Natural, R-parity violating supersymmetry and horizontal flavor symmetries

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Outline

1. Current limits on SUSY by ATLAS and CMS: unnatural SUSY?
2. Horizontal symmetry: hierarchies of masses and mixings
   - *R*-parity violation: textures of couplings
   - leptonic RPV, baryonic RPV, or both?
   - Phenomenological constraints: upper and LOWER limits on RPV couplings
3. Natural Supersymmetry weaknesses and solutions
   - Flavor changing neutral currents: quark-squark alignment
   - Extra contributions to the Higgs mass: the NMSSM
4. Conclusions

LHC SUSY searches

So far, the LHC has

- given us a Higgs boson at 126 GeV.
- confirmed the standard Model / constrained extensions.
- shown no hints of supersymmetry. Actually, no BSM at all!

(see all the other talks in this parallel session)

Exclusion limits go all the way up to the TeV range. Tension with tuning of Higgs mass

$$m_h^2 = m_{h,bare}^2 + m_{h,loop}^2$$

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: EPS 2013

ATLAS Preliminary

$\int \mathcal{L}\,dt = (4.4 - 22.9)\ \mathrm{fb}^{-1}$ $\sqrt{s}$ = 7, 8 TeV

	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\,dt [\mathrm{fb}^{-1}]$	Mass limit		Reference
Inclusive Searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	$\tilde{q}, \tilde{g}$ 1.7 TeV	$m(\tilde{q})=m(\tilde{g})$	ATLAS-CONF-2013-047
	MSUGRA/CMSSM	1 e,μ	3-6 jets	Yes	20.3	$\tilde{g}$ 1.2 TeV	any $m(\tilde{q})$	ATLAS-CONF-2013-062
	MSUGRA/CMSSM	0	7-10 jets	Yes	20.3	$\tilde{g}$ 1.1 TeV	any $m(\tilde{q})$	ATLAS-CONF-2013-054
	$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}^0_1$	0	2-6 jets	Yes	20.3	$\tilde{q}$ 740 GeV	$m(\tilde{\chi}^0_1)$=0 GeV	ATLAS-CONF-2013-047
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}\tilde{\chi}^0_1$	0	2-6 jets	Yes	20.3	$\tilde{g}$ 1.3 TeV	$m(\tilde{\chi}^0_1)$=0 GeV	ATLAS-CONF-2013-047
	$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}^\pm_1\to qqW^\pm\tilde{\chi}^0_1$	1 e,μ	3-6 jets	Yes	20.3	$\tilde{g}$ 1.18 TeV	$m(\tilde{\chi}^0_1)$<200 GeV, $m(\tilde{\chi}^\pm)=0.5(m(\tilde{\chi}^0_1)+m(\tilde{g}))$	ATLAS-CONF-2013-062
	$\tilde{g}\tilde{g}\to qqqq\ell\ell(\ell\ell)\tilde{\chi}^0_1\tilde{\chi}^0_1$	2 e,μ (SS)	3 jets	Yes	20.7	$\tilde{g}$ 1.1 TeV	$m(\tilde{\chi}^0_1)$<650 GeV	ATLAS-CONF-2013-007
	GMSB ($\tilde{\ell}$ NLSP)	2 e,μ	2-4 jets	Yes	4.7	$\tilde{g}$ 1.24 TeV	$\tan\beta$<15	1208.4688
	GMSB ($\tilde{\tau}$ NLSP)	1-2 τ	0-2 jets	Yes	20.7	$\tilde{g}$ 1.4 TeV	$\tan\beta$>18	ATLAS-CONF-2013-026
	GGM (bino NLSP)	2 γ	0	Yes	4.8	$\tilde{g}$ 1.07 TeV	$m(\tilde{\chi}^0_1)$>50 GeV	1209.0753
	GGM (wino NLSP)	1 $e,\mu+\gamma$	0	Yes	4.8	$\tilde{g}$ 619 GeV	$m(\tilde{\chi}^0_1)$>50 GeV	ATLAS-CONF-2012-144
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	4.8	$\tilde{g}$ 900 GeV	$m(\tilde{\chi}^0_1)$>220 GeV	1211.1167
	GGM (higgsino NLSP)	2 e,μ (Z)	0-3 jets	Yes	5.8	$\tilde{g}$ 690 GeV	$m(\tilde{H})$>200 GeV	ATLAS-CONF-2012-152
	Gravitino LSP	0	mono-jet	Yes	10.5	$F^{1/2}$ scale 645 GeV	$m(\tilde{g})>10^{-4}$ eV	ATLAS-CONF-2012-147
3rd gen. $\tilde{g}$ med.	$\tilde{g}\to b\bar{b}\tilde{\chi}^0_1$	0	3 b	Yes	20.1	$\tilde{g}$ 1.2 TeV	$m(\tilde{\chi}^0_1)$<600 GeV	ATLAS-CONF-2013-061
	$\tilde{g}\to t\bar{t}\tilde{\chi}^0_1$	0	7-10 jets	Yes	20.3	$\tilde{g}$ 1.14 TeV	$m(\tilde{\chi}^0_1)$ <200 GeV	ATLAS-CONF-2013-054
	$\tilde{g}\to t\bar{t}\tilde{\chi}^0_1$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$ 1.34 TeV	$m(\tilde{\chi}^0_1)$<400 GeV	ATLAS-CONF-2013-061
	$\tilde{g}\to b\bar{t}\tilde{\chi}^+_1$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$ 1.3 TeV	$m(\tilde{\chi}^0_1)$<300 GeV	ATLAS-CONF-2013-061
3rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to b\tilde{\chi}^0_1$	0	2 b	Yes	20.1	$\tilde{b}_1$ 100-630 GeV	$m(\tilde{\chi}^0_1)$<100 GeV	ATLAS-CONF-2013-053
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to t\tilde{\chi}^\pm_1$	2 e,μ (SS)	0-3 b	Yes	20.7	$\tilde{b}_1$ 430 GeV	$m(\tilde{\chi}^\pm_1)$=2 $m(\tilde{\chi}^0_1)$	ATLAS-CONF-2013-007
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to b\tilde{\chi}^\pm_1$	1-2 e,μ	1-2 b	Yes	4.7	$\tilde{t}_1$ 167 GeV	$m(\tilde{\chi}^0_1)$=55 GeV	1208.4305, 1209.2102
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to Wb\tilde{\chi}^0_1$	2 e,μ	0-2 jets	Yes	20.3	$\tilde{t}_1$ 220 GeV	$m(\tilde{\chi}^0_1)=m(\tilde{t}_1)-m(W)$-50 GeV, $m(\tilde{t}_1)<<m(\tilde{\chi}^\pm_1)$	ATLAS-CONF-2013-048
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to t\tilde{\chi}^0_1$	2 e,μ	2 jets	Yes	20.3	$\tilde{t}_1$ 225-525 GeV	$m(\tilde{\chi}^0_1)$=0 GeV	ATLAS-CONF-2013-065
