Status of Supersymmetry

(Is SUSY still alive?)

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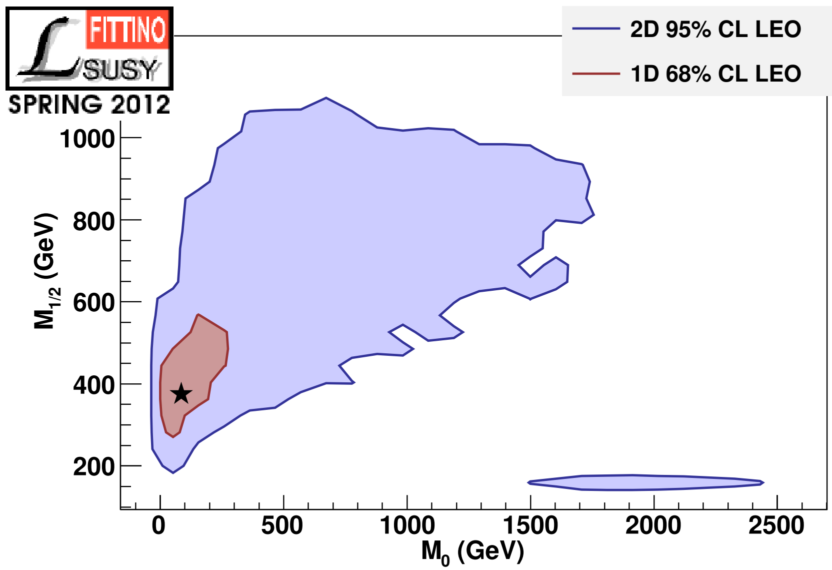
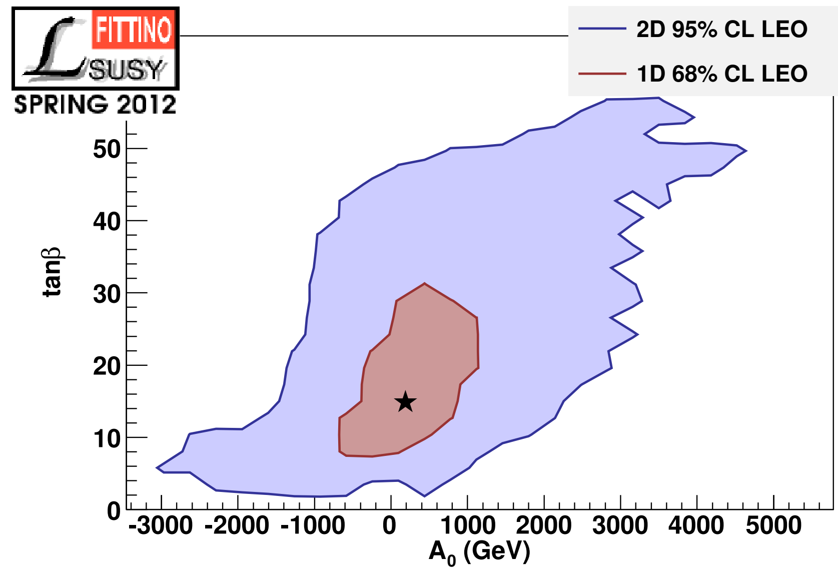
Content

- Higgs discovery and LHC BSM results: implications
- ‘Natural’ MSSM, a challenge
- ‘Natural’ SUSY and extended gauge groups
- Conclusions

Expectations before LHC, mSUGRA/CMSSM





$\mathcal{B}(b \to s\gamma)$	$(3.55 \pm 0.34) \times 10^{-4}$
$\mathcal{B}(B_s \to \mu\mu)$	$< 4.5 \times 10^{-9}$
$\mathcal{B}(B \to \tau\nu)$	$(1.67 \pm 0.39) \times 10^{-4}$
Δm_{B_s}	$17.78 \pm 5.2\,\mathrm{ps}^{-1}$
$a_\mu^{\mathrm{exp}} - a_\mu^{\mathrm{SM}}$	$(28.7 \pm 8.2) \times 10^{-10}$
m_W	(80.385 ± 0.015) GeV
$\sin^2\theta_{\mathrm{eff}}$	0.23113 ± 0.00021
$\Omega_{\mathrm{CDM}} h^2$	0.1123 ± 0.0118

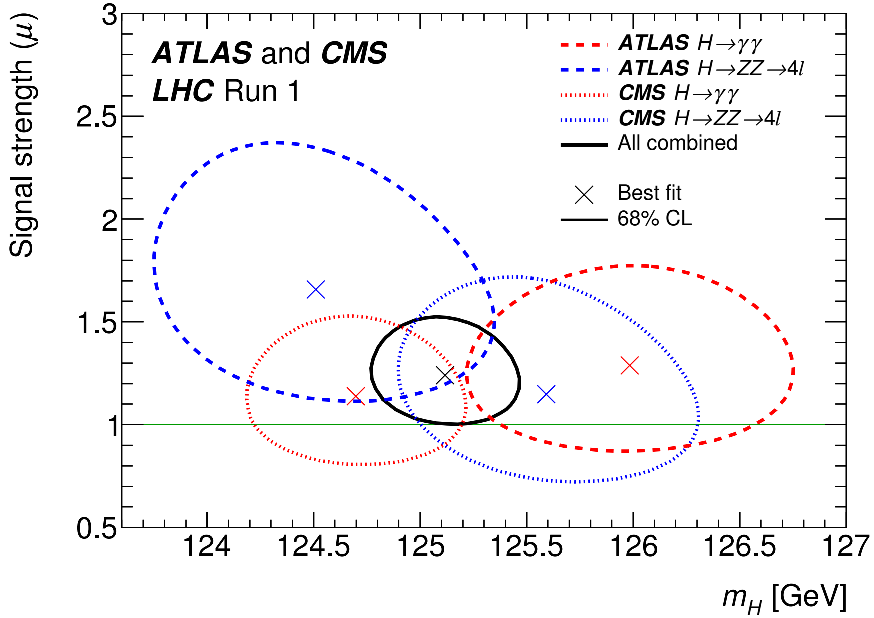
$\Rightarrow M_0 = 84^{+145}_{-28}$ GeV, $M_{1/2} = 375^{+175}_{-88}$ GeV,
$\tan\beta = 15^{+17}_{-7}$ $A_0 = 186^{+831}_{-844}$ GeV,
$\chi^2/ndf = 10.3/8$

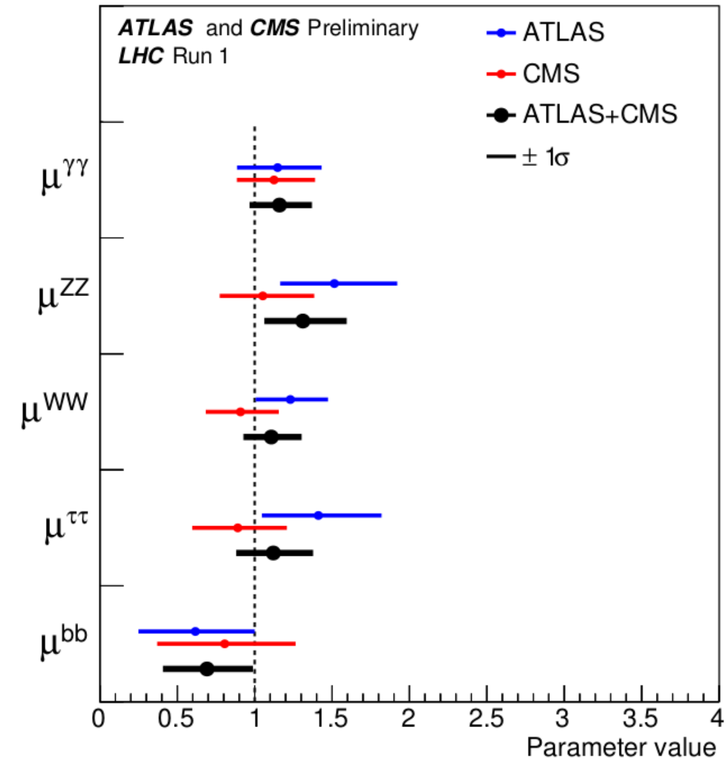
$\Rightarrow m_h = 116$ GeV

P. Bechtle et al., arXiv:1204.4199

similar results by other groups
e.g. MasterCode, O. Buchmueller et al.
BayesFITS, L. Roszkowski et al.

