Supersymmetric models with extended gauge symmetries

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Motivation

- Origin of R-parity

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

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

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  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}

Model I

	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
	$\hat{d}^c$	$(\overline{\mathbf{3}}, \mathbf{1}, +\frac{1}{2}, -\frac{1}{6})$	3
	$\hat{u}^c$	$(\overline{\mathbf{3}}, \mathbf{1}, -\frac{1}{2}, -\frac{1}{6})$	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

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

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

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

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

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

Higgs sector, II

$$
\begin{aligned}
M^2_{hh} &= \begin{pmatrix} m^2_{LL} & m^2_{LR} \\ m^{2,T}_{LR} & m^2_{RR} \end{pmatrix} \\
m^2_{LL} &= \begin{pmatrix} g^2_Z v^2 c^2_\beta + m^2_A s^2_\beta & -\frac{1}{2}\left(m^2_A + g^2_Z v^2\right) s_{2\beta} \\ -\frac{1}{2}\left(m^2_A + g^2_Z v^2\right) s_{2\beta} & g^2_Z v^2 s^2_\beta + m^2_A c^2_\beta \end{pmatrix} , \\
m^2_{LR} &= \begin{pmatrix} g^2_R v v_R c_\beta c_{\beta_R} & -g^2_R v v_R c_\beta s_{\beta_R} \\ -g^2_R v v_R s_\beta c_{\beta_R} & g^2_R v v_R s_\beta s_{\beta_R} \end{pmatrix} , \\
m^2_{RR} &= \begin{pmatrix} g^2_{Z_R} v^2_R c^2_{\beta_R} + m^2_{A_R} s^2_{\beta_R} & -\frac{1}{2}\left(m^2_{A_R} + g^2_{Z_R} v^2_R\right) s_{2\beta_R} \\ -\frac{1}{2}\left(m^2_{A_R} + g^2_{Z_R} v^2_R\right) s_{2\beta_R} & g^2_{Z_R} v^2_R s^2_{\beta_R} + m^2_{A_R} c^2_{\beta_R} \end{pmatrix} \\
v^2_R &= v^2_{\chi_R} + v^2_{\bar{\chi}_R} \ , \ v^2 = v^2_d + v^2_u \\
s_x &= \sin(x) \ , \ c_x = \cos(x) \ , \ g^2_Z = \frac{1}{4}(g^2_L + g^2_R) \ , \ g^2_{Z_R} = \frac{1}{4}(g^2_{BL} + g^2_R)
\end{aligned}
$$

$\Rightarrow$ new D-term contributions at tree-level

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

Neutral gauge sector

basis: $[SU(2)_L, U(1)_R, U(1)_{B-L}]$

$$M^2_{VV} = \frac{1}{4}\begin{pmatrix} g_L^2 v^2 & 0 & -g_L g_R v^2 \\ 0 & g_{BL}^2 v_R^2 & -g_{BL} g_R v_R^2 \\ -g_L g_R v^2 & -g_{BL} g_R v_R^2 & g_R^2 \left(v^2 + v_R^2\right) \end{pmatrix}$$

$$\Rightarrow m^2_{Z'} \simeq g^2_{Z_R} v_R^2 + O(v^2/v_R^2) \qquad Z' \simeq Z_\chi$$

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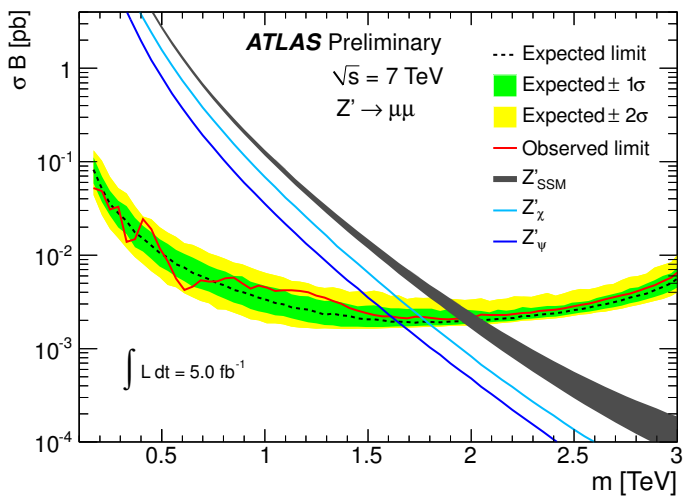
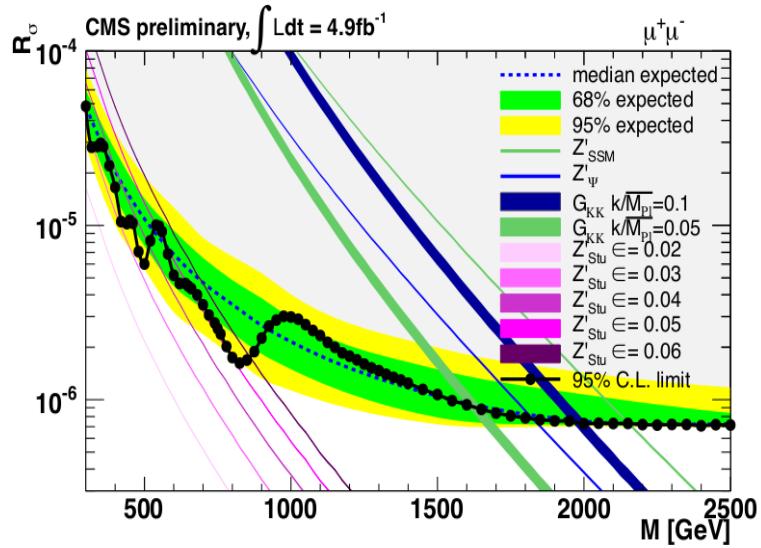
LHC results

