Searches for Signatures of R-Parity Violating Models with the CMS Detector

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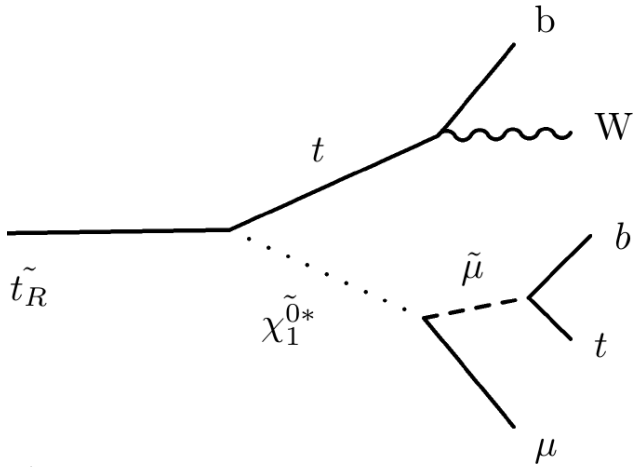
R-Parity Violating SUSY

- R-parity:
  - A multiplicative quantum number
  - Standard model (SM) particles: $R_p = +1$
  - SUSY partners: $R_p = -1$
- R-parity conservation (RPC):
  - Lightest SUSY particle (LSP) becomes stable.
  - Proton lifetime is protected.



- The SUSY Lagrangian can be expanded with the RPV terms†:

$$W_{\text{RPV}} = \frac{1}{2}\lambda_{ijk}L_iL_j\overline{E}_k + \lambda'_{ijk}L_iQ_j\overline{D}_k + \frac{1}{2}\lambda''_{ijk}\overline{U}_i\overline{D}_j\overline{D}_k$$

  - Any one of the λs doesn't facilitate proton decay by itself.
- General approach is:
  - An underlying RPC SUSY scenario is responsible for the production.
  - Focus on a given $\lambda > 0$ at a time.
  - λs are large enough to cause prompt decays.

† R. Barbier et al., "R-Parity-violating supersymmetry", *Phys. Rept.* **420** (2005) 1.

CMS Searches

- At CMS, RPV(-like) signatures are searched for in two categories:

	Benchmark Model (pair-production)	Final State	CMS PAS
SUSY: LSP RPV Decay†	$\tilde{g} \to uds/udb/csb$	$\geq 6j$	EXO-12-049
	$\tilde{g} \to tbs$	$\ell + \geq 6j$	SUS-12-015
	$\tilde{b} \to ts/td$	$\geq 2\ell + \geq 2b + \geq 2j\not{b}$	B2G-12-008
	$\tilde{t} \to t\mu tb/t\tau\mu\nu/t\mu e\nu$	$\geq 3\ell + \geq 1b$	SUS-13-003
	$\tilde{q} \to q\ell\ell\nu$ / $\tilde{g} \to q\bar{q}\ell\ell\nu$	4ℓ	SUS-13-010
Leptoquarks: mBRW model	$LQ_1 \to eq/\nu q$	$eejj,\ e\nu jj$	EXO-12-041*
	$LQ_2 \to \mu q/\nu q$	$\mu\mu jj,\ \mu\nu jj$	EXO-12-042
	$LQ_3 \to \tau b$ / $\tilde{t} \to q\bar{q}\tau b$	$\ell\tau_{had} + \geq 2j$	EXO-12-032
	$LQ_3 \to \tau t$	$\mu\tau_{had} + \geq 2j$	EXO-13-010*

All analyses presented here use the full $\sqrt{s} = 8$ TeV CMS dataset.

† A combined "RPV SUSY Searches at the CMS" paper will be available soon.

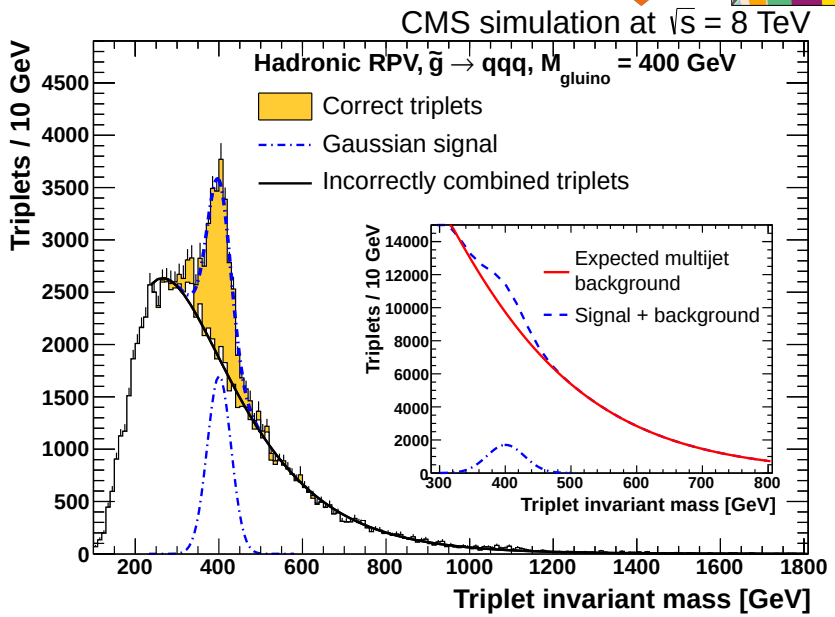
*NEW

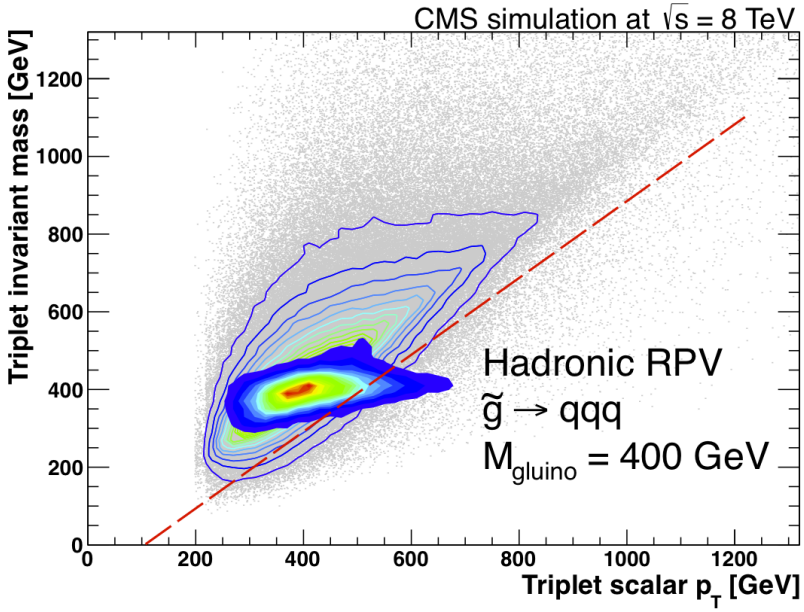
- Final states are characterized by an abundance of leptons and jets.
- All CMS results presented here are publicly available at:
  - https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS (Supersymmetry)
  - https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO (Exotica)
  - https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G (Beyond-two-generations)

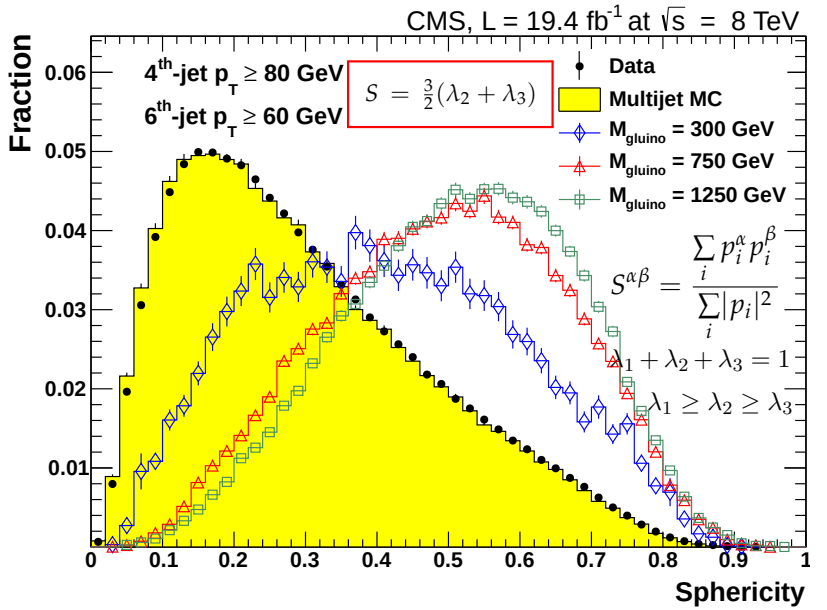
EXO-12-049: $\tilde{g} \to uds/udb/csb$

- $\tilde{g} \to q\tilde{q} \to qqq$ via $\lambda''_{112,113,223}$ RPV couplings.
- An all-hadronic search, where a 3-jet invariant mass peak is sought after over QCD and $t\bar{t}$+jets backgrounds.
- 3 signal regions are defined with at least 6 jets:

Selection criteria	Inclusive search	Heavy-flavour search low mass	Heavy-flavour search high mass
Mass range	400–1500 GeV	200–600 GeV	600–1500 GeV
Δ	110 GeV	110 GeV	110 GeV
Min. fourth-jet p_T	110 GeV	80 GeV	110 GeV
Min. sixth-jet p_T	110 GeV	60 GeV	110 GeV
Min. sphericity	0.4	—	0.4

