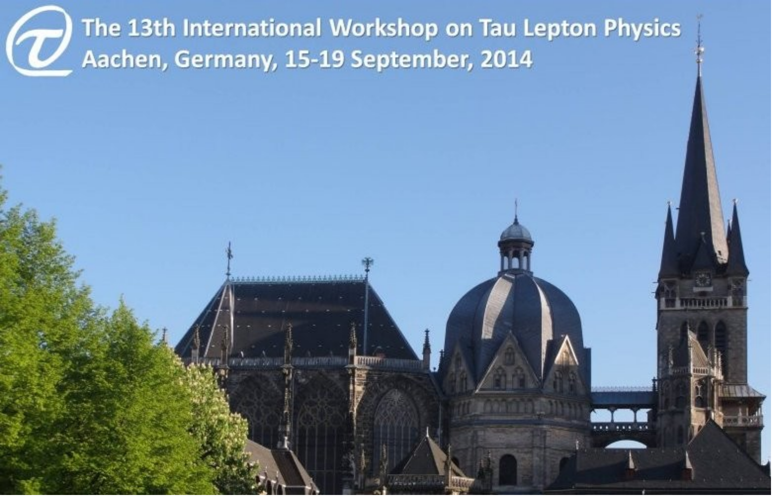

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Exotica and SUSY Results with τ Leptons at the LHC

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CMS

ATLAS

BSM Physics: Exotica and SUSY

Results from LHCb, ATLAS and CMS with Tau Leptons

- Exotica:
  - 3rd Generation Leptoquarks
    LQ→ top + tau and LQ → bottom +tau
  - Zprime → tau tau
  - ...
- SUSY:
  - 3 or more leptons (e,mu,tau) + MET
  - Ditau + MET
  - Stop in b, tau and WIP
  - Jets + MET and at least on tau
  - RPV stop with l ≥ 3 and b-jets
  - Heavy resonance decay to e / μ + tau
  - …
- LFV @ LHCb:
  - Search for LFV tau decays (dedicated talk; not shown here)

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS

Motivation for BSM Searches with Taus

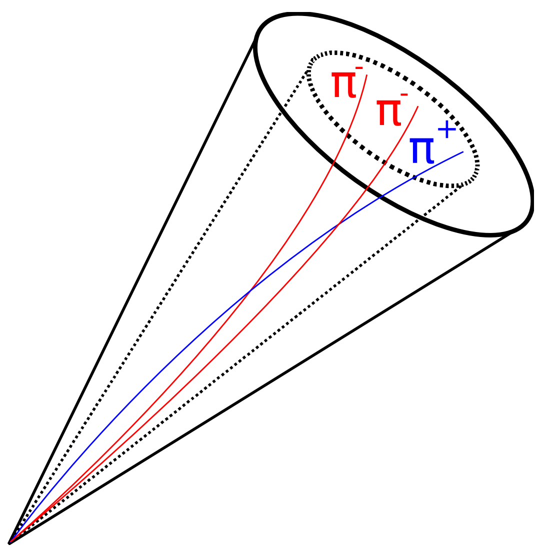
- **Tau lepton is very interesting as a subject of new physics (LFV decays).**
- **Important probe for new phenomena:**
  - Lepton with highest mass → strongest couplings to Higgs-Bosons.
  - Many BSM theories contain enhanced 3rd generation couplings.

Reconstruction of Hadronically Decaying Taus

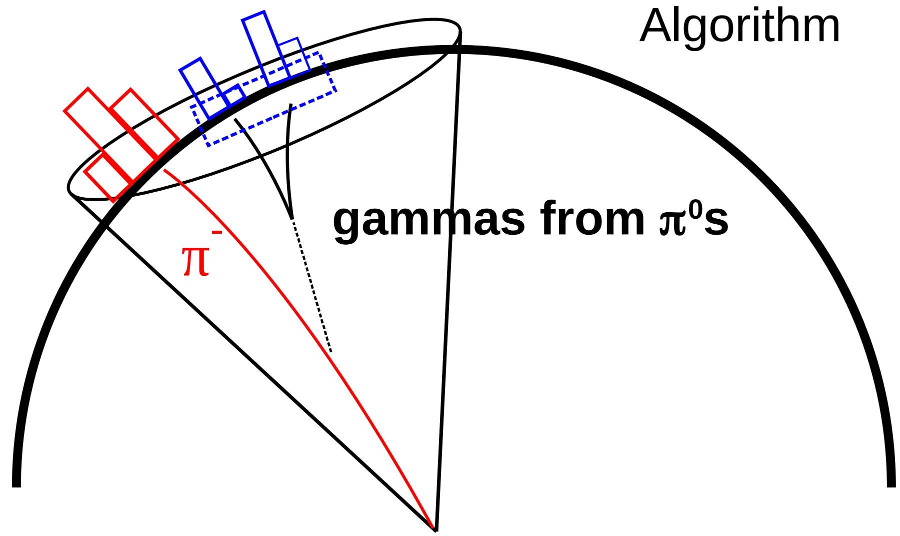
Leptons from tau decays cannot be distinguished from prompt decays.

Decay mode	Mass (MeV)	Resonance	Branching fraction (%)
$\tau \to h\nu_\tau$			11.6 %
$\tau^- \to h^-\pi^0\nu_\tau$	770	ρ^-	26.0 %
w $\tau^- \to h^-\pi^0\pi^0\nu_\tau$	1200	a_1^-	9.5 %
$\tau^- \to h^-h^+h^-\nu_\tau$	1200	a_1^-	9.8 %
$\tau^- \to h^-h^+h^-\pi^0\nu_\tau$			4.8 %

Narrow jet with one or three tracks

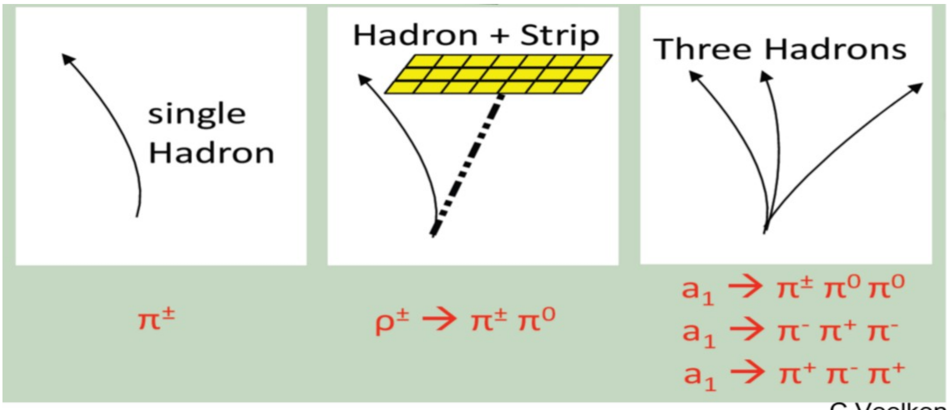


Hadron Plus Strips Algorithm



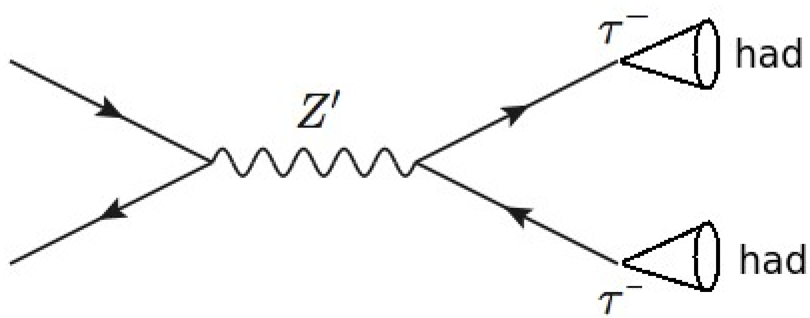
Discrimination against jets, electrons and muons by isolation, shower-shape and vertex information.

Due to the neutrino it is not possible to reconstruct the full energy:
In the following, tau energy denotes the visible part.

