Supersymmetric neutrino mass models at the LHC

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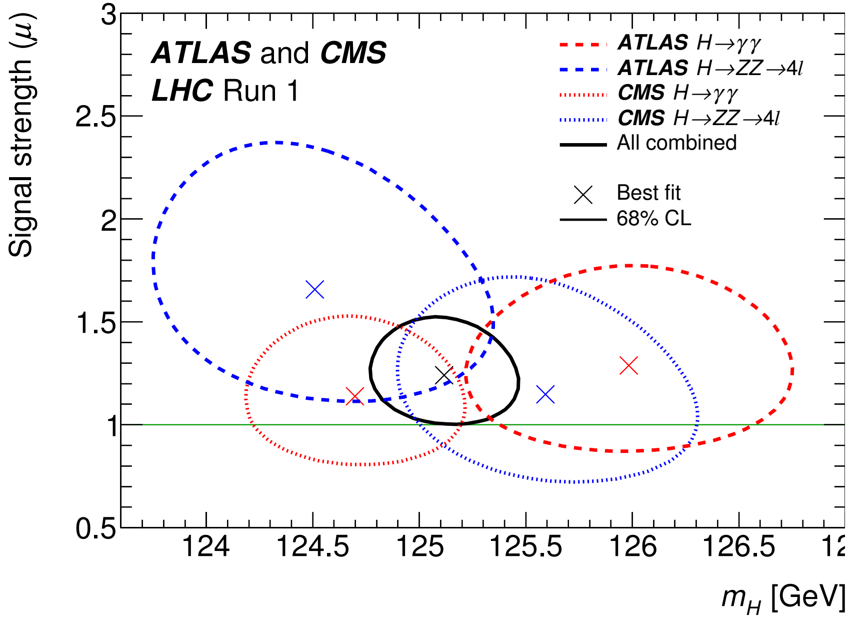
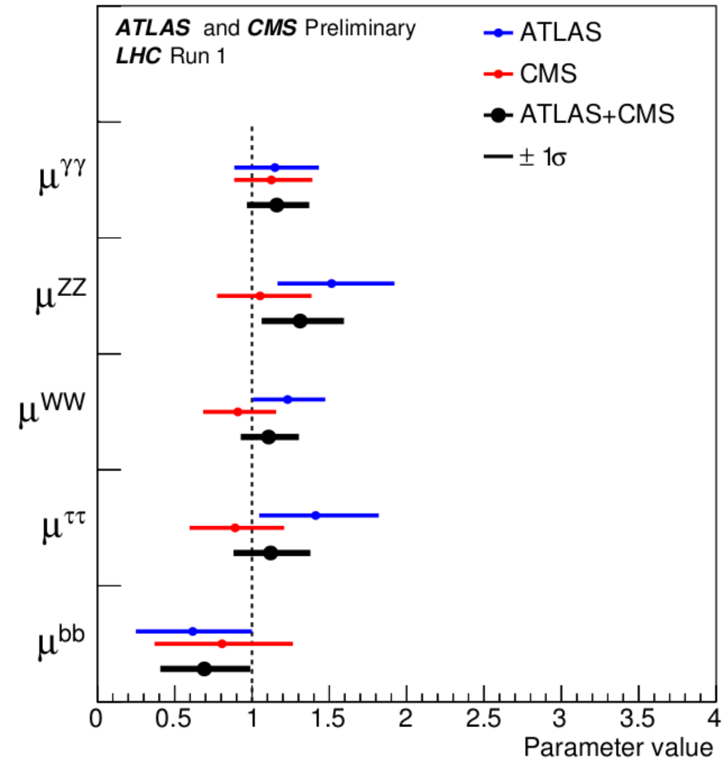
Content

- Higgs discovery and LHC BSM results: implications
- SUSY and Extended gauge groups
- ‘Natural’ SUSY and ν_R, $\tilde{\nu}_R$
- Conclusions

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-CONF-2015-044

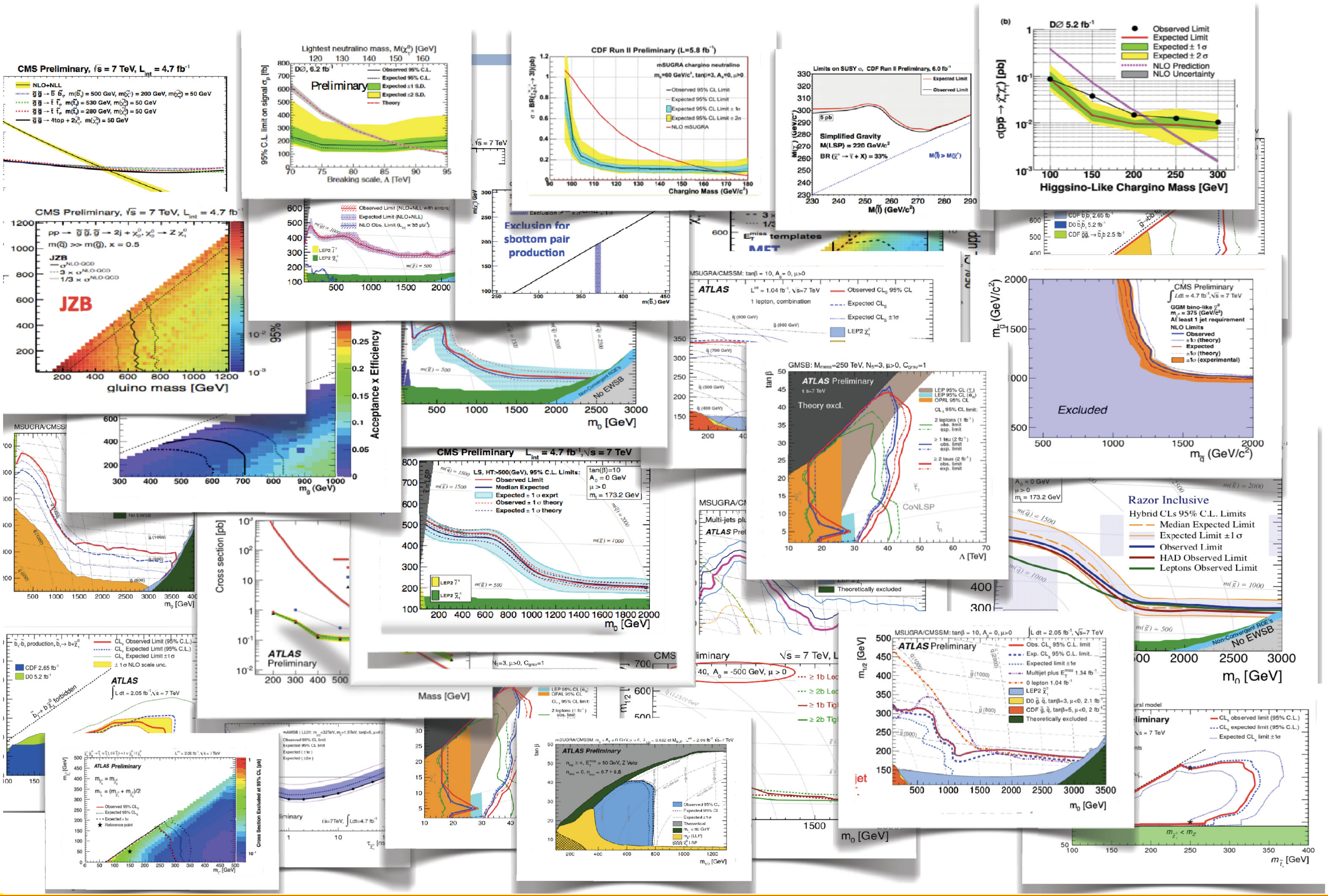
CMS-PAS-HIG-15-002

$m_H = 125.25 \pm 0.20$ (stat) ± 0.08 (sys) GeV

run 2, talk by R. Nicolaidou @ Moriond'17, QCD

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

BSM searches, so far hardly anything . . .



