Supersymmetry, Neutrinos and the LHC

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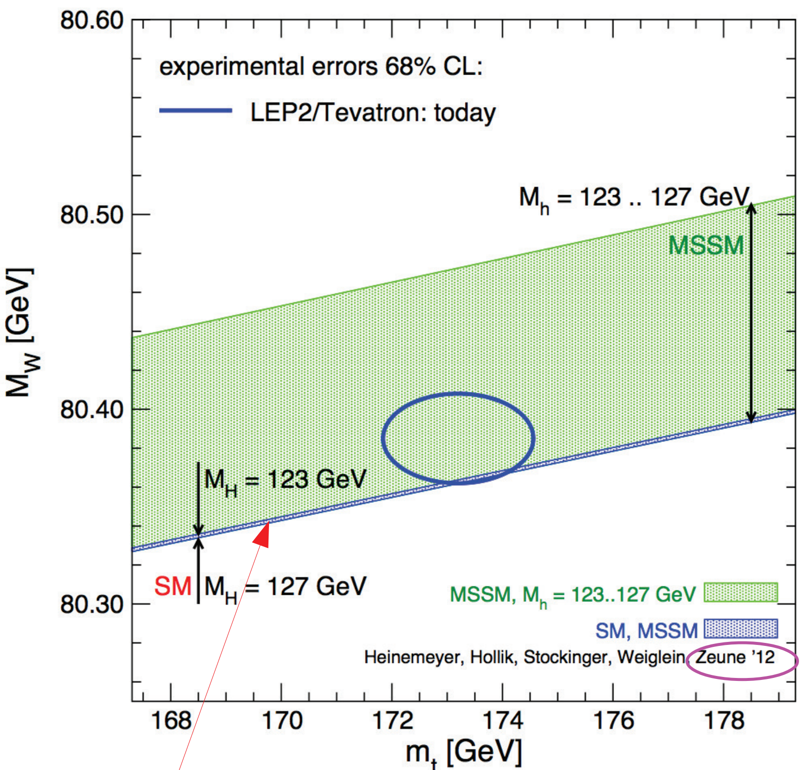
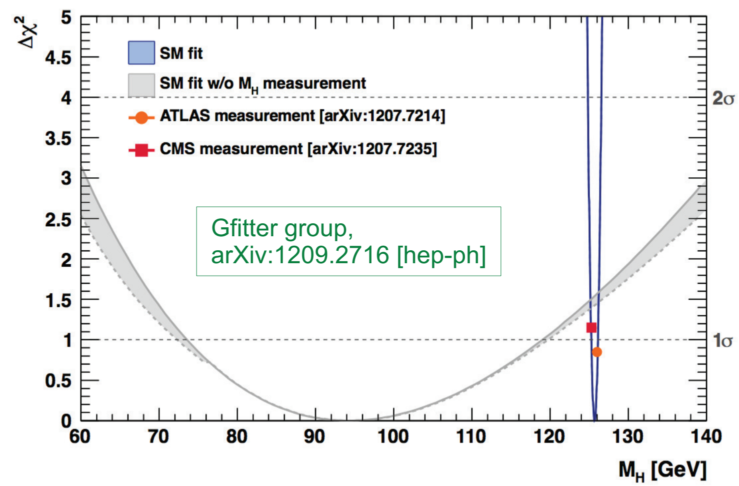
Content

W boson mass



In the context of the standard model, the mass of the new boson discovered by ATLAS+CMS is inside this blue band.

Comparison of indirect constraints on the Standard Model Higgs boson and the direct measurements of the mass of the new boson discovered by ATLAS and CMS:



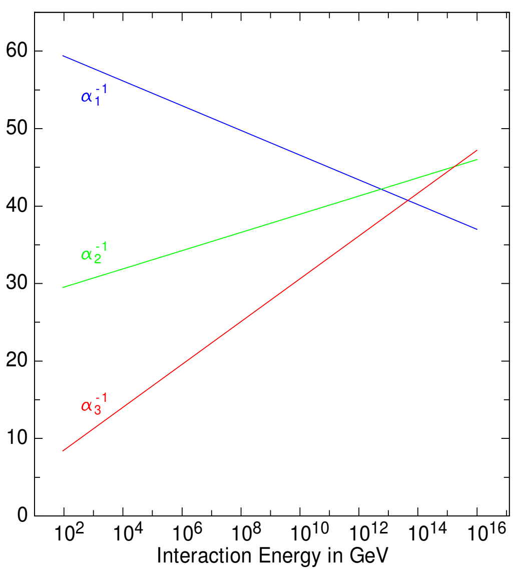
Consistent at the 1.3 σ level.

Why do we want to extend the SM

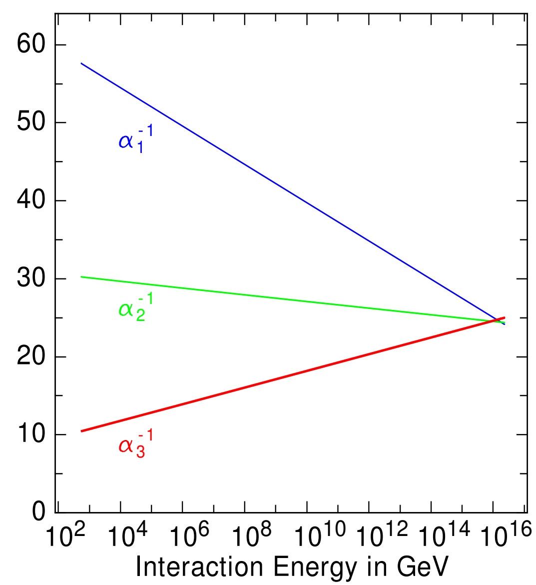
- How to combine gravity with the SM?
  $\Rightarrow$ local Supersymmetry (SUSY) implies gravity
- SM particles can be put in multiplets of larger gauge groups
  - in $SU(5)$: $1 = \nu_R^c$, $5 = (d_{\alpha,R}^c, \nu_{l,L}, l_L)$, $10 = (u_{\alpha,L}, u_{\alpha,R}^c, d_{\alpha,L}, l_R)$
  - in $SO(10)$: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

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

SM

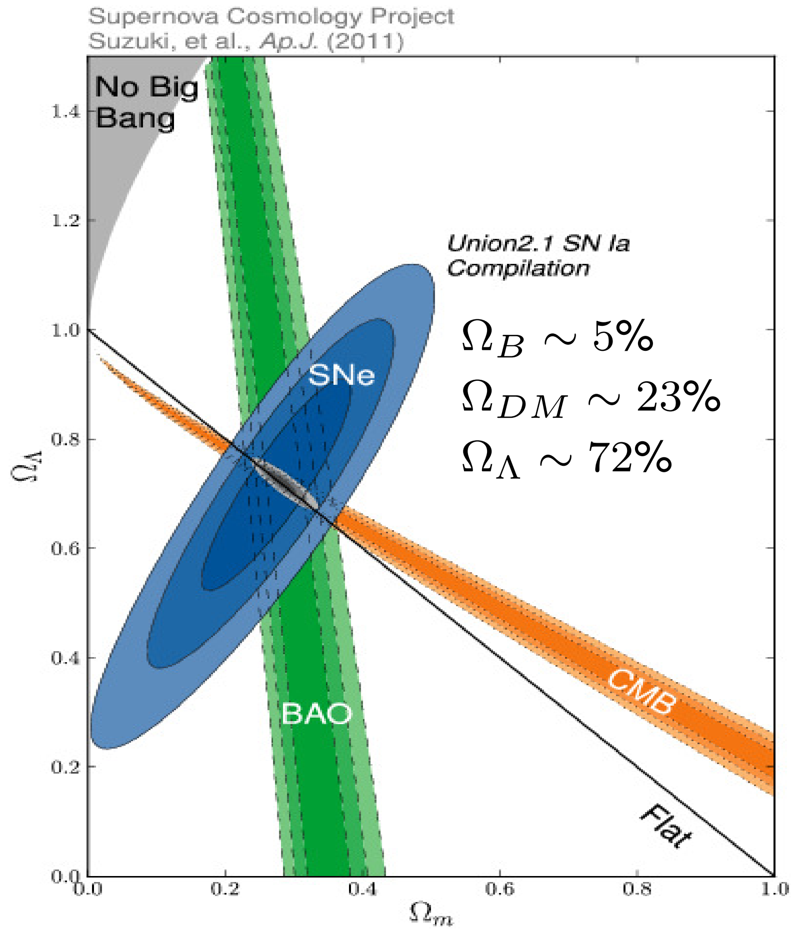


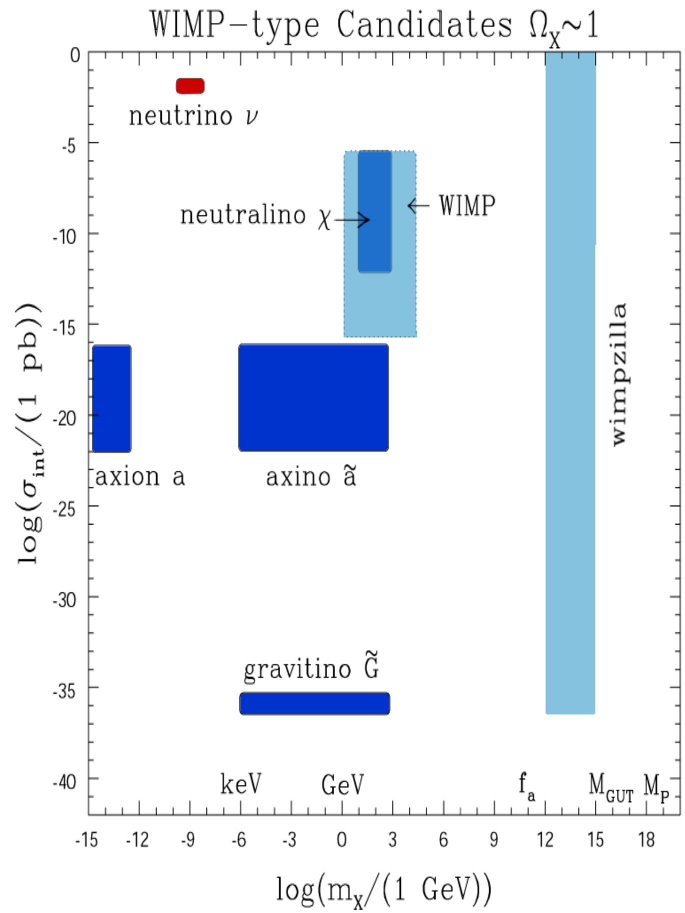
MSSM



Why do we want to extend the SM

- What is the nature of dark matter ?



