SUSY overview

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Supersymmetry, MSSM, in a nut-shell

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

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 $\subset$ supersymmetric models

- MSSM, e.g. mSUGRA, GMSB, AMSB, 'natural' MSSM
- NMSSM
- extended gauge groups, e.g. BLSSM, E6SSM
- R-parity violation
- Dirac gauginos

$\vdots$

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

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

MSSM, generalities

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

- mSUGRA/CMSSM: M_{GUT}

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

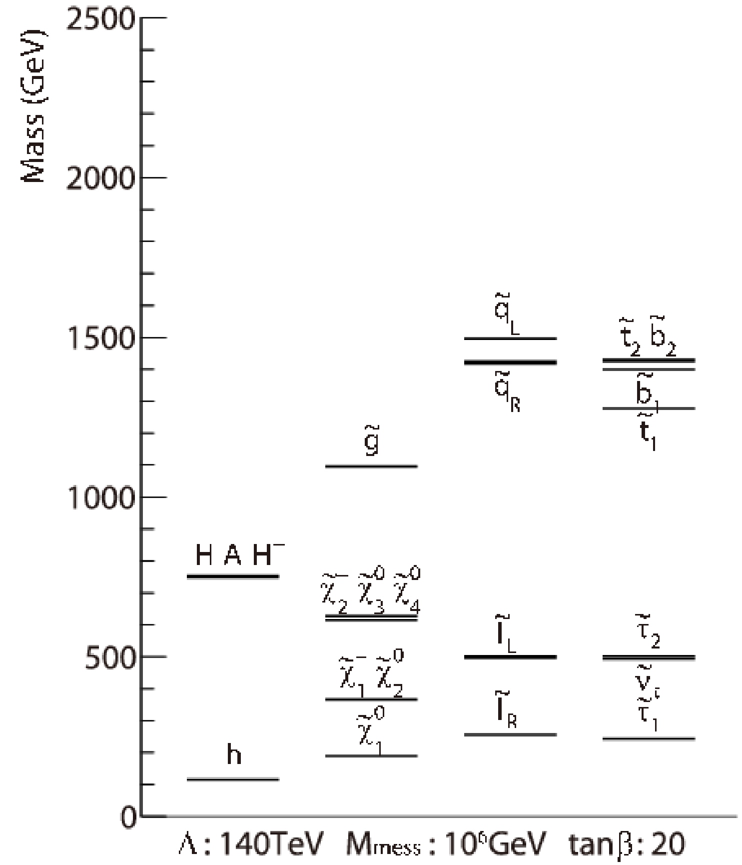
  NUHM1/NHUM2: $m_{H_d}^2, m_{H_u}^2 \neq m_0^2$

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

Typical spectrum, collider signatures



typically cascade decays

$$\tilde{q}_L \to q\tilde{\chi}^0_2 \to q l^+ l^- \tilde{\chi}^0_1 \;,\; q q' \bar{q}' \tilde{\chi}^0_1$$

$$\tilde{g} \to q\bar{q}\chi^0_2 \to q\bar{q} l^+ l^- \tilde{\chi}^0_1 \;,\; q\bar{q} q' \bar{q}' \tilde{\chi}^0_1$$

generic collider signature: n hard jets $+\, m$ hard leptons $+ \not{E}_T$

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

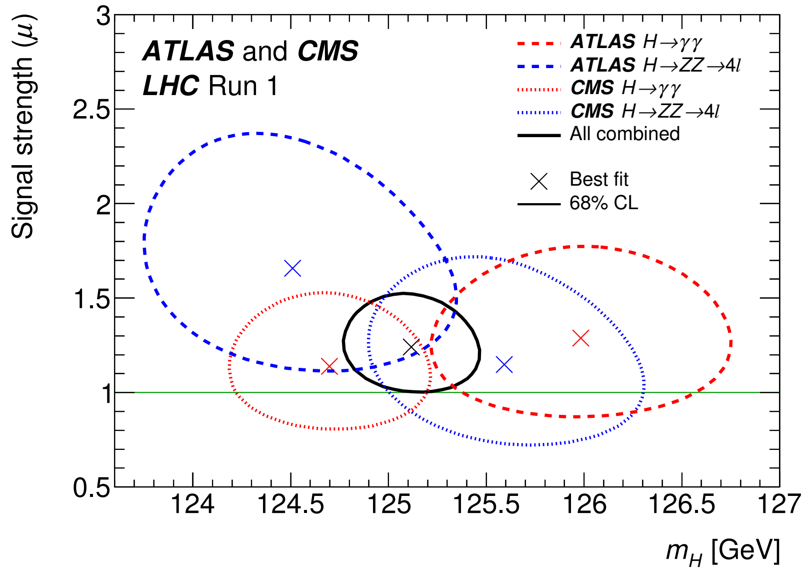
  Ellis et al; Okada et al; Haber,Hempfling; Hoang et al; Carena et al; Heinemeyer et al; Zhang et al; Brignole et al; Harlander et al; ...

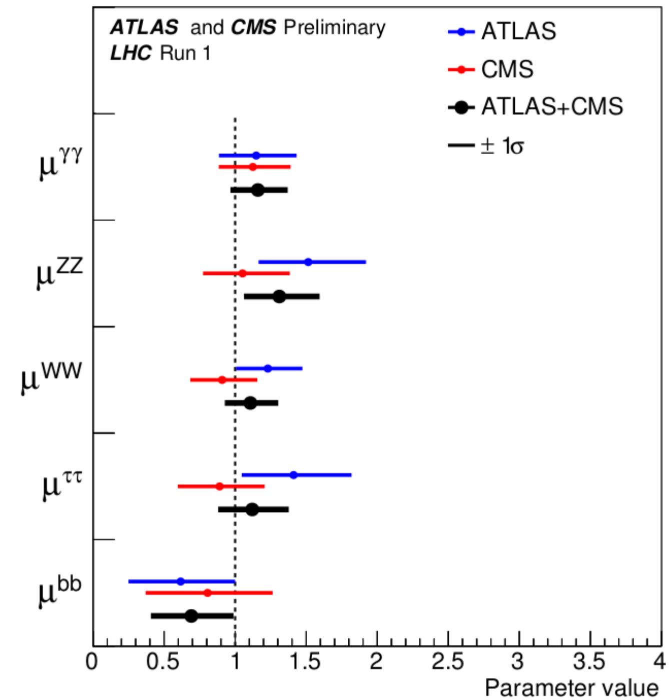
  higher order:

