Resonant stop signatures of RPV and fresh 13 TeV limits

Angelo Monteux

1601.03737 + work in progress w/ M. Buckley, S. Macaluso, D. Feld, D. Shih

New High Energy Theory Center
Rutgers University

A First Glance Beyond the Energy Frontier
ICTP Trieste, Sept 5th 2016

The State University of New Jersey
Rutgers
Department of Physics and Astronomy

Vanilla SUSY at ICHEP

Null results for vanilla SUSY well above 1 TeV(almost 2!):

(see C.Rogan's, D.Shih's talks)

R-parity violation (RPV) as an alternative to hide SUSY:

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

B,L violation $\rightarrow$ proton decay: $\tau_p > 10^{34}$years

$$\Longrightarrow \; |\lambda'_{l1k}\lambda''_{11k}| \lesssim 2 \times 10^{-27} \left(\frac{\tilde{m}}{100 \text{ GeV}}\right)^2$$

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

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

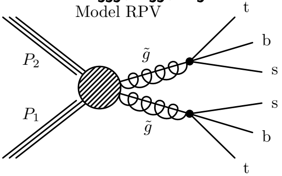
Still, proton is stable is B or L separately conserved*.
Leptonic RPV relatively better constrained (some exceptions of Run I in [Graham,Rajendran,Saraswat, 1403.7197]), so I will consider baryonic RPV,

$$W_{\not{B}} = \frac{\lambda''_{ijk}}{2} u_i^c d_j^c d_k^c, \quad i,j,k = 1,2,3, \; j \neq k$$

Baryonic RPV: *standard* searches at 8 TeV

No MET but large jet multiplicities, large H_T, many b's, SS leptons.

- gluino $\rightarrow$ jjj, tjj, 5j:

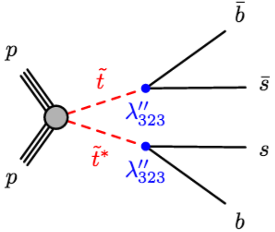


- paired 3j resonances [CMS,1311.1799]
- multijets [ATLAS, 1502.05686]
- same-sign leptons: [ATLAS-CONF-2013-007] [CMS,1311.6736]

$m_{\tilde{g}} \gtrsim 1$ TeV (beyond simplified spectra)

[Evans,Kats,Shih,Strassler,1310.5758][Graham et al,1403.7197]

- squark (stop) $\rightarrow$ jj, bj: paired jj resonances

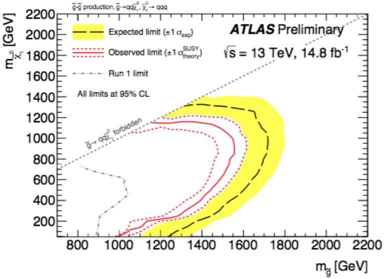


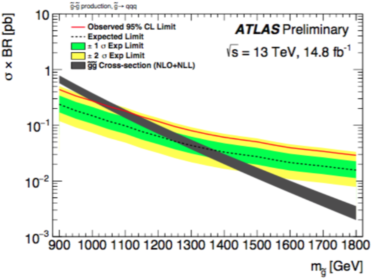
[CMS, 1412.7706], [ATLAS, ATLAS-CONF-2015-026]

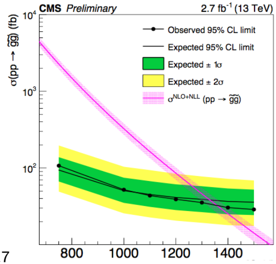
$m_{\tilde{t}} \gtrsim 350 - 400$ GeV (stop LSP)

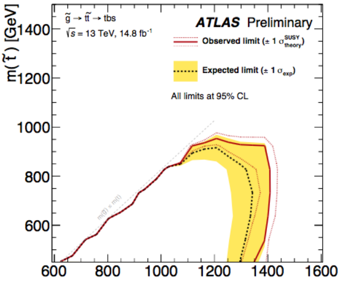
Baryonic RPV: *standard* searches at 13 TeV

- gluino $\rightarrow$ jjj, tjj, 5j: (new results last week!)









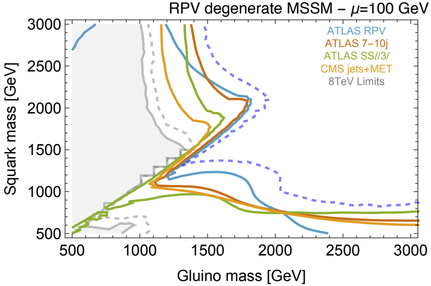
[ATLAS, CONF-2016-057]

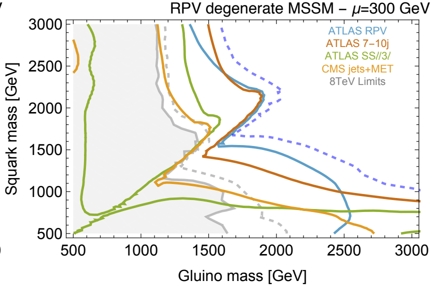
[CMS, SUS-16-013-PAS]

[ATLAS, CONF-2016-094]