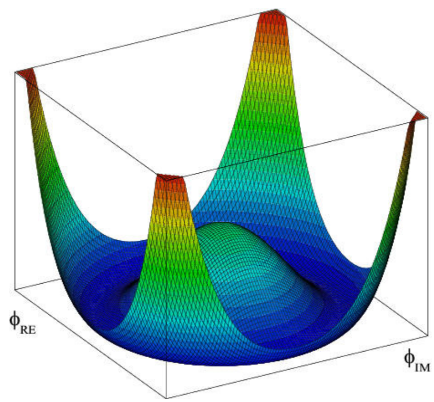


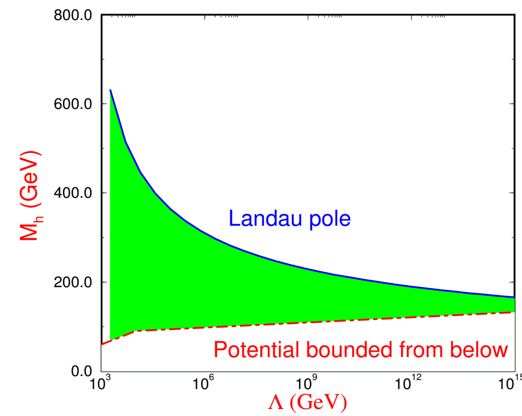
L. Roszkowski, astro-ph/0404052

- What is the origin of the observed baryon asymmetry?

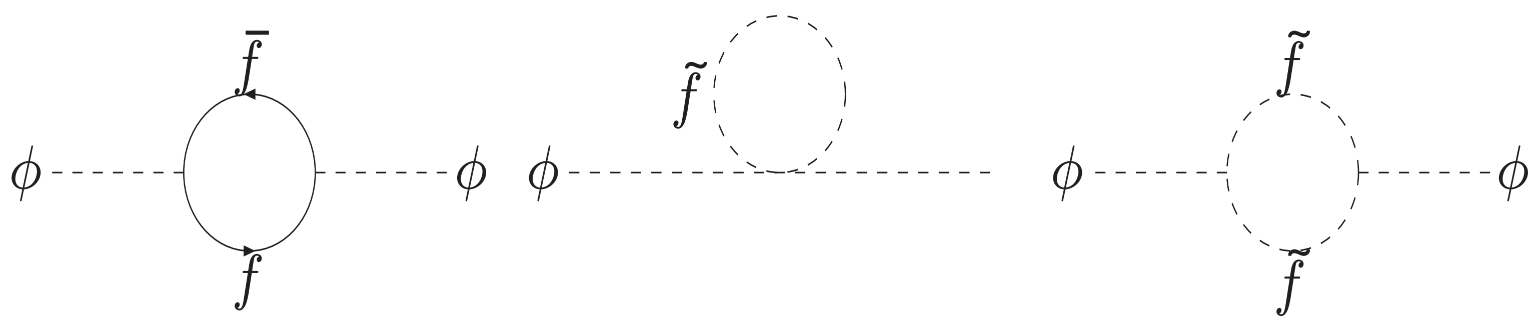
Why do we want to extend the SM

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

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

MSSM, generalities

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

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

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

soft SUSY breaking terms

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

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, $x = \Lambda/M$, $\Lambda = O(100TeV) < M$

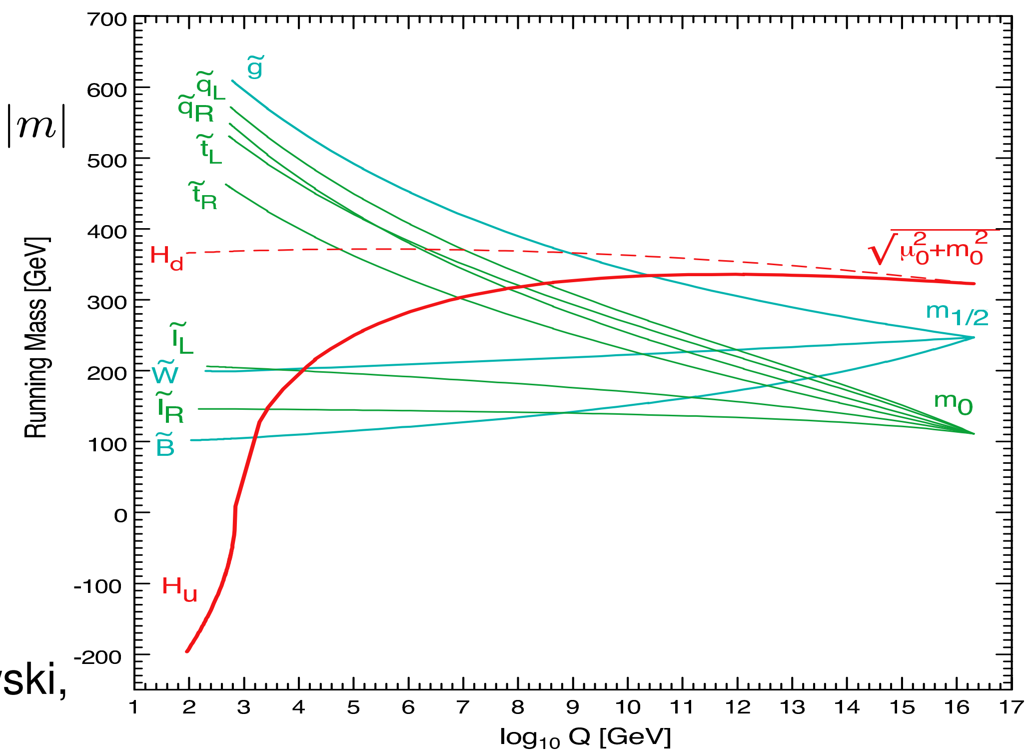
MSSM, generalities

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
  $m_A, \tan\beta = v_u/v_d$
  $m_h \leq m_Z$

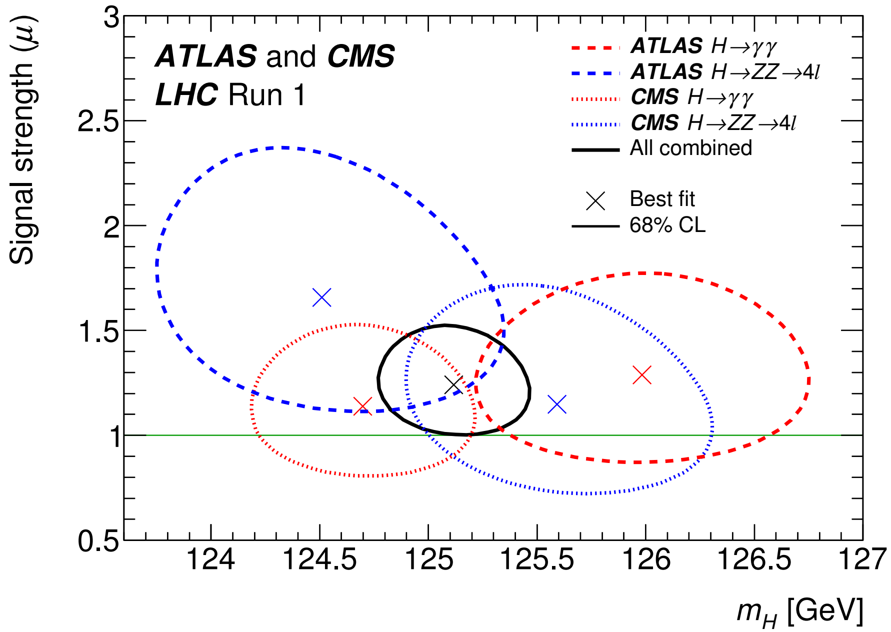
  Ellis et al; Okada et al; Haber,Hempfling; Hoang et al; Carena et al; Heinemeyer et al; Zhang et al; Brignole et al; Harlander et al; Kant,Harlander,Mihaila,Steinhauser;...

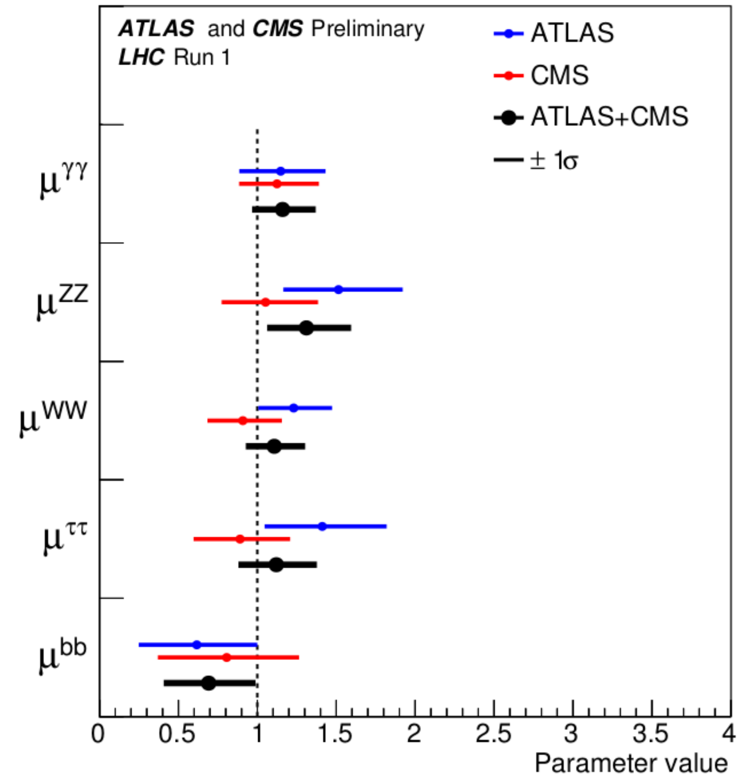
  at higher order:

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

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

Higgs results in a nut-shell, status 2015/16





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

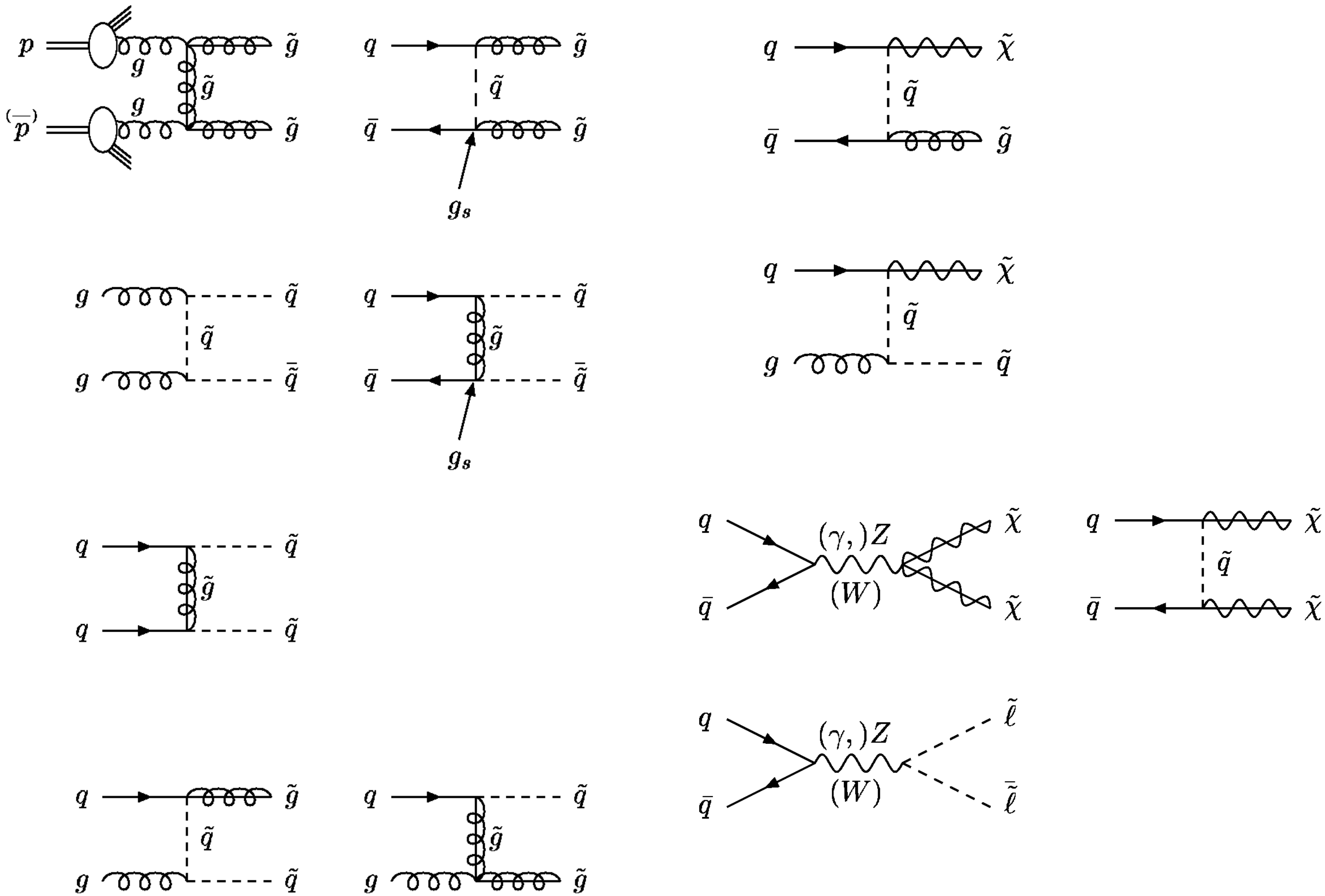
PRL **114** (2015) 191803

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

SUSY @ LHC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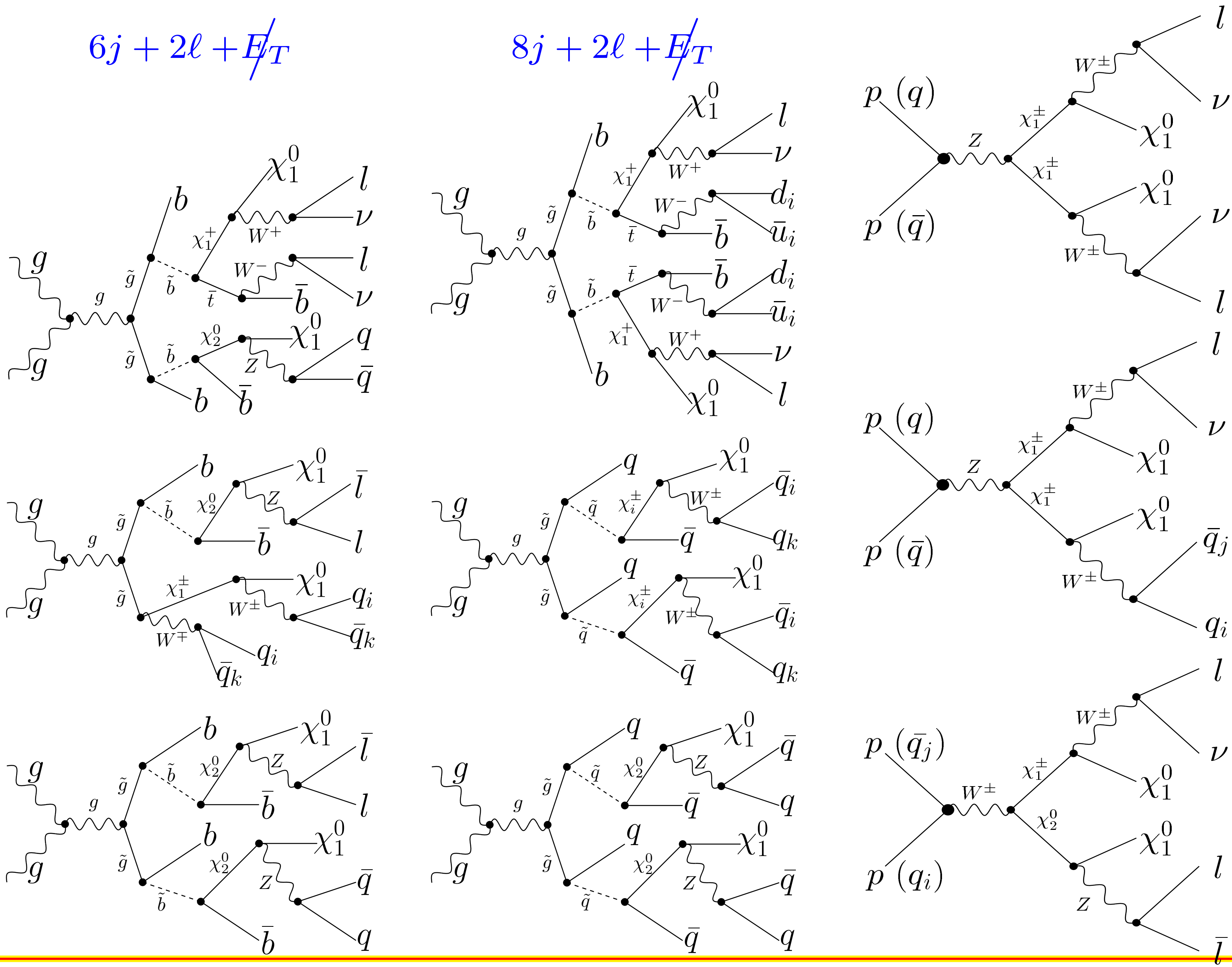
$6j + 2\ell + \not{E}_T$ $\qquad$ $8j + 2\ell + \not{E}_T$



