Dynamical R-parity Violation

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



Particle Theory Seminar UC Irvine, April 2, 2014





No sign of superpartners as of today from LHC

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: SUSY 2013

ATLAS Preliminary

 $\int \mathcal{L} dt = (4.6 - 22.9) \text{ fb}^{-1}$ $\sqrt{s} = 7, 8 \text{ TeV}$

	Model	e, μ, τ, γ	Jets	ET	∫£ dt[fb	1] Mass limit		Reference
Inclusive Searches	$\begin{array}{l} \text{MSUGRA/CMSSM} \\ \text{MSUGRA/CMSSM} \\ \text{MSUGRA/CMSSM} \\ \tilde{q}, \tilde{q} \rightarrow q \tilde{\tilde{q}}_{1} \\ \tilde{x}, \tilde{z}, \tilde{z} \rightarrow q \tilde{\tilde{q}}_{1} \\ \tilde{x}, \tilde{z}, \tilde{z} \rightarrow q \tilde{q}_{1} \\ \tilde{x}, \tilde{z}, \tilde{z} \rightarrow q \tilde{q}_{1} \\ \tilde{z}, \tilde{z}, \tilde{z} \rightarrow q \tilde{q}_{1} \\ \tilde{z}, \tilde{z}, \tilde{z} \rightarrow q \tilde{q}_{1} \\ (M,SP) \\ \text{GMS 6} (\tilde{r}, N,SP) \\ \text{GGM (bino NLSP)} \\ \text{GGM (hipgsino-bino NLSP)} \\ \text{GGM (hipgsino NLSP)} \\ \text{GGM (hipgsino NLSP)} \\ \text{GGM (hipgsino NLSP)} \\ \text{GGM (hipgsino LSP)} \\ \text{GAM in LSP} \\ \end{array}$	$\begin{smallmatrix} 0 \\ 1 & e, \mu \\ 0 \\ 0 \\ 1 & e, \mu \\ 2 & e, \mu \\ 2 & e, \mu \\ 2 & e, \mu \\ 1 & e, \mu + \gamma \\ 2 & e, \mu + \gamma \\ 1 & e, \mu + \gamma \\ 2 & e, \mu (Z) \\ 0 \end{smallmatrix}$	2-6 jets 3-6 jets 7-10 jets 2-6 jets 2-6 jets 2-6 jets 3-6 jets 0-3 jets 0-3 jets mono-jet	Yes Yes Yes Yes Yes Yes Yes Yes Yes Yes	20.3 20.3 20.3 20.3 20.3 20.3 20.3 20.3	0.8 1.7 TeV 2 1.2 TeV 2 1.2 TeV 2 1.1 TeV 3 740 GeV 8 1.3 TeV 8 1.3 TeV 8 1.3 TeV 8 1.12 TeV 8 1.2 TeV 8 1.2 TeV 8 1.2 TeV 8 1.2 TeV 8 0.07 TeV 8 619 GeV 600 GeV 600 GeV F ¹⁷ scale 645 GeV	n(၃)=m(૩) any m(၃) any m(၃) ang(2)=0 GeV m(2)=0 GeV m(2)=0 GeV m(2)=0 GeV m(2)=0 GeV m(2)=0 GeV m(2)=0 GeV m(2)=0 GeV m(2)=0 GeV m(2)=20 GeV m(2)=20 GeV m(2)=20 GeV m(2)=20 GeV	ATLAS CONF-2013 047 ATLAS CONF-2013 042 1308,1841 ATLAS CONF-2013 047 ATLAS CONF-2013 047 ATLAS CONF-2013 047 ATLAS CONF-2013 048 ATLAS CONF-2013 048 ATLAS CONF-2013 048 1209,0753 ATLAS CONF-2013 044 1211,1167 ATLAS CONF-2012-1457
3 rd gen. <i>§</i> med.	$\hat{\vec{s}} \rightarrow b \bar{b} \bar{k}_{1}^{0}$ $\hat{\vec{s}} \rightarrow t \bar{t} \bar{k}_{1}^{0}$ $\hat{\vec{s}} \rightarrow t \bar{t} \bar{k}_{1}^{1}$ $\hat{\vec{s}} \rightarrow b \bar{t} \bar{k}_{1}^{1}$	0 0 0-1 e,µ 0-1 e,µ	3 b 7-10 jets 3 b 3 b	Yes Yes Yes Yes	20.1 20.3 20.1 20.1	2 1.2 TeV 2 1.1 TeV 2 1.3 TeV 2 1.3 TeV	m(Ř ²) - 600 GeV m(Ř ²) - 350 GeV m(Ř ²) - 400 GeV m(Ř ²) - 300 GeV	ATLAS-CONF-2013-061 1308.1841 ATLAS-CONF-2013-061 ATLAS-CONF-2013-061
