SUSY models with extended gauge symmetries in the light of m_h=125 GeV

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Content

- Why do go beyond the SM and MSSM: Higgs, ν, $R_P = (-1)^{2s+3(B-L)}$
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  - model realisations: GMSB, SUGRA inspired, NUHM
  - Higgs physics
  - ν physics @ LHC
  - changes in SUSY phenomenology
- $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$ model
  - Z' physics
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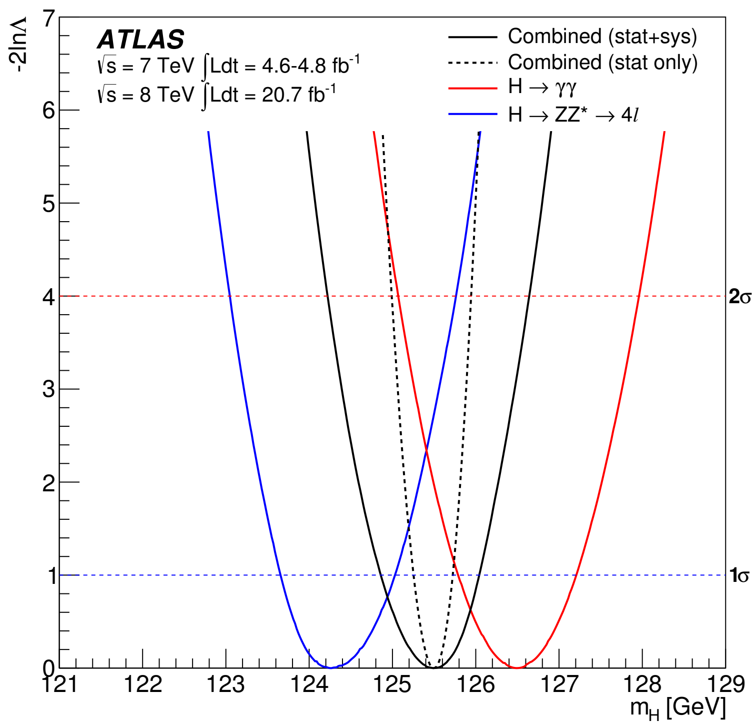
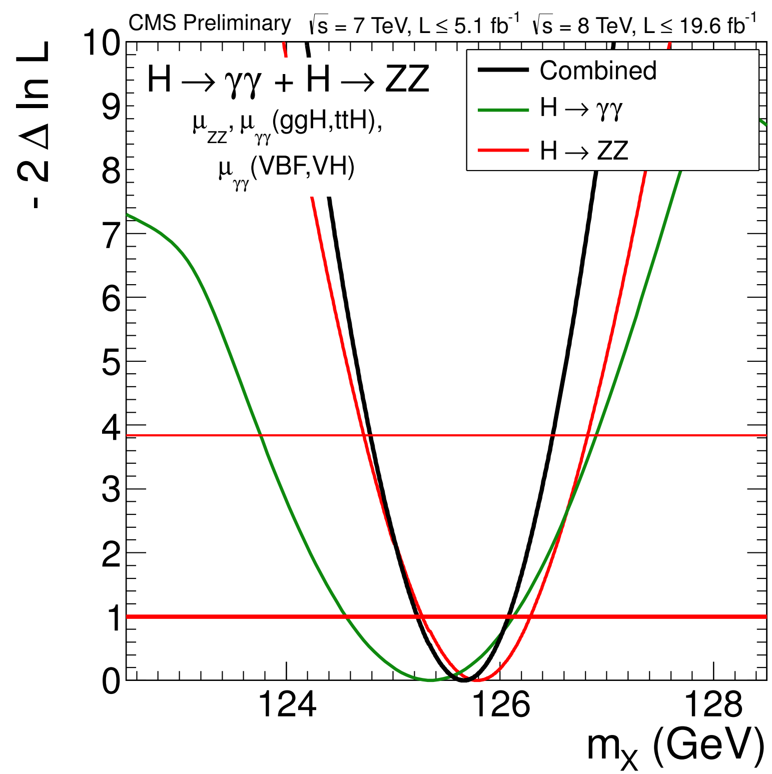
Higgs results in a nut-shell, I

ATLAS, arXiv:1307.1427



$M_H = 125.5 \pm 0.2_{\text{stat}} \pm 0.6_{\text{sys}}$ GeV

CMS, CMS-PAS-HIG-13-005

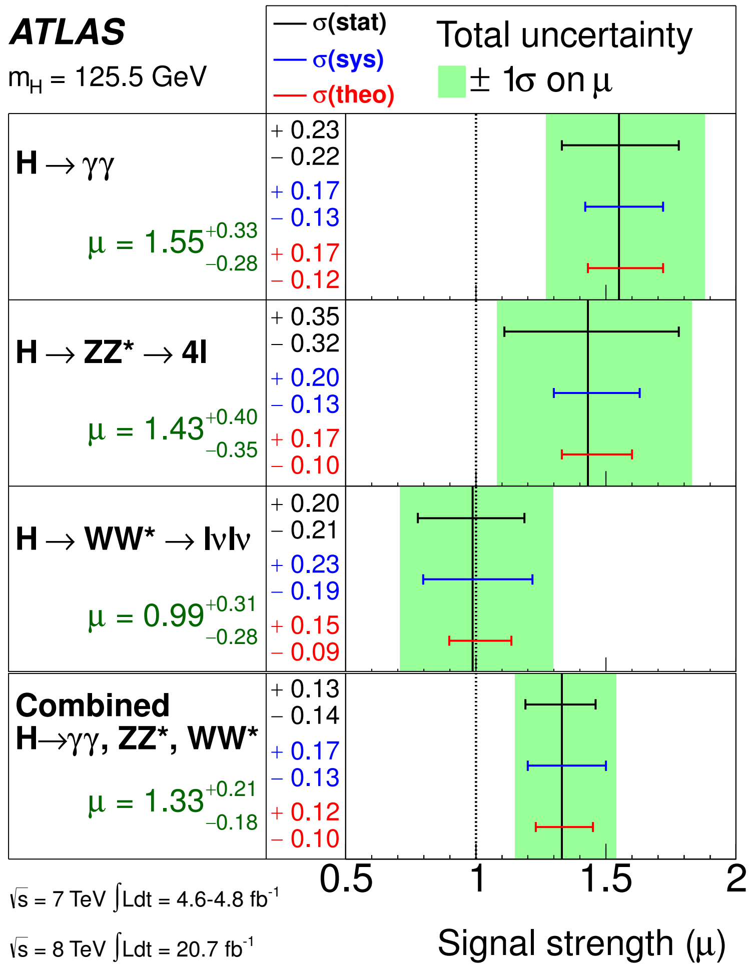


$M_H = 125.7 \pm 0.3_{\text{stat}} \pm 0.3_{\text{sys}}$ GeV

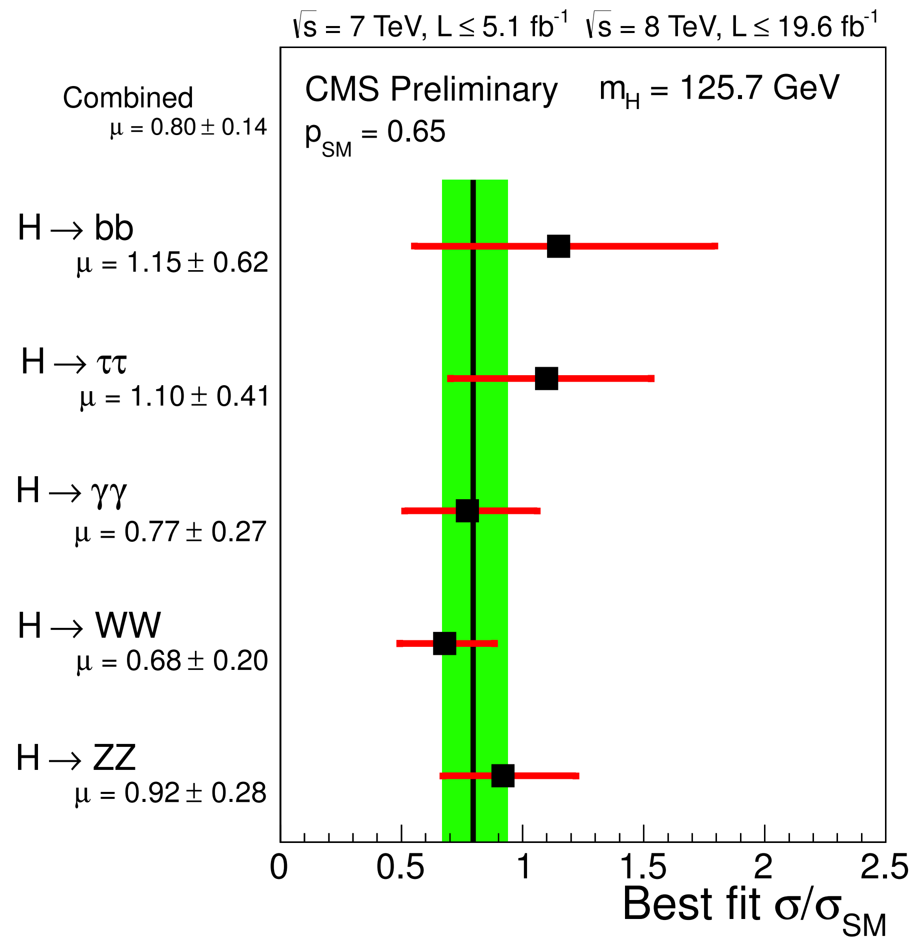
for latest details see e.g. talks by G. Landsberg and F. Cerutti @ EPS-HEP, Stockholm, 2013