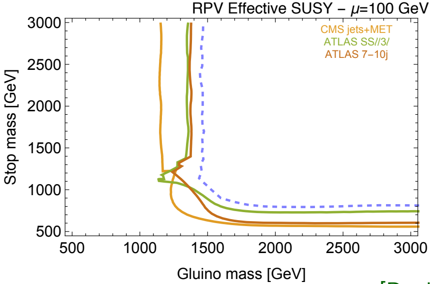
recasting for general spectra:

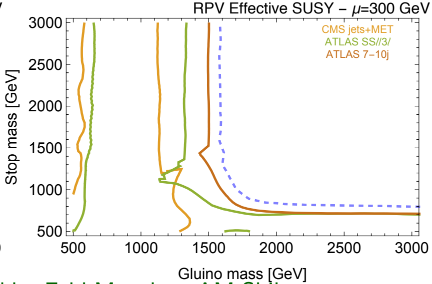
- degenerate squarks + higgsino LSP decaying to light jets:





- 3rd gen. squarks ($\tilde{t}_1, \tilde{t}_2, \tilde{b}_1$) + higgsino LSP decaying to light jets:





[Buckley,Feld,Macaluso,AM,Shih, in preparation]

Baryonic RPV: *standard* searches after ICHEP

- gluino $\to$ jjj, tjj, 5j:

  $m_{\tilde{g}} \gtrsim 1.2 - 1.4$ TeV (beyond simplified spectra)
  [Buckley, Feld, Macaluso, AM, Shih, in preparation]

- stop NLSP: $m_{\tilde{t}} \gtrsim 700$ GeV (beyond simplified spectra)
  [Buckley, Feld, Macaluso, AM, Shih, in preparation]

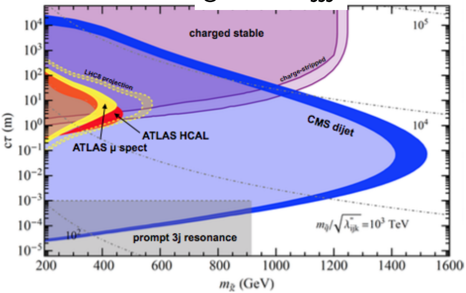
- stop LSP: paired jj resonances $m_{\tilde{t}} \gtrsim 510$ GeV (stop LSP)
  (except small bump allowing 405 GeV $< m_{\tilde{t}} <$ 445 GeV)
  [ATLAS, CONF-2016-084]

More complicated spectra (e.g. bino or winos) typically lead to longer decay chains and stronger signals/exclusions.
Stops and higgsinos of primary importance for naturalness.
Even independently from fine-tuning concerns, is there anything else that we could be forgetting?

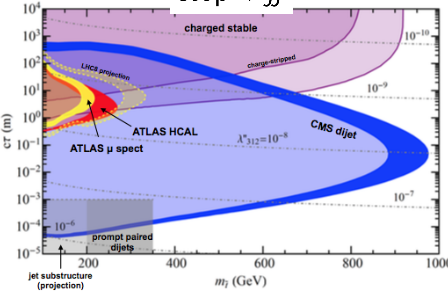
Displaced RPV

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

gluino$\to jjj$



stop$\to jj$



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

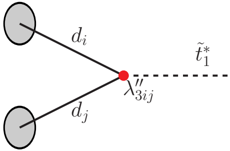
Have not seen 13 TeV updates, but 8 TeV limits already strong. If there are light squarks, prompt decays (large-ish RPV) are preferred (or, not excluded yet!).

Possible connection to low-T baryogenesis: $\lambda'' > O(10^{-3})$. (backup slides)

Resonant production

[AM,1601.03737]

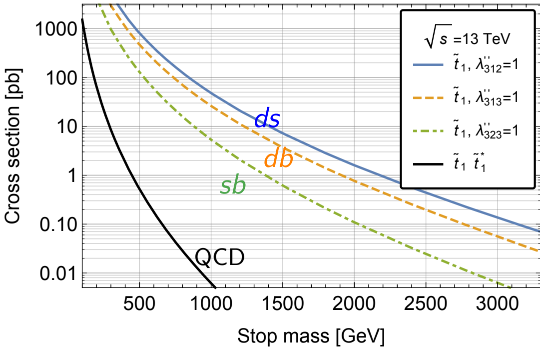
Focus on stop couplings,
$\lambda''_{3ij}\tilde{t}^* d_i d_j + h.c.$, $ij = 12, 13, 23$



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

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

NLO cross sections [Plehn,hep-ph/0006182]



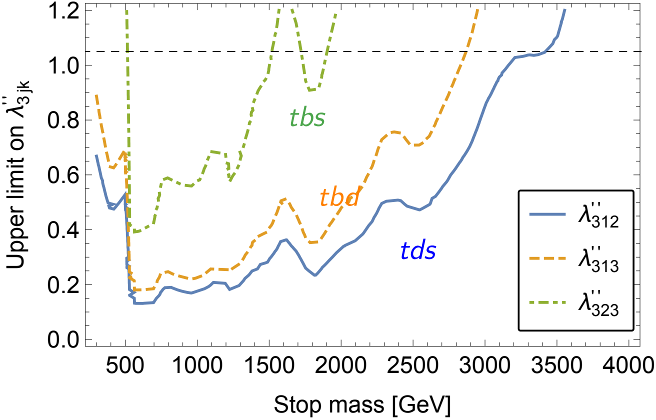
Disclaimer: old idea.[Dreiner,Ross,1991] Tevatron [Berger,Harris,Sullivan,1999], pre-LHC [Choudhury,Datta,Maity,2011], CMS and ATLAS: resonant $\tilde{\nu}$ search (LRPV).