3rd gen. squarks direct production	$ \begin{array}{c} \overline{i}_{1} \overline{i}_{1}, \overline{j}_{1}, \overline{j}_{1}, \overline{j}_{2}, \overline{j}_{2}, \overline{j}_{2}, \overline{j}_{1}, \overline{j}_{2}, \overline{j}_{2}, \overline{j}_{1}, \overline{j}_{1},$	$\begin{array}{c} 0 \\ 2 \ e, \mu (SS) \\ 1-2 \ e, \mu \\ 2 \ e, \mu \\ 2 \ e, \mu \\ 0 \\ 1 \ e, \mu \\ 0 \\ 1 \ e, \mu \\ 0 \\ 3 \ e, \mu (Z) \end{array}$	2 b 0-3 b 1-2 b 0-2 jets 2 jets 2 b 1 b 2 b ono-jet/c-1 1 b 1 b	Yes Yes Yes Yes Yes Yes Yes Yes Yes	20.1 20.7 4.7 20.3 20.3 20.1 20.7 20.5 20.3 20.7 20.7 20.7	bit 100-620 GeV bit 275-430 GeV bit 110-167 GeV bit 130-220 GeV bit 130-220 GeV bit 150-500 GeV bit 150-500 GeV bit 200-610 GeV bit 320-660 GeV bit 90-200 GeV bit 500 GeV bit 271-520 GeV	$\begin{split} n(\tilde{t}_1^1) <& 0 \mbox{ GeV } \\ n(\tilde{t}_1) <& n(\tilde{t}_1) \\ n(\tilde{t}_1) <& n(\tilde{t}_1) \\ n(\tilde{t}_1) <& 0 \mbox{ GeV } \\ n(\tilde{t}_1) <& n(\tilde{t}_1) \\ n(\tilde{t}_1) <& 0 \mbox{ GeV } \\ n(\tilde{t}_1) <& 0 $	1308.2631 ATLAS-CONF-2013-007 1208.4365, I209.2102 ATLAS-CONF-2013-048 ATLAS-CONF-2013-048 ATLAS-CONF-2013-047 ATLAS-CONF-2013-047 ATLAS-CONF-2013-048 ATLAS-CONF-2013-048 ATLAS-CONF-2013-045 ATLAS-CONF-2013-045
EW direct	$\begin{array}{l} \tilde{t}_{\perp p} \tilde{t}_{\perp q}, \tilde{t}_{\perp} \tilde{t}_{\perp} \tilde{t}_{\perp}^{-1} \tilde{t}_{\perp}^{0} \\ \tilde{x}_{\perp}^{-1} \tilde{x}_{\perp}^{-1} \tilde{x}_{\perp}^{-1} \tilde{t}_{\perp} (\ell \tau) \\ \tilde{x}_{\perp}^{-1} \tilde{x}_{\perp}^{-1} \tilde{x}_{\perp}^{-1} \tilde{\tau}_{\tau} (\tau \tau) \\ \tilde{x}_{\perp}^{-1} \tilde{x}_{\perp}^{-2} \tilde{t}_{\perp} \tilde{t}_{\perp}^{-1} (\tau \tau) \\ \tilde{x}_{\perp}^{-1} \tilde{x}_{\perp}^{-2} \tilde{t}_{\perp} \tilde{t}_{\perp}^{-1} \tilde{t}_{\perp} (\tau \tau) \\ \tilde{x}_{\perp}^{-1} \tilde{x}_{\perp}^{-2} \tilde{t}_{\perp} W \tilde{x}_{\perp}^{0} \tilde{t}_{\perp} \tilde{x}_{\perp}^{0} \\ \tilde{x}_{\perp}^{-1} \tilde{x}_{\perp}^{-2} W \tilde{x}_{\perp}^{0} \tilde{t}_{\perp} \tilde{t}_{\perp} \\ \tilde{t}_{\perp}^{-2} \tilde{t}_{\perp} W \tilde{t}_{\perp}^{0} \tilde{t}_{\perp} \tilde{t}_{\perp} \\ \end{array}$	2 e, µ 2 e, µ 2 τ 3 e, µ 