

Status of supersymmetric models after run 2

Werner Porod

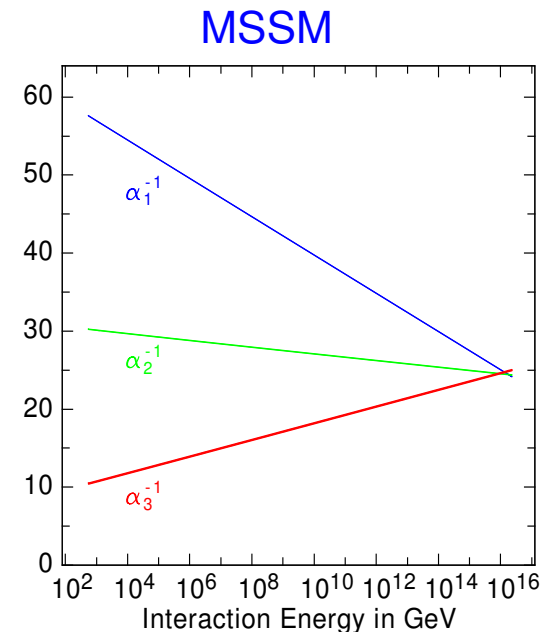
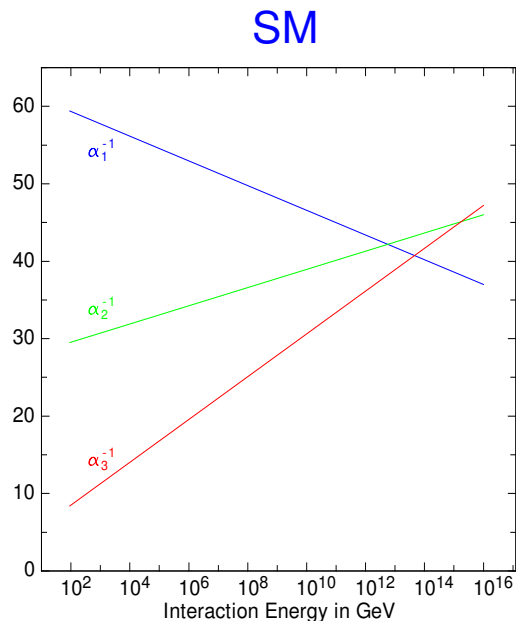
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- MSSM
 - Higgs mass: consequences for GMSB & CMSSM
 - general MSSM, 'natural SUSY'
- SUSY and extended gauge groups
 - implications for SUSY cascade decays
 - 'Natural SUSY' and $\tilde{\nu}_R$ -LSP
- Conclusions

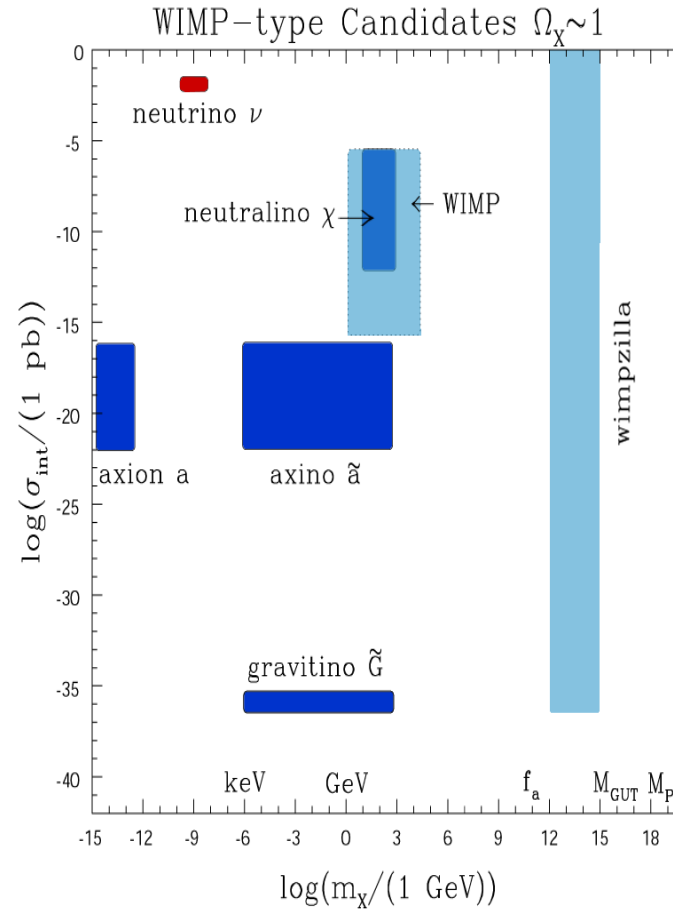
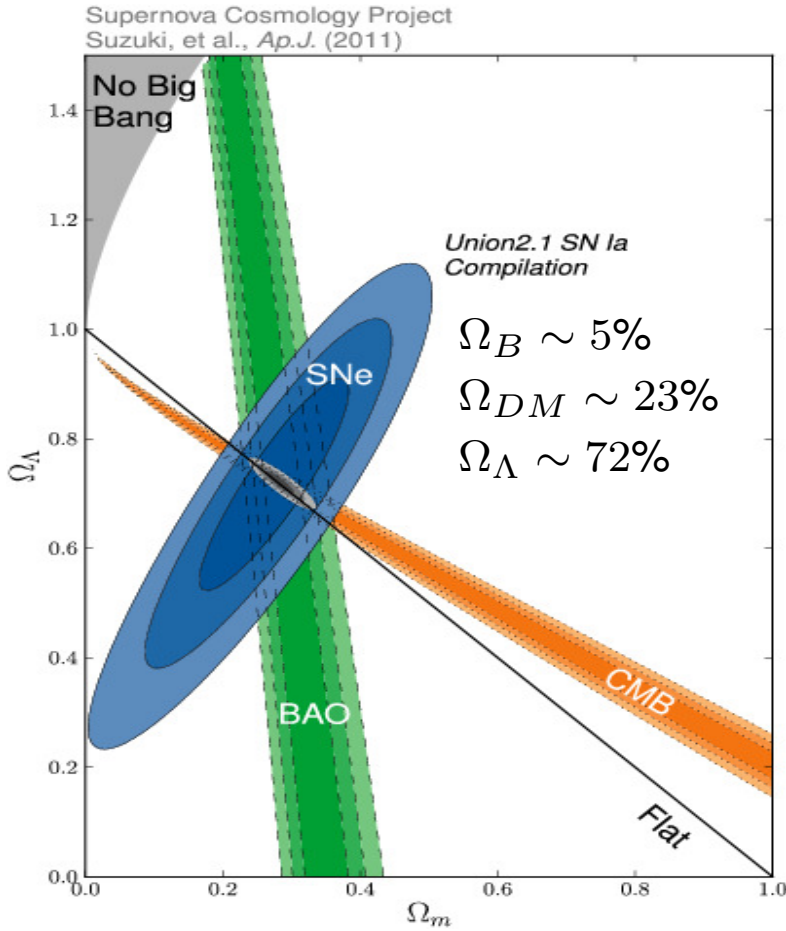
- How to combine gravity with the SM?
⇒ local Supersymmetry (SUSY) implies gravity
- SM particles can be put in multiplets of larger gauge groups
 - in $SU(5)$: $1 = \nu_R^c$, $5 = (d_{\alpha,R}^c, \nu_{l,L}, l_L)$, $10 = (u_{\alpha,L}, u_{\alpha,R}^c, d_{\alpha,L}, l_R)$
 - in $SO(10)$: $16 = (u_{\alpha,L},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

However there are two problems in the SM but not in SUSY:

- proton decay (also in SUSY $SU(5)$ a problem)
- gauge coupling unification



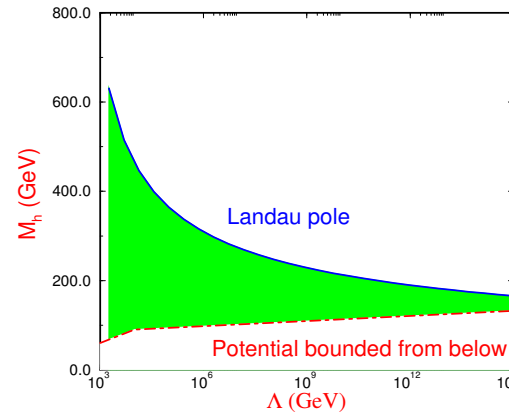
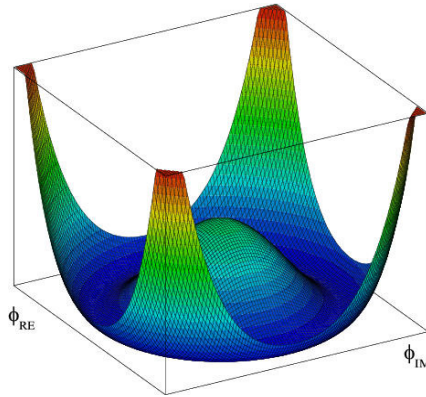
What is the nature of dark matter ?



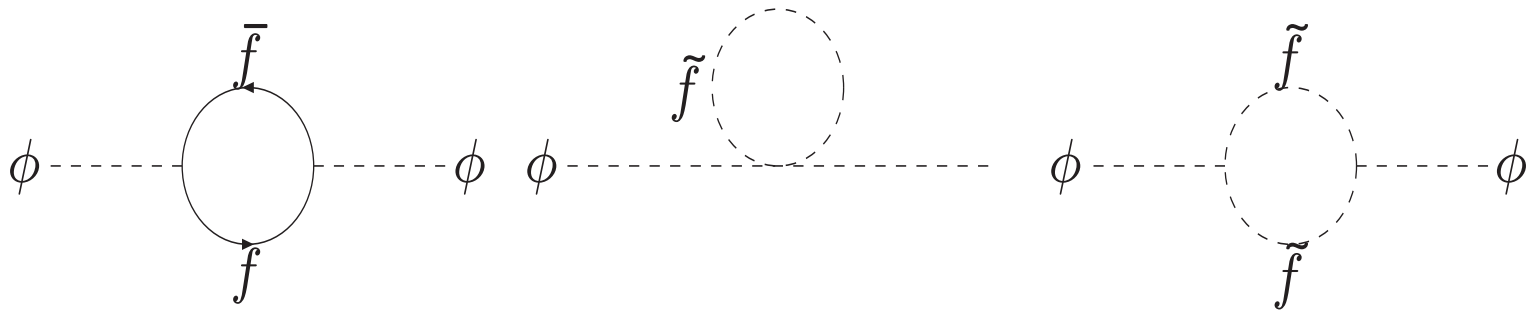
L. Roszkowski, astro-ph/0404052

What is the origin of the observed baryon asymmetry?

