Searches for RPV SUSY via LQD couplings at CMS Experiment

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Outline

- Introduction
- Details of selected analyses with opposite charge dilepton + jets events (EXO-12-032, EXO-14-013)
  - Event Selections
  - Background Estimation
  - Systematic Uncertainties
  - Results
- Conclusion

RPV Searches

Lepton number violating terms — Baryon number violating term

$$W_{\not R_p} = \mu_i H_u L_i + \frac{1}{2}\lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \frac{1}{2}\lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k.$$

RPV Searches

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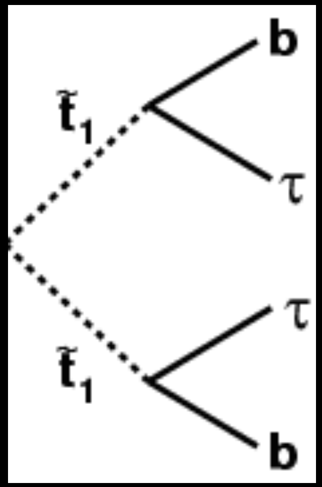
t~→lj



EXO-12-032/041/042

m(t~) > 700 GeV

RPV Searches

Lepton number violating terms — Baryon number violating term

$$W_{\not R_p} = \mu_i H_u L_i + \frac{1}{2}\lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \frac{1}{2}\lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k$$

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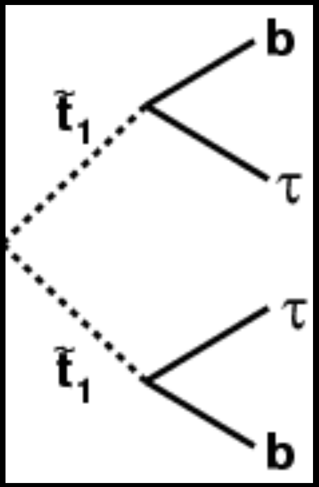
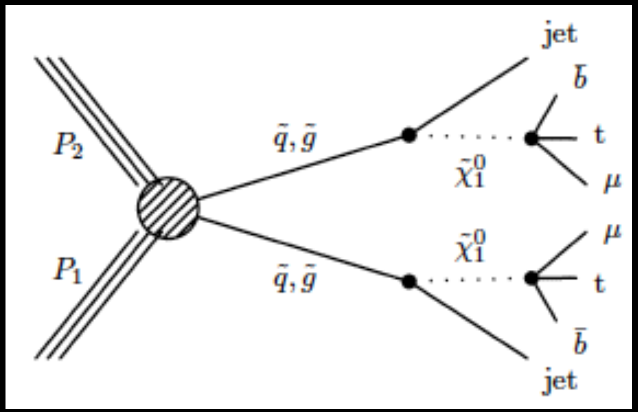


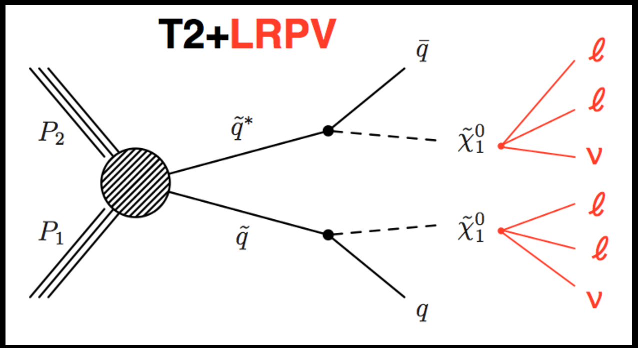
EXO-12-032/041/042

m(t~) > 700 GeV

t~/g~→ltbj, llvj



SUS-12-027



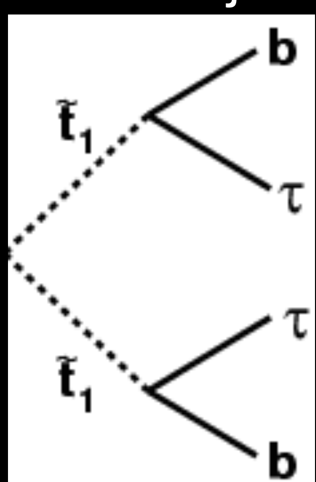
SUS-13-010

RPV Searches

Lepton number violating terms — Baryon number violating term

$$W_{\not{R}_p} = \mu_i H_u L_i + \frac{1}{2}\lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \frac{1}{2}\lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k$$