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to b\tilde{\chi}^\pm_1$	0	2 b	Yes	20.1	$\tilde{t}_1$ 150-580 GeV	$m(\tilde{\chi}^0_1)$<200 GeV, $m(\tilde{\chi}^\pm_1)-m(\tilde{\chi}^0_1)$=5 GeV	ATLAS-CONF-2013-053
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}^0_1$	1 e,μ	1 b	Yes	20.7	$\tilde{t}_1$ 200-610 GeV	$m(\tilde{\chi}^0_1)$=0 GeV	ATLAS-CONF-2013-037
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}^0_1$	0	2 b	Yes	20.5	$\tilde{t}_1$ 320-660 GeV	$m(\tilde{\chi}^0_1)$=0 GeV	ATLAS-CONF-2013-024
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to c\tilde{\chi}^0_1$	0	mono-jet/c-tag	Yes	20.3	$\tilde{t}_1$ 200 GeV	$m(\tilde{t}_1)-m(\tilde{\chi}^0_1)$<85 GeV	ATLAS-CONF-2013-068
	$\tilde{t}_1\tilde{t}_1$(natural GMSB)	2 e,μ (Z)	1 b	Yes	20.7	$\tilde{t}_1$ 500 GeV	$m(\tilde{\chi}^0_1)$>150 GeV	ATLAS-CONF-2013-025
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1+Z$	3 e,μ (Z)	1 b	Yes	20.7	$\tilde{t}_2$ 520 GeV	$m(\tilde{t}_1)=m(\tilde{\chi}^0_1)$+180 GeV	ATLAS-CONF-2013-025
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell}\to\ell\tilde{\chi}^0_1$	2 e,μ	0	Yes	20.3	$\tilde{\ell}$ 85-315 GeV	$m(\tilde{\chi}^0_1)$=0 GeV	ATLAS-CONF-2013-049
	$\tilde{\chi}^+_1\tilde{\chi}^-_1, \tilde{\chi}^+_1\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e,μ	0	Yes	20.3	$\tilde{\chi}^\pm_1$ 125-450 GeV	$m(\tilde{\chi}^0_1)$=0 GeV, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}^\pm_1)+m(\tilde{\chi}^0_1))$	ATLAS-CONF-2013-049
	$\tilde{\chi}^+_1\tilde{\chi}^-_1, \tilde{\chi}^+_1\to\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	0	Yes	20.7	$\tilde{\chi}^\pm_1$ 180-330 GeV	$m(\tilde{\chi}^0_1)$=0 GeV, $m(\tilde{\tau},\tilde{\nu})=0.5(m(\tilde{\chi}^\pm_1)+m(\tilde{\chi}^0_1))$	ATLAS-CONF-2013-028
	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu), \ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e,μ	0	Yes	20.7	$\tilde{\chi}^\pm_1, \tilde{\chi}^0_2$ 600 GeV	$m(\tilde{\chi}^\pm_1)=m(\tilde{\chi}^0_2)$, $m(\tilde{\chi}^0_1)$=0, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}^\pm_1)+m(\tilde{\chi}^0_1))$	ATLAS-CONF-2013-035
	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2\to W^*\tilde{\chi}^0_1Z^*\tilde{\chi}^0_1$	3 e,μ	0	Yes	20.7	$\tilde{\chi}^\pm_1, \tilde{\chi}^0_2$ 315 GeV	$m(\tilde{\chi}^\pm_1)=m(\tilde{\chi}^0_2)$, $m(\tilde{\chi}^0_1)$=0, sleptons decoupled	ATLAS-CONF-2013-035
Long-lived particles	Direct $\tilde{\chi}^+_1\tilde{\chi}^-_1$ prod., long-lived $\tilde{\chi}^\pm_1$	Disapp. trk	1 jet	Yes	20.3	$\tilde{\chi}^\pm_1$ 270 GeV	$m(\tilde{\chi}^\pm_1)-m(\tilde{\chi}^0_1)$=160 MeV, $\tau(\tilde{\chi}^\pm_1)$=0.2 ns	ATLAS-CONF-2013-069
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	22.9	$\tilde{g}$ 857 GeV	$m(\tilde{\chi}^0_1)$=100 GeV, 10 μs<$\tau(\tilde{g})$<1000 s	ATLAS-CONF-2013-057
	GMSB, stable $\tilde{\tau}$, $\tilde{\chi}^0_1\to\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$	1-2 μ	0	-	15.9	$\tilde{\chi}^0_1$ 475 GeV	10<$\tan\beta$<50	ATLAS-CONF-2013-058
	GMSB, $\tilde{\chi}^0_1\to\gamma\tilde{G}$, long-lived $\tilde{\chi}^0_1$	2 γ	0	Yes	4.7	$\tilde{\chi}^0_1$ 230 GeV	0.4<$\tau(\tilde{\chi}^0_1)$<2 ns	1304.6310
	$\tilde{\chi}^0_1\to qq\mu$ (RPV)	1 μ	0	Yes	4.4	$\tilde{q}$ 700 GeV	1 mm<$c\tau$<1 m, $\tilde{g}$ decoupled	1210.7451
RPV	LFV $pp\to\tilde{\nu}_\tau+X, \tilde{\nu}_\tau\to e+\mu$	2 e,μ	0	-	4.6	$\tilde{\nu}_\tau$ 1.61 TeV	λ'_{311}=0.10, λ_{132}=0.05	1212.1272
	LFV $pp\to\tilde{\nu}_\tau+X, \tilde{\nu}_\tau\to e(\mu)+\tau$	1 $e,\mu+\tau$	0	-	4.6	$\tilde{\nu}_\tau$ 1.1 TeV	λ'_{311}=0.10, $\lambda_{1(2)33}$=0.05	1212.1272
	Bilinear RPV CMSSM	1 e,μ	7 jets	Yes	4.7	$\tilde{q}, \tilde{g}$ 1.2 TeV	$m(\tilde{q})=m(\tilde{g})$, $c\tau_{LSP}$<1 mm	ATLAS-CONF-2012-140
	$\tilde{\chi}^+_1\tilde{\chi}^-_1, \tilde{\chi}^+_1\to W\tilde{\chi}^0_1, \tilde{\chi}^0_1\to ee\tilde{\nu}_\mu, e\mu\tilde{\nu}_e$	4 e,μ	0	Yes	20.7	$\tilde{\chi}^\pm_1$ 760 GeV	$m(\tilde{\chi}^0_1)$>300 GeV, λ_{121}>0	ATLAS-CONF-2013-036
	$\tilde{\chi}^+_1\tilde{\chi}^-_1, \tilde{\chi}^+_1\to W\tilde{\chi}^0_1, \tilde{\chi}^0_1\to\tau\tau\tilde{\nu}_e, e\tau\tilde{\nu}_\tau$	3 $e,\mu+\tau$	0	Yes	20.7	$\tilde{\chi}^\pm_1$ 350 GeV	$m(\tilde{\chi}^0_1)$>80 GeV, λ_{133}>0	ATLAS-CONF-2013-036
	$\tilde{g}\to qqq$	0	6 jets	-	4.6	$\tilde{g}$ 666 GeV		1210.4813
	$\tilde{g}\to\tilde{t}_1t, \tilde{t}_1\to bs$	2 e,μ (SS)	0-3 b	Yes	20.7	$\tilde{g}$ 880 GeV		ATLAS-CONF-2013-007
Other	Scalar gluon	0	4 jets	-	4.6	sgluon 100-287 GeV	incl. limit from 1110.2693	1210.4826
	WIMP interaction (D5, Dirac χ)	0	mono-jet	Yes	10.5	M* scale 704 GeV	$m(\chi)$<80 GeV, limit of<687 GeV for D8	ATLAS-CONF-2012-147

