Dynamical R-parity Violation

Csaba Csáki (Cornell)
with
Eric Kuflik (Cornell)
Salvator Lombardo (Cornell)
Oren Slone (Tel Aviv)
Tomer Volansky (Tel Aviv)

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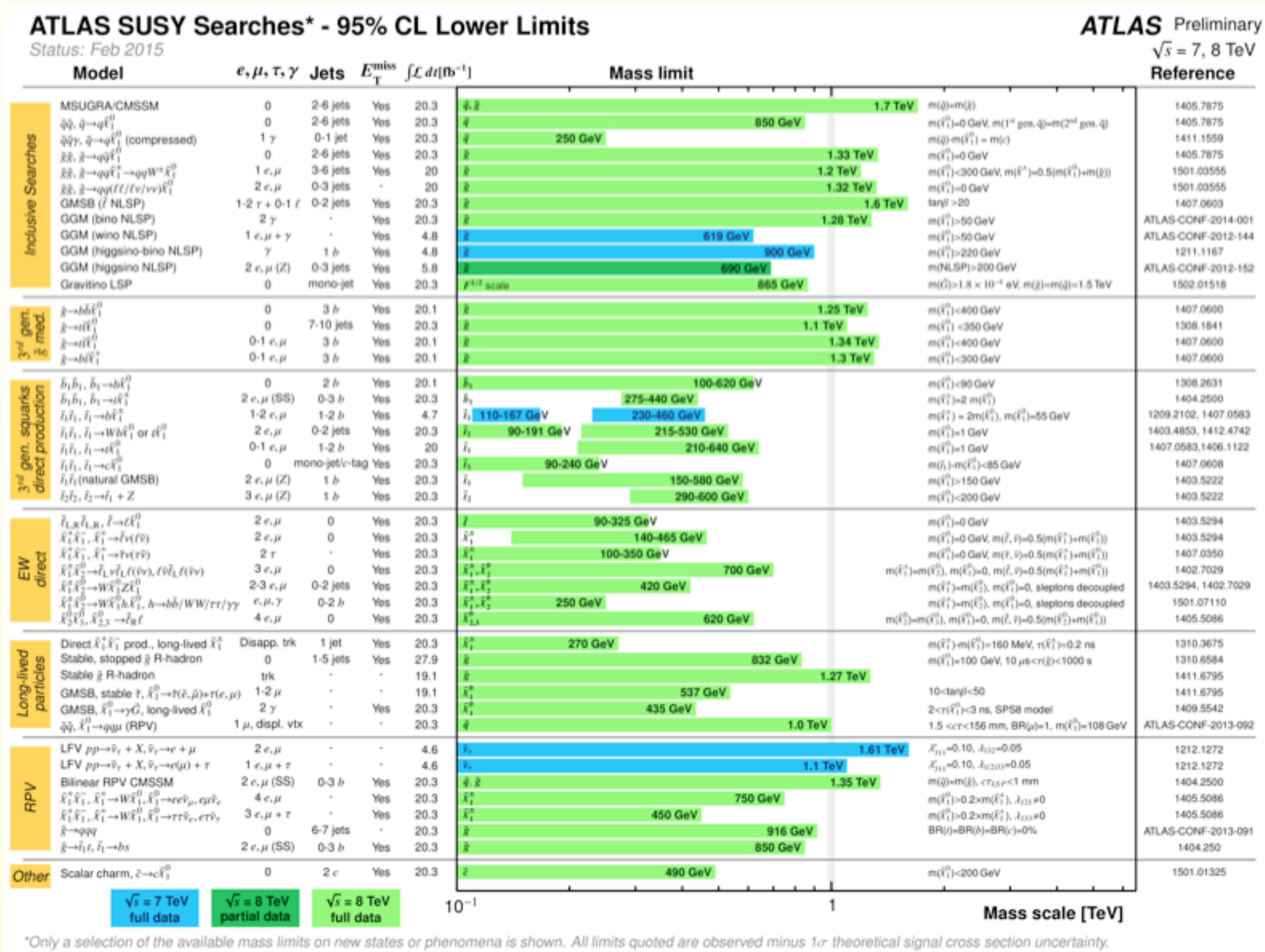
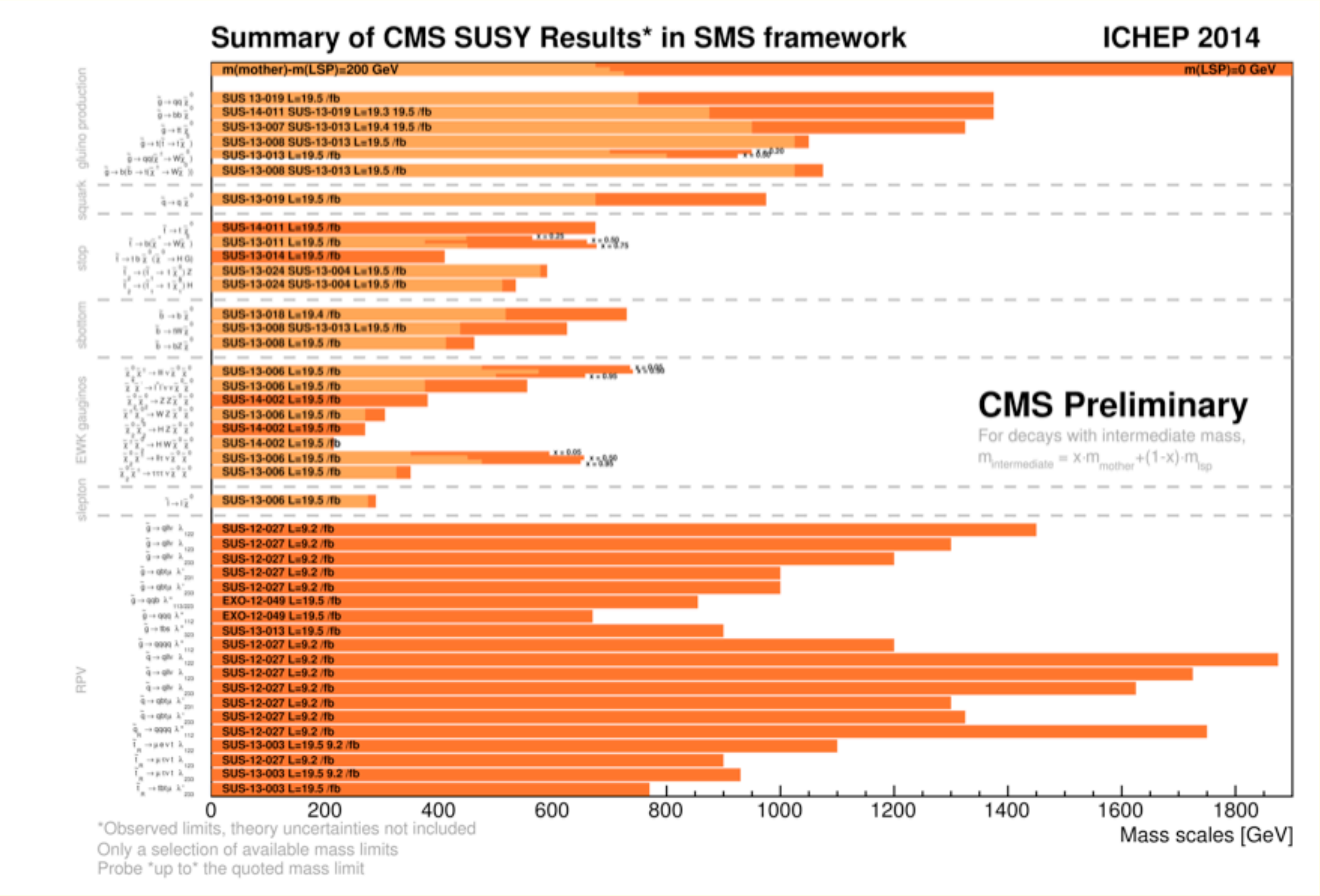
No sign of superpartners as of today from LHC



