GAUGING THE MAY TO MEV



DANIEL STOLARSKI



GORDAN KRNJAIC, DS, arXiv:1212.4860

SM describes all short distance phenomena down to d ~ 10^{-18} cm.



CN MINDY CECTMD

 $\mathcal{L}_{\text{quark}} = i\bar{q}_i \not\!\!\!D q_i + i\bar{u}_i \not\!\!\!D u_i + i\bar{d}_i \not\!\!\!D d_i$ $+ q_i \mathbf{y}_{ij}^u \psi_j u + q_i \mathbf{y}_{ij}^d d_j \phi + \text{h.c.}$

 $\mathcal{L}_{\text{quark}} = i\bar{q}_i \mathcal{D}q_i + i\bar{u}_i \mathcal{D}u_i + id_i \mathcal{D}d_i$

Without Yukawa couplings, SM possesses a large global flavor symmetry: $U(3)_Q \times U(3)_U \times U(3)_D$

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 $\mathcal{L}_{\text{quark}} = i\bar{q}_i \mathcal{D}q_i + i\bar{u}_i \mathcal{D}u_i + i\bar{d}_i \mathcal{D}d_i$ $+ q_i \mathbf{y}_{ij}^u \psi_j u + q_i \mathbf{y}_{ij}^d d_j \phi + \text{h.c.}$

Without Yukawa couplings, SM possesses a large global flavor symmetry: $U(3)_Q \times U(3)_U \times U(3)_D$

With Yukawa couplings, flavor structure still very predicative, supressed FCNC's, small CP violation, lepton and baryon number conservation, etc.

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SM flavor structure very delicate

$$\mathcal{L}_{\text{Higgs}} = |D_{\mu}\phi|^2 - m^2 \phi^{\dagger}\phi - \frac{\lambda}{4} (\phi^{\dagger}\phi)^2$$

Higgs potential has only dimensionful parameter in SM



Quantum corrections make the mass parameter unstable: the hierarchy problem.

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Introduce "superpartner" of different spin to cancel quadratic divergences



Quantum corrections only log sensitive to cutoff

- Rich and interesting collider phenomenology
- Elegant extension of spacetime symmetries
- Grand unification works better than SM
- Well motivated R-parity automatically gives dark matter candidate



SUSY must be broken, many new flavor violating

$$\begin{pmatrix} \tilde{q}_{1} & \tilde{q}_{2} & \tilde{q}_{3} \end{pmatrix}^{\dagger} \times \begin{pmatrix} \# & \# & \# \\ \# & \# & \# \\ \# & \# & \# \end{pmatrix} \times \begin{pmatrix} \tilde{q}_{1} \\ \tilde{q}_{2} \\ \tilde{q}_{3} \end{pmatrix}$$

Generic TeV scale values of mass matrix are badly ruled out

by low energy flavor tests μ^{-} , $\tilde{\mu}_{R}$, \tilde{e}_{R} , $\tilde{e$

Assume mediation of SUSY breaking is flavor blind

Supersymmetry breaking origin (Hidden sector)



MSSM (Visible sector)

Martin, Supersymmetry Primer, arXiv:9709356 [hep-ph].

Alternatively, a framework like gauge mediation predicts flavor blind soft masses



Promote SU(3) flavor group to full symmetry

	$SU(3)_Q$	$SU(3)_U$	$SU(3)_D$	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$
Q	3	1	1	3	2	+1/6
\overline{u}	1	3	1	$\overline{3}$	1	-2/3
\overline{d}	1	1	3	$\overline{3}$	1	+1/3
Y_u	$\overline{3}$	$\overline{3}$	1	1	1	0
Y_d	$\overline{3}$	1	$\overline{3}$	1	1	0

Ansatz that all flavor violation proportional to Y_u and Y_d Chivukula and Georgi, 1987. Hall and Randall, 1990. Ciuchini et. al. 1998. Buras et. al. 2001. D'Ambrosio et. al. 2002. Cirigliano et. al. 2005.

Soft SUSY parameters now fixed up to flavor universal dimensionful coefficients

$$m_{\text{soft}}^2 \tilde{u}_i^{\dagger} \left(1\!\!1 + Y_u^{\dagger} Y_u + \ldots \right)_{ij} \tilde{u}_j$$

$$A_{\text{soft}}(Y_u + \dots)_{ij}\tilde{q}_i\tilde{u}_jh_u$$

Flavor universality up to corrections that are largest for 3rd generation

Flavor bounds are much more easily satisfied

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Soft SUSY parameters parametrically the same size as Yukawa's, matrices not aligned Nomura, Papucci, DS, 2007. Nomura, DS 2008.

$$\mathbf{a}_{ij} \sim A_{\text{soft}} Y_{ij} \qquad \qquad \mathbf{a} \not\propto Y$$

Low energy constraints can still be easily satisfied, phenomenology often quite be different

Much easier to build models which satisfy this property Nomura, Papucci, DS 2008.

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- Elegant solution to the hierarchy problem with many nice features
- Makes a big mess of flavor in simplest incarnation
- Many solutions including gauge mediation, MFV, flavorful SUSY
- In 2010, we were very hopeful that the LHC would turn on find huge excesses in missing energy events

ATLAS SUSY Searches* - 95% CL Lower Limits (Status: HCP 2012)

