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

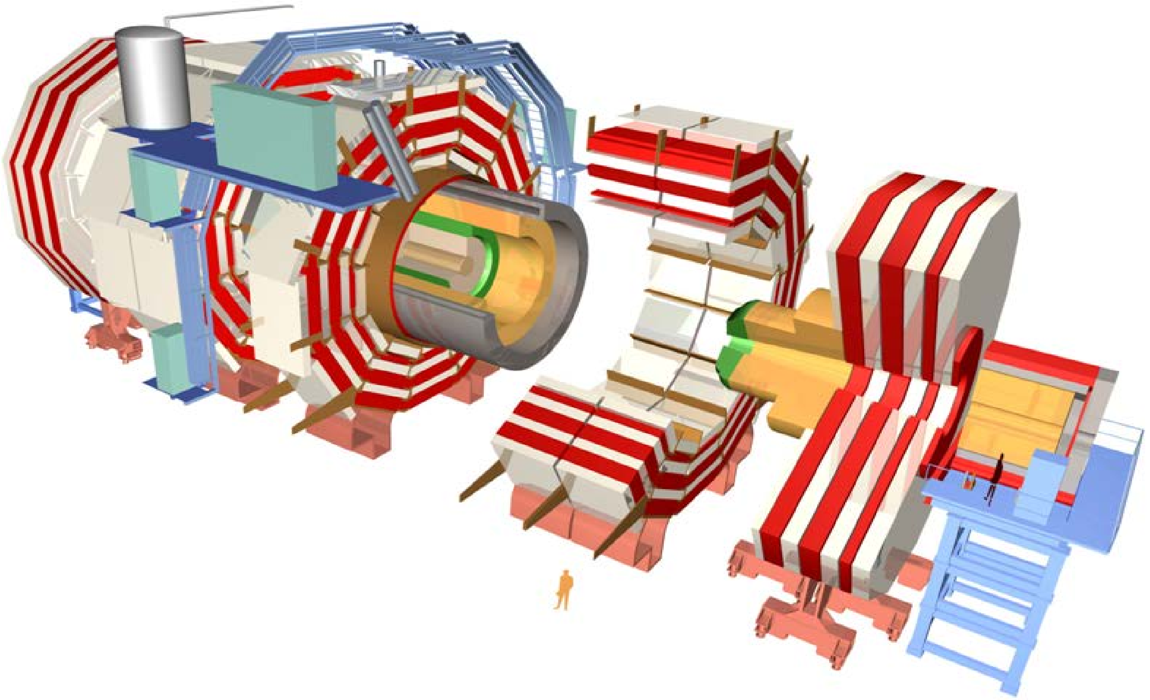
Kevin Pedro
(University of Maryland)
for the CMS Collaboration
May 5, 2014

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: $LQ_3 \rightarrow t + \tau$ search (CDS, twiki)
  - CMS-EXO-12-032: $LQ_3 \rightarrow b + \tau$ & RPV stop search (CDS, twiki)

Outline:

1. Leptoquarks
2. $LQ_3 \rightarrow t + \tau$ results
3. $LQ_3 \rightarrow b + \tau$ results
4. R-parity violation
5. RPV stop results
6. Conclusions