- 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

$$\begin{aligned}
 W_{MSSM} &= -\mu \hat{H}_d \hat{H}_u + \hat{H}_d \hat{L} Y_e \hat{E}^c + \hat{H}_d \hat{Q} Y_d \hat{D}^c - \hat{H}_u \hat{Q} Y_u \hat{U}^c \\
 W_{\mathcal{L}} &= \epsilon_i \hat{L}_i \hat{H}_u^b + \lambda_{ijk} \hat{L}_i \hat{L}_j \hat{E}_k^c + \lambda'_{ijk} \hat{L}_i \hat{Q}_j \hat{D}_k \\
 W_{\mathcal{B}} &= \lambda''_{ijk} \hat{U}_i^c \hat{D}_j^c \hat{D}_k^c
 \end{aligned}$$

$W_{\mathcal{L}} + W_{\mathcal{B}} \Rightarrow$ proton decay $\Rightarrow R$ -parity

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

soft SUSY breaking terms

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

general MSSM: more than 100 parameters

reduction assuming correlations between various parameters

● mSUGRA/CMSSM: M_{GUT}

$$M_{1/2} = M_1 = M_2 = M_3$$

$$m_0^2 = m_{H_d}^2 = m_{H_u}^2, m_0^2 \cdot \mathbb{1}_3 = m_{\tilde{Q}}^2 = m_{\tilde{U}}^2 = m_{\tilde{D}}^2 = m_{\tilde{L}}^2 = m_{\tilde{E}}^2$$

$$T_f = A_0 Y_f \quad (f = u, d, e)$$

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

● GMSB, $M \gtrsim 100 \text{ TeV}$

$$M_i = g(x, n) \alpha_i \Lambda$$

$$m_{\tilde{F}}^2 = f(x, n) \sum_i C_2(R) \alpha_i^2 \Lambda^2 \mathbb{1}_3$$

$$T_f \simeq 0$$

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

- after EWSB:
neutral CP-even: h, H neutral CP-odd: A charged: H^+, H^-

- Higgs masses:
at tree level

$$m_A, \tan \beta = v_u/v_d$$

$$m_h \leq m_Z$$

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:

$$m_h^2 \simeq m_Z^2 \cos^2(2\beta) + \frac{3m_t^4}{4\pi^2 v^2} \left[\ln \left(\frac{M_S^2}{m_t^2} \right) + \frac{X_t^2}{M_S^2} \left(1 - \frac{X_t^2}{12M_S^2} \right) \right]$$

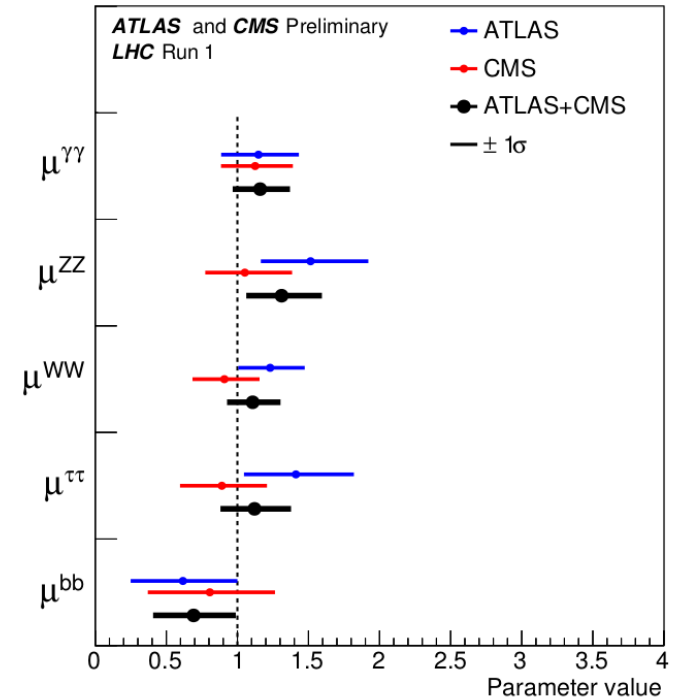
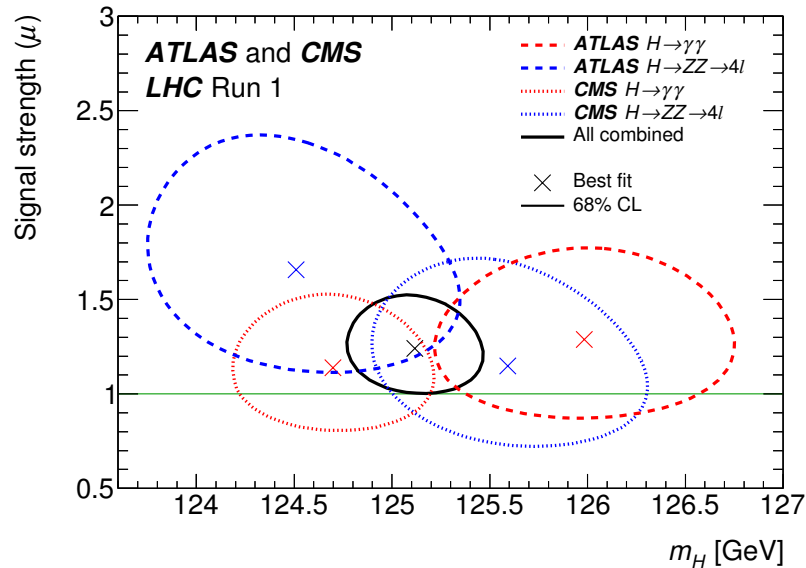
$$M_S^2 = m_{\tilde{t}_1} m_{\tilde{t}_2}, \quad X_t = A_t - \mu \cot \beta$$

$$m_H, m_A, m_{H^\pm} : O(v) \dots O(\text{TeV})$$

$$m_{H^\pm}^2 = m_A^2 + m_W^2$$

$$v^2 = v_u^2 + v_d^2 = 4m_W^2/g^2$$

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



$$m_H = 125.09 \pm 0.21 \text{ (stat)} \pm 0.11 \text{ (sys)} \text{ GeV}$$

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

$$\text{ATLAS: } m_H = 124.98 \pm 0.19 \text{ (stat)} \pm 0.21 \text{ (sys)} \text{ GeV}$$

$$\text{CMS: } m_H = 125.26 \pm 0.20 \text{ (stat)} \pm 0.08 \text{ (sys)} \text{ GeV}$$

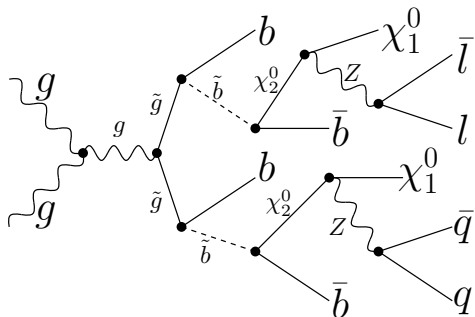
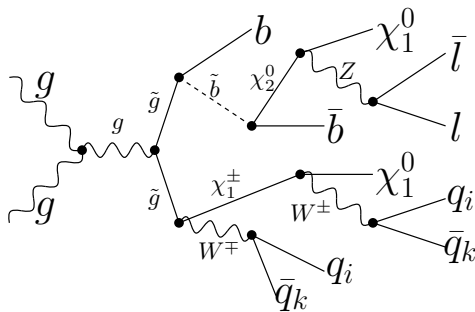
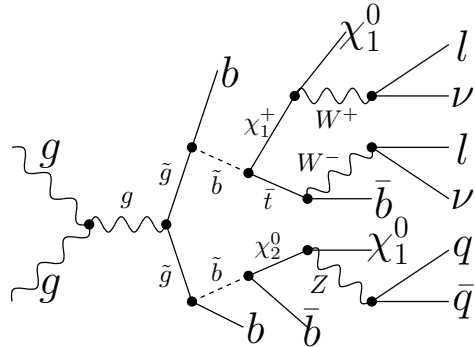
see talk by A.-M. Magnan, ALPS 2018

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

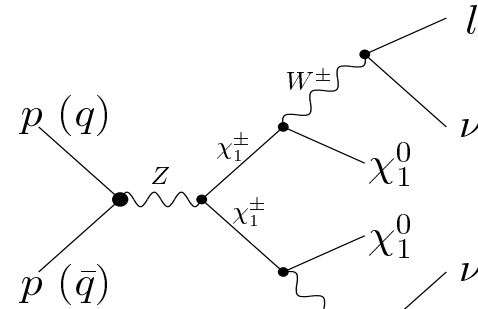
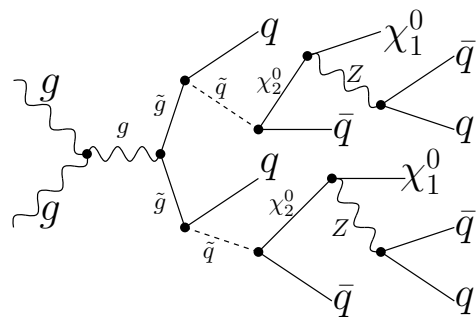
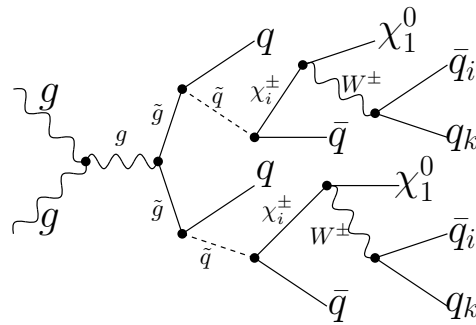
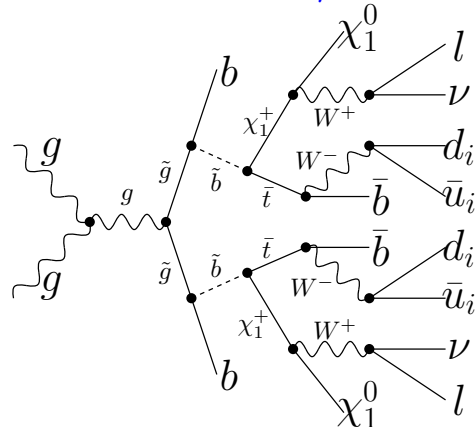
ATLAS-CONF-2015-044

