Searches for R-parity violating supersymmetry in CMS

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Where is SUSY hiding?

- *Natural SUSY* (MSSM) is popular because:
  1. Solves the Naturalness problem,
  2. Provides dark matter (DM) candidate,
  3. Predicts unification of SM forces at high scale.

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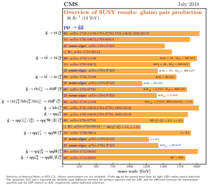
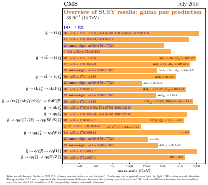
- For instance, a summary of the CMS SUSY searches $\Longrightarrow$ Gluino/squark limits $> 1.5 - 2.0$ TeV; stops limits > 1 TeV.





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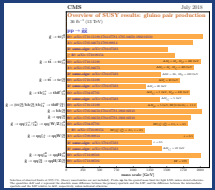
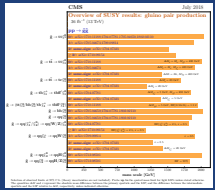
- **Perhaps is time to reconsider the basis of MSSM?**





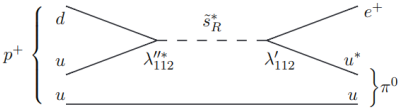
R-parity violation (RPV)

Original reason for R-parity ($R = (-1)^{3(B-L)+2s}$) in MSSM is to avoid a rapid proton decay:

Leptonic: $W_{\Delta L=1} = \frac{1}{2}\lambda_{ijk} L_i L_j E^c_k + \lambda'_{ijk} L_i Q_j D^c_k + \mu_i H_u L_i$

Baryonic: $W_{\Delta B=1} = \frac{1}{2}\lambda''_{ijk} U^c_i D^c_j D^c_k$

$L = l_L/\nu_L$, $E = l_R$, $Q = q_L$, $U, D = q_R$, $i, j, k =$ generations



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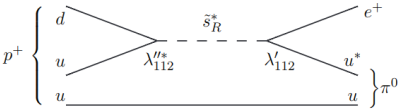

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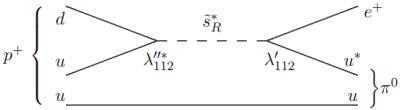

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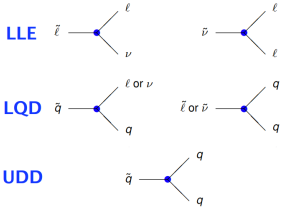


RPV SUSY allows the vertices shown on the right, but the price to pay:

- No new exact symmetry,
- No DM candidate: lightest SUSY particle is allowed to decay.

RPV SUSY searches

Going from something bizarre...

RPV SUSY searches

... to something **more bizarre**

RPV SUSY searches

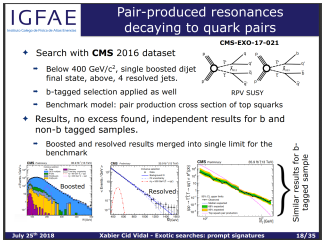
CMS has also an extensive search program for RPV signatures, here just an example:

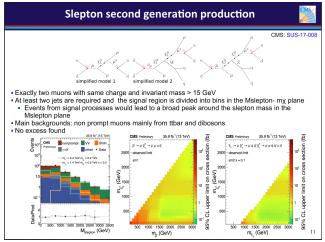
RPV Coupling	LLE	LQD	UDD
some	Multileptons (SUS-14-003)	RPV sleptons $\rightarrow qq$ (SUS-17-008)	RPV stops $\rightarrow qq$ (EXO-17-021)
examples	RPV $\tilde{\nu}_\tau \rightarrow e\mu$ (EXO-16-058)	RPV stops $\rightarrow lq$ (EXO-17-003) (EXO-17-009)	squark $\rightarrow qq$ (EXO-17-022)
			gluino $\rightarrow tbs$ (SUS-16-040)

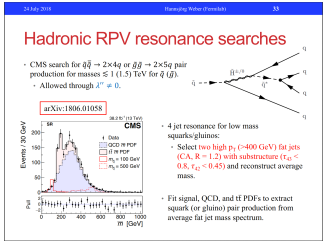
Following slides show a summary of the most recent results.