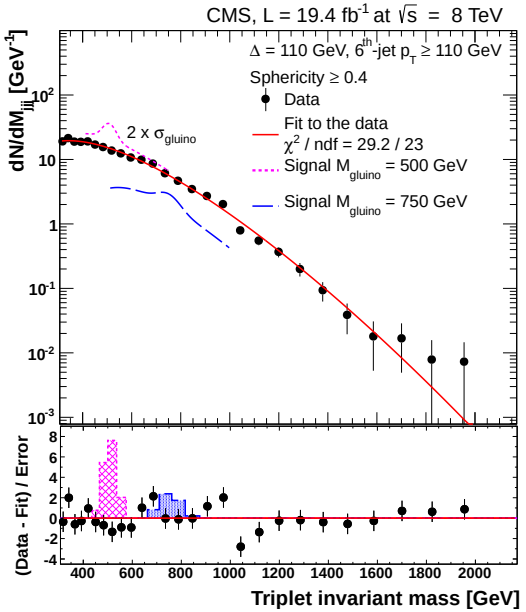


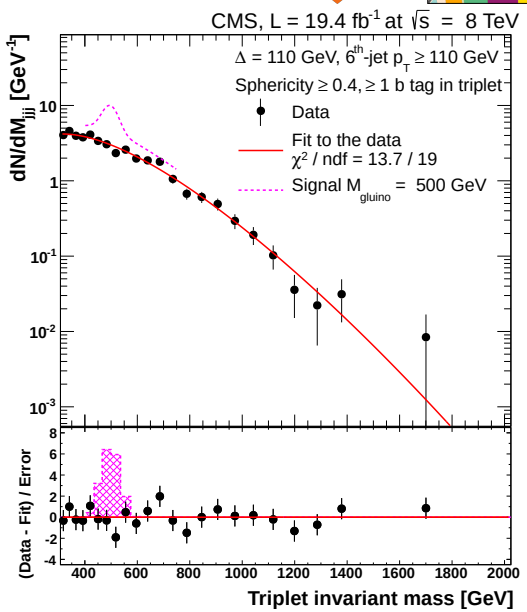


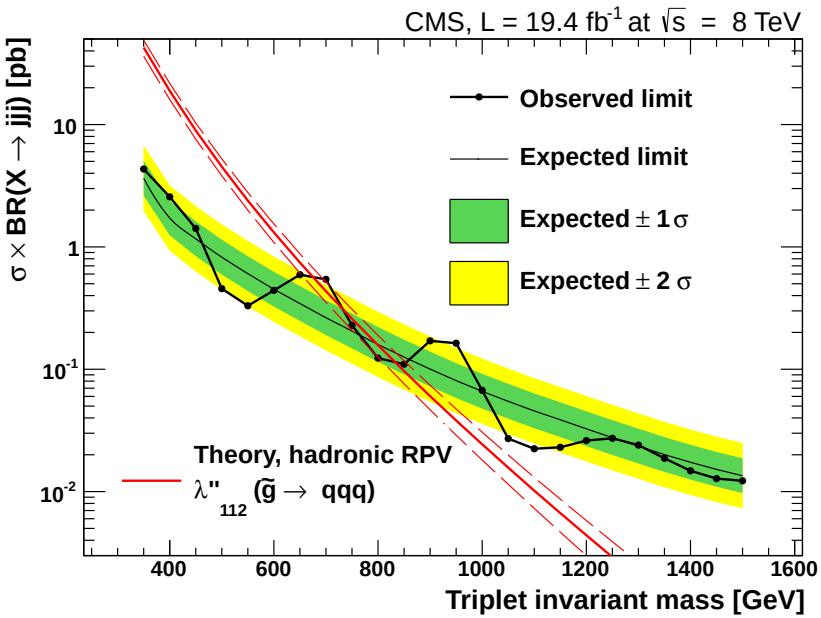


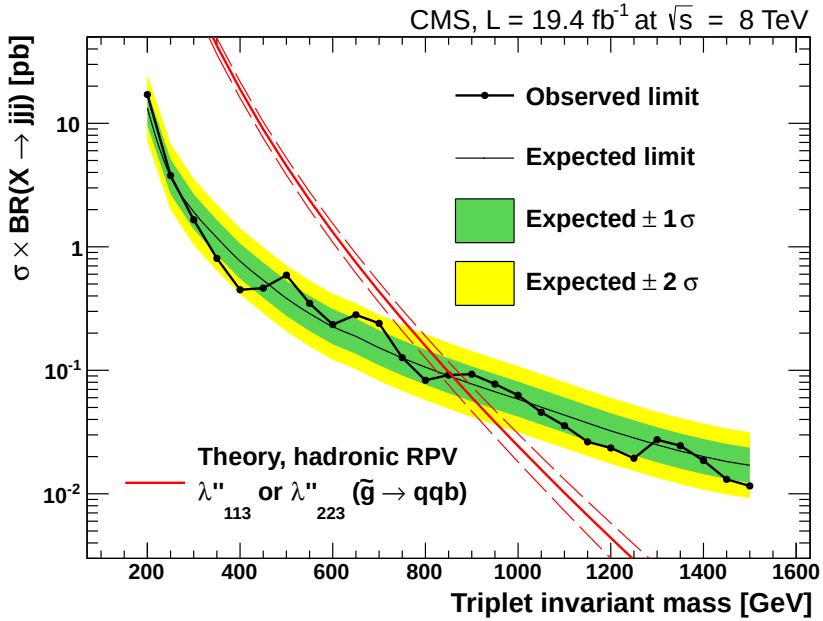
EXO-12-049: $\tilde{g} \to uds/udb/csb$

- Decays into light-flavor jets are excluded at 95% CL for $M_{\tilde{g}} < 650$ GeV.
- Decays into heavy-flavor containing jets are excluded at 95% CL for $200 < M_{\tilde{g}} < 835$ GeV.

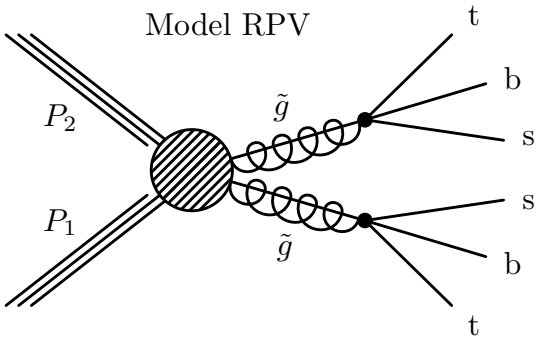




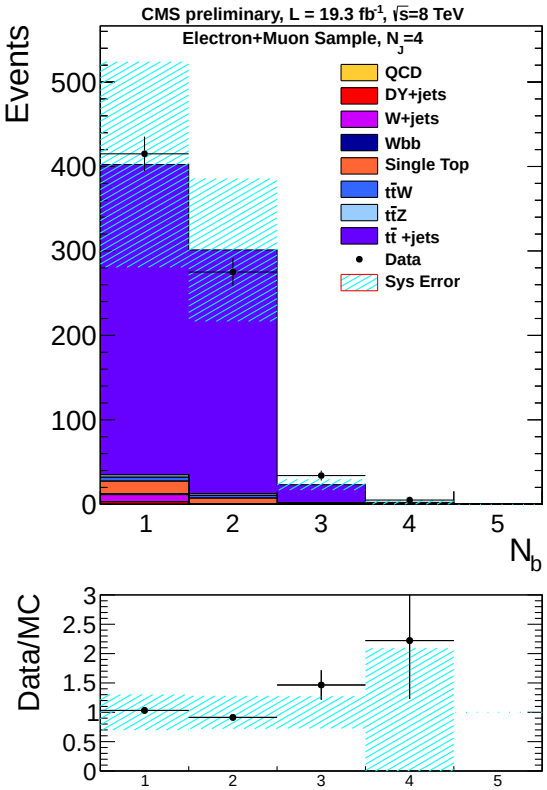


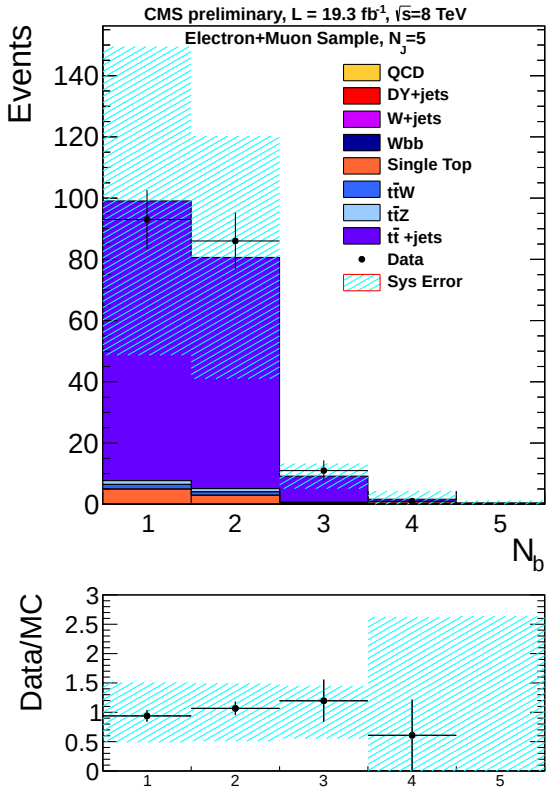


SUS-12-015: $\tilde{g} \to tbs$



electron	$p_T > 35$ GeV	$\lvert\eta\rvert < 2.5$
muon	$p_T > 35$ GeV	$\lvert\eta\rvert < 2.1$
jet	$p_T > 30$ GeV	$\lvert\eta\rvert < 2.4$

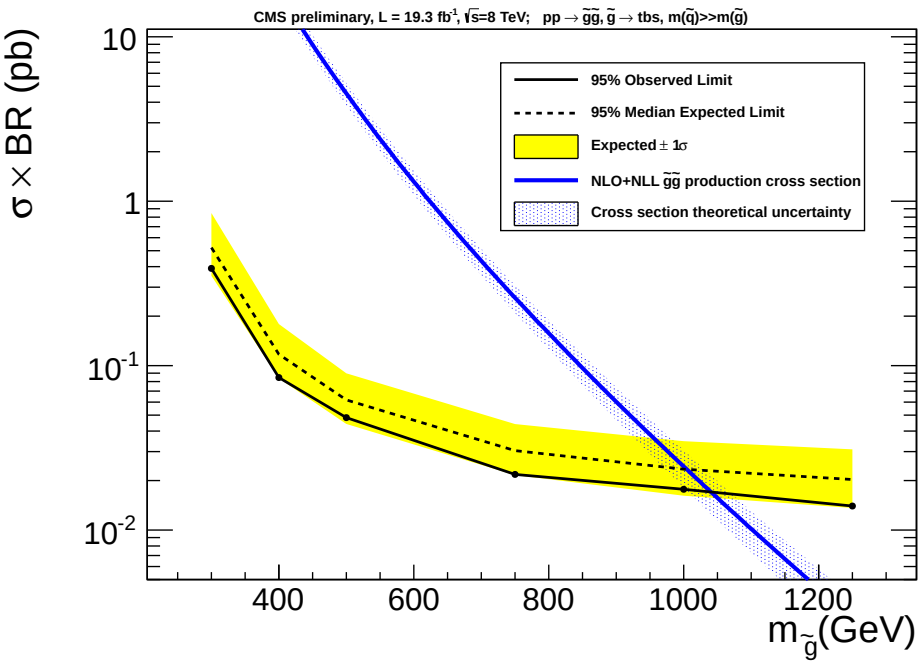


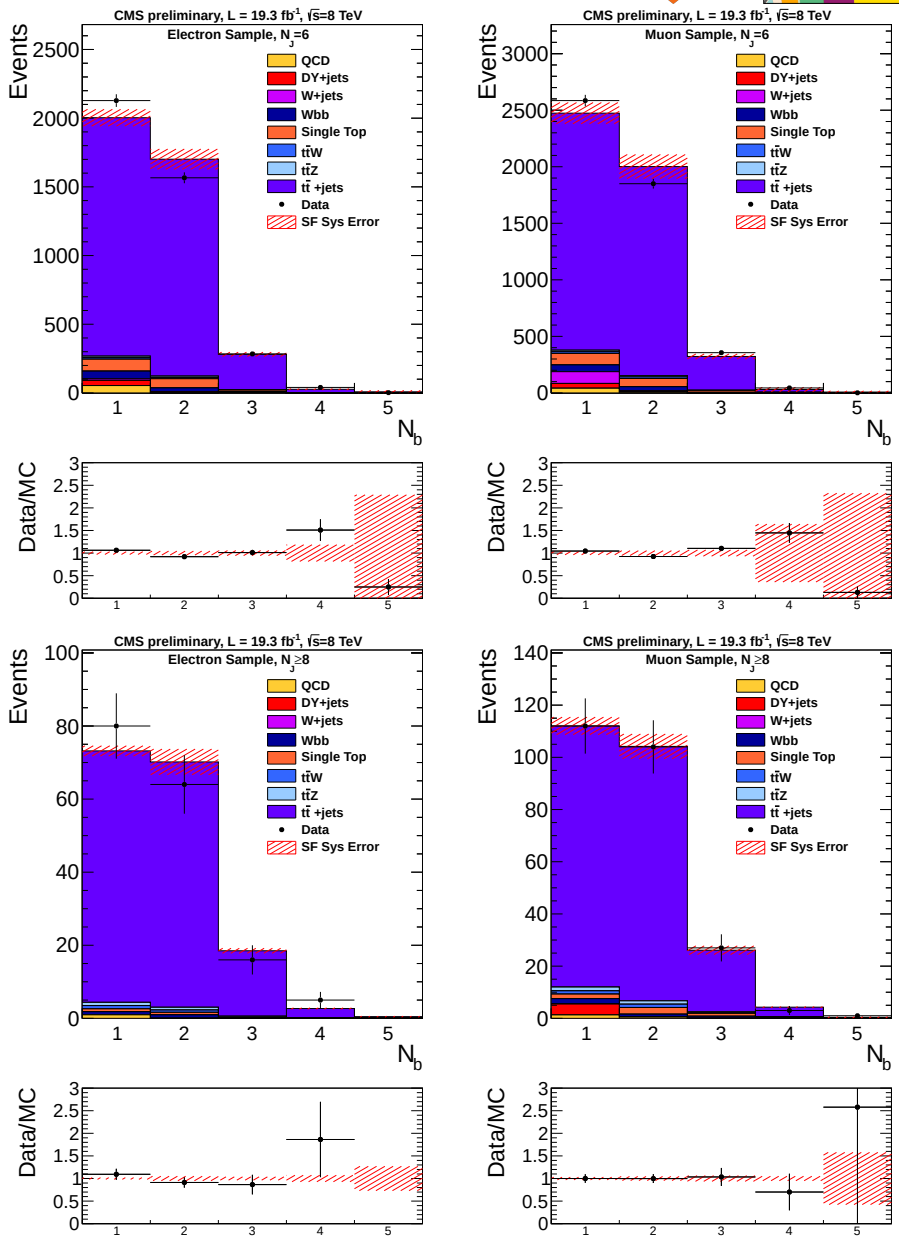


- $\tilde{g} \to t\tilde{t} \to tbs$
  via λ''_{332} RPV coupling.
- 6 search regions:
  $e/\mu + 6, 7, \geq 8$ jets (with $\geq$1 b-jet).
- Dominant backgrounds are $t\bar{t}$+jets, and $t\bar{t}Z/W$ for high b-jet multiplicities.
- B-tagging/mistagging scale factors and MC b-tag multiplicity modeling are verified in signal depleted regions ($N_{jet} < 6$).