	NOURD WONDOW STREET						
	MSUGRA/CMSSM : 0 lep + J'S + $E_{T,miss}$	L=5.8 fb ⁻⁺ , 8 TeV [ATLAS-CONF-2012-109]	1.50 TeV $q = g$ mass	1			
	MSUGRA/UMSSM : 1 lep + J'S + $E_{T,miss}$	L=5.8 fb ⁻⁺ , 8 TeV [ATLAS-CONF-2012-104]	1.24 TeV $q = g$ mass	ATIAS			
S	Pheno model : 0 lep + J'S + $E_{T,miss}$	L=5.8 fb ⁻⁺ , 8 TeV [ATLAS-CONF-2012-109]	1.18 TeV g mass $(m(q) < 2 \text{ TeV}, \text{ light } \chi_1)$	Breliminary			
che	Pheno model : 0 lep + J's + $E_{T,miss}$	L=5.8 fb ⁻⁺ , 8 TeV [ATLAS-CONF-2012-109]	1.38 TeV Q Mass $(m(g) < 2$ TeV, light χ				
ear	Gluino med. χ (g \rightarrow qq χ) : 1 lep + J's + $E_{T,miss}$	L=4.7 fb ⁻¹ , 7 TeV [1208.4688]	900 GeV g mass $(m(\chi_1) < 200 \text{ GeV}, m(\chi^-) = \frac{1}{2}(m(\chi_1) < 200 \text{ GeV}, m(\chi^-))$	$n(\chi^{-})+m(g))$			
S S	GMSB (I NLSP) : 2 lep (OS) + j's + $E_{T,miss}$	L=4.7 fb ⁻¹ , 7 TeV [1208.4688]	1.24 TeV g mass (tan β < 15)				
ive	GMSB (τ NLSP): 1-2 τ + 0-1 lep + JS + E	L=4.7 fb ⁻¹ , 7 TeV [1210.1314]	1.20 TeV g mass $(\tan \beta > 20)$	C			
lus	GGIVI (DITIO INLSP) . $\gamma\gamma + E$	L=4.8 fb ⁻¹ , 7 TeV [1209.0753]	1.07 TeV g mass $(m(\chi_1) > 50 \text{ GeV})$	$Ldt = (2.1 - 13.0) \text{ fb}^{-1}$			
Inc	GGIVI (WITO NLSP) . γ + IEP + E	L=4.8 fb ⁻¹ , 7 TeV [ATLAS-CONF-2012-144]	619 GeV g mass	J			
	GGM (niggsino-bino NLSP) $\gamma + D + E$	L=4.8 fb ⁻¹ , 7 TeV [1211.1167]	900 GeV g mass $(m(\tilde{\chi}_1) > 220 \text{ GeV})$	∎s = 7, 8 TeV			
	GGM (higgsino NLSP) : $Z + jets + E_{T,miss}$	L=5.8 fb ⁻¹ , 8 TeV [ATLAS-CONF-2012-152]	690 GeV $g_{-1/2}^{mass}$ (<i>m</i> (H) > 200 GeV)				
	Gravitino LSP : 'monojet' + $E_{T,miss}$	L=10.5 fb ⁻¹ , 8 TeV [ATLAS-CONF-2012-147]	645 GeV F^{max} SCale $(m(G) > 10^{-4} \text{ eV})$				
sq.	$\widetilde{g} \rightarrow b \overline{b} \widetilde{\chi}_{m}^{\circ}$ (virtual b) : 0 lep + 3 b-j's + $E_{T,miss}$	L=12.8 fb ⁻¹ , 8 TeV [ATLAS-CONF-2012-145]	1.24 TeV g mass $(m(\tilde{\chi}) < 200 \text{ GeV})$				
л. s те	$\widetilde{g} \rightarrow tt \widetilde{\chi}_1^{\circ}$ (virtual t) : 2 lep (SS) + j's + $E_{T,miss}$	L=5.8 fb ⁻¹ , 8 TeV [ATLAS-CONF-2012-105]	850 GeV $\underset{m(\widetilde{\chi}_{j})}{\text{gmass}} < 300 \text{ GeV}$				
gei no	$\widetilde{g} \rightarrow t \widetilde{\chi}_{1}^{\sim}$ (virtual t) : 3 lep + j's + $E_{T,miss}$	L=13.0 fb ⁻¹ , 8 TeV [ATLAS-CONF-2012-151]	860 GeV $\widetilde{g} \underset{\sim}{\text{mass}} (m(\widetilde{\chi}_1^\circ) < 300 \text{ GeV})$	o lev results			
rd	$\widetilde{g} \rightarrow t t \widetilde{\chi}_{1}^{\circ}$ (virtual t): 0 lep + multi-j's + $E_{T, miss}$	L=5.8 fb ⁻¹ , 8 TeV [ATLAS-CONF-2012-103]	1.00 TeV $[g \text{ mass } (m(\widetilde{\chi}_1) < 300 \text{ GeV})]$	7 TeV results			
~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~	$\widetilde{g} \rightarrow t \widetilde{\chi}_{1}^{\circ}$ (virtual t) : 0 lep + 3 b-j's + $E_{\tau, miss}$	L=12.8 fb ⁻¹ , 8 TeV [ATLAS-CONF-2012-145]	$1.15 \text{ TeV}  \widehat{g} \text{ mass}  (m(\widetilde{\chi}_1) < 200 \text{ GeV})$				
5 6	bb, $b_1 \rightarrow b \tilde{\chi}_1$ : 0 lep + 2-b-jets + $E_{T,\text{miss}}$	L=4.7 fb ⁻¹ , 7 TeV [ATLAS-CONF-2012-106]	480 GeV b mass $(m(\tilde{\chi}_1) < 150 \text{ GeV})$				
tior	bb, $b_1 \rightarrow t \tilde{\chi}_1^{\pm}$ : 3 lep + j's + $E_{T,miss}$	L=13.0 fb ⁻¹ , 8 TeV [ATLAS-CONF-2012-151]	<b>405 GeV</b> b mass $(m(\tilde{\chi}_1^{\pm}) = 2 m(\tilde{\chi}_1^{\cup}))$				
nci	$\underset{\sim}{}$ tt (very light), t $\rightarrow$ b $\tilde{\chi}_{1}^{\pm}$ : 2 lep + $E_{T,\text{miss}}$	<i>L</i> =4.7 fb ⁻¹ , 7 TeV [1208.4305] <b>130 GeV</b>	t mass $(m(\tilde{\chi}_1) < 70 \text{ GeV})$				
sc od	$\widetilde{t}$ (light), t $\rightarrow b\widetilde{\chi}_{1}^{\pm}$ : 1/2 lep + b-jet + $E_{T,\text{miss}}$	L=4.7 fb ⁻¹ , 7 TeV [1209.2102] 123-167	GeV t mass $(m(\tilde{\chi}_1^0) = 55 \text{ GeV})$				
en. t pi	tt (medium), t $\rightarrow$ t $\tilde{\chi}_{0}^{\circ}$ : 2 lep + b-jet + $E_{T,\text{miss}}$	L=4.7 fb ⁻¹ , 7 TeV [1209.4186]	<b>298-305 GeV</b> t mass $(m(\tilde{\chi}_1^{\vee}) = 0)$				
d g	$\underbrace{\text{tt}}_{T,\text{miss}}$ (heavy), $\underbrace{t} \rightarrow t \widetilde{\chi_{n}}$ : 1 lep + b-jet + $E_{T,\text{miss}}$	L=4.7 fb ⁻¹ , 7 TeV [1208.2590]	<b>230-440 GeV</b> t mass $(m(\tilde{\chi}_1^0) = 0)$				
3rc dir	$\widetilde{tt}$ (heavy), $t \rightarrow t \widetilde{\chi}_1^* : 0$ lep + b-jet + $E_{T,\text{miss}}$	L=4.7 fb ⁻¹ , 7 TeV [1208.1447]	<b>370-465</b> GeV t mass $(m(\tilde{\chi}_1^0) = 0)$				
