Heavy Flavor Signatures from RPV and GMSB

Jared A. Evans

jaredaevans@gmail.com

UIUC

arxiv:1209.0764 – JAE, Y. Kats
arxiv:1303.0228 – JAE, D. Shih
arxiv:1311.0890 – JAE, Y. Kats
arxiv:1402.4481 – JAE
In Progress – JAE, Y. Kats

Outline

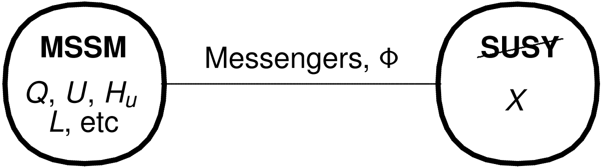
Motivation

- GMSB
- RPV
- Signature Generators
- Simulation

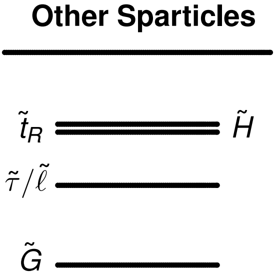
Signatures

- Natural GMSB: $b\bar{b}\tau^+\tau^- + \not{E}_T$
- RPV stops: $b\bar{b}\tau^+\tau^- + 4j$
- RPV stops: $\geq 5b$
- RPV higgsinos: $4\tau + \not{E}_T$
- RPV higgsinos: SS τ
- RPV higgsinos: internal resonances

"Natural" GMSB



$$W \sim X(\Phi\tilde{\Phi} + \bar{\Phi}\tilde{\bar{\Phi}}) + \kappa_3 U_3 \Phi\bar{\Phi} + \{\text{MSSM yukawas}\}$$



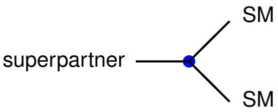
R-parity Violation (RPV)

- *R*-parity is **nice**: *B* and *L* conservation, DM candidate
- But *R*-parity is **unnecessary**: e.g., $\not{B}$ or $\not{L}$ only, other DM sector

R-parity violation $\Rightarrow$ LSP can decay

- Cascade decays without $\not{E}_T$
- 2-body, 3-body resonances (+ other objects), often in pairs
- Many, many final states: jets-only to multi-leptons
- Violation of lepton flavor universality

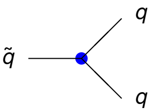
RPV Interactions



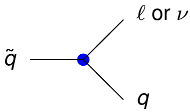
$$W = \frac{1}{2}\lambda_{ijk}\, L_i L_j E^c_k + \lambda'_{ijk}\, L_i Q_j D^c_k + \frac{1}{2}\lambda''_{ijk}\, U^c_i D^c_j D^c_k + \mu_i L_i H_u$$

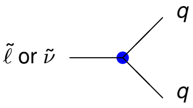
i, j, k = generation indices

UDD

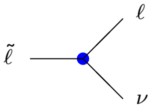


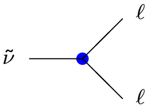
LQD





LLE





The RPV MSSM: a font of possibilities

The RPV MSSM is an effective signature generator

	$\not{E}_T$	ℓs	τs	*b*s	*t*s	jets
	High	Many	Many	Many	Many	Many
RPV yields:	Some	Few	Few	Few	Few	Few
	No	No	No	No	No	No

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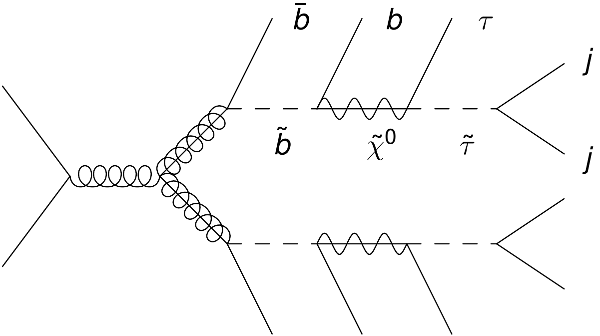
	No	No	No	No	No	No



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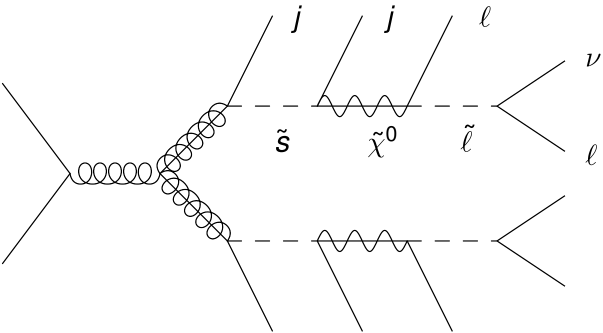
	No	No	No	No	No	No



RPV as Signature Generator

Each signature is a simplified model [Alves et al – 2011]

These simplified models go *beyond* RPV!