3 e, µ 1 e, µ	0 0 0 2 b	Yes Yes Yes Yes Yes	20.3 20.3 20.7 20.7 20.7 20.7 20.3	μ 85-315 GeV k1 125-450 GeV k1 130-330 GeV k1 160-330 GeV k1 150-330 GeV k1 150-330 GeV k1 150-330 GeV k1 150-330 GeV k1 150 GeV	$\begin{split} m[\tilde{t}_{1}^{2}] = 0 \text{GeV} \\ m[\tilde{t}_{1}^{2}] = 0 \text{GeV}, m[\tilde{t}, \tilde{\gamma}] = 0.5 (m[\tilde{t}_{1}^{2}] = m[\tilde{t}_{1}^{2}]) \\ m[\tilde{t}_{1}^{2}] = 0 \text{GeV}, m[\tilde{t}, \tilde{\gamma}] = 0.5 (m[\tilde{t}_{1}^{2}] = m[\tilde{t}_{1}^{2}]) \\ m[\tilde{t}_{1}^{2}] = m[\tilde{t}_{1}^{2}] = 0.5 (m[\tilde{t}_{1}^{2}] = 0.5 (m[\tilde{t}_{1}^{2}]) = m[\tilde{t}_{1}^{2}]) \\ m[\tilde{t}_{1}^{2}] = m[\tilde{t}_{1}^{2}] = m[\tilde{t}_{1}^{2}] = 0.5 (m[\tilde{t}_{1}^{2}]) = 0.5 (m[\tilde{t}_{1}^{2}]) \\ m[\tilde{t}_{1}^{2}] = m[\tilde{t}_{1}^{2}], m[\tilde{t}_{1}^{2}] = 0.5 (m[\tilde{t}_{1}^{2}]) \\ m[\tilde{t}_{1}^{2}] = m[\tilde{t}_{1}^{2}], m[\tilde{t}_{1}^{2}], m[\tilde{t}_{1}^{2}]] \\ m[\tilde{t}_{1}^{2}] = m[\tilde{t}_{1}^{2}], m[\tilde{t}_{1}^{2}], m[\tilde{t}_{1}^{2}]] \\ m[\tilde{t}_{1}^{2}] = m[\tilde{t}_{1}^{2}], m[\tilde{t}_{1}^{2}], m[\tilde{t}_{1}^{2}]] \\ m[\tilde{t}_{1}^{2}] = m[\tilde{t}_{1}^{2}], m[\tilde{t}_{1}^{2}], m[\tilde{t}_{1}^{2}]] \\ m[\tilde{t}_{1}^{2}] = m[\tilde{t}_{1}^{2}], m[\tilde{t}_{1}^{2}]] \\ m[\tilde{t}_{1}^{2}] = m[\tilde{t}_{1}^{2}], m[\tilde{t}_{1}^{2}]] \\ m[\tilde{t}_{1}^{2}] = m[\tilde{t}_{1}^{2}], m[\tilde{t}_{1}^{2}] \\ m[\tilde{t}_{1}^{2}] = m[\tilde{t}_{1}^{2}], m[\tilde{t}_{1}^{2}]] \\ m[\tilde{t}_{1}^{2}] = m[\tilde{t}_{1}^{2}], m[\tilde{t}_{1}^$	ATLAS-CONF-2013-049 ATLAS-CONF-2013-049 ATLAS-CONF-2013-028 ATLAS-CONF-2013-035 ATLAS-CONF-2013-035 ATLAS-CONF-2013-035
Long-lived particles	$\begin{array}{l} \text{Direct} \ & \widehat{x}_1^+ \widehat{k}_1^- \ \text{prod., long-lived} \ & \widehat{k}_1^+ \\ \text{Stable, stopped} \ & \mathbb{R}^-\text{hadron} \\ \text{GMSB, stable} \ & \widehat{\tau}, \ & \widehat{k}_1^0 \rightarrow \widehat{\tau}(\widehat{e}, \widehat{\mu}) + r(e \\ \text{GMSB,} \ & \widehat{k}_1^0 \rightarrow \gamma \ & \widehat{c}, \ \text{long-lived} \ & \widehat{k}_1^0 \\ \text{GMSB,} \ & \widehat{k}_1^0 \rightarrow q \mu \ (\text{RPV}) \end{array}$	Disapp. trk 0 t. µ) 1-2 µ 2 y 1 µ, displ. vtx	1 jet 1-5 jets - -	Yes Yes Yes	20.3 22.9 15.9 4.7 20.3	k1 270 GeV 832 GeV 2 832 GeV 832 GeV k_1^0 475 GeV 475 GeV k_1^0 230 GeV 1.0 TeV	$\begin{split} & \pi(\tilde{E}_1^1) + \pi(\tilde{E}_2^1) = 