Dynamical R-parity Violation

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Particle Theory Seminar
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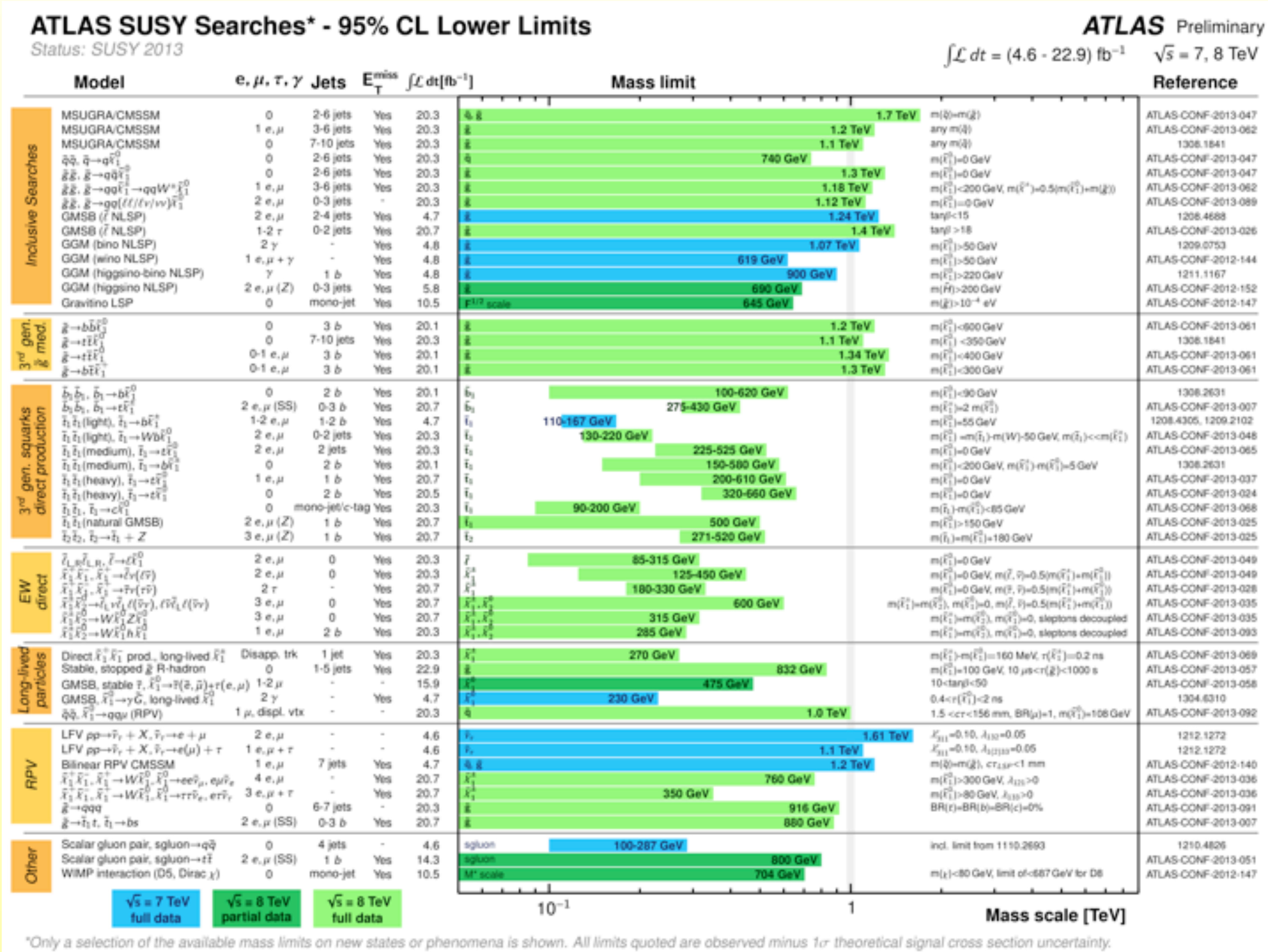
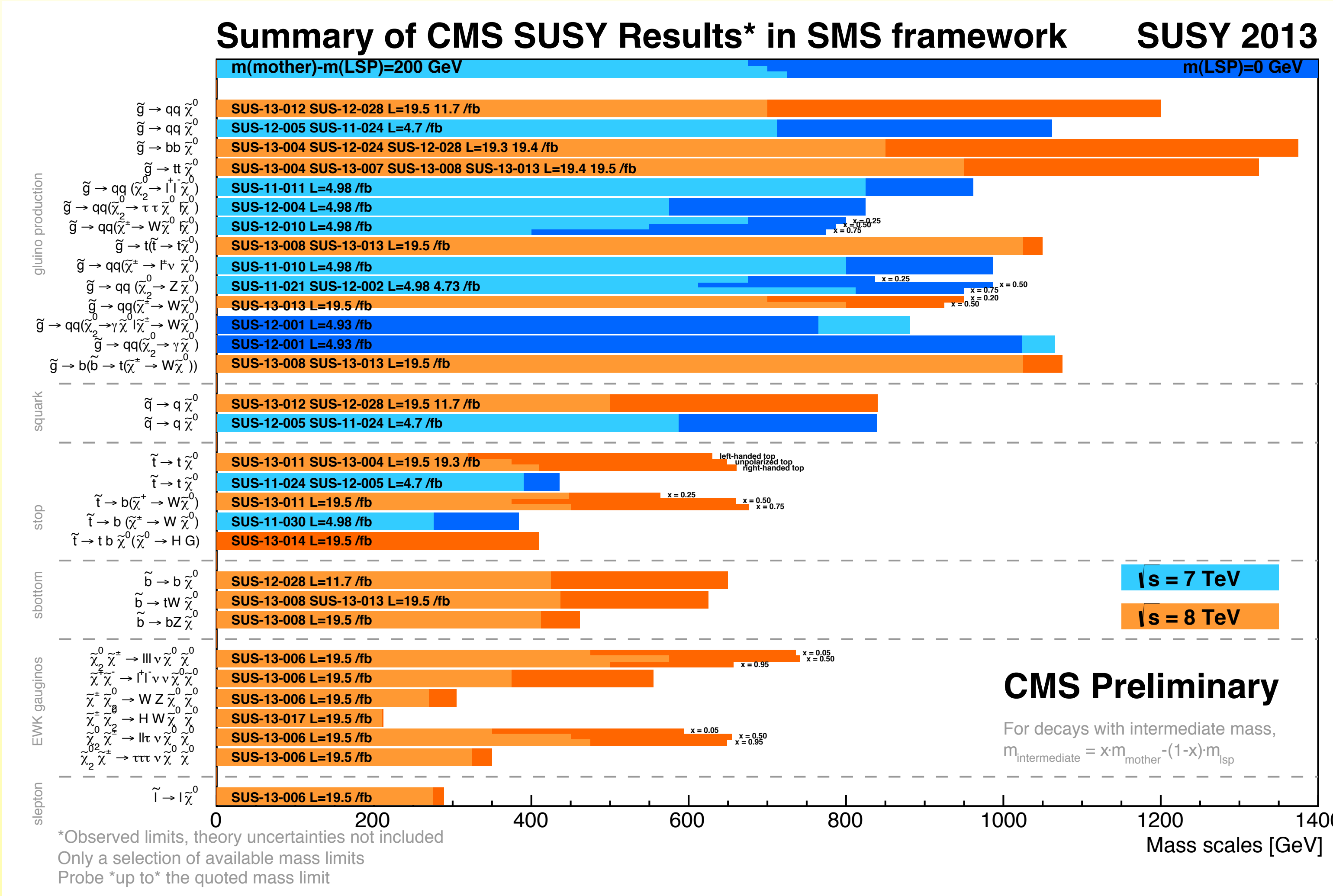
No sign of superpartners as of today from LHC