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

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

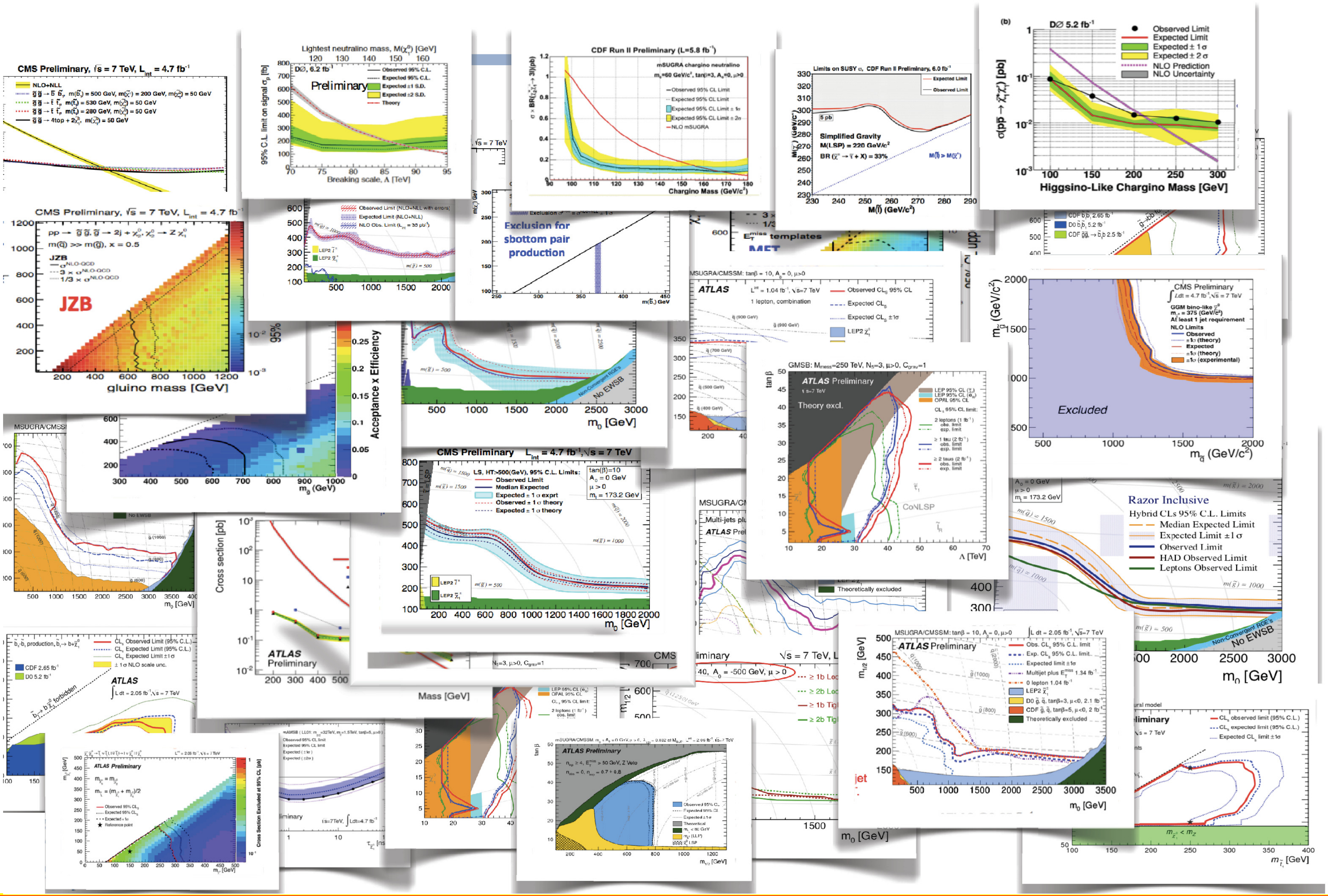
see talk by A.-M. Magnan

ATLAS-CONF-2015-044

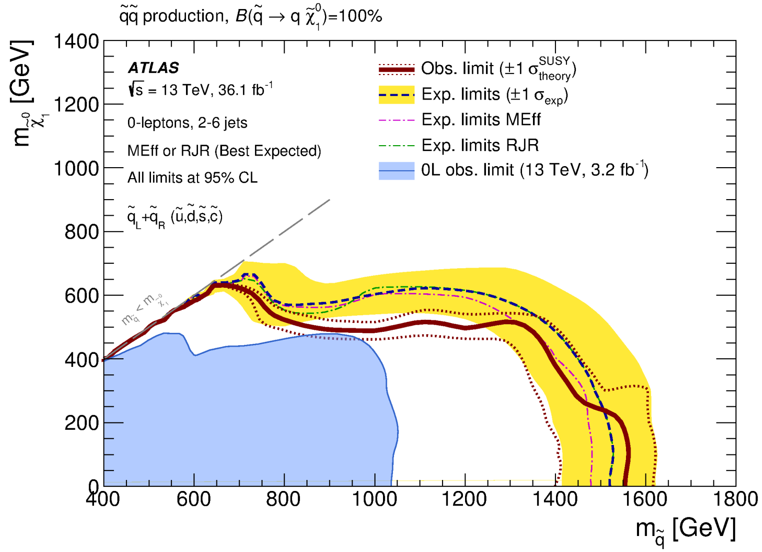
CMS-PAS-HIG-15-002

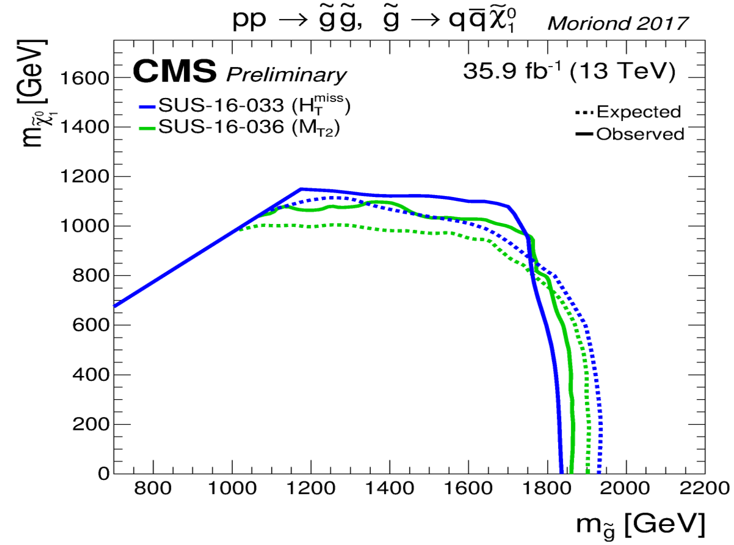
$(125\ \text{GeV})^2 \simeq m_Z^2 + (86\ \text{GeV})^2 \Rightarrow$ large corrections within MSSM

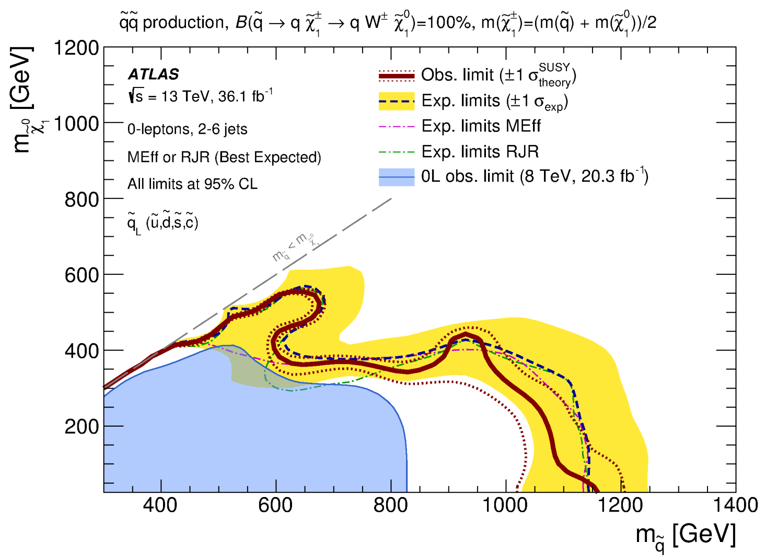
BSM searches, so far hardly anything ...

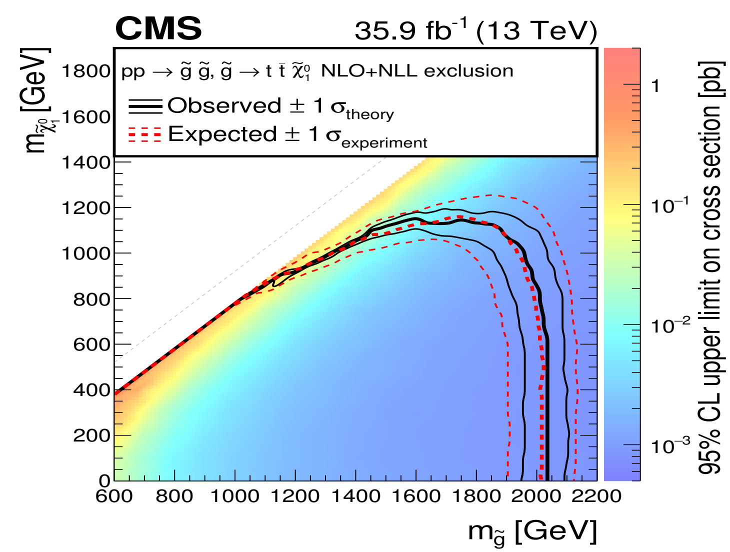


Examples for SUSY searches 13 TeV data









arXiv:1712.02332

arXiv:1710.11188

LHC data, in particular m_h, high scale models

$m_h = 125$ 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

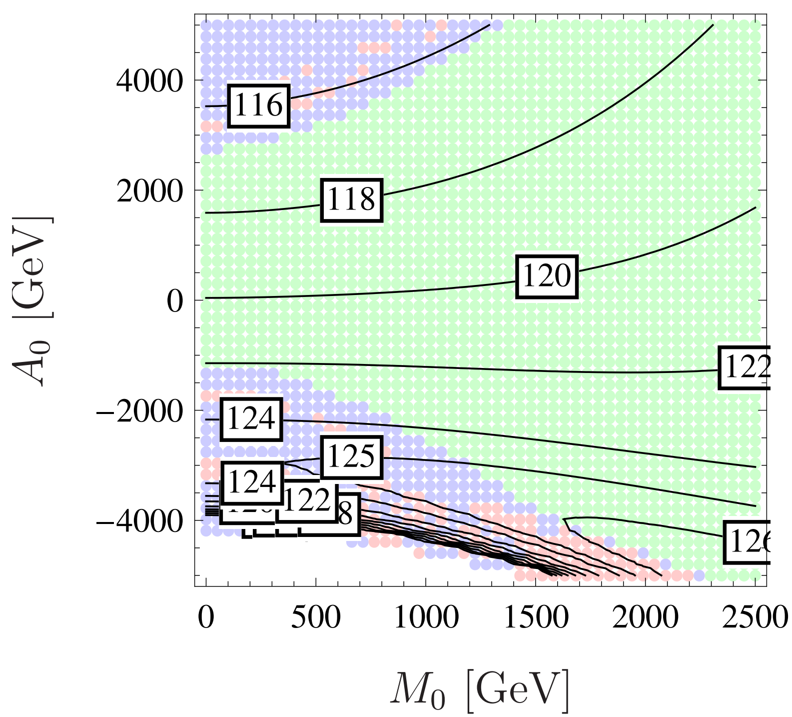
  more complicated models based on P. Meade, N. Seiberg and D. Shih, arXiv:0801.3278 $\Rightarrow$ allow additional terms
e.g. S. Knappen, D. Redigolo, arXive:1606.07501 $m_{\tilde{t}_1} \simeq m_{\tilde{b}_1} \gtrsim 1$ TeV if $M_{\text{mess}} \gtrsim 10^{15}$ GeV

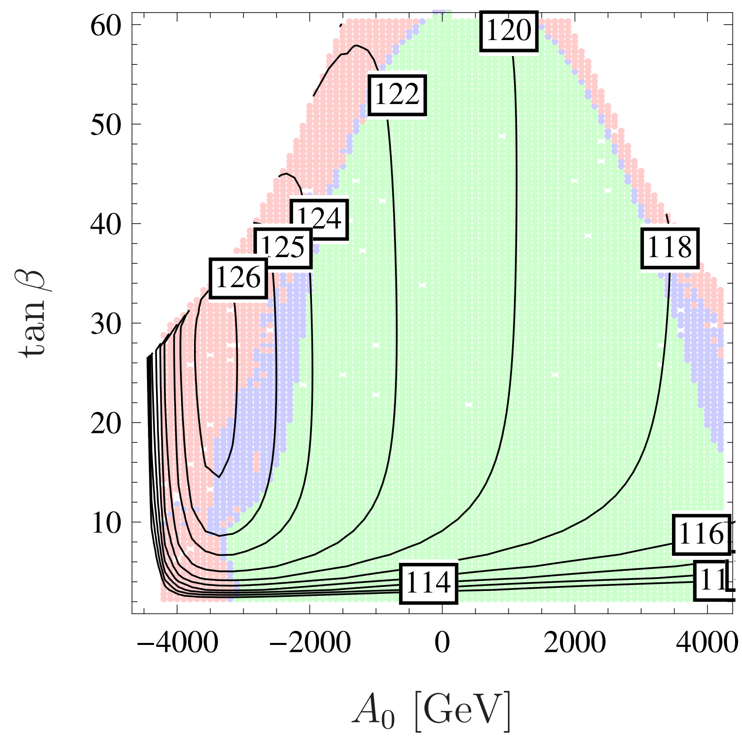
- CMSSM, NUHM models: $|A_0| \simeq 2m_0$,
H. Baer, V. Barger and A. Mustafayev, arXiv:1112.3017; M. Kadastik *et al.*, arXiv:1112.3647; O. Buchmueller *et al.*, arXiv:1112.3564; J. Cao, Z. Heng, D. Li, J. M. Yang, arXiv:1112.4391; L. Aparicio, D. G. Cerdeno, L. E. Ibanez, arXiv:1202.0822; J. Ellis, 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!