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

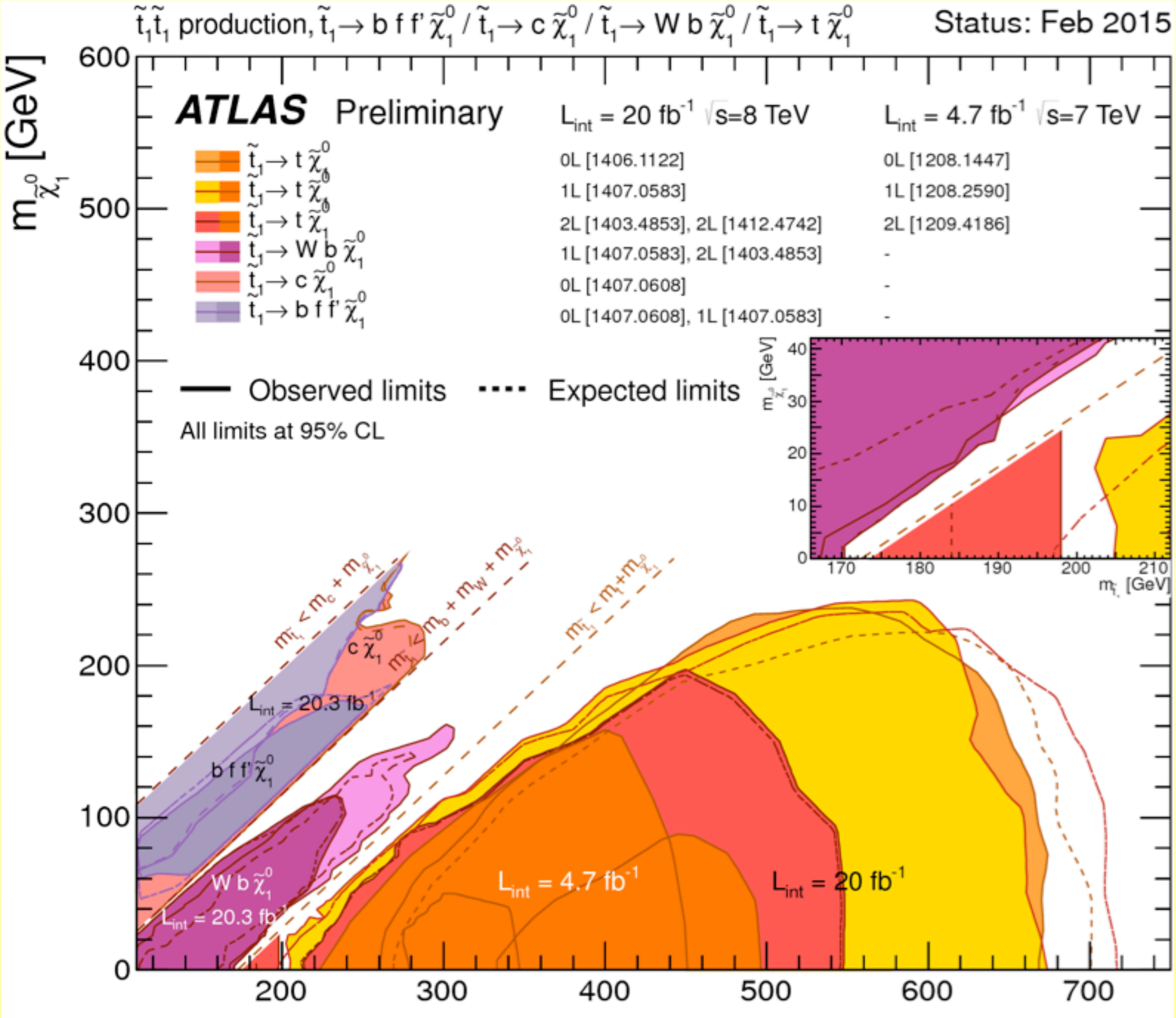
2. No MET due to RPV - focus of this talk

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)

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

- Non-holomorphic RPV (non-renormalizable)

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

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

- 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

	$\mathrm{U}(1)_{B-L}$	$\mathrm{U}(1)_R$
$\mathcal{O}_{nhRPV}$:	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

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

- Non-holomorphic will dominate

	$\mathrm{U}(1)_{B-L}$	$\mathrm{U}(1)_R$
$\mathcal{O}_{nhRPV}$:	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 $\bar{d} \to \bar{d} - \langle S^* \rangle qq/|M|^2$

- 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 $h_d q \bar{d}$ 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

$$K_{\not B,\not L} = \frac{\lambda^{\not B,\not L}_{ijmn}}{2M^2} q_i q_j \bar{u}^*_m \bar{e}^*_n + \frac{\langle S^* \rangle}{M^2} \left(\eta_{ijk} \bar{u}_i \bar{e}_j \bar{d}^*_k + \eta'_{ijk} q_i \bar{u}_j \ell^*_k + \frac{1}{2} \eta''_{ijk} q_i q_j \bar{d}^*_k \right) + h.c.$$