Other theories could produce the same signatures

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Why Study R-Parity Violation?

Examining simplified models within RPV
– an expansive signature generator –
can highlight gaps in existing LHC searches

RPV as Signature Generator
A Simple Example

Consider consider color singlet fermions, X^0, $X^\pm$

List all possible decays of X to 3 SM fermions: (ignoring $\nu \leftrightarrow \bar{\nu}$)

- $X^0 \to u_i d_j d_k$
- $X^0 \to \bar{u}_i \bar{d}_j \bar{d}_k$
- $X^0 \to \nu_i \ell_j^+ \ell_k^-$
- $X^0 \to \ell_i^- u_j \bar{d}_k$
- $X^0 \to \nu_i d_j \bar{d}_k$
- $X^0 \to \ell_i^+ \bar{u}_j d_k$
- $X^0 \to \nu_i u_j \bar{u}_k$
- $X^0 \to \nu_i \nu_j \bar{\nu}_k$

- $X^+ \to u_i d_j u_k$
- $X^+ \to \bar{d}_i \bar{d}_j \bar{d}_k$
- $X^+ \to \ell_i^+ \ell_j^+ \ell_k^-$
- $X^+ \to \ell_i^+ \nu_j \bar{\nu}_k$
- $X^+ \to \ell_i^+ u_j \bar{u}_k$
- $X^+ \to \ell_i^+ d_j \bar{d}_k$
- $X^+ \to \nu_i u_j \bar{d}_k$

RPV as Signature Generator

A Simple Example

Consider consider color singlet fermions, X^0, $X^\pm$

List all possible decays of X to 3 SM fermions: (ignoring $\nu \leftrightarrow \bar{\nu}$)

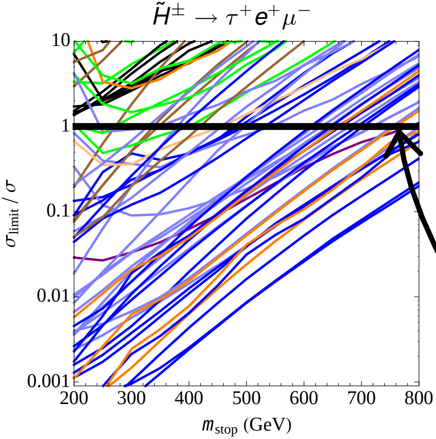
- $X^0 \to u_i d_j d_k$ UDD ($j \neq k$)
- $X^0 \to \bar{u}_i \bar{d}_j \bar{d}_k$ UDD ($j \neq k$)
- $X^0 \to \nu_i \ell_j^+ \ell_k^-$ LLE
- $X^0 \to \ell_i^- u_j \bar{d}_k$ LQD
- $X^0 \to \nu_i d_j \bar{d}_k$ LQD
- $X^0 \to \ell_i^+ \bar{u}_j d_k$ LQD
- $X^0 \to \nu_i u_j \bar{u}_k$ ✗
- $X^0 \to \nu_i \nu_j \bar{\nu}_k$ ✗

- $X^+ \to u_i d_j u_k$ UDD ($j \neq k$)
- $X^+ \to \bar{d}_i \bar{d}_j \bar{d}_k$ UDD ($j \neq k$)
- $X^+ \to \ell_i^+ \ell_j^+ \ell_k^-$ LLE ($i \neq j$)
- $X^+ \to \ell_i^+ \nu_j \bar{\nu}_k$ LLE
- $X^+ \to \ell_i^+ u_j \bar{u}_k$ LQD
- $X^+ \to \ell_i^+ d_j \bar{d}_k$ LQD
- $X^+ \to \nu_i u_j \bar{d}_k$ LQD

RPV Higgsinos can give almost all possible decays!