Mass scale [TeV]: 10^{-1}, 1

$\sqrt{s}$ = 7 TeV full data | $\sqrt{s}$ = 8 TeV partial data | $\sqrt{s}$ = 8 TeV full data

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

Missing energy

Most of the searches above assume large $\not{E}_T$. This is a natural choice when considering a *generic* spectra, and assuming R-parity.

$$R_p = (-1)^{2S+3B+L}$$

With R-parity, the lightest superpartner is stable. If it is neutral it gives a DM candidate, and when produced at the LHC it leaves the detector without depositing energy $\rightarrow \not{E}_T$.

R-parity is introduced to forbid dimension-4 operators violating both lepton and baryon number that cause fast proton decay. Still, there are dimension-5 operators that make the proton decay, and only a specific flavor structure can keep them under control (e.g. GUTs).

So why not think about flavor first and see if R-parity was superfluous?

- less or no missing energy in supersymmetric events. LHC limits are weaker
- DM can be a gravitino, or an axion/axino.
- proton stability?

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Horizontal symmetry

[Froggatt-Nielsen, 1979]
[Leurer,Nir,Seiberg, hep-ph/9212278]

Following Froggat and Nielsen, and in the supersymmetric case, Nir and Seiberg, we impose a **horizontal symmetry**, $U(1)_{\mathcal{H}}$, with family-dependent charges. The high-energy theory is invariant under $U(1)_{\mathcal{H}}$, broken by a vev of the **flavon** field S, with charge -1.

In the low-energy theory, heavy fields that have been integrated out generate effective operators proportional to a spurion $\varepsilon = \frac{\langle S \rangle}{M}$, where M is the heavy scale.

Only terms that are invariant under the symmetry are allowed in the superpotential: the Yukawa couplings

$$Y^d_{ij}\phi_d Q_i \bar{d}_j + Y^u_{ij}\phi_u Q_i \bar{u}_j + Y^\ell_{ij}\phi_d L_i \bar{\ell}_j$$

become

$$\varepsilon^{m_{ij}}\phi_d Q_i \bar{d}_j + \varepsilon^{n_{ij}}\phi_u Q_i \bar{u}_j + \varepsilon^{p_{ij}}\phi_d L_i \bar{\ell}_j$$

with $m_{ij} = \mathcal{H}[\phi_d] + \mathcal{H}[Q_i] + \mathcal{H}[\bar{d}_j] - r$, and so on. The exponents must be *non-negative* and *non-fractional*. Unknown $\mathcal{O}(1)$ factors are neglected in front of each operator.