Higgs results in a nut-shell





$m_H = 125.09 \pm 0.21$ (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

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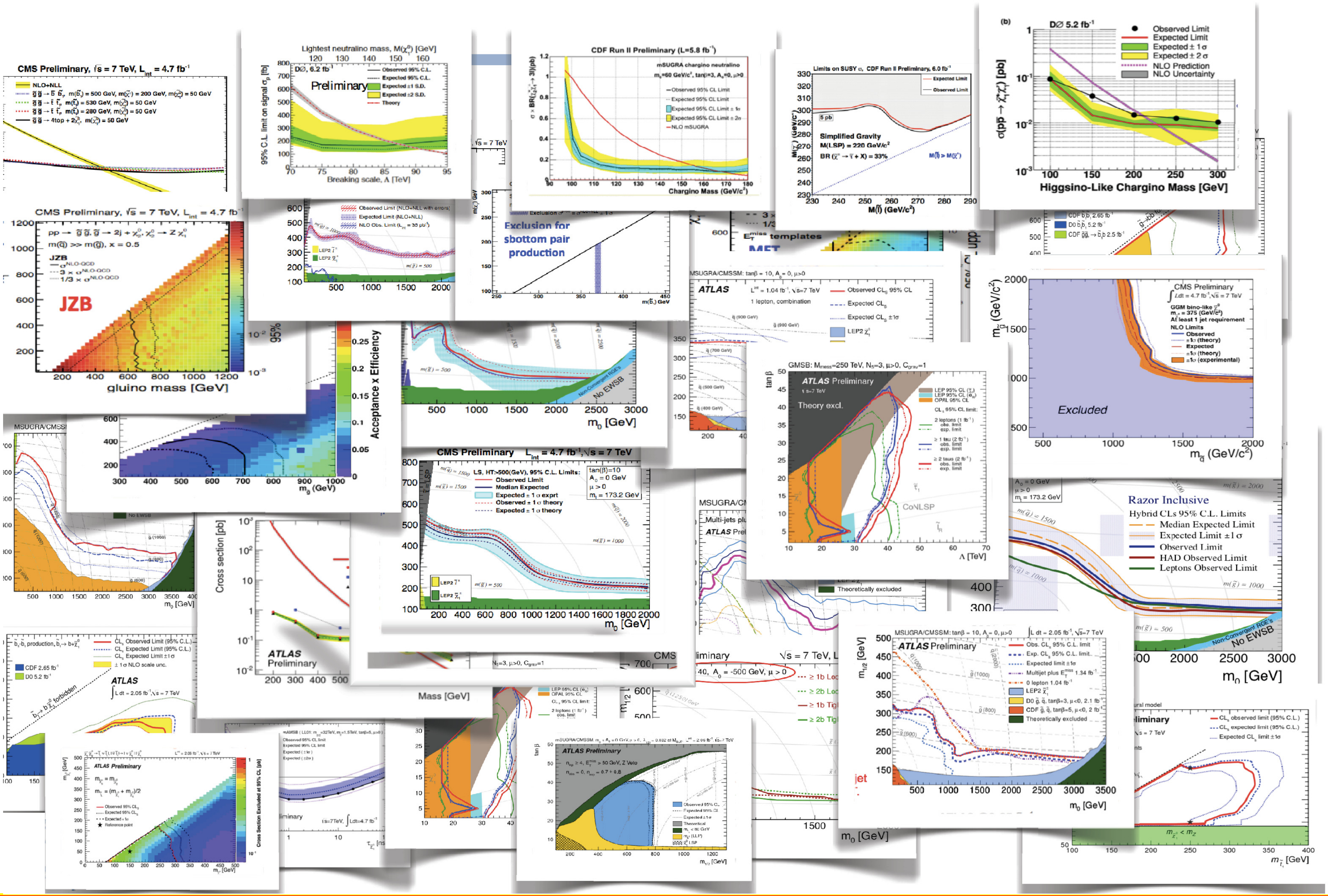
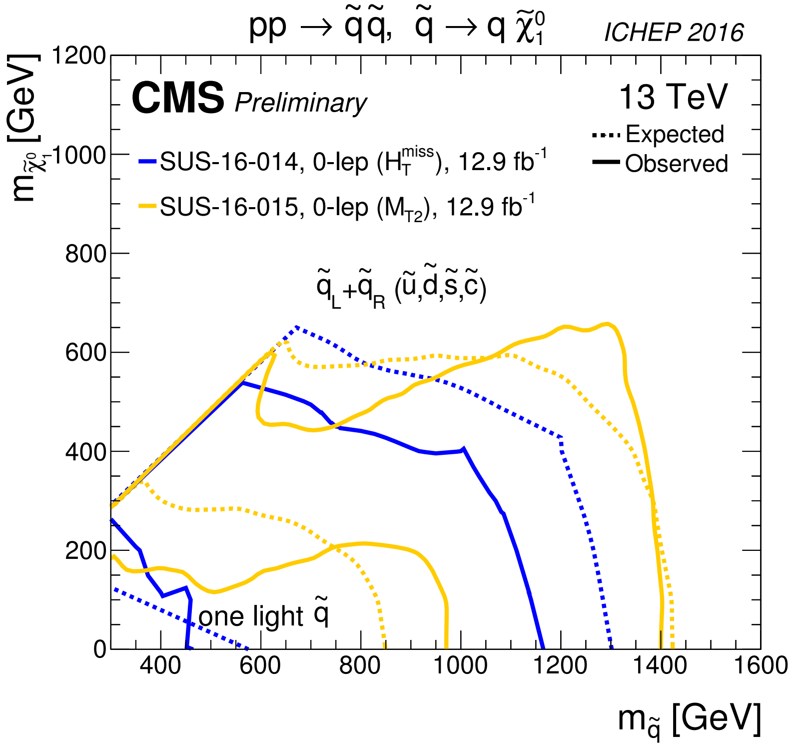
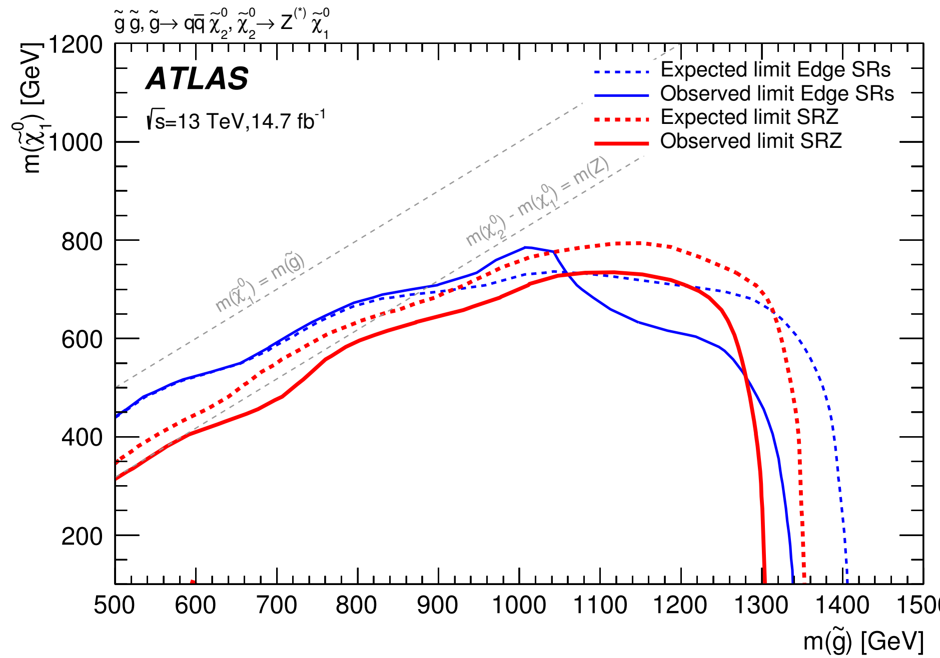
BSM searches, so far hardly anything …



Examples for SUSY searches 13 TeV data





LHC data, in particular m_h, high scale models

$m_h = 125.1$ GeV ⇒ large loop contributions

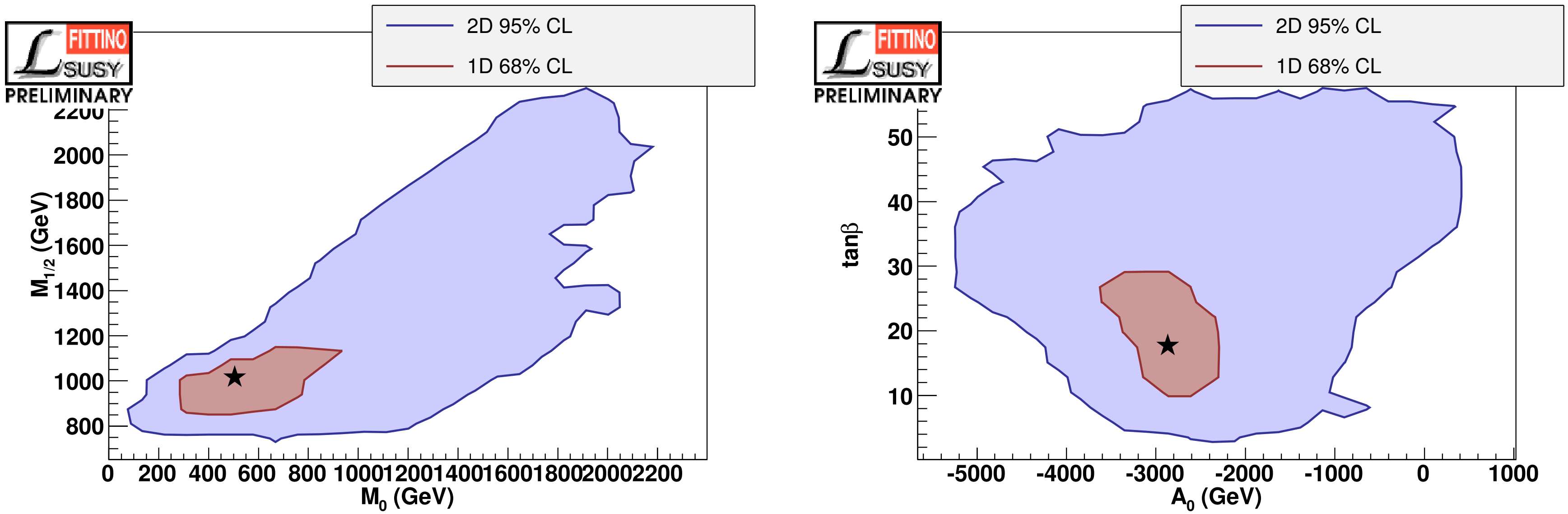
⇒ heavy stops and/or large left-right mixing for stops

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

  more complicated models based on P. Meade, N. Seiberg and D. Shih, arXiv:0801.3278 ⇒ allow additional terms
  e.g. S. Knappen, D. Redigolo, arXive:1606.07501 $m_{\tilde{t}_1} \simeq m_{\tilde{b}_1} \gtrsim 1$ TeV if $M_{\text{mess}} \gtrsim 10^{15}$ GeV
- CMSSM, NUHM models: $|A_0| \simeq 2m_0$,
  H. Baer, V. Barger and A. Mustafayev, arXiv:1112.3017; M. Kadastik *et al.*, arXiv:1112.3647; O. Buchmueller *et al.*, arXiv:1112.3564; J. Cao, Z. Heng, D. Li, J. M. Yang, arXiv:1112.4391; L. Aparicio, D. G. Cerdeno, L. E. Ibanez, arXiv:1202.0822; J. Ellis, K. A. Olive, arXiv:1202.3262; . . .
- 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 including LHC bounds & m_h

Fitting low energy observables, m_h, $BR(h \to X)$, LHC bounds



P. Bechtle et al., arXiv:1508.05951

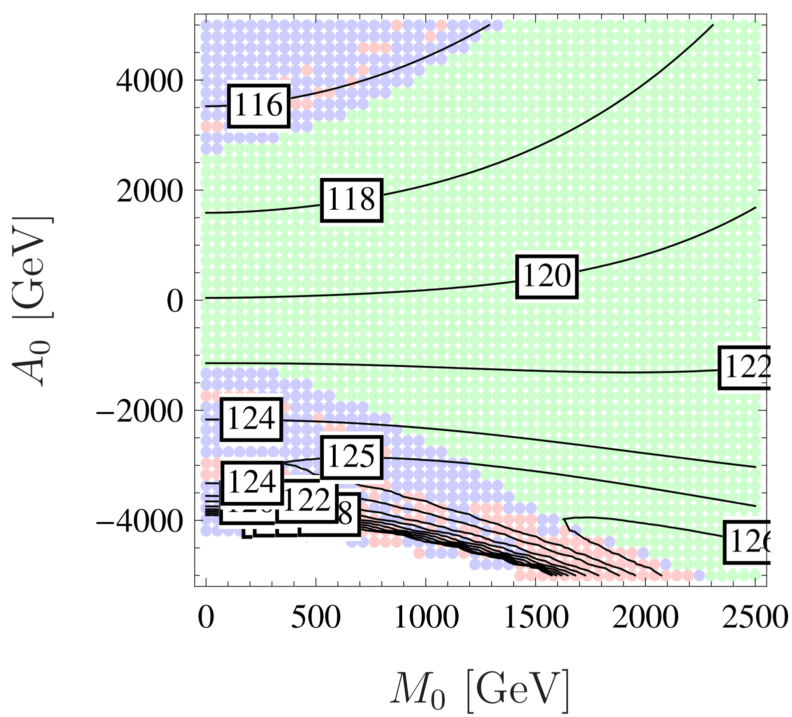
implications for LHC: $m_{\tilde{g}}, m_{\tilde{q}} \gtrsim 2$ TeV, $m_{\tilde{l}_R} \simeq 600$ GeV, $m_{\tilde{\chi}_1^0} \simeq 450$ GeV