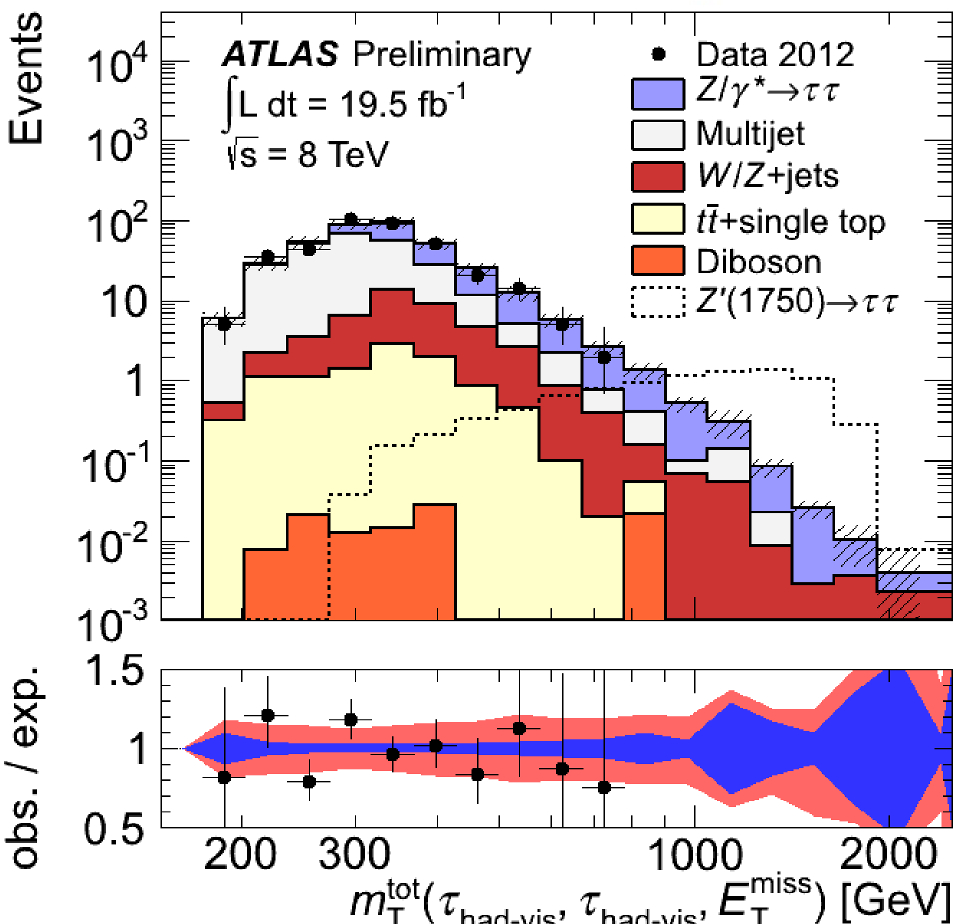


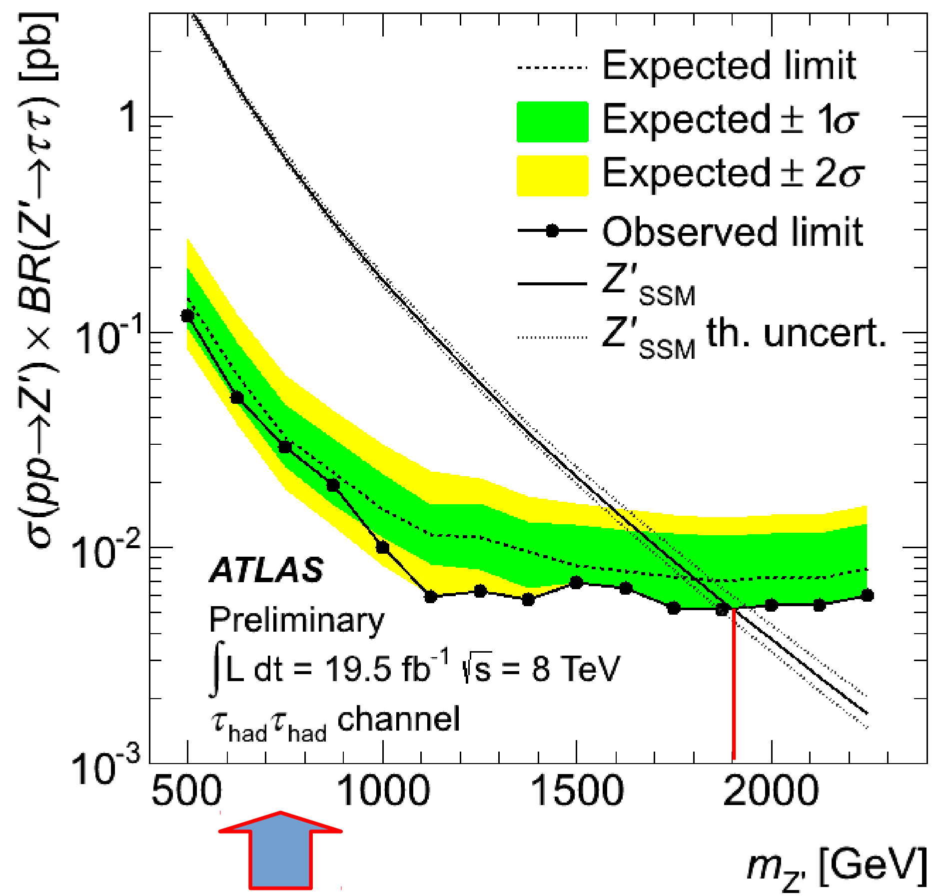
Decay mode reconstruction by resonance identification

Search for Z' → $\tau_{had}\ \tau_{had}$ with ATLAS @ 8 TeV [1]



- Many BSM scenarios predict additional heavy gauge bosons.
- Sequential Standard Model as benchmark:
  Same couplings as Z_{SM} +
  additional decay to top quarks.



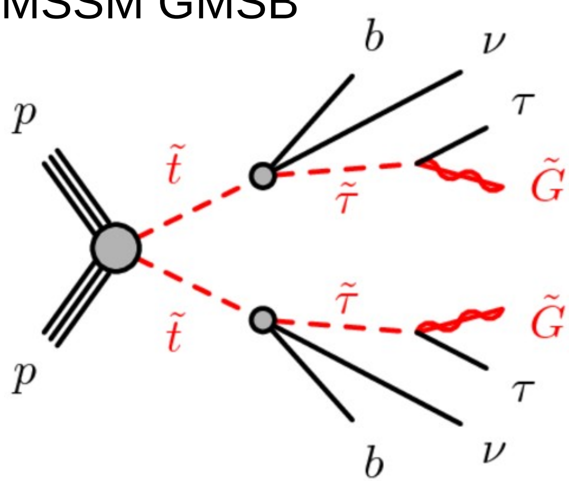


Bayesian 95% limit from a single bin with lower m_T threshold depending on $m_{Z'}$

$m_{Z'} < 1900$ GeV

stop pairs to b + τ + MET with ATLAS @ 8 TeV [2]