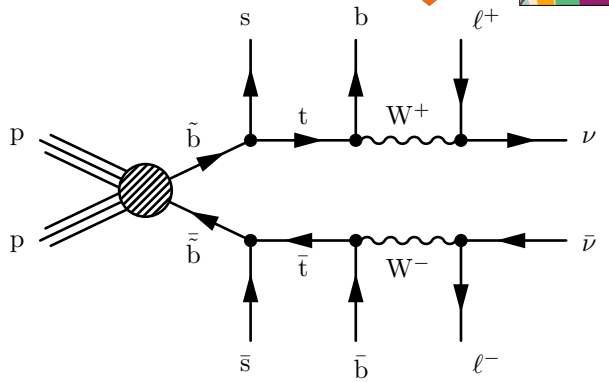
SUS-12-015: $\tilde{g} \to tbs$

- B-tag multiplicity distributions are used to discriminate signal vs. background.
- 95% CL exclusion for $M_{\tilde{g}} < 1036$ GeV, $\beta(\tilde{g} \to tbs) = 1$.



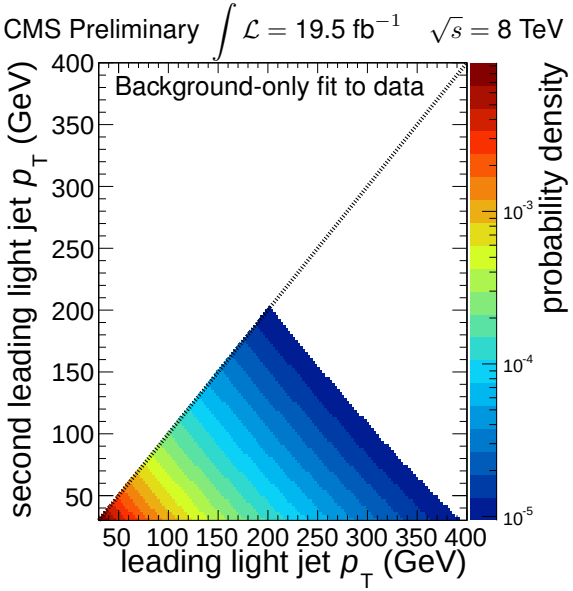


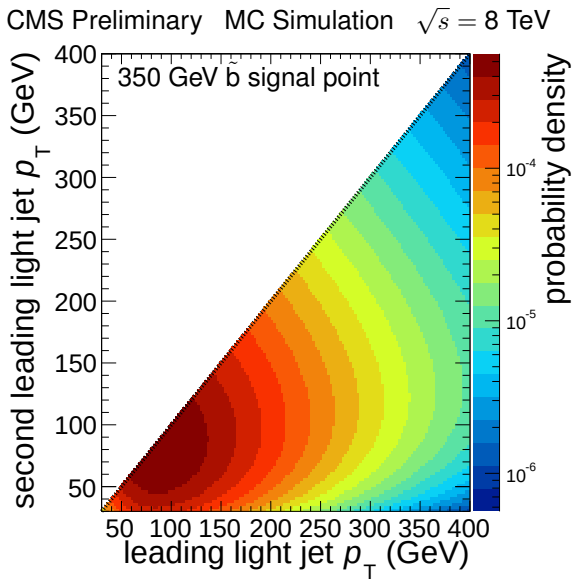
B2G-12-008: $\tilde{b} \to ts/td$



- Analysis requires fully leptonic decays of top quarks: $\geq 2\ell + \geq 2b + \geq 2j\not{E}$.
- Sensitive to decays via RPV couplings λ''_{332} and λ''_{331}.
- Dominant background is fully leptonic $t\bar{t}$+jets process.
- 3 signal (and 1 control) regions are defined using the p_T of the second leading light-jet:
  - [30-50] GeV, [50-80] GeV, [80-110] GeV, >110 GeV.

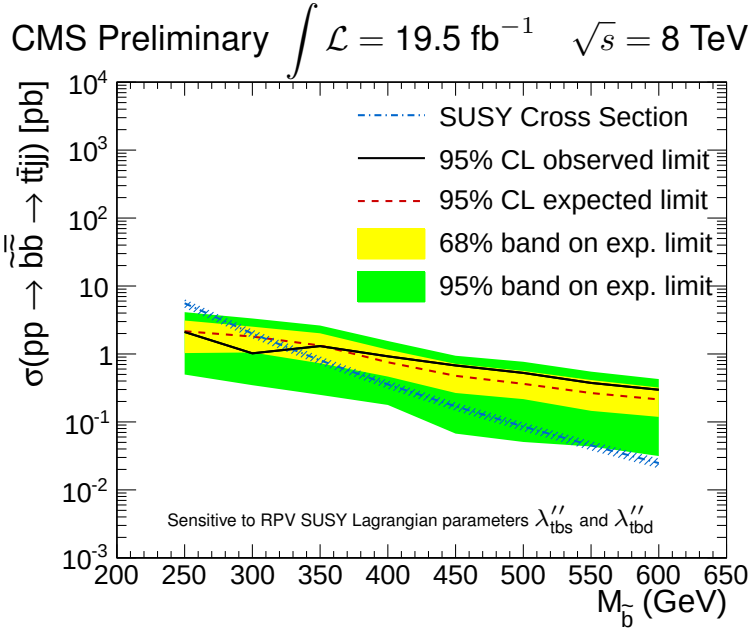
muon	$p_T > 20$ GeV	$\lvert\eta\rvert < 2.4$
electron	$p_T > 20$ GeV	$\lvert\eta\rvert < 2.5$
jet	$p_T > 30$ GeV	$\lvert\eta\rvert < 2.4$

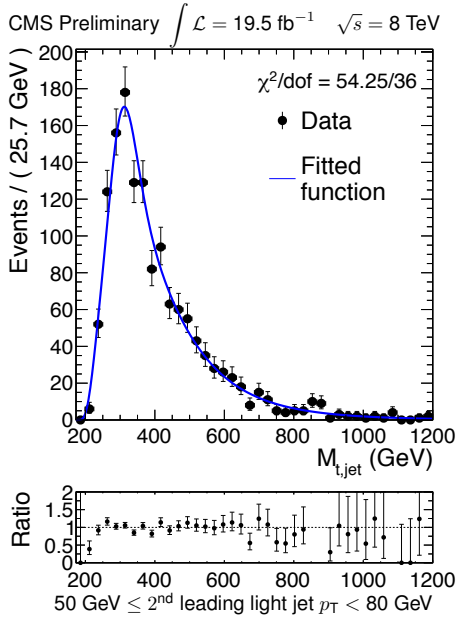


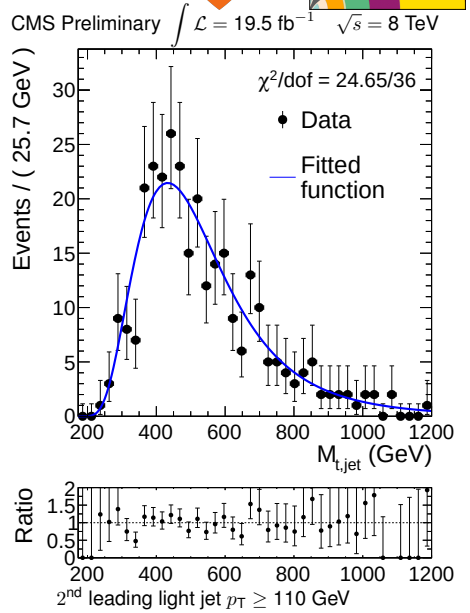


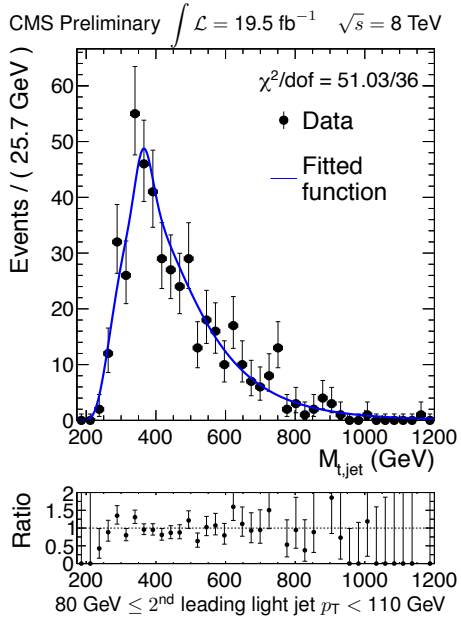
B2G-12-008: $\tilde{b} \to ts/td$

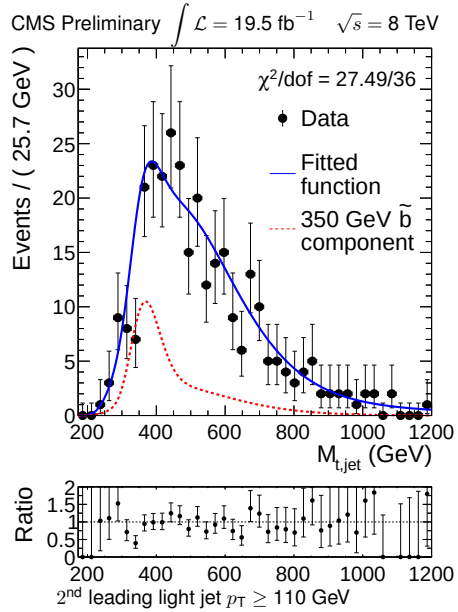
- Search is conducted over the 3D distribution of $p_{\mathrm{T}}^{1}(j_{\not b})$, $p_{\mathrm{T}}^{2}(j_{\not b})$ and $M(t_{reco}, j_{\not b})$.
  - Forms of background fit functions are guided by MC.
  - Signal shapes are extracted using MC entirely.
- 95% CL exclusion for $M_{\tilde{b}} < 307$ GeV, $\beta(\tilde{b} \to tj) = 1$.