- Effective Lagrangian for B, L violation:

$$\mathcal{L}_{\not B,\not L} = \left[\frac{|\langle S \rangle|^2}{2M^4} \frac{1}{m^2_{\tilde{d}_{L,k}}} \left(m^d_j (\eta''_{ikj} + \eta''_{kij}) + m^d_k (\eta''_{ijk} + \eta''_{jik}) \right) \left(m^d_k \eta^*_{mnk} + m^e_n \eta'^*_{kmn} \right) \right.$$

$$\left. + \frac{|\langle S \rangle|^2}{2M^4} \frac{1}{m^2_{\tilde{d}_{R,i}}} (\eta''^{\bar{\theta}^2}_{ijk} + \eta''^{\bar{\theta}^2}_{jik}) \eta^{\bar{\theta}^2 *}_{mnk} + \frac{1}{2M^2} (\lambda^{\not B,\not L}_{ijmn} + \lambda^{\not B,\not L}_{jimn}) \right] u^i_L d^j_L u^m_R e^n_R + h.c.$$

$$\equiv \tilde{\Lambda}^{-2}_{ijmn} u^i_L d^j_L u^m_R e^n_R + h.c.$$

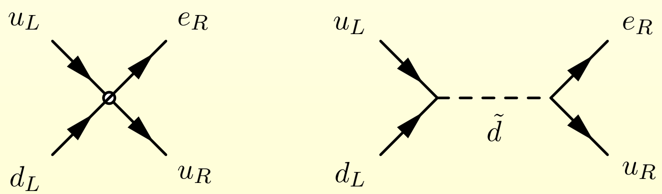
$$\eta \equiv \eta^0 (1 + M \epsilon_X \bar{\theta}^2)$$

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

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

Proton decay

- Proton decay diagrams



- If chirally suppressed terms dominate

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

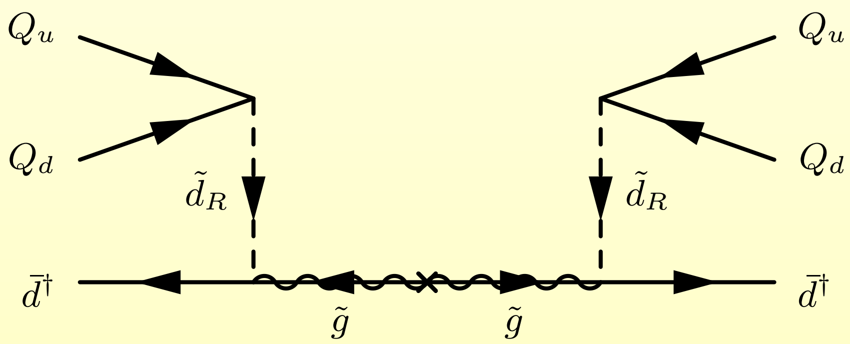
- If SUSY breaking terms dominate:

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

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

Low-energy constraints: ΔB=2

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



$$\frac{1}{\Lambda^5_{ijk}}(Q_iQ_iQ_jQ_j\bar{d}^\dagger_k\bar{d}^\dagger_k)$$

- Dim 9 operator generated

- Suppression scale: $$\frac{1}{\Lambda^5_{ijk}} = \pi\alpha_s\frac{\eta''_{iik}\eta''_{jjk}}{m_{\tilde{g}}m^4_{\tilde{d}._{R,k}}}\epsilon^2_X$$

Low-energy constraints: ΔB=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):

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

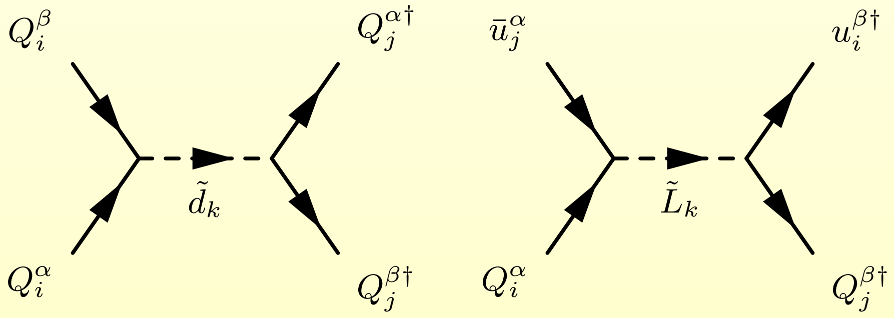
$$\Gamma \simeq \frac{8}{\pi}\frac{\rho_N}{m_N^2}\frac{\tilde{\Lambda}_{QCD}^{10}}{\Lambda_{pp}^{10}}$$

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

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

Low-energy constraints: ΔF=2

- FCNC's generated at tree-level:



- Operators generated:

$$\begin{aligned} \mathcal{Q}_1^{q_i q_j} &\equiv -\tfrac{1}{2}(Q_i^\alpha Q_i^\beta)(Q_j^{\alpha\dagger} Q_j^{\beta\dagger}) \\ \mathcal{Q}_4^{q_i q_j} &\equiv \bar{u}_j^\alpha Q_i^\alpha Q_j^{\beta\dagger} \bar{u}_i^{\beta\dagger} \end{aligned}$$

- Suppression scales:

$$\frac{1}{\Lambda_{1,ij}^2} = \frac{\eta''_{iik}\eta''^{*}_{jjk}}{m^2_{\tilde{d}_{R,k}}}\epsilon_X^2, \qquad \frac{1}{\Lambda_{4,ij}^2} = \frac{|\eta'_{ijk}|^2}{m^2_{\tilde{\nu}_{L,k}}}\epsilon_X^2$$

Low-energy constraints: ΔF=2

- Bounds from neutral meson mixings:

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

- 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

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

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

- This way we see the dRPV term

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

- 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

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

- 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:

$$W_{eff} = \frac{1}{S} h_d qqq.$$

- 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

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

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

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

Doubly suppressed dRPV

- Last term equivalent to

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

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

A complete model

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

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

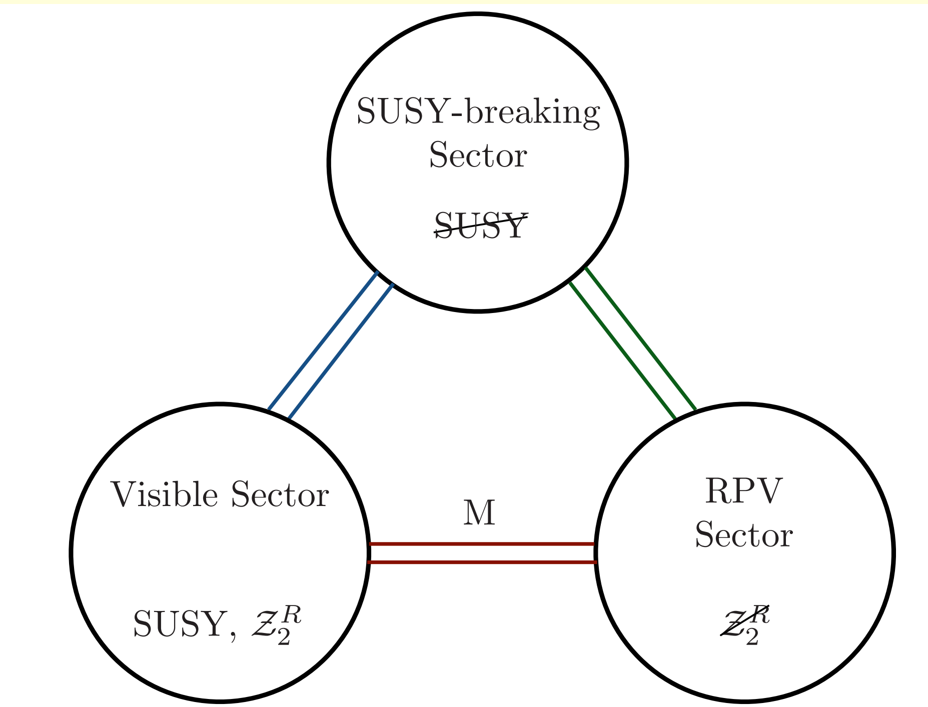
- Low energy effective theory:

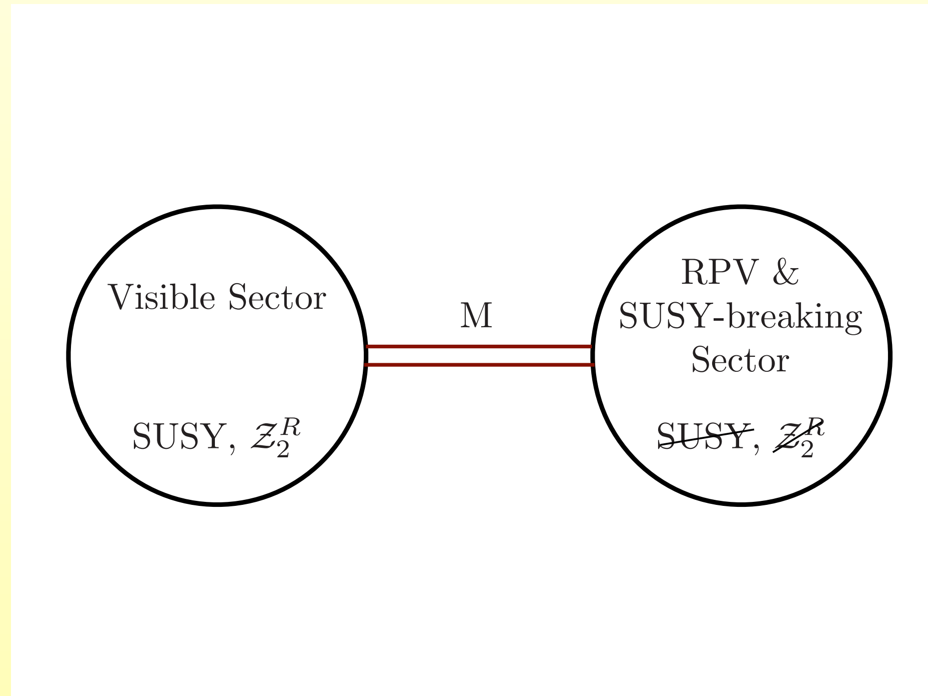
$$
\begin{aligned}
W_{\mathrm{eff}} = & W_{\mathrm{MSSM}} \\
K_{\mathrm{eff}} = & |q_i|^2 + |\bar{u}_i|^2 + |\bar{e}_i|^2 + \left(\delta_{ij} + \alpha^d_{ij} \frac{|S|^2}{M^2} \right) \bar{d}^*_j \bar{d}_i + \left(\delta_{ij} + \alpha^\ell_{ij} \frac{|S|^2}{M^2} \right) \ell^*_j \ell_i \\
& + \eta_{ijk} \frac{S^*}{M^2} \bar{u}_i \bar{e}_j \bar{d}^*_k + \eta'_{ijk} \frac{S^*}{M^2} q_i \bar{u}_j \ell^*_k + \frac{1}{2} \eta''_{ijk} \frac{S^*}{M^2} q_i q_j \bar{d}^*_k + h.c. \\
& + \frac{1}{M^2} \left(\frac{1}{4} \lambda''_{ijmn} q_i q_j q^*_m q^*_n + \lambda'_{ijmn} q_i \bar{u}_j q^*_m \bar{u}^*_n + \lambda_{ijmn} \bar{u}_i \bar{e}_j \bar{u}^*_m \bar{e}^*_n \right. \\
& \qquad \left. + \frac{1}{2} \lambda^{\not{B}, \not{L}}_{ijmn} q_i q_j \bar{u}^*_m \bar{e}^*_n + h.c. \right) + \mathcal{O}(M^{-4}) \, ,
\end{aligned}
$$

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

Effect of SUSY breaking

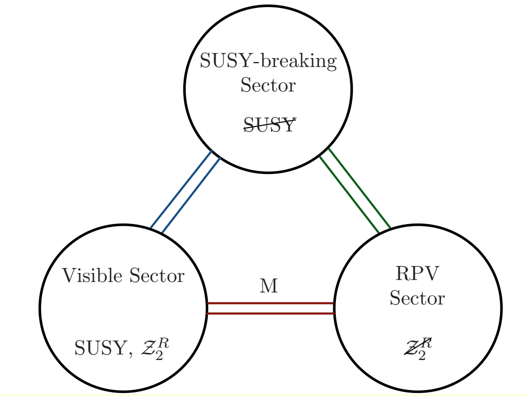
- Could be external to RPV sector or have same spurion and messengers





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

$$M \to M z_D z_{\bar{D}}, \qquad S \to S z_D z_{\bar{d}}, \qquad \lambda \to \lambda z_q^2 z_D \ .$$

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

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

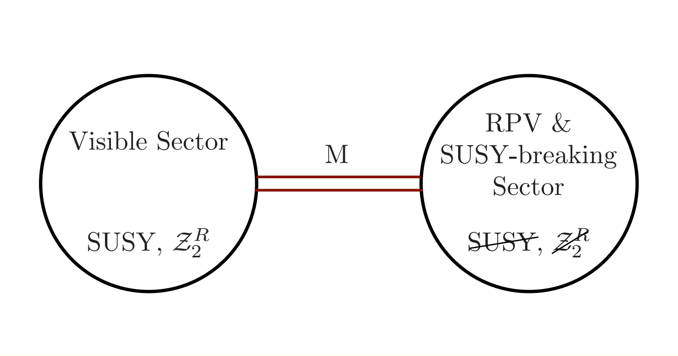
- z's have F-terms

- 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

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

- Effective Kähler potential:

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

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

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

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

$$W = M_+ D_+ \bar{D}_+ + M_- D_- \bar{D}_- + S\bar{D}_+ D_- + mD_-\bar{d} + qqD_+$$

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

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

- 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

$$\tau_p \simeq 10^{32}\mathrm{yr}\left(\frac{7\times 10^{-8}}{|\eta''_{ij3}\eta^*_{k\ell 3}|}\right)^2\left(\frac{m_{\tilde{b}_L}}{\mathrm{TeV}}\right)^4\left(\frac{M}{10^8\mathrm{GeV}}\right)^4\left(\frac{0.1}{\langle S\rangle/M}\right)^4$$

- 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

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

- 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 suprions $\epsilon_1 \sim \epsilon \sim 0.2, \quad \epsilon_2 \sim \epsilon^2 \sim 0.04$

- Suppression factors large...

