f}_\mu \cdot p_\tau & -\hat{f}_\mu \cdot \hat{p}_\tau \\
f_\mu \cdot f_\tau & -f_\mu \cdot \hat{f}_\tau & -\hat{f}_\mu \cdot f_\tau & \hat{f}_\mu \cdot \hat{f}_\tau
\end{pmatrix}
\begin{pmatrix}
N_{LL} \\
N_{LT} \\
N_{TL} \\
N_{TT}
\end{pmatrix}
\end{align*}

\text{Minor backgrounds estimated from MC}
LQ$_3 \rightarrow t + \tau$ Details

- $S_T$ is the scalar sum of $p_T$ for all final state objects (leptons, jets, MET)
- $\mu^\pm \tau_h^\pm + \geq 2$ jets, $S_T > 400$ GeV
- Split into central and forward channels ($|\eta| < 0.9, |\eta| \geq 0.9$) based on event centrality
- Final cuts on $S_T$ and $p_T(\tau_h)$ are optimized for each LQ$_3$ mass hypothesis using Punzi figure of merit $\chi$ (maximize signal-background separation)

Mathematical expression for Punzi figure of merit:

$$
\chi(p_T^{\tau}, S_T) = \frac{\varepsilon(p_T^{\tau}, S_T)}{1 + \sqrt{B(p_T^{\tau}, S_T)}}
$$
Assuming $\beta(LQ_3 \to t + \tau) = 1$, pair production of $Q = -1/3$ scalar $LQ_3$ excluded at 95% CL for masses up to 550 GeV (582 GeV expected).

- Leading systematic uncertainty from LTEM: 21-28% (central), 21-36% (forward)
LQ$_3 \rightarrow b + \tau$ Search

- Reducible background from jets misidentified as $\tau_h$ estimated from data

\[ N_{\text{misID} \tau}^{(\text{main})} = \sum_{\text{events}} \frac{1 - \prod_{\tau}[1 - f(p_T(\tau))]}{\prod_{\tau}[1 - f(p_T(\tau))]} \]

- Irreducible background from $t\bar{t} + \text{jets}$ with genuine $\tau_h$ estimated from data

\[ N_{\ell \tau_h} = N_{e\mu} \times \frac{\varepsilon_{\tau_h}^{\text{sel}} \rho_{\tau_h}^{\text{sel}}}{\varepsilon_{e\mu}^{\text{sel}} \rho_{e\mu}^{\text{sel}}} \times \frac{\varepsilon_{\tau_h}^{\text{ID}}}{\varepsilon_{e}^{\text{ID}}} \times \frac{\varepsilon_{\tau_h}^{\text{ID}}}{\varepsilon_{\mu}^{\text{ID}}} \times \frac{A_{\ell \tau_h} B_{W \ell} B_{W \tau_h} + A_{\tau_h \tau_h} B_{W \tau_h} B_{W \tau_h}}{A_{e\mu} B_{W e} B_{W \mu} + A_{\mu \tau_{e}} B_{W \mu} B_{W \tau_{e}} + A_{e \tau_{\mu}} B_{W e} B_{W \tau_{\mu}} + A_{\tau_{e} \tau_{\mu}} B_{W \tau_{e}} B_{W \tau_{\mu}}} \]

- Minor backgrounds estimated from MC
LQ₃ → b + τ Details

- Sᵀ is the scalar sum of pᵀ for all required final state objects (e/μ, τ_h, 2 jets)
- e⁺/μ⁺ + τ⁺ + ≥ 2 jets, with at least 1 jet b-tagged
- Require mass of the τ_h and a paired jet, M(τ,j), to be greater than 250 GeV
  - Pairing is chosen to minimize the difference between the mass of the tau and one jet and the mass of the e/μ and the other jet
- Limits are set using the Sᵀ distribution
Assuming $B(LQ_3 \rightarrow b + \tau) = 1$, pair production of $Q = -2/3$ or $-4/3$ scalar $LQ_3$ excluded at 95% CL for masses up to 740 GeV (754 GeV expected)