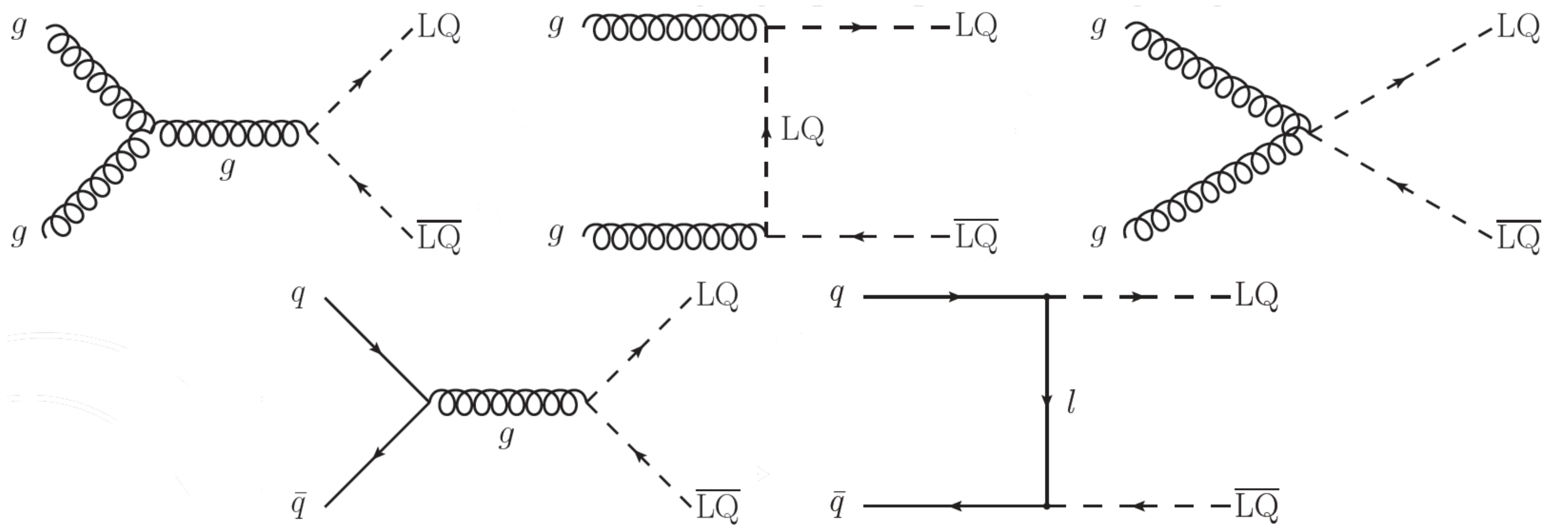


Leptoquarks

- 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 α_s



$LQ_3 \to t + \tau$ Search

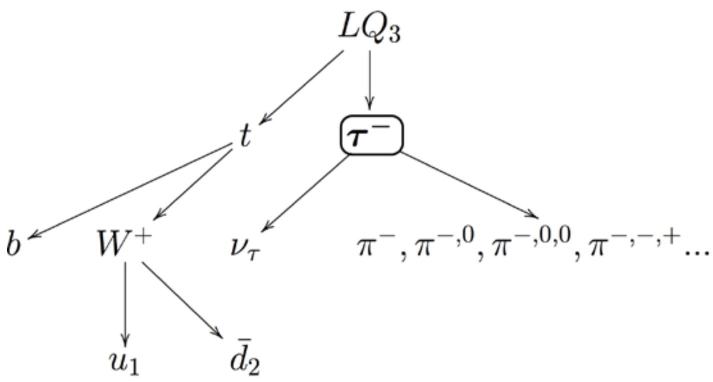
$Q = -1/3$

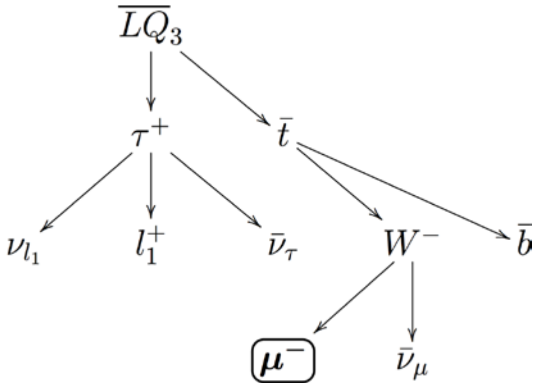
$\beta(LQ_3 \to t + \tau) = 1$

$\mu^{\pm}\tau_{h}^{\pm}\ell^{\mp}2jb\bar{b}$,

$\mu^{\pm}\tau_{h}^{\pm}\ell^{\mp}\ell^{\mp}b\bar{b}$

$(\ell \in \{e, \mu, \tau\})$



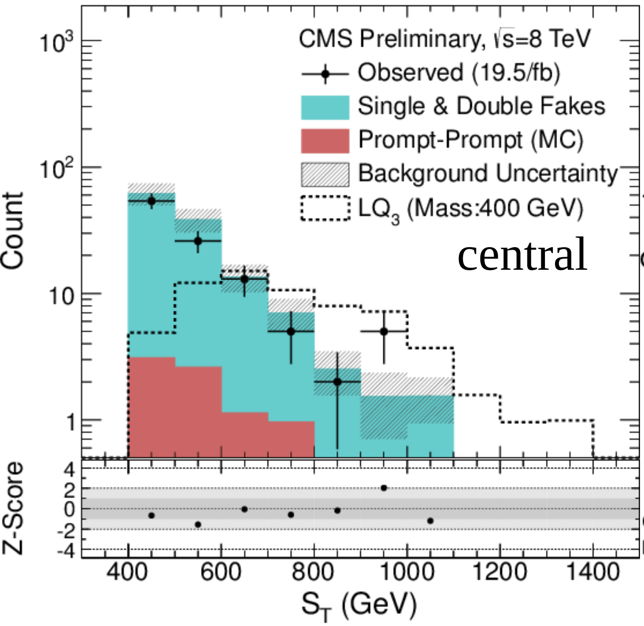


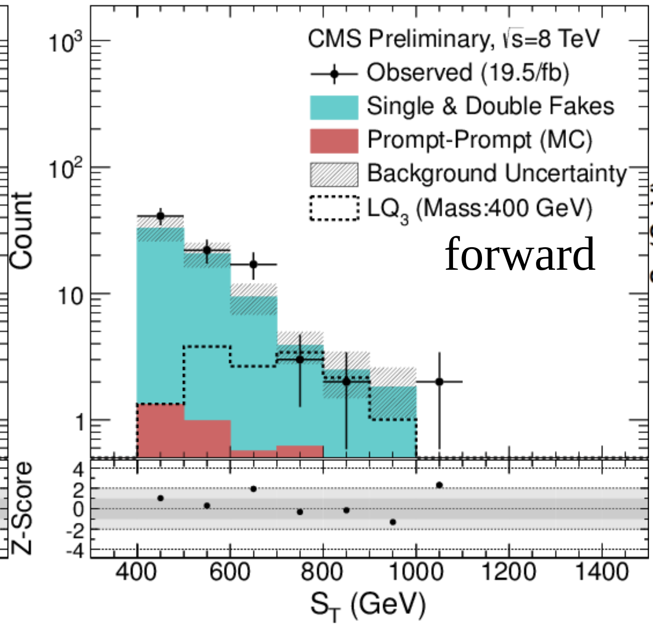
- Required same-sign $\mu\tau_h$ pair reduces SM backgrounds
- Major background mainly from jets misidentified as τ_h ("fakes") and also from leptons from heavy flavor decays within jets, estimated from data using Loose-to-Tight Extrapolation Method (LTEM): ($\hat{x} = 1 - x$)