	tt (natural GMSB) $(2) (\rightarrow II) + b - jet + E_T miss$	L=2.1 fb ⁻¹ , 7 TeV [1204.6736]	<b>310 GeV</b> t mass (115 < $m(\tilde{\chi}_1^0)$ < 230 GeV)				
t	$I_L I_L, I \rightarrow I \widetilde{\chi}_{0}^{\circ}$ : 2 lep + $E_{T, \text{miss}}$	L=4.7 fb ⁻¹ , 7 TeV [1208.2884] 85-19	<b>95 GeV</b> I mass $(m(\tilde{\chi}_1^0) = 0)$				
ec.	$\widetilde{\chi}_{1}^{\dagger}\widetilde{\chi}_{2}^{\dagger}, \widetilde{\chi}_{2}^{\dagger} \rightarrow lv(\widetilde{v}) \rightarrow lv\widetilde{\chi}_{1}^{\bullet}: 2 \text{ lep } + E_{T,\text{miss}}$	L=4.7 fb ⁻¹ , 7 TeV [1208.2884]	<b>110-340 GeV</b> $\widetilde{\chi}_{1}^{\pm}$ <b>MASS</b> $(m(\widetilde{\chi}_{1}^{0}) < 10 \text{ GeV}, m(\widetilde{l}, \widetilde{v}) = \frac{1}{2}(m(\widetilde{\chi}_{1}^{\pm}) + m(\widetilde{\chi}_{1}^{0})))$				
Щ i	$\widetilde{\chi}_{1}^{\pm}\widetilde{\chi}_{2}^{\circ} \rightarrow  _{L}^{\prime}v _{L}^{\prime} (\widetilde{v}v),  \widetilde{v} _{L} (\widetilde{v}v) : 3 \text{ lep } + E_{T \text{ miss}}$	L=13.0 fb ⁻¹ , 8 TeV [ATLAS-CONF-2012-154]	<b>580 GeV</b> $\widetilde{\chi}_{1}^{\pm}$ <b>MASS</b> $(m(\widetilde{\chi}_{1}^{\pm}) = m(\widetilde{\chi}_{2}^{0}), m(\widetilde{\chi}_{1}^{0}) = 0, m(\widetilde{l}, \widetilde{v})$ as a	above)			
	$\widetilde{\chi}_{1}^{\pm}\widetilde{\chi}_{2}^{\circ} \rightarrow W^{\prime*}\widetilde{\chi}_{1}^{\circ}Z^{\prime*}\widetilde{\chi}_{1}^{\circ}: 3 \text{ lep } + E_{T,\text{miss}}$	L=13.0 fb ⁻¹ , 8 TeV [ATLAS-CONF-2012-154]	<b>140-295 GeV</b> $\chi_1^-$ <b>MASS</b> $(m(\tilde{\chi}_1^{\pm}) = m(\tilde{\chi}_2^{\circ}), m(\tilde{\chi}_1^{\circ}) = 0$ , sleptons decoupled)				
D (	Direct $\chi_1^{-1}$ pair prod. (AMSB) : long-lived $\chi_1^{-1}$	L=4.7 fb ⁻¹ , 7 TeV [1210.2852]	<b>220 GeV</b> $\chi_1^-$ <b>MASS</b> $(1 < \tau(\tilde{\chi}_1^{\pm}) < 10 \text{ ns})$				
live Sles	Stable $\tilde{g}$ R-hadrons : low $\beta$ , $\beta\gamma$ (full detector)	L=4.7 fb ⁻¹ , 7 TeV [1211.1597]	985 Gev g mass				
ng-	Stable $\tilde{t}$ R-hadrons : low $\beta$ , $\beta\gamma$ (full detector)	L=4.7 fb ⁻¹ , 7 TeV [1211.1597]	683 Gev t mass				
pa	GMSB : stable ĩ	L=4.7 fb ⁻¹ , 7 TeV [1211.1597]	<b>300 GeV</b> τ MASS (5 < tanβ < 20)				
	$\widetilde{\chi}_{1}^{\circ} \rightarrow qq\mu (RPV) : \mu + heavy displaced vertex$	L=4.4 fb ⁻¹ , 7 TeV [1210.7451]	<b>700 GeV Q mass</b> $(0.3 \times 10^{-5} < \lambda_{211}^{2} < 1.5 \times 10^{-5}, 1 \text{ mm} < 20^{-5} < \lambda_{211}^{2} < 1.5 \times 10^{-5}, 1 \text{ mm} < 20^{-5} < 10^{-5}$	$c\tau < 1 m, \tilde{g}$ decoupled)			
	LFV : pp $\rightarrow \tilde{v}_{\tau} + X, \tilde{v}_{\tau} \rightarrow e + \mu$ resonance	L=4.6 fb ⁻¹ , 7 TeV [Preliminary]	<b>1.61 TeV</b> $v_{\tau}$ mass $(\lambda_{311}^{2}=0.10, \lambda_{132}=0.10, \lambda_{132}=0.10, \lambda_{132}=0.10, \lambda_{133}=0.10, \lambda_{133}=0.10,$	0.05)			
	LFV : $pp \rightarrow \tilde{v}_{\tau} + X, \tilde{v}_{\tau} \rightarrow e(\mu) + \tau$ resonance	L=4.6 fb ⁻¹ , 7 TeV [Preliminary]	<b>1.10 TeV</b> $v_{t}$ mass $(\lambda'_{311}=0.10, \lambda_{1(2)33}=0.05)$				
PV	Bilinear RPV CMSSM : 1 lep + 7 j's + $E_{T,miss}$	L=4.7 fb ⁻¹ , 7 TeV [ATLAS-CONF-2012-140]	<b>1.2 TeV</b> $q = g \text{ mass} (c\tau_{LSP} < 1 \text{ mm})$				
Ċ,	$\widetilde{\chi}_{1}^{+}\widetilde{\chi}_{2}^{+}\widetilde{\chi}_{1}^{+} \rightarrow W\widetilde{\chi}_{0}^{\circ}, \widetilde{\chi}_{0}^{\circ} \rightarrow eev_{\mu}, e\muv_{\mu} : 4 lep + E_{T,miss}$	L=13.0 fb ⁻¹ , 8 TeV [ATLAS-CONF-2012-153]	<b>700 GeV</b> $\chi_1^{+}$ <b>MASS</b> $(m(\tilde{\chi}_1^{\circ}) > 300 \text{ GeV}, \lambda_{121} \text{ or } \lambda_{122} > 0 \text{ or } \lambda_{122}$	0)			
	$ L_L, L_{\perp} \rightarrow  \widetilde{\chi}_1, \widetilde{\chi}_1 \rightarrow eev_{\mu}, e\mu v_{\perp} : 4 lep + E_{T,miss}$	L=13.0 fb ⁻¹ , 8 TeV [ATLAS-CONF-2012-153]	<b>430 GeV I MASS</b> $(m(\tilde{\chi}_1) > 100 \text{ GeV}, m(l_e) = m(l_{\mu}) = m(l_{\tau}), \lambda_{121} \text{ or } \lambda$	₁₂₂ > 0)			
	$\tilde{g} \rightarrow qqq$ : 3-jeť resonance pair	L=4.6 fb ⁻¹ , 7 TeV [1210.4813]	666 GeV g mass				
14/18	Scalar gluon : 2-jet resonance pair	L=4.6 fb ⁻¹ , 7 TeV [1210.4826]	<b>100-287 GeV</b> Sgluon mass (incl. limit from 1110.2693)				
VVIIV	Trmiss	L=10.5 fb ⁻¹ , 8 TeV [ATLAS-CONF-2012-147]	<b>704 GeV</b> M [*] <b>SCale</b> ( $m_{\chi}$ < 80 GeV, limit of < 687 GeV	for D8)			
		10 ⁻¹	1	10			
*On	ly a selection of the available mass limits on new sta	ates or phenomena shown.		iviass scale [10V]			