95% CL limits also calculated for varying branching fraction (right)

- Leading systematic uncertainties from data-driven background estimations: 16% (reducible), 19-21% (irreducible)
R-Parity Violation

- R-parity is a discrete symmetry which separates SM and SUSY particles.
- R-parity violation allows SUSY particles to decay to final states containing only SM particles; RPV SUSY still solves the hierarchy problem.

\[ W \supset \frac{1}{2} \lambda_{ijk} L_i L_j E_k^c + \lambda'_{ijk} L_i Q_j D_k^c + \frac{1}{2} \lambda''_{ijk} U_i^c D_j^c D_k^c + \mu_i L_i H_u \]

- These decays present signatures without high MET, avoiding strong limits on much of the parameter space of R-parity conserving SUSY.
- Stops and higgsinos are typically lighter than the other scalar SUSY particles in natural models.

➢ Third generation of superpartners potentially accessible at LHC energies.
- Searches consider simplified models with other SUSY particles decoupled.
RPV Stop Searches

- Limits on pair production of stops decaying directly through $\lambda'_{333}$ coupling can be extracted from $LQ_3 \rightarrow b + \tau$ search
- Limits on pair production of sbottoms decaying directly through $\lambda'_{333}$ coupling can be extracted from $LQ_3 \rightarrow t + \tau$ search

- The stop can have a chargino-mediated decay if the chargino is lighter than the stop, involving RPV coupling $\lambda'_{3jk}$ ($j, k = 1, 2$)
  - Produces final state similar to $LQ_3 \rightarrow b + \tau$ search, but with extra jets: $\ell^\pm \tau_1^\pm bb4j$ ($\ell \in \{e, \mu\}$)
  - Search proceeds in same way, but requires $N_{\text{jet}} \geq 5$ (instead of $M(\tau, j)$ cut)
  - $S_T$ is the scalar sum of $p_T$ for all required final state objects ($e/\mu, \tau_1, 5$ jets)
Assuming 100% branching fraction for the chargino-mediated decay of the stop involving the $\lambda'_{3jk}$ coupling, pair production of stops excluded at 95% CL for masses up to 576 GeV (588 GeV expected)

- Leading systematic uncertainties from data-driven background estimations: 23-24% (reducible), 20-22% (irreducible)
Results were obtained using the full 8 TeV CMS 2012 dataset, 19.7 fb⁻¹

Pair production of third generation scalar leptoquarks with $Q = -1/3$ has been excluded for masses up to 550 GeV, assuming $\beta(LQ_3 \rightarrow t + \tau) = 1$

Pair production of third generation scalar leptoquarks with $Q = -2/3, -4/3$ has been excluded for masses up to 740 GeV, assuming $\beta(LQ_3 \rightarrow b + \tau) = 1$

Limits for $LQ_3 \rightarrow b + \tau$ are also set for varying branching fraction

These limits are the most stringent to date

Limits on RPV stops and sbottoms decaying via $\lambda'_{333}$ can be extracted from the $LQ_3 \rightarrow b + \tau$ and $LQ_3 \rightarrow t + \tau$ searches, respectively

Pair production of RPV stops with a chargino-mediated decay involving $\lambda'_{3jk}$ has been excluded for masses up to 576 GeV, assuming a branching fraction of 100%

This is the first direct search for stops decaying to such a final state

Stay tuned for 13 TeV results, including new RPV SUSY searches and reinterpretations!
Backup
References


For full lists of references, see the Physics Analysis Summaries from CMS-EXO-12-030, CMS-EXO-12-032 (CDS links on slide 2).
Hadron Plus Strips Algorithm

• ~65% of tau leptons will decay to hadrons, typically producing:
  • 1 or 3 charged hadrons ($\pi^\pm$, $\kappa^\pm$)
  • 0 or more neutral hadrons ($\pi^0$)
  • $\nu_\tau$