SM fermions hierarchies

Given the superpotential above, and the notation $\mathcal{H}[\Phi_i] = \Phi_i$, $\Phi_{ij} = \Phi_i - \Phi_j$,

$$Y^a_{ij} \sim \varepsilon^{\phi_a + Q_i + a_j - r} \qquad a = u, d;\;\; i,j = 1,2,3;$$

$$\frac{m^a_i}{m^a_j} \sim \varepsilon^{Q_i + a_i - Q_j - a_j}, \qquad |V_{ij}| \sim \varepsilon^{|Q_i - Q_j|},$$

$$Y^\ell_{ij} \sim v_d \varepsilon^{\phi_d + L_i + \ell_j - r}; \qquad \frac{m^\ell_i}{m^\ell_j} \sim \varepsilon^{L_i + \ell_i - L_j - \ell_j}; \qquad |U_{ij}| \sim \varepsilon^{|L_i - L_j|}$$

- For the quarks, we take $\varepsilon = \sin\theta_C = 0.226$

$$m_t/v = 1 \sim \varepsilon^0, \quad m_c/m_t \sim .0035 \sim \varepsilon^4, \quad m_u/m_c = .002 \sim \varepsilon^4,$$

$$m_b/m_t = .017 \sim \varepsilon^{2.7}, \quad m_s/m_b = .019 \sim \varepsilon^3, \quad m_d/m_s = .053 \sim \varepsilon^2$$

$$|V| = \begin{pmatrix} 1 & \varepsilon & \varepsilon^3 \\ & 1 & \varepsilon^2 \\ & & 1 \end{pmatrix}$$

SM fermions hierarchies

Given the superpotential above, and the notation $\mathcal{H}[\Phi_i] = \Phi_i$, $\Phi_{ij} = \Phi_i - \Phi_j$,

$$Y^a_{ij} \sim \varepsilon^{\phi_a + Q_i + a_j - r} \qquad a = u, d;\ \ i, j = 1, 2, 3;$$

$$\frac{m^a_i}{m^a_j} \sim \varepsilon^{Q_i + a_i - Q_j - a_j}, \quad |V_{ij}| \sim \varepsilon^{|Q_i - Q_j|},$$

$$Y^\ell_{ij} \sim v_d \varepsilon^{\phi_d + L_i + \ell_j - r}; \quad \frac{m^\ell_i}{m^\ell_j} \sim \varepsilon^{L_i + \ell_i - L_j - \ell_j}; \quad |U_{ij}| \sim \varepsilon^{|L_i - L_j|}$$

- For the leptons,

$$m_\tau / m_t = .01 \sim \varepsilon^{3.1}, \quad m_\mu / m_\tau = .059 \sim \varepsilon^2, \quad m_e / m_\mu = .0047 \sim \varepsilon^4$$

$$|U| = \begin{pmatrix} 0.82 & 0.55 & 0.16 \\ 0.36 & 0.7 & 0.62 \\ 0.44 & 0.46 & 0.77 \end{pmatrix} \sim$$

$$\sim \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix} \text{ or } \begin{pmatrix} 1 & \varepsilon & \varepsilon \\ \varepsilon & 1 & 1 \\ \varepsilon & 1 & 1 \end{pmatrix} \text{ or } \begin{pmatrix} 1 & 1 & \varepsilon \\ 1 & 1 & \varepsilon \\ \varepsilon & \varepsilon & 1 \end{pmatrix}$$

Solutions

All the phenomenological constraints fix the following charge differences

Q_{12}	Q_{13}	Q_{23}	d_{12}	d_{13}	d_{23}	u_{12}	u_{13}	u_{23}	L_{12}	L_{13}	L_{23}	ℓ_{12}	ℓ_{13}	ℓ_{23}
1	3	2	1	2	1	3	5	2	0	0	0	4	6	2

$$\phi_u + Q_3 + u_3 = r, \qquad \phi_d + Q_3 + d_3 \; = \; \phi_d + L_3 + \ell_3 = 2 - x_\beta + r$$

We are left with 4 independent variables, which can be taken as $\{Q_3, u_3, d_3, L_3\}$.

Additionally, if $n_\mu = \phi_u + \phi_d < 0$, the μ term $\mu\phi_u\phi_d$ is generated by a Giudice-Masiero-like term $\delta K = X\phi_u\phi_d \left(\frac{S^*}{M}\right)^{-n_\mu}$

$$m_{3/2}\varepsilon^{|n_\mu|}\phi_u\phi_d$$

For $n_\mu \sim -1$ the μ term is automatically suppressed with respect to the SUSY breaking scale.

Anomalies: Green-Schwarz cancellation, or not

Given the $U(1)_{\mathcal{H}}$, it should be checked that the symmetry is anomaly-free;

$$\psi_j \to e^{iq_j\alpha}\psi_j, \quad \lambda \to e^{iq_\theta\alpha}\lambda :$$
$$\mathcal{A}_{SU(N)\times SU(N)\times U(1)_{\mathcal{H}}} = \sum_j \ell(\mathbf{r}_j)q_j + \ell(Adj)q_\theta$$

if there is a mixed gauge-gauge-$U(1)_{\mathcal{H}}$ anomaly, it can be cancelled by an axion-like field transforming non-linearly under the symmetry.
In string theory, a Green-Schwarz cancellation of anomalies takes place in some heterotic models. The model-independent dilaton couples universally to the field strengths of different gauge groups. This is referred to as *anomaly universality*, and is usually assumed when studying horizontal symmetries. It is not that common, and several axions can cancel the different anomalies.
Assuming anomaly universality is not generically justified from a bottom-up approach.

[Dine,Monteux, 1212.4371]

[Nibbelink Groot,Nilles,Trapletti, hep-th/0703211]

R-parity violating couplings

Without R-parity, the MSSM field content allows additional gauge-invariant terms in the superpotential:

$$W_{\not{R}_p} = \bar{\mu}_i L_i \phi_u + \lambda_{ijk} L_i L_j \bar{\ell}_k + \lambda'_{ijk} L_i Q_j \bar{d}_k + \lambda''_{ijk} \bar{u}_i \bar{d}_j \bar{d}_k$$

which break B and L. With a horizontal symmetry, the magnitude of the couplings is related to the horizontal charges

$$(\bar{\mu}_i, \lambda_{ijk}, \lambda'_{ijk}, \lambda''_{ijk}) \sim \quad \varepsilon^{-r}(m\varepsilon^{L_i+\phi_u}, \varepsilon^{L_i+L_j+\ell_k}, \varepsilon^{L_i+Q_j+d_k}, \varepsilon^{u_i+d_j+d_k})$$

In particular, factoring out the couplings involving third generation fields, the **relative** structure is fixed:

$$\frac{\bar{\mu}_i}{\bar{\mu}_3} = \varepsilon^{L_{i3}}, \quad \frac{\lambda_{ijk}}{\lambda_{233}} = \varepsilon^{L_{i2}+L_{j3}+\ell_{k3}}, \quad \frac{\lambda'_{ijk}}{\lambda'_{333}} = \varepsilon^{L_{i3}+Q_{j3}+d_{k3}},$$

$$\frac{\lambda''_{ijk}}{\lambda''_{323}} = \varepsilon^{u_{i3}+d_{j2}+d_{k3}}$$

Because the charge differences are uniquely fixed by the masses and mixings, the horizontal symmetry predicts **definite textures**.