CMS-PAS-HIG-15-002

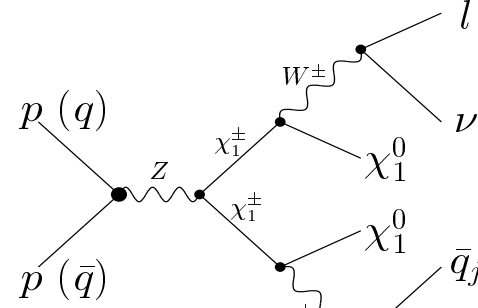
$$6j + 2l + E/T$$



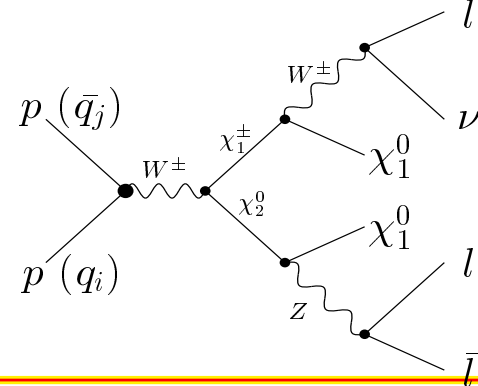
$$8j + 2l + E/T$$



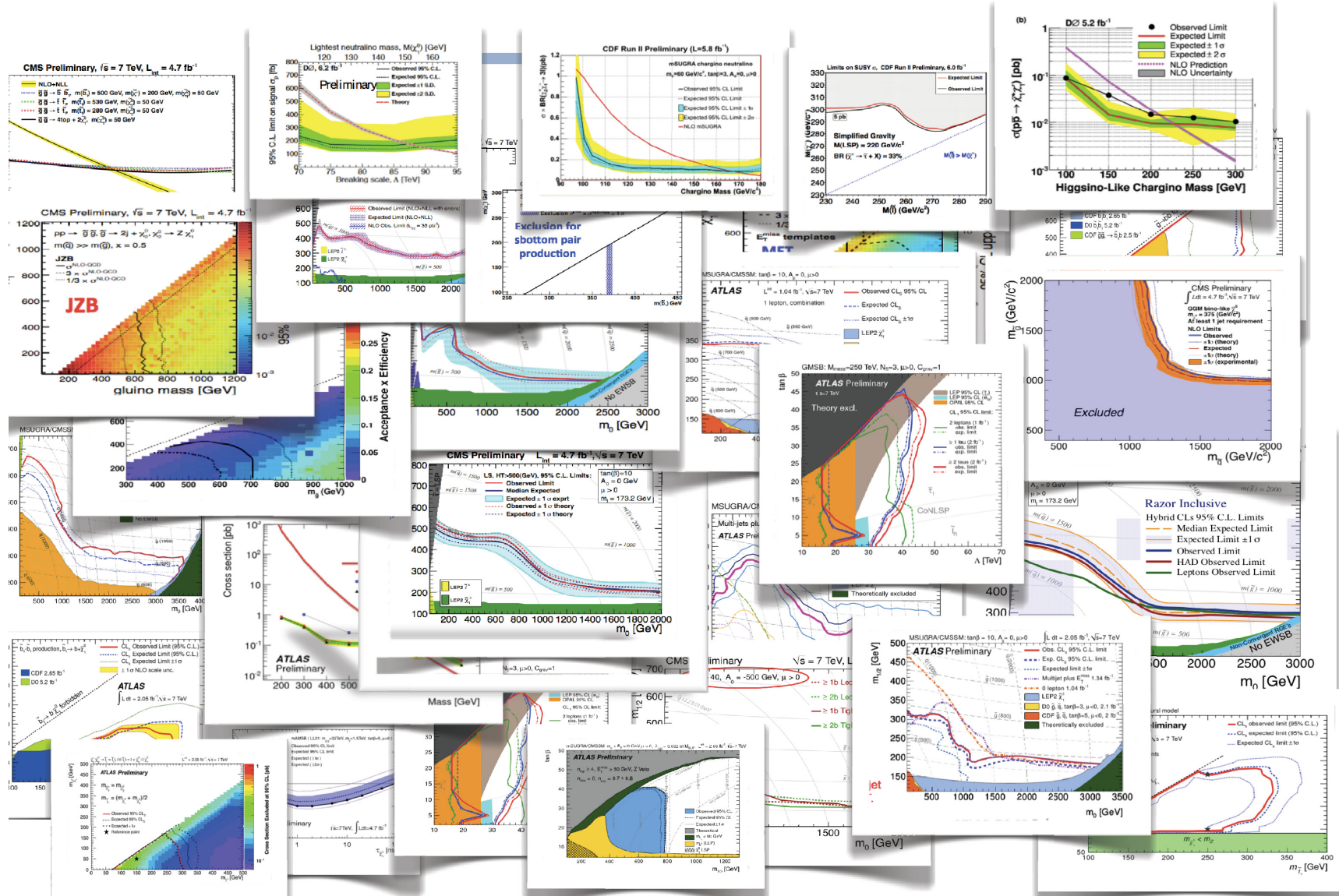
$$2l + E/T$$

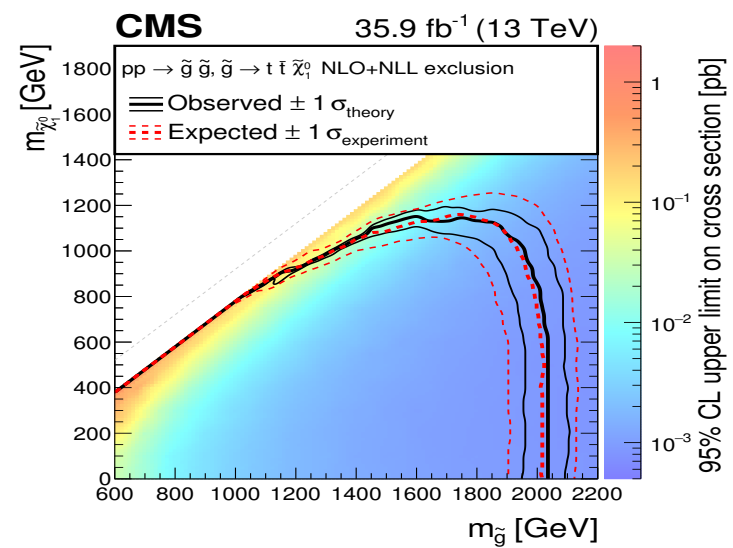
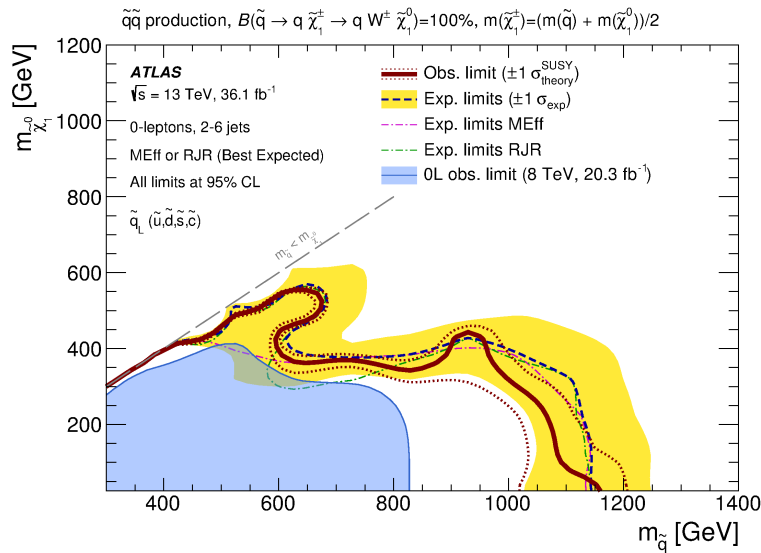
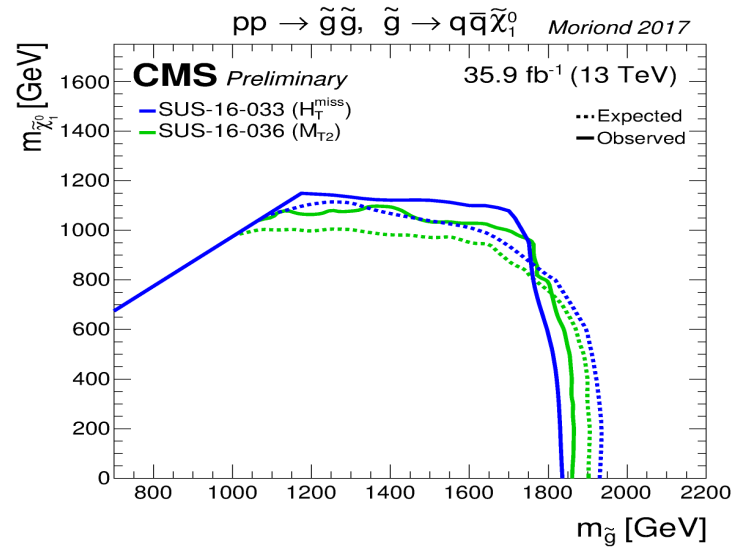
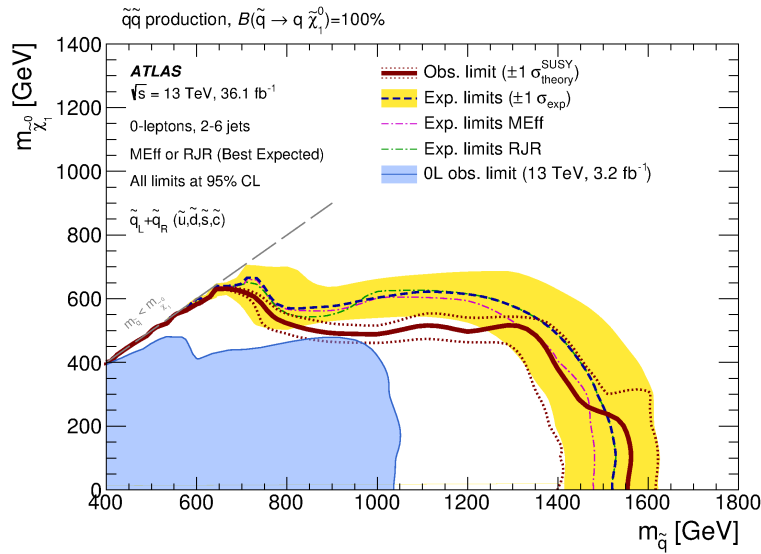


$$l + 2j + E/T$$



$$3l + E/T$$





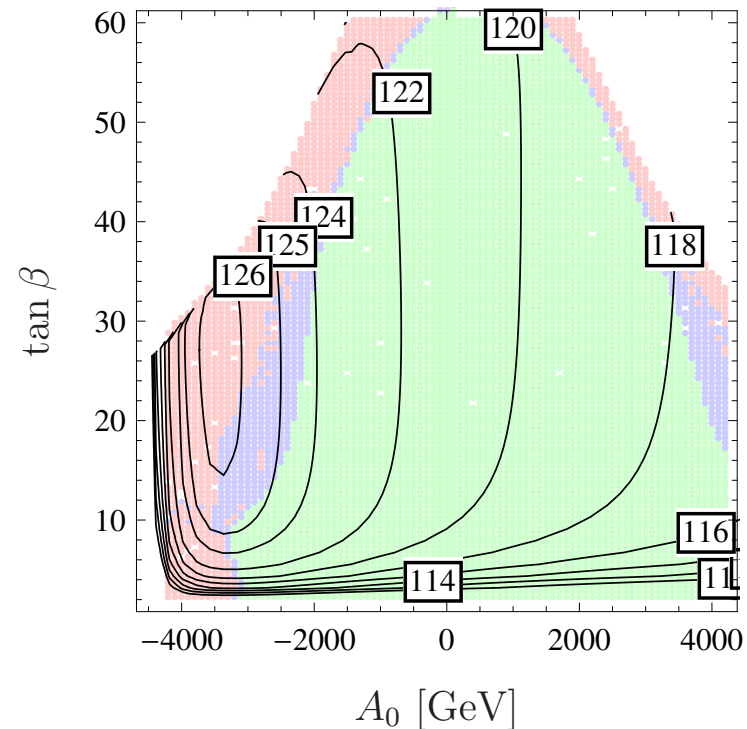
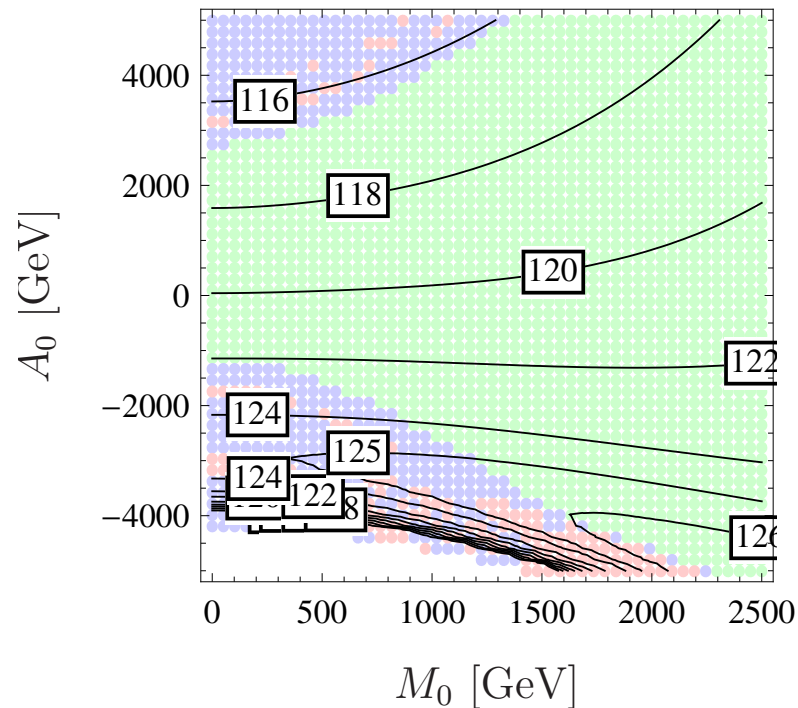
arXiv:1712.02332

arXiv:1710.11188

$m_h = 125.2 \text{ GeV} \Rightarrow$ large loop contributions
 \Rightarrow heavy stops and/or large left-right mixing for stops

