Supersymmetric neutrino mass models at the LHC

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- Why extending the SM at all, why supersymmetry
- MSSM
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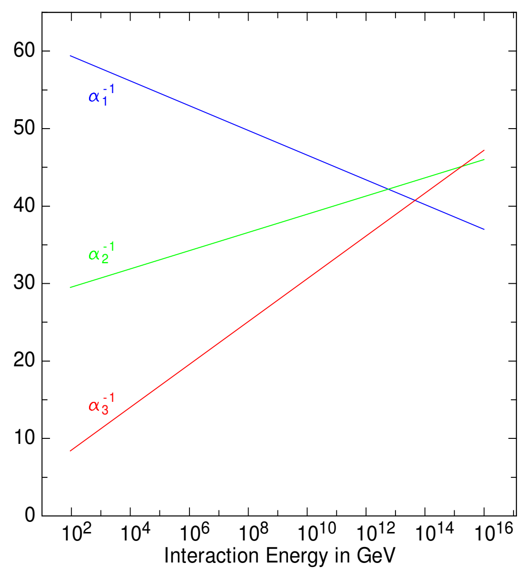
  - implications for SUSY cascade decays
  - ‘Natural SUSY’ and $\tilde{\nu}_R$-LSP
- Conclusions

Why do we want to extend the SM

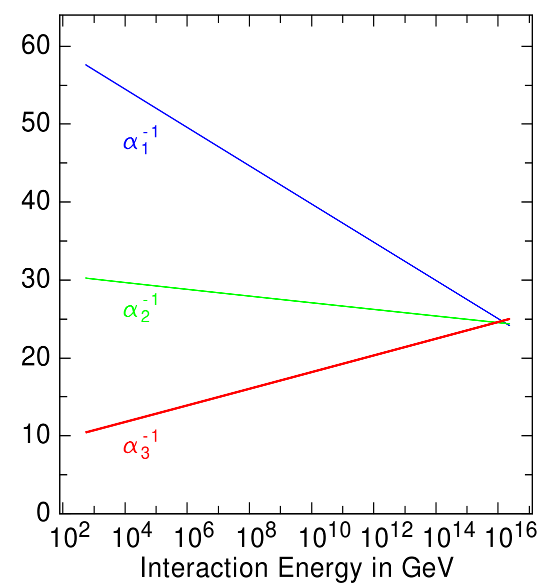
- How to combine gravity with the SM?
  $\Rightarrow$ local Supersymmetry (SUSY) implies gravity
- SM particles can be put in multiplets of larger gauge groups
  - in $SU(5)$: $1 = \nu_R^c$, $5 = (d^c_{\alpha,R}, \nu_{l,L}, l_L)$, $10 = (u_{\alpha,L}, u^c_{\alpha,R}, d_{\alpha,L}, l_R)$
  - in $SO(10)$: $16 = (u_{\alpha,L}, u^c_{\alpha,R}, d_{\alpha,L}, d^c_{\alpha,R}, l_L, l_R, \nu_{l,L}, \nu_R^c)$

  However there are two problems in the SM but not in SUSY:
  - proton decay (also in SUSY $SU(5)$ a problem)
  - gauge coupling unification

SM

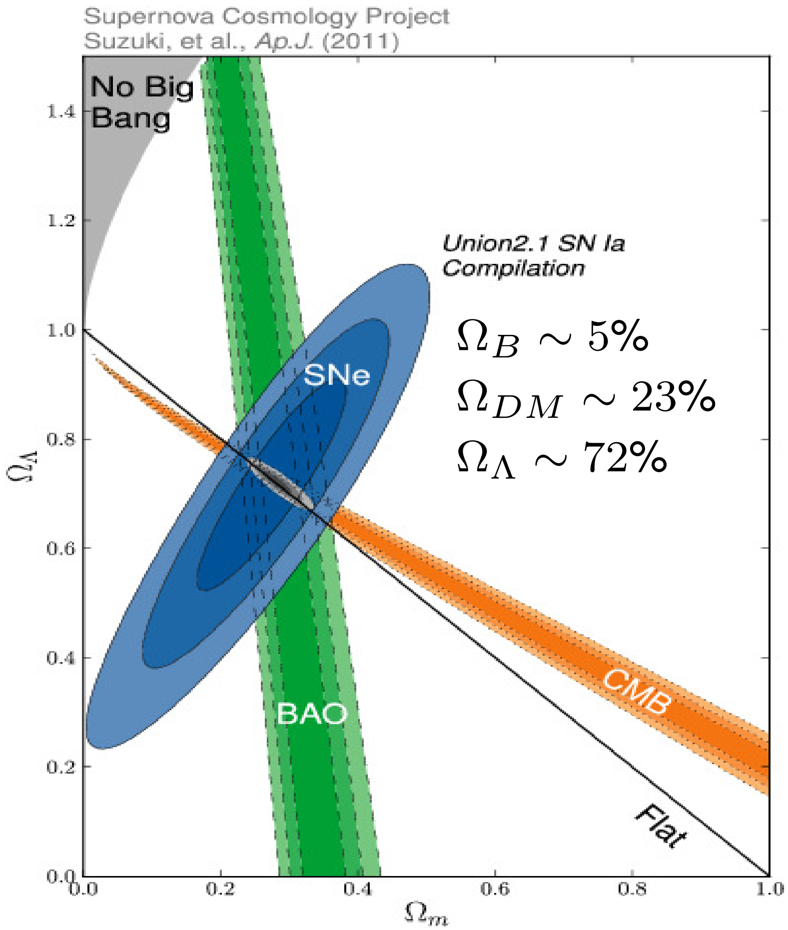


MSSM

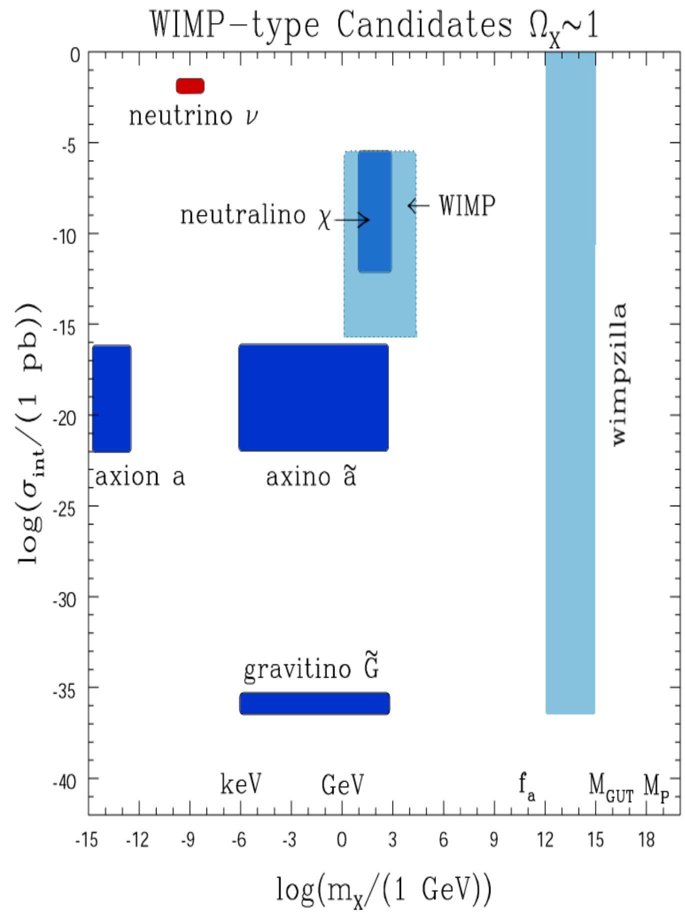


Why do we want to extend the SM

- What is the nature of dark matter ?



$$\Omega_B \sim 5\%$$
$$\Omega_{DM} \sim 23\%$$
$$\Omega_\Lambda \sim 72\%$$

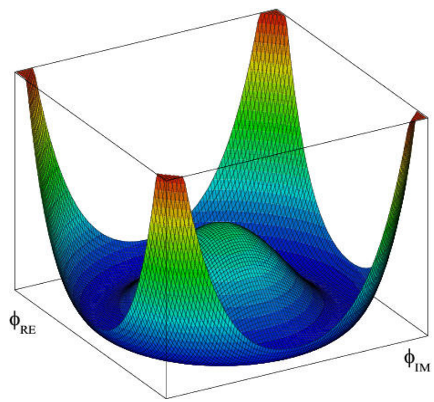


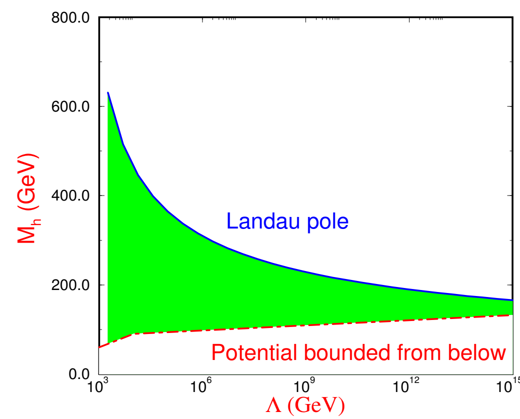
L. Roszkowski, astro-ph/0404052

- What is the origin of the observed baryon asymmetry?

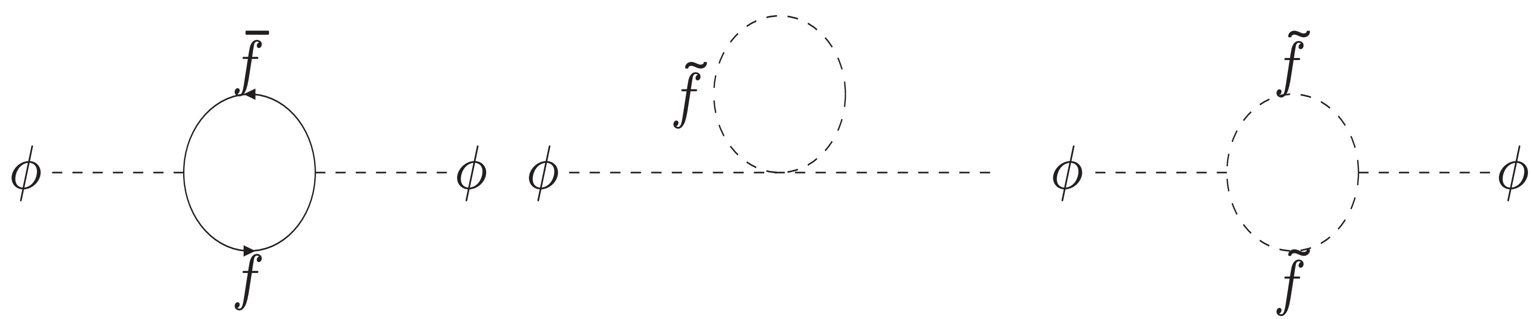
Why do we want to extend the SM

- SM & $m_h = 125.1$ GeV: potentially meta-stable (G. Degrassi *et al.*, arXiv:1205.6497)





- "Why does electroweak symmetry break?" or "Why is $\mu^2 < 0$ in the SM?"
- Hierarchy problem



$\delta m_h^2 \propto \Lambda^2$: Sensitivity to highest mass scale of unknown physics symmetry relating bosons ⇔ fermions

	Standard Model					MSSM			
matter:	e	d	d	d	⇔	$\tilde{e}$	$\tilde{d}$	$\tilde{d}$	$\tilde{d}$
	ν_e	u	u	u		$\tilde{\nu}_e$	$\tilde{u}$	$\tilde{u}$	$\tilde{u}$
gauge sector:	γ	Z^0	$W^\pm$	g	⇔	$\tilde{\gamma}$	$\tilde{z}^0$	$\tilde{w}^\pm$	$\tilde{g}$
Higgs sector:	h	H	A	$H^\pm$	⇔	$\tilde{h}^0_d$	$\tilde{h}^0_u$	$\tilde{h}^\pm$	

R-Parity: $(-1)^{(3(B-L)+2s)}$

$(\tilde{\gamma}, \tilde{z}^0, \tilde{h}^0_d, \tilde{h}^0_u) \to \tilde{\chi}^0_i$, $(\tilde{w}^\pm, \tilde{h}^\pm) \to \tilde{\chi}^\pm_j$

$$
\begin{aligned}
W_{MSSM} &= -\mu \hat{H}_d \hat{H}_u + \hat{H}_d \hat{L} Y_e \hat{E}^c + \hat{H}_d \hat{Q} Y_d \hat{D}^c - \hat{H}_u \hat{Q} Y_u \hat{U}^c \\
W_{\not{L}} &= \epsilon_i \hat{L}_i \hat{H}_u^b + \lambda_{ijk} \hat{L}_i \hat{L}_j \hat{E}_k^c + \lambda'_{ijk} \hat{L}_i \hat{Q}_j \hat{D}_k \\
W_{\not{B}} &= \lambda''_{ijk} \hat{U}_i^c \hat{D}_j^c \hat{D}_k^c
\end{aligned}
$$

$W_{\not{L}} + W_{\not{B}} \Rightarrow$ proton decay $\Rightarrow$ R-parity

$$
R \equiv (-1)^{3(B-L)+2s} \quad \text{or} \quad (-1)^{3B+L+2s}
$$

soft SUSY breaking terms

$$
\begin{aligned}
-\mathcal{L}_{soft} &= \frac{1}{2}\left(M_3 \tilde{g}\tilde{g} + M_2 \widetilde{W}\widetilde{W} + M_1 \tilde{B}\tilde{B}\right) \\
&+ m^2_{\tilde{Q}} \tilde{Q}^* \tilde{Q} + m^2_{\tilde{u}} \tilde{u}^*_R \tilde{u}_R + m^2_{\tilde{d}} \tilde{d}^*_R \tilde{d}_R \\
&+ m^2_{\tilde{L}} \tilde{L}^* \tilde{L} + m^2_{\tilde{e}} \tilde{e}^*_R \tilde{e}_R + m^2_{H_d} |H_d|^2 + m^2_{H_u} \mid H_u \mid^2 \\
&- B\mu \epsilon_{ij} (H_d^i H_u^j + \text{h.c.}) \\
&+ \epsilon_{ij} \left(H_d^i \tilde{Q}^j T_d \tilde{d}^*_R + H_u^j \tilde{Q}^i T_u \tilde{u}^*_R + H_d^i \tilde{L}^j T_e \tilde{e}^*_R + \text{h.c.} \right)
\end{aligned}
$$

MSSM, generalities

general MSSM: more than 100 parameters
reduction assuming correlations between various parameters