LHC data, in particular m_h, high scale models

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

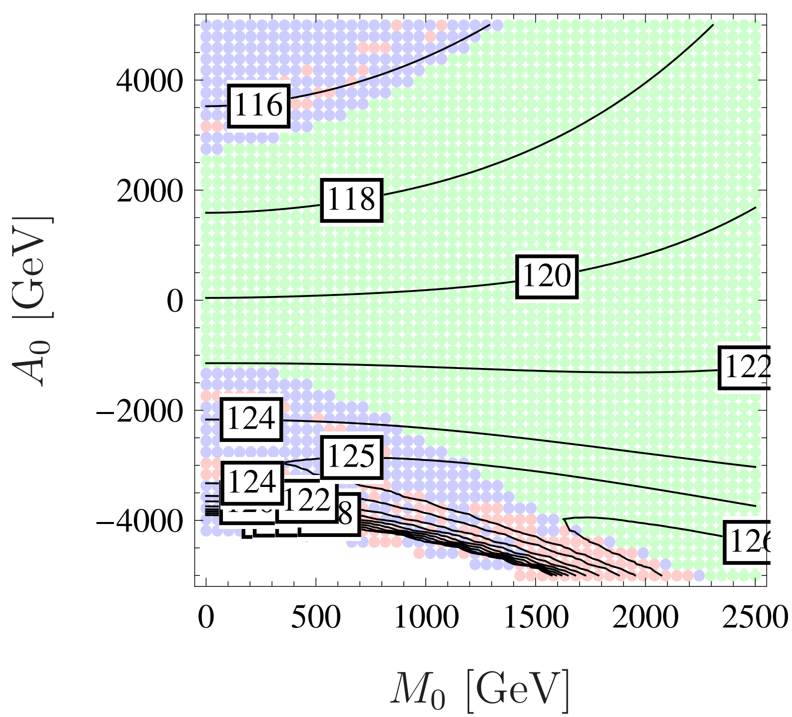
$\Rightarrow$ heavy stops and/or large left-right mixing for stops

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

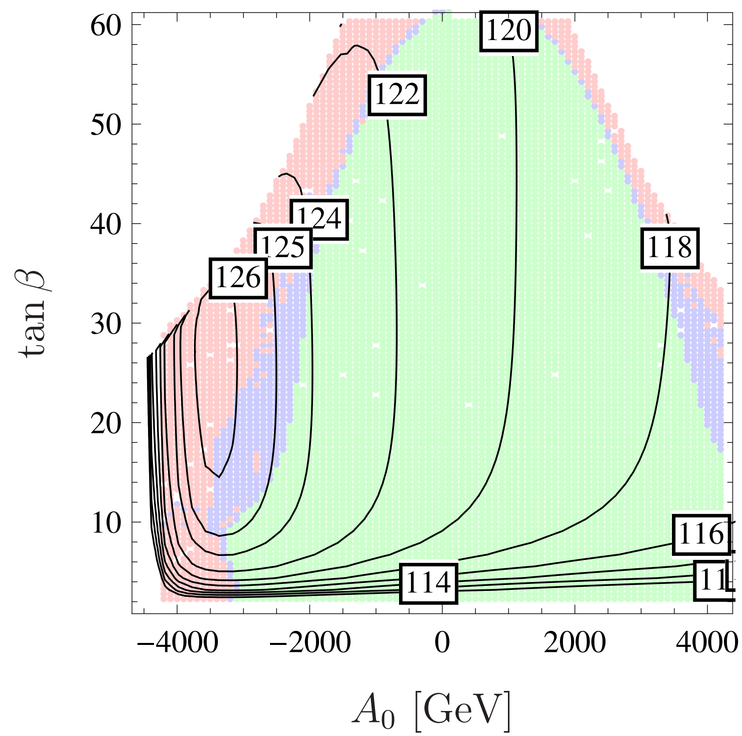
  more complicated models based on P. Meade, N. Seiberg and D. Shih, arXiv:0801.3278 $\Rightarrow$ allow additional terms
  e.g. S. Knappen, D. Redigolo, arXive:1606.07501 $m_{\tilde{t}_1} \simeq m_{\tilde{b}_1} \gtrsim 1$ TeV if $M_{\text{mess}} \gtrsim 10^{15}$ GeV
- CMSSM, NUHM models: $|A_0| \simeq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

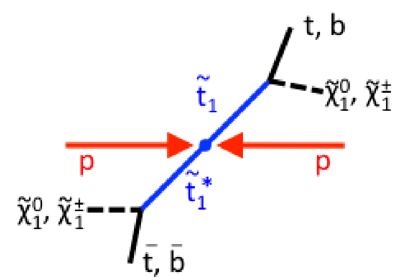
several studies, see e.g. S. Sekmen et al., arXiv:1109.5119; A. Arbey, M. Battaglia, A. Djouadi and F. Mahmoudi, arXiv:1211.4004; M. Cahill-Rowley, J. Hewett, A. Ismail and T. Rizzo, arXiv:1308.0297

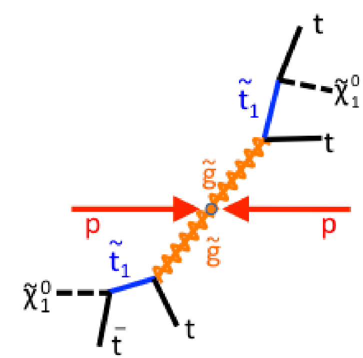
- generic signatures are well known: multi-lepton, multi-jets + missing E_T
- sub-class of general MSSM: 'natural SUSY'
  see e.g. M. Papucci, J. T. Ruderman and A. Weiler, arXiv:1110.6926;
  H. Baer, V. Barger, P. Huang, A. Mustafayev, X. Tata, arXiv:1207.3343
  keep only SUSY particles light needed 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

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





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
  extra $U(1)_\chi$: $m^2_{h,tree} \leq m_Z^2 + \frac{1}{4} g_\chi^2 v^2$