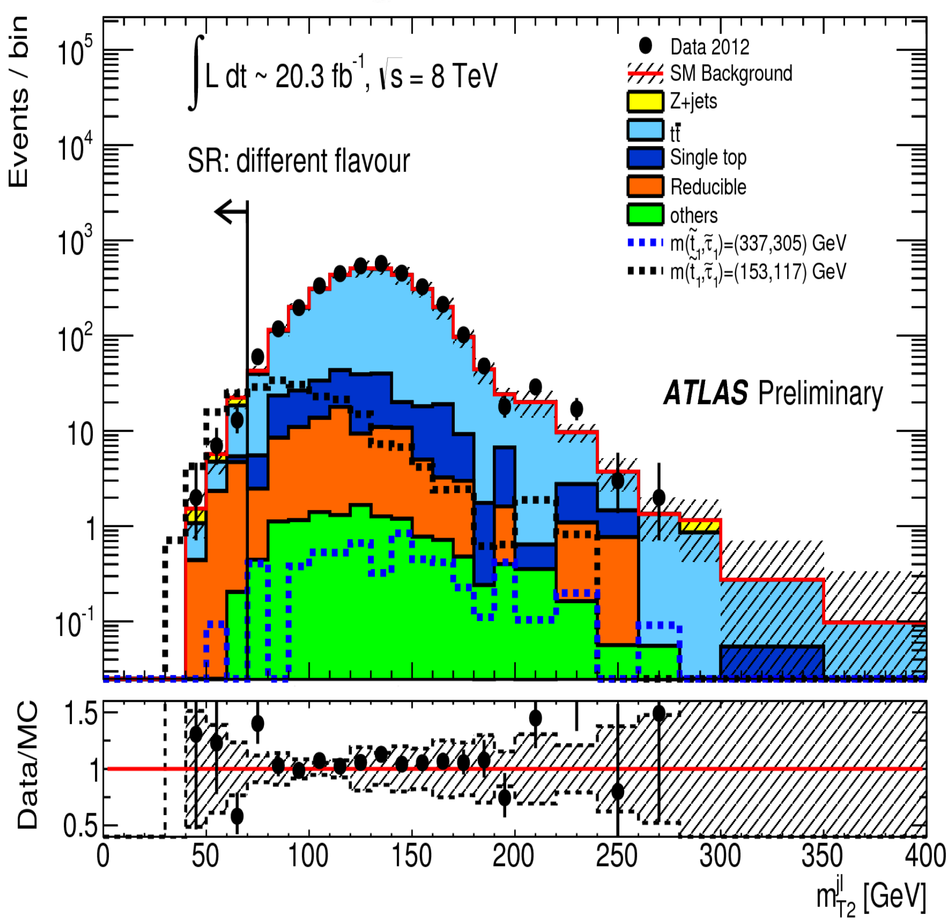
MSSM GMSB

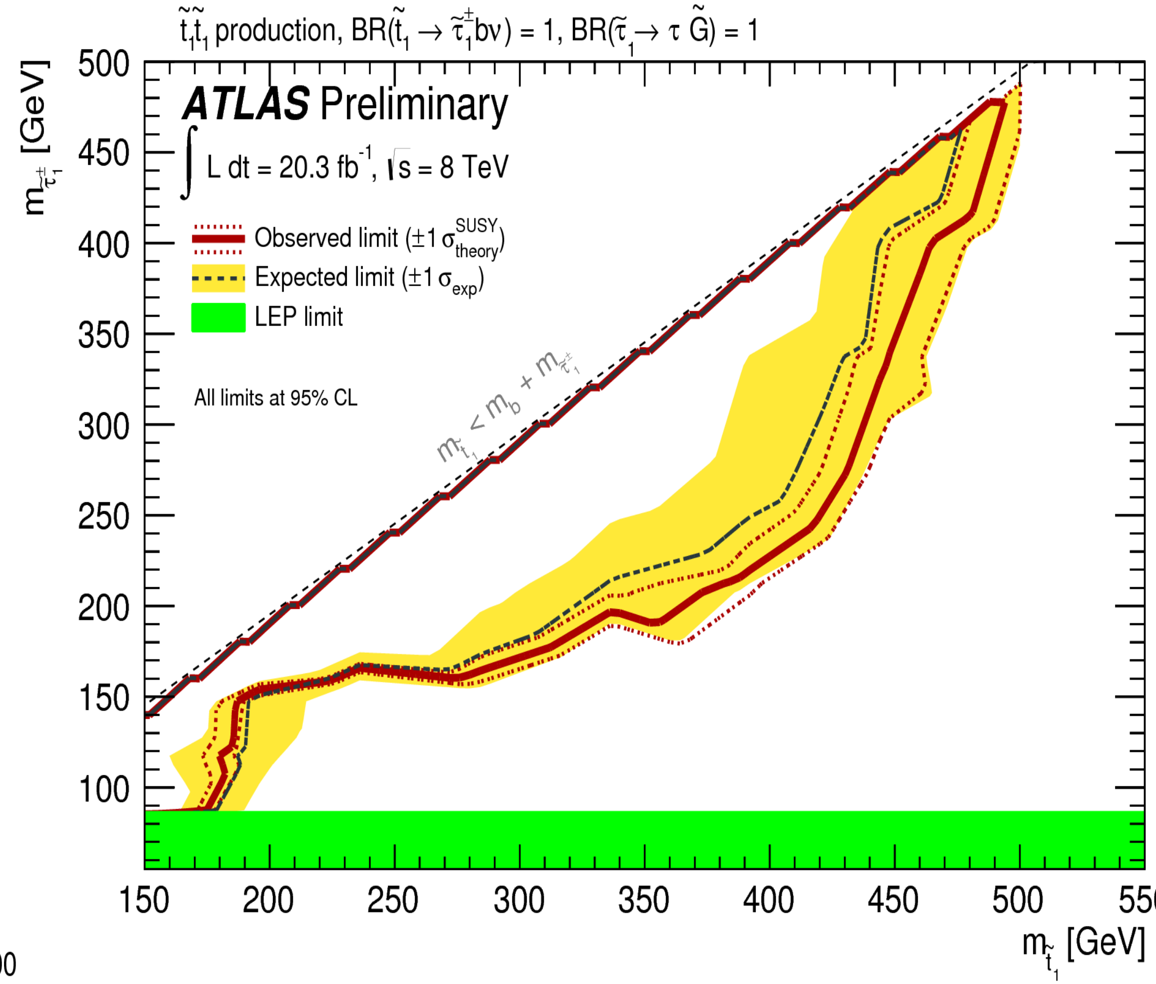


If $m_{stau} < m_{top}$ and $m_{\chi} < m_{stop}$ then this is the dominant decay.

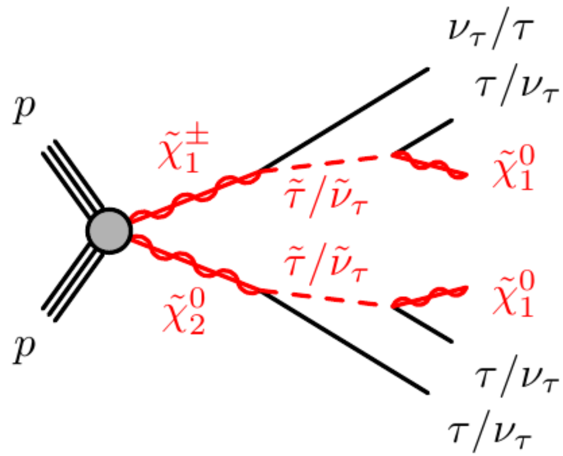
Light 3rd gen. sparticles are well motivated by naturalness arguments: Protect the Higgs from quadratically divergent quantum corrections.

Consider only leptonic decays of the tau in this analysis.





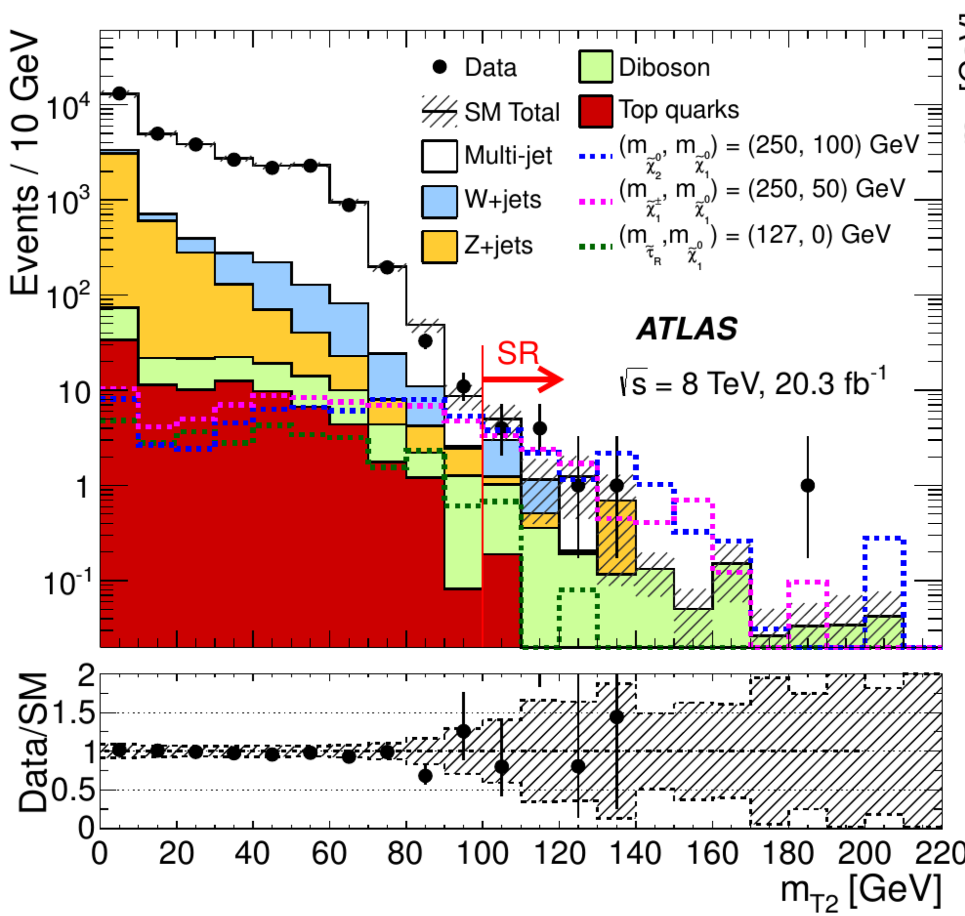
distau → ditau + MET with ATLAS @ 8 TeV [3]

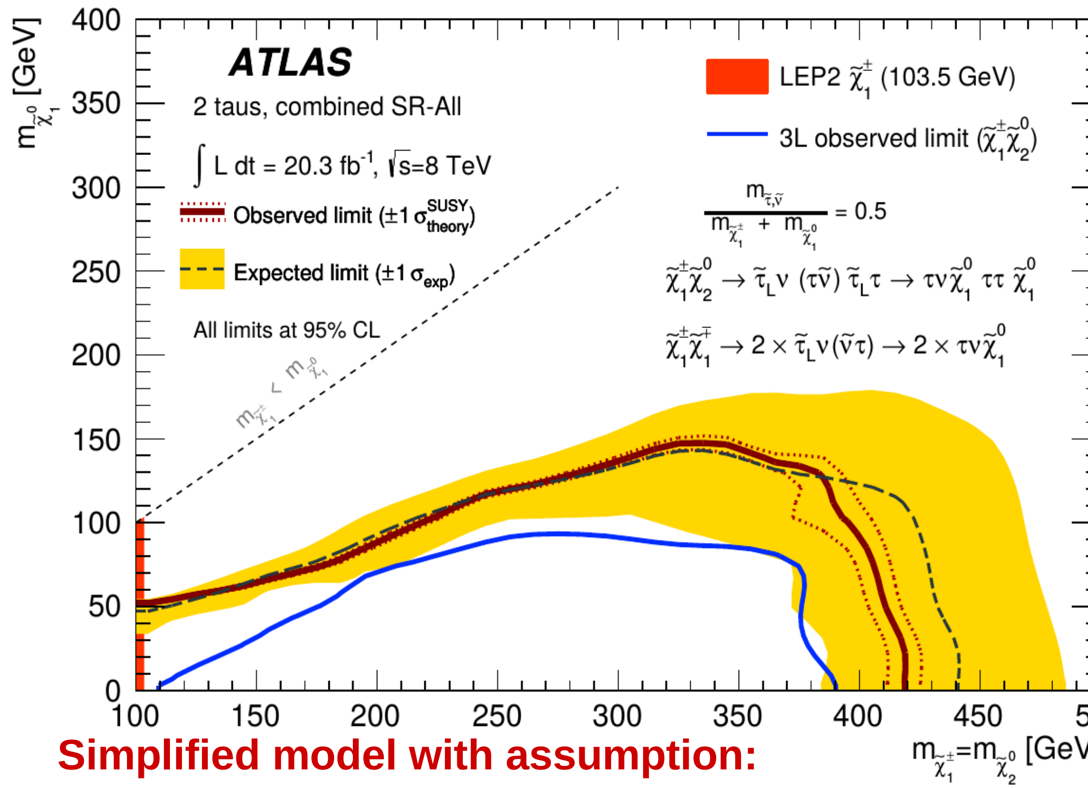


The stau pair can be produced directly, or via chargino and neutralino pair-production.
Leads to the same final state: τ τ + MET.