RPV SUSY searches

But my task today is easier...







All the following highlighted analysis have been presented already!

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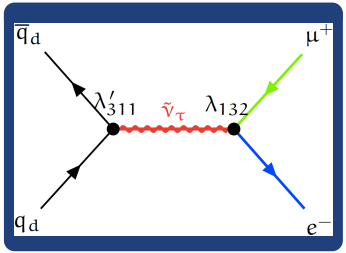
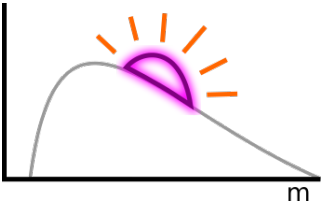
RPV $\tilde{\nu}_\tau$ to $e\mu$ (EXO-16-058)

Strategy: model independent bump-hunt, interpret with leptonic RPV SUSY.





RPV $\tilde{\nu}_\tau$ to $e\mu$ (EXO-16-058)

Strategy: model independent bump-hunt, interpret with leptonic RPV SUSY.

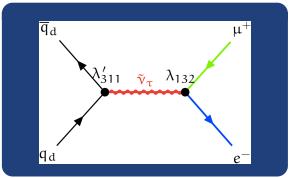
Selection:

Trigger: at least one μ with $pt > 50$ GeV
OR one γ with $pt > 175$ GeV.

Muons: $pt > 53$ GeV, $|\eta| < 2.4$, loose isolation.

Electrons: $E_T > 35$GeV, $|\eta| < 1.46$ and $1.5 < |\eta| < 2.5$, pass high-energy electron pairs (HEEP) selection.

Isolation: $\Delta R(\mu, e) < 0.1$



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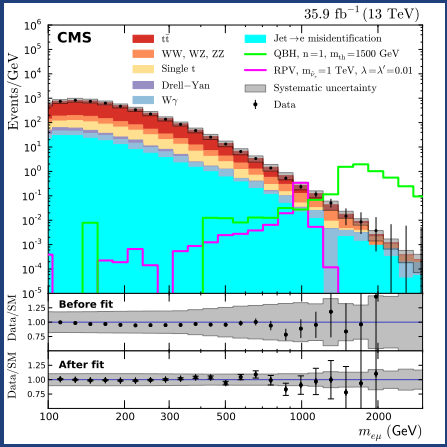
Backgrounds

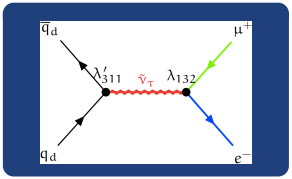
Real leptons from MC simulations.
Main components:

WW (high mass),

$t\bar{t}$ (low mass).

Fake leptons:
γ faking e ($W\gamma$) from MC simulations.
Jet faking e ($W + jets$, QCD) from data driven in control region (CR).





RPV $\tilde{\nu}_\tau$ to $e\mu$ (EXO-16-058)

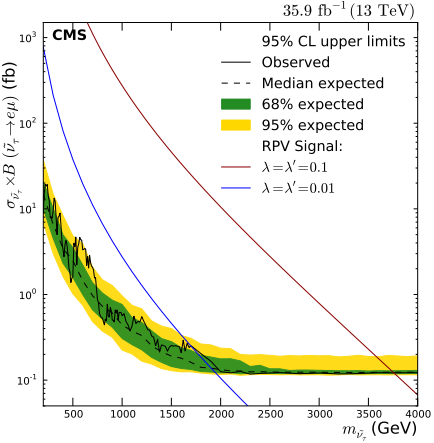
Strategy: model independent bump-hunt, interpret with leptonic RPV SUSY.

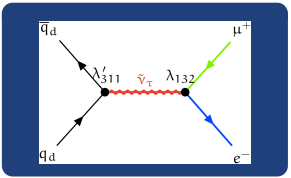
No excess observed in $e\mu$ inv mass.

Main syst. unc.: shape of $t\bar{t}$ dist. and PDF unc. at $m > 1$ TeV.

RPV Signal acceptance and efficiency from fits to MC simulations.