Simulation and Limits from Recast Searches

Example: LLE132 with $\tilde{t} \to b\tilde{H}^\pm$



different lines = different *searches*

- Production in MG5 or Pythia 8
- Showering in Pythia 8
- Private detector sim + FastJet
  - lepton ID efficiencies
  - lepton isolation
  - jet energy resolution
  - *b*-tagging, etc
- **Recast** LHC searches
  - Mirror cuts, ID and iso.
  - Use data from search
  - Use best bin for limit

Normalized to the production xsec

Searches – (no searches with MVA, BDT, Neural Net or jet substructure)

ATLAS **CMS**

Final State	$\sqrt{s}$	$\mathcal{L}$	Reference
3ℓ+jets+MET	8	13.0	CONF-2012-151
3ℓ+MET (old)	8	13.0	CONF-2012-154
3ℓ+MET	8	20.7	CONF-2013-035
4ℓ (old)	8	13.0	CONF-2012-153
4ℓ+MET	8	20.7	CONF-2013-036
3-4ℓ	8	19.5	PAS-SUS-13-003
3ℓ	8	19.5	PAS-SUS-13-008
4ℓ	8	19.5	PAS-SUS-13-010
b' (3ℓ)	7	4.9	arXiv:1204.1088
3ℓ	7	1.02	CONF-2011-158
4ℓ	7	1.02	CONF-2011-144
3ℓ+MET	7	2.06	arXiv:1204.5638
3ℓ+MET	7	4.7	arXiv:1208.3144
4ℓ+MET	7	2.06	CONF-2012-001
3-4ℓ	7	4.98	arXiv:1204.5341

Final State	$\sqrt{s}$	$\mathcal{L}$	Reference
SS DIL+MET	8	5.8	CONF-2012-105
SS DIL w/b (SUSY)	8	20.7	CONF-2013-007
SS DIL w/b (Exo.)	8	14.3	CONF-2013-051
SS DIL w/b	8	10.5	arXiv:1212.6194
SS DIL	8	19.5	PAS-SUS-13-013
t' (SS DIL)	8	19.6	PAS-B2G-13-015
SS DIL	7	4.98	arXiv:1205.6615
SS DIL w/b	7	4.98	arXiv:1205.3933
SSSF DIL	7	4.98	arXiv:1207.6079
SSSF DIL	7	1.6	arXiv:1201.1091
SS DIL	7	4.7	arXiv:1210.4538
SS DIL+jets+MET	7	2.05	arXiv:1203.5763
SS DIL+MET	7	1.04	arXiv:1110.6189
b' (SS DIL)	7	4.7	CONF-2012-130
b' (SS DIL)	7	4.9	arXiv:1204.1088

Final State	$\sqrt{s}$	$\mathcal{L}$	Reference
t' (OS DIL)	8	19.6	PAS-B2G-13-015
OS DIL+MET	7	1.04	arXiv:1110.6189
OS DIL+jets+MET	7	4.7	arXiv:1208.4688
OS DIL+MET	7	4.98	arXiv:1206.3949
leptonic m_{T2}	7	4.7	arXiv:1209.4186
Z+jets+MET	7	4.98	arXiv:1204.3774
Z+jets+MET	7	2.05	arXiv:1204.6736

Final State	$\sqrt{s}$	$\mathcal{L}$	Reference
ℓ+jets+MET	8	5.8	CONF-2012-104
ℓ+3b+jets+MET	8	20.1	CONF-2013-061
ℓ+b+6j+MET	8	19.4	PAS-SUS-13-007
ℓ+7j+MET	7	4.7	CONF-2012-140
ℓ+jets+MET	7	4.7	PAS-SUS-12-010
ℓ+jets+MET	7	4.7	CONF-2012-041
ℓ+b+jets+MET	7	2.05	arXiv:1203.6193
ℓ+b+jets+MET	7	4.98	PAS-SUS-11-027
ℓ+b+jets+MET	7	4.98	PAS-SUS-11-028

Final State	$\sqrt{s}$	$\mathcal{L}$	Reference
1/2τ+jets+MET	8	20.7	CONF-2013-026
4ℓ+MET w/τ	8	20.7	CONF-2013-036
3-4ℓ w/τ	8	19.5	PAS-SUS-13-003
1/2τ+jets+MET	7	4.7	arXiv:1210.1314
τ+ℓ+jets+MET	7	4.7	arXiv:1210.1314
τ+jets+MET (old)	7	2.05	CONF-2012-005
2τ+jets+MET (old)	7	2.05	arXiv:1203.6580
OS DIL+MET w/τ	7	4.98	arXiv:1206.3949
SS DIL w/τ	7	4.98	arXiv:1205.6615
3-4ℓ w/1τ	7	4.98	arXiv:1204.5341
3-4ℓ w/2τ	7	4.98	arXiv:1204.5341