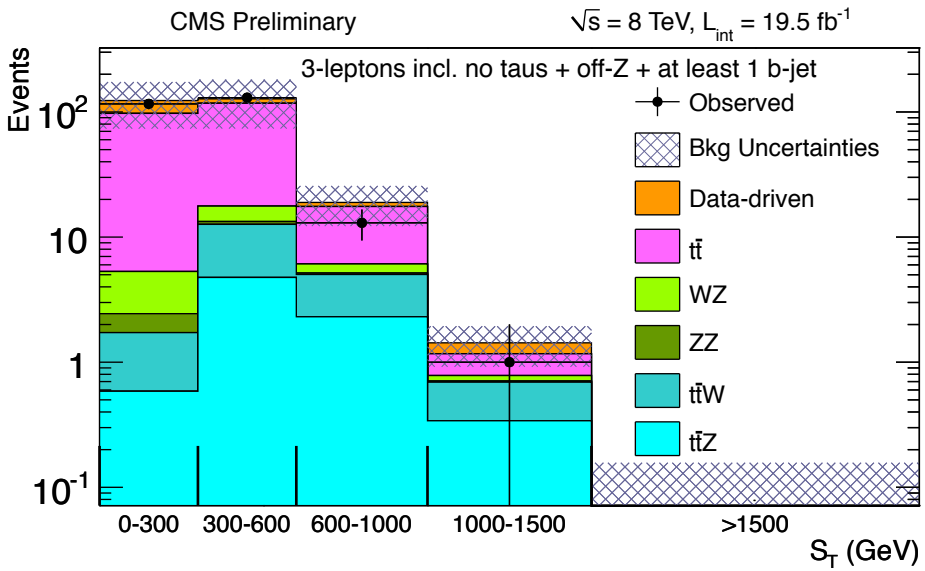
SUS-13-003: $\tilde{t} \to t\mu tb/t\tau\mu\nu/t\mu e\nu$

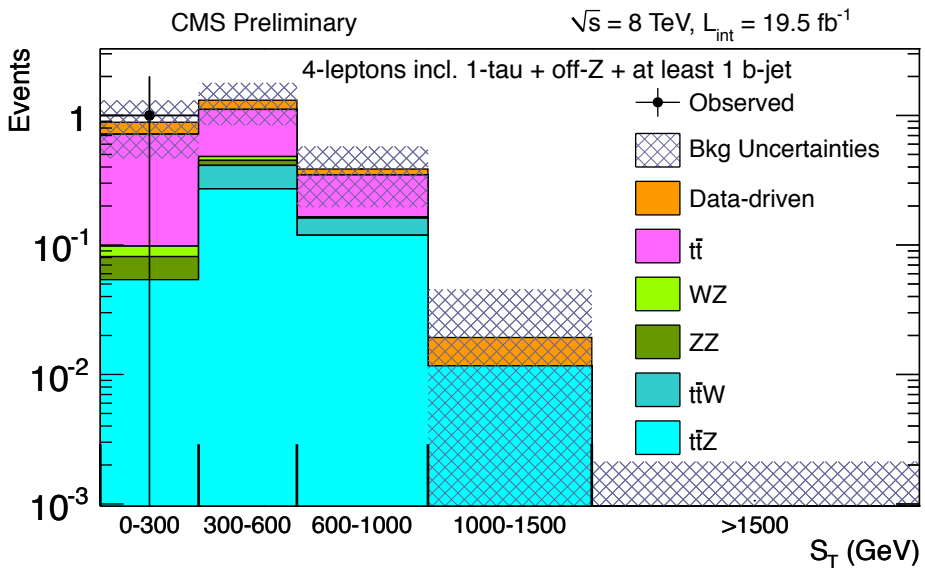
- $\tilde{t} \to t\tilde{\chi}^{0*} \to t\ell^{\pm}\tilde{\ell}^{\mp} \to t\ell^{\pm}\ell^{\mp}\nu\ (tb)$
- 4 signal regions:
  - $3(4)\ell$ including $0(1)\tau_{had} + \geq 1b$
  - Veto opposite-sign same-flavor (OSSF) pairs compatible with M_Z.
  - Each signal region is split to 5 S_T bins.

electron	$p_T > 20(10)^{\dagger}$ GeV	$\lvert\eta\rvert < 2.4$
muon	$p_T > 20(10)^{\dagger}$ GeV	$\lvert\eta\rvert < 2.4$
tau	$p_T > 20$ GeV	$\lvert\eta\rvert < 2.3$
jet	$p_T > 30$ GeV	$\lvert\eta\rvert < 2.5$

† subleading lepton

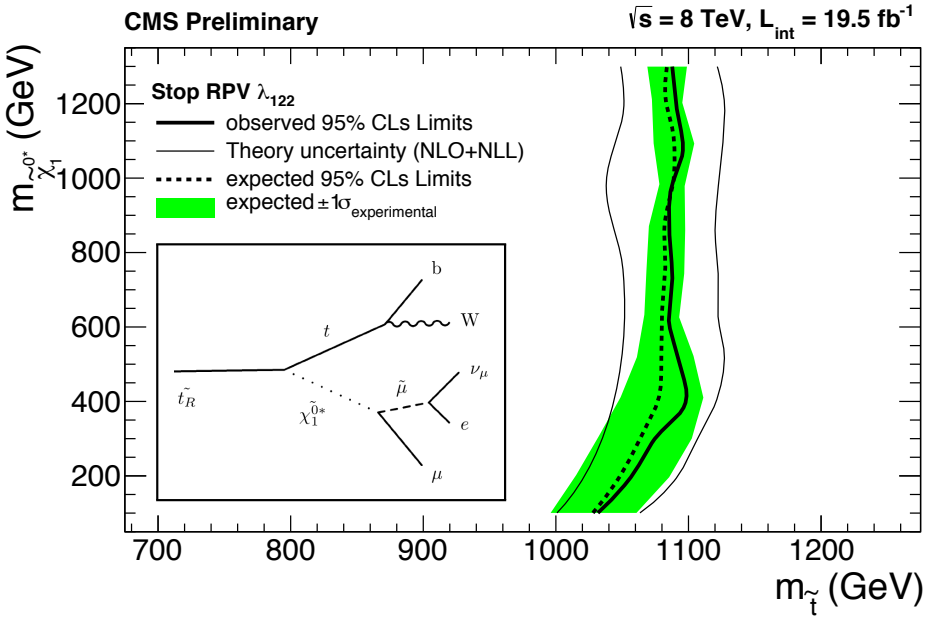
- Dominant prompt lepton background contributions are estimated using MC:
  - WZ, ZZ $t\bar{t}Z$, $t\bar{t}W$.
- Misidentified lepton contributions are estimated via data-driven methods (except $t\bar{t}$):
  - jet$\to e/\mu/\tau_{had}$ (fake-rate method), $\gamma^* \to e/\mu$ (asymmetric conversions)

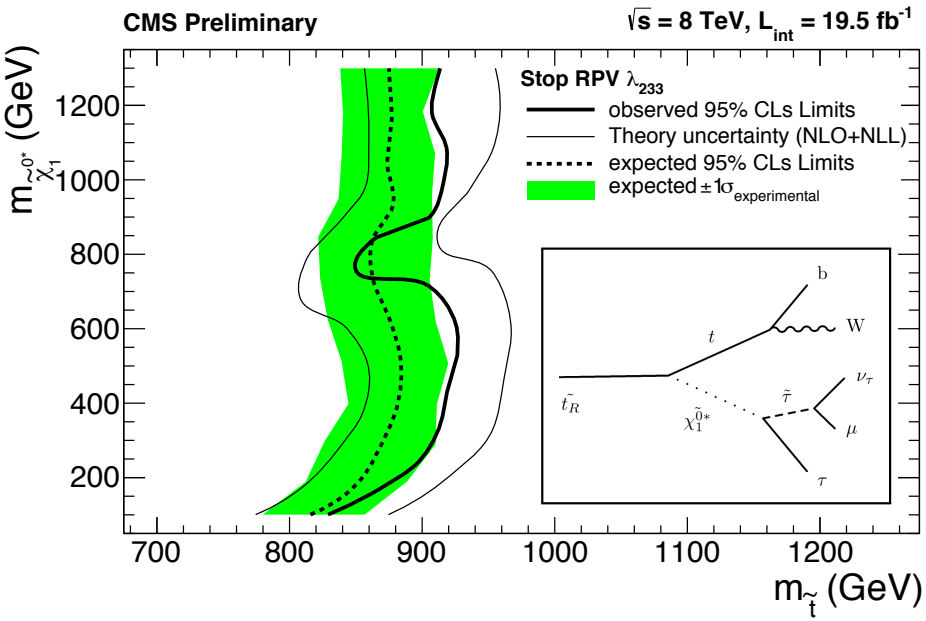


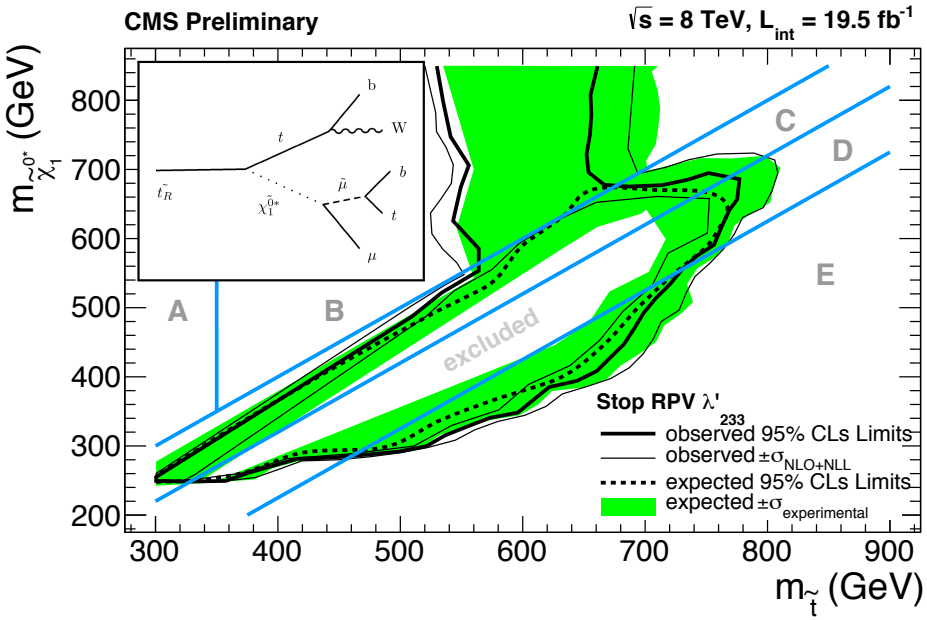


SUS-13-003: $\tilde{t} \to t\mu tb/t\tau\mu\nu/t\mu e\nu$

- 95% CL exclusion for:
  - $M_{\tilde{t}} < 1100$ GeV, $\lambda_{122} > 0$
  - $M_{\tilde{t}} < 900$ GeV, $\lambda_{233} > 0$
- Results in the $\lambda'_{233} > 0$ scenario depend on the $\tilde{t}$ vs. $\tilde{\chi}^0$ mass hierarchy.
  - If $M_{\tilde{t}} \sim M_t + M_{\tilde{\chi}^0}$, soft leptons are produced (reduces sensitivity).







SUS-13-010: $\tilde{q} \to q\ell\ell\nu$ / $\tilde{g} \to q\bar{q}\ell\ell\nu$

- $\tilde{q}(\tilde{g}) \to q(q\bar{q})\tilde{\chi}^0 \to q(q\bar{q})\ell^{\pm}\tilde{\ell}^{\mp} \to q(q\bar{q})\ell^{\pm}\ell^{\mp}\nu$
- Exactly 4-lepton requirement (e/μ) with an OSSF pair.

electron	$p_T > 20(10)^{\dagger}$ GeV	$\lvert\eta\rvert < 2.4$
muon	$p_T > 20(10)^{\dagger}$ GeV	$\lvert\eta\rvert < 2.4$

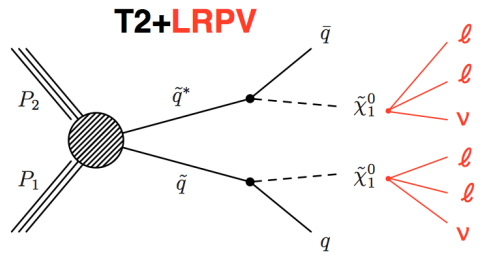
† subleading lepton

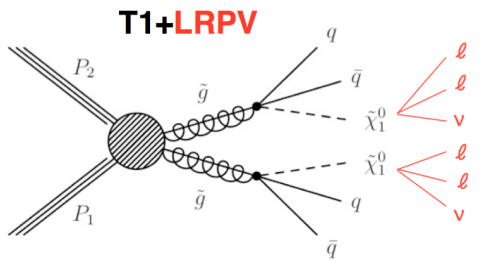
- 9 signal regions:
  - M_1: mass of the OSSF pair closest to the Z mass.
  - M_2: mass of the remaining pair.
- Backgrounds are:
  - ≥4-prompt (ZZ,tt̄Z,tt̄WW) MC
  - 3-prompt (WZ,tt̄W) Fake-rate Method
  - 2-prompt (DY) Fake-rate Method
- Sensitive to the following RPV couplings:
  - Esp. λ_{121}, λ_{122}
  - Also λ_{131}, λ_{132}, λ_{231}, and λ_{232}.