Resonant Signatures I: stop LSP

[ATLAS-1407.1376, 20.3fb^{-1}@8TeV]
[CMS-1501.04198, 19.7fb^{-1}@8TeV]
[CMS-PAS-EXO-14-005, 19.7fb^{-1}@8TeV]
[ATLAS-CONF-2016-069, 15.7fb^{-1}@13TeV]
[CMS-PAS-EXO-16-032, 12.9fb^{-1}@13TeV]

$pp \to \tilde{t}_1^{(*)} \to ds, db, bs$: dijet resonance

Combined, they set limits on $\sigma \times A$ from 300 GeV to 5 TeV:

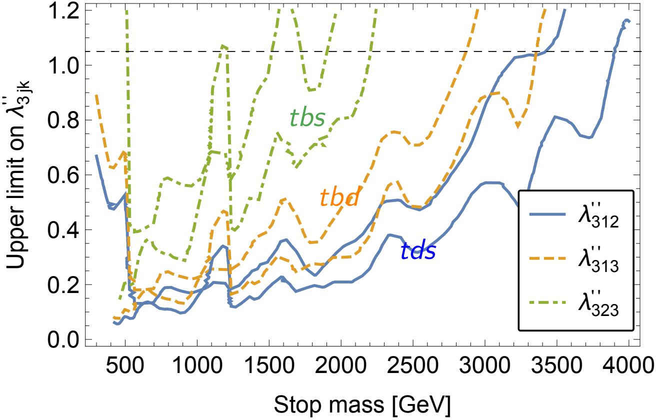


Resonant Signatures I: stop LSP

[ATLAS-1407.1376, 20.3fb^{-1}@8TeV]
[CMS-1501.04198, 19.7fb^{-1}@8TeV]
[CMS-PAS-EXO-14-005, 19.7fb^{-1}@8TeV]
[ATLAS-CONF-2016-069, 15.7fb^{-1}@13TeV]
[CMS-PAS-EXO-16-032, 12.9fb^{-1}@13TeV]

$pp \to \tilde{t}_1^{(*)} \to ds, db, bs$: dijet resonance

Combined, they set limits on $\sigma \times A$ from 300 GeV to 5 TeV:



New ICHEP limits

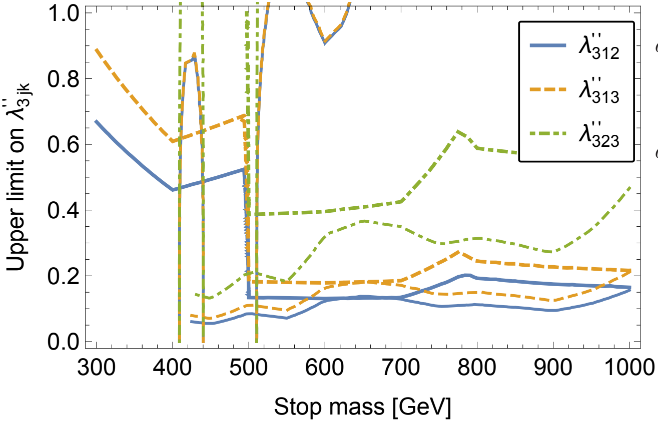
Dijets below 1 TeV: challenges and rewards

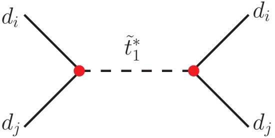
Below 1 TeV, best limits from *scouting / trigger level analysis searches*.

New techniques: recoil off of hard ISR γ/jet

[Shimmin,Whiteson, 1602.07727]

[ATLAS-CONF-2016-070, 15.7fb^{-1}@13TeV]





Below$\sim$ 400 GeV, limits from QCD-produced paired dijets.

[ATLAS, CONF-2016-084]

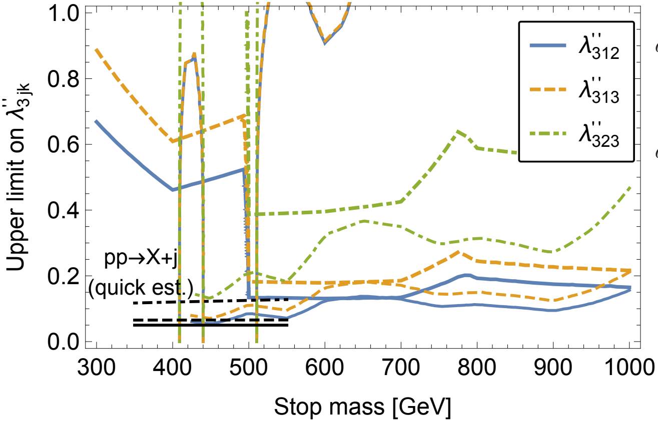
Dijets below 1 TeV: challenges and rewards

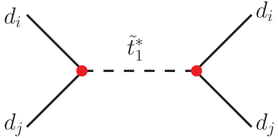
Below 1 TeV, best limits from *scouting / trigger level analysis searches*.

