

Extending RPV stops coverage via resonant production

Angelo Monteux

based on arXiv:1601.03737

New High Energy Theory Center
Rutgers University

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SUSY waiting for LHC13

At the end of 8 TeV Run, (first 13 TeV results marginally better!)

- $m_{\tilde{g}} \gtrsim 1.4$ TeV
 - $m_{\tilde{q}_{1,2}} \gtrsim 1 - 1.3$ TeV
 - $m_{\tilde{t}} \gtrsim 700 - 800$ GeV
- $\oplus \quad m_H = 125$ GeV $\xrightarrow{?} \tilde{m} \sim 1 - 10$ TeV

R -parity violation (RPV) was once thought that a way to **hide** SUSY:

$$W_{RPV} \sim \mu'_i L_i H_u + \lambda_{ijk} L_i L_j \ell_k^c + \lambda'_{ijk} L_i Q_j d_k^c + \lambda''_{ijk} u_i^c d_j^c d_k^c$$

proton decay $\tau_p > 10^{34}$ years $\implies |\lambda'_{11k} \lambda''_{11k}| \lesssim 2 \times 10^{-27} (\tilde{m}/100 \text{ GeV})^2$

A Z_2 symmetry, $R_p = (-1)^{2S+3B+L}$ forbids the operators. [Farrar, Fayet, 1978]

Bonus: stable LSP (\rightarrow DM), MET at colliders.

Still, proton is stable is B or L separately conserved*. I will consider baryonic RPV,

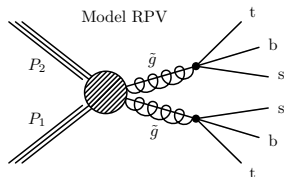
$$W = \frac{\lambda''_{ijk}}{2} u_i^c d_j^c d_k^c, \quad i, j, k = 1, 2, 3, \quad j \neq k$$

RPC vs. baryonic RPV

No MET but large jet multiplicities, large H_T , SS leptons.

- gluino \rightarrow jjj, tjj:

[CMS, 1208.2931], [ATLAS, 1502.05686]

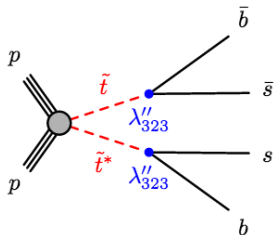


$m_{\tilde{g}} \gtrsim 1$ TeV (spectrum-independent)

[Evans, Kats, Shih, Strassler, 1310.5758],

[Graham, Rajendran, Saraswat, 1403.7197]

- squark \rightarrow jj, tj:

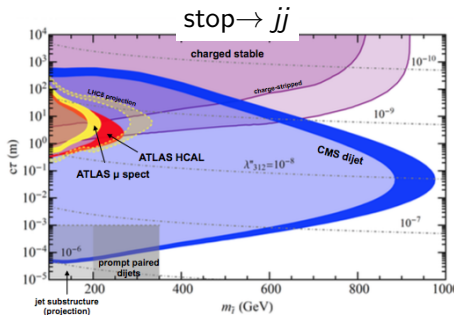
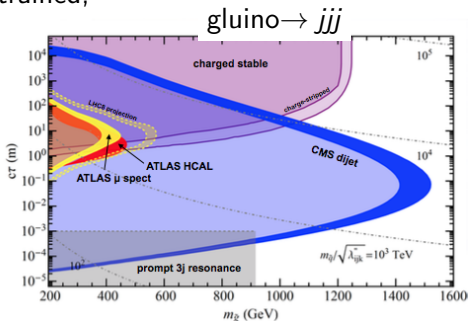


[CMS, 1412.7706], [ATLAS, ATLAS-CONF-2015-026]

$m_{\tilde{t}} \gtrsim 350 - 400$ GeV (stop LSP)

Displaced RPV

For small RPV couplings ($\lambda'' \lesssim 10^{-7}$) displaced decays even more constrained,



[Liu, Tweedie, 1503.05923], [Csaki et al, 1505.00784]

$$m_{\tilde{g}} \gtrsim 1.2 - 1.4 \text{ TeV}$$

$$m_{\tilde{t}} \gtrsim 800 \text{ GeV} - 1 \text{ TeV}$$

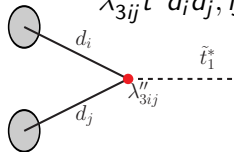
If there are light squarks, prompt decays (large-ish RPV) are preferred.

Possible connection to baryogenesis $\implies \lambda'' > O(10^{-3})$. (backup slides)

Resonant production

Focus on stop couplings,

$$\lambda''_{3ij} \tilde{t}^* d_i d_j, ij = 12, 13, 23$$



$$\hat{\sigma} = \frac{8\pi}{3} \frac{|\lambda''_{ijk}|^2}{m_{\tilde{t}}^2} \sin^2 \theta_{\tilde{t}} \delta(\hat{s} - m_{\tilde{t}}^2)$$

For $\lambda'' \gtrsim 10^{-2} - 10^{-3}$, cross section can be larger than stop pair-production (even from non-valence quarks bs).

