

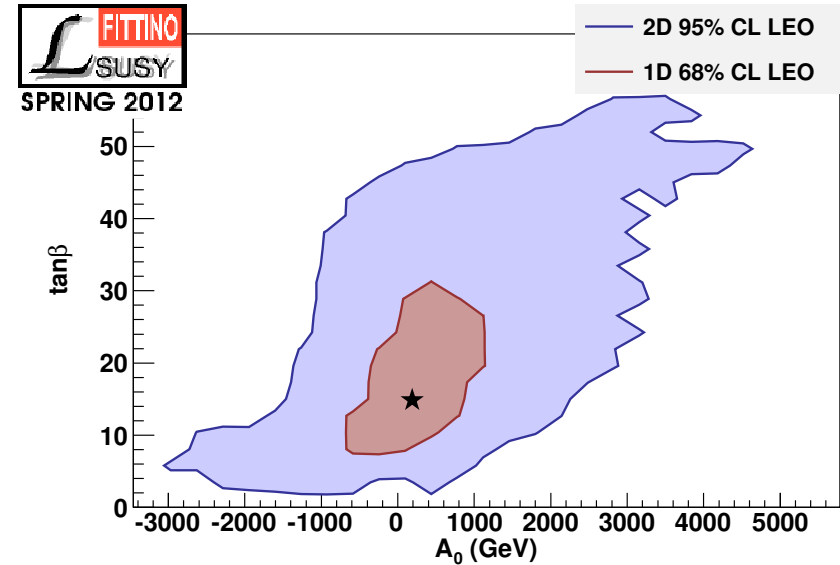
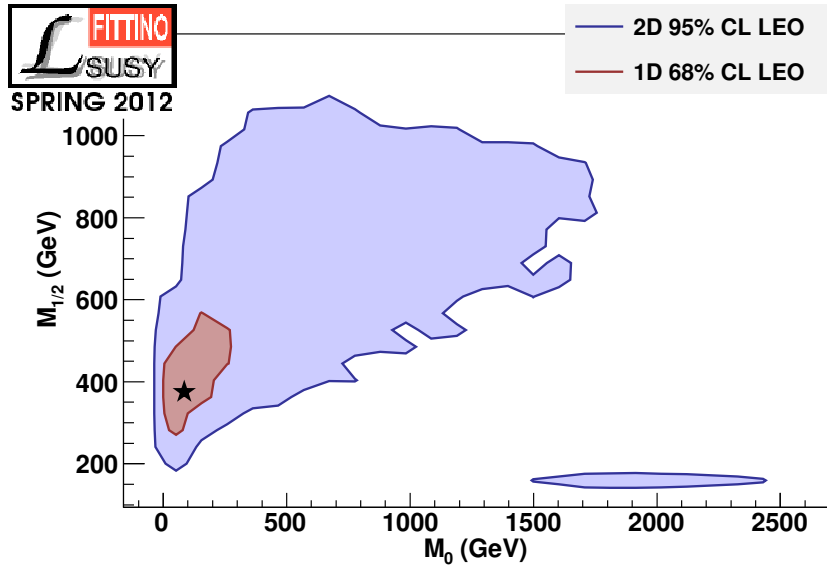
Is supersymmetry still alive?

(A few thoughts on Natural SUSY)

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



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

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

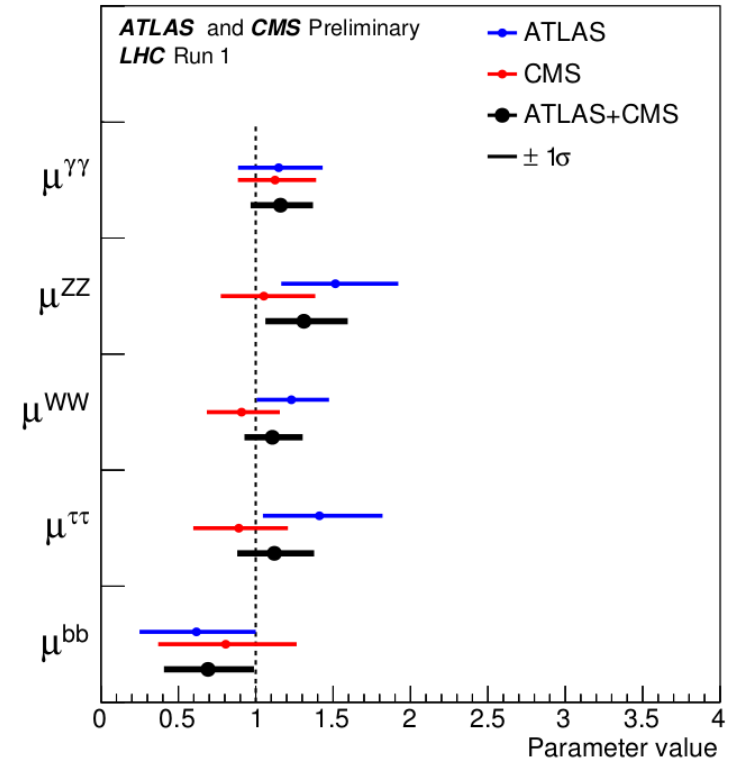
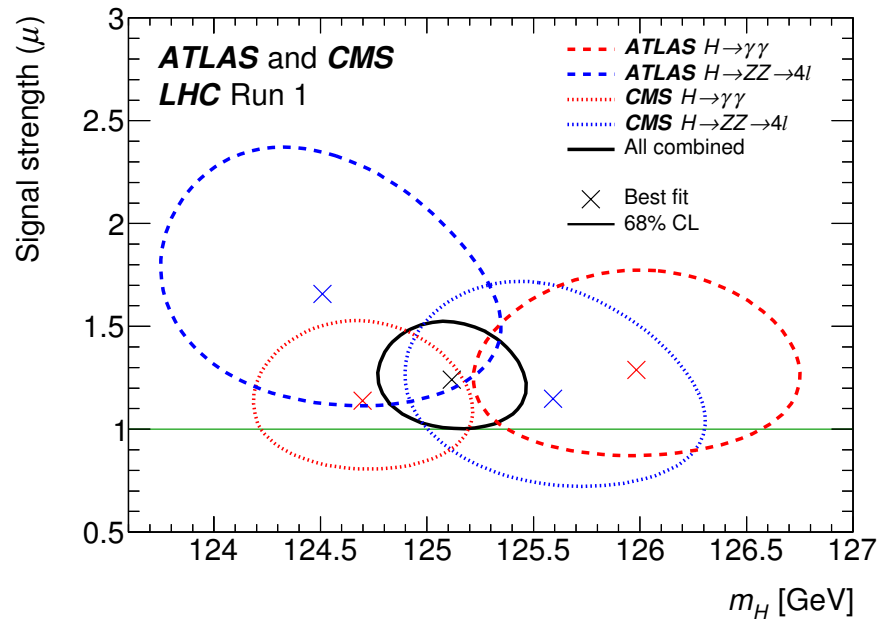
$\Rightarrow m_h = 116 \text{ GeV}$