New techniques: recoil off of hard ISR γ/jet

[Shimmin,Whiteson, 1602.07727]

[ATLAS-CONF-2016-070, 15.7fb^{-1}@13TeV]





Below$\sim$ 400 GeV, limits from QCD-produced paired dijets.

[ATLAS, CONF-2016-084]

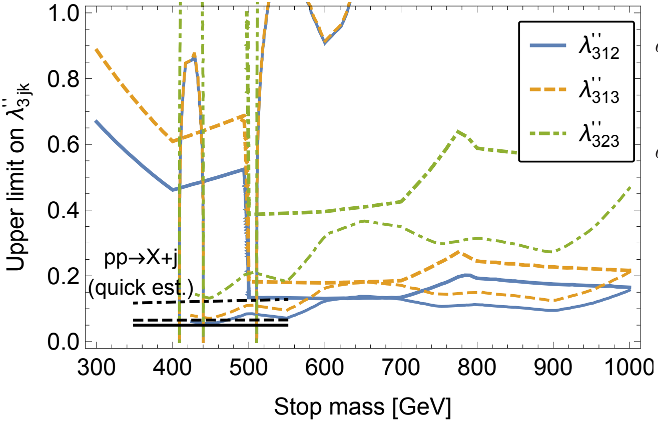
Dijets below 1 TeV: challenges and rewards

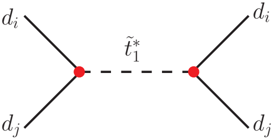
Below 1 TeV, best limits from *scouting / trigger level analysis searches*.

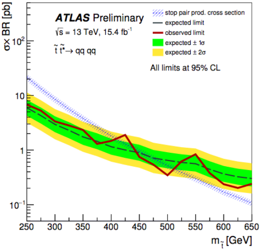
New techniques: recoil off of hard ISR γ/jet

[Shimmin,Whiteson, 1602.07727]

[ATLAS-CONF-2016-070, 15.7fb^{-1}@13TeV]







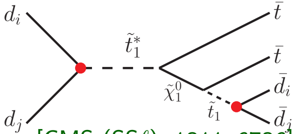
Below∼ 400 GeV, limits from QCD-produced paired dijets.

[ATLAS, CONF-2016-084]

Resonant Signatures II: Neutralino LSP

Light neutralinos arise naturally (GUTs/tuning). New decays dilute dijets. Two simplified spectra:

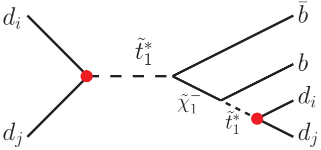
- bino-like: $M_1 \ll M_2, \mu$. Light states: $\tilde{\chi}_1^0, \tilde{t}$



$\Longrightarrow$ same-sign tops + jets

[CMS (SSℓ), 1311.6736]
[ATLAS-CONF-2016-037, 13.2fb^{-1}@13TeV]

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



$\Longrightarrow$ four-jet resonances

(dominates over SStops b/c phase space)

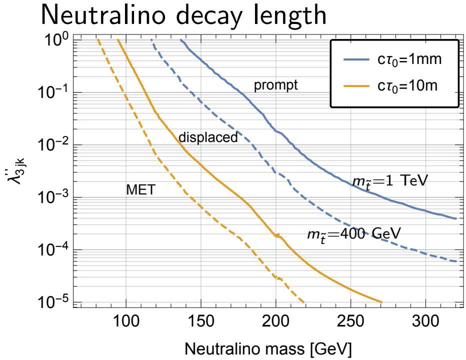
In addition to resonant signatures, stop pair-production *doubles* the signatures: four tops ($tt\bar{t}\bar{t} + 4j$) and multijets/paired four-jet resonances.

[ATLAS (4t), 1505.04306]

Also more exotic signals like $ttt\bar{t} + 4j$ (three SS tops).

Resonant Signatures III: displaced neutralino LSP

If very light, the neutralino can be displaced: $\tilde{t} \to t + (\tilde{\chi}_1^0 \xrightarrow{DV} t^* jj \to bWjj)$



Displaced decays to jets are highly constrained:

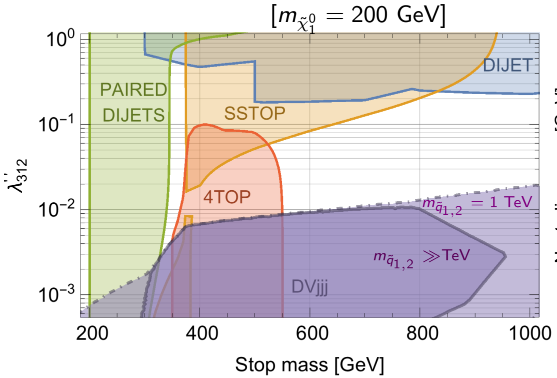
$$\sigma(pp \to XX, X \to jjj) < 0.2 - 1fb \qquad \text{for } c\tau = 3cm - 1mm$$

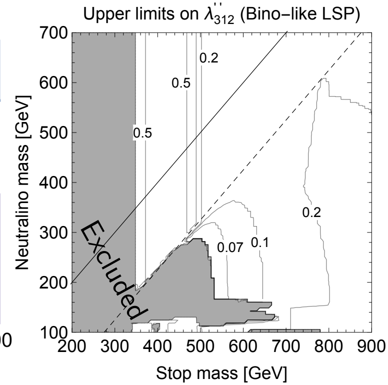
[Cui,Shuve, 1409.6729]

If neutralino detector-stable → monotop or MET and RPC SUSY.