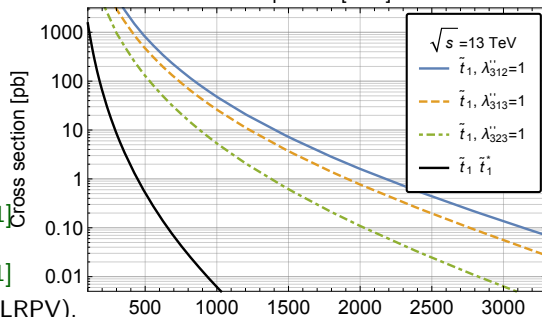
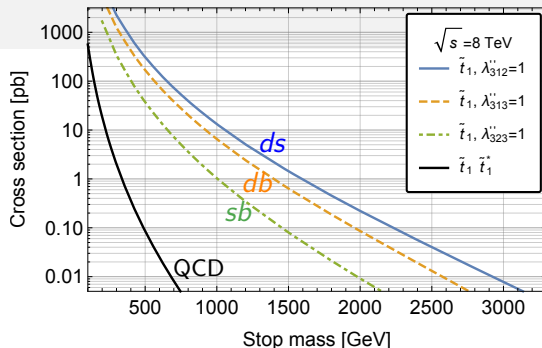
Possibly, asymmetry: \tilde{t}^* vs. \tilde{t} .

Disclaimer: old idea. [Dreiner, Ross, 1991]

Tevatron [Berger, Harris, Sullivan, 1999]

pre-LHC [Choudhury, Datta, Maity, 2011]

CMS and ATLAS: resonant $\tilde{\nu}$ search (LRPV).



Signatures I: stop LSP

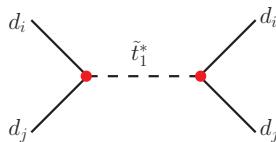
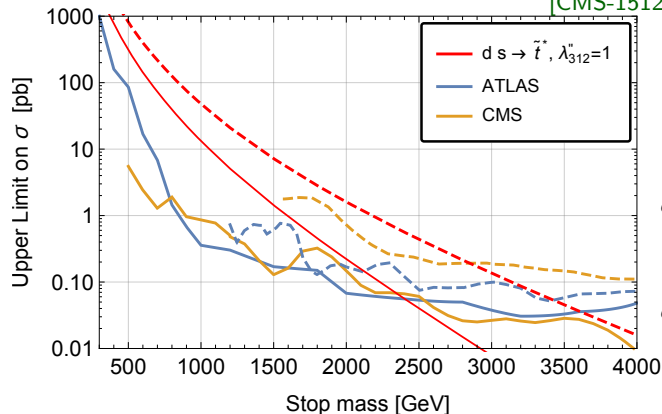
[ATLAS-1407.1376, 20.3fb⁻¹@8TeV]

[CMS-1501.04198, 19.7fb⁻¹@8TeV]

$pp \rightarrow \tilde{t}_1^{(*)} \rightarrow ds, db, bs$: dijet resonance [CMS-PAS-EXO-14-005, 19.7fb⁻¹@8TeV]

[ATLAS-1512.01530, 3.6fb⁻¹@13TeV]

[CMS-1512.01224, 2.4fb⁻¹@13TeV]



Combined, they set limits from 300 GeV to 5 TeV.

Signatures I: stop LSP

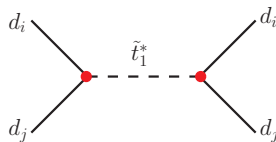
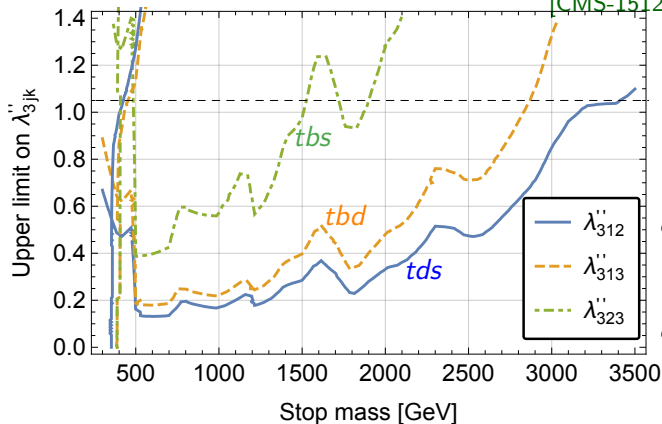
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Best limits from CMS *scouting* search below 1 TeV. Below ~ 400 GeV, limits from QCD-produced paired dijets. [CMS, 1412.7706], [ATLAS, CONF-2015-026]

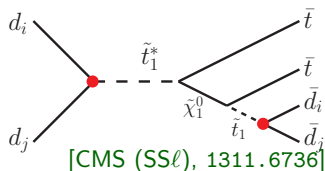
Signatures II: Neutralino LSP

Light neutralinos arise naturally. New decay channels dilute dijets.