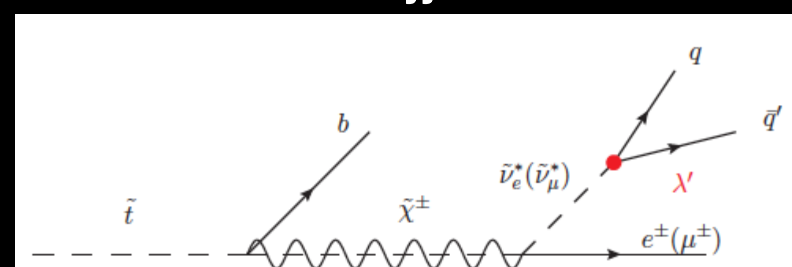
t~→lj



EXO-12-032/041/042

m(t~) > 700 GeV

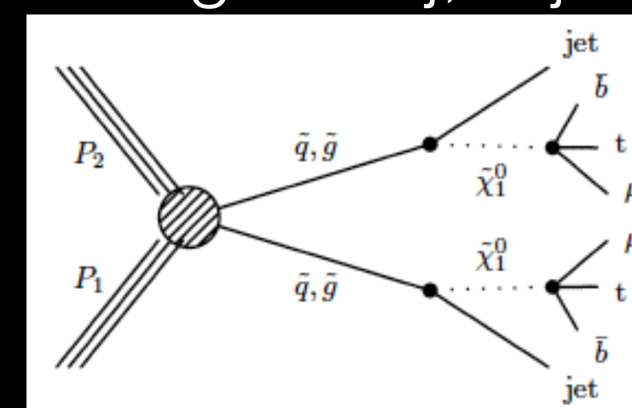
t~→ljjb



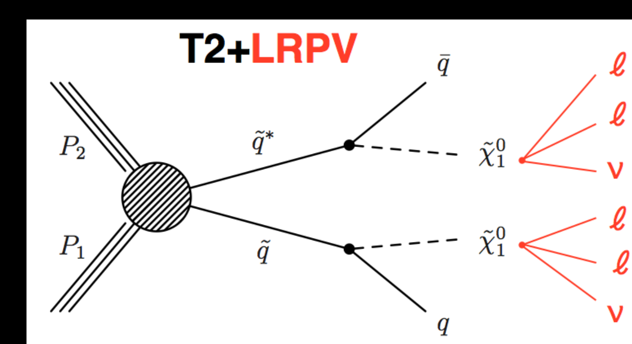
EXO-14-013/032

m(t~) > 0.9-1.0 TeV

t~/g~→ltbj, llvj



SUS-12-027



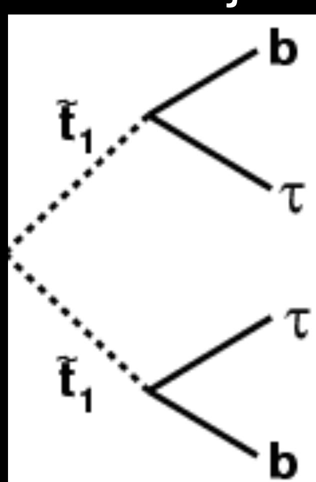
SUS-13-010

RPV Searches

Lepton number violating terms | Baryon number violating term

$$W_{\not{R}_p} = \mu_i H_u L_i + \frac{1}{2}\lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \frac{1}{2}\lambda''_{ijk}\bar{U}_i \bar{D}_j \bar{D}_k$$

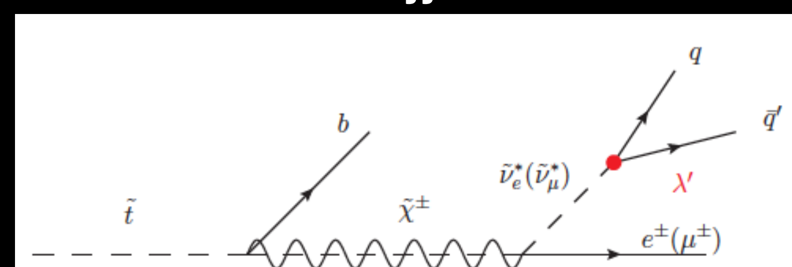
t~→lj



EXO-12-032/041/042

m(t~) > 700 GeV

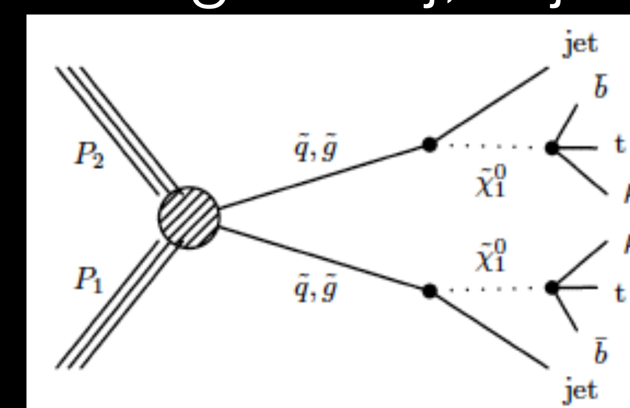
t~→ljjb



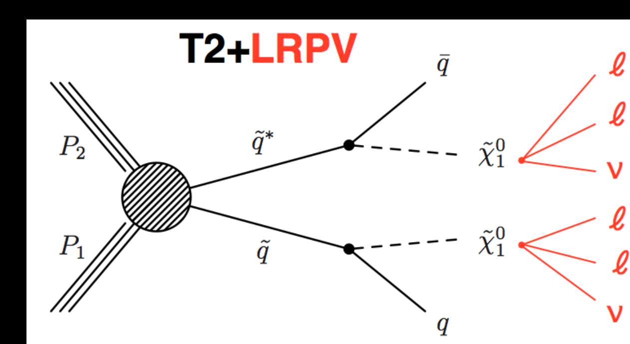
EXO-14-013/032

m(t~) > 0.9-1.0 TeV

t~/g~→ltbj, llvj



SUS-12-027

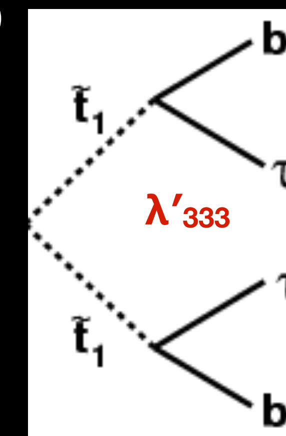


SUS-13-010

- LQD models have been searched in
  - multileptons+jets+MET, and OS dilepton pairs(ee, μμ, ττ +jets)+jets +**no MET**

RPV Stop Searches in di-tau+jets

EXO-12-032

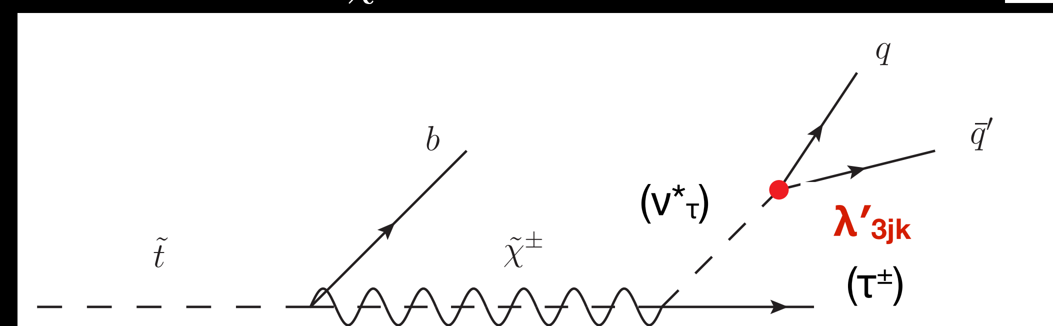


- Assuming the coupling λ'_{333} , and λ'_{3jk} (j,k≤2) is non-zero
- λ'_{333}: trilinear RPV operator
  - Reinterpretation of LQ3, as it has the same final states