Set exclusion limits in production $\sigma_{\tilde{\nu}_\tau}$ for masses below 3.8 TeV.





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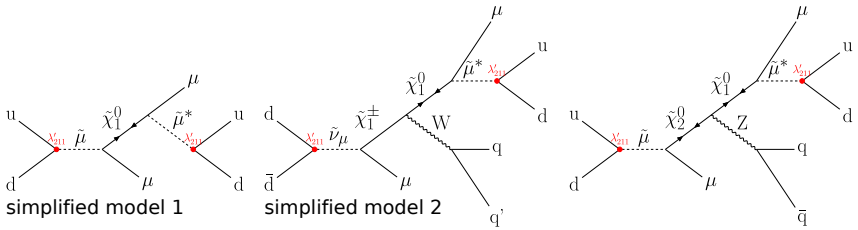

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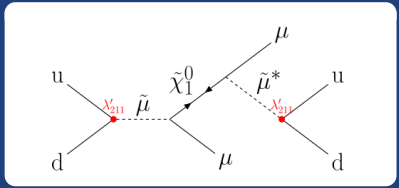

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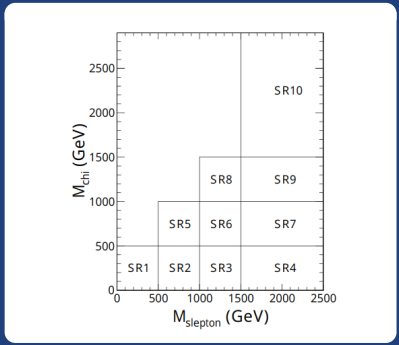
Selection:

Trigger: at least one μ with $pt > 50$ GeV.

Muons: exact two μ with $pt > 60(20)$ GeV, same charge, tight isolation, and $m_{\mu\mu} > 15$ GeV.

Jets: at least two jets with $pt > 40$ GeV.

Vetos: no e, τ or bjets.



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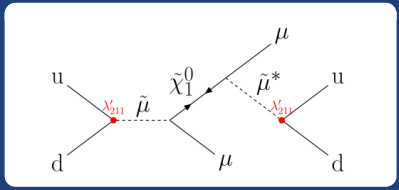

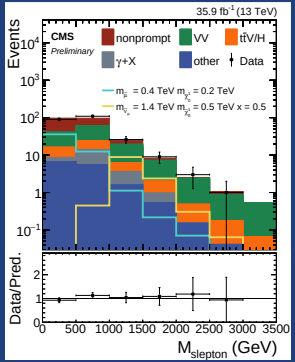

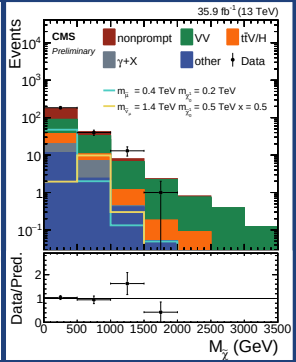

- Same-sign sel. rejects most of the SM bkg.
- Non-prompt μ ($t\bar{t}$, $W/Z + jets$) from data driven method.
- Dibosons and $t\bar{t}Z$ from MC sim. validated in CR.
- Internal photon conversion, validated in three lepton CR.

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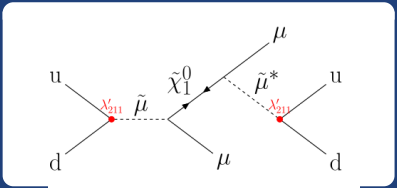
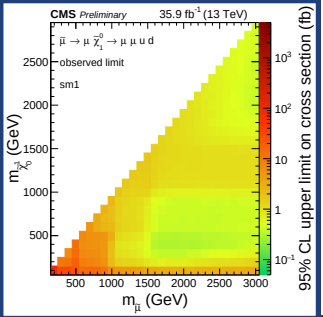
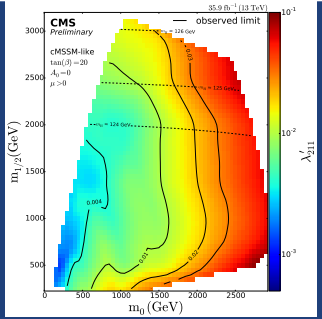


- Main syst. unc. coming from the non-promt μ estimate.
- No significant excess from SM in binned SRs, upper limits in one of the models and on the coupling limits of m_0 as a function of $m_{1/2}$ on the right.