2ℓ

$\not{E}_T$

ℓ

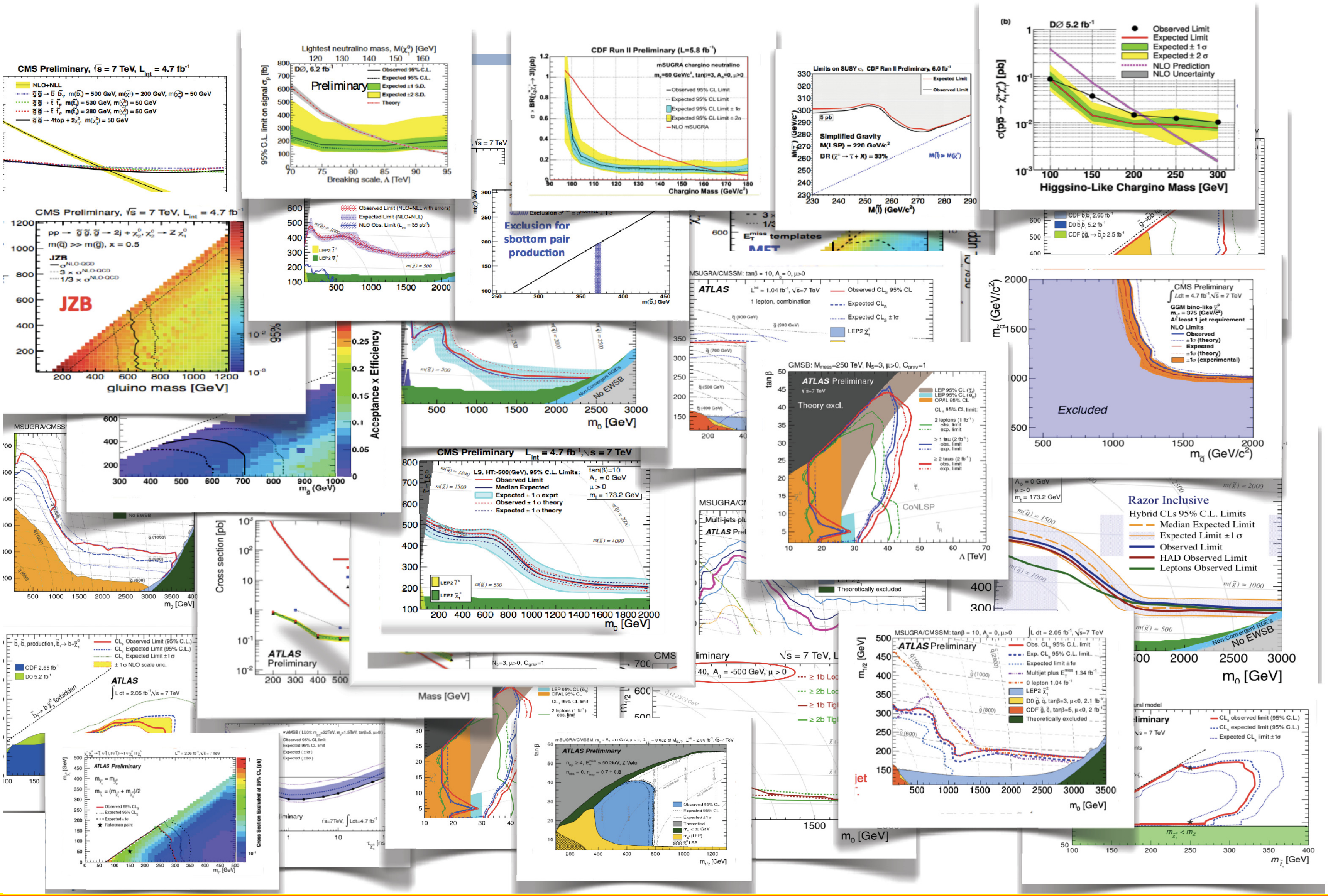
$2j$

$\not{E}_T$

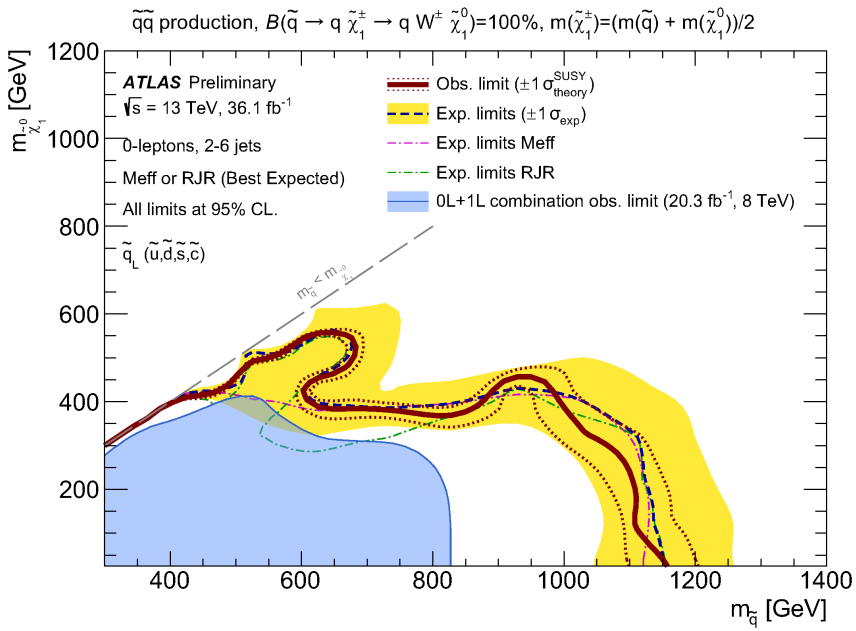
3ℓ

$\not{E}_T$

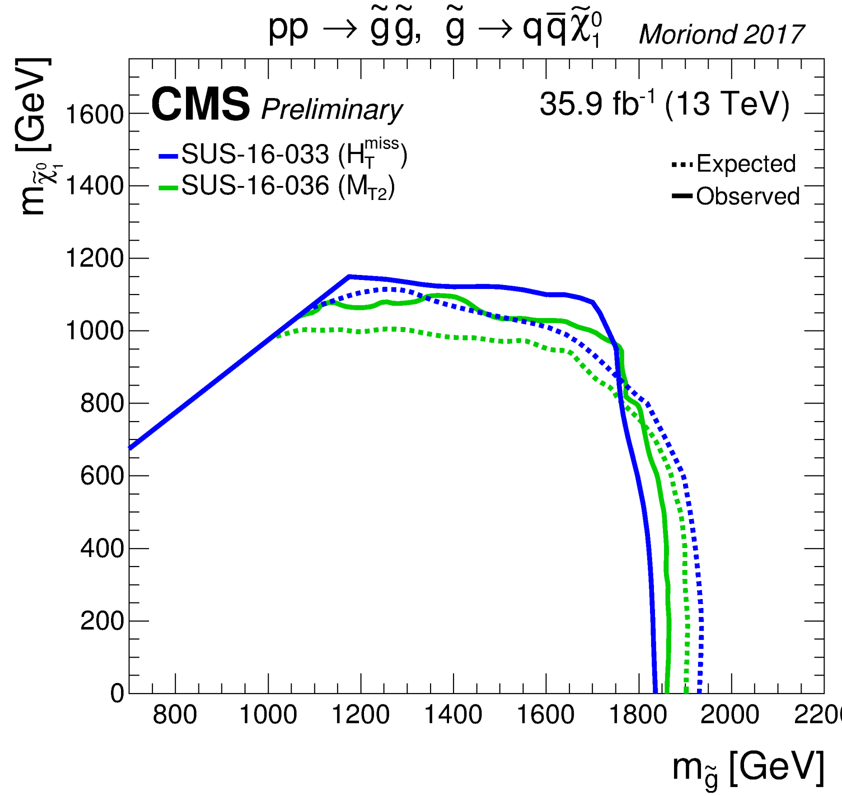
BSM searches, so far hardly anything …



Examples for SUSY searches 13 TeV data



ATLAS-CONF-2017-022



LHC data, in particular m_h, high scale models

$m_h = 125.2$ GeV $\Rightarrow$ large loop contributions

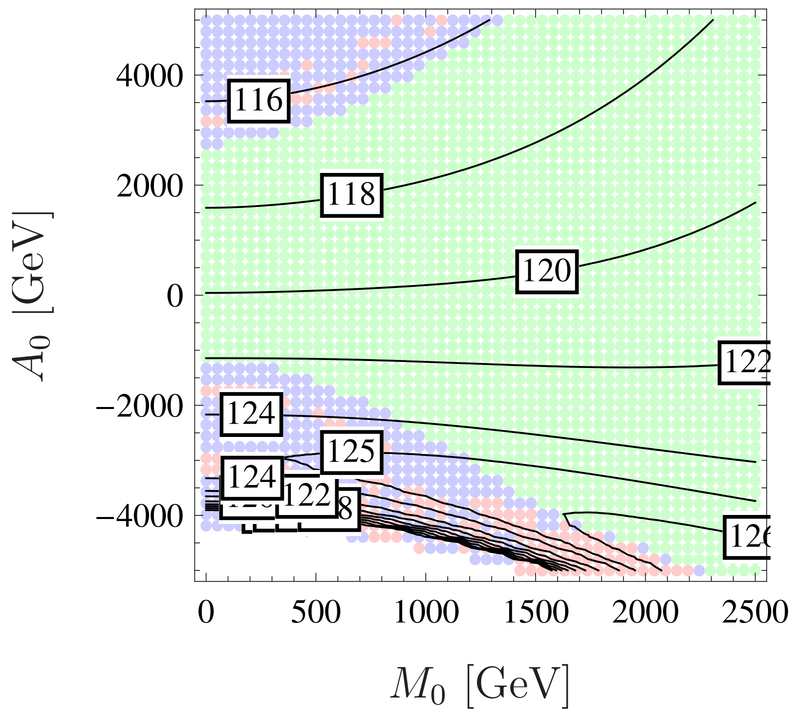
$\Rightarrow$ heavy stops and/or large left-right mixing for stops

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

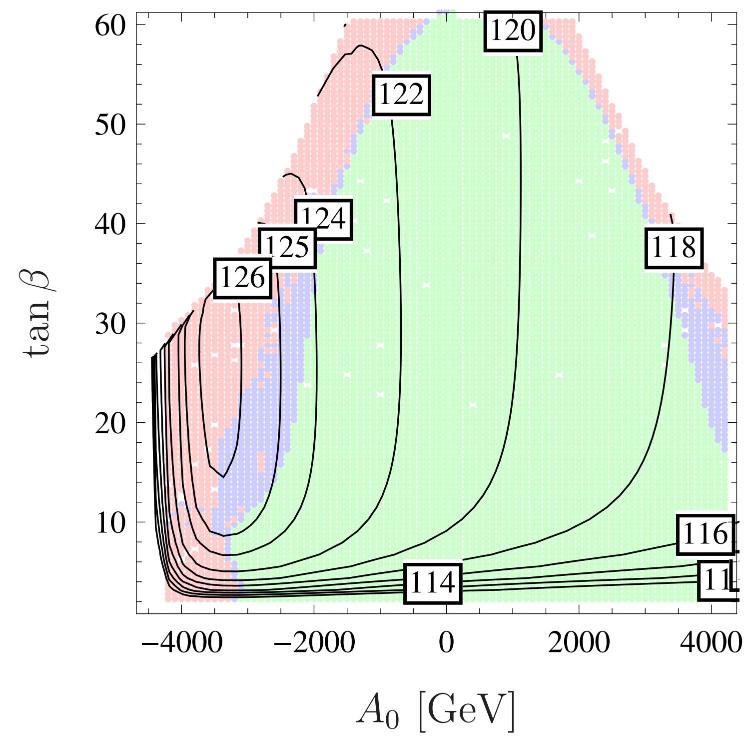
  more complicated models based on P. Meade, N. Seiberg and D. Shih, arXiv:0801.3278 $\Rightarrow$ allow additional terms
  e.g. S. Knappen, D. Redigolo, arXive:1606.07501 $m_{\tilde{t}_1} \simeq m_{\tilde{b}_1} \gtrsim 1$ TeV if $M_{\text{mess}} \gtrsim 10^{15}$ GeV
- CMSSM, NUHM models: $|A_0| \simeq 2m_0$,
  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 $\Rightarrow$ 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, $\tan\beta = 10$, $\mu > 0$



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

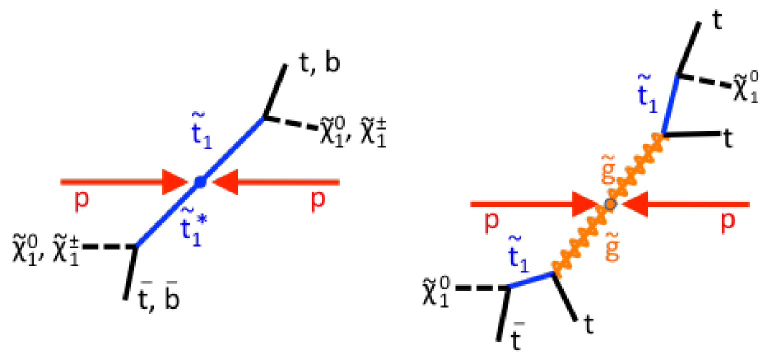
J.E. Camargo-Molina, B. O'Leary, W.P., F. Staub, arXiv:1309.7212

General MSSM

several studies, see e.g. S. Sekmen et al., arXiv:1109.5119; A. Arbey, M. Battaglia, A. Djouadi and F. Mahmoudi, arXiv:1211.4004; M. Cahill-Rowley, J. Hewett, A. Ismail and 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

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



BRs depend on the nature of $\tilde{t}_1$ and $\tilde{b}_1$
Higgsino mass: $\mu + \mu'$ with soft SUSY breaking parameter: $\mathcal{L} = -\mu' \tilde{H}_d \tilde{H}_u$

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

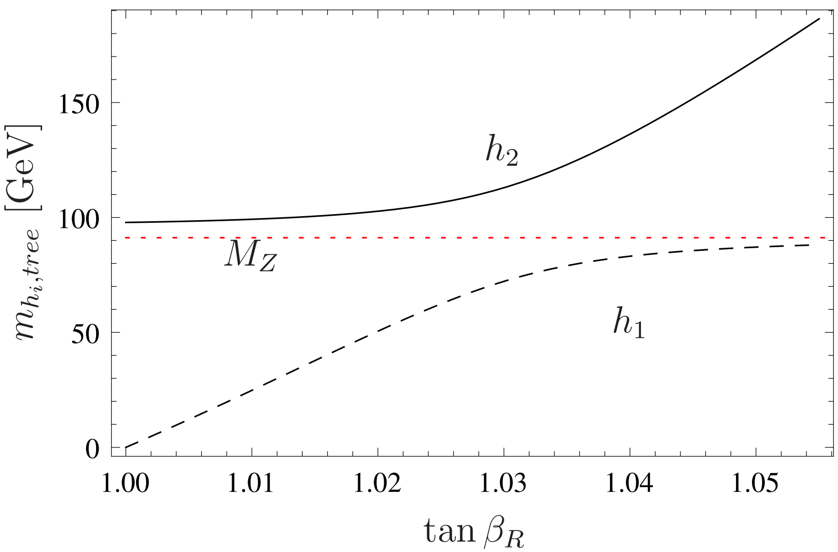
- $\tilde{\nu}_R^*$ or other exotic neutral scalar as DM candidate

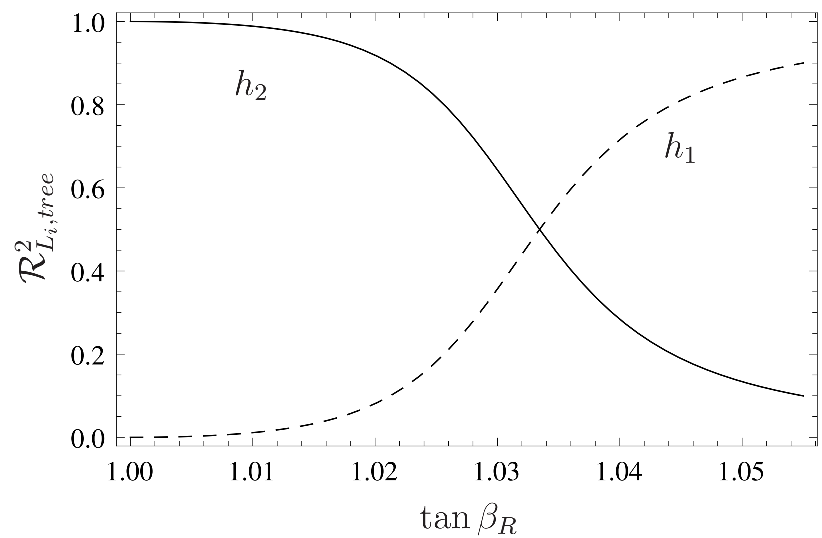
  $\Rightarrow$ interesting for (modified) Natural SUSY