P. Bechtle et al., arXiv:1204.4199

similar results by other groups

e.g. MasterCode, O. Buchmueller et al.

BayesFITS, L. Roszkowski et al.



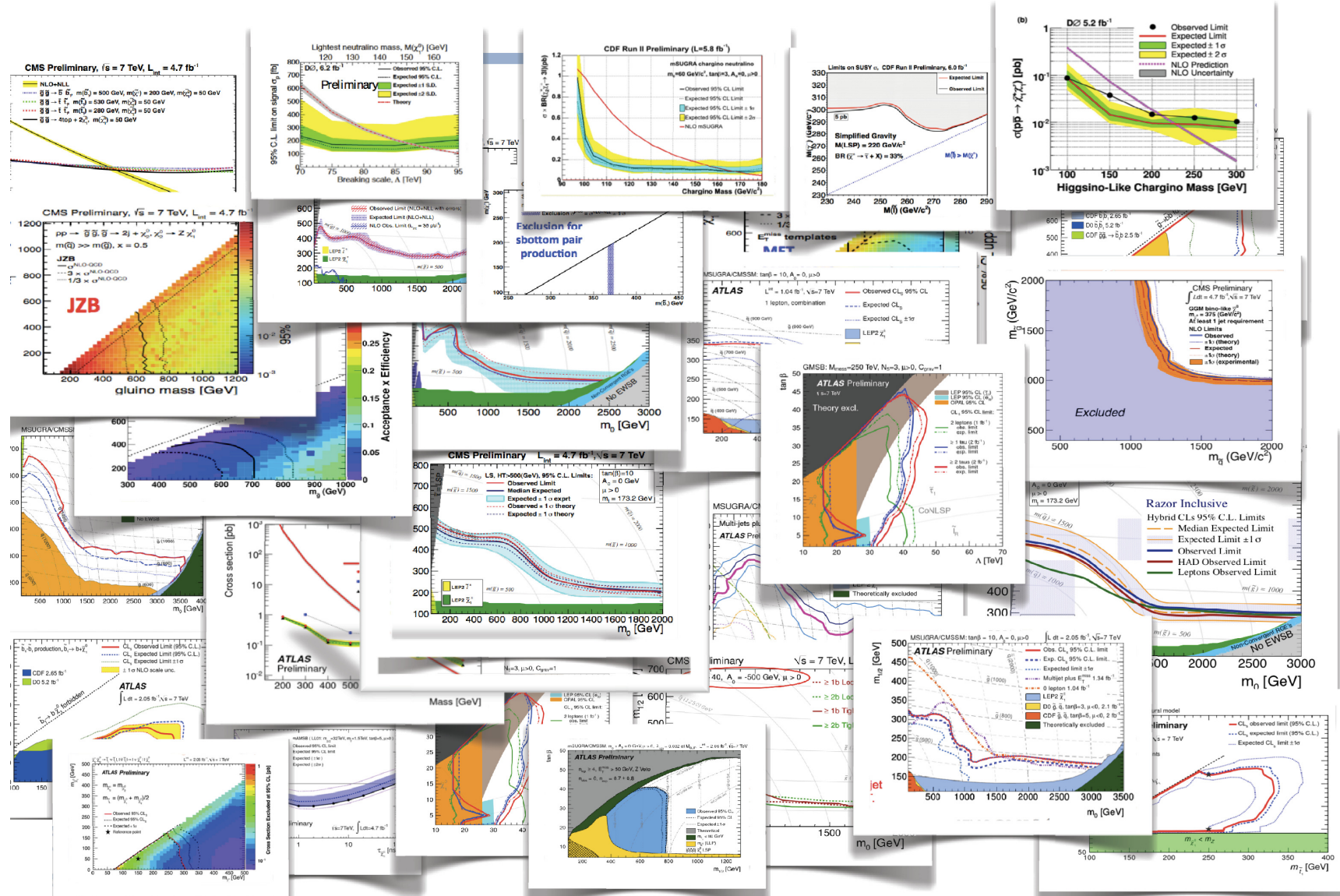
$$m_H = 125.09 \pm 0.21 \text{ (stat)} \pm 0.11 \text{ (sys)} \text{ GeV}$$