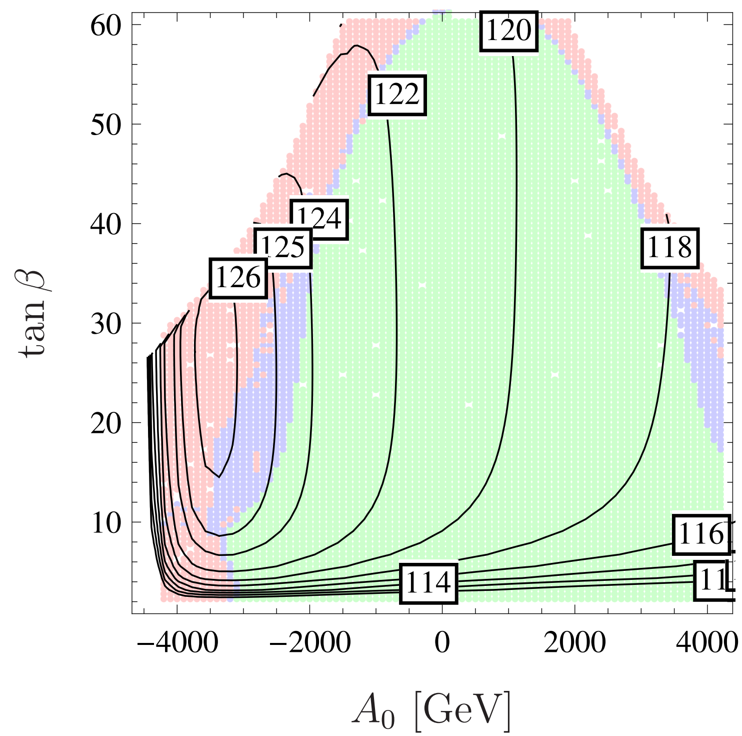
can be tested at LHC 13 TeV [14 TeV]

so far so good, but . . .

mSUGRA/CMSSM, charge/color breaking minima

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





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

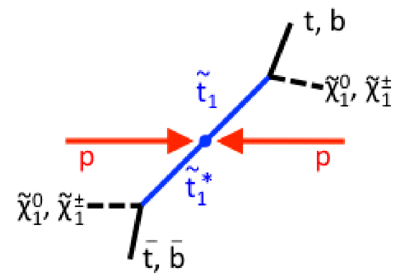
J.E. Camargo-Molina, B. O'Leary, W.P., F. Staub, arXiv:1309.7212

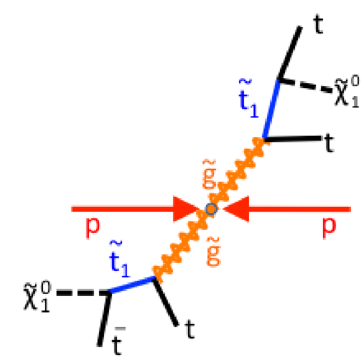
General MSSM

several studies, 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

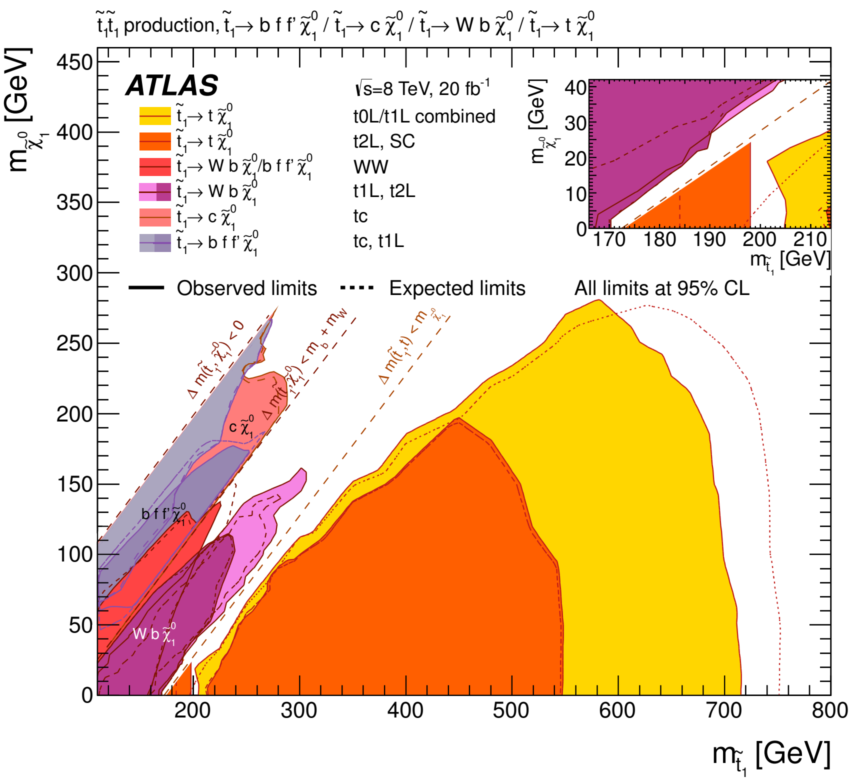
$$\begin{aligned} \tilde{g} &\to \tilde{t}_1 t, \tilde{b}_1 b \\ \tilde{t}_1 &\to t\tilde{\chi}^0_{1,2}, b\tilde{\chi}^+_1, W^+\tilde{b}_1 \\ \tilde{b}_1 &\to b\tilde{\chi}^0_{1,2}, t\tilde{\chi}^-_1, W^-\tilde{t}_1 \end{aligned}$$

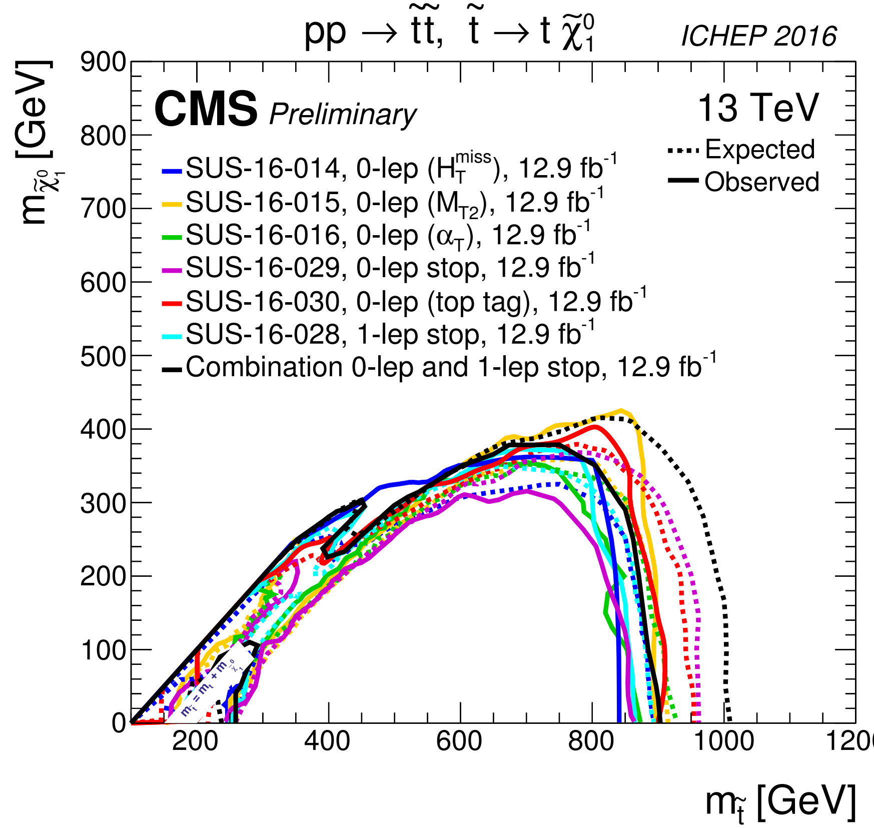




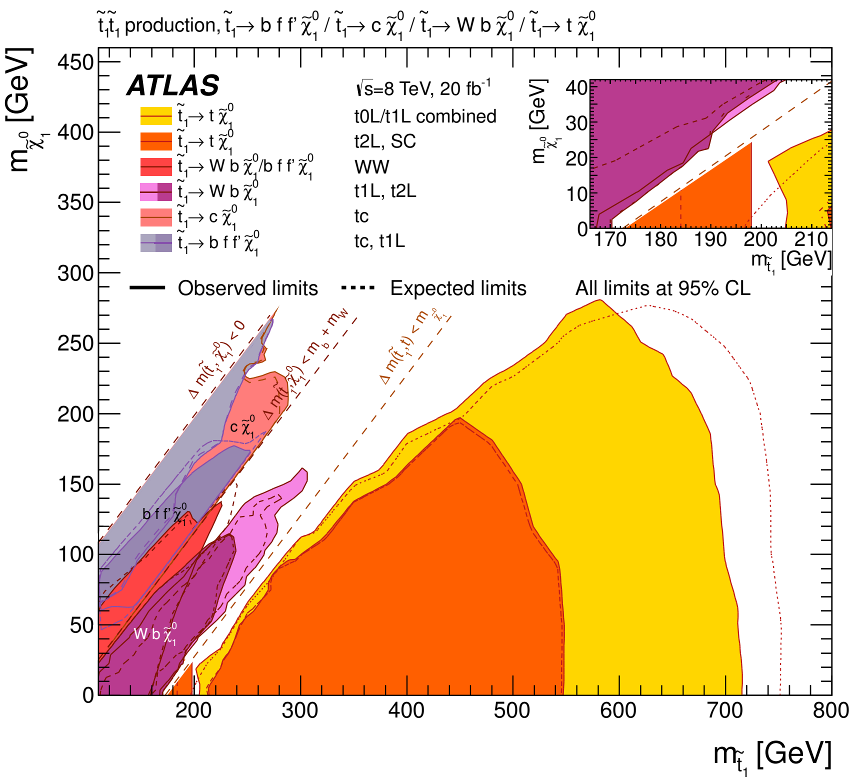
BRs depend on the nature of $\tilde{t}_1$ and $\tilde{b}_1$