- GMSB: $m_{\tilde{t}_1} \gtrsim 6 \text{ TeV}$,
 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 \Rightarrow allow additional terms
 e.g. S. Knappen, D. Redigolo, arXiv:1606.07501 $m_{\tilde{t}_1} \simeq m_{\tilde{b}_1} \gtrsim 1 \text{ TeV}$ if
 $M_{\text{mess}} \gtrsim 10^{15} \text{ GeV}$
- 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
 $m_{\tilde{g}}, m_{\tilde{q}} \gtrsim 2 \text{ TeV}$, $m_{\tilde{l}_R} \simeq 600 \text{ GeV}$, $m_{\tilde{\chi}_1^0} \simeq 450 \text{ GeV}$
- 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

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



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

$$M_{1/2} = M_0 = 1 \text{ TeV}$$

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

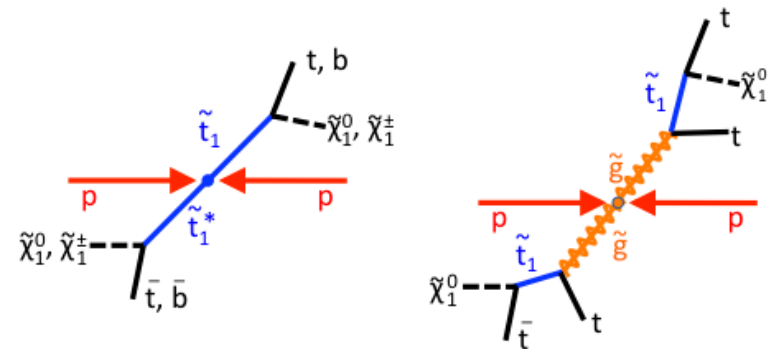
several studies: S. Sekmen et al., arXiv:1109.5119; A. Arbey, M. Battaglia, A. Djouadi, F. Mahmoudi, arXiv:1211.4004; M. Cahill-Rowley, J. Hewett, A. Ismail, T. Rizzo, arXiv:1308.0297 ...

- 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':

$$\tilde{t}_1, \tilde{b}_1, \tilde{g}, \tilde{\chi}_{1,2}^0 \simeq \tilde{h}_{1,2}^0, \tilde{\chi}_1^+ \simeq \tilde{h}^+$$

$$\Rightarrow 100 \text{ MeV} \lesssim m_{\tilde{\chi}_1^+} - m_{\tilde{\chi}_1^0} \simeq m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} \lesssim 5 - 10 \text{ GeV}$$

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



BRs depend on the nature of \tilde{t}_1 and \tilde{b}_1

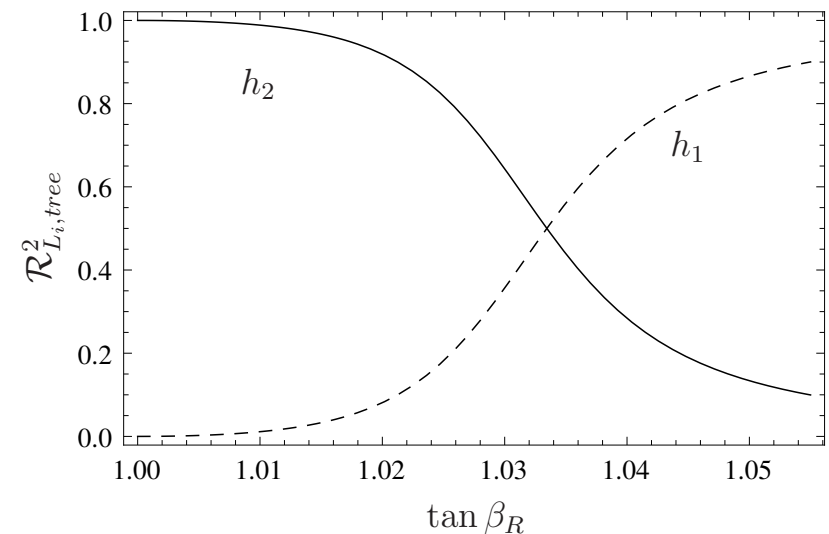
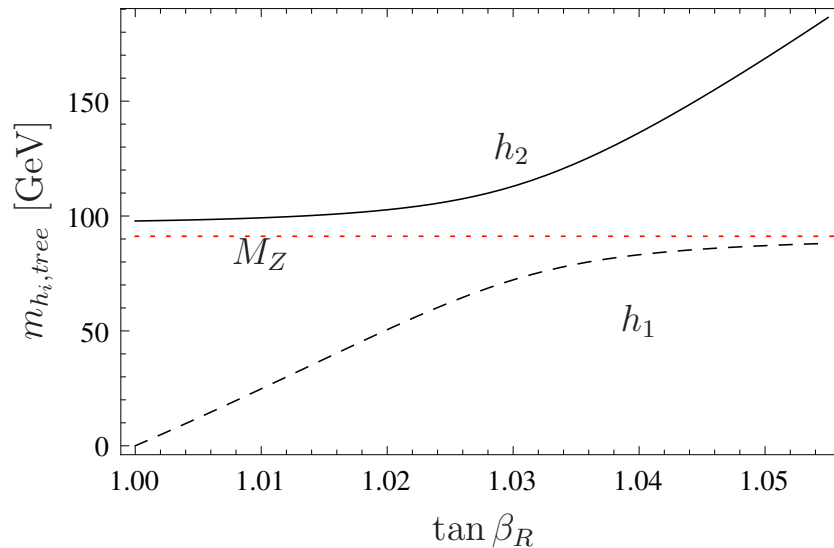
Higgsino mass: $\mu + \mu'$ with soft SUSY breaking parameter: $\mathcal{L} = -\mu' \tilde{H}_d \tilde{H}_u$

(G. G. Ross, K. Schmidt-Hoberg and F. Staub, arXiv:1701.03480)

- additional D-term contributions to m_h at tree-level
- Origin of R -parity $R_P = (-1)^{2s+3(B-L)}$
 - $\Rightarrow SO(10) \rightarrow SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$
 - $\rightarrow SU(3)_C \times SU(2)_L \times U(1)_R \times U(1)_{B-L}$
 - $\cong SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_X$
 - or $E(8) \times E(8) \rightarrow SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$
- 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: $m_{h,tree}^2 \leq m_Z^2 + \frac{1}{4}g_\chi^2 v^2$

H.E. Haber, M. Sher, PRD 35 (1987) 2206; M. Drees, PRD 35 (1987) 2910; M. Cvetič 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, $\tan \beta = 30$, $\text{sign}(\mu_R) = -$, $\text{diag}(Y_S) = (0.7, 0.6, 0.6)$, $Y_\nu^{ii} = 0.01$, $v_R = 7$ TeV

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

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

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

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

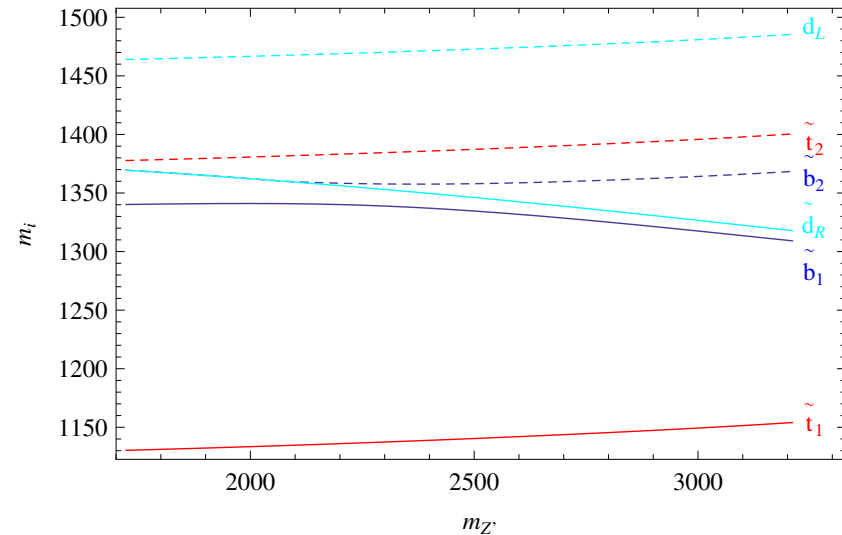
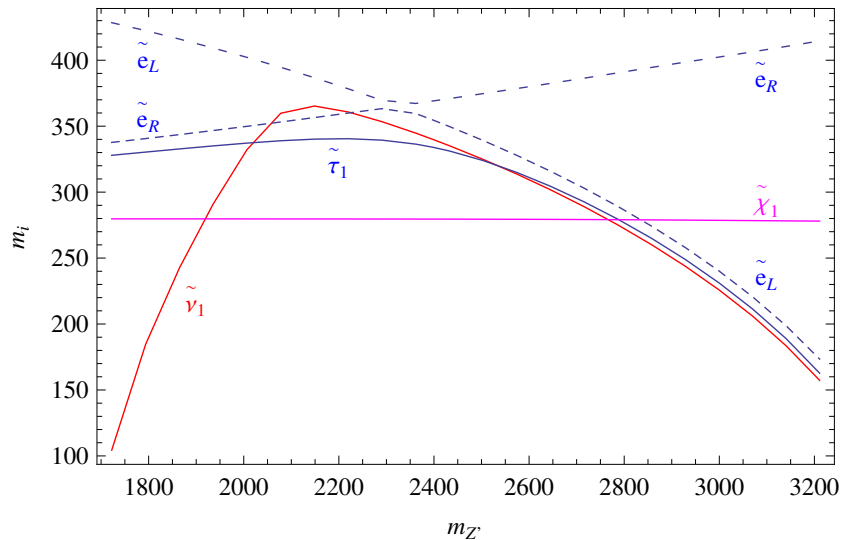
$$D_L = \frac{1}{32} \left(2(-3g_\chi^2 + g_\chi g_{Y_\chi} + 2(g_2^2 + g'^2 + g_{Y_\chi}^2))v^2 c_{2\beta} - 5g_\chi(3g_\chi + 2g_{Y_\chi})v_R^2 c_{2\beta_R} \right) \mathbf{1}$$