- mSUGRA/CMSSM: M_{GUT}

$$\begin{aligned} M_{1/2} &= M_1 = M_2 = M_3 \\ m_0^2 &= m_{H_d}^2 = m_{H_u}^2 \;,\; m_0^2 \cdot \mathbb{1}_3 = m_{\tilde{Q}}^2 = m_{\tilde{U}}^2 = m_{\tilde{D}}^2 = m_{\tilde{L}}^2 = m_{\tilde{E}}^2 \\ T_f &= A_0 Y_f \;\; (f = u, d, e) \end{aligned}$$

  NUHM1/NHUM2: $m_{H_d}^2, m_{H_u}^2 \neq m_0^2$

- GMSB, $M \gtrsim 100$ TeV

$$\begin{aligned} M_i &= g(x,n)\alpha_i\Lambda \\ m_{\tilde{F}}^2 &= f(x,n)\sum_i C_2(R)\alpha_i^2\Lambda^2 \; \mathbb{1}_3 \\ T_f &\simeq 0 \end{aligned}$$

  n # of messenger fields, $x = \Lambda/M$, $\Lambda = O(100TeV) < M$

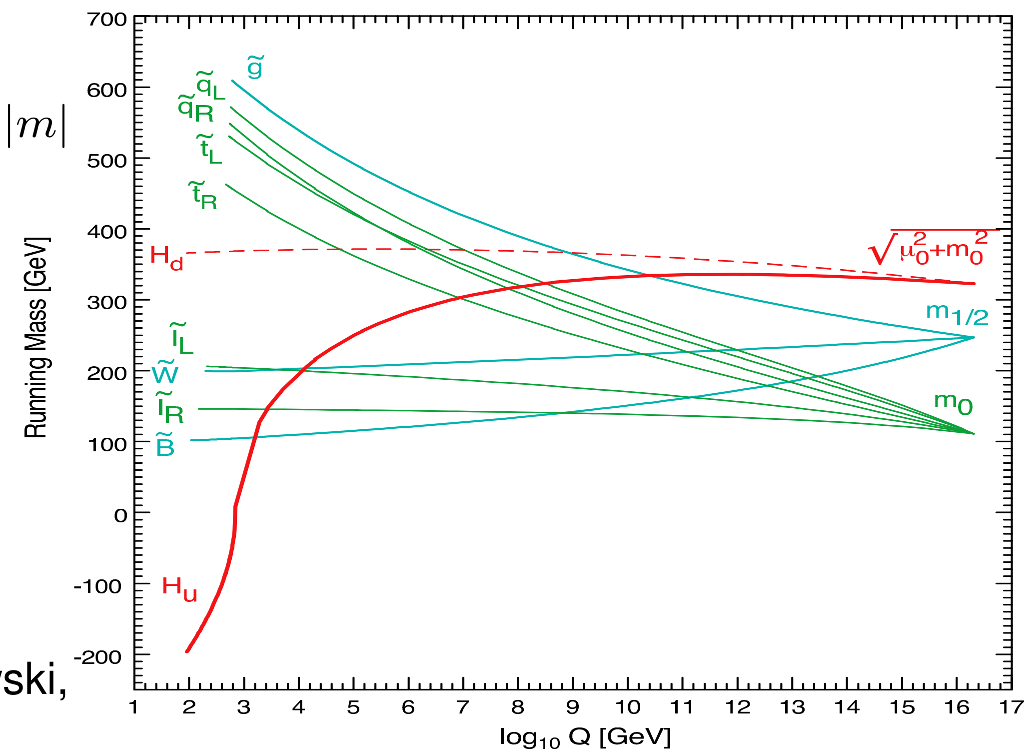
MSSM, generalities

radiative electroweak symmetry breaking

$$\frac{d}{dt}\begin{pmatrix} m^2_{H_u} \\ m^2_{\tilde{t}_R} \\ m^2_{\tilde{Q}^3_L} \end{pmatrix} = -\frac{8\alpha_s}{3\pi} M_3^2 \begin{pmatrix} 0 \\ 1 \\ 1 \end{pmatrix} + \frac{Y_t^2}{8\pi^2}\left(m^2_{\tilde{Q}^3_L} + m^2_{\tilde{t}_R} + m^2_{H_u} + A_t^2\right)\begin{pmatrix} 3 \\ 2 \\ 1 \end{pmatrix}$$

with $t = \ln Q/m_Z$

sign$(m^2)|m|$



G. Kane, C. Kolda, L. Roszkowski, J. Wells, PRD 1994

MSSM, Higgs sector

- after EWSB:
  neutral CP-even: h, H neutral CP-odd: A charged: H^+, H^-
- Higgs masses:
  at tree level
  $m_A, \tan\beta = v_u/v_d$
  $m_h \le m_Z$

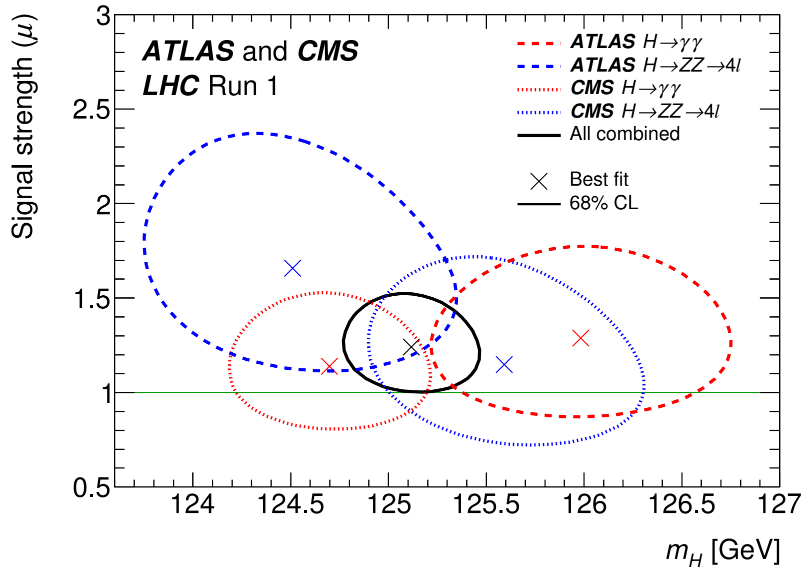
  Ellis et al; Okada et al; Haber,Hempfling; Hoang et al; Carena et al; Heinemeyer et al; Zhang et al; Brignole et al; Harlander et al; Kant,Harlander,Mihaila,Steinhauser;...

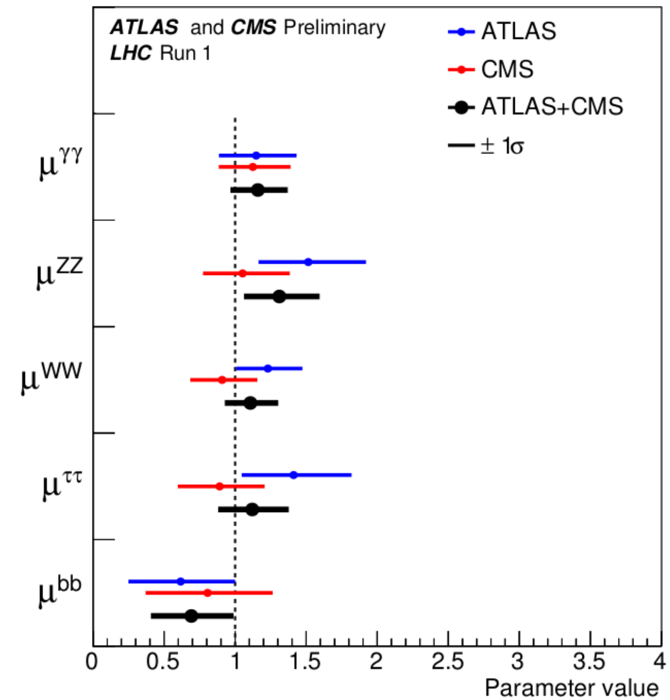
  at higher order:

$$
\begin{aligned}
m_h^2 &\simeq m_Z^2 \cos^2(2\beta) + \frac{3m_t^4}{4\pi^2 v^2}\left[\ln\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12M_S^2}\right)\right] \\
M_S^2 &= m_{\tilde{t}_1} m_{\tilde{t}_2} \quad , \quad X_t = A_t - \mu\cot\beta \\
m_H, m_A, m_{H+} &: O(v)\ldots O(TeV) \\
m_{H+}^2 &= m_A^2 + m_W^2 \\
v^2 &= v_u^2 + v_d^2 = 4m_W^2/g^2
\end{aligned}
$$

decoupling limit: $m_A \gg v$, $\tan\beta \gg 1$

Higgs results in a nut-shell





$m_H = 125.09 \pm 0.21$ (stat) ± 0.11 (sys) GeV

run 1, PRL **114** (2015) 191803

ATLAS: $m_H = 124.98 \pm 0.19$ (stat) ± 0.21 (sys) GeV

CMS: $m_H = 125.26 \pm 0.20$ (stat) ± 0.08 (sys) GeV

see talk by A.-M. Magnan, ALPS 2018

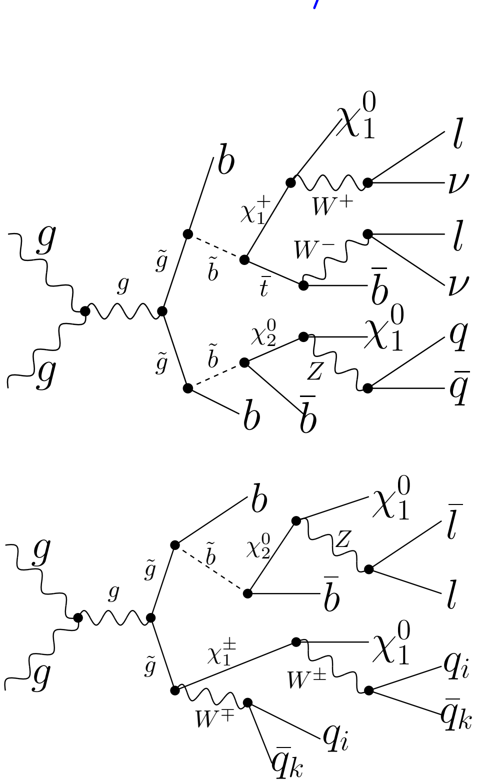
ATLAS-CONF-2015-044

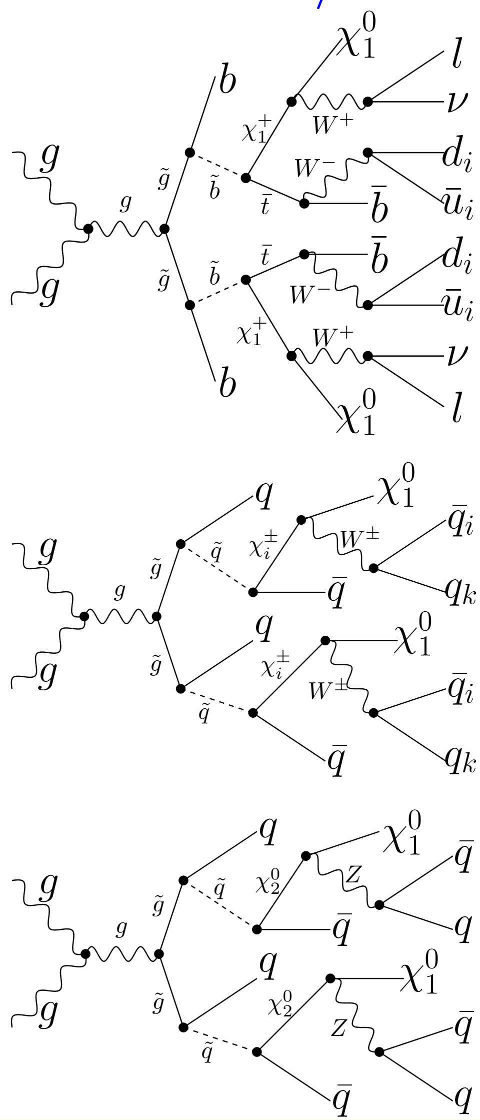
CMS-PAS-HIG-15-002

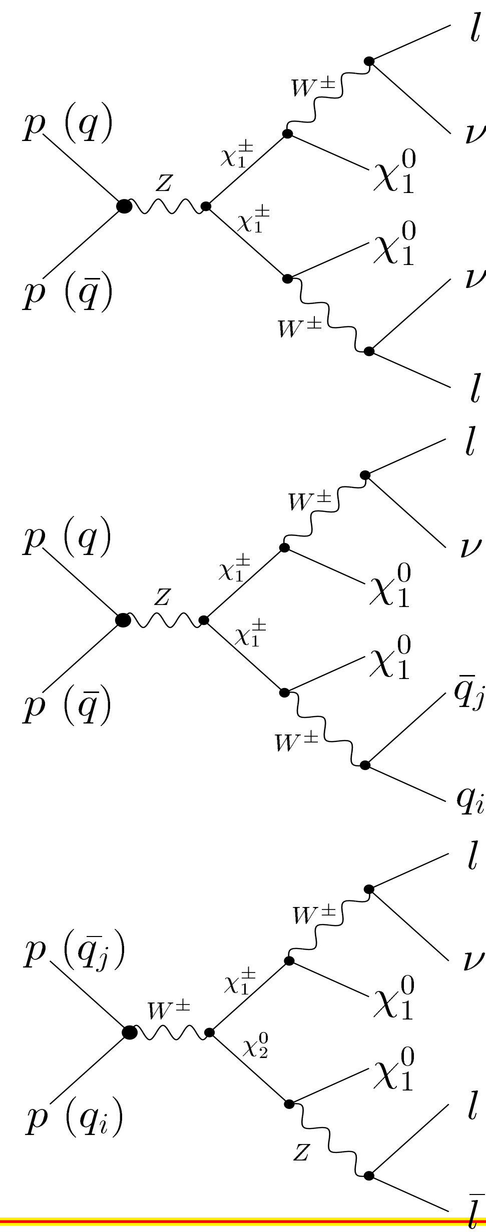
$(125\text{ GeV})^2 \simeq m_Z^2 + (86\text{ GeV})^2 \Rightarrow$ large corrections within MSSM

