

Dynamical R-parity Violation

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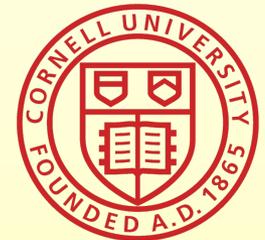
with

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CERN Theory Institute on Neutral Naturalness
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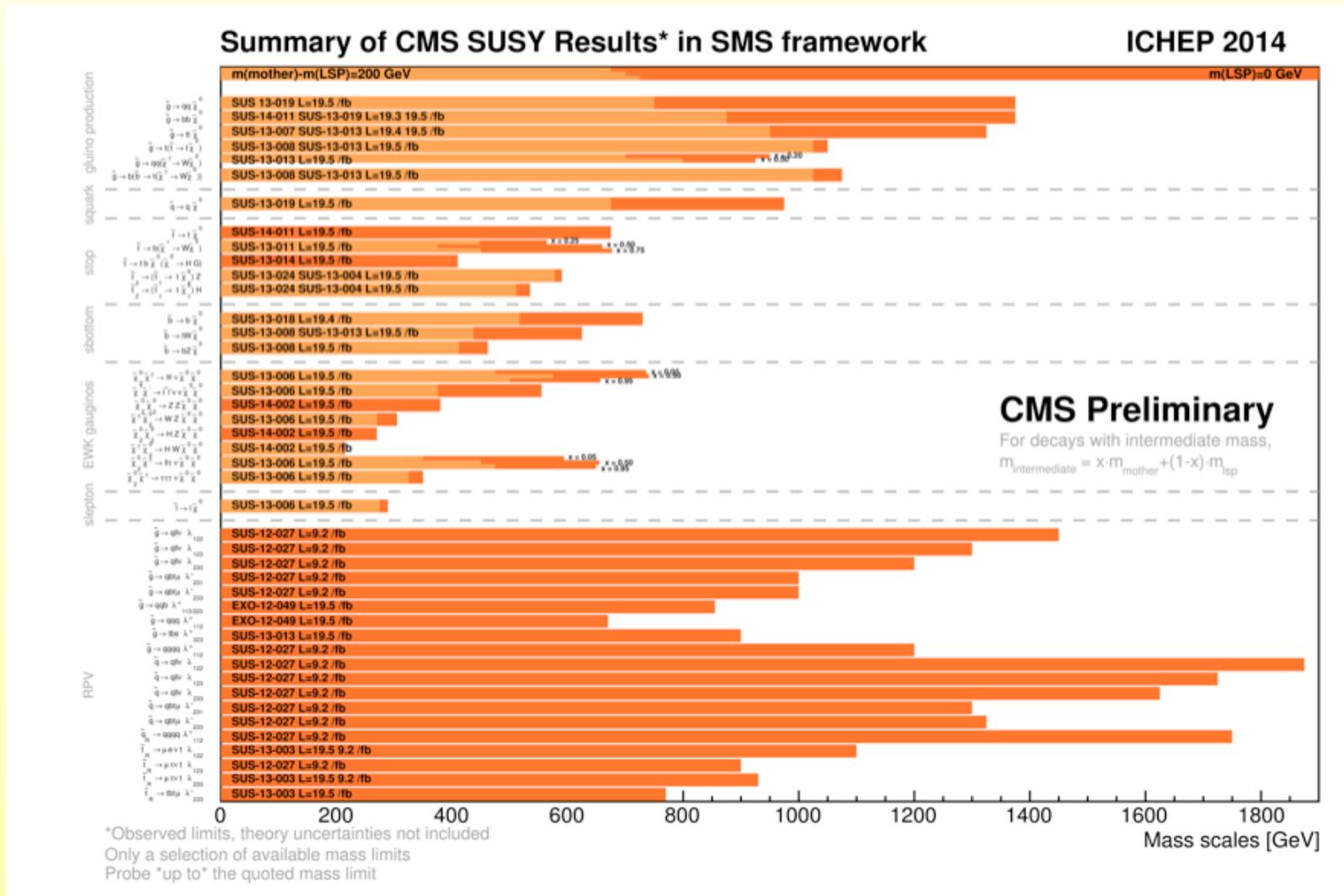
No sign of superpartners as of today from LHC

ATLAS SUSY Searches* - 95% CL Lower Limits						ATLAS Preliminary				
Status: Feb 2015						$\sqrt{s} = 7, 8 \text{ TeV}$				
Model	e, μ, τ, γ	Jets	E_T^{miss} [TeV]	Mass limit	Reference					
Inclusive Searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	\tilde{g}, \tilde{g}	1.7 TeV	$m(\tilde{g})=m(\tilde{g})$	1405.7875	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}\tilde{g}$	0	2-6 jets	Yes	20.3	\tilde{g}	850 GeV	$m(\tilde{g})=0 \text{ GeV}, m(1^{\text{st}} \text{ gen. } \tilde{q})=m(2^{\text{nd}} \text{ gen. } \tilde{q})$	1405.7875	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}\tilde{g}$ (compressed)	1 γ	0-1 jet	Yes	20.3	\tilde{g}	250 GeV	$m(\tilde{g})=m(\tilde{g})=m(\tilde{q})$	1411.1559	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}\tilde{g}$	0	2-6 jets	Yes	20.3	\tilde{g}	1.33 TeV	$m(\tilde{g})=0 \text{ GeV}$	1405.7875	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}\tilde{g}$	1 e, μ	3-6 jets	Yes	20	\tilde{g}	1.2 TeV	$m(\tilde{g})=300 \text{ GeV}, m(\tilde{g})=0.5(m(\tilde{g})+m(\tilde{g}))$	1501.03555	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}\tilde{g}$	2 e, μ	0-3 jets	-	20	\tilde{g}	1.32 TeV	$m(\tilde{g})=0 \text{ GeV}$	1501.03555	
	GMSB (\tilde{g} NLSP)	1-2 $\tau + 0-1 \ell$	0-2 jets	Yes	20.3	\tilde{g}	1.6 TeV	$\tan\beta > 20$	1407.0603	
	GGM (bino NLSP)	2 γ	-	Yes	20.3	\tilde{g}	1.28 TeV	$m(\tilde{g}) > 50 \text{ GeV}$	ATLAS-CONF-2014-001	
	GGM (wino NLSP)	1 $e, \mu + \gamma$	-	Yes	4.8	\tilde{g}	619 GeV	$m(\tilde{g}) > 50 \text{ GeV}$	ATLAS-CONF-2012-144	
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	4.8	\tilde{g}	900 GeV	$m(\tilde{g}) > 220 \text{ GeV}$	1211.1167	
3 rd gen. & med.	GGM (higgsino NLSP)	2 e, μ (Z)	0-3 jets	Yes	5.8	\tilde{g}	690 GeV	$m(\text{NLSP}) > 200 \text{ GeV}$	ATLAS-CONF-2012-152	
	Gravitino LSP	0	mono-jet	Yes	20.3	$\tilde{g}^{1/2}$ scale	865 GeV	$m(\tilde{G}) > 1.8 \times 10^{-4} \text{ eV}, m(\tilde{g})=m(\tilde{g})=1.5 \text{ TeV}$	1502.01518	
	$\tilde{g} \rightarrow b\bar{b}\tilde{g}$	0	3 b	Yes	20.1	\tilde{g}	1.25 TeV	$m(\tilde{g}) < 400 \text{ GeV}$	1407.0600	
	$\tilde{g} \rightarrow t\bar{t}\tilde{g}$	0	7-10 jets	Yes	20.3	\tilde{g}	1.1 TeV	$m(\tilde{g}) < 350 \text{ GeV}$	1308.1841	
	$\tilde{g} \rightarrow t\bar{t}\tilde{g}$	0-1 e, μ	3 b	Yes	20.1	\tilde{g}	1.34 TeV	$m(\tilde{g}) < 400 \text{ GeV}$	1407.0600	
	$\tilde{g} \rightarrow b\bar{b}\tilde{g}$	0-1 e, μ	3 b	Yes	20.1	\tilde{g}	1.3 TeV	$m(\tilde{g}) < 300 \text{ GeV}$	1407.0600	
	3 rd gen. squarks direct production	$\tilde{d}_1\tilde{d}_1, \tilde{d}_1 \rightarrow b\bar{b}\tilde{g}$	0	2 b	Yes	20.1	\tilde{d}_1	100-620 GeV	$m(\tilde{d}_1) < 90 \text{ GeV}$	1308.2631
		$\tilde{d}_1\tilde{d}_1, \tilde{d}_1 \rightarrow t\bar{t}\tilde{g}$	2 e, μ (SS)	0-3 b	Yes	20.3	\tilde{d}_1	275-440 GeV	$m(\tilde{d}_1) > 2 m(\tilde{g})$	1404.2500
		$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow b\bar{b}\tilde{g}$	1-2 e, μ	1-2 b	Yes	4.7	\tilde{t}_1	110-167 GeV	$m(\tilde{t}_1) = 2m(\tilde{g}), m(\tilde{t}_1) > 55 \text{ GeV}$	1209.2102, 1407.0583
		$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow W\bar{b}\tilde{g}$ or $t\bar{t}\tilde{g}$	2 e, μ	0-2 jets	Yes	20.3	\tilde{t}_1	90-191 GeV	$m(\tilde{t}_1) > 1 \text{ GeV}$	1403.4853, 1412.4742
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow t\bar{t}\tilde{g}$		1-2 e, μ	1-2 b	Yes	20	\tilde{t}_1	210-640 GeV	$m(\tilde{t}_1) > 1 \text{ GeV}$	1407.0583, 1406.1122	
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow c\bar{c}\tilde{g}$		0	mono-jet/ ℓ -tag	Yes	20.3	\tilde{t}_1	90-240 GeV	$m(\tilde{t}_1) + m(\tilde{g}) < 85 \text{ GeV}$	1407.0608	
$\tilde{t}_1\tilde{t}_1$ (natural GMSB)		2 e, μ (Z)	1 b	Yes	20.3	\tilde{t}_1	150-580 GeV	$m(\tilde{t}_1) > 150 \text{ GeV}$	1403.5222	
$\tilde{t}_2\tilde{t}_2, \tilde{t}_2 \rightarrow t\bar{t}\tilde{g}$		3 e, μ (Z)	1 b	Yes	20.3	\tilde{t}_2	290-600 GeV	$m(\tilde{t}_2) < 200 \text{ GeV}$	1403.5222	
EW direct		$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow t\bar{t}\tilde{g}$	2 e, μ	0	Yes	20.3	\tilde{t}_1	90-325 GeV	$m(\tilde{t}_1) < 0 \text{ GeV}$	1403.5294
		$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow \tau\bar{\tau}\tilde{g}$	2 e, μ	0	Yes	20.3	\tilde{t}_1	140-465 GeV	$m(\tilde{t}_1) > 0 \text{ GeV}, m(\tilde{t}_1, \tilde{t}_2) = 0.5(m(\tilde{t}_1) + m(\tilde{t}_2))$	1403.5294
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow \tau\bar{\nu}\tilde{g}$	2 τ	-	Yes	20.3	\tilde{t}_1	100-350 GeV	$m(\tilde{t}_1) > 0 \text{ GeV}, m(\tilde{t}_1, \tilde{t}_2) = 0.5(m(\tilde{t}_1) + m(\tilde{t}_2))$	1407.0350	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow \ell\bar{\nu}_\ell\tilde{g}$ ($\ell = \tau, \nu_\tau$)	3 e, μ	0	Yes	20.3	\tilde{t}_1	700 GeV	$m(\tilde{t}_1) = m(\tilde{t}_2), m(\tilde{t}_1) > 0, m(\tilde{t}_1, \tilde{t}_2) = 0.5(m(\tilde{t}_1) + m(\tilde{t}_2))$	1402.7029	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow W\bar{Z}\tilde{g}$	2-3 e, μ	0-2 jets	Yes	20.3	\tilde{t}_1	420 GeV	$m(\tilde{t}_1) = m(\tilde{t}_2), m(\tilde{t}_1) = 0$, sleptons decoupled	1403.5294, 1402.7029	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow W\bar{Z}\tilde{g}$	e, μ, γ	0-2 b	Yes	20.3	\tilde{t}_1	250 GeV	$m(\tilde{t}_1) = m(\tilde{t}_2), m(\tilde{t}_1) = 0$, sleptons decoupled	1501.07110	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow \ell\bar{\nu}_\ell\tilde{g}$	4 e, μ	0	Yes	20.3	\tilde{t}_1	620 GeV	$m(\tilde{t}_1) = m(\tilde{t}_2), m(\tilde{t}_1) = 0, m(\tilde{t}_1, \tilde{t}_2) = 0.5(m(\tilde{t}_1) + m(\tilde{t}_2))$	1405.5086	
	Long-lived particles	Direct $\tilde{t}_1\tilde{t}_1$ prod., long-lived \tilde{t}_1	Disapp. trk	1 jet	Yes	20.3	\tilde{t}_1	270 GeV	$m(\tilde{t}_1) = m(\tilde{t}_2) = 160 \text{ MeV}, \tau(\tilde{t}_1) = 0.2 \text{ ns}$	1310.3675
		Stable, stopped \tilde{g} R-hadron	0	1-5 jets	Yes	27.9	\tilde{g}	832 GeV	$m(\tilde{g}) = 100 \text{ GeV}, 10 \mu\text{s} < \tau(\tilde{g}) < 1000 \text{ s}$	1310.6584
		Stable \tilde{g} R-hadron	trk	-	-	-	\tilde{g}	1.27 TeV	-	1411.6795
GMSB, stable $\tilde{t}_1, \tilde{t}_1 \rightarrow \tau(\bar{\nu}, \mu) + \tau(e, \mu)$		1-2 μ	-	-	19.1	\tilde{t}_1	537 GeV	$10 < \tan\beta < 50$	1411.6795	
GMSB, $\tilde{t}_1 \rightarrow \gamma\tilde{G}$, long-lived \tilde{t}_1		2 γ	-	Yes	20.3	\tilde{t}_1	435 GeV	$2 < \tau(\tilde{t}_1) < 3 \text{ ns}$, SPS8 model	1409.5542	
RPV	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}\tilde{g}$ (RPV)	1 μ , displ. vtx	-	-	20.3	\tilde{g}	1.0 TeV	$1.5 < \tau < 156 \text{ ns}$, BR(μ)=1, $m(\tilde{g})=108 \text{ GeV}$	ATLAS-CONF-2013-092	
	LFV $pp \rightarrow \tilde{\nu}_\tau + X, \tilde{\nu}_\tau \rightarrow e + \mu$	2 e, μ	-	-	4.6	$\tilde{\nu}_\tau$	1.61 TeV	$X_{111} = 0.10, X_{112} = 0.05$	1212.1272	
	LFV $pp \rightarrow \tilde{\nu}_\tau + X, \tilde{\nu}_\tau \rightarrow e\mu + \tau$	1 $e, \mu + \tau$	-	-	4.6	$\tilde{\nu}_\tau$	1.1 TeV	$X_{111} = 0.10, X_{112} = 0.05$	1212.1272	
	Bilinear RPV CMSSM	2 e, μ (SS)	0-3 b	Yes	20.3	\tilde{g}	1.35 TeV	$m(\tilde{g}) = m(\tilde{g}), \epsilon_{7,2,3} < 1 \text{ mm}$	1404.2500	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow W\bar{Z}\tilde{g}, \tilde{t}_1 \rightarrow e\bar{\nu}_e, g\mu\tilde{\nu}_\tau$	4 e, μ	-	Yes	20.3	\tilde{t}_1	750 GeV	$m(\tilde{t}_1) > 0.2 \times m(\tilde{t}_2), A_{212} \neq 0$	1405.5086	
Other	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow W\bar{Z}\tilde{g}, \tilde{t}_1 \rightarrow \tau\bar{\nu}_\tau, e\tau\tilde{\nu}_\tau$	3 $e, \mu + \tau$	-	Yes	20.3	\tilde{t}_1	450 GeV	$m(\tilde{t}_1) > 0.2 \times m(\tilde{t}_2), A_{133} \neq 0$	1405.5086	
	$\tilde{g} \rightarrow q\bar{q}\tilde{g}$	0	6-7 jets	Yes	20.3	\tilde{g}	916 GeV	BR(\tilde{g})=BR(\tilde{g})=BR(\tilde{g})=0%	ATLAS-CONF-2013-091	
	$\tilde{g} \rightarrow t\bar{t}\tilde{g}, \tilde{t}_1 \rightarrow b\bar{s}$	2 e, μ (SS)	0-3 b	Yes	20.3	\tilde{g}	850 GeV	-	1404.250	