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

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

$$D_L \simeq \left(-\frac{1}{2} + \sin^2_{\theta_W}\right) m_Z^2 c_{2\beta} - \frac{5}{4} m_{Z'}^2 c_{2\beta_R} \quad \text{and} \quad D_R \simeq -\sin^2_{\theta_W} m_Z^2 c_{2\beta} + \frac{5}{4} m_{Z'}^2 c_{2\beta_R}$$

neglecting gauge kinetic effects; similarly for squarks



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

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

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

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

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

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

$$\tilde{q}_R \rightarrow q\tilde{\chi}_1^0 \rightarrow q\nu_k\tilde{\nu}_1 \rightarrow q\nu_j Z\tilde{\nu}_1 \quad (k = 4, \dots, 9, j = 1, 2, 3)$$

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

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

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

BLRSP3: usual cascades similar to CMSSM, but

$$\tilde{\chi}_1^0 \rightarrow l^\pm \tilde{l}^\mp \rightarrow l^\pm W^\mp \tilde{\nu}_1$$

$$\tilde{\chi}_1^0 \rightarrow l^\pm \tilde{l}^\mp \rightarrow l^\pm W^\mp \tilde{\nu}_{2,3} \rightarrow l^\pm W^\mp f \bar{f} \tilde{\nu}_1$$

$$\tilde{\chi}_1^0 \rightarrow \nu_j \tilde{\nu}_{2,3} \rightarrow \nu_{1,2,3} f \bar{f} \tilde{\nu}_1$$

$$\tilde{\chi}_1^0 \rightarrow \nu_j \tilde{\nu}_k \rightarrow \nu_j h_{1,2} \tilde{\nu}_1 \quad (j, k = 1, 2, 3)$$

$$\tilde{\chi}_1^0 \rightarrow \nu_j \tilde{\nu}_k \rightarrow \nu_j h_{1,2} f \bar{f} \tilde{\nu}_1$$

⇒ enhanced jet and lepton multiplicities, study of ν_R

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

$$(Y_\nu)_{l5} = \pm (Z_\ell^{\text{NH}})^* \sqrt{\frac{2m_3 M_5}{v_u}} \cosh \gamma_{56} e^{\mp i\theta_{56}}$$

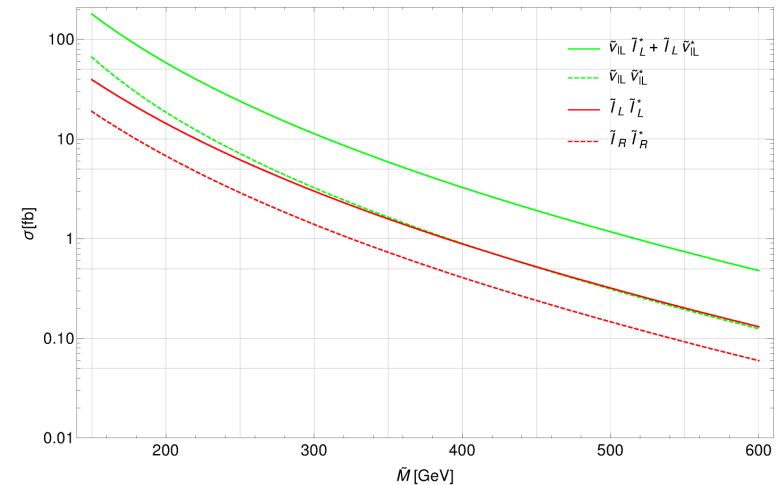
$$(Y_\nu)_{l6} = -i (Z_\ell^{\text{NH}})^* \sqrt{\frac{2m_3 M_6}{v_u}} \cosh \gamma_{56} e^{\mp i\theta_{56}}$$

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

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

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

search for sleptons



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

dominant decays:

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

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

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

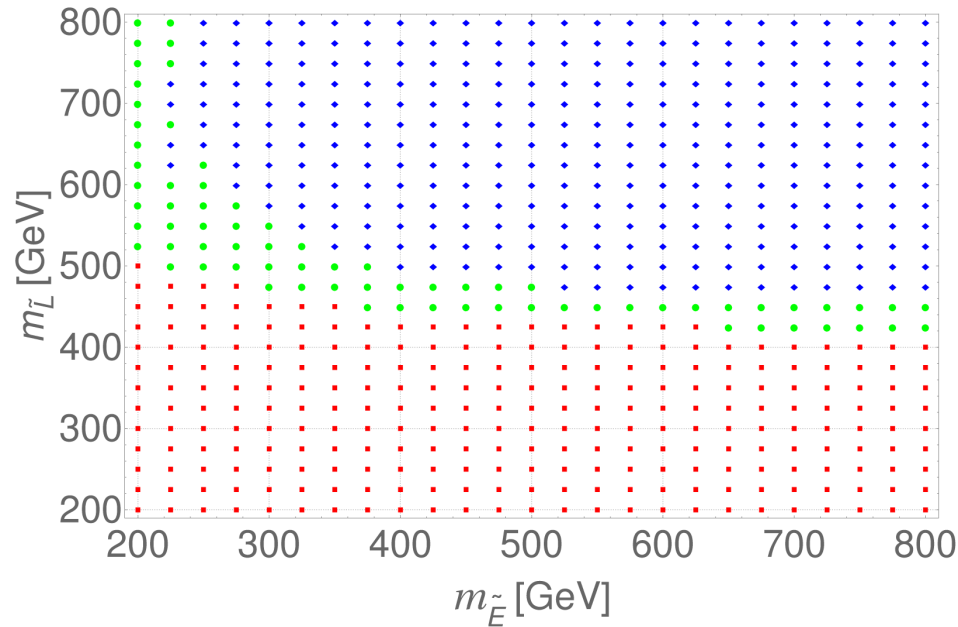
$$(Y_\nu)_{l5} = \pm (Z_\ell^{NH})^* \sqrt{\frac{2m_3 M_5}{v_u}} \cosh \gamma_{56} e^{\mp i\theta_{56}}$$

$$(Y_\nu)_{l6} = -i (Z_\ell^{NH})^* \sqrt{\frac{2m_3 M_6}{v_u}} \cosh \gamma_{56} e^{\mp i\theta_{56}}$$

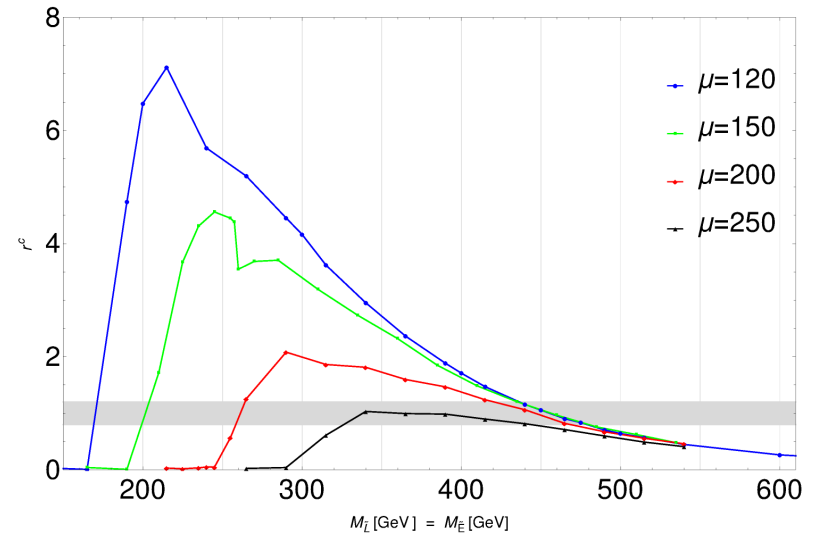
$$R = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \phi_{56} & \sin \phi_{56} \\ 0 & -\sin \phi_{56} & \cos \phi_{56} \end{pmatrix}$$

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

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



$\mu = 120 \text{ GeV}, \tan \beta = 10$



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

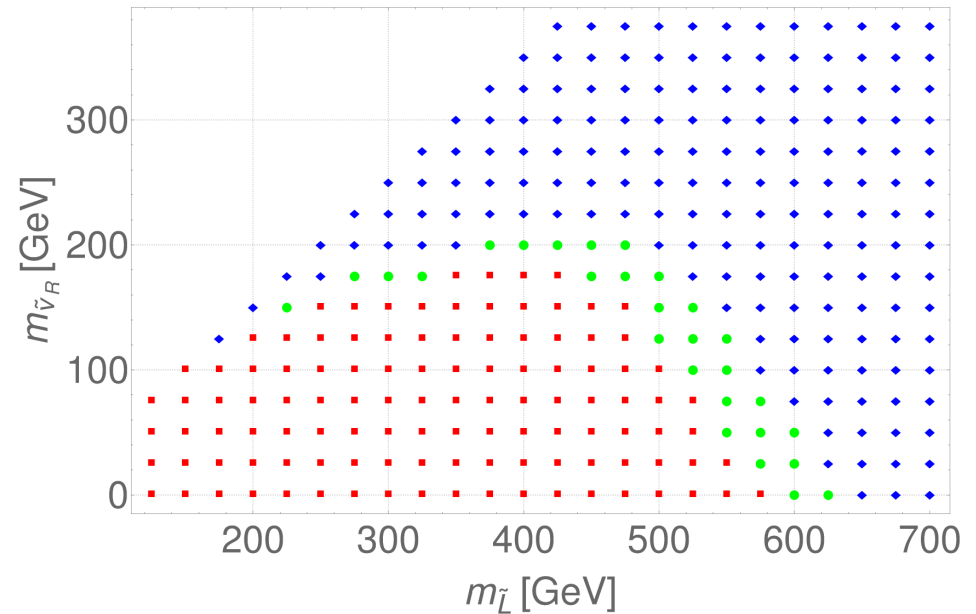
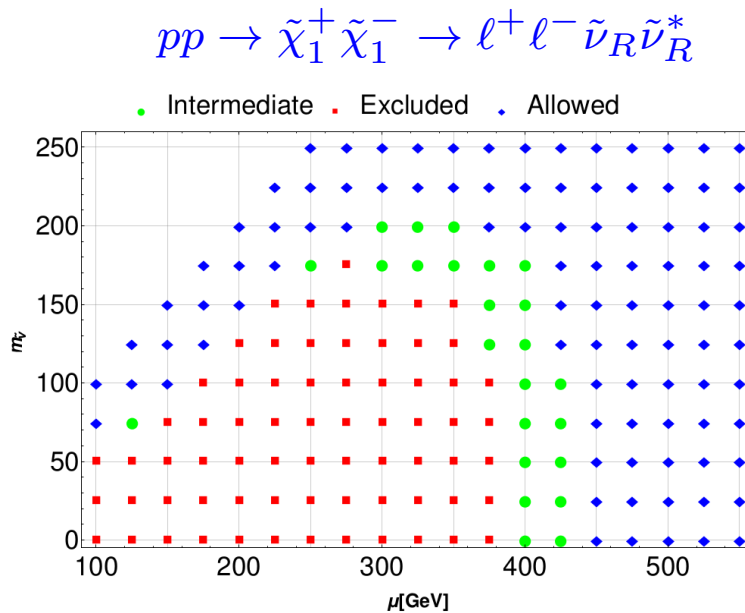
■ excluded, ● ambiguous, ◇ allowed