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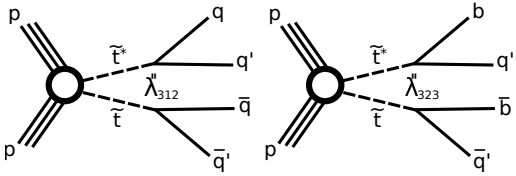
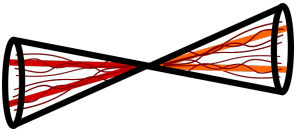
RPV Stop $\rightarrow qq(bq)$ (EXO-17-021)

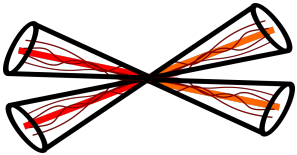
Strategy: resonance search in boosted AK8 dijet mass (low mass) and paired AK4 dijet mass (high mass), in qq (inclusive) and bq (b-tagged) final states.



Boosted search



Resolved search



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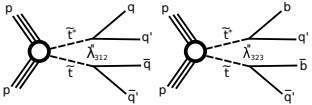
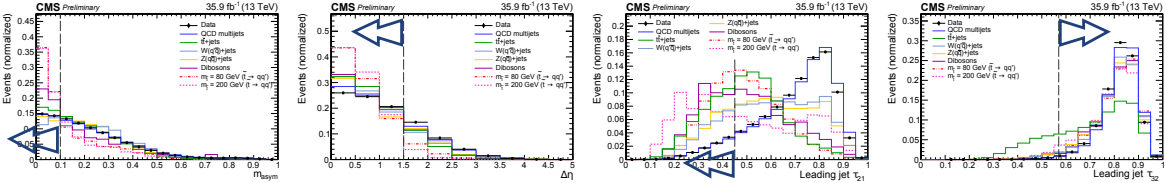


Boosted search ($80 \leq m_{\tilde{t}} \leq 400$ **GeV)**

Uses grooming and substructure techniques to access low mass dijet spectra with jets.

Dedicated triggers with substructure techniques developed ($HT > 900$ GeV).



RPV Stop → $qq(bq)$ (EXO-17-021)

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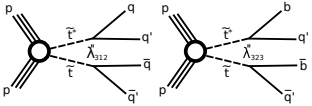
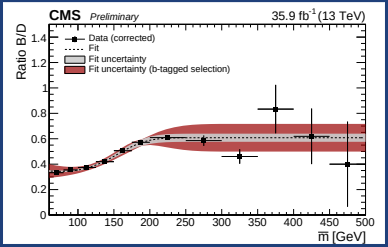


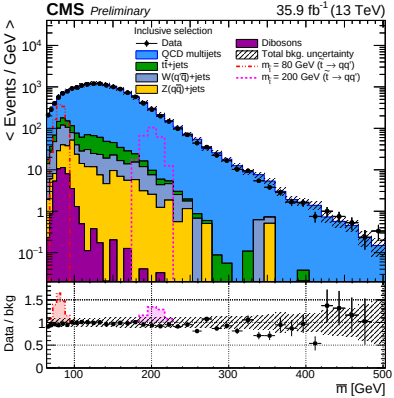
Background estimation

Main bkg: QCD multijets, estimated with a data-driven ABCD method.

	$m_{asym} < 0.1$	$m_{asym} > 0.1$
$\Delta\eta > 1.5$	Region B	Region D
$\Delta\eta < 1.5$	Region A	Region C



Subdominant bkgs ($t\bar{t}$, W/Z+jets) from MC sim. validated in CR.