Higgs sector I

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

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



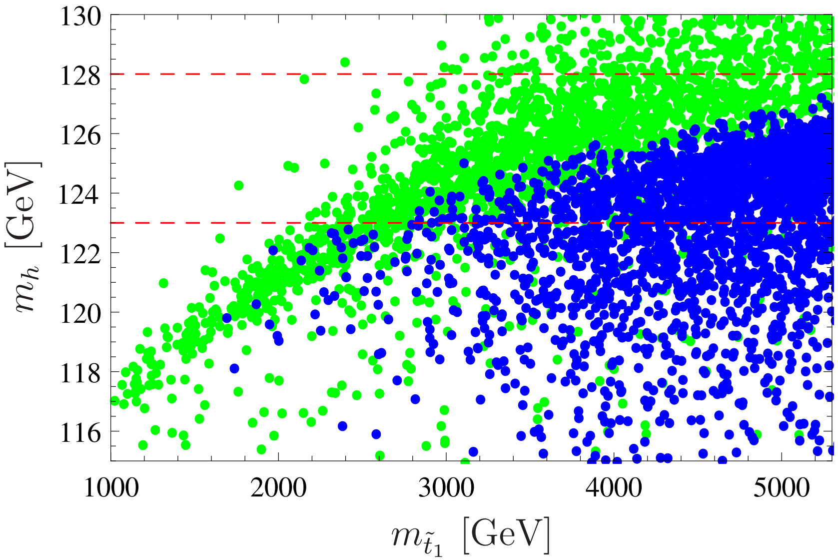


$n = 1,\ \Lambda = 5 \cdot 10^5$ GeV, $M = 10^{11}$ GeV, $\tan\beta = 30$, sign$(\mu_R) = -$, $diag(Y_S) = (0.7, 0.6, 0.6)$, $Y_\nu^{ii} = 0.01$, $v_R = 7$ TeV

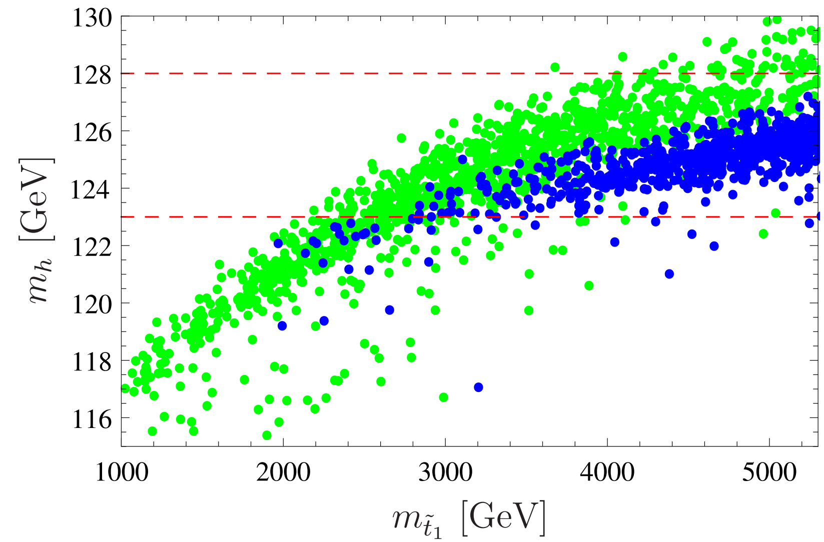
M.E. Krauss, W.P., F. Staub, arXiv:1304.0769

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

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

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

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

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

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

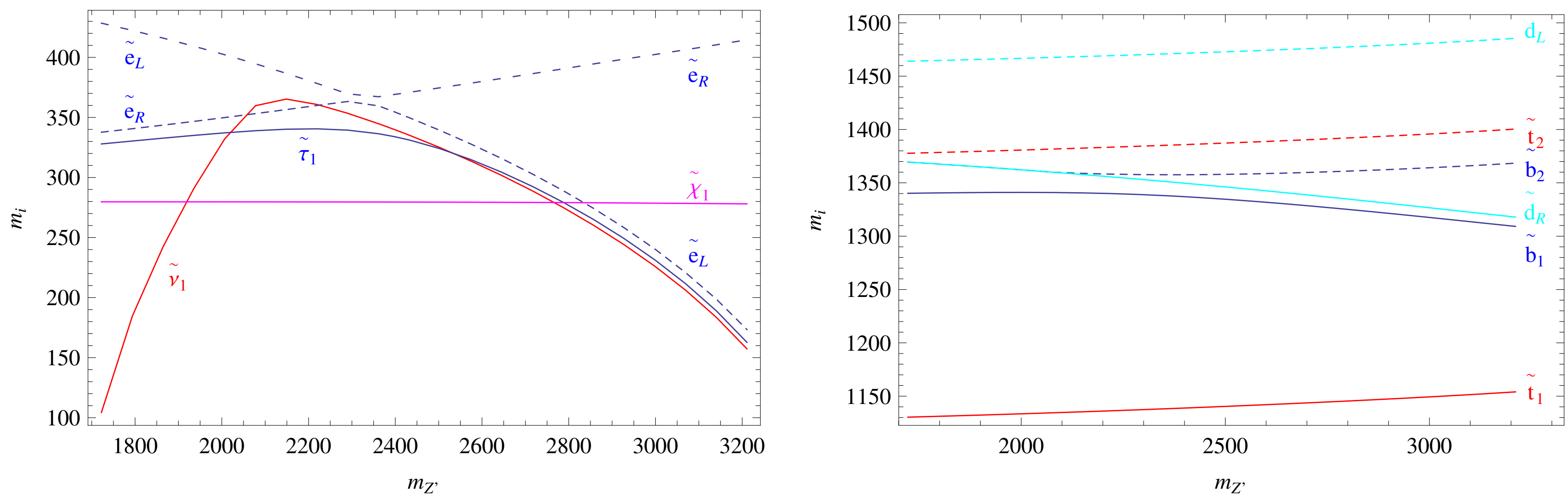
$$D_R = \frac{5 g_\chi}{32}\Big(2(g_\chi - g_{Y\chi}) v^2 c_{2\beta} + 5 g_\chi v_R^2 c_{2\beta_R}\Big)\mathbf{1}$$

Sfermions

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

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

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

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

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

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

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

BLRSP3: usual cascades similar to CMSSM, but

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

$\Rightarrow$ 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

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

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

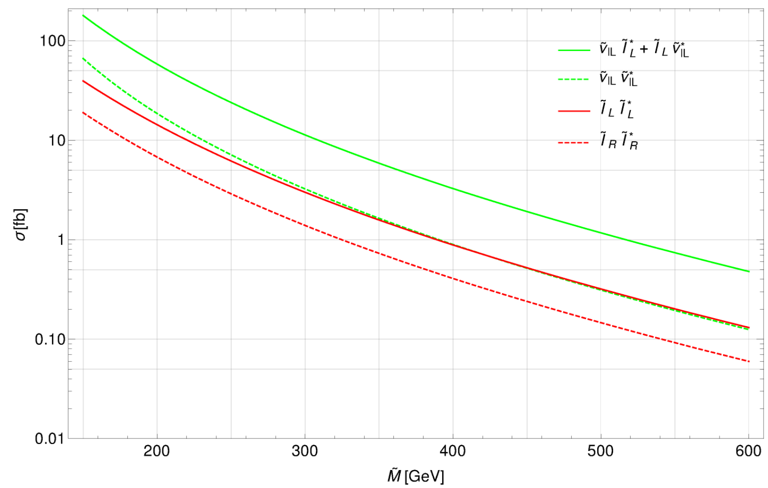
$$(Y_\nu)_{\ell 6} = -i (Z_\ell^{\rm NH})^* \sqrt{\frac{2 m_3 M_6}{v_u}} \cosh\gamma_{56}\, e^{\mp i\theta_{56}}$$

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

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

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

search for sleptons

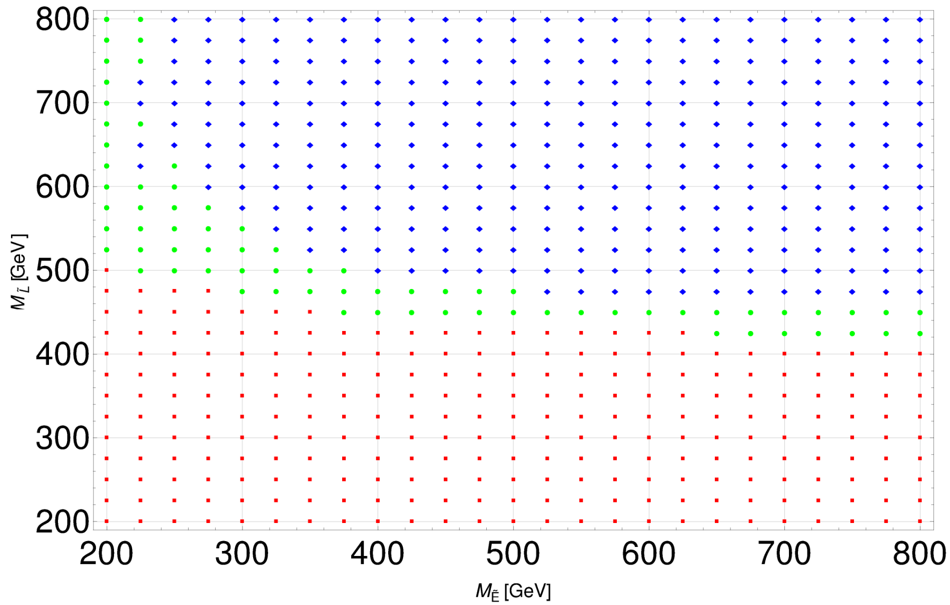


LHC, 13 TeV, tree-level
for searches: $\times$ K-factor 1.17
(B. Fuks et al., arXiv:1304.0790)