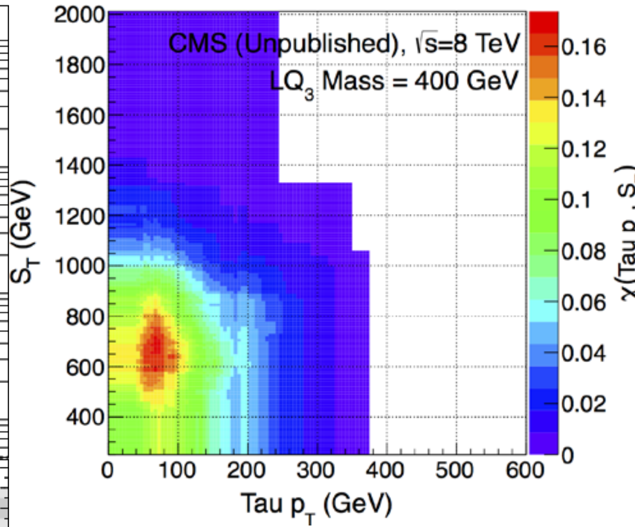
$$\begin{pmatrix} N_{FF} \\ N_{FP} \\ N_{PF} \\ N_{PP} \end{pmatrix} = \frac{1}{(p_\mu - f_\mu)(p_\tau - f_\tau)} \begin{pmatrix} p_\mu \cdot p_\tau & -p_\mu \cdot \widehat{p_\tau} & -\widehat{p_\mu} \cdot p_\tau & \widehat{p_\mu} \cdot \widehat{p_\tau} \\ -p_\mu \cdot f_\tau & p_\mu \cdot \widehat{f_\tau} & \widehat{p_\mu} \cdot f_\tau & -\widehat{p_\mu} \cdot \widehat{f_\tau} \\ -f_\mu \cdot p_\tau & f_\mu \cdot \widehat{p_\tau} & \widehat{f_\mu} \cdot p_\tau & -\widehat{f_\mu} \cdot \widehat{p_\tau} \\ f_\mu \cdot f_\tau & -f_\mu \cdot \widehat{f_\tau} & -\widehat{f_\mu} \cdot f_\tau & \widehat{f_\mu} \cdot \widehat{f_\tau} \end{pmatrix} \begin{pmatrix} N_{LL} \\ N_{LT} \\ N_{TL} \\ N_{TT} \end{pmatrix}$$

- Minor backgrounds estimated from MC

$LQ_3 \rightarrow t + \tau$ Details







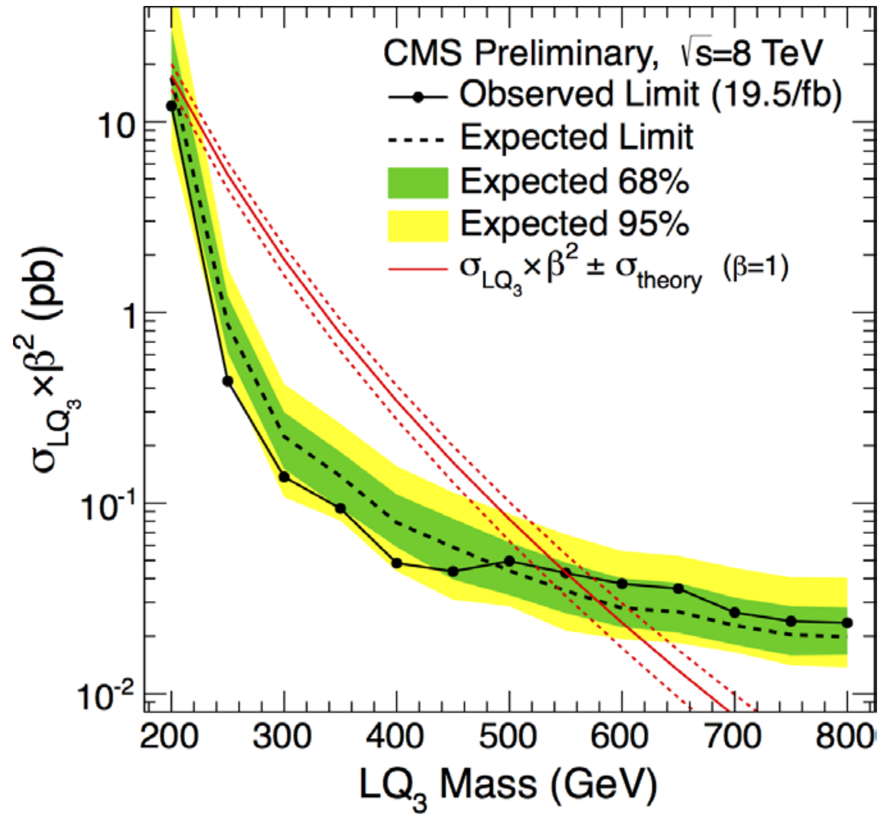
$$\chi\left(p_{\mathrm{T}}^{\tau}, S_{\mathrm{T}}\right) = \frac{\varepsilon\left(p_{\mathrm{T}}^{\tau}, S_{\mathrm{T}}\right)}{1 + \sqrt{B\left(p_{\mathrm{T}}^{\tau}, S_{\mathrm{T}}\right)}}$$

- 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 ($|\tilde{\eta}| < 0.9$, $|\tilde{\eta}| \geq 0.9$) based on event centrality

$$\widetilde{|\eta|} = \Theta^{-1}\left(\frac{1}{N_\mu + N_\tau + N_e} \sum_{All\ leptons:\ \ell} \Theta(|\eta_\ell|)\right)$$

- Final cuts on S_T and $p_T(\tau_h)$ are optimized for each LQ_3 mass hypothesis using Punzi figure of merit χ (maximize signal-background separation)

$LQ_3 \rightarrow t + \tau$ Results



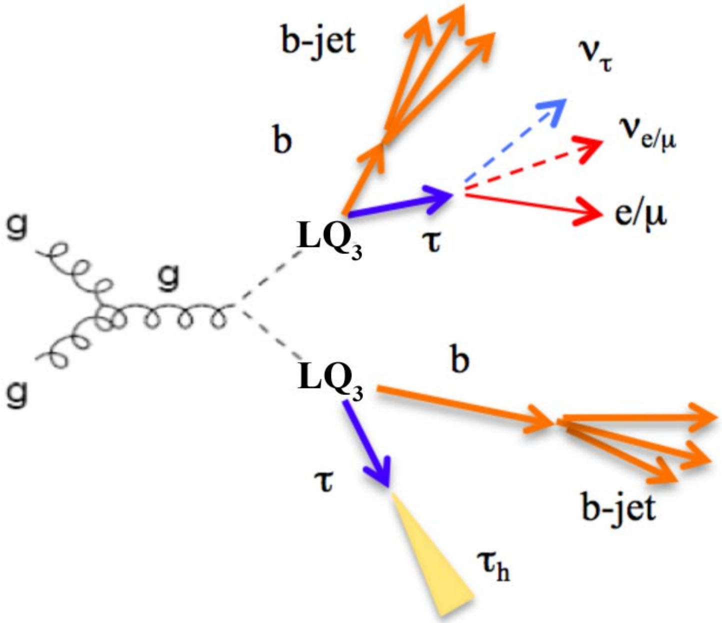
- ➢ Assuming $\beta(LQ_3 \rightarrow t + \tau) = 1$, pair production of $Q = -1/3$ scalar LQ_3 excluded at 95% CL for masses up to **550 GeV** (582 GeV expected)
- Leading systematic uncertainty from LTEM:
  21-28% (central), 21-36% (forward)