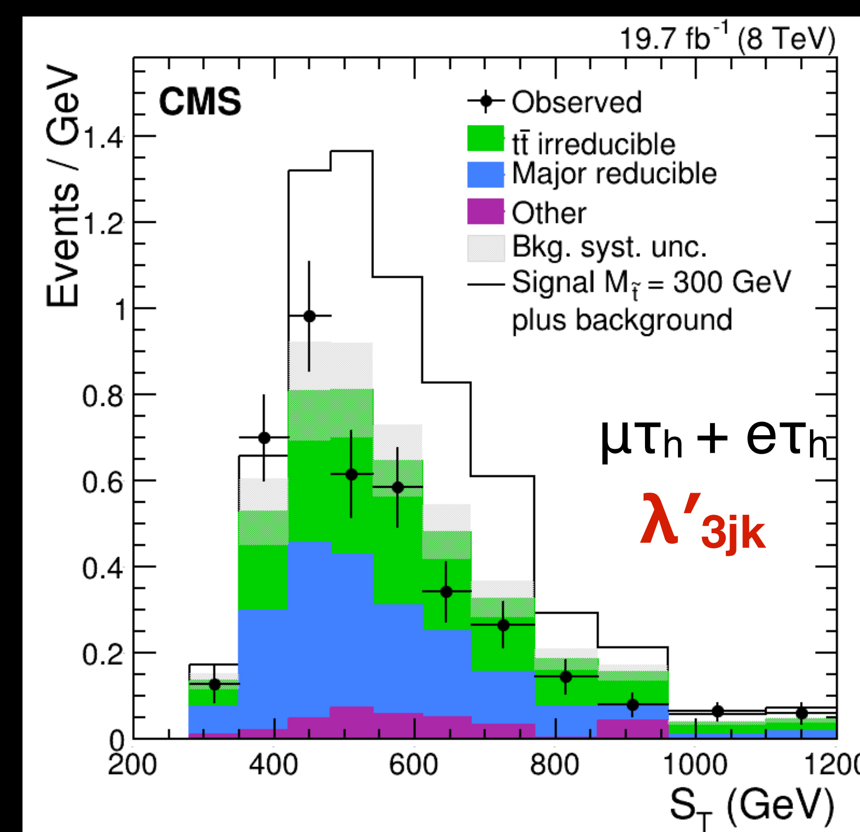
$$M_{\tilde{\chi}^{\pm}} = M_{\tilde{t}} - 100\ GeV$$

- λ'_{3jk}: $\tilde{t} \to \tilde{\chi}^{\pm} b \to \tilde{\nu}_{\tau}^{*} \tau^{\pm} b$

$$(\tilde{\nu}_{\tau}^{*} \to jj)\tau^{\pm} b$$



- **Selection**
  - Require one τ_l and one τ_h
  - e, μ: $p_T > 30$ GeV and veto 2nd lepton
  - τ_h: $p_T > 50$ GeV
  - $M(\tau_h, j) > 250$ GeV for λ'_{333}
  - ≥ 2 (≥ 5 jets), ≥ 1 b-jet for $\lambda'_{333}(\lambda'_{3jk})$
- **Strategy**
  - $S_T = p_T(l) + p_T(\tau_h) + \Sigma_{j\geq 2(5)} p_T(j)$



Backgrounds

EXO-12-032

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	

- **tt+jets:** All selections except τ_h . The eμ events are scaled by the relative difference of the selection efficiencies between the l,τ_h and eμ, which already corrected using data

- **Fake τ_h:** Use Z+jets, Z →μμ: $M_{\mu\mu}$> 50 GeV and event requires ≥ 1τ_h. MisID probability is calculated as fraction of τ_h passing isolation criteria (as a function of pt), where background yield is calculated when τ_h failed the isolation. The anit-isolated events are then weighted by the misID probability

- **QCD:** Appears only in e τ_h. Use data with e and τ_h having same electric charge

	$\mu\tau_h$ 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

Systematic Uncertainties

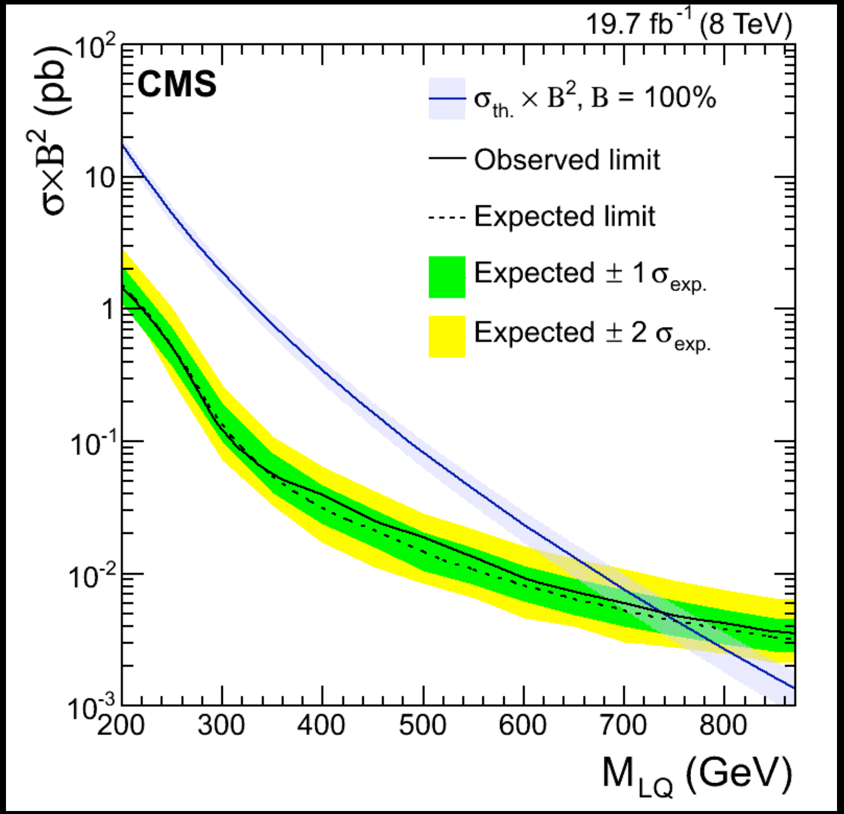
EXO-12-032

Source	Uncertainty (%)
Luminosity	2.6
Lepton Trigger+Efficiency	2
τ_h	6
b-tagging efficiency	4-10
Irreducible bkg normalizaion	19-22
Other major bkg normalization	16-24
Jet Energy Scale	2-4
Jet Energy Resolution	5-10
ISR/FSR modeling for signal	4
MC Stats on small bkg	20-50
τ_h	3
τ_h	10