Higgs results in a nut-shell, II

ATLAS, arXiv:1307.1427



CMS, CMS-PAS-HIG-13-005



for latest details see e.g. talk F. Cerutti @ EPS-HEP, Stockholm, 2013

Higgs in the MSSM scenarios; nut-shell again

SM: potentially meta-stable (G. Degrassi *et al.*, arXiv:1205.6497), hierarchy problem
$\Rightarrow$ supersymmetry (SUSY)

Minimal SUSY (MSSM), tree level: $m_h \leq m_Z \Rightarrow$ need for large radiative corrections

- GMSB: $m_{\tilde{t}_1} \gtrsim 6$ TeV,
  M. A. Ajaib, I. Gogoladze, F. Nasir, Q. Shafi, arXiv:1204.2856
- general MSSM: corrections maximised for $|(A_t - \mu/\tan\beta)/\sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}| \simeq 2$,
  M. S. Carena, H. E. Haber, S. Heinemeyer, W. Hollik, C. E. M. Wagner, G. Weiglein, hep-ph/0001002
- CMSSM, NUHM models: $|A_0| \simeq 2m_0$,
  H. Baer, V. Barger and A. Mustafayev, arXiv:1112.3017; M. Kadastik *et al.*, arXiv:1112.3647; O. Buchmueller *et al.*, arXiv:1112.3564; J. Cao, Z. Heng, D. Li, J. M. Yang, arXiv:1112.4391; L. Aparicio, D. G. Cerdeno, L. E. Ibanez, arXiv:1202.0822; J. Ellis, K. A. Olive, arXiv:1202.3262; ...
- general high scale models: $A_0 \simeq -(1-3)\max(M_{1/2}, m_{Q_3,GUT}, m_{U_3,GUT})$
  among other cases, details in F. Brümmer, S. Kraml and S. Kulkarni, arXiv:1204.5977

However: several cases excluded by charge/color breaking minima,
E. Camargo, B. O'Leary, W.P., F. Staub, in preparation

Motivation for extended gauge groups

- Origin of R-parity $R_P = (-1)^{2s+3(B-L)}$

  $\Rightarrow SO(10) \to SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$
  $\to SU(3)_C \times SU(2)_L \times U(1)_R \times U(1)_{B-L}$
  $\cong SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_\chi$
  or $E(8) \times E(8) \to SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$

- Neutrino masses

  $B - L$ anomaly free $\Rightarrow \nu_R$
  usual seesaw, inverse seesaw

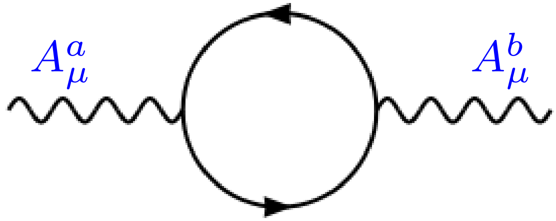
- SM-like Higgs boson at 125 GeV

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

Gauge kinetic mixing

$U(1)_a \times U(1)_b$ models allow for (B. Holdom, PLB **166**m0 = 250 (1986) 196)

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



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

equivalent

$$D_\mu = \partial_\mu - i(Q_a, Q_b) \underbrace{\begin{pmatrix} g_{aa} & g_{ab} \\ g_{ba} & g_{bb} \end{pmatrix}}_{NG} \begin{pmatrix} A^a_\mu \\ A^b_\mu \end{pmatrix}$$

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

$SU(3)_C \times SU(2)_L \times U(1)_R \times U(1)_{B-L}$ model

	Superfield	$SU(3)_c \times SU(2)_L \times U(1)_R \times U(1)_{B-L}$ / $SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_\chi$	Generations
Matter	$\hat{Q}$	$(\mathbf{3}, \mathbf{2}, 0, +\frac{1}{6})$ / $(\mathbf{3}, \mathbf{2}, +\frac{1}{6}, +\frac{1}{4})$	3
	$\hat{d^c}$	$(\overline{\mathbf{3}}, \mathbf{1}, +\frac{1}{2}, -\frac{1}{6})$ / $(\overline{\mathbf{3}}, \mathbf{1}, +\frac{1}{3}, -\frac{3}{4})$	3
	$\hat{u^c}$	$(\overline{\mathbf{3}}, \mathbf{1}, -\frac{1}{2}, -\frac{1}{6})$ / $(\overline{\mathbf{3}}, \mathbf{1}, -\frac{2}{3}, \frac{1}{4})$	3
	$\hat{L}$	$(\mathbf{1}, \mathbf{2}, 0, -\frac{1}{2})$ / $(\mathbf{1}, \mathbf{2}, -\frac{1}{2}, -\frac{3}{4})$	3
	$\hat{e^c}$	$(\mathbf{1}, \mathbf{1}, +\frac{1}{2}, +\frac{1}{2})$ / $(\mathbf{1}, \mathbf{1}, +1, +\frac{1}{4})$	3
	$\hat{\nu^c}$	$(\mathbf{1}, \mathbf{1}, -\frac{1}{2}, +\frac{1}{2})$ / $(\mathbf{1}, \mathbf{1}, 0, +\frac{5}{4})$	3
	$\hat{S}$	$(\mathbf{1}, \mathbf{1}, 0, 0)$ / $(\mathbf{1}, \mathbf{1}, 0, 0)$	3
Higgs	$\hat{H}_u$	$(\mathbf{1}, \mathbf{2}, +\frac{1}{2}, 0)$ / $(\mathbf{1}, \mathbf{2}, +\frac{1}{2}, -\frac{1}{2})$	1
	$\hat{H}_d$	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2}, 0)$ / $(\mathbf{1}, \mathbf{2}, -\frac{1}{2}, +\frac{1}{2})$	1
	$\hat{\chi}_R$	$(\mathbf{1}, \mathbf{1}, +\frac{1}{2}, -\frac{1}{2})$ / $(\mathbf{1}, \mathbf{1}, 0, -\frac{5}{4})$	1
	$\hat{\bar{\chi}}_R$	$(\mathbf{1}, \mathbf{1}, -\frac{1}{2}, +\frac{1}{2})$ / $(\mathbf{1}, \mathbf{1}, 0, +\frac{5}{4})$	1

$Y = T_R + B - L$ and $Q = T_L^3 + Y$.

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

M. Hirsch et al., arXiv:1110.3037

Boundary conditions I: CMSSM-like

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:

$$m_0^2 \mathbf{1}_3 = m_D^2 = m_U^2 = m_Q^2 = m_E^2 = m_L^2 = m_{\nu^c}^2 = m_S^2$$
$$M_{1/2} = M_{BL} = M_R = M_2 = M_3 \ , \ M_{BLR} = 0$$
$$T_i = A_0 Y_i, \qquad i = e, d, u, \nu, s$$

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

Boundary conditions II: GMSB-like

Use $SO(10)$ 10-plets as messengers:

	$SU(3)_C \times SU(2)_L$	$U(1)_R \times U(1)_{B-L}$	$U(1)_Y \times U(1)_\chi$
$\hat{\Phi}_1$	$(\mathbf{1},\mathbf{2})$	$(\frac{1}{2},0)$	$(\frac{1}{2},-\frac{1}{2})$
$\hat{\bar{\Phi}}_1$	$(\mathbf{1},\mathbf{2})$	$(-\frac{1}{2},0)$	$(-\frac{1}{2},\frac{1}{2})$
$\hat{\Phi}_2$	$(\mathbf{3},\mathbf{1})$	$(0,-\frac{1}{3})$	$(-\frac{1}{3},-\frac{1}{2})$
$\hat{\bar{\Phi}}_2$	$(\bar{\mathbf{3}},\mathbf{1})$	$(0,\frac{1}{3})$	$(\frac{1}{3},\frac{1}{2})$

$$M_{A\neq Abelian} = \frac{g_A^2}{16\pi^2} n\Lambda g(x)\,, \qquad \Lambda = F/M\,, x = |\Lambda/M|\,,$$

$$M_{kl=Abelian} = \frac{1}{16\pi^2} n g(x)\Lambda \Big(\sum_i G^T N Q_i Q_i^T N G\Big)_{kl}\,,$$

$$m_k^2 = \frac{2}{(16\pi^2)^2} n\Lambda^2 f(x)\Big(\sum_{A\neq Abelian} C_A(k) g_A^4 + \sum_i (Q_k^T N G G^T N Q_i)^2\Big)\,,$$

$$m_S^2 \simeq \frac{Y_S^2}{16\pi^2}(m_{\chi_R}^2 + m_{\nu^c}^2)\,.$$

M.E. Krauss, W.P., F. Staub, arXiv:1304.0769

Vector bosons

basis (W^0, B_Y, B_χ)

$$
\begin{aligned}
M^2_{VV} &= \frac{1}{4}\begin{pmatrix} g_2^2 v^2 & -g_2 g' v^2 & g_2 \tilde{g}_\chi v^2 \\ -g_2 g' v^2 & g'^2 v^2 & -g' \tilde{g}_\chi v^2 \\ g_2 \tilde{g}_\chi v^2 & -g' \tilde{g}_\chi v^2 & \frac{25}{4} g_\chi^2 v_R^2 + \tilde{g}_\chi^2 v^2 \end{pmatrix} \\
\tilde{g}_\chi &= g_\chi - g_{Y\chi} \\
v^2 &= v_d^2 + v_u^2 \ , \ \ v_R^2 = v_{\chi_R}^2 + v_{\bar{\chi}_R}^2
\end{aligned}
$$

expanding in v^2/v_R^2

$$
\begin{aligned}
m_Z^2 &\simeq \frac{1}{4}\left(g'^2 + g_2^2\right) v^2 \left(1 - \frac{4}{25}\left(1 - \frac{g_{Y\chi}}{g_\chi}\right)^2 \frac{v^2}{v_R^2}\right) \\
m_{Z'}^2 &\simeq \left(\frac{5}{4} g_\chi v_R\right)^2
\end{aligned}
$$

M. Hirsch, W.P., L. Reichert, F. Staub, arXiv:1206:3516;
M.E. Krauss, W.P., F. Staub, arXiv:1304.0769

Higgs sector, I

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

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

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

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

$$m^2_A = B_\mu(\tan\beta + \cot\beta)\,, \qquad m^2_{A_R} = B_{\mu_R}(\tan\beta_R + \cot\beta_R)$$

independent of gauge kinetic mixing!