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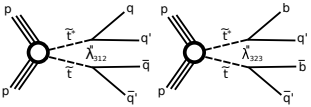
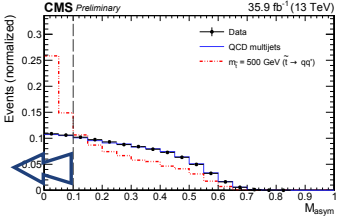
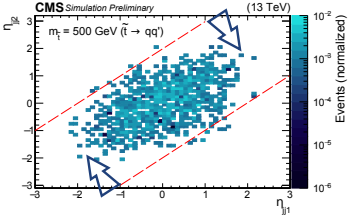


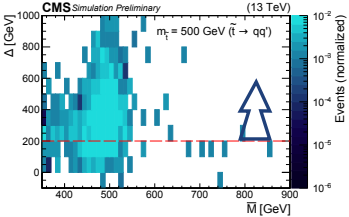
Resolved search ($m_{\tilde{t}} \geq 400$ GeV)

Bump-hunt in paired dijet mass spectra with AK4 jets.

Hadronic triggers ($HT > 900$ GeV).

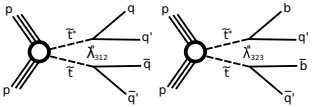






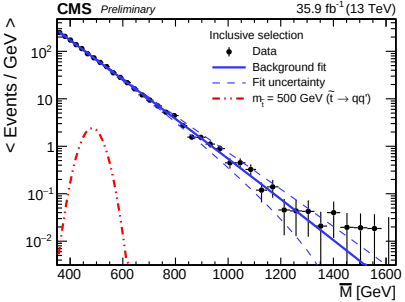
RPV Stop → $qq(bq)$ (EXO-17-021)

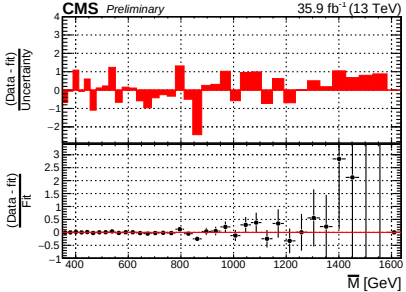
Strategy: resonance search in boosted AK8 dijet mass (low mass) and paired AK4 dijet mass (high mass), in qq (inclusive) and bq (b-tagged) final states.



Background estimation

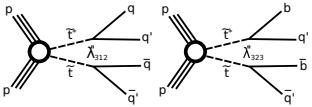
Main bkg: QCD multijets, estimated with functional form.



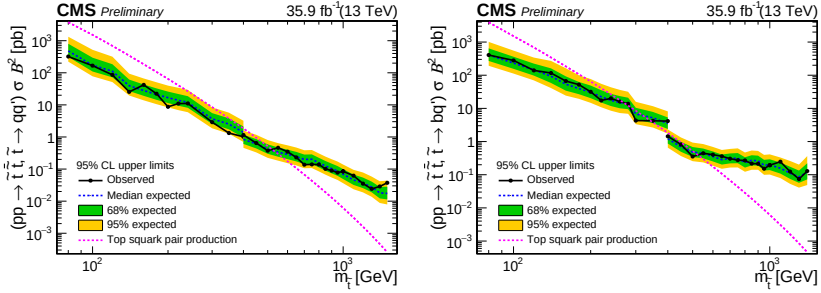


RPV Stop $\rightarrow qq(bq)$ (EXO-17-021)

Strategy: resonance search in boosted AK8 dijet mass (low mass) and paired AK4 dijet mass (high mass), in qq (inclusive) and bq (b-tagged) final states.

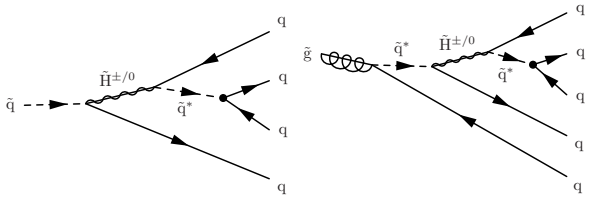


- No excess found in dijet pruned mass (boosted search) and paired dijet mass (resolved search).
- Results interpreted in the context of pair production hadronic RPV stops. Limits set from $80 \geq m_{\tilde{t}} \geq 520$ GeV for inclusive search, and $\geq m_{\tilde{t}} \geq 525$ (except for $270 \geq m_{\tilde{t}} \geq 340$ and $340 \geq m_{\tilde{t}} \geq 400$) for b-tagged search.