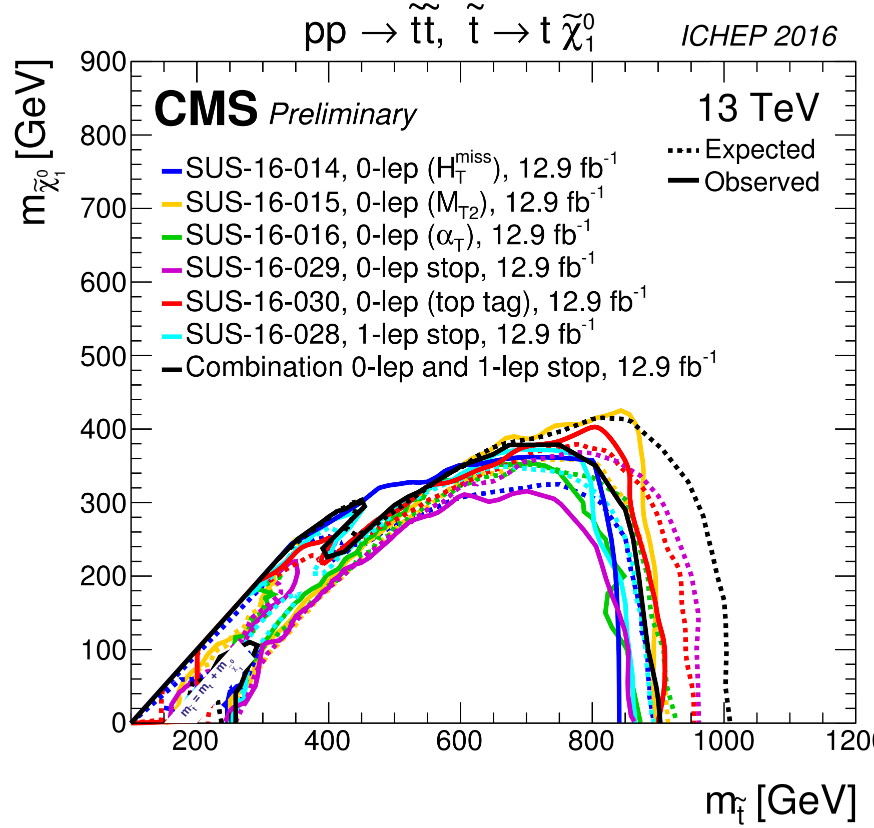
LHC bounds on $\tilde{t}_1$





LHC bounds on $\tilde{t}_1$



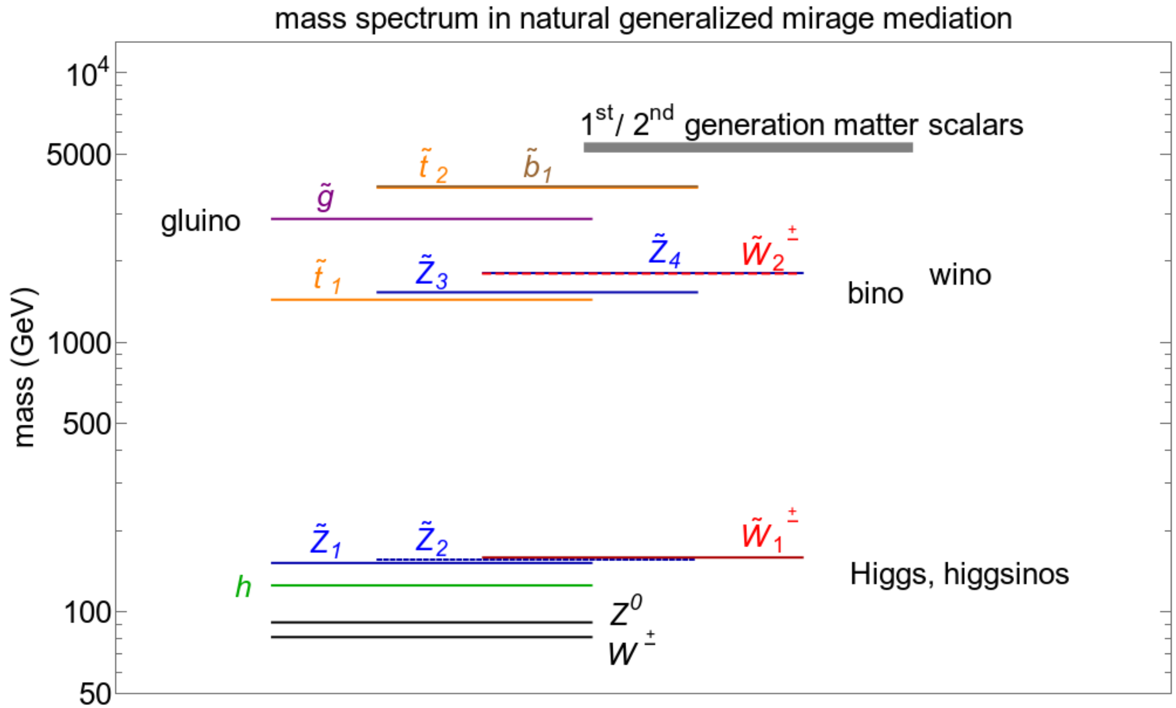


$$\frac{d}{dt}\begin{pmatrix} m^2_{H_u} \\ m^2_{\tilde{t}_R} \\ m^2_{\tilde{Q}^3_L} \end{pmatrix} = -\frac{8\alpha_s}{3\pi} M_3^2 \begin{pmatrix} 0 \\ 1 \\ 1 \end{pmatrix} + \frac{Y_t^2}{8\pi^2}\left(m^2_{\tilde{Q}^3_L} + m^2_{\tilde{t}_R} + m^2_{H_u} + A_t^2 \right) \begin{pmatrix} 3 \\ 2 \\ 1 \end{pmatrix}$$

General Mirrage Mediation

Different sources for soft SUSY breaking: moduli & AMSB

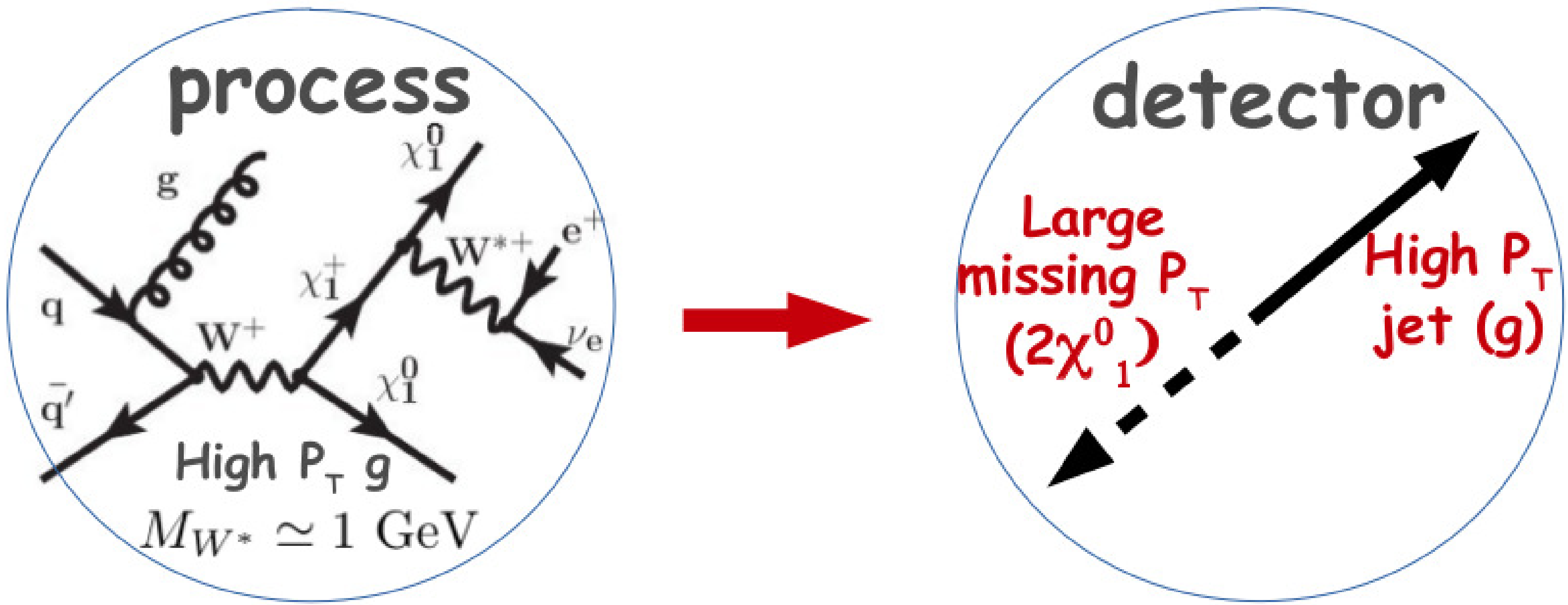
main consequence: gaugino masses unify at a (vastly) different scale then gauge couplings



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

Higgsino LSP: Challenge for LHC

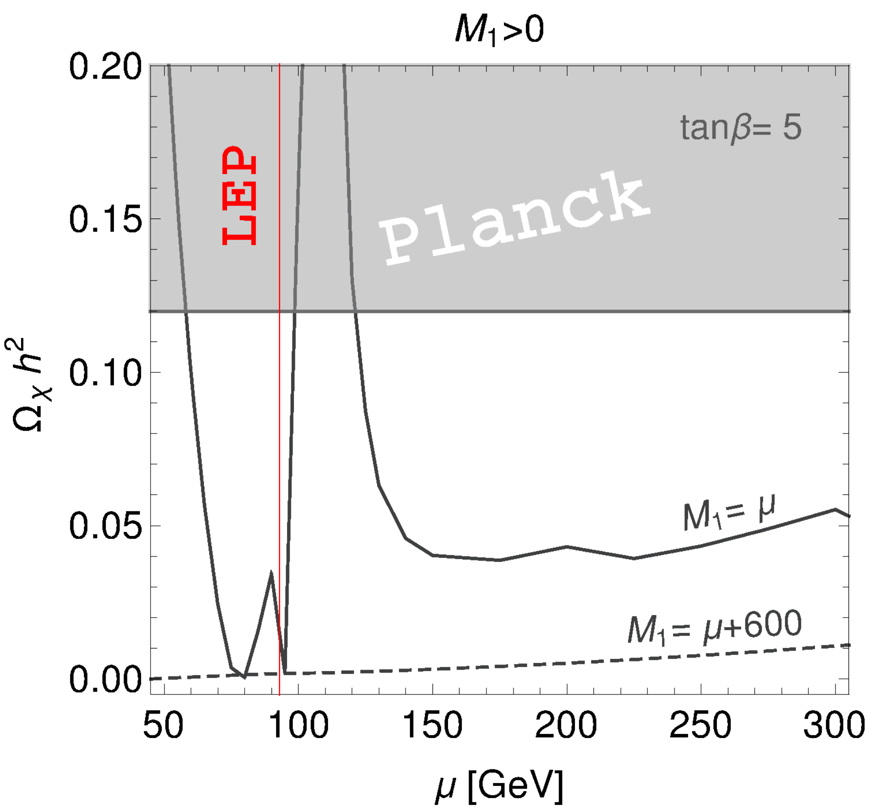
Most challenging case: only higgsinos accessible but nothing else and ΔM to small for any leptonic signature