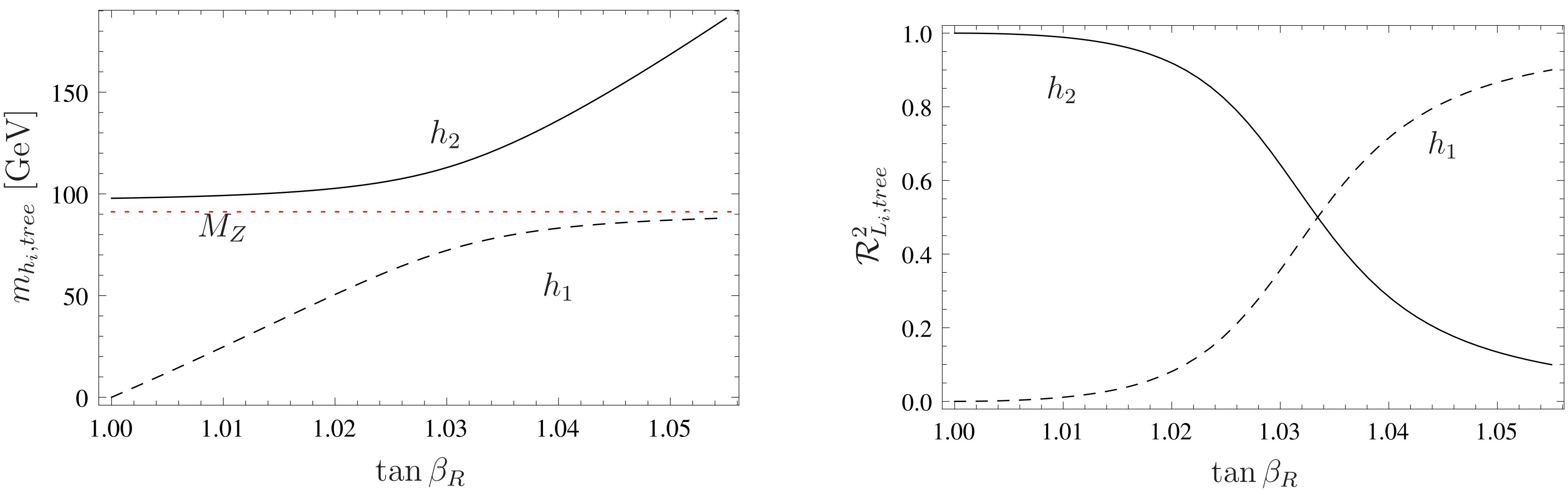
Higgs sector, II

$$
\begin{aligned}
M^2_{hh} &= \begin{pmatrix} m^2_{LL} & m^2_{LR} \\ m^{2,T}_{LR} & m^2_{RR} \end{pmatrix} \\
m^2_{LL} &= \begin{pmatrix} g^2_\Sigma v^2 c^2_\beta + m^2_A s^2_\beta & -\frac{1}{2}\left(m^2_A + g^2_\Sigma v^2\right) s_{2\beta} \\ -\frac{1}{2}\left(m^2_A + g^2_\Sigma v^2\right) s_{2\beta} & g^2_\Sigma v^2 s^2_\beta + m^2_A c^2_\beta \end{pmatrix} , \\
m^2_{LR} &= \frac{5}{8} g_\chi \tilde{g}_\chi v v_R \begin{pmatrix} c_\beta c_{\beta_R} & -c_\beta s_{\beta_R} \\ -s_\beta c_{\beta_R} & s_\beta s_{\beta_R} \end{pmatrix} , \\
m^2_{RR} &= \begin{pmatrix} g^2_{Z_R} v^2_R c^2_{\beta_R} + m^2_{A_R} s^2_{\beta_R} & -\frac{1}{2}\left(m^2_{A_R} + g^2_{\Sigma_R} v^2_R\right) s_{2\beta_R} \\ -\frac{1}{2}\left(m^2_{A_R} + g^2_{\Sigma_R} v^2_R\right) s_{2\beta_R} & g^2_{\Sigma_R} v^2_R s^2_{\beta_R} + m^2_{A_R} c^2_{\beta_R} \end{pmatrix} \\
v^2_R &= v^2_{\chi_R} + v^2_{\bar{\chi}_R} \ , \ v^2 = v^2_d + v^2_u \ , \ s_x = \sin(x) \ , \ c_x = \cos(x) \\
g^2_\Sigma &= \frac{1}{4}(g^2_2 + g'^2 + \tilde{g}^2_\chi) \ , \ g^2_{\Sigma_R} = \frac{25}{16} g^2_\chi \ , \ \tilde{g}_\chi = g_\chi - g_{Y\chi}
\end{aligned}
$$

⇒ new D-term contributions at tree-level: $m^2_{h^0,tree} \le m^2_Z + \frac{1}{4}\tilde{g}^2_\chi v^2$

H.E. Haber, M. Sher, PRD 35 (1987) 2206; M. Drees, PRD 35 (1987) 2910; M. Cvetic et al., PRD 56 (1997) 2861; E. Ma, arXiv:1108.4029; M. Hirsch et al., arXiv:1110.3037, arXiv:1206:3516

Higgs sector III

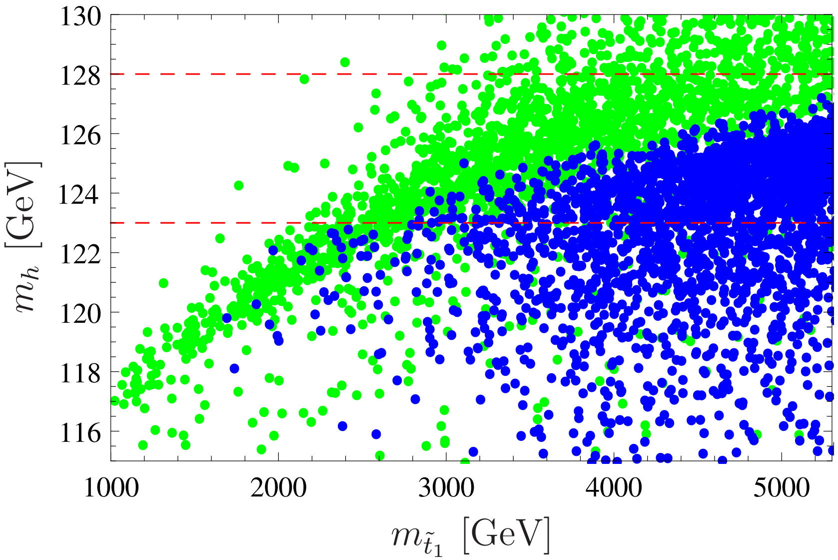


$n = 1,\ \Lambda = 5 \cdot 10^5$ GeV, $M = 10^{11}$ GeV, $\tan\beta = 30,$ sign$(\mu_R) = -,\ diag(Y_S) = (0.7, 0.6, 0.6),\ Y_\nu^{ii} = 0.01,\ v_R = 7$ TeV

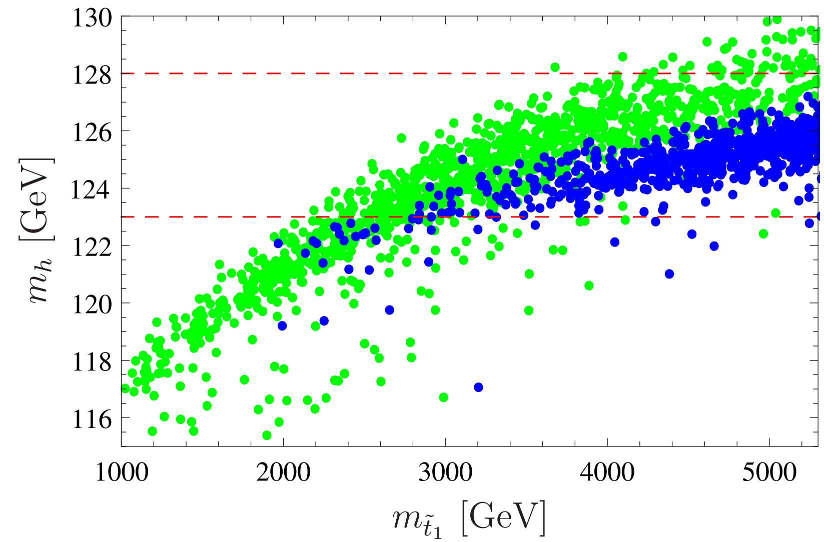
M.E. Krauss, W.P., F. Staub, arXiv:1304.0769