- 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

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 $B_{\mu_S} = 0$

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

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

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

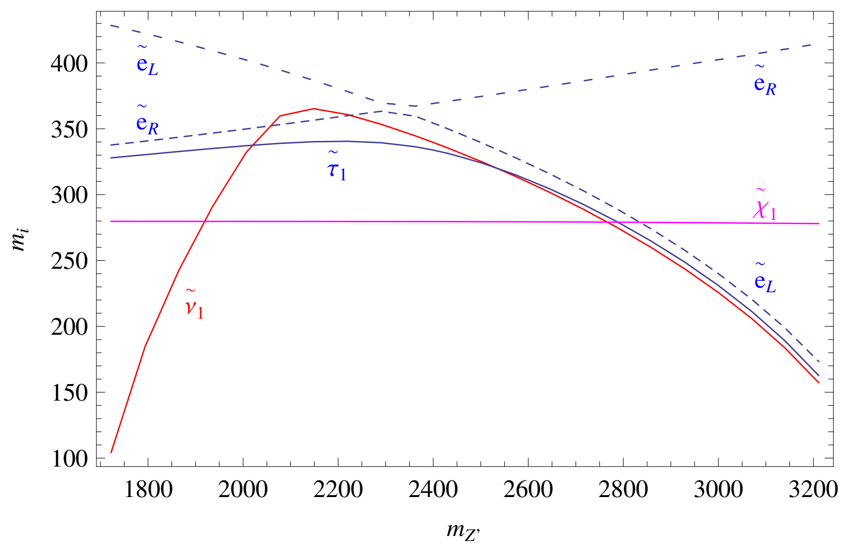
$$D_R = \frac{5g_\chi}{32}\Big(2(g_\chi - g_{Y\chi})v^2 c_{2\beta} + 5g_\chi v_R^2 c_{2\beta_R}\Big)\mathbf{1}$$

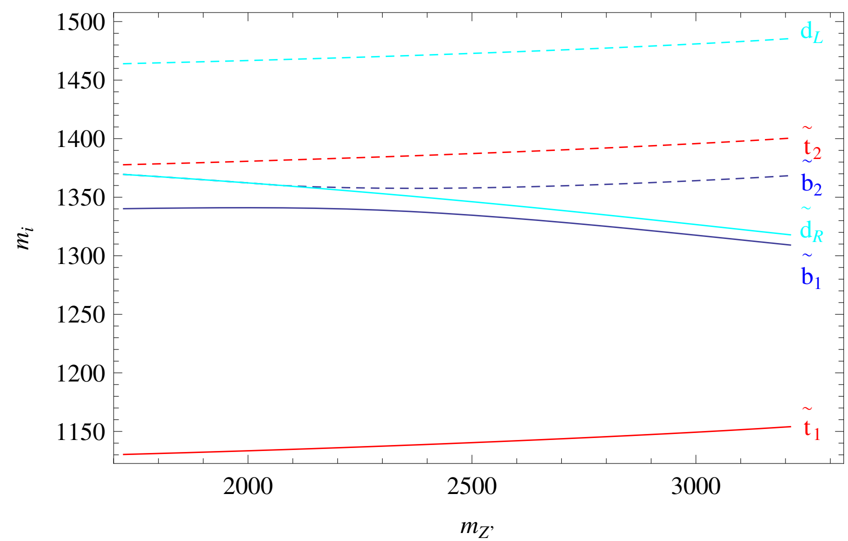
Sfermions

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

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

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

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

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

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

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)

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

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

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

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

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

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

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

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

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

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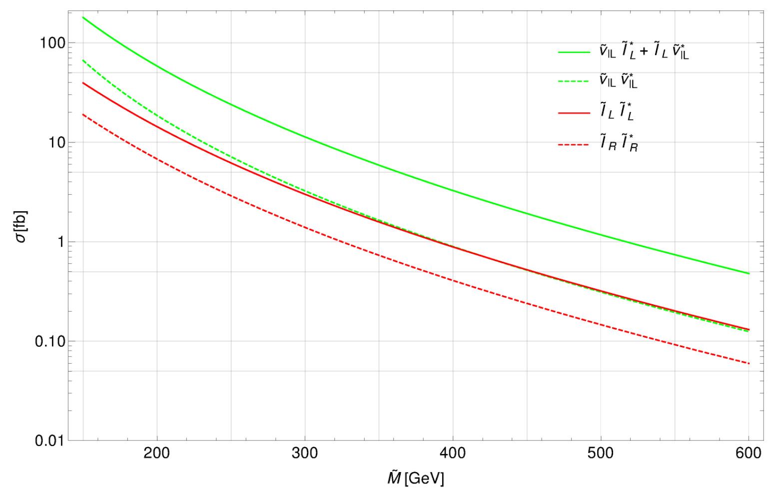
search for sleptons

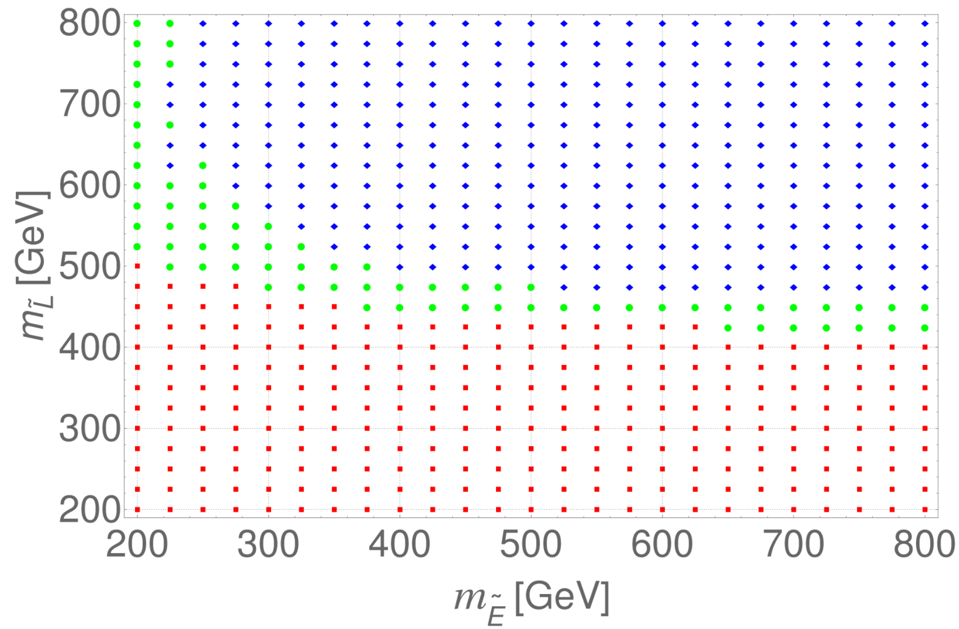


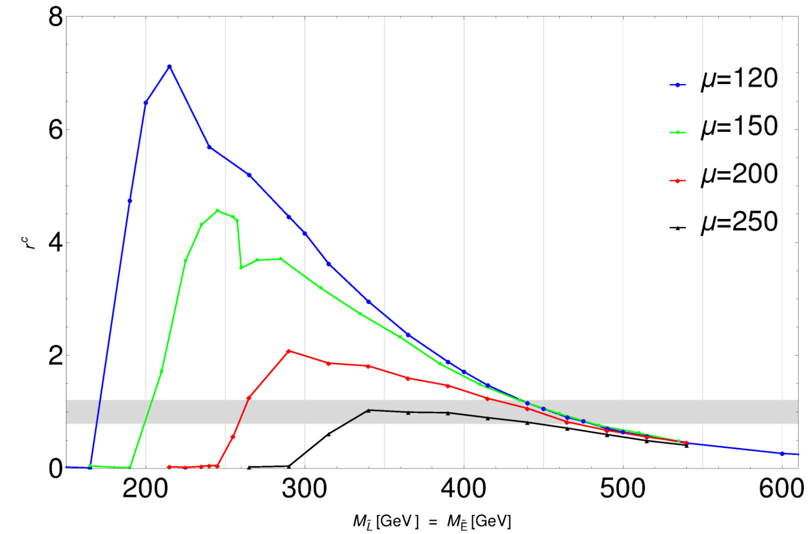
LHC, 13 TeV, tree-level
for searches: $\times$ K-factor 1.17
(B. Fuks et al., arXiv:1304.0790)

dominant decays:

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

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

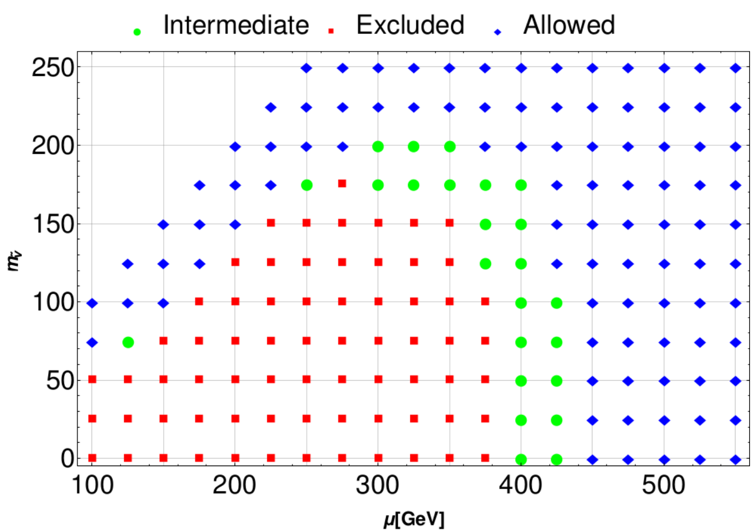
8+13 TeV data (13.9 fb^{-1})

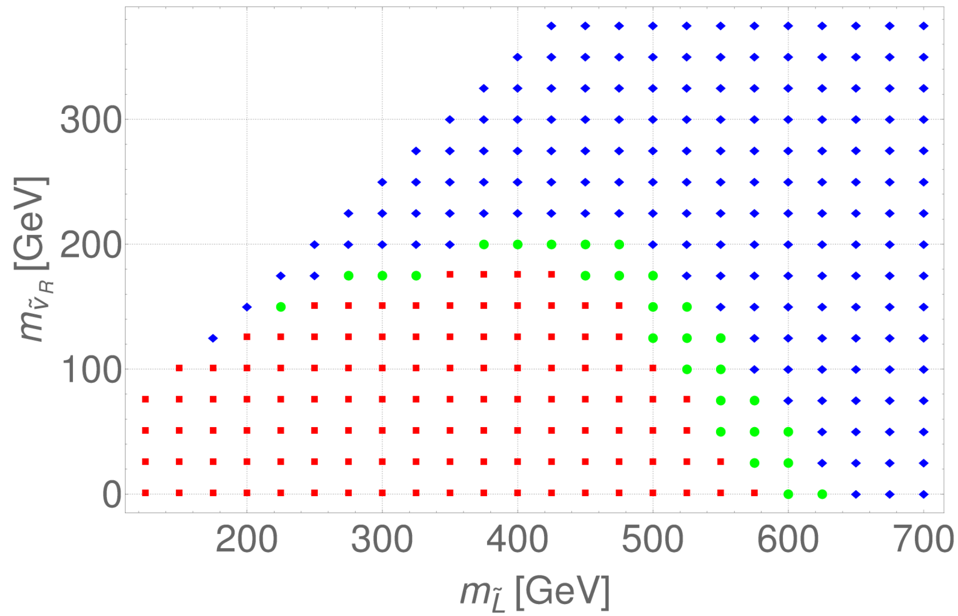
using `CheckMATE 2.0` Nh. Cerna-Velazco, Th. Faber, J. Jones, WP arXiv:1705.06583

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

additional constraint

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





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

using `CheckMATE 2.0`

$m_{\nu_R} = 20$ GeV

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

$M_1 = M_2 = 2$ TeV, $\tan\beta = 6$

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

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

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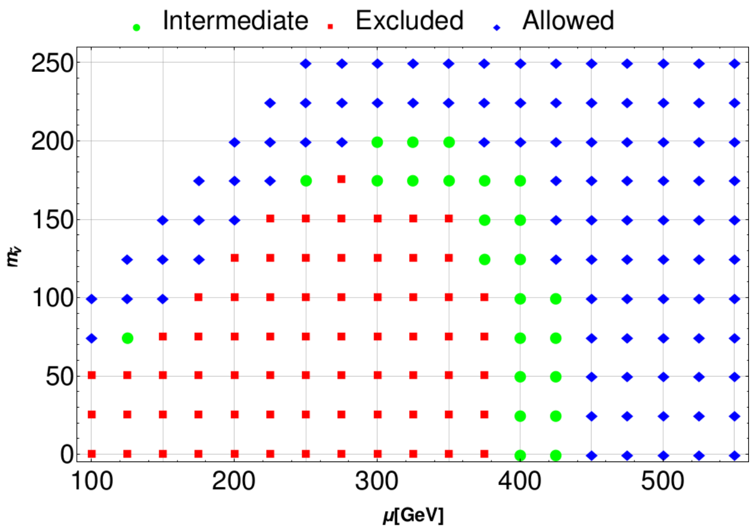
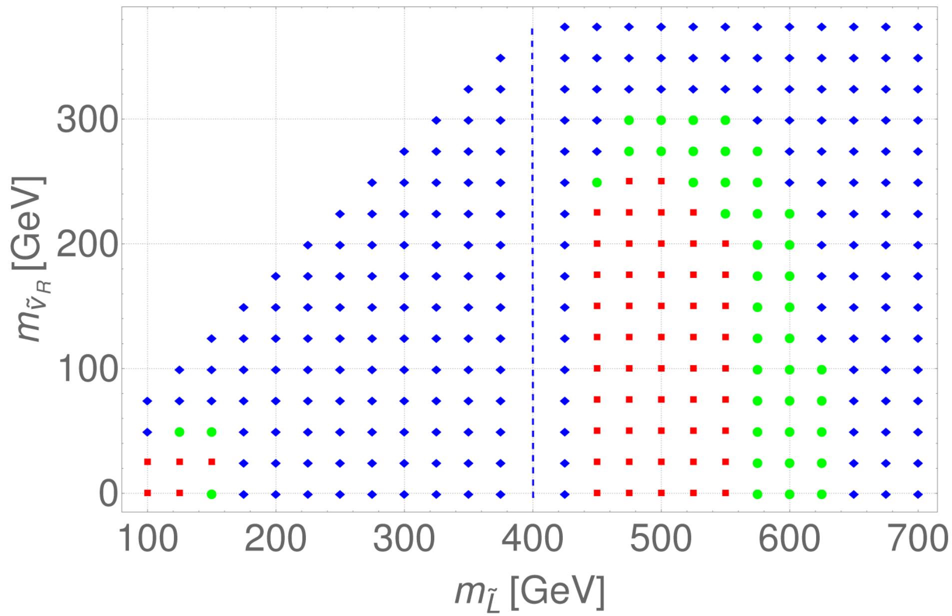