**14** D, *Only a selection of the available mass limits on new states or phenomena shown. All limits quoted are observed minus  $1\sigma$  theoretical signal cross section uncertainty.

### Supersymmetry may not be dead but these latest results have certainly put it in the HOSPITAL.

- Prof. Chris Parkes, quoted by the BBC

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Additional allowed operators usually forbidden by R-

$$\begin{aligned} \mathbf{parity} & W_{\text{RPV}} = \frac{1}{2} \lambda^{ijk} L_i L_j e_k + \lambda'^{ijk} L_i Q_j d_k + \mu'^i L_i H_u \\ & + \frac{1}{2} \lambda''^{ijk} u_i d_j d_k \end{aligned}$$

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Can decay the proton and make a (bigger) mess of flavor



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- Rich and interesting collider phenomenology
- Elegant extension of spacetime symmetries
- Grand unification works better than SM
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Imposing MFV on the RPV sector dramatically reduces the allowed parameter space and ameliorates the flavor problem. Nikolidakis and Smith, 2008.

Requiring flavor breaking spurions to couple holomorphically allows only one operator. Csaki, Grossman, Heidenreich, 2012.

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$$W_{\rm RPV} = \frac{1}{2} \lambda^{ijk} L_i L_j e_k + \lambda^{\prime ijk} L_i Q_j d_k + \mu^{\prime i} L_i H_{\rm sc} \left\{ \Delta L = 1 + \frac{1}{2} \lambda^{\prime\prime ijk} u_i d_j d_k \right\} \Delta B = 1$$

	$SU(3)_Q$	$SU(3)_U$	$SU(3)_D$	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$
Q	3	1	1	3	2	+1/6
$\overline{u}$	1	3	1	$\overline{3}$	1	-2/3
$\overline{d}$	1	1	3	$\overline{3}$	1	+1/3
$Y_u$	$\overline{3}$	$\overline{3}$	1	1	1	0
$Y_d$	$\overline{3}$	1	$\overline{3}$	1	1	0

$$W_{\rm RPV} = \frac{1}{2} \lambda^{ijk} L_i L_j e_k + \lambda^{\prime ijk} L_i Q_j d_k + \mu^{\prime i} L_i H_u \} \Delta L = 1$$
$$+ \frac{1}{2} \lambda^{\prime\prime ijk} u_i d_j d_k \} \Delta B = 1$$
$$\lambda^{\prime\prime}_{\alpha^\prime \beta^\prime \gamma^\prime} = \epsilon^{\alpha \beta \gamma} (Y^u_{\alpha \alpha^\prime}) (Y^d_{\beta \beta^\prime}) (Y^d_{\gamma \gamma^\prime})$$

$$W_{\rm MFV} = \frac{1}{2} \lambda^{\prime\prime\alpha\beta\gamma} u_{\alpha} d_{\beta} d_{\gamma}$$