Resonant Results - 8 TeV - bino-like $\tilde{\chi}_1^0$

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



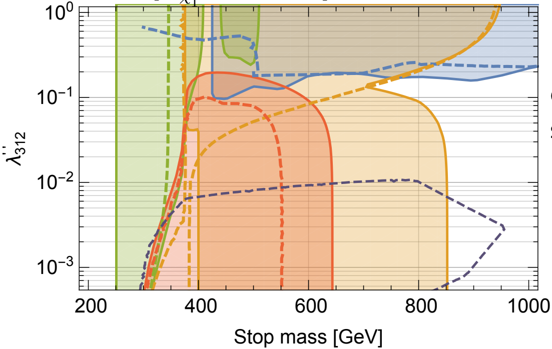


Reach stops up to 500-650 GeV: *comparable to RPC searches!*

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

Current 13 TeV limits - bino-like $\tilde{\chi}_1^0$

Recasting searches presented at ICHEP, we find significant improvements over Run I: $[m_{\tilde{\chi}_1^0} = 200\ \text{GeV}]$



dashed = 8 TeV limits
solid = 13 TeV limits

- DIJET
- SStop
- PAIRED DIJET
- 4TOP
- DVjjj

We can already reach up to 800 GeV-1 TeV!

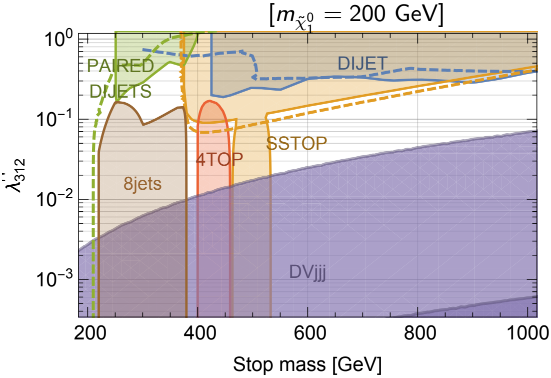
Most important searches are the multi-top searches, not currently optimized for these signatures. Extra jets (possibly b's) in final state.

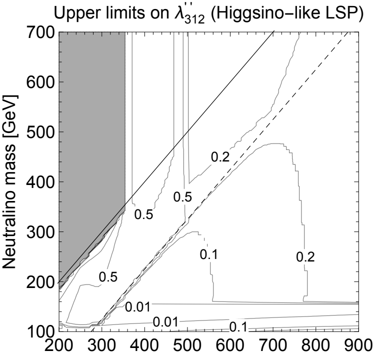
Resonant $\rightarrow$ 2 SS tops + 2 jets. Pair-produced $\rightarrow$ 4 tops + 4 jets.

4 tops could be $tt\bar{t}\bar{t}$, or $ttt\bar{t}$ (3 SS leptons).

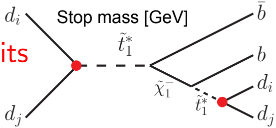
Resonant Results - higgsino-like $\tilde{\chi}_1^0$

In this case limits from available 8&13 TeVsearches are much weaker:





Chargino decay mode dominates ($\tilde{t} \to 4j$) $\to$ no limits



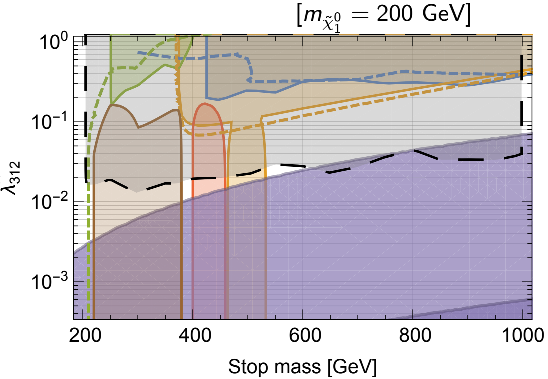
Pair-produced stops $\to 8j$ in brown

[ATLAS-CONF-2016-095]

For a higgsino LSP and $\lambda'' \approx 0.1$, 300 GeV stops allowed! In addition, 8j limits are barely above σ_{prod}, recasting uncertainties almost removes it.

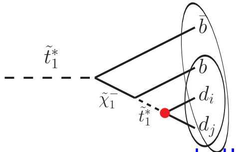
13 TeV reach - higgsino-like $\tilde{\chi}_1^0$

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



Colored:
dashed = 8 TeV limits
solid = 13 TeV limits

— — = projected limits for resonant $4j$ search, for $\sigma^{95}_{lim} \sim 1 - 0.1pb$



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

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

Outlook

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

Using existing searches at 8 and 13 TeV, one can fully constrain RPV stops, e.g. one can exclude stops up to 500-700 GeV for a bino LSP. The higgsino LSP case needs dedicated searches. This was overlooked so far in the analysis of LHC data.