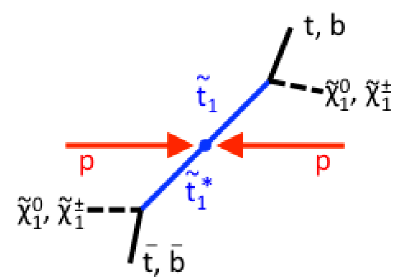


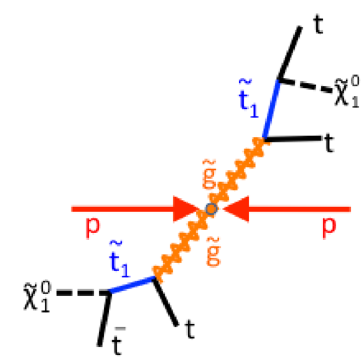
$M_{1/2} = 1$ TeV, $\tan\beta = 10$, $\mu > 0$ $\qquad$ $M_{1/2} = M_0 = 1$ TeV

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':
  $$\tilde{t}_1, \tilde{b}_1, \tilde{g}, \tilde{\chi}^0_{1,2} \simeq \tilde{h}^0_{1,2}, \tilde{\chi}^+_1 \simeq \tilde{h}^+$$
  $\Rightarrow$ 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

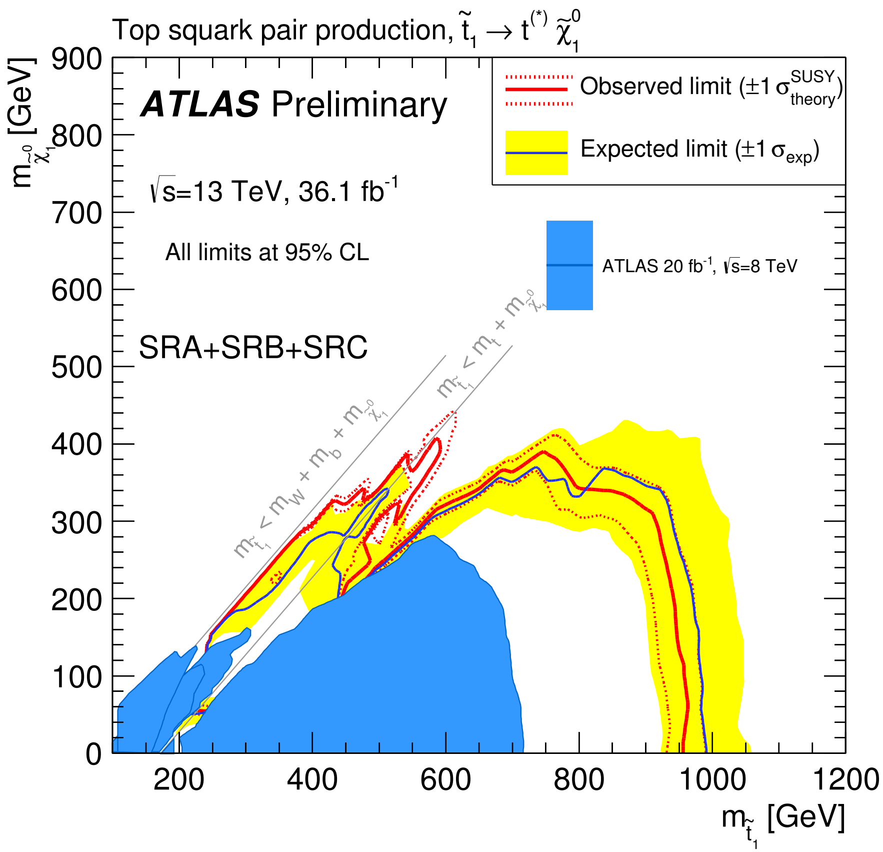
$$\begin{aligned} \tilde{g} &\rightarrow \tilde{t}_1 t, \tilde{b}_1 b \\ \tilde{t}_1 &\rightarrow t\tilde{\chi}^0_{1,2}, b\tilde{\chi}^+_1, W^+\tilde{b}_1 \\ \tilde{b}_1 &\rightarrow b\tilde{\chi}^0_{1,2}, t\tilde{\chi}^-_1, W^-\tilde{t}_1 \end{aligned}$$

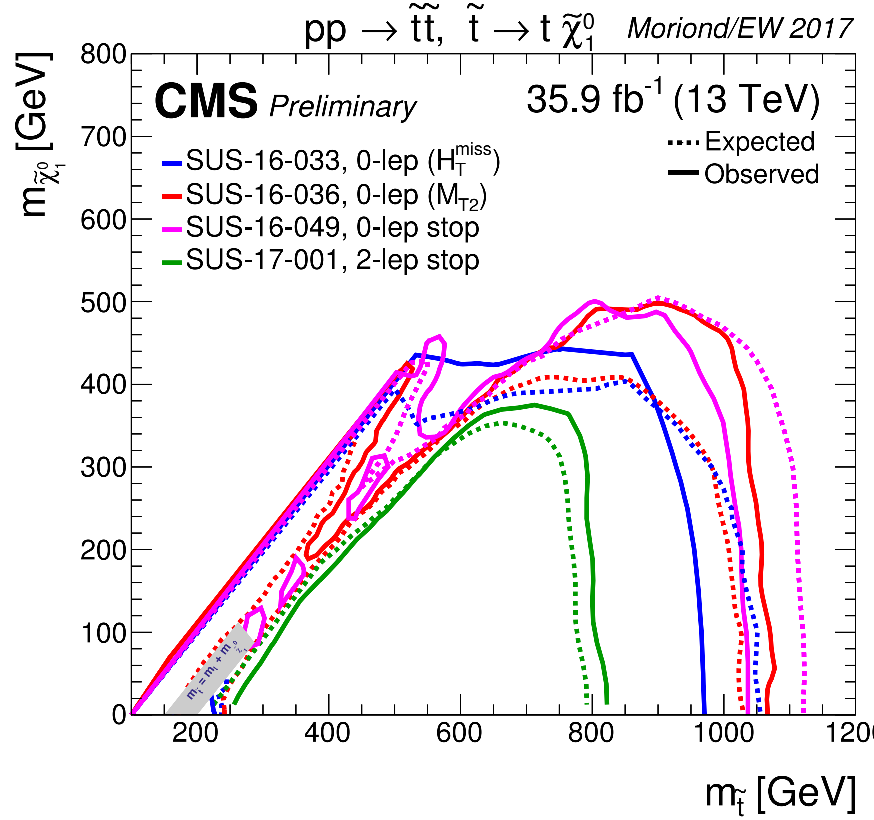




BRs depend on the nature of $\tilde{t}_1$ and $\tilde{b}_1$
Higgsino mass: $\mu + \mu'$ with soft SUSY breaking parameter: $\mathcal{L} = -\mu' \tilde{H}_d \tilde{H}_u$
(G. G. Ross, K. Schmidt-Hoberg and F. Staub, arXiv:1701.03480)

LHC bounds on $\tilde{t}_1$



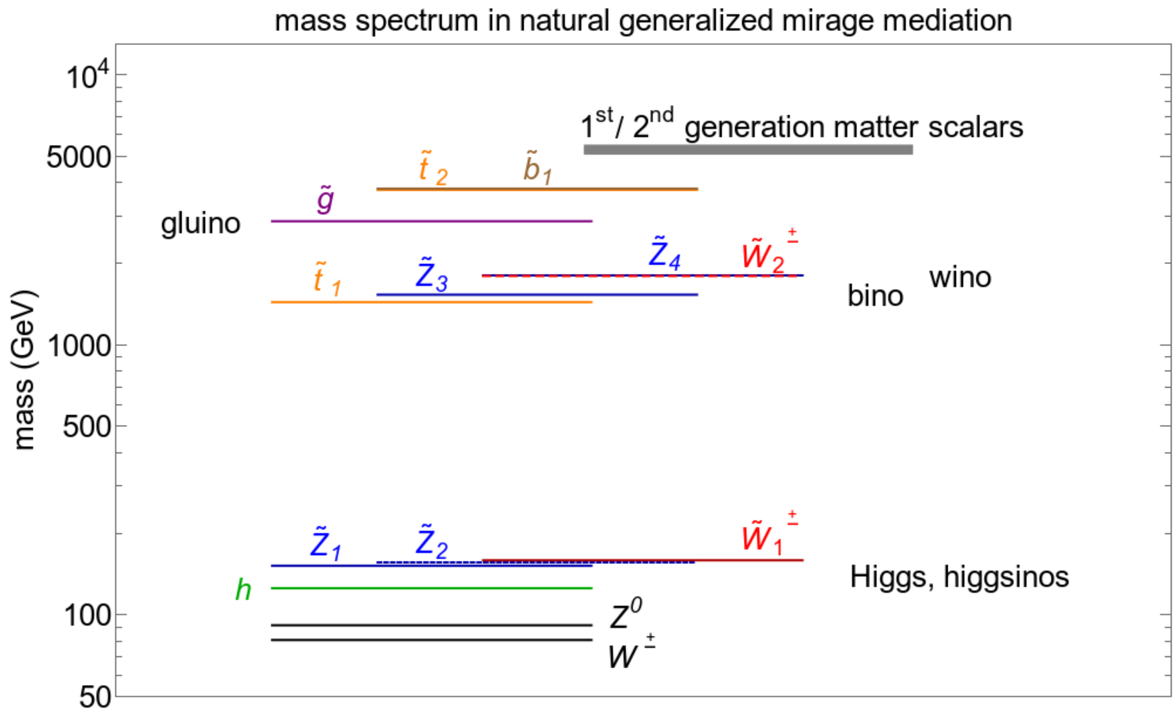


$$\frac{d}{dt}\begin{pmatrix} m^2_{H_u} \\ m^2_{\tilde{t}_R} \\ m^2_{\tilde{Q}^3_L} \end{pmatrix} = -\frac{8\alpha_s}{3\pi}M_3^2\begin{pmatrix} 0 \\ 1 \\ 1 \end{pmatrix} + \frac{Y_t^2}{8\pi^2}\left(m^2_{\tilde{Q}^3_L} + m^2_{\tilde{t}_R} + m^2_{H_u} + A_t^2\right)\begin{pmatrix} 3 \\ 2 \\ 1 \end{pmatrix}$$

General Mirrage Mediation

Different sources for soft SUSY breaking: moduli & AMSB

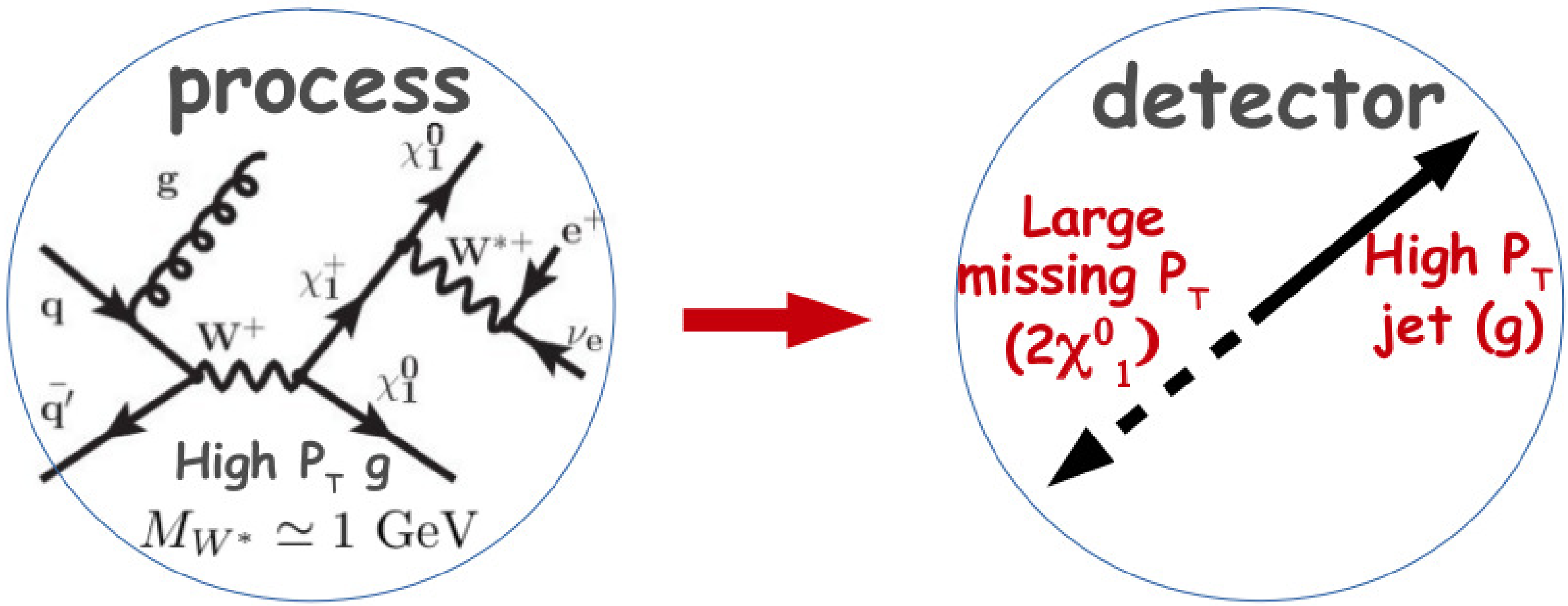
main consequence: gaugino masses unify at a (vastly) different scale then gauge couplings