*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

ATLAS SUSY bounds from Feb. 2015
 Most involve missing ET, stable charged particle, or LFV

No sign of superpartners as of today from LHC



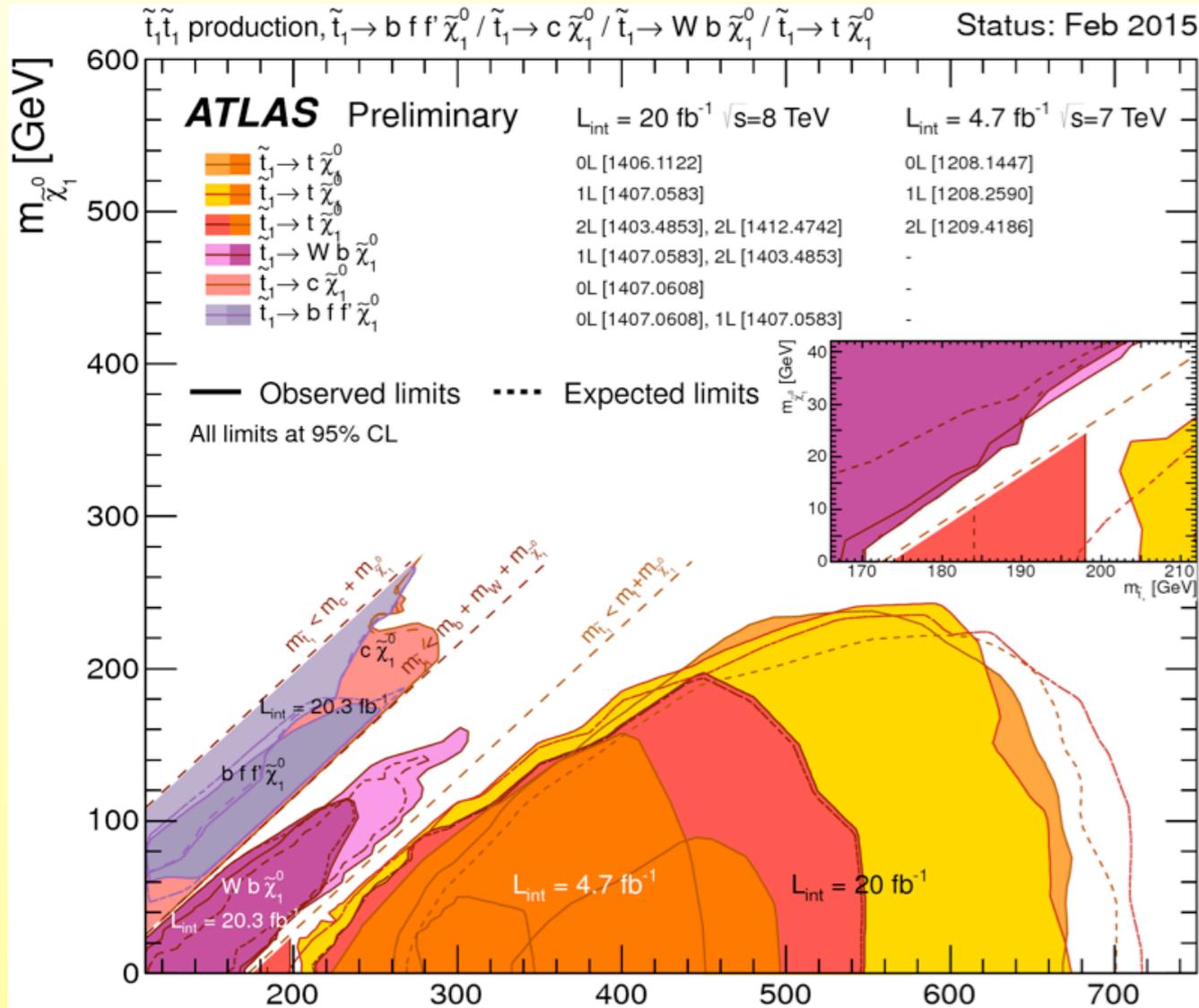
CMS SUSY bounds from summer 2014 ICHEP
Most involve missing ET, stable charged particle, or LFV

- Bounds usually assume **large MET**, and/or **leptons**
- Bounds often assume almost **degenerate** squarks/gluino

Ways out

1. No SUSY - neutral naturalness? - focus of meeting
2. No MET due to **RPV** - focus of this talk
3. Spectrum not that degenerate - ``**Natural SUSY**''
bounds are starting to creep up
4. Spectrum more **degenerate/decays stealthy**
5. Production more suppressed than in MSSM, R- sym.
SUSY with **Dirac gaugino** masses (little gain)