Simplified spectra:

- bino-like: $M_1 \ll M_2, \mu$. Light states: $\tilde{\chi}_1^0, \tilde{t}$

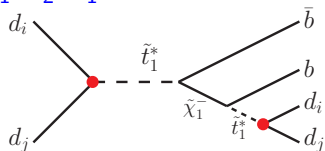
\Rightarrow same-sign tops + jets



- higgsino-like: $\mu \ll M_1, M_2$. Light states: $\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_1^\pm, \tilde{t}$

\Rightarrow four-jet resonances

(dominates over SStops b/c phase space)



In addition to resonant signatures, stop QCD-production yields the same signatures *twice*: four tops ($tt\bar{t}\bar{t} + 4j$) and paired four-jet resonances.

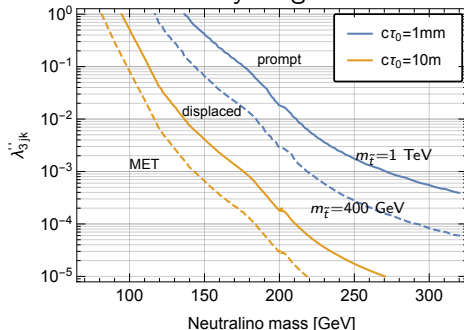
[ATLAS (4t), 1505.04306]

Signatures III: displaced neutralino LSP

If very light, the neutralino can be displaced:

$$\tilde{t} \rightarrow t + (\tilde{\chi}_1^0 \xrightarrow{DV} tjj)$$

Neutralino decay length



Displaced decays to jets are highly constrained:

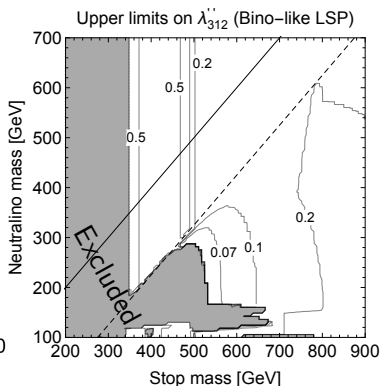
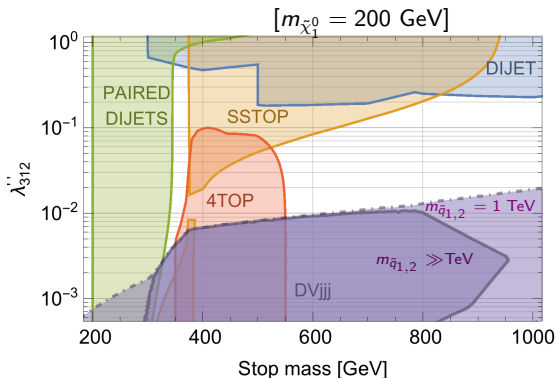
$$\sigma(pp \rightarrow XX, X \rightarrow jjj) < 0.2 - 1 \text{ fb} \quad \text{for } c\tau = 3 \text{ cm} - 1 \text{ mm}$$

[Cui, Shuve, 1409.6729]

If neutralino detector-stable \rightarrow **monotop** or MET and RPC SUSY.

Results - bino-like $\tilde{\chi}_1^0$

Putting together all the signatures, limits from available (8 TeV) searches:

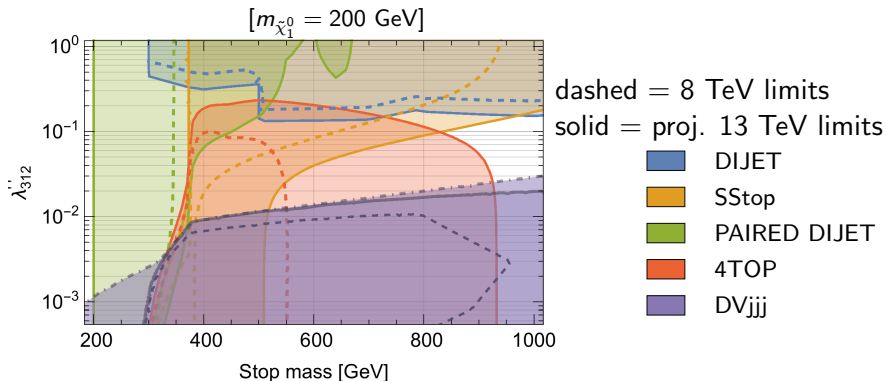


Reach stops up to 500-650 GeV: *comparable to RPC searches!*

Similar results for λ_{313}'' , λ_{323}'' (weaker: resonant production penalized by non-valence quarks)
(backup slides)