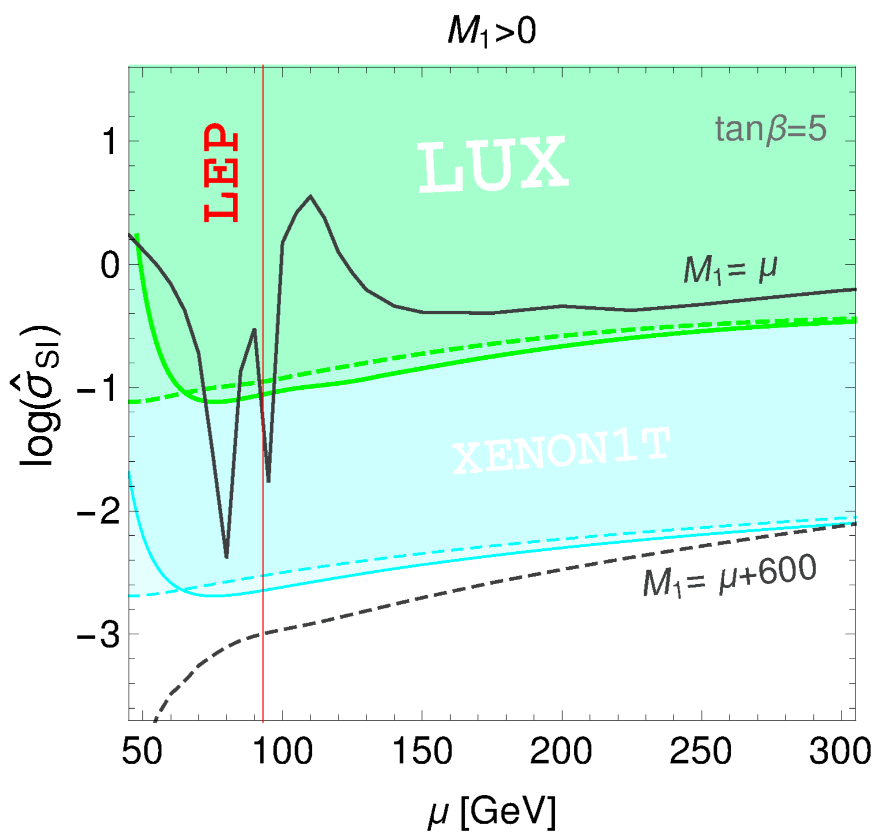


The only way to probe compressed higgsinos is a mono-jet signature:
'Where the Sidewalk Ends? . . . ' Alves, Izaguirre,Wacker 2011

which has been used in studies on compressed SUSY spectra, e.g. Dreiner,Kramer,Tattersall 2012; Han,Kobakhidze,Liu,Saavedra,Wu 2013; Han,Kribs,Martin,Menon 2014

DM relic density and direct detection



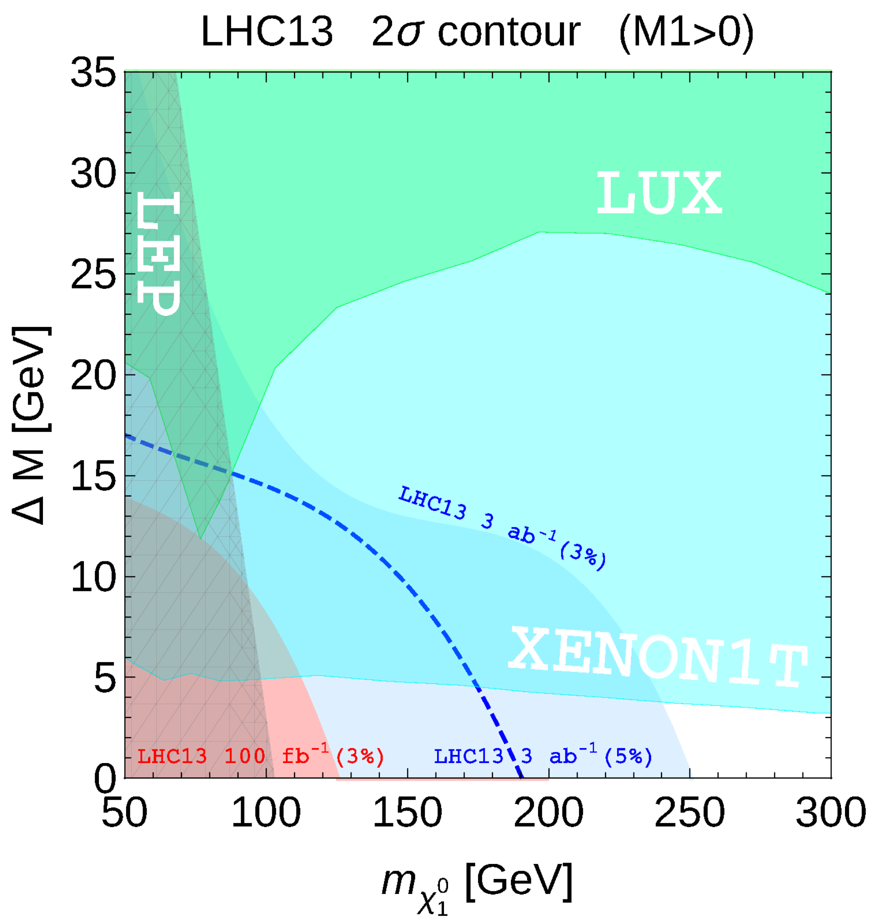


- relic density too low because higgsinos couple ‘strongly’ to W and Z
- DD cross section rescaled with relic density $\rightarrow$ chance for LHC?

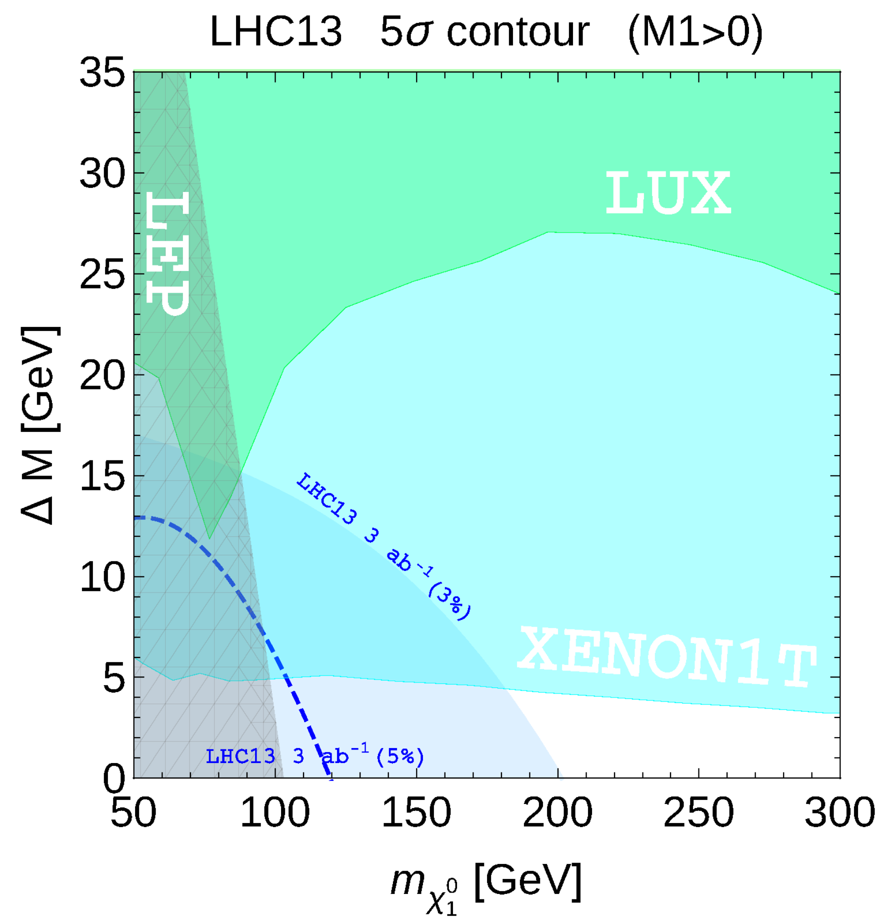
D. Barducci, A. Belyaev, A. Bharucha, WP, V. Sanz, arXiv:1504.02472

LHC @ 13 TeV: signal versus background

exclusion reach



discovery reach



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

Extended gauge groups, motivation

- additional D-term contributions to m_h at tree-level
- Origin of R-parity $R_P = (-1)^{2s+3(B-L)}$

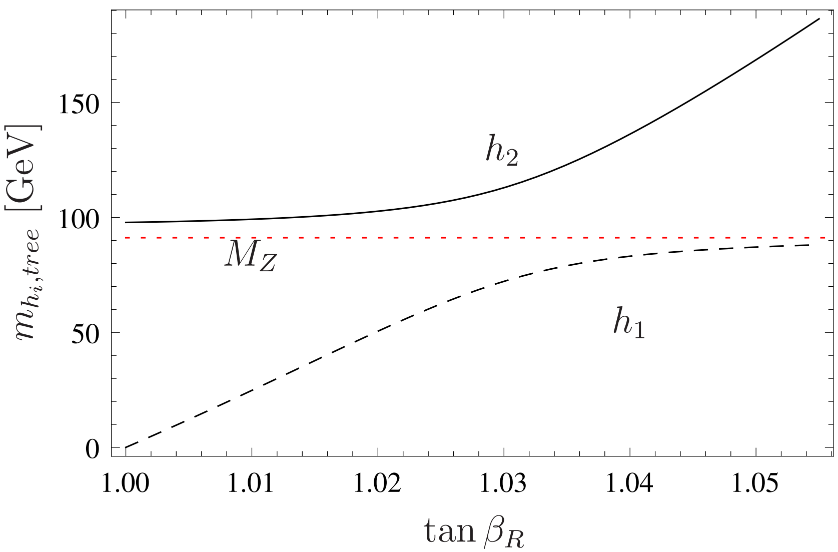
  $\Rightarrow SO(10) \to SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$
  $\to SU(3)_C \times SU(2)_L \times U(1)_R \times U(1)_{B-L}$
  $\cong SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_\chi$
  or $E(8) \times E(8) \to SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$