$LQ_3 \rightarrow b + \tau$ Search

$Q = -2/3, -4/3$

$LQ_3 \rightarrow b + \tau$

$\ell^{\pm}\tau_{\mathrm{h}}^{\mp}b\bar{b} \quad (\ell \in \{e, \mu\})$



- Reducible background from jets misidentified as τ_h estimated from data

$$N_{\mathrm{misID}\ \tau}^{(\mathrm{main})} = \sum_{\mathrm{events}}^{(\mathrm{anti\text{-}iso})} \frac{1 - \prod_\tau [1 - f(p_\mathrm{T}(\tau))]}{\prod_\tau [1 - f(p_\mathrm{T}(\tau))]}$$

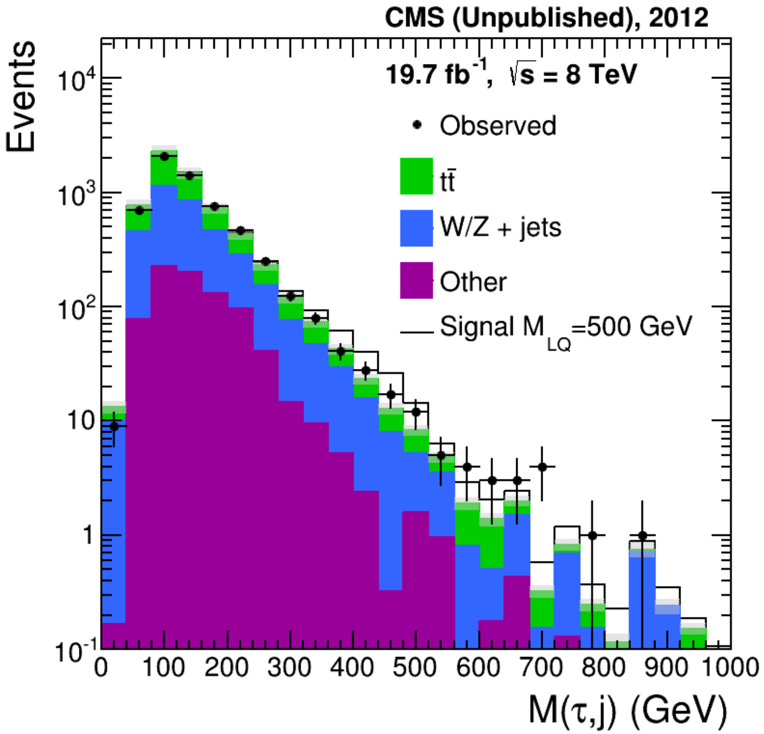
- Irreducible background from $t\bar{t}$ + jets with genuine τ_h estimated from data

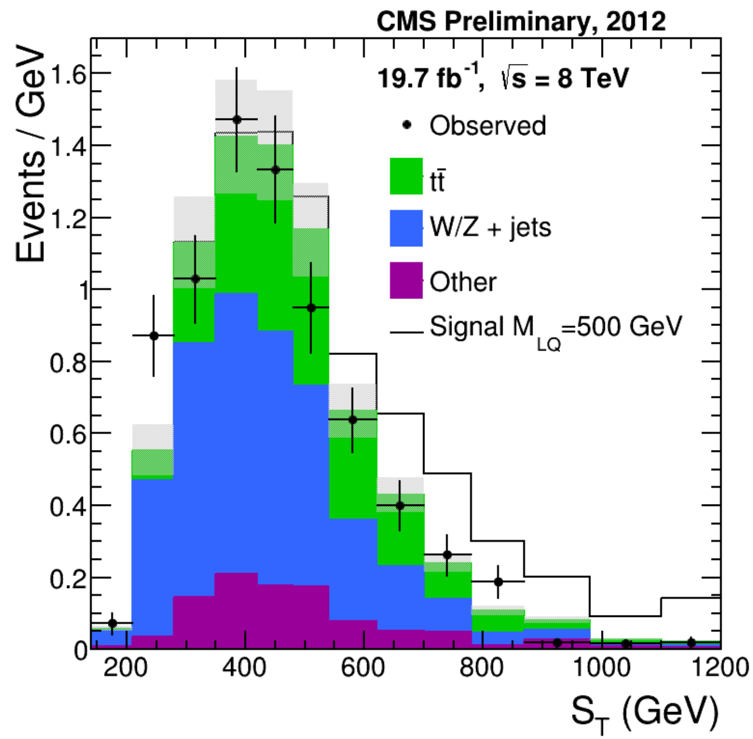
$$N_{\ell\tau_h} = N_{e\mu} \times \frac{\varepsilon^{\mathrm{sel}}_{\ell\tau_h}\rho^{\mathrm{sel}}_{\ell\tau_h}}{\varepsilon^{\mathrm{sel}}_{e\mu}\rho^{\mathrm{sel}}_{e\mu}} \times \frac{\varepsilon^{\mathrm{ID}}_{\ell}\varepsilon^{\mathrm{ID}}_{\tau_h}}{\varepsilon^{\mathrm{ID}}_{e}\varepsilon^{\mathrm{ID}}_{\mu}}$$
$$\times \frac{\mathcal{A}_{\ell\tau_h} B_{W\ell} B_{W\tau_h} + \mathcal{A}_{\tau_\ell\tau_h} B_{W\tau_\ell} B_{W\tau_h}}{\mathcal{A}_{e\mu} B_{We} B_{W\mu} + \mathcal{A}_{\mu\tau_e} B_{W\mu} B_{W\tau_e} + \mathcal{A}_{e\tau_\mu} B_{We} B_{W\tau_\mu} + \mathcal{A}_{\tau_e\tau_\mu} B_{W\tau_e} B_{W\tau_\mu}}$$