RPV textures

- $\bar{\mu}_1 = \bar{\mu}_2 = \bar{\mu}_3 = m\varepsilon^{n_{\bar{\mu}}}, \qquad n_{\bar{\mu}} = L_3 + \phi_u - r$
- $\lambda_{233} = \lambda'_{333} \equiv \varepsilon^{n_{LNV}},$

$$\begin{pmatrix} \lambda_{121} & \lambda_{122} & \lambda_{123} \\ \lambda_{131} & \lambda_{132} & \lambda_{133} \\ \lambda_{231} & \lambda_{232} & \lambda_{233} \end{pmatrix} = \varepsilon^{n_{LNV}} \begin{pmatrix} \varepsilon^6 & \varepsilon^2 & 1 \\ \varepsilon^6 & \varepsilon^2 & 1 \\ \varepsilon^6 & \varepsilon^2 & 1 \end{pmatrix}$$

$$\begin{pmatrix} \lambda'_{i11} & \lambda'_{i12} & \lambda'_{i13} \\ \lambda'_{i21} & \lambda'_{i22} & \lambda'_{i23} \\ \lambda'_{i31} & \lambda'_{i32} & \lambda'_{i33} \end{pmatrix} = \varepsilon^{n_{LNV}} \begin{pmatrix} \varepsilon^5 & \varepsilon^4 & \varepsilon^3 \\ \varepsilon^4 & \varepsilon^3 & \varepsilon^2 \\ \varepsilon & 1 & 1 \end{pmatrix}$$

- $\lambda''_{323} \equiv \varepsilon^{n_{BNV}}$

$$\begin{pmatrix} \lambda''_{112} & \lambda''_{212} & \lambda''_{312} \\ \lambda''_{113} & \lambda''_{213} & \lambda''_{313} \\ \lambda''_{123} & \lambda''_{223} & \lambda''_{323} \end{pmatrix} = \varepsilon^{n_{BNV}} \begin{pmatrix} \varepsilon^7 & \varepsilon^4 & \varepsilon^2 \\ \varepsilon^6 & \varepsilon^3 & \varepsilon \\ \varepsilon^5 & \varepsilon^2 & 1 \end{pmatrix}$$

with $n_{LNV} = L_2 + Q_3 + d_3 - r = L_2 + L_3 + \ell_3 - r,$

$n_{BNV} = u_3 + d_2 + d_3 - r.$

RPV textures

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- $\lambda_{233} = \lambda'_{333} \equiv \varepsilon^{n_{LNV}},$

$$\begin{pmatrix} \lambda_{121} & \lambda_{122} & \lambda_{123} \\ \lambda_{131} & \lambda_{132} & \lambda_{133} \\ \lambda_{231} & \lambda_{232} & \lambda_{233} \end{pmatrix} = \varepsilon^{n_{LNV}} \begin{pmatrix} \varepsilon^6 & \varepsilon^2 & 1 \\ \varepsilon^6 & \varepsilon^2 & 1 \\ \varepsilon^6 & \varepsilon^2 & 1 \end{pmatrix}$$

$$\begin{pmatrix} \lambda'_{i11} & \lambda'_{i12} & \lambda'_{i13} \\ \lambda'_{i21} & \lambda'_{i22} & \lambda'_{i23} \\ \lambda'_{i31} & \lambda'_{i32} & \lambda'_{i33} \end{pmatrix} = \varepsilon^{n_{LNV}} \begin{pmatrix} \varepsilon^5 & \varepsilon^4 & \varepsilon^3 \\ \varepsilon^4 & \varepsilon^3 & \varepsilon^2 \\ \varepsilon & 1 & 1 \end{pmatrix}$$

- $\lambda''_{323} \equiv \varepsilon^{n_{BNV}}$

$$\begin{pmatrix} \lambda''_{112} & \lambda''_{212} & \lambda''_{312} \\ \lambda''_{113} & \lambda''_{213} & \lambda''_{313} \\ \lambda''_{123} & \lambda''_{223} & \lambda''_{323} \end{pmatrix} = \varepsilon^{n_{BNV}} \begin{pmatrix} \varepsilon^7 & \varepsilon^4 & \varepsilon^2 \\ \varepsilon^6 & \varepsilon^3 & \varepsilon \\ \varepsilon^5 & \varepsilon^2 & 1 \end{pmatrix}$$

with $n_{LNV} = L_2 + Q_3 + d_3 - r = L_2 + L_3 + \ell_3 - r,$
$n_{BNV} = u_3 + d_2 + d_3 - r.$

RPV textures

- $\bar{\mu}_1 = \bar{\mu}_2 = \bar{\mu}_3 = m\varepsilon^{n_{\bar{\mu}}}, \qquad n_{\bar{\mu}} = L_3 + \phi_u - r$
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BNV, LNV

We will parametrize everything in terms of 3 independent 'phenomenological' variables $(n_\mu, n_{\bar\mu}, n_{BNV})$. Possible scenarios in terms of $n_{\bar\mu}, n_{BNV}$:

- both fractional: R-parity is effectively conserved; LHC searches relying on missing energy apply and the weak scale is generically fine-tuned.
- both integers: B and L are not conserved, proton decay

$$p \to K^+ \bar\nu : |\lambda'_{i23} \lambda''^{*}_{113}| \lesssim 10^{-27} \left(\frac{m_{\tilde b_R}}{100\text{ GeV}} \right)^2 = \varepsilon^{41} \left(\frac{m_{\tilde b_R}}{100\text{ GeV}} \right)^2$$

$$n_{LNV} + n_{BNV} > 32 \implies n_{LNV}, n_{BNV} \gtrsim \mathcal{O}(15)$$

But, *extremely small* RPV coefficients would mimic RPC SUSY, or give stable massive particles: for $\tilde t \overset{RPV}{\to} d_i d_j$

$$\Gamma = \frac{m_{\tilde t}}{8\pi} \sin^2\theta_{\tilde t} |\lambda''_{3ij}|^2, \qquad c\tau \sim 10^{-16} |\lambda''_{3ij}|^{-2} \left(\frac{100\text{ GeV}}{m_{\tilde t}} \right) \text{m}$$

For $n_{BNV} \gtrsim 13$, $c\tau \gtrsim 1$m and a $\tilde t$ LSP forms an R-hadron which stops or decays within the detector.

A light stop with $m_{\tilde t} < 850$ GeV requires $n_{BNV}, n_{LNV} < 13$

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BNV, LNV

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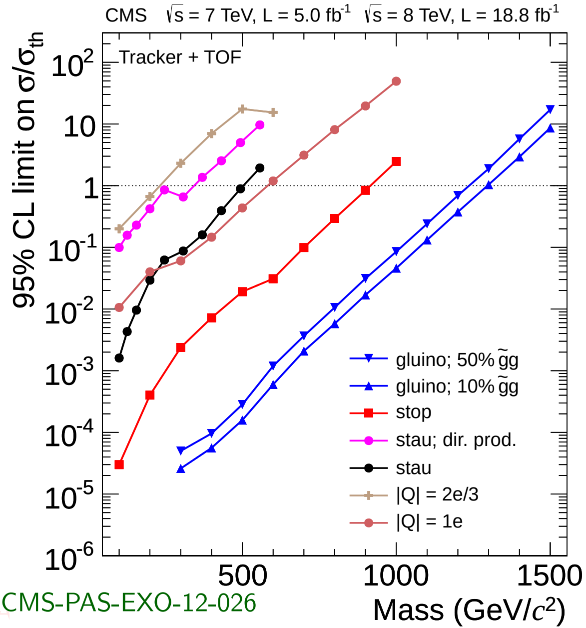

CMS-PAS-EXO-12-026

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- n_{LNV} integer, n_{BNV} fractional; baryon number violation is forbidden, lepton number violation is allowed. If it is the main decay channel, multi-leptons signatures, LHC limits are around 1 TeV.
- n_{LNV} fractional, n_{BNV} integer: no LNV, there is a $\bar{u}\bar{d}\bar{d}$ operator giving hadronic decays of superpartners, without missing energy.

This is the scenario we will study. Let's recall

$$\begin{pmatrix} \lambda''_{112} & \lambda''_{212} & \lambda''_{312} \\ \lambda''_{113} & \lambda''_{213} & \lambda''_{313} \\ \lambda''_{123} & \lambda''_{223} & \lambda''_{323} \end{pmatrix} = \varepsilon^{n_{BNV}} \begin{pmatrix} \varepsilon^7 & \varepsilon^4 & \varepsilon^2 \\ \varepsilon^6 & \varepsilon^3 & \varepsilon \\ \varepsilon^5 & \varepsilon^2 & 1 \end{pmatrix}$$

A single parameter determines all the R-parity violating phenomenology.

Phenomenology: LOWER limits on RPV couplings

If a squark LSP is produced at the LHC but cannot decay because its RPV coupling is too small, it will either exit the detector as missing energy if neutral (the limits on RPC SUSY would apply), or hadronize as a new stable massive particle (an R-hadron). For an R-hadron, ATLAS and CMS exclude a stop LSP up to 680 GeV and 850 GeV.

$$\Gamma(\tilde{t} \to d_i d_j) = \frac{m_{\tilde{t}}}{8\pi} \sin^2 \theta_{\tilde{t}} |\lambda''_{3ij}|^2$$

$$\implies n_{BNV} < 13 \qquad \lambda''_{323} > 10^{-9}$$

Displaced vertices for $11 \lesssim n_{BNV} \lesssim 13$.

Phenomenology: UPPER limits on RPV couplings

- dinucleon decay $NN \to KK$: $n_{BNV} \gtrsim 2$

$$|\lambda''_{112}| \lesssim 3 \times 10^{-7} \left(\frac{1.7 \times 10^{32}\,\text{yr}}{\tau_{NN\to KK}}\right)^{1/4} \left(\frac{m_{\tilde{s}_R}}{300\text{ GeV}}\right)^{2} \left(\frac{m_{\tilde{g}}}{300\text{ GeV}}\right)^{1/2} \cdot \left(\frac{75\text{ MeV}}{\tilde{\Lambda}}\right)^{5/2}$$

- $n - \bar{n}$ oscillation: $n_{BNV} \gtrsim 2$

$$|\lambda''_{113}| \lesssim (10^{-6} - 10^{-5}) \frac{10^8 s}{\tau_{n-\bar{n}}} \left(\frac{m_{\tilde{b}_R}}{100\text{ GeV}}\right)^{2} \left(\frac{m_{\tilde{g}}}{100\text{ GeV}}\right)^{1/2}$$

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[redacted]

Take home message:

$$\mathbf{3 < n_{BNV} < 13, \qquad 10^{-9} < \lambda''_{323} < 10^{-2}}$$

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Natural RPV SUSY with a $U(1)_{\mathcal{H}}$

also see other talks in this section, e.g. Tweedie, Seitz

ATLAS searches:

- multi-jets: $\tilde{g} \to q\tilde{q} \overset{RPV}{\to} qqq$ [ATLAS, 1210.4813]

$$m_{\tilde{g}} > 666 \text{ GeV at } 95\% \ CL$$

- same-sign leptons: $\tilde{g} \to \bar{t}\tilde{t} \overset{RPV}{\to} \bar{t}bs$ [ATLAS, ATLAS-CONF-2013-007]

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Limits on gluino masses, independent on stop masses. Relevant for naturalness only because gluino mass enters stops RGE.
E.g., $m_{\tilde{g}} \sim 1.4$ TeV $\implies$ 1% tuning of the weak scale.