PRL 114 (2015) 191803

ATLAS-CONF-2015-044

CMS-PAS-HIG-15-002

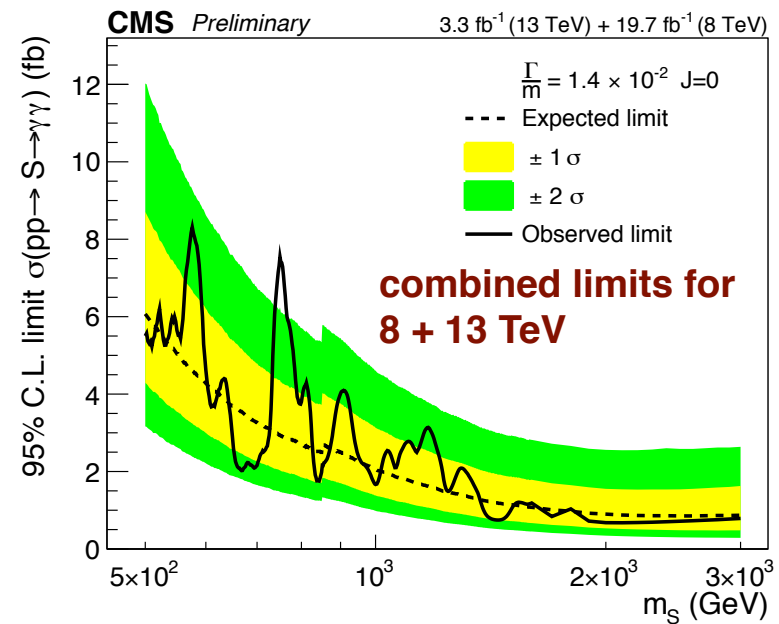
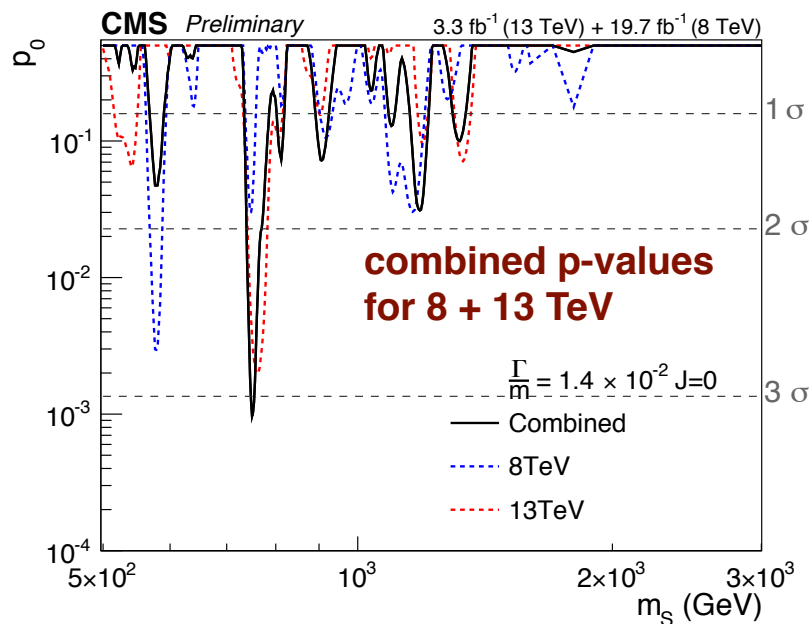
$$(125 \text{ GeV})^2 \simeq m_Z^2 + (86 \text{ GeV})^2 \Rightarrow \text{large corrections within MSSM}$$