- Minor backgrounds estimated from MC

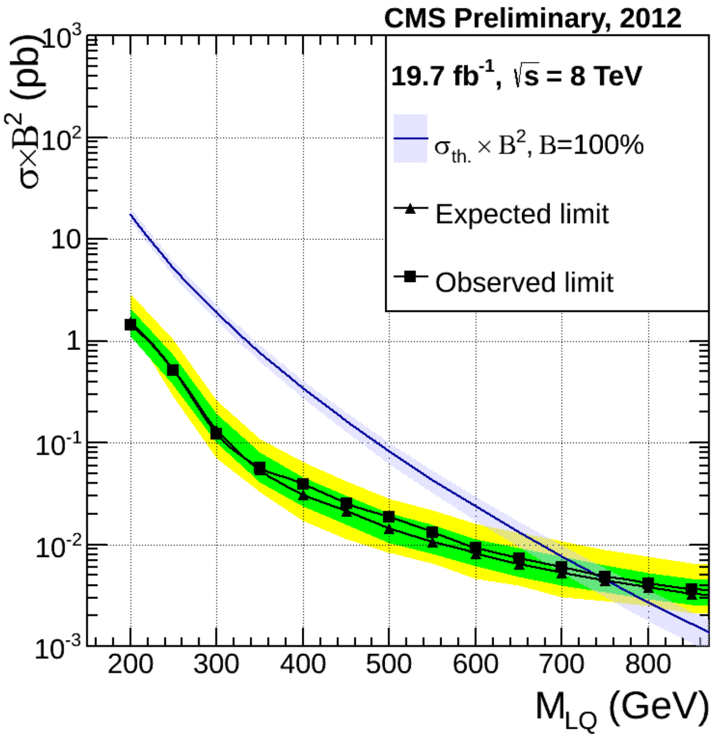
$LQ_3 \rightarrow b + \tau$ Details

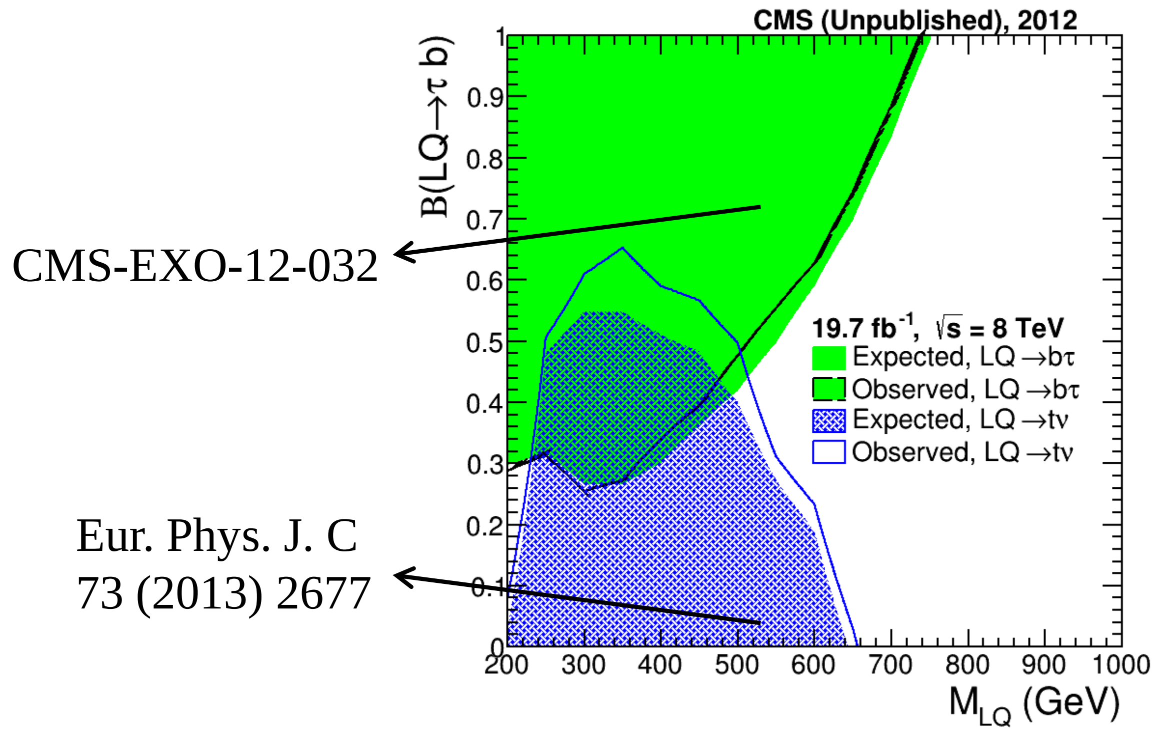
- S_T is the scalar sum of p_T for all required final state objects (e/μ, τ_h, 2 jets)
- $e^{\pm}/\mu^{\pm} + \tau_h^{\mp} + \geq 2$ jets, with at least 1 jet b-tagged
- Require mass of the τ_h and a paired jet, M(τ,j), to be greater than 250 GeV
  - Pairing is chosen to minimize the difference between the mass of the tau and one jet and the mass of the e/μ and the other jet
- Limits are set using the S_T distribution