η	$\bar{u}_1\bar{e}_1$	$\bar{u}_1\bar{e}_2$	$\bar{u}_2\bar{e}_1$	$\bar{u}_2\bar{e}_2$
$\bar{d}_1$	ϵ^6	ϵ^6	ϵ^8	ϵ^8
$\bar{d}_2$	ϵ^7	ϵ^7	ϵ^7	ϵ^7
$\bar{d}_3$	ϵ^{15}	ϵ^{15}	ϵ	ϵ

η'	$\bar{u}_1\ell_1^*$	$\bar{u}_1\ell_2^*$	$\bar{u}_2\ell_1^*$	$\bar{u}_2\ell_2^*$
q_1	ϵ^7	ϵ^5	ϵ^7	ϵ^9
q_2	ϵ^{14}	ϵ^{12}	1	ϵ^2
q_3	ϵ^{20}	ϵ^{18}	ϵ^6	ϵ^4

η''	q_1q_1	q_1q_2	q_2q_2	q_1q_3	q_2q_3	q_3q_3
$\bar{d}_1$	ϵ^{37}	ϵ^{30}	ϵ^{23}	ϵ^{24}	ϵ^{17}	ϵ^{11}
$\bar{d}_2$	ϵ^{36}	ϵ^{29}	ϵ^{22}	ϵ^{23}	ϵ^{16}	ϵ^{10}
$\bar{d}_3$	ϵ^{28}	ϵ^{21}	ϵ^{14}	ϵ^{15}	ϵ^8	ϵ^2

Unifying flavor and RPV mediation

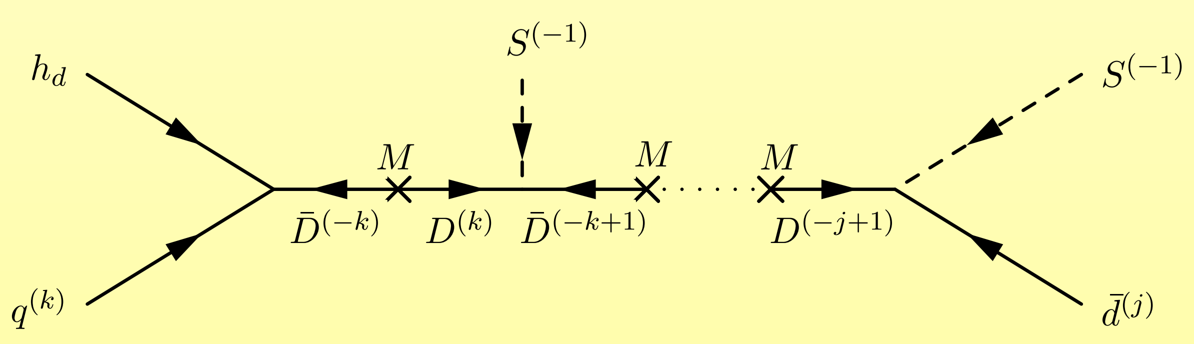
- FN messengers and RPV messengers same

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

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

- 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

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

- 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	$\bar{u}_1\bar{e}_1$	$\bar{u}_1\bar{e}_2$	$\bar{u}_2\bar{e}_1$	$\bar{u}_2\bar{e}_2$
$\bar{d}_1$	ϵ^{28}	ϵ^{28}	ϵ^{14}	ϵ^{14}
$\bar{d}_2$	ϵ^{27}	ϵ^{27}	ϵ^{13}	ϵ^{13}
$\bar{d}_3$	ϵ^{19}	ϵ^{19}	ϵ^{5}	ϵ^{5}

η'	$\bar{u}_1\ell_1^*$	$\bar{u}_1\ell_2^*$	$\bar{u}_2\ell_1^*$	$\bar{u}_2\ell_2^*$
q_1	ϵ^{9}	ϵ^{7}	ϵ^{11}	ϵ^{9}
q_2	ϵ^{16}	ϵ^{14}	ϵ^{6}	ϵ^{4}
q_3	ϵ^{22}	ϵ^{20}	ϵ^{8}	ϵ^{6}

η''	q_1q_1	q_1q_2	q_2q_2	q_1q_3	q_2q_3	q_3q_3
$\bar{d}_1$	ϵ^{37}	ϵ^{30}	ϵ^{23}	ϵ^{32}	ϵ^{17}	ϵ^{11}
$\bar{d}_2$	ϵ^{36}	ϵ^{29}	ϵ^{22}	ϵ^{24}	ϵ^{16}	ϵ^{10}
$\bar{d}_3$	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

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

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

<u>LHC bounds</u>

- Looked at cases motivated by naturalness

- Light stops, gluinos or higgsinos

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

Experimental searches

- Displaced vertex searches by ATLAS, CMS

ATLAS DV $+\ \mu/e/$**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

$\tilde{t} \to dd$ paired dijet resonance searches

$\tilde{t} \to dl^+$ leptoquark searches(Tevatron+LHC)