 $\lambda_{\alpha'\beta'\gamma'}'' = \epsilon^{\alpha\beta\gamma} (Y_{\alpha\alpha'}^u) (Y_{\beta\beta'}^d) (Y_{\gamma\gamma'}^d)$ 

$$\lambda'' \simeq \frac{sb}{c} \frac{bd}{4 \times 10^{-7}} \frac{ds}{6 \times 10^{-9}} \frac{ds}{3 \times 10^{-12}}}{t 2 \times 10^{-5}} \frac{1.2 \times 10^{-5}}{1.2 \times 10^{-5}} \frac{1.2 \times 10^{-8}}{4 \times 10^{-5}} \times \left(\frac{\tan\beta}{50}\right)^2$$

- R-parity is an approximate symmetry
- Lepton number is an exact symmetry (up to neutrino

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LHC pheno depends strongly on who is the LSP Csaki, Grossman, Heidenreich, 2012.

### Squark LSP Case:

- Squark pair production lead to pairs of di-jets
- Gluino pair production gives pairs of tri-jets



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### Squark LSP Case:

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- Previous work assumed MFV as an **ansatz**
- Is there a model that can reproduce MFV?

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Promote  $SU(3)_Q x SU(3)_U x SU(3)_D$  flavor group to full gauge symmet

	$SU(3)_Q$	$SU(3)_U$	$SU(3)_D$	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$
Q	3	1	1	3	<b>2</b>	+1/6
$\overline{u}$	1	3	1	$\overline{3}$	1	-2/3
$\overline{d}$	1	1	3	$\overline{3}$	1	+1/3

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$\psi_{u^c}$	$\overline{3}$	1	1	$\overline{3}$	1	-2/3
$\psi_{d^c}$	$\overline{3}$	1	1	$\overline{3}$	1	+1/3
$\psi_u$	1	$\overline{3}$	1	3	1	+2/3
$\psi_d$	1	1	$\overline{3}$	3	1	-1/3

Promote  $SU(3)_Q x SU(3)_U x SU(3)_D$  flavor group to full gauge symmet

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$\psi_{u^c}$	$\overline{3}$	1	1	$\overline{3}$	1	-2/3
$\psi_{d^c}$	$\overline{3}$	1	1	$\overline{3}$	1	+1/3
$\psi_u$	1	$\overline{3}$	1	3	1	+2/3
$\psi_d$	1	1	$\overline{3}$	3	1	-1/3
$Y_u$	3	3	1	1	1	0
$Y_d$	3	1	3	1	1	0

Promote  $SU(3)_Q x SU(3)_U x SU(3)_D$  flavor group to full gauge symmet

	$SU(3)_Q$	$SU(3)_U$	$SU(3)_D$	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$
Q	3	1	1	3	2	+1/6
$\overline{u}$	1	3	1	$\overline{3}$	1	-2/3
$\overline{d}$	1	1	3	$\overline{3}$	1	+1/3
$\psi_{u^c}$	$\overline{3}$	1	1	$\overline{3}$	1	-2/3
$\psi_{d^c}$	$\overline{3}$	1	1	$\overline{3}$	1	+1/3
$\psi_u$	1	$\overline{3}$	1	3	1	+2/3
$\psi_d$	1	1	$\overline{3}$	3	1	-1/3
$Y_u$	3	3	1	1	1	0
$Y_d$	3	1	3	1	1	0
$Y_u^c$	$\overline{3}$	$\overline{3}$	1	1	1	0
$Y_d^c$	$\overline{3}$	1	$\overline{3}$	1	1	0

- Gauge full non-abelian SM flavor group Grinstein, Redi, Villadoro, 2010.
- Add minimal matter content to cancel anomalies
- $\psi_u$  and are vectorlike under all gauge symmetries
- In addition to MSSM matter, theory contains exotics, and flavor gauge fields
- Previous LR-SUSY version: Mohapatra, 2012.

 $W = \lambda_u H_u Q \psi_{u^c} + \lambda'_u Y_u \psi_u \psi_{u^c} + M_u \psi_u \bar{u} + (u \to d)$ 

 $W = \lambda_u H_u Q \psi_{u^c} + \lambda'_u Y_u \psi_u \psi_{u^c} + M_u \psi_u \bar{u} + (u \rightarrow d)$ O(1) flavor universal couplings

 $W = \lambda_u H_u Q \psi_{u^c} + \lambda'_u Y_u \psi_u \psi_{u^c} + M_u \psi_u \bar{u} + (u \rightarrow d)$ O(1) flavor universal couplings

### Can't write down usual Yukawa coupling

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 $W = \lambda_u H_u Q \psi_{u^c} + \lambda'_u Y_u \psi_u \psi_{u^c} + M_u \psi_u \bar{u} + (u \to d)$ 

 $Y_u \to \langle Y_u \rangle \qquad \qquad \psi_{u^c} \text{ mixes with } \bar{u}$ 

 $W = \lambda_u H_u Q \psi_{u^c} + \lambda'_u Y_u \psi_u \psi_{u^c} + M_u \psi_u \bar{u} + (u \to d)$ 

 $Y_u \to \langle Y_u \rangle \qquad \qquad \psi_{u^c} \text{ mixes with } \bar{u}$ 



$$W = \lambda_u H_u Q \psi_{u^c} + \lambda'_u Y_u \psi_u \psi_{u^c} + M_u \psi_u \bar{u} + (u \to d)$$



$$W = \lambda_u H_u Q \psi_{u^c} + \lambda'_u Y_u \psi_u \psi_{u^c} + M_u \psi_u \bar{u} + (u \to d)$$



$$H_u Q^{\alpha}(\psi_{u^c})_{\alpha} \to H_u Q^{\alpha}(\mathcal{V}^u_{\alpha\beta'}\bar{U}^{\beta'}) \equiv (\mathcal{Y}_u)_{\alpha\beta'}H_u Q^{\alpha}\bar{U}^{\beta'}$$