$LQ_3 \rightarrow b + \tau$ Results





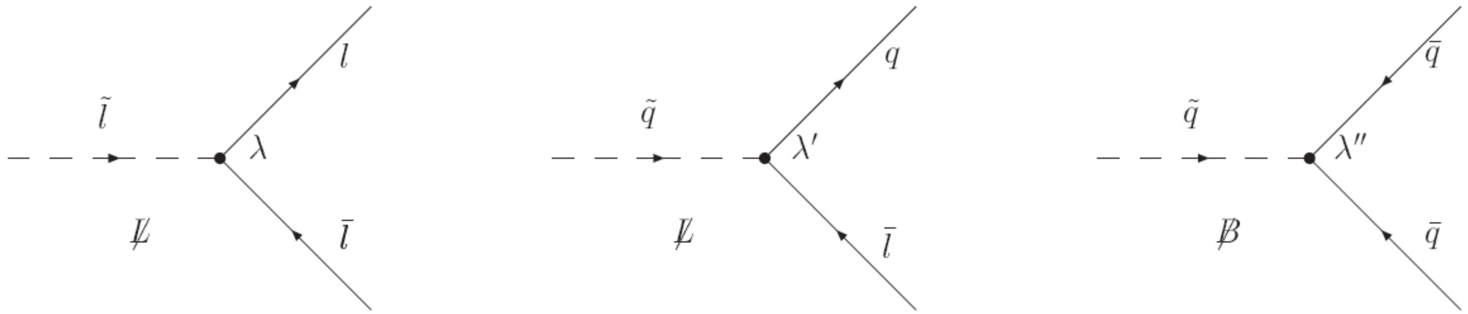
- Assuming $B(LQ_3 \rightarrow b + \tau) = 1$, pair production of Q = –2/3 or –4/3 scalar LQ_3 excluded at 95% CL for masses up to **740 GeV** (754 GeV expected)
- 95% CL limits also calculated for varying branching fraction (right)

- 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

$$W \ni \frac{1}{2}\lambda_{ijk}L_iL_jE_k^c + \lambda'_{ijk}L_iQ_jD_k^c + \frac{1}{2}\lambda''_{ijk}U_i^cD_j^cD_k^c + \mu_iL_iH_u$$



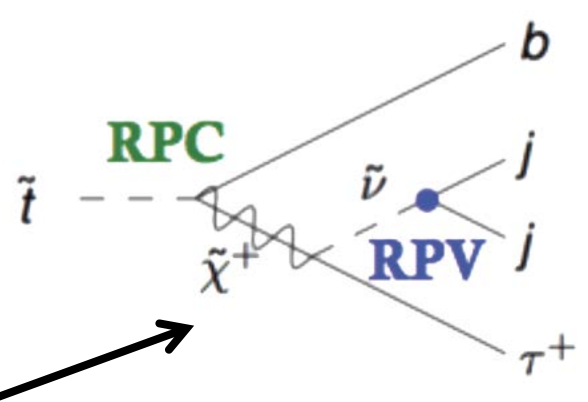
- These decays present signatures without high MET, avoiding strong limits on much of the parameter space of R-parity conserving SUSY
- Stops and higgsinos are typically lighter than the other scalar SUSY particles in natural models

➢ Third generation of superpartners potentially accessible at LHC energies

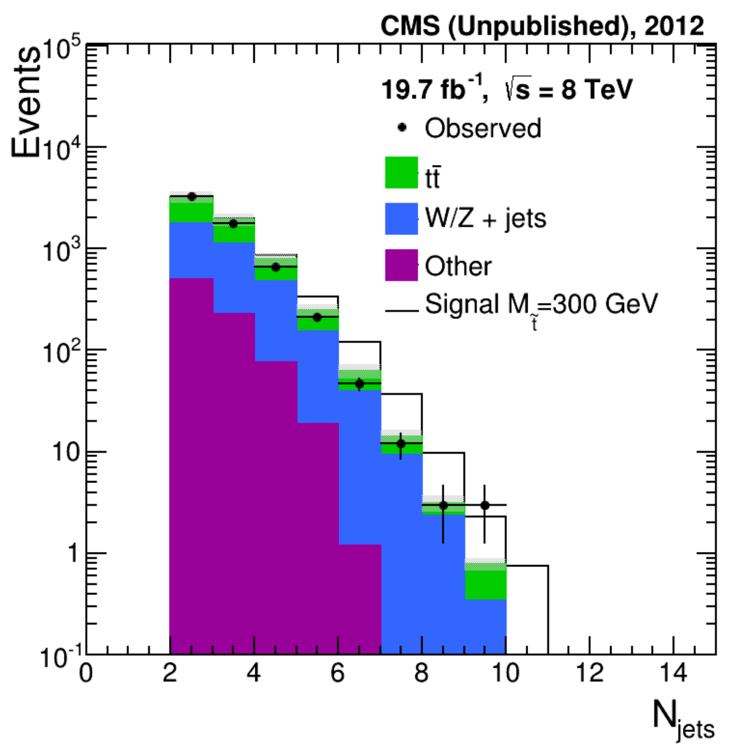
- Searches consider simplified models with other SUSY particles decoupled

RPV Stop Searches

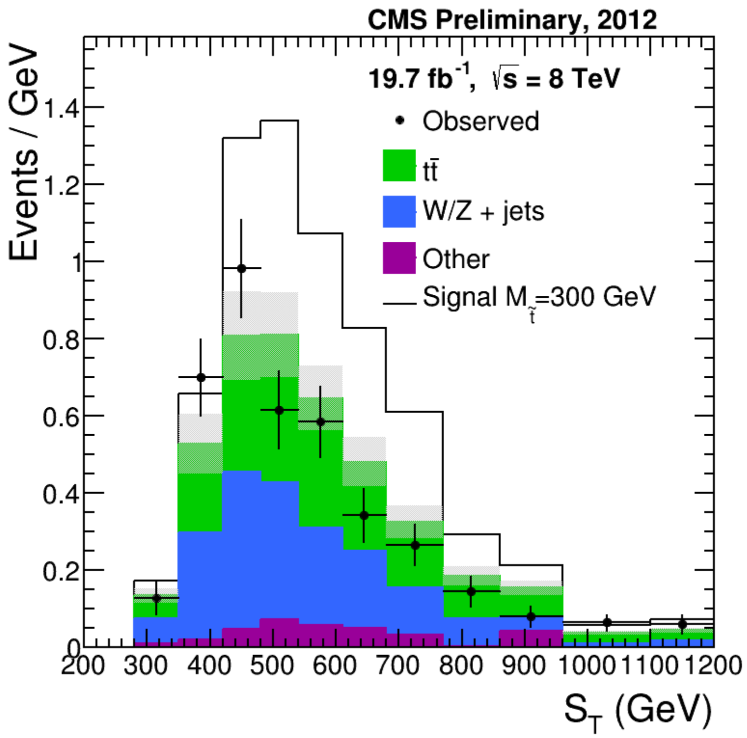
- Limits on pair production of stops decaying directly through λ'_{333} coupling can be extracted from $LQ_3 \rightarrow b + \tau$ search
- Limits on pair production of sbottoms decaying directly through λ'_{333} coupling can be extracted from $LQ_3 \rightarrow t + \tau$ search

