

Phenomenology of SUSY models with an extended gauge sector

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in coll. with M. Hirsch, M. Krauss, B. O'Leary, L. Reichert, F. Staub

● Origin of R -parity

$$\begin{aligned} \Rightarrow SO(10) &\rightarrow SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L} \\ &\rightarrow SU(3)_C \times SU(2)_L \times U(1)_R \times U(1)_{B-L} \\ &\cong SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_\chi \end{aligned}$$

or $E(8) \times E(8) \rightarrow SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$

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● Neutrino masses

$B - L$ anomaly free $\Rightarrow \nu_R$

usual seesaw, inverse seesaw

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● Neutrino masses

$B - L$ anomaly free $\Rightarrow \nu_R$

usual seesaw, inverse seesaw

● Hints for an SM-like Higgs boson at 125 GeV

in SUSY: additional D-term contributions to m_{h^0}

- Gauge kinetic mixing
- $SO(10)/E(6)$ based model
 - model building
 - Z' physics
 - SUSY cascade decays
- $E_8 \times E_8$ based model
 - Z' physics
 - $\tilde{l}$ searches at 14 TeV

in this talk:

	gauge kinetic mixing effects	neutrino masses
$SO(10)/E(6)$	small	inverse seesaw
$E_8 \times E_8$	large	low scale seesaw I

$U(1)_a \times U(1)_b$ models allow for

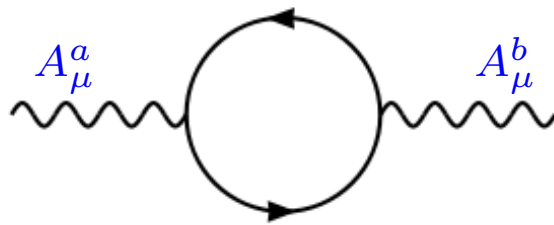
(B. Holdom, PLB 166 (1986) 196)

$$\mathcal{L} \supset -\chi_{ab} \hat{F}^{a,\mu\nu} \hat{F}_{\mu\nu}^b$$

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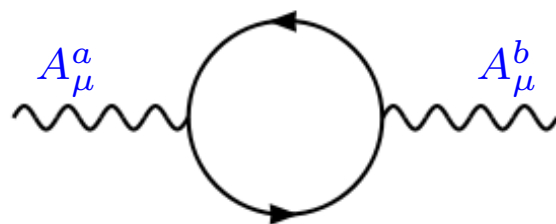


$$\gamma_{ab} = \frac{1}{16\pi^2} \text{Tr}(Q_a Q_b)$$

$U(1)_a \times U(1)_b$ models allow for

(B. Holdom, PLB 166 (1986) 196)

$$\mathcal{L} \supset -\chi_{ab} \hat{F}^{a,\mu\nu} \hat{F}_{\mu\nu}^b$$



$$\Longleftrightarrow \gamma_{ab} = \frac{1}{16\pi^2} \text{Tr}(Q_a Q_b)$$

equivalent

$$D_\mu = \partial_\mu - i \begin{pmatrix} Q_a \\ Q_b \end{pmatrix} \begin{pmatrix} g_{aa} & g_{ab} \\ g_{ba} & g_{bb} \end{pmatrix} \begin{pmatrix} A_\mu^a \\ A_\mu^b \end{pmatrix}$$

both $U(1)$ unbroken $\Rightarrow$ chose basis with e.g. $g_{ba} = 0$

affects also RGE running of soft SUSY parameters:

R. Fonseca, M. Malinsky, W.P., F. Staub, NPB 854 (2012) 28

	Superfield	$SU(3)_c \times SU(2)_L \times U(1)_R \times U(1)_{B-L}$	Generations
Matter	$\hat{Q}$	$(\mathbf{3}, \mathbf{2}, 0, +\frac{1}{6})$	3
	$\hat{d}^c$	$(\bar{\mathbf{3}}, \mathbf{1}, +\frac{1}{2}, -\frac{1}{6})$	3
	$\hat{u}^c$	$(\bar{\mathbf{3}}, \mathbf{1}, -\frac{1}{2}, -\frac{1}{6})$	3
	$\hat{L}$	$(\mathbf{1}, \mathbf{2}, 0, -\frac{1}{2})$	3
	$\hat{e}^c$	$(\mathbf{1}, \mathbf{1}, +\frac{1}{2}, +\frac{1}{2})$	3
	$\hat{\nu}^c$	$(\mathbf{1}, \mathbf{1}, -\frac{1}{2}, +\frac{1}{2})$	3
	$\hat{S}$	$(\mathbf{1}, \mathbf{1}, 0, 0)$	3
Higgs	$\hat{H}_u$	$(\mathbf{1}, \mathbf{2}, +\frac{1}{2}, 0)$	1
	$\hat{H}_d$	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2}, 0)$	1
	$\hat{\chi}_R$	$(\mathbf{1}, \mathbf{1}, +\frac{1}{2}, -\frac{1}{2})$	1
	$\hat{\bar{\chi}}_R$	$(\mathbf{1}, \mathbf{1}, -\frac{1}{2}, +\frac{1}{2})$	1

$$Y = T_R + B - L \text{ and } Q = T_L^3 + Y.$$

$$W = Y_u \hat{u}^c \hat{Q} \hat{H}_u - Y_d \hat{d}^c \hat{Q} \hat{H}_d + Y_\nu \hat{\nu}^c \hat{L} \hat{H}_u - Y_e \hat{e}^c \hat{L} \hat{H}_d + \mu \hat{H}_u \hat{H}_d - \mu_R \hat{\chi}_R \hat{\bar{\chi}}_R + Y_s \hat{\nu}^c \hat{\chi}_R \hat{S}$$

based on M. Hirsch et al., arXiv:1110.3037

$$\begin{aligned}\chi_R &= \frac{1}{\sqrt{2}} (\sigma_R + i\varphi_R + v_{\chi_R}) , \quad \bar{\chi}_R = \frac{1}{\sqrt{2}} (\bar{\sigma}_R + i\bar{\varphi}_R + v_{\bar{\chi}_R}) \\ H_d^0 &= \frac{1}{\sqrt{2}} (\sigma_d + i\varphi_d + v_d) , \quad H_u^0 = \frac{1}{\sqrt{2}} (\sigma_u + i\varphi_u + v_u)\end{aligned}$$

pseudo scalars, basis $(\varphi_d, \varphi_u, \bar{\varphi}_R, \varphi_R)$

$$\begin{aligned}M_{AA}^2 &= \begin{pmatrix} M_{AA,L}^2 & 0 \\ 0 & M_{AA,R}^2 \end{pmatrix} \\ M_{AA,L}^2 &= B_\mu \begin{pmatrix} \tan \beta & 1 \\ 1 & \cot \beta \end{pmatrix} , \quad M_{AA,R}^2 = B_{\mu_R} \begin{pmatrix} \tan \beta_R & 1 \\ 1 & \cot \beta_R \end{pmatrix}\end{aligned}$$

$\tan \beta = v_u/v_d$ and $\tan \beta_R = v_{\chi_R}/v_{\bar{\chi}_R}$
two physical states

$$m_A^2 = B_\mu (\tan \beta + \cot \beta) , \quad m_{A_R}^2 = B_{\mu_R} (\tan \beta_R + \cot \beta_R)$$

independent of gauge kinetic mixing!

neglecting gauge kinetic mixing

$$\begin{aligned}
 M_{hh}^2 &= \begin{pmatrix} m_{LL}^2 & m_{LR}^2 \\ m_{LR}^{2,T} & m_{RR}^2 \end{pmatrix} \\
 m_{LL}^2 &= \begin{pmatrix} g_Z^2 v^2 c_\beta^2 + m_A^2 s_\beta^2 & -\frac{1}{2} (m_A^2 + g_Z^2 v^2) s_{2\beta} \\ -\frac{1}{2} (m_A^2 + g_Z^2 v^2) s_{2\beta} & g_Z^2 v^2 s_\beta^2 + m_A^2 c_\beta^2 \end{pmatrix}, \\
 m_{LR}^2 &= \begin{pmatrix} g_R^2 v v_R c_\beta c_{\beta_R} & -g_R^2 v v_R c_\beta s_{\beta_R} \\ -g_R^2 v v_R s_\beta c_{\beta_R} & g_R^2 v v_R s_\beta s_{\beta_R} \end{pmatrix}, \\
 m_{RR}^2 &= \begin{pmatrix} g_{Z_R}^2 v_R^2 c_{\beta_R}^2 + m_{A_R}^2 s_{\beta_R}^2 & -\frac{1}{2} (m_{A_R}^2 + g_{Z_R}^2 v_R^2) s_{2\beta_R} \\ -\frac{1}{2} (m_{A_R}^2 + g_{Z_R}^2 v_R^2) s_{2\beta_R} & g_{Z_R}^2 v_R^2 s_{\beta_R}^2 + m_{A_R}^2 c_{\beta_R}^2 \end{pmatrix} \\
 v_R^2 &= v_{\chi_R}^2 + v_{\tilde{\chi}_R}^2, \quad v^2 = v_d^2 + v_u^2 \\
 s_x &= \sin(x), \quad c_x = \cos(x), \quad g_Z^2 = \frac{1}{4}(g_2^2 + g_R^2), \quad g_{Z_R}^2 = \frac{1}{4}(g_{B_L}^2 + g_R^2)
 \end{aligned}$$