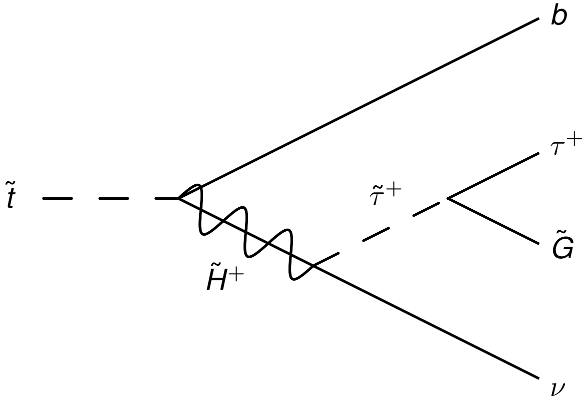
Final State	$\sqrt{s}$	$\mathcal{L}$	Reference
$t\bar{t}$ xsec (DIL)	8	2.4	PAS-TOP-12-007
$t\bar{t}$ xsec (DIL)	7	0.70	arXiv:1202.4892
$t\bar{t}$ xsec (DIL)	7	2.3	arXiv:1208.2671
$t\bar{t}$ xsec (DIL w/τ)	7	$\sim$ 2	arXiv:1203.6810
$t\bar{t}$+jet (LJ)	7	5.0	PAS-EXO-11-056
$t\bar{t}$+m_T (LJ)	7	1.04	arXiv:1109.4725

Final State	$\sqrt{s}$	$\mathcal{L}$	Reference
2-6 jets+MET	8	20.3	CONF-2013-047
2-6 jets+MET (old)	8	5.8	CONF-2012-109
7-10 jets+MET w/b	8	20.3	CONF-2013-054
7-10 jets+MET w/M_J^{Σ}	8	20.3	CONF-2013-054
6-9 jets+MET	8	5.8	CONF-2012-103
jets+MET	8	19.5	PAS-SUS-13-012
b+jets+MET	8	19.4	arXiv:1305.2390
3b+jets+MET (old)	8	12.8	CONF-2012-145
3b+jets+MET	8	20.1	CONF-2013-061
jets w/α_T w/b	8	11.7	arXiv:1303.2985
monojet+MET	8	19.5	PAS-EXO-12-048
monojet+MET	8	10.5	CONF-2012-147
2-6 jets+MET	7	4.7	CONF-2012-033
6-9 jets+MET	7	4.7	CONF-2012-037
jets+MET	7	4.98	arXiv:1207.1898
jets+MET (old)	7	1.1	PAS-SUS-11-004
b+jets+MET	7	2.05	arXiv:1203.6193
b+jets+MET	7	4.98	arXiv:1208.4859
b+jets+MET (old)	7	1.1	PAS-SUS-11-006
3b+jets+MET	7	4.7	CONF-2012-058
jets w/α_T w/b	7	4.98	PAS-SUS-11-022
jets w/α_T (old)	7	1.14	arXiv:1109.2352

Final State	$\sqrt{s}$	$\mathcal{L}$	Reference
ℓ+b+jets (low MET)*	7	5.0	arXiv:1210.7471
ℓ+3b+jets (low MET)	8	14.3	CONF-2013-018
6-7 jets (no MET)	8	20.3	CONF-2013-091
6 jets (no MET)	7	4.6	arXiv:1210.4813
up to 10 objects ("BH")	8	12.1	arXiv:1303.5338
$(\mu j)(\mu j)$	8	19.6	PAS-EXO-12-042
$(\tau b)(\tau b)$	7	4.8	PAS-EXO-12-002

