Displaced Physics at the LHC: RPV and Displaced Higgs

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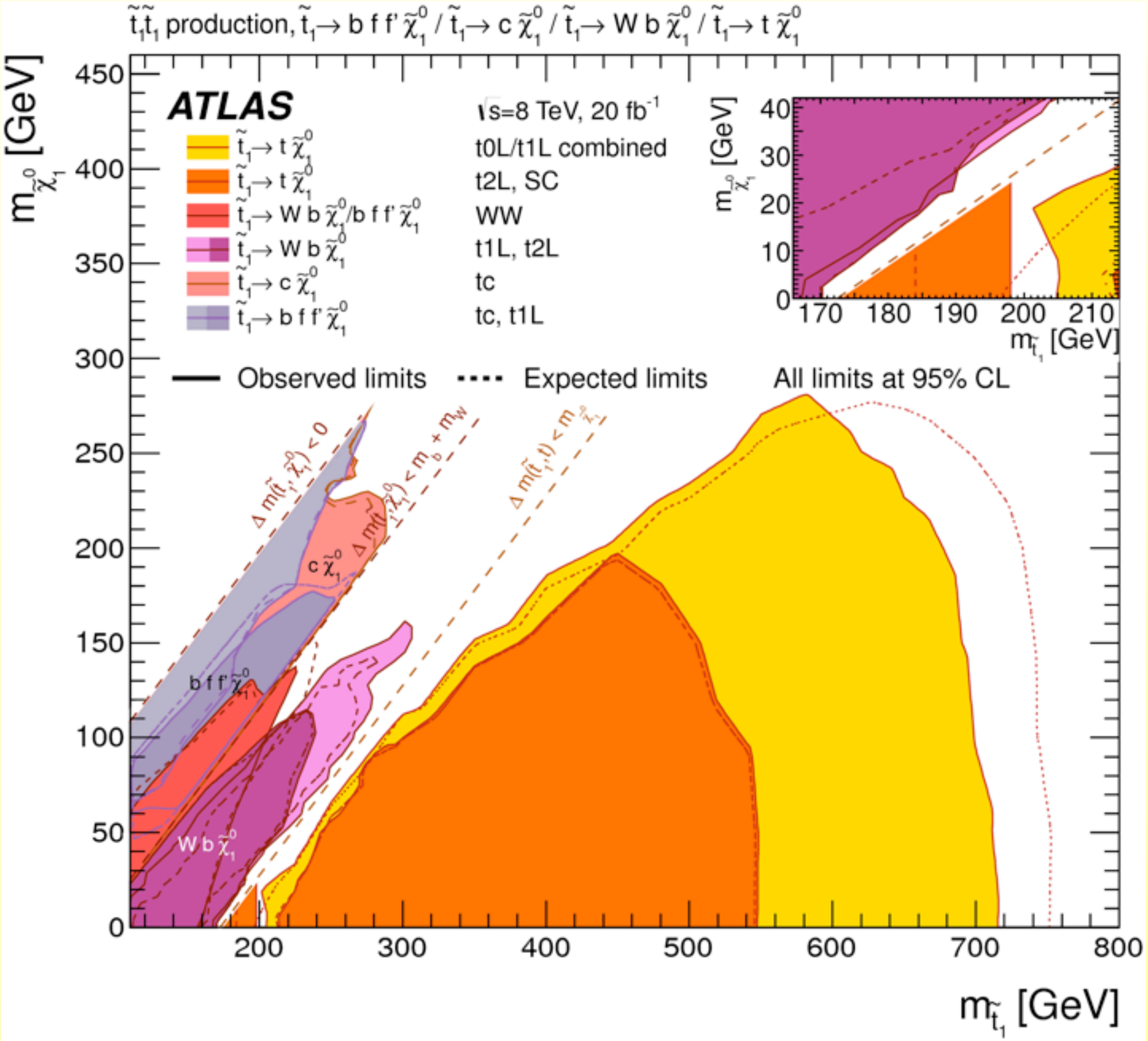
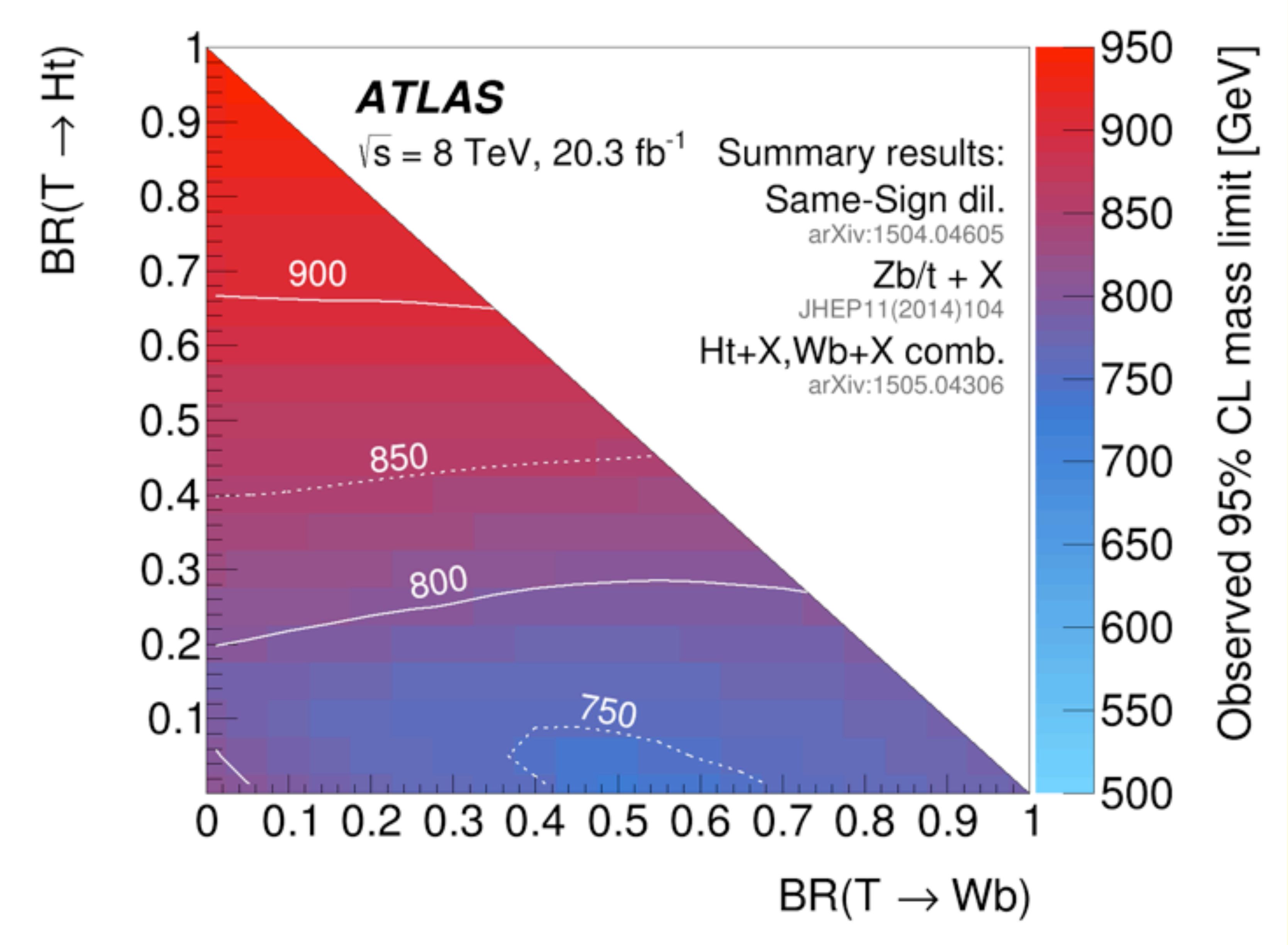
GGI Conference Gearing up for LHC 13
October 15, 2015

No sign of top partners as of today from LHC



No sign of top partners as of today from LHC



Look for non-traditional signals

- In addition to pursuing traditional searches for colored top partners consider variations

- Non-traditional decays of superpartners due to RPV

- Search for signals of models with non-colored top partners

RPV in SUSY

- Exact R-parity conservation is not mandatory

- If R-parity is broken, breaking must be small

- Holomorphic RPV terms - usually assumed to be leading (renormalizable)

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

- Non-holomorphic RPV (non-renormalizable)

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

$$\mathcal{O}_{\rm nhBL} = \kappa'_i L^\dagger_i H_d$$

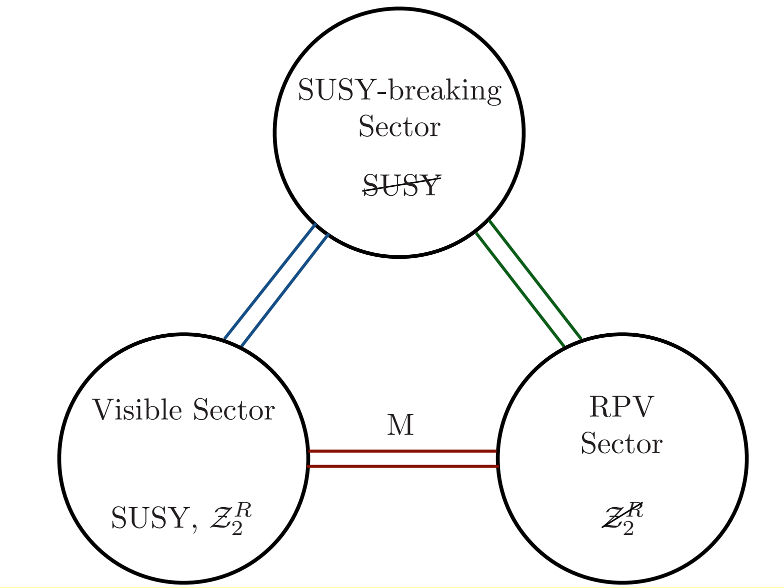
dRPV

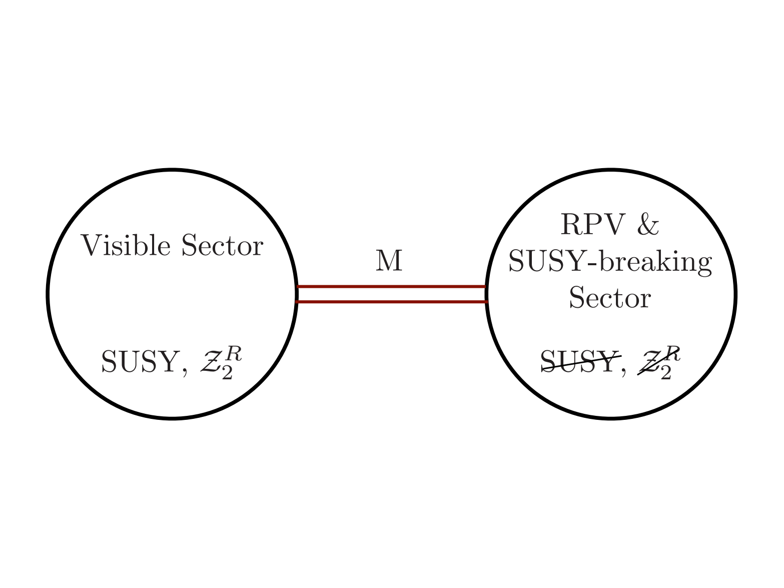
(Kuflik, Slone, Volansky, C.C.)