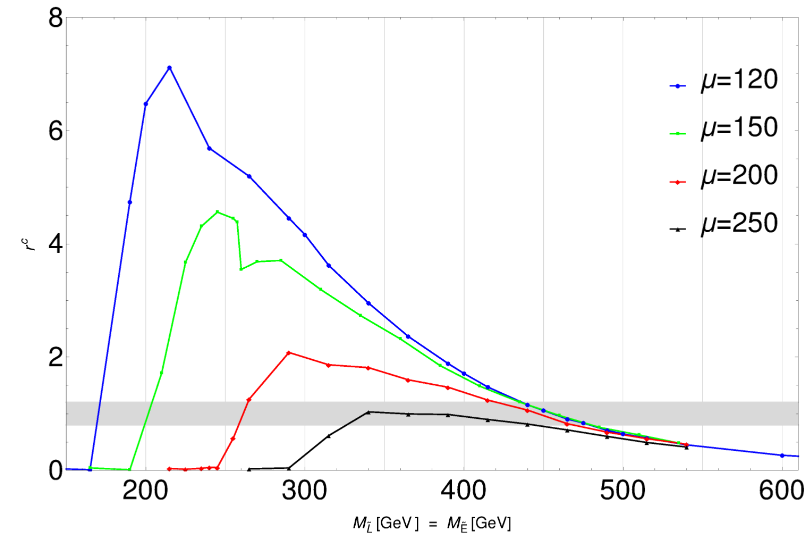
dominant decays:

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

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



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



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

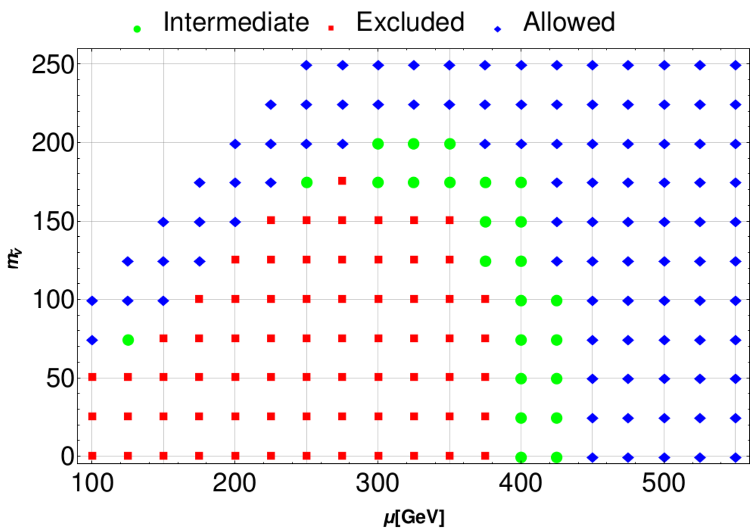
■ excluded, ● ambigous, ◇ allowed

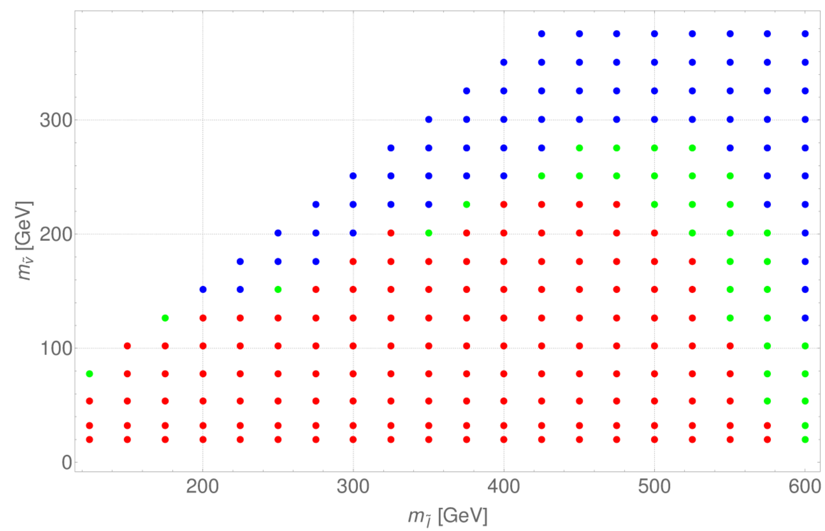
8+13 TeV data (13.9 fb^{-1})

using `CheckMATE 2.0` Th. Faber, J. Jones, Nh. Cerna-Velazco, WP arXiv:1705.xxxxx additional constraint

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

preliminary





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

$\mu = 25 + m_{\tilde{\nu}} < m_{\tilde{l}} = M_{\tilde{L}} = M_{\tilde{E}}$

using CheckMATE 2.0

Th. Faber, J. Jones, Nh. Cerna-Velazco, WP arXiv:1705.xxxxx

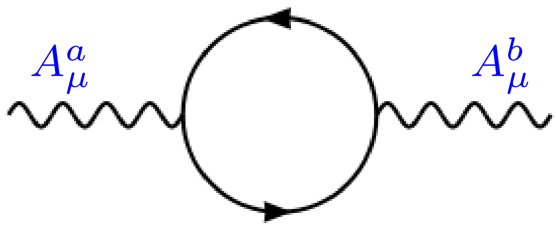
Conclusions

- 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)

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

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

$$v^2 = v_d^2 + v_u^2 \ , \ v_R^2 = v_{\chi_R}^2 + v_{\bar{\chi}_R}^2$$

expanding in v^2/v_R^2

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

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

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

Higgs sector, I

$$\chi_R = \frac{1}{\sqrt{2}}(\sigma_R + i\varphi_R + v_{\chi_R}) \; , \; \bar{\chi}_R = \frac{1}{\sqrt{2}}(\bar{\sigma}_R + i\bar{\varphi}_R + v_{\bar{\chi}_R})$$

$$H_d^0 = \frac{1}{\sqrt{2}}(\sigma_d + i\varphi_d + v_d) \; , \quad H_u^0 = \frac{1}{\sqrt{2}}(\sigma_u + i\varphi_u + v_u)$$

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

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

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

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

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

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

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

$\Rightarrow$ 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

Neutralinos I

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

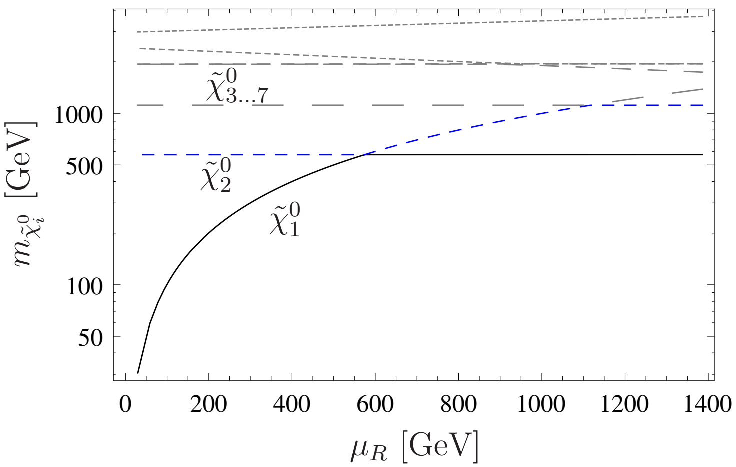
$$M_{\tilde{\chi}^0} =$$

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

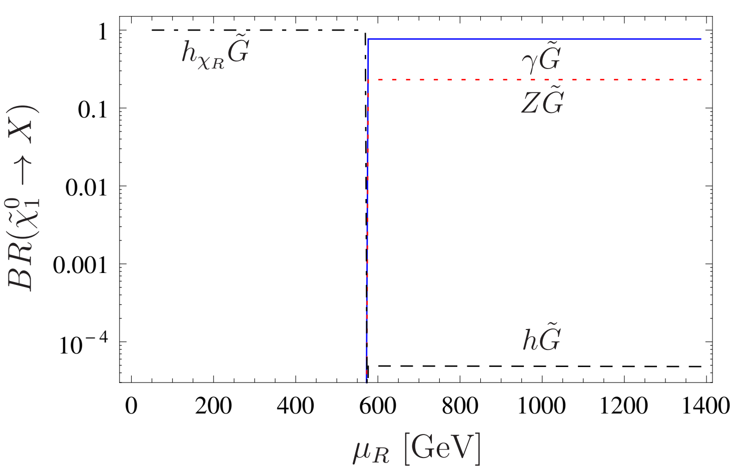
neglecting the mixing between the two sectors and setting $\tan\beta_R = 1$

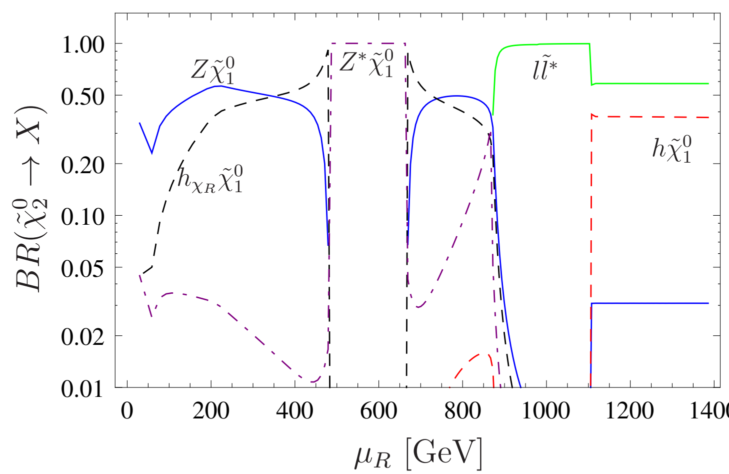
$$m_i: \ \mu_R\,, \quad \frac{1}{2}\left(M_\chi + \mu_R \pm \sqrt{\frac{1}{4} m_{Z'}^2 + (M_\chi - \mu_R)^2}\right)$$

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

Example spectra from high scale models

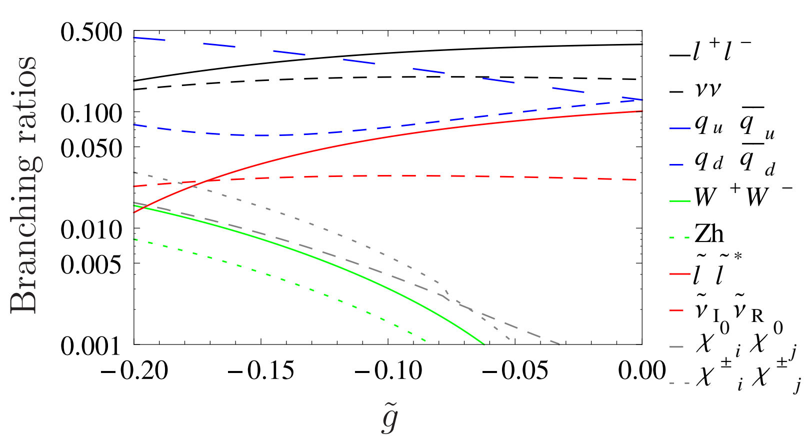
	BLRSP1	BLRSP2	BLRSP3	BLRSP4	BLRSP5
$m_{\tilde{\nu}_1}$	105.0	797.	91.6	542.	921.
$m_{\tilde{\nu}_{2/3}}$	215.0	797.	92.6	542.	924.
$m_{\tilde{\nu}_4}$	604.	1120.	253.	585.	940.
$m_{\tilde{e}_1}$	524.	1014.	255.	263.	693.
$m_{\tilde{e}_{2,3}}$	557.	1055.	266.	271.	706.
$m_{\tilde{u}_1}$	1436.	1185.	1247.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