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

Higgsino LSP: Challenge for LHC

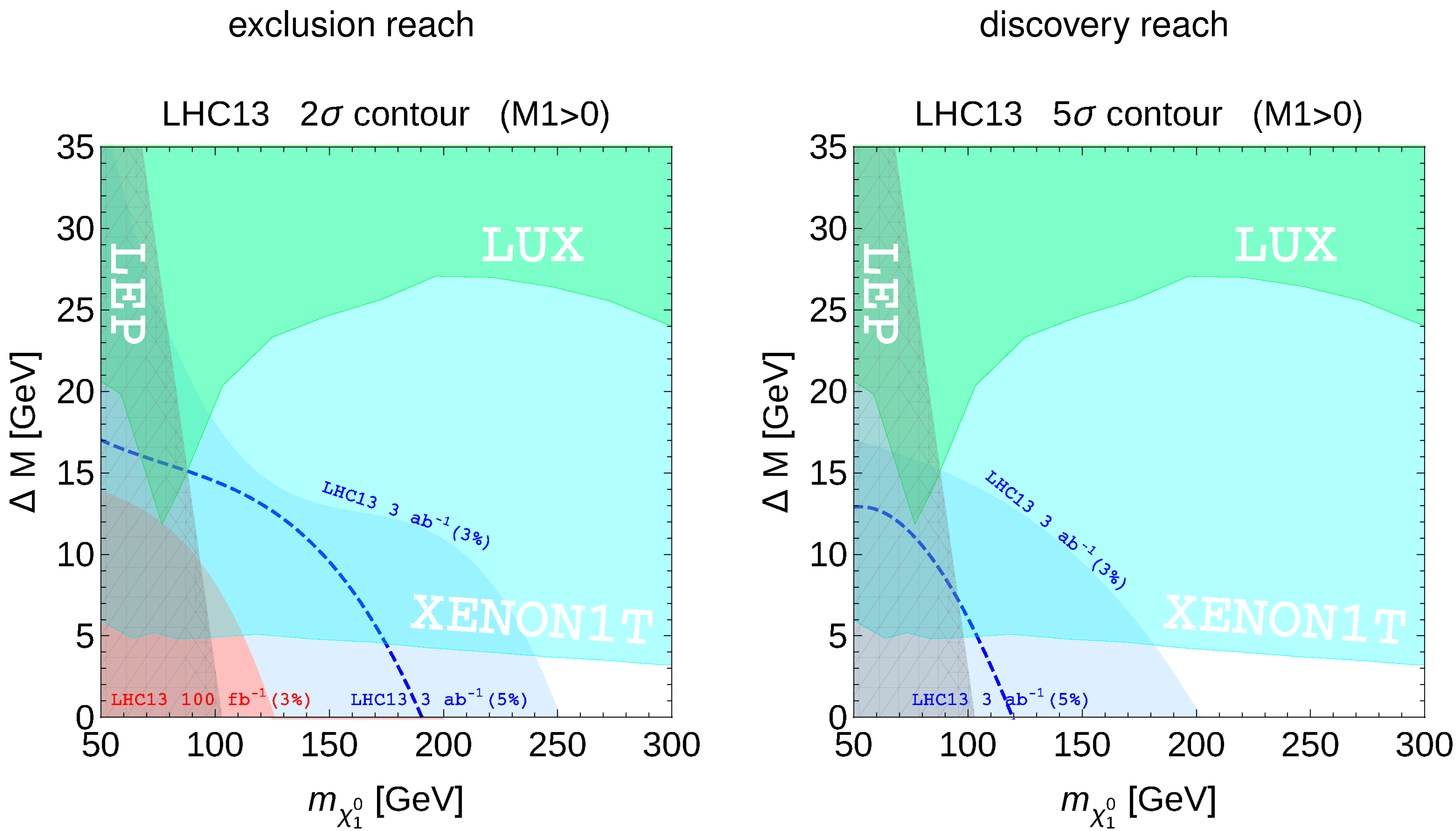
Most challenging case: only higgsinos accessible but nothing else
and ΔM to small for any leptonic signature



The only way to probe compressed higgsinos is a mono-jet signature:
'Where the Sidewalk Ends? . . . ' Alves, Izaguirre,Wacker 2011

related work C. Han et al., arXiv:1310.4274; P. Schwaller, J. Zurita, arXiv:1312.7350;
Z. Han et al, arXiv:1401.1235; H. Baer et al.,arXiv:1401.1162, . . .

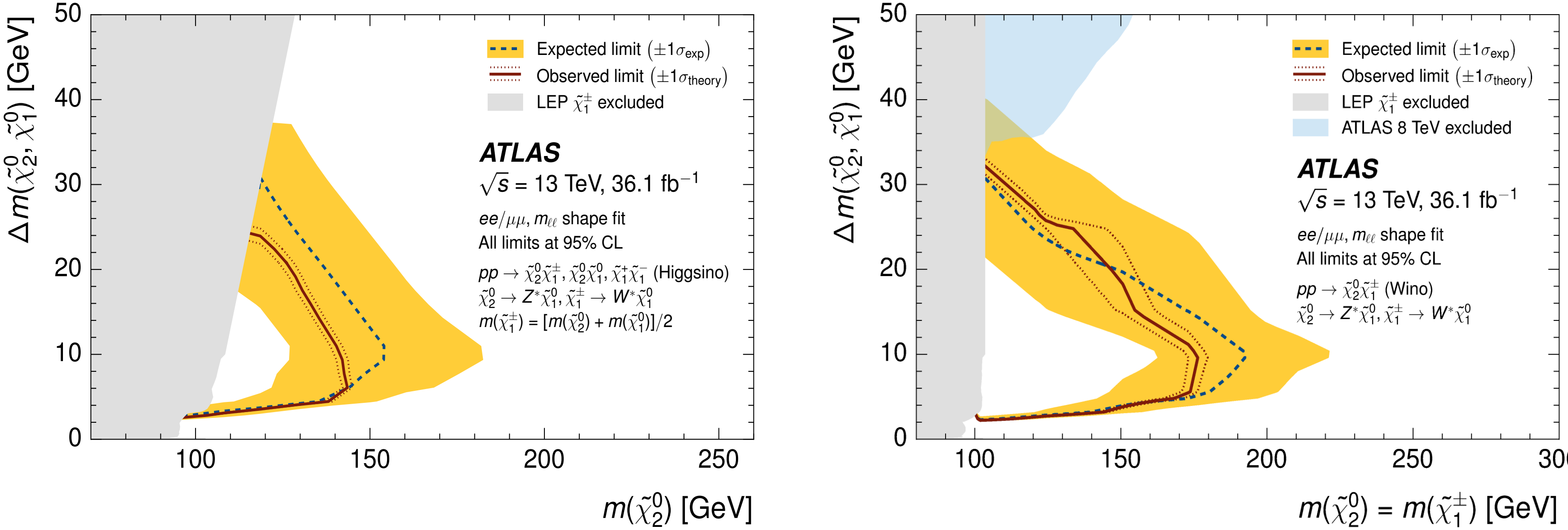
Complementarity: LHC @ 13 TeV versus DM direct detection



D. Barducci, A. Belyaev, A. Bharucha, WP, V. Sanz, arXiv:1504.02472

ATLAS, search for compressed charginos/neutralinos

arXiv:1712.08119



assumption for production:

pure Higgsinos | pure winos

NMSSM in nut-shell

μ-problem of the MSSM $\Rightarrow$ add singlet $\Rightarrow$ $\mu = \lambda \langle S \rangle$

$$W_{MSSM} = \hat{H}_d \hat{L} Y_e \hat{E}^C + \hat{H}_d \hat{Q} Y_d \hat{D}^C + \hat{H}_u \hat{Q} Y_u \hat{U}^C - \lambda \hat{H}_d \hat{H}_u \hat{S} + \frac{\kappa}{3} \hat{S}^3$$

$$m_h^2 = (m_h^2)_{MSSM} + \lambda^2 m_Z^2 \sin^2 2\beta + \dots$$

Higgs physics: J. F. Gunion, Y. Jiang and S. Kraml, arXiv:1201.0982; S. F. King, M. Muhlleitner and R. Nevzorov, arXiv:1201.2671; U. Ellwanger and C. Hugonie, arXiv:1203.5048; G. G. Ross, K. Schmidt-Hoberg and F. Staub, arXiv:1205.1509; R. Benbrik, M. Gomez Bock, S. Heinemeyer, O. Stal, G. Weiglein and L. Zeune, arXiv:1207.1096; K. Agashe, Y. Cui and R. Franceschini, arXiv:1209.2115; . . .

natural SUSY implementation: L. J. Hall, D. Pinner and J. T. Ruderman, arXiv:1112.2703; S. F. King, M. Mühlleitner, R. Nevzorov and K. Walz, arXiv:1211.5074; R. Barbieri, D. Buttazzo, K. Kannike, F. Sala and A. Tesi, arXiv:1304.3670; . . .