- Non-holomorphic RPV (non-renormalizable) could be leading operators

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

- In dRPV - RPV in hidden sector mediated to visible sector





Holomorphic 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.

Holomorphic or non-holomorphic?

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

$\frac{S^*}{M^2}\mathcal{O}_{nhRPV}$ and $\frac{S}{M}\mathcal{O}_{hRPV}$ 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	$3/2$

Effects of non-holomorphic operators

- Either chirally suppressed or suppressed by SUSY breaking

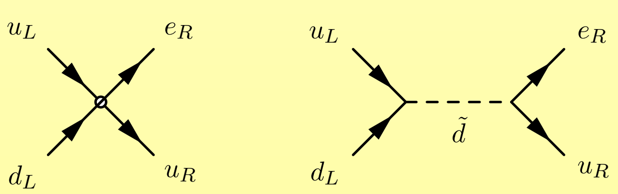
$$\int d^2\theta \left[\frac{\langle S\rangle^*}{|M|^2} qq \frac{\partial W}{\partial \bar{d}} + \frac{\langle F_S\rangle^*}{|M|^2} qq\bar{d}^* \right]$$

- Proton decay requires coefficients to be small. 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:

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



Different ways of generating dRPV

- Integrating out heavy fields - suppression factor:

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

- SUSY breaking term suppressed by:

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

- Flavor suppression also expected - RPV terms also violate flavor, for example FN suppression in simplest models

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

Different ways of generating dRPV

- Either way strongly suppressed (as expected also by absence of B,L violation)
- Suppressed by messenger masses, flavor factors or perhaps SUSY breaking (at least two of them)
- Expect that in many relevant cases will give displaced vertices at LHC (or collider stable - but then not so interesting unless charged...)
- Studied phenomenology of displaced RPV both using traditional holomorphic RPV or dRPV

dRPV gives different decays

- Stop LSP: $\tilde{t} \rightarrow \bar{b}\bar{b}$ special to dRPV. 4b final state.
- Sneutrino LSP: $\tilde{\nu} \rightarrow t_L t_R^\dagger$. Final state 4t
- Gluino LSP: $\tilde{g} \rightarrow tbb$
- Sbottom LSP: $\tilde{b} \rightarrow \bar{t} + \bar{b}$

LHC bounds

(Kuflik, Lombardo, Slone, Volansky, C.C., see also Liu and Tweedie)

- Looked at cases motivated by naturalness

- Light stops, gluinos or higgsinos

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

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 grid of LSP masses lifetimes of 100 GeV, decay lengths 0.03,0.1,0.3,1,...mm

- Feynrules→Madgraph→Pythia→Delphes3 pipeline

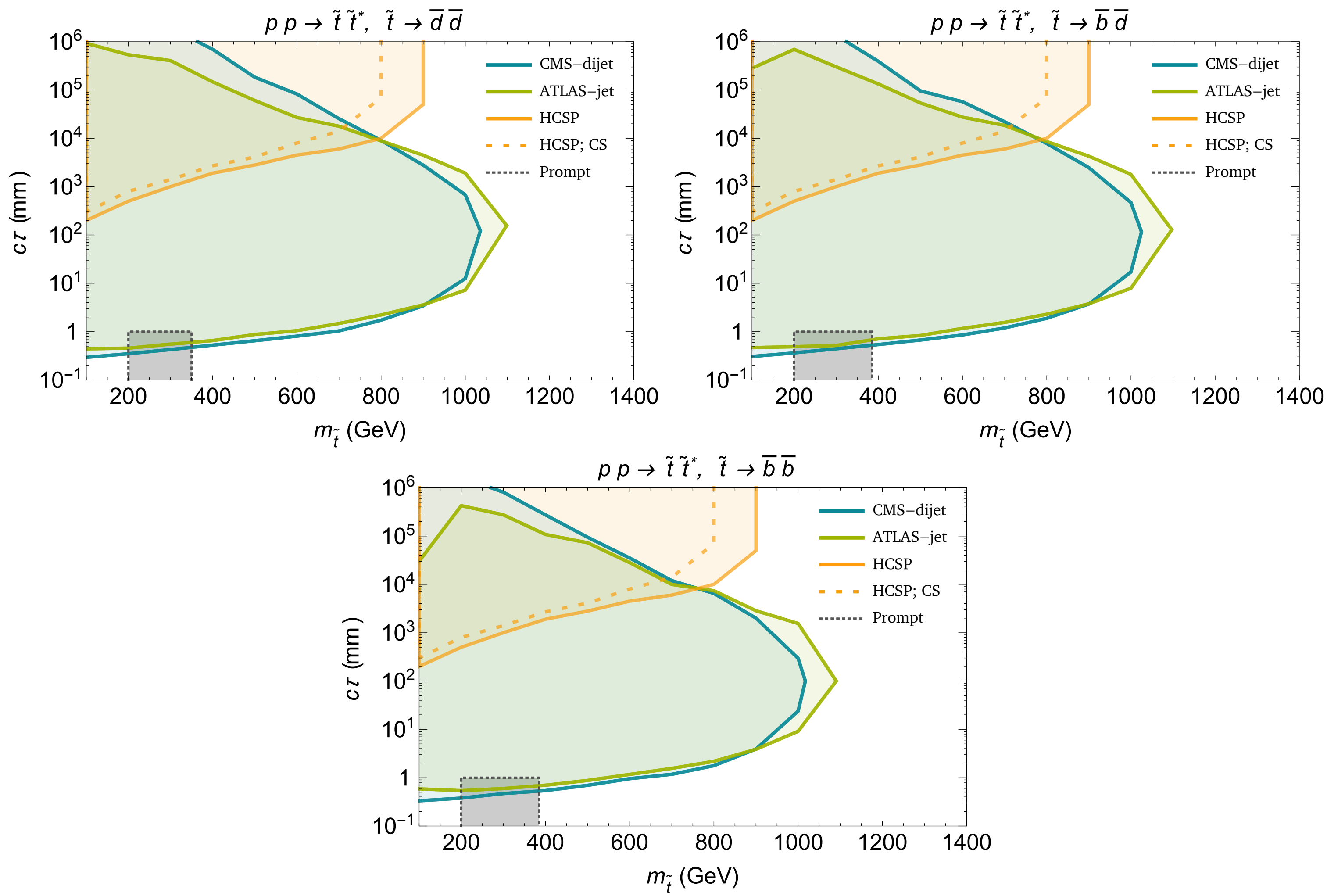
- Wherever efficiency very small generated additional events

- 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)

- Simulated R-hadrons for stop LSP, that is why dijet search can constrain decay to single quark+neutrino