ATLAS SUSY bounds from SUSY 2013 Conference

Most involve missing ET, stable charged particle, or LFV

No sign of superpartners as of today from LHC



CMS SUSY bounds from SUSY 2013 Conference

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 MET due to RPV - focus of this talk

2. Spectrum not that degenerate - ``Natural SUSY" can be achieved via compositeness

3. Spectrum more degenerate/decays stealthy

4. Production more suppressed than in MSSM, eg. R-symmetric SUSY with Dirac gaugino masses

RPV in SUSY

- In my last talk here ~ 2 years ago showed an interesting scenario where

- RPV related to Yukawa couplings. Use existing small couplings. Very simple and predictive frameworks possible: MFV SUSY

(C.C., Grossman, Heidenreich ’11-`13 +Berger)

- This talk: RPV broken in hidden sector only. RPV operators automatically suppressed by F/M^2 . Operators can originate from Kähler potential - some not even catalogued till now!

(C.C., Kuflik, Volansky ’13 +Slone)

RPV in SUSY

- Usual MSSM assumptions:

R-parity conservation to eliminate large B,L violating superpotential terms

$$W_{RPV} = \lambda L L \bar{e} + \lambda' Q L \bar{d} + \lambda'' \bar{u}\bar{d}\bar{d} + \mu' L H_u$$

- Original observation:

``Matter parity”

$$(Q, \bar{u}, \bar{d}, L, \bar{e}) \rightarrow -(Q, \bar{u}, \bar{d}, L, \bar{e})$$

is a symmetry of wanted terms, but not of RPV terms

Usually impose this.

RPV in SUSY

- R-parity clearly NOT necessary in MSSM

- Can add very small RPV couplings and all experimental bounds satisfied, very different pheno

- Not very appealing: why would those very small numbers show up? Not natural...

- Also, many possibilities, not clear how to organize them...

- RPV usually not taken very seriously...

Recap of MFV SUSY

- Simple observation:

(C.C., Grossman, Heidenreich '11-`13 +Berger)

RPV terms are also not invariant under SU(3)^5 flavor symmetries

$$W_{RPV} = \lambda L L \bar{e} + \lambda' Q L \bar{d} + \lambda'' \bar{u}\bar{d}\bar{d} + \mu' L H_u$$

- If not too many sources of flavor violation survive at low-energies: could expect that RPV related to Yukawas

- Simplest (though not unique) assumption: only source for flavor breaking are Yukawas (MFV assumption)

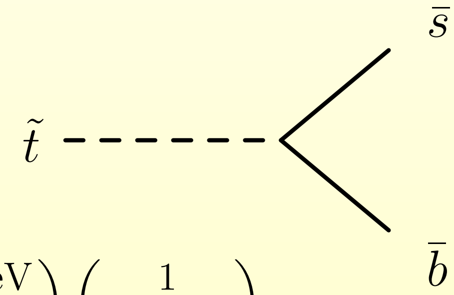
- Simplest model expect single chiral invariant

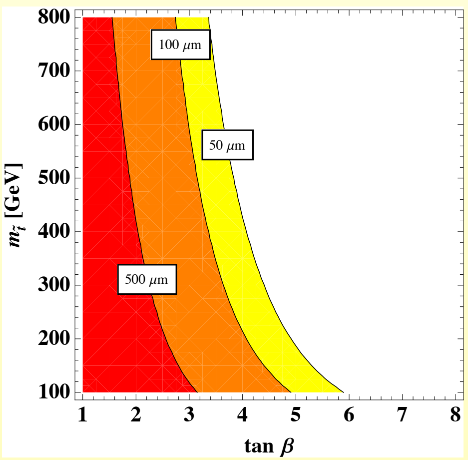
$$(Y_u \bar{u})(Y_d \bar{d})(Y_d \bar{d})$$

LHC phenomenology of MFV SUSY

- Depends on who is LSP

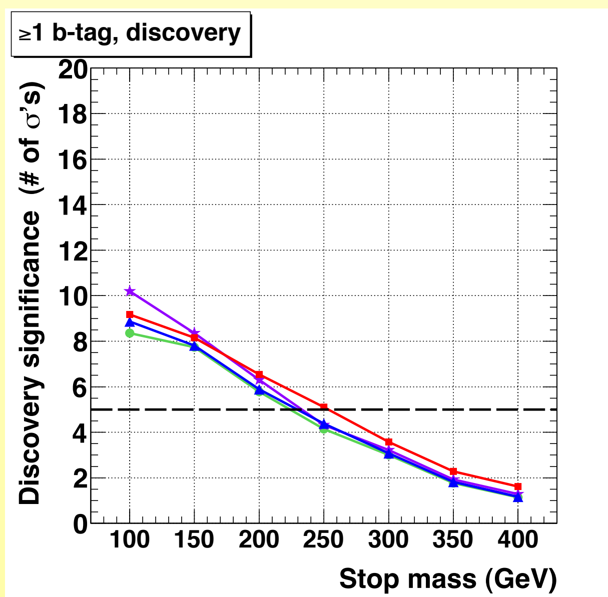
- Simplest possibility: stop LSP

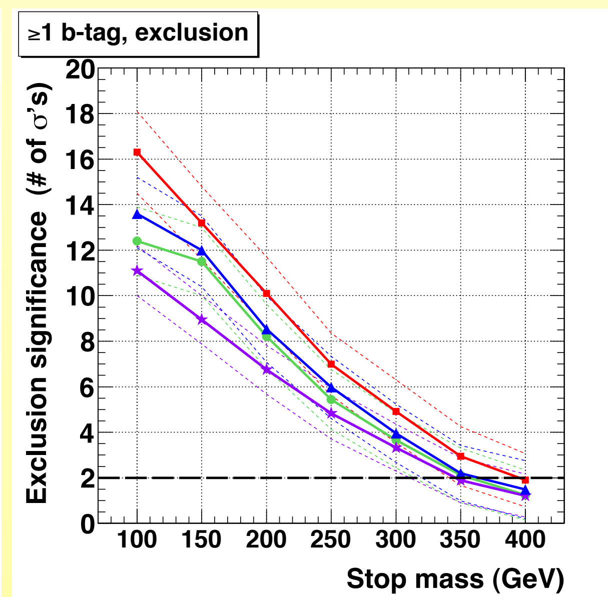




$$\tau_{\tilde{t}} \sim (2\ \mu\text{m}) \left(\frac{10}{\tan\beta}\right)^4 \left(\frac{300\ \text{GeV}}{m_{\tilde{t}}}\right) \left(\frac{1}{2\sin^2\theta_{\tilde{t}}}\right)$$