$6j + 2\ell + \not{E}_T$

$8j + 2\ell + \not{E}_T$





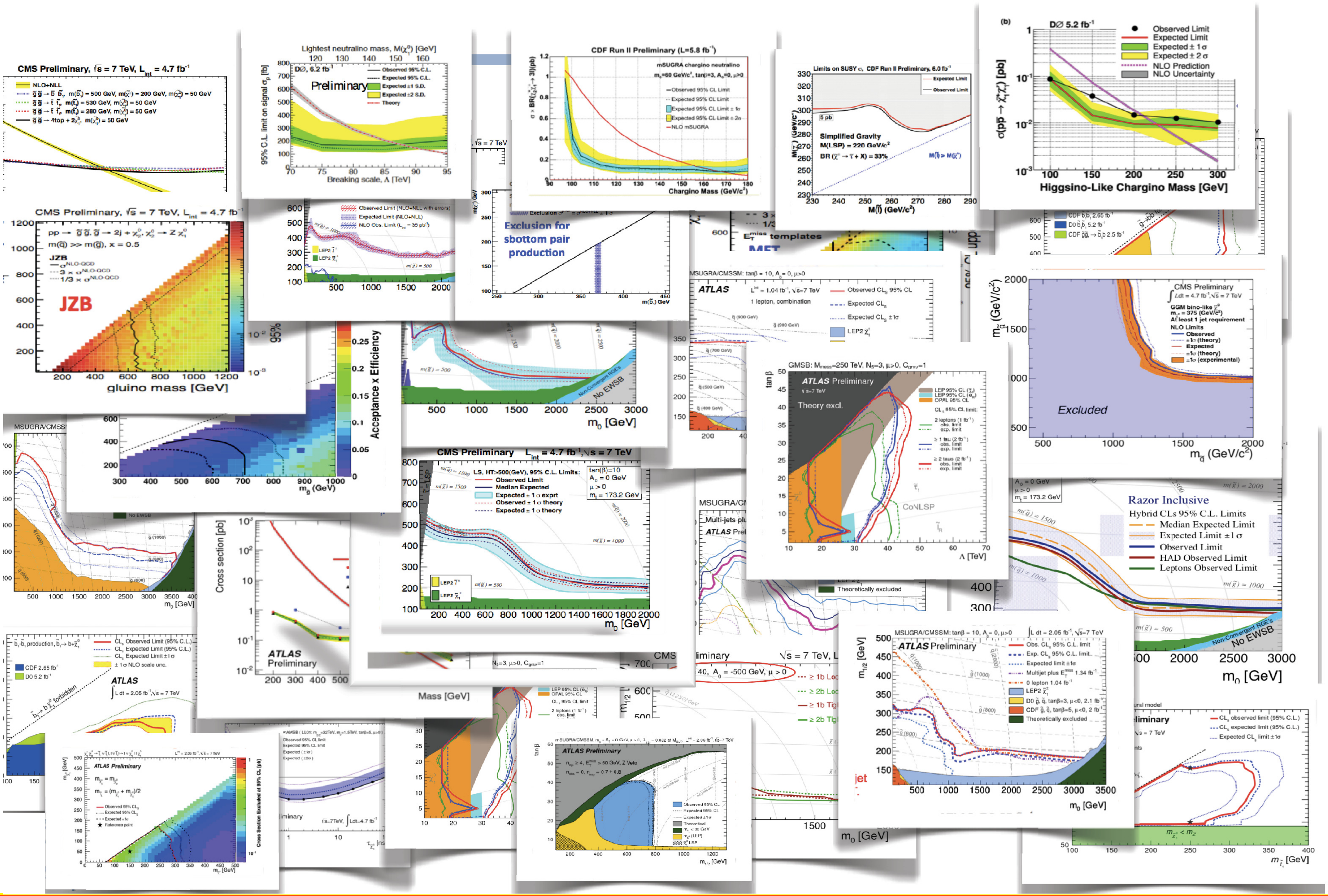


2ℓ $\not{E}_T$

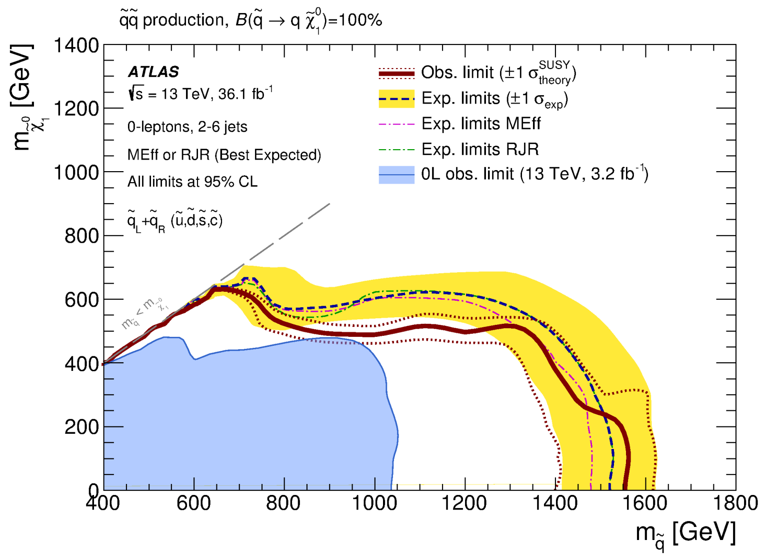
ℓ $2j$ $\not{E}_T$

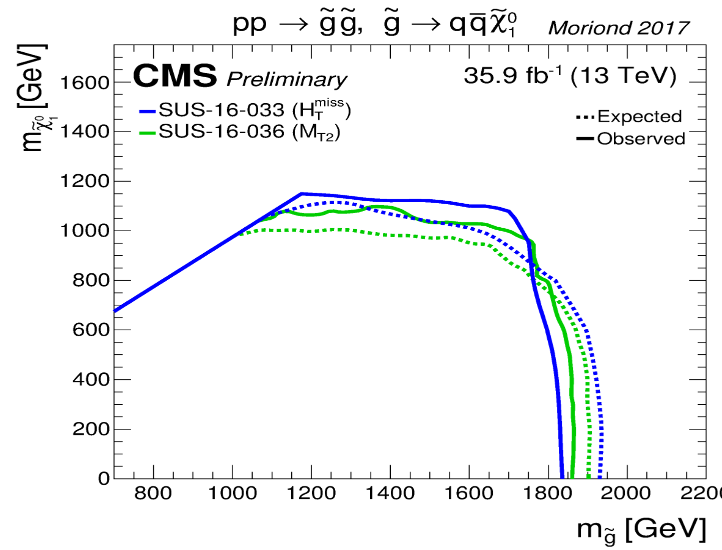
3ℓ $\not{E}_T$

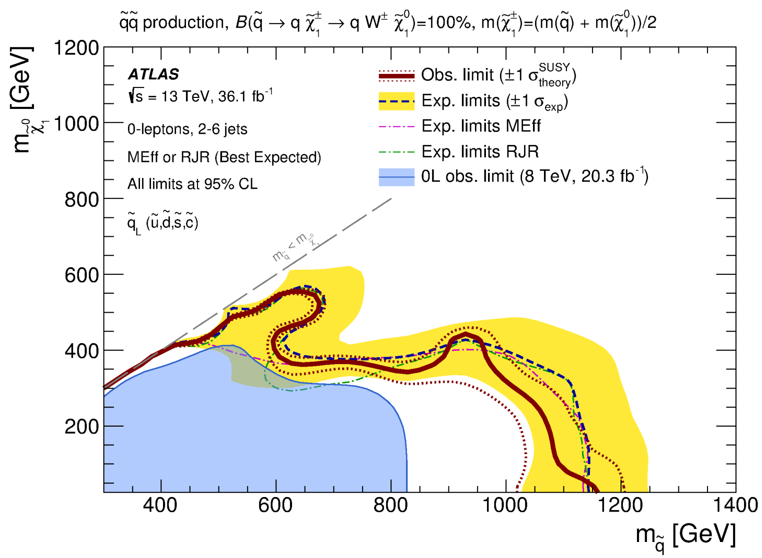
BSM searches, so far hardly anything …

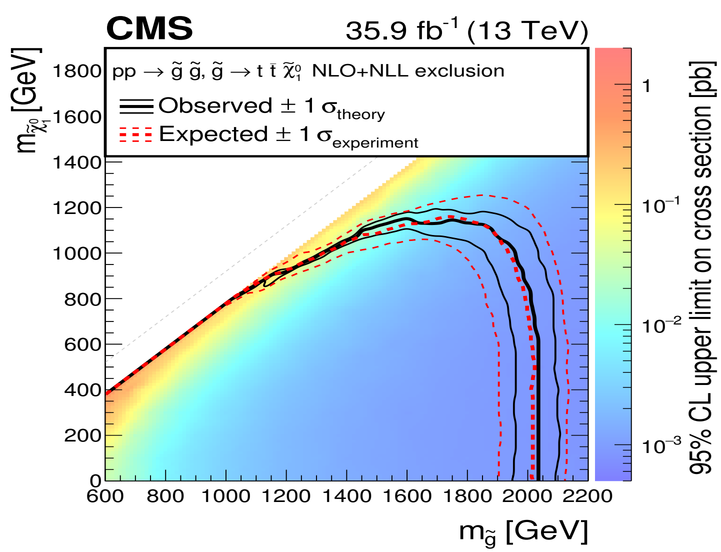


Examples for SUSY searches 13 TeV data









arXiv:1712.02332

arXiv:1710.11188

LHC data, in particular m_h, high scale models

$m_h = 125.2$ GeV ⇒ large loop contributions

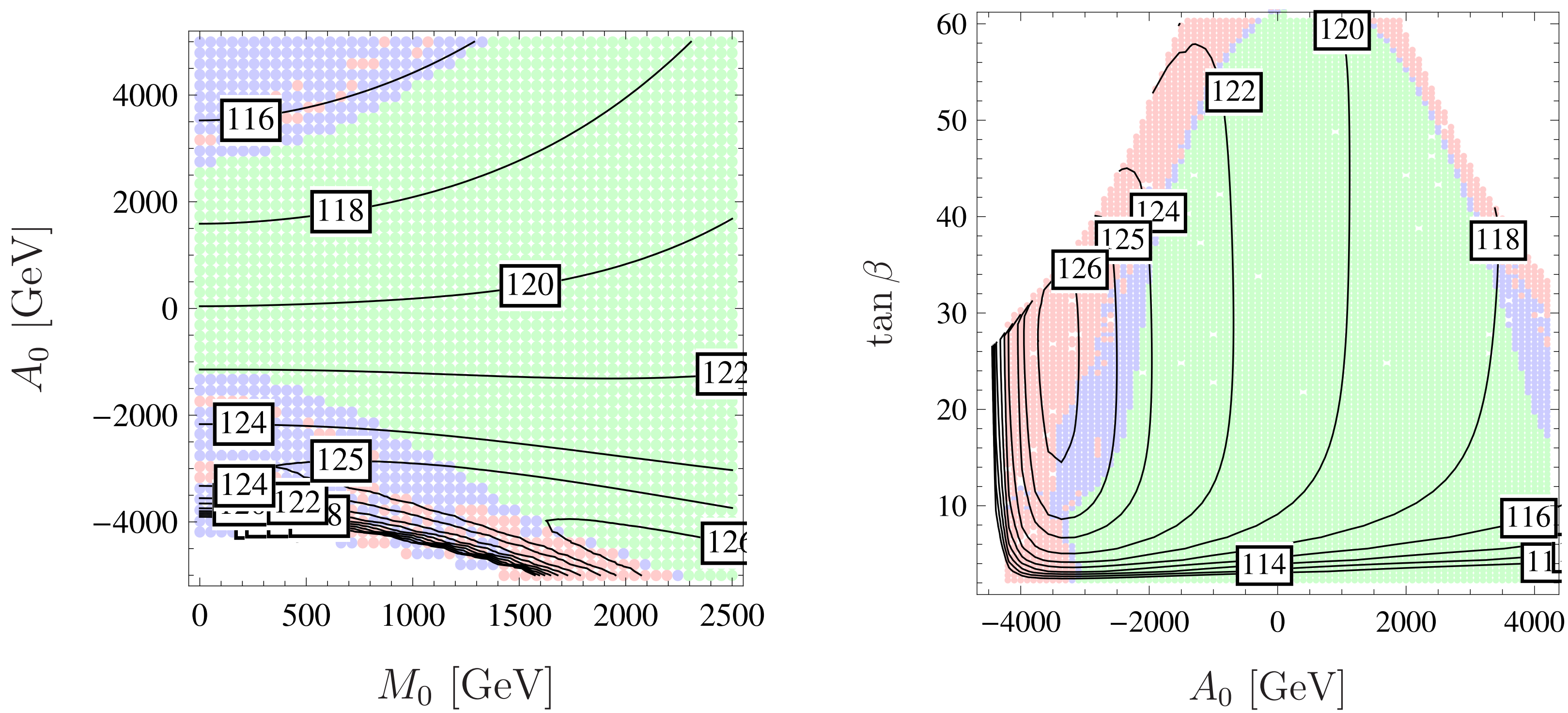
⇒ heavy stops and/or large left-right mixing for stops

- GMSB: $m_{\tilde{t}_1} \gtrsim 6$ TeV,
  M. A. Ajaib, I. Gogoladze, F. Nasir, Q. Shafi, arXiv:1204.2856

  more complicated models based on P. Meade, N. Seiberg and D. Shih, arXiv:0801.3278 ⇒ allow additional terms
  e.g. S. Knappen, D. Redigolo, arXive:1606.07501 $m_{\tilde{t}_1} \simeq m_{\tilde{b}_1} \gtrsim 1$ TeV if $M_{\text{mess}} \gtrsim 10^{15}$ GeV
- 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; . . .
  CMSSM fit to data P. Bechtle et al., arXiv:1508.05951: best fit point with $m_{\tilde{g}}, m_{\tilde{q}} \gtrsim 2$ TeV, $m_{\tilde{l}_R} \simeq 600$ GeV, $m_{\tilde{\chi}_1^0} \simeq 450$ GeV
- general high scale models: $A_0 \simeq -(1-3)\max(M_{1/2}, m_{Q_3}, m_{U_3})$ @ M_{GUT}
  among other cases, details in F. Brümmer, S. Kraml and S. Kulkarni, arXiv:1204.5977

mSUGRA/CMSSM, charge/color breaking minima

- SUSY models contain many scalars ⇒ complicated potential
- usually some parameters (μ, B) are choosen to obtain correct EWSB
- does not exclude the existence of other minima breaking charge and/or color!