ATLAS-CONF-2012-007

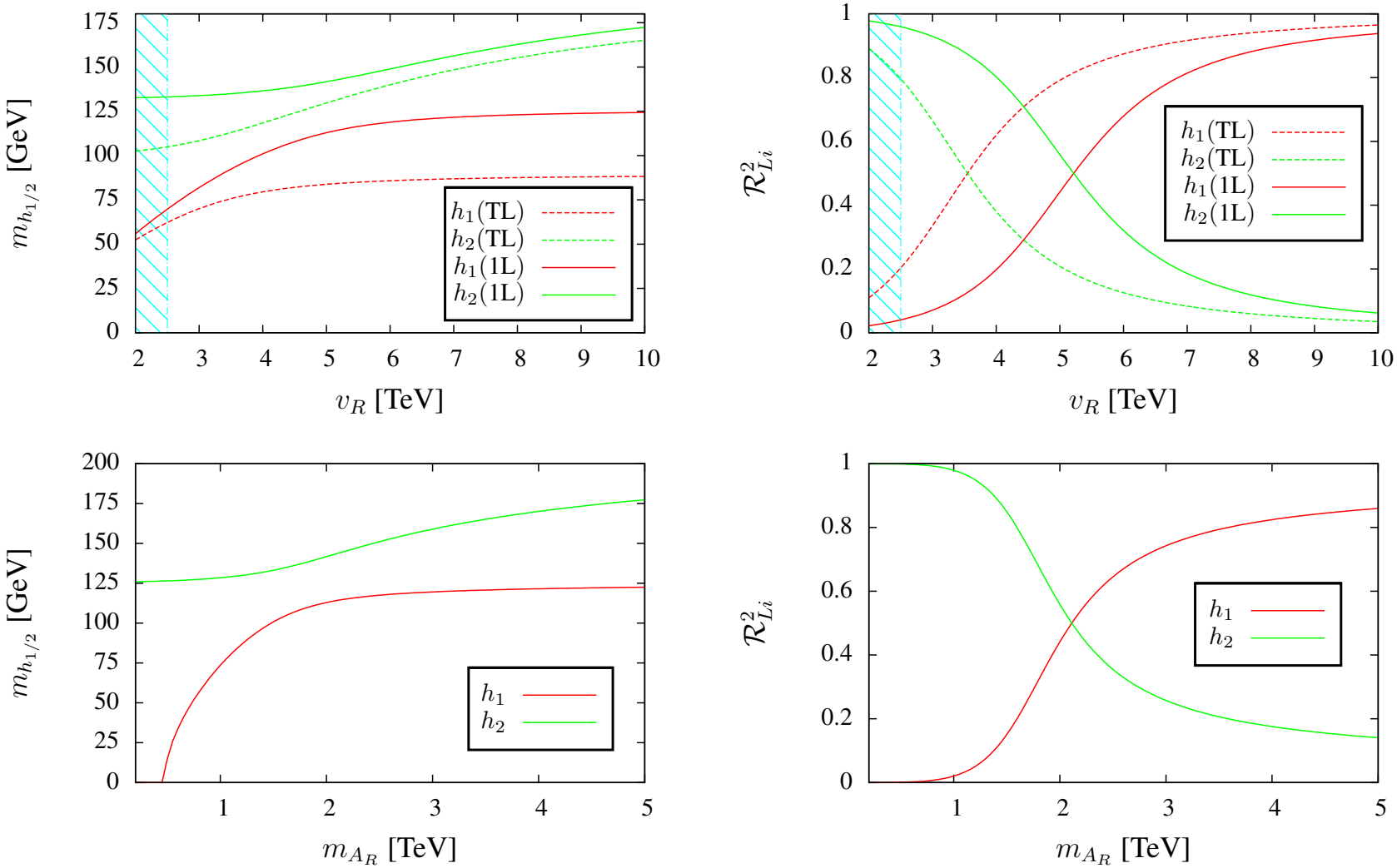


CMS EXO11019



see talks by E. Etzion and Ch. Leonidopoulos

Higgs III



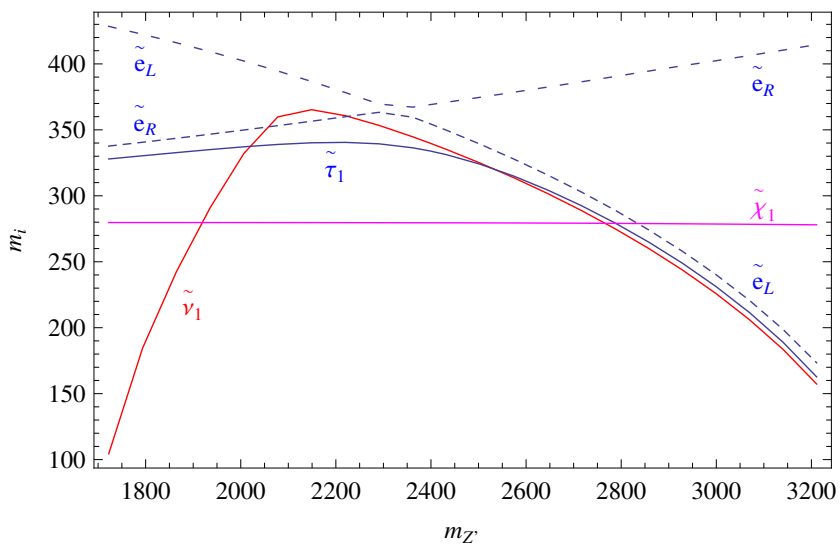
$M_{1/2} = 600$ GeV, $m_0 = 120$ GeV, $A_0 = 0$, $\tan\beta = 10$, $\mu = 800$ GeV, $m_A = 800$ GeV
$v_R = 5$ TeV, $\mu_\chi = -500$ GeV, $m_{A_R} = 2$ TeV, $\tan\beta_R = 1.1$