⇒ new D-term contributions at tree-level

H.E. Haber, M. Sher, PRD 35 (1987) 2206; M. Drees, PRD 35 (1987) 2910; M. Cvetič et al., PRD 56 (1997) 2861; E. Ma, arXiv:1108.4029; M. Hirsch et al., arXiv:1110.3037, arXiv:1206.xxxx

basis (W^0, B_{B-L}, B_R)

$$M_{VV}^2 = \frac{1}{4} \begin{pmatrix} g_2^2 v^2 & -g_2 g_{RBL} v^2 & g_2 g_R v^2 \\ -g_2 g_{RBL} v^2 & g_{RBL}^2 v^2 + \tilde{g}_{BL}^2 v_R^2 & g_R g_{RBL} v^2 - \tilde{g}_R \tilde{g}_{BL} v_R^2 \\ -g_2 g_R v^2 & g_R g_{RBL} v^2 - \tilde{g}_R \tilde{g}_{BL} v_R^2 & g_R^2 v^2 + \tilde{g}_R^2 v_R^2 \end{pmatrix}$$

$$\tilde{g}_{BL} = (g_{BL} - g_{RBL}), \quad \tilde{g}_R = (g_R - g_{BLR})$$

$$\det(M_{VV}^2) = 0$$

expanding in v^2/v_R^2 and setting $g_{BLR} = g_{RBL} = 0$

$$m_Z^2 = \frac{(g_{BL}^2 g_2^2 + g_{BL}^2 g_R^2 + g_2^2 g_R^2)}{4(g_{BL}^2 + g_R^2)} v^2 + O\left(\frac{v^2}{v_R^2}\right)$$

$$m_{Z'}^2 = \frac{1}{4}(g_{BL}^2 + g_R^2) v_R^2 + \frac{g_R^4}{4(g_{BL}^2 + g_R^2)} v^2 + O\left(\frac{v^2}{v_R^2}\right)$$

M. Hirsch, W.P., L. Reichert, F. Staub, arXiv:1206:xxxx

- model implementation via SARAH (F. Staub, arXiv:0909.2863, arXiv:1002.0840)
- numerics via SPheno (W.P. CPC **153** (2003) 275; W.P., F. Staub arXiv:1104.1573)
- MC-studies using WHIZARD (W. Kilian, T. Ohl, and J. Reuter, EPJC **71** (2011) 1742)
- model file via Toolbox (F. Staub, T. Ohl, W.P., C. Speckner, arXiv:1109.5147)
- tricky: relations between gauge couplings, e.g.

$$g_Y = \sqrt{\frac{5(g_{BL}g_R - g_{BLR}g_{RBL})^2}{3(g_{BL}^2 + g_{BLR}) + 2(g_R^2 + g_{RBL}^2) - 2\sqrt{6}(g_Rg_{BLR} + g_{BL}g_{RBL})}}$$

- 2-loop RGEs
- tadpoles at 1-loop (+ 2-loop corrections in the MSSM part)
- 1-loop mass spectrum (+ 2-loop corrections in the MSSM part of the Higgs sector)

GUT embedding: $g_{BL} = g_R = g_2 \Rightarrow M_{GUT}$, set $g_{RBL} = g_{BLR} = 0$ at M_{GUT}

$$\gamma_{ab} = \frac{1}{16\pi^2} \begin{pmatrix} \frac{15}{2} & -\sqrt{\frac{3}{8}} \\ -\sqrt{\frac{3}{8}} & \frac{27}{4} \end{pmatrix}$$

soft breaking parameters:

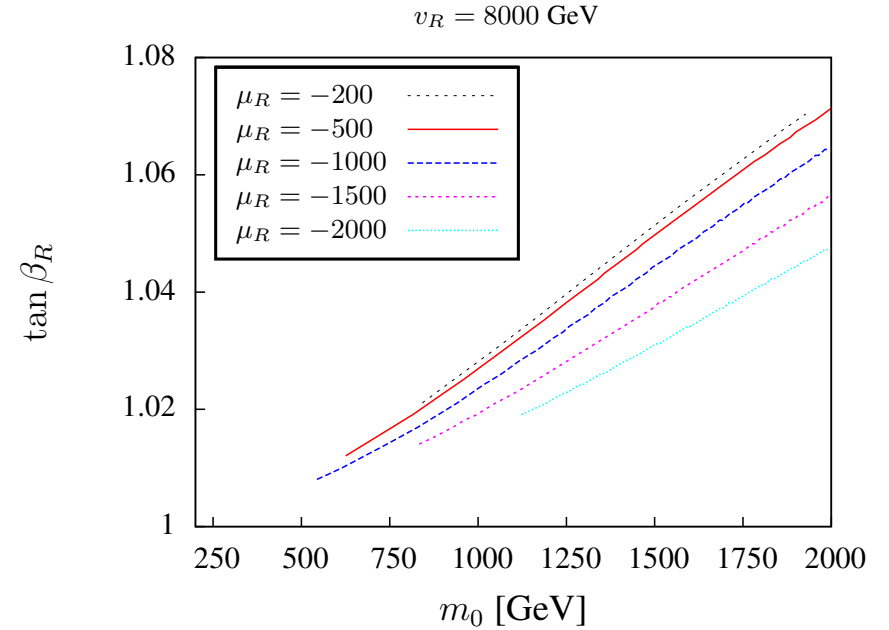
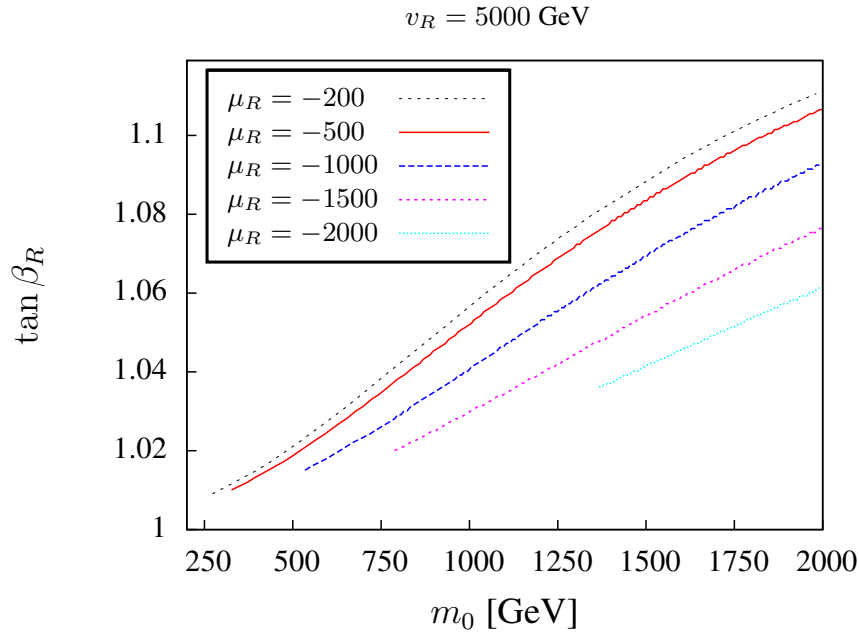
$$m_0^2 \mathbf{1}_3 = m_D^2 = m_U^2 = m_Q^2 = m_E^2 = m_L^2 = m_{\nu^c}^2 = m_S^2$$

$$M_{1/2} = M_{BL} = M_R = M_2 = M_3, \quad M_{BLR} = 0$$

$$T_i = A_0 Y_i, \quad i = e, d, u, \nu, s$$

Higgs sector: $m_0 = m_{H_d} = m_{H_u}$ and either

1. $m_0 = m_{\chi_R} = m_{\bar{\chi}_R}$ at M_{GUT} or
2. m_{A_R}, μ' at M_{SUSY} as input