DIPHOTON RESONANCES

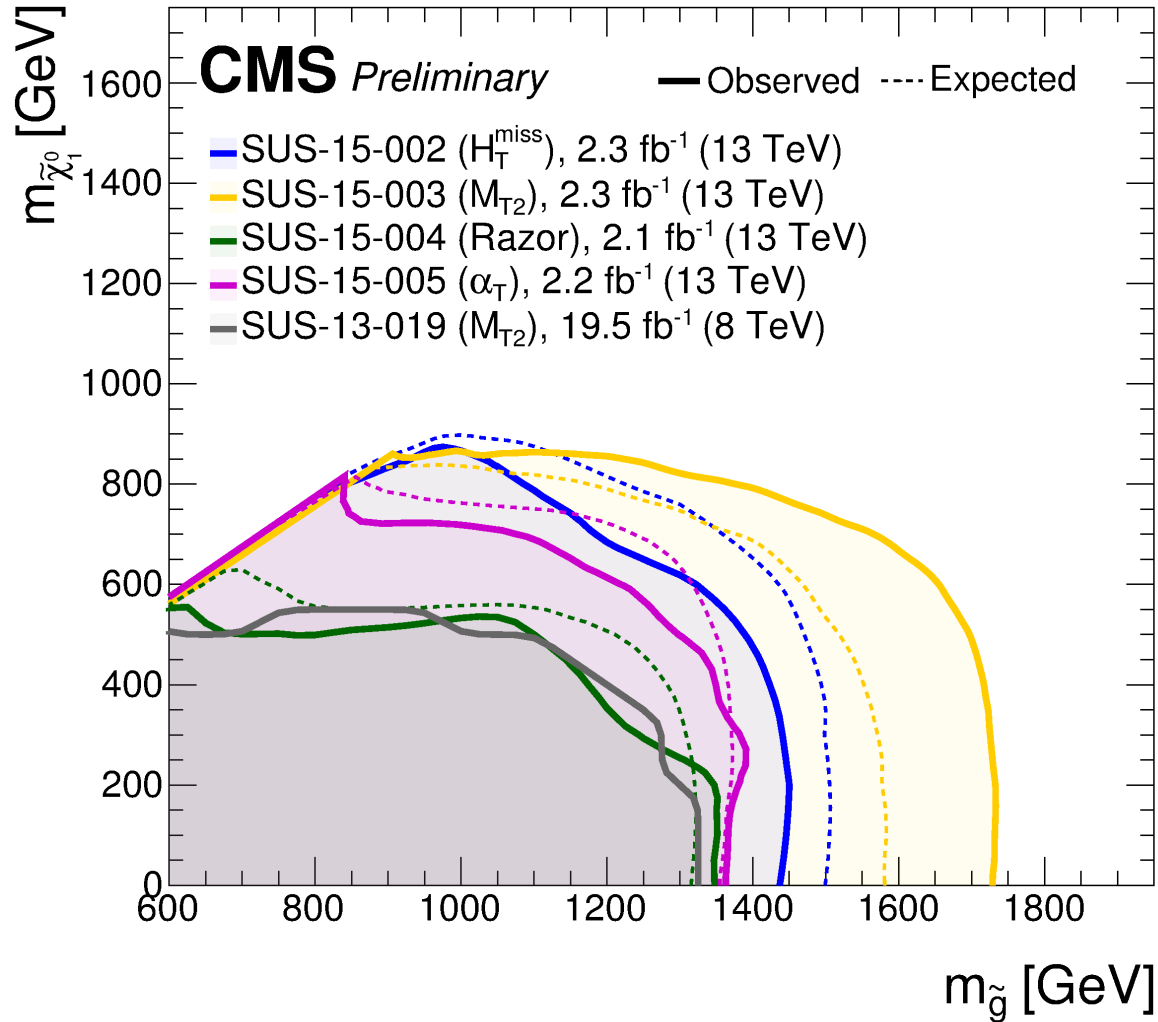
[EXO-16-018]

- Combined 8 TeV + 13 TeV results
 - Largest excess is observed for **750 GeV, spin-0, narrow width**
 - local significance of 3.4σ , 1.6σ after look-elsewhere effect



- Dec '15 result: largest excess at 760 GeV for $\Gamma/M=1.4 \times 10^{-2}$
 - local significance of $\sim 3\sigma$, $< 1.7\sigma$ after look-elsewhere effect

$pp \rightarrow \tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$ *Moriond 2016*



$m_h = 125.1 \text{ GeV} \Rightarrow$ large loop contributions
 \Rightarrow heavy stops and/or large left-right mixing for stops