160 \ \text{MeV}, \ \pi(\tilde{E}_1^1) = 0.2 \ \text{ns} \\ & \pi(\tilde{E}_1^1) = 100 \ \text{GeV}, \ 10 \ \mu\text{s} < \pi(\tilde{g}_1^1) < 1000 \ \text{s} \\ & 10 \ \tan g < 50 \\ & 0.4 < \pi(\tilde{E}_1^1) < 2 \ \text{ns} \\ & 1.5 \ < cr < 156 \ \text{mm}, \ BR(\mu) = 1, \ \pi(\tilde{E}_1^2) = 108 \ \text{GeV} \end{split}$	ATLAS-CONF-2013-089 ATLAS-CONF-2013-057 ATLAS-CONF-2013-058 1304-0310 ATLAS-CONF-2013-092
NdH	$ \begin{array}{l} LFV\;\rho\rho\!\!\rightarrow\!\!\tilde{r}_{r}+X_{r}\bar{v}_{r}\!\rightarrow\!\!e+\mu\\ LFV\;\rho\rho\!\!\rightarrow\!\!\tilde{v}_{r}+X_{r}\bar{v}_{r}\!\rightarrow\!\!e(\mu)+\tau\\ Binaar\;RPV\;CMSSM\\ \tilde{x}_{1}^{++}\tilde{x}_{1}^{}\tilde{x}_{1}^{+}\!\rightarrow\!W\tilde{x}_{1}^{0}\tilde{x}_{1}^{0}\!\rightarrow\!\!ee^{\bar{\rho}}_{\mu},e\mu\bar{r}\\ \tilde{x}_{1}^{+}\tilde{x}_{1}^{}\tilde{x}_{1}^{+}\!\rightarrow\!W\tilde{x}_{1}^{0}\tilde{x}_{1}^{0}\!\rightarrow\!\!ee^{\bar{\rho}}_{\mu},e\mu\bar{r}\\ \tilde{x}_{1}^{+}\tilde{x}_{1}^{-}\tilde{x}_{1}^{+}\!\rightarrow\!W\tilde{x}_{1}^{0}\tilde{x}_{1}^{+}\!\rightarrow\!\!\tau\tau\bar{v}_{e},er\bar{r}\\ \tilde{g}_{n}^{+}\!\rightarrow\!\!eq\!\!q\\ \tilde{g}_{n}\!\rightarrow\!\!eq\!\!q\\ \tilde{g}_{n}\!\rightarrow\!\!eq\!\!q\\ \tilde{g}_{n}\!\rightarrow\!\!eq\!\!q\\ \tilde{g}_{n}\!\rightarrow\!\!tq\!\!t,\ \tilde{t}_{1}\!\rightarrow\!\!bs \end{array}$	$2 e, \mu$ $1 e, \mu + \tau$ $1 e, \mu$ $4 e, \mu$ $3 e, \mu + \tau$ 0 $2 e, \mu$ (SS)	7 jets 6-7 jets 0-3 b	Yes Yes Yes Yes	4.6 4.6 4.7 20.7 20.7 20.3 20.3	i, 1.61 TeV i, 1.1 TeV i,i 1.2 TeV x ¹ ₁ 760 GeV x ¹ ₁ 350 GeV i 880 GeV	$\begin{array}{l} \xi_{211}=0,10, \mathcal{A}_{132}=0.06\\ \xi_{211}=0,10, \mathcal{A}_{12123}=0.06\\ m(\emptyset)-m(\emptyset), c_{1,23}=v-1 mm\\ m(\tau_{1}^{2})>300 GeV, \mathcal{A}_{123}>0\\ m(\tau_{1}^{2})>300 GeV, \mathcal{A}_{123}>0\\ BR(\tau)=BR(b)=BR(c)=0\% \end{array}$	1212.1272 1212.1272 ATLAS-CONF-2012-140 ATLAS-CONF-2013-036 ATLAS-CONF-2013-036 ATLAS-CONF-2013-091 ATLAS-CONF-2013-097
Other	Scalar gluon pair, sgluon⊸ağ Scalar gluon pair, sgluon⊸t∓ WIMP Interaction (D5, Dirac χ) VS = 7 TeV fulli data	$2 e_{\mu}^{0}(SS)$ 0 $\sqrt{s} = 8 \text{ TeV}$ artial data	4 jets 1 b mono-jet √s = full	Yes Yes 8 TeV data	4.6 14.3 10.5	sgluon 100-287 GeV 800 GeV m* scale 704 GeV 10 ⁻¹ 1	ncl. limit from 1119.2693 m(z)-80 GeV, limit of-687 GeV for D8 Mass scale [TeV]	1210.4826 ATLAS-CONF-2013-051 ATLAS-CONF-2012-147