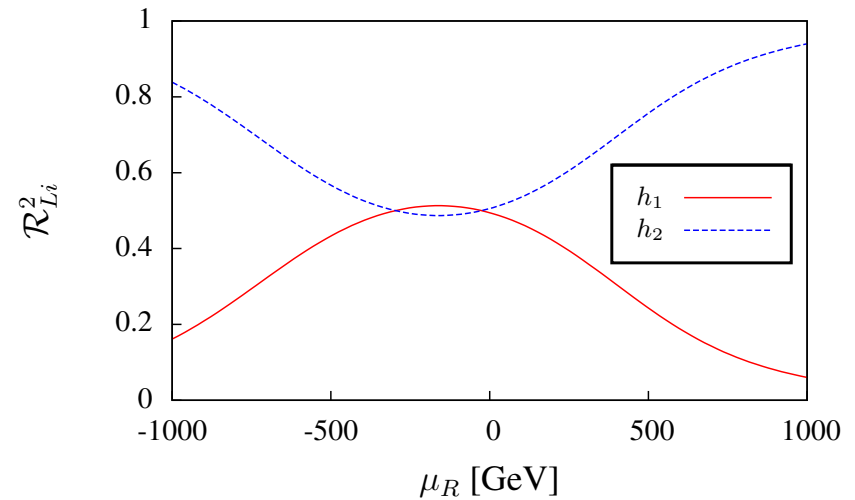
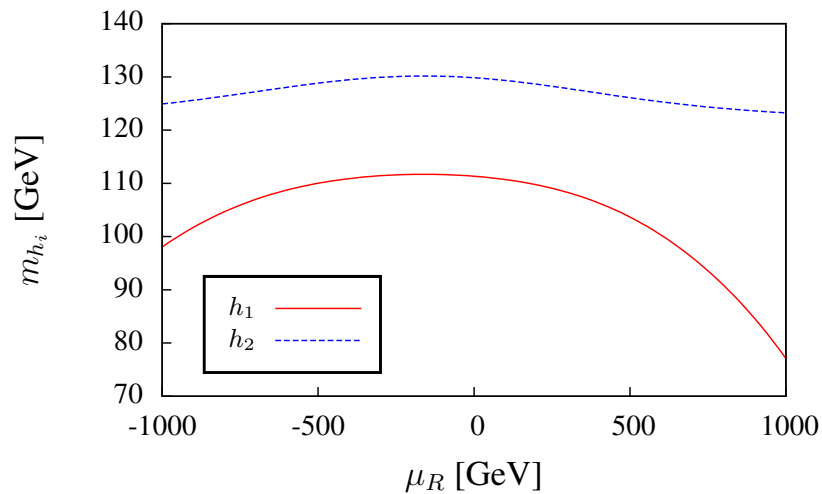
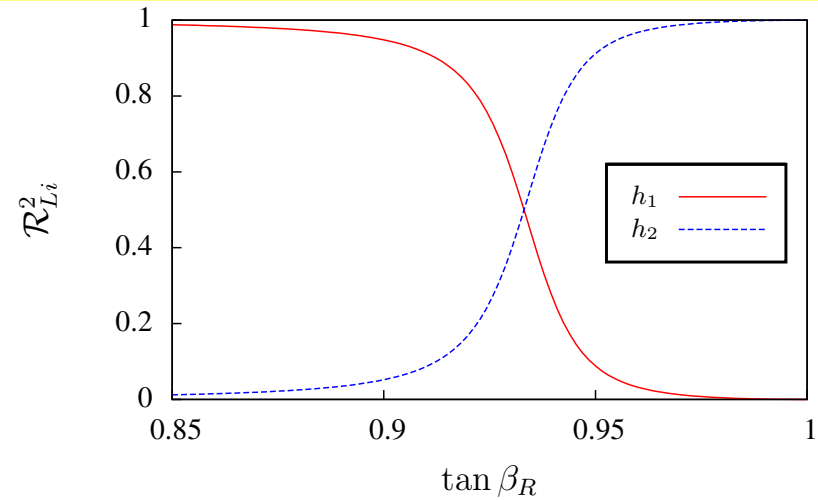
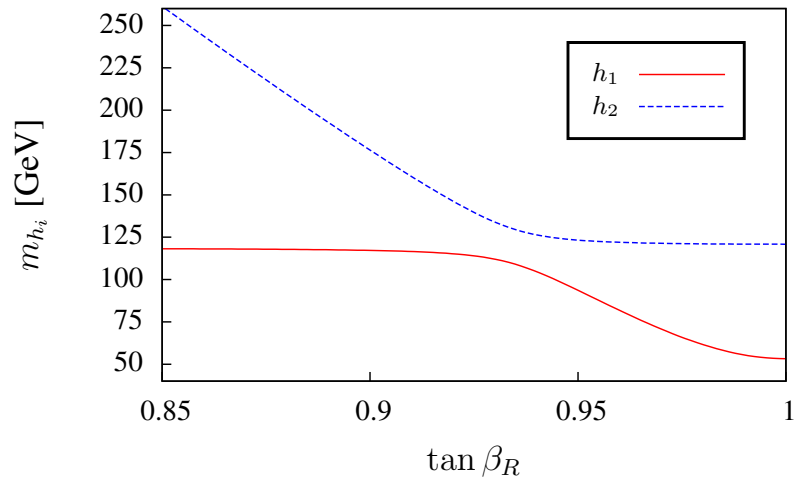


$$M_{1/2} = 1000 \text{ GeV}, \tan \beta = 10, A_0 = 0$$

$$m_{Z'}^2 \simeq \frac{1}{4} \left((g_{BLR} - g_R)^2 + (g_{BL} - g_{RBL})^2 \right) v_R^2$$

$$\simeq -2(|\mu_R|^2 + m_{\tilde{\chi}_R}^2) + \frac{g_R^2}{4} v^2 \cos(2\beta) \frac{\tan \beta_R^2 + 1}{\tan \beta_R^2 - 1} + \Delta m_{\chi_R}^2 \frac{2 \tan \beta_R^2}{\tan \beta_R^2 - 1}$$

$$\Delta m_{\chi_R}^2 = m_{\tilde{\chi}_R}^2 - m_{\chi_R}^2 \simeq \frac{1}{4\pi^2} \text{Tr}(Y_s Y_s^\dagger) (3m_0^2 + A_0^2) \log \left(\frac{M_{GUT}}{M_{SUSY}} \right)$$



$m_0 = 250 \text{ GeV}$, $M_{1/2} = 800 \text{ GeV}$, $\tan \beta = 10$, $A_0 = 0$

$v_R = 6000 \text{ GeV}$, $\tan \beta_R = 0.94$, $m_{A_R} = 2350 \text{ GeV}$, $\mu_R = -800 \text{ GeV}$

including complete 1-loop + 2-loop in the MSSM part

$$M_\nu = \begin{pmatrix} 0 & \frac{1}{\sqrt{2}}v_u Y_\nu^T & 0 \\ \frac{1}{\sqrt{2}}v_u Y_\nu & 0 & \frac{1}{\sqrt{2}}v_{\chi_R} Y_s \\ 0 & \frac{1}{\sqrt{2}}v_{\chi_R} Y_s & \mu_S \end{pmatrix} \xrightarrow{1\text{gen}, \mu_S=0} m_\nu = \begin{pmatrix} 0 & & \\ & -\sqrt{|Y_\nu|^2 v_u^2 + |Y_s|^2 v_{\chi_R}^2} & \\ & \sqrt{|Y_\nu|^2 v_u^2 + |Y_s|^2 v_{\chi_R}^2} & \end{pmatrix}$$

setting $\mu_S = 0$ and $B_{\mu_S} = 0$

$$M_\nu^2 = \begin{pmatrix} m_L^2 + \frac{v_u^2}{2} Y_\nu^\dagger Y_\nu + D_L & \frac{1}{\sqrt{2}}v_u (T_\nu^\dagger - Y_\nu^\dagger \cot \beta \mu) & \frac{1}{2}v_u v_{\chi_R} Y_\nu^\dagger Y_s \\ \frac{1}{\sqrt{2}}v_u (T_\nu - Y_\nu \cot \beta \mu^*) & m_\nu^2 + \frac{v_u^2}{2} Y_\nu Y_\nu^\dagger + \frac{v_{\chi_R}^2}{2} Y_s^\dagger Y_s + D_R & \frac{1}{\sqrt{2}}v_{\chi_R} (T_s - Y_s \cot \beta_R \mu_R^*) \\ \frac{1}{2}v_u v_{\chi_R} Y_s^\dagger Y_\nu & \frac{1}{\sqrt{2}}v_{\chi_R} (T_s^\dagger - Y_s^\dagger \cot \beta_R \mu_R) & m_S^2 + \frac{v_{\chi_R}^2}{2} Y_s^\dagger Y_s \end{pmatrix}$$

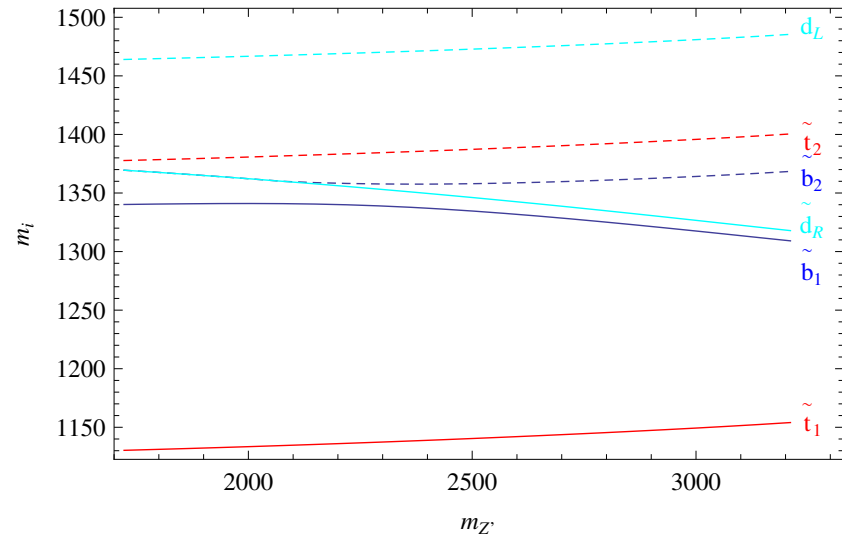
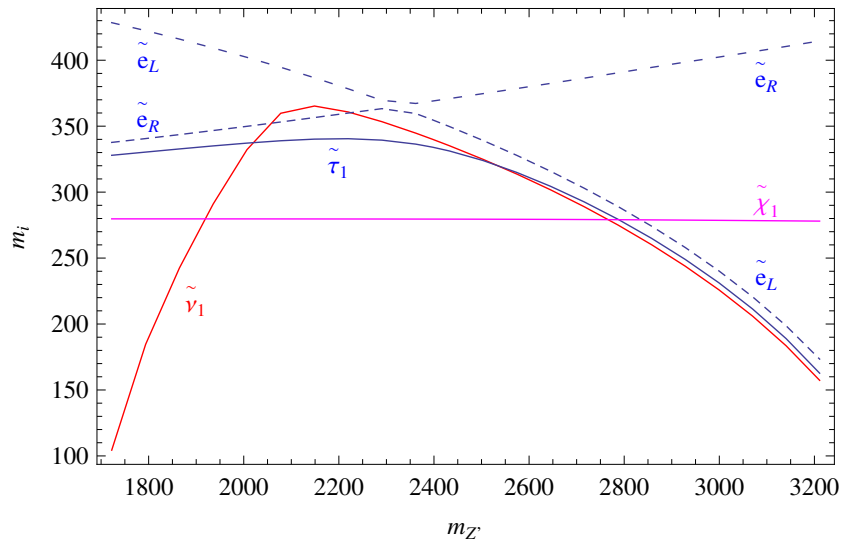
$$D_L = \frac{1}{8} \left((g_{BL}^2 + g_{BLR}^2 - g_{BL}g_{RBL})(v_{\bar{\chi}_R}^2 - v_{\chi_R}^2) + (g_L^2 + g_R^2 + g_{BL}g_{RBL})(v_d^2 - v_u^2) \right) \mathbf{1}$$