$M_{1/2} = 1$ TeV, $\tan\beta = 10$, $\mu > 0$ $\qquad$ $M_{1/2} = M_0 = 1$ TeV

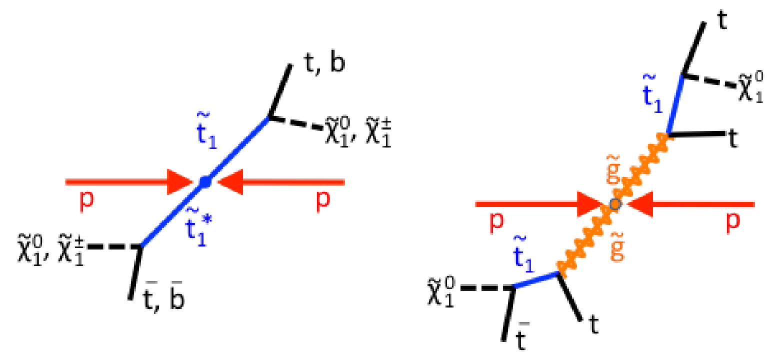
J.E. Camargo-Molina, B. O'Leary, W.P., F. Staub, arXiv:1309.7212

General MSSM

several studies: S. Sekmen et al., arXiv:1109.5119; A. Arbey, M. Battaglia, A. Djouadi, F. Mahmoudi, arXiv:1211.4004; M. Cahill-Rowley, J. Hewett, A. Ismail, T. Rizzo, arXiv:1308.0297 . . .

- generic signatures are well known: multi-lepton, multi-jets + missing E_T
- sub-class of general MSSM: ‘natural SUSY’
  see e.g. M. Papucci, J. T. Ruderman and A. Weiler, arXiv:1110.6926;
  H. Baer, V. Barger, P. Huang, A. Mustafayev, X. Tata, arXiv:1207.3343
  keep only SUSY particles light needed for ’natural Higgs’:
  $$\tilde{t}_1, \tilde{b}_1, \tilde{g}, \tilde{\chi}^0_{1,2} \simeq \tilde{h}^0_{1,2}, \tilde{\chi}^+_1 \simeq \tilde{h}^+$$
  $\Rightarrow$ 100 MeV $\lesssim m_{\tilde{\chi}^+_1} - m_{\tilde{\chi}^0_1} \simeq m_{\tilde{\chi}^0_2} - m_{\tilde{\chi}^0_1} \lesssim 5 - 10$ GeV

$$\begin{aligned} \tilde{g} &\to \tilde{t}_1 t, \tilde{b}_1 b \\ \tilde{t}_1 &\to t\tilde{\chi}^0_{1,2}, b\tilde{\chi}^+_1, W^+\tilde{b}_1 \\ \tilde{b}_1 &\to b\tilde{\chi}^0_{1,2}, t\tilde{\chi}^-_1, W^-\tilde{t}_1 \end{aligned}$$



BRs depend on the nature of $\tilde{t}_1$ and $\tilde{b}_1$
Higgsino mass: $\mu + \mu'$ with soft SUSY breaking parameter: $\mathcal{L} = -\mu' \tilde{H}_d \tilde{H}_u$
(G. G. Ross, K. Schmidt-Hoberg and F. Staub, arXiv:1701.03480)

Extended gauge groups, motivation

- additional D-term contributions to m_h at tree-level
- 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 $E(8) \times E(8) \to SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$

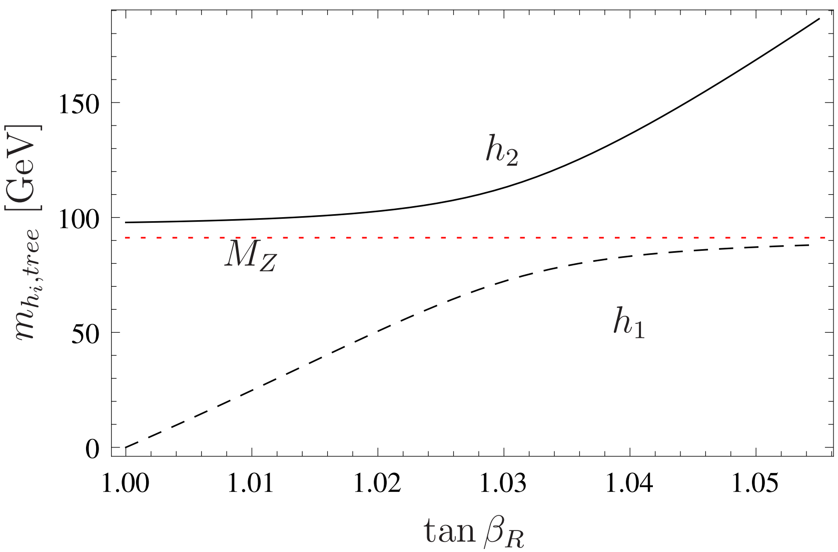
- Neutrino masses

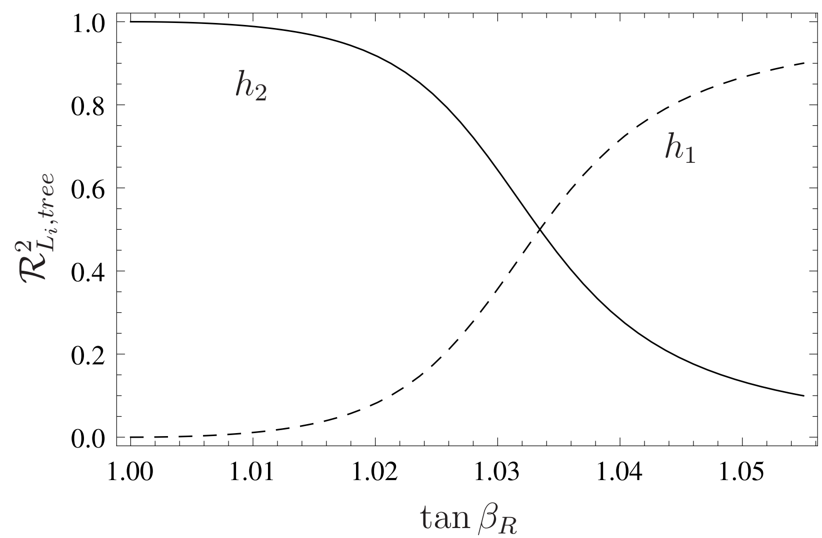
  $B - L$ anomaly free $\Rightarrow \nu_R$
  usual seesaw, inverse seesaw

- $\tilde{\nu}^*_R$ or other exotic neutral scalar as DM candidate
  $\Rightarrow$ interesting for (modified) Natural SUSY

extra $U(1)_\chi$ with new D-term contributions at tree-level: $m^2_{h,tree} \leq m^2_Z + \frac{1}{4} g^2_\chi v^2$

H.E. Haber, M. Sher, PRD 35 (1987) 2206; M. Drees, PRD 35 (1987) 2910; M. Cvetic et al., hep-ph/9703317; E. Ma, arXiv:1108.4029; M. Hirsch et al., arXiv:1110.3037



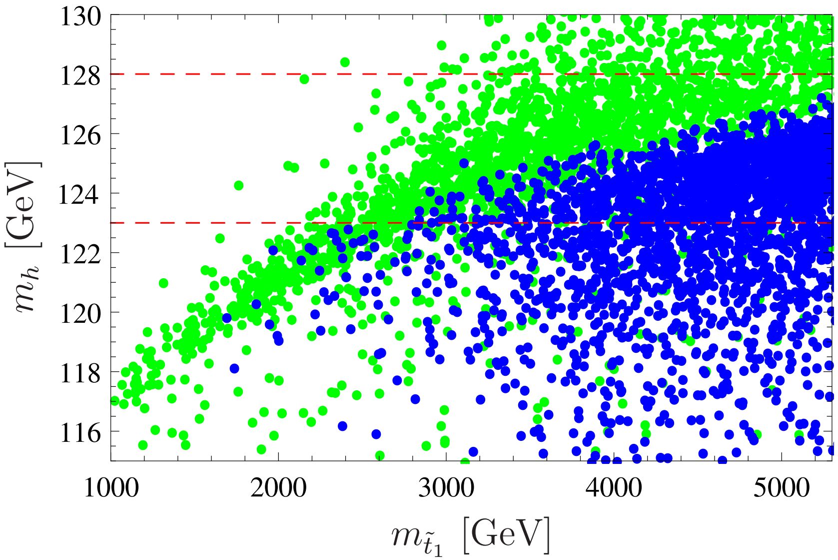


$n = 1,\ \Lambda = 5 \cdot 10^5$ GeV, $M = 10^{11}$ GeV, $\tan\beta = 30$, sign$(\mu_R) = -$, $diag(Y_S) = (0.7, 0.6, 0.6)$, $Y^{ii}_\nu = 0.01$, $v_R = 7$ TeV

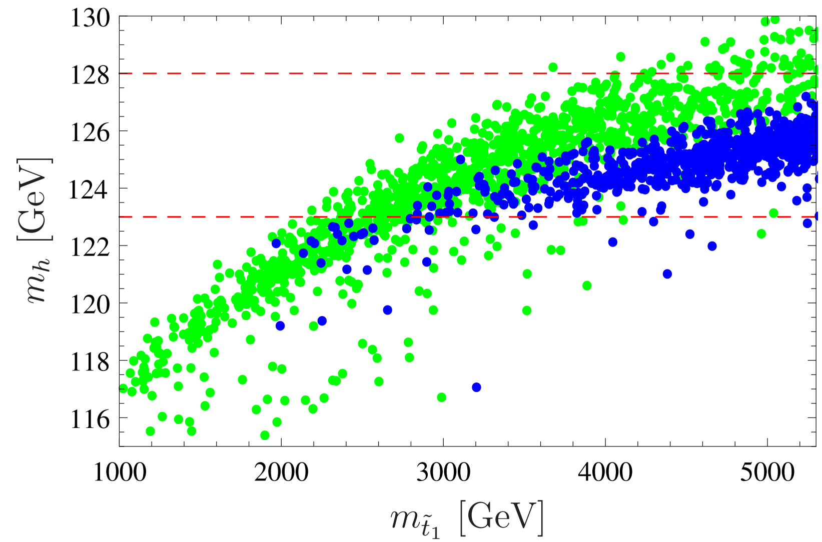
M.E. Krauss, W.P., F. Staub, arXiv:1304.0769

Higgs sector II

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



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



scan over GMSB parameters: $1 \leq n \leq 4$, $10^5 \leq M \leq 10^{12}$ 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: $h_1 \simeq h$, green points: $h_2 \simeq h$

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

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

Neutrinos and sneutrinos

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

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

$$M_{\tilde\nu}^2 =$$

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

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

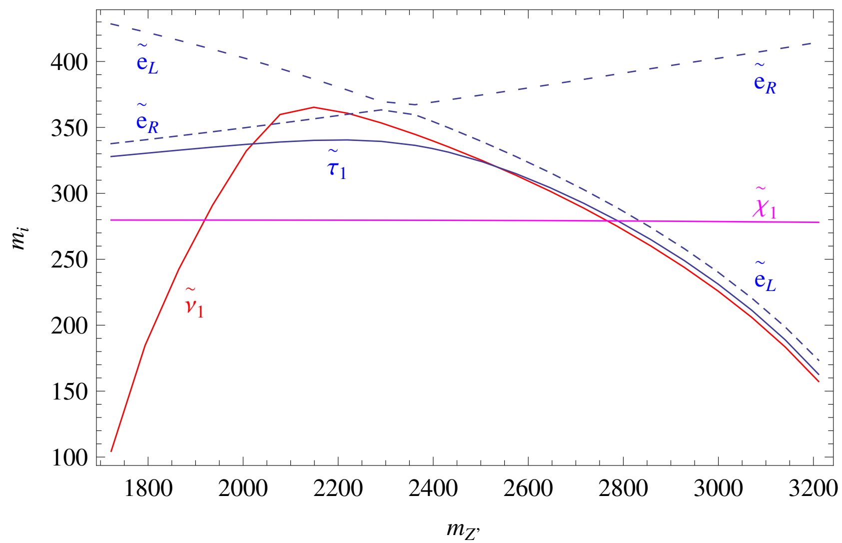
$$D_R = \frac{5 g_\chi}{32}\Big(2 (g_\chi - g_{Y\chi}) v^2 c_{2\beta} + 5 g_\chi v_R^2 c_{2\beta_R}\Big) \mathbf{1}$$

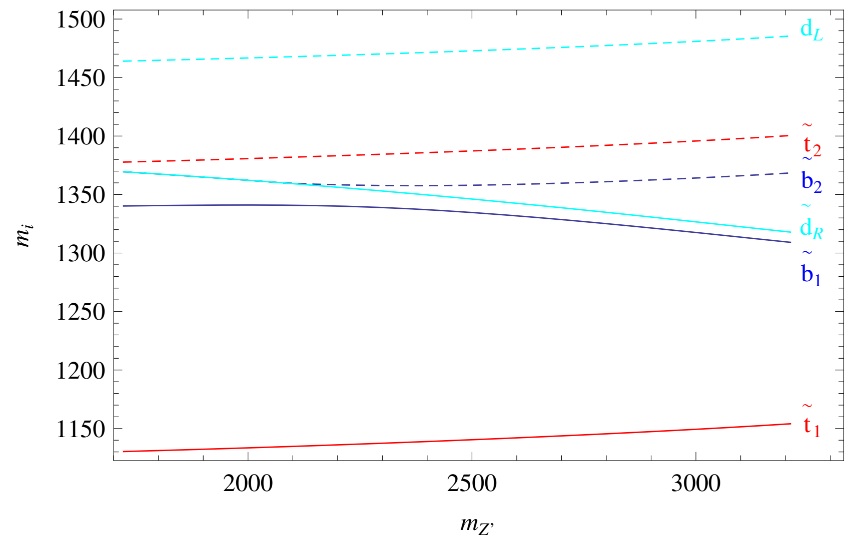
Sfermions

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

$D_L \simeq (-\frac{1}{2} + \sin^2_{\theta_W}) m^2_Z c_{2\beta} - \frac{5}{4} m^2_{Z'} c_{2\beta_R}$ and $D_R \simeq -\sin^2_{\theta_W}\, m^2_Z c_{2\beta} + \frac{5}{4} m^2_{Z'} c_{2\beta_R}$

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

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

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

Changes in SUSY cascades

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

BLRSP1: $\tilde{\nu}$ LSP, $m_{\nu_h} \simeq 100$ GeV (from B. O'Leary, W.P., F. Staub, arXiv:1112.4600)

$$\begin{aligned}
\tilde{q}_R &\to q\tilde{\chi}^0_1 \to q\nu_k\tilde{\nu}_1 \to q\nu_j Z\tilde{\nu}_1 \qquad (k = 4,\dots,9\,,\ j = 1,2,3)\\
\tilde{q}_R &\to q\tilde{\chi}^0_1 \to q\nu_k\tilde{\nu}_1 \to q l^\pm W^\mp\tilde{\nu}_1\\
\tilde{q}_R &\to q\tilde{\chi}^0_1 \to q\nu_k\tilde{\nu}_3 \to q l^\pm W^\mp l'^+ l'^- \tilde{\nu}_1\\
\tilde{d}_R &\to d\tilde{\chi}^0_5 \to d l^\pm \tilde{l}^\mp_i \to d l^\pm l^\mp \tilde{\chi}^0_1 \to d l^\pm l^\mp \nu_k \tilde{\nu}_1 \to d l^\pm l^\mp l'^\pm W^\mp \tilde{\nu}_1
\end{aligned}$$