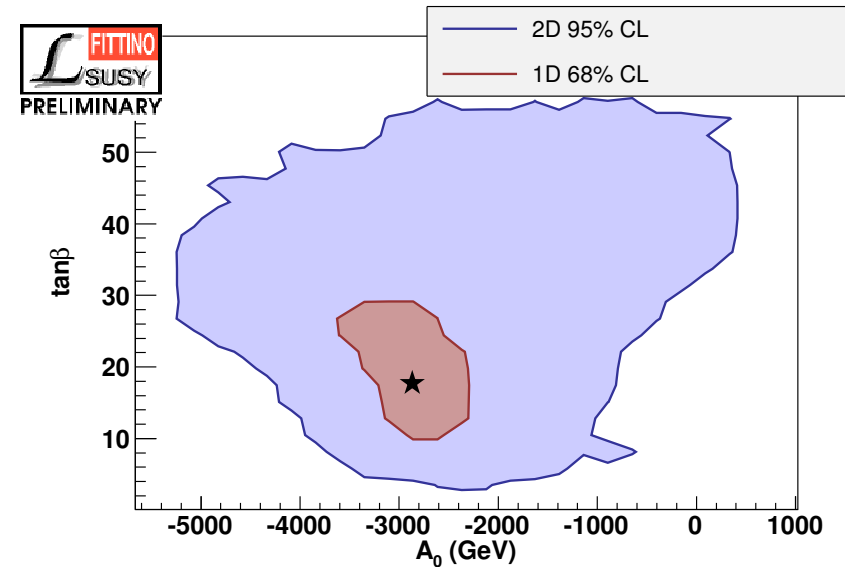
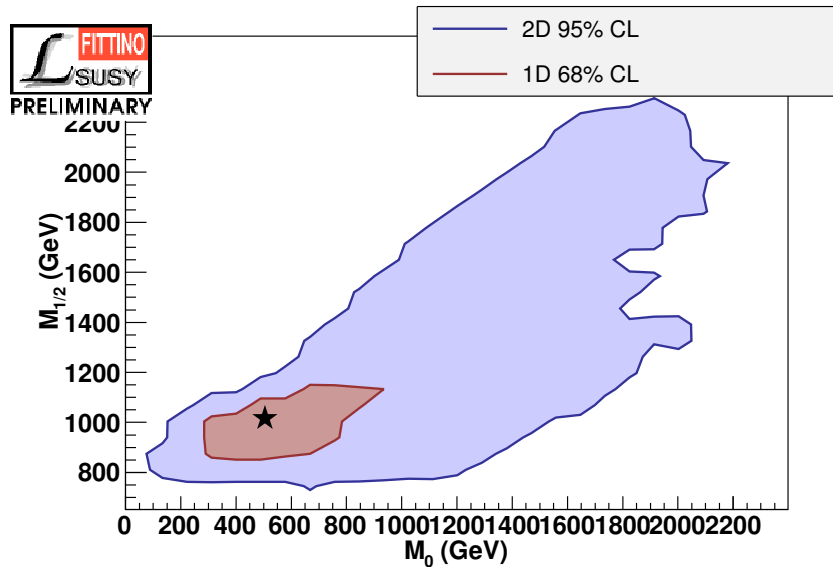
- GMSB: $m_{\tilde{t}_1} \gtrsim 6 \text{ TeV}$,
 M. A. Ajaib, I. Gogoladze, F. Nasir, Q. Shafi, arXiv:1204.2856

more complicated models based on P. Meade, N. Seiberg and D. Shih,
 arXiv:0801.3278 \Rightarrow allow additional terms, choice not well motivated \Rightarrow generic MSSM

- 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

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



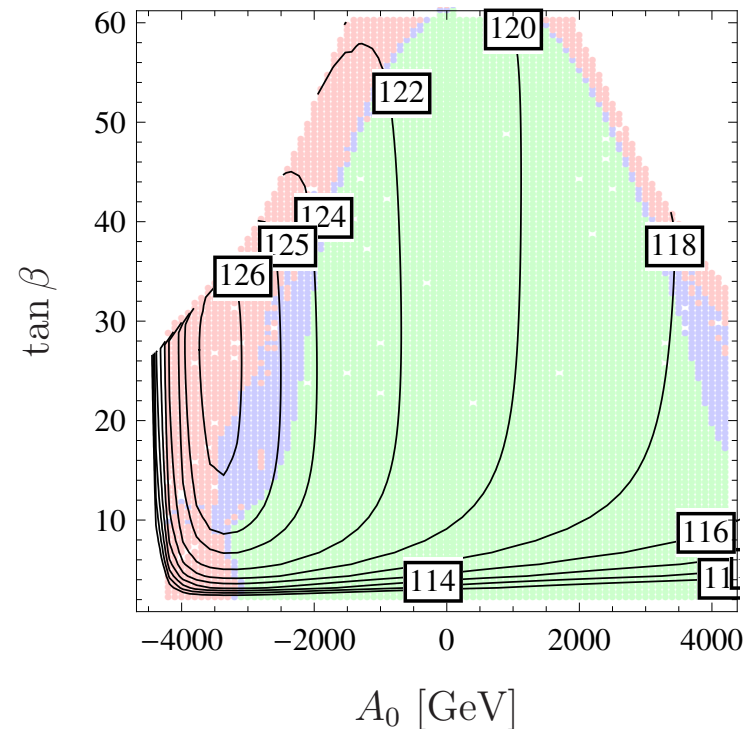
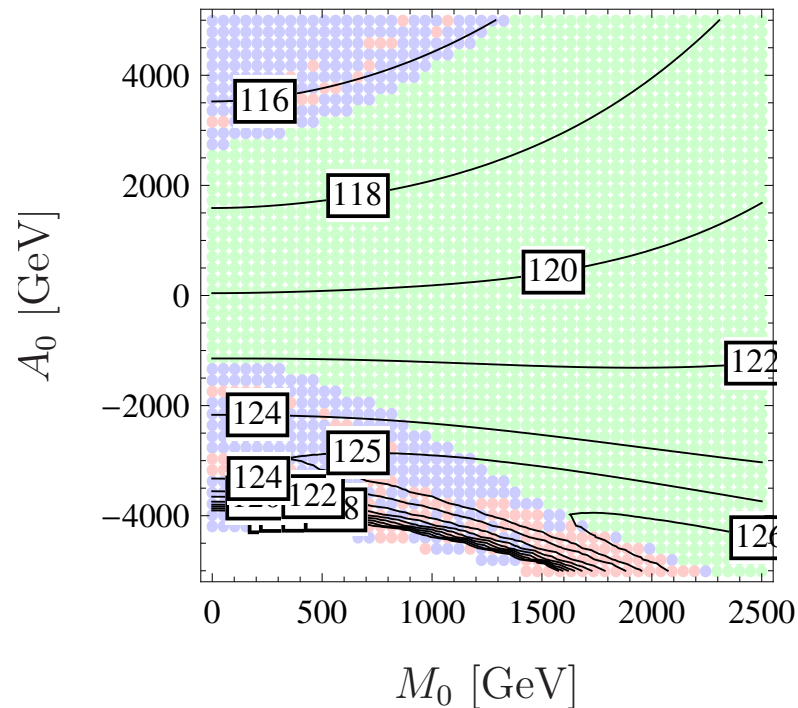
P. Bechtle et al., arXiv:1508.05951