Prospects for 13 TeV- bino-like $\tilde{\chi}_1^0$

If LHC13 reaches *current* limits on cross section for each signature,

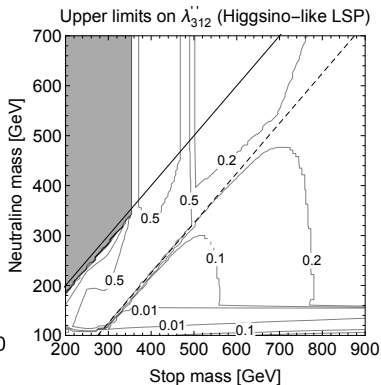
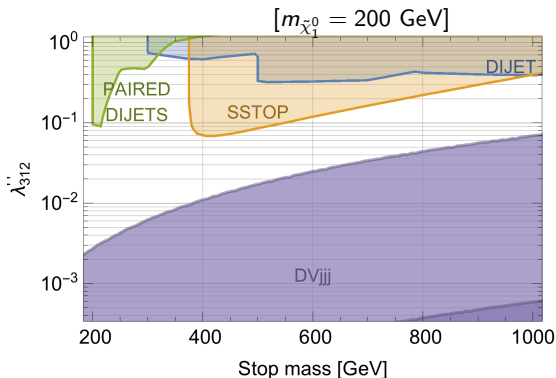


Reach up to 800 GeV-1 TeV!

The four-top search can be made stronger by requiring 4 tops + 4 jets. Also possible exotic final states such as $ttt\bar{t}$ or $\bar{t}\bar{t}\bar{t}t$.

Results - higgsino-like $\tilde{\chi}_1^0$

Putting together all the signatures, limits from available (8 TeV) searches:

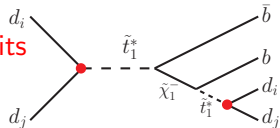


The chargino decay mode ($4j$) dominates \rightarrow no limits

Pair-produced stops $\rightarrow 8j$?

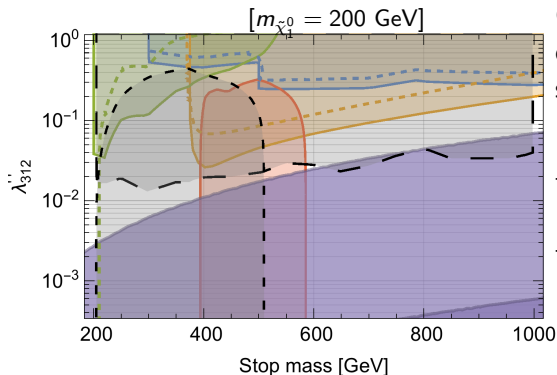
above ATLAS multijet limits [Evans,Kats,1311.0890]

For a higgsino LSP, stops allowed down to 200 GeV!



Prospects for 13 TeV- higgsino-like $\tilde{\chi}_1^0$

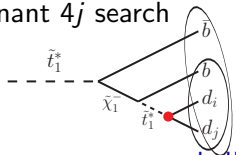
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Colored:

dashed = 8 TeV limits
solid = proj. 13 TeV limits

----- = projected limits
for ATLAS multi-jet
- - - = projected limits
for resonant 4j search



New searches for single and pair-produced **four-jet** resonances are needed!
Bonus: **three-jet** sub-resonance. Could reach $m_{\tilde{t}} \gtrsim 1 \text{ TeV}$!

Need to be sensitive to low stop masses. For resonant production, can use large σ and live far off tail of H_T distribution. (backup slides)

Outlook

The reach of RPV SUSY searches can rival R -parity conserving SUSY.

I have presented a series of **NEW** limits on RPV stops when those are produced through resonant scattering through the RPV interaction. This was overlooked so far in the analysis of LHC data. These are the **first direct limits on individual RPV couplings**, as opposed to flavor physics constraints.

Using existing searches at 8 TeV, I have showed that one can exclude stops up to 500-700 GeV for a bino LSP. The higgsino LSP case needs new dedicated searches.

My recommendations for improvement in specific searches at 13 TeV:

- jj searches: **do not forget low masses (scouting is great!).**
- S Stop and four-tops: $\tilde{t} \rightarrow S\text{Stop}+2j$: **count extra jets for each stop.**
- $4j$ resonance: **new signature, spectacular $3j$ sub-resonance.**
- $(3j)^2$ gluino search (CMS): **modify to look for chargino decays.**
- multijet gluino search (ATLAS): **add $8j$ bin instead of stopping at $6j$.**

Thanks for listening!