$$D_R = \frac{1}{8} \left((\tilde{g}_{BL}^2 + \tilde{g}_R^2)(v_{\bar{\chi}_R}^2 - v_{\chi_R}^2) + (g_R^2 + g_{RBL}^2 - g_{BL}g_{RBL} - g_Rg_{BLR})(v_d^2 - v_u^2) \right) \mathbf{1}$$

$$M_{\tilde{l}}^2 = \begin{pmatrix} M_{\tilde{L}}^2 + \frac{1}{8}M_{DL}^2 + m_l^2 & \frac{1}{\sqrt{2}}(v_d T_l - \mu Y_l v_u) \\ \frac{1}{\sqrt{2}}(v_d T_l - \mu Y_l v_u) & M_{\tilde{E}}^2 + \frac{1}{8}M_{DR}^2 + m_l^2 \end{pmatrix},$$

$$M_{DL}^2 = g_{BL}^2(v_{\chi_R}^2 - v_{\tilde{\chi}_R}^2) + g_2^2(v_u^2 - v_d^2) \quad \text{and} \quad M_{DR}^2 = (g_R^2 - g_{BL}^2)(v_{\chi_R}^2 - v_{\tilde{\chi}_R}^2) + g_R^2(v_u^2 - v_d^2)$$

neglecting gauge kinetic effects; similarly for squarks

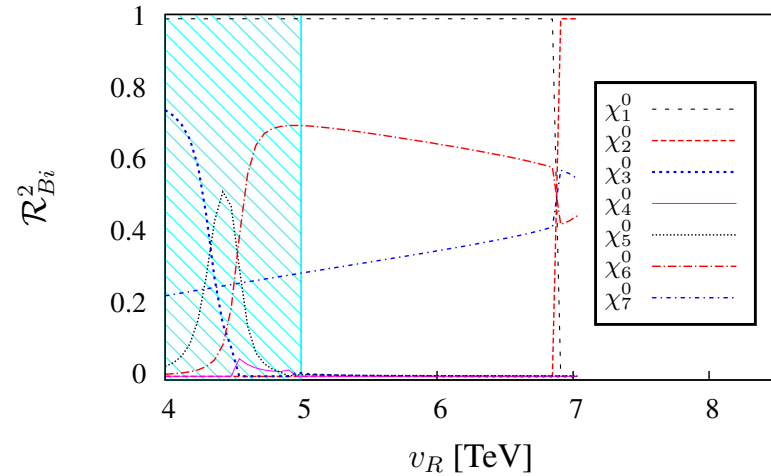
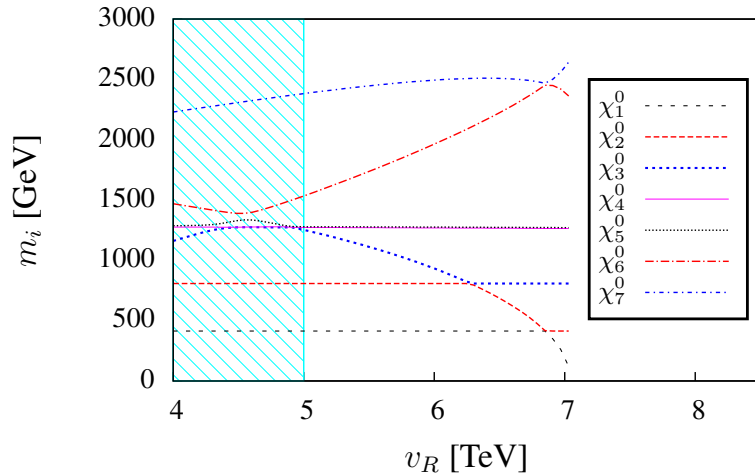


$$m_0 = 100 \text{ GeV}, m_{1/2} = 700 \text{ GeV}, A_0 = 0, \tan \beta = 10, \mu > 0$$

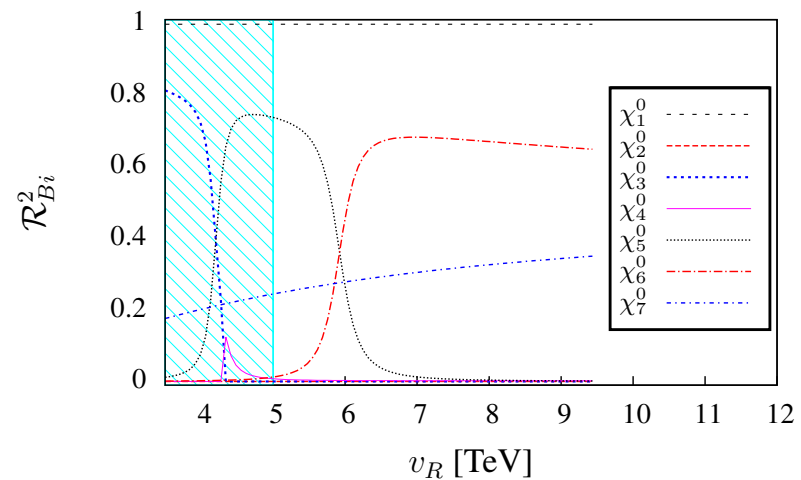
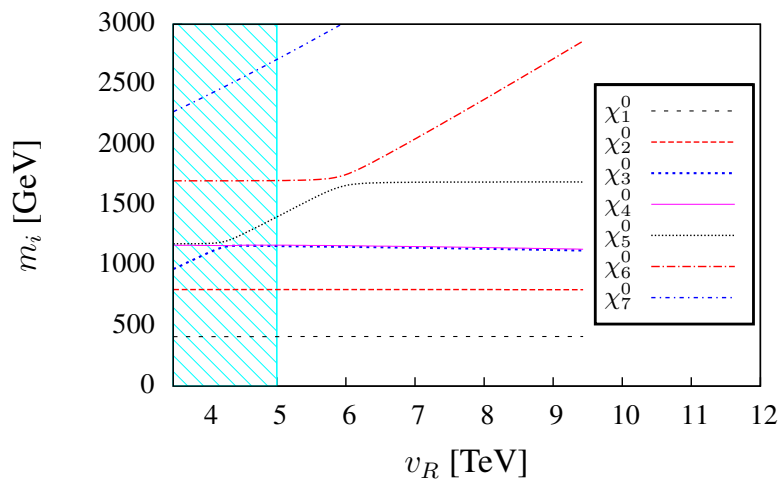
$$\tan \beta_R = 0.94, m_{A_R} = 2 \text{ TeV}, \mu_R = -800 \text{ GeV}$$

basis $(\lambda_{BL}, \lambda_L^0, \tilde{h}_d^0, \tilde{h}_u^0, \lambda_R, \tilde{\chi}_R, \tilde{\chi}_R)$

$$M_{\tilde{\chi}^0} = \begin{pmatrix} M_{BL} & 0 & -\frac{1}{2}g_{RBL}v_d & \frac{1}{2}g_{RBL}v_u & \frac{M_{BLR}}{2} & \frac{1}{2}v_{\tilde{\chi}_R}\tilde{g}_{BL} & -\frac{1}{2}v_{\chi_R}\tilde{g}_{BL} \\ 0 & M_2 & \frac{1}{2}g_Lv_d & -\frac{1}{2}g_Lv_u & 0 & 0 & 0 \\ -\frac{1}{2}g_{RBL}v_d & \frac{1}{2}g_Lv_d & 0 & -\mu & -\frac{1}{2}g_Rv_d & 0 & 0 \\ \frac{1}{2}g_{RBL}v_u & -\frac{1}{2}g_Lv_u & -\mu & 0 & \frac{1}{2}g_Rv_u & 0 & 0 \\ \frac{M_{BLR}}{2} & 0 & -\frac{1}{2}g_Rv_d & \frac{1}{2}g_Rv_u & M_R & -\frac{1}{2}v_{\tilde{\chi}_R}\tilde{g}_R & \frac{1}{2}v_{\chi_R}\tilde{g}_R \\ \frac{1}{2}v_{\tilde{\chi}_R}\tilde{g}_{BL} & 0 & 0 & 0 & -\frac{1}{2}v_{\tilde{\chi}_R}\tilde{g}_R & 0 & -\mu_R \\ -\frac{1}{2}v_{\chi_R}\tilde{g}_{BL} & 0 & 0 & 0 & \frac{1}{2}v_{\chi_R}\tilde{g}_R & -\mu_R & 0 \end{pmatrix}$$