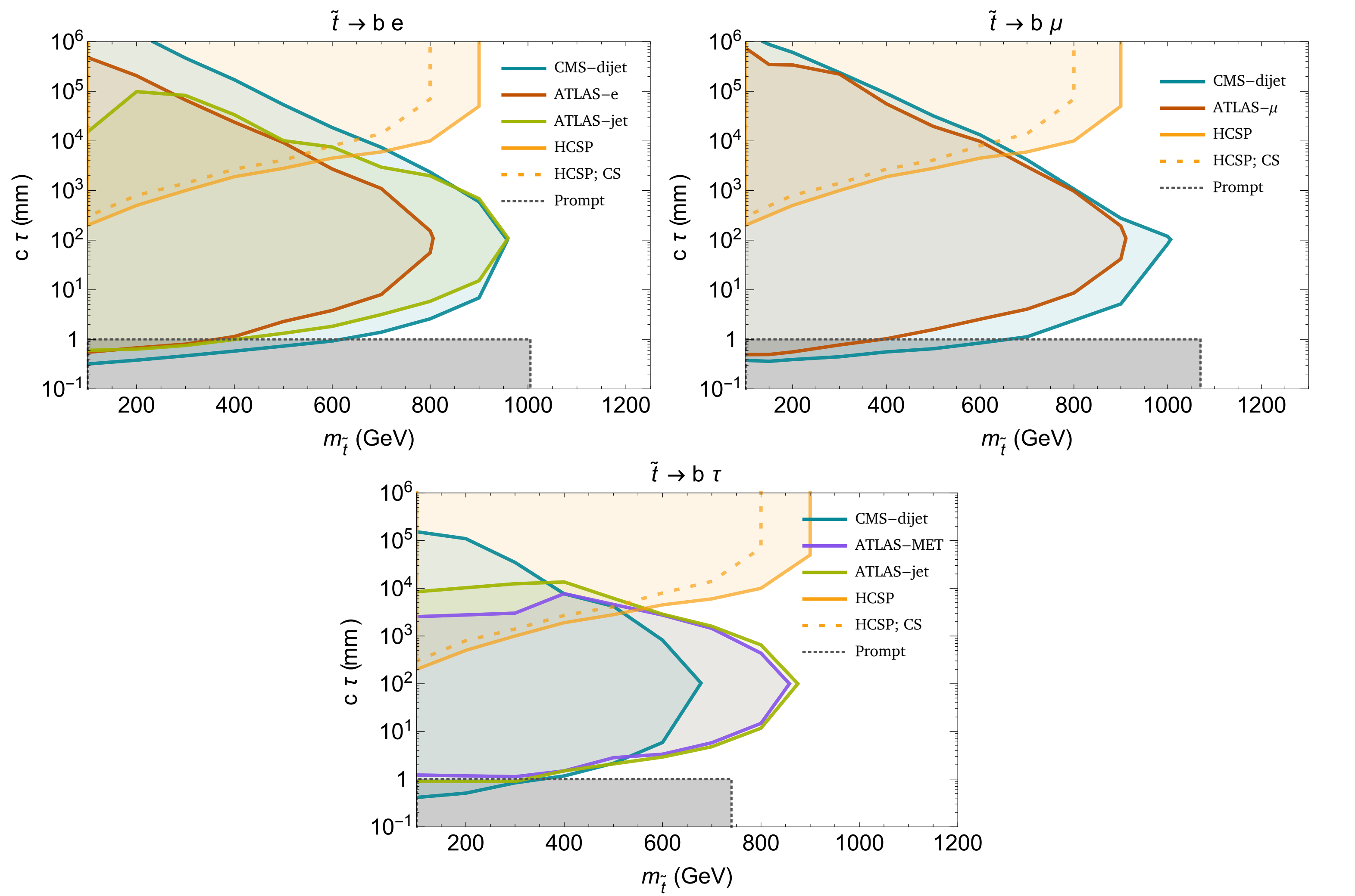
Stop bounds

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



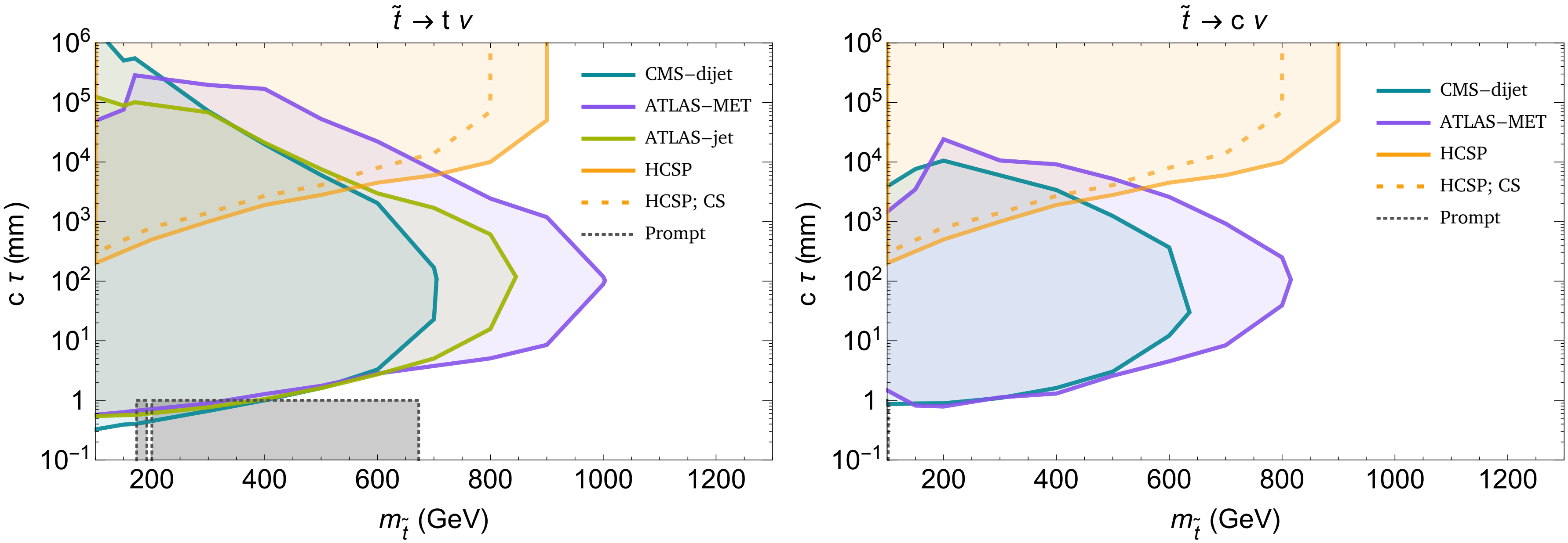
Stop bounds

• Direct stop production, $\tilde{t} \to d l^+$ type decay



Stop bounds

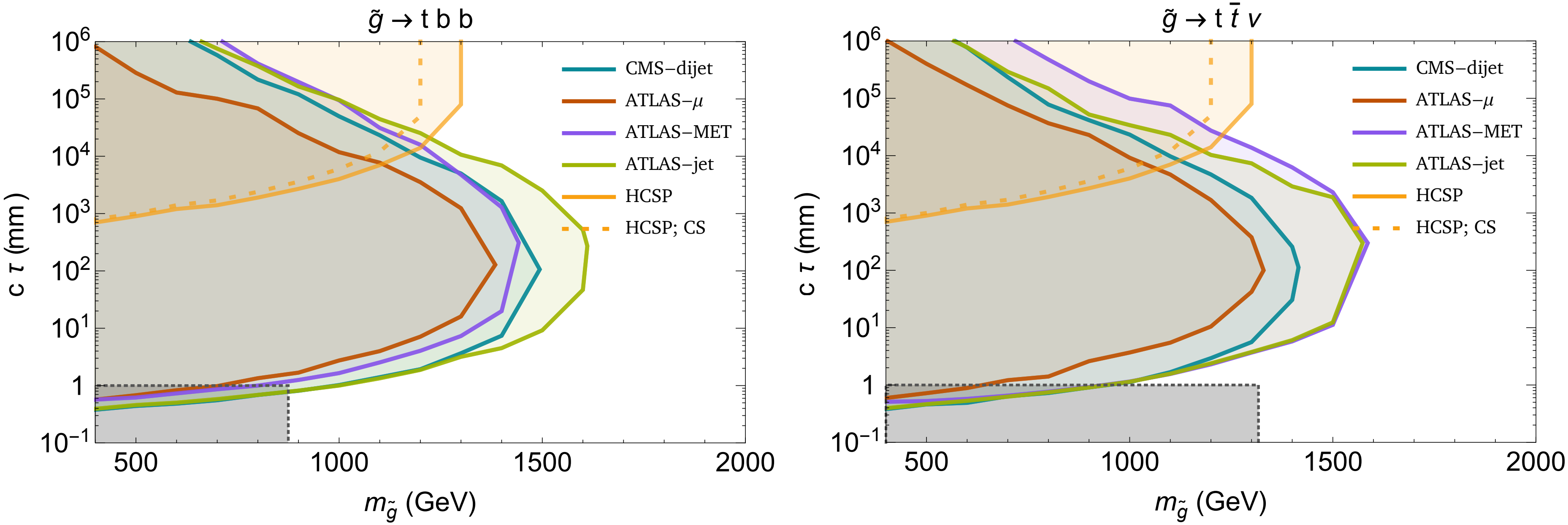
• Direct stop production, $\tilde{t} \to u\nu$ type decay



• Prompt decays likely constrained, but no search result directly applicable, need recasting)

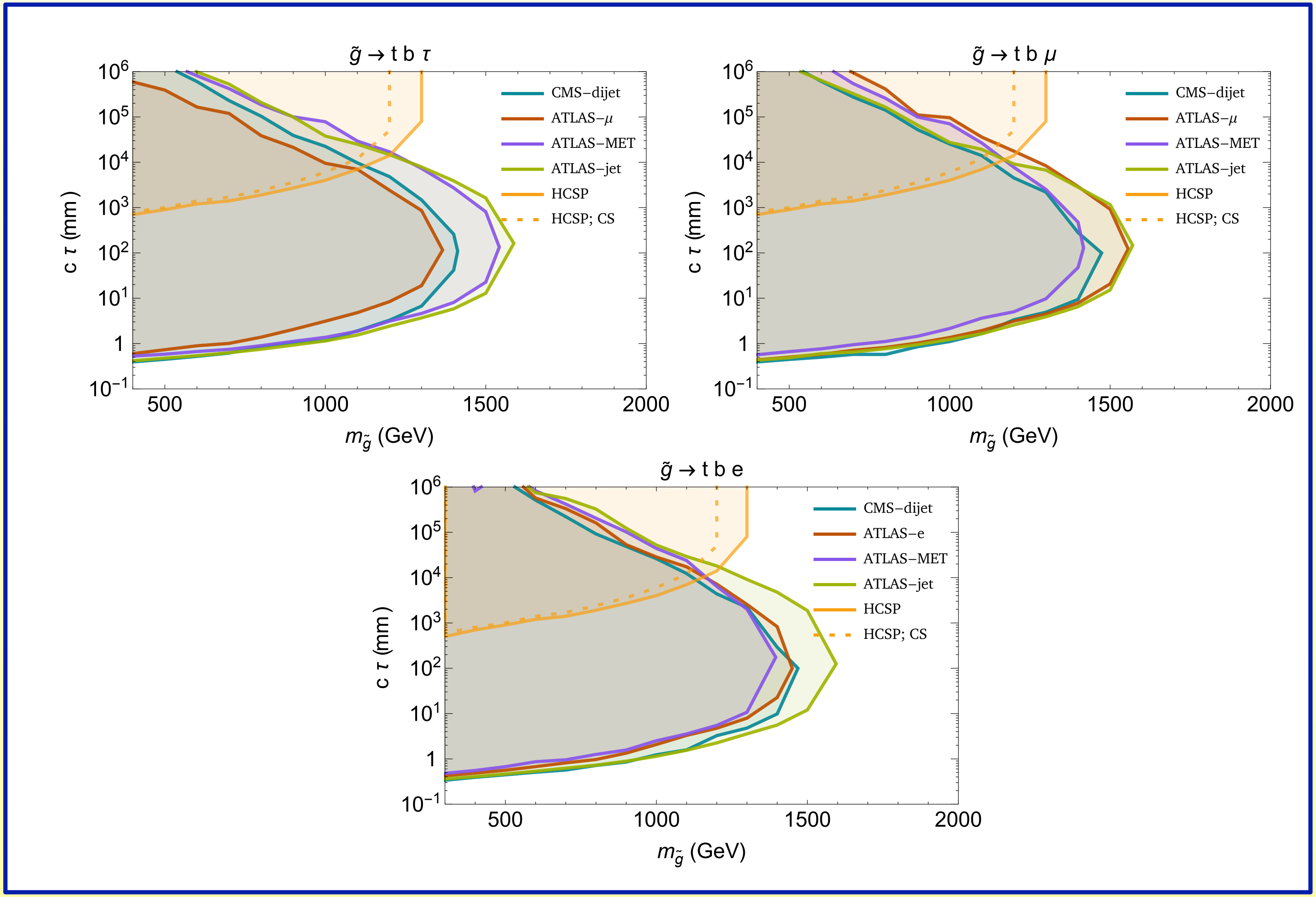
Gluino bounds

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



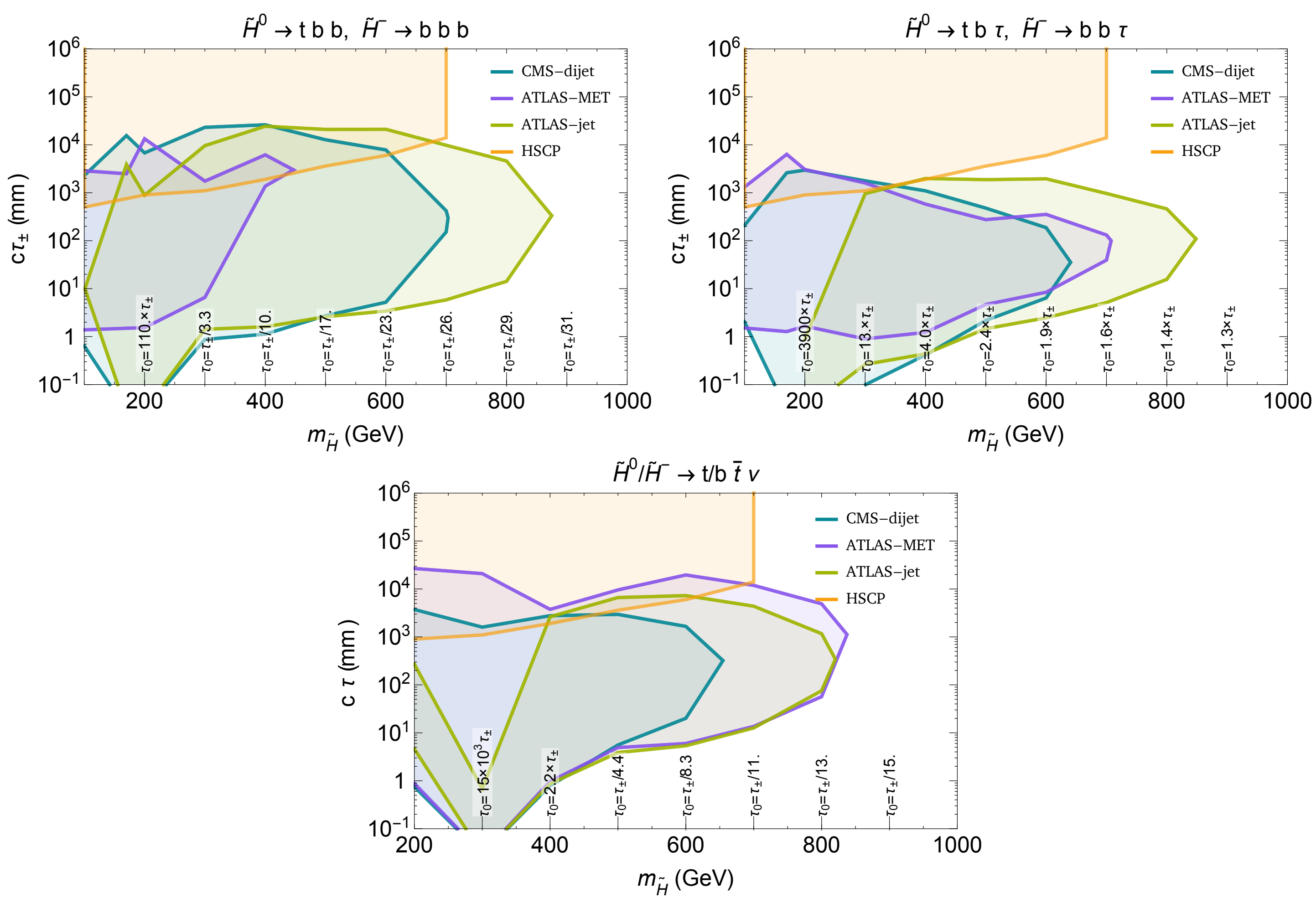
Gluino bounds

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



Higgsino bounds

- Direct higgsino production, three body decays via stop



Displaced SUSY

- Bounds quite strong, usually > TeV

- Displaced SUSY does not save naturalness, best bet is prompt fully hadronic decays