$\tilde{t} \to t\nu$ stop→top+neutralino search

$\tilde{g} \to t\bar{t}\nu$ gluino→ttbar neutralino search

$\tilde{g} \to tbb$ gluino→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

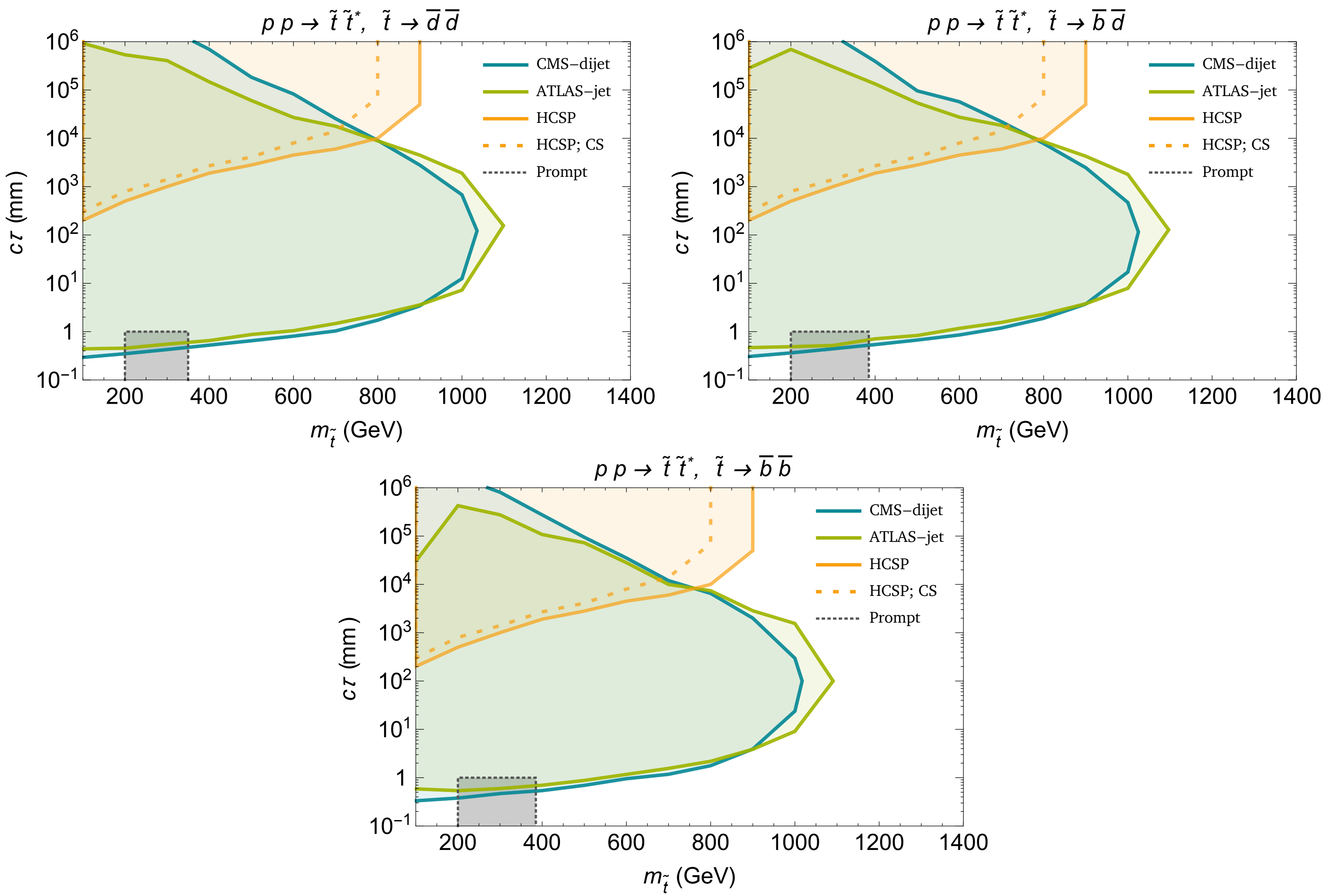
- Used Feynrules→Madgraph→Pythia→Delphes3 pipeline

- 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)