GUT-version: $m_0 = 1000$ GeV, $M_{1/2} = 1000$ GeV, $\tan \beta = 10$, $A_0 = -600$, $\tan \beta_R = 1.04$



$m_0 = 630$ GeV, $M_{1/2} = 1000$ GeV, $\tan \beta = 10$, $A_0 = 0$, $\tan \beta_R = 1.05$, $\mu_R = -1700$ GeV,
 $m_{A_R} = 4800$ GeV

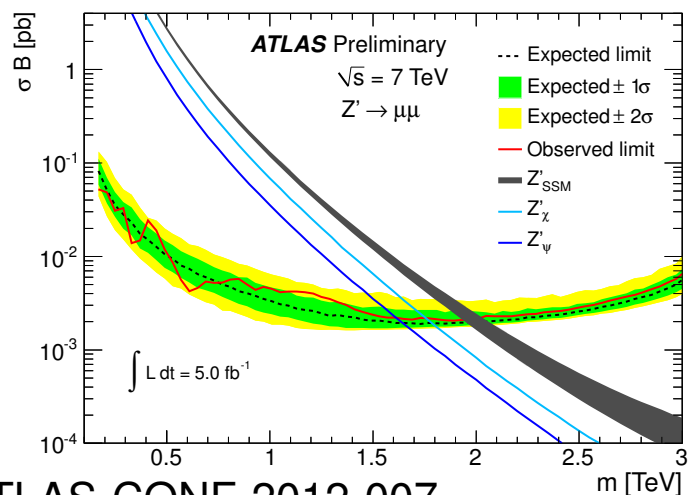
	BLRSP1	BLRSP2	BLRSP3	BLRSP4	BLRSP5
m_0 [GeV]	470	1000	120	165	500
$M_{1/2}$ [GeV]	700	1000	780	700	850
$\tan \beta$	20	10	10	10	10
A_0	0	-3000	-300	0	-600
v_R [GeV]	4700	6000	6000	5400	5000
$\tan \beta_R$	1.05	1.025	0.85	1.06	1.023
μ_R [GeV]	-1650	-780	-1270	260	(-905)
m_{A_R} [GeV]	4800	7600	800	2350	(1482)
$Y_{\nu,11} = Y_{\nu,22} = Y_{\nu,33}$	0.04	0.1	0.1	0.1	0.1
$Y_{s,11}$	0.04	0.042	0.3	0.3	0.3
$Y_{s,22} = Y_{s,33}$	0.05	0.042	0.3	0.3	0.3

BLRSP1-BLRSP4: μ_R and m_{A_R} are input

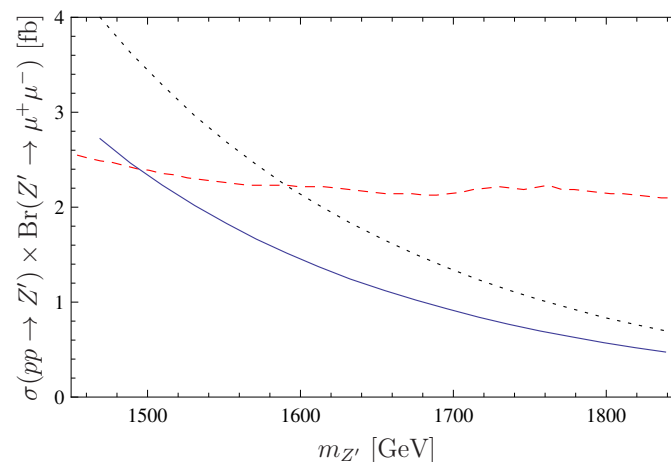
BLRSP5: GUT version

final state	BLRSP1	BLRSP2	BLRSP3	BLRSP4	BLRSP5
$BR(dd)$	0.31	0.35	0.35	0.37	0.43
$BR(uu)$	0.06	0.07	0.07	0.07	0.08
$BR(ll)$	0.12	0.14	0.14	0.14	0.16
$BR(\nu_l \nu_l)$	0.10	0.11	0.12	0.12	0.12
$BR(\nu_h \nu_h)$	0.27	0.30	0.13	0.11	0.13
$BR(\tilde{\nu} \tilde{\nu})$	0.05	—	0.05	0.03	—
$BR(\tilde{l} \tilde{l})$	—	—	0.05	0.03	—
$BR(\tilde{\chi}_2^+ \tilde{\chi}_2^-) + BR(\tilde{\chi}_4^0 \tilde{\chi}_5^0)$	—	—	—	0.04	—

final state	BLRSP1	BLRSP2	BLRSP3	BLRSP4	BLRSP5
$BR(dd)$	0.31	0.35	0.35	0.37	0.43
$BR(uu)$	0.06	0.07	0.07	0.07	0.08
$BR(ll)$	0.12	0.14	0.14	0.14	0.16
$BR(\nu_l \nu_l)$	0.10	0.11	0.12	0.12	0.12
$BR(\nu_h \nu_h)$	0.27	0.30	0.13	0.11	0.13
$BR(\tilde{\nu} \tilde{\nu})$	0.05	—	0.05	0.03	—
$BR(\tilde{l} \tilde{l})$	—	—	0.05	0.03	—
$BR(\tilde{\chi}_2^+ \tilde{\chi}_2^-) + BR(\tilde{\chi}_4^0 \tilde{\chi}_5^0)$	—	—	—	0.04	—



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Constraints from Z -width: $m_{\nu_h} \gtrsim m_Z$
invisible width

$$\left| 1 - \sum_{ij=1, i \leq j}^3 \left| \sum_{k=1}^3 U_{ik}^\nu U_{jk}^{\nu,*} \right|^2 \right| < 0.009$$

dominant decays

$$\nu_j \rightarrow W^\pm l^\mp$$

$$\nu_j \rightarrow Z \nu_i$$

$$\nu_j \rightarrow h_k \nu_i$$

roughly

$$BR(\nu_j \rightarrow W^\pm l^\mp) : BR(\nu_j \rightarrow Z \nu_i) : BR(\nu_j \rightarrow h_k \nu_i) \simeq 0.5 : 0.25 : 0.25$$

in BLRSP4

$$BR(\nu_k \rightarrow \tilde{\nu}_i \tilde{\chi}_1^0) \simeq 0.03 \quad , (k = 4, 5, 6) \text{ and } (i = 1, 2, 3)$$

	BLRSP1	BLRSP2	BLRSP3	BLRSP4	BLRSP5
$m_{\tilde{\nu}_1}$	105.0	797.	91.6	542.	921.
$m_{\tilde{\nu}_{2/3}}$	215.0	797.	92.6	542.	924.
$m_{\tilde{\nu}_4}$	604.	1120.	253.	585.	940.
$m_{\tilde{e}_1}$	524.	1014.	255.	263.	693.
$m_{\tilde{e}_{2,3}}$	557.	1055.	266.	271.	706.
$m_{\tilde{e}_4}$	832.	1222.	448.	592.	933.
$m_{\tilde{u}_1}$	1436.	1185.	1247.	1111.	1545.
$m_{\tilde{u}_2}$	1721.	1852.	1527.	1361.	1905.
$m_{\tilde{u}_{3,4}}$	1799.	2155.	1566.	1392.	2008.
$m_{\tilde{u}_{5,6}}$	1871.	2227.	1634.	1449.	2089.
$m_{\chi_1^0}$	367.	417.	313.	259. $\tilde{h}_R$	412.
$m_{\chi_2^0}$	718.	780. $\tilde{h}_R$	615.	280.	739. $\tilde{h}_R$
$m_{\chi_3^0}$	1047.	818.	1087.	549.	804.
$m_{\chi_4^0}$	1054.	1866.	1093.	845.	1288.
$m_{\chi_5^0}$	1348. ($\tilde{B}_\perp$)	1866.	1232. ($\tilde{B}_\perp$)	857.	1294.
$m_{\chi_6^0}$	1802. $\tilde{h}_R$	2018. ($\tilde{B}_\perp$)	1811. ($\tilde{B}_\perp$)	1639. ($\tilde{B}_\perp$)	1688. ($\tilde{B}_\perp$)

CMSSM, GMSB: $\tilde{q}_R \rightarrow q\tilde{\chi}_1^0$

here: $\tilde{\nu}$ LSP, $m_{\nu_h} \simeq 100$ GeV

$$\tilde{q}_R \rightarrow q\tilde{\chi}_1^0 \rightarrow q\nu_k\tilde{\nu}_1 \rightarrow q\nu_j Z\tilde{\nu}_1$$

$$\tilde{q}_R \rightarrow q\tilde{\chi}_1^0 \rightarrow q\nu_k\tilde{\nu}_1 \rightarrow ql^\pm W^\mp \tilde{\nu}_1$$

$$\tilde{q}_R \rightarrow q\tilde{\chi}_1^0 \rightarrow q\nu_k\tilde{\nu}_3 \rightarrow ql^\pm W^\mp \tilde{l}'^+ l'^- \nu_1$$

$$\tilde{d}_R \rightarrow d\tilde{\chi}_5^0 \rightarrow dl^\pm \tilde{l}_i^\mp \rightarrow dl^\pm l^\mp \tilde{\chi}_1^0 \rightarrow dl^\pm l^\mp \nu_k \tilde{\nu}_1 \rightarrow dl^\pm l^\mp l'^\pm W^\mp \tilde{\nu}_1$$

with $k \in \{4, 5, 6, 7, 8, 9\}$ and $j \in \{1, 2, 3\}$.