Higgs sector IV

$R_{h\to\gamma\gamma} \geq 0.5$



$R_{h\to\gamma\gamma} \geq 0.9$



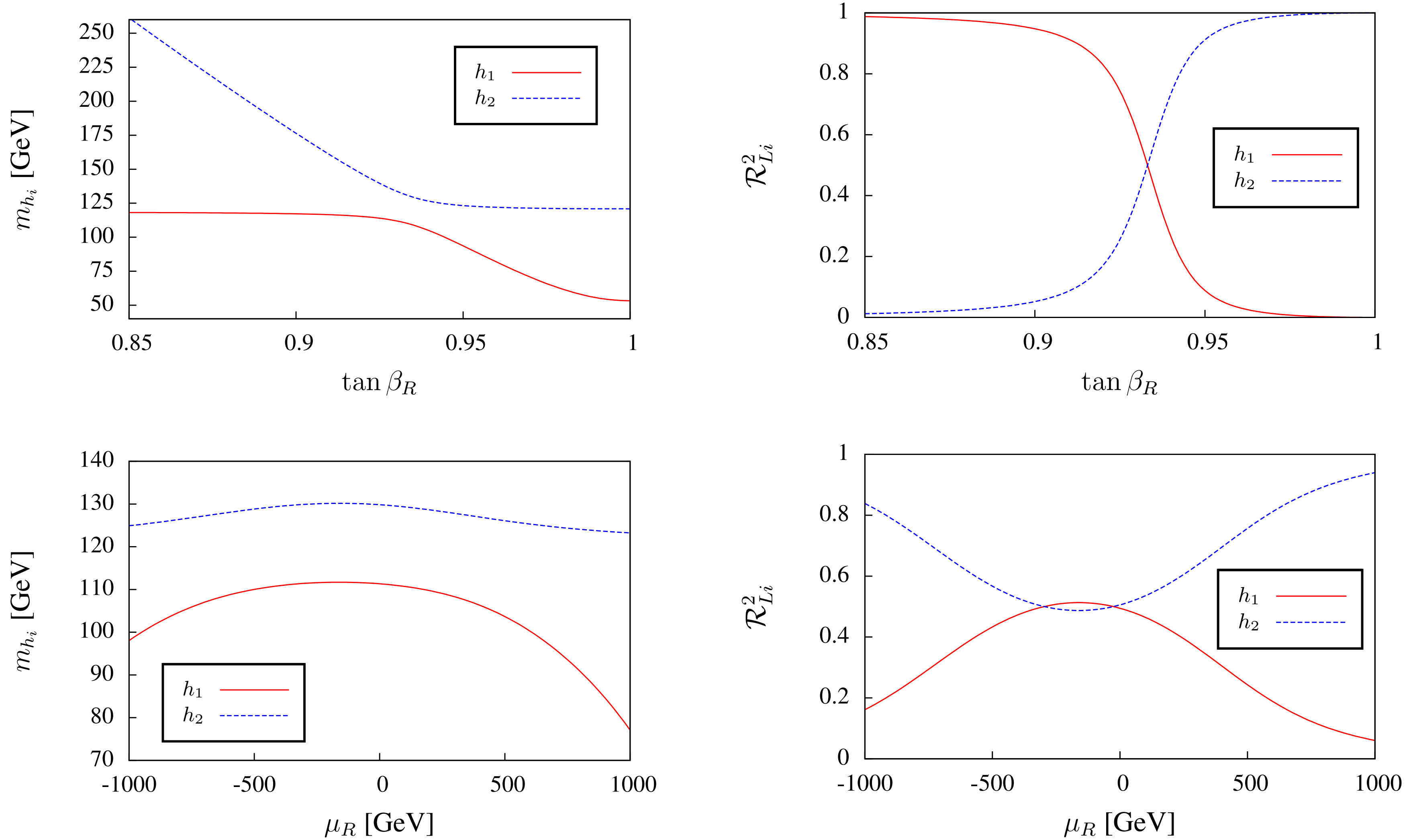
scan over: $1 \leq n \leq 4$, $10^5 \leq M \leq 10^{12}$ GeV, $10^5 \leq \sqrt{n}\Lambda \leq 10^6)$ GeV, $1.5 \leq \tan\beta \leq 40$, $1 < \tan\beta_R \leq 1.15$, sign$(\mu_R) \pm 1$, sign$(\mu) = 1$, $6.5 \leq v_R \leq 10$ TeV, $0.01 \leq Y_S^{ii} \leq 0.8$, $10^{-5} \leq Y_\nu^{ii} \leq 0.5$

blue points: $h_1 \simeq h^0$, green points: $h_2 \simeq h^0$

$$R_{h\to\gamma\gamma} = \frac{[\sigma(pp \to h) \times BR(h \to \gamma\gamma)]_{BLR}}{[\sigma(pp \to h) \times BR(h \to \gamma\gamma)]_{SM}} \,.$$

M.E. Krauss, W.P., F. Staub, arXiv:1304.0769

Higgs sector V



$m_0 = 250$ GeV, $M_{1/2} = 800$ GeV, $\tan\beta = 10$, $A_0 = 0$
$v_R = 6000$ GeV, $\tan\beta_R = 0.94$, $m_{A_R} = 2350$ GeV, $\mu_R = -800$ GeV
including complete 1-loop + 2-loop in the MSSM part

Neutralinos I

basis $(\lambda_Y, \lambda_{W^3}, \tilde{h}_d^0, \tilde{h}_u^0, \lambda_\chi, \tilde{\bar{\chi}}_R, \tilde{\chi}_R)$

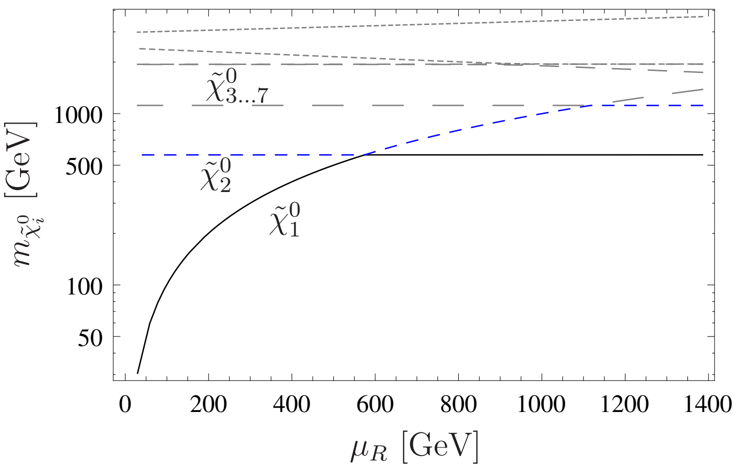
$$M_{\tilde{\chi}^0} =$$

$$\begin{pmatrix}
M_1 & 0 & -\frac{g' v_d}{2} & \frac{g' v_u}{2} & \frac{M_{Y\chi}}{2} & 0 & 0 \\
0 & M_2 & \frac{g_2 v_d}{2} & -\frac{g_2 v_u}{2} & 0 & 0 & 0 \\
-\frac{g' v_d}{2} & \frac{g_2 v_d}{2} & 0 & -\mu & \frac{(g_\chi - g_{Y\chi}) v_d}{2} & 0 & 0 \\
\frac{g' v_u}{2} & -\frac{g_2 v_u}{2} & -\mu & 0 & -\frac{(g_\chi - g_{Y\chi}) v_u}{2} & 0 & 0 \\
\frac{M_{Y\chi}}{2} & 0 & \frac{(g_\chi - g_{Y\chi}) v_d}{2} & -\frac{(g_\chi - g_{Y\chi}) v_u}{2} & M_\chi & \frac{5 g_\chi v_{\bar{\chi}_R}}{4} & -\frac{5 g_\chi v_{\chi_R}}{4} \\
0 & 0 & 0 & 0 & \frac{5 g_\chi v_{\bar{\chi}_R}}{4} & 0 & -\mu_R \\
0 & 0 & 0 & 0 & -\frac{5 g_\chi v_{\chi_R}}{4} & -\mu_R & 0
\end{pmatrix}$$

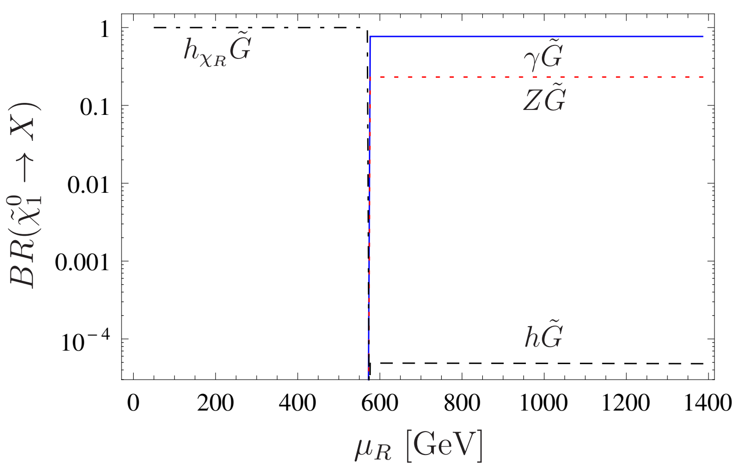
neglecting the mixing between the two sectors and setting $\tan\beta_R = 1$

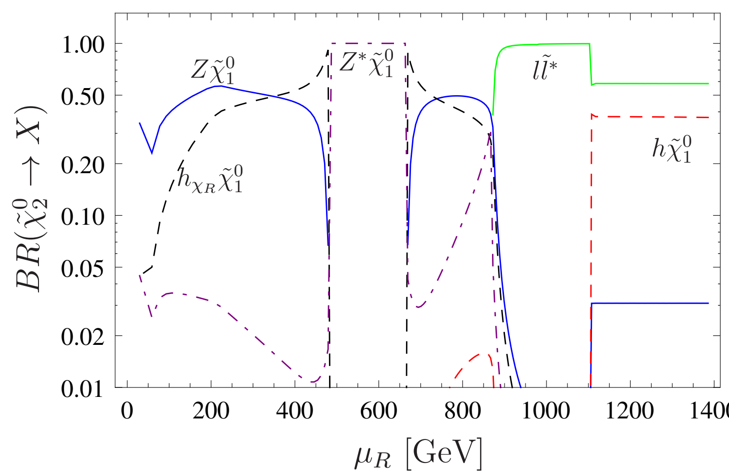
$$m_i: \ \mu_R\,, \quad \frac{1}{2}\left(M_\chi + \mu_R \pm \sqrt{\frac{1}{4} m_{Z'}^2 + (M_\chi - \mu_R)^2}\right)$$