Four different signal selections, depending on the production process:
Example shown here for C1N2 production:

≥ 2 OS hadronic taus, b-jet veto, Z-veto, MET > 40 Gev, m_{T2} > 100 GeV





Simplified model with assumption:

$m_{stau} = m_{\nu\ stau}$

$m_{\tilde{\chi}_1^\pm} = m_{\tilde{\chi}_2^0}$ and $\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$ pure wino and $\tilde{\chi}_1^0$ pure bino

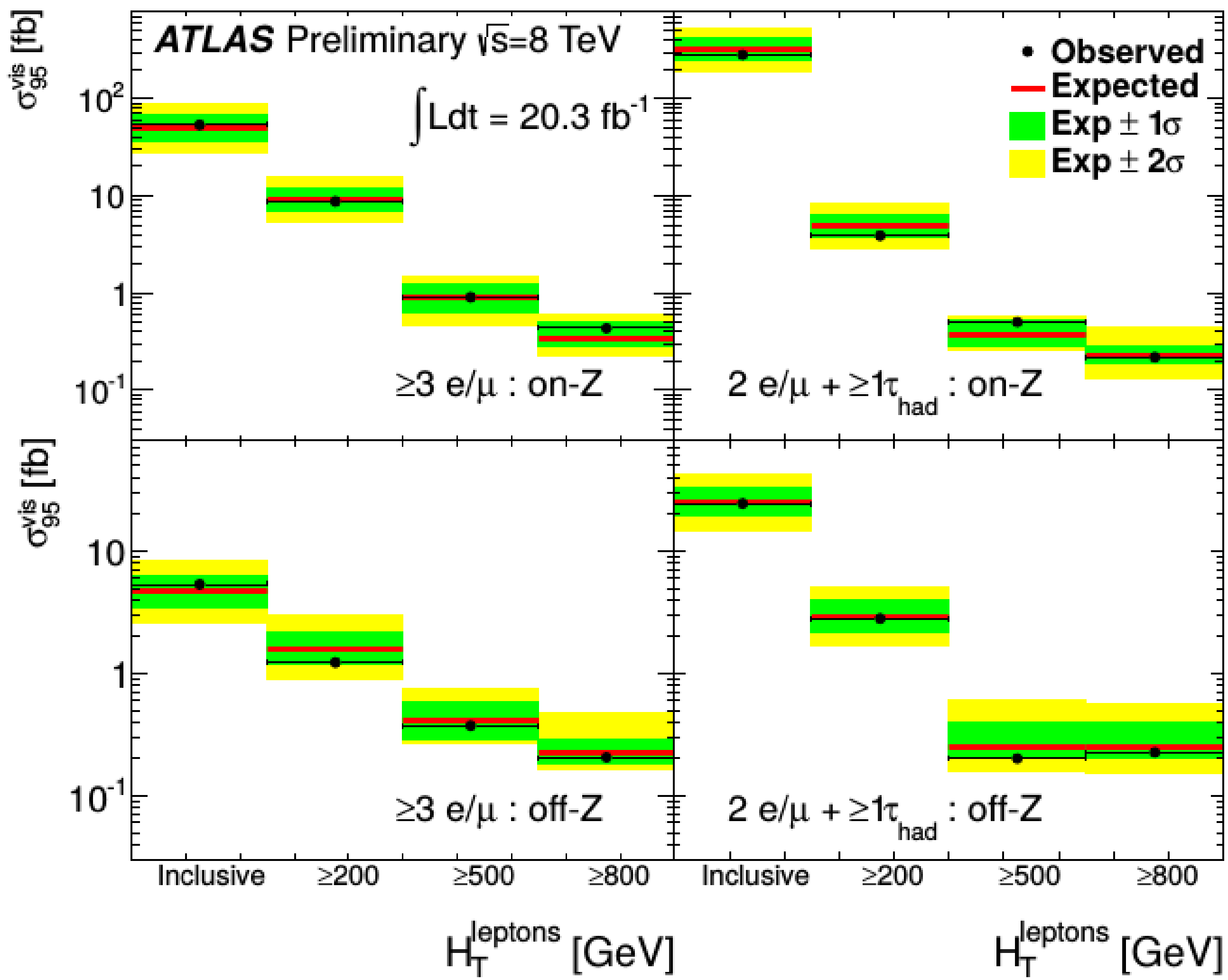
All other sparticles heavy ($\approx 2\,TeV$)

New Phys with 3 Leptons with ATLAS @ 8 TeV [4]

Many BSM scenarios predict final states with multiple leptons.
Determine signature based limits instead of theory limits.
→ These can be interpreted in terms of many theories later on.

Define signal regions based on the number of leptons in the final state and kinematic properties:

Results: Limits on the visible cross-section in signal region:



Interpret limits in terms of a specific theory:

$$\sigma_{95}^{\mathrm{fid}} = \frac{N_{95}}{\epsilon_{fid} \int L dt} = \frac{\sigma_{95}^{\mathrm{vis}}}{\epsilon_{fid}}$$

theory specific

New Phys with 3 Leptons with CMS @ 8 TeV

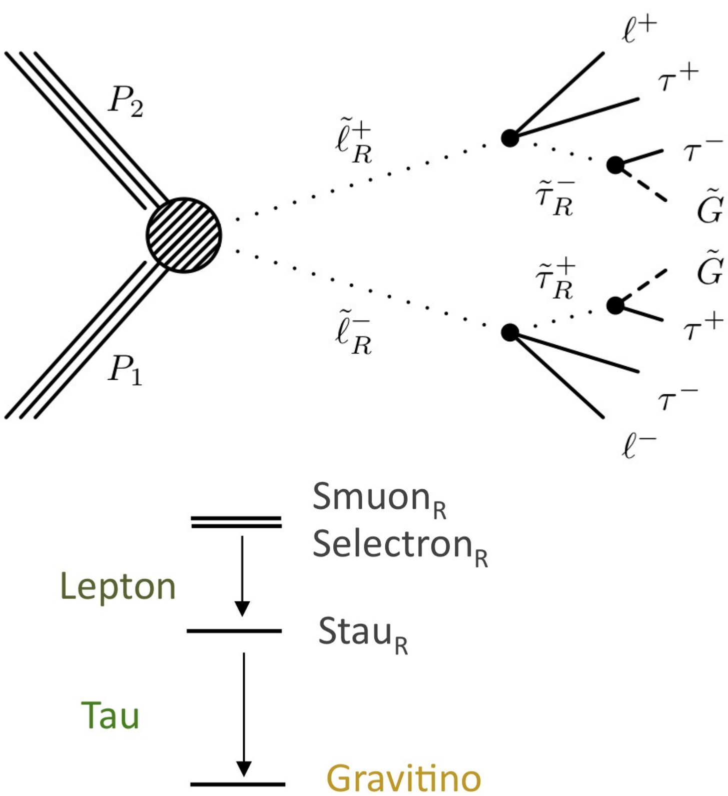
[5]

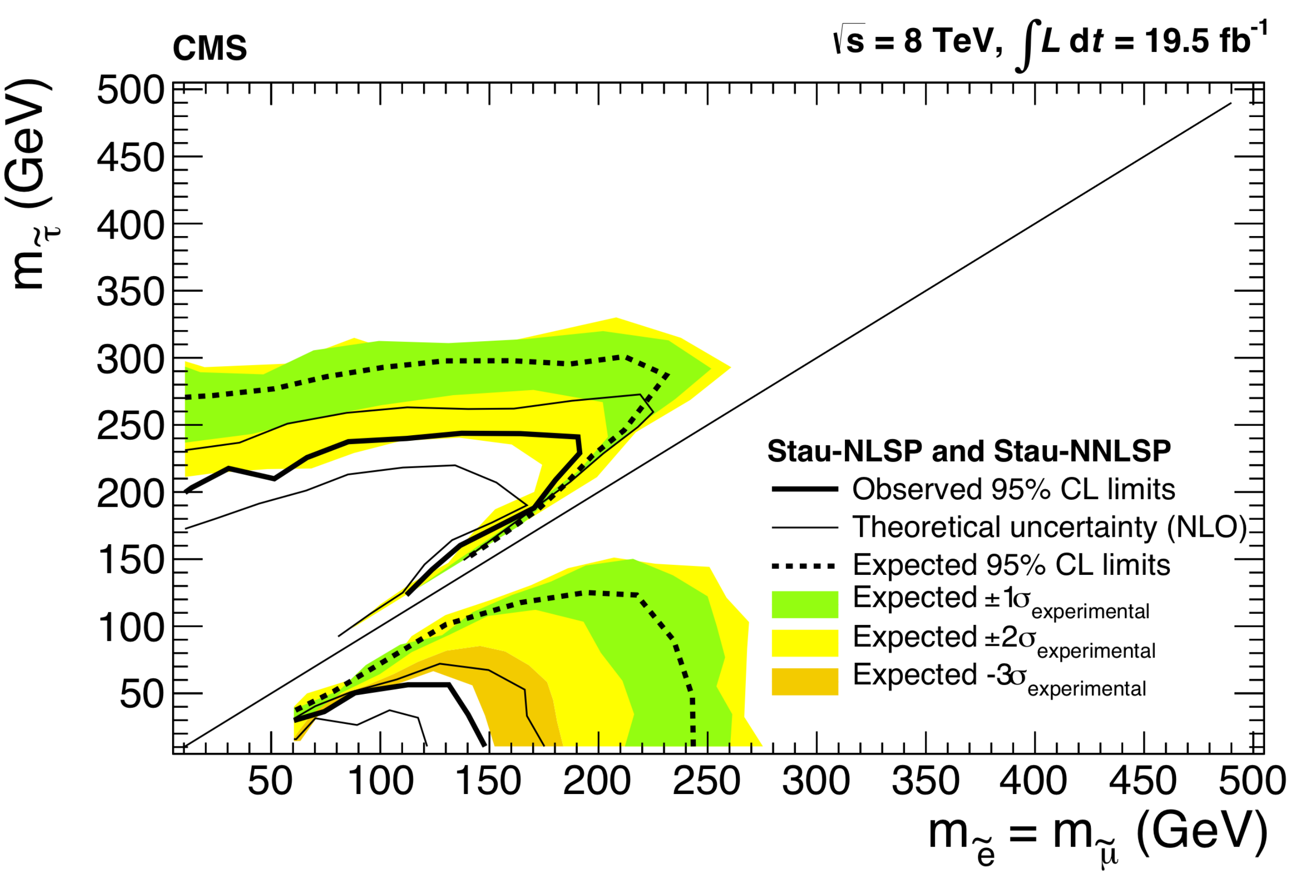
Similar approach as the ATLAS analysis. Search region definitions differ a bit. CMS does not calculate limits on visible cross-section, but uses the search regions to set limits on various SUSY models.