Displaced Higgs decays as signals of Neutral Naturalness

- A radical approach to hierarchy problem is top partners not colored (or maybe not charged under SM at all)

- Twin Higgs is most well-known example

(Chacko, Goh, Harnik)

- SM gauge group doubled, twin sector related by Z_2 symmetry to SM

- Other examples: Folded SUSY, quirky little Higgs, orbifold Higgs

Displaced Higgs decays as signals of Neutral Naturalness

•Phenomenology depends strongly on details of mirror sector.

•Interesting possibility: no light mirror quarks. In models with EW charged mirror this is a must.

•``Fraternal twin Higgs", only twin partner for 3rd generation (Craig, Katz, Strassler, Sundrum)

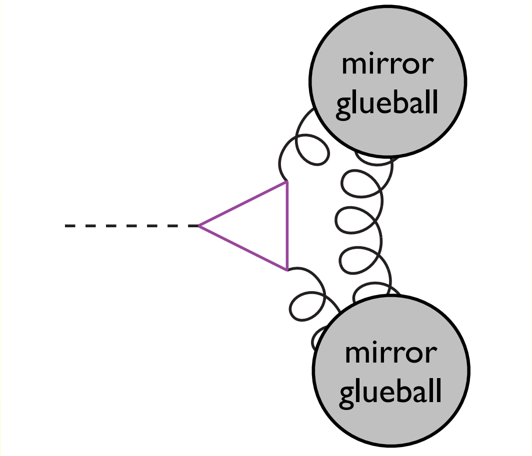
•Folded SUSY (Burdman, Chacko, Goh, Harnik)

•This case there will be light glueballs of QCD' which can mix with SM Higgs

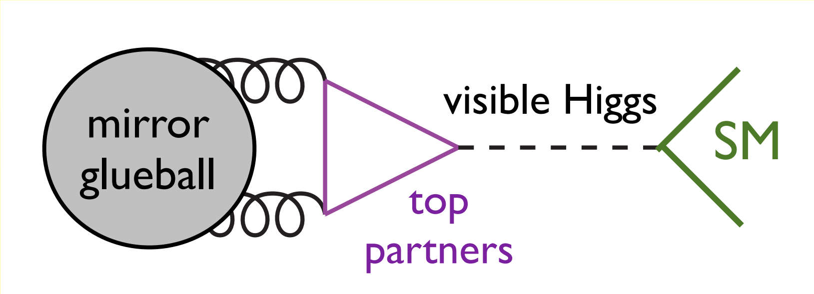
$$\mathcal{L}^{(6)} = \frac{\alpha_v\, y^2}{3\pi\, M^2}\, H^\dagger H \,\mathrm{tr}\, \mathcal{F}_{\mu\nu}\mathcal{F}^{\mu\nu}$$

Displaced Higgs decays as signals of Neutral Naturalness

- SM Higgs can decay to mirror glueballs



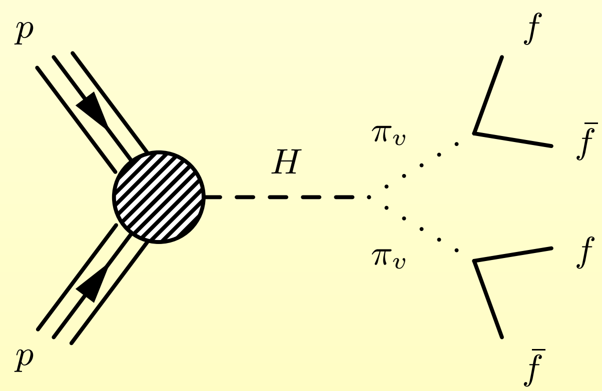
- Which can decay back to SM particles via mixing with Higgs



(Figures from David Curtin)

Displaced Higgs decays as signals of Neutral Naturalness

- Results in exotic Higgs decays which can be displaced depending on the lifetimes of the glueballs



- We will be looking for this decay, without assuming anything else about the model, leave glueball mass, lifetime free parameter. Assume decay according to Higgs couplings.

Displaced Higgs decays

(Kuflik, Lombardo, Slone, C.C.)

- Run I analysis: assuming Higgs decays to 2 invisible particles, which in turn decay with couplings set by the SM Higgs couplings (but branching ratios differ due to phase space)

- Existing ATLAS analysis: require two displaced decays in same event. Two possible signals

- Decays in muon chamber (solid line)

- Decays in hadronic calorimeter (dashed line)

- No sensitivity for smaller lifetimes - most unconstrained region for twin Higgs type models

Displaced Higgs decays

- Used existing tracker analysis to set bounds from existing Run I data on smaller lifetimes

- Used CMS displaced dijet search based on displaced jet trigger (requiring two displaced jets)

- ATLAS displaced tracker searches give no constraint - usually require higher momentum triggers, but Higgs 125 GeV, intermediate particles 10-60 GeV mass, nothing really hard...

- Also light particles imply low track multiplicities, and typical DV searches require ≥ 5 tracks.

Displaced Higgs decays

- CMS displaced dijet trigger has track displacement requirement in the trigger

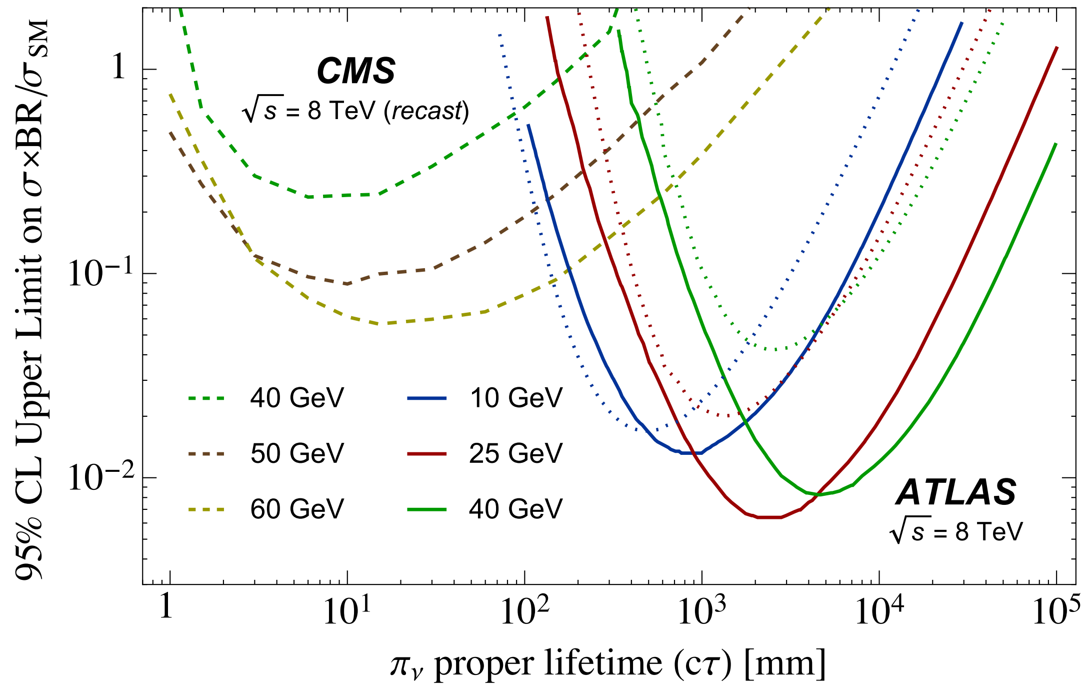
- ATLAS has no displacement requirement in triggers relevant for shorter lifetimes (displaced triggers are used for the ATLAS muon and HCAL searches)

- CMS trigger can have much lower momentum thresholds for short lifetimes helping for displaced Higgs decays

- This issue might also be also relevant for Run II

Bounds from Run I

- First bounds on short lifetimes ≤10 cm from CMS displaced dijet search



Triggers for Run II

Trigger	Trigger Requirement
Displaced jet	$H_T > 175$ GeV or three jets with $p_T^{j_{1,2,3}} > (92, 76, 64)$ GeV, $\|\eta_{j_{1,2,3}}\| < (5.2, 5.2, 2.6)$ with $\|\eta_{j_1}\|$ or $\|\eta_{j_2}\| < 2.6$, and two of the three jets satisfying $m_{jj} > 500$ GeV, and $\Delta\eta > 3.0$. A displaced jet satisfying $p_T > 40$ GeV, at most 1 prompt track (2D IP $<$ 2.0 mm) [a], and at least 2 displaced tracks.
Inclusive VBF	Two jets with $\|\eta_{j_1,j_2}\| > 2$, $\eta_{j_1} \cdot \eta_{j_2} < 0$, $\|\eta_{j_1} - \eta_{j_2}\| > 3.6$ and $m_{j_1,j_2} > 1000$ GeV.
VBF, h $\to b\bar{b}$	Three jets with $p_T^{j_{1,2,3}} > (112, 80, 56)$ GeV and $\|\eta_{j_{1,2,3}}\| < (5.2, 5.2, 2.6)$ and at least one of the two first jets with $\|\eta_{j_1}\|$ or $\|\eta_{j_2}\| <$ 2.6.
Isolated Lepton	One lepton with $p_T > 25$ GeV, $\|\eta\| < 2.4$, and 3D IP $<$ 1 mm. Isolation requires the summed p_T of all tracks with $p_T > 1$ and within $\Delta R < 0.2$ of the lepton is less than 10% of the lepton p_T.
Trackless jets	A jet with $p_T > 40$ GeV and $\|\eta\| < 2.5$ matched with a muon with $p_T > 10$ GeV within $\Delta R = 0.4$. No tracks with $p_T > 0.8$ GeV in the ID within a $\Delta\phi \times \Delta\eta$ region of 0.2×0.2.