BLRSP3: usual cascades similar to CMSSM, but

$$\begin{aligned}
\tilde{\chi}^0_1 &\to l^\pm \tilde{l}^\mp \to l^\pm W^\mp \tilde{\nu}_1\\
\tilde{\chi}^0_1 &\to l^\pm \tilde{l}^\mp \to l^\pm W^\mp \tilde{\nu}_{2,3} \to l^\pm W^\mp f\bar{f}\tilde{\nu}_1\\
\tilde{\chi}^0_1 &\to \nu_j \tilde{\nu}_{2,3} \to \nu_{1,2,3} f\bar{f}\tilde{\nu}_1\\
\tilde{\chi}^0_1 &\to \nu_j \tilde{\nu}_k \to \nu_j h_{1,2}\tilde{\nu}_1 \qquad (j,k = 1,2,3)\\
\tilde{\chi}^0_1 &\to \nu_j \tilde{\nu}_k \to \nu_j h_{1,2} f\bar{f}\tilde{\nu}_1
\end{aligned}$$

$\Rightarrow$ enhanced jet and lepton multiplicities, study of ν_R

Natural SUSY + $\tilde{\nu}_R$: minimal inverse seesaw model

$$\mathcal{W}_{eff} = \mathcal{W}_{\text{MSSM}} + \frac{1}{2}(M_R)_{ij}\, \hat{\nu}_{R,i}\, \hat{\nu}_{R,j} + (Y_\nu)_{ij}\, \widehat{L}_i \cdot \widehat{H}_u\, \hat{\nu}_{R,j}$$

$$(Y_\nu)_{\ell 5} = \pm (Z_\ell^{\text{NH}})^* \sqrt{\frac{2 m_3 M_5}{v_u}} \cosh\gamma_{56}\, e^{\mp i\theta_{56}}$$

$$(Y_\nu)_{\ell 6} = -i (Z_\ell^{\text{NH}})^* \sqrt{\frac{2 m_3 M_6}{v_u}} \cosh\gamma_{56}\, e^{\mp i\theta_{56}}$$

$$R = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\phi_{56} & \sin\phi_{56} \\ 0 & -\sin\phi_{56} & \cos\phi_{56} \end{pmatrix}$$

$\phi_{56} \in \mathbb{C}$

$m_{\nu_h,i} \simeq M_{i-3}$, $M_4 = O$(keV),
$M_5 \simeq M_6 = O$(few - 100 GeV)

Natural SUSY + $\tilde{\nu}_R$: minimal inverse seesaw model

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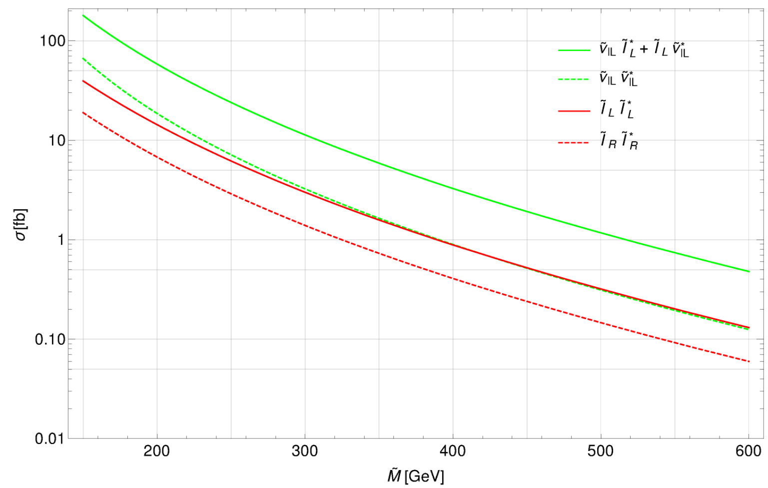
$\phi_{56} \in \mathbb{C}$

$m_{\nu_h,i} \simeq M_{i-3}$, $M_4 = O$(keV),
$M_5 \simeq M_6 = O$(few - 100 GeV)

search for sleptons

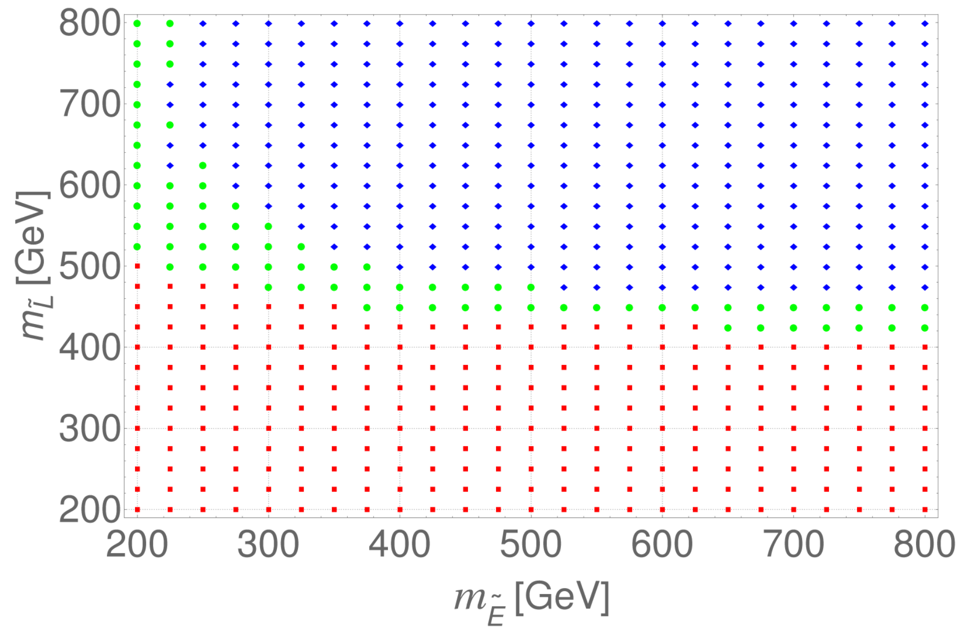


LHC, 13 TeV, tree-level
for searches: × K-factor 1.17
(B. Fuks et al., arXiv:1304.0790)

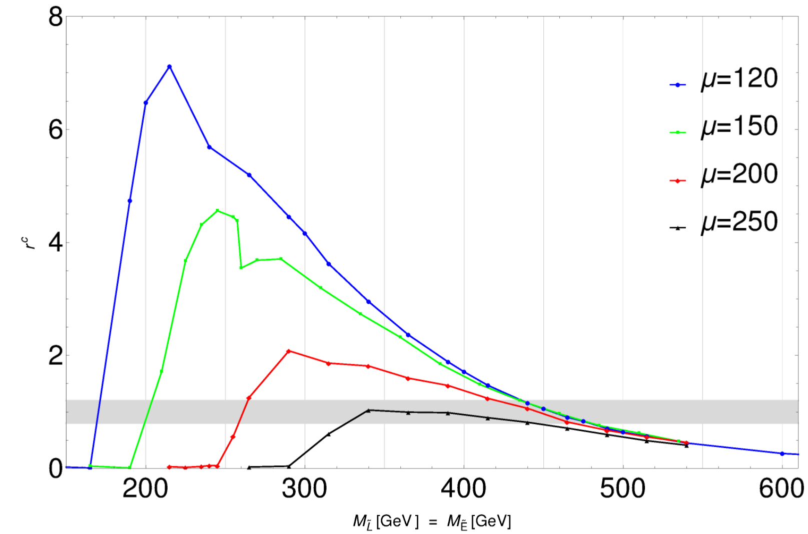
dominant decays:

$$\tilde{l}_L \to l\tilde{\chi}^0_1\ ,\ \nu\tilde{\chi}^-_1$$
$$\tilde{\nu}_L \to l^-\tilde{\chi}^+_1\ ,\ \nu\tilde{\chi}^0_1$$

Natural SUSY + $\tilde{\nu}_R$: Higgsino LSP



$\mu = 120$ GeV, $\tan\beta = 10$



$m_{\tilde{L}} = m_{\tilde{E}}$, $\tan\beta = 10$

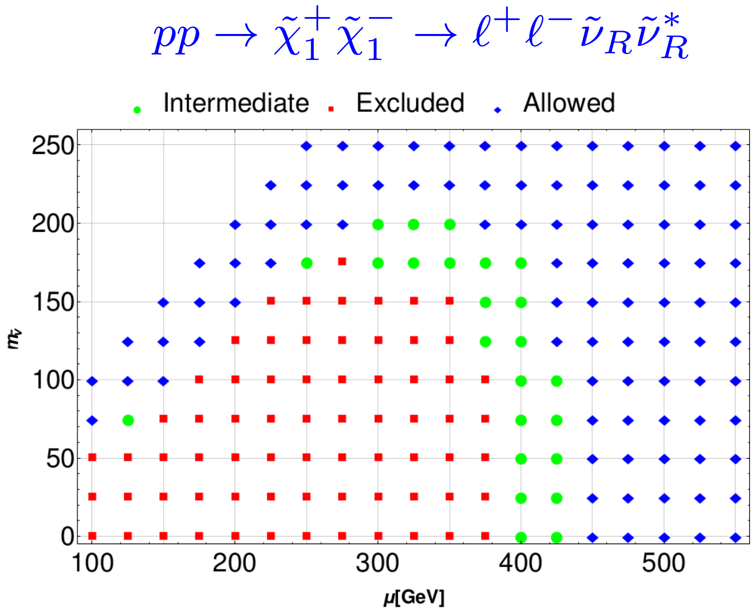
■ excluded, ● ambigous, ◇ allowed

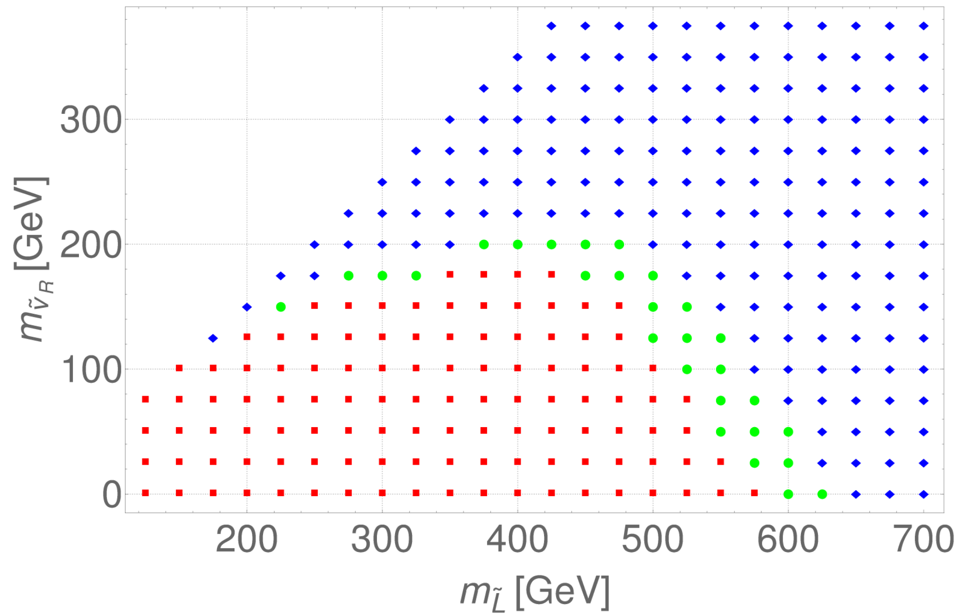
8+13 TeV data (13.9 fb^{-1})

using `CheckMATE 2.0` Nh. Cerna-Velazco, Th. Faber, J. Jones, WP arXiv:1705.06583

Natural SUSY + $\tilde{\nu}_R$: $\tilde{\nu}_R$-LSP

additional constraint





8+13 TeV data (13.9 fb^{-1})
using `CheckMATE 2.0`
$m_{\nu_R} = 20$ GeV

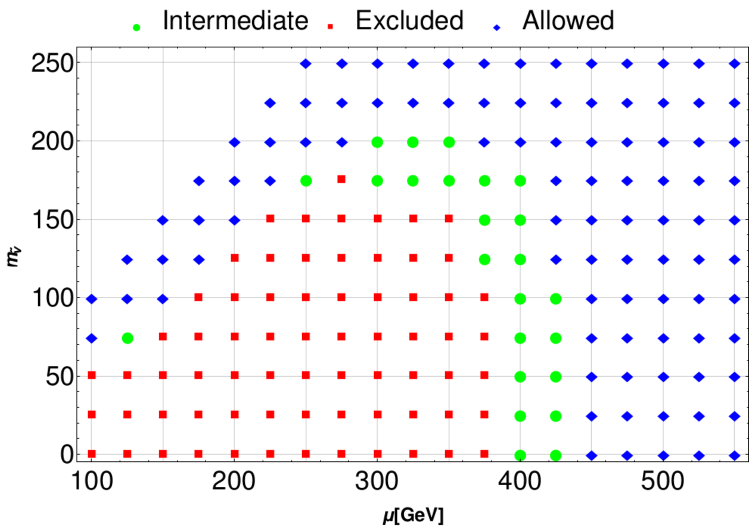
$\mu = 25 + m_{\tilde{\nu}} < m_{\tilde{l}} \simeq m_{\tilde{L}} = m_{\tilde{E}}$
$M_1 = M_2 = 2$ TeV, $\tan\beta = 6$