• CMS uses the Hadron Plus Strips (HPS) algorithm to reconstruct $\tau_h$ decays
  1. Start from a Particle Flow jet
  2. Photons from $\pi^0$ decays are reconstructed as electromagnetic strips, to account for conversions in the tracker
  3. Identified strips are combined with charged hadrons
  4. Four-momenta of the constituent particles are reconstructed according to decay and mass hypotheses
  5. Isolation is computed using the $p_T$ of nearby charged hadron and photon candidates, with a $\Delta\beta$ pileup correction
  6. Discriminators are applied to reject electrons or muons misidentified as hadronic taus
Backgrounds

LQ\(_3 \rightarrow t + \tau\):
• Major reducible background from misidentified leptons, especially jets misidentified as \(\tau_h\) (e.g. \(t\bar{t} + \text{jets}, W + \text{jets}\))
• Minor irreducible backgrounds: SM processes with genuine same-sign dilepton pairs (e.g. VV, \(t\bar{t}W, ttZ, W^\pm W^\pm qq\))
• Minor reducible background: Charge-mismeasured dilepton events (e.g. \(Z/\gamma^* + \text{jets}\))

LQ\(_3 \rightarrow b + \tau\):
• Major reducible background from jets misidentified as \(\tau_h\) (\(t\bar{t} + \text{jets}, W + \text{jets}, Z + \text{jets}, \text{QCD multijets}\))
• Major irreducible background from \(t\bar{t} + \text{jets}\) with genuine \(\tau_h\)
• Minor backgrounds: VV, single top, \(Z \rightarrow \tau^+\tau^- + \text{jets}\), and processes where a lepton is misidentified as a \(\tau_h\) (\(t\bar{t} + \text{jets}, Z + \text{jets}\))

MC simulation:
• \textit{PYTHIA6}: LQ, stop, VV, QCD
• \textit{MADGRAPH}: \(t\bar{t}, V + \text{jets}, ttV, W^\pm W^\pm qq\)
• \textit{POWHEG}: single top
• \textit{TAUOLA} is used for processes containing real taus
Loose-to-Tight Extrapolation Method

\[
\begin{pmatrix}
N_{LL} \\
N_{LT} \\
N_{TL} \\
N_{TT}
\end{pmatrix} = \begin{pmatrix}
\hat{f}_\mu \cdot \hat{f}_\tau & \hat{f}_\mu \cdot \hat{p}_\tau & \hat{p}_\mu \cdot \hat{f}_\tau & \hat{p}_\mu \cdot \hat{p}_\tau \\
\hat{f}_\mu \cdot f_\tau & f_\mu \cdot p_\tau & p_\mu \cdot f_\tau & p_\mu \cdot p_\tau \\
\hat{f}_\mu \cdot f_\tau & f_\mu \cdot p_\tau & p_\mu \cdot f_\tau & p_\mu \cdot p_\tau \\
\hat{f}_\mu \cdot f_\tau & f_\mu \cdot p_\tau & p_\mu \cdot f_\tau & p_\mu \cdot p_\tau
\end{pmatrix} \begin{pmatrix}
N_{FF} \\
N_{FP} \\
N_{PF} \\
N_{PP}
\end{pmatrix}
\]

\[
\begin{pmatrix}
N_{FF} \\
N_{FP} \\
N_{PF} \\
N_{PP}
\end{pmatrix} = \frac{1}{(p_\mu - f_\mu)(p_\tau - f_\tau)} \begin{pmatrix}
p_\mu \cdot p_\tau & -p_\mu \cdot \hat{p}_\tau & -\hat{p}_\mu \cdot \hat{p}_\tau & \hat{p}_\mu \cdot \hat{p}_\tau \\
-p_\mu \cdot f_\tau & p_\mu \cdot \hat{f}_\tau & \hat{p}_\mu \cdot f_\tau & -\hat{p}_\mu \cdot \hat{f}_\tau \\
-f_\mu \cdot p_\tau & \hat{f}_\mu \cdot \hat{p}_\tau & \hat{f}_\mu \cdot \hat{p}_\tau & -f_\mu \cdot \hat{p}_\tau \\
f_\mu \cdot f_\tau & -f_\mu \cdot \hat{f}_\tau & -f_\mu \cdot \hat{f}_\tau & \hat{f}_\mu \cdot \hat{f}_\tau
\end{pmatrix} \begin{pmatrix}
N_{LL} \\
N_{LT} \\
N_{TL} \\
N_{TT}
\end{pmatrix}
\]