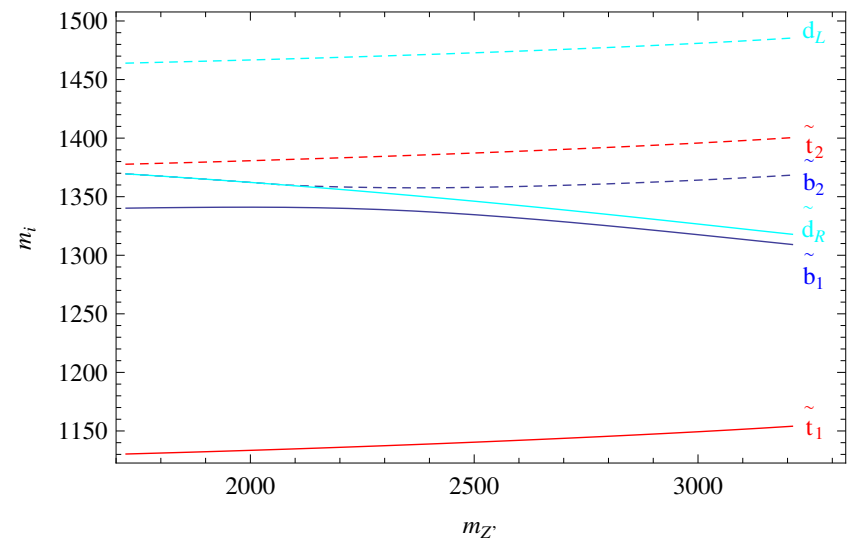
Sfermions

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

$M^2_{DL} = g^2_{BL}(v^2_{\chi_R} - v^2_{\bar{\chi}_R}) + g^2_L(v^2_u - v^2_d)$ and $M^2_{DR} = (g^2_R - g^2_{BL})(v^2_{\chi_R} - v^2_{\bar{\chi}_R}) + g^2_R(v^2_u - v^2_d)$