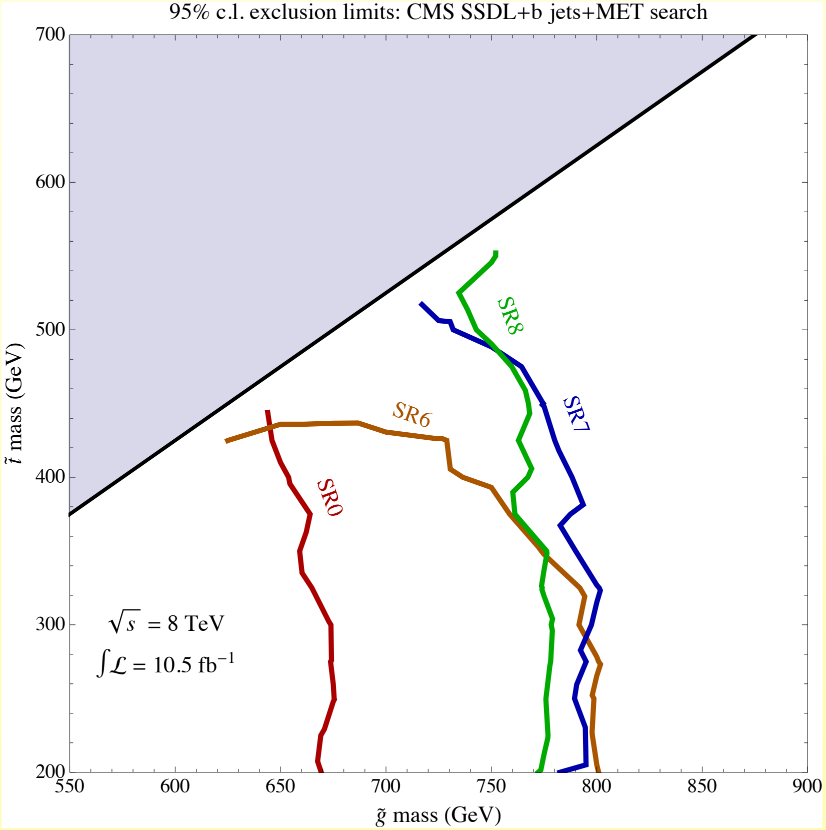
- Expected bounds from LHC run 1 (Bai, Katz, Tweedie `13)





Gluino bounds

- Same sign dilepton via gluino production (Berger, Perelstein, Saelim, Tanedo)



- m_{gluino}> 800 GeV, squarks could still be ~ 300 GeV

Dynamical RPV

(C.C., Kuflik, Volansky, ’13)

•Idea: RP conserved in visible sector

•Only broken in hidden sector where SUSY is broken. Same dynamics could be responsible for SUSY breaking and RPV!

•RPV operators may naturally be induced via Kähler potential and may or may not be present in superpotential

•Often $W_{RPV} = \lambda L L \bar{e} + \lambda' Q L \bar{d} + \lambda'' \bar{u}\bar{d}\bar{d} + \mu' L H_u$
NOT leading source for RPV!

Dynamical RPV

(C.C., Kuflik, Volansky, '13)

•Assumptions:

1. Dynamical RPV: RPV is broken dynamically in hidden sector

2. RPV is related to SUSY breaking: novel non-holomorphic operators may show up in the Kähler pot:

$$\mathcal{O}_{\rm nhRPV} = \eta_{ijk}\bar{u}_i\bar{e}_j\bar{d}_k^\dagger + \eta'_{ijk}Q_i\bar{u}_jL_k^\dagger + \frac{1}{2}\eta''_{ijk}Q_iQ_j\bar{d}_k^\dagger + \kappa_i\bar{e}_iH_dH_u^\dagger$$

$$\mathcal{O}_{\rm nhBL} = \kappa'_iL_i^\dagger H_d$$

Dynamical RPV

(C.C., Kuflik, Volansky, '13)

- Expectation: when coupled to SUSY breaking spurion $X = M + \theta^2 F_X$
- Will show up in Kähler potential

$$K_{\rm dRPV} = \frac{1}{X^\dagger}\mathcal{O}_{\rm nhRPV} + \frac{X}{M_{\rm Pl}}\mathcal{O}_{\rm nhBL}$$

- Can give new non-holomorphic (and often SUSY breaking) RPV terms
- SUSY breaking terms suppressed by

$$\epsilon_X \equiv F_X/M^2 \qquad \mathcal{O}(1) \text{ to } \mathcal{O}(10^{-16})$$

- SUSY preserving derivative coupling even more suppressed **explains smallness of RPV terms!**

Dynamical RPV (C.C., Kuflik, Volansky `13)

- Assumptions:

1. Dynamical RPV
2. RPV is related to SUSY breaking

3. Dynamical solution to SM flavor hierarchy. Use flavor dependent mediation scheme to generate additional hierarchies in the RPV terms.

E.g. a Frogatt-Nielsen type gauged U(1) could be responsible for most of gauge mediation (=flavor mediation), which will generate the hierarchies in the RPV terms. Could also use partial compositeness...

Holomorphic or non-holomorphic?

- Which operator will dominate?

$$\mathcal{O}_{\rm hRPV} = \frac{1}{2}\lambda_{ijk}L_iL_j\bar{e_k} + \lambda'_{ijk}L_iQ_j\bar{d}_k + \frac{1}{2}\lambda''_{ijk}\bar{u}_i\bar{d}_j\bar{d}_k$$

$$\mathcal{O}_{\rm nhRPV} = \eta_{ijk}\bar{u}_i\bar{e}_j\bar{d}_k^\dagger + \eta'_{ijk}Q_i\bar{u}_jL_k^\dagger + \frac{1}{2}\eta''_{ijk}Q_iQ_j\bar{d}_k^\dagger$$

- Depends on dynamics, often non-holo will!

- E.g. assume B-L conserved in visible sector, broken by spurion X $X = M + \theta^2 F_X$

- B-L charge of $\mathcal{O}_{\rm nhRPV} + \mathcal{O}_{\rm nhBL}$ +1, while for $\mathcal{O}_{\rm hRPV} + \mathcal{O}_{\rm hBL}$ -1: will appear differently

Holomorphic or non-holomorphic?

- If B-L charge of X -1

$$K_{\rm dRPV} = \frac{1}{X^\dagger}\mathcal{O}_{\rm nhRPV} + \frac{X}{M_{\rm Pl}}\mathcal{O}_{\rm nhBL} + \frac{X^\dagger}{M_{\rm Pl}^2}\left(\mathcal{O}_{\rm hRPV} + \mathcal{O}_{\rm hBL}\right) + h.c.\,,$$

$$W_{\rm dRPV} = \frac{X}{M_{\rm Pl}^2}\left(\rho_{ijk} H_d Q_i Q_j Q_k + \rho'_{ijk} H_d Q_i \bar{u}_j \bar{e}_k\right)$$

- Non-holomorphic will dominate!