 $W = \lambda_u H_u Q \psi_{u^c} + \lambda'_u Y_u \psi_u \psi_{u^c} + M_u \psi_u \bar{u} + (u \to d)$ 

Consider  $\langle Y_u \rangle \gg M_u$ 

Massless state : 
$$\bar{U} \simeq \bar{u} - \frac{M_u}{\langle Y_u \rangle} \psi_{u^c}$$

Yukawa coupling : 
$$\mathcal{Y}_u \simeq \lambda_u \frac{M_u}{\langle Y_u \rangle}$$

Mass of exotic  $\simeq \langle Y_u \rangle$ 

Ų

 Seesaw mechanism for quarks

 Exotics and flavor gauge multiplets have opposite hierarchy of SM





## $W_{\rm RPV} = \bar{u}\bar{d}\bar{d}$

$$W_{\rm RPV} = \bar{u}\bar{d}\bar{d}$$

$$\mathbf{3} \text{ of } SU(3)_U$$

$$W_{\rm RPV} = \bar{u}\bar{d}\bar{d}$$

$$\uparrow$$

$$J \uparrow$$

$$J \circ f SU(3)_D$$

$$J \circ f SU(3)_U$$

$$W_{\rm RPV} = \overline{u}\overline{d}\overline{d}$$

$$\begin{vmatrix} \overline{u} \\ \overline{d} \\ 3 \text{ of } SU(3)_D$$

$$3 \text{ of } SU(3)_U$$

 $W_{\rm RPV} = \bar{u} dd$  $W_{\rm RPV} = \psi_{u^c} \psi_{d^c} \psi_{d^c}$ 

 $W_{\rm RPV} = \bar{u} dd$  $W_{\rm RPV} = \psi_{u^c} \psi_{d^c} \psi_{d^c}$ **3** of  $SU(3)_Q$ 

 $W_{\rm RPV} = \bar{u} dd$  $W_{\rm RPV} = \psi_{u^c} \psi_{d^c} \psi_{d^c}$ **3** of  $SU(3)_Q$ **3** of  $SU(3)_Q$ 



$$W_{
m RPV} = ar{u} ar{d} ar{d}$$
  
 $W_{
m RPV} = \psi_{u^c} \psi_{d^c} \psi_{d^c}$  Only allowed operator that  
breaks R-parity

# $Y \to \langle Y \rangle$ : transform to mass basis $W \to \epsilon^{abc} \epsilon^{\alpha\beta\gamma} (\mathcal{Y}^{u}_{\alpha\alpha'} \bar{U}^{\alpha'}_{a}) (\mathcal{Y}^{d}_{\beta\beta'} \bar{D}^{\beta'}_{b}) (\mathcal{Y}^{d}_{\gamma\gamma'} \bar{D}^{\gamma'}_{c})$

$$W_{
m RPV} = ar{u} ar{d} ar{d}$$
  
 $W_{
m RPV} = \psi_{u^c} \psi_{d^c} \psi_{d^c}$  Only allowed operator that  
breaks R-parity

$$\begin{array}{l} Y \rightarrow \langle Y \rangle : \text{ transform to mass basis} \\ W \rightarrow \epsilon^{abc} \epsilon^{\alpha\beta\gamma} (\mathcal{Y}^u_{\alpha\alpha'} \bar{U}^{\alpha'}_a) (\mathcal{Y}^d_{\beta\beta'} \bar{D}^{\beta'}_b) (\mathcal{Y}^d_{\gamma\gamma'} \bar{D}^{\gamma'}_c) \\ \end{array}$$
Color indices
Flavor indices

$$W_{
m RPV} = ar{u} \overline{d} \overline{d}$$
  
 $W_{
m RPV} = \psi_{u^c} \psi_{d^c} \psi_{d^c}$  Only allowed operator that  
breaks R-parity

$$\begin{array}{l} Y \rightarrow \langle Y \rangle : \text{ transform to mass basis} \\ W \rightarrow \epsilon^{abc} \epsilon^{\alpha\beta\gamma} (\mathcal{Y}^u_{\alpha\alpha'} \bar{U}^{\alpha'}_a) (\mathcal{Y}^d_{\beta\beta'} \bar{D}^{\beta'}_b) (\mathcal{Y}^d_{\gamma\gamma'} \bar{D}^{\gamma'}_c) \\ \\ \text{Color indices} \\ \text{Flavor indices} \end{array}$$
Exactly the MFV form!

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Supersymmetry breaking origin (Hidden sector)

Flavor-blind Monocology interactions

MSSM (Visible sector)

Supersymmetry breaking origin (Hidden sector)

Flavor-blind Monocompositions MSSM (Visible sector)

 $\Lambda\,({\rm GeV})$ 



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Supersymmetry breaking origin (Hidden sector)

Arbitrary Monocomous interactions

MSSM (Visible sector)

 $\Lambda\,({\rm GeV})$ 



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 $H_u Q^{\alpha}(\psi_{u^c})_{\alpha} \to H_u Q^{\alpha}(\mathcal{V}^u_{\alpha\beta'}\bar{U}^{\beta'}) \equiv (\mathcal{Y}_u)_{\alpha\beta'}H_u Q^{\alpha}\bar{U}^{\beta'}$ 













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Need  $\mathcal{V}_{\rm fermion} = \mathcal{V}_{\rm scalar}$ 

up to small corrections.

Equivalent to  $m_s^2 = M_f^\dagger M_f$  small

 $\frac{m_{\rm soft}^2}{{\rm Deviation \ goes \ like}\langle Y\rangle^2}$ 

, so SUSY breaking is

Inverted hierarchy comes to the rescue again!