Yields are denoted as \(N_{(\mu)(\tau)}\), where \((\mu)\) is status of the muon and \((\tau)\) is status of the \(\tau_h\)

- tight selection = loose selection + stricter isolation

\(L\): lepton passing loose selection but not tight selection
\(T\): lepton passing loose selection and tight selection
\(P\): prompt lepton (from W or Z decay, well-isolated)
\(F\): fake lepton (from misreconstructed jets or from heavy flavor decay within jets)
\(f\): fake rate (probability that a fake lepton is \(T\)), \(f = 1 - \hat{f}\)
\(p\): prompt rate (probability that a prompt lepton is \(T\)), \(\hat{p} = 1 - p\)
LQ_3 \rightarrow t + \tau \text{ Systematic Uncertainties}

- Reducible background estimation: 21-28% (central), 21-36% (forward)
  - from propagation of uncertainties on prompt rates and fake rates
- Irreducible background normalization: 20-30%
  - from data/MC agreement in signal-depleted region or theoretical uncertainties on NLO cross-sections
- \(\tau_h\) ID efficiency: 6%, \(\mu\) ID: 1%, trigger matching: 0.5%
- Luminosity: 2.6%, pileup: 1% (central), 2.5% (forward)
- Jet ES: 4.0-6.7% (background), 1.8-7.8% (signal)
  - \(\tau_h\) ES: 4.5-8.7% (background), 0.4-3.8% (signal)
  - ES: energy scale
  - jet ES depends on \(p_T\) and \(\eta\)
- Signal acceptance: 1.7-13.1% (central), 2.1-20.8% (forward)
  - from PDF uncertainties in production, using CTEQ6L1
- Signal cross-section: 15-33%
  - from PDF uncertainties, normalization/factorization scale uncertainties
### \( LQ_3 \rightarrow t + \tau \) Results Table