$BR(\tilde{d}_R \rightarrow d\tilde{\chi}_5^0) \simeq 0.2 \Rightarrow$ softer jets

BLRSP3: usual cascades similar to CMSSM, but

$$\begin{aligned}
 \tilde{\chi}_1^0 &\rightarrow l^\pm \tilde{l}^\mp \rightarrow l^\pm W^\mp \tilde{\nu}_1 \\
 \tilde{\chi}_1^0 &\rightarrow l^\pm \tilde{l}^\mp \rightarrow l^\pm W^\mp \tilde{\nu}_{2,3} \rightarrow l^\pm W^\mp f \bar{f} \tilde{\nu}_1 \\
 \tilde{\chi}_1^0 &\rightarrow \nu_j \tilde{\nu}_{2,3} \rightarrow \nu_{1,2,3} f \bar{f} \tilde{\nu}_1 \\
 \tilde{\chi}_1^0 &\rightarrow \nu_j \tilde{\nu}_1 \\
 \tilde{\chi}_1^0 &\rightarrow \nu_j \tilde{\nu}_k \rightarrow \nu_j h_{1,2} \tilde{\nu}_1 \\
 \tilde{\chi}_1^0 &\rightarrow \nu_j \tilde{\nu}_k \rightarrow \nu_j h_{1,2} f \bar{f} \tilde{\nu}_1
 \end{aligned}$$

with $j = 1, 2, 3$ and $k = 4, 5, 6$

⇒ enhancement of multiplicities compared to standard case, e.g.

$$\tilde{d}_R \rightarrow d \tilde{\chi}_1^0 \rightarrow dX$$

BLRSP4: similar to NMSSM with singlino LSP

Superfield	Generations	$U(1)_Y \times SU(2)_L \times SU(3)_C \times U(1)_{B-L}$
$\hat{Q}$	3	$(\frac{1}{6}, \mathbf{2}, \mathbf{3}, \frac{1}{6})$
$\hat{D}$	3	$(\frac{1}{3}, \mathbf{1}, \bar{\mathbf{3}}, -\frac{1}{6})$
$\hat{U}$	3	$(-\frac{2}{3}, \mathbf{1}, \bar{\mathbf{3}}, -\frac{1}{6})$
$\hat{L}$	3	$(-\frac{1}{2}, \mathbf{2}, \mathbf{1}, -\frac{1}{2})$
$\hat{E}$	3	$(1, \mathbf{1}, \mathbf{1}, \frac{1}{2})$
$\hat{\nu}$	3	$(0, \mathbf{1}, \mathbf{1}, \frac{1}{2})$
$\hat{H}_d$	1	$(-\frac{1}{2}, \mathbf{2}, \mathbf{1}, 0)$
$\hat{H}_u$	1	$(\frac{1}{2}, \mathbf{2}, \mathbf{1}, 0)$
$\hat{\eta}$	1	$(0, \mathbf{1}, \mathbf{1}, -1)$
$\hat{\bar{\eta}}$	1	$(0, \mathbf{1}, \mathbf{1}, 1)$

$$\begin{aligned}
 W = & Y_u^{ij} \hat{U}_i \hat{Q}_j \hat{H}_u - Y_d^{ij} \hat{D}_i \hat{Q}_j \hat{H}_d - Y_e^{ij} \hat{E}_i \hat{L}_j \hat{H}_d + \mu \hat{H}_u \hat{H}_d + Y_\nu^{ij} \hat{L}_i \hat{H}_u \hat{\nu}_j \\
 & - \mu' \hat{\eta} \hat{\bar{\eta}} + Y_x^{ij} \hat{\nu}_i \hat{\eta} \hat{\nu}_j
 \end{aligned}$$

based on B. O'Leary, W.P., F. Staub, arXiv:1112.4600

● $Z_{B-L} \Leftrightarrow Z_\chi$

$$\gamma = \frac{1}{16\pi^2} \begin{pmatrix} \frac{33}{5} & 6\sqrt{\frac{2}{5}} \\ 6\sqrt{\frac{2}{5}} & 9 \end{pmatrix}$$

● upper limit on m_{h^0} increased compared to MSSM but less additional D -term, only due to $U(1)$ gauge kinetic mixing

● neutrino masses via seesaw I $\Rightarrow Y_\nu$ much smaller

● effect on sfermion masses less pronounced

except $\tilde{\nu}$: $Y_x^{ij} \hat{\nu}_i \hat{\eta} \hat{\nu}_j$ is $\Delta L = 2$ after symmetry breaking

$\Rightarrow$ large splitting between scalar and pseudoscalar parts of $\tilde{\nu}_R$

$\Rightarrow$ reduces $\sum_{i,j} BR(Z' \rightarrow \tilde{\nu}_i \tilde{\nu}_j)$

enlarges parameter space with $\tilde{\nu}$ LSP

● larger mass splitting between sleptons and sneutrinos $\Rightarrow$ harder leptons

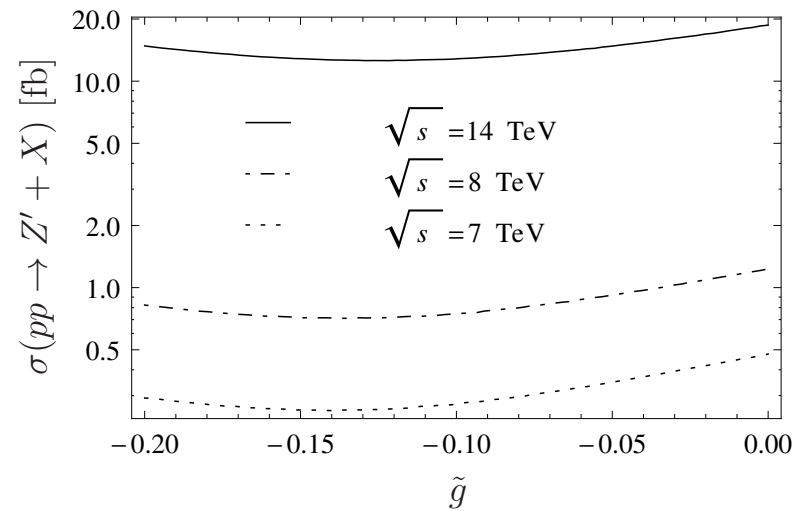
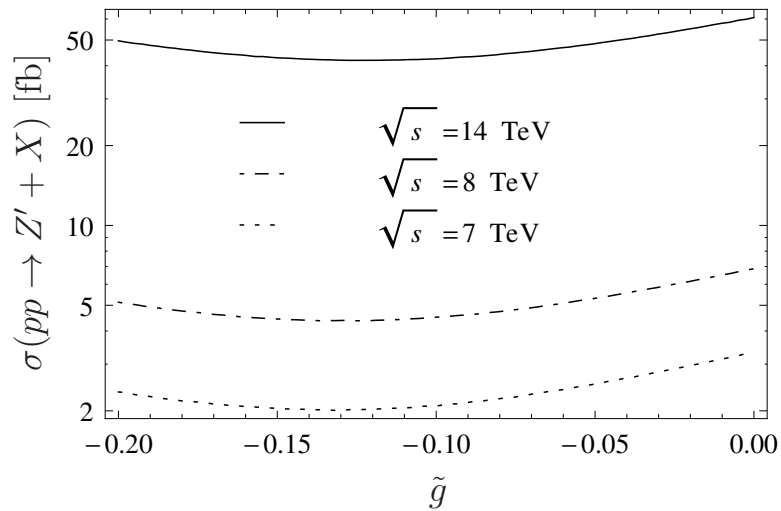
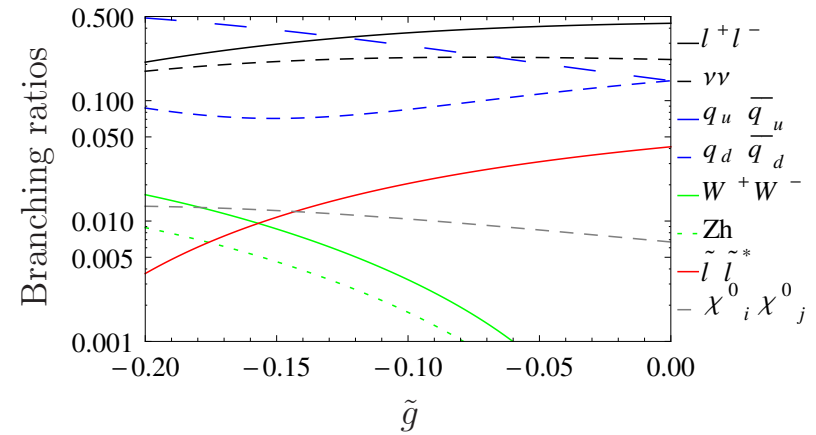
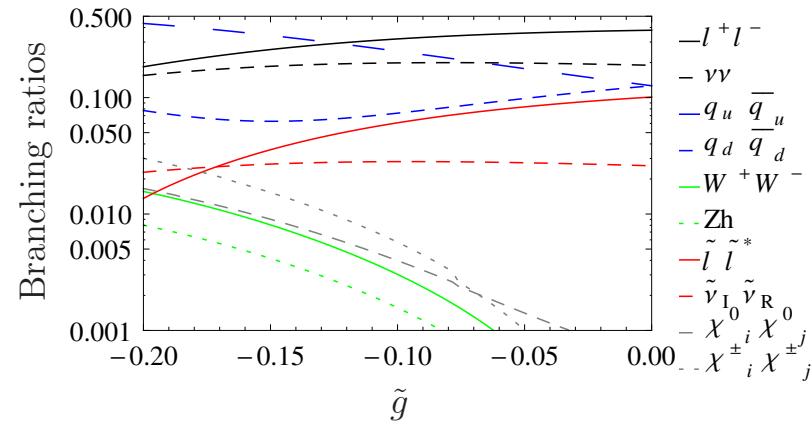
all masses in GeV