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

using CheckMATE 2.0

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

additional constraint



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

using CheckMATE 2.0

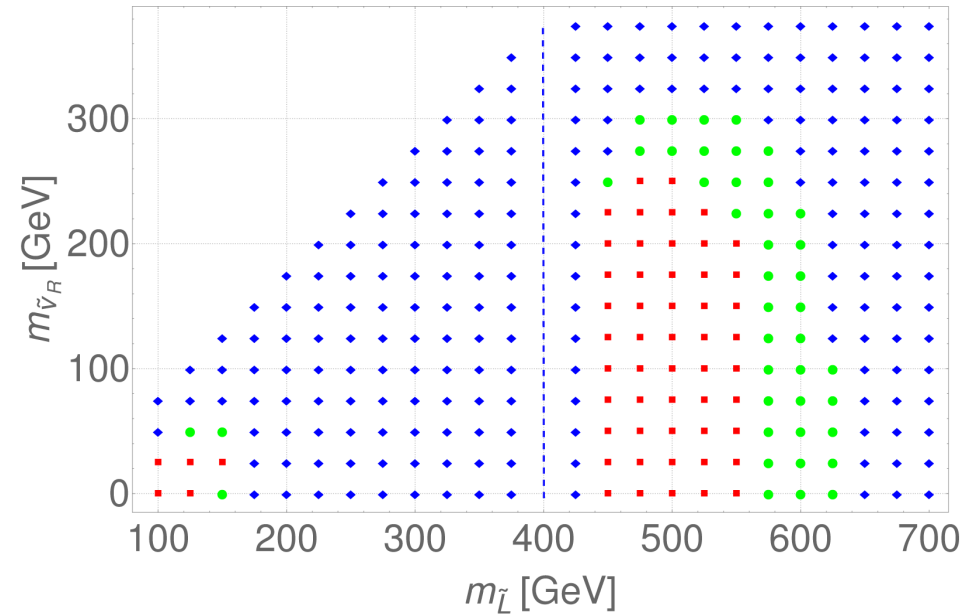
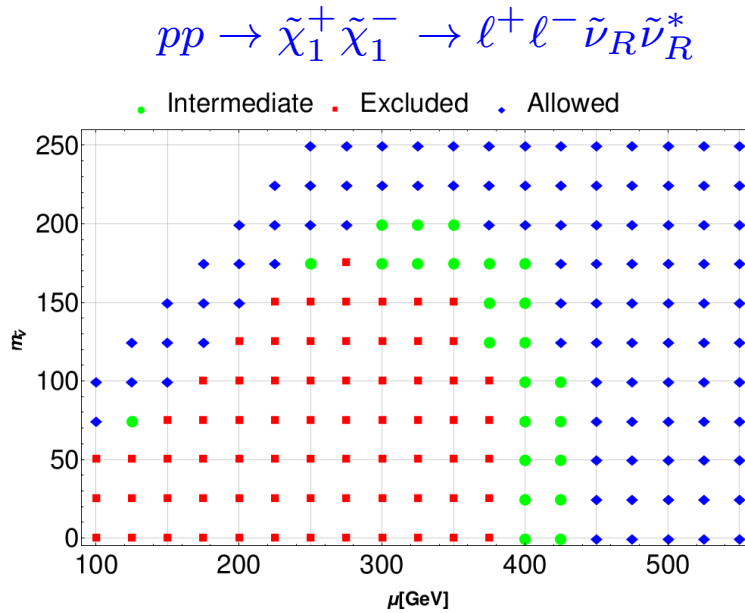
$m_{\nu_R} = 20 \text{ GeV}$

$$\mu = 25 + m_{\tilde{\nu}} < m_{\tilde{t}} \simeq m_{\tilde{L}} = m_{\tilde{E}}$$

$$M_1 = M_2 = 2 \text{ TeV}, \tan \beta = 6$$

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

additional constraint



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

using CheckMATE 2.0

$m_{\nu_R} = 20 \text{ GeV}$

$\mu = 400 \text{ GeV}, m_{\tilde{t}} \simeq m_{\tilde{L}} = m_{\tilde{E}}$

$M_1 = M_2 = 2 \text{ TeV}, \tan \beta = 6$

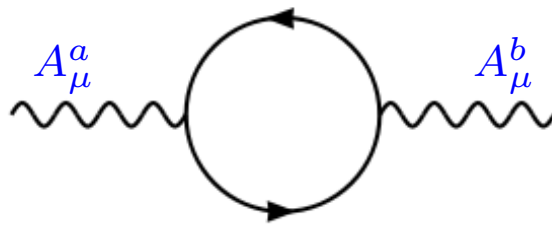
Nh. Cerna-Velazco, Th. Faber, J. Jones, WP arXiv:1705.06583

- 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
 - motivated 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

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

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

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



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

equivalent

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

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

basis (W^0, B_Y, B_χ)

$$M_{VV}^2 = \frac{1}{4} \begin{pmatrix} g_2^2 v^2 & -g_2 g' v^2 & g_2 \tilde{g}_\chi v^2 \\ -g_2 g' v^2 & g'^2 v^2 & -g' \tilde{g}_\chi v^2 \\ g_2 \tilde{g}_\chi v^2 & -g' \tilde{g}_\chi v^2 & \frac{25}{4} g_\chi^2 v_R^2 + \tilde{g}_\chi^2 v^2 \end{pmatrix}$$

$$\tilde{g}_\chi = g_\chi - g_{Y\chi}$$

$$v^2 = v_d^2 + v_u^2, \quad v_R^2 = v_{\chi R}^2 + v_{\tilde{\chi} R}^2$$

expanding in v^2/v_R^2

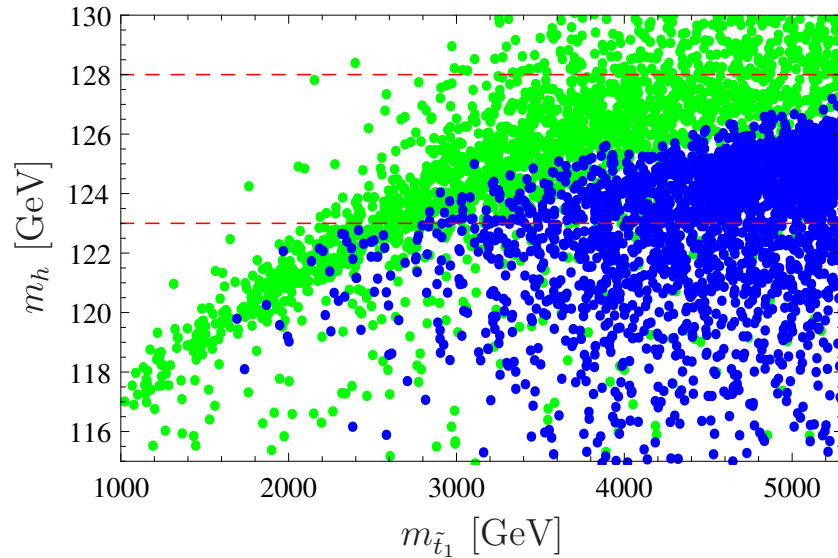
$$m_Z^2 \simeq \frac{1}{4} (g'^2 + g_2^2) v^2 \left(1 - \frac{4}{25} \left(1 - \frac{g_{Y\chi}}{g_\chi} \right)^2 \frac{v^2}{v_R^2} \right)$$

$$m_{Z'}^2 \simeq \left(\frac{5}{4} g_\chi v_R \right)^2$$

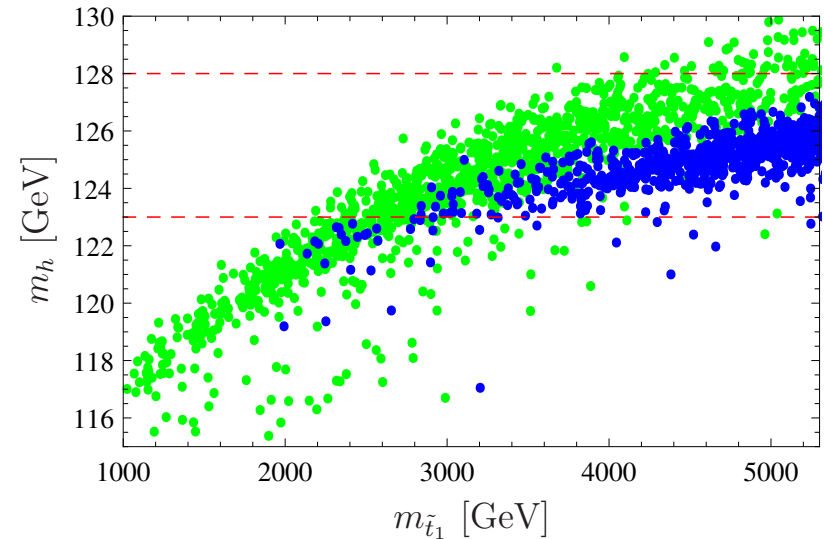
M. Hirsch, W.P., L. Reichert, F. Staub, arXiv:1206:3516;

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

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



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



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,
 $1.5 \leq \tan \beta \leq 40$, $1 < \tan \beta_R \leq 1.15$, $\text{sign}(\mu_R) \pm 1$, $\text{sign}(\mu) = 1$, $6.5 \leq v_R \leq 10$ 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: $h_2 \simeq h$

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

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

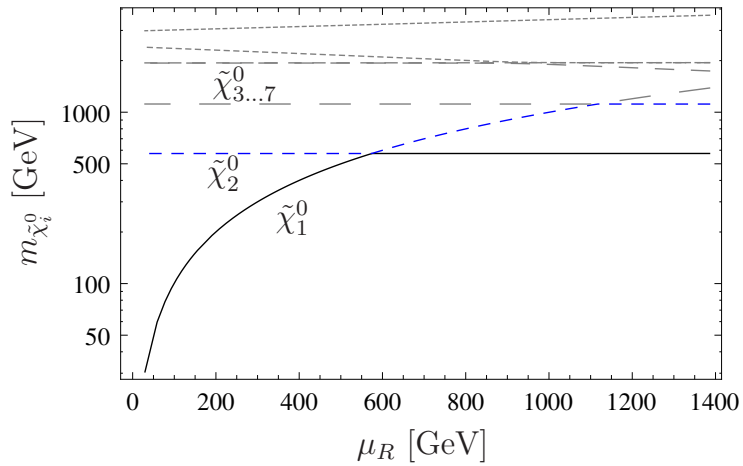
basis $(\lambda_Y, \lambda_{W^3}, \tilde{h}_d^0, \tilde{h}_u^0, \lambda_\chi, \tilde{\chi}_R, \tilde{\chi}_R)$