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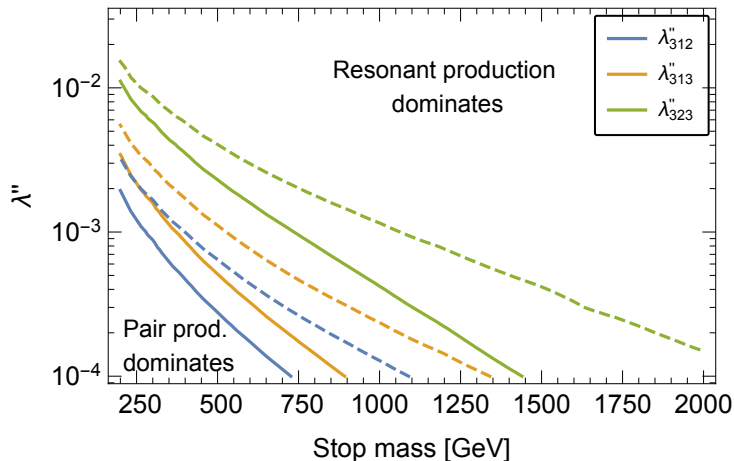
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Extra slides

RPV vs. QCD production

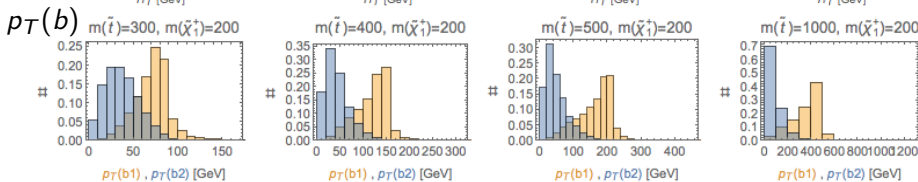
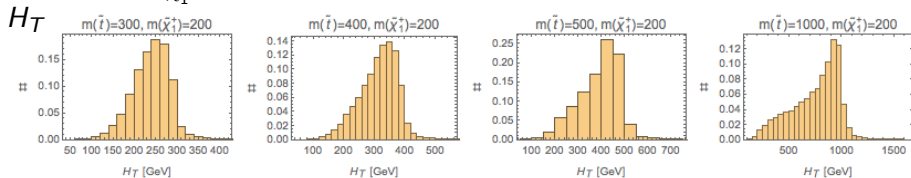
solid (dashed) lines \rightarrow 8 (13) TeV



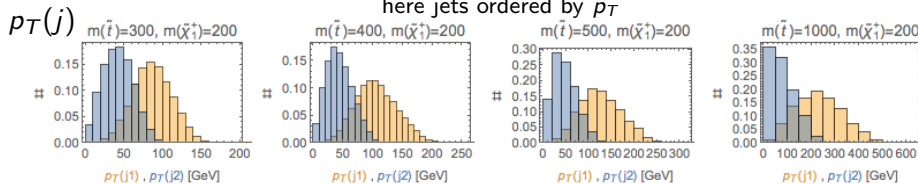
4j resonance search: Event distributions

$$\begin{cases} y(j, b) \lesssim 2.5 \\ 1 \lesssim \Delta R \lesssim 3 \end{cases}$$

$$m_{\tilde{\chi}_1^\pm} = 200 \text{ GeV}$$



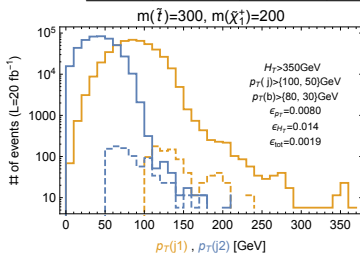
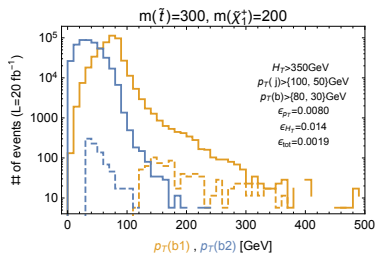
here jets ordered by p_T



4j resonance search: Event distributions

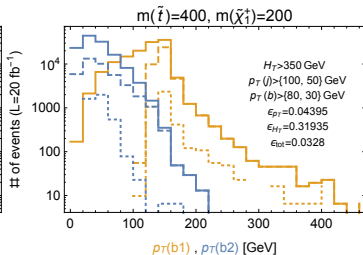
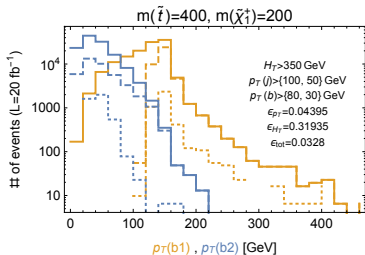
Cuts :				
H_T	$p_T^{b_1}$	$p_T^{b_2}$	$p_T^{j_1}$	$p_T^{j_2}$
350	80	30	100	50