	BL1	BL2		BL1	BL2		BL1	BL2
m_0	600	1000	$m_{Z'}$	2000	2500	$m_{\tilde{\chi}_1^\pm}$	475.4	1242.0
$M_{1/2}$	600	1500	$m_{\tilde{\chi}_1^0}$	280.7	678.0	$m_{\tilde{\chi}_2^\pm}$	733.9	1872.0
A_0	0	-1500	$m_{\tilde{\chi}_2^0}$	475.4	735.2	$m_{\tilde{\tau}_1}$	603.7	1002.0
$\tan \beta$	10	20	$m_{\tilde{\chi}_3^0}$	719.1	1241.9	$m_{\tilde{\tau}_2}$	759.9	1446.5
$\text{sign } \mu$	+	+	$m_{\tilde{\chi}_4^0}$	733.9	1827.0	$m_{\tilde{\mu}_1}$	610.8	1094.2
$\tan \beta'$	1.07	1.15	$m_{\tilde{\chi}_5^0}$	798.2	1867.5	$m_{\tilde{\mu}_2}$	761.9	1477.4
$\text{sign } \mu'$	+	+	$m_{\tilde{\chi}_6^0}$	1488.7	1871.5	$m_{\tilde{e}_1}$	610.8	1094.5
Y_X^{11}	0.42	0.37	$m_{\tilde{\chi}_7^0}$	2530.6	3131.4	$m_{\tilde{e}_2}$	761.9	1477.5
Y_X^{22}	0.43	0.4						
Y_X^{33}	0.44	0.4						

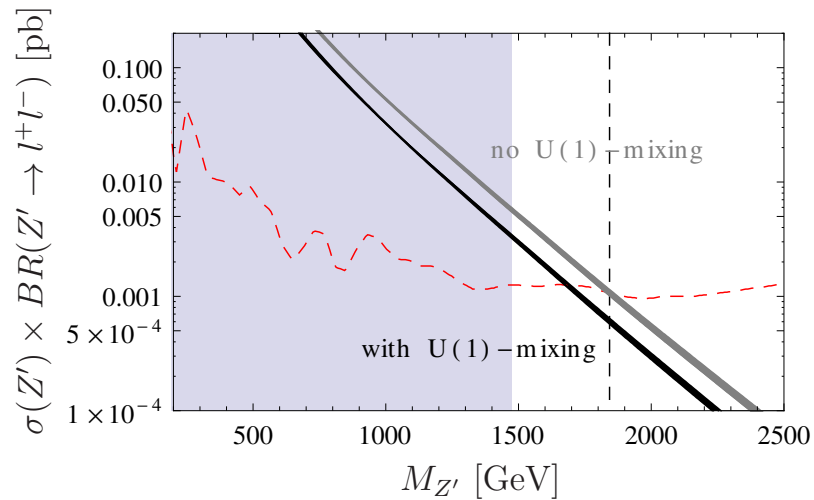
M. Krauss, B. O'Leary, W.P., F. Staub, arXiv:1206.yyyy

BL1

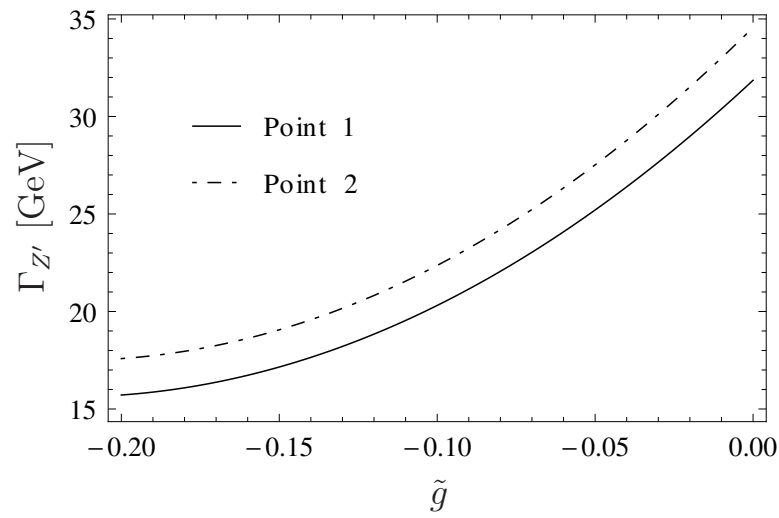
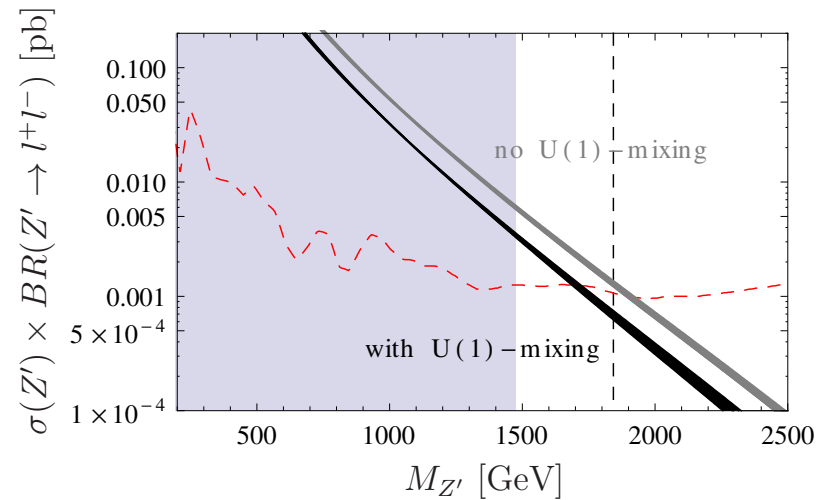
BL2



BL1

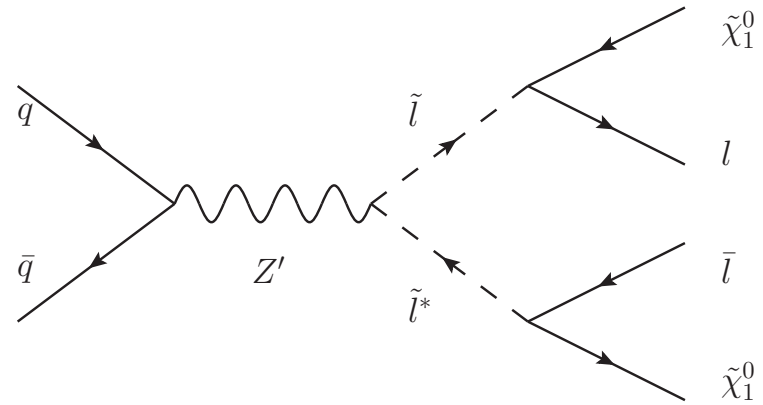
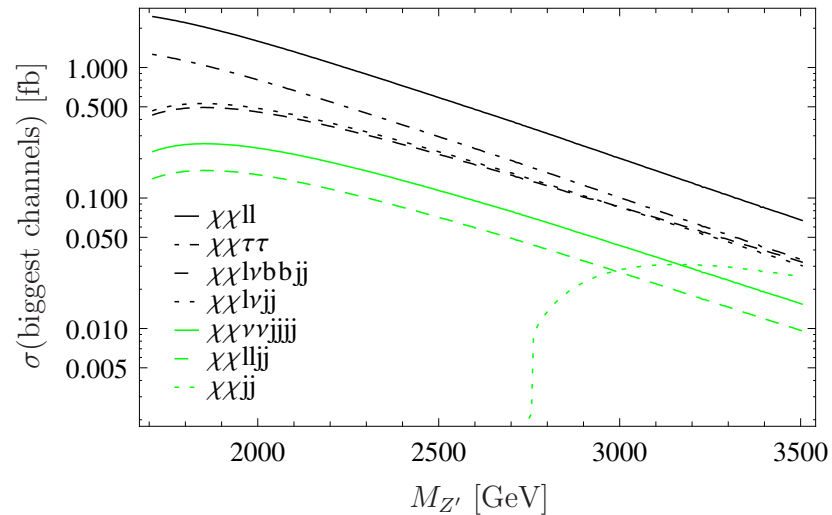