"Natural" GMSB: $b\bar{b}\tau^+\tau^- + \not{E}_T$

$$\tilde{t} \to b\tilde{H}^{+*} \to b\nu\tilde{\tau} \to b\nu\tau\tilde{G}$$



If $m_b < m_{\tilde{t}} - m_{\tilde{\tau}} < m_t$ or $m_b < m_{\tilde{t}} - m_{\tilde{H}} < m_t$ – dominant decay path:

$$\tilde{t}\tilde{t}^* \rightarrow b\bar{b}\tau^+\tau^-\nu\bar{\nu}\tilde{G}\tilde{G} \quad \rightarrow \quad b\bar{b}\tau_h^+\ell^- \left(\nu\nu\bar{\nu}\nu\bar{\nu}\tilde{G}\tilde{G}\right)$$

$$\sum \left|p_{t,miss}\right| \gg \sum \left|p_{t,vis}\right|$$

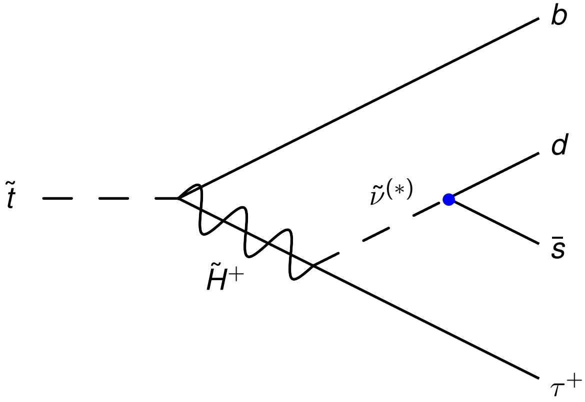
Low visible energy, high $\not\!\!E_T$

Some sensitivity from M_{T2} τ/ℓ-based searches ($\sim$ 500 GeV)
Limits weaken with decreasing $m_{\tilde{t}} - m_{\tilde{\tau}}$

Conclusion: Natural GMSB deserves own search!

LQD321: $\tilde{t} \to b(\tau jj)$

$$\tilde{t} \to b\tilde{H}^+ \to b(\tau^+ \tilde{\nu}^{(*)}) \xrightarrow{RPV} \tau^+ jjb$$



$\tau^+\tau^- + 6$ jets ($2b$): different picture

CMS 7 TeV $t\bar{t}$ w/ τs does best

7 TeV 3rd gen LQ insensitive!

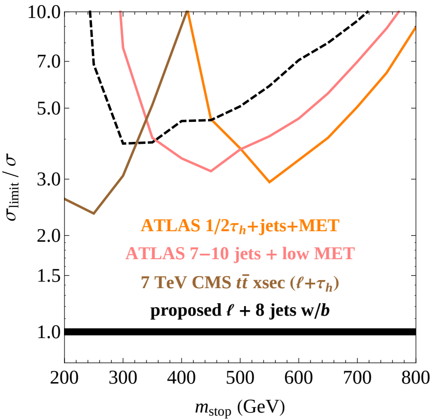
Note: NEW CMS 8 TeV LQ3

$\not{E}_T \ll \not{E}_T(SUSY)$

τ searches don't utilize extra jets!

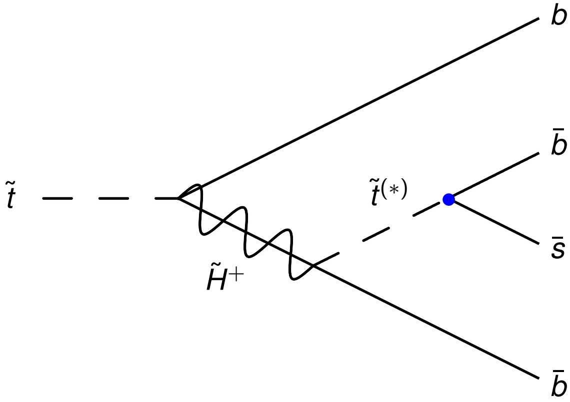
τ searches don't utilize any b-tags!

Conclusion: General OS $\tau + n$ jet search!



UDD323: $\tilde{t} \rightarrow b(\bar{b}\bar{b}j)$

$$\tilde{t} \rightarrow b\tilde{H}^{+} \rightarrow b(\bar{b}\tilde{t}^{(*)}) \xrightarrow{RPV} b\bar{b}\bar{b}j$$



RPV Stops

A swarm of *b*s

Natural MFV SUSY signature!!! 8 jets (6*b*)

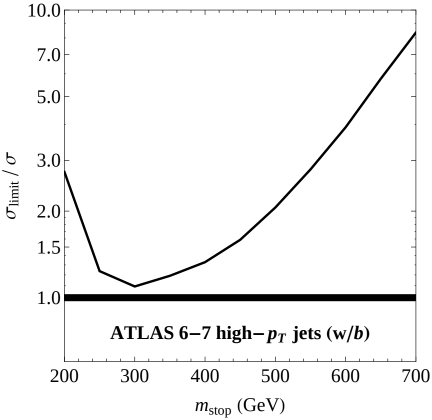
Atlas 6-7 jets (w/ 2 *b*-tags) is close to exclusion

3*b*-tag bin could set limits now!