	$\sigma[\lambda'' = 0.1] \times \varepsilon$ [pb]		
$m_{\tilde{t}}$	λ''_{312}	λ''_{313}	λ''_{323}
300	0.091	0.053	0.017
400	0.39	0.23	0.067











σ_{13}^0 TeV [pb]
 $\{50, 29, 9.7\}$
 even with low ε ,
 $N_{events} \sim 1000$

$\sigma_{13}^{\lambda''=0.1}$ TeV [pb]
 $\{18, 11, 3.2\}$
 larger ε ,
 $N_{events} \sim 10^4$



Projected 13 TeV limits

Instead of giving expected limits for a given luminosity (as is usually done), a useful exercise is to see what happens if, in the absence of any discovery, the experimental upper limits on the cross sections for each corresponding signature reaches a certain value. For definiteness, we take these “projected” limits to be the current limits for each signature based on 20fb^{-1} at 8 TeV.

Process	Stop mass [GeV]					Line/ filling style	Searches
	200	400	600	800	1000		
$pp \rightarrow \tilde{t} \rightarrow jj$	-	160	2.4	1.45	0.39		Existing
$pp \rightarrow \tilde{t} \rightarrow tt + X$	0.035	0.035	0.035	0.035	0.035		
$pp \rightarrow \tilde{t}\tilde{t}^* \rightarrow (jj)(jj)$	4.05	0.52	0.17	0.13	0.037		
$pp \rightarrow \tilde{t}\tilde{t}^* \rightarrow (bj)(bj)$	5.7	0.44	0.14	0.086	0.092		
$pp \rightarrow \tilde{t}\tilde{t}^* \rightarrow t\bar{t}\bar{t} + X$	-	0.049	0.018	0.0085	0.004		
$pp \rightarrow \tilde{t} \rightarrow (bbjj)$	4.05	0.52	0.17	0.13	0.037		New
$pp \rightarrow \tilde{t}\tilde{t}^* \rightarrow (bbjj)(bbjj)$	-	2.67	0.45	0.12	0.064		
$pp \rightarrow \tilde{t}\tilde{t}^* \rightarrow (bjj)(bjj) + X$	16.7	0.46	0.24	0.081	0.062		

Scouting: CMS PAS EXO-14-005

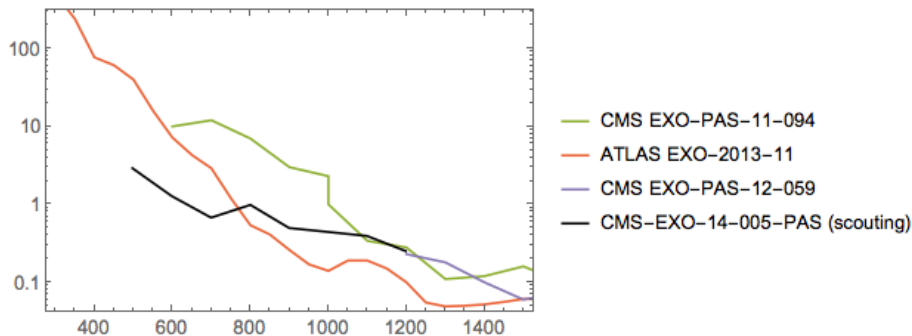
Low mass range: large QCD background \rightarrow tighter triggers to reduce bitrate to tape.

Alternative: reduce event size (only four-momenta) $500kB \rightarrow 10kB$.

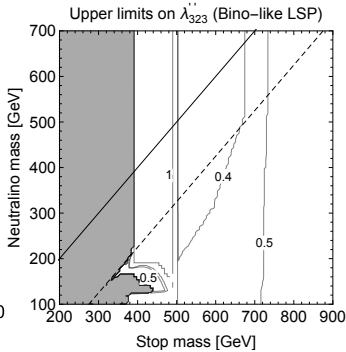
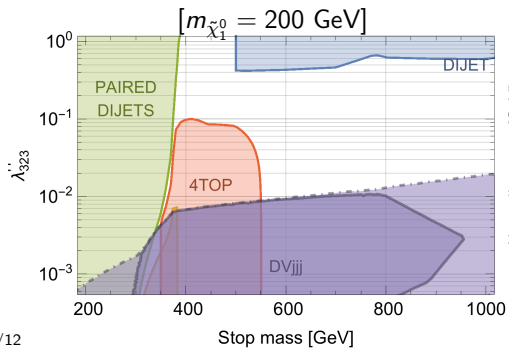
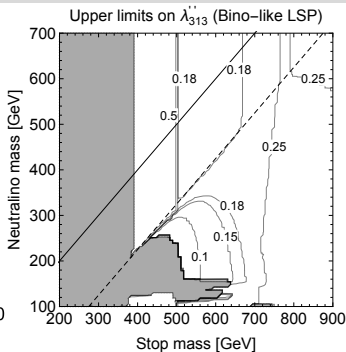
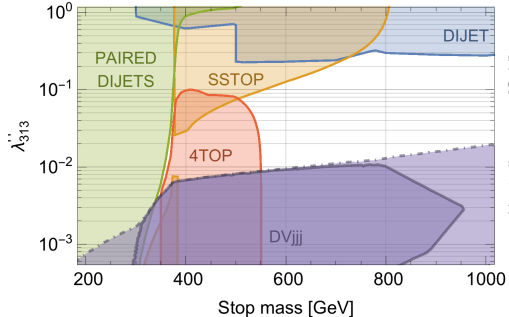
L1 trigger: $H_T > 100$ GeV