Triggers for Run II

- CMS displaced jet trigger: similar as for Run I but lower trigger thresholds (but 4 x larger Impact Parameter) and only one displaced jet

- VBF: usual VBF trigger - forward and backward jet, large invariant mass

- Isolated lepton: isolated from jets (to exclude decays from heavy quarks)

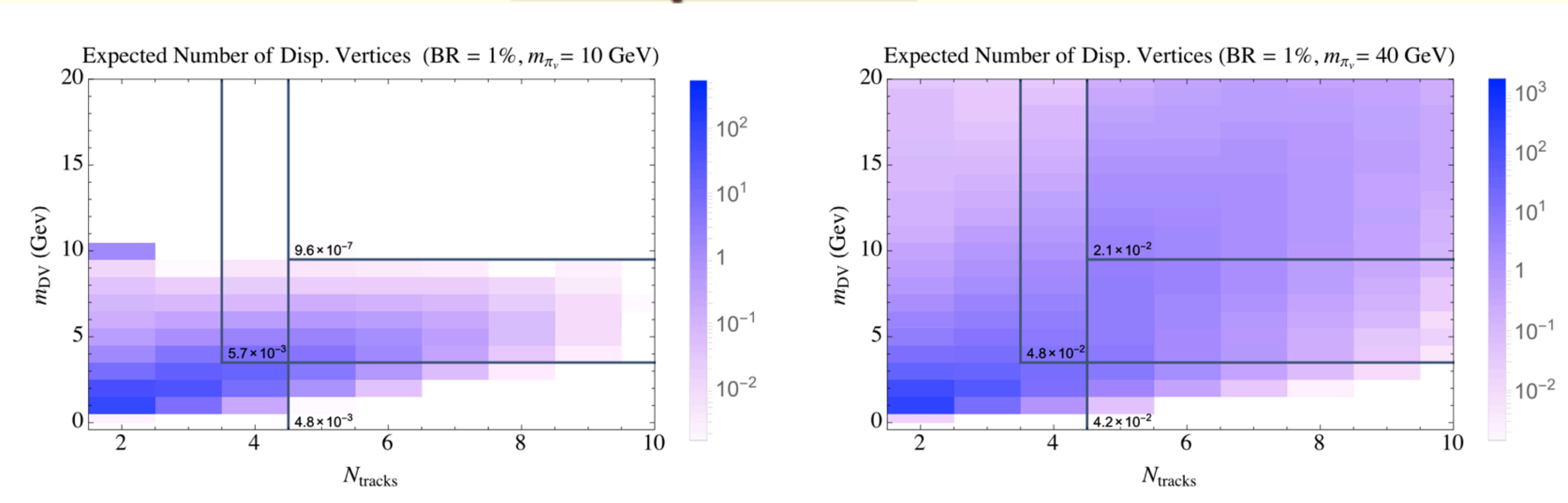
- Trackless jets (ATLAS only): jets w/o tracks in pixel detector

Acceptances

Trigger	m_{π_v} (GeV)	$c\tau = 1$ mm				$c\tau = 10$ mm				$c\tau = 100$ mm			
		ϵ_{ggF}	ϵ_{VBF}	ϵ_{VH}	ϵ_{Total}	ϵ_{ggF}	ϵ_{VBF}	ϵ_{VH}	ϵ_{Total}	ϵ_{ggF}	ϵ_{VBF}	ϵ_{VH}	ϵ_{Total}
Displaced jet	10	0.4%	1.3%	1.1%	**0.5%**	12.6%	20.2%	25.1%	**13.7%**	17.1%	42.0%	34.7%	**19.8%**
	25	0.2%	0.8%	0.7%	**0.3%**	7.6%	20.4%	16.9%	**8.9%**	17.2%	45.3%	37.3 %	**20.2%**
	40	0.3%	1.0%	0.9%	**0.4%**	7.3%	19.7%	16.4%	**8.6%**	16.3%	44.6%	36.3%	**19.3%**
Inclusive VBF	10	1.9%	15.5%	0.8%	**2.8%**	1.8%	15.5%	0.7%	**2.8%**	1.6%	15.1%	0.6%	**2.6%**
	25	1.7%	15.3%	0.7%	**2.7%**	1.7%	15.3%	0.7%	**2.7%**	1.6%	15.2%	0.6%	**2.6%**
	40	1.6%	15.2%	0.7%	**2.6%**	1.6%	15.2%	0.7%	**2.6%**	1.6%	15.2%	0.6%	**2.6%**
VBF, $h \to b\bar{b}$	10	5.8%	20.3%	13.1%	**7.2%**	5.8%	20.2%	13.0%	**7.2%**	3.5%	13.3%	8.1%	**4.4%**
	25	4.6%	16.6%	10.9%	**5.8%**	4.7%	16.7%	10.9%	**5.9%**	4.2%	15.2%	9.7%	**5.3%**
	40	4.0%	14.2%	9.2%	**5.0%**	4.0%	14.2%	9.2%	**5.0%**	3.8%	13.9%	8.9%	**4.8%**
Isolated Lepton	10	3.6%	3.7%	14.7%	**4.1%**	1.0%	1.0%	12.5%	**1.5%**	0.1%	0.2%	11.8%	**0.6%**
	25	1.0%	1.5%	13.0%	**1.6%**	0.3%	0.4%	11.9%	**0.8%**	0.05%	0.07%	11.7%	**0.6%**
	40	1.0%	1.4%	12.6%	**1.6%**	0.3%	0.4%	11.9%	**0.8%**	0.05%	0.07%	11.6%	**0.6%**
Trackless jet	10	0.02%	0.04%	0.04%	**0.02%**	0.8%	1.5%	1.3%	**0.9%**	2.0%	2.4%	2.2%	**2.0%**
	25	0.02%	0.04%	0.06%	**0.02%**	0.5%	1.0%	0.8%	**0.6%**	3.6%	5.9%	5.0%	**3.8%**
	40	0.01%	0.02%	0.03%	**0.01%**	0.1%	0.2%	0.2%	**0.1%**	2.1%	4.1%	3.3%	**2.3%**

- Displaced dijet trigger is best except for very short lifetimes
- VBF with additional bbbar is taking over for <10 mm

Acceptances

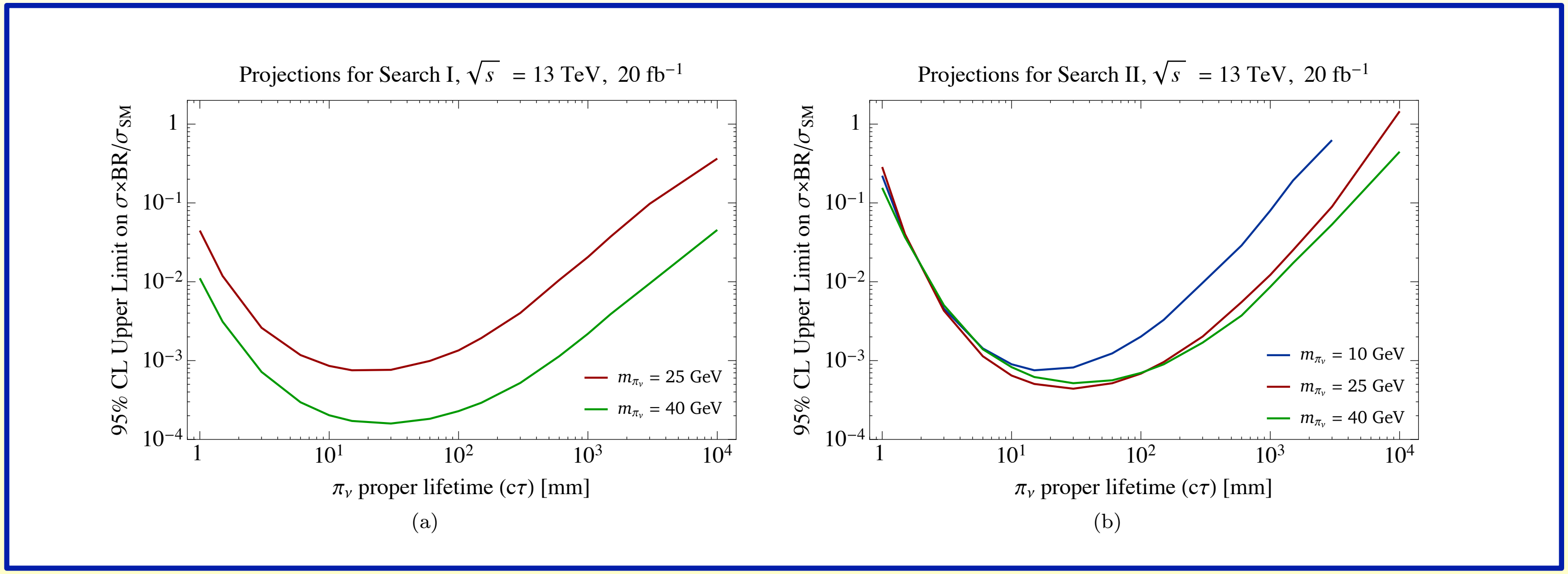


- Boxed regions: signal regions (# of tracks vs. mass of displaced vertex) - detector backgrounds outside

- For heavier particles fraction of signal in signal region. For light particles little signal left. Need to extend signal region - may have some background!

- Low track multiplicity! Need to modify tracker searches for light intermed. particles!

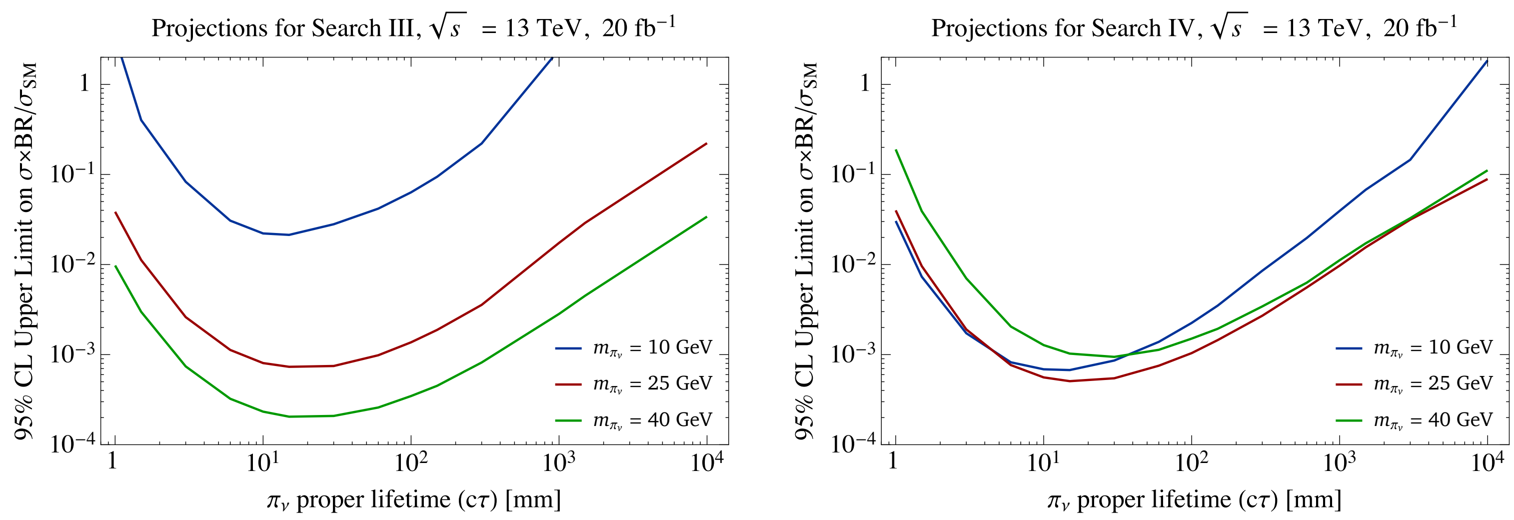
Projected Sensitivities Run II 20 1/fb



- Search I: one high mass (≥10 GeV) and ≥5 tracks single DV based on ATLAS search. Good for high mass ≥40 GeV