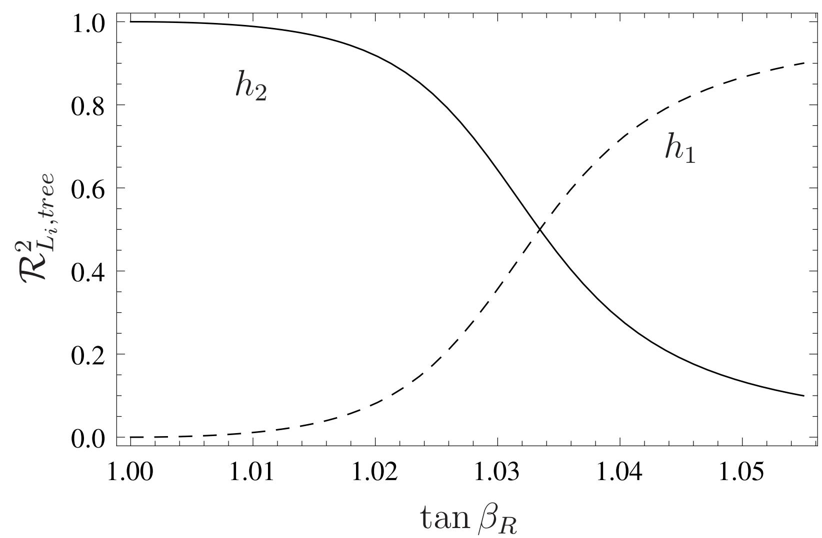
- Neutrino masses

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

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

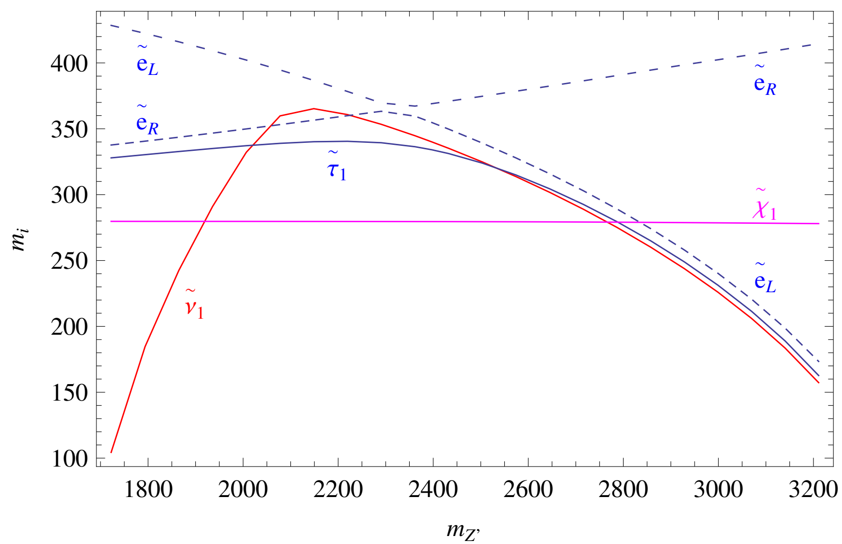
M.E. Krauss, W.P., F. Staub, arXiv:1304.0769

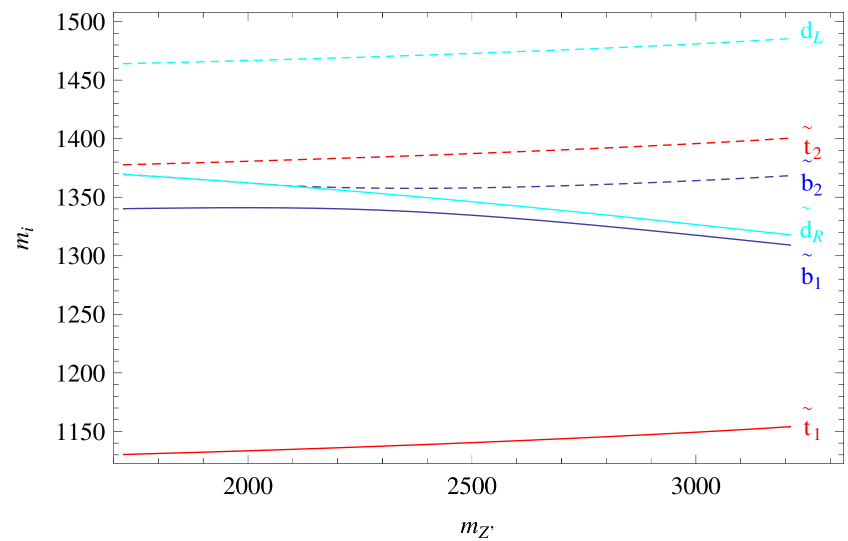
Sfermions

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

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

neglecting gauge kinetic effects; similarly for squarks





$m_0 = 100$ 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

Parameters considered

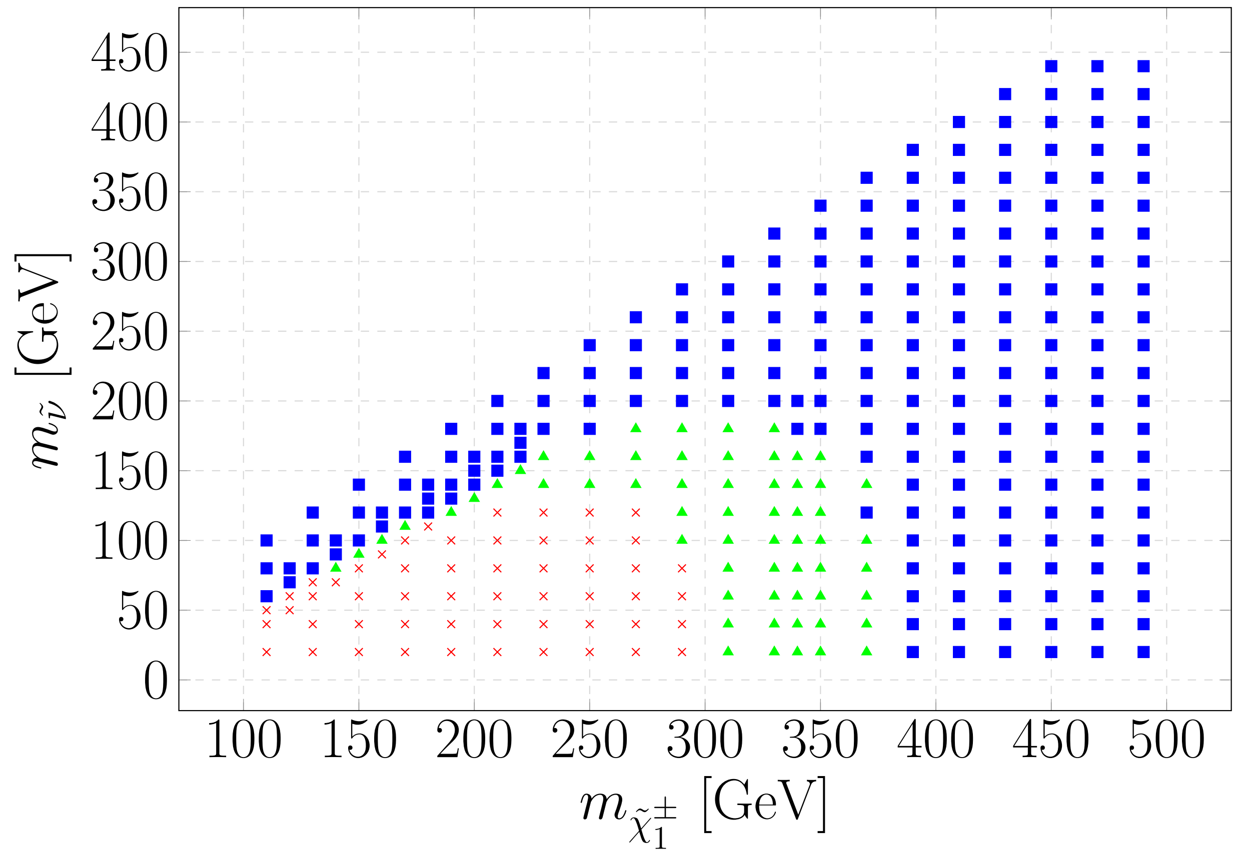
- $m_{\tilde{t}_1}$ in GeV: 300, 400, 500, 600, 700, 800, 900, 1000
- $m_{\tilde{b}_1}$ in GeV: 300, 400, 500, 600, 700, 800, 900, 1000
- $m_{\tilde{\nu}_R}$ in GeV : 60, 100, 200, 300, 400, 500
- μ in GeV: 110, 190, 290, 390, 490, 590 and require $m_{\tilde{\nu}_R} < \mu$
- $\tan\beta$: 10, 50
- $\theta_{\tilde{t}}$: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

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

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

Constraints on μ:

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



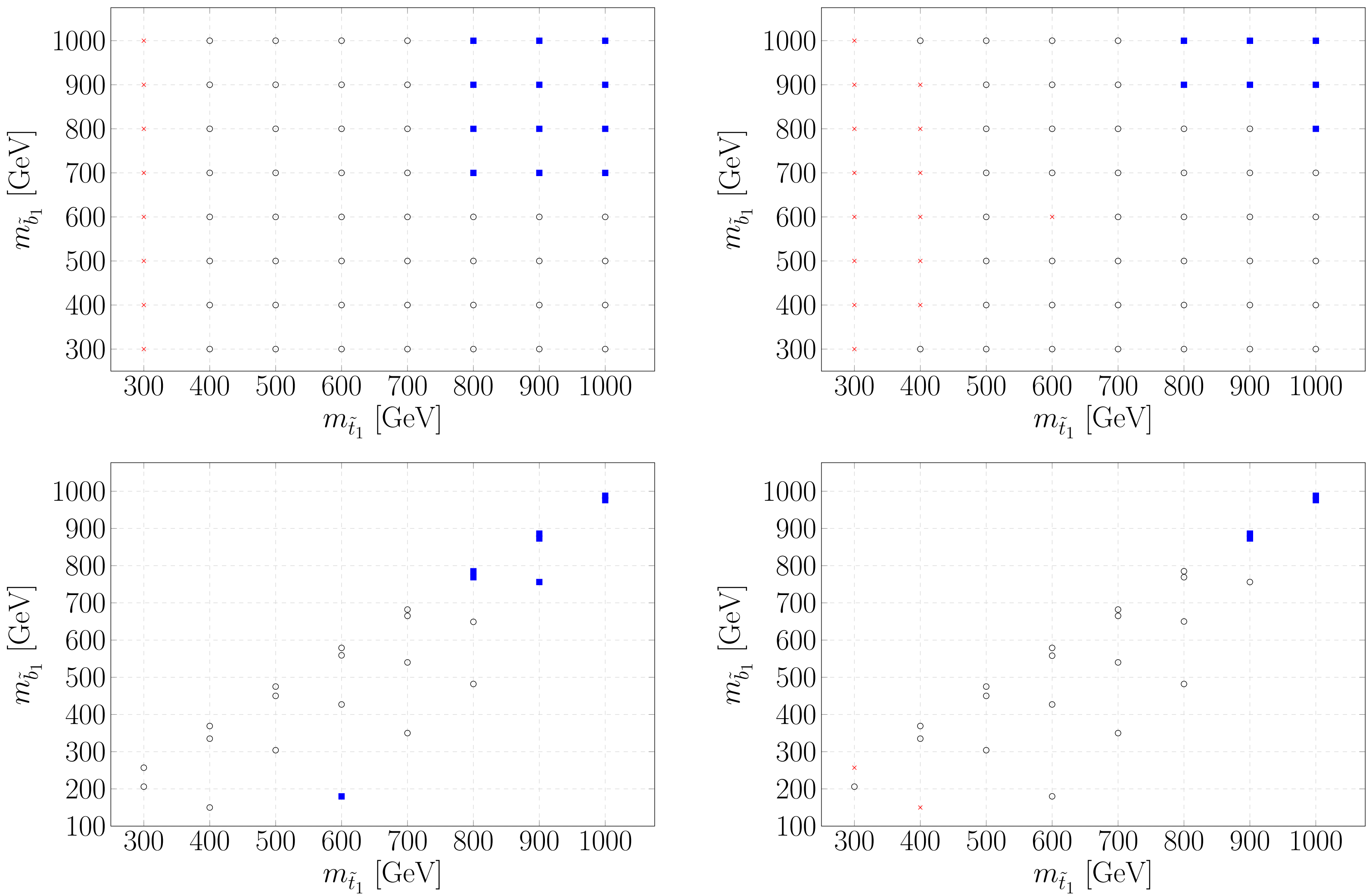
× excluded, ▲ ambigous, ■ allowed

using CheckMATE

L. Mitzka, WP arXiv:1603.06130

Summary results

ambigous as allowed ambigous as forbidden



× excluded for all parameters, ○ exclusion depends on parameters, ■ allowed for all parameters L. Mitzka, WP arXiv:1603.06130