Higher masses? Use 5*b* or 6*b* tags

Very low SM background

Conclusion: High multiplicity *b* search!



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A swarm of *b*s

Preselection Cuts					
$H_T(p_T > 40; \|\eta\| < 2.5) > 750$ GeV No isolated leptons with $p_T > 20$ GeV, $\|\eta\| < 2.4$ and $I_{rel} < 0.15$					
Cuts	**Region 1**	**Region 2**	**Region 3**	**Region 4**	**Region 5**
H_T (GeV)	750	1000	1250	1500	1750
b_{eff} (%)	50	60		70	
c_{eff} (%)	4.0	9.0		19	
j_{eff} (%)	0.07	0.30		1.5	
n_b	≥ 5 *b*-tagged jets w/ $p_T > 30$ GeV and $\|\eta\| < 2.5$				

Backgrounds	K-factor	# events in 20 fb^{-1} at 8 TeV				
		Region 1	Region 2	Region 3	Region 4	Region 5
$b\bar{b}b\bar{b} + \{\text{jets}\}$	3	5.3	4.3	1.3	1.4	0.5
$b\bar{b}b\bar{b}b\bar{b}$	3	0.5	0.2	< 0.1	< 0.1	< 0.1
$b\bar{b}b\bar{b}c\bar{c}$	3	0.1	0.1	< 0.1	< 0.1	< 0.1
$t\bar{t}b\bar{b}$	–	0.9	1.3	0.5	0.7	0.3
Total		**6.8**	**5.9**	**1.9**	**2.1**	**0.7**

Signal		# events in 20 fb^{-1} at 8 TeV				
$m_{\tilde{t}}$ (GeV)	$m_{\tilde{\chi}^\pm}$ (GeV)	Region 1	Region 2	Region 3	Region 4	Region 5
150	100	**63.7**	18.3	5.1	3.9	1.3
300	200	**109.5**	78.0	22.2	15.9	5.1
500	350	44.5	**50.0**	19.7	15.2	5.7
700	600	6.0	12.6	**8.1**	7.9	3.4
800	600	2.7	6.1	5.1	**6.0**	2.9
900	875	0.2	0.6	0.6	1.1	**0.7**

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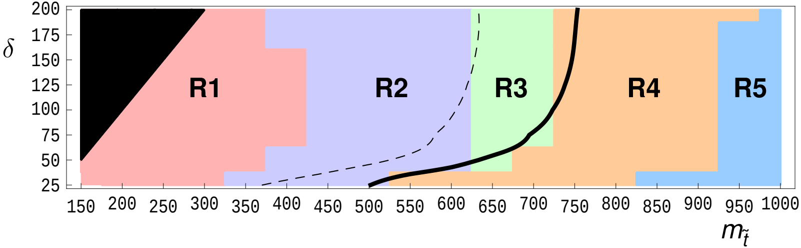
$m_{\tilde{t}}$ vs. $\delta \equiv m_{\tilde{t}} - m_{\tilde{\chi}^\pm}$



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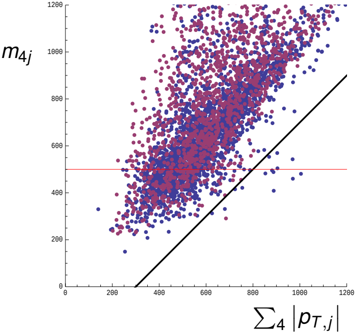
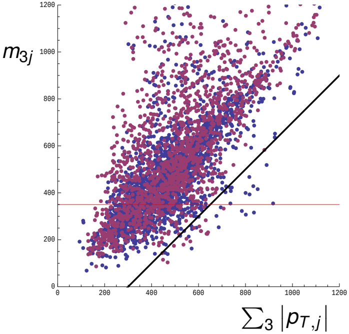