<table>
<thead>
<tr>
<th>( M_{LQ_3} ) (GeV)</th>
<th>( \tau ) pT (GeV)</th>
<th>( S_T ) (GeV)</th>
<th>( N_{\text{PP Bckg}}^{\text{stat.}} )</th>
<th>( N_{\text{Exp Bckg}}^{\text{stat.}, \text{sys.}} )</th>
<th>( N_{\text{Obs}}^{\text{stat.}} )</th>
<th>Z-Score</th>
<th>( N_{\text{Exp LQ_3}}^{\text{stat.}} )</th>
<th>( \varepsilon_{LQ_3} ) %</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Central Channel: ( \vec{\eta} \leq 0.9 )</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>35</td>
<td>410</td>
<td>8.51±0.98</td>
<td>127.71±5.35±25.48</td>
<td>105</td>
<td>-1.0</td>
<td>52.61±20.55</td>
<td>0.08</td>
</tr>
<tr>
<td>250</td>
<td>35</td>
<td>410</td>
<td>8.51±0.98</td>
<td>127.71±5.35±25.48</td>
<td>105</td>
<td>-1.0</td>
<td>251.88±24.41</td>
<td>1.31</td>
</tr>
<tr>
<td>300</td>
<td>50</td>
<td>470</td>
<td>4.21±0.51</td>
<td>39.91±2.92±8.25</td>
<td>27</td>
<td>-1.5</td>
<td>153.46±11.08</td>
<td>2.22</td>
</tr>
<tr>
<td>350</td>
<td>50</td>
<td>490</td>
<td>4.04±0.50</td>
<td>34.62±2.73±7.14</td>
<td>25</td>
<td>-1.2</td>
<td>92.44±5.56</td>
<td>3.29</td>
</tr>
<tr>
<td>400</td>
<td>65</td>
<td>680</td>
<td>0.91±0.20</td>
<td>7.20±1.15±1.74</td>
<td>4</td>
<td>-1.0</td>
<td>28.36±2.07</td>
<td>2.27</td>
</tr>
<tr>
<td>450</td>
<td>65</td>
<td>700</td>
<td>0.78±0.18</td>
<td>6.34±1.08±1.56</td>
<td>4</td>
<td>-0.8</td>
<td>17.27±1.10</td>
<td>2.90</td>
</tr>
<tr>
<td>500</td>
<td>65</td>
<td>770</td>
<td>0.47±0.15</td>
<td>3.23±0.81±0.76</td>
<td>4</td>
<td>+0.5</td>
<td>9.76±0.59</td>
<td>3.25</td>
</tr>
<tr>
<td>550</td>
<td>65</td>
<td>800</td>
<td>0.38±0.14</td>
<td>2.73±0.75±0.63</td>
<td>4</td>
<td>+0.7</td>
<td>6.13±0.34</td>
<td>3.89</td>
</tr>
<tr>
<td>600</td>
<td>65</td>
<td>850</td>
<td>0.20±0.08</td>
<td>1.76±0.61±0.44</td>
<td>3</td>
<td>+0.9</td>
<td>3.61±0.19</td>
<td>4.20</td>
</tr>
<tr>
<td>650</td>
<td>65</td>
<td>850</td>
<td>0.20±0.08</td>
<td>1.76±0.61±0.44</td>
<td>3</td>
<td>+0.9</td>
<td>2.19±0.11</td>
<td>4.54</td>
</tr>
<tr>
<td>700</td>
<td>85</td>
<td>850</td>
<td>0.12±0.07</td>
<td>1.08±0.49±0.25</td>
<td>2</td>
<td>+0.8</td>
<td>1.28±0.06</td>
<td>4.60</td>
</tr>
<tr>
<td>750</td>
<td>85</td>
<td>850</td>
<td>0.12±0.07</td>
<td>1.08±0.49±0.25</td>
<td>2</td>
<td>+0.8</td>
<td>0.82±0.04</td>