NMSSM phenomenology in a nut-shell

- Higgs sector: h_i^0 (i=1,2,3), a_i^0 (i=1,2); non-standard Higgs decays[a]:

$$
\begin{aligned}
h_i^0 &\rightarrow a_1^0 a_1^0 \rightarrow 4b, 2b\tau^+\tau^-, \tau^+\tau^-\tau^+\tau^- \\
&\rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0
\end{aligned}
$$

- additional neutralino: higher lepton and jet multiplicities possibles[b]
- Neutralinos, Singlino LSP $|\lambda| \ll 1 \Rightarrow$ displaced vertex[c], e.g.

$$\Gamma(\tilde{\tau}_1 \rightarrow \tilde{\chi}_1^0 \tau) \propto \lambda^2 \sqrt{m^2_{\tilde{\tau}_1} - m^2_{\tilde{\chi}_1^0} - m^2_\tau}$$

- singlino as dark matter[d]

see e.g. [a] U. Ellwanger, J. F. Gunion and C. Hugonie, hep-ph/0503203; [b] D. Das, U. Ellwanger and A. M. Teixeira, arXiv:1202.5244 ; [c] U. Ellwanger and C. Hugonie, hep-ph/9712300; S. Hesselbach, F. Franke and H. Fraas, hep-ph/0007310; [d] C. Hugonie, G. Belanger and A. Pukhov, arXiv:0707.0628

Extended gauge groups, motivation

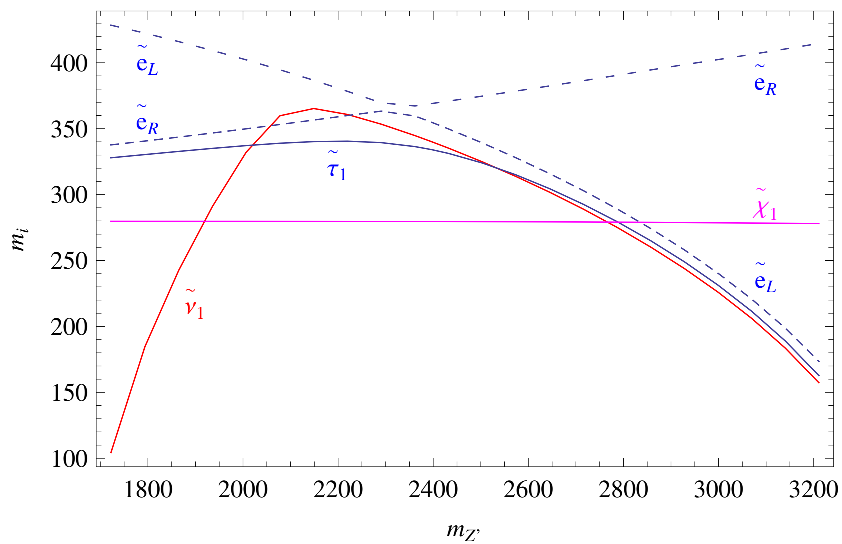
- additional D-term contributions to m_h at tree-level
  extra $U(1)_\chi$: $m^2_{h,tree} \leq m_Z^2 + \frac{1}{4} g_\chi^2 v^2$
- Origin of R-parity $R_P = (-1)^{2s+3(B-L)}$
  $\Rightarrow SO(10) \to SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$
  $\to SU(3)_C \times SU(2)_L \times U(1)_R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

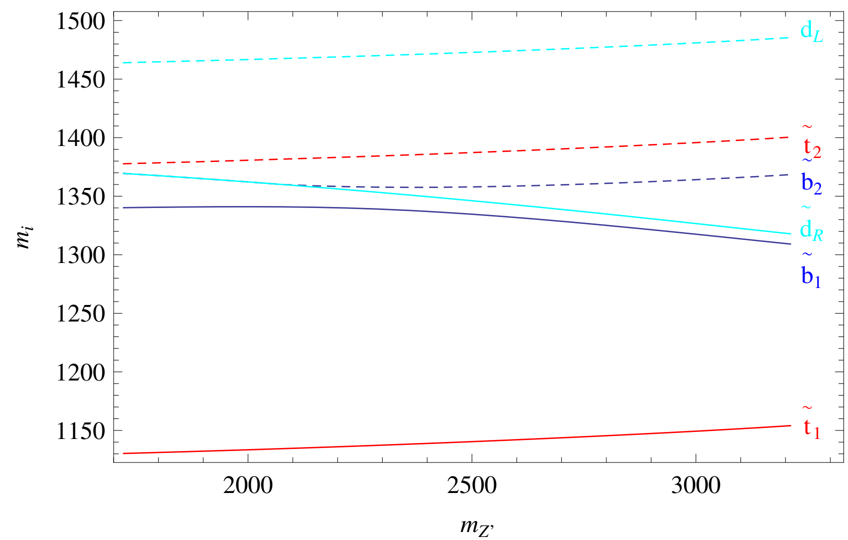
Sfermions

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

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

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

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

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

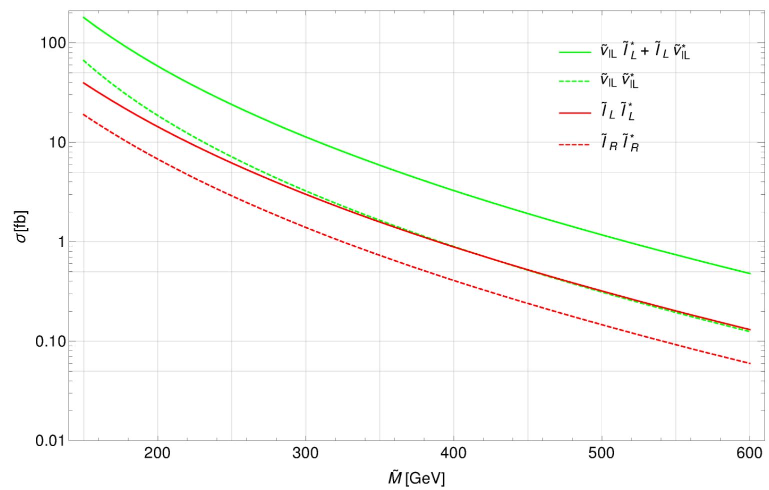
$$(Y_\nu)_{\ell 6} = -i (Z_\ell^{\rm NH})^* \sqrt{\frac{2 m_3 M_6}{v_u}} \cosh\gamma_{56}\, e^{\mp i\theta_{56}}$$

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

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

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

search for sleptons

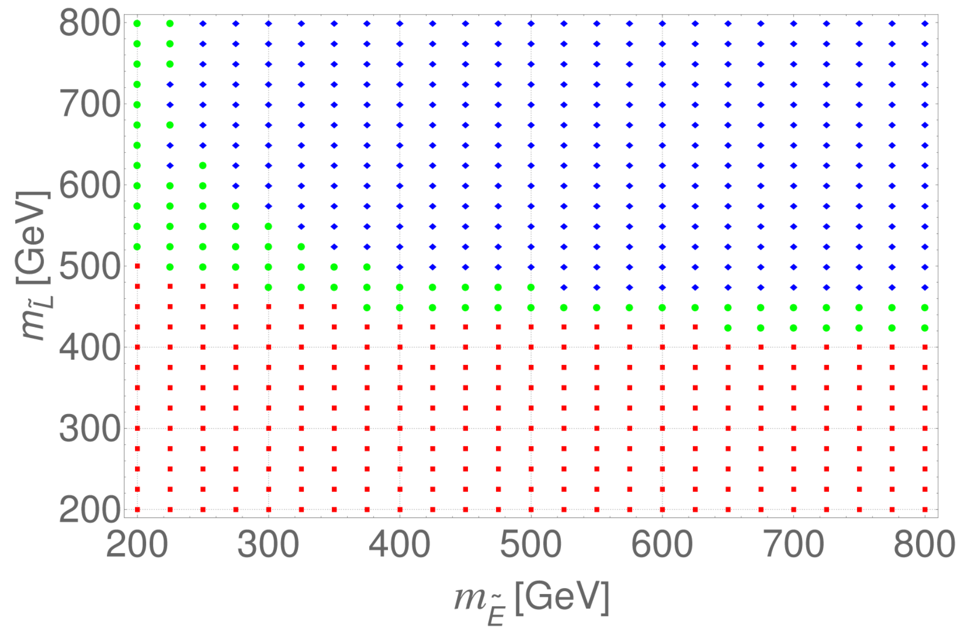


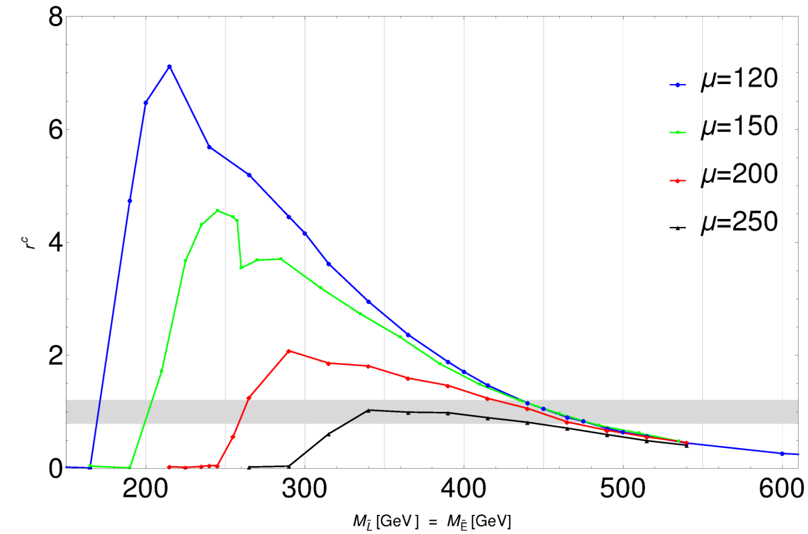
LHC, 13 TeV, tree-level
for searches: $\times$ K-factor 1.17
(B. Fuks et al., arXiv:1304.0790)

dominant decays:

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

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





$\mu = 120$ GeV, $\tan\beta = 10$ $\quad\quad$ $m_{\tilde{L}} = m_{\tilde{E}}, \tan\beta = 10$

■ excluded, ● ambigous, ◇ allowed , via

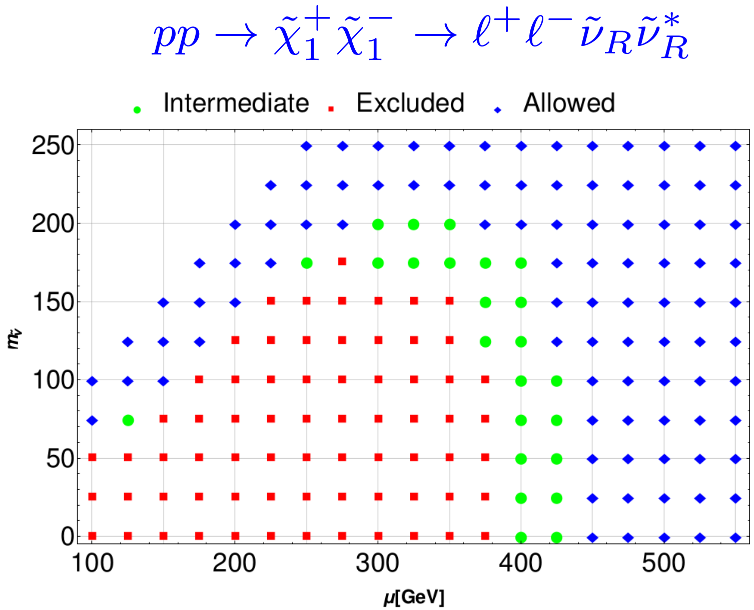
$$r = \frac{S - 1.96\Delta S}{S_{obs}}$$