Squark to *qq* (EXO-17-022)

Strategy: resonance search in boosted CA12 dijet mass.



Squark to qq (EXO-17-022)

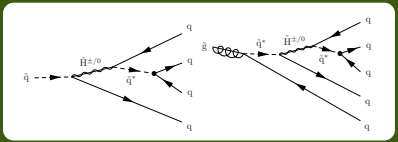
Strategy: resonance search in boosted CA12 dijet mass.

Selection:

Trigger: hadronic and substructure triggers ($HT > 900$ GeV).

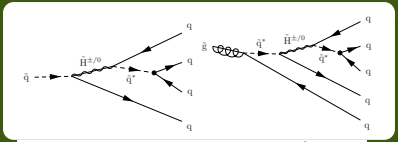
CA12 Jets: at least two jets with $pt > 400$ GeV and $|\eta| < 2$, n-subjetiness ($\tau_{21} < 0.75$, $\tau_{42} < 0.50$, $\tau_{43} < 0.80$).

Analysis: $\Delta\eta(j_1, j_2) < 1$ and $m_{asym} < 0.1$.



Squark to *qq* (EXO-17-022)

Strategy: resonance search in boosted CA12 dijet mass.

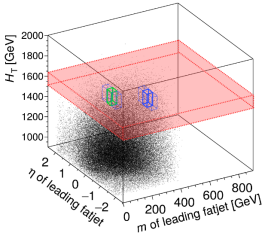


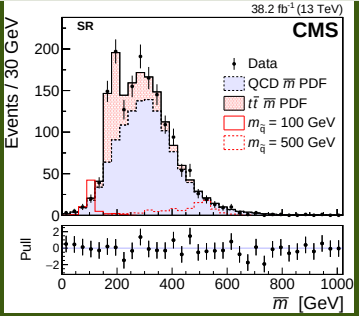
Background estimation

Main bkg QCD multijet, estimated with novel data-driven method:

> The leading jet mass spectra is treated as a probability distribution from which two tagged jets are sampled.

$t\bar{t}$ contribution is modelled with MC sim.
Both components are validated in CR.

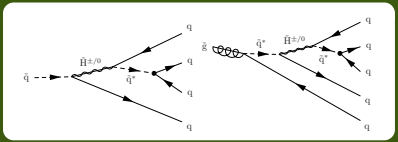


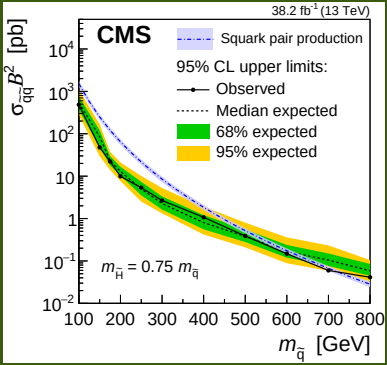


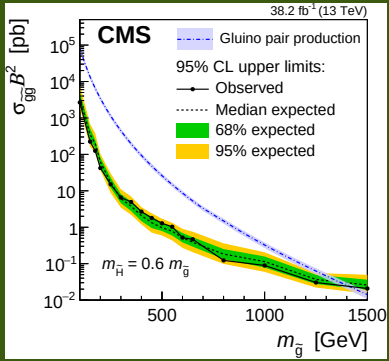
Squark to *qq* (EXO-17-022)

Strategy: resonance search in boosted CA12 dijet mass.

- Main syst. unc. is due to $t\bar{t}$ modelling.
- No excess found in mass spectra. Results interpret in the context of squark (left) and gluino (right) pair production:

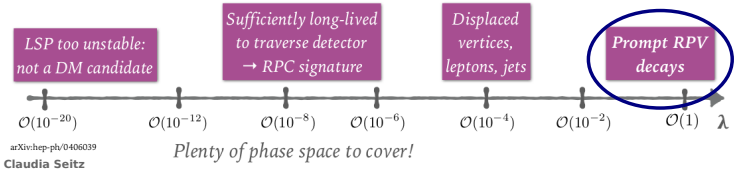




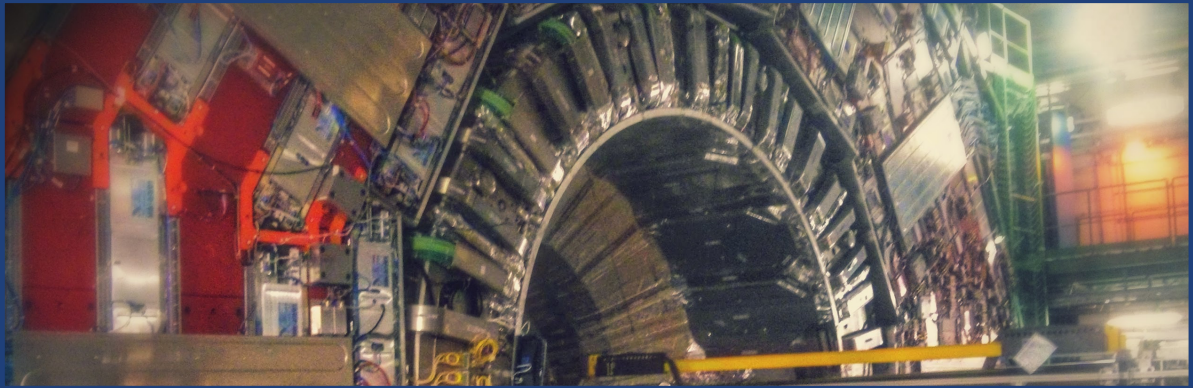


Conclusions

- Theoretically, RPV SUSY is an alternative to MSSM. It opens an unexplored phase space in regular SUSY searches.
- Experimentally, it offers challenging topologies which allow us to develop new techniques.
- CMS has a strong search program for RPV scenarios. Here only a couple of results were shown.
- But there is plenty of phase space to cover!



Thank you for the attention…



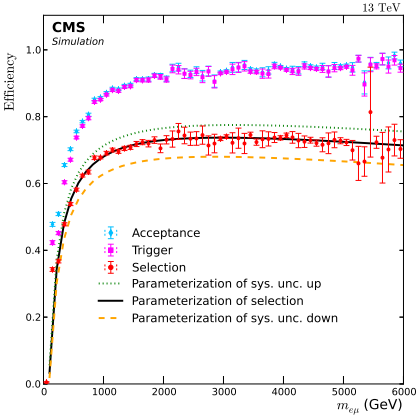
… questions?

RPV $\tilde{\nu}_\tau$ to $e\mu$ (EXO-16-058)

Event yields

Mass range (GeV)	$m_{e\mu} < 500$	$500 < m_{e\mu} < 1000$	$1000 < m_{e\mu} < 1500$	$m_{e\mu} > 1500$
Jet→e misidentification	3601	82.8	2.92	0.849
Wγ	2462	56.2	2.76	0.562
Drell–Yan	2638	5.31	0.343	0.0145
Single t	9930	141	2.81	0.178
WW, WZ, ZZ	11126	239	13.0	2.03
$t\bar{t}$	96754	971	18.5	1.01
Total background	126513	1495	40.3	4.64
Systematic uncertainty	23495	420	13.5	1.28
Data	123150	1426	41	4

Signal acceptance



RPV sleptons to *qq* (SUS-17-008)

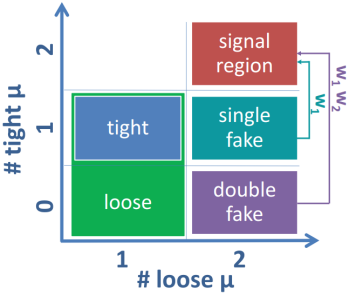
BACKGROUND ESTIMATION FROM DATA

goal: estimate contribution of non-prompt muon background to signal region

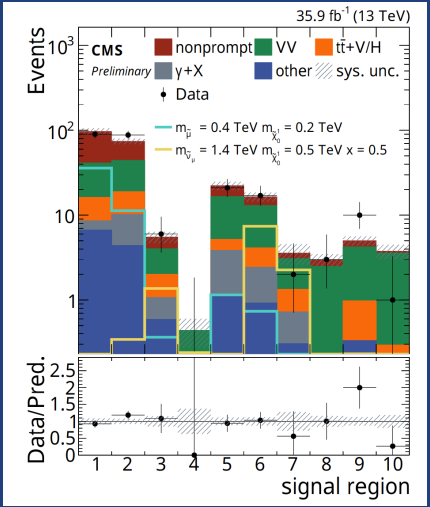
tight to loose ratio method:

2. extrapolate to signal region

- use events in application regions
- reweight based on r_{tl}
- $w = \frac{r_{tl}}{1-r_{tl}}$
- single fake region
  - events with 1 loose $\wedge$ $\neg$tight and 1 tight μ
- double fake region
  - events with 2 loose $\wedge$ $\neg$tight μ



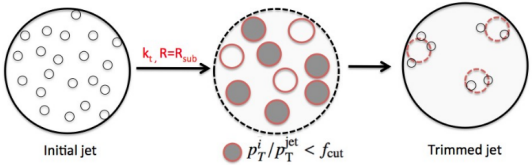
RPV sleptons to *qq* (SUS-17-008)



Source	Value range (%) (background)	Impact range (%) (background)	Typical impact (%) (signal)
Luminosity	2.5	1–2	2.5
Pileup	0–8	0–6	1–3
Trigger efficiency	2	1–2	1
Muon selection	6	3–6	6
b-tagging	1–2	0–2	1–5
Jet energy scale/resolution	1–8	1–8	1–5
Nonprompt muon estimate	32–56	0–21	
Normalization WZ	14	1–3	
Normalization $t\bar{t}Z$	50	0–3	
Scale and PDF variations	5–19	2–18	
Stat. precision of simulations	3–32	3–32	
$W^{\pm}W^{\pm}$ generator comparison	1–25	0–13	
WZ lost lepton	7–24	1–4	
Normalization $\gamma + X$	50	0–13	
Normalization other/$t\bar{t}H$	50	1–7	
ISR uncertainty			0–2
Stat. precision signal efficiency			1–3
Muon efficiencies signal			4

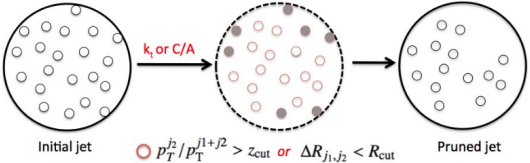
Grooming techniques

- **"Trimming"** http://arxiv.org/abs/0912.1342 (D. Krohn, J. Thaler, L. Wang)
  - uses k_t algorithm to create subjets of size R_{sub} from the constituents of the large-R jet: any subjets failing $p_T i / p_T < f_{cut}$ are removed



Tuned parameters: f_{cut} and R_{sub}

- **"Pruning"** http://arxiv.org/abs/0912.0033 (S. Ellis, C. Vermilion, J. Walsh)
  - Recombine jet constituents with C/A or kt while vetoing wide angle (R_{cut}) and softer (z_{cut}) constituents. Does not recreate subjets but prunes at each point in jet reconstruction



Tuned parameters: R_{cut} and z_{cut}

RPV Stop $\rightarrow qq(bq)$ (EXO-17-021)

Search	Source of Systematic	Effect	Value
Boosted and resolved	Luminosity	Yield	2.7%
	Trigger	Yield	3.0%
	Pileup	Yield	1.0%
	PDF	Yield	1.0%
	Jet energy scale	Yield	1.2–1.5%
		Shape	2.0%
	Jet energy resolution	Yield	1.8–6.0%
		Shape	10.0–14.0%
	Simulation statistical precision	-	bin-by-bin
	b tagging (only for b-tagged selection)	Yield	1.0%
Boosted	Two-prong scale factor	Yield	23.0%
	Anti-three-prong scale factor	Yield	2.0%

Search	Background	Source of Systematic	Effect	Value
Boosted	QCD multijets	Closure	Yield	10.0%
		Transfer factor fit	Shape	1.0–8.0%
		Statistics in region (C)	Shape	bin-by-bin
	Resonant	Simulation modeling	Yield	10.0%
		Simulation statistical precision	Shape	bin-by-bin
Resolved	QCD multijets	Fit parameters	Shape and Yield	bin-by-bin

Squark to *qq* (EXO-17-022)

Bkg estimation control regions