HLT; $H_T > 350$ GeV | ($m_{jj} > 400$ GeV & $|\Delta\eta_{jj}| < 2$);

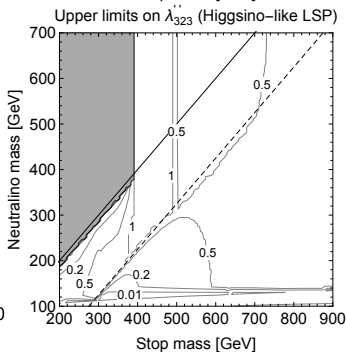
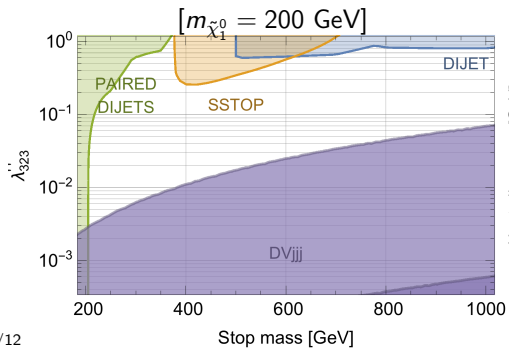
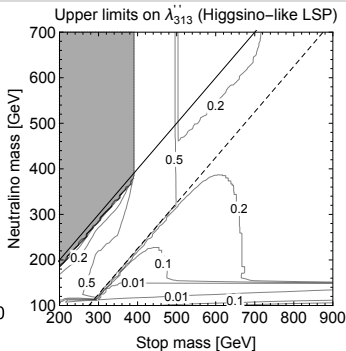
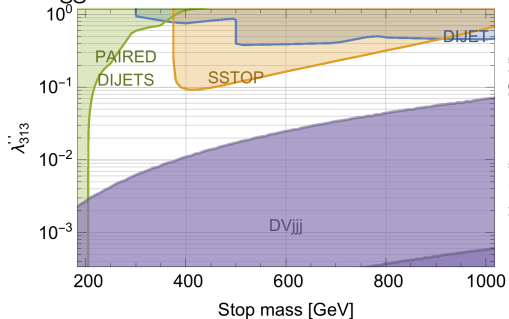
throw away most of event to reduce bandwidth.



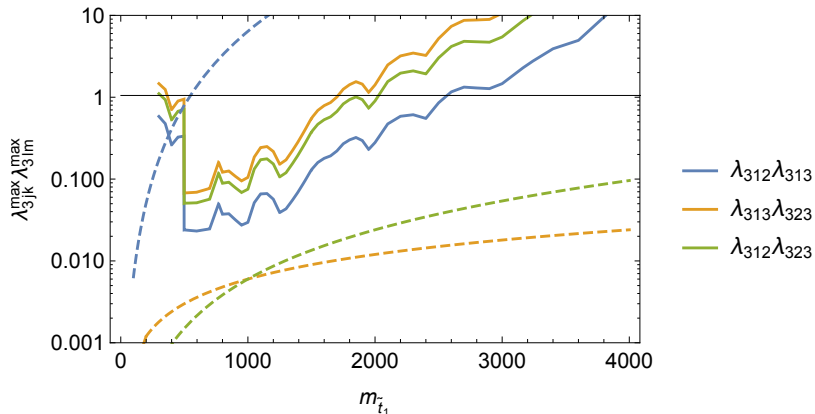
Bino LSP



Higgsino LSP



compare dijet limits to $K - \bar{K}$ limits on products of couplings:



SStop limits can match or exceed the kaon limits at low stop masses.

Baryogenesis and RPV:

udd breaks baryon number: if pre-existing baryon asymmetry at TeV scale,

$$\text{washout of } \Delta B \implies \lambda''_{all} < 10^{-7}$$

Coincidentally, $\lambda'' < 10^{-7} \implies$ displaced vertices, very constrained!