Define signal regions based on:

Number of: e, μ, τ, b-jet, OSSF dilepton pairs, M(OSSF) on/below/above Z, binned in MET and H_T

Example: Interpretation for the stau-(N)NLSP scenario





Most sensitive search region:

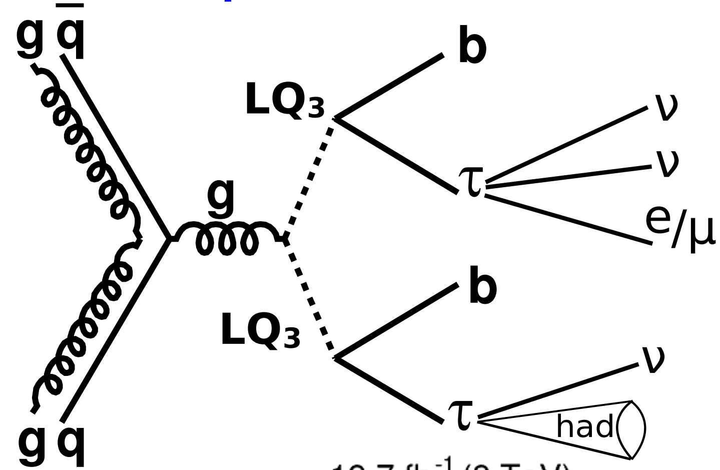
$N_\tau > 1$, $N_{b\text{-jet}} = 0$, off-Z OSSF pairs and large MET

3rd Gen Leptoquarks → b + τ with CMS @ 8 TeV [6]

Many BSM theories predict bosons with non-zero lepton and baryon number.
The LQ3 decays into 3rd gen SM particles where the BR is model dependent.

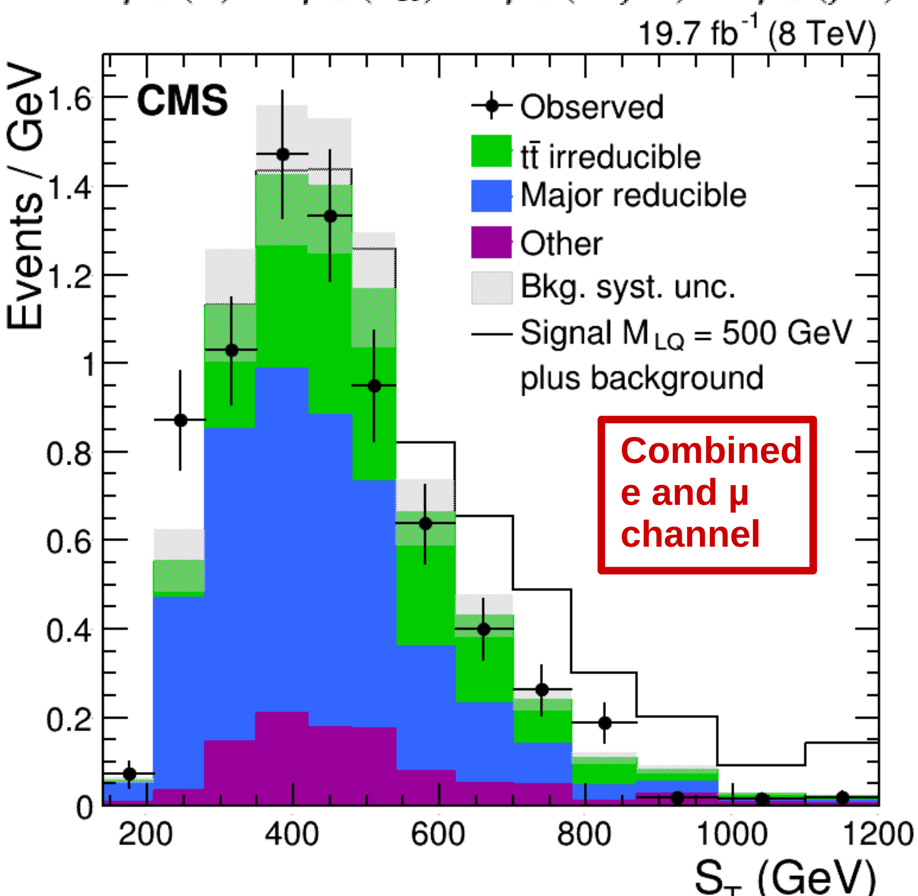
In this analysis, search for pair-produced LQ in two semi-leptonic channels depending on the flavor of the lepton from the second tau decay:

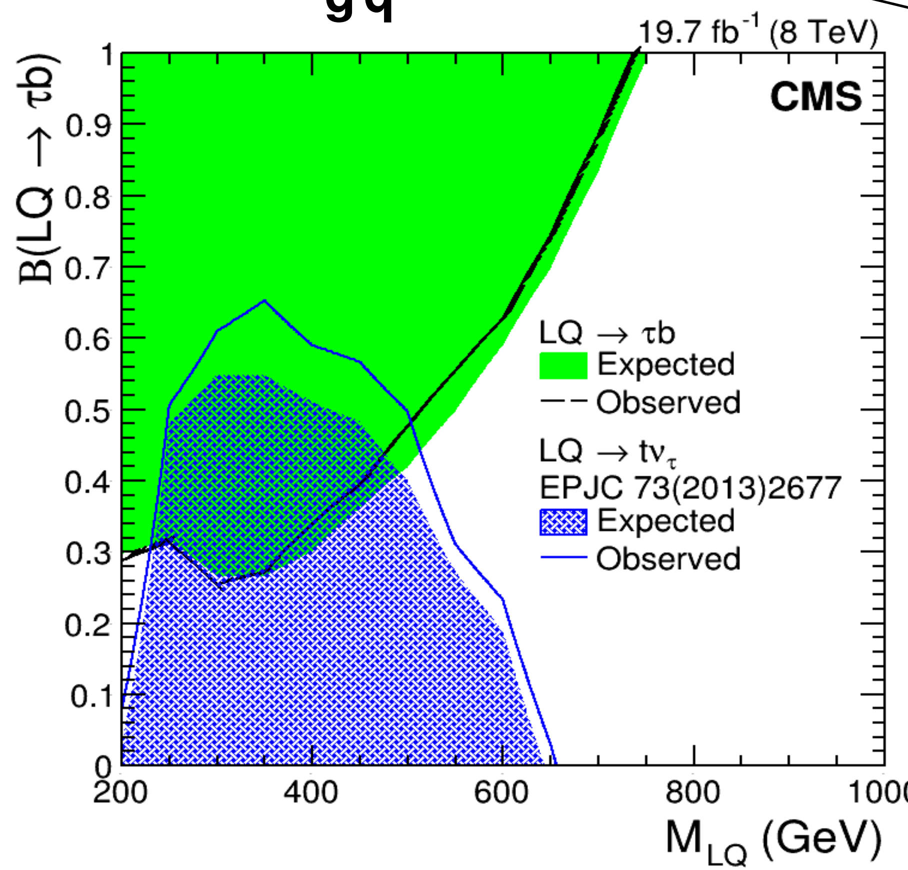
$$\mathbf{LQ_3 + LQ_3 \rightarrow b\ \tau\ b\ \tau \rightarrow b\ \tau_{had}\ \nu + b\ (e/\mu)\ \nu\ \nu}$$