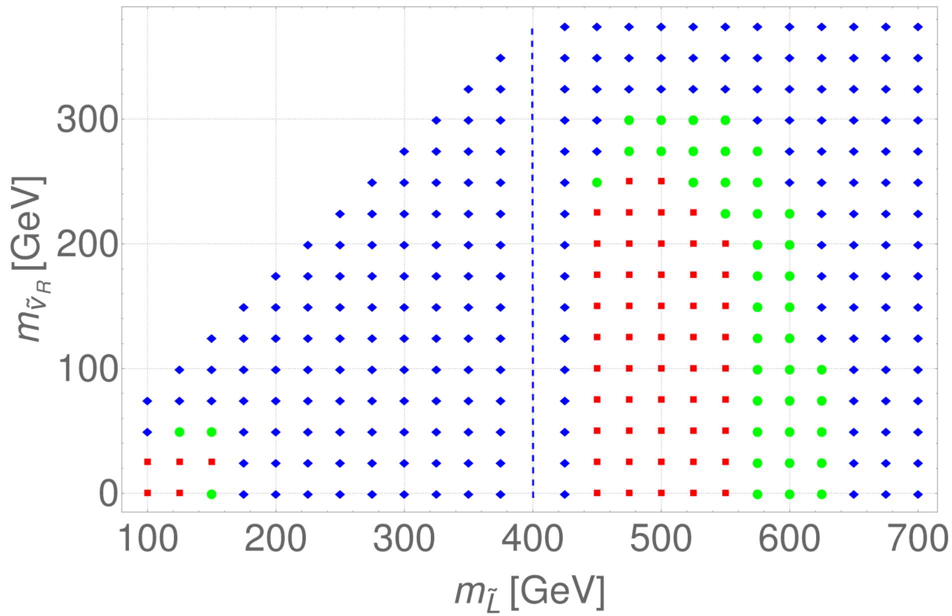
Nh. Cerna-Velazco, Th. Faber, J. Jones, WP arXiv:1705.06583

Natural SUSY + $\tilde{\nu}_R$: $\tilde{\nu}_R$-LSP

additional constraint

$pp \to \tilde{\chi}_1^+ \tilde{\chi}_1^- \to \ell^+ \ell^- \tilde{\nu}_R \tilde{\nu}_R^*$





8+13 TeV data (13.9 fb^{-1})
using `CheckMATE 2.0`
$m_{\nu_R} = 20$ GeV

$\mu = 400$ GeV, $m_{\tilde{l}} \simeq m_{\tilde{L}} = m_{\tilde{E}}$
$M_1 = M_2 = 2$ TeV, $\tan\beta = 6$

Nh. Cerna-Velazco, Th. Faber, J. Jones, WP arXiv:1705.06583

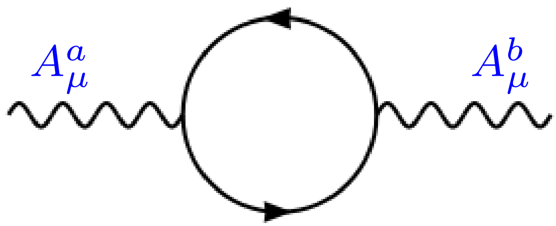
Conclusions

- LHC: $m_h \simeq 125$ GeV, no conclusive BSM physics found $\Rightarrow$
  - GMSB, CMSSM, NUHM: $m_{\tilde{g}}, m_{\tilde{q}} \gtrsim 2$ TeV
  - CMSSM, NUHM: large A_0, danger of color and charge breaking minima
- general MSSM: SUSY particles with masses of few 100 GeV still allowed if spectra compressed, in particular light $\tilde{t}_1$ still allowed
- 'Natural SUSY': take only those states light which contribute to EWSB: $\tilde{h}^{0,\pm}, \tilde{t}_1, \tilde{g}, \tilde{b}_i$
  disadvantage: cannot explain dark matter relic density
- extended gauge groups
  - motived by ν-physics $\Rightarrow$ extended (s)neutrino sector
  - can easier accommodate $m_h \simeq 125$ GeV
  - CMSSM-like realisation: different spectrum compared to CMSSM
    $\Rightarrow$ substantial changes of cascade decays
  - $\tilde{\nu}_R$ LSP: compatible with DM, no direct DM constraint apply
  - 'Natural SUSY' + $\tilde{\nu}_R$
    - $m_{\tilde{h}^+} \lesssim 400$ GeV excluded if $m_{\tilde{h}^+} - m_{\tilde{\nu}_R} \gtrsim 150$ GeV
    - slepton masses up to 600 GeV excluded

Gauge kinetic mixing

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

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



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

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

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

$$M^2_{hh} = \begin{pmatrix} m^2_{LL} & m^2_{LR} \\ m^{2,T}_{LR} & m^2_{RR} \end{pmatrix}$$

$$m^2_{LL} = \begin{pmatrix} g^2_\Sigma v^2 c^2_\beta + m^2_A s^2_\beta & -\frac{1}{2}\left(m^2_A + g^2_\Sigma v^2\right) s_{2\beta} \\ -\frac{1}{2}\left(m^2_A + g^2_\Sigma v^2\right) s_{2\beta} & g^2_\Sigma v^2 s^2_\beta + m^2_A c^2_\beta \end{pmatrix},$$

$$m^2_{LR} = \frac{5}{8} g_\chi \tilde{g}_\chi v v_R \begin{pmatrix} c_\beta c_{\beta_R} & -c_\beta s_{\beta_R} \\ -s_\beta c_{\beta_R} & s_\beta s_{\beta_R} \end{pmatrix},$$

$$m^2_{RR} = \begin{pmatrix} g^2_{Z_R} v^2_R c^2_{\beta_R} + m^2_{A_R} s^2_{\beta_R} & -\frac{1}{2}\left(m^2_{A_R} + g^2_{\Sigma_R} v^2_R\right) s_{2\beta_R} \\ -\frac{1}{2}\left(m^2_{A_R} + g^2_{\Sigma_R} v^2_R\right) s_{2\beta_R} & g^2_{\Sigma_R} v^2_R s^2_{\beta_R} + m^2_{A_R} c^2_{\beta_R} \end{pmatrix}$$

$$v^2_R = v^2_{\chi_R} + v^2_{\bar{\chi}_R}\ ,\ v^2 = v^2_d + v^2_u\ ,\ s_x = \sin(x)\ ,\ c_x = \cos(x)$$

$$g^2_\Sigma = \frac{1}{4}(g^2_2 + g'^2 + \tilde{g}^2_\chi)\ ,\ g^2_{\Sigma_R} = \frac{25}{16} g^2_\chi\ ,\ \tilde{g}_\chi = g_\chi - g_{Y\chi}$$

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

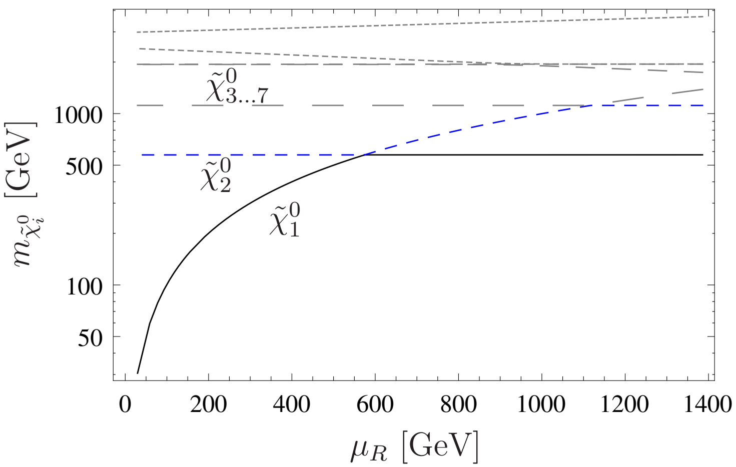
$$M_{\tilde{\chi}^0} =$$

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

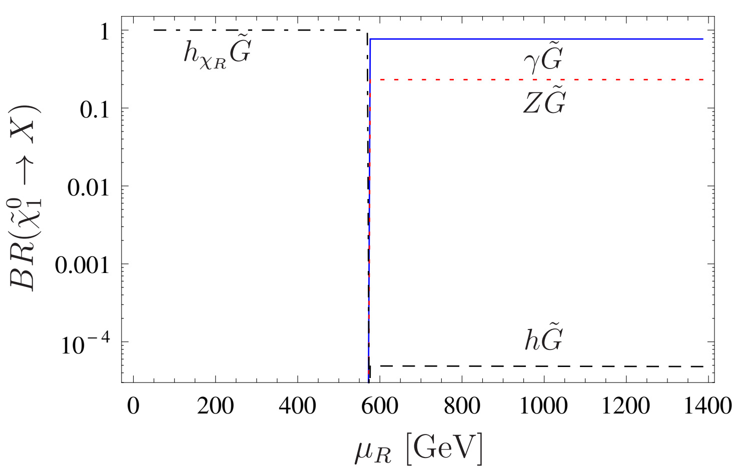
neglecting the mixing between the two sectors and setting $\tan\beta_R = 1$

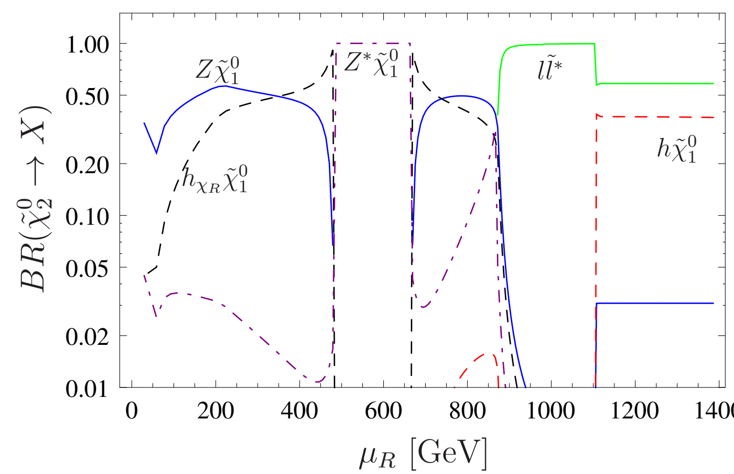
$$m_i : \ \mu_R\,, \quad \frac{1}{2}\left(M_\chi + \mu_R \pm \sqrt{\frac{1}{4} m_{Z'}^2 + (M_\chi - \mu_R)^2} \right)$$

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

Example spectra from high scale models

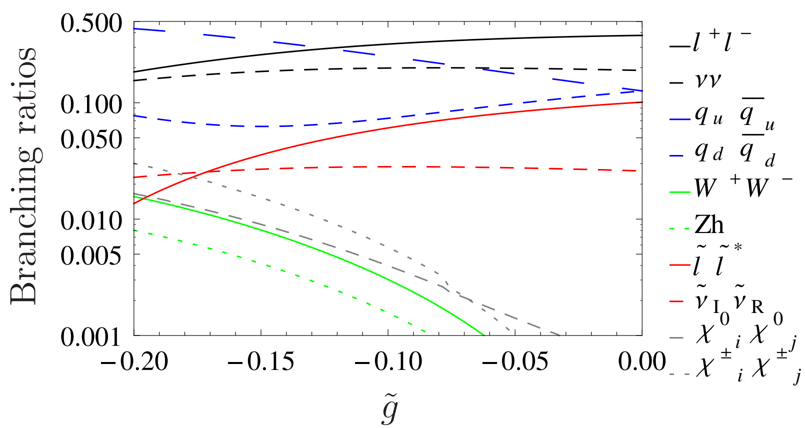
	BLRSP1	BLRSP2	BLRSP3	BLRSP4	BLRSP5
$m_{\tilde{\nu}_1}$	105.0	797.	91.6	542.	921.
$m_{\tilde{\nu}_{2/3}}$	215.0	797.	92.6	542.	924.
$m_{\tilde{\nu}_4}$	604.	1120.	253.	585.	940.
$m_{\tilde{e}_1}$	524.	1014.	255.	263.	693.
$m_{\tilde{e}_{2,3}}$	557.	1055.	266.	271.	706.
$m_{\tilde{u}_1}$	1436.	1185.	1247.	1111.	1545.
$m_{\tilde{u}_2}$	1721.	1852.	1527.	1361.	1905.
$m_{\tilde{u}_{3,4}}$	1799.	2155.	1566.	1392.	2008.
$m_{\chi_1^0}$	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.
$m_{\chi_5^0}$	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. $(\tilde{B}_\perp)$

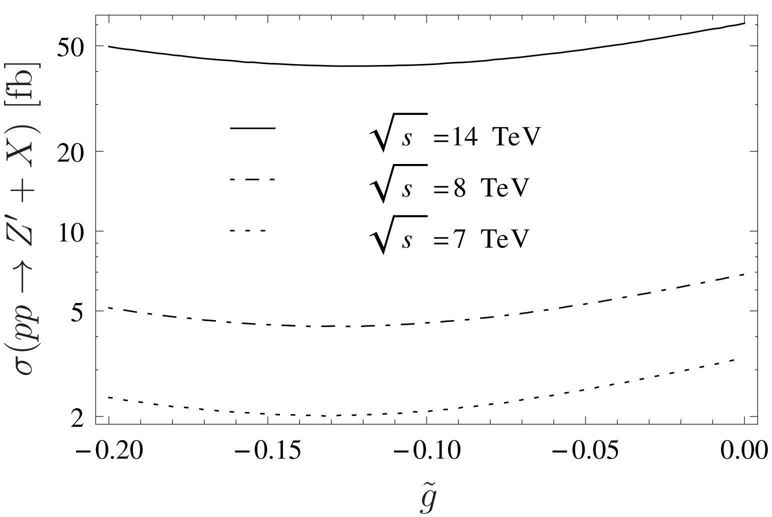
B. O'Leary, W.P., F. Staub, arXiv:1112.4600

Z' physics, effect of gauge kinetic mixing I

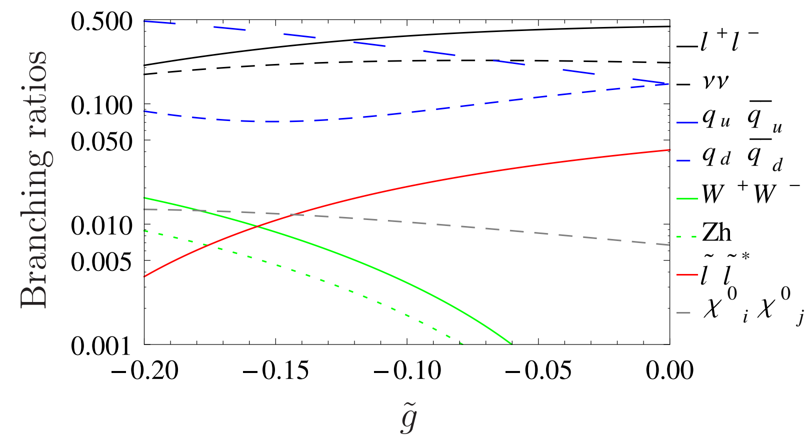
Z' couplings: $Q_{B-L} \cdot g_{B-L} \rightarrow Q_{B-L} \cdot g_{B-L} + Q_Y \cdot \tilde{g}$