- Stop bounds are approaching 700 GeV



RPV in SUSY

- **Exact** R-parity conservation is **not mandatory**
- If R-parity is broken, **breaking** must be **small**
- **Why** would **RPV** **suppressed** compared to RPC?
- Should be **suppressed** by **flavor** factors (C.C., Grossman, Heidenreich + Berger)
- Could be **broken** in **hidden** sector, and mediated to visible sector via heavy vectorlike field - **all RPV** terms will be **suppressed** (C.C., Kuflik, Slone, Volansky)
- Dynamical R-parity violation (**dRPV**) - focus here

dRPV

- Since RPV terms small and suppressed, **not clear which ones will be leading operators**
- **Holomorphic RPV terms** - usually **assumed to be leading (renormalizable)**

$$W_{\text{RPV}} = \mu_i l_i h_u + \lambda_{ijk} l_i l_j \bar{e}_k + \lambda'_{ijk} l_i q_j \bar{d}_k + \lambda''_{ijk} \bar{u}_i \bar{d}_j \bar{d}_k$$

- **Non-holomorphic RPV (non-renormalizable)**

$$\mathcal{O}_{\text{nhRPV}} = \eta_{ijk} \bar{u}_i \bar{e}_j \bar{d}_k^* + \eta'_{ijk} q_i \bar{u}_j l_k^* + \eta''_{ijk} q_i q_j \bar{d}_k^* + \kappa_i \bar{e}_i H_d H_u^\dagger$$

$$\mathcal{O}_{\text{nhBL}} = \kappa'_i L_i^\dagger H_d$$

- In **dRPV** all non-renormalizable - **either could lead**

Holomorphics or non-holomorphic?

- Assumption: RP broken in hidden sector via field S
- Use S as spurion in low-energy effective theory
- Charges of MSSM: standard $U(1)_{B-L}$
 $U(1)_R$ with q,u,d,l,e charges 1/2, Higgses charge 1
- Charges of RPV operators

	$U(1)_{B-L}$	$U(1)_R$
\mathcal{O}_{nhRPV} :	1	1/2
\mathcal{O}_{hRPV} :	-1	3/2
- Charge of S will determine which terms are leading.

Holomorphics or non-holomorphic?

- For example if charge of S is 1, 1/2 under B-L, R

$$\frac{S^*}{M^2} \mathcal{O}_{nhRPV} \quad \text{and} \quad \frac{S}{M} \mathcal{O}_{hRPV} \quad \text{allowed}$$

- Holomorphic will dominate

- If charge of S is -1, -1/2 under B-L, R

$$\text{only } \frac{S}{M^2} \mathcal{O}_{nhRPV} \quad \text{allowed}$$

- Non-holomorphic will dominate

	$U(1)_{B-L}$	$U(1)_R$
\mathcal{O}_{nhRPV} :	1	1/2
\mathcal{O}_{hRPV} :	-1	3/2

Effect of non-holomorphic dRPV operators

- Chirally suppressed or suppressed by SUSY breaking

$$- \int d^4\theta \frac{S^*}{|M|^2} qq\bar{d}^* = \int d^2\theta \frac{qq}{|M|^2} \frac{1}{4} \mathcal{D}^{\dagger 2} (S^* \bar{d}^*) \xrightarrow{EOM} \int d^2\theta \left[\frac{\langle S \rangle^*}{|M|^2} qq \frac{\partial W}{\partial \bar{d}} + \frac{\langle F_S \rangle^*}{|M|^2} qq\bar{d}^* \right]$$

- Using $\int d^4\theta V = \int d^2\theta \left(-\frac{1}{4} \mathcal{D}^{\dagger 2} V \right)$ and EOM's for MSSM fields

$$\frac{1}{4} \mathcal{D}^2 \Phi = \frac{\delta W^*}{\delta \Phi^*}$$

- Suggests in limit of no MSSM Yukawas or SUSY breaking no RPV. Kähler term:

$$K = |\bar{d}|^2 + |q|^2 + \frac{S^*}{|M|^2} qq\bar{d}^* + h.c.$$

Effect of non-holomorphic dRPV operators

- Field redefinition $\bar{d} \rightarrow \bar{d} - \langle S^* \rangle qq / |M|^2$.

- Kahler potential becomes

$$K = |\bar{d}|^2 + |q|^2 + \left(\frac{S^* - \langle S^* \rangle}{|M|^2} qq \bar{d}^* + h.c. \right) + \left| \frac{\langle S \rangle}{M^2} \right|^2 |q|^4$$

- If no $h_d q d$ and no SUSY breaking **no RPV**

- RPV must be proportional to **fermion masses** (chirally suppressed) or **SUSY breaking**

- Also **suppressed** by **M** scale (see later)

Proton decay

- Assume non-holomorphic operators dominate

$$K_{\mathcal{B},\mathcal{L}} = \frac{\lambda_{ijmn}^{\mathcal{B},\mathcal{L}}}{2M^2} q_i q_j \bar{u}_m^* \bar{e}_n^* + \frac{\langle S^* \rangle}{M^2} \left(\eta_{ijk} \bar{u}_i \bar{e}_j \bar{d}_k^* + \eta'_{ijk} q_i \bar{u}_j \ell_k^* + \frac{1}{2} \eta''_{ijk} q_i q_j \bar{d}_k^* \right) + h.c.$$

- Effective Lagrangian for B, L violation:

$$\begin{aligned} \mathcal{L}_{\mathcal{B},\mathcal{L}} = & \left[\frac{|\langle S \rangle|^2}{2M^4} \frac{1}{m_{\tilde{d}_{L,k}}^2} \left(m_j^d (\eta''_{ikj} + \eta''_{kij}) + m_k^d (\eta''_{ijk} + \eta''_{jik}) \right) (m_k^d \eta_{mnk}^* + m_n^e \eta_{kmn}^*) \right. \\ & \left. + \frac{|\langle S \rangle|^2}{2M^4} \frac{1}{m_{\tilde{d}_{R,i}}^2} (\eta''_{ijk} \bar{\theta}^2 + \eta''_{jik} \bar{\theta}^2) \eta_{mnk} \bar{\theta}^{2*} + \frac{1}{2M^2} (\lambda_{ijmn}^{\mathcal{B},\mathcal{L}} + \lambda_{jimn}^{\mathcal{B},\mathcal{L}}) \right] u_L^i d_L^j u_R^m e_R^n + h.c. \end{aligned}$$

$$\equiv \tilde{\Lambda}_{ijmn}^{-2} u_L^i d_L^j u_R^m e_R^n + h.c.$$

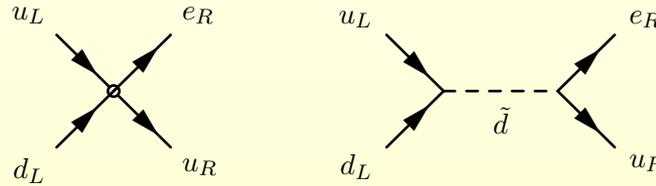
$$\eta \equiv \eta^0 (1 + M \epsilon_X \bar{\theta}^2)$$

$$\epsilon_X \sim g^2 16\pi^2 \frac{m_0}{M}$$

- 4-Fermi operator, coefficients determined by SUSY breaking, RPV, fermion masses etc.

Proton decay

- Proton decay diagrams



- If chirally suppressed terms dominate

$$\tau_p \simeq 10^{32} \text{yr} \left(\frac{7 \times 10^{-8}}{|\eta''_{ij3} \eta^*_{mn3}|} \right)^2 \left(\frac{m_{\tilde{b}_L}}{\text{TeV}} \right)^4 \left(\frac{M}{10^8 \text{GeV}} \right)^4 \left(\frac{0.1}{\langle S \rangle / M} \right)^4$$

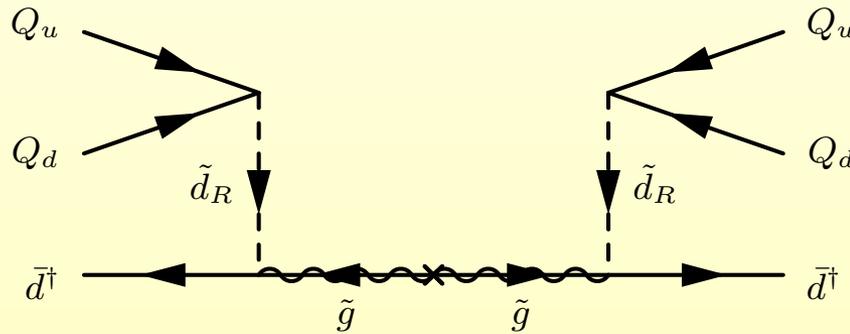
- If SUSY breaking terms dominate:

$$\tau_p \simeq 10^{32} \text{yr} \left(\frac{10^{-8}}{|\eta''_{ijk} \eta^*_{mnk}|} \right)^2 \left(\frac{m_{\tilde{d}_{L,k}}}{\text{TeV}} \right)^4 \left(\frac{10^{-7}}{\epsilon_X} \right)^4 \left(\frac{0.1}{\langle S \rangle / M} \right)^4$$

- Where $\epsilon_X \sim \frac{F_X}{M^2}$ for direct coupling of SUSY br.