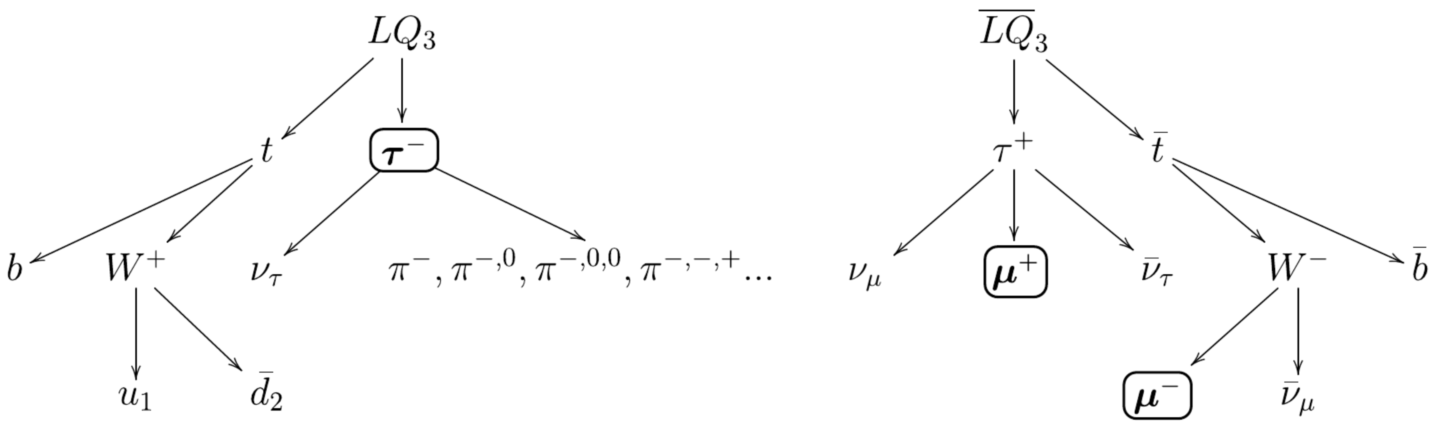
Main discriminating variable:

$$S_T^{(LQ)} = p_T(\ell) + p_T(\tau_h) + p_T(\text{b-jet}) + p_T(\text{jet})$$

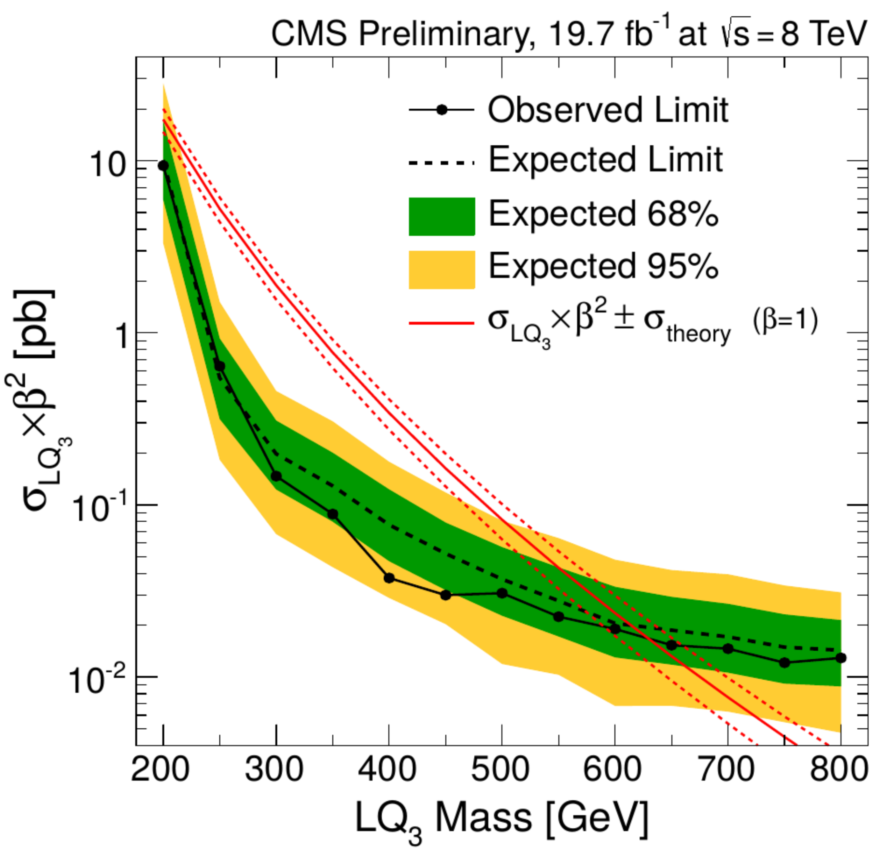


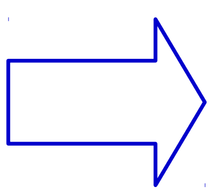


3rd Gen Leptoquarks → t + τ with CMS @ 8 TeV [7]

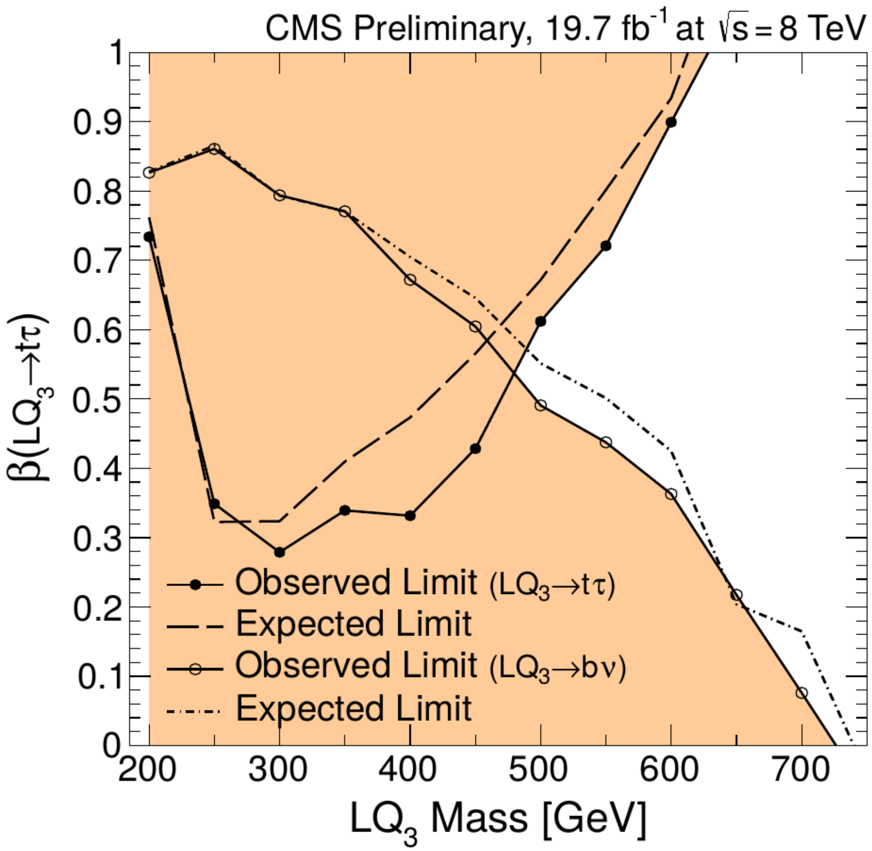


Search in two categories: A) SS-$\mu\tau_{had}$ pair, B) OS-$\mu\tau_{had}$ pair (+ kinematic selection)



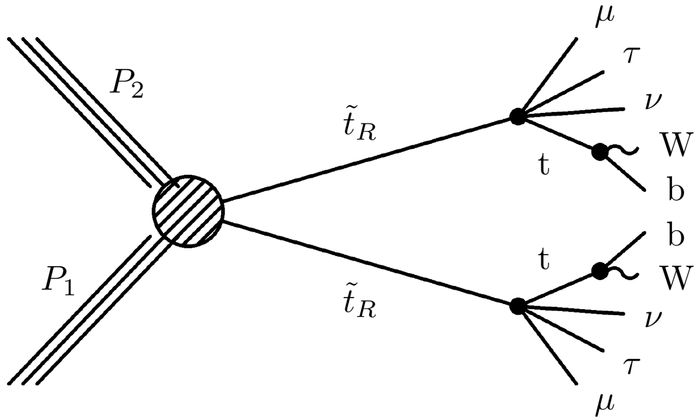


Combined with: CMS-PAS -SUS-13-018



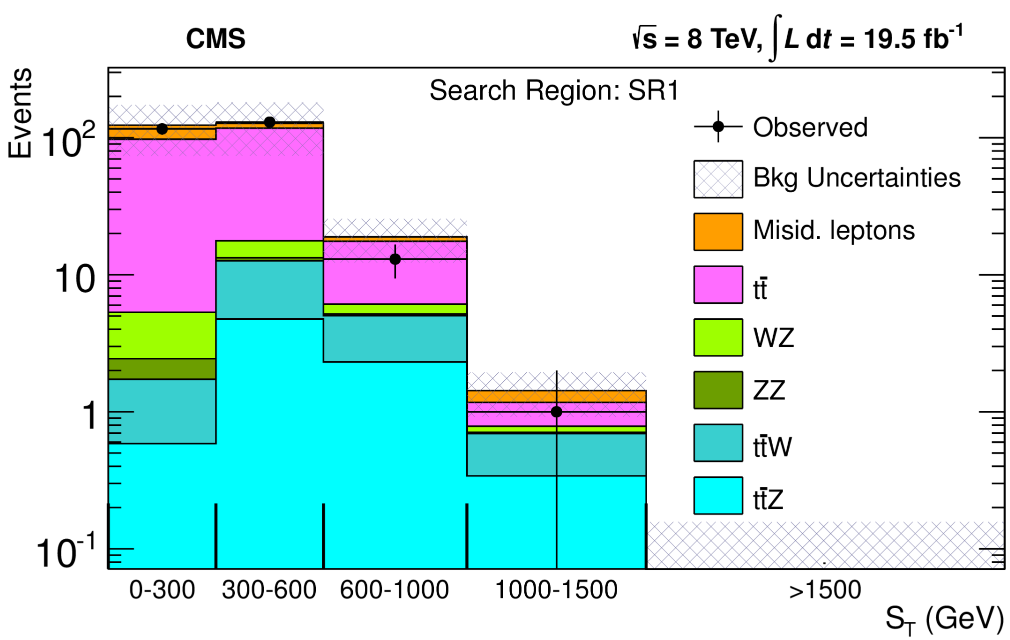
RPV stop with l ≥ 3 and b-jets with CMS @ 8 TeV [8]