Holomorphic or non-holomorphic?

- For B-L charge +1: $\frac{1}{X^\dagger}O_{hRPV}$ vs. $\frac{1}{X}O_{nhRPV}$

- Naively same order, but for non-holo need F-term from $d^+ \propto m_d$. Likely more suppressed...

- Fractional charge: assuming no fractional powers of fields, only $B\text{-}L_X=1/n$ can generate RPV terms.

- For n even: $(X/X^\dagger)^n O_{hRPV}/M_{Pl}$ vs. $(X^\dagger/X)^n O_{nhRPV}/M_{Pl}$ equally suppressed

- For n odd: depending on sign of n holo or non-holo will dominate

Structure of dRPV operators

- Assume non-holomorphic operators dominate

$$K_{\mathrm{dRPV}} = \frac{1}{X^\dagger}\mathcal{O}_{\mathrm{nhRPV}}$$

- Will get terms of the form

$$\int d^2\theta \frac{F_X}{M^2}\left(\eta_{ijk}\bar{u}_i\bar{e}_j\bar{d}_k^\dagger + \eta'_{ijk}Q_i\bar{u}_jL_k^\dagger + \frac{1}{2}\eta''_{ijk}Q_iQ_j\bar{d}_k^\dagger\right)$$

- Strange SUSY structure (e.g. scalar must come from the operators with dagger), does NOT have to be flavor antisymmetric (additional SU(2) ε)

- Will also get ordinary Kähler terms

$$\int d^4\theta \frac{1}{M}\left(\eta_{ijk}\bar{u}_i\bar{e}_j\bar{d}_k^\dagger + \eta'_{ijk}Q_i\bar{u}_jL_k^\dagger + \frac{1}{2}\eta''_{ijk}Q_iQ_j\bar{d}_k^\dagger \right)$$

Structure of dRPV operators

- The structure of the ordinary Kähler terms:

$$\mathcal{L}_{\frac{1}{X^*}\Phi_j\Phi_k\Phi^{*i}} = \frac{1}{\langle\phi_X^*\rangle}\left[i(\phi_j\psi_k + \phi_k\psi_j)\sigma^\mu\partial_\mu\psi^{\dagger i} - \psi_j\psi_k F^{*i} + \phi_j\phi_k\partial_\mu\partial^\mu\phi^{*i} + (\phi_k F_j + \phi_j F_k)F^{*i}\right]$$
$$+ \frac{\langle F_X^*\rangle}{\langle\phi_X^*\rangle^2}\left[\psi_j\psi_k\phi^{*i} - (\phi_j F_k + \phi_k F_j)\phi^{*i}\right] + \text{total derivatives}$$

- From EOM proportional to Yukawas:

$$\partial_\mu\partial^\mu\phi^{*i} = \left.\frac{\delta W}{\delta\phi_i}\right|_F \qquad -i\sigma^\mu\partial_\mu\psi^{\dagger i} = \left.\frac{\delta W}{\delta\phi_i}\right|_\psi \qquad F^{*i} = \left.\frac{\delta W}{\delta\phi_i}\right|_\phi$$

$$\frac{\delta W}{\delta\phi_i} \sim y_i\langle h\rangle$$

- Like dim. 5 superpotential term

$$W = \frac{1}{X}\left(\rho_{ijk}y_{d_k}H_dQ_iQ_jQ_k + \rho'_{ijk}y_{e_k}H_dQ_i\bar{u}_j\bar{e}_k\right)$$

Flavor structure

- Expectation in a F-N-type model:

$$\eta''_{ijk} \sim \epsilon^{|q_{Q_i}+q_{Q_j}-q_{d_k}|}$$

- q's are F-N charges of the various SM fields

- $\epsilon \sim 0.2$ small flavor parameter

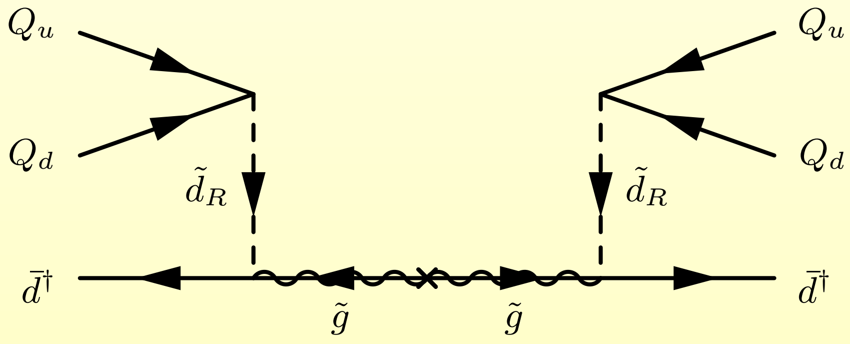
- Or q's can correspond to parameters describing partial compositeness...

- Will give additional suppression in addition to

$$\epsilon_X \equiv \frac{F_X}{M^2} \sim 10^{-3} - 10^{-5}$$

Low-energy constraints: ΔB=2

- n-nbar oscillation and dinucleon decay



- Dim 9 operator generated

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

- 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:

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

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

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

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

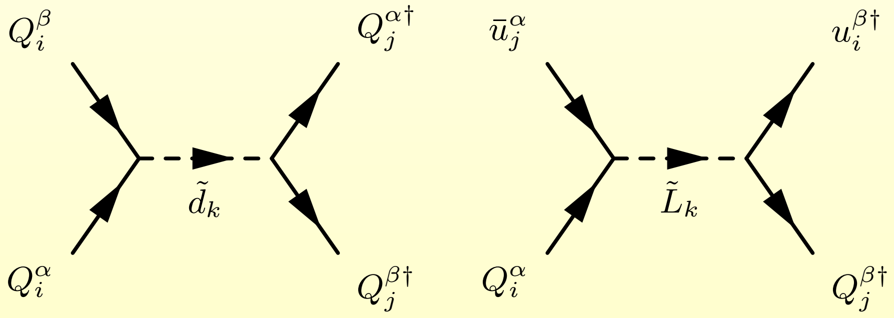
$$\Gamma \simeq \frac{8}{\pi}\frac{\rho_N}{m_N^2}\frac{\tilde{\Lambda}_{QCD}^{10}}{\Lambda_{pp}^{10}}$$

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

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

Low-energy constraints: ΔF=2

• FCNC's generated at tree-level:



• Operators generated:

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

• 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

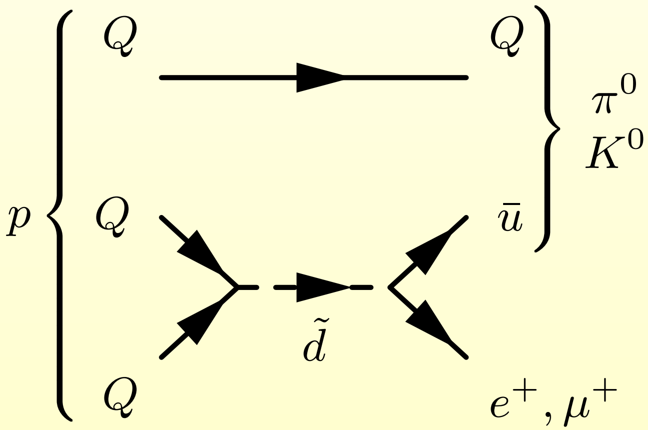
- Bounds from neutral meson mixings:

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

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

Proton decay to leptons

- If both B and L violated:

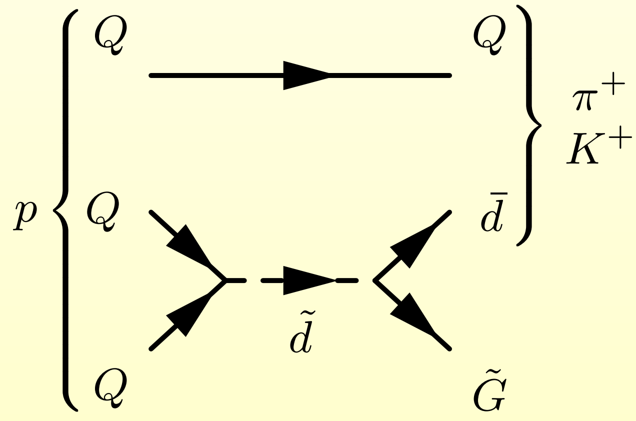


- Lifetime: $$\tau_p \simeq 5 \times 10^{33}\text{yr} \left(\frac{m_{\tilde{d}_{R\,k}}}{\text{TeV}}\right)^4 \left(\frac{10^{-14}}{|\eta_{m\ell k}\eta''_{11k}|}\right)^2 \left(\frac{10^{-5}}{\epsilon_X}\right)^4$$

- Strong bound on η η" but can be easily satisfied with FN charges

Proton decay to light gravitino

- Don't need L violation



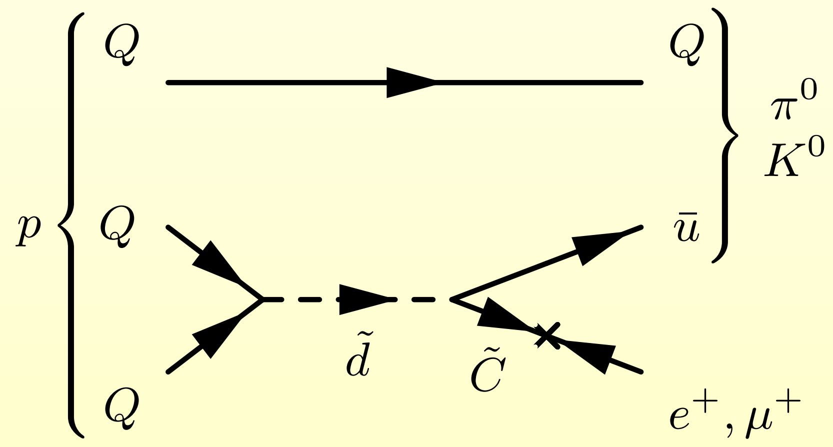
- Lifetime:

$$\tau_p \sim 2\times 10^{33}\mathrm{yr}\left(\frac{m_{\tilde{d}_i}}{\mathrm{TeV}}\right)^4\left(\frac{M}{10^8\mathrm{GeV}}\right)^4\left(\frac{10^{-8}}{|\eta''_{11i}|}\right)^2\left(\frac{F}{F_X}\right)^2$$

- If F_X the only source of SUSY breaking F drops out from expression, depends only on M and couplings. Can be reduced by $F_X<F$.

Proton decay via BL RPV

- BL RPV term generate electron/chargino mixing



- Lifetime:

$$\tau_p \simeq 3 \times 10^{33}\text{yr} \left(\frac{m_{\tilde{d}_{R\,k}}}{\text{TeV}}\right)^4 \left(\frac{3 \times 10^{-20}}{|\kappa_k^{\text{eff}} \eta''_{11k}|}\right)^2 \left(\frac{10^{-5}}{\epsilon_X}\right)^2 ,$$

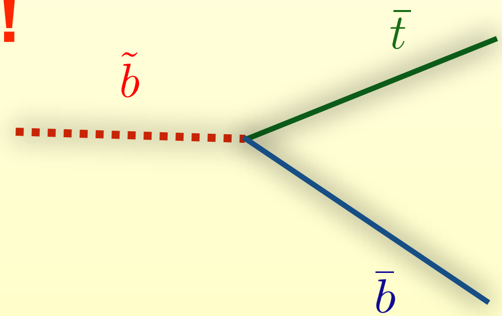
where

$$\kappa_k^{\text{eff}} = \kappa_k \frac{v_d}{M} + \kappa_k \epsilon_X \frac{m_{e_k} v_u}{m_{\tilde{C}}} + \kappa'_k \frac{M}{M_{Pl}}$$

LHC phenomenology

- Depends crucially on who the LSP is

- **LHC searches have to be modified!**



1. Sbottom LSP

Can decay $\tilde{b} \rightarrow \bar{t} + \bar{b}$ unusual mode, not there in usual RPV.

$$\tau_{\tilde{b}}^{-1} = \frac{|\eta''_{333}|^2}{8\pi} \epsilon_X^2 m_{\tilde{b}}$$

- These sbottom decays expected to be prompt

LHC phenomenology

2. Stop LSP

- More subtle: decay amplitude chirally suppressed

$$\frac{i}{M}(\tilde{Q}_i Q_j + \tilde{Q}_j Q_i)\sigma^\mu \partial_\mu \bar{d}^{\dagger k} \subset \int d^4\theta \frac{1}{X^\dagger} Q_i Q_j \bar{d}^{*k}$$