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

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

<u>Ways out</u>

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

<u>RPV in SUSY</u>

 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/M². Operators can originate from Kähler potential - some not even catalogued till now!

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



•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

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

Depends on who is LSP

Simplest possibility: stop LSP







Stop mass (GeV)

 \overline{S}

 \overline{b}

Gluino bounds

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



•mgluino> 800 GeV, squarks could still be ~ 300 GeV

•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 $W_{RPV} = \lambda LL\bar{e} + \lambda'QL\bar{d} + \lambda''\bar{u}\bar{d}\bar{d} + \mu'LH_u$ 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 nonholomorphic operators may show up in the Kähler pot:

$$\mathcal{O}_{\mathrm{nhRPV}} = \eta_{ijk} \bar{u}_i \bar{e}_j \bar{d}_k^{\dagger} + \eta'_{ijk} Q_i \bar{u}_j L_k^{\dagger} + \frac{1}{2} \eta''_{ijk} Q_i Q_j \bar{d}_k^{\dagger} + \kappa_i \bar{e}_i H_d H_u^{\dagger}$$

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

• 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

 $\epsilon_X \equiv F_X/M^2$ $\mathcal{O}(1)$ 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?

$$\mathcal{O}_{\mathrm{hRPV}} = \frac{1}{2} \lambda_{ijk} L_i L_j \bar{e_k} + \lambda'_{ijk} L_i Q_j \bar{d_k} + \frac{1}{2} \lambda''_{ijk} \bar{u_i} \bar{d_j} \bar{d_k}$$
$$\mathcal{O}_{\mathrm{hRPV}} = \eta_{ijk} \bar{u_i} \bar{e_j} \bar{d_k}^{\dagger} + \eta'_{ijk} Q_i \bar{u_j} L_k^{\dagger} + \frac{1}{2} \eta''_{ijk} Q_i Q_j \bar{d_k}^{\dagger}$$

- •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 $\mathcal{O}_{nhRPV} + \mathcal{O}_{nhBL}$ +1, while for $\mathcal{O}_{hRPV} + \mathcal{O}_{hBL}$ -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 $B-L_X=1/n$ 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 nonholo will dominate

Structure of dRPV operators

Assume non-holomorphic operators dominate

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

•Will get terms of the form

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

•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

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

Structure of dRPV operators

•The structure of the ordinary Kähler terms:

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

• 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

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

Flavor structure

•Expectation in a F-N-type model:

$$\eta_{ijk}^{\prime\prime} \sim \epsilon^{|q_{Q_i} + q_{Q_j} - q_{d_k}|}$$

•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

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

•Suppression scale:

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

Low-energy constraints: ΔB=2

•n-nbar oscillation bound:

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

~ 10

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

•Dinucleon decay (T>10³² yr):
$$\Gamma \simeq \frac{8}{\pi} \frac{\rho_N}{m_N^2} \frac{\Lambda_{QCD}^{10}}{\Lambda_{pp}^{10}}$$

 $pp \rightarrow \pi^+ \pi^+ (K^+ K^+)$ $\Lambda_{pp} \equiv \min\{\Lambda_{11k}, \Lambda_{1k1}\}$

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

Low-energy constraints: ΔF=2

•FCNC's generated at tree-level:



•Operators generated:

$$\begin{aligned}
\mathcal{Q}_{1}^{q_{i}q_{j}} &\equiv -\frac{1}{2} (Q_{i}^{\alpha}Q_{i}^{\beta}) (Q_{j}^{\alpha\dagger}Q_{j}^{\beta\dagger}) \\
\mathcal{Q}_{4}^{q_{i}q_{j}} &\equiv \bar{u}_{j}^{\alpha}Q_{i}^{\alpha}Q_{j}^{\beta\dagger}\bar{u}_{i}^{\beta\dagger}
\end{aligned}$$