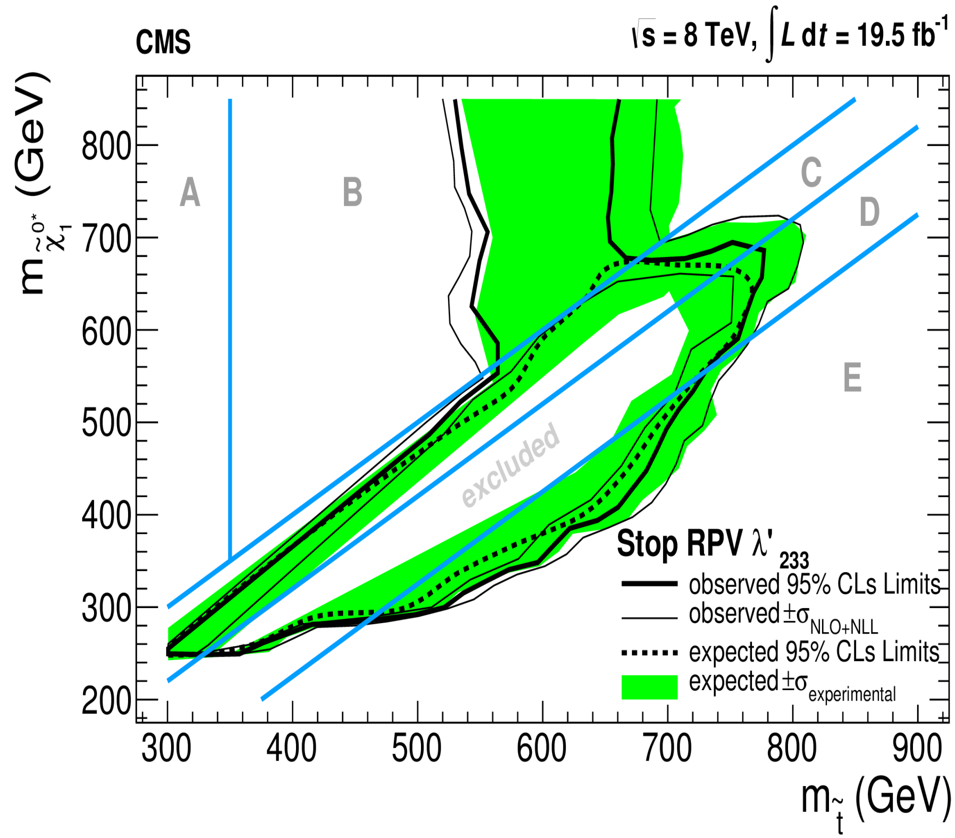
R-parity-violating SUSY models allow the resonant production of SUSY particles and their decay solely into SM particles.



region label	kinematic region	stop decay mode(s)
A	$m_t < m_{\tilde{t}} < 2m_t, m_{\tilde{\chi}_1^0}$	$\tilde{t} \to t\nu b\bar{b}$
B	$2m_t < m_{\tilde{t}} < m_{\tilde{\chi}_1^0}$	$\tilde{t} \to t\mu t\bar{b} + t\nu b\bar{b}$
C	$m_{\tilde{\chi}_1^0} < m_{\tilde{t}} < m_W + m_{\tilde{\chi}_1^0}$	$\tilde{t} \to \ell\nu b\tilde{\chi}_1^0 + jjb\tilde{\chi}_1^0$
D	$m_W + m_{\tilde{\chi}_1^0} < m_{\tilde{t}} < m_t + m_{\tilde{\chi}_1^0}$	$\tilde{t} \to Wb\tilde{\chi}_1^0$
E	$m_t + m_{\tilde{\chi}_1^0} < m_{\tilde{t}}$	$\tilde{t} \to t\tilde{\chi}_1^0$

Limits are set by combining many search regions which are definded by the particle content in the event.





Conclusion

- **Many searches for BSM physics performed at LHC.**

- **No new phenomena observed so far.**

  But many insights in new regions have been obtained:
  - M(Z') > 1.9 TeV (> 400 GeV @ CDF)
  - M(LQ_3) > 700 GeV (First limits in the tau + top channel.)
  - Excluded various regions of SUSY parameter space.

- **Tau Reconstruction is challenging at proton-colliders, but:**
  - Algorithms performed well in both experiments.
  - Excellent results have been achieved.
  - Many more interesting results expected in the future.