Neutralinos II



M.E. Krauss, W.P., F. Staub, arXiv:1304.0769





$n = 1$, $\Lambda = 3.8 \cdot 10^5$ GeV, $M = 9 \cdot 10^{11}$ GeV, $\tan\beta = 30$ $v_R = 6.7$ GeV, $\tan\beta_R$ varied

Neutrinos and sneutrinos

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

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

$$M^2_{\tilde\nu} =$$

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

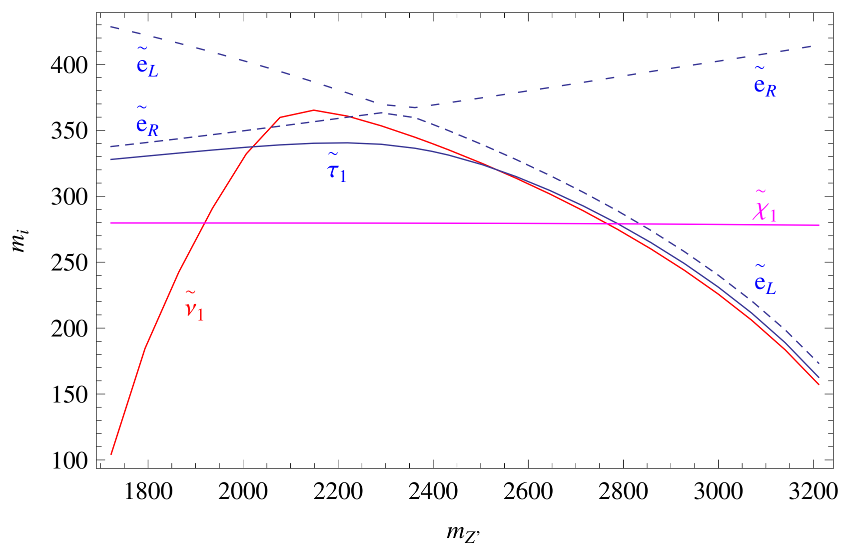
$$D_L = \frac{1}{32}\Big(2\big(-3g_\chi^2 + g_\chi g_{Y\chi} + 2(g_2^2 + g'^2 + g_{Y\chi}^2)\big) v^2 c_{2\beta} - 5 g_\chi (3 g_\chi + 2 g_{Y\chi}) v_R^2 c_{2\beta_R}\Big)\mathbf{1}$$

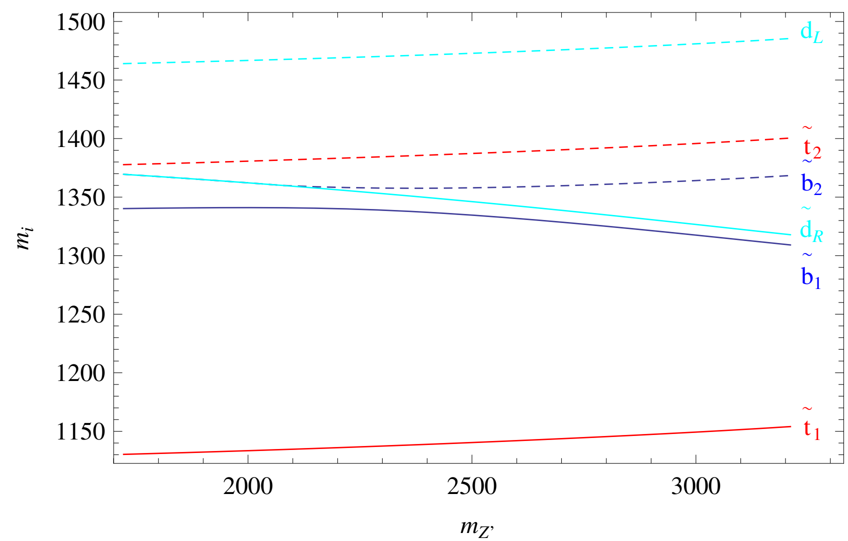
$$D_R = \frac{5 g_\chi}{32}\Big(2(g_\chi - g_{Y\chi}) v^2 c_{2\beta} + 5 g_\chi v_R^2 c_{2\beta_R}\Big)\mathbf{1}$$

$$M^2_{\tilde{l}} = \begin{pmatrix} M^2_{\tilde{L}} + D'_L + m_l^2 & \frac{1}{\sqrt{2}}\left(v_d T_l - \mu Y_l v_u\right) \\ \frac{1}{\sqrt{2}}\left(v_d T_l - \mu Y_l v_u\right) & M^2_{\tilde{E}} + D'_R + m_l^2 \end{pmatrix},$$

$D_L = (\frac{1}{8}(g'^2 - g_2^2) - \frac{3}{16} g_\chi^2) v^2 c_{2\beta} - \frac{15}{32} g_\chi^2 v_R^2 c_{2\beta_R}$ and $D_R = (\frac{1}{16} g_\chi^2 - \frac{1}{4} g'^2) v^2 c_{2\beta} + \frac{5}{32} g_\chi^2 v_R^2 c_{2\beta_R}$

neglecting gauge kinetic effects; similarly for squarks





$m_0 = 100$ GeV, $m_{1/2} = 700$ GeV, $A_0 = 0$, $\tan\beta = 10$, $\mu > 0$
$\tan\beta_R = 0.94$, $m_{A_R} = 2$ TeV, $\mu_R = -800$ GeV

Benchmark points

	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

Spectra (in GeV)

	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.
$m_{\chi^0_1}$	367.	417.	313.	259. $\tilde{h}_R$	412.
$m_{\chi^0_2}$	718.	780. $\tilde{h}_R$	615.	280.	739. $\tilde{h}_R$
$m_{\chi^0_3}$	1047.	818.	1087.	549.	804.
$m_{\chi^0_4}$	1054.	1866.	1093.	845.	1288.
$m_{\chi^0_5}$	1348. $(\tilde{B}_\perp)$	1866.	1232. $(\tilde{B}_\perp)$	857.	1294.
$m_{\chi^0_6}$	1802. $\tilde{h}_R$	2018. $(\tilde{B}_\perp)$	1811. $(\tilde{B}_\perp)$	1639. $(\tilde{B}_\perp)$	1688. $(\tilde{B}_\perp)$

Changes in SUSY cascades, BLRSP1

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

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

$$
\begin{aligned}
\tilde{q}_R &\to q\tilde{\chi}^0_1 \to q\nu_k\tilde{\nu}_1 \to q\nu_j Z\tilde{\nu}_1 \\
\tilde{q}_R &\to q\tilde{\chi}^0_1 \to q\nu_k\tilde{\nu}_1 \to ql^\pm W^\mp\tilde{\nu}_1 \\
\tilde{q}_R &\to q\tilde{\chi}^0_1 \to q\nu_k\tilde{\nu}_3 \to ql^\pm W^\mp l'^+ l'^- \tilde{\nu}_1 \\
\tilde{d}_R &\to d\tilde{\chi}^0_5 \to dl^\pm\tilde{l}^\mp_i \to dl^\pm l^\mp\tilde{\chi}^0_1 \to dl^\pm l^\mp\nu_k\tilde{\nu}_1 \to dl^\pm l^\mp l'^\pm W^\mp\tilde{\nu}_1
\end{aligned}
$$

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

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

Changes in SUSY cascades, BLRSP3 + BLRSP4

BLRSP3: usual cascades similar to CMSSM, but

$$
\begin{aligned}
\tilde\chi^0_1 &\to l^\pm \tilde l^\mp \to l^\pm W^\mp \tilde\nu_1 \\
\tilde\chi^0_1 &\to l^\pm \tilde l^\mp \to l^\pm W^\mp \tilde\nu_{2,3} \to l^\pm W^\mp f\bar f \tilde\nu_1 \\
\tilde\chi^0_1 &\to \nu_j \tilde\nu_{2,3} \to \nu_{1,2,3} f\bar f \tilde\nu_1 \\
\tilde\chi^0_1 &\to \nu_j \tilde\nu_1 \\
\tilde\chi^0_1 &\to \nu_j \tilde\nu_k \to \nu_j h_{1,2} \tilde\nu_1 \\
\tilde\chi^0_1 &\to \nu_j \tilde\nu_k \to \nu_j h_{1,2} f\bar f \tilde\nu_1
\end{aligned}
$$

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

$\Rightarrow$ enhancement of multiplicities compared to standard case, e.g.

$$\tilde d_R \to d\tilde\chi^0_1 \to dX$$

BLRSP4: similar to NMSSM with singlino LSP

$SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$ model

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	$(\frac{1}{3}, \mathbf{1}, \overline{\mathbf{3}}, -\frac{1}{6})$
$\hat{U}$	3	$(-\frac{2}{3}, \mathbf{1}, \overline{\mathbf{3}}, -\frac{1}{6})$
$\hat{L}$	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	$(0, \mathbf{1}, \mathbf{1}, 1)$

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

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

Model similarities/differences

- $Z_{B-L} \Leftrightarrow Z_\chi$

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

- 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 $\tilde{\nu}_R$

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

  reduces $\sum_{i,j} BR(Z' \to \tilde{\nu}_i \tilde{\nu}_j)$
- larger mass splitting between sleptons and sneutrinos $\Rightarrow$ harder leptons