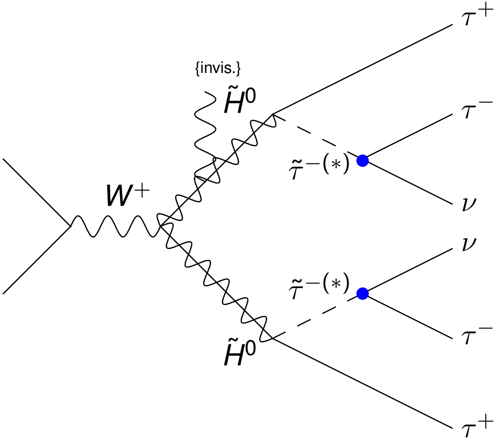


RPV Higgsinos

Four τ

$$\textbf{LLE233: } \tilde{H}^+ \rightarrow \tilde{H}^0 + \{\text{invisible}\},\ \tilde{H}^0 \rightarrow \tau\tau\nu$$

$$pp \rightarrow \tilde{H}^+\tilde{H}^0 \rightarrow \tilde{H}^0\tilde{H}^0 \rightarrow (\tau\tilde{\tau})(\tau\tilde{\tau}) \xrightarrow{RPV} \tau\tau\tau\tau\nu\nu$$



RPV Higgsinos

Four τ

$\tau^+\tau^-\tau^+\tau^-\nu\nu \Rightarrow$ lots of $\not{E}_T$

7 TeV CMS ML: 2τ beats 1τ

8 TeV All ML: No 2τ regions!

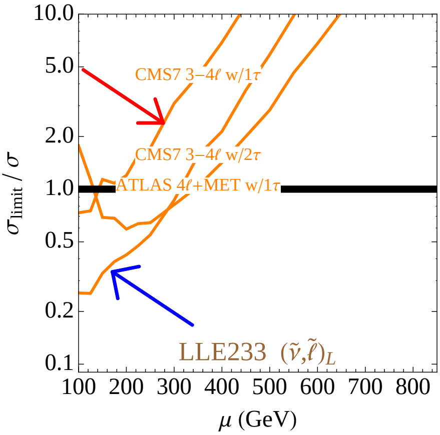
$$\sum |p_{t,miss}| > \sum |p_{t,visible}|$$

$$p_{T,\tau_h} \sim 2p_{T,\tau_\ell}$$

$$\frac{\sigma_{\text{sys.+stat.}}(\ell\ell\tau_h\tau_h)}{\sigma_{\text{sys.+stat.}}(\ell\ell\ell\tau_h)} \lesssim \frac{\text{Efficiency}(4\tau\to\ell\ell\tau_h\tau_h)}{\text{Efficiency}(4\tau\to\ell\ell\ell\tau_h)}$$

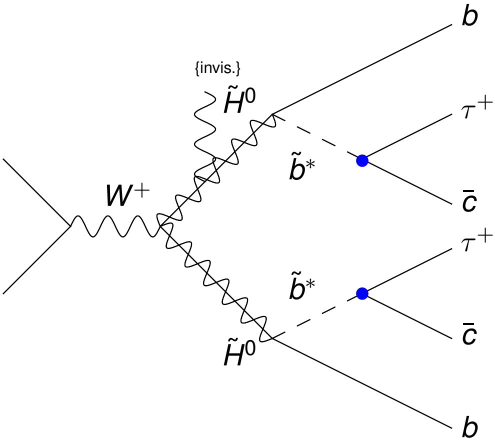
$\Rightarrow \ell\ell\tau_h\tau_h$ does better

Conclusion: $2\tau + 2$ (or 1)ℓ regions still important



LQD323: $\tilde{H}^+ \to \tilde{H}^0 + \{\text{invisible}\}$, $\tilde{H}^0 \to \tau jb$ or νjb,

$$pp \to \tilde{H}^+\tilde{H}^0 \to \tilde{H}^0\tilde{H}^0 \to (b\tilde{b}^*)(b\tilde{b}^*) \xrightarrow{RPV} (\tau^+ jb)(\tau^+ jb)$$