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

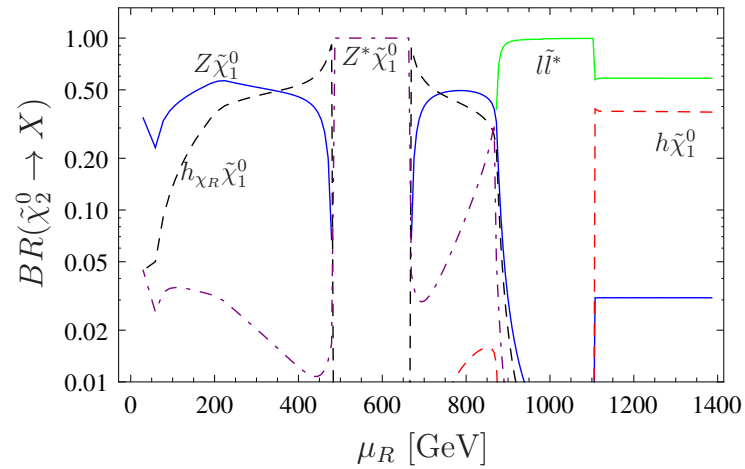
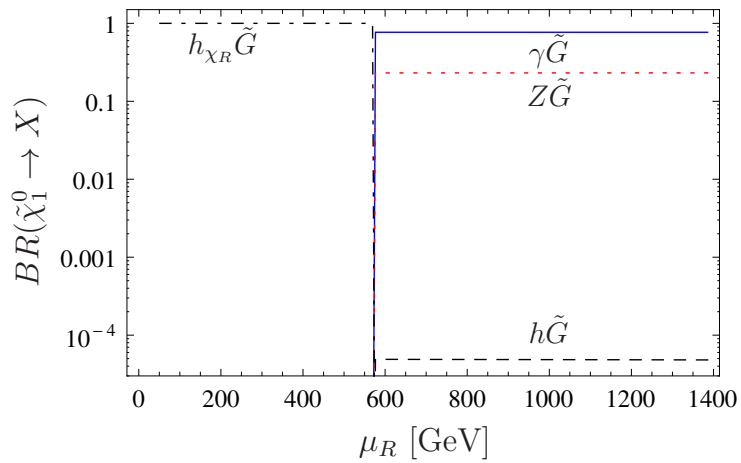
$$\begin{pmatrix} M_1 & 0 & -\frac{g'v_d}{2} & \frac{g'v_u}{2} & \frac{M_{Y\chi}}{2} & 0 & 0 \\ 0 & M_2 & \frac{g_2v_d}{2} & -\frac{g_2v_u}{2} & 0 & 0 & 0 \\ -\frac{g'v_d}{2} & \frac{g_2v_d}{2} & 0 & -\mu & \frac{(g_\chi - g_{Y\chi})v_d}{2} & 0 & 0 \\ \frac{g'v_u}{2} & -\frac{g_2v_u}{2} & -\mu & 0 & -\frac{(g_\chi - g_{Y\chi})v_u}{2} & 0 & 0 \\ \frac{M_{Y\chi}}{2} & 0 & \frac{(g_\chi - g_{Y\chi})v_d}{2} & -\frac{(g_\chi - g_{Y\chi})v_u}{2} & M_\chi & \frac{5g_\chi v_{\tilde{\chi}_R}}{4} & -\frac{5g_\chi v_{\chi_R}}{4} \\ 0 & 0 & 0 & 0 & \frac{5g_\chi v_{\tilde{\chi}_R}}{4} & 0 & -\mu_R \\ 0 & 0 & 0 & 0 & -\frac{5g_\chi v_{\chi_R}}{4} & -\mu_R & 0 \end{pmatrix}$$

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

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



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



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

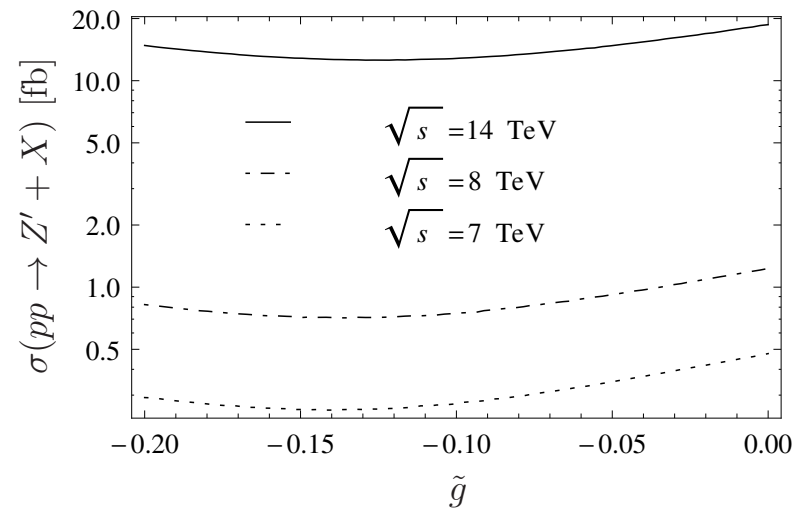
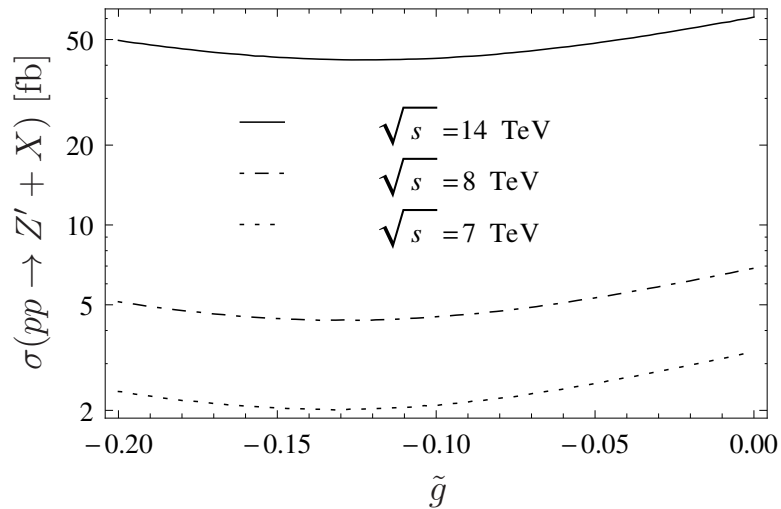
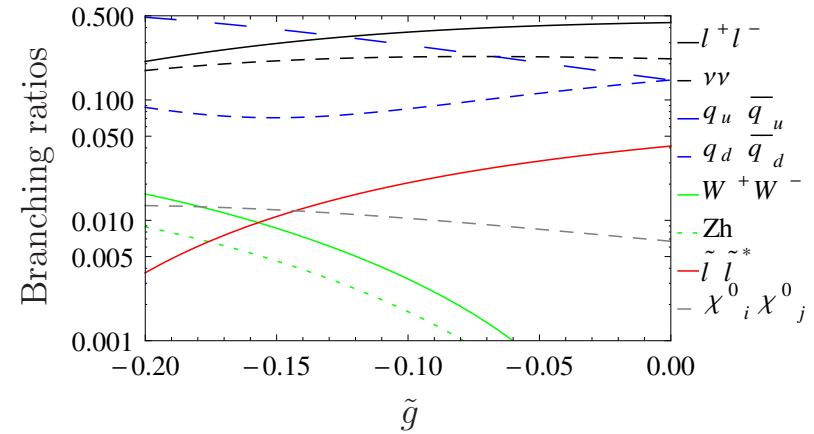
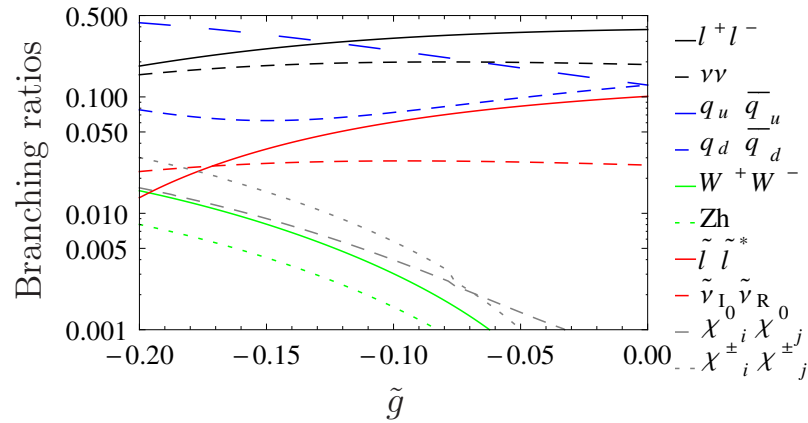
	BLRSP1	BLRSP2	BLRSP3	BLRSP4	BLRSP5
$m_{\tilde{\nu}_1}$	105.0	797.	91.6	542.	921.
$m_{\tilde{\nu}_{2/3}}$	215.0	797.	92.6	542.	924.
$m_{\tilde{\nu}_4}$	604.	1120.	253.	585.	940.
$m_{\tilde{e}_1}$	524.	1014.	255.	263.	693.
$m_{\tilde{e}_{2,3}}$	557.	1055.	266.	271.	706.
$m_{\tilde{u}_1}$	1436.	1185.	1247.	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

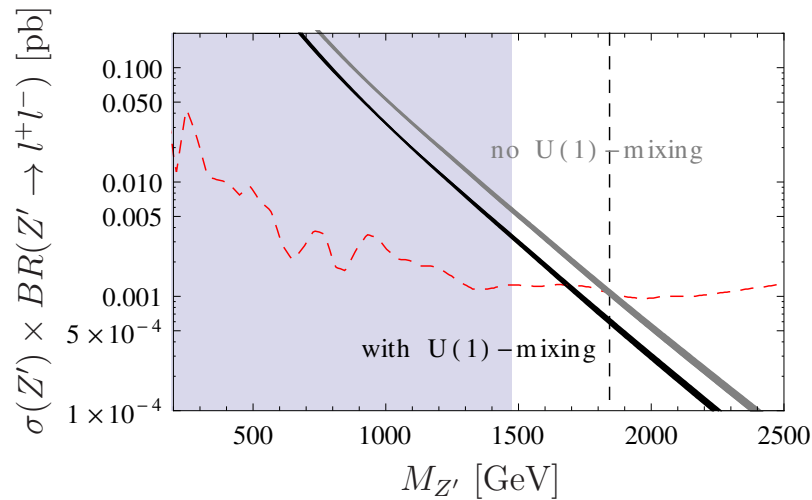
Z' couplings: $Q_{B-L} \cdot g_{B-L} \rightarrow Q_{B-L} \cdot g_{B-L} + Q_Y \cdot \tilde{g}$

BL1

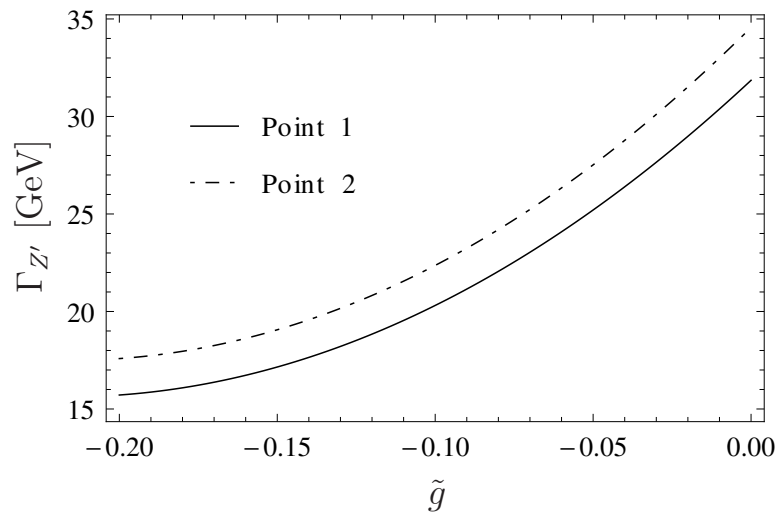
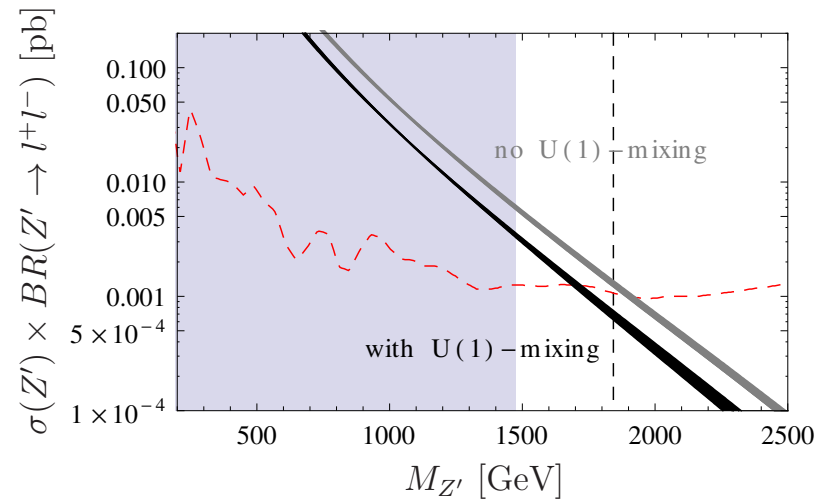
BL2