Benchmark points

all masses in GeV

	BL1	BL2
m_0	600	1000
$M_{1/2}$	600	1500
A_0	0	-1500
$\tan\beta$	10	20
sign μ	+	+
$\tan\beta'$	1.07	1.15
sign μ'	+	+
Y_X^{11}	0.42	0.37
Y_X^{22}	0.43	0.4
Y_X^{33}	0.44	0.4

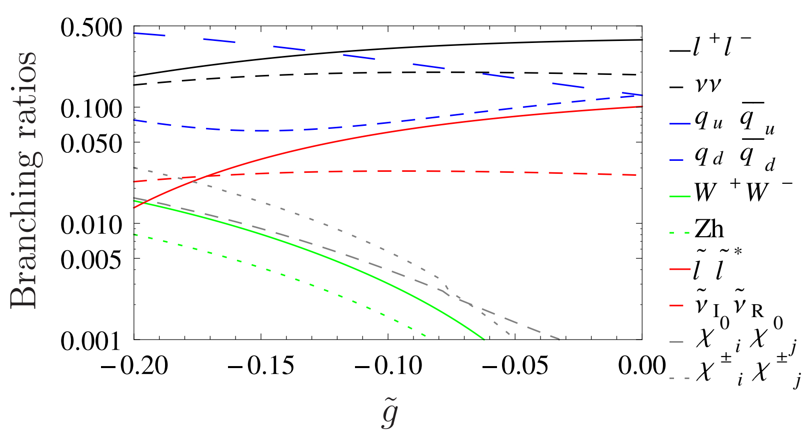
	BL1	BL2
$m_{Z'}$	2000	2500
$m_{\tilde{\chi}_1^0}$	280.7	678.0
$m_{\tilde{\chi}_2^0}$	475.4	735.2
$m_{\tilde{\chi}_3^0}$	719.1	1241.9
$m_{\tilde{\chi}_4^0}$	733.9	1827.0
$m_{\tilde{\chi}_5^0}$	798.2	1867.5
$m_{\tilde{\chi}_6^0}$	1488.7	1871.5
$m_{\tilde{\chi}_7^0}$	2530.6	3131.4

	BL1	BL2
$m_{\tilde{\chi}_1^\pm}$	475.4	1242.0
$m_{\tilde{\chi}_2^\pm}$	733.9	1872.0
$m_{\tilde{\tau}_1}$	603.7	1002.0
$m_{\tilde{\tau}_2}$	759.9	1446.5
$m_{\tilde{\mu}_1}$	610.8	1094.2
$m_{\tilde{\mu}_2}$	761.9	1477.4
$m_{\tilde{e}_1}$	610.8	1094.5
$m_{\tilde{e}_2}$	761.9	1477.5

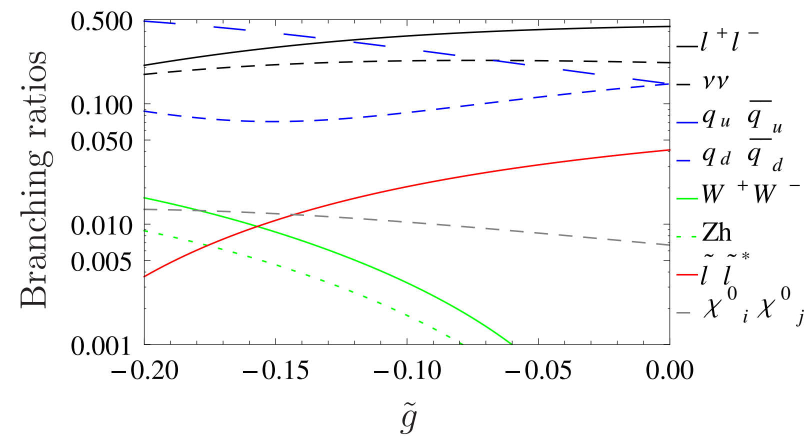
M. Krauss, B. O'Leary, W.P., F. Staub, arXiv:1206.3513

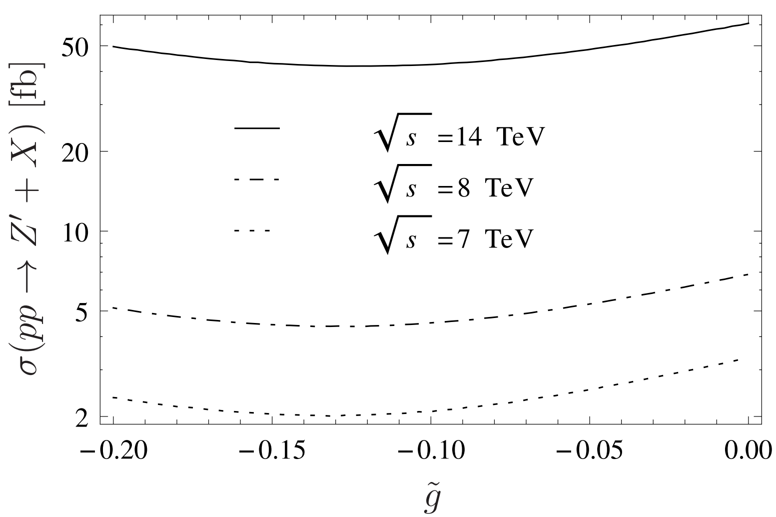
Z' couplings: $Q_{B-L} \cdot g_{B-L} \rightarrow Q_{B-L} \cdot g_{B-L} + Q_Y \cdot \tilde{g}$