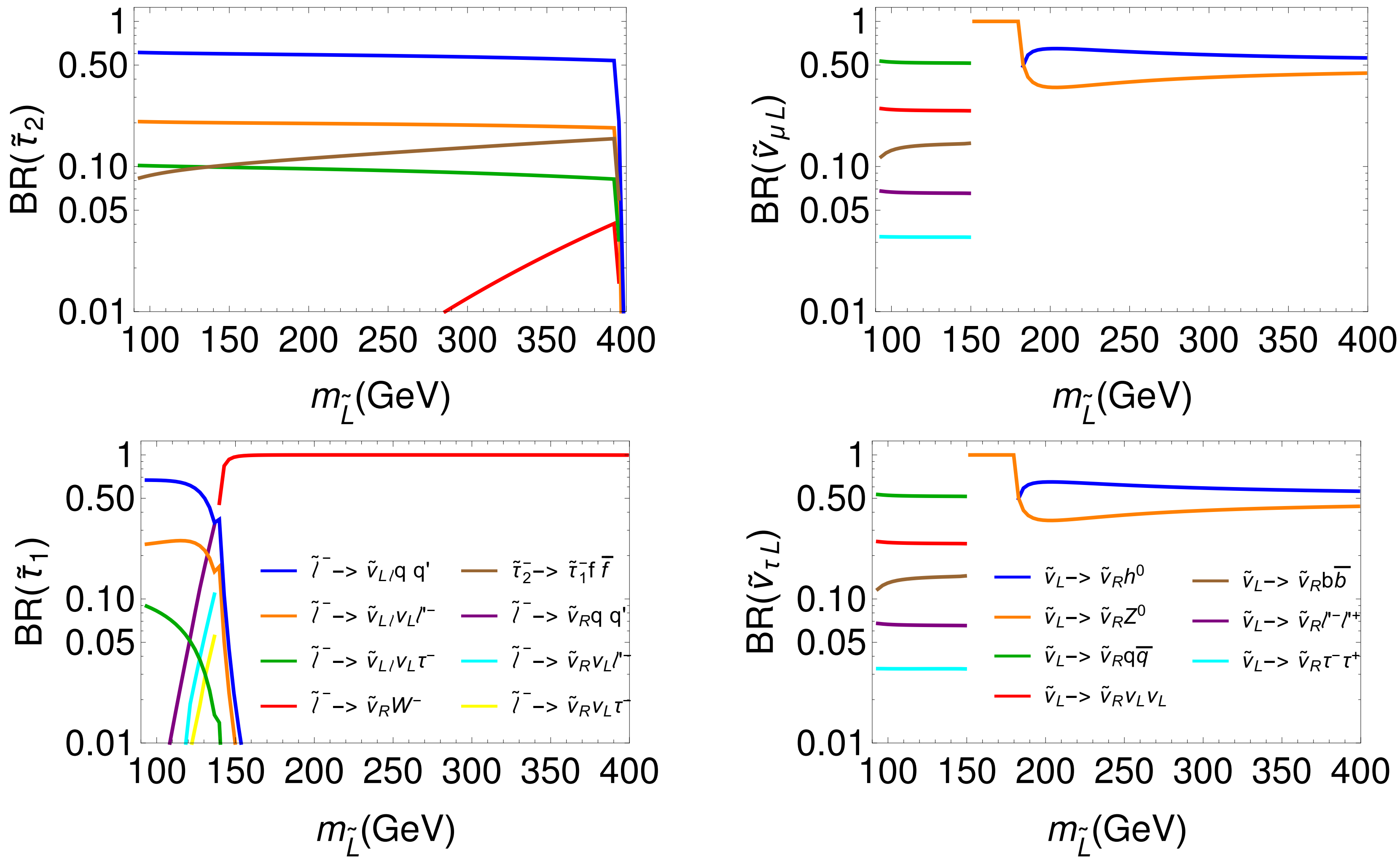
8+13 TeV data (13.9 fb^{-1})
using `CheckMATE 2.0`
$m_{\nu_R} = 20$ GeV

$\mu = 400$ 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

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

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



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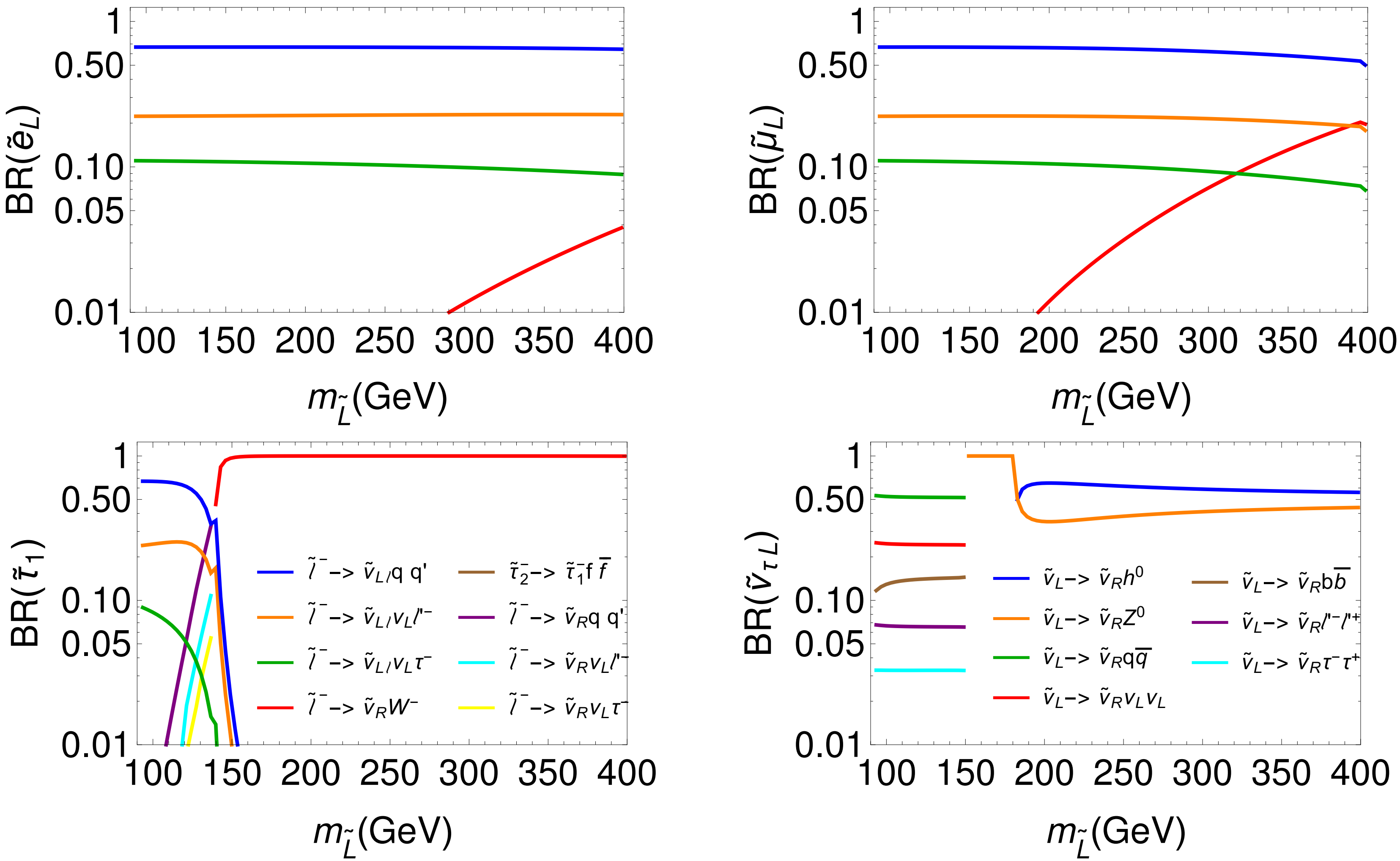