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 ...

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



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

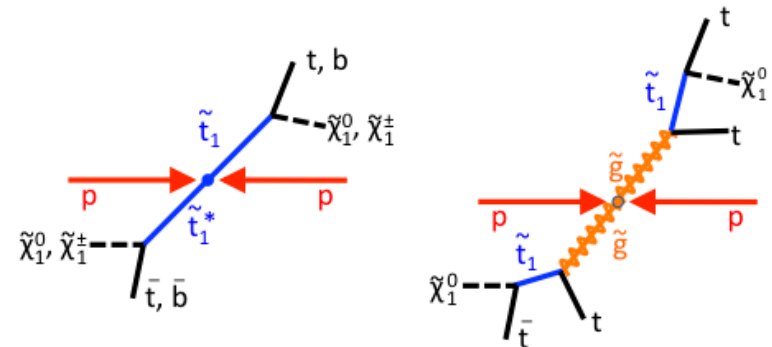
$$M_{1/2} = M_0 = 1 \text{ TeV}$$

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

several studies, 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

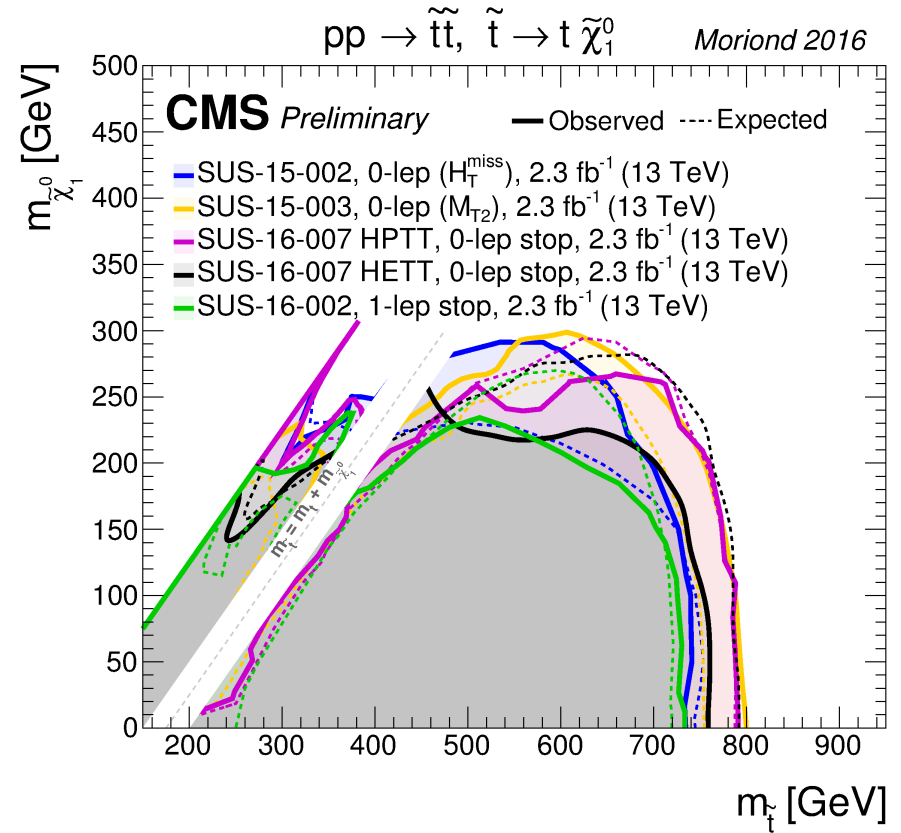
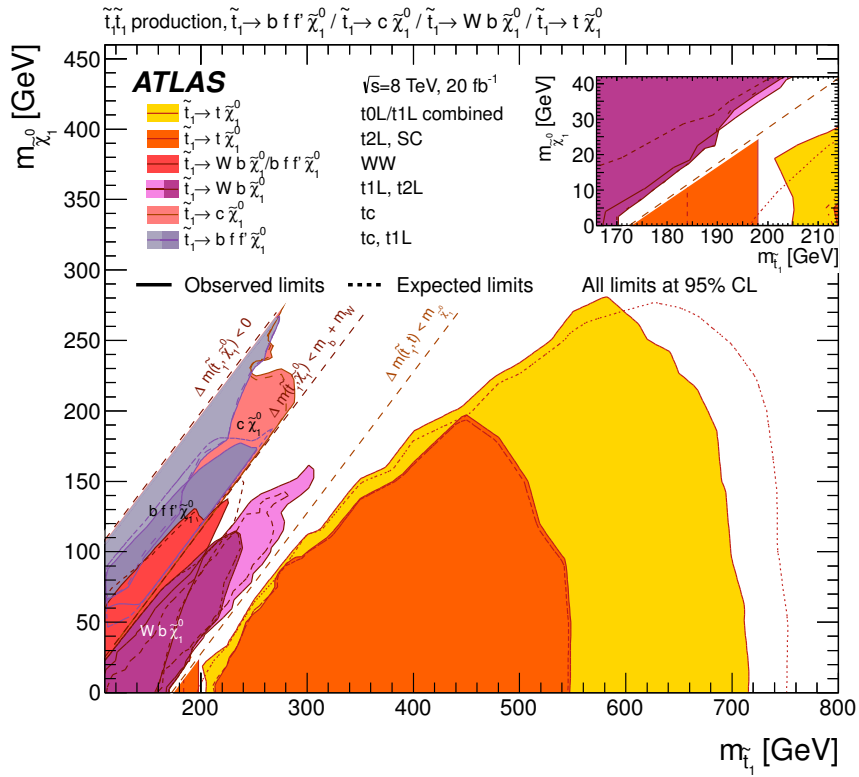
- generic signatures are well known: multi-lepton, multi-jets + missing E_T
- sub-class of general MSSM: ‘natural SUSY’
see e.g. M. Papucci, J. T. Ruderman and A. Weiler, arXiv:1110.6926;
H. Baer, V. Barger, P. Huang, A. Mustafayev, X. Tata, arXiv:1207.3343
keep only SUSY particles light needed for ‘natural Higgs’: $\tilde{t}_1, \tilde{b}_1, \tilde{g}, \tilde{h}^{+,0,-}$
 $\Rightarrow 100 \text{ MeV} \lesssim m_{\tilde{\chi}_1^+} - m_{\tilde{\chi}_1^0} \simeq m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} \lesssim 5 - 10 \text{ GeV}$