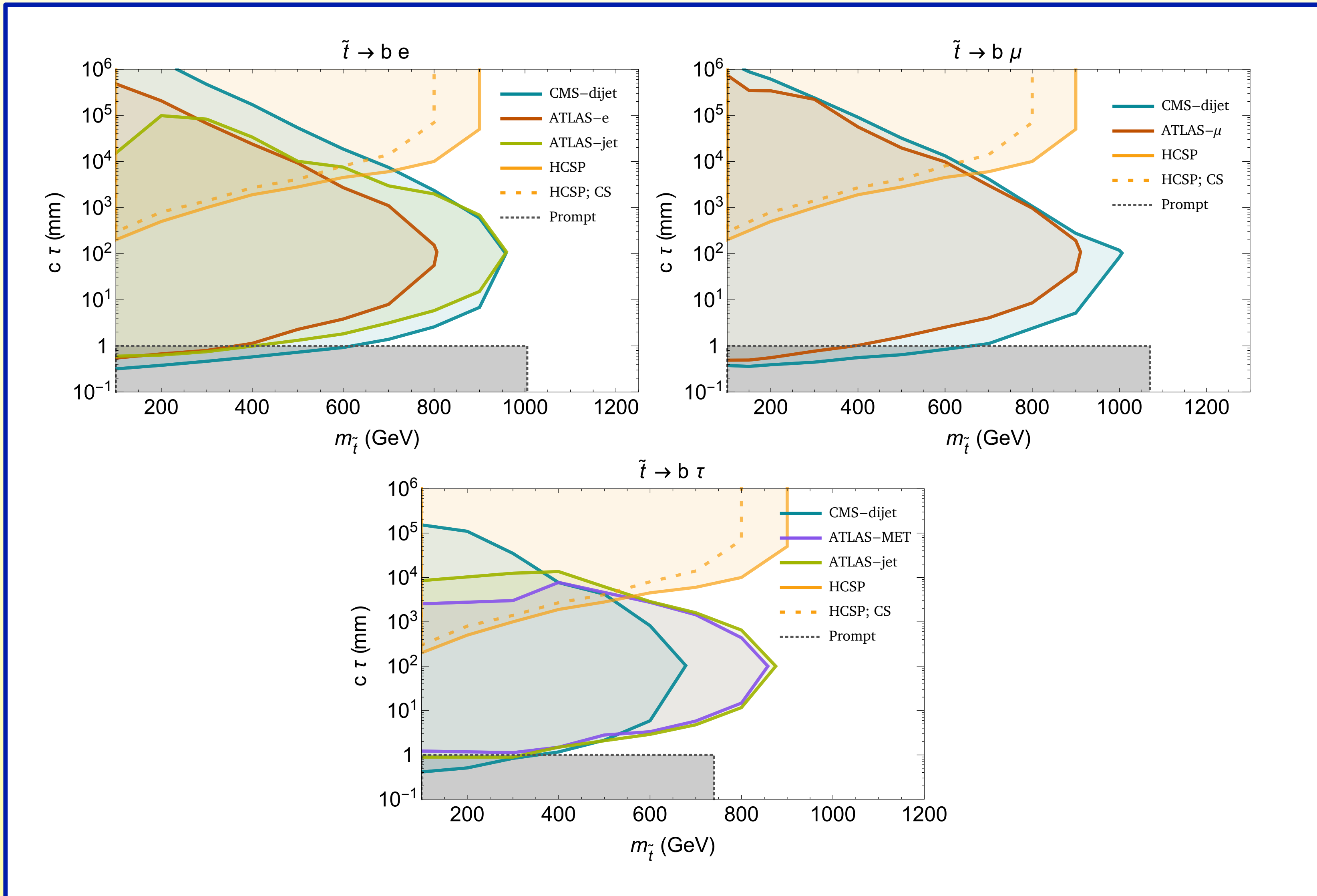
Stop bounds

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



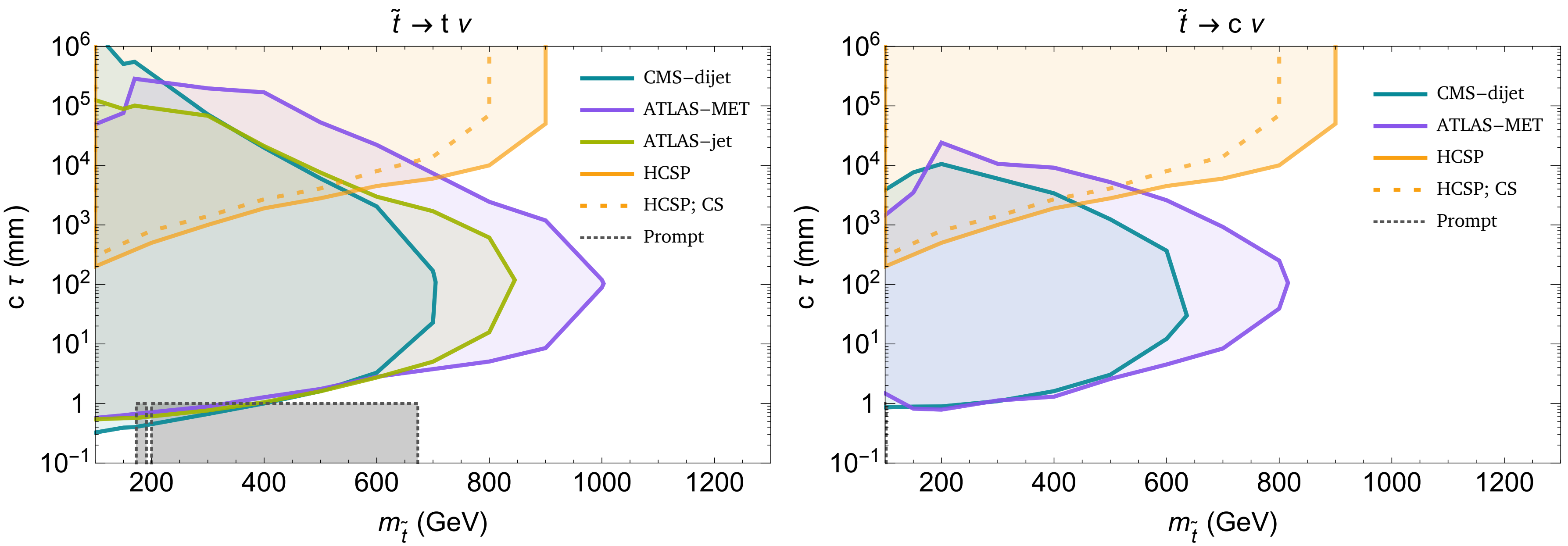
Stop bounds

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



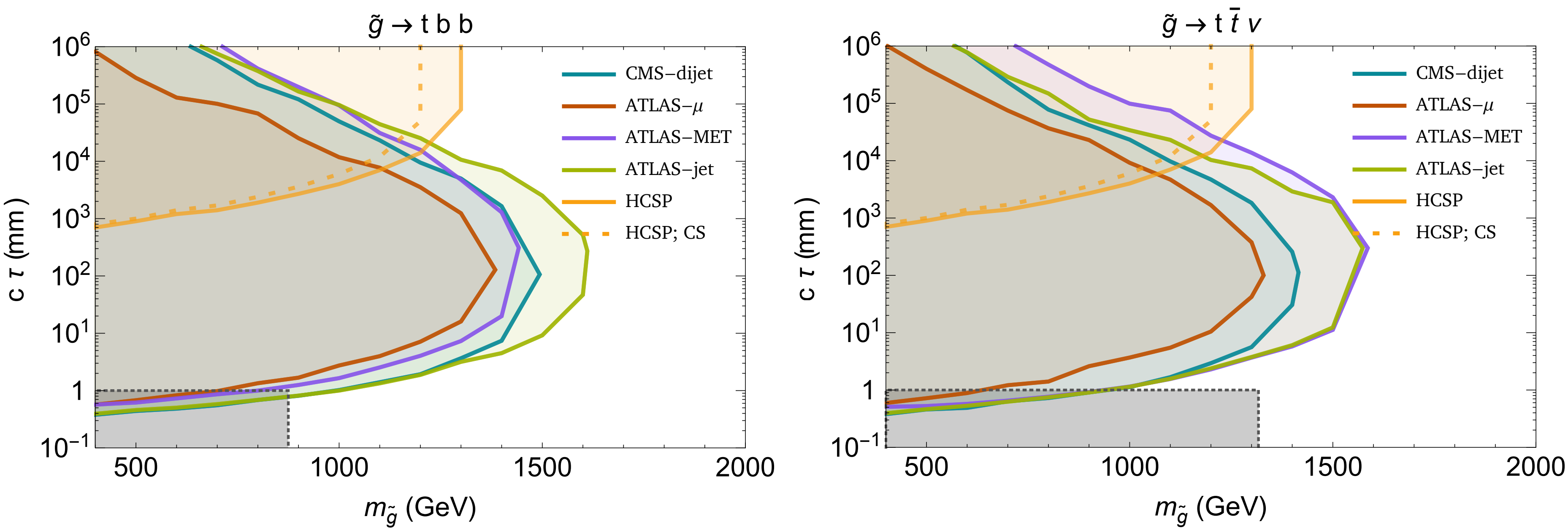
Stop bounds

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



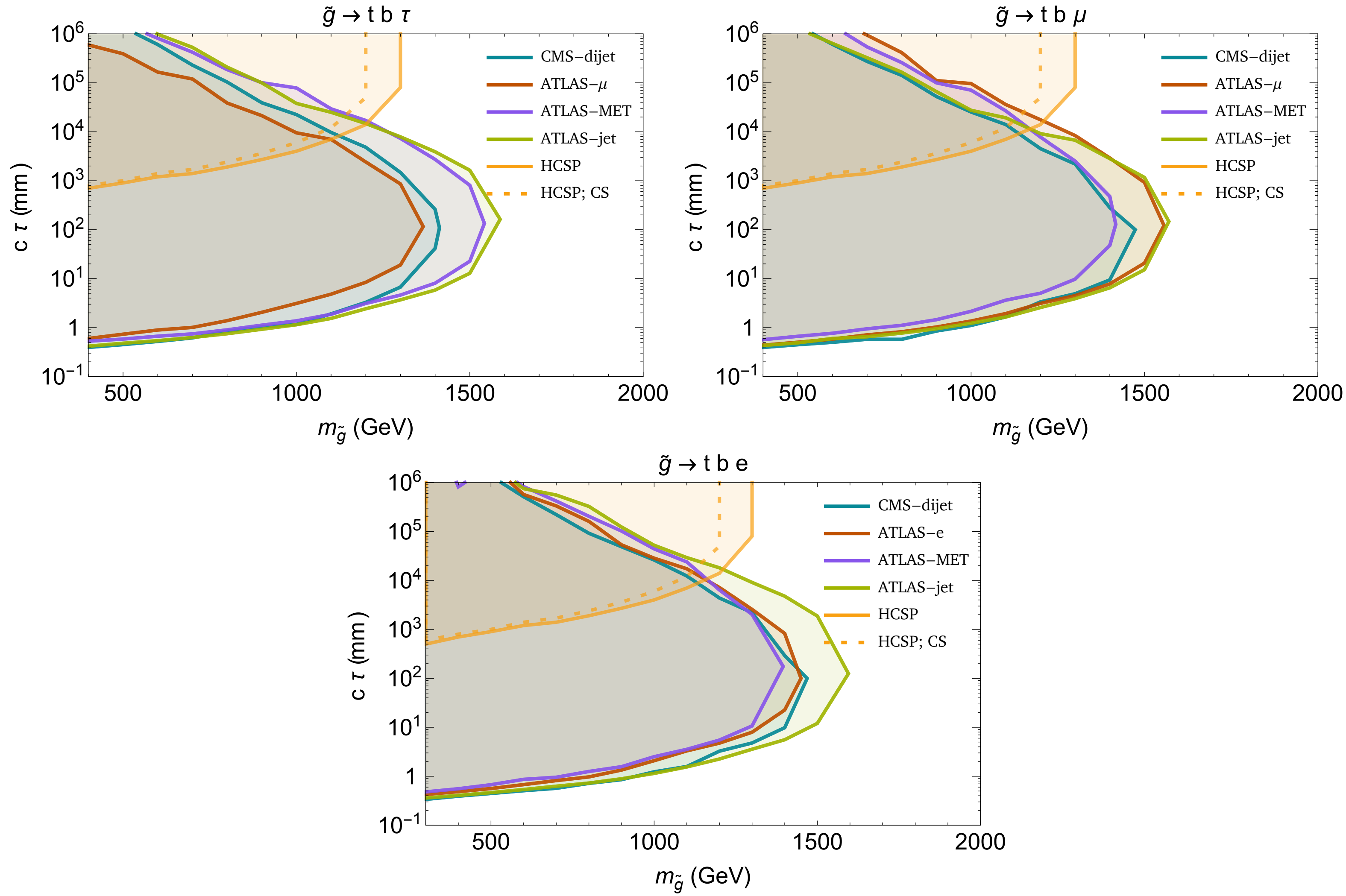