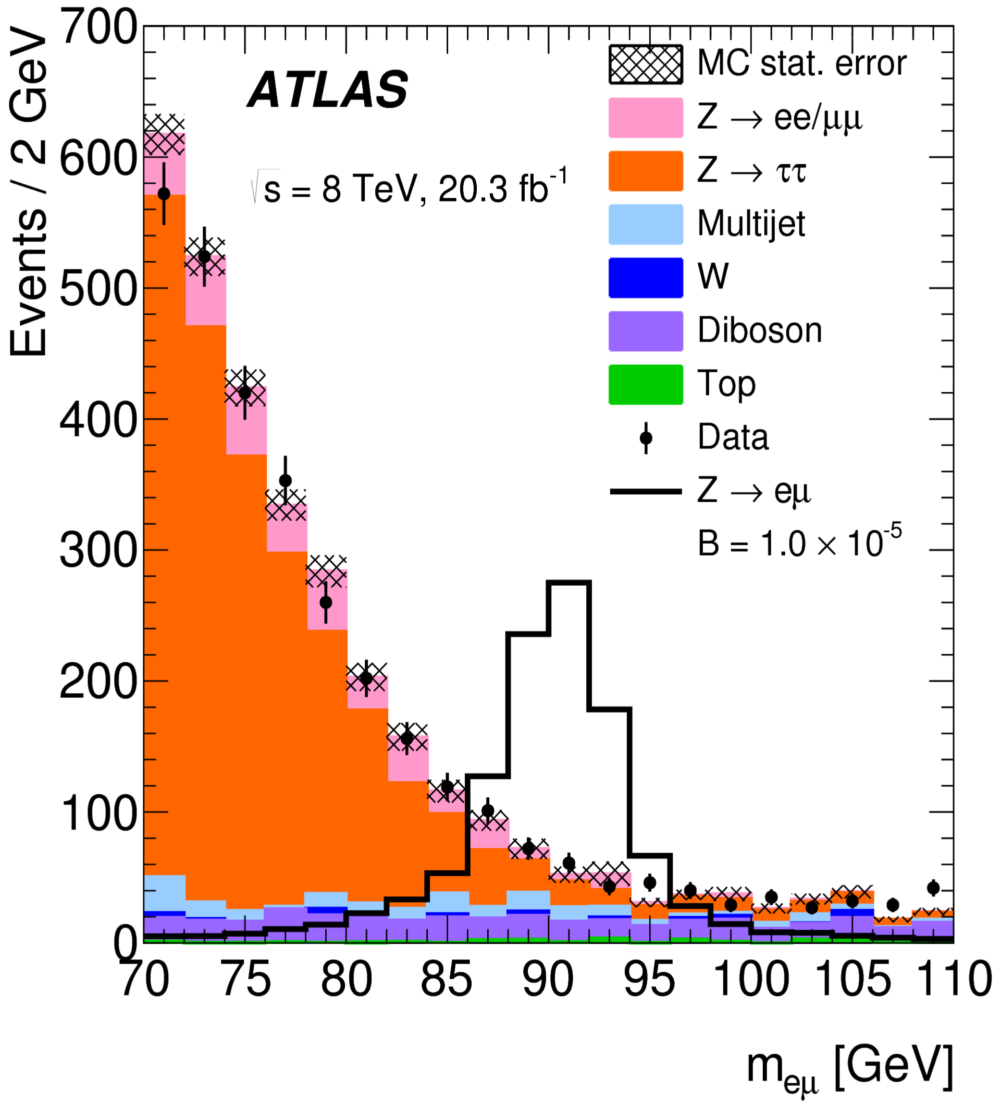
Bibliography

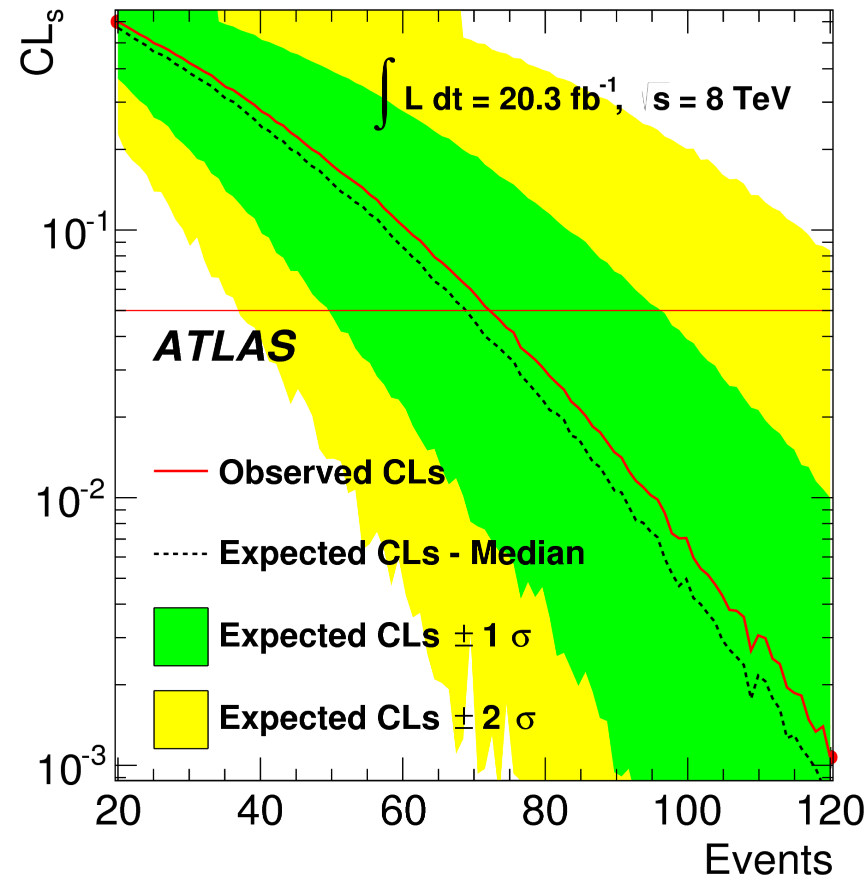
- [1] A search for high-mass ditau resonances decaying in the fully hadronic final state in pp collisions at √s=8 TeV with the ATLAS detector
  ATLAS-CONF-2013-066
- [2] Search for the direct pair production of top squarks decaying to a b quark, a tau lepton, and weakly interacting particles, in √s = 8TeV pp collisions using 20 fb^{-1} of ATLAS data
  ATLAS-CONF-2014-014
- [3] Search for the direct production of charginos, neutralinos and staus in final states with at least two hadronically decaying taus and missing transverse momentum in pp collisions at s√ = 8 TeV with the ATLAS detector
  arXiv1407.0350
- [4] Search for New Phenomena in Events with Three Charged Leptons at a Center-of-Mass Energy of 8 TeV with the ATLAS detector
  ATLAS-CONF-2013-070
- [5] Search for anomalous production of events with three or more leptons using 19.5fb−1 of √s = 8 TeV LHC data
  arXiv1404.5801v1
- [6] Search for pair production of third-generation scalar leptoquarks and top squarks in proton-proton collisions at sqrt(s) = 8 TeV
  arXiv1408.0806
- [7] Search for Third Generation Scalar Leptoquarks Decaying to Top Quark - Tau Lepton Pairs in pp Collisions
  CMS-PAS-EXO-13-010
- [8] Search for top squarks in R-parity-violating supersymmetry using three or more leptons and b-tagged jets
  arXiv1306.6643

Search for LFV $Z \rightarrow e\mu$ with ATLAS @ 8 TeV

- **Select events with isolated, opposite sign, same flavor leptons and small hadronic activity and low MET.**
- **Derive Limit on BR($Z \rightarrow e\mu$) from limit on number of signal events and overall number of Z-bosons.**

arXiv:1408.5774





Z decay	Efficiency (%)	N_Z (10^8)
ee	10.8 ± 0.3	7.85 ± 0.24
$\mu\mu$	17.8 ± 0.4	7.79 ± 0.17
$\langle ee, \mu\mu \rangle$		7.80 ± 0.15
$e\mu$	14.2 ± 0.4	

$$\mathcal{B}(Z \rightarrow e\mu) < 7.5 \times 10^{-7}$$

Transverse Mass

Transverse mass (m_T) is the invariant mass calculated from the transverse components of the momentum vectors in the final state.

W-like final state (W→ tau + nu) :

$$M_T = \sqrt{2 \cdot E_T^{\tau jet} \cdot MET(1 - cos\Delta\Phi(\vec{E}_T^{\tau jet}, M\vec{E}T))}$$

Z-like final state (Z→ tau + tau) :

$$m_{\mathrm{T}}^{\mathrm{tot}} = \sqrt{2 p_{\mathrm{T}1} p_{\mathrm{T}2} C + 2|E_{\mathrm{T}}^{\mathrm{miss}}| p_{\mathrm{T}1} C_1 + 2|E_{\mathrm{T}}^{\mathrm{miss}}| p_{\mathrm{T}2} C_2}, \qquad C = 1 - \cos\Delta\phi$$

Combinatoric m_T (Susy searches):

$$m_{\mathrm{T2}}(\mathbf{p}_{\mathrm{T},1}, \mathbf{p}_{\mathrm{T},2}, \mathbf{p}_{\mathrm{T}}^{\mathrm{miss}}) = \min_{\mathbf{q}_{\mathrm{T},1} + \mathbf{q}_{\mathrm{T},2} = \mathbf{p}_{\mathrm{T}}^{\mathrm{miss}}} \{\max[\, m_{\mathrm{T}}(\mathbf{p}_{\mathrm{T},1}, \mathbf{q}_{\mathrm{T},1}), m_{\mathrm{T}}(\mathbf{p}_{\mathrm{T},2}, \mathbf{q}_{\mathrm{T},2}) \,]\}$$

New Phys with 3 Leptons with ATLAS @ 8 TeV

Define signal regions based on the number of leptons in the final state and kinematic properties:

≥ 3 e / μ | 2e / μ + ≥ 1 τ
2 e / μ on- or off-Z

Variable	Signal Region Definition				Additional Requirements
H_T^{leptons}	Inclusive	$\geq$200 GeV	$\geq$ 500 GeV	$\geq$ 800 GeV	
Min. p_T^{ℓ}	Inclusive	$\geq$ 50 GeV	$\geq$ 100 GeV	$\geq$ 150 GeV	
E_T^{miss}	Inclusive	$\geq$100 GeV	$\geq$ 200 GeV	$\geq$ 300 GeV	$H_T^{\text{jets}} < 150$ GeV
E_T^{miss}	Inclusive	$\geq$100 GeV	$\geq$ 200 GeV	$\geq$ 300 GeV	$H_T^{\text{jets}} \geq 150$ GeV
m_{eff}	Inclusive	$\geq$600 GeV	$\geq$1000 GeV	$\geq$1500 GeV	
m_{eff}	Inclusive	$\geq$600 GeV	$\geq$1200 GeV		$E_T^{\text{miss}} \geq 100$ GeV
m_{eff}	Inclusive	$\geq$600 GeV	$\geq$1200 GeV		$m_T^W \geq 100$ GeV, on-Z
b-tags	Inclusive	$\geq$ 1	$\geq$ 2		

Table 1: Kinematic signal regions defined in the analysis.

Event yield in inclusive signal channels:

Flavor Chan.	Z Chan.	Expected			Observed
$\geq 3e/\mu$	off-Z	260 ±	10 ±	40	280
$2e/\mu+ \geq 1\tau_{\text{had}}$	off-Z	1200 ±	10 ±	290	1193
$\geq 3e/\mu$	on-Z	3100 ±	40 ±	500	3199
$2e/\mu+ \geq 1\tau_{\text{had}}$	on-Z	17000 ±	40 ±	4000	14733

RPV stop with l ≥ 3 and b-jets with CMS @ 8 TeV

SR1-4:
No OSSF on-Z and $N_{bjet} \geq 1$

SR4-8:
1 OSSF on-Z or $N_{bjet} \geq 1$

SR	N_L	N_τ	$0 < S_T < 300$		$300 < S_T < 600$		$600 < S_T < 1000$		$1000 < S_T < 1500$		$S_T > 1500$	
			obs	exp	obs	exp	obs	exp	obs	exp	obs	exp
SR1	3	0	116	123 ± 50	130	127 ± 54	13	18.9 ± 6.7	1	1.43 ± 0.51	0	0.208 ± 0.096
SR2	3	≥ 1	710	698 ± 287	746	837 ± 423	83	97 ± 48	3	6.9 ± 3.9	0	0.73 ± 0.49
SR3	4	0	0	0.186 ± 0.074	1	0.43 ± 0.22	0	0.19 ± 0.12	0	0.037 ± 0.039	0	0.000 ± 0.021
SR4	4	≥ 1	1	0.89 ± 0.42	0	1.31 ± 0.48	0	0.39 ± 0.19	0	0.019 ± 0.026	0	0.000 ± 0.021
SR5	3	0	—	—	—	—	165	174 ± 53	16	21.4 ± 8.4	5	2.18 ± 0.99
SR6	3	≥ 1	—	—	—	—	276	249 ± 80	17	19.9 ± 6.8	0	1.84 ± 0.83
SR7	4	0	—	—	—	—	5	8.2 ± 2.6	2	0.96 ± 0.37	0	0.113 ± 0.056
SR8	4	≥ 1	—	—	—	—	2	3.8 ± 1.3	0	0.34 ± 0.16	0	0.040 ± 0.033

Supersymmetric models with RPV interactions violate either B or L but can avoid proton decay limits [9, 10]. The superpotential W_{RPV} includes three trilinear terms parametrized by the Yukawa couplings λ_{ijk}, λ'_{ijk}, and λ''_{ijk}:

$$W_{\mathrm{RPV}} = \frac{1}{2}\lambda_{ijk} L_i L_j \overline{E}_k + \lambda'_{ijk} L_i Q_j \overline{D}_k + \frac{1}{2}\lambda''_{ijk} \overline{U}_i \overline{D}_j \overline{D}_k, \tag{1}$$

where i, j, and k are generation indices; L and Q are the $SU(2)_L$ doublet superfields of the lepton and quark; and the $\overline{E}$, $\overline{D}$, and $\overline{U}$ are the $SU(2)_L$ singlet superfields of the charged lepton, down-like quark, and up-like quark. The third term violates baryon number conservation, while the first two terms violate lepton number conservation. These terms do not preclude a natural hierarchy [11].