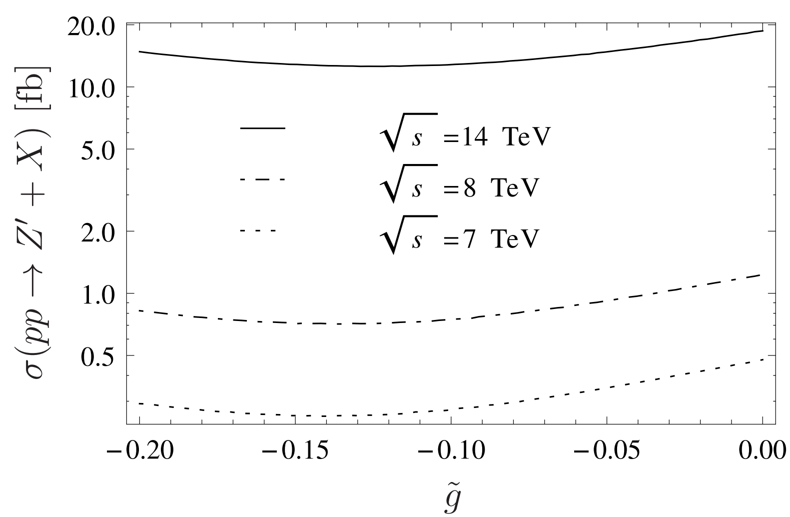
BL1



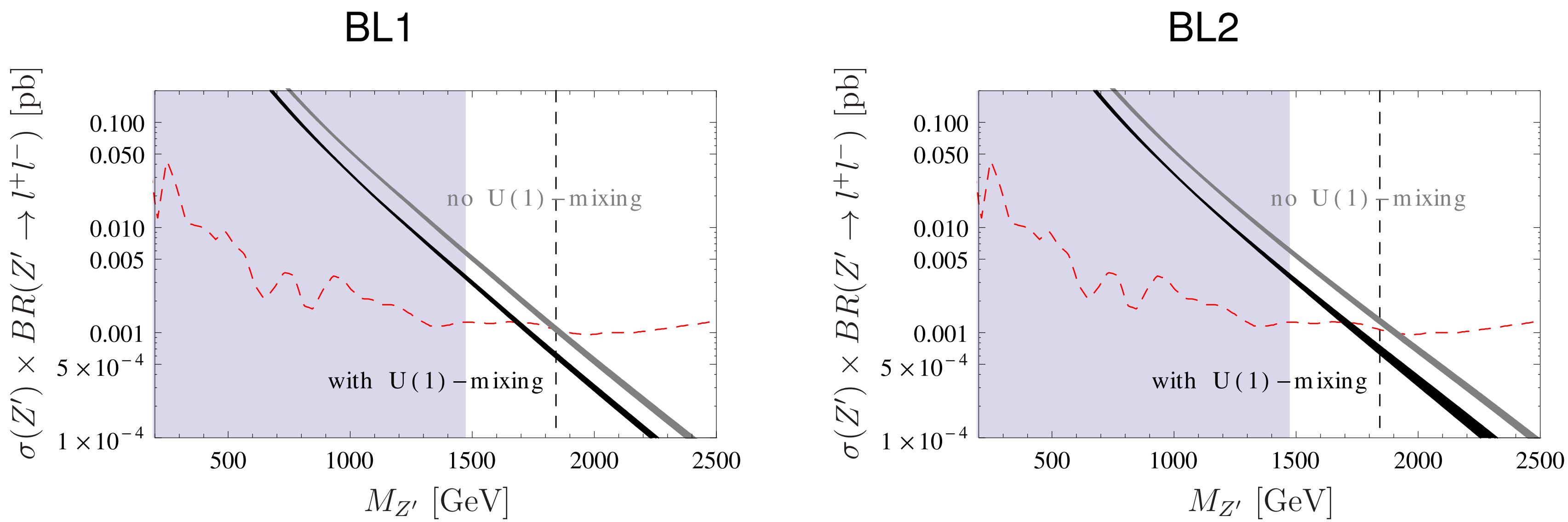


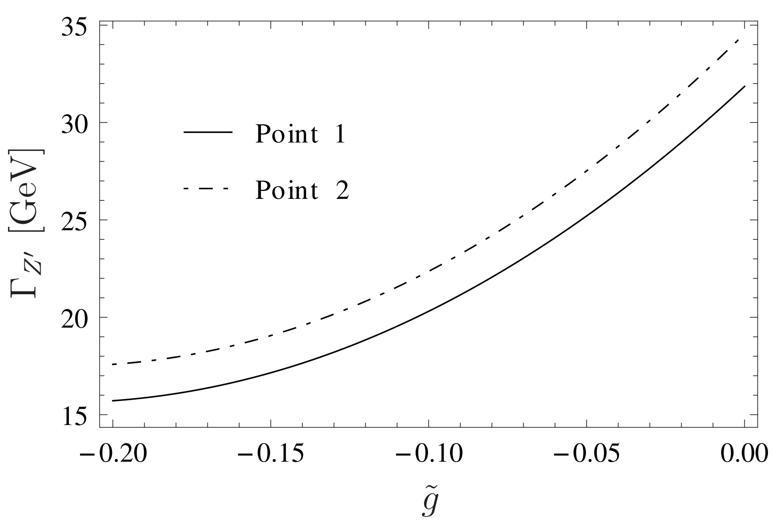
BL2





Z' physics, effect of gauge kinetic mixing II



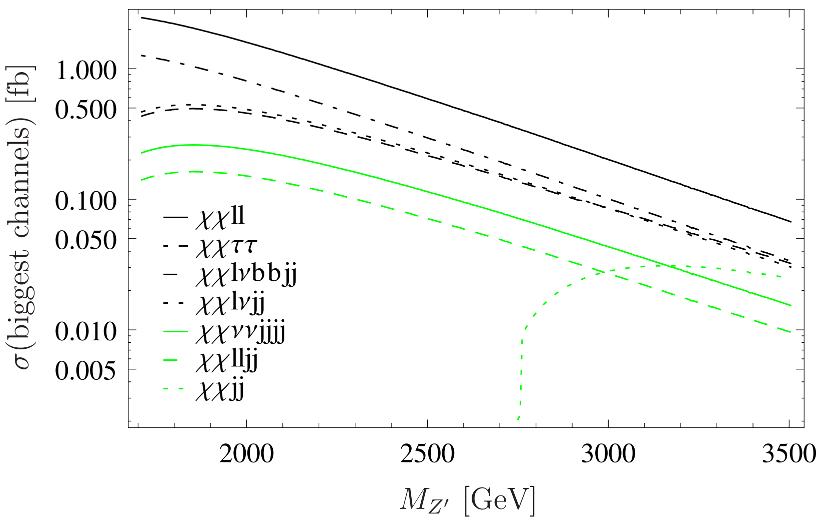


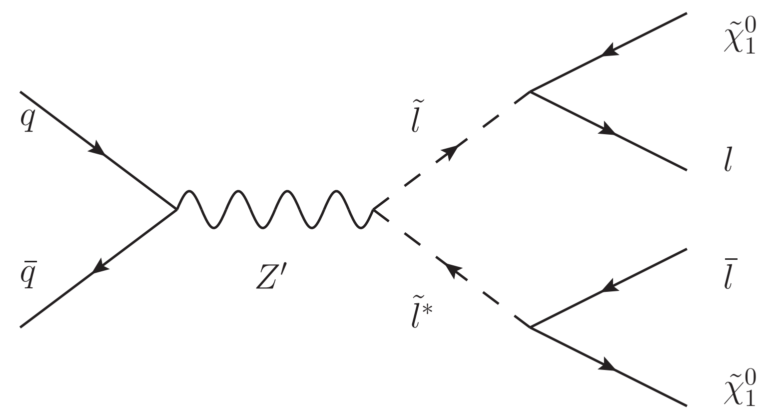
Z' couplings:

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

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

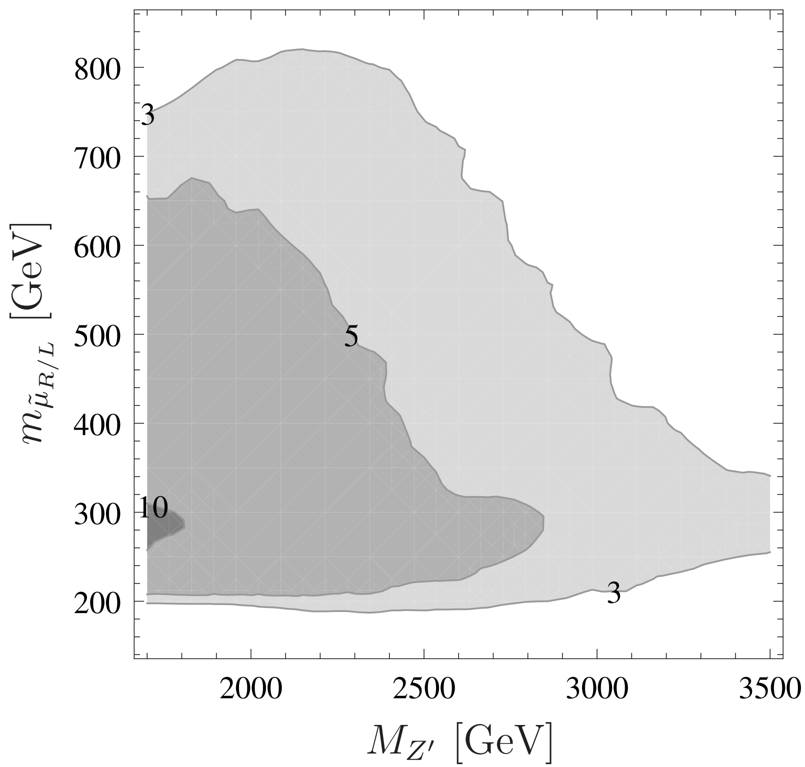
see also: J. Kang and P. Langacker, PRD **71** (2005) 035014; M. Baumgart, T. Hartman, C. Kilic, and L.-T. Wang, JHEP **0711** (2007) 084; C.-F. Chang, K. Cheung, and T.-C. Yuan, JHEP **1109** (2011) 058; G. Corcella and S. Gentile, arXiv:1205.5780

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

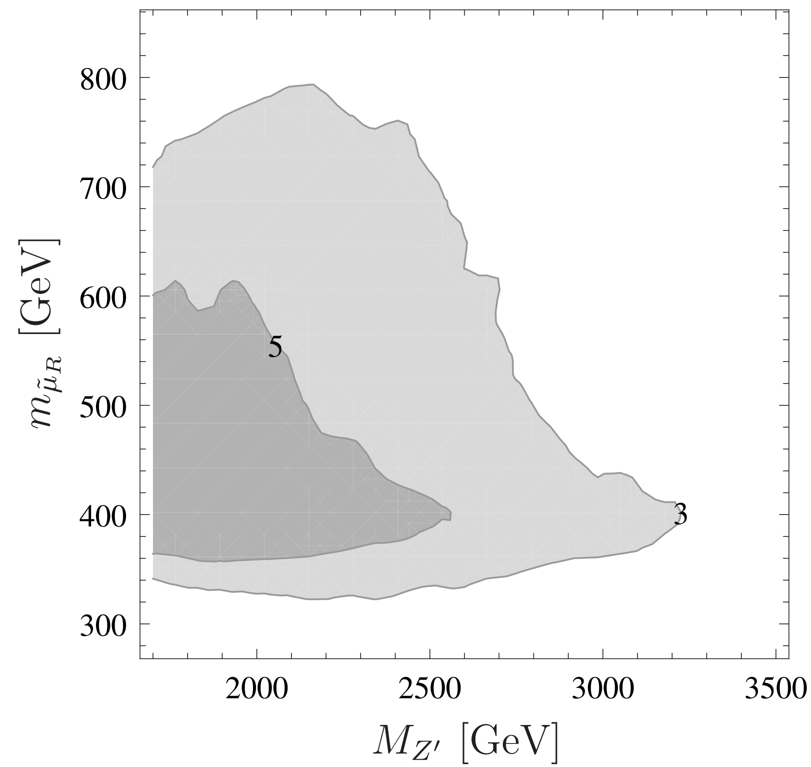
main dependence on masses $\Rightarrow$ vary $m_{\tilde{l}}$ and $m_{Z'}$, $M_L = 1.2 M_E$

100 fb^{-1}, $\sqrt{s} = 14$ TeV

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



$m_{\tilde{\chi}_1^0} = 280$ GeV



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

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

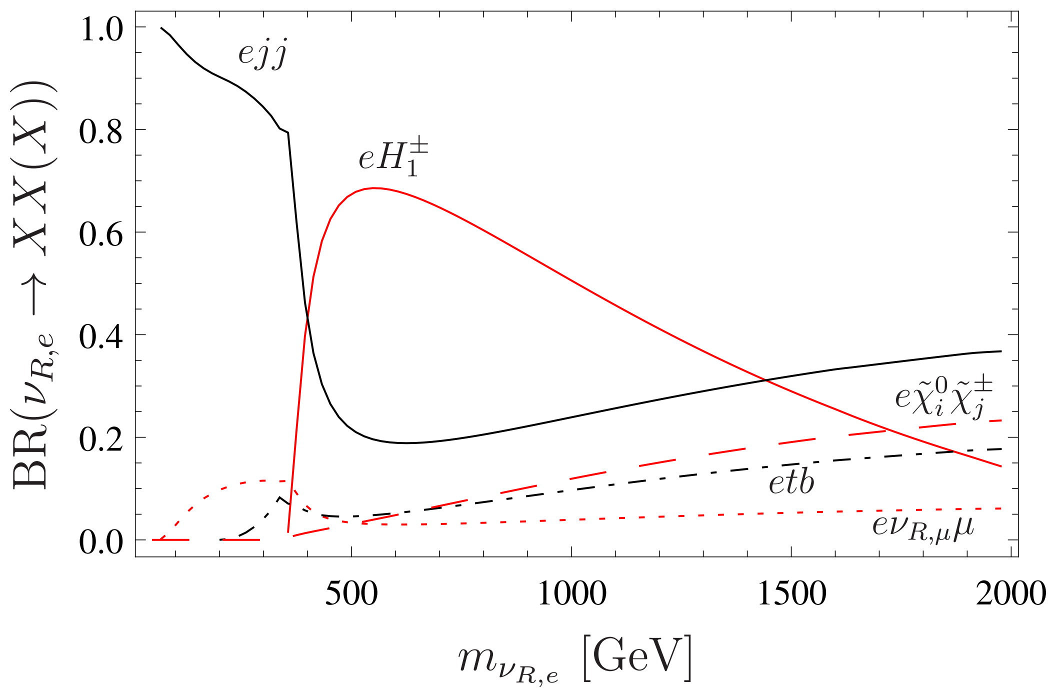
- invariant mass of the muon pair: $M_{\mu\mu} > 200$ GeV
- missing transverse momentum: $p_T(\not{E}) > 200$ GeV
- transverse cluster mass