Low-energy constraints: $\Delta B=2$

- **n-nbar** oscillation and **dinucleon** decay (only looked at SUSY breaking contribution)



$$\frac{1}{\Lambda_{ijk}^5} (Q_i Q_i Q_j Q_j \bar{d}_k^\dagger \bar{d}_k^\dagger)$$

- **Dim 9** operator generated

- **Suppression scale:**
$$\frac{1}{\Lambda_{ijk}^5} = \pi \alpha_s \frac{\eta''_{iik} \eta''_{jjk}}{m_{\tilde{g}} m_{\tilde{d},R,k}^4} \epsilon_X^2$$

Low-energy constraints: $\Delta B=2$

- **n-nbar oscillation bound:**

$$\tau_{n-\bar{n}} \simeq \frac{\Lambda_{111}^5}{2\pi \tilde{\Lambda}_{QCD}^6}$$

$$\tau_{n-\bar{n}} \simeq 3 \times 10^8 \text{ s} \left(\frac{m_{\tilde{d}_{R1}}}{\text{TeV}} \right)^4 \left(\frac{m_{\tilde{g}}}{\text{TeV}} \right) \left(\frac{4 \times 10^{-2}}{\eta''_{111}} \right)^2 \left(\frac{10^{-5}}{\epsilon_X} \right)^2$$

- **Dinucleon decay ($\tau > 10^{32}$ yr):**

$$pp \rightarrow \pi^+ \pi^+ (K^+ K^+)$$

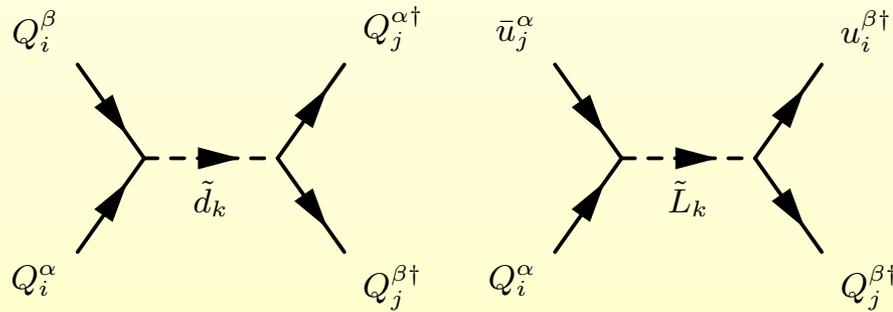
$$\Gamma \simeq \frac{8}{\pi} \frac{\rho_N}{m_N^2} \frac{\tilde{\Lambda}_{QCD}^{10}}{\Lambda_{pp}^{10}}$$

$$\Lambda_{pp} \equiv \min\{\Lambda_{11k}, \Lambda_{1k1}\}$$

$$\tau_{pp} \simeq 5 \times 10^{32} \text{ yr} \left(\frac{m_{\tilde{d}_{R,k}}^8 m_{\tilde{g}}^2}{\text{TeV}^{10}} \right) \left(\frac{10^{-1}}{\eta''_{pp}} \right)^4 \left(\frac{10^{-5}}{\epsilon_X} \right)^4$$

Low-energy constraints: $\Delta F=2$

- FCNC's generated at tree-level:



- Operators generated:

$$Q_1^{q_i q_j} \equiv -\frac{1}{2} (Q_i^\alpha Q_i^\beta) (Q_j^{\alpha\dagger} Q_j^{\beta\dagger})$$

$$Q_4^{q_i q_j} \equiv \bar{u}_j^\alpha Q_i^\alpha Q_j^{\beta\dagger} \bar{u}_i^{\beta\dagger}$$

- Suppression scales:

$$\frac{1}{\Lambda_{1,ij}^2} = \frac{\eta''_{ik} \eta''_{jk}^*}{m_{\tilde{d}_{R,k}}^2} \epsilon_X^2, \quad \frac{1}{\Lambda_{4,ij}^2} = \frac{|\eta'_{ijk}|^2}{m_{\tilde{\nu}_{L,k}}^2} \epsilon_X^2$$

Low-energy constraints: $\Delta F=2$

- **Bounds** from neutral meson mixings:

$$\begin{aligned}\Delta m_K & : |\eta''_{11k} \eta''_{22k} \epsilon_X^2| \lesssim 10^{-10}, \\ \Delta m_D & : |\eta''_{11k} \eta''_{22k} \epsilon_X^2| \lesssim 10^{-8}, \quad |\eta'_{12k} \epsilon_X|^2 \lesssim 10^{-9} \\ \Delta m_{B_d} & : |\eta''_{11k} \eta''_{33k} \epsilon_X^2| \lesssim 10^{-7}, \\ \Delta m_{B_s} & : |\eta''_{23k} \eta''_{33k} \epsilon_X^2| \lesssim 10^{-7}.\end{aligned}$$

- If $\epsilon_X \sim \mathcal{O}(10^{-5})$ **no additional** flavor suppression needed to satisfy FCNC bounds!

dRPV from integrating out heavy fields

- Integrate out heavy messengers of RPV

$$W = MD\bar{D} + SD\bar{d} + \lambda qqD$$

- S responsible for RPV, D heavy vectorlike quark
- Integrating out D effective Kahler potential

$$K_{eff} = |q|^2 + |\bar{d}|^2 + \frac{1}{|M|^2} |S\bar{d} + \lambda qq|^2 + \mathcal{O}\left(\frac{1}{M^4}\right)$$

- Contains dRPV terms

$$K_{dRPV} = \frac{\lambda S^*}{|M|^2} qq\bar{d}^* + h.c.$$

dRPV from integrating out heavy fields

- Origin of this term: small unusual mixing

$$D \sim -\frac{1}{4} \frac{\langle S \rangle^*}{|M|^2} \mathcal{D}^{\dagger 2} \bar{d}^*$$

- From sub-leading term in EOM $MD = -\frac{1}{4} \mathcal{D}_\alpha^{\dagger 2} \bar{D}^*$
together with D EOM $\bar{D} = -\frac{S}{M} \bar{d}$ gives above mixing

- This way we see the dRPV term

$$\int d^2\theta \lambda qq D \longrightarrow \int d^2\theta \lambda qq \left(-\frac{\langle S \rangle^*}{4|M|^2} \mathcal{D}^{\dagger 2} \bar{d}^* \right) = \int d^4\theta \frac{\lambda \langle S \rangle^*}{|M|^2} qq \bar{d}^*$$

- Nice instructive toy model, but not hidden sector

dRPV from hidden sector

- Previous toy model also allows holomorphic RPV

$$W = MD\bar{D} + SD\bar{d} + \lambda qqD$$

- Can also add $\bar{u}\bar{d}\bar{D}$

- Will give you $W_{eff} = -\frac{S}{M}\bar{u}\bar{d}\bar{d}$ leading RPV

- Also follows from spurion counting: charges of S

- U(1) B-L: +1, U(1) R: 1/2, exactly the choice that allows hRPV.

- Also S couples directly to visible sector

dRPV from hidden sector

- Two sets of messengers with opposite R-parity

$$W = M(D_+ \bar{D}_+ + D_- \bar{D}_-) + S \bar{D}_+ D_- + m D_- \bar{d} + qq D_+$$

- Low energy Kähler term generated:

$$\frac{\langle S \rangle m^*}{|M|^2 M} qq \bar{d}^* + h.c.$$

- Allowed additional term $\bar{u} \bar{d} \bar{D}_+$

- Now does not generate hRPV $W_{eff} = \frac{1}{M} \bar{u} \bar{d} qq$

- Spurion charges U(1) B-L: -1, R: -1/2.

- Leading holomorphic RPV small $\frac{m}{|M|^4} \langle S^* \rangle (\mathcal{D}_\alpha^2 \bar{d}) \bar{u} \bar{d}$

Superpotential dRPV

- Mixing induced by EWSB

$$W = SD\bar{D} + h_d q\bar{D} + qq\bar{D}.$$

- Low-energy effective superpotential:

$$W_{eff} = \frac{1}{S} h_d qq\bar{q}.$$

- Effects similar to that of non-holomorphic $qq\bar{d}^*$ in absence of SUSY breaking

Doubly suppressed dRPV

- Use **doublet** messengers

$$W = MQ\bar{Q} + S\bar{Q}q + \lambda\bar{Q}\bar{Q}\bar{d}.$$

- Will get **mixing** again as before

$$\bar{Q} \sim -\frac{1}{4} \frac{1}{|M|^2} \mathcal{D}^{\dagger 2} S^* \bar{q}^*.$$

- But now need **two insertions** of this mixing

$$K = |\bar{d}|^2 + |q|^2 \left(1 + \frac{|S|^2}{|M|^2} \right) - \frac{1}{4} \frac{\lambda^* S}{|M|^4} (\mathcal{D}^2 S q) q \bar{d}^* + h.c.$$

- Effect is $-\frac{1}{4} \frac{\lambda^* S}{|M|^4} (\mathcal{D}^2 S q) q \bar{d}^* \rightarrow \frac{\lambda^* \langle S \rangle}{|M|^4} \left(\langle F_S \rangle q q \bar{d}^* - \langle S \rangle \frac{\partial W^*}{\partial q^*} q \bar{d}^* \right)$

- **Doubly suppressed** (SUSY br + fermion masses, two sets of fermion masses, or two sets of SUSY br)

Doubly suppressed dRPV

- Last term equivalent to

$$\int d^2\theta \frac{\lambda \langle S^* \rangle^2}{|M|^2} \frac{\langle h_u h_d \rangle}{M^2} y_d y_u \bar{u} d \bar{d}$$

- Like ordinary RPV, but highly suppressed by Yukawas and heavy fermion masses

A complete model

- At least **two sets** of messengers, add **indices...**

$$\begin{aligned}
 W = & M_{D_i} D_i \bar{D}_i + M_{L_i} L_i \bar{L}_i + \lambda_{ij}^d S D_i \bar{d}_j + \lambda_{ij}^\ell S \bar{L}_i \ell_j \\
 & + \gamma_{ijk} \bar{u}_i \bar{e}_j D_k + \gamma'_{ijk} q_i \bar{u}_j \bar{L}_k + \frac{1}{2} \gamma''_{ijk} q_i q_j D_k \\
 & + W_{\text{MSSM}} ,
 \end{aligned}$$

- Low energy **effective theory**:

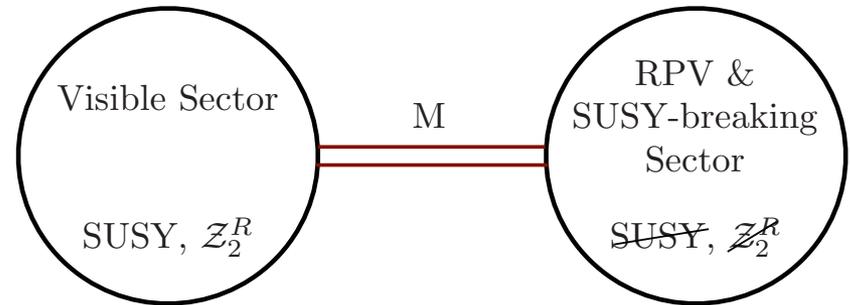
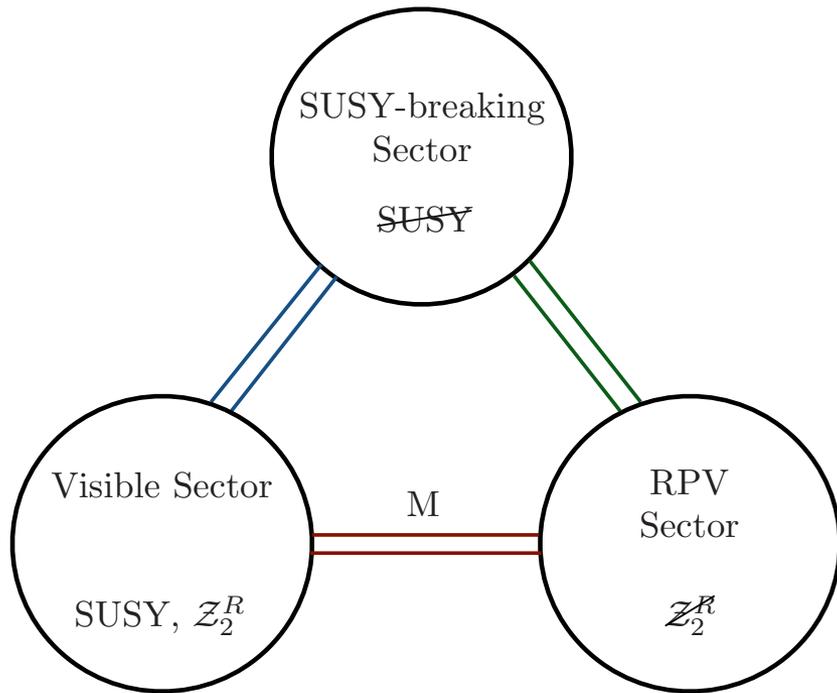
$$W_{\text{eff}} = W_{\text{MSSM}}$$