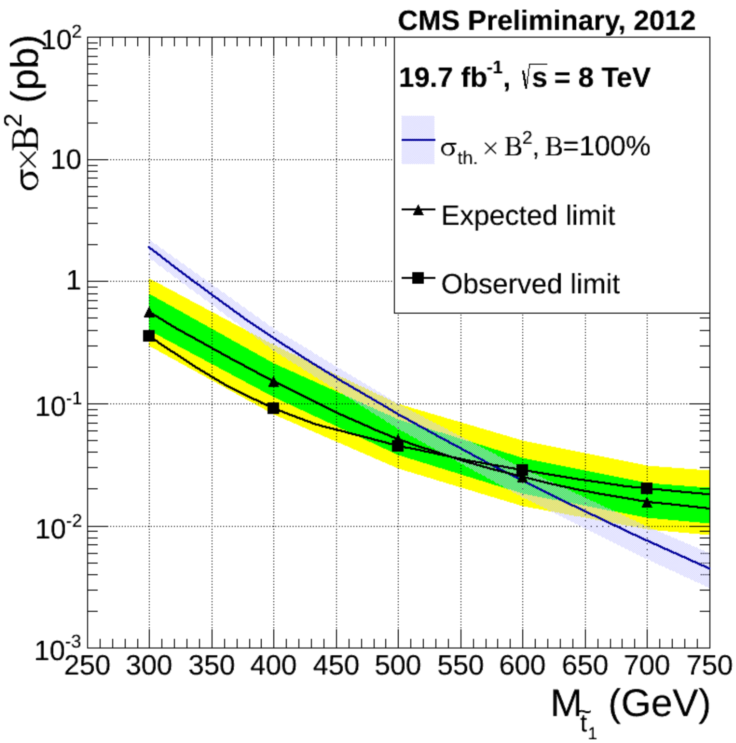


- The stop can have a chargino-mediated decay if the chargino is lighter than the stop, involving RPV coupling λ'_{3jk} (j, k = 1, 2)
  - Produces final state similar to $LQ_3 \rightarrow b + \tau$ search, but with extra jets: $\ell^{\pm}\tau_h^{\mp}b\bar{b}4j \quad (\ell \in \{e, \mu\})$
  - Search proceeds in same way, but requires $N_{jet} \geq 5$ (instead of $M(\tau,j)$ cut)
  - S_T is the scalar sum of p_T for all required final state objects (e/μ, τ_h, 5 jets)



RPV Stop Results





- Assuming 100% branching fraction for the chargino-mediated decay of the stop involving the λ'_{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)

Conclusions

- 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 $\boldsymbol{\lambda'_{333}}$ 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 $\boldsymbol{\lambda'_{3jk}}$ 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

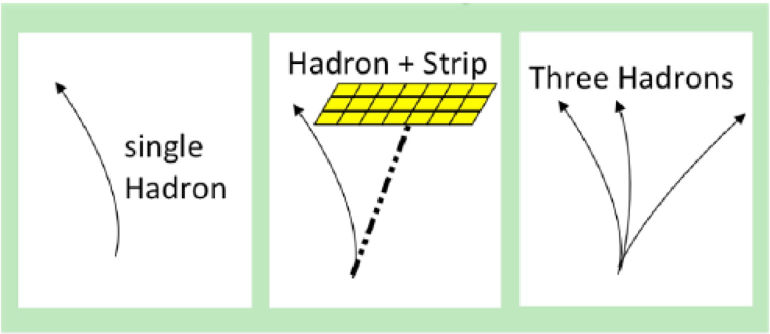
References

1. W. Buchmüller, R. Rückl, and D. Wyler, "Leptoquarks in lepton-quark collisions", *Phys. Lett. B* 191 (1987), no. 4, 442 – 448.
2. S. Davidson, D. Bailey, B. Campbell, "Model independent constraints on leptoquarks from rare processes", *Z. Phys. C* 61, 613-643 (1994).
3. M. Krämer, T. Plehn, M. Spira, and P. M. Zerwas, "Pair production of scalar leptoquarks at the CERN LHC", *Phys. Rev. D* 71 (Mar, 2005) 057503
4. J. Evans and Y. Kats, "LHC searches examined via the RPV MSSM", in *The 2013 European Physical Society Conference on High Energy Physics*. SISSA, 2013. arXiv:1311.0890. PoS(EPS2013)287.
5. R. Barbier et al., "R-Parity-violating supersymmetry", *Physics Reports* 420 (2005), no. 16, 1 – 195.
6. CMS Collaboration, "Performance of tau-lepton reconstruction and identification in CMS", *JINST* 7 (2012) 01001.
7. A. L. Read, "Modified frequentist analysis of search results (the CLs method)", CERN Report CERN-OPEN-2000-005, 2000.