Nh. Cerna-Velazco, Th. Faber, J. Jones, WP arXiv:1705.06583

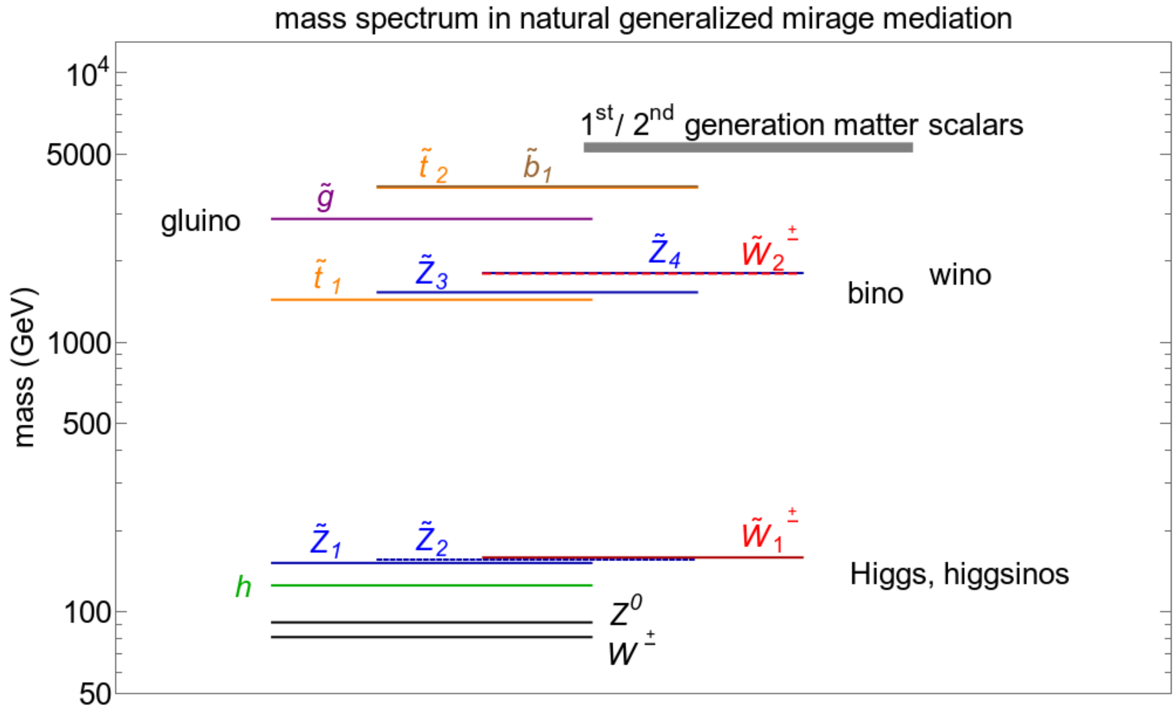
Conclusions

- 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
- '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
      but: in case of $m_{\tilde{L}} < |\mu|$ the bounds seem to be significantly weaker

General Mirrage Mediation

Different sources for soft SUSY breaking: moduli & AMSB

main consequence: gaugino masses unify at a (vastly) different scale then gauge couplings



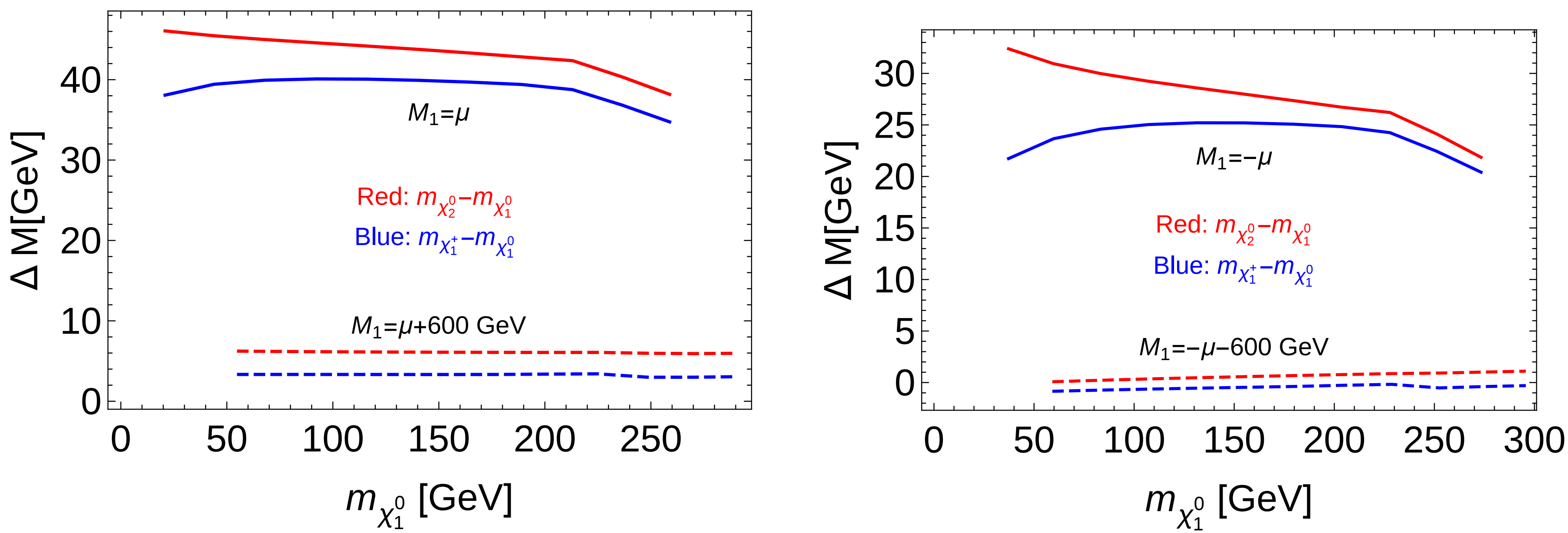
H. Baer, V. Barger, H. Serce and X. Tata, arXiv:1610.06205