$$\begin{aligned}
 K_{\text{eff}} = & |q_i|^2 + |\bar{u}_i|^2 + |\bar{e}_i|^2 + \left(\delta_{ij} + \alpha_{ij}^d \frac{|S|^2}{M^2} \right) \bar{d}_j^* \bar{d}_i + \left(\delta_{ij} + \alpha_{ij}^\ell \frac{|S|^2}{M^2} \right) \ell_j^* \ell_i \\
 & + \eta_{ijk} \frac{S^*}{M^2} \bar{u}_i \bar{e}_j \bar{d}_k^* + \eta'_{ijk} \frac{S^*}{M^2} q_i \bar{u}_j \ell_k^* + \frac{1}{2} \eta''_{ijk} \frac{S^*}{M^2} q_i q_j \bar{d}_k^* + h.c. \\
 & + \frac{1}{M^2} \left(\frac{1}{4} \lambda''_{ijmn} q_i q_j q_m^* q_n^* + \lambda'_{ijmn} q_i \bar{u}_j q_m^* \bar{u}_n^* + \lambda_{ijmn} \bar{u}_i \bar{e}_j \bar{u}_m^* \bar{e}_n^* \right. \\
 & \quad \left. + \frac{1}{2} \lambda_{ijmn}^{\mathcal{B}, \mathcal{L}} q_i q_j \bar{u}_m^* \bar{e}_n^* + h.c. \right) + \mathcal{O}(M^{-4}) ,
 \end{aligned}$$

- Get **all non-holomorphic** terms and 4-Fermi **B,L** violating operator

Effect of SUSY breaking

- Could be **external** to RPV sector or have **same** spurion and messengers

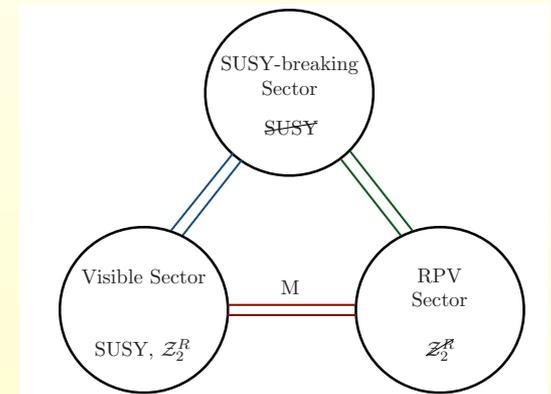


Effect of external SUSY breaking

- SUSY breaking **external**

- SUSY breaking **spurion**

$$X = \langle X \rangle + \theta^2 F_X$$



- Included in **wave function renormalization** of messengers:

$$\int d^4\theta Z_i(X, X^*) \Phi_i \Phi^{i*}$$

- Carrying in through $M \rightarrow M z_D z_{\bar{D}}, \quad S \rightarrow S z_D z_{\bar{d}}, \quad \lambda \rightarrow \lambda z_q^2 z_D .$

$$\Phi_i \rightarrow Z_i^{-1/2} \left(1 - \frac{1}{Z_i} \frac{\partial Z_i}{\partial X} F_X \theta^2 \right) \Phi_i \equiv z_i \Phi_i$$

- **Final effect**

$$K_{dRPV} = \frac{z_{\bar{d}}^*}{z_{\bar{D}}^*} \frac{z_q^2}{z_{\bar{D}}} \frac{\lambda S^*}{|M|^2} q q \bar{d}^* + h.c. .$$

Effect of external SUSY breaking

- Final effect
$$K_{dRPV} = \frac{z_{\bar{d}}^*}{z_{\bar{D}}^*} \frac{z_q^2}{z_{\bar{D}}} \frac{\lambda S^*}{|M|^2} qq\bar{d}^* + h.c..$$

- z's have F-terms

- **Suppression** of dRPV operator from **SUSY** breaking by

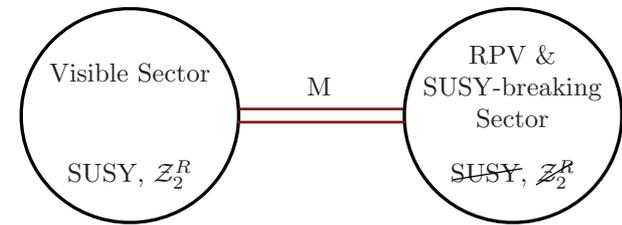
$$\frac{F_{z_i^*}}{M} \sim \frac{\langle X^* \rangle F_X^*}{\Lambda^2 M} \sim \frac{\langle X^* \rangle}{\Lambda} \frac{m_0}{M}$$

- For example for **gauge mediation**
$$\frac{\langle X \rangle}{\Lambda} \sim \frac{\alpha}{4\pi}$$

- Usually much **smaller than** chirally suppressed terms

Unifying SUSY breaking & RPV mediation

- Same messengers mediate SUSY breaking and RPV



- Effect simply obtained by

$$M \rightarrow X = M + \theta^2 F_X$$

- Effective Kähler potential:

$$K_{eff} = |q|^2 + |\bar{d}|^2 + \frac{|S|^2}{|X|^2} |\bar{d}|^2 + \frac{\lambda S^*}{|X|^2} qq\bar{d}^* + h.c. + \dots$$

- Second term what we want, but first term might be problematic, negative mass squares

$$m_{\tilde{\ell}, \tilde{d}}^2 \simeq -\frac{\langle S \rangle^2}{M^2} \frac{F_X^2}{M^2}$$

Unifying SUSY breaking & RPV mediation

- For realistic model need $\langle S \rangle / M \lesssim \alpha_2 / 4\pi \sim 10^{-3}$

- Truly hidden sector models don't have to have negative mass squares

$$W = M_+ D_+ \bar{D}_+ + M_- D_- \bar{D}_- + S \bar{D}_+ D_- + m D_- \bar{d} + qq D_+$$

- Only D_- mixes with SM fields, so if SUSY breaking spurion M_+ or S no problem

$$K_{eff} = |q|^2 + |\bar{d}|^2 + \frac{1}{|M_-|^2} \left(|m|^2 |\bar{d}|^2 + \frac{|S|^2}{|M_+|^2} |q|^4 - \frac{m^* S}{M_+} qq \bar{d}^* + h.c. \right) + \dots$$

- Only F-term for M_- should be avoided!

Flavor and dRPV

- RPV terms also break $U(3)^5$ SM flavor symmetries
- Expect that they have non-trivial flavor structure
- (Flavor on its own might be enough to suppress B, L violation - see MFV SUSY approach)
- Typical proton decay lifetime

$$\tau_p \simeq 10^{32} \text{yr} \left(\frac{7 \times 10^{-8}}{|\eta''_{ij3} \eta^*_{kl3}|} \right)^2 \left(\frac{m_{\tilde{b}_L}}{\text{TeV}} \right)^4 \left(\frac{M}{10^8 \text{GeV}} \right)^4 \left(\frac{0.1}{\langle S \rangle / M} \right)^4$$

- If we suppress by S/M - all RPV very suppressed, LSP will turn out collider stable - like usual SUSY
- Expect flavor dependent suppression significant

Flavor breaking external

- Pick simplest flavor mechanism Froggatt-Nielsen
- Horizontal U(1) symmetries, broken by FN spurion

$$\epsilon \equiv \frac{\langle \phi \rangle}{M_{\text{FN}}}$$

- Expect flavor dependent suppression of dRPV terms

$$\alpha, \eta, \lambda \propto \epsilon^{\mathcal{Q}}$$

- For example assuming heavy fields not charged get

$$\eta_{ijk} \propto \epsilon^{|\mathcal{Q}_{u_i} + \mathcal{Q}_{\bar{e}_j}| + |\mathcal{Q}_{\bar{d}_k}|}, \quad \eta'_{ijk} \propto \epsilon^{|\mathcal{Q}_{q_i} + \mathcal{Q}_{\bar{u}_j}| + |\mathcal{Q}_{\ell_k}|}, \quad \eta''_{ijk} \propto \epsilon^{|\mathcal{Q}_{q_i} + \mathcal{Q}_{q_j}| + |\mathcal{Q}_{\bar{d}_k}|}$$

Flavor breaking external

- A particularly **successful** scenario Leurer, Nir, Seiberg

	q_1	q_2	q_3	\bar{u}_1	\bar{u}_2	\bar{u}_3	\bar{d}_1	\bar{d}_2	\bar{d}_3	L_1	L_2	L_3	\bar{e}_1	\bar{e}_2	\bar{e}_3
$U(1)_1$	-5	-2	0	11	3	0	7	6	2	1	1	0	0	0	0
$U(1)_2$	4	2	0	-4	-1	0	-2	-2	0	1	0	0	1	1	1

- **Two** $U(1)$'s with suprimons $\epsilon_1 \sim \epsilon \sim 0.2, \quad \epsilon_2 \sim \epsilon^2 \sim 0.04$

- **Suppression factors large...**

η	$\bar{u}_1 \bar{e}_1$	$\bar{u}_1 \bar{e}_2$	$\bar{u}_2 \bar{e}_1$	$\bar{u}_2 \bar{e}_2$	η'	$\bar{u}_1 l_1^*$	$\bar{u}_1 l_2^*$	$\bar{u}_2 l_1^*$	$\bar{u}_2 l_2^*$	η''	$q_1 q_1$	$q_1 q_2$	$q_2 q_2$	$q_1 q_3$	$q_2 q_3$	$q_3 q_3$
\bar{d}_1	ϵ^6	ϵ^6	ϵ^8	ϵ^8	q_1	ϵ^7	ϵ^5	ϵ^7	ϵ^9	\bar{d}_1	ϵ^{37}	ϵ^{30}	ϵ^{23}	ϵ^{24}	ϵ^{17}	ϵ^{11}
\bar{d}_2	ϵ^7	ϵ^7	ϵ^7	ϵ^7	q_2	ϵ^{14}	ϵ^{12}	1	ϵ^2	\bar{d}_2	ϵ^{36}	ϵ^{29}	ϵ^{22}	ϵ^{23}	ϵ^{16}	ϵ^{10}
\bar{d}_3	ϵ^{15}	ϵ^{15}	ϵ	ϵ	q_3	ϵ^{20}	ϵ^{18}	ϵ^6	ϵ^4	\bar{d}_3	ϵ^{28}	ϵ^{21}	ϵ^{14}	ϵ^{15}	ϵ^8	ϵ^2