- Search II: One DV with high track multiplicity, no mass requirement to allow softer objects, but reproduce Higgs and intermed. particle masses

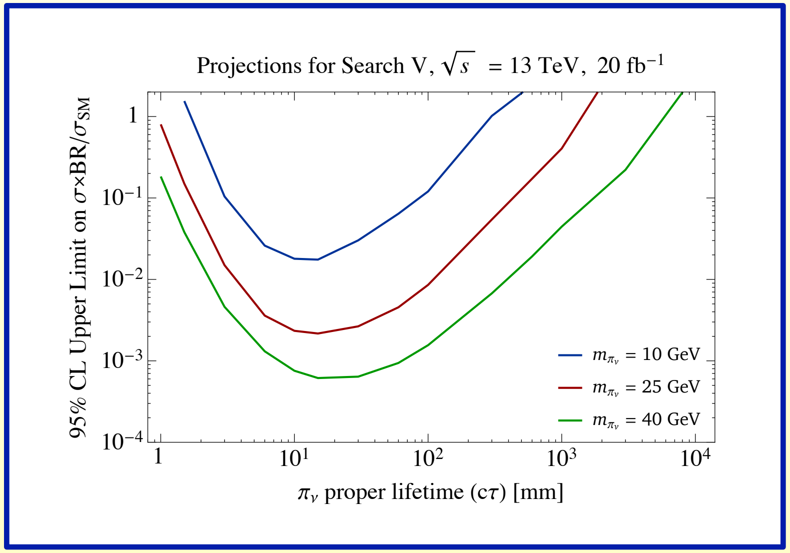
Projected Sensitivities Run II 20 1/fb



•Search III: one high mass (≥4 GeV), ≥4 tracks, pT≥ 8 GeV single DV with displaced dijet, similar to CMS dijet search

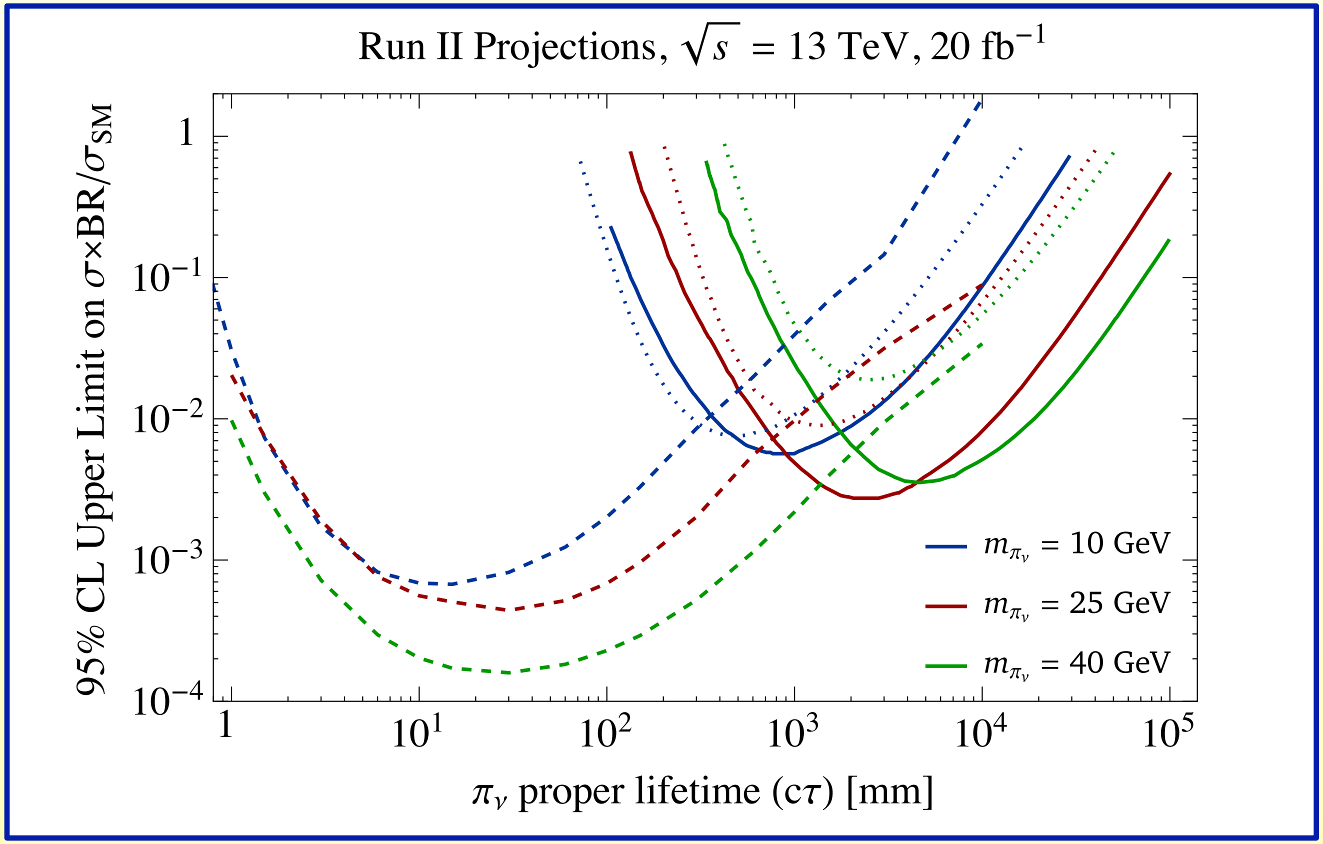
•Search IV: Same DV requirements as III but within a displaced jet with 2-prong substructure

Projected Sensitivities Run II 20 1/fb



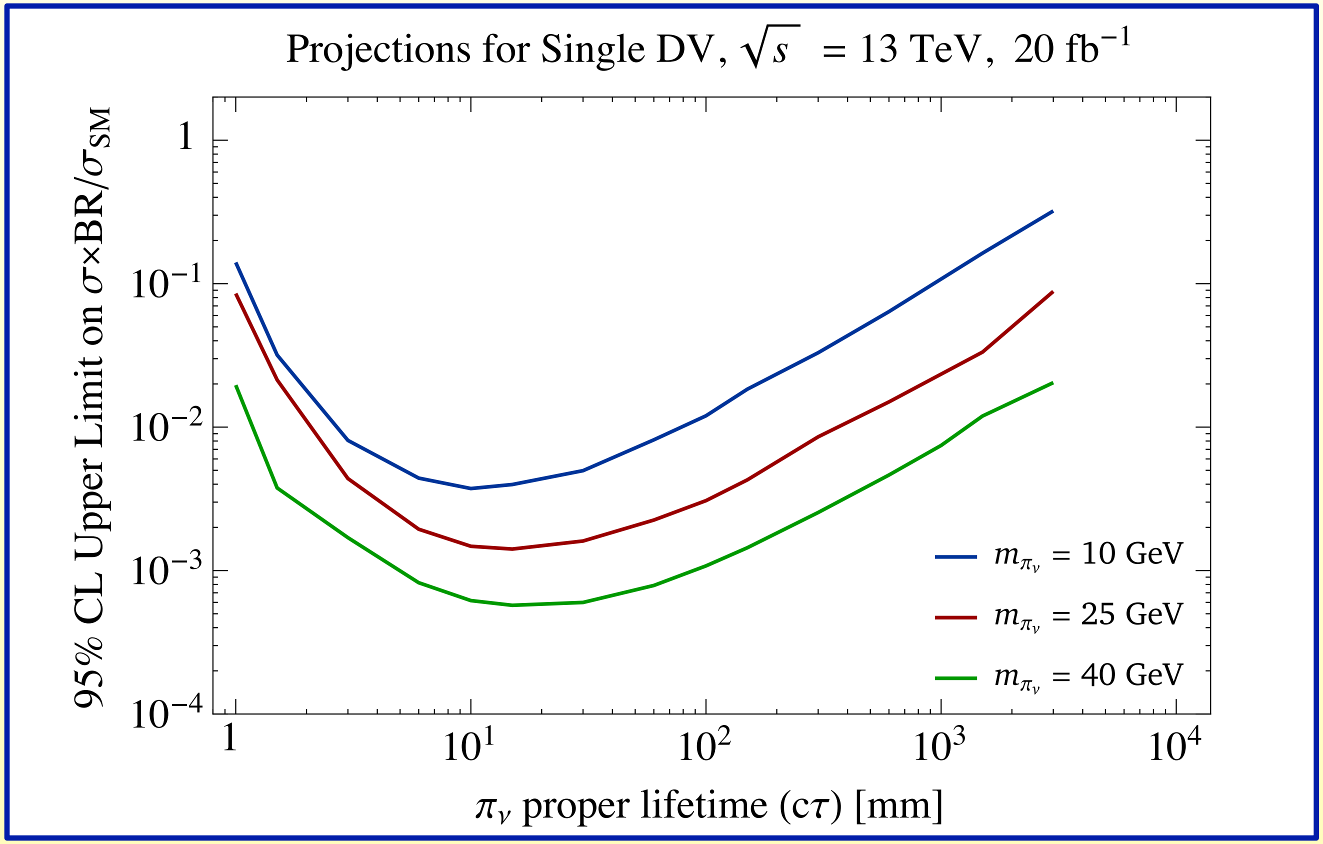
- Search V: two DV's with ≥5 tracks, as in ATLAS searches.