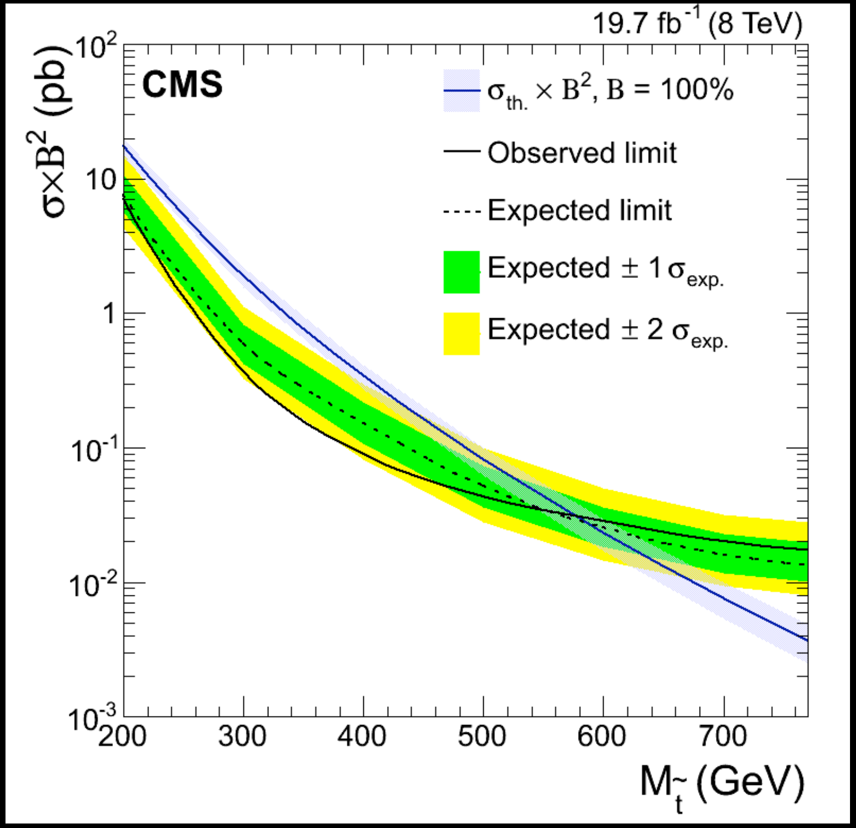
Results

EXO-12-032

- Assuming the coupling λ'_{333}
  - exclude $M(\tilde{t}) < 740$ GeV at 95% C.L assuming 100% BR of $\tilde{t}$ decay



- Assuming the coupling λ'_{3jk} (j,k≤2) is non-zero
  - exclude $M(\tilde{t}) < 850$ GeV at 95% C.L assuming 100% BR of $\tilde{t}$ decay



RPV Stop Searches in dilepton+jets

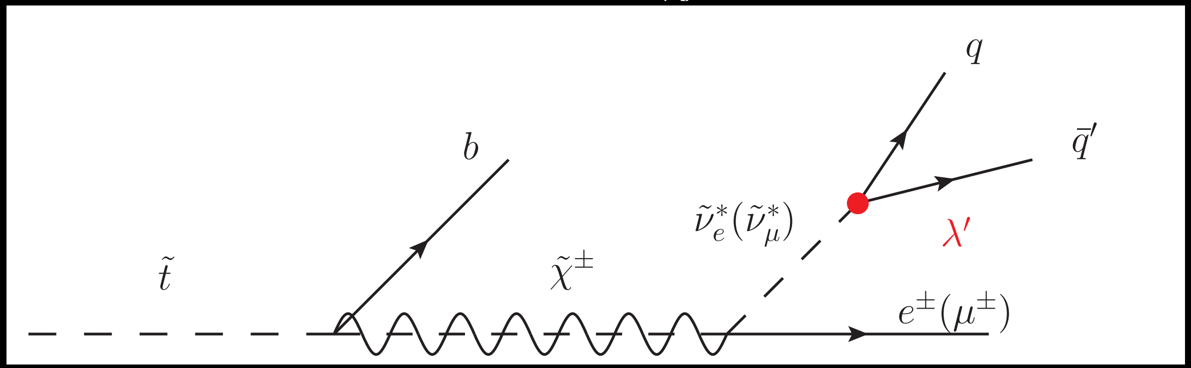
EXO-14-013

- Assuming the coupling λ'_{ijk} (i,j,k≤2) is non-zero

$$\tilde{t} \rightarrow \tilde{\chi}^{\pm} b \rightarrow \tilde{\nu}^{*} \ell^{\pm} b$$

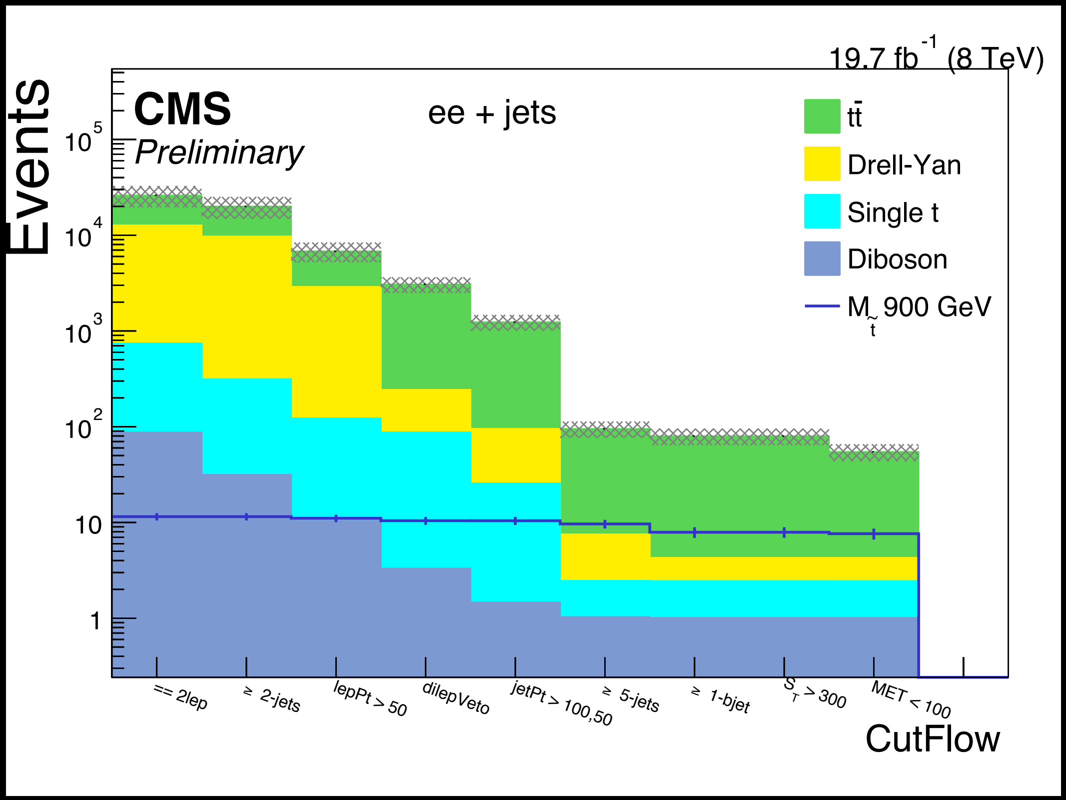
$$(\tilde{\nu}^{*} \rightarrow jj) \ell^{\pm} b$$

$$M_{\tilde{\chi}^{\pm}} = M_{\tilde{t}} - 100\ GeV$$



- Final states involve two OS same flavor dileptons, with six jets
  - i=1: electrons, i=2: muons
  - j,k=1,2: light flavor jets (d,s)