•Suppression scales:

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

Low-energy constraints: ΔF=2

•Bounds from neutral meson mixings:

$$\begin{array}{ll} \Delta m_K &: & |\eta_{11k}'' \eta_{22k}'' \epsilon_X^2| \lesssim 10^{-10}, \\ \Delta m_D &: & |\eta_{11k}'' \eta_{22k}'' \epsilon_X^2| \lesssim 10^{-8}, \\ \Delta m_{B_d} &: & |\eta_{11k}'' \eta_{33k}'' \epsilon_X^2| \lesssim 10^{-7}, \\ \Delta m_{B_s} &: & |\eta_{23k}'' \eta_{33k}'' \epsilon_X^2| \lesssim 10^{-7}. \end{array}$$

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

Proton decay to leptons



•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 $\eta \eta$ " but can be easily satisfied with FN charges

Proton decay to light gravitino



•Don't need L violation

•Lifetime:

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

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

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

•Depends crucially on who the LSP is

•LHC searches have to be modified!

1. Sbottom LSP

Can decay ${}^{\cdot}\widetilde{b} \to \overline{t} + \overline{b}$ unusual mode, not there in usual RPV.

 \tilde{b}

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

These sbottom decays expected to be prompt

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: $\tilde{t} \rightarrow \bar{b}\bar{b}$ again special to dRPV
- •Might be displaced $\Gamma_{\tilde{t}\to \bar{b}\bar{b}} = \frac{|\eta_{333}'|^2}{\pi} \left(\frac{m_b}{M}\right)^2 m_{\tilde{t}_L}$

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

•Stop signal: 4 displaced bottom quarks



3. Sneutrino LSP

- •Decay through η' coupling $\eta'_{ijk}Q_i\bar{u}_jL_k^{\dagger}$ which contains $u_{Li}u_{Rj}^{\dagger}\tilde{\nu}_k + d_{Li}u_{Rj}^{\dagger}\tilde{e}_{Li}^{\dagger}$
- •Leading decay: $\tilde{\nu} \rightarrow t_L t_R^{\dagger}$

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

Could give 4 displaced tops

4. Gluino LSP

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

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

•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

• $\tilde{
u}$



•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

$$\frac{\phi}{M}H_dQ\bar{d}$$

-And need SUSY breaking field $\,X\,$

•The couplings needed:

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

•The couplings needed:

 $W \supset XD\bar{D} + \phi D\bar{d} + H_d Q\bar{D} + QQD$ \downarrow $X = M + \theta^2 F_X$

•Will give rise to messenger masses and usual gauge mediation



•The couplings needed:

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

•Will give rise via usual FN mixing to ordinary Yukawas



•The couplings needed:

 $\bullet X$ assumed RP odd, QQD is needed for RPV



•The EOM's from

 $W \supset XD\bar{D} + \phi D\bar{d} + H_dQ\bar{D} + QQD$ •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 $10\cdot 10\cdot \overline{5}^{\dagger}$

Fields in a full model

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

•The most general couplings needed:

$$W_{\text{flavor}} = X(\overline{T}_i T_i + \overline{F}_i F_i) + \Phi(\overline{T}_i T_j + \overline{F}_i F_j) + S(\overline{T}_i t_j + \overline{f}_i F_j)$$
$$W_{\text{Yukawa}} = h_u(T_i + t_i)(T_j + t_j) + h_d(T_i + t_i)(\overline{F}_j + \overline{f}_j)$$
$$W_{\text{dRPV}} = (T_i + t_i)(T_j + t_j)F_k$$

Generation of Yukawa terms



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

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

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

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

•The FN-suppressed Yukawa couplings

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

$$K = \epsilon^{|q_i-q_j|} \left| \frac{S}{X} \right|^2 t_i t_j^* + \epsilon^{|q_i-q_j|} \left| \frac{S}{X} \right|^2 \bar{f}_k \bar{f}_j^* + \epsilon^{|q_i+q_j-q_k|} \frac{S*}{|X|^2} t_i t_j \bar{f}_k^*$$
•The dRPV terms (both K and W)

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

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

•Soft scalar masses with wrong sign & flavor violating

•Can not be leading term, need other sources.

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

<u>Summary</u>

- •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

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

<u>Summary</u>

•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