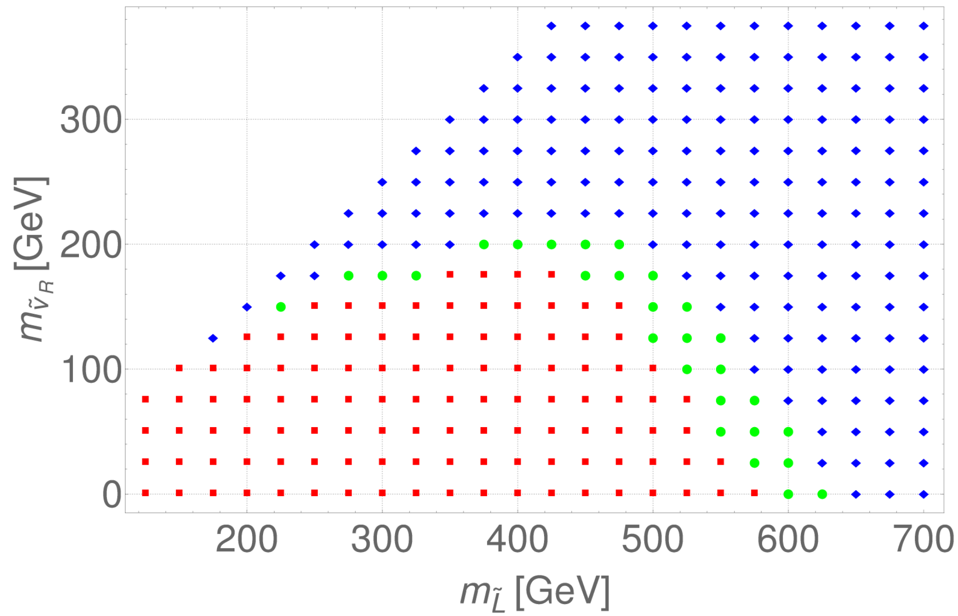
8+13 TeV data (13.9 fb^{-1})

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





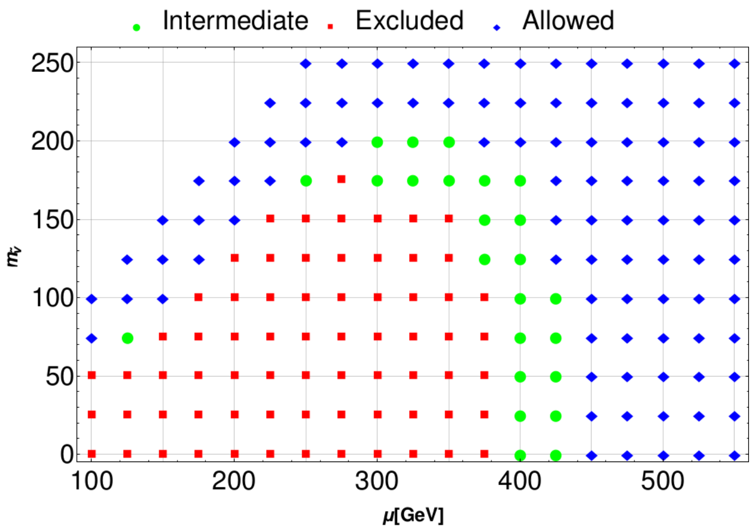
8+13 TeV data (13.9 fb^{-1})
using `CheckMATE 2.0`
$m_{\nu_R} = 20$ GeV

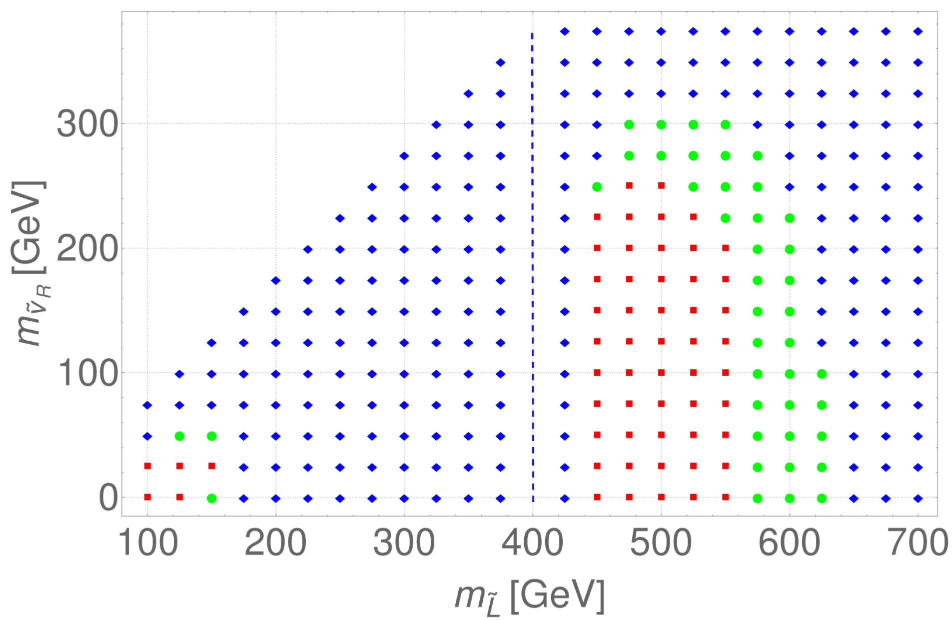
$\mu = 25 + m_{\tilde{\nu}} < m_{\tilde{l}} \simeq m_{\tilde{L}} = m_{\tilde{E}}$
$M_1 = M_2 = 2$ TeV, $\tan\beta = 6$

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

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

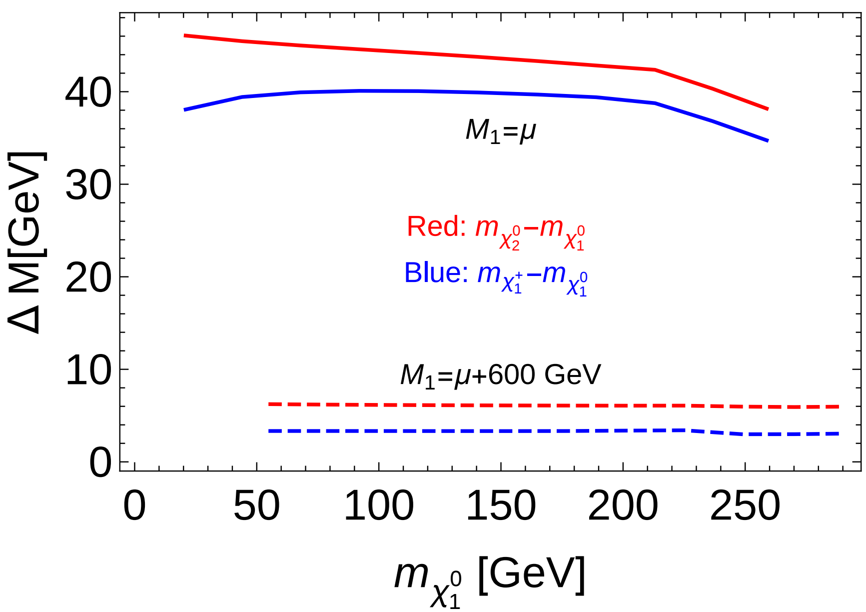
- LHC: $m_h \simeq 125$ GeV, no conclusive BSM physics found $\Rightarrow$
  - CMSSM, NUHM: $m_{\tilde{g}}, m_{\tilde{q}} \gtrsim 2$ TeV
    GMSB: $m_{\tilde{g}}, m_{\tilde{q}} \gtrsim 6$ TeV $\Rightarrow$ Fcc-hh @ 100 TeV
  - CMSSM, NUHM: large A_0, danger of color and charge breaking minima
- 'Natural SUSY': take only those states light which contribute to EWSB: $\tilde{h}^{0,\pm}, \tilde{t}_1, \tilde{g}, \tilde{b}_1$
  disadvantage: a priori cannot explain dark matter relic density
  extra soft parameter $\mu' \Rightarrow$ potential case for ILC @ 1 TeV
- extended gauge groups
  - motived by ν-physics $\Rightarrow$ extended (s)neutrino sector
  - can easier accommodate $m_h \simeq 125$ GeV
  - $\tilde{\nu}_R$ 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