- Selection:
  - $e^{\pm}e^{\mp}$ or $\mu^{\pm}\mu^{\mp}$; M_{ll} > 130 GeV
  - ≥ 5 jets, ≥ 1 b-jet ;
  - Jet p_T > 100, 50, 30 GeV for 1st, 2nd, and ≥ 3rd jets
  - MET < 100 GeV;
  - S_T > 300 GeV



Analysis Strategy

EXO-14-013

- Discriminant: N_{Jets} and S_T
  - Optimize S_T^{min} using S/sqrt(S+B) for each stop mass hypothesis
  - Perform independently for all N_{jets}
  - Count number of events in jet bin after S_T^{min} selection

μμ+jets

Mass (GeV)	N_{jets}	S_T^{min} (GeV)	Data	Expected background	Signal
300	5	475	43	46.3 ± 7.2	696.0 ± 52.4
300	6	475	10	11.3 ± 3.8	450.2 ± 42.5
300	≥ 7	325	4	4.1 ± 1.9	261.0 ± 32.6
400	5	525	39	36.8 ± 7.2	266.4 ± 13.5
400	6	525	10	10.8 ± 3.9	280.9 ± 14.1
400	≥ 7	325	4	4.1 ± 1.9	222.6 ± 12.4
500	5	725	16	16.0 ± 3.8	81.1 ± 4.0
500	6	675	9	7.3 ± 3.2	114.4 ± 4.8
500	≥ 7	675	3	3.1 ± 1.6	101.8 ± 4.5
600	5	875	5	5.2 ± 1.5	23.6 ± 1.1
600	6	825	5	4.6 ± 1.6	36.0 ± 1.3
600	≥ 7	825	2	2.3 ± 1.0	44.2 ± 1.5
700	5	1075	2	1.3 ± 0.4	7.7 ± 0.4
700	6	975	4	2.4 ± 0.8	13.2 ± 0.5
700	≥ 7	975	2	1.0 ± 0.5	17.8 ± 0.5
800	5	1175	0	0.9 ± 0.3	2.9 ± 0.2
800	6	1175	2	0.8 ± 0.3	4.5 ± 0.2
800	≥ 7	1125	1	0.4 ± 0.2	7.3 ± 0.2
900	5	1475	0	0.1 ± 0.1	0.9 ± 0.1
900	6	1325	0	0.4 ± 0.2	1.8 ± 0.1
900	≥ 7	1175	1	0.4 ± 0.2	2.9 ± 0.1
1000	5	1575	0	0.1 ± 0.1	0.4 ± 0.1
1000	6	1525	0	< 0.1	0.6 ± 0.1
1000	≥ 7	1425	0	0.2 ± 0.2	1.2 ± 0.1

ee+jets

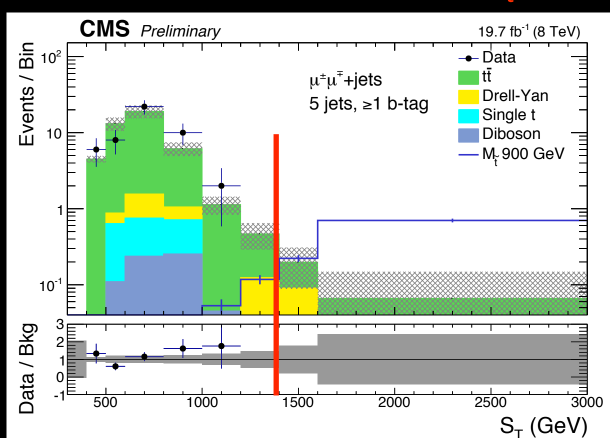
Mass (GeV)	N_{jets}	S_T^{min} (GeV)	Data	Expected background	Signal
300	5	325	39	38.1 ± 5.9	621.8 ± 49.1
300	6	325	13	9.0 ± 3.3	442.0 ± 41.1
300	≥ 7	325	4	2.9 ± 1.7	266.2 ± 32.9
400	5	525	27	28.7 ± 5.6	256.3 ± 13.6
400	6	325	13	9.0 ± 3.3	245.5 ± 13.1
400	≥ 7	325	4	2.9 ± 1.7	180.5 ± 11.5
500	5	725	12	14.1 ± 3.3	69.2 ± 3.3
500	6	675	9	5.3 ± 2.5	88.1 ± 3.8
500	≥ 7	675	4	2.2 ± 1.4	89.7 ± 3.8
600	5	925	1	3.4 ± 1.1	19.0 ± 0.9
600	6	875	3	2.7 ± 1.0	28.8 ± 1.2
600	≥ 7	825	4	1.8 ± 0.9	38.7 ± 1.3
700	5	1025	1	1.6 ± 0.5	7.1 ± 0.3
700	6	975	2	1.3 ± 0.5	10.5 ± 0.4
700	≥ 7	975	2	1.1 ± 0.6	14.8 ± 0.5
800	5	1225	1	0.4 ± 0.2	2.7 ± 0.2
800	6	1175	0	0.4 ± 0.2	3.6 ± 0.2
800	≥ 7	1075	2	0.7 ± 0.4	5.7 ± 0.2
900	5	1325	1	0.2 ± 0.1	1.0 ± 0.1
900	6	1375	0	0.2 ± 0.1	1.5 ± 0.1
900	≥ 7	1375	1	0.2 ± 0.1	2.4 ± 0.1
1000	5	1475	0	0.1 ± 0.1	0.3 ± 0.1
1000	6	1425	0	0.2 ± 0.1	0.6 ± 0.1
1000	≥ 7	1525	0	0.1 ± 0.1	1.0 ± 0.1