First direct limits on individual RPV couplings, as opposed to indirect flavor physics constraints.

My recommendations for optimize specific searches at 13 TeV:

- jj searches: scouting/ISR is great.
- multi-tops: $\tilde{t} \to SStop+2j$: count extra jets. Also, $ttt\bar{t}+4j$.
- $4j$ resonances: new signature, spectacular $3j$ sub-resonance.
- current RPV gluino searches can look for direct higgsino production at 13 TeV. Keep looking at low masses, limits are still stuck at LEP. Zero bias events?
- only CONF NOTES so far, the full analyses will be more constraining

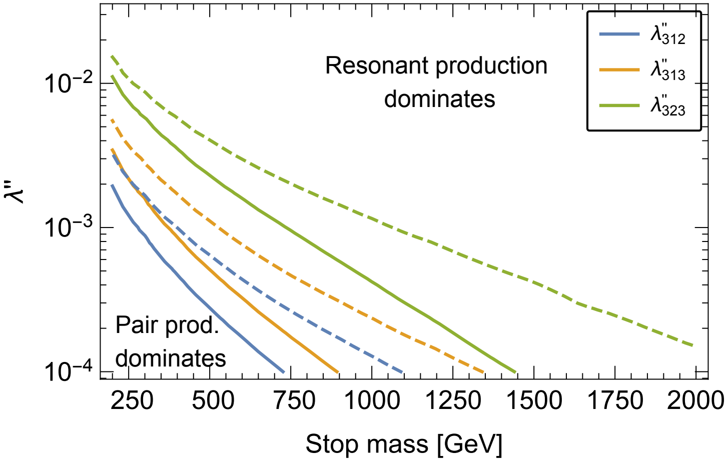
Thank you

Thanks for listening!

Extra slides

RPV vs. QCD production

solid (dashed) lines $\to$ 8 (13) TeV

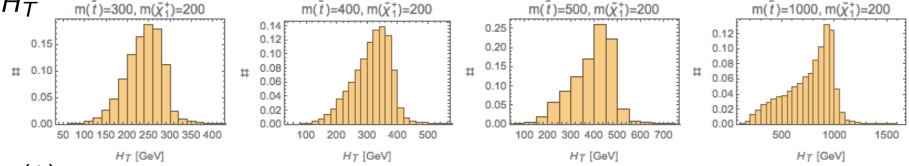


4j resonance search: Event distributions

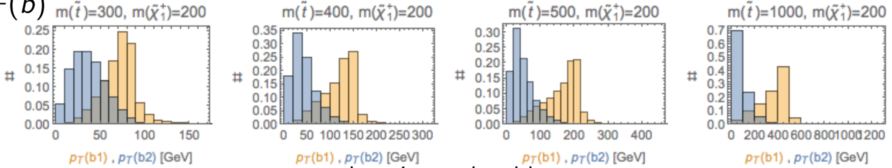
$$\begin{cases} y(j,b) \lesssim 2.5 \\ 1 \lesssim \Delta R \lesssim 3 \end{cases}$$

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

H_T

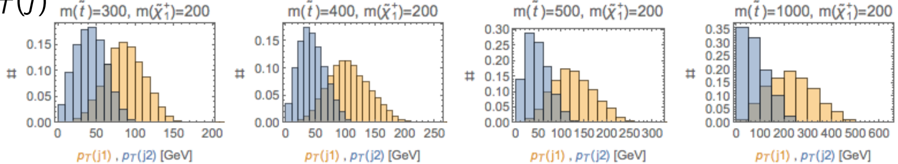


$p_T(b)$



here jets ordered by p_T

$p_T(j)$

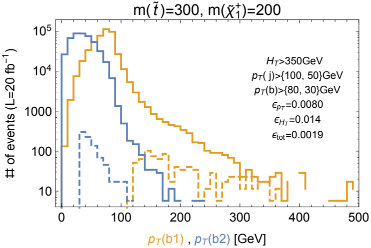


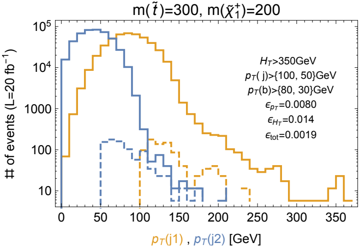
Let's analyze the low stop masses in more details

4j resonance search: Event distributions

Proposed 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

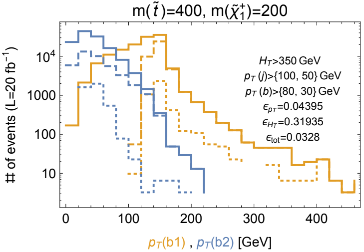


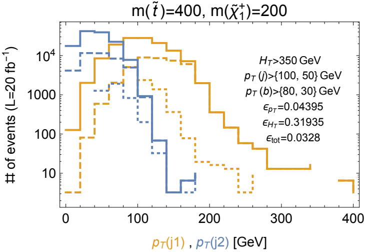


$\sigma^0_{13\text{ TeV}}$[pb]
$\{50, 29, 9.7\}$
even with low ε,
$N_{events} \sim 1000$