Conclusions

Is SUSY still alive? $\Rightarrow$ Yes, it is (at least as much as any other BSM model)

- LHC: $m_h \simeq 125$ GeV, no conclusive BSM physics found
- 'Natural SUSY': take only those states light which contribute to EWSB: $\tilde{h}^{0,\pm}, \tilde{t}_1, \tilde{g}, \tilde{b}_i$
- extreme case with higgsinos only:
  - very challenging: DM direkt detection and LHC probe complementary parameter space regions
  - LHC: can discover higgsinos up to $|\mu| \simeq 120$ GeV (200 GeV) for $\mathcal{L}$=3 ab^{-1}

  Clear need for e^+e^- collider
- light stop still consistent with data
- extended gauge groups, taking only 8 TeV data into account
  - $\tilde{\nu}_R$ LSP: compatible with DM, no direct DM constraint apply
  - $m_{\tilde{H}^\pm} \lesssim 290$ GeV excluded if $m_{\tilde{H}^\pm} - m_{\tilde{\nu}_R} \gtrsim 150$ GeV
  - independent of other parameters: $m_{\tilde{t}_1} \lesssim 300$ GeV excluded
  - for 300 GeV $\lesssim m_{\tilde{t}_1} \lesssim 800$ GeV: exclusion depends on parameters, in particular on $\cos\theta_{\tilde{t}}$

Higgsino LSP: mass matrices

$$
M_{\tilde{\chi}_0} = \begin{pmatrix} M_1 & 0 & -M_Z s_\omega c_\beta & M_Z s_\omega s_\beta \\ 0 & M_2 & M_Z c_\omega c_\beta & -M_Z c_\omega s_\beta \\ -M_Z s_\omega c_\beta & M_Z c_\omega c_\beta & & -\mu \\ M_Z s_\omega s_\beta & -M_Z c_\omega s_\beta & -\mu & 0 \end{pmatrix}
$$

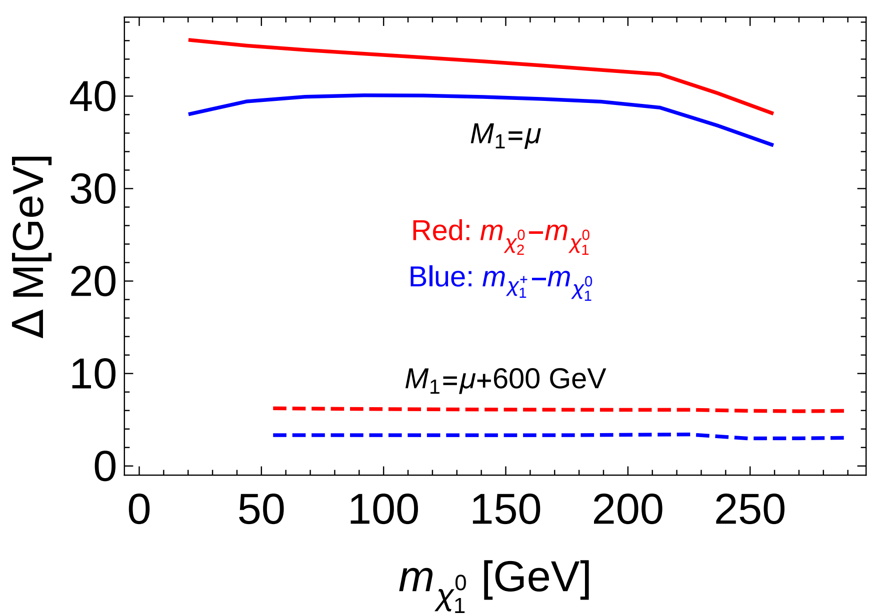
$$
M_{\tilde{\chi}_\pm} = \begin{pmatrix} M_2 & \sqrt{2} M_W s_\beta \\ \sqrt{2} M_W c_\beta & \mu \end{pmatrix}
$$

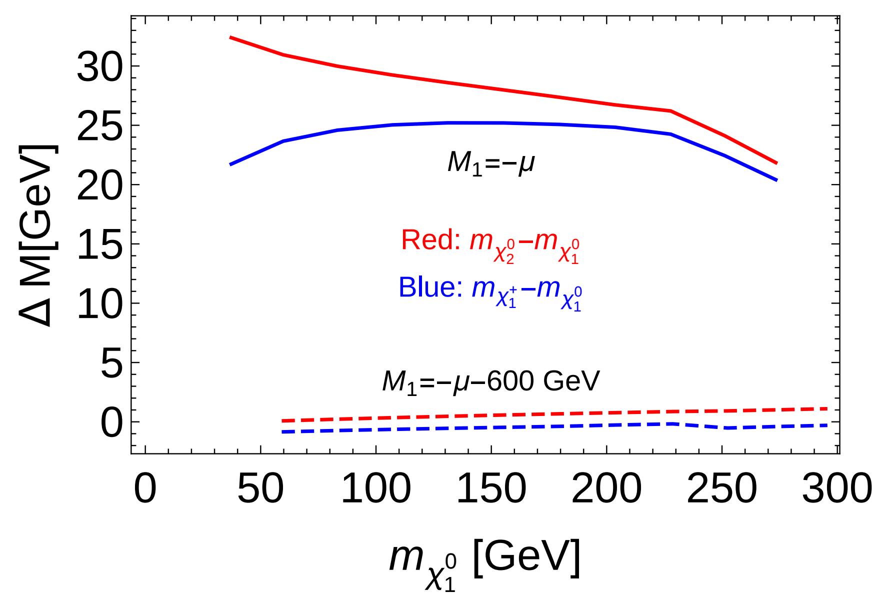
Higgsino LSP: spectrum

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

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

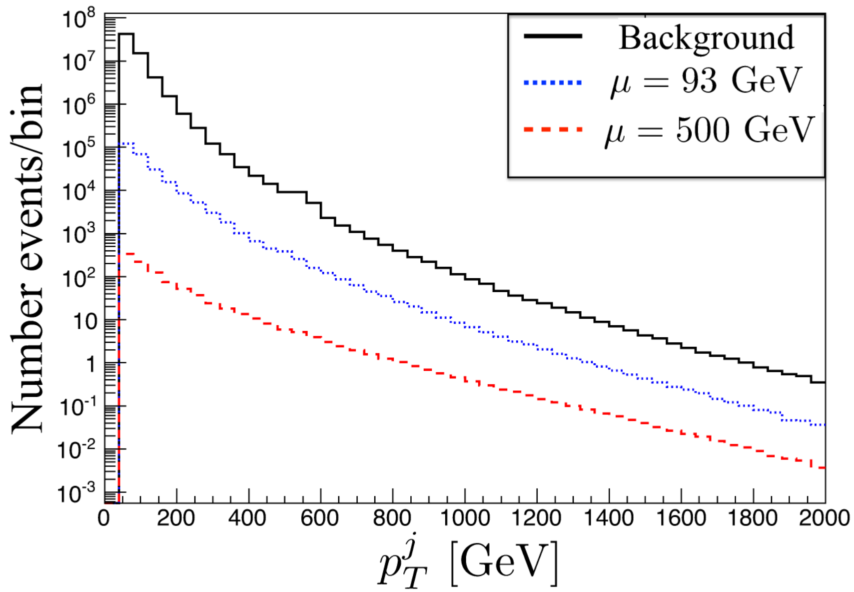
$$\Delta m_\pm = m_{\tilde\chi^\pm_1} - m_{\tilde\chi^0_1} \simeq \frac{\Delta m_0}{2} + |\mu| \frac{\alpha(m_Z)}{\pi} \left(2 + \ln \frac{m_Z^2}{\mu^2} \right)$$