<td>5.01</td>
</tr>
<tr>
<td>800</td>
<td>85</td>
<td>850</td>
<td>0.12±0.07</td>
<td>1.08±0.49±0.25</td>
<td>2</td>
<td>+0.8</td>
<td>0.51±0.02</td>
<td>5.19</td>
</tr>
<tr>
<td><strong>Forward Channel: ( \vec{\eta} \geq 0.9 )</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>35</td>
<td>410</td>
<td>4.20±0.52</td>
<td>71.94±4.16±14.61</td>
<td>87</td>
<td>+1.1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>250</td>
<td>35</td>
<td>410</td>
<td>4.20±0.52</td>
<td>71.94±4.16±14.61</td>
<td>87</td>
<td>+1.1</td>
<td>50.21±10.53</td>
<td>0.26</td>
</tr>
<tr>
<td>300</td>
<td>50</td>
<td>470</td>
<td>1.77±0.31</td>
<td>20.28±2.15±3.87</td>
<td>23</td>
<td>+0.5</td>
<td>33.42±5.23</td>
<td>0.48</td>
</tr>
<tr>
<td>350</td>
<td>50</td>
<td>490</td>
<td>1.68±0.30</td>
<td>18.16±2.02±3.53</td>
<td>19</td>
<td>+0.2</td>
<td>18.45±2.51</td>
<td>0.66</td>
</tr>
<tr>
<td>400</td>
<td>65</td>
<td>680</td>
<td>0.71±0.20</td>
<td>2.71±0.68±0.57</td>
<td>1</td>
<td>-0.9</td>
<td>6.11±0.95</td>
<td>0.49</td>
</tr>
<tr>
<td>450</td>
<td>65</td>
<td>700</td>
<td>0.71±0.20</td>
<td>2.33±0.63±0.44</td>
<td>1</td>
<td>-0.7</td>
<td>3.84±0.54</td>
<td>0.64</td>
</tr>
<tr>
<td>500</td>
<td>65</td>
<td>770</td>
<td>0.53±0.14</td>
<td>1.19±0.43±0.23</td>
<td>1</td>
<td>0.0</td>
<td>1.61±0.24</td>
<td>0.54</td>
</tr>
<tr>
<td>550</td>
<td>65</td>
<td>800</td>
<td>0.42±0.13</td>
<td>0.89±0.38±0.16</td>
<td>1</td>
<td>+0.3</td>
<td>1.15±0.15</td>
<td>0.73</td>
</tr>
<tr>
<td>600</td>
<td>65</td>
<td>850</td>
<td>0.27±0.10</td>
<td>0.57±0.33±0.12</td>
<td>1</td>
<td>+0.6</td>
<td>0.56±0.08</td>
<td>0.65</td>
</tr>
<tr>
<td>650</td>
<td>65</td>
<td>850</td>
<td>0.27±0.10</td>
<td>0.57±0.33±0.12</td>
<td>1</td>
<td>+0.6</td>
<td>0.29±0.04</td>
<td>0.60</td>
</tr>
<tr>
<td>700</td>
<td>85</td>
<td>850</td>
<td>0.14±0.06</td>
<td>0.36±0.22±0.08</td>
<td>0</td>
<td>-0.4</td>
<td>0.18±0.02</td>
<td>0.65</td>
</tr>
<tr>
<td>750</td>
<td>85</td>
<td>850</td>
<td>0.14±0.06</td>
<td>0.36±0.22±0.08</td>
<td>0</td>
<td>-0.4</td>
<td>0.13±0.02</td>
<td>0.79</td>
</tr>
<tr>
<td>800</td>
<td>85</td>
<td>850</td>
<td>0.14±0.06</td>
<td>0.36±0.22±0.08</td>
<td>0</td>
<td>-0.4</td>
<td>0.08±0.01</td>
<td>0.81</td>
</tr>
</tbody>
</table>
Reducible Bkg. Est. (LQ₃ → b + τ)