Higgsino LSP: spectrum

limit $|\mu| \ll |M_1|, |M_2|$:

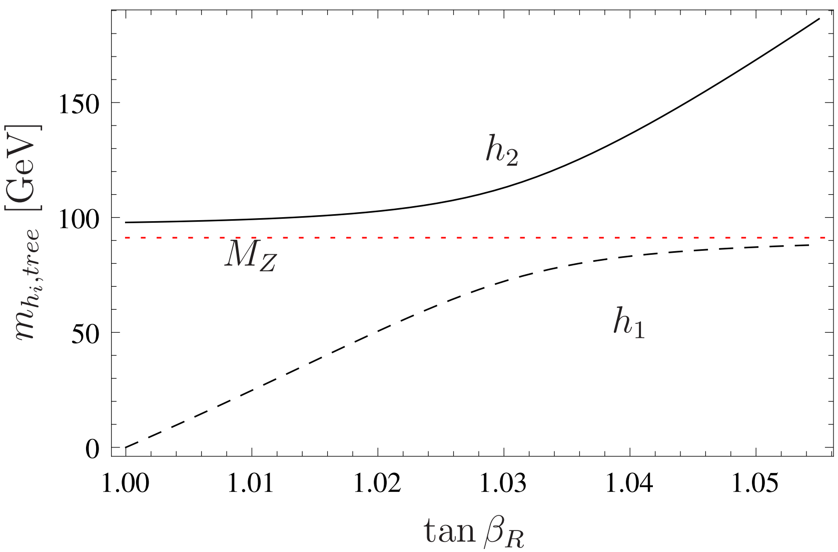
$$\Delta m_0 = m_{\tilde{\chi}^0_2} - m_{\tilde{\chi}^0_1} \simeq m_Z^2 \left(\frac{s_\omega^2}{M_1} + \frac{c_\omega^2}{M_2} \right)$$

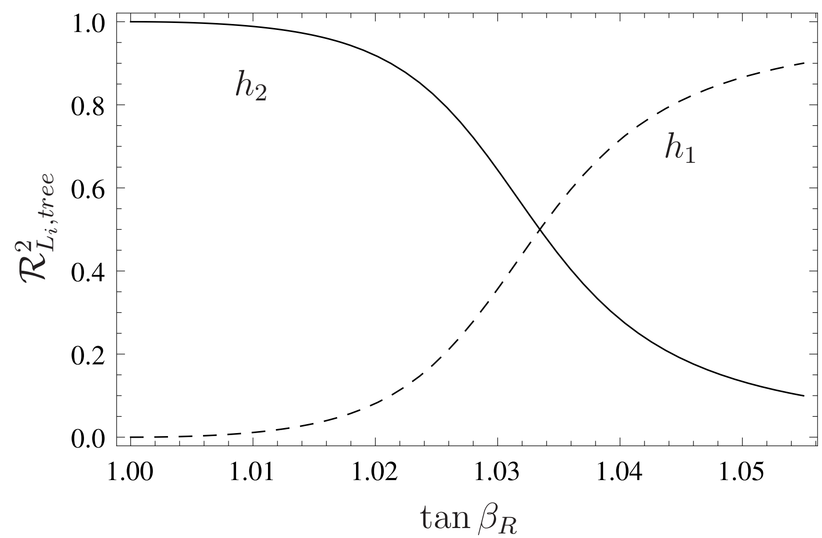
$$\Delta m_\pm = m_{\tilde{\chi}^\pm_1} - m_{\tilde{\chi}^0_1} \simeq \frac{\Delta m_0}{2} + |\mu| \frac{\alpha(m_Z)}{\pi} \left(2 + \ln \frac{m_Z^2}{\mu^2} \right)$$



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





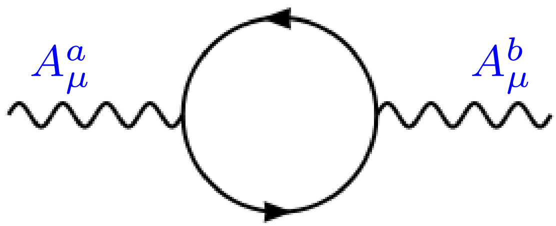
$n = 1$, $\Lambda = 5 \cdot 10^5$ GeV, $M = 10^{11}$ GeV, $\tan\beta = 30$, sign$(\mu_R) = -$, $diag(Y_S) = (0.7, 0.6, 0.6)$, $Y^{ii}_\nu = 0.01$, $v_R = 7$ TeV

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

Gauge kinetic mixing

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

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



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

equivalent

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

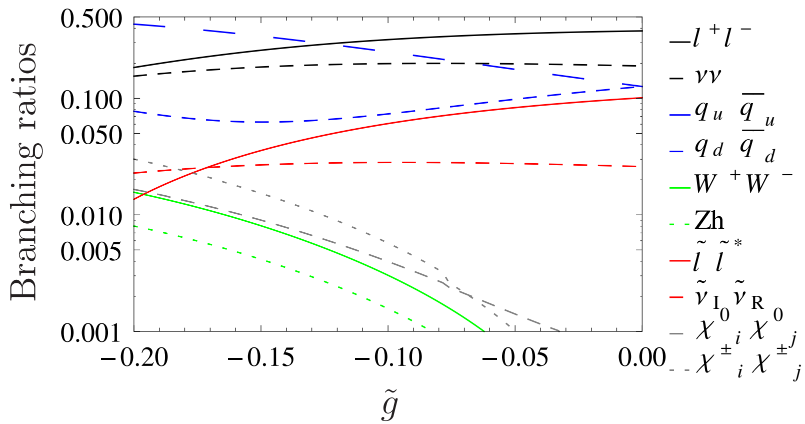
both $U(1)$ unbroken $\Rightarrow$ chose basis with e.g. $g_{ba} = 0$

affects also RGE running of soft SUSY parameters:
R. Fonseca, M. Malinsky, W.P., F. Staub, NPB **854** (2012) 28

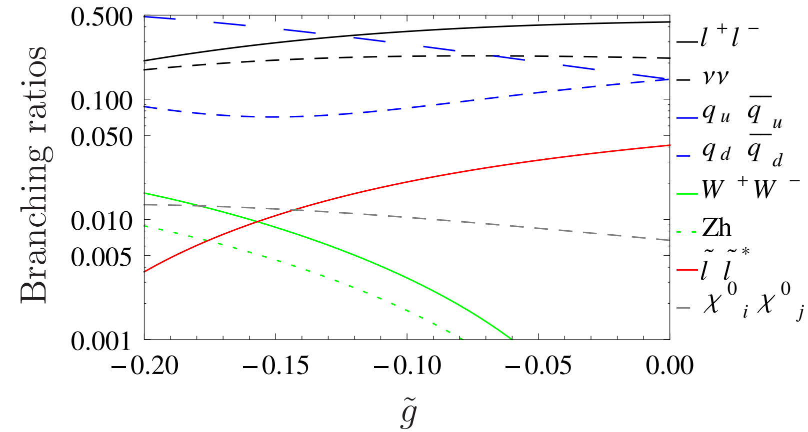
Z' physics, effect of gauge kinetic mixing I