Natural SUSY, no *R*-parity, definite range and textures for the RPV couplings

What are the issues of low-energy SUSY?

Natural RPV SUSY with a $U(1)_{\mathcal{H}}$

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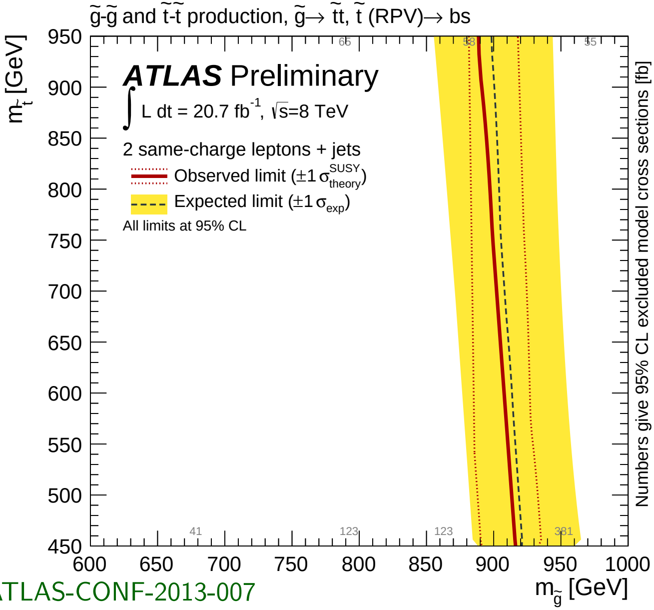

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What

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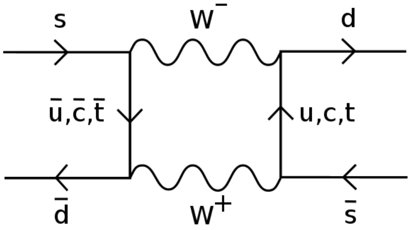
Natural SUSY, no *R*-parity, definite range and textures for the RPV couplings

What are the issues of low-energy SUSY?

Flavor changing neutral currents

Take the kaon; in the SM, we have the GIM mechanism



In the MSSM, we have the same graphs with gauginos and squarks. With generic squark masses the GIM mechanism does not operate. This can be solved by either squark degeneracy, or quark-squark alignment;

[Nir,Seiberg, 1993]

Horizontal symmetries can naturally generate aligned models. Take a horizontal symmetry $U(1)_{\mathcal{H}_1} \times U(1)_{\mathcal{H}_2}$ with two spurions ε_1, ε_2 carrying charges $(-1, 0)$ and $(0, -1)$. With appropriate charges, the masses and mixings are explained, and FCNCs are suppressed. The limits on RPV couplings remain the same.

The Higgs mass and the NMSSM

The Higgs mass is

$$m_h = 126 \text{ GeV}$$

In the MSSM,

$$m_h^2 \simeq M_Z^2 \cos^2 2\beta + \frac{3m_t^4}{4\pi^2 v^2}\left(\log\frac{m_{\tilde{t}}^2}{m_t^2} + \frac{A_t^2}{m_{\tilde{t}}^2}\left(1 - \frac{A_t^2}{12 m_{\tilde{t}}^2}\right)\right)$$

In the NMSSM,

$$W \supset \lambda N \phi_u \phi_d + \frac{\kappa}{3} N^3,$$

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$$+ \lambda^2 v^2 \sin^2 2\beta - \frac{\lambda^2 v^2}{\kappa^2}(\lambda - \kappa \sin 2\beta)^2$$

For $\lambda \sim 0.7$, $tan\beta \sim 2$ we can accomodate 500 GeV stops.
[L.Hall,D.Pinner,J.Ruderman, 1112.2703]

There are some more operators involving N and they are not problematic.

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Conclusions

- The LHC constraints on *R*-parity conserving SUSY are not too far from excluding low-energy supersymmetry.
- It is reasonable to expect that what decides the hierarchical flavor structure of the SM also fixes the RPV structure. E.g. a horizontal symmetry fixes the RPV textures (*without anomaly constraints*)
- while leptonic RPV has clear signatures and excludes superpartners above 1 TeV, baryonic RPV could still be hiding.
- There is still space for low energy RPV SUSY. Horizontal symmetries predict that the biggest RPV coupling is

$$\lambda''_{323}\bar{t}\bar{b}\bar{s}$$

with $10^{-9} < \lambda''_{323} < 10^{-2}$

10^{-9}: $\not{E}_T$, *R*-hadrons searches

10^{-2}: low energy ΔB processes

Thank you!

Backups

Alignment

[Leurer,Nir,Seiberg, 1993]

$$\frac{\Delta m_K}{m_K} \sim 7 \cdot 10^{-15}, \qquad \frac{\Delta m_B}{m_B} \sim 7 \cdot 10^{-14}, \qquad \frac{\Delta m_D}{m_D} \sim 8 \cdot 10^{-15}$$

$$V_L^q M^q V_R^{q\dagger} = \text{diag}\{m_{q\,k}\} \qquad \tilde{V}_L^q \tilde{M}_{LL}^{q2} \tilde{V}_L^{q\dagger} = \text{diag}\{\tilde{m}_{q\,k}^2\}$$

In the basis in which both quark and squark mass matrices are diagonal, gaugino interactions depend on

$$K_L^q = V_L^q \tilde{V}_L^{q\dagger}$$

A FCNC box diagram gives

$$\sum_{I,J} (K_M^q)_{iI} (K_M^q)_{jI}^* (K_N^q)_{iJ} (K_N^q)_{jJ}^* \times f(\tilde{m}_I^2, \tilde{m}_J^2)$$

Any non-diagonal term $I \neq J$ should be suppressed

- degenerate squarks: f is independent of I, J and $\sum_I (K_M^q)_{iI} (K_M^q)_{jI}^* = 0$
- K is almost diagonal: $(K_M^q)_{ij} \ll 1$ for $i \neq j$; this means that V and $\tilde{V}$ are approximately equal.