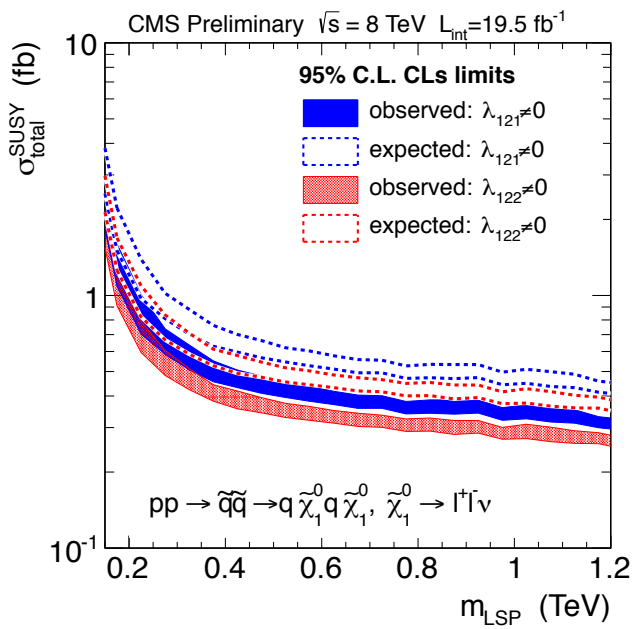
		$M_1 < 75$ GeV	$75 < M_1 < 105$ GeV	$M_1 > 105$ GeV
$M_2 > 105$ GeV	ZZ	0.76±0.18	15±4	0.30±0.07
	rare	0.28±0.13	2.7±1.0	0.12±0.05
	fakes	0.4±0.4	0.7±0.7	0.05±0.05
	all backgrounds	1.4±0.5	18±4	0.47±0.10
	observed	0	20	0
$75 < M_2 < 105$ GeV	ZZ	0.10±0.03	150*	0.05±0.01
	rare	0.12±0.05	2.5±1.2	0.06±0.03
	fakes	0.3±0.3	0.6±0.6	0.05±0.05
	all backgrounds	0.52±0.34	153*	0.16±0.06
	observed	0	160	0
$M_2 < 75$ GeV	ZZ	9.8±2.0	32±8	0.98±0.20
	rare	0.31±0.14	2.5±1.2	0.011±0.005
	fakes	0.3±0.3	0.8±0.8	0.06±0.06
	all backgrounds	10.4±2.0	35±8	1.0±0.2
	observed	14	30	1

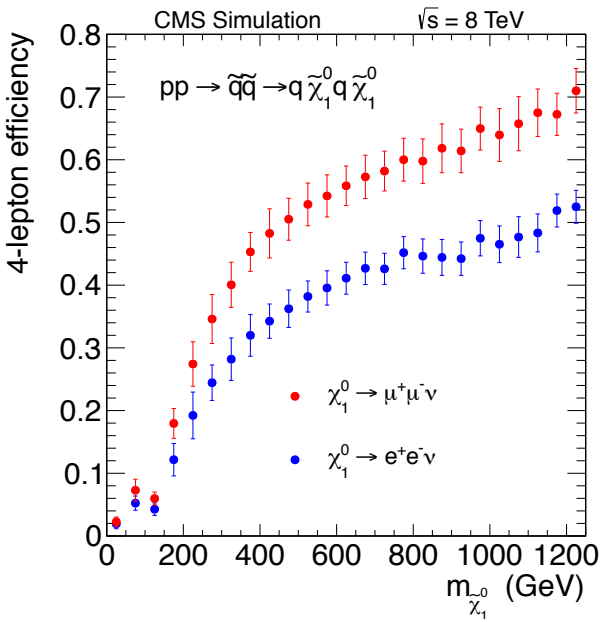
SUS-13-010: $\tilde{q} \to q\ell\ell\nu$ / $\tilde{g} \to q\bar{q}\ell\ell\nu$

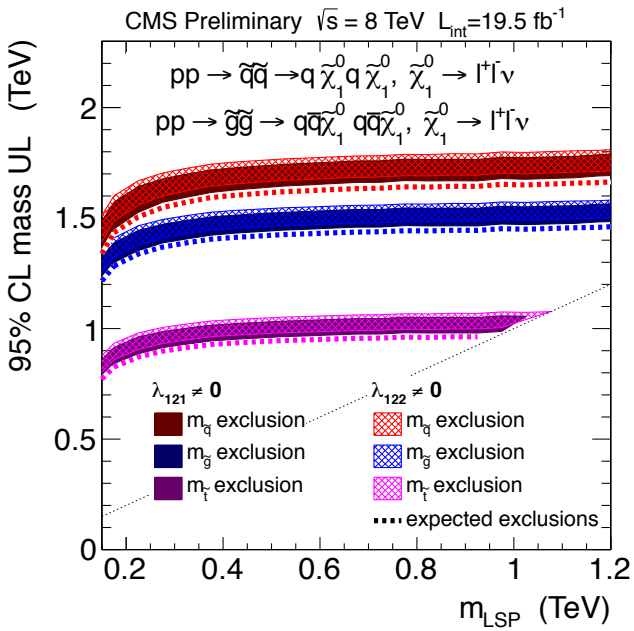
- ϵ(T1) $\sim$ ϵ(T2) :
  Hence, only T2 interpretations are presented.
- Results can be interpreted in a variety of pMSSM models (4-lepton efficiencies are provided).
- 95% CL exclusion for $M_{\tilde{g}} < 1.4$ TeV, assuming $\lambda_{121} > 0$ or $\lambda_{122} > 0$, and $M_{\tilde{\chi}^0} > 400$ GeV.











Leptoquarks

- LQs are bosons, carry both baryon and lepton number, and have fractional electric charge.
- Phenomenology is described by the effective mBRW† model:
  - Expand the SM to allow all terms respecting the gauge invariance.
  - Group LQs into 3 generations (one for each fermion family).
  - Require chiral couplings, and only to a given generation of SM fermions.
  - Pair-production cross-section at the LHC is calculable ($gg \to LQ\overline{LQ}$, $q\bar{q} \to LQ\overline{LQ}$).
- Unknown parameters are:
  - M_{LQ} and spin (CMS 8 TeV searches are for *scalar* leptoquarks).
  - lepton-quark-leptoquark Yukawa couplings, λ.
  - Branching fraction, β, for $LQ \to \ell q$.
    The complementary $LQ \to \nu q'$ channel is given as $1 - \beta$.
- LQs $\leftrightarrow$ RPV LSPs with $\lambda'_{ijk} > 0$:
  - Final states may slightly differ due to lower jet & lepton multiplicites.

† W. Buchmuller, R. Ruckl, and D. Wyler, "Leptoquarks in lepton-quark collisions", *Phys. Lett. B* **191** (1987).

EXO-12-041: $LQ_1 \to eq/\nu q$

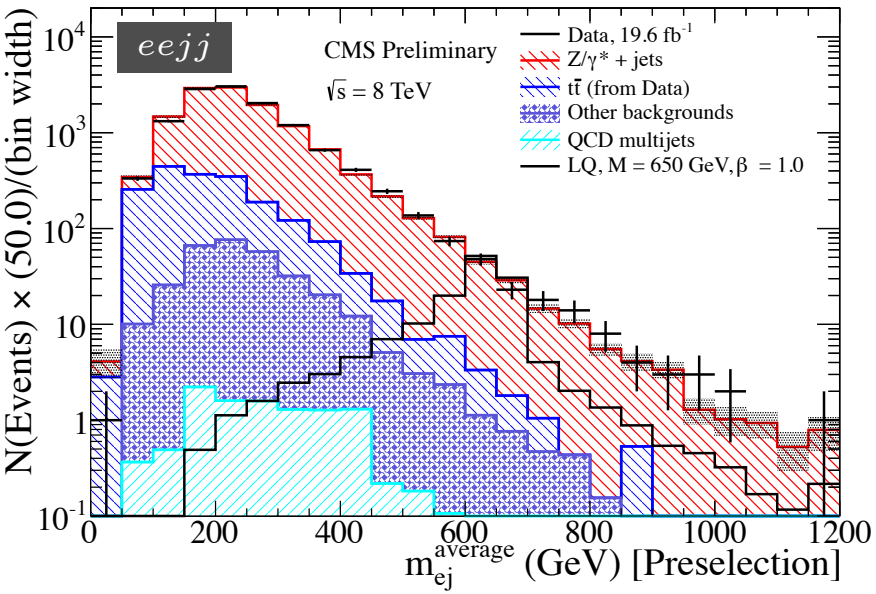
- 2 search regions:
  - $\beta = 1 \quad [eejj] : ee + \geq 2j$
  - $\beta = 0.5\ [e\nu jj] : \quad e + \geq 2j + E_{\mathrm{T}}^{miss}$>55 GeV

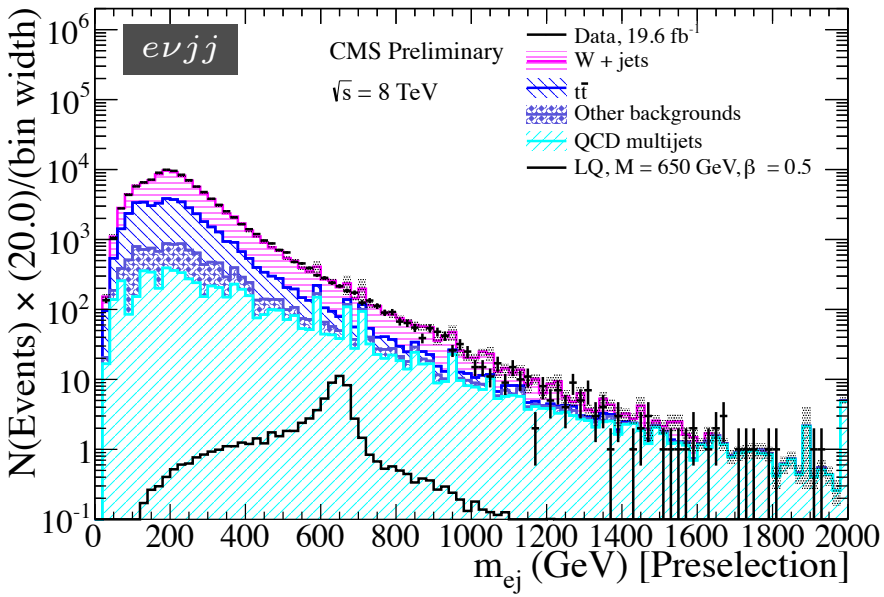
electron	$p_{\mathrm{T}} > 45$ GeV	$\lvert\eta\rvert < 2.5(2.1)^{\ddagger}$
jet	$p_{\mathrm{T}} > 125(45)^{\dagger}$ GeV	$\lvert\eta\rvert < 2.4$
muon*	$p_{\mathrm{T}} > 10$ GeV	$\lvert\eta\rvert < 2.4$