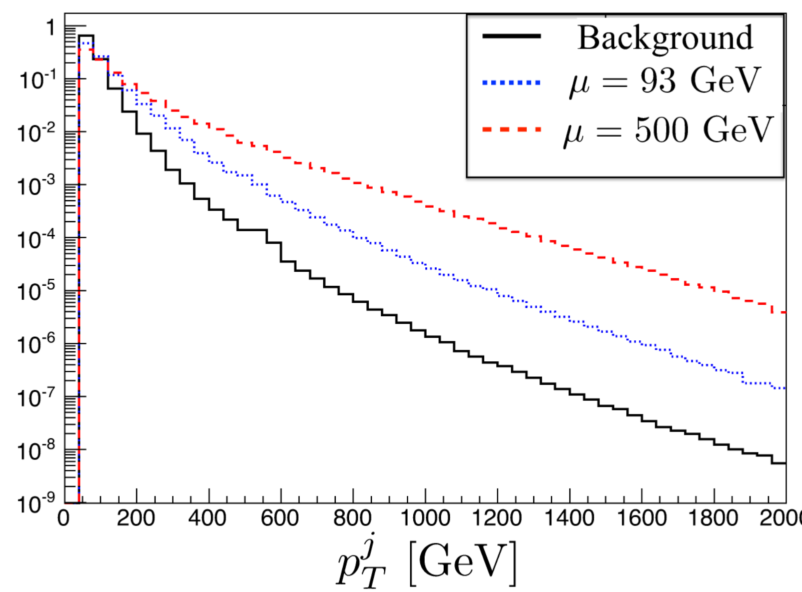


LHC @ 13 TeV: signal versus background

differences in rates: depressing



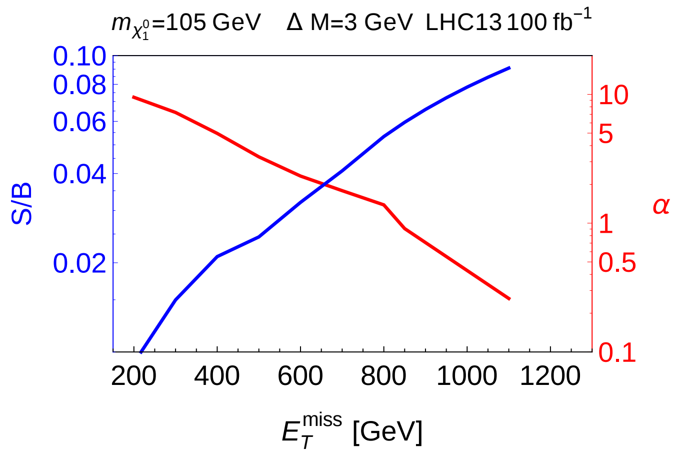
but differences in shape is encouraging

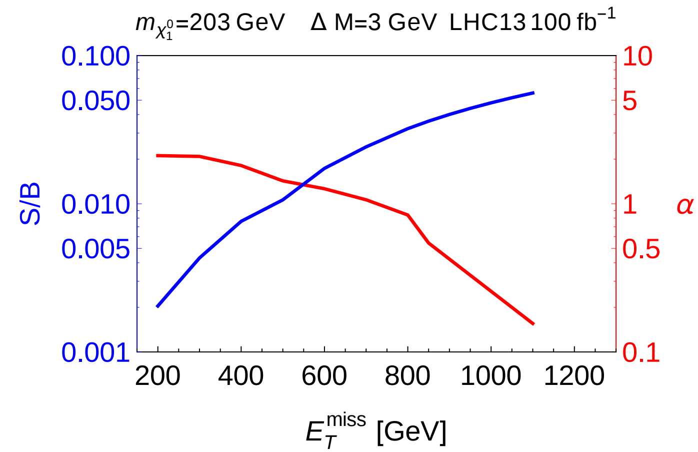


D. Barducci, A. Belyaev, A. Bharucha, WP, V. Sanz, arXiv:1504.02472

S/B versus signal significance α

signal significance a la CMS: $\alpha = 2(\sqrt{S+B} - \sqrt{B})$





	$Z(\nu\bar{\nu})j$	$W(l\nu)j$	$\mu =$ 100 GeV	$\mu =$ 200 GeV
Initial # of events	3.15·10^6	1.25·10^7	3.63·10^5	6.45·10^3
$p_T^j >$ 200 GeV $\lvert\eta^j\rvert < 2.4$	1.05·10^6	4.11·10^6	1.73·10^5	3528
Jet veto ($n \geq 3$)	8.7·10^5	3.13·10^6	1.33·10^5	2691
$\Delta\phi(j_1, j_2) < 2.5$	7.2·10^5	2.3 ·10^6	1.10·10^5	2320
Veto $e^\pm, \mu^\pm, \tau^\pm$	7.2·10^5	6.8 ·10^5	1.08·10^5	2301
$E_T^{\rm miss} >$ 200 GeV	6.4·10^5	4.3·10^5	9846	2188
$E_T^{\rm miss} >$ 600 GeV	4353	1002	171	93
$E_T^{\rm miss} >$ 800 GeV	694	0	37	22

Simplified Model

$$\mathcal{W}_{eff} = \mu \widehat{H}_u \cdot \widehat{H}_d + Y_t \widehat{t}_R \widehat{H}_u \cdot \widehat{Q} + Y_b \widehat{b}_R \widehat{Q} \cdot \widehat{H}_d + \sum_k \left(Y_{\nu,k} \widehat{\nu}_{R,k} \widehat{H}_u \cdot \widehat{L}_k + M_k \widehat{S}_k \widehat{\nu}_{R,k} \right) \quad ,$$

$$\mathcal{V}^{soft} = \frac{1}{2} M_3 \tilde{g}\tilde{g} + \sum_S m_S^2 |S|^2 + B_\mu H_u \cdot H_d + \sum_k \left(B_{M_k} \tilde{S}_k \tilde{\nu}_{R,k} + T_{\nu k} \tilde{\nu}_{R,k} \tilde{H}_u \cdot \tilde{L}_k \right)$$

$$+ T_t \tilde{t}_R H_u \cdot \tilde{Q} + T_b \tilde{b}_R \tilde{Q} \cdot H_d$$

$$S = H_u, H_d, \tilde{Q}, \tilde{t}_R, \tilde{b}_R, \tilde{\nu}_R$$

assume $Y_{\nu,k} = Y_\nu$; tree level relation

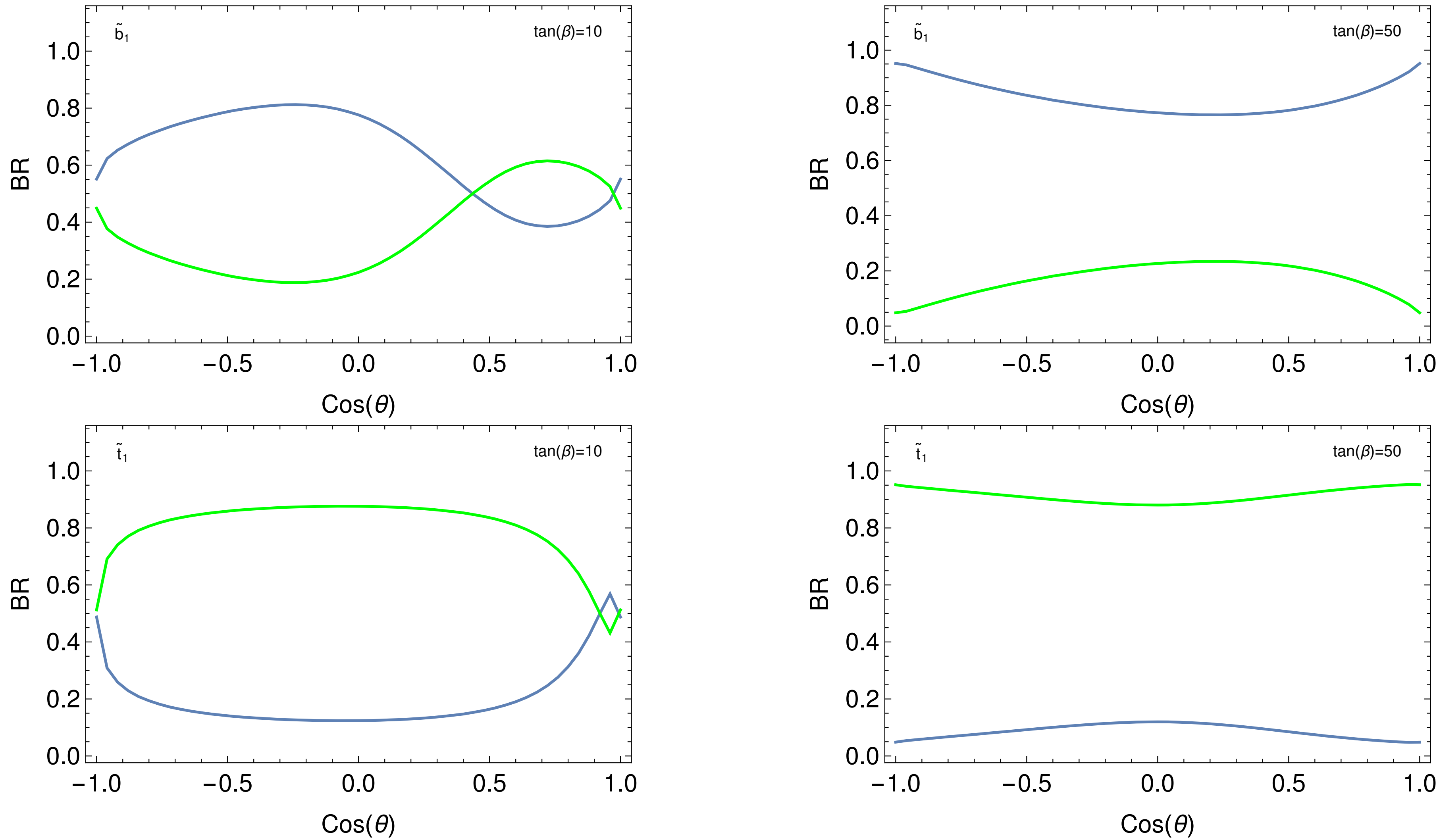
$$m_W^2 \cos 2\beta \ = \ m_{\tilde{t}_1}^2 \cos^2\theta_{\tilde{t}} + m_{\tilde{t}_2}^2 \sin^2\theta_{\tilde{t}} - m_{\tilde{b}_1}^2 \cos^2\theta_{\tilde{b}} - m_{\tilde{b}_2}^2 \sin^2\theta_{\tilde{b}} - m_t^2 + m_b^2$$

simplified $\tilde{\nu}_R, \tilde{S}$ mass matrix (one generation):

$$M^2_{\tilde{\nu}_R,\tilde{S}} = \begin{pmatrix} |M_k|^2 & B_{M_k} \\ B_{M_k} & |M_k|^2 \end{pmatrix} \Rightarrow m^2_{1,2} = |M_k|^2 \pm |B_{M_k}|$$

$\Rightarrow$ expect lightest ‘sneutrino’ as LSP,

Branching ratios



$m_{\tilde{q}_1} = 500$ GeV ($q = b, t$), $m_{\tilde{\nu}_R} = 100$ GeV, $\mu = 590$ GeV, $M_1 = M_2 = 1$ TeV. blue line: $\tilde{q}_1 \to q\nu\tilde{\nu}_R$, green line $\tilde{q}_1 \to q' l \tilde{\nu}_R$ summing over l; L. Mitzka, WP arXiv:1603.06130

CheckMATE analyses used

atlas_1403_2500	$\tilde{g}$ and $\tilde{q}$	jets, 2SS/3 leptons
atlas_conf_2013_036	RPV & RPC SUSY	four or more leptons
atlas_1402_7029	$\tilde{\chi}^{\pm}$ and $\tilde{\chi}^0$	3 leptons and $E_T^{\rm miss}$
atlas_1403_4853	$\tilde{t}$	two leptons and 2 b jets
atlas_1403_5294	$\tilde{\ell}, \tilde{\chi}^{0,\pm}$	two leptons and $E_T^{\rm miss}$
atlas_conf_089	$\tilde{t}$	two leptons via the razor variable
atlas_conf_2013_049	$\tilde{\chi}^{0,\pm}, \tilde{\ell}$	two leptons
atlas_conf_2013_014	$\tilde{t}$	2 b jets, two leptons (vie τ), $E_T^{\rm miss}$
atlas_1407_0583	$\tilde{t}$	1 lepton, jets and $E_T^{\rm miss}$
atlas_conf_2013_062	$\tilde{t}, \tilde{g}$	1 lepton, jets and $E_T^{\rm miss}$
atlas_conf_2013_104	$\tilde{t}$	1 lepton, jets and $E_T^{\rm miss}$
atlas_conf_2013_061	$\tilde{g}$	three b-jets and $E_T^{\rm miss}$
atlas_1308_2631	$\tilde{b}, \tilde{t}$	2 b jets and $E_T^{\rm miss}$
atlas_conf_2013_047	$\tilde{q}, \tilde{g}$	jets and $E_T^{\rm miss}$
atlas_conf_2013_024	$\tilde{t}$	hadronic $t\bar{t}$ final states