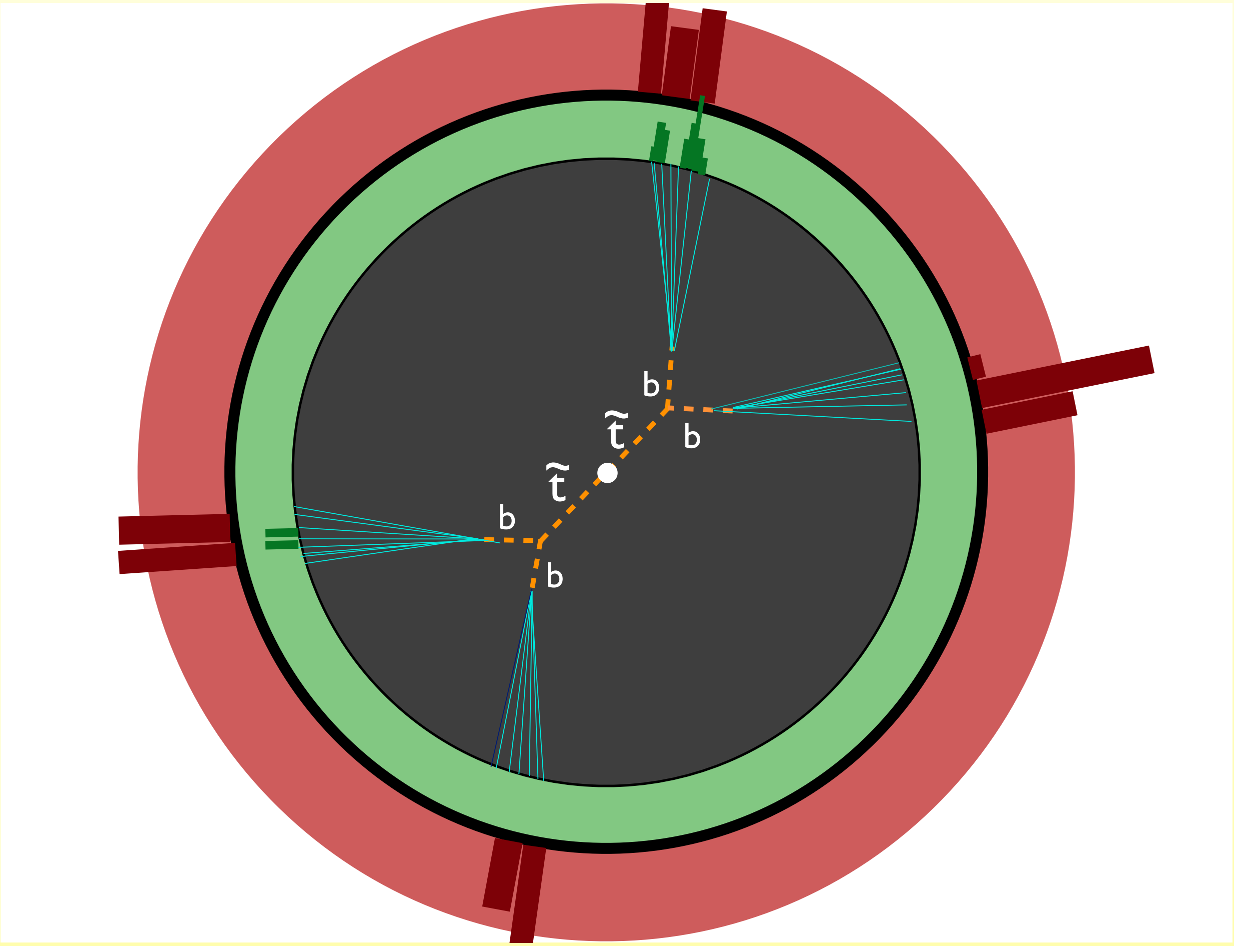
- Resulting decay: $\tilde{t} \to \bar{b}\bar{b}$ again special to dRPV

- Might be displaced $\Gamma_{\tilde{t}\to\bar{b}\bar{b}} = \frac{|\eta''_{333}|^2}{\pi}\left(\frac{m_b}{M}\right)^2 m_{\tilde{t}_L}$

$$c\tau_{\tilde{t}} \simeq 1\ \mathrm{mm}\left(\frac{300\ \mathrm{GeV}}{m_{\tilde{t}}}\right)\left(\frac{M}{10^8\mathrm{GeV}}\right)^2\left(\frac{1}{|\eta''_{333}|}\right)^2$$

LHC phenomenology

- Stop signal: 4 displaced bottom quarks



LHC phenomenology

3. Sneutrino LSP

- Decay through η' coupling $\eta'_{ijk} Q_i \bar{u}_j L^\dagger_k$
which contains $u_{Li} u^\dagger_{Rj} \tilde{\nu}_k + d_{Li} u^\dagger_{Rj} \tilde{e}^\dagger_{L}$

- Leading decay: $\tilde{\nu} \to t_L t^\dagger_R$

$$c\tau_{\tilde{\nu}} \simeq 1 \text{ mm} \left| \frac{10^{-2}}{\eta'_{331}} \right|^2 \left(\frac{10^{-5}}{\epsilon_X} \right)^2 \frac{165 \text{ GeV}}{(1 - 2\frac{m_t^2}{m_{\tilde{\nu}}^2})\sqrt{m_{\tilde{\nu}}^2 - 4m_t^2}}$$

- Could give 4 displaced tops

LHC phenomenology

4. Gluino LSP

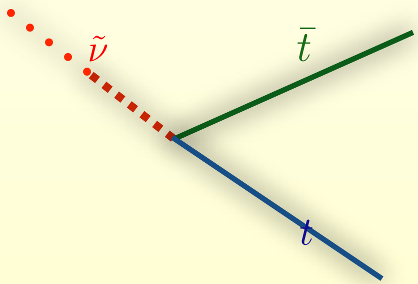
- Decays off-shell: $\tilde{g} \to tbb$

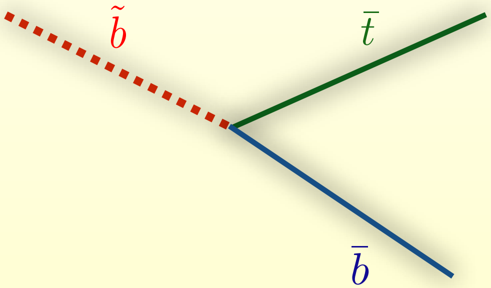
$$c\tau_{\tilde{g}} \simeq 1\,\mathrm{mm} \left|\frac{1}{\eta''_{333}}\right|^2 \left(\frac{m_{\tilde{t}}}{400\mathrm{GeV}}\right)^4 \left(\frac{350\mathrm{GeV}}{m_{\tilde{g}}}\right)^5 \left(\frac{M}{10^6\mathrm{GeV}}\right)^2$$

- If displaced, could be less constrained than prompt

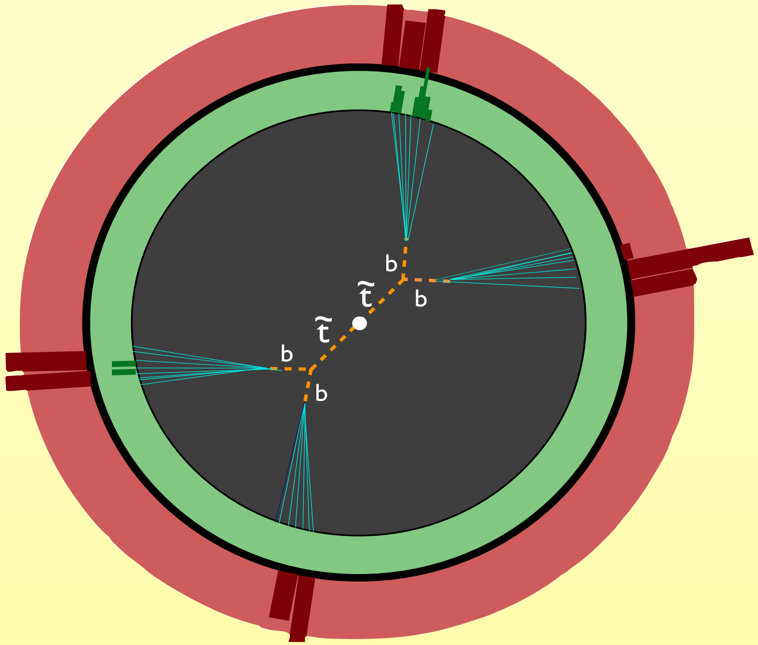
Potentially relevant searches

- Muon+displaced vertex **ATLAS-CONF-2013-092**





- Displaced vertex to dijets **CMS EXO-12-028**



•Prompt searches

	Leptons	Jets (b-jets)	Missing ET
CMS SUS-13-008	≥ 3	≥ 2 (1)	≥ 50 GeV
CMS SUS-13-010	≥ 4		
ATLAS-CONF-2012-153	≥ 4		≥ 50 GeV
CMS SUS-13-013	SSDL	≥ 2 (0 or 2)	
ATLAS-CONF-2013-007	SSDL	≥ 4 (3)	≤ 150 GeV
ATLAS-CONF-2013-051	SSDL	≥ 3 (3)	≥ 40 GeV
ATLAS-CONF-2013-091		≥ 6-7 (0-2)	