Anomaly universality

The standard GS cancellation is

$$\int d^2\theta \left(\frac{1}{g^2} + iA(x) \right) \sum_k W_\alpha^2 \supset \frac{1}{g^2} \sum_k F_k^2 + iA(x) \sum_k F_k \tilde{F}_k$$

with $A(x) \to A(x) - \alpha\delta_{GS}$. Then, to be cancelled by one axion, the mixed anomalies are the same (assuming unification).

A standard GS anomaly cancellation is not that common in string theory. Take Type IIB string theory compactified on T^6/Z_3 orbifolds, and the anomalies are cancelled by several twisted RR fields. One sees that there are non-universal discrete anomalies.

[Dine,Monteux, 1212.4371]

$$Tr(\gamma_k \lambda_i) B_k \wedge F_{U(1)_i}$$
$$Tr(\gamma_k^\alpha \lambda_i^\alpha) = -2 n_i i \sin 2\pi k V_i^\alpha$$

For heterotic orbifold blow-ups, we can have multiple non-universal axions too.

[Nibbelink Groot,Nilles,Trapletti, hep-th/0703211]

In general, any heavy field with SM charges will mess the anomaly constraints.

Assuming anomaly universality is not generically justified from a bottom-up approach.

Anomaly cancellation and the μ term

Assuming universal anomalies cancellation, there are 2 additional constraints on the horizontal charges; with these, the μ term magnitude is fixed:

[Dreiner,Thormeier, hep-ph/0305270]

$$\varepsilon^{n_\mu} = \frac{m_d m_s m_b}{m_e m_\mu m_\tau} = 5.14^{+4.40}_{-3.02} \sim \varepsilon^{0,-1,-2}$$

For $n_\mu = -1$, a Giudice-Masiero-like term $\delta K = X\phi_u\phi_d \left(\frac{S^*}{M}\right)^{-n_\mu}$ predicts

$$\mu = \varepsilon m_{3/2}$$

so that the SUSY breaking scale cannot be too high.

Being agnostic w.r.t. the anomaly cancellation mechanism, the prediction is lost. In particular, a rather high scale of SUSY breaking can still accomodate a weak scale μ term.

dimension 5 operators

$$W_5 = \frac{(\kappa_1)_{ijkl}}{M_P} Q_i Q_j Q_k L_l + \frac{(\kappa_2)_{ijkl}}{M_P} \bar{u}_i \bar{u}_j \bar{d}_k \bar{\ell}_l + \frac{(\kappa_3)_{ijk}}{M_P} Q_i Q_j Q_k \phi_d + \frac{(\kappa_4)_{ijk}}{M_P} Q_i \phi_d \bar{u}_j \bar{\ell}_k$$

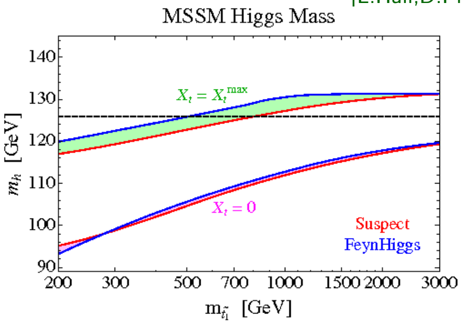
$$+ \frac{(\kappa_5)_{ij}}{M_P} L_i \phi_u L_j \phi_u + \frac{(\kappa_6)_i}{M_P} L_i \phi_u \phi_d \phi_u$$

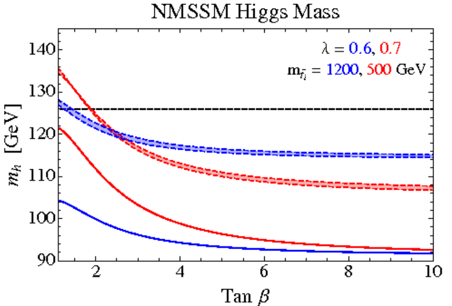
$$K_5 = \frac{(\kappa_7)_{ijk}}{M_P} \bar{u}_i \bar{d}_j^* \bar{\ell}_k + \frac{(\kappa_8)_i}{M_P} \phi_u^* \phi_d \bar{\ell}_i + \frac{(\kappa_9)_{ijk}}{M_P} Q_i L_j^* \bar{u}_k + \frac{(\kappa_{10})_{ijk}}{M_P} Q_i Q_j \bar{d}$$

$\mathcal{O}_1$	$6 + r - 2x_\beta - n_{BNV} - 2n_\mu + n_{\bar{\mu}}$	$\mathcal{O}_2$	$-2 - r + x_\beta + n_{BNV} + n_\mu - n_{\bar{\mu}}$
$\mathcal{O}_3$	$6 + r - 2x_\beta - n_{BNV} - n_\mu$	$\mathcal{O}_4$	$2 - x_\beta + r - n_{\bar{\mu}}$
$\mathcal{O}_5$	$2n_{\bar{\mu}} + 2r$	$\mathcal{O}_6$	$n_\mu + n_{\bar{\mu}} + 2r$
$\mathcal{O}_7$	$-n_{\bar{\mu}}$	$\mathcal{O}_8$	$2 - x_\beta - n_{\bar{\mu}}$
$\mathcal{O}_9$	$-n_{\bar{\mu}}$	$\mathcal{O}_{10}$	$2 - x_\beta - n_{BNV} -$

MSSM/NMSSM fine-tuning

[L.Hall,D.Pinner,J.Ruderman, 1112.2703]





MSSM/NMSSM fine-tuning

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