BL1



BL2

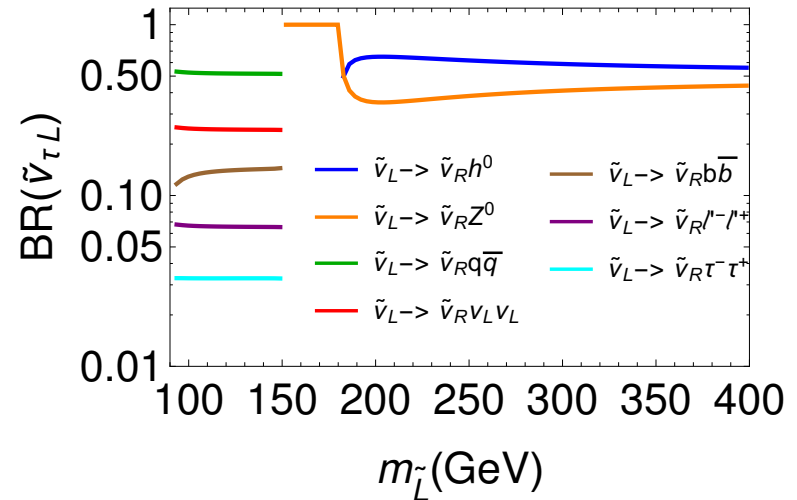
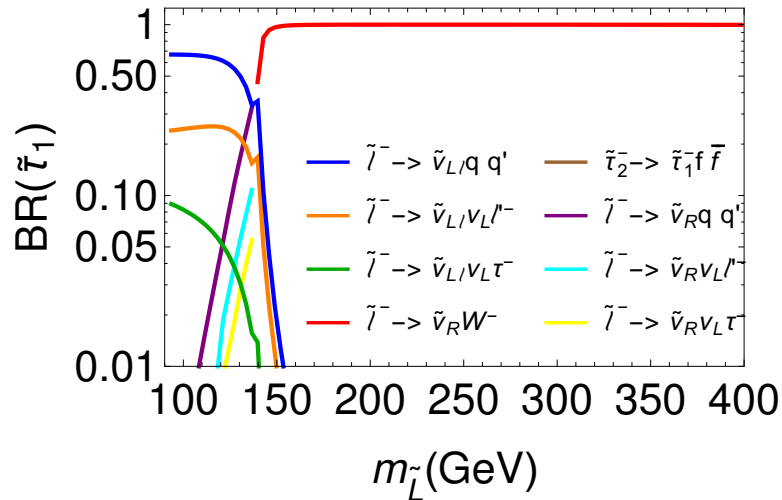
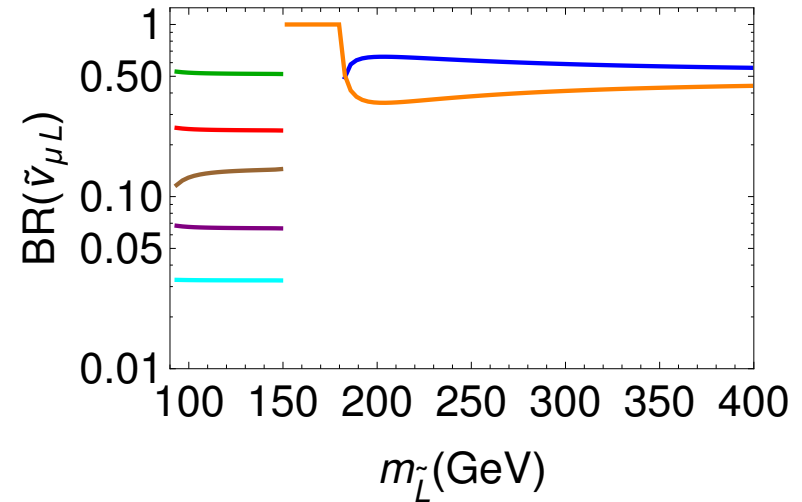
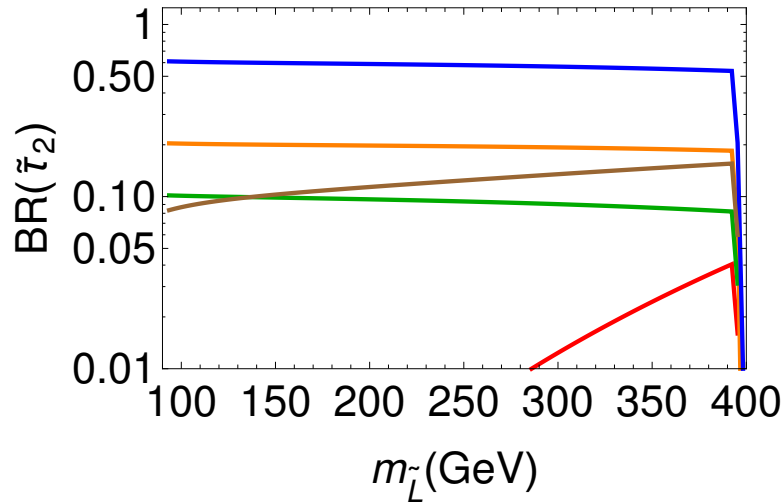


Z' couplings:

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

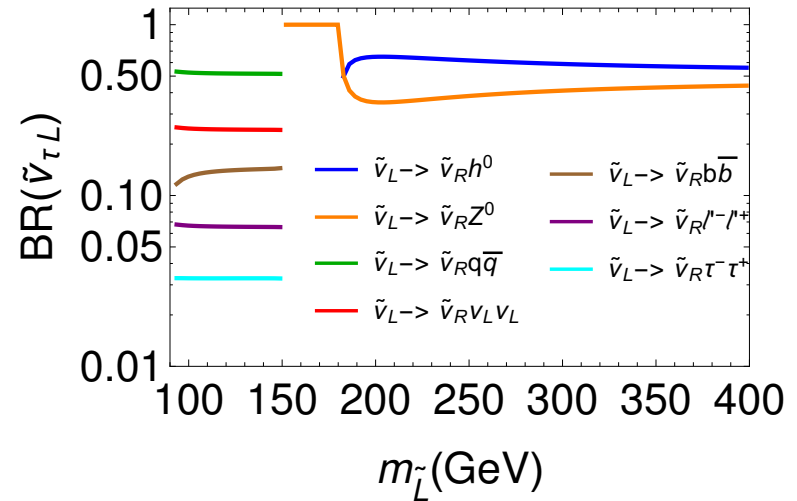
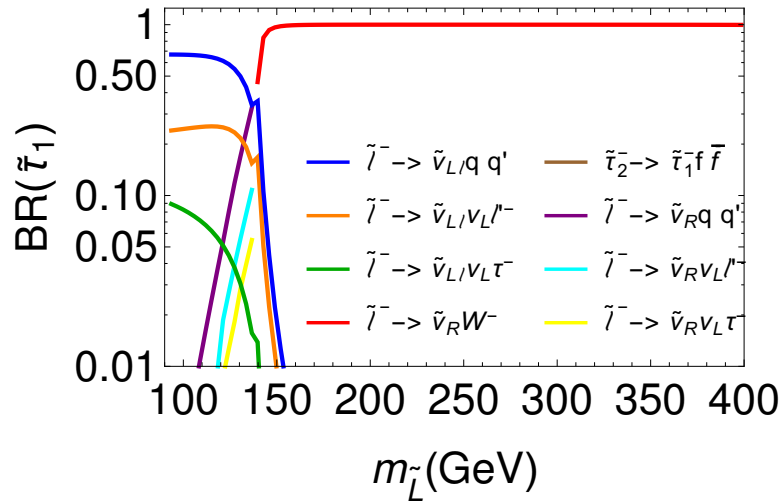
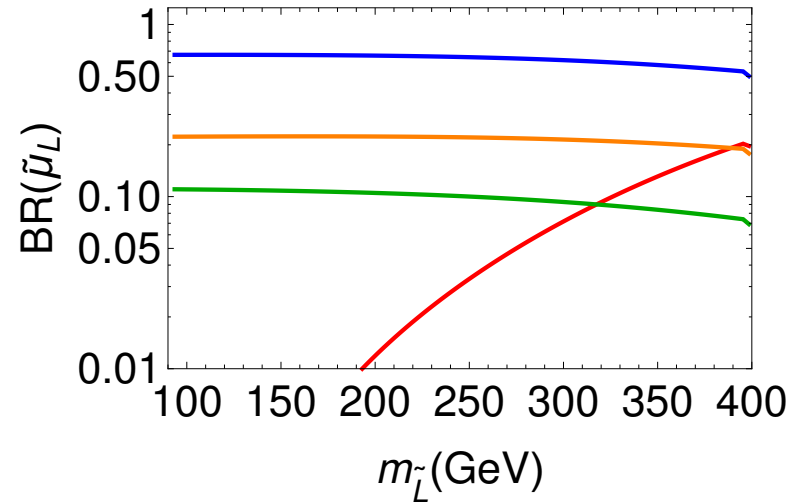
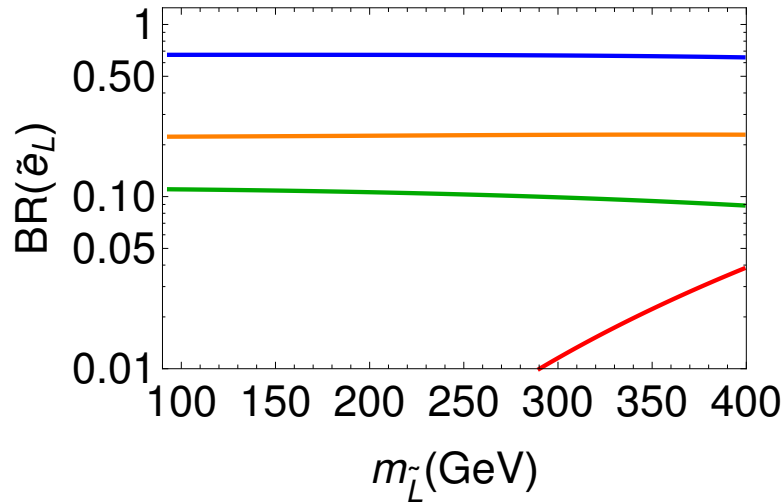
No.	$\tilde{g} \neq 0$	$\tilde{g} = 0$
BL1	1680 GeV	1840 GeV
BL2	1700 GeV	1910 GeV

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



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

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



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