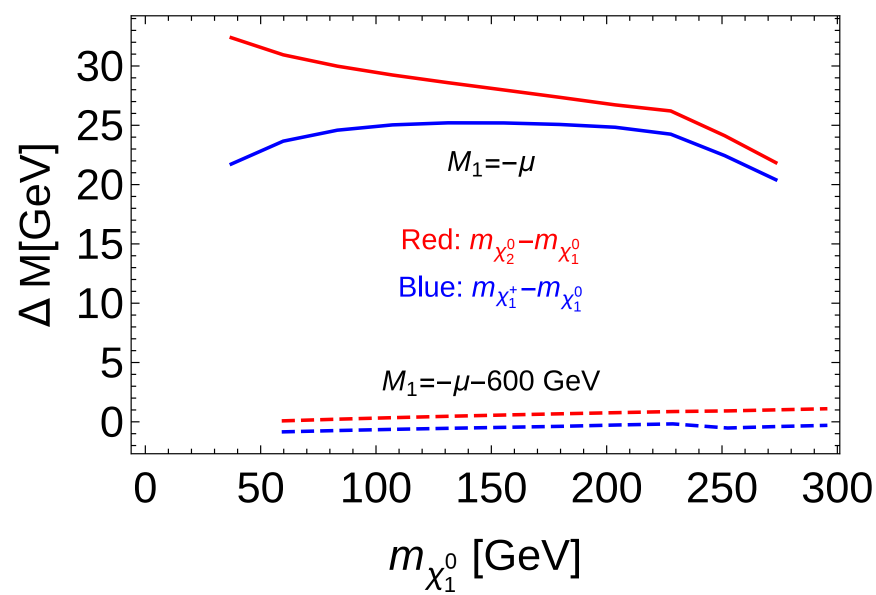
Higgsino LSP: spectrum

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

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

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

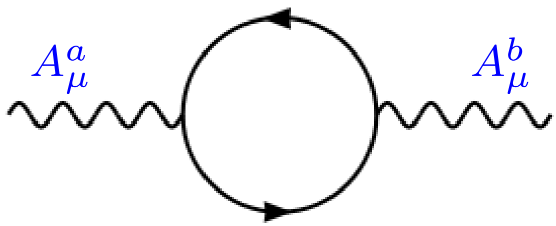




Gauge kinetic mixing

$U(1)_a \times U(1)_b$ 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

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

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, arXiv:1107.2670

A SUSY Z'-model

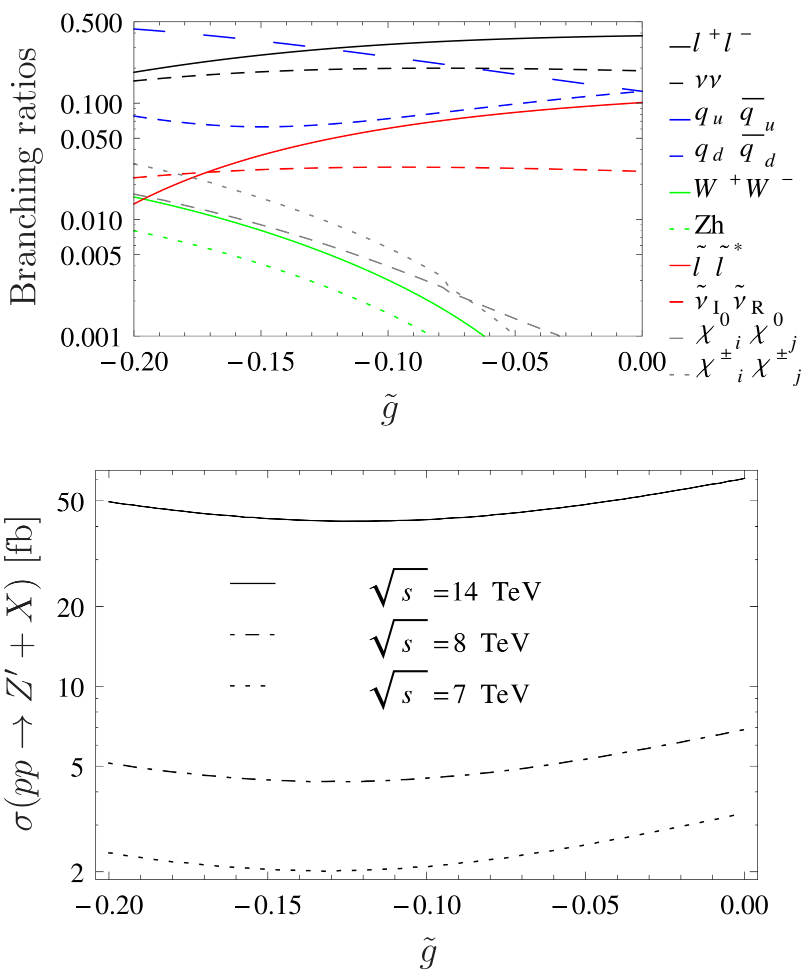
Superfield	Generations	$U(1)_Y \times SU(2)_L \times SU(3)_C \times U(1)_{B-L}$
$\hat{Q}$	3	$(\frac{1}{6}, \mathbf{2}, \mathbf{3}, \frac{1}{6})$
$\hat{D}$	3	$(\frac{1}{3}, \mathbf{1}, \overline{\mathbf{3}}, -\frac{1}{6})$
$\hat{U}$	3	$(-\frac{2}{3}, \mathbf{1}, \overline{\mathbf{3}}, -\frac{1}{6})$
$\hat{L}$	3	$(-\frac{1}{2}, \mathbf{2}, \mathbf{1}, -\frac{1}{2})$
$\hat{E}$	3	$(1, \mathbf{1}, \mathbf{1}, \frac{1}{2})$
$\hat{\nu}$	3	$(0, \mathbf{1}, \mathbf{1}, \frac{1}{2})$
$\hat{H}_d$	1	$(-\frac{1}{2}, \mathbf{2}, \mathbf{1}, 0)$
$\hat{H}_u$	1	$(\frac{1}{2}, \mathbf{2}, \mathbf{1}, 0)$
$\hat{\eta}$	1	$(0, \mathbf{1}, \mathbf{1}, -1)$
$\hat{\bar{\eta}}$	1	$(0, \mathbf{1}, \mathbf{1}, 1)$

$$W = Y_u^{ij}\, \hat{U}_i\, \hat{Q}_j\, \hat{H}_u - Y_d^{ij}\, \hat{D}_i\, \hat{Q}_j\, \hat{H}_d - Y_e^{ij}\, \hat{E}_i\, \hat{L}_j\, \hat{H}_d + \mu\, \hat{H}_u\, \hat{H}_d + Y_\nu^{ij}\, \hat{L}_i\, \hat{H}_u\, \hat{\nu}_j$$
$$- \mu'\, \hat{\eta}\, \hat{\bar{\eta}} + Y_x^{ij}\, \hat{\nu}_i\, \hat{\eta}\, \hat{\nu}_j$$

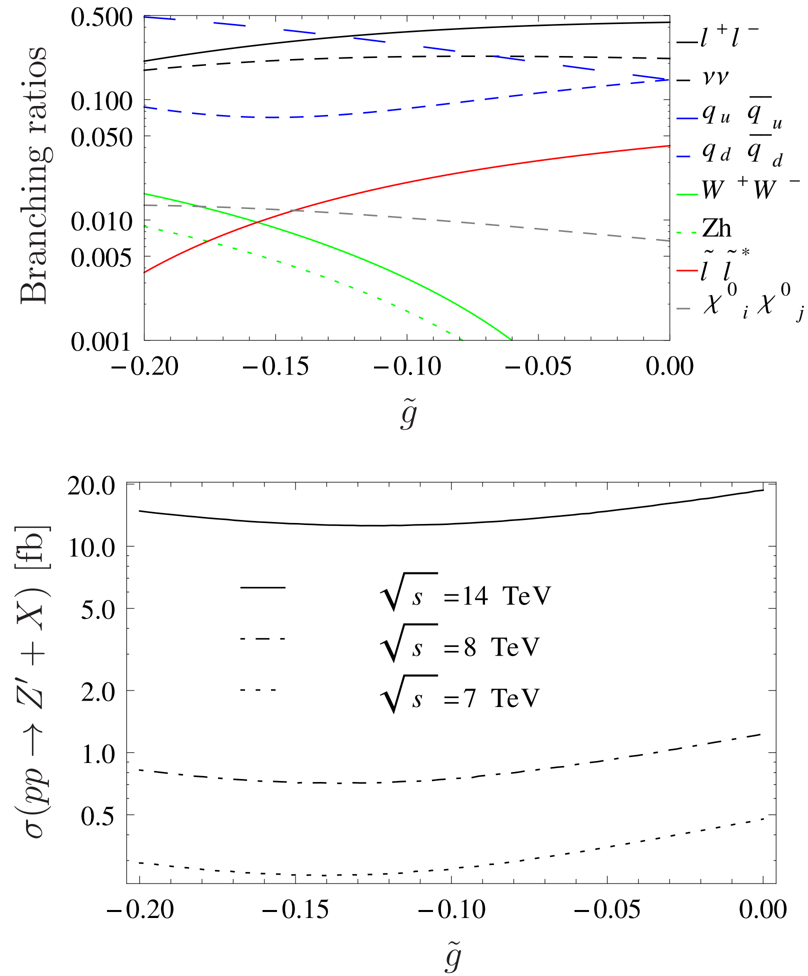
based on B. O'Leary, W.P., F. Staub, arXiv:1112.4600

K-factor for leptonic channels: ~ 1.2

BL1



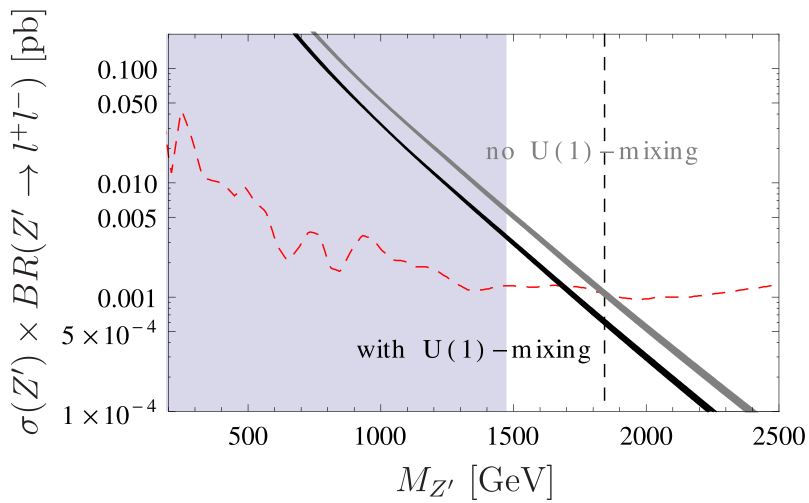
BL2



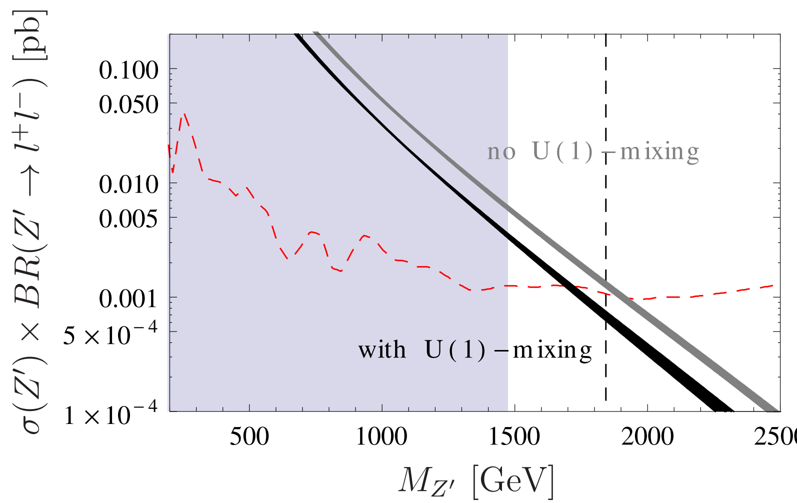
M. Krauss, B. O'Leary, W.P., F. Staub, arXiv:1206.3513