Projected Sensitivities Run II 20 1/fb



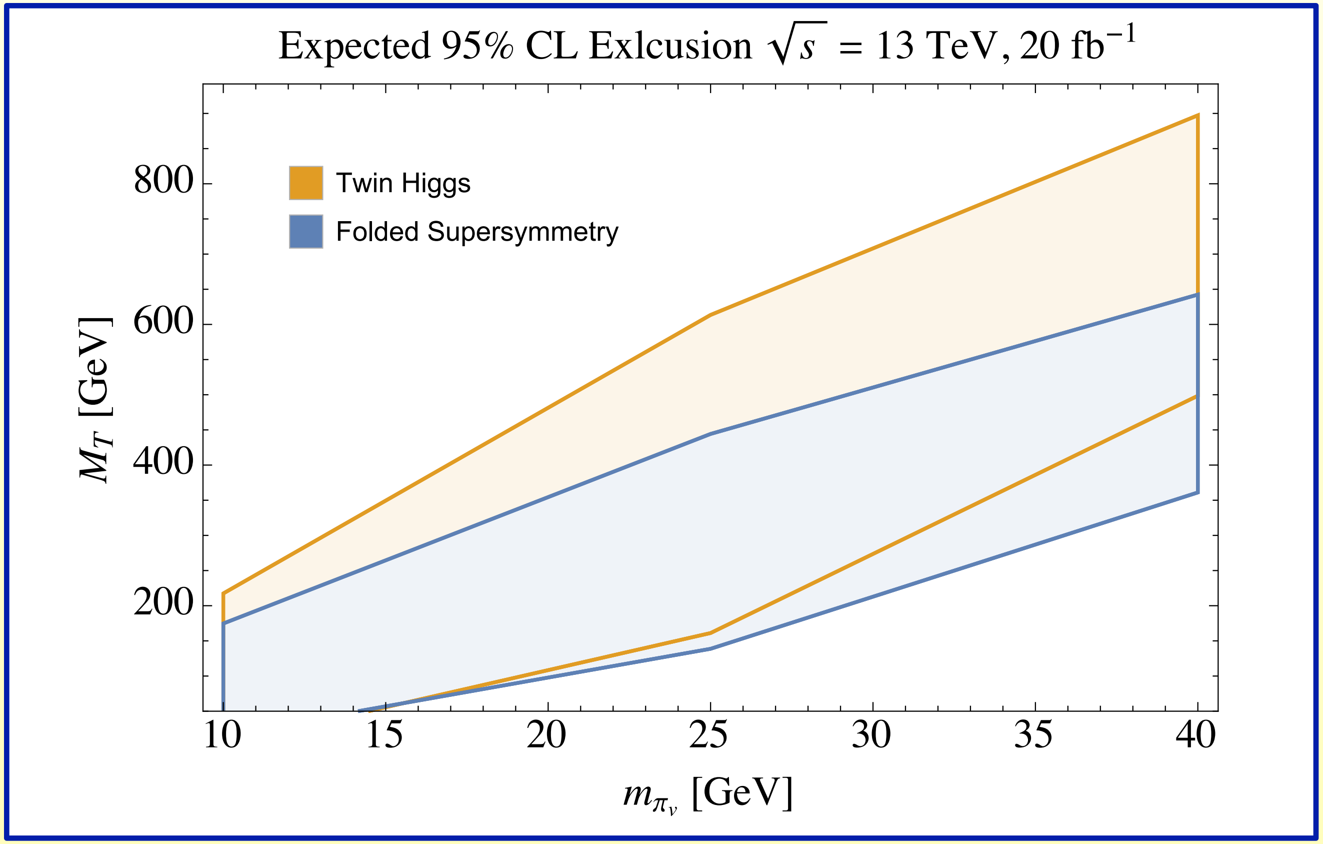
- Combined best sensitivities for five tracker searches and projected ATLAS result based on rescaling cross sections

Projected Sensitivities Run II 20 1/fb



- Combined sensitivity for case with just one displaced vertex, assuming the second particle just escapes the detector.

Projected Sensitivities Run II 20 1/fb



- Exclusion regions for top-partner mass vs. mirror glueball mass in Fraternal Twin Higgs (mirror top) and Folded SUSY (stop) models expected in Run II

Summary

- RPV can give different phenomenology

- dRPV: generate RPV in hidden sector. Mediation to visible sector will make it naturally suppressed

- Often gives rise to displaced vertices.

- Recasted CMS and ATLAS displaced vertex searches

- Bounds generically very strong, unless prompt fully hadronic decays of LSP. Stop > TeV.

- Neutral naturalness models often result in displaced Higgs decays

- Considered shorter lifetime tracker searches for displaced Higgs decays. First bounds from Run I, Run II can have sensitivities down to ~ 10^{-4} branching ratios

BACKUP SLIDES

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:

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

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

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

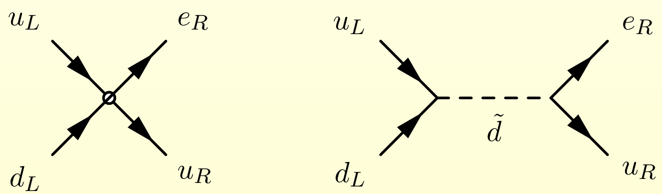
$$\eta \equiv \eta^0(1 + M\epsilon_X\bar{\theta}^2)$$

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

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

Proton decay

- Proton decay diagrams



- If chirally suppressed terms dominate

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

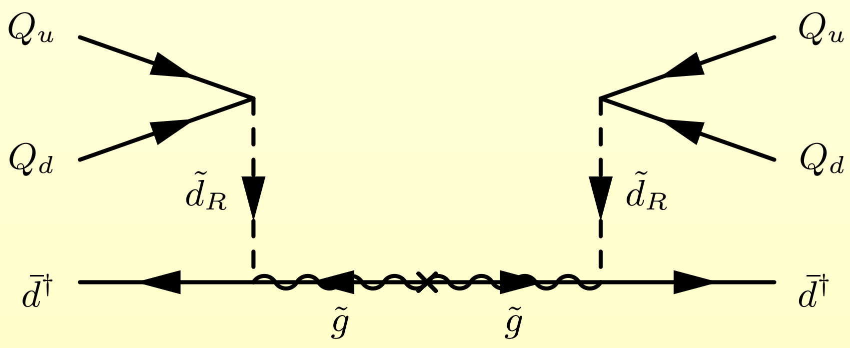
- If SUSY breaking terms dominate:

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

- 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)



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

- Dim 9 operator generated

- Suppression scale:

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

Low-energy constraints: ΔB=2

•n-nbar oscillation bound:

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

$$\tau_{n-\bar{n}} \simeq 3\times10^8 \text{ s} \left(\frac{m_{\tilde{d}_{R1}}}{\text{TeV}}\right)^4 \left(\frac{m_{\tilde{g}}}{\text{TeV}}\right) \left(\frac{4\times10^{-2}}{\eta''_{111}}\right)^2 \left(\frac{10^{-5}}{\epsilon_X}\right)^2$$

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

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

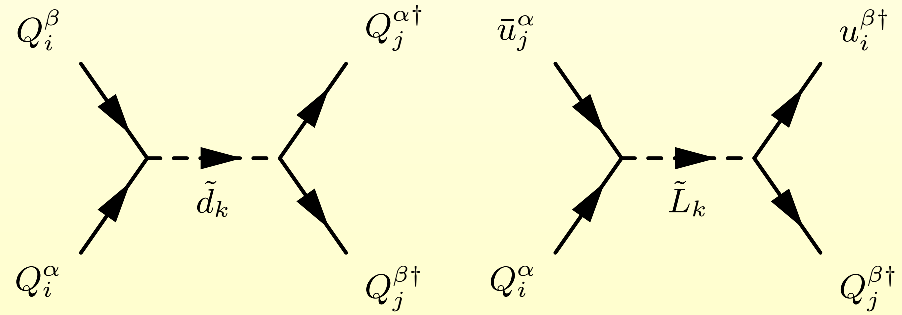
$$\Gamma \simeq \frac{8}{\pi}\frac{\rho_N}{m_N^2}\frac{\tilde{\Lambda}_{QCD}^{10}}{\Lambda_{pp}^{10}}$$

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

$$\tau_{pp} \simeq 5\times10^{32} \text{ yr} \left(\frac{m_{\tilde{d}_{R,k}}^8 m_{\tilde{g}}^2}{\text{TeV}^{10}}\right) \left(\frac{10^{-1}}{\eta''_{pp}}\right)^4 \left(\frac{10^{-5}}{\epsilon_X}\right)^4$$

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...

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

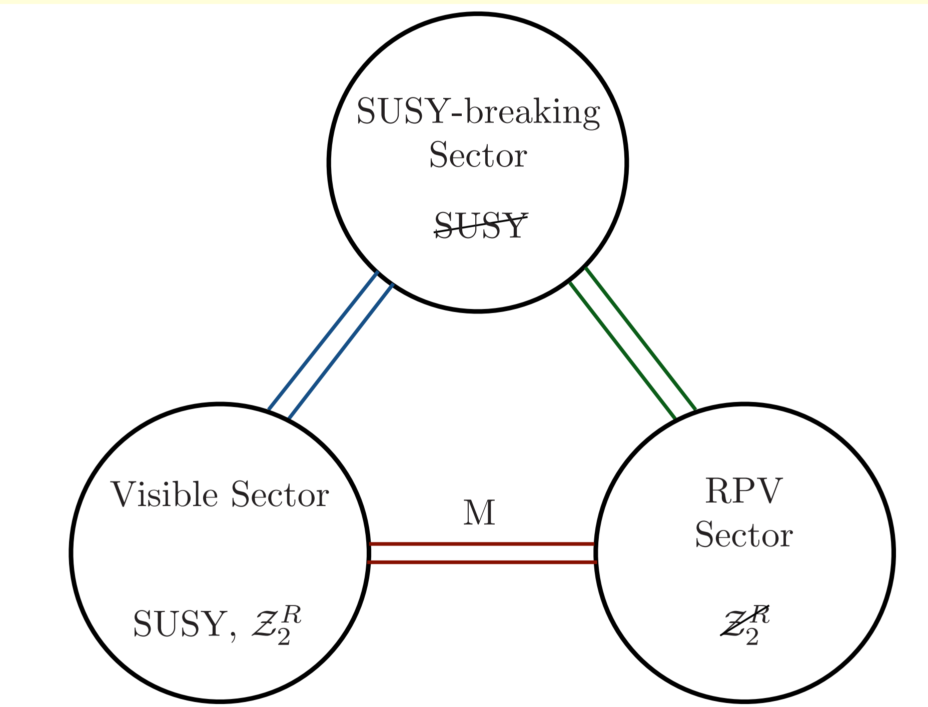
- Low energy effective theory:

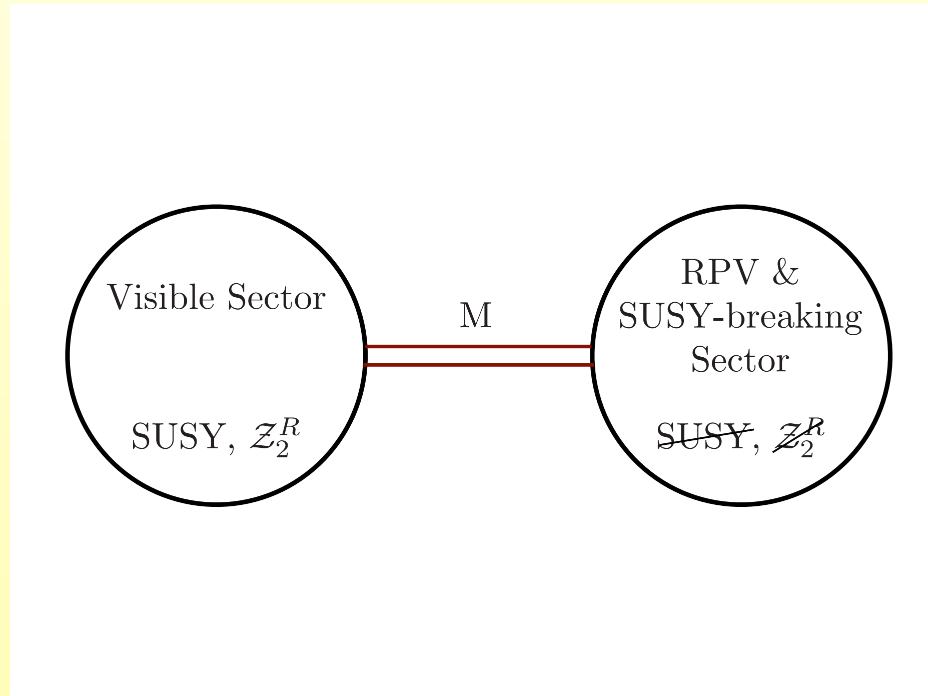
$$
\begin{aligned}
W_{\rm eff} \;=\; & W_{\rm MSSM} \\
K_{\rm eff} \;=\; & |q_i|^2 + |\bar{u}_i|^2 + |\bar{e}_i|^2 + \left(\delta_{ij} + \alpha^d_{ij} \frac{|S|^2}{M^2} \right) \bar{d}^*_j \bar{d}_i + \left(\delta_{ij} + \alpha^\ell_{ij} \frac{|S|^2}{M^2} \right) \ell^*_j \ell_i \\
& + \eta_{ijk} \frac{S^*}{M^2}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