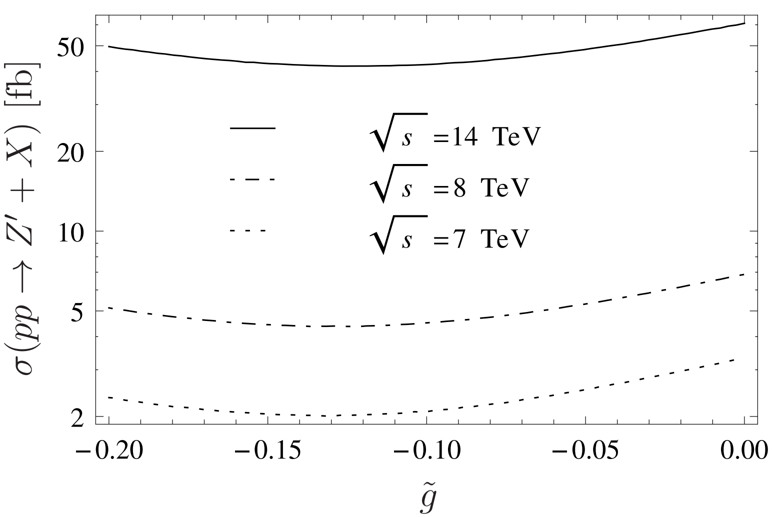
Z' couplings: $Q_{B-L} \cdot g_{B-L} \to Q_{B-L} \cdot g_{B-L} + Q_Y \cdot \tilde{g}$

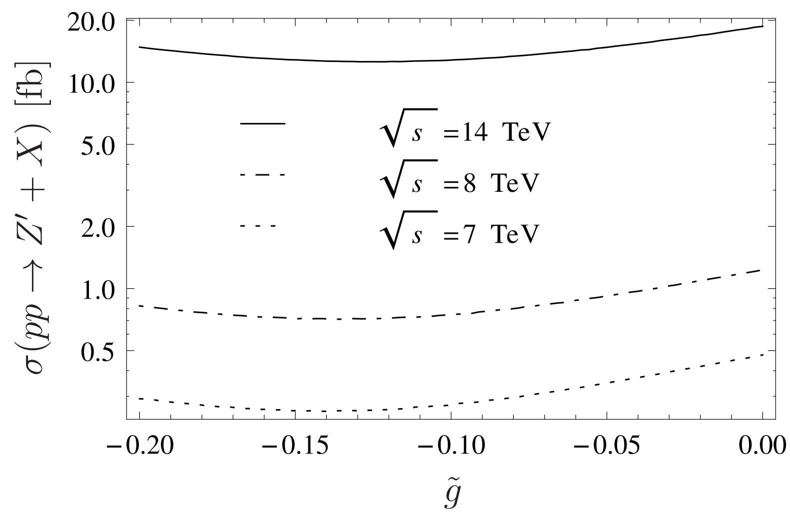
BL1



BL2

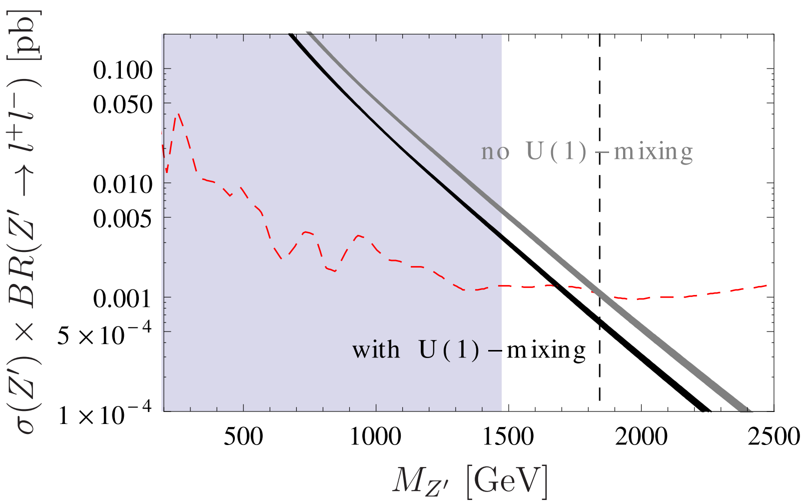




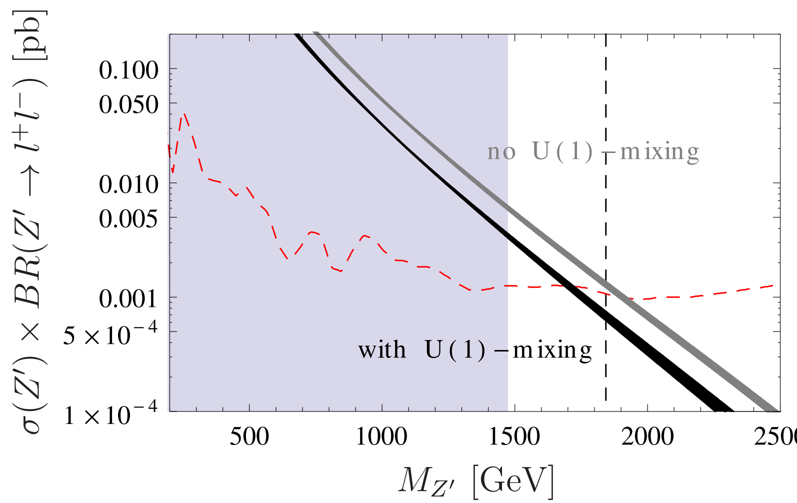


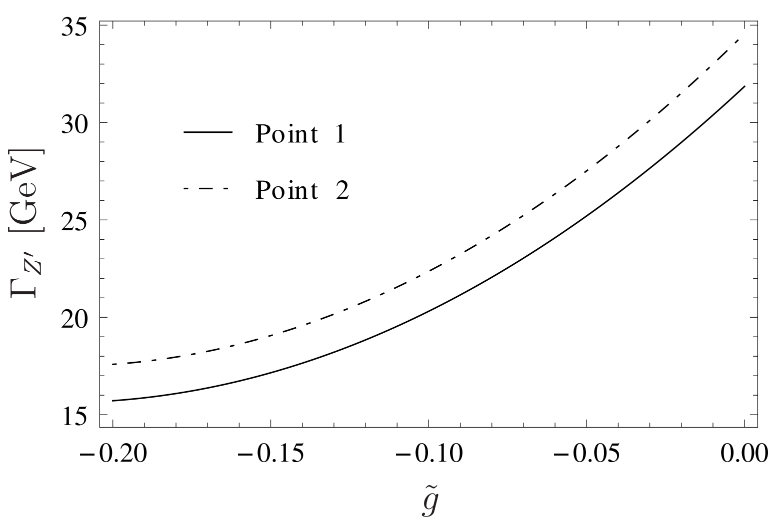
Z' physics, effect of gauge kinetic mixing II

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