	$SU(3)_Q$	$SU(3)_U$	$SU(3)_D$
$Y_u$	3	3	1
$Y_d$	3	1	3
$Y_u^c$	$\overline{3}$	$\overline{3}$	1
$Y_d^c$	$\overline{3}$	1	$\overline{3}$

 $W_Y = \lambda_{Y_u} Y_u Y_u Y_u + \lambda_{Y_u^c} Y_u^c Y_u^c Y_u^c + \mu_{Y_u} Y_u Y_u^c + (u \to d)$ 

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$$W_Y = \lambda_{Y_u} Y_u Y_u Y_u + \lambda_{Y_u^c} Y_u^c Y_u^c Y_u^c + \mu_{Y_u} Y_u Y_u^c + (u \to d)$$

All these parameters must because they induce additional SUSY breaking

$$-F_Y^* = \lambda_Y Y Y + \mu_Y Y^c$$
  
$$|D_Q|^2 = \frac{g_Q^2}{2} \left| Y_u^* T_Q^a Y_u - Y_u^c T_Q^a Y_u^{c*} + \widetilde{Q}^* T_Q^a \widetilde{Q} - \widetilde{\psi}_{u^c} T_Q^a \widetilde{\psi}_{u^c}^* + (u \to d) \right|^2$$

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 $A\left[\mathcal{Y} + \mathcal{O}\left(\mathcal{Y}\lambda_Y\right) + \mathcal{O}\left(\mathcal{Y}\frac{\mu_Y}{\langle Y \rangle}\right) + \mathcal{O}\left(\mathcal{Y}\frac{m_S^2}{\langle Y \rangle^2}\right)\right]H_u\widetilde{Q}\widetilde{U}$
$$A\left[\mathcal{Y} + \mathcal{O}\left(\mathcal{Y}\lambda_{Y}\right) + \mathcal{O}\left(\mathcal{Y}\frac{\mu_{Y}}{\langle Y \rangle}\right) + \mathcal{O}\left(\mathcal{Y}\frac{m_{\mathcal{S}}^{2}}{\langle Y \rangle^{2}}\right)\right]H_{u}\widetilde{Q}\widetilde{U}$$

### **Exactly MFV**

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 $A\left[\mathcal{Y} + \mathcal{O}\left(\mathcal{Y}\lambda_{Y}\right) + \mathcal{O}\left(\mathcal{Y}\frac{\mu_{Y}}{\langle Y \rangle}\right) + \mathcal{O}\left(\mathcal{Y}\frac{m_{\mathcal{S}}^{2}}{\langle Y \rangle^{2}}\right)\right]H_{u}\widetilde{Q}\widetilde{U}$ 

Exactly MFV Flavorful SUSY

$$A\left[\mathcal{Y} + \mathcal{O}\left(\mathcal{Y}\lambda_{Y}\right) + \mathcal{O}\left(\mathcal{Y}\frac{\mu_{Y}}{\langle Y \rangle}\right) + \mathcal{O}\left(\mathcal{Y}\frac{m_{\mathcal{S}}^{2}}{\langle Y \rangle^{2}}\right)\right]H_{u}\widetilde{Q}\widetilde{U}$$

$$\begin{split} m_{\mathcal{S}}^{2} \bigg\{ 1\!\!1 + & \frac{v^{2}}{m_{\mathcal{S}}^{2}} \mathcal{Y}^{\dagger} \mathcal{Y} + \mathcal{Y} \left[ \mathcal{O}\left(\mathcal{Y}\lambda_{Y}\right) + \mathcal{O}\left(\mathcal{Y}\frac{\mu_{Y}}{\langle Y \rangle}\right) + \mathcal{O}\left(\mathcal{Y}\frac{m_{\mathcal{S}}^{2}}{\langle Y \rangle^{2}}\right) \right] \\ & + g_{F}^{2} \left[ \mathcal{O}(1) + \mathcal{O}\left(\frac{\lambda_{Y}^{4}}{\lambda_{S}^{4}} \frac{\langle Y \rangle^{2}}{m_{\mathcal{S}}^{2}}\right) \right] \bigg\} \end{split}$$

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$$A\left[\mathcal{Y} + \mathcal{O}\left(\mathcal{Y}\lambda_{Y}\right) + \mathcal{O}\left(\mathcal{Y}\frac{\mu_{Y}}{\langle Y \rangle}\right) + \mathcal{O}\left(\mathcal{Y}\frac{m_{\mathcal{S}}^{2}}{\langle Y \rangle^{2}}\right)\right]H_{u}\widetilde{Q}\widetilde{U}$$

# Flavor universal $m_{\mathcal{S}}^{2} \left\{ 11 + \frac{v^{2}}{m_{\mathcal{S}}^{2}} \mathcal{Y}^{\dagger} \mathcal{Y} + \mathcal{Y} \left[ \mathcal{O} \left( \mathcal{Y} \lambda_{Y} \right) + \mathcal{O} \left( \mathcal{Y} \frac{\mu_{Y}}{\langle Y \rangle} \right) + \mathcal{O} \left( \mathcal{Y} \frac{m_{\mathcal{S}}^{2}}{\langle Y \rangle^{2}} \right) \right] + g_{F}^{2} \left[ \mathcal{O}(1) + \mathcal{O} \left( \frac{\lambda_{Y}^{4}}{\lambda_{S}^{4}} \frac{\langle Y \rangle^{2}}{m_{\mathcal{S}}^{2}} \right) \right] \right\}$

$$A\left[\mathcal{Y} + \mathcal{O}\left(\mathcal{Y}\lambda_{Y}\right) + \mathcal{O}\left(\mathcal{Y}\frac{\mu_{Y}}{\langle Y \rangle}\right) + \mathcal{O}\left(\mathcal{Y}\frac{m_{\mathcal{S}}^{2}}{\langle Y \rangle^{2}}\right)\right]H_{u}\widetilde{Q}\widetilde{U}$$