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

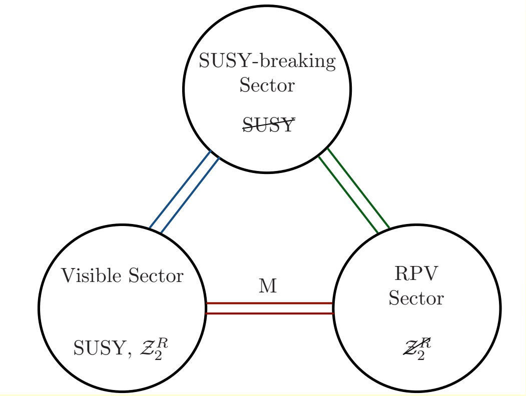
Effect of SUSY breaking

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

- z's have F-terms

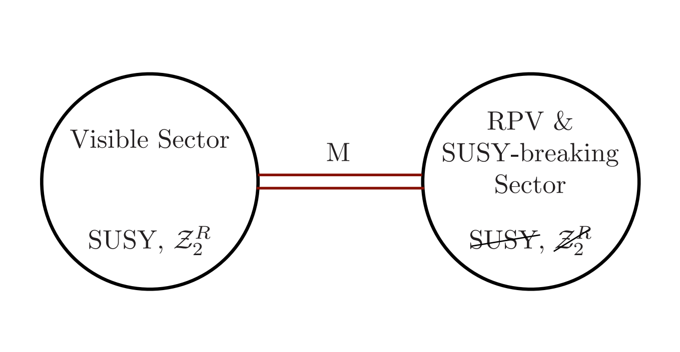
- Suppression of dRPV operator from SUSY breaking by $$\frac{F_{z^*_i}}{M} \sim \frac{\langle X^* \rangle F^*_X}{\Lambda^2 M} \sim \frac{\langle X^* \rangle}{\Lambda} \frac{m_0}{M}$$

- 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

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

- 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

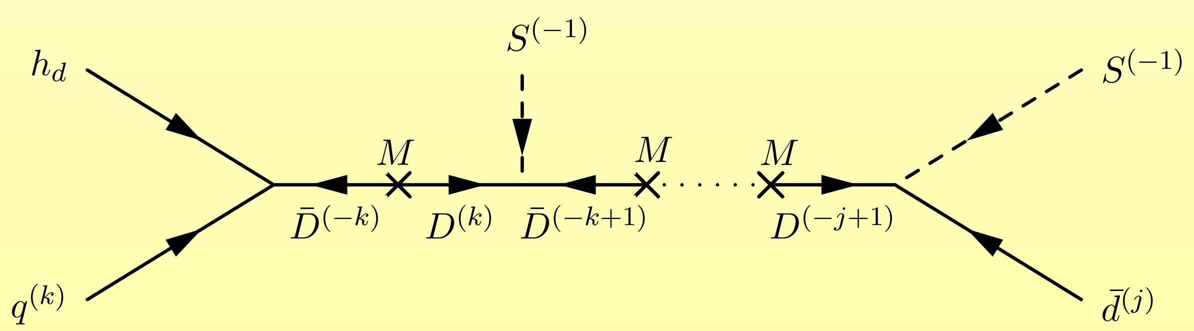
- FN messengers and RPV messengers same

- 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!)

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

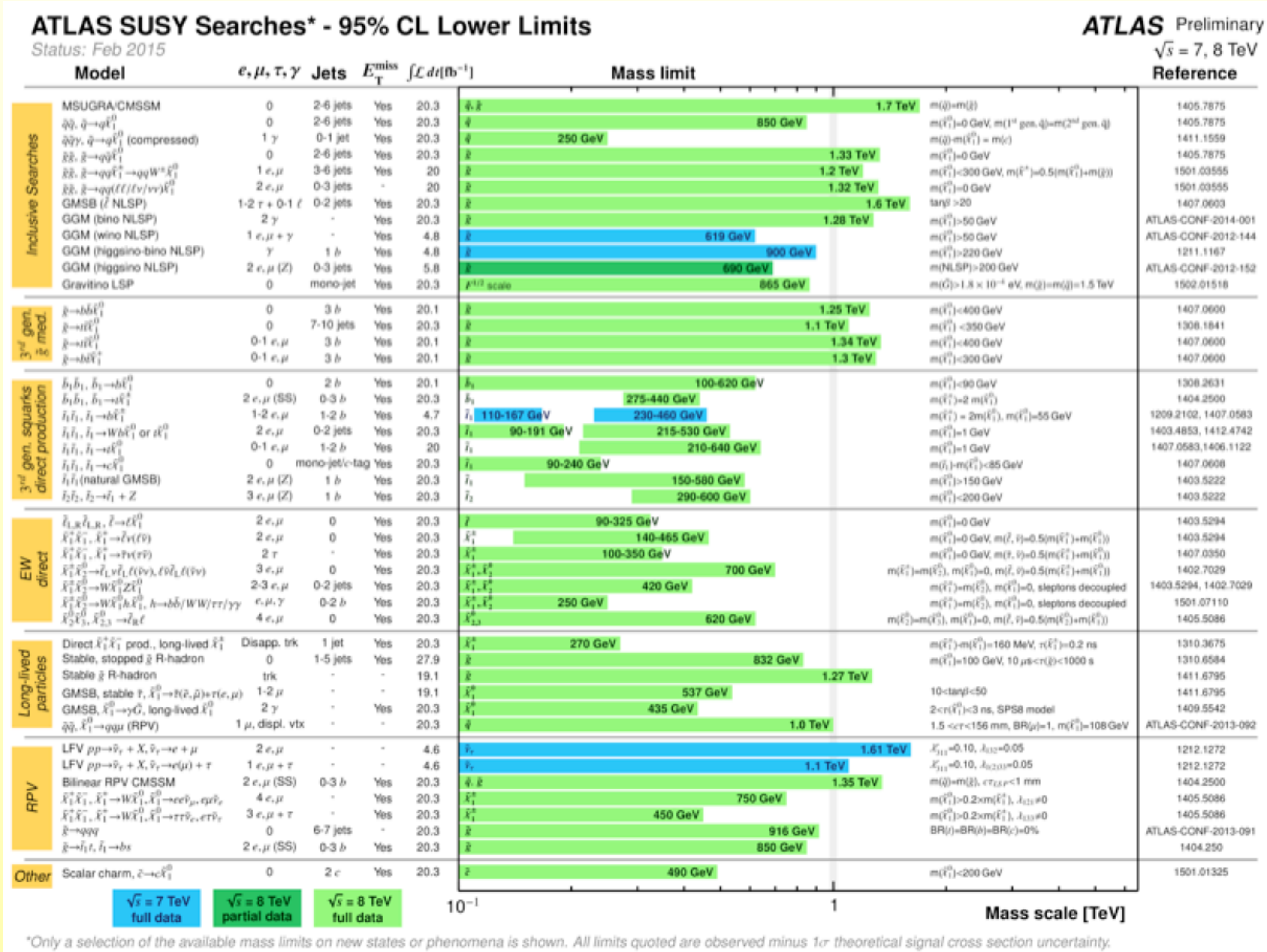
- Ways out: need additional sfermion masses either new gauge interactions or more messengers

- Hidden sector model does not have problem

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

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

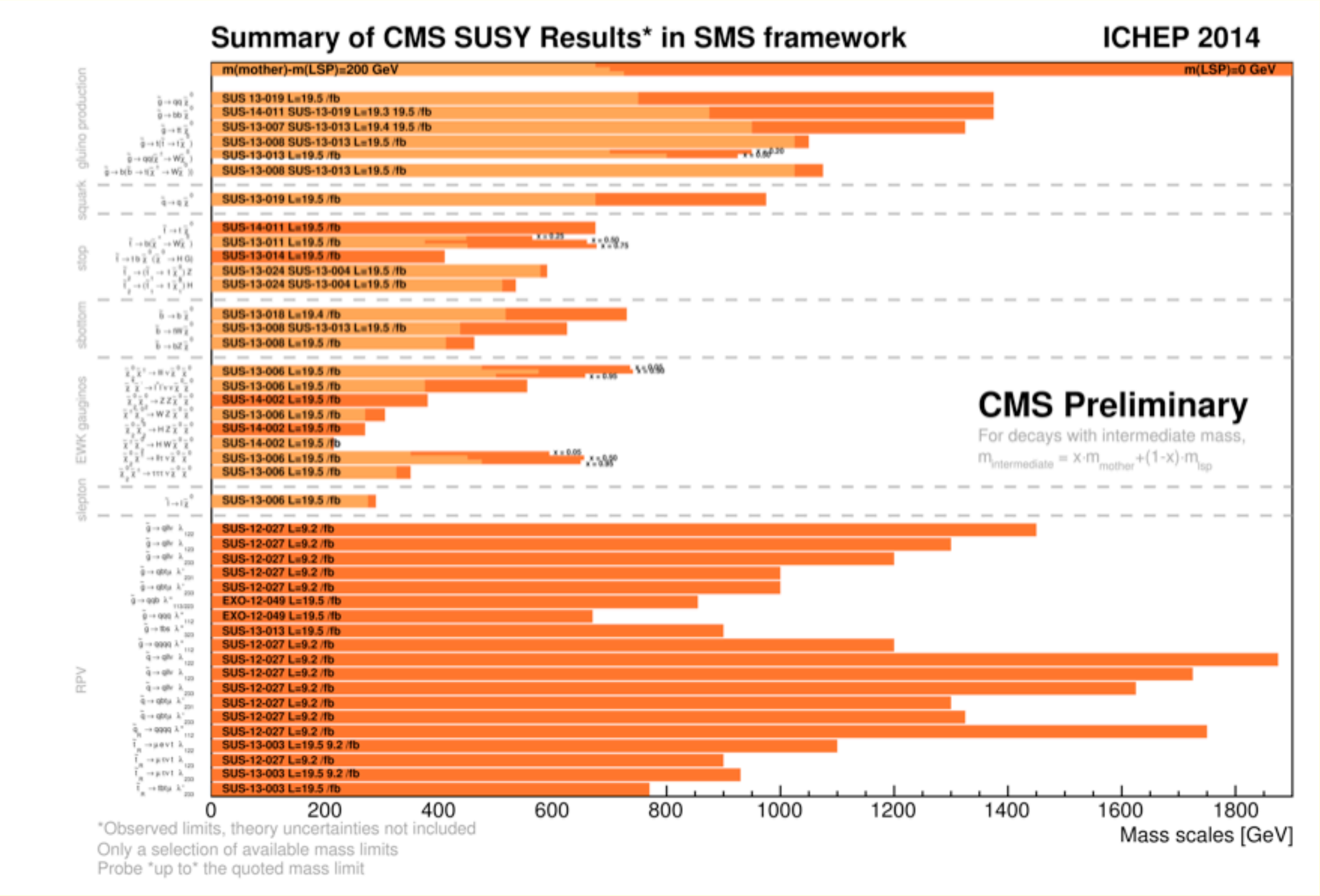
No sign of superpartners as of today from LHC



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