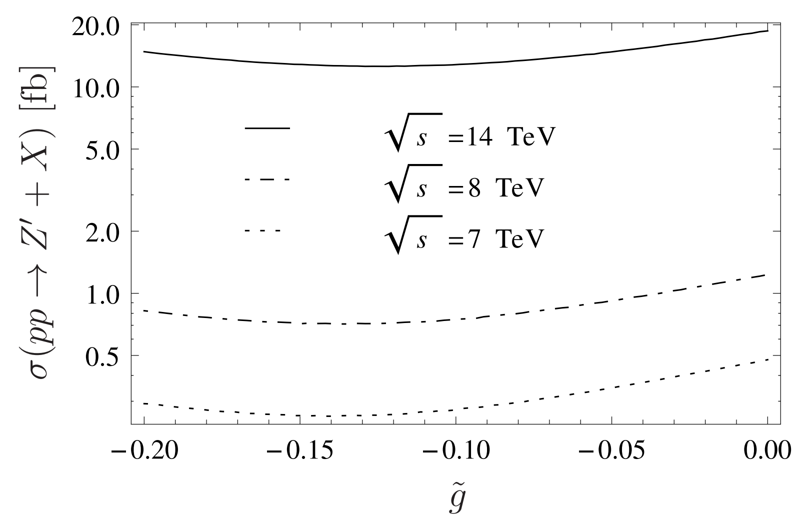
BL1



BL2

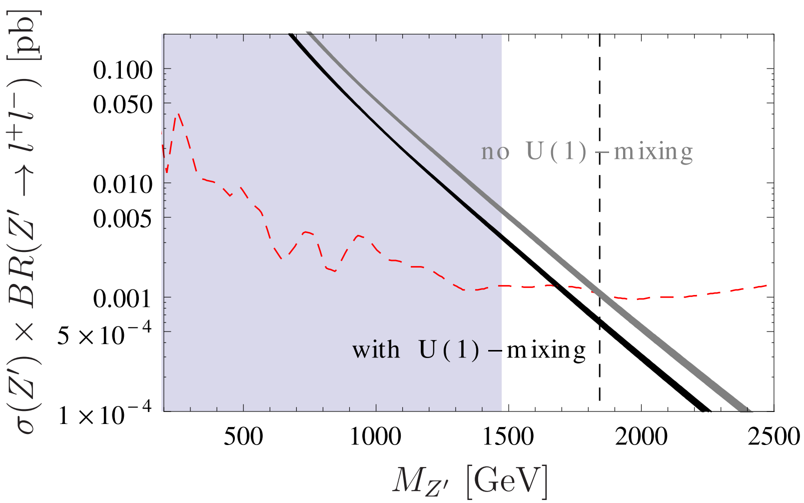




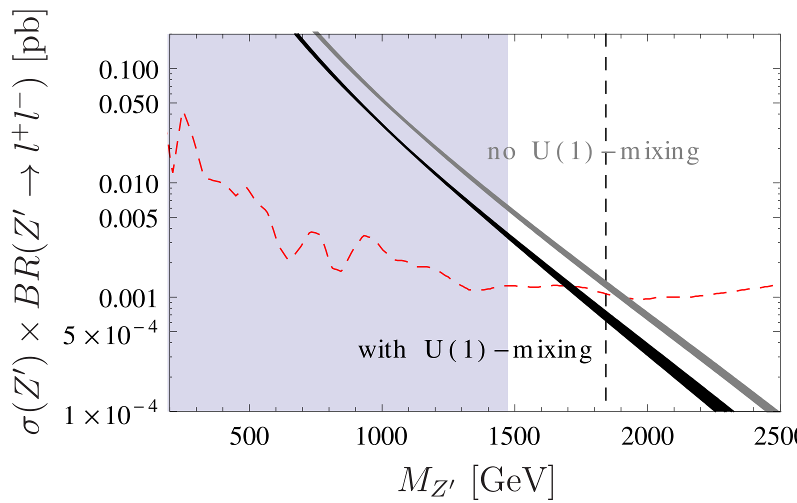


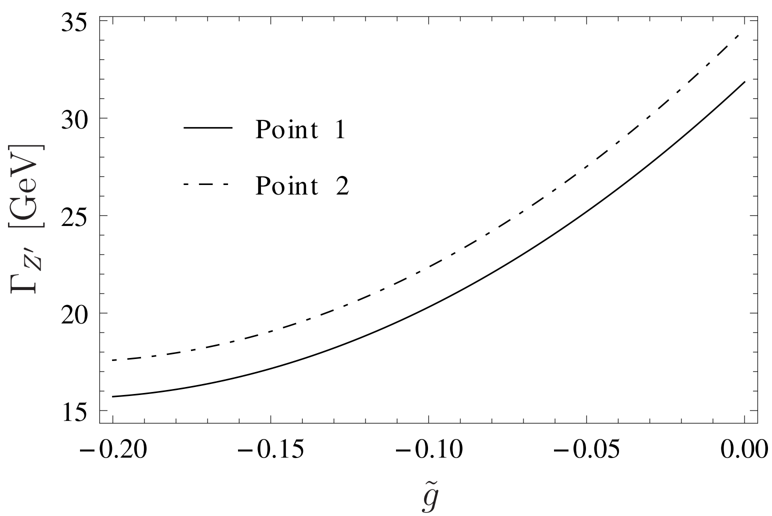
Z' physics, II

BL1



BL2



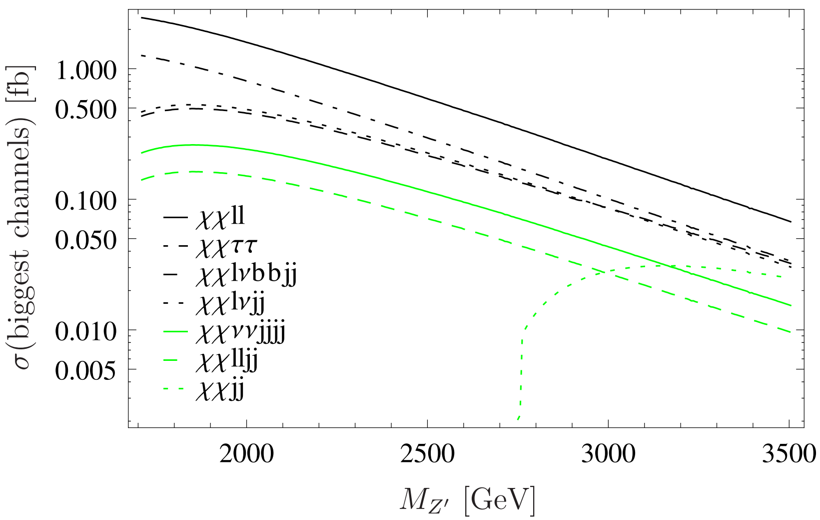


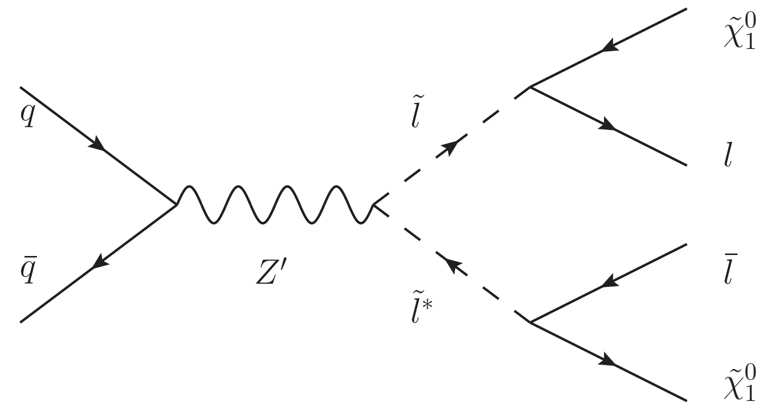
Z' couplings:

$$Q_{B-L} \cdot g_{B-L} \to Q_{B-L} \cdot g_{B-L} + Q_Y \cdot \tilde{g}$$

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

LHC 14 TeV: Sleptons via Z' in BL1, I





M. Krauss, B. O'Leary, W.P., F. Staub, arXiv:1206.3513:

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

LHC 14 TeV: Sleptons via Z' in BL1, II

- invariant mass of the muon pair: $M_{\mu\mu} > 200$ GeV
- missing transverse momentum: $p_T(\not{E}) > 200$ GeV
- transverse cluster mass

$$M_T = \sqrt{\left(\sqrt{p_T^2(\mu^+\mu^-) + M_{\mu\mu}^2} + p_T(\not{E})\right)^2 - (\vec{p}_T(\mu^+\mu^-) + \vec{p}_T(\not{E}))^2}$$

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

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

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

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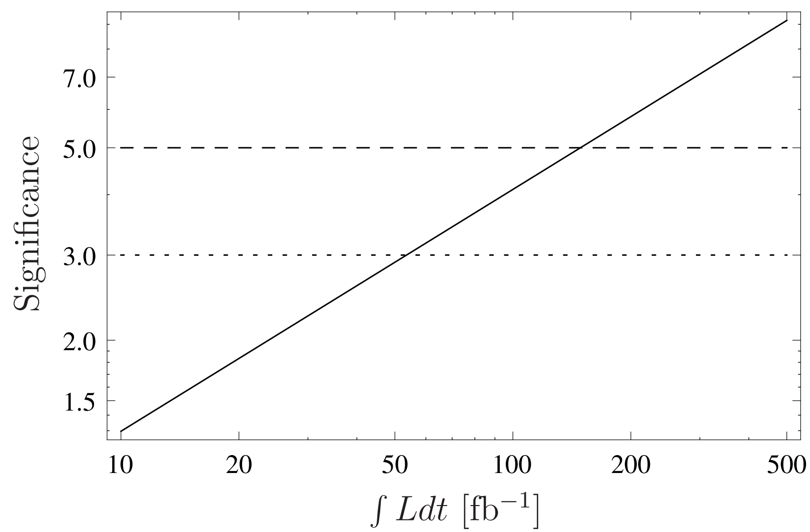
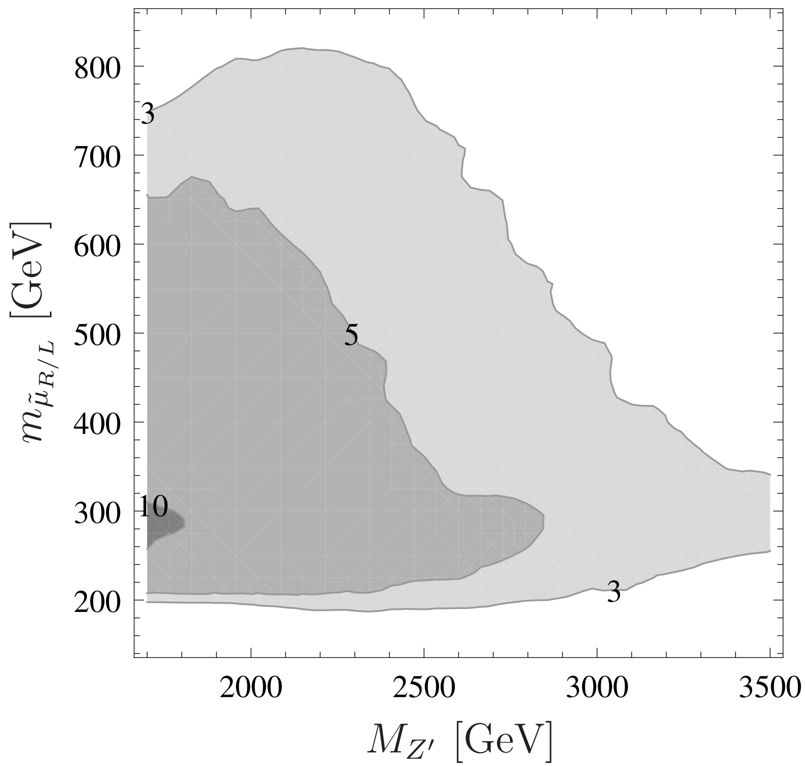
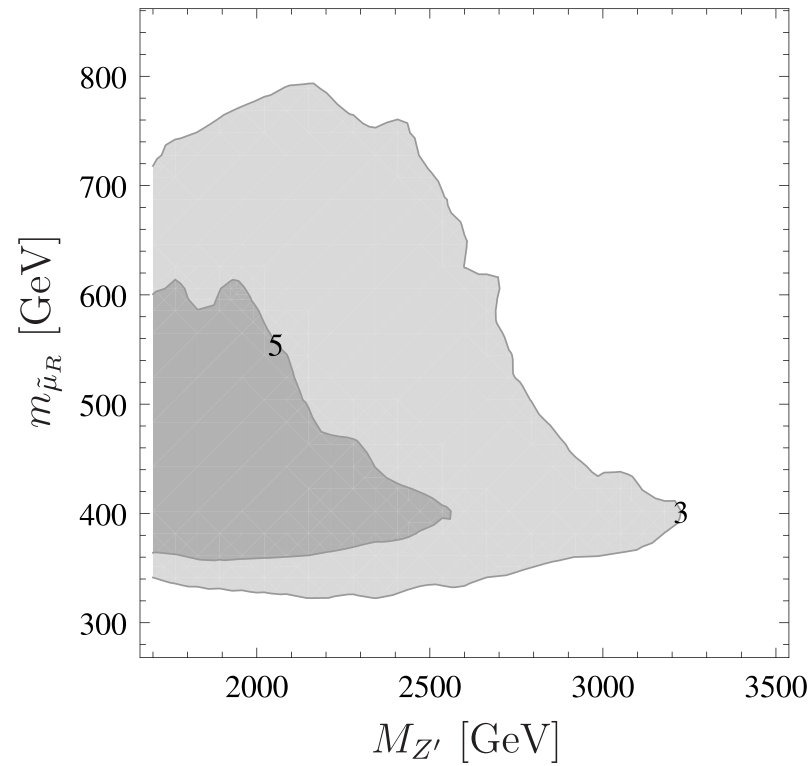


main dependence on masses $\Rightarrow$ vary $m_{\tilde{l}}$ and $m_{Z'}$, $M_L = 1.2 M_E$