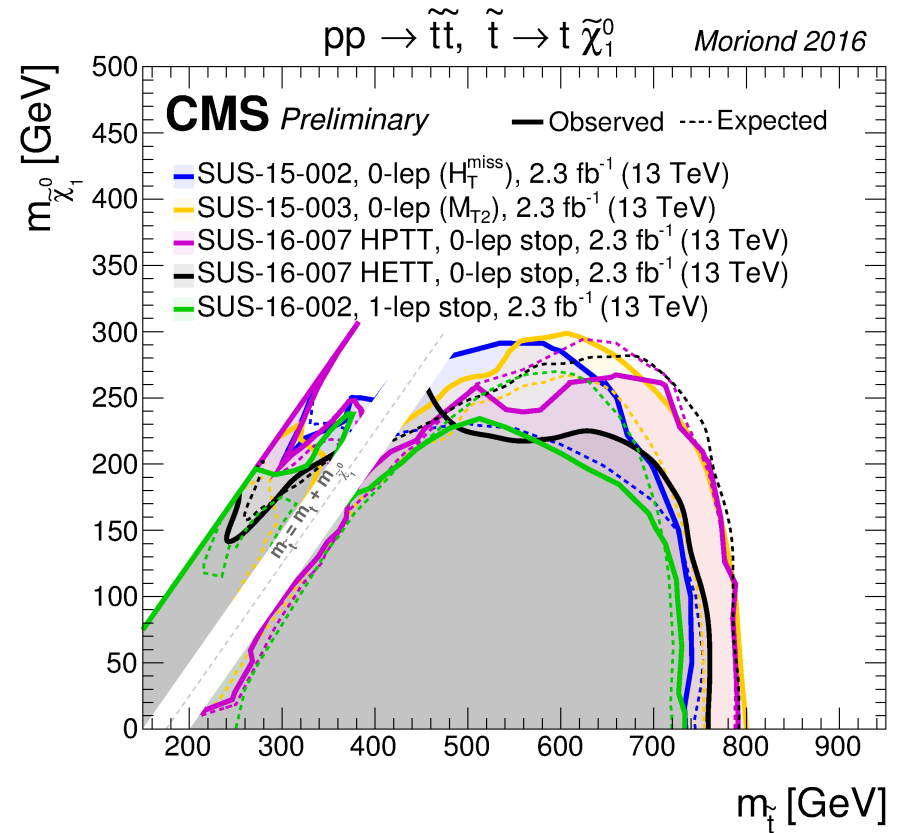
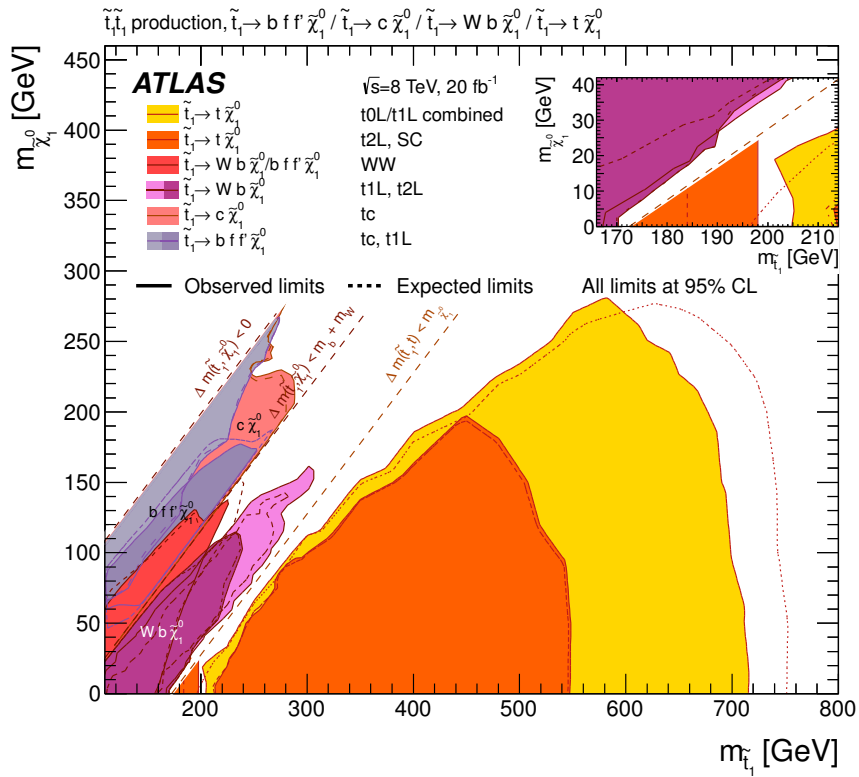
$$\begin{aligned} \tilde{g} &\rightarrow \tilde{t}_1 t, \tilde{b}_1 b \\ \tilde{t}_1 &\rightarrow t \tilde{\chi}_{1,2}^0, b \tilde{\chi}_1^+, W^+ \tilde{b}_1 \\ \tilde{b}_1 &\rightarrow b \tilde{\chi}_{1,2}^0, t \tilde{\chi}_1^-, W^- \tilde{t}_1 \end{aligned}$$