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 (π^0)
  - ν_τ



- CMS uses the **Hadron Plus Strips** (HPS) algorithm to reconstruct τ_h decays
  1. Start from a Particle Flow jet
  2. Photons from π^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 τ_h (e.g. $t\bar{t}$ + jets, W + jets)
- Minor irreducible backgrounds: SM processes with genuine same-sign dilepton pairs (e.g. VV, $t\bar{t}W$, $t\bar{t}Z$, $W^{\pm}W^{\pm}qq$)
- Minor reducible background: Charge-mismeasured dilepton events (e.g. Z/γ^* + jets)

$LQ_3 \rightarrow b + \tau$:

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

MC simulation:

- *PYTHIA6*: LQ, stop, VV, QCD
- *MADGRAPH*: $t\bar{t}$, V + jets, $t\bar{t}V$, $W^{\pm}W^{\pm}qq$
- *POWHEG*: single top
- *TAUOLA* is used for processes containing real taus

Loose-to-Tight Extrapolation Method

$$\begin{pmatrix} N_{LL} \\ N_{LT} \\ N_{TL} \\ N_{TT} \end{pmatrix} = \begin{pmatrix} \widehat{f_\mu}\cdot\widehat{f_\tau} & \widehat{f_\mu}\cdot\widehat{p_\tau} & \widehat{p_\mu}\cdot\widehat{f_\tau} & \widehat{p_\mu}\cdot\widehat{p_\tau} \\ \widehat{f_\mu}\cdot f_\tau & \widehat{f_\mu}\cdot p_\tau & \widehat{p_\mu}\cdot f_\tau & \widehat{p_\mu}\cdot p_\tau \\ f_\mu\cdot\widehat{f_\tau} & f_\mu\cdot\widehat{p_\tau} & p_\mu\cdot\widehat{f_\tau} & p_\mu\cdot\widehat{p_\tau} \\ f_\mu\cdot f_\tau & f_\mu\cdot p_\tau & p_\mu\cdot f_\tau & p_\mu\cdot p_\tau \end{pmatrix} \begin{pmatrix} N_{FF} \\ N_{FP} \\ N_{PF} \\ N_{PP} \end{pmatrix}$$

$$\begin{pmatrix} N_{FF} \\ N_{FP} \\ N_{PF} \\ N_{PP} \end{pmatrix} = \frac{1}{(p_\mu - f_\mu)(p_\tau - f_\tau)} \begin{pmatrix} p_\mu\cdot p_\tau & -p_\mu\cdot\widehat{p_\tau} & -\widehat{p_\mu}\cdot p_\tau & \widehat{p_\mu}\cdot\widehat{p_\tau} \\ -p_\mu\cdot f_\tau & p_\mu\cdot\widehat{f_\tau} & \widehat{p_\mu}\cdot f_\tau & -\widehat{p_\mu}\cdot\widehat{f_\tau} \\ -f_\mu\cdot p_\tau & f_\mu\cdot\widehat{p_\tau} & \widehat{f_\mu}\cdot p_\tau & -\widehat{f_\mu}\cdot\widehat{p_\tau} \\ f_\mu\cdot f_\tau & -f_\mu\cdot\widehat{f_\tau} & -\widehat{f_\mu}\cdot f_\tau & \widehat{f_\mu}\cdot\widehat{f_\tau} \end{pmatrix} \begin{pmatrix} N_{LL} \\ N_{LT} \\ N_{TL} \\ N_{TT} \end{pmatrix}$$

Yields are denoted as $N_{(\mu)(\tau)}$, where (μ) is status of the muon and (τ) is status of the τ_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*), $\hat{f} = 1 - f$
p: prompt rate (probability that a prompt lepton is *T*), $\hat{p} = 1 - p$

$LQ_3 \rightarrow t + \tau$ 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
- τ_h ID efficiency: 6%, μ 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)
  τ_h ES: 4.5-8.7% (background), 0.4-3.8% (signal)
  - ES: energy scale
  - jet ES depends on p_T and η
- 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

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

Reducible Bkg. Est. ($LQ_3 \rightarrow b + \tau$)

The reducible background from jets misidentified as τ_h can be estimated from data using two control samples:

1. $Z \rightarrow \mu^+\mu^- +$ jets
2. Events in which all τ_h objects fail isolation ("anti-isolated")

from $Z \rightarrow \mu\mu$ control region

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

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

from anti-isolated control region
(in each $\ell\tau_h$ 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 eμ control region can be used to estimate the irreducible $t\bar{t}$ background (containing real taus) from data for the $\ell\tau$ channels.

$$N_{\ell\tau_h} = N_{e\mu}$$

→ eμ channel

$$\times \frac{\varepsilon^{\text{sel}}_{\ell\tau_h}\rho^{\text{sel}}_{\ell\tau_h}}{\varepsilon^{\text{sel}}_{e\mu}\rho^{\text{sel}}_{e\mu}}$$

→ $t\bar{t}$ simulation, scale factors on control samples

$$\times \frac{\varepsilon^{\text{ID}}_{\ell}\varepsilon^{\text{ID}}_{\tau_h}}{\varepsilon^{\text{ID}}_{e}\varepsilon^{\text{ID}}_{\mu}}$$

→ $t\bar{t}$ simulation (with scale factors)

$$\times \frac{\mathcal{A}_{\ell\tau_h}B_{W\ell}B_{W\tau_h} + \mathcal{A}_{\tau_\ell\tau_h}B_{W\tau_\ell}B_{W\tau_h}}{\mathcal{A}_{e\mu}B_{We}B_{W\mu} + \mathcal{A}_{\mu\tau_e}B_{W\mu}B_{W\tau_e} + \mathcal{A}_{e\tau_\mu}B_{We}B_{W\tau_\mu} + \mathcal{A}_{\tau_e\tau_\mu}B_{W\tau_e}B_{W\tau_\mu}}$$

→ Madgraph, PDG

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

$LQ_3 \rightarrow b + \tau$ Systematic Uncertainties

- Reducible background estimation: 16-24%
  - from statistical uncertainty on fake rate, variation in fake rate for $t\bar{t}$ 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

$LQ_3 \rightarrow b + \tau$ & RPV Stop Results Tables

$LQ_3 \rightarrow b + \tau$, and RPV stop decaying through λ'_{333}

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

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

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

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 θ 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:

$$Q = \prod_{i}^{\text{(channel)}} \prod_{j}^{(S_{\mathrm{T}}\ \text{bin})} \frac{P_{i,j}(\theta; N_{H_1})}{P_{i,j}(\theta; N_{H_0})}$$

- Perform numerous pseudo-experiments, varying θ, to compute a distribution of Q values for each hypothesis; compute Q with $\theta = N_{obs}$ to get Q_{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 α confidence level