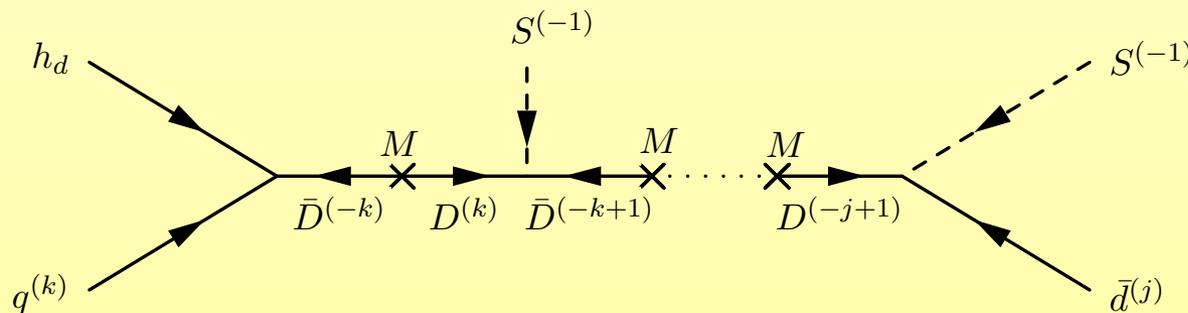
Unifying flavor and RPV mediation

- FN messengers and RPV messengers same
- Can also use same spurion S for breaking RPV, FN

$$W = XD\bar{D} + SDd\bar{d} + \lambda qqD + h_d q\bar{D}$$

- Effective Yukawa (as expected in FN) $\frac{S}{X} h_d q\bar{d}$,

- Now FN suppression $\epsilon \equiv \frac{\langle S \rangle}{X}$



Unifying flavor and RPV mediation

- Best version again hidden sector model

$$W = M(D_+ \bar{D}_+ + D_- \bar{D}_-) + S \bar{D}_+ D_- + m D_- \bar{d} + qq D_+ + h_d q \bar{D}_-$$

- FN messengers D_- , \bar{D}_- , no additional RPV source like X needed

- All RPV terms suppressed by Yukawa factors

$$\eta_{ijk} \propto \epsilon^{|\mathcal{Q}_{u_i} + \mathcal{Q}_{\bar{e}_j} - \mathcal{Q}_{\bar{d}_k}|}, \quad \eta'_{ijk} \propto \epsilon^{|\mathcal{Q}_{q_i} + \mathcal{Q}_{\bar{u}_j} - \mathcal{Q}_{\ell_k}|}, \quad \eta''_{ijk} \propto \epsilon^{|\mathcal{Q}_{q_i} + \mathcal{Q}_{q_j} - \mathcal{Q}_{\bar{d}_k}|}$$

- Slightly different since now messengers carry FN charge

Unifying flavor and RPV mediation

- The **suppression** factors in the Leurer, Nir, Seiberg model now

η	$\bar{u}_1 \bar{e}_1$	$\bar{u}_1 \bar{e}_2$	$\bar{u}_2 \bar{e}_1$	$\bar{u}_2 \bar{e}_2$	η'	$\bar{u}_1 \ell_1^*$	$\bar{u}_1 \ell_2^*$	$\bar{u}_2 \ell_1^*$	$\bar{u}_2 \ell_2^*$	η''	$q_1 q_1$	$q_1 q_2$	$q_2 q_2$	$q_1 q_3$	$q_2 q_3$	$q_3 q_3$
\bar{d}_1	ϵ^{28}	ϵ^{28}	ϵ^{14}	ϵ^{14}	q_1	ϵ^9	ϵ^7	ϵ^{11}	ϵ^9	\bar{d}_1	ϵ^{37}	ϵ^{30}	ϵ^{23}	ϵ^{32}	ϵ^{17}	ϵ^{11}
\bar{d}_2	ϵ^{27}	ϵ^{27}	ϵ^{13}	ϵ^{13}	q_2	ϵ^{16}	ϵ^{14}	ϵ^6	ϵ^4	\bar{d}_2	ϵ^{36}	ϵ^{29}	ϵ^{22}	ϵ^{24}	ϵ^{16}	ϵ^{10}
\bar{d}_3	ϵ^{19}	ϵ^{19}	ϵ^5	ϵ^5	q_3	ϵ^{22}	ϵ^{20}	ϵ^8	ϵ^6	\bar{d}_3	ϵ^{28}	ϵ^{21}	ϵ^{14}	ϵ^{15}	ϵ^8	ϵ^2

Unifying flavor, SUSY and RPV mediation?

- All mediated by **same** messengers
- **Tension**: negative mass square suppression now determined by FN spurion (not too small!)

$$\tilde{m}^2 \simeq (\langle S \rangle / M)^2 F_X^2 / M^2$$

- Ways out: need **additional sfermion** masses either new gauge interactions or more messengers
- **Hidden sector model does not have problem**

$$W = M_+ D_+ \bar{D}_+ + M_- D_- \bar{D}_- + S \bar{D}_+ D_- + \phi D_- \bar{d} + qq D_+ + h_d q \bar{D}_-$$

- S breaks SUSY and RP, ϕ FN spurion, **no negative mass squares**

LHC bounds

- Looked at cases motivated by naturalness
- Light stops, gluinos or higgsinos

LSP	Production	Decay	Operator
\tilde{t}	$pp \rightarrow \tilde{t}\tilde{t}^*$	$\bar{d}\bar{d}'$ $u\bar{\nu}$ $d\ell^+$	λ'', η'' η' λ', η
\tilde{g}	$pp \rightarrow \tilde{g}\tilde{g}$	$t d d' + c.c$ $t \bar{u} \bar{\nu} + c.c$ $t \bar{d} \ell^- + c.c$	λ'', η'' η' λ', η
\tilde{H}	$pp \rightarrow \tilde{g}\tilde{g}$ $\rightarrow (t\bar{t}\tilde{H})(t\bar{t}\tilde{H})$ $pp \rightarrow \tilde{t}\tilde{t}^*$ $\rightarrow (t\tilde{H})(t^*\tilde{H})$	$t d d' + c.c$ $t \bar{u} \bar{\nu} + c.c$ $t \bar{d} \ell^- + c.c$	λ'', η'' η' λ', η

Experimental searches

- **Displaced vertex** searches by ATLAS, CMS

ATLAS DV + μ/e /jets/MET

- 8 TeV, 20 fb⁻¹, DV in inner tracker + (1) muon (2) electron (3) jets (4) MET
- All background **free**

CMS Displaced Dijet

- 8 TeV, 18.6 fb⁻¹, dijets originating from DV. **Not restrictive** to just models with jets. Isolated leptons treated as jets, three jets also have large efficiency to be captured

Experimental searches

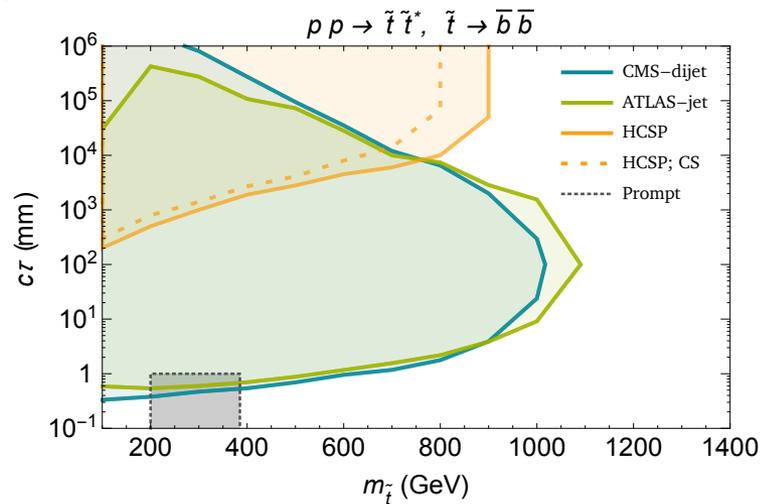
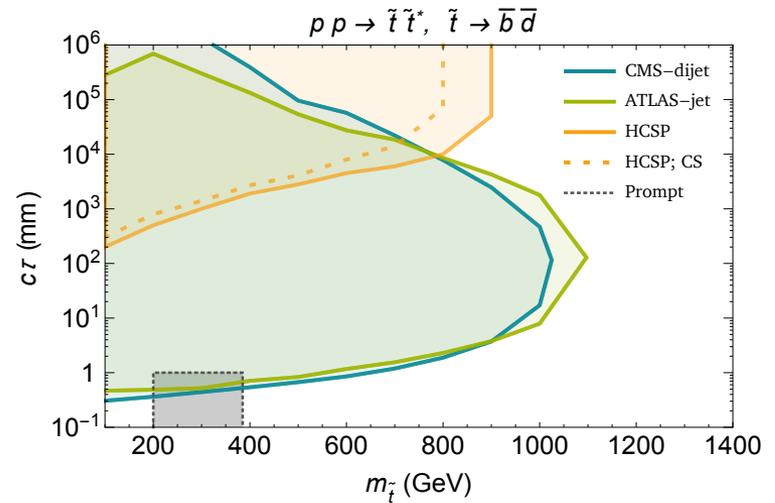
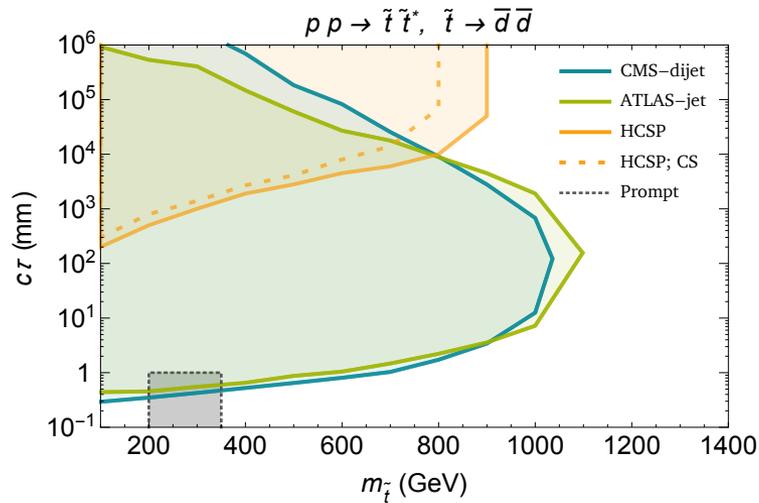
- CMS Heavy Charged Stable Particle (HCSP) search
- 8 TeV, 18.8 fb⁻¹, look for longer **time-of-flight** to muon system or anomalous **energy loss**
- Prompt searches
 - $\tilde{t} \rightarrow dd$ paired dijet resonance searches
 - $\tilde{t} \rightarrow dl^+$ leptoquark searches (Tevatron+LHC)
 - $\tilde{t} \rightarrow t\nu$ stop \rightarrow top + neutralino search
 - $\tilde{g} \rightarrow t\bar{t}\nu$ gluino \rightarrow ttbar neutralino search
 - $\tilde{g} \rightarrow tbb$ gluino \rightarrow tbs search