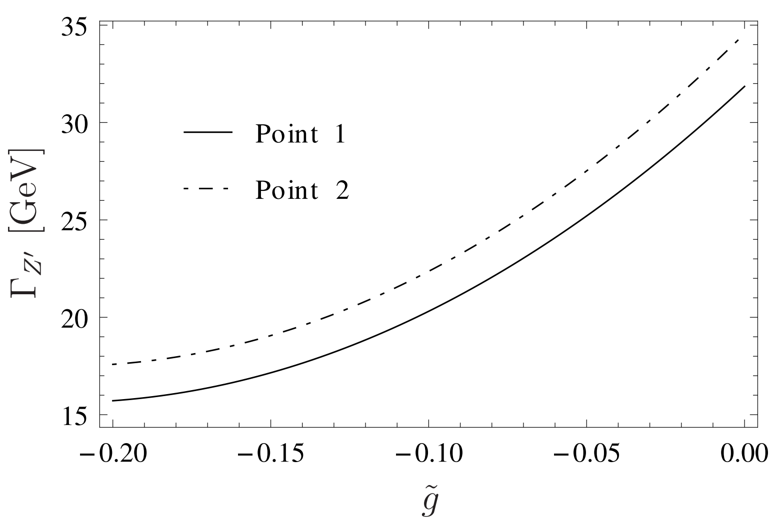
Z' physics, II

BL1



BL2



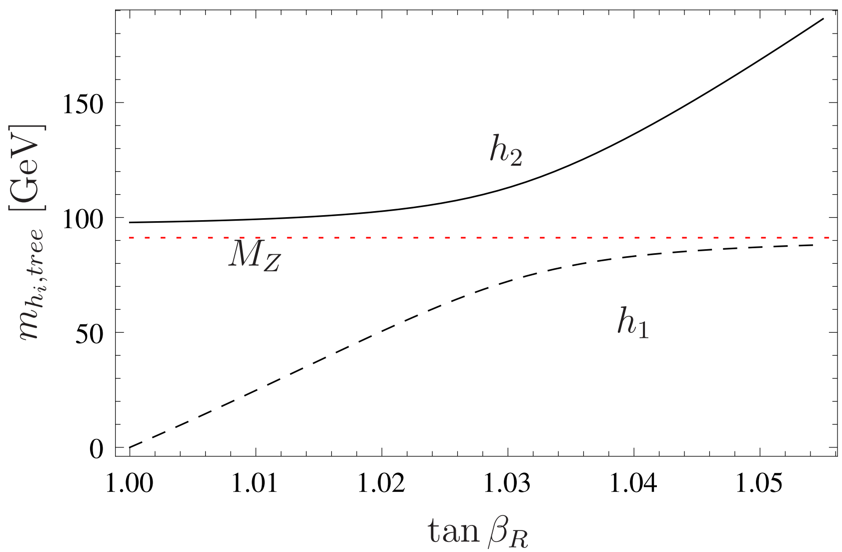


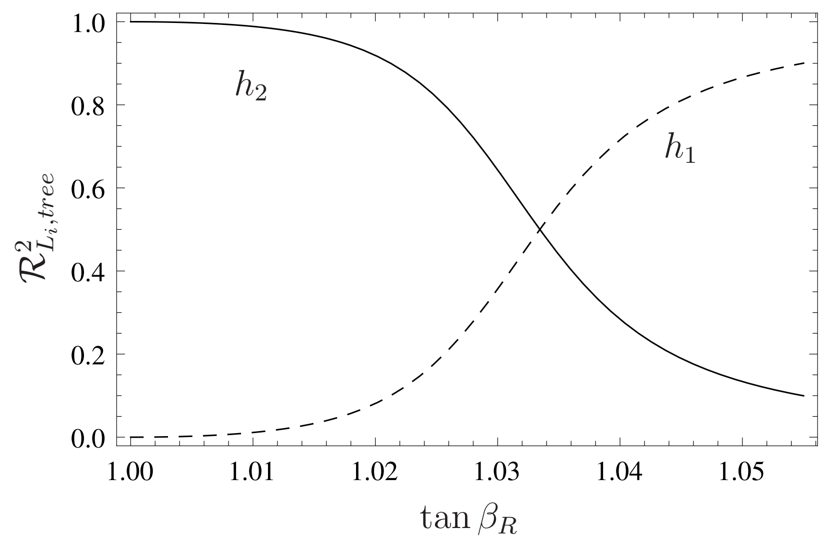
No.	$\tilde{g} = -0.11$	$\tilde{g} = 0$
BL1	1680 GeV	1840 GeV
BL2	1700 GeV	1910 GeV

Higgs sector

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



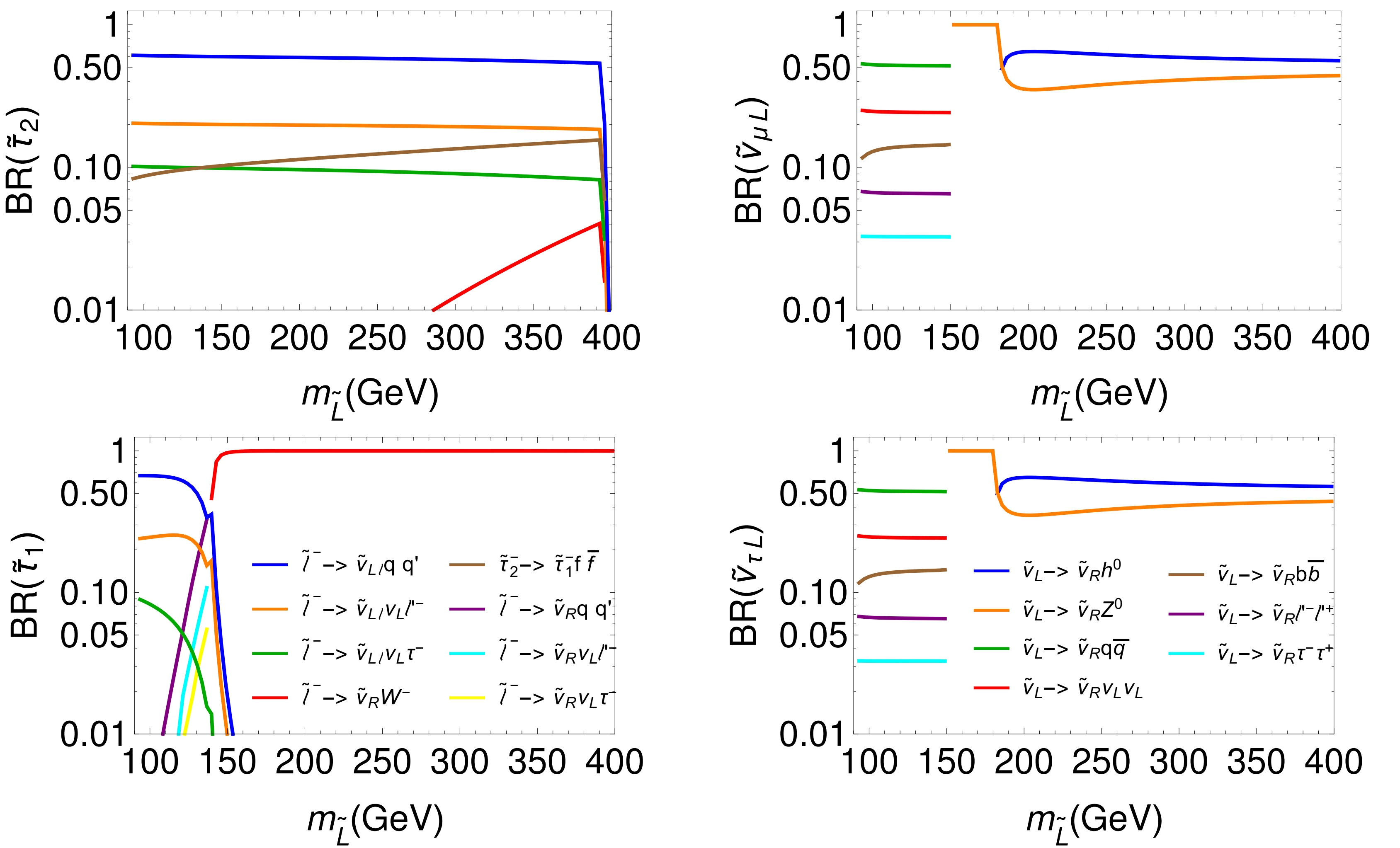


$n = 1$, $\Lambda = 5 \cdot 10^5$ GeV, $M = 10^{11}$ GeV, $\tan\beta = 30$, sign$(\mu_R) = -$, $diag(Y_S) = (0.7, 0.6, 0.6)$, $Y_\nu^{ii} = 0.01$, $v_R = 7$ TeV

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

$\tilde{\nu}_R$-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

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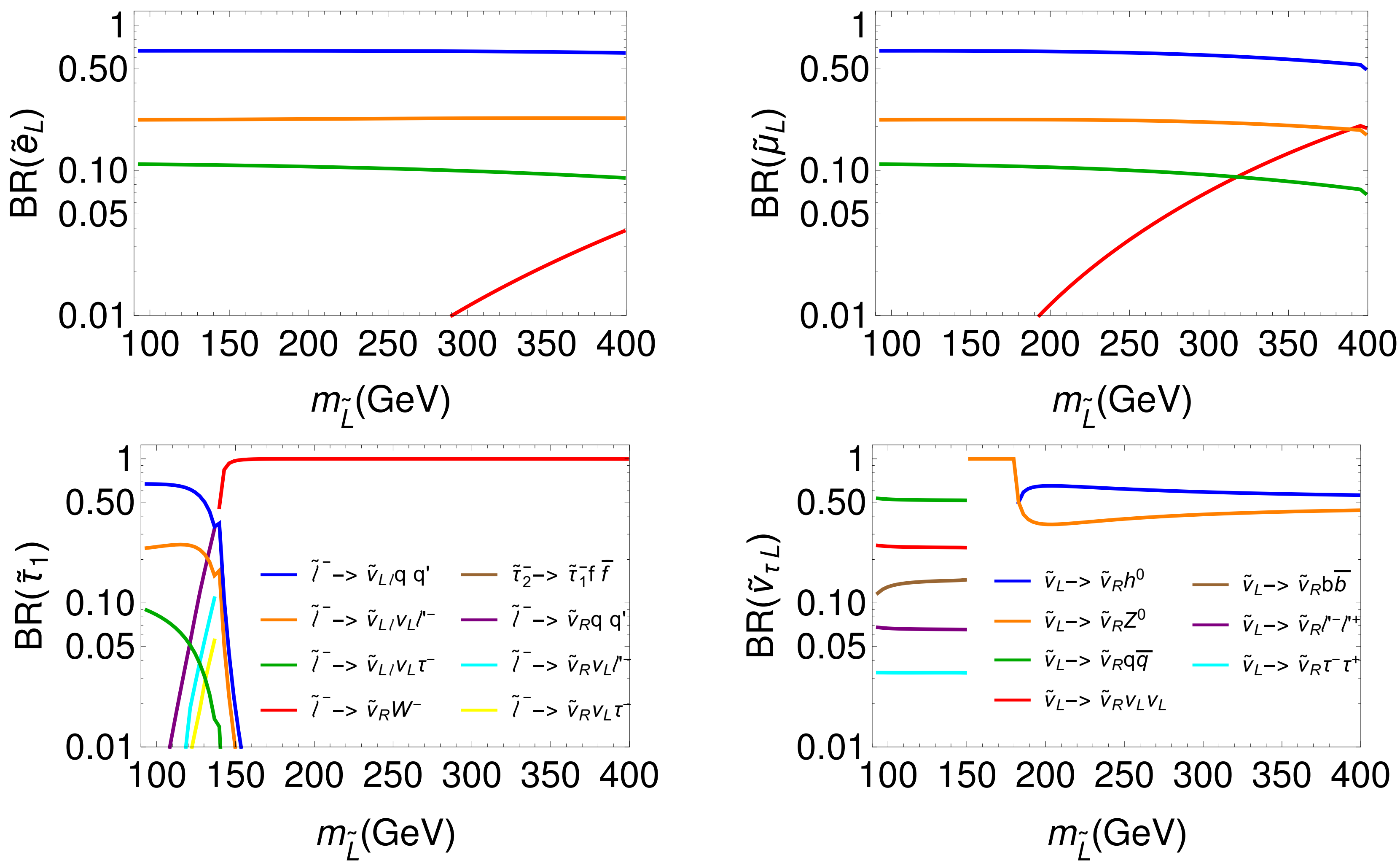

Nh. Cerna-Velazco, Th. Faber, J. Jones, WP arXiv:1705.06583