$*$ muon veto † subleading jets ‡ $e\nu jj$ channel

- $\beta = 1$ results are also applicable to pair-produced stop decays via RPV λ'_{131}.
- Dominant backgrounds:

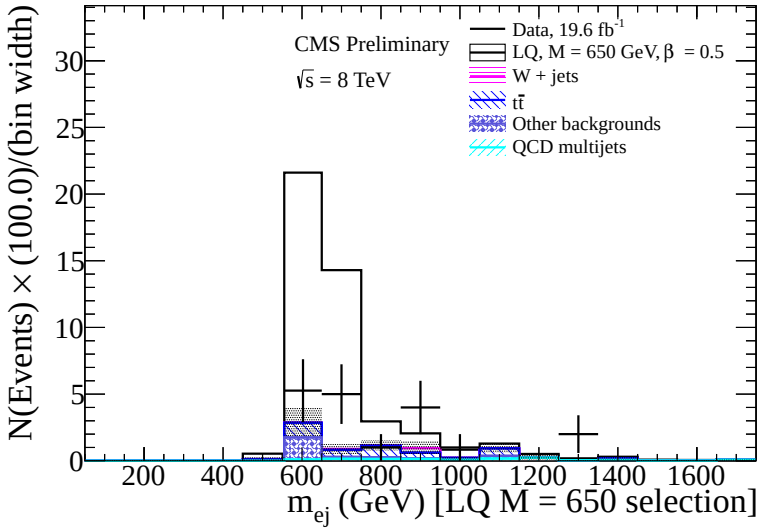
$eejj$ Channel	$e\nu jj$ Channel
Z+jets (MC, norm. to data)	$t\bar{t}$+jets (MC, norm. to data)
$t\bar{t}$+jets (Data, "$e\mu$" method)	W+jets (MC, norm. to data)

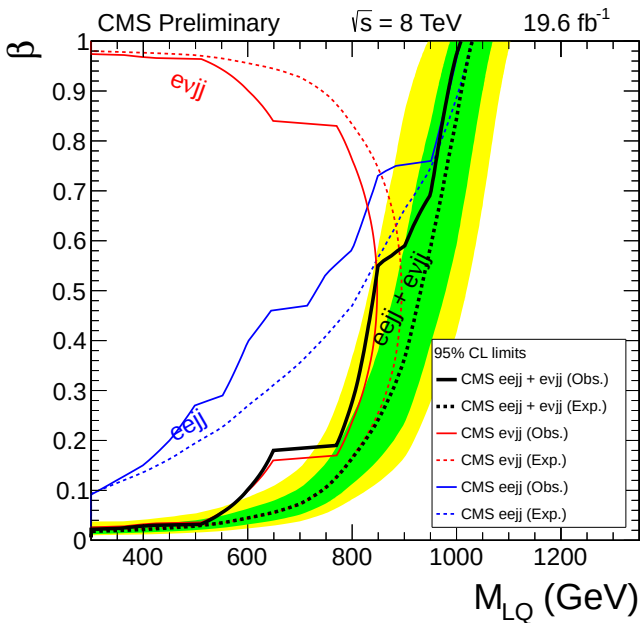


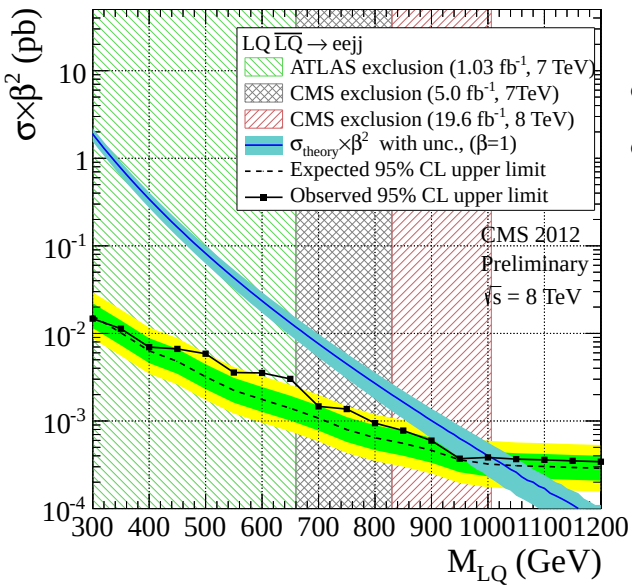


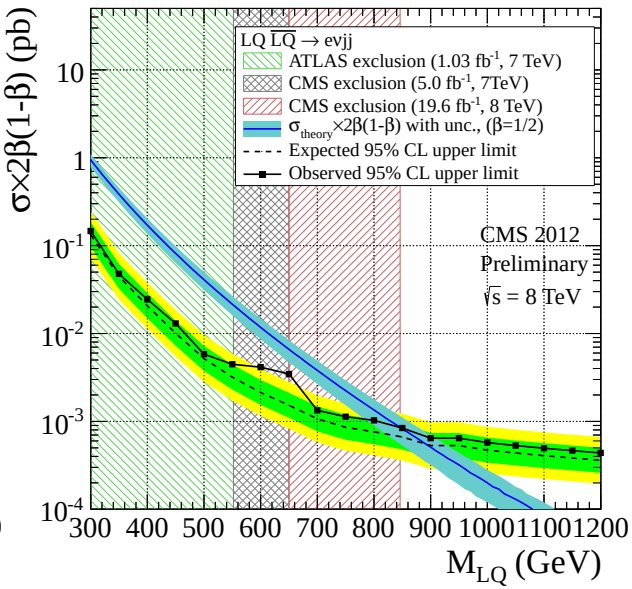
EXO-12-041: $LQ_1 \to eq/\nu q$

- Selection optimization for each M_{LQ} hypothesis:
  - $\beta = 1 \quad [eejj]: \; S_{\mathrm{T}}, \; M_{min}(e,j), \; M(e,e)$
  - $\beta = 0.5 \; [e\nu jj]: \; S_{\mathrm{T}}, \; M(e,j), \; E_{\mathrm{T}}^{miss}, \; M_{\mathrm{T}}(e,\nu)$
- A broad excess is observed:
  - Excess is *background-like* in $eejj$ channel.
  - $M_{LQ} = 650$ GeV, $\beta < 0.15$ can't be excluded.
- 95% CL exclusion for $M_{LQ} < 1005(845)$ GeV, $\beta = 1(0.5)$.









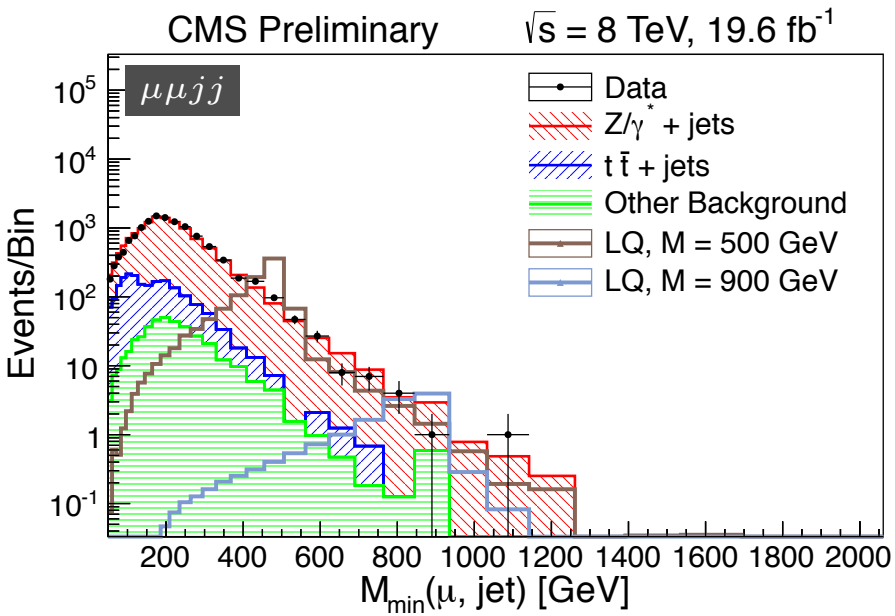
EXO-12-042: $LQ_2 \to \mu q/\nu q$

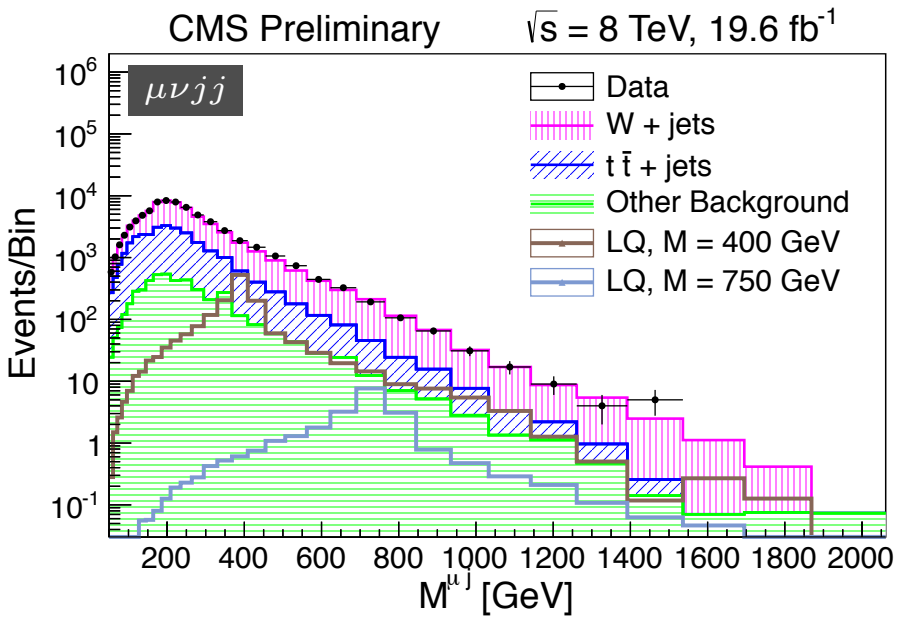
muon	$p_T > 45$ GeV	$\lvert\eta\rvert < 2.1$
jet	$p_T > 125(45)^{\dagger}$ GeV	$\lvert\eta\rvert < 2.4$
electron*	$p_T > 45$ GeV	$\lvert\eta\rvert < 2.1$

$*$ electron veto for $\beta = 0.5$ $\dagger$ subleading jets

- 2 search regions:
  - $\beta = 1 \quad [\mu\mu jj] : \geq \mu\mu + \geq 2j$
  - $\beta = 0.5\ [\mu\nu jj] : \mu + \geq 2j + E_T^{miss}$>55 GeV
- $\beta = 1$ results are also applicable to pair-produced stop decays via RPV λ'_{232}.
- Dominant backgrounds:

$\mu\mu jj$ Channel	$\mu\nu jj$ Channel
Z+jets (MC, normalized to data)	W+jets (MC, normalized to data)
$t\bar{t}$+jets (Data, "$e\mu$" method)	$t\bar{t}$+jets (MC, normalized to data)