The reducible background from jets misidentified as τₕ can be estimated from data using two control samples:
1. \( Z \rightarrow \mu^+\mu^- + \text{jets} \)
2. Events in which all τₕ objects fail isolation (“anti-isolated”)

\[
f(p_T(\tau)) = \frac{N_{\text{iso}}(Z \rightarrow \mu^+\mu^-)(p_T(\tau))}{N_{\text{all}}(Z \rightarrow \mu^+\mu^-)(p_T(\tau))}
\]

\[
N_{\text{misID}}^{(\text{main})}(\tau) = \sum_{\text{events}} \frac{1 - \prod_{\tau}[1 - f(p_T(\tau))]}{\prod_{\tau}[1 - f(p_T(\tau))]} \quad \text{from anti-isolated control region (in each } \ell\tau_{\text{h}} \text{ channel)}
\]

Yield in signal region is calculated from anti-isolated control sample (mostly misidentified jets) using misidentification probability \( f(p_T(\tau)) \) for weighting
Irreducible $t\bar{t}$ Bkg. Est. ($LQ_3 \rightarrow b + \tau$)

The $e\mu$ control region can be used to estimate the irreducible $t\bar{t}$ background (containing real taus) from data for the $\ell\tau$ channels.

$$N_{\ell\tau_h} = N_{e\mu} \times \frac{\varepsilon_{e\mu}^\text{sel} \rho_{e\mu}^\text{sel}}{\varepsilon_{e\mu}^\text{ID} \rho_{e\mu}^\text{ID}} \times \frac{\varepsilon_{e\mu}^\text{ID} \rho_{e\mu}^\text{ID}}{\varepsilon_{\ell\tau_h}^\text{ID} \rho_{\ell\tau_h}^\text{ID}} \times \frac{A_{\ell\tau_h} B_{W\ell} B_{W\tau_h} + A_{\ell\tau_h} B_{W\tau_h} B_{W\tau_h}}{A_{e\mu} B_{W\ell} B_{W\mu} + A_{\mu\tau_e} B_{W\mu} B_{W\tau_e} + A_{\mu\tau_e} B_{W\mu} B_{W\tau_e} + A_{\mu\tau_e} B_{W\mu} B_{W\tau_e} + A_{\mu\tau_e} B_{W\mu} B_{W\tau_e}}$$

The yield from the $e\mu$ channel is multiplied by a combination of selection efficiencies, data/MC scale factors, identification efficiencies, acceptances, and branching ratios. This relates the $e\mu$ channel to the $\ell\tau$ channels for $\ell = e, \mu$. 

Pheno2014 (CMS-EXO-12-032)  
Kevin Pedro  
22
LQ₃ → b + τ Systematic Uncertainties

- Reducible background estimation: 16-24%
  - from statistical uncertainty on fake rate, variation in fake rate for ττ̅ events, variation in fake rate when requiring extra jets
- Irreducible background estimation: 19-22%
  - from statistical uncertainty in control samples, propagation of uncertainties on acceptances, efficiencies, and scale factors
- Small backgrounds: 20-50%
  - due to limited number of MC events and normalization uncertainties
- b-tagging efficiency: ~4% (2% on signal, 0-2% on backgrounds), mistagging probability: ~10% (2% on signal, 2-7% on backgrounds)
  - dependent on p_T and η
- τ_h ID efficiency: 6%, e/μ ID: 2%, trigger efficiency: 2%
- Luminosity: 2.6%, pileup: 3%, ISR/FSR: 4% (signal only)
- Jet ES: 2-4%, jet ER: 5-10%, τ_h ES: 3%, τ_h ER: 10%
- ES: energy scale, ER: energy resolution
- Jet ES depends on p_T and η, jet ER depends on η
- These uncertainties also affect S_T distributions
\[ \text{LQ}_3 \rightarrow b + \tau \text{ & RPV Stop Results Tables} \]

LQ\(_3\) → \(b + \tau\), and RPV stop decaying through \(\lambda'_{333}\)

RPV stop, chargino-mediated decay involving \(\lambda'_{3jk}\) (\(j,k = 1,2\))