$$\tilde{\nu}\,\tilde{\nu} \to (t\bar{t})(t\bar{t})$$

$$\tilde{b}\,\tilde{b} \to (\bar{t}\,\bar{b})(\bar{t}\,\bar{b})$$

$$\tilde{g}\,\tilde{g} \to (tbb)(tbb)$$

Towards a realistic model

(In progress with Kuflik, Slone, Volansky)

Introduce Froggatt-Nielsen-type model

- Heavy fields $D, \bar{D}$ (like messengers, but also generate flavor hierarchy), + FN field ϕ

- Ordinary Yukawas suppressed by FN VEV

$$\frac{\phi}{M} H_d Q \bar{d}$$

- And need SUSY breaking field X

The essential parts of a FN model

- The couplings needed:

$$W \supset X D \bar{D} + \phi D \bar{d} + H_d Q \bar{D} + Q Q D$$

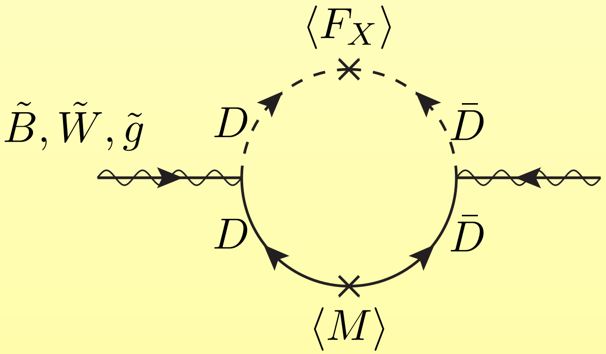
The essential parts of a FN model

- The couplings needed:

$$W \supset XD\bar{D} + \phi D\bar{d} + H_d Q\bar{D} + QQD$$

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

- Will give rise to messenger masses and usual gauge mediation



The essential parts of a FN model

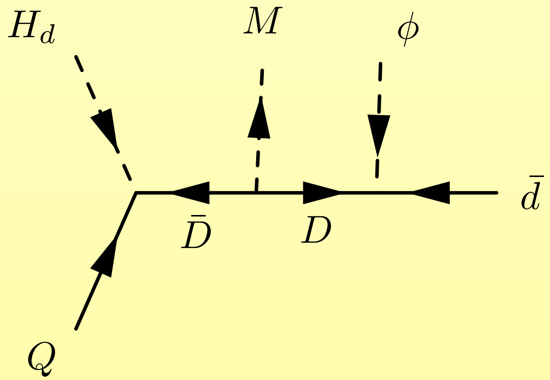
- The couplings needed:

$$W \supset X D \bar{D} + \phi D \bar{d} + H_d Q \bar{D} + QQD$$

$$\downarrow$$

$$\frac{\phi}{M} H_d Q \bar{d}$$

- Will give rise via usual FN mixing to ordinary Yukawas



The essential parts of a FN model

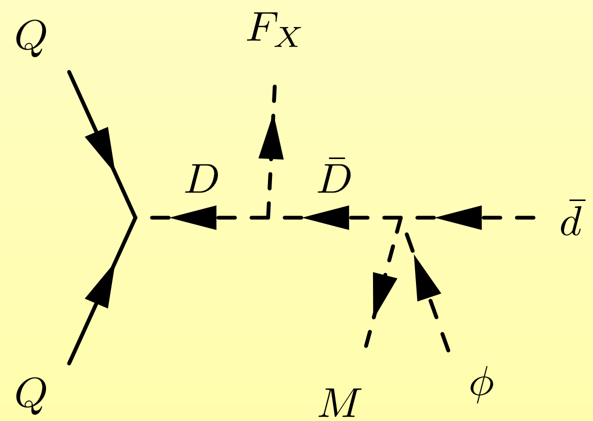
- The couplings needed:

$$W \supset XD\bar{D} + \phi D\bar{d} + H_d Q\bar{D} + QQD$$

$$\downarrow$$

$$\frac{\phi}{X^2} QQ\bar{d}^\dagger$$

- X assumed RP odd, QQD is needed for RPV



The essential parts of a FN model

- The EOM's from

$$W \supset X D \bar{D} + \phi D \bar{d} + H_d Q \bar{D} + Q Q D$$

- Expression for $\bar{D}$

$$\frac{\partial W}{\partial D} \Rightarrow \bar{D} \propto -\frac{1}{X}\left[\phi \bar{d} + H_d Q + Q Q\right]$$

- Cross term in Kähler term $\bar{D}^\dagger \bar{D}$ will contain non-holomorphic term

$$\int d^4\theta \frac{\phi^\dagger}{|X|^2} Q Q \bar{d}^\dagger \supset \int d^2\theta \frac{\phi^* F_X}{M^3} Q Q \bar{d}^\dagger$$

The full set of couplings needed

- The full superpotential:

$$W = X(D\bar{D} + l\bar{l}) + \phi(D\bar{d} + \bar{l}L)$$
$$+\bar{u}\bar{e}D + QQD + Q\bar{u}\bar{l}$$

- After integrating out messengers get all dRPV ops:

$$K \supset \frac{\phi^\dagger}{|X|^2}\left[QQ\bar{d}^\dagger + \bar{e}\bar{u}\bar{d}^\dagger + Q\bar{u}L^\dagger\right]$$

- In SU(5) language all would come from

$$\mathbf{10}\cdot\mathbf{10}\cdot\bar{\mathbf{5}}^\dagger$$

Fields in a full model

	$SU(5)$		$SU(5)$		$SU(5)$
$(Q, \bar{u}, \bar{e}) \in t_i$	$\mathbf{10}$	T_i	$\mathbf{10}$	X	$\mathbf{1}$
$(\bar{d}, L) \in \bar{f}_i$	$\bar{\mathbf{5}}$	$\overline{T}_i$	$\overline{\mathbf{10}}$	Φ	$\mathbf{1}$
h_u	$\mathbf{5}$	F_i	$\mathbf{5}$	S	$\mathbf{1}$
h_d	$\bar{\mathbf{5}}$	$\overline{F}_i$	$\bar{\mathbf{5}}$		