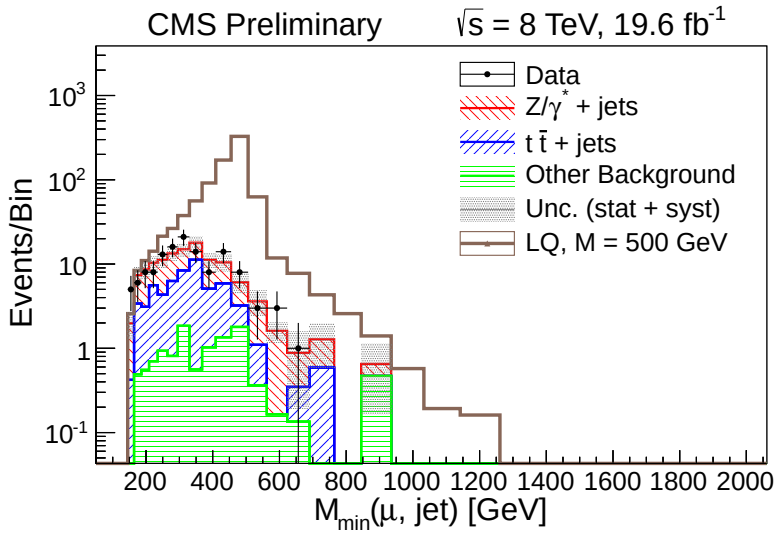


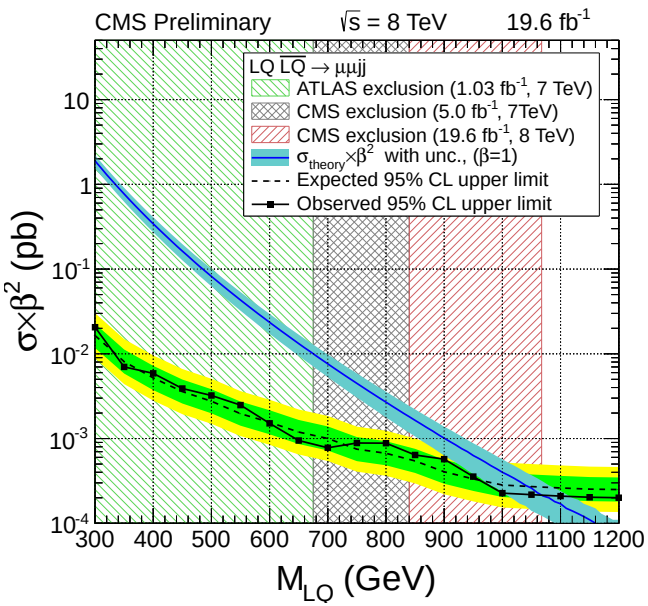


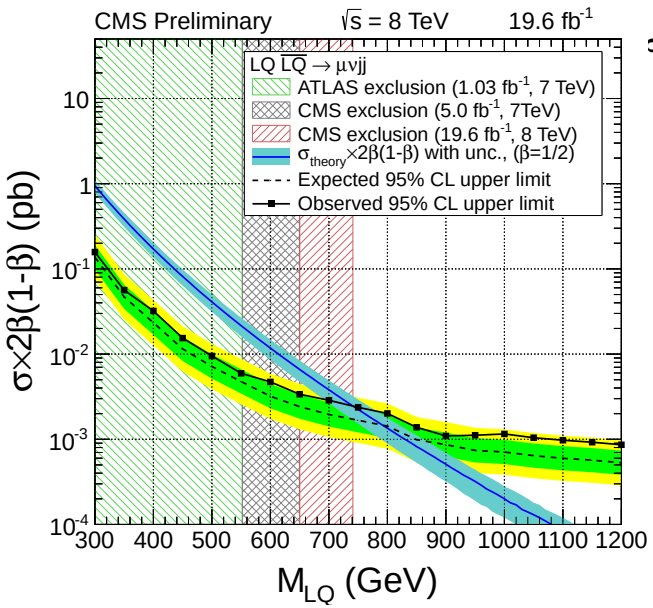
EXO-12-042: $LQ_2 \to \mu q/\nu q$

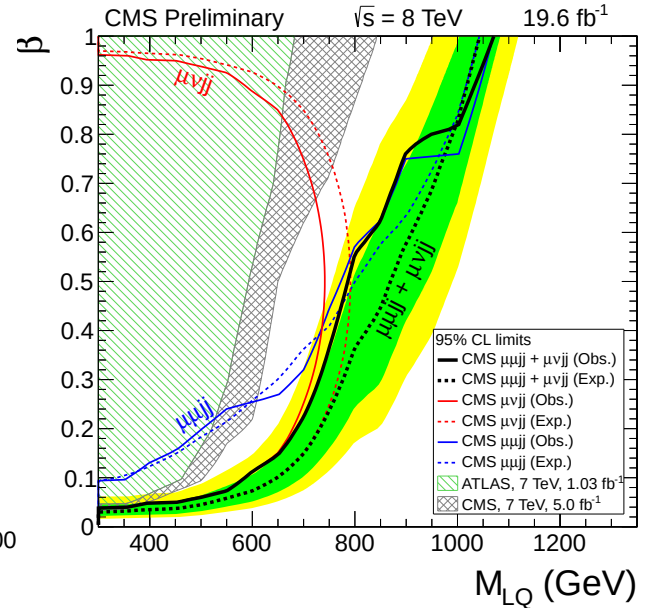
- Selection optimization for each M_{LQ} hypothesis:
  - $\beta = 1 \quad [\mu\mu jj]: \; S_{\mathrm{T}}, \; M_{\mathrm{min}}(\mu, j), \; M(\mu, \mu)$
  - $\beta = 0.5 \; [\mu\nu jj]: \; S_{\mathrm{T}}, \; M(\mu, j), \; M_{\mathrm{T}}(\mu, \nu)$

- 95% CL exclusion for $M_{LQ} < 1070(785)$ GeV, $\beta = 1(0.5)$.









EXO-12-032: $LQ_3 \to \tau b$ / $\tilde{t} \to q\bar{q}\tau b$

- $LQ_3 \to \tau b$ search:
  - $e\tau_{had}/\mu\tau_{had} + \geq 2j$ (with $\geq$1 b-tag)
  - $M(\tau_{had}, j) > 250$ GeV

tau	$p_T > 50$ GeV	$\lvert\eta\rvert < 2.3$
muon	$p_T > 30$ GeV	$\lvert\eta\rvert < 2.1$
electron	$p_T > 30$ GeV	$\lvert\eta\rvert < 2.1$
jet	$p_T > 30$ GeV	$\lvert\eta\rvert < 2.4$

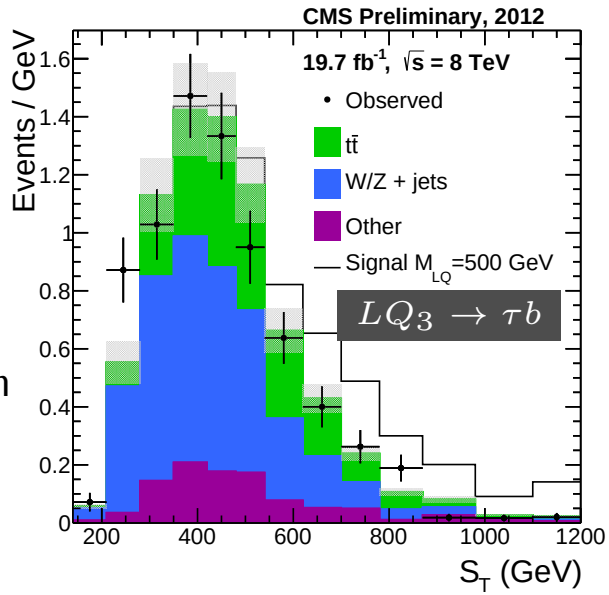
- $\tilde{t} \to q\bar{q}\tau b$ search: ($\tilde{t} \to \tilde{\chi}^+ b \to \tilde{\nu}\tau^+ b \to q\bar{q}\tau^+ b$ via λ'_{3jk} for $j, k < 3$)
  - $e\tau_{had}/\mu\tau_{had} + \geq 5j$ (with $\geq$1 b-tag)
- $LQ_3 \to \tau b$ results are also applicable to pair-produced stop decays via RPV λ'_{333}.
- Dominant Backgrounds:

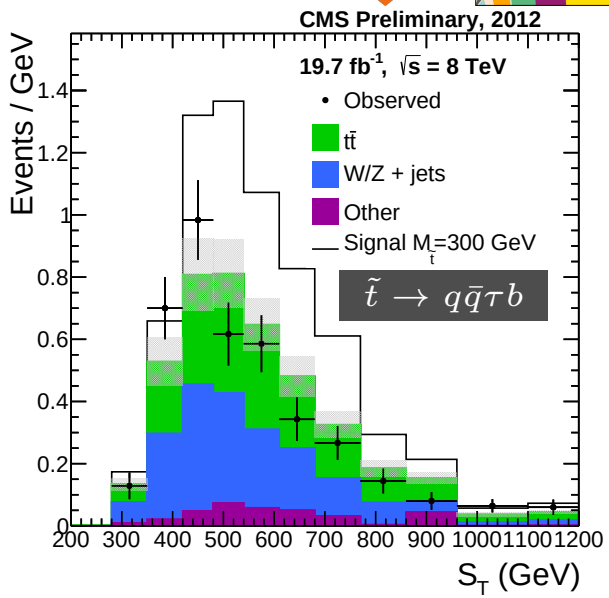
Irreducible $t\bar{t}$+jets	Data-driven "$e\mu$" method	(S_T shape from MC)
Fake τ_{had}	Data-driven fake-rate method	(S_T shape from MC)
QCD (for $e\tau_{had}$ channel)	Data-driven "SS OS" method	
Other prompt-prompt	MC	

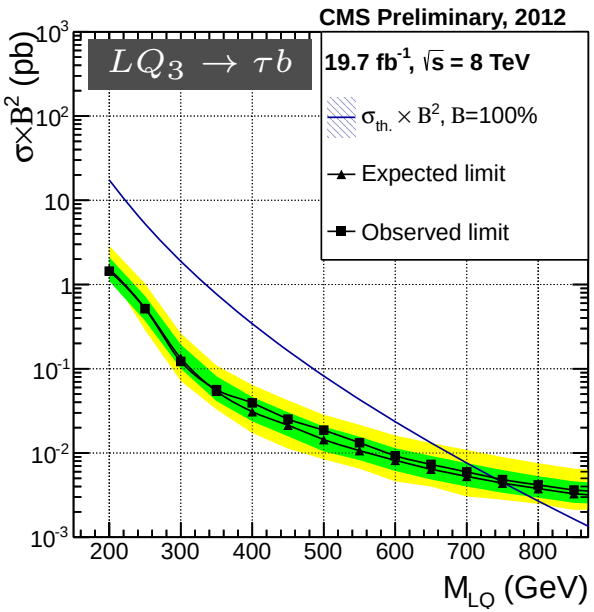
- S_T distribution is used to discriminate signal vs. background.

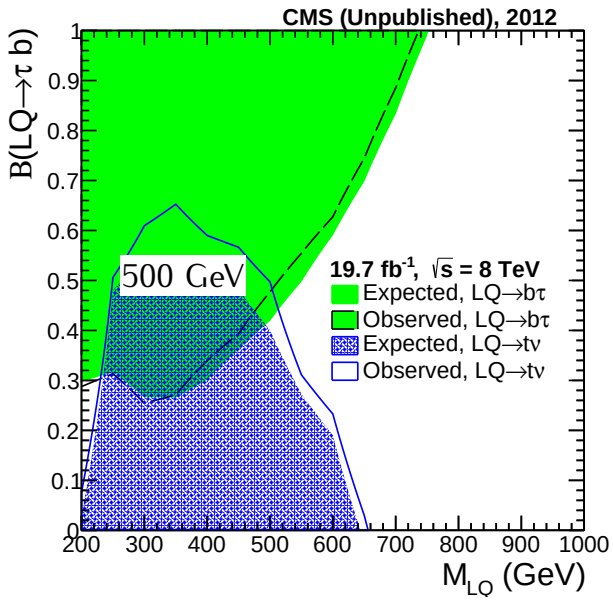
EXO-12-032: $LQ_3 \to \tau b$ / $\tilde{t} \to q\bar{q}\tau b$

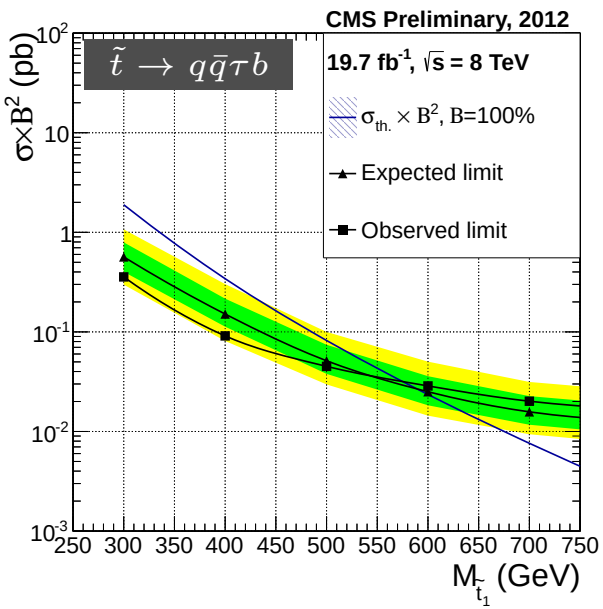
- 95% CL exclusion for
  - $M_{LQ} < 740$ GeV, $\beta = 1$.
  - $M_{\tilde{t}} < 576$ GeV, $\lambda'_{3jk} > 0$.
- $LQ_3 \to t\nu$ limits follow from SUS-13-011 ($\tilde{t} \to t\tilde{\chi}^0$).