M. Krauss, B. O'Leary, W.P., F. Staub, arXiv:1206.3513

Conclusions

- $m_{h^0} \simeq 125$ 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, partially testable @ LHC and ILC
- extra Z' $\Rightarrow$ additional D-terms for scalars,
  e.g. SM-like Higgs with tree-level mass of up to 110 GeV
  $\Rightarrow$ less constraining for GMSB and CMSSM like scenarios
- 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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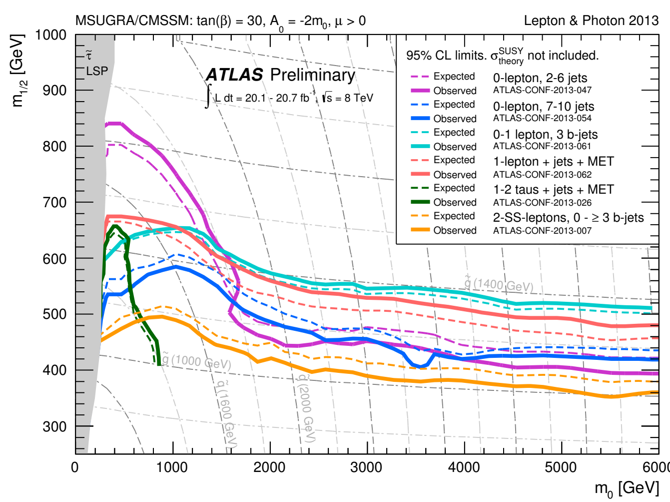
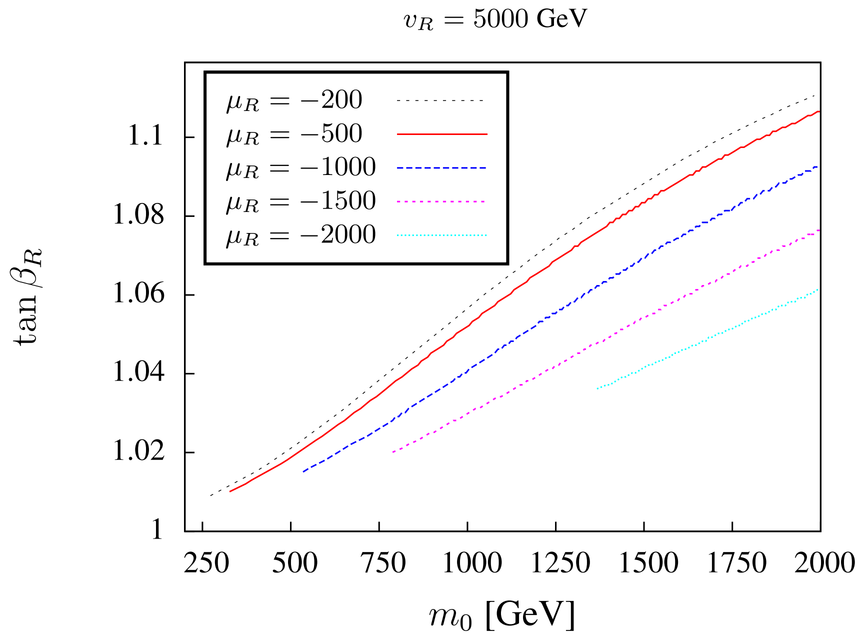
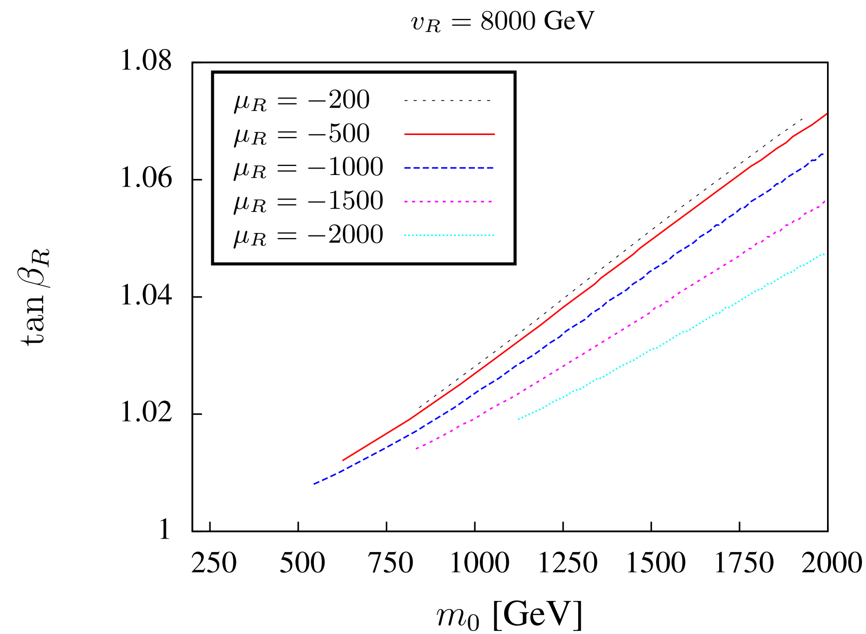
- direct $\tilde{l}$ production via Z'
- regions with $\tilde{\nu}$-LSP and/or additional gauginos
  $\Rightarrow$ higher multiplicities, in particular leptons
  $\Rightarrow$ expect less stringent exclusions depending on m'_Z and extended Higgs sector



Boundary conditions, III





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

$$m^2_{Z'} \simeq \frac{1}{4}\left((g_{BLR} - g_R)^2 + (g_{BL} - g_{RBL})^2\right) v_R^2 = \left(\frac{5}{4} g_\chi v_R\right)^2$$

$$\simeq -2(|\mu_R|^2 + m^2_{\bar\chi_R}) + \frac{g_R^2}{4} v^2 \cos(2\beta) \frac{\tan\beta_R^2 + 1}{\tan\beta_R^2 - 1} + \Delta m^2_{\chi_R} \frac{2\tan\beta_R^2}{\tan\beta_R^2 - 1}$$

$$\Delta m^2_{\chi_R} = m^2_{\bar\chi_R} - m^2_{\chi_R} \simeq \frac{1}{4\pi^2} \mathrm{Tr}(Y_s Y_s^\dagger)(3m_0^2 + A_0^2) \log\left(\frac{M_{GUT}}{M_{SUSY}}\right)$$

$$v_R^2 = v^2_{\chi_R} + v^2_{\bar\chi_R}$$

Heavy neutrinos

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

invisible width

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

dominant decays

$$\begin{aligned} \nu_j &\to W^{\pm} l^{\mp} \\ \nu_j &\to Z \nu_i \\ \nu_j &\to h_k \nu_i \end{aligned}$$

roughly

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

in BLRSP4

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

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

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

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

$$\det\left(M^2_{VV}\right) = 0$$

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:1206:3516

Neutralinos I

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

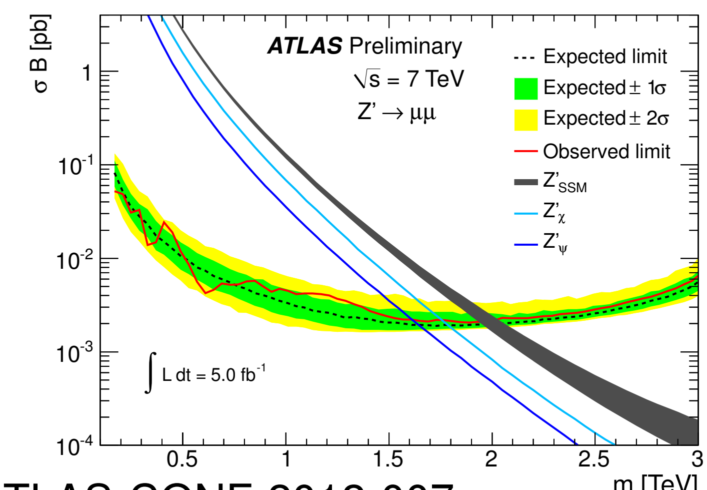
$$M_{\tilde{\chi}^0} =$$

$$\begin{pmatrix}
M_{BL} & 0 & -\frac{1}{2}g_{RBL}v_d & \frac{1}{2}g_{RBL}v_u & \frac{M_{BLR}}{2} & \frac{1}{2}v_{\bar{\chi}_R}\tilde{g}_{BL} & -\frac{1}{2}v_{\chi_R}\tilde{g}_{BL} \\
0 & M_2 & \frac{1}{2}g_2 v_d & -\frac{1}{2}g_2 v_u & 0 & 0 & 0 \\
-\frac{1}{2}g_{RBL}v_d & \frac{1}{2}g_2 v_d & 0 & -\mu & -\frac{1}{2}g_R v_d & 0 & 0 \\
\frac{1}{2}g_{RBL}v_u & -\frac{1}{2}g_2 v_u & -\mu & 0 & \frac{1}{2}g_R v_u & 0 & 0 \\
\frac{M_{BLR}}{2} & 0 & -\frac{1}{2}g_R v_d & \frac{1}{2}g_R v_u & M_R & -\frac{1}{2}v_{\bar{\chi}_R}\tilde{g}_R & \frac{1}{2}v_{\chi_R}\tilde{g}_R \\
\frac{1}{2}v_{\bar{\chi}_R}\tilde{g}_{BL} & 0 & 0 & 0 & -\frac{1}{2}v_{\bar{\chi}_R}\tilde{g}_R & 0 & -\mu_R \\
-\frac{1}{2}v_{\chi_R}\tilde{g}_{BL} & 0 & 0 & 0 & \frac{1}{2}v_{\chi_R}\tilde{g}_R & -\mu_R & 0
\end{pmatrix}$$

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	—

Z’ limits and phenomenology

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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