# Flavor universal $$\begin{split} m_{\mathcal{S}}^{2} & \left\{ 1\!\!1 + \!\frac{v^{2}}{m_{\mathcal{S}}^{2}} \mathcal{Y}^{\dagger} \mathcal{Y} \!+\! \mathcal{Y} \left[ \mathcal{O}\left(\mathcal{Y}\lambda_{Y}\right) \!+\! \mathcal{O}\left(\mathcal{Y}\frac{\mu_{Y}}{\langle Y \rangle}\right) \!+\! \mathcal{O}\left(\mathcal{Y}\frac{m_{\mathcal{S}}^{2}}{\langle Y \rangle^{2}}\right) \right] \right. \\ & \left. + g_{F}^{2} \left[ \mathcal{O}(1) + \mathcal{O}\left(\frac{\lambda_{Y}^{4}}{\lambda_{S}^{4}} \frac{\langle Y \rangle^{2}}{m_{\mathcal{S}}^{2}}\right) \right] \right\} \\ \\ & \mathsf{Exactly MFV} \end{split}$$

$$A\left[\mathcal{Y} + \mathcal{O}\left(\mathcal{Y}\lambda_{Y}\right) + \mathcal{O}\left(\mathcal{Y}\frac{\mu_{Y}}{\langle Y \rangle}\right) + \mathcal{O}\left(\mathcal{Y}\frac{m_{\mathcal{S}}^{2}}{\langle Y \rangle^{2}}\right)\right]H_{u}\widetilde{Q}\widetilde{U}$$



$$A\left[\mathcal{Y} + \mathcal{O}\left(\mathcal{Y}\lambda_{Y}\right) + \mathcal{O}\left(\mathcal{Y}\frac{\mu_{Y}}{\langle Y \rangle}\right) + \mathcal{O}\left(\mathcal{Y}\frac{m_{\mathcal{S}}^{2}}{\langle Y \rangle^{2}}\right)\right]H_{u}\widetilde{Q}\widetilde{U}$$



### Exact MFV

- $\langle Y \rangle \ll M_*$
- $\mu_Y \ll \langle Y \rangle$
- $\lambda_Y \ll 1$
- $g_F \ll 1$
- $m_{\mathcal{S}}, v \ll \langle Y \rangle$

### <u>Exact MFV</u>

- $\langle Y \rangle \ll M_*$
- $\mu_Y \ll \langle Y \rangle$
- $\lambda_Y \ll 1$
- $g_F \ll 1$
- $m_{\mathcal{S}}, v \ll \langle Y \rangle$

Not a corner of parameter space, but a tool for computation

# Many of the constrained processes in this model are studied in the literature.

Nomura, DS, 2008. Grinstein, Redi, Villadoro, 2010. Csaki Grossman, Heidenreich, 2011. Buras et. al. 2012.

#### Direct constraints:

- RPV gluino search
- Search for Z', W'
- Search for top partners

### Indirect constraints:

- $K \bar{K}$  mixing
- Neutron EDM
- $n \bar{n}$  oscillations
- Proton decay
- $Z \to b\overline{b}$
- $V_{tb}$



	$SU(3)_L$	$SU(3)_E$	$SU(3)_N$	$U(1)_Y$
	3	1	1	-1/2
$\bar{e}$	1	3	1	+1
$\bar{N}$	1	1	3	0
$\psi_{e^c}$	$\overline{3}$	1	1	+1
$\psi_N$	$\overline{3}$	1	1	0
$\psi_{e}$	1	$\overline{3}$	1	-1
$\psi_{m  u}$	1	1	$\overline{3}$	0
$Y_{\nu}$	3	1	3	0
$Y^c_{\nu}$	$\overline{3}$	1	$\overline{3}$	0
$Y_e$	3	3	1	0
$Y_e^c$	$\overline{3}$	$\overline{3}$	1	0

$$W_L = \lambda_e H_d L \psi_{e^c} + \lambda'_e Y_e \psi_e \psi_{e^c} + M_e \psi_e \bar{e}$$
$$+ (d \to u, \ e \to \nu, \ \bar{e} \to \bar{N})$$
$$\mathcal{Y}_\nu \sim \lambda_\nu M_\nu / \lambda'_\nu \langle Y_\nu \rangle$$

### Marjoana mass for N forbidden by $SU(3)_N$

Natural realization of pure Dirac neutrinos, still reminiscent of traditional seesaw scenario

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- SUSY can solve the hierarchy problem, makes a mess of flavor
- Natural SUSY is in trouble, even lepton violating RPV
- MFV RPV allowed, can be natural, interesting pheno
- Lots of interest in baryon number RPV since our paper: Bhattacherjee, Evans, Ibe, Matsumoto, Yanagida, 2013. Franceschini, Mohapatra, 2013. Csaki, Heidenreich, 2013.

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- Maximal gauge flavor allows model of approximate MFV
- MFV limit allows computation, all bounds can be satisfied
- 3rd generation structure could be accessible at LHC
- Could give a window into SM flavor puzzle

# TEMNIK YOU

	$SU(3)_Q$	$SU(3)_U$	$SU(3)_D$	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$
$\psi_{u^c}$	$\overline{3}$	1	1	$\overline{3}$	1	-2/3
$\psi_{d^c}$	$\overline{3}$	1	1	$\overline{3}$	1	+1/3
$\psi_u$	1	$\overline{3}$	1	3	1	+2/3
$\psi_d$	1	1	$\overline{3}$	3	1	-1/3

Additional matter charged under SM group, not in complete SU(5) multiplets

Hypercharge hits landau pole as low as 10¹⁴ GeV

SU(3)⁶ gauge symmetry not compatible with naive SU(5) unification

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Can generate vev for Y and Y^c with a singlet S

$$W = \lambda_S S \left( YY^c - w^2 \right)$$

Single Y field not enough to break all gauge symmetries and generate SM Yukawa's

Extend to M copies of Y and Y^c and add N singlets S

$$W = \lambda_{S_i} S^i \left( C_{ijk} Y^j (Y^c)^k - w_i^2 \right)$$
  
Replace  $Y_u$  with  $\sum_i Y_u^i$  in superpotential

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