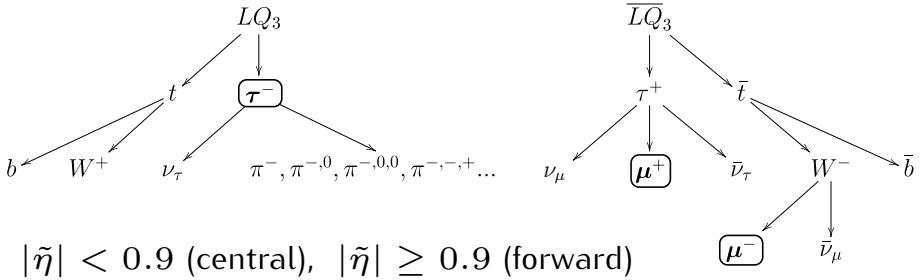








EXO-13-010: $LQ_3 \to \tau t$



- 2 categories:
  - **Cat. A**: Same-sign $\mu\tau_{had} + \geq 2j$
    Split into 2 channels of average leptonic $|\eta|$: $|\tilde{\eta}| < 0.9$ (central), $|\tilde{\eta}| \geq 0.9$ (forward)
    Tau p_{T}, S_{T} cuts are optimized for each M_{LQ} hypothesis.
  - **Cat. B**: $\mu\tau_{had} + \geq 3j + E_{\mathrm{T}}^{miss} > 50$ GeV
    Cat. B uses a looser tau ID, and Cat. A is vetoed.
    Split into 4 tau p_{T} bins. S_{T}, jet$_{1,2,3}$ p_{T} cuts are optimized for the best expected limit.

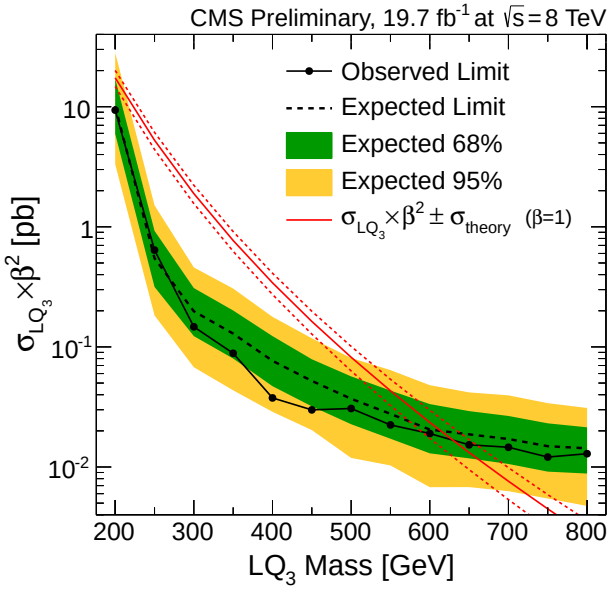
tau	$p_{\mathrm{T}} > 20$ GeV	$\lvert\eta\rvert < 2.1$
muon	$p_{\mathrm{T}} > 25(30)^{\dagger}$ GeV	$\lvert\eta\rvert < 2.1$
electron	$p_{\mathrm{T}} > 15(30)^{\dagger}$ GeV	$\lvert\eta\rvert < 2.5(2.1)^{\dagger}$
jet	$p_{\mathrm{T}} > 40(30)^{\dagger}$ GeV	$\lvert\eta\rvert < 2.5$
		† Category B

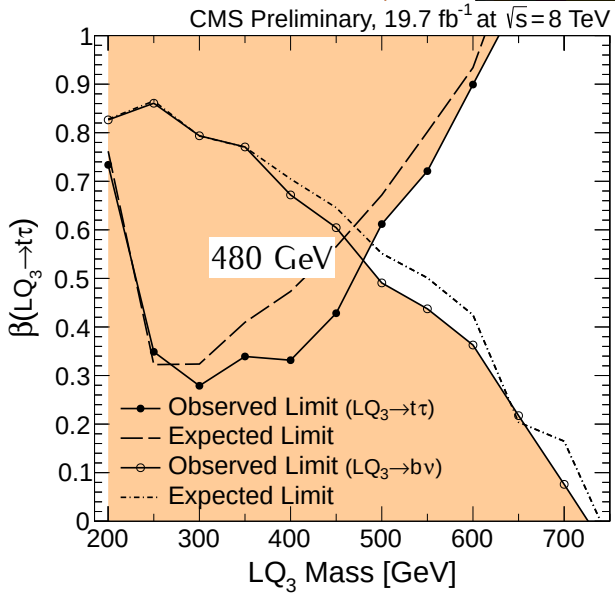
- Results are also applicable to pair-produced sbottom decays via RPV λ'_{333}.
- Backgrounds:

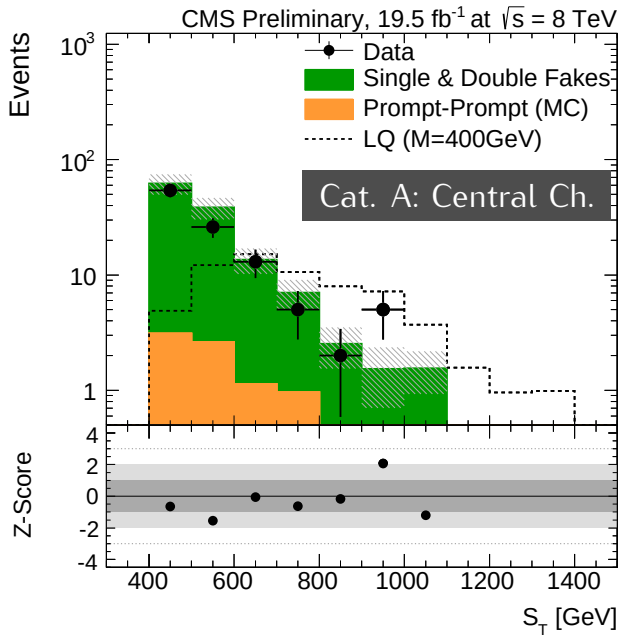
Cat. A	Cat. B
Single/Double Fakes (Matrix Method)	τ_{had} fakes (fake-rate corrected MC)
$t\bar{t}$+jets, W+jets	$t\bar{t}$+jets, W+jets, DY+jets
Prompt-prompt (MC)	τ_{had} prompts (MC)
Diboson, $t\bar{t}W$, $t\bar{t}Z$, etc.	Diboson, $t\bar{t}W$, $t\bar{t}Z$, etc.

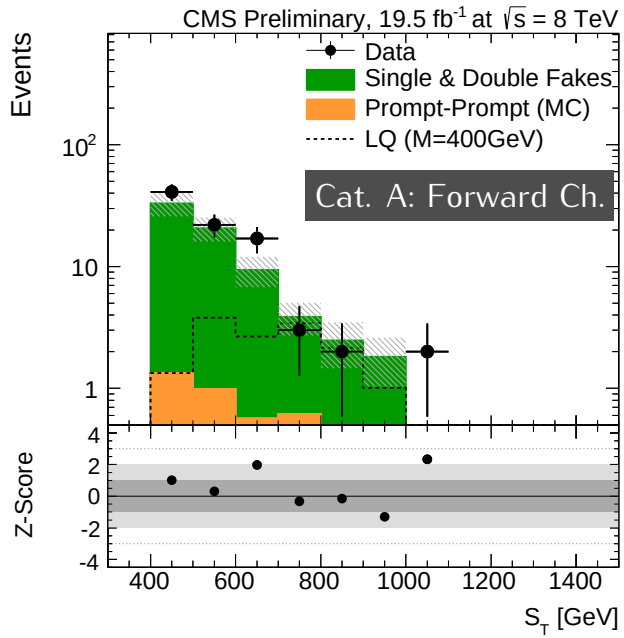
EXO-13-010: $LQ_3 \to \tau t$

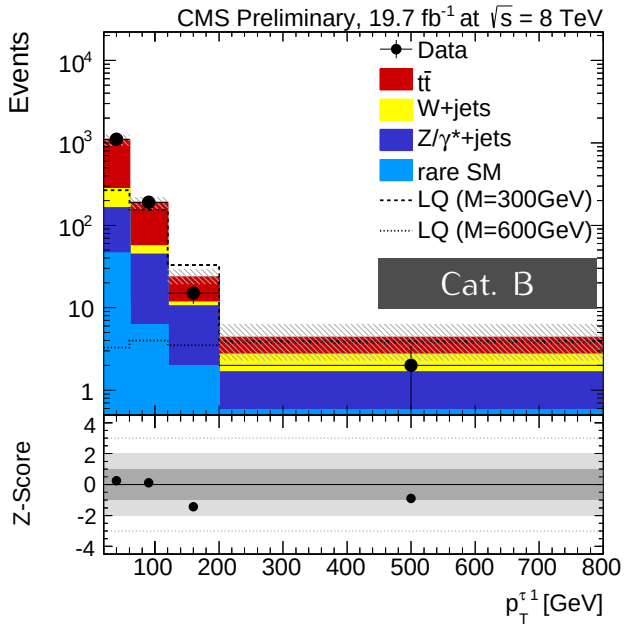
- 95% CL exclusion for $M_{LQ} < 634$ GeV, $\beta = 1$.
- $LQ_3 \to b\nu$ limits follow from SUS-13-018 ($\tilde{b} \to b\tilde{\chi}^0$).











Conclusions

- CMS efforts are varied, cover a variety of multi-lepton, multi-jet final states.
  - A systematic approach to all possible scenarios.
  - Limited subset of model interpretations are presented here today.

RPV SUSY

Benchmark	Limit	Coupling
$\tilde{g} \to udb$	200-835	λ''_{113}
$\tilde{g} \to uds$	650	λ''_{112}
$\tilde{g} \to tbs$	1036	λ''_{332}
$\tilde{g} \to q\ell\ell\nu$	1400	$\lambda_{121,122}$
$\tilde{b} \to ts/td$	307	$\lambda''_{332,331}$
$\tilde{t} \to t\ell\ell\nu$	1100	λ_{122}
$\tilde{t} \to t\ell\ell\nu$	900	λ_{233}

Leptoquarks

$\beta(LQ \to \ell q)$:	1	0.5	0
$LQ_1 \to eq$	1005	845	N/A
$LQ_2 \to \mu q$	1070	785	N/A
$LQ_3 \to \tau b$	740	510*	660†
$LQ_3 \to \tau t$	634	495*	724‡

† Obtained by reinterpreting SUS-13-011.
‡ Obtained by reinterpreting SUS-13-018.
∗ No statistical combination of $\beta = 1, 0$.
All mass limits are in units of GeV.

- No discoveries yet, but the journey continues to 13 TeV and beyond.

Backup

EXO-12-041: $LQ_1 \to eq/\nu q$