Similarly for squarks, sneutrino mass matrix depends on absence/presence of S fields





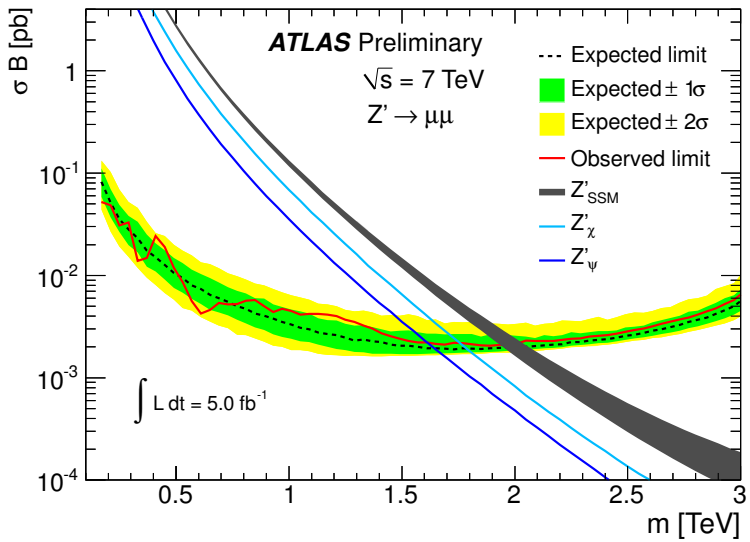
$m_0 = 100$ GeV, $m_{1/2} = 700$ GeV, $A_0 = 0$, $\tan\beta = 10$, $\mu > 0$
$\tan\beta_R = 0.94$, $m_{A_R} = 2$ TeV, $\mu_R = -800$ GeV

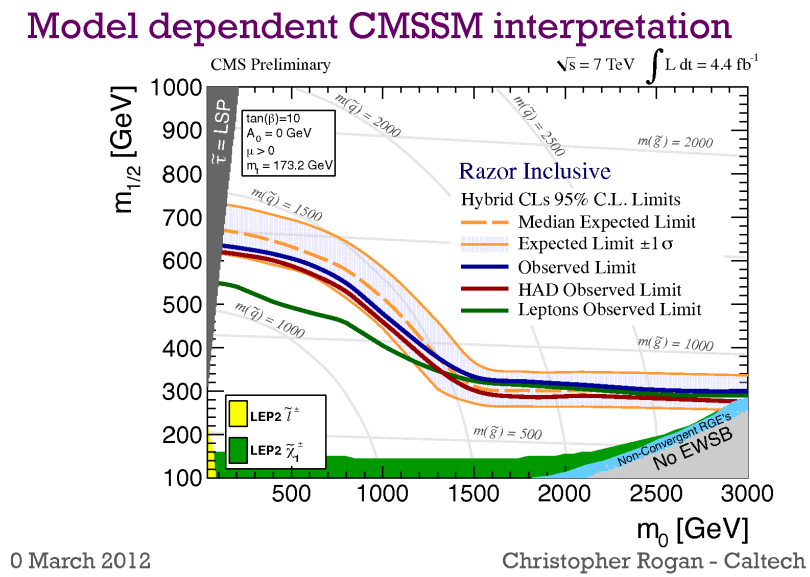
Implications for searches and parameter constraints I

- Z': typically
  - $\sum BR(Z' \to \tilde{l}_i \tilde{l}_j) + BR(Z' \to \tilde{\nu}_i \tilde{\nu}_j) \lesssim 0.2$
  - $\sum BR(Z' \to \tilde{q}_i \tilde{q}_j) \lesssim 0.05$
  - $\sum BR(Z' \to \tilde{\chi}_i^0 \tilde{\chi}_j^0) + BR(Z' \to \tilde{\chi}_i^+ \tilde{\chi}_j^-) \lesssim 0.02$
- cascade decays, regions with $m_{\tilde{\chi}_1^0} > m_{\tilde{l}_i} > m_{\tilde{\nu}_j}$
  - $\tilde{q}_R \to q\tilde{\chi}_1^0 \to ql\tilde{l} \to ql^+l^-\nu\tilde{\nu}_1$
    contains soft and hard leptons
  - $\tilde{q}_L$: up to two additional leptons or jets compared to $\tilde{q}_R$

  expect more leptons than in CMSSM
- additional gaugino-like $\tilde{\chi}^0$ below squarks: enhancements of lepton and jet multiplicities

Implications for searches and parameter constraints II





expected changes in CMSSM-like scenarios depend on details of the extra $U(1)$ sector, main effects:

- for large $m_{Z'}$: lighter sleptons $\Rightarrow$ additional leptons, less full hadronic events
- somewhat reduced bounds on Z' if SUSY final states are present, as cross section can be reduced by 50 %

Model II

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

- $Z_{B-L} \Leftrightarrow Z_\chi$
- upper limit on m_{h^0} increased compared to MSSM but less additional D-term, only due to $U(1)$ gauge kinetic mixing
- effect on sfermion masses less pronounced

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

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

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

  enlarges paramter space with $\tilde{\nu}$ LSP
- larger mass splitting between sleptons and sneutrinos $\Rightarrow$ harder leptons

LHC @ 14 TeV

- additional Higgs and gaugino hardly produced directly
  in cascade decays: small BRs at most O(1%) $\Rightarrow$ large Lumi
- additional higgsinos: can appear in Z' decays
- direct production of $\tilde{l}$ via Z'

LHC @ 14 TeV

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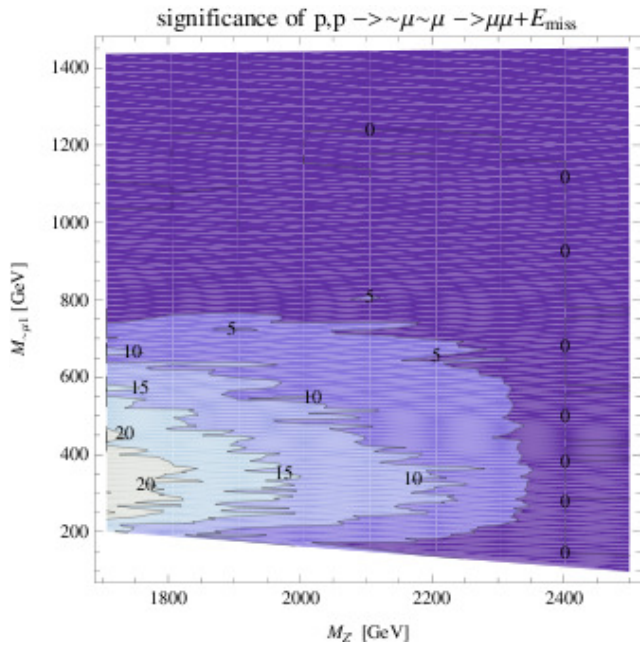
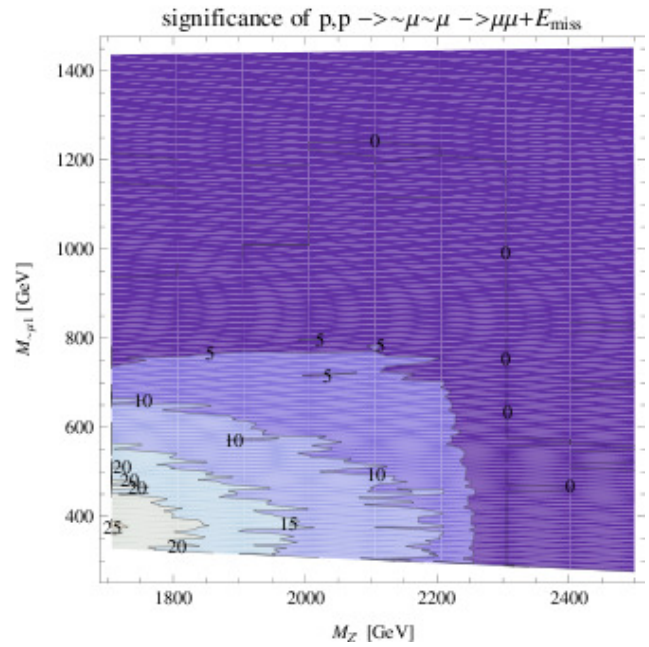
$m_{\tilde{\chi}_1^0} = 140$ GeV



$m_{\tilde{\chi}_1^0} = 230$ GeV



$\mathcal{L} = 100\, fb^{-1}$, $p_T(\mu) > 20$ GeV, $E_T(miss) > 200$ GeV, $m_{\mu^+\mu^-} > 200$ GeV, $|\eta| < 2.7$, $p_T(j) < 40$ GeV

thanks to M. Krauss, preliminary results

Conclusions

- if $m_{h^0} \simeq 125$ GeV $\Rightarrow$ hint to go beyond 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
- regions with $\tilde{\nu}$-LSP $\Rightarrow$ additional leptons in cascades
- direct $\tilde{l}$ production via Z'