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

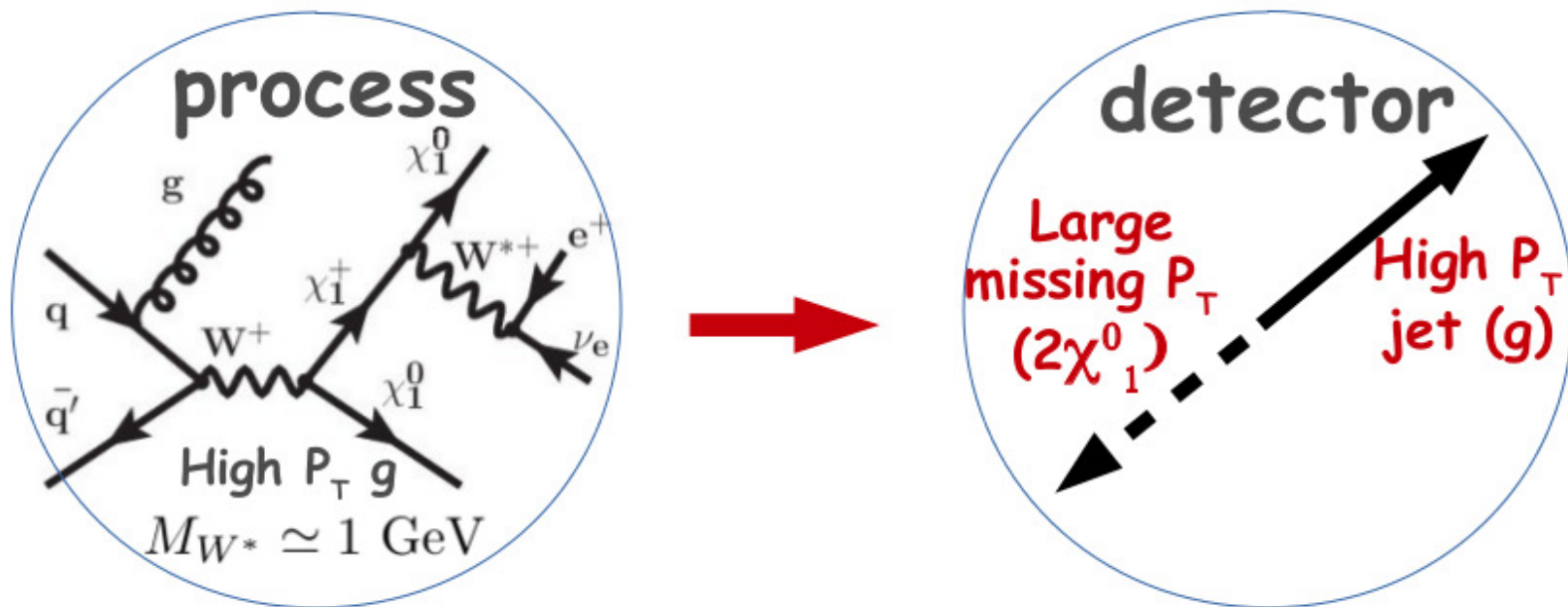
- If 750 GeV resonance is real:
MSSM (like any 2-Higgs doublet model) cannot explain data