On the other hand, if ΔB generated at $T < \tilde{m}/10 \approx \mathcal{O}(10 - 100)$ GeV, no washout.

Plenty of models using baryonic RPV for Baryogenesis:

Dimopoulos, Hall (1987), Cline, Raby (1991), Cui (2013), AM, Shin (2014), Arcadi, Covi, Nardecchia (2015)

In general, out-of-equilibrium decay $X \rightarrow B, \bar{B}$ gives

$$\varepsilon \equiv \frac{\Gamma_{X \rightarrow B} - \bar{\Gamma}_{X \rightarrow \bar{B}}}{2\Gamma} \propto \frac{|\lambda''|^2}{(8\pi)^{loops}} \Phi_{CP} f(\tilde{m}_i \dots)$$

$$\left\{ \begin{array}{l} 10^{-10} \simeq \frac{n_B}{s} = \varepsilon \left(\frac{n_X}{s}\right)_{t=\frac{1}{\Gamma}} \\ \frac{n_X}{s} \lesssim 10^{-3} \end{array} \right. \implies \boxed{|\lambda''| \gtrsim \mathcal{O}(10^{-3})}$$

Here if X thermal, $Y_X < Y_{eq} \sim \frac{0.4}{g_*(T)} \lesssim 10^{-3}$, if non-thermal $Y_X \sim 10^{-3} \frac{T_{RH}/1 \text{ GeV}}{m_\phi/1 \text{ TeV}} \lesssim 10^{-3}$

RPV - flavor symmetries

Flavor physics constraints ($\Delta B = 2$ transitions, $K - \bar{K}$, $n - \bar{n}$):

[Barbier et al., hep-ph/0406039]

$$|\lambda''_{11k}| \lesssim 10^{-7} \left(\frac{\tilde{m}}{100 \text{ GeV}} \right)^{5/2} \quad n - \bar{n}$$

$$|\lambda''_{312,313}| \lesssim O(10^{-2}), \quad (100 \text{ GeV} \lesssim \tilde{m} \lesssim 200 \text{ GeV}) \quad n - \bar{n}$$

$$|\lambda''_{i23} \lambda''_{i13}|_{i=2,3} \lesssim 10^{-3} \left(\frac{m_{\tilde{u}_i}}{100 \text{ GeV}} \right) \quad K - \bar{K}$$

Flavor models also favor hierarchies with large 3rd generation couplings.

- horizontal flavor symmetries: Froggatt-Nielsen mechanism, known fermion masses and mixing *imply* hierarchies in RPV sector.

[AM, 1305.2921]

$$\begin{pmatrix} \lambda''_{112} & \lambda''_{212} & \lambda''_{312} \\ \lambda''_{113} & \lambda''_{213} & \lambda''_{313} \\ \lambda''_{123} & \lambda''_{223} & \lambda''_{323} \end{pmatrix} = \lambda''_{323} \begin{pmatrix} 3 \times 10^{-5} & 3 \times 10^{-3} & 5 \times 10^{-2} \\ 10^{-4} & 10^{-2} & 2 \times 10^{-1} \\ 6 \times 10^{-4} & 5 \times 10^{-2} & 1 \end{pmatrix}$$

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[Barbier et al., hep-ph/0406039]

$$|\lambda''_{11k}| \lesssim 10^{-7} \left(\frac{\tilde{m}}{100 \text{ GeV}} \right)^{5/2} \quad n - \bar{n}$$

$$|\lambda''_{312,313}| \lesssim O(10^{-2}), \quad (100 \text{ GeV} \lesssim \tilde{m} \lesssim 200 \text{ GeV}) \quad n - \bar{n}$$

$$|\lambda''_{i23} \lambda''_{i13}|_{i=2,3} \lesssim 10^{-3} \left(\frac{m_{\tilde{u}_i}}{100 \text{ GeV}} \right) \quad K - \bar{K}$$

Flavor models also favor hierarchies with large 3rd generation couplings.

- MFV: assume Y_{ij}^f only flavor violation as spurion of SM flavor $SU(3)^5$.

[Nikolidakis, Smith, 0710.3129]

[Csaki, Grossman, Heidenreich, 1111.1239]

$$\begin{pmatrix} \lambda''_{112} & \lambda''_{212} & \lambda''_{312} \\ \lambda''_{113} & \lambda''_{213} & \lambda''_{313} \\ \lambda''_{123} & \lambda''_{223} & \lambda''_{323} \end{pmatrix} = \frac{1}{2} \left(\frac{\tan \beta}{50} \right)^2 \begin{pmatrix} 10^{-8} & 10^{-4} & 2 \times 10^{-1} \\ 3 \times 10^{-5} & 5 \times 10^{-2} & 3 \times 10^{-1} \\ 2 \times 10^{-3} & 2 \times 10^{-1} & 1 \end{pmatrix}$$