RPV Higgsinos
SS τ

$\mathrm{BR}(\tilde{H}^0\tilde{H}^0 \rightarrow \tau^\pm\tau^\pm) = \frac{1}{8}$

SS τ (i.e. $\tau_\ell^\pm\tau_h^\pm$) is unexplored

$$\frac{\sigma_{\text{sys.+stat.}}(\ell^\pm\tau_h^\pm)}{\sigma_{\text{sys.+stat.}}(\ell^\pm\ell^\pm)} \lesssim \frac{\text{Efficiency}(\tau^\pm\tau^\pm\rightarrow\ell^\pm\tau_h^\pm)}{\text{Efficiency}(\tau^\pm\tau^\pm\rightarrow\ell^\pm\ell^\pm)}$$

7 TeV: Large $\not{E}_T$, Large H_T only

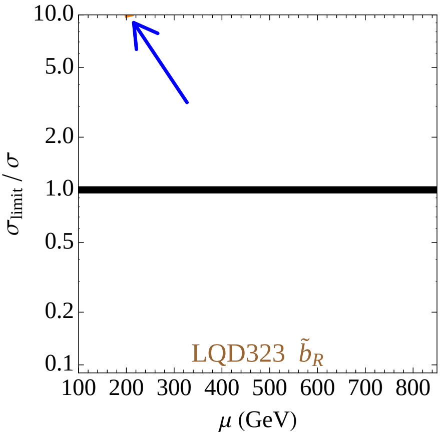
Add b-tags, Lower $\not{E}_T$

Many S_T, High p_{t,τ_h}, etc.

Conclusion: SS τ is wanting 8 TeV expansion

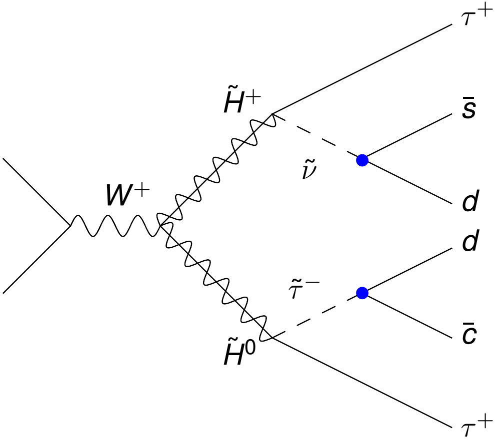
(SSτ CDF result)

Only one SS τ search at 7 TeV



LQD321: $\tilde{H}^+ \to \tau jj$ or νjj, $\tilde{H}^0 \to \tau jj$ or νjj

$$pp \to \tilde{H}^+ \tilde{H}^0 \to (\tau\tilde{\nu})(\tau\tilde{\tau}) \xrightarrow{RPV} (\tau(jj))(\tau(jj))$$



RPV Higgsinos

Internal resonances

- Light $\tilde{\tau}/\tilde{\nu}$ realistic, but have miniscule cross-sections
- Higgsino production portal: $\tilde{H}^0 \to \tau^{\pm}\tilde{\tau}^{\mp}$ and $\tilde{H}^{\pm} \to \tau^{\pm}\tilde{\nu}, \nu\tilde{\tau}^{\pm}$
- Internal resonances!
  - LQD321: $\tau^{\pm}\tau^{\pm}\{jj\}\{jj\}$ / $\tau^{\pm}\nu\{jj\}\{jj\}$
  - LQD323: $\tau^{\pm}\tau^{\pm}\{jb\}\{jb\}$ / $\tau^{\pm}\nu\{jb\}\{jb\}$
  - LQD333: $\tau^{\pm}\tau^{\pm}\{tb\}\{bb\}$ / $\tau^{\pm}\nu\{tb\}\{tb\}$ / $\nu\nu\{tb\}\{tb\}$
  - LQD1ij/LQD2ij: $\tilde{W}/\tilde{B}$ allow $\tau \to e, \mu$
- Also, $\tilde{H}^{\pm}\tilde{H}^0 \to W^{\pm}\tilde{H}^0\tilde{H}^0 \to \ell^{\pm}\nu(jjb)(jjb)$

Conclusion: Searches for paired dijets/trijets in association with τ(s)/ℓ(s)/$\not{E}_T$ could be feasible

Summary

Many heavy flavor opportunities to expand search strategies!

These are gaps in the LHC program – not just in RPV coverage!

SUSY or other new physics could be sitting in these channels!

- "Natural" GMSB: $b\bar{b}\tau^+\tau^- + \not{E}_T$
- OS $\tau + n$ jets
- High b-multiplicity, no $\not{E}_T$
- $\ell\ell\tau_h\tau_h$ searches (8 TeV)
- SS τ
- Internal resonances