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

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

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

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



$m_{W'} = 2.2$ TeV, $\tan\beta_R = 1.02$ and $\mu_{\text{eff}} = 150$ GeV
M. Krauss, W.P., arXiv:1507.04349

Natural SUSY + $\tilde{\nu}_R$, parameters considered

effective model with $\tilde{t}_1$, $\tilde{b}_1$, $\tilde{h}^0_{1,2}$, $\tilde{h}^+$, $\tilde{\nu}_R$

- $m_{\tilde{t}_1}$ in GeV: 300, 400, 500, 600, 700, 800, 900, 1000
- $m_{\tilde{b}_1}$ in GeV: 300, 400, 500, 600, 700, 800, 900, 1000
- $m_{\tilde{\nu}_R}$ in GeV : 60, 100, 200, 300, 400, 500
- μ in GeV: 110, 190, 290, 390, 490, 590 and require $m_{\tilde{\nu}_R} < \mu$
- $\tan\beta$: 10, 50
- $\theta_{\tilde{t}}$: $0^\circ, 45^\circ, 90^\circ$
- $\theta_{\tilde{b}}$: $0^\circ, 45^\circ, 90^\circ$
- $M_1 = M_2 = 1$ TeV
- everything else, including $\tilde{t}_2$, and $m_{\tilde{g}}$: 2 TeV, $\tilde{b}_2$ calculated

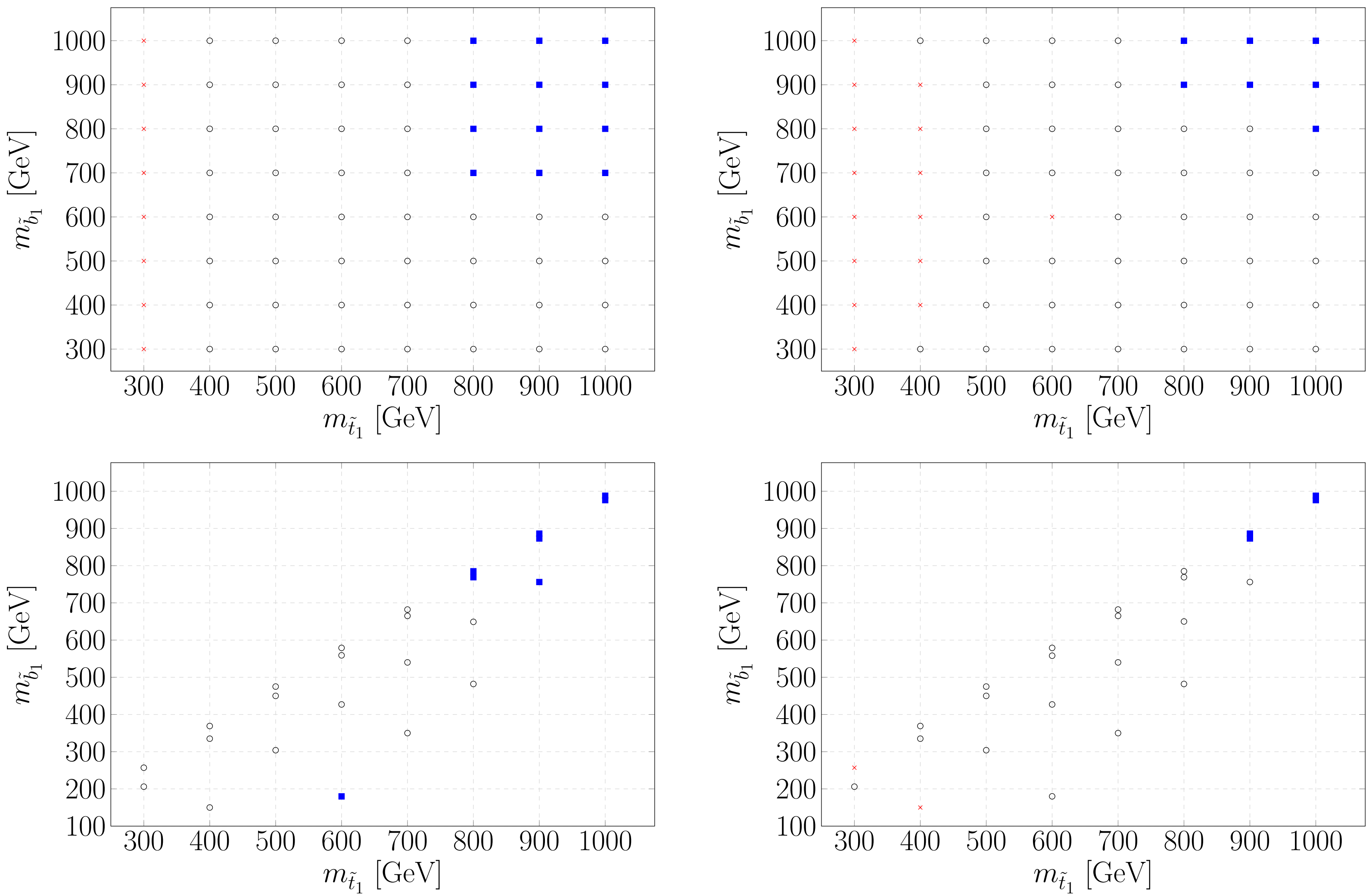
$$m_W^2 \cos 2\beta = m^2_{\tilde{t}_1} \cos^2\theta_{\tilde{t}} - m^2_{\tilde{t}_2} \sin^2\theta_{\tilde{t}} - m^2_{\tilde{b}_1} \cos^2\theta_{\tilde{b}} - m^2_{\tilde{b}_2} \sin^2\theta_{\tilde{b}} - m_t^2 + m_b^2$$

$\Rightarrow m_{\tilde{b}_2} \leftrightarrow m_{\tilde{b}_1}$ if necessary

$m_{\tilde{t}_2} \leftrightarrow m_{\tilde{t}_1}$ (if $\cos\theta_{\tilde{b}} = 1$)

Summary results, $\tilde{t}_1$, $\tilde{b}_1$, 8 TeV data

ambigous as allowed — ambigous as forbidden

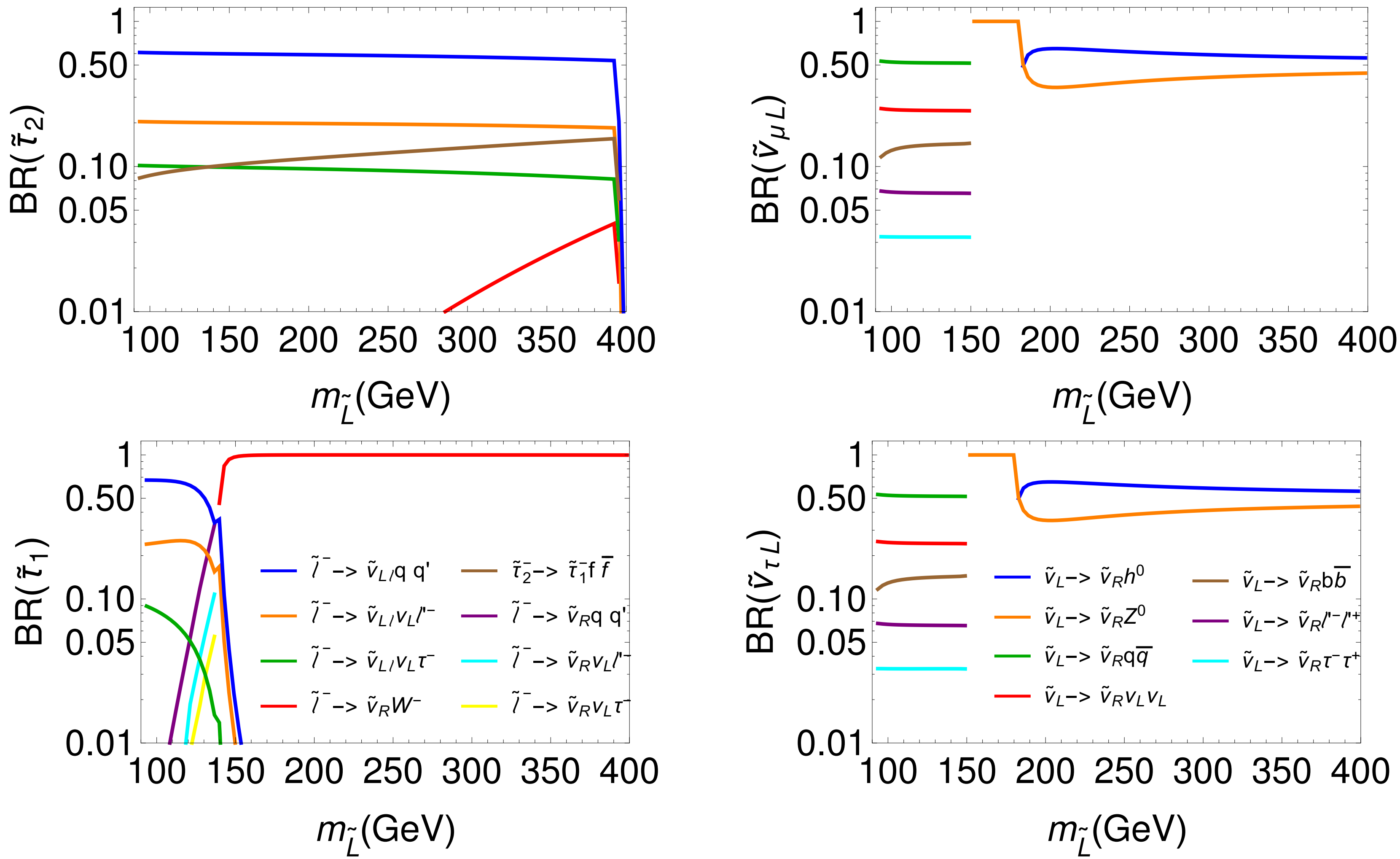


× excluded for all parameters, ○ exclusion depends on parameters, ■ allowed for all parameters

L. Mitzka, WP arXiv:1603.06130

$\tilde{\nu}_R$-LSP, 3-body decays

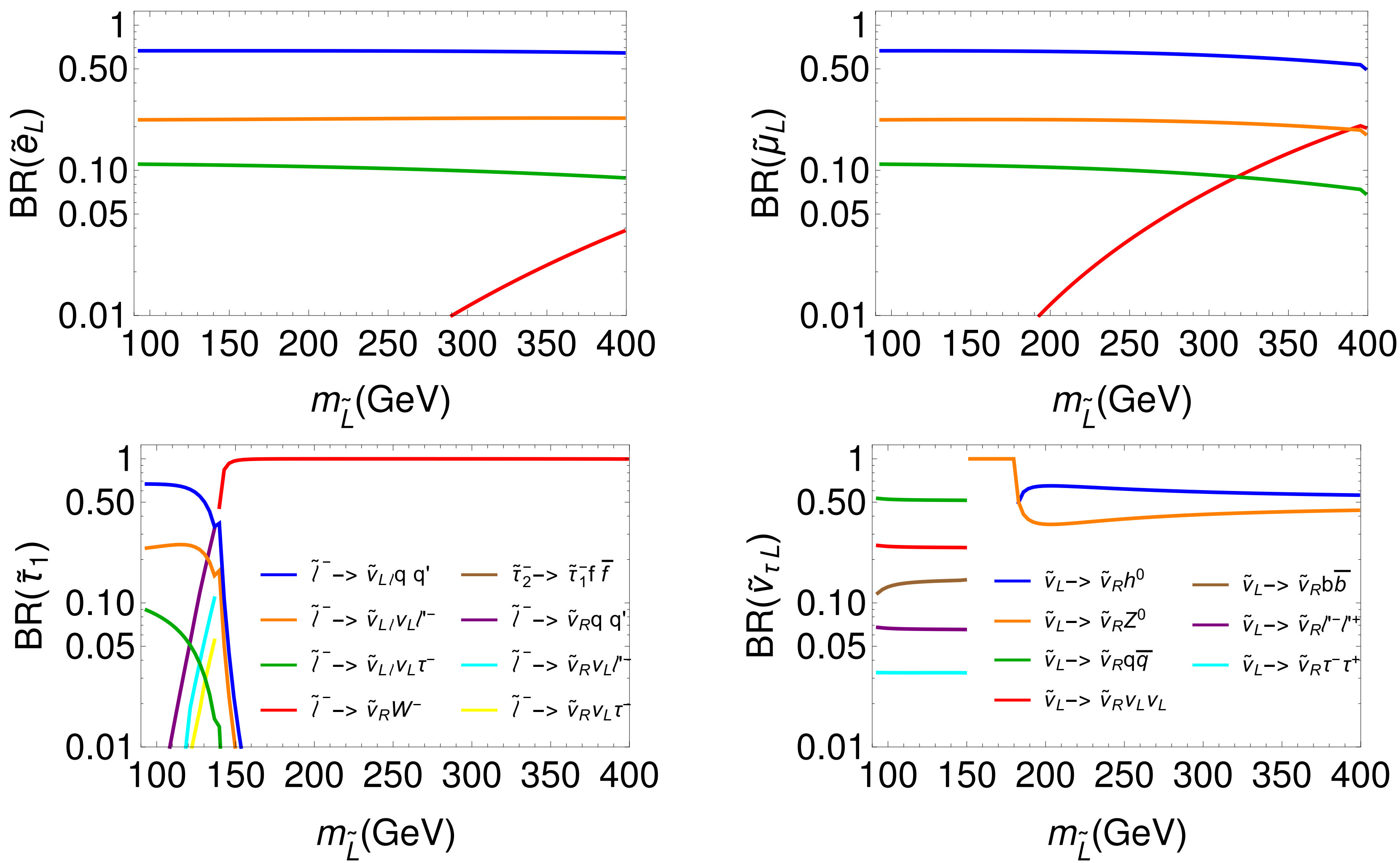
for $\mu = 400$ GeV $> m_{\tilde{L}} = m_{\tilde{E}}, \tan\beta = 6,\ M_1, M_2 \geq 500$ GeV



Nh. Cerna-Velazco, Th. Faber, J. Jones, WP arXiv:1705.06583

$\tilde{\nu}_R$-LSP, 3-body decays

for $\mu = 400$ GeV $> m_{\tilde{L}} = m_{\tilde{E}}, \tan\beta = 6$, $M_1, M_2 \geq 500$ GeV



Nh. Cerna-Velazco, Th. Faber, J. Jones, WP arXiv:1705.06583