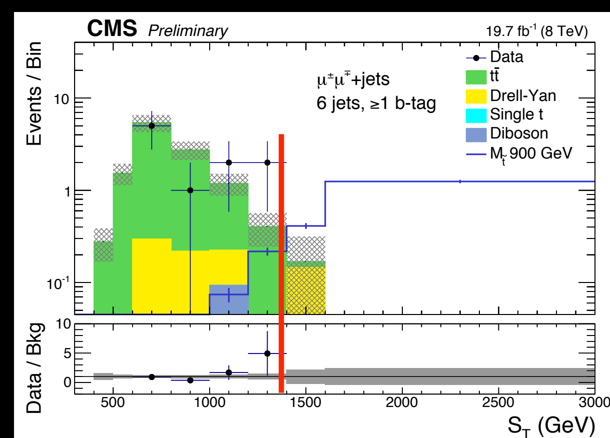
Analysis Strategy

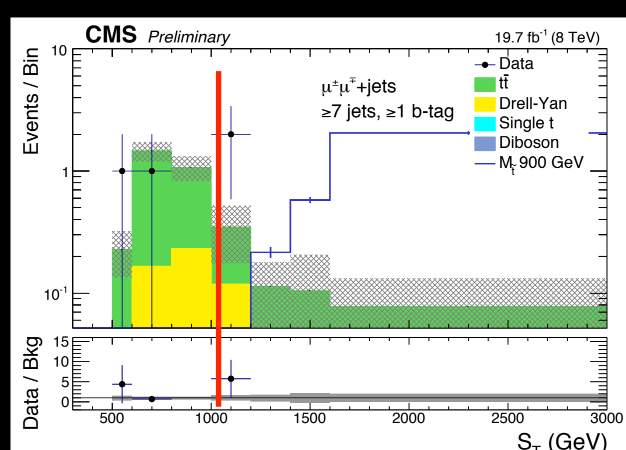
EXO-14-013

- The S_T distribution for each $\tilde{t}$ mass is different, hence require optimization
  - Optimize S_T^{min} using S/sqrt(S+B) for each stop mass hypothesis and independently for all N_{jets}

$M_{\tilde{t}}$ = 900 GeV







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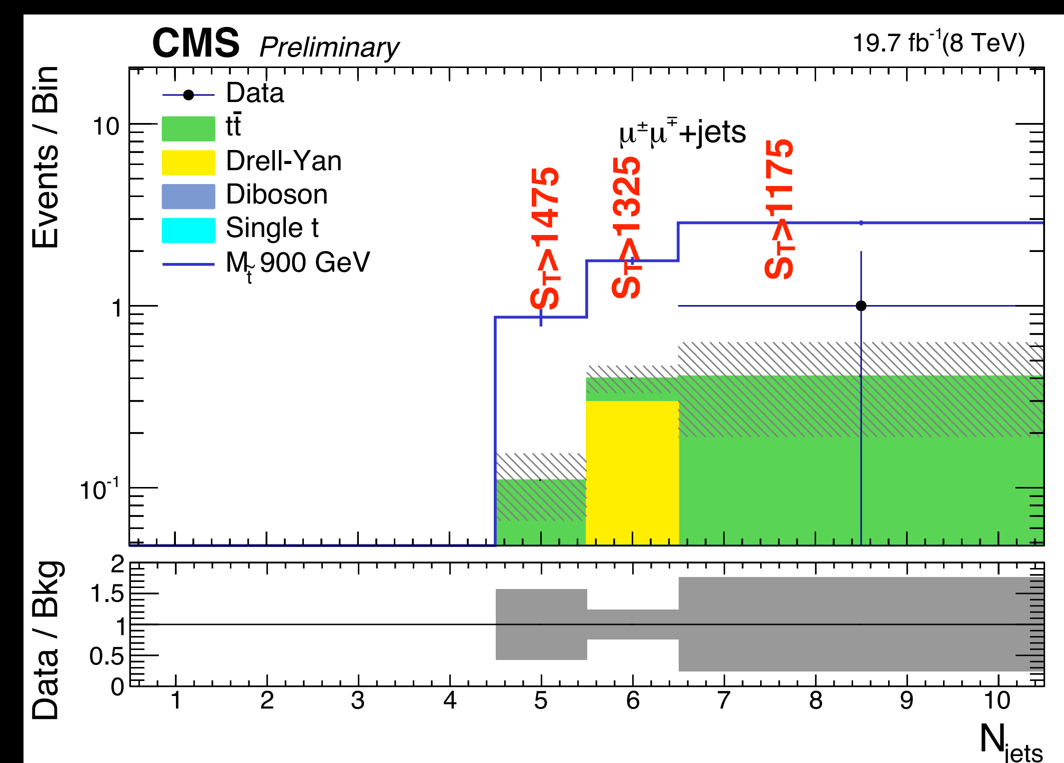


- S_T distributions in 5-, 6-, and more than 7-jet bins

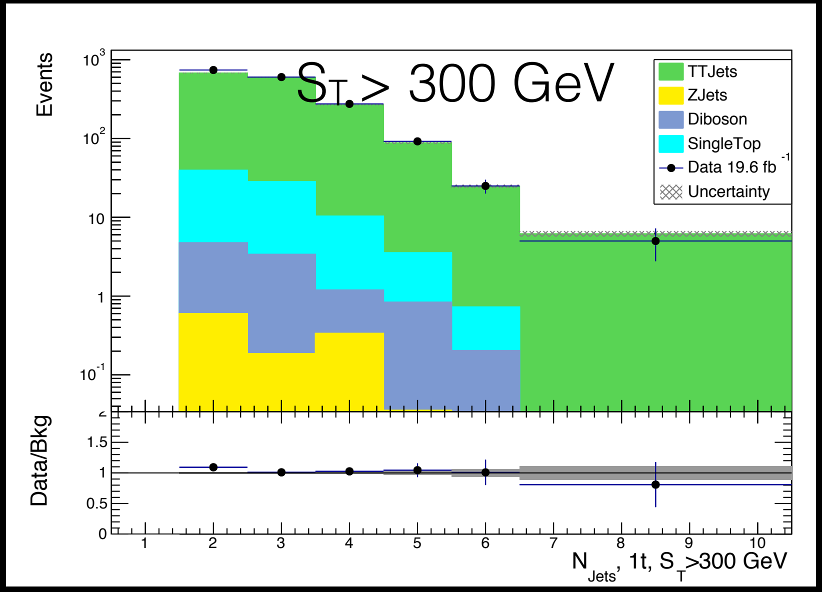
Backgrounds

EXO-14-013

- Corrections factors for the largest backgrounds are obtained from data
  - ttbar+jets : $e^{\pm}\mu^{\mp}$ region is signal free
  - DY: Shape from 0-btag region and normalization by fitting the Z mass peak