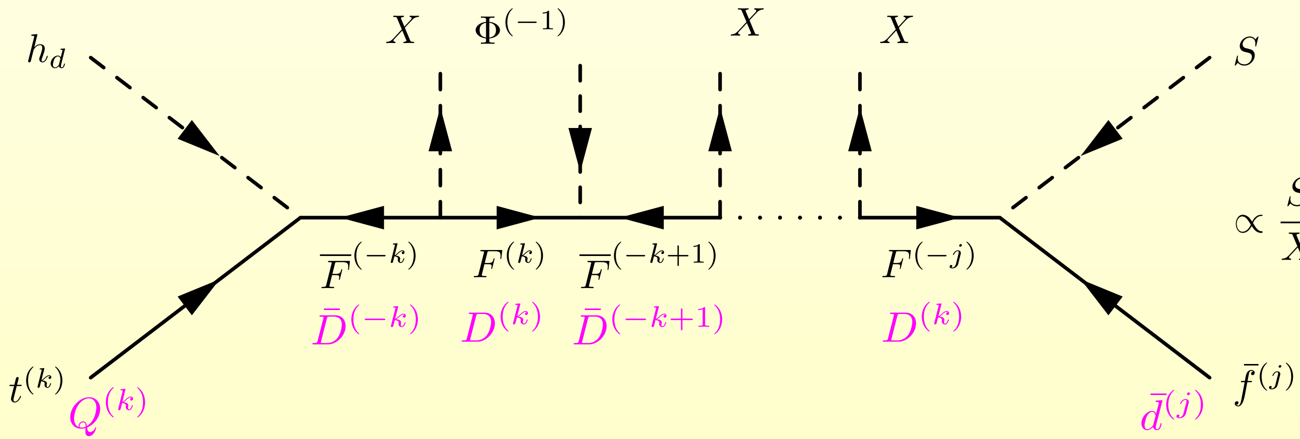
- The most general couplings needed:

$$W_{\rm flavor} = X(\overline{T}_i T_i + \overline{F}_i F_i) + \Phi(\overline{T}_i T_j + \overline{F}_i F_j) + S(\overline{T}_i t_j + \bar{f}_i F_j)$$

$$W_{\rm Yukawa} = h_u (T_i + t_i)(T_j + t_j) + h_d (T_i + t_i)(\overline{F}_j + \bar{f}_j)$$

$$W_{\rm dRPV} = (T_i + t_i)(T_j + t_j) F_k$$

Generation of Yukawa terms



$$\propto \frac{S}{X}\left(\frac{\Phi}{X}\right)^{k+j} h_d t^{(k)} \bar{f}^{(j)}$$

$$h_d Q^{(k)} \bar{d}^{(j)}$$

The full low-energy Lagrangian

$$W = \epsilon^{q_i+q_j}\frac{S}{X}h_d t\bar{f} + \epsilon^{q_i+q_j}\frac{S}{X}h_u t_i t_j + \epsilon^{q_i+q_j+q_k}\frac{S}{X^2}H_d Q_i Q_j Q_k + \epsilon^{q_i+q_j+q_k}\frac{S}{X^2}H_d Q_i \bar{u}_j \bar{e}_k$$

$$K = \epsilon^{|q_i-q_j|}\left|\frac{S}{X}\right|^2 t_i t_j^* + \epsilon^{|q_i-q_j|}\left|\frac{S}{X}\right|^2 \bar{f}_i \bar{f}_j^* + \epsilon^{|q_i+q_j-q_k|}\frac{S*}{|X|^2}t_i t_j \bar{f}_k^*$$

The full low-energy Lagrangian

$$W = \epsilon^{q_i+q_j}\frac{S}{X}h_d t\bar{f} + \epsilon^{q_i+q_j}\frac{S}{X}h_u t_i t_j + \epsilon^{q_i+q_j+q_k}\frac{S}{X^2}H_d Q_i Q_j Q_k + \epsilon^{q_i+q_j+q_k}\frac{S}{X^2}H_d Q_i \bar{u}_j \bar{e}_k$$

$$K = \epsilon^{|q_i-q_j|}\left|\frac{S}{X}\right|^2 t_i t_j^* + \epsilon^{|q_i-q_j|}\left|\frac{S}{X}\right|^2 \bar{f}_i \bar{f}_j^* + \epsilon^{|q_i+q_j-q_k|}\frac{S*}{|X|^2}t_i t_j \bar{f}_k^*$$

- The FN-suppressed Yukawa couplings

The full low-energy Lagrangian

$$W = \epsilon^{q_i+q_j}\frac{S}{X}h_d t\bar{f} + \epsilon^{q_i+q_j}\frac{S}{X}h_u t_i t_j + \epsilon^{q_i+q_j+q_k}\frac{S}{X^2}H_d Q_i Q_j Q_k + \epsilon^{q_i+q_j+q_k}\frac{S}{X^2}H_d Q_i \bar{u}_j \bar{e}_k$$

$$K = \epsilon^{|q_i-q_j|}\left|\frac{S}{X}\right|^2 t_i t_j^* + \epsilon^{|q_i-q_j|}\left|\frac{S}{X}\right|^2 \bar{f}_i \bar{f}_j^* + \epsilon^{|q_i+q_j-q_k|}\frac{S*}{|X|^2}t_i t_j \bar{f}_k^*$$

- The dRPV terms (both K and W)

The full low-energy Lagrangian

$$W = \epsilon^{q_i+q_j}\frac{S}{X}h_d t\bar{f} + \epsilon^{q_i+q_j}\frac{S}{X}h_u t_i t_j + \epsilon^{q_i+q_j+q_k}\frac{S}{X^2}H_d Q_i Q_j Q_k + \epsilon^{q_i+q_j+q_k}\frac{S}{X^2}H_d Q_i \bar{u}_j \bar{e}_k$$

$$K = \epsilon^{|q_i-q_j|}\left|\frac{S}{X}\right|^2 t_i t_j^* + \epsilon^{|q_i-q_j|}\left|\frac{S}{X}\right|^2 \bar{f}_i \bar{f}_j^* + \epsilon^{|q_i+q_j-q_k|}\frac{S*}{|X|^2}t_i t_j \bar{f}_k^*$$

•Soft scalar masses with wrong sign & flavor violating

•Can not be leading term, need other sources.

1. GM off $U(1)_{FN}$ with largish coupling
2. More messengers with smaller mass

Summary

- No hint for SUSY from LHC yet, no MET events

- RPV provides a potential way out (and keep SUSY natural)

- Why is RPV so small?

- RPV from the hidden sector. Expect couplings suppressed

$$\frac{F}{M^2}\epsilon^{q_i+q_j+q_k}$$

- Different operators could be leading RPV

$$\int d^2\theta \frac{F_X}{M^2}\left(\eta_{ijk}\bar{u}_i\bar{e}_j\bar{d}_k^\dagger + \eta'_{ijk}Q_i\bar{u}_jL_k^\dagger + \frac{1}{2}\eta''_{ijk}Q_iQ_j\bar{d}_k^\dagger\right)$$

Summary

- Satisfies low-energy constraints (n-nbar, dinucleon, ...)

- Gives distinct LHC phenomenology

- LHC searches have to be modified to take into account these possibilities

- Not so hard to build (almost) complete models

- Main sticking point negative contributions to scalar masses need to be overcome by additional contributions