BL2



No.	$\tilde{g} \neq 0$	$\tilde{g} = 0$
BL1	1680 GeV	1840 GeV
BL2	1700 GeV	1910 GeV

M. Krauss:



see also: J. Kang and P. Langacker, PRD 71 (2005) 035014; M. Baumgart, T. Hartman, C. Kilic, and L.-T. Wang, JHEP 0711 (2007) 084; C.-F. Chang, K. Cheung, and T.-C. Yuan, JHEP 1109 (2011) 058; G. Corcella and S. Gentile, arXiv:1205.5780

- invariant mass of the muon pair: $M_{\mu\mu} > 200 \text{ GeV}$
- missing transverse momentum: $p_T(\cancel{E}) > 200 \text{ GeV}$
- transverse cluster mass

$$M_T = \sqrt{\left(\sqrt{p_T^2(\mu^+\mu^-) + M_{\mu\mu}^2} + p_T(\cancel{E}) \right)^2 - (\vec{p}_T(\mu^+\mu^-) + \vec{p}_T(\cancel{E}))^2}$$

$$M_T > 800 \text{ GeV}$$

- for $t\bar{t}$ suppresssion and squark/gluino cascade decays:

$$p_{T,\text{hardest jet}} < 40 \text{ GeV}$$

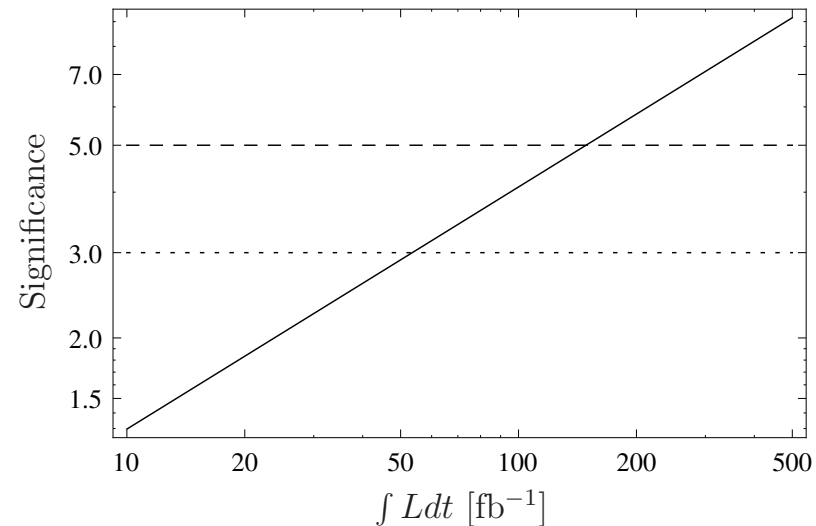
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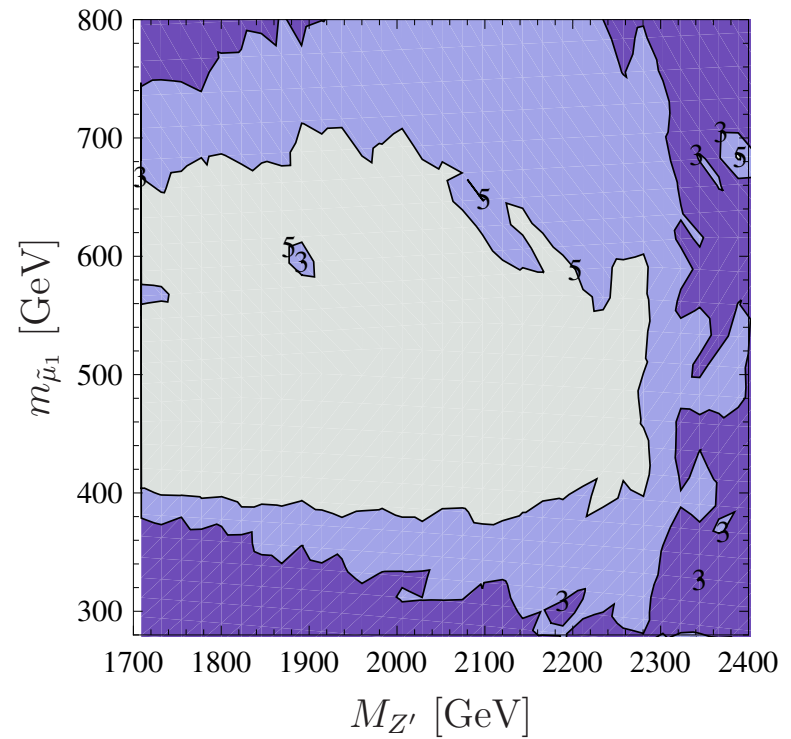
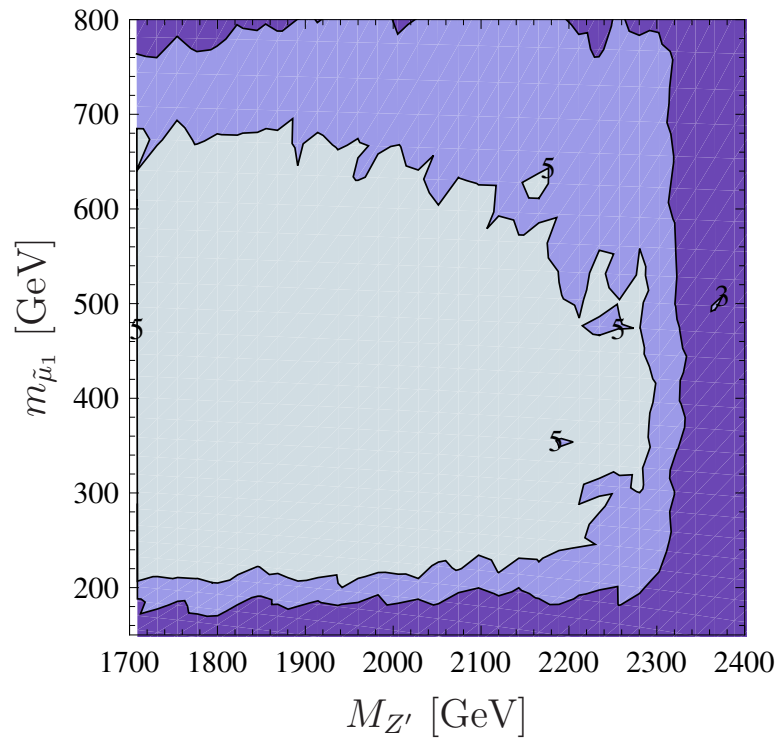
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main dependence on masses $\Rightarrow$ vary $m_{\tilde{l}}$ and $m_{Z'}$, $M_L = 1.2M_E$

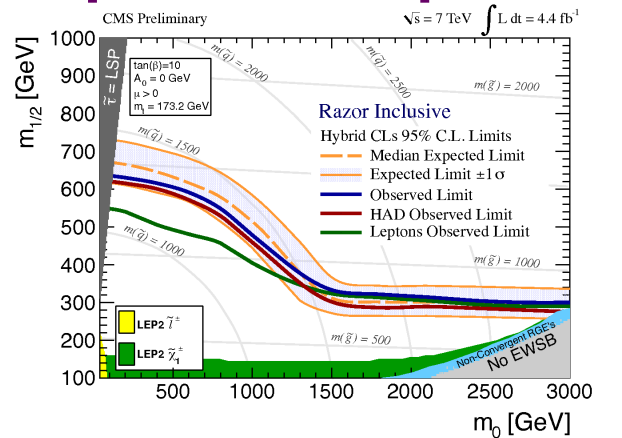


M. Krauss, B. O'Leary, W.P., F. Staub, arXiv:1206.yyyy

- if $m_{h^0} \simeq 125 \text{ GeV} \Rightarrow$ hint to go beyond (C)MSSM
- models with extra $U(1)$: motivated by embedding in $SO(10)$, $E(6)$ etc.
can nicely explain neutrino physics
- extra $Z' \Rightarrow$ additional D-terms for scalars,
e.g. SM-like Higgs with tree-level mass of 110 GeV
- direct $\tilde{l}$ production via Z'
- regions with $\tilde{\nu}$ -LSP and/or additional gauginos
 $\Rightarrow$ higher multiplicities, in particular leptons

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- regions with $\tilde{\nu}$ -LSP and/or additional gauginos
 $\Rightarrow$ higher multiplicities, in particular leptons
 $\Rightarrow$ expect less stringent exclusions depending on m'_Z and extended Higgs sector

Model dependent CMSSM interpretation



0 March 2012

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