$\sigma^{\lambda''=0.1}_{13\text{ TeV}}$[pb]
$\{18, 11, 3.2\}$

larger ε,
$N_{events} \sim 10^4$





Flavor and RPV

Flavor physics constraints ($K-\bar{K}$, $\Delta B = 2$ transitions, e.g. $n-\bar{n}$):
2025(?)@Lund's ESS

$$n-\bar{n}: \quad |\lambda''_{11k}| \lesssim 10^{-7}\left(\frac{\tilde{m}}{100\ \mathrm{GeV}}\right)^{5/2}, \quad |\lambda''_{312,313}| \lesssim 10^{-2}\left(\frac{\tilde{m}}{200\ \mathrm{GeV}}\right)^{5/2}$$

$$K-\bar{K}: \quad |\lambda''^{*}_{323}\lambda''_{313}| \lesssim 10^{-3}\left(\frac{m_{\tilde{u}_i}}{100\ \mathrm{GeV}}\right)$$

[Barbier et al., hep-ph/0406039]
[Calibbi,Ferretti,Milstead,Petersson, 1602.04821]

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

$$\begin{pmatrix} \lambda''_{112} & \lambda''_{212} & \lambda''_{312} \\ \lambda''_{113} & \lambda''_{213} & \lambda''_{313} \\ \lambda''_{123} & \lambda''_{223} & \lambda''_{323} \end{pmatrix}_{horiz.U(1)} = \lambda''_{323}\begin{pmatrix} 3\times10^{-5} & 3\times10^{-3} & 0.05 \\ 10^{-4} & 10^{-2} & 0.2 \\ 6\times10^{-4} & 0.05 & 1 \end{pmatrix}$$

$$\begin{pmatrix} \lambda''_{112} & \lambda''_{212} & \lambda''_{312} \\ \lambda''_{113} & \lambda''_{213} & \lambda''_{313} \\ \lambda''_{123} & \lambda''_{223} & \lambda''_{323} \end{pmatrix}_{MFV} = \frac{1}{2}\left(\frac{\tan\beta}{50}\right)^2\begin{pmatrix} 10^{-8} & 10^{-4} & 0.2 \\ 3\times10^{-5} & 5\times10^{-2} & 0.3 \\ 2\times10^{-3} & 0.2 & 1 \end{pmatrix}.$$

RPV involving the stop is much less constrained, and also more relevant in terms of naturalness. Large couplings are still possible.

Flavor and RPV

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

2025(?)@Lund's ESS

$$n-\bar{n}: \quad |\lambda''_{11k}| \lesssim 10^{-7}\left(\frac{\tilde{m}}{100\ \mathrm{GeV}}\right)^{5/2}, \quad |\lambda''_{312,313}| \lesssim 10^{-2}\left(\frac{\tilde{m}}{200\ \mathrm{GeV}}\right)^{5/2}$$

$$K-\bar{K}: \quad |\lambda''^{*}_{323}\lambda''_{313}| \lesssim 10^{-3}\left(\frac{m_{\tilde{u}_i}}{100\ \mathrm{GeV}}\right)$$

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

[Calibbi,Ferretti,Milstead,Petersson, 1602.04821]

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

$$\begin{pmatrix} \lambda''_{112} & \lambda''_{212} & \lambda''_{312} \\ \lambda''_{113} & \lambda''_{213} & \lambda''_{313} \\ \lambda''_{123} & \lambda''_{223} & \lambda''_{323} \end{pmatrix}_{horiz.U(1)} = \lambda''_{323}\begin{pmatrix} 3\times10^{-5} & 3\times10^{-3} & 0.05 \\ 10^{-4} & 10^{-2} & 0.2 \\ 6\times10^{-4} & 0.05 & 1 \end{pmatrix}$$

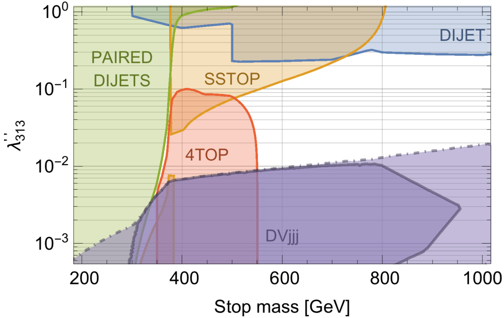
$$\begin{pmatrix} \lambda''_{112} & \lambda''_{212} & \lambda''_{312} \\ \lambda''_{113} & \lambda''_{213} & \lambda''_{313} \\ \lambda''_{123} & \lambda''_{223} & \lambda''_{323} \end{pmatrix}_{MFV} = \frac{1}{2}\left(\frac{\tan\beta}{50}\right)^{2}\begin{pmatrix} 10^{-8} & 10^{-4} & 0.2 \\ 3\times10^{-5} & 5\times10^{-2} & 0.3 \\ 2\times10^{-3} & 0.2 & 1 \end{pmatrix}.$$

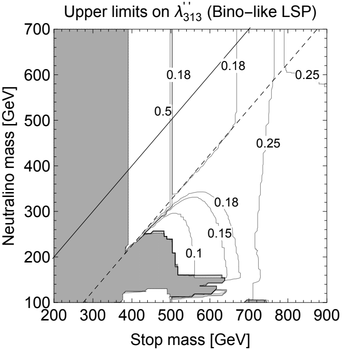
RPV involving the stop is much less constrained, and also more relevant in terms of naturalness. Large couplings are still possible.