Gluino bounds

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



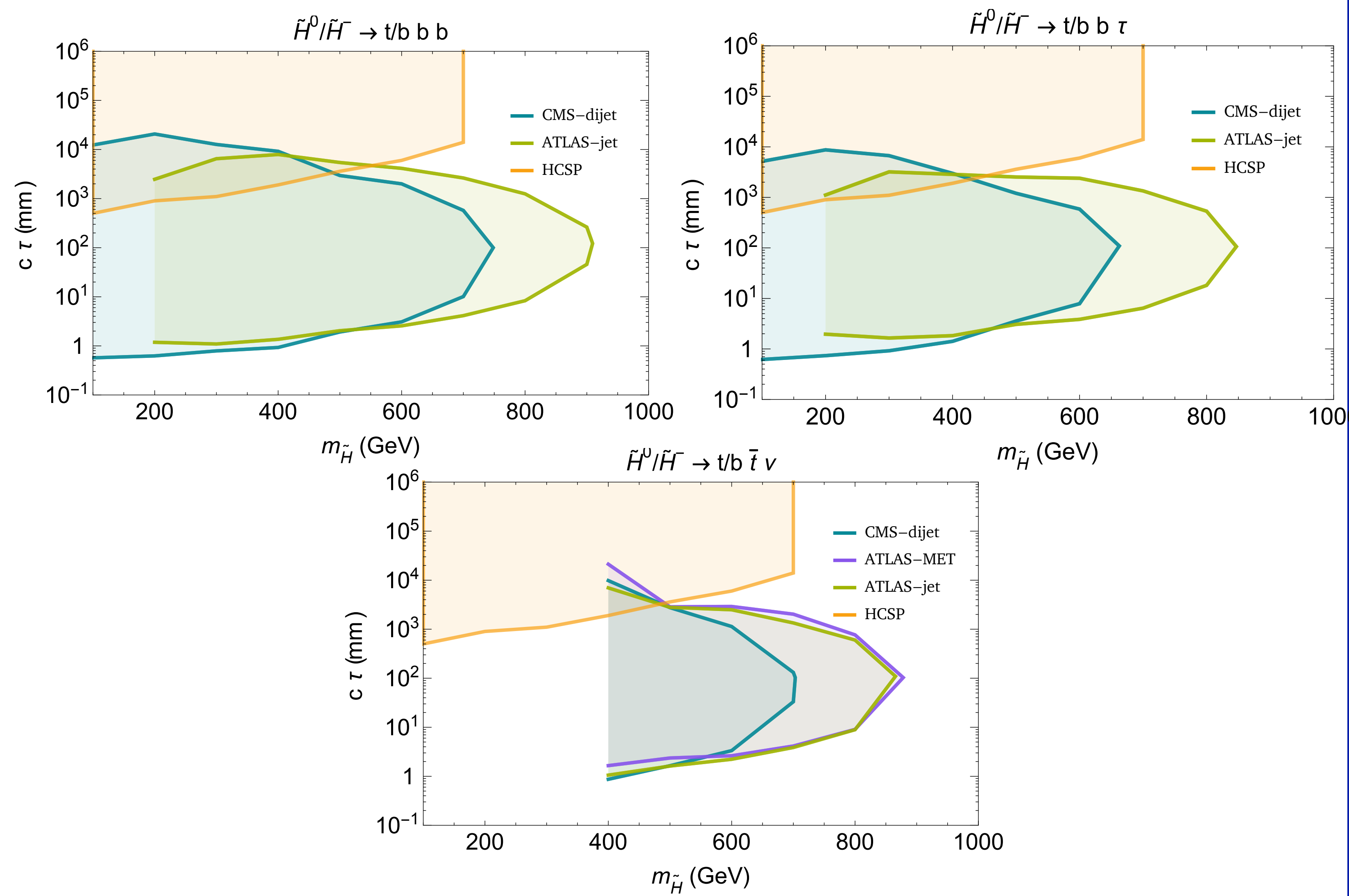
Gluino bounds

- Direct gluino production, three-body $\tilde{g} \to tbl$



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

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

- 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