<table>
<thead>
<tr>
<th>(\text{tt (irreducible)})</th>
<th>(\mu \tau_h) Channel</th>
<th>(e \tau_h) Channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reducible</td>
<td>66.7 ± 12.6</td>
<td>105.6 ± 18.1</td>
</tr>
<tr>
<td></td>
<td>117.3 ± 18.9</td>
<td>147.8 ± 33.0</td>
</tr>
<tr>
<td>(Z(\ell\ell/\tau\tau)+\text{jets})</td>
<td>7.5 ± 4.6 ± 0.2</td>
<td>21.4 ± 7.4 ± 4.9</td>
</tr>
<tr>
<td>Single-t VV</td>
<td>17.3 ± 2.8 ± 4.7</td>
<td>16.0 ± 2.8 ± 4.4</td>
</tr>
<tr>
<td></td>
<td>2.6 ± 0.5 ± 0.8</td>
<td>4.1 ± 0.6 ± 1.3</td>
</tr>
<tr>
<td>Total Bkg.</td>
<td>211.4 ± 5.4 ± 23.4</td>
<td>294.9 ± 7.9 ± 39.1</td>
</tr>
<tr>
<td>Observed</td>
<td>216</td>
<td>289</td>
</tr>
<tr>
<td>Signal (500 GeV)</td>
<td>51.6 ± 1.3 ± 5.3</td>
<td>57.7 ± 1.4 ± 5.9</td>
</tr>
<tr>
<td>Signal (600 GeV)</td>
<td>17.7 ± 0.4 ± 1.6</td>
<td>20.1 ± 0.5 ± 1.9</td>
</tr>
<tr>
<td>Signal (700 GeV)</td>
<td>6.2 ± 0.1 ± 5.5</td>
<td>7.1 ± 0.2 ± 6.3</td>
</tr>
<tr>
<td>Signal (800 GeV)</td>
<td>2.3 ± 0.1 ± 0.2</td>
<td>2.7 ± 0.1 ± 0.2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>(\text{tt (irreducible)})</th>
<th>(\mu \tau_h) Channel</th>
<th>(e \tau_h) Channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reducible</td>
<td>55.0 ± 9.5</td>
<td>88.3 ± 13.7</td>
</tr>
<tr>
<td></td>
<td>59.8 ± 13.8</td>
<td>65.7 ± 16.4</td>
</tr>
<tr>
<td>(Z(\ell\ell/\tau\tau)+\text{jets})</td>
<td>11.6 ± 5.5 ± 2.7</td>
<td>4.9 ± 2.5±</td>
</tr>
<tr>
<td>Single-t VV</td>
<td>3.5 ± 1.3 ± 0.9</td>
<td>3.9 ± 1.5±</td>
</tr>
<tr>
<td></td>
<td>0.4 ± 0.2 ± 0.1</td>
<td>0.6 ± 0.2 ± 0.2</td>
</tr>
<tr>
<td>Total Bkg.</td>
<td>130.3 ± 5.6 ± 17.1</td>
<td>162.5 ± 2.9 ± 21.5</td>
</tr>
<tr>
<td>Observed</td>
<td>123</td>
<td>156</td>
</tr>
<tr>
<td>Signal (300 GeV)</td>
<td>82.8 ± 8.0 ± 11.7</td>
<td>94.3 ± 8.5 ± 13.2</td>
</tr>
<tr>
<td>Signal (400 GeV)</td>
<td>38.3 ± 2.3 ± 3.8</td>
<td>43.9 ± 2.6 ± 4.3</td>
</tr>
<tr>
<td>Signal (500 GeV)</td>
<td>15.4 ± 0.7 ± 1.5</td>
<td>19.4 ± 0.8 ± 1.8</td>
</tr>
<tr>
<td>Signal (600 GeV)</td>
<td>5.7 ± 0.3 ± 0.5</td>
<td>6.9 ± 0.9 ± 0.7</td>
</tr>
</tbody>
</table>
**CL$_s$ Limits from S$_T$ Distribution**

- Null hypothesis $H_0$: $b$, background-only
  Signal hypothesis $H_1$: $s + b$, signal + background
- $P(\theta; N_H)$: Poisson probability to observe $\theta$ events in data given the hypothesis $H$ which predicts $N_H$ events, accounting for nuisance parameters
- Define the test statistic $Q$ using the binned $S_T$ distribution, split into $e\tau_h$ and $\mu\tau_h$ channels:

\[
Q = \prod_i \prod_j \frac{P_{i,j}(\theta; N_{H_1})}{P_{i,j}(\theta; N_{H_0})}
\]

- Perform numerous pseudo-experiments, varying $\theta$, to compute a distribution of $Q$ values for each hypothesis; compute $Q$ with $\theta = N_{\text{obs}}$ to get $Q_{\text{obs}}$
- Calculate CL$_s$ as follows:
  \[
  CL_{s+b} = P(Q \leq Q_{\text{obs}} | H_1) \\
  CL_b = P(Q \leq Q_{\text{obs}} | H_0) \\
  CL_s = CL_{s+b} / CL_b
  \]
- Repeat the calculation of CL$_s$ for different signal mass hypotheses
- Masses with $CL_s \leq 1 - \alpha$ are excluded at the $\alpha$ confidence level