Recasting: 13 TeV searches used

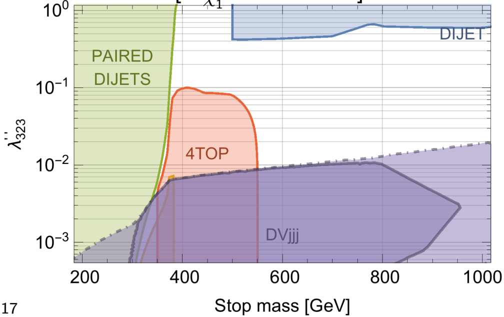
CONF NOTE	label	$\mathcal{L}$ [fb^{-1}]
ATLAS-CONF-2016-037	ATLAS SSL/3L + MET	13.2
ATLAS-CONF-2016-052	ATLAS multi-b+MET	14.8
ATLAS-CONF-2016-054	ATLAS 1 lepton + jets + MET	14.8
ATLAS-CONF-2016-057	ATLAS multijet [gluino RPV]	14.8
ATLAS-CONF-2016-078	ATLAS 2-6 jets+MET	13.3
ATLAS-CONF-2016-094	ATLAS 1L + many jets	14.8
ATLAS-CONF-2016-095	ATLAS 8-10 jets	18.2
SUS-16-014-PAS	CMS jets+MET	12.9
SUS-16-020-PAS	CMS SS leptons	12.9

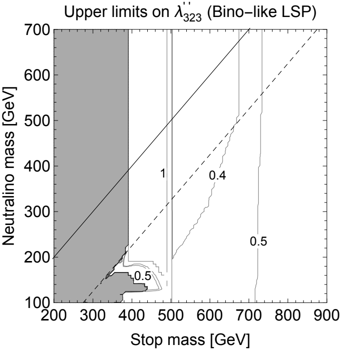
Bino LSP



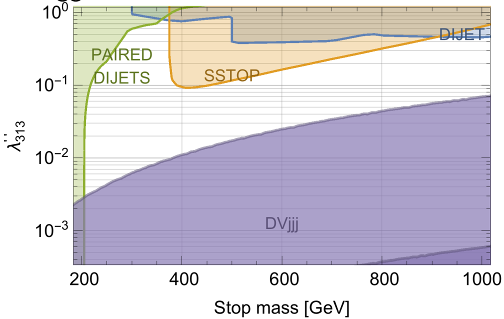


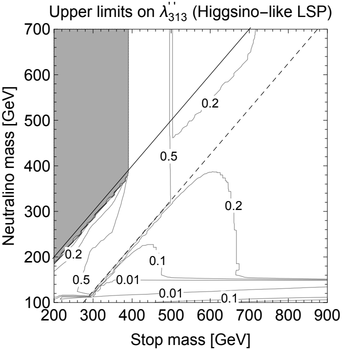
$[m_{\tilde{\chi}_1^0} = 200 \text{ GeV}]$



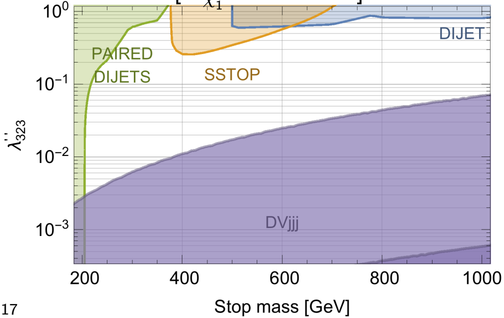


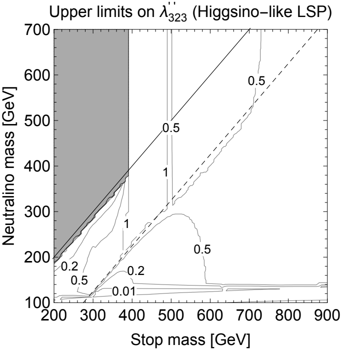
Higgsino LSP



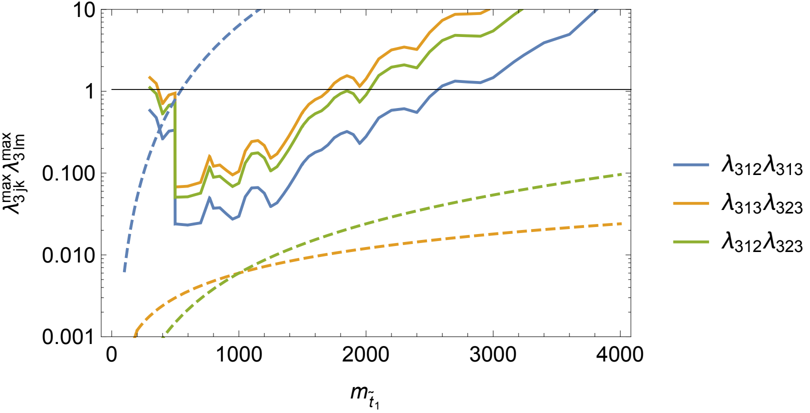


$[m_{\tilde{\chi}^0_1} = 200 \text{ GeV}]$





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 $X \to B, \bar{B}$ gives

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

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

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