Results

- **Generated** 10000 events for a grid of LSP masses and lifetimes of 100 GeV, and decay lengths 0.03, 0.1, 0.3, 1, ... mm
- Used Feynrules → Madgraph → Pythia → Delphes3 **pipeline**
- Wherever **efficiency** very **small** generated **additional** events
- Applied all **cuts** and **reconstruction** procedure of all displaced searches, recast HCSP searches at parton level, prompt searches bounds directly applied (no recasting for prompt)

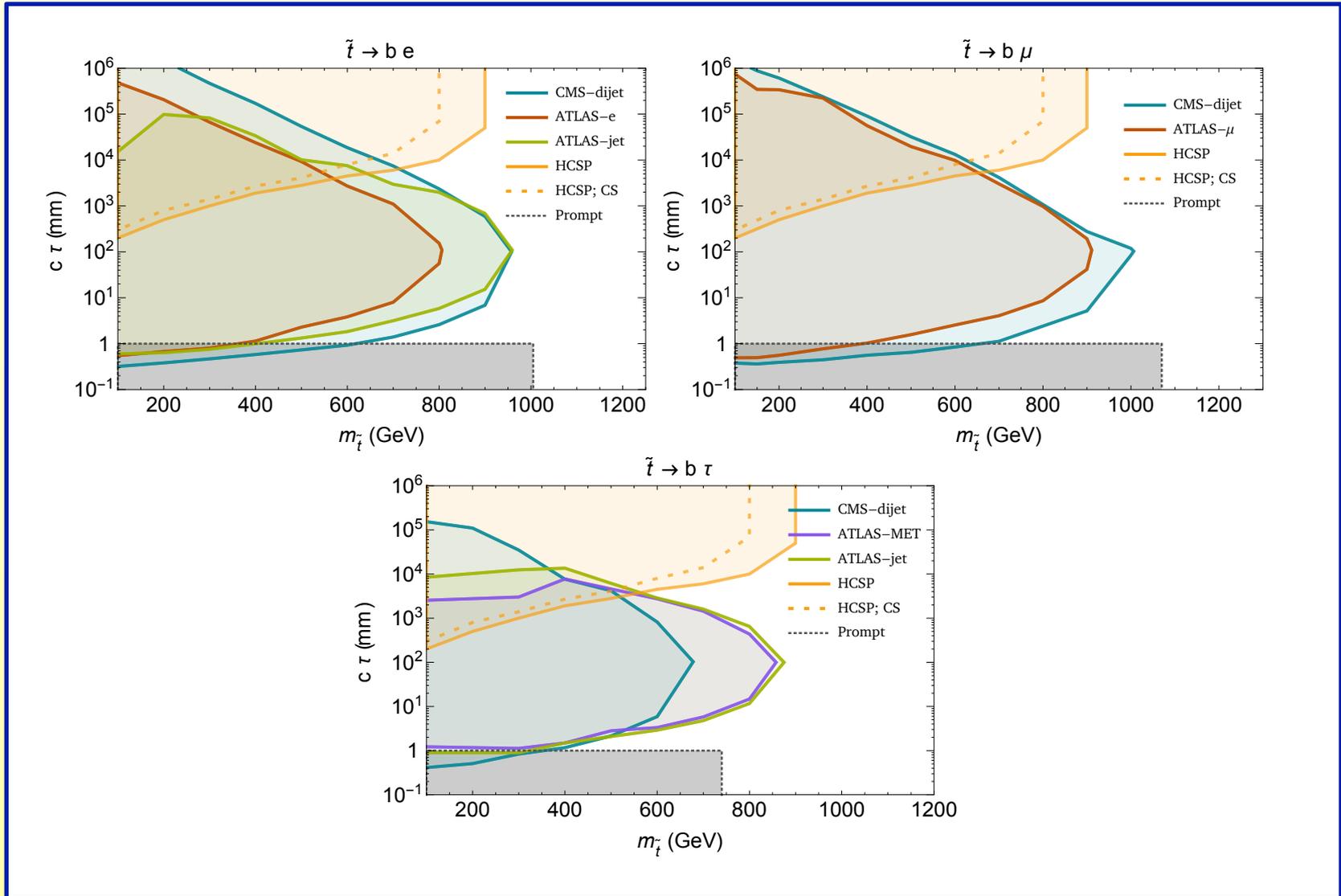
Stop bounds

- Direct **stop** production, $\tilde{t} \rightarrow \bar{d}\bar{d}$ type decay



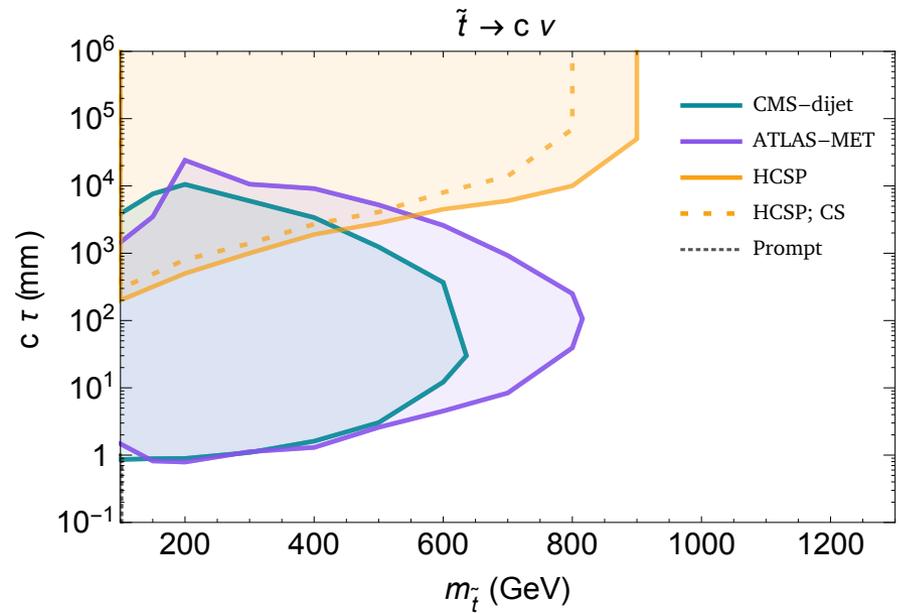
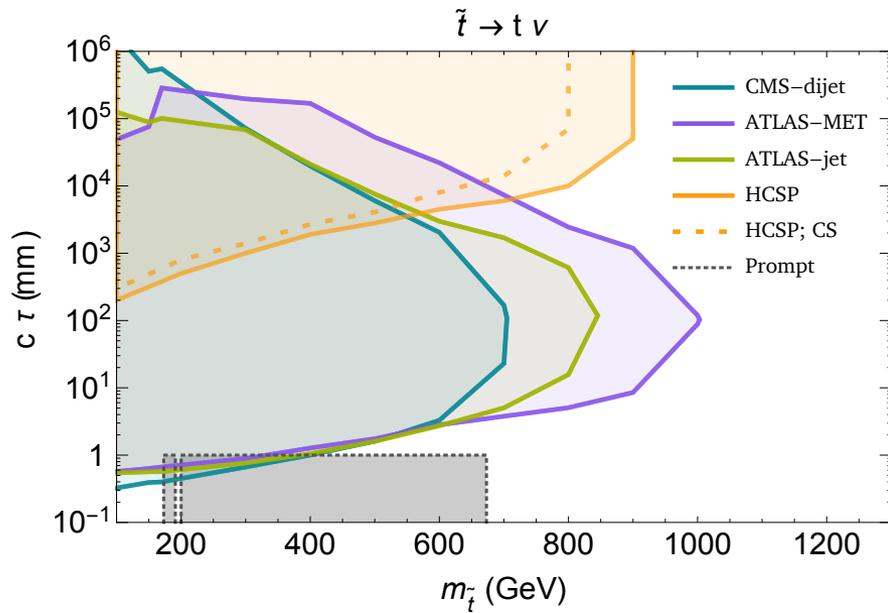
Stop bounds