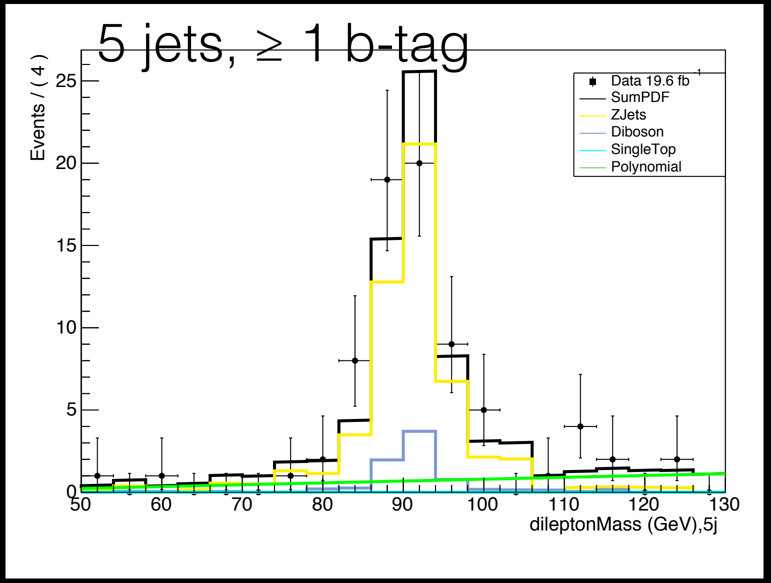
Selection	Leptons	N_{jets}	$N_{\text{b-tags}}$
Search	$e^{\pm}e^{\mp}(\mu^{\pm}\mu^{\mp})$ $M_{\ell\ell} > 130$ GeV	≥ 5	≥ 1
$t\bar{t}$	$e^{\pm}\mu^{\mp}$	≥ 5	≥ 1
DY normalization	$e^{\pm}e^{\mp}(\mu^{\pm}\mu^{\mp})$, $50 < M_{\ell\ell} < 130$ GeV	≥ 2	≥ 1
DY shape	$e^{\pm}e^{\mp}(\mu^{\pm}\mu^{\mp})$, $50 < M_{\ell\ell} < 130$ GeV	≥ 2	0

Top Background



Scan in S_T^{min} bin of 25 GeV [300 - 775 GeV]

DY Background



Replace ttbar+jets histogram with a polynomial, such that signal is absorbed as a non-peaking dist. and gives an unbiased DY SF