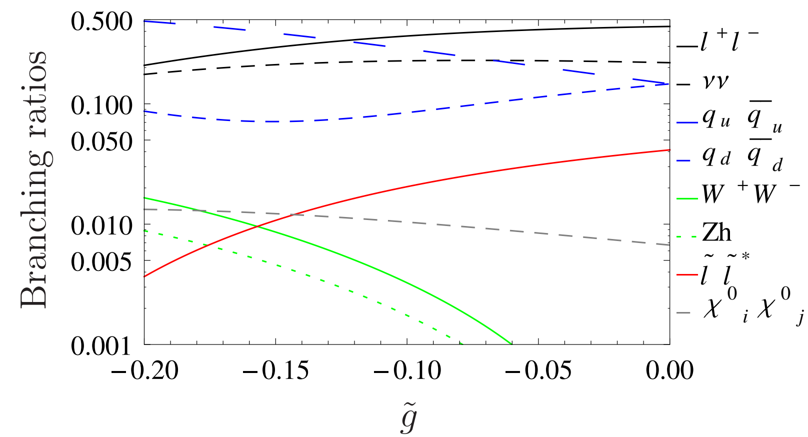
Z' physics, effect of gauge kinetic mixing I

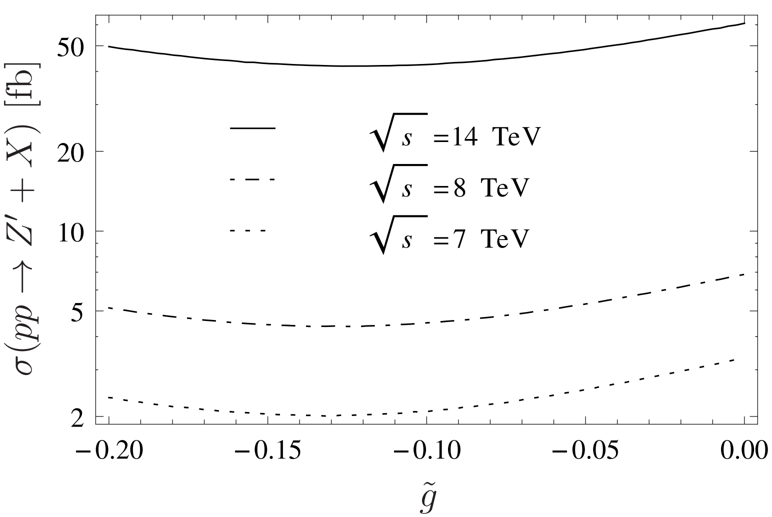
Z' couplings: $Q_{B-L} \cdot g_{B-L} \to Q_{B-L} \cdot g_{B-L} + Q_Y \cdot \tilde{g}$

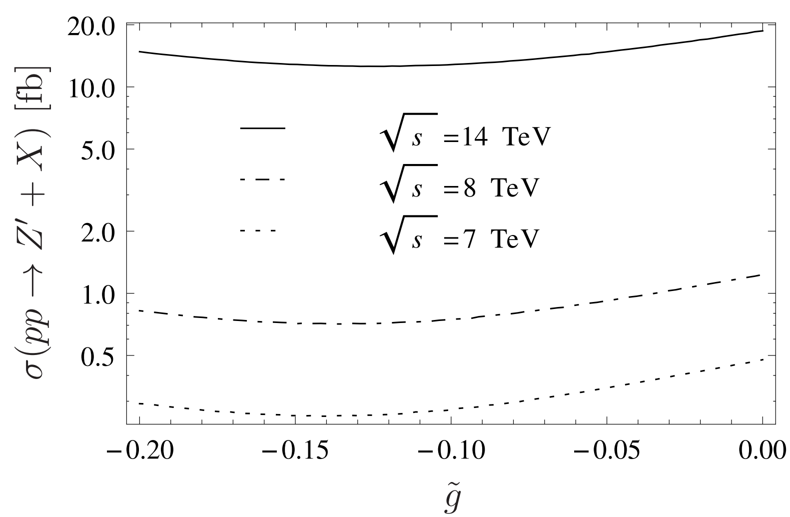
BL1



BL2

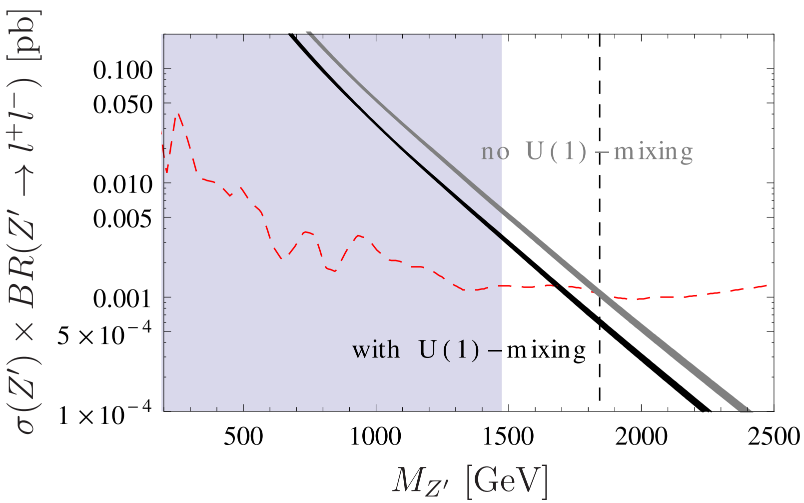




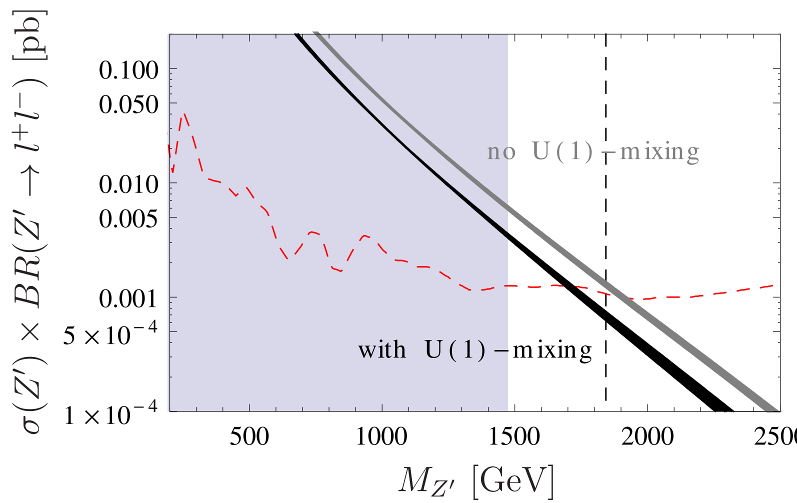


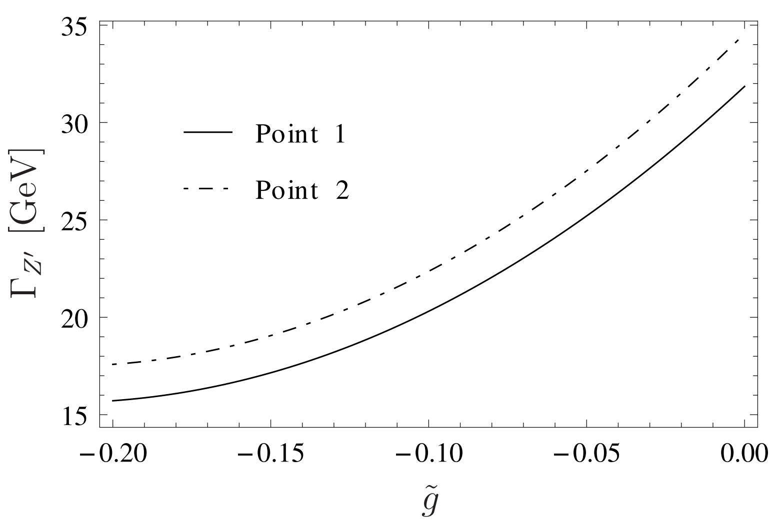
Z' physics, effect of gauge kinetic mixing II

BL1



BL2



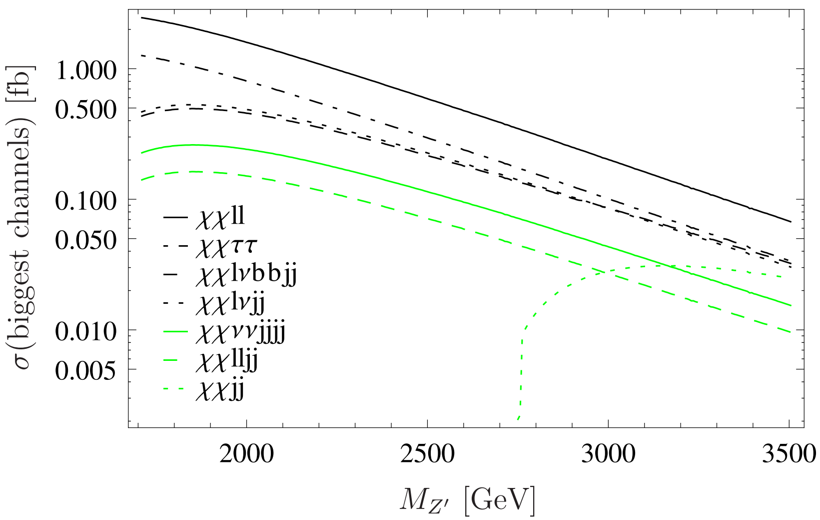


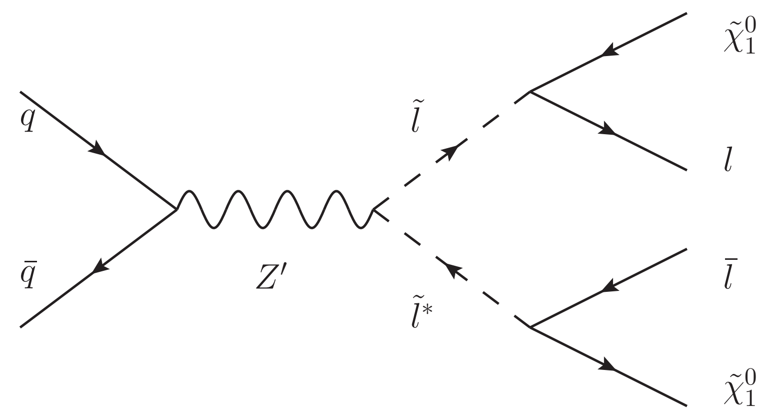
Z' couplings:

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

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



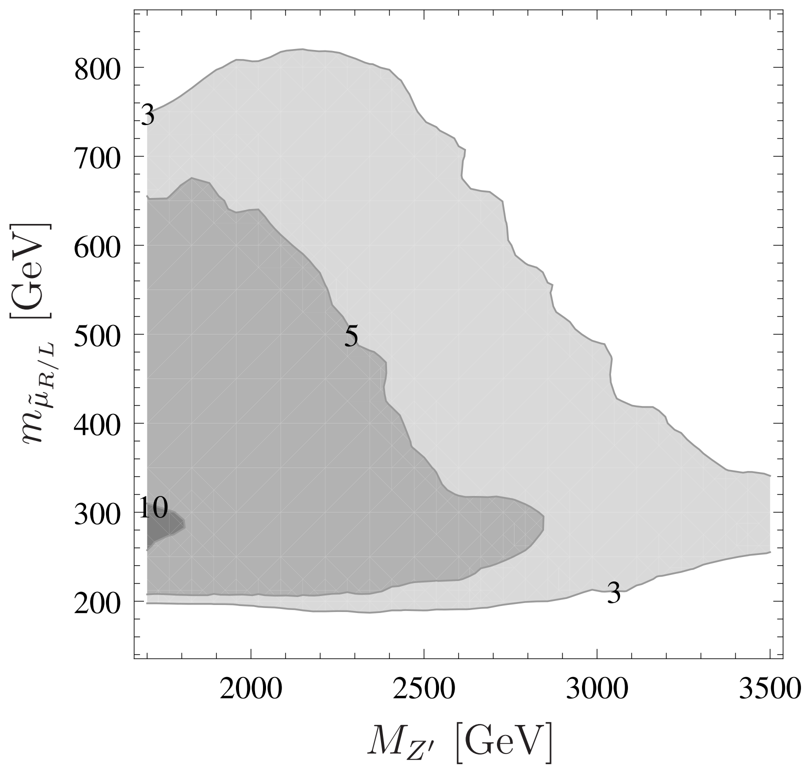


M. Krauss, B. O'Leary, W.P., F. Staub, arXiv:1206.3513

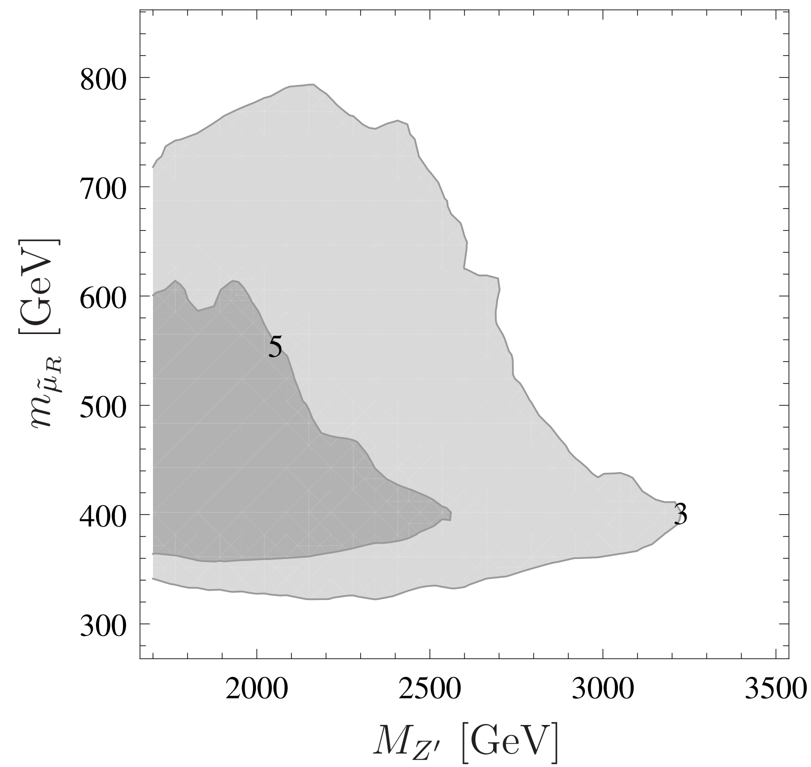
see also: J. Kang and P. Langacker, PRD **71** (2005) 035014; M. Baumgart, T. Hartman, C. Kilic, and L.-T. Wang, JHEP **0711** (2007) 084; C.-F. Chang, K. Cheung, and T.-C. Yuan, JHEP **1109** (2011) 058; G. Corcella and S. Gentile, arXiv:1205.5780 main dependence on masses ⇒ vary $m_{\tilde{l}}$ and $m_{Z'}$, $M_L = 1.2 M_E$

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

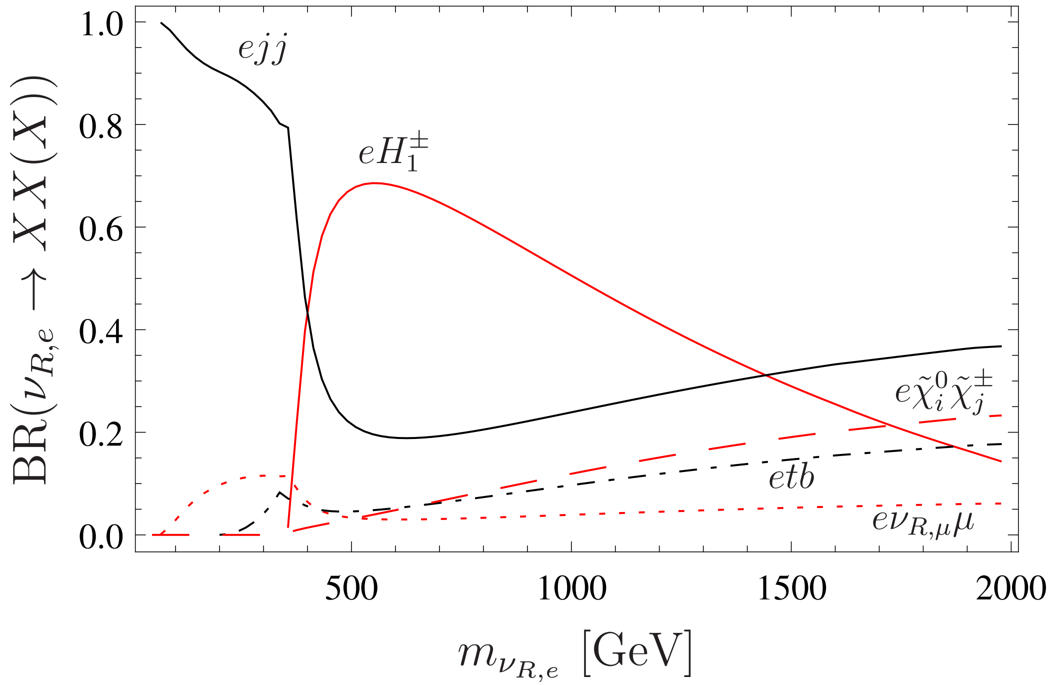
$$M_T = \sqrt{\left(\sqrt{p_T^2(\mu^+\mu^-) + M_{\mu\mu}^2} + p_T(\not{E})\right)^2 - (\vec{p}_T(\mu^+\mu^-) + \vec{p}_T(\not{E}))^2}$$

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

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

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

$SU(2)_L \times SU(2)_R \times U(1)_{B-L}$, ν_R decays



$m_{W'} = 2.2$ 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
- $\theta_{\tilde{t}}$: $0°, 45°, 90°$
- $\theta_{\tilde{b}}$: $0°, 45°, 90°$
- $M_1 = M_2 = 1$ TeV
- everything else, including $\tilde{t}_2$, and $m_{\tilde{g}}$: 2 TeV, $\tilde{b}_2$ calculated

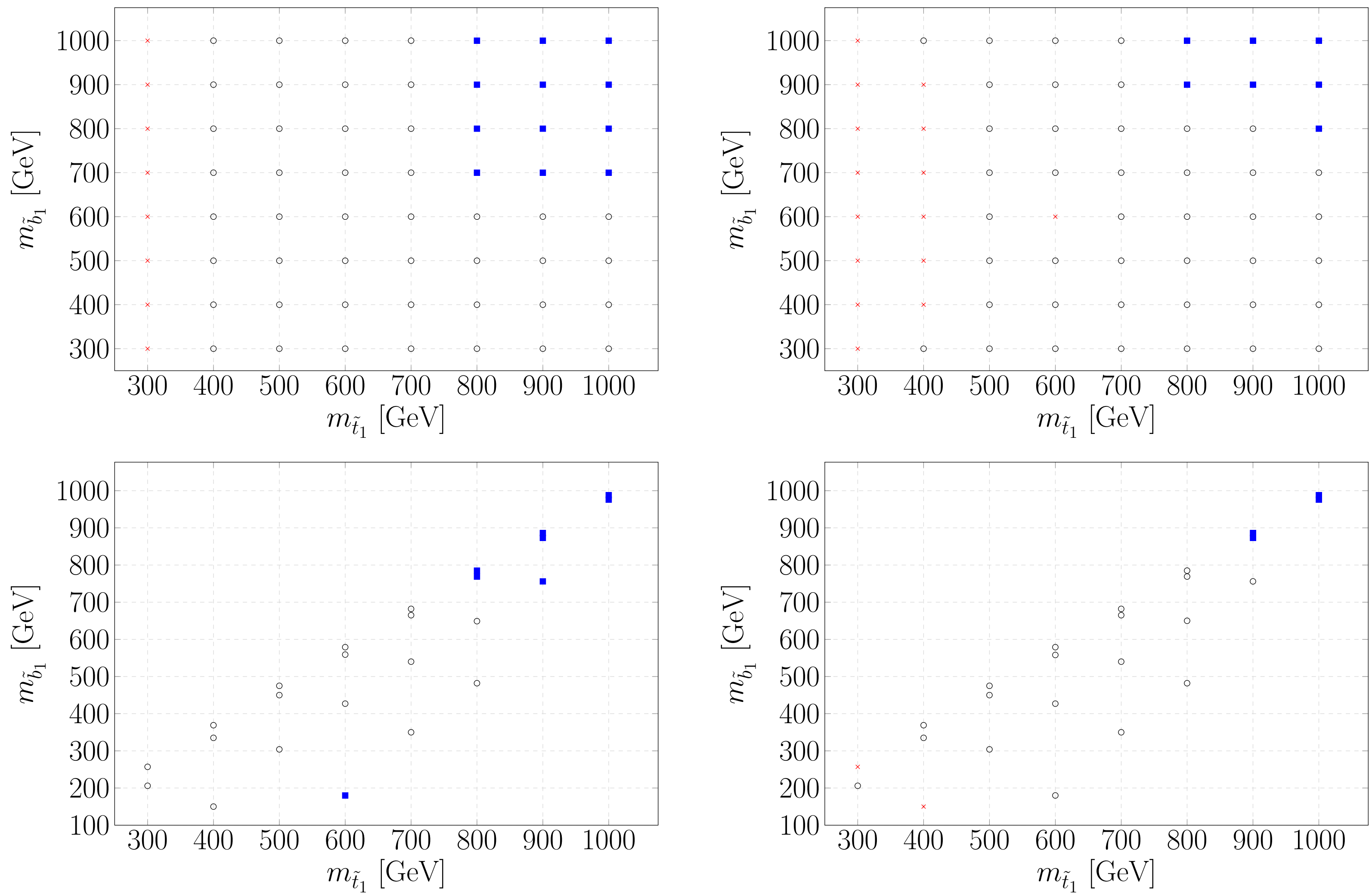
$$m_W^2 \cos 2\beta \;=\; m^2_{\tilde{t}_1}\cos^2\theta_{\tilde{t}} - m^2_{\tilde{t}_2}\sin^2\theta_{\tilde{t}} - m^2_{\tilde{b}_1}\cos^2\theta_{\tilde{b}} - m^2_{\tilde{b}_2}\sin^2\theta_{\tilde{b}} - m_t^2 + m_b^2$$

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