- Direct **stop** production, $\tilde{t} \rightarrow dl^+$ type decay



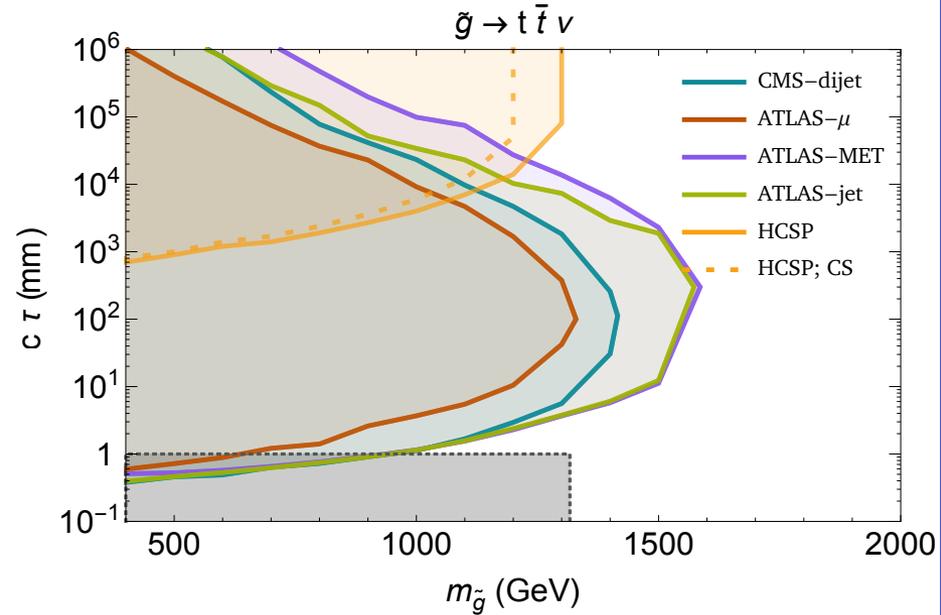
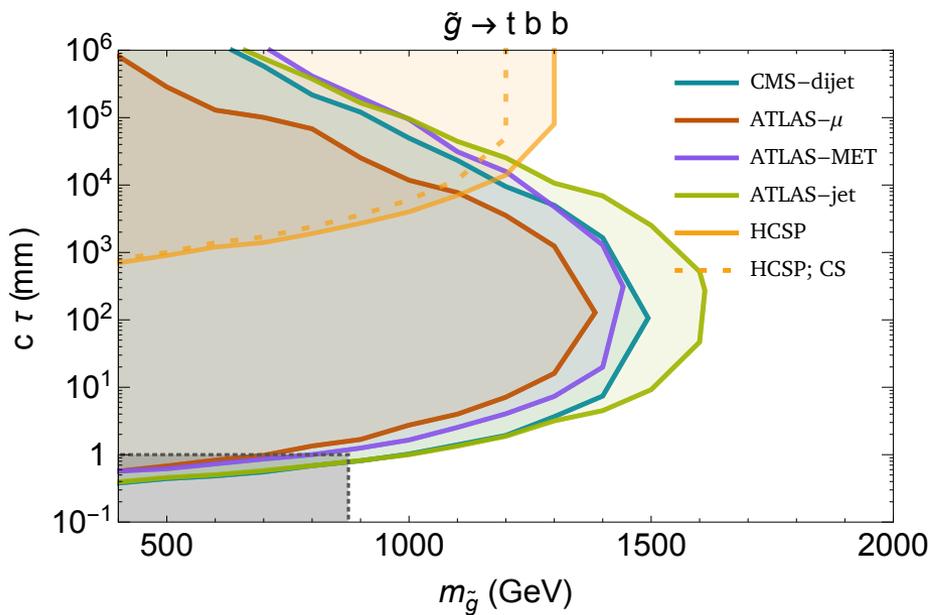
Stop bounds

- Direct **stop** production, $\tilde{t} \rightarrow u\nu$ type decay



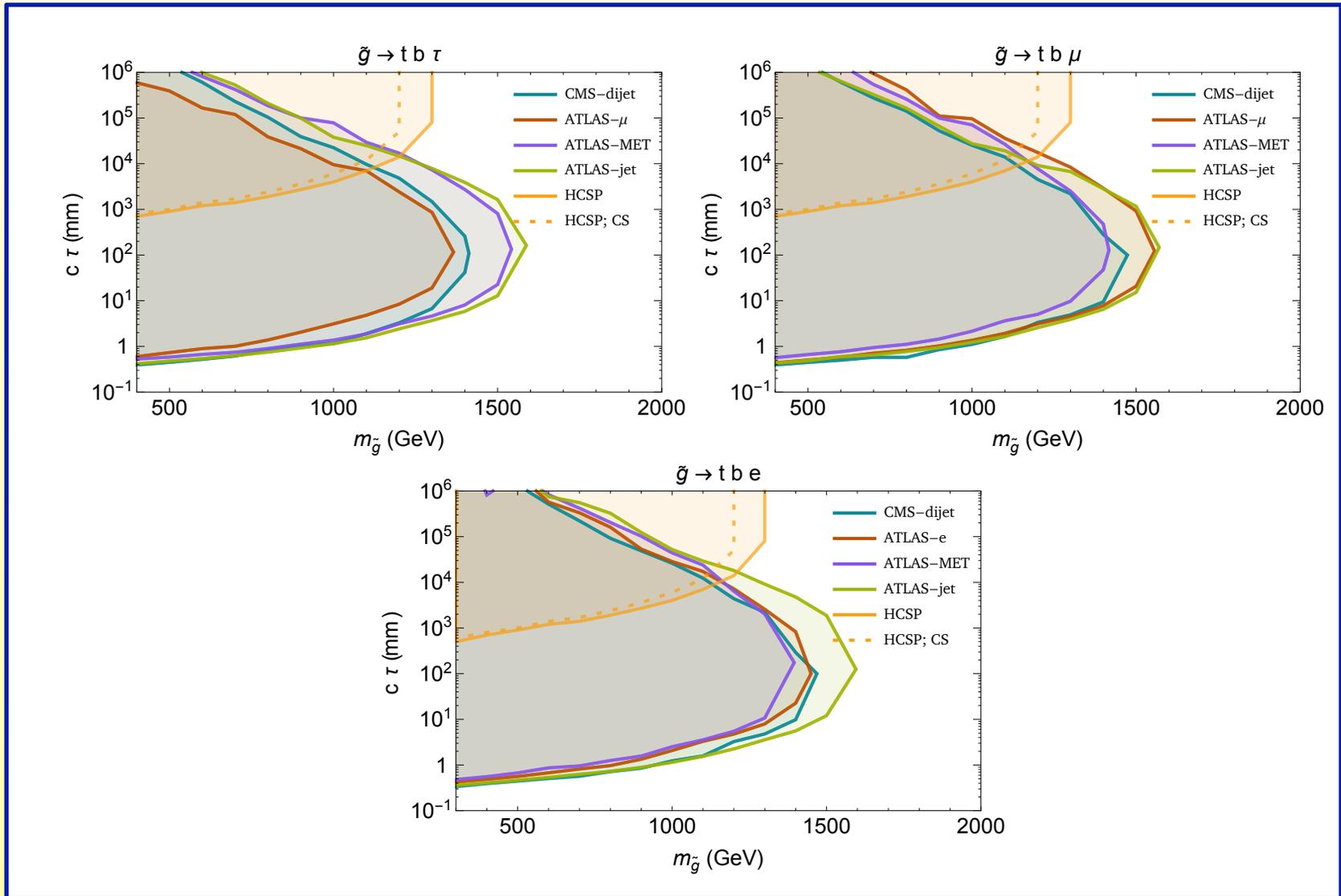
Glauino bounds

- Direct **gluino** production, three-body decay w/o charged leptons



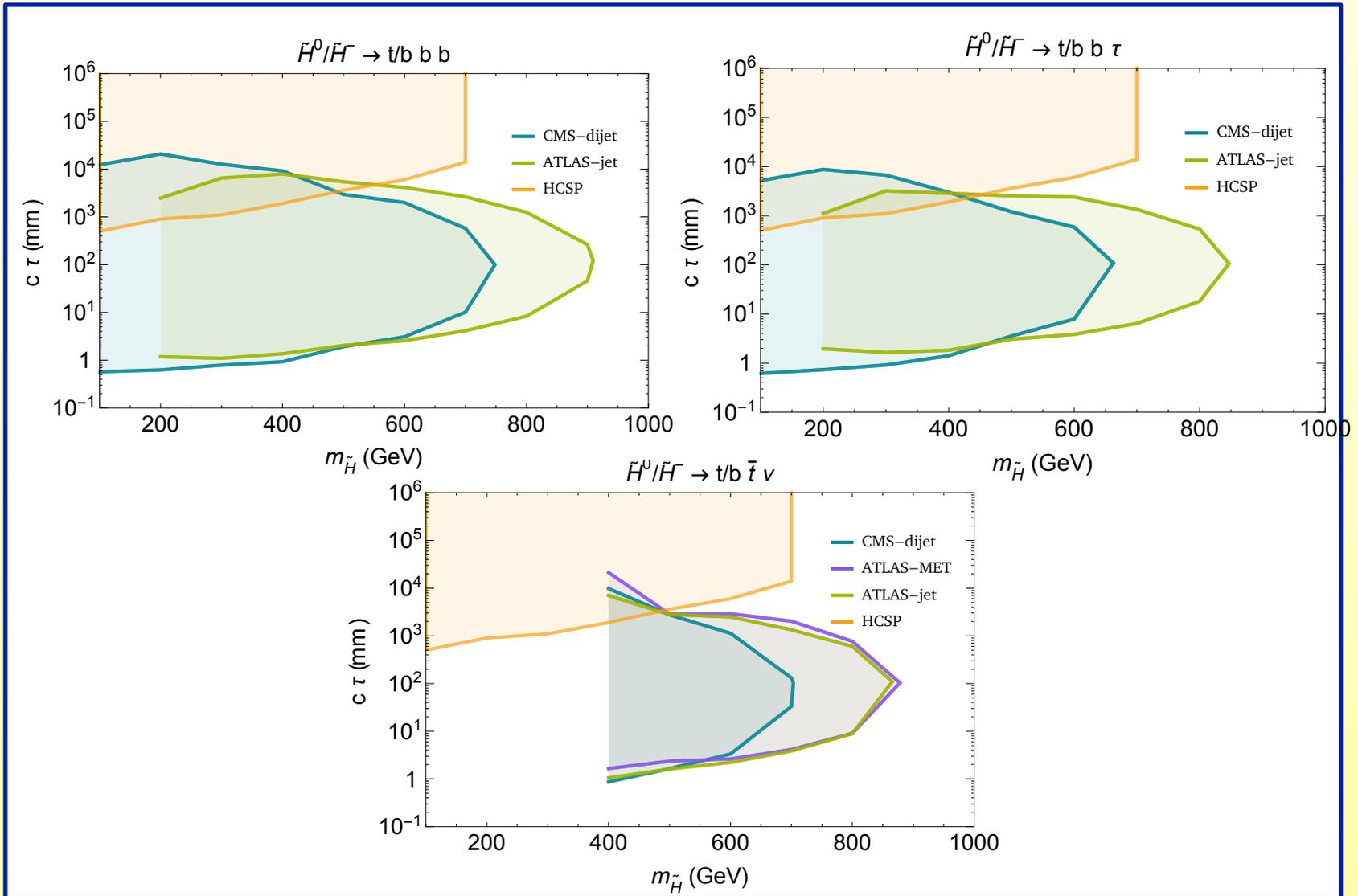
Glauino bounds

- Direct gluino production, three-body $\tilde{g} \rightarrow t b l$



Higgsino bounds

- Direct higgsino production, three decays via stop



Summary

- RPV can give different SUSY phenomenology
- Need to explain why RPV is small
- dRPV: broken in hidden sector and mediated to visible fields
- Non-holomorphic operators might be leading

$$\mathcal{O}_{\text{nhRPV}} = \eta_{ijk} \bar{u}_i \bar{e}_j \bar{d}_k^* + \eta'_{ijk} q_i \bar{u}_j \ell_k^* + \eta''_{ijk} q_i q_j \bar{d}_k^*$$

- Found simple models where these generated and most important source of RPV, may be related to flavor and SUSY breaking as well
- If LSP long lived, constraints are quite strong
- Remaining natural region hadronic prompt LSP decays