- Use expected normalization for diboson+single top backgrounds

Systematic Uncertainties

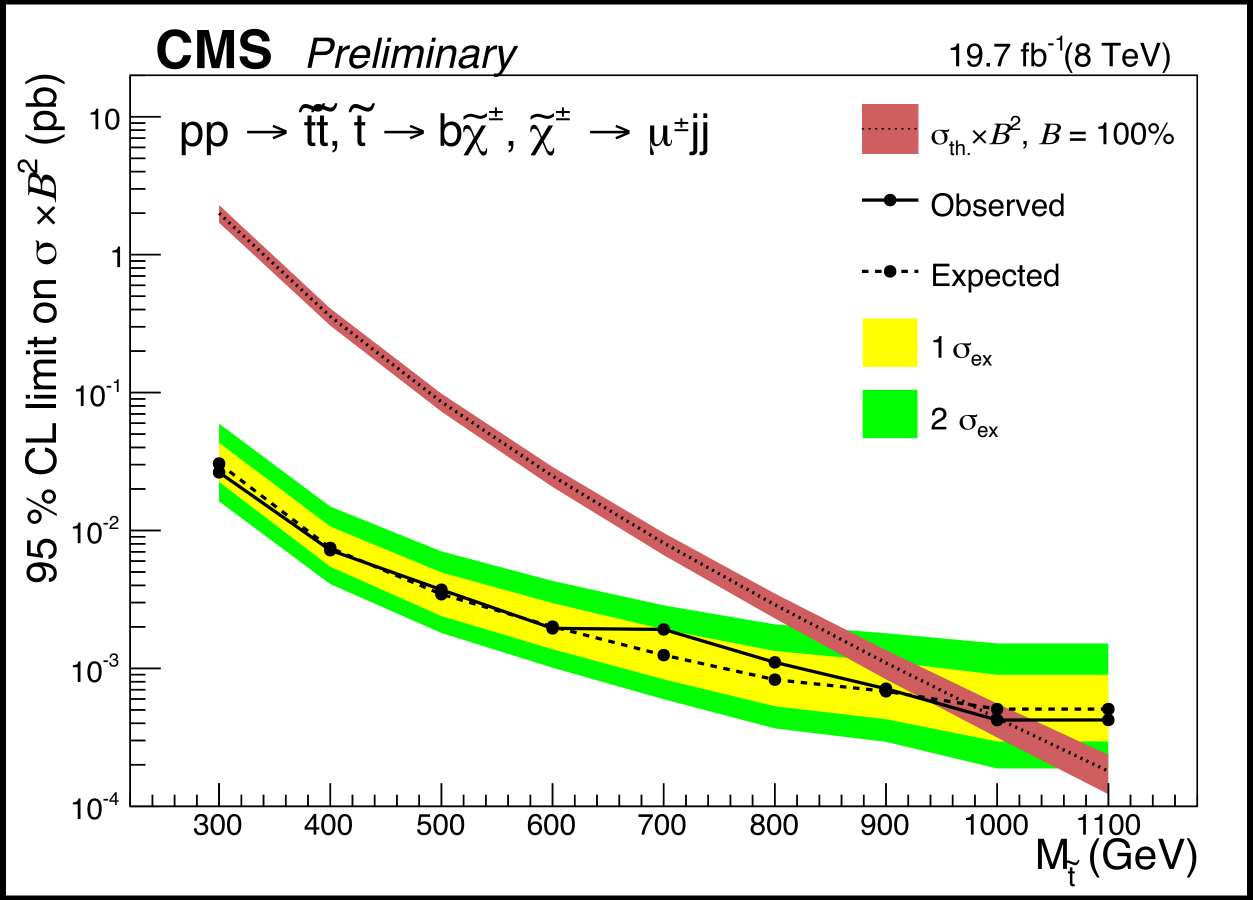
EXO-14-013

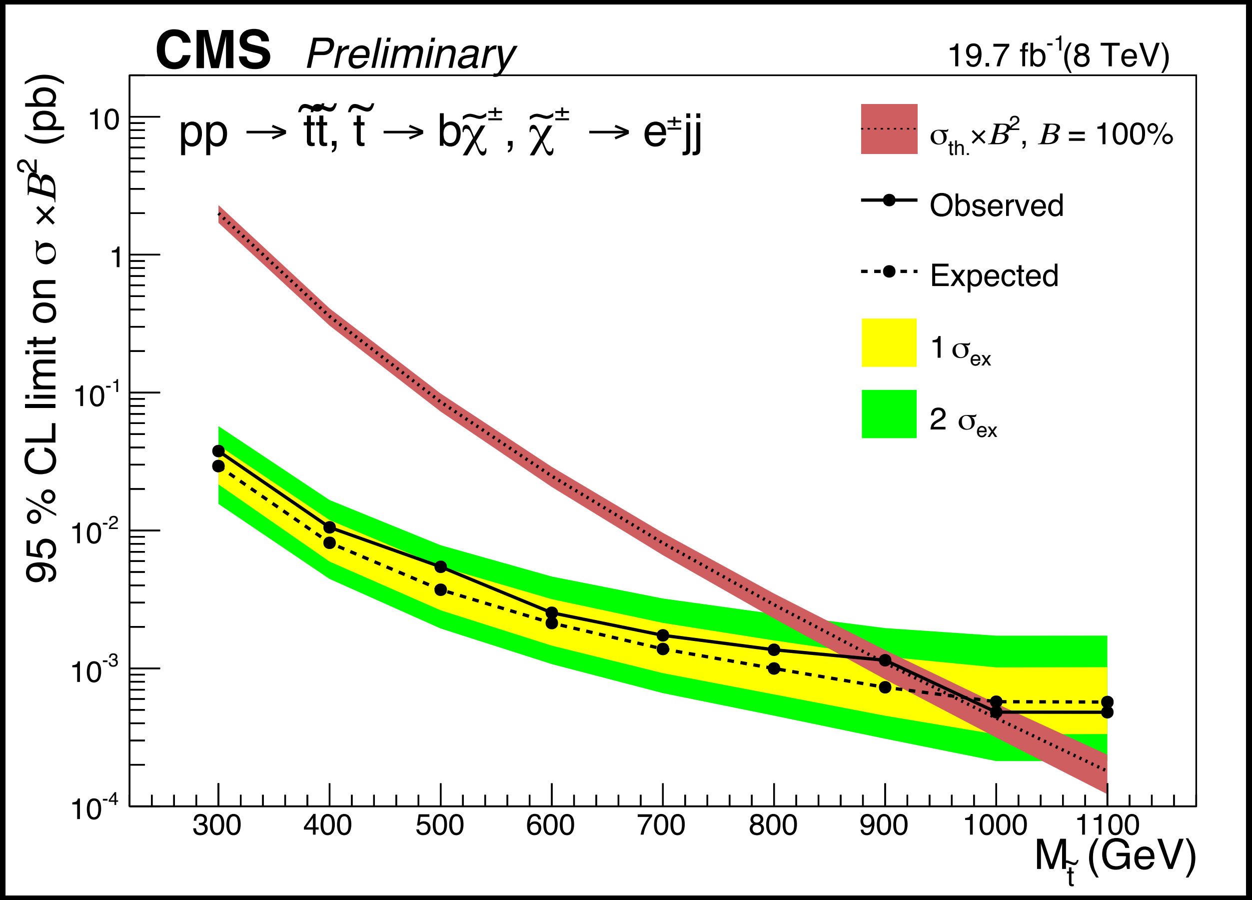
Parameter type	Source	Uncertainty (%)
Background Normalization	$t\bar{t}$+jets	10-50
	Drell-Yan	50-100
	Diboson	30
	Single top	30
	MC statistics	10-30
Signal Efficiency	Jet energy scale	5
	b-tagging scale factor	1-3
	Luminosity	2.6
	Lepton id/reco	3
	Electron energy scale	2
	Muon momentum scale	0.9
	Trigger	1
	Lepton isolation	5
	MC statistics	2-7

RPV SUSY Searches in dilepton+jets

EXO-14-013

- Result





- Assuming 100% BR of $\tilde{t} \rightarrow \tilde{\chi}^{\pm} b \rightarrow jj\ell^{\pm} b$ and non-zero λ'_{ijk} (i,j,k≤2) we exclude the t˜ mass below 1000 (890) GeV for the muon (electron) at 95% CL
- The expected limits are 970 (950) GeV for the muon (electron) channel

Conclusion

- CMS has searched for many of the RPV models at 8 TeV, for non-zero couplings of λ''_{ijk}, λ'_{ijk}, λ_{ijk}, corresponding to LLE, LQD, UDD terms.
- I summarized results for the searches for λ'_{ijk} (i,j,k≤3), in oppositely charged dilepton + multiple jets and no MET events
- These searches are currently active with LHC Run2 data at 13 TeV

Thank you

Additional Material

DY background

EXO-12-032

- Procedure
  - Fit the dilepton mass in control region between 50-130 GeV in $l^{\pm}l^{\mp}$ sample

Component	Fix parameter	Floating paramter
DY	Shape from 0 b-tag data	DY normalization (N
Diboson	Shape and normalization from MC	-
Single Top	Shape and normalization from MC	-
ttbar+jets	-	polynomial slope and normalization
Signal	-	polynomial slope and normalization

- Correct DY MC in search region with $SF=N_{DY}^{fit}/N_{DY}^{MC}$ in N_{jet} bins
- Performed two tests:
  - Self consistency test: Does polynomial describes the top background ?
  - Signal Injection test: Inject $M_{\tilde{t}}$ = 300 GeV and check if polynomial can predict the top background correctly

DY background

EXO-12-032

- Self consistency test:

	Fit inputs: ee+jets					Fit results: ee+jets				
N_{Jets}	N_{DY}	N_{VV}	N_t	$N_{t\bar{t}}$	N_{sig}	N_{DY}	N_{VV}	N_t	N_{pol}	p1
3	291	27	6	83	0	291 ± 9	27	6	83 ± 3	0.7 ± 0.0
4	125	16	1	39	0	123 ± 5	16	1	41 ± 2	0.7 ± 0.0
5	34	5	0	13	0	34 ± 2	5	0	13 ± 1	0.6 ± 0.1
≥ 6	10	2	0	5	0	9 ± 1	2	0	5 ± 1	0.6 ± 0.2

Table 12: Inputs and results for fit to combination of background MC samples.

- Signal Injection test:

	Fit inputs: ee+jets					Fit results: ee+jets				
N_{Jets}	N_{DY}	N_{VV}	N_t	$N_{t\bar{t}}$	N_{sig}	N_{DY}	N_{VV}	N_t	N_{pol}	p1
3	291	27	6	83	53	285 ± 8	27	6	150 ± 6	0.6 ± 0.0
4	125	16	1	39	189	121 ± 4	16	1	247 ± 12	0.5 ± 0.0
5	34	5	0	13	218	35 ± 2	5	0	240 ± 17	0.7 ± 0.1
≥ 6	10	2	0	5	230	11 ± 2	2	0	233 ± 19	0.7 ± 0.1

Table 13: Input and results for fit to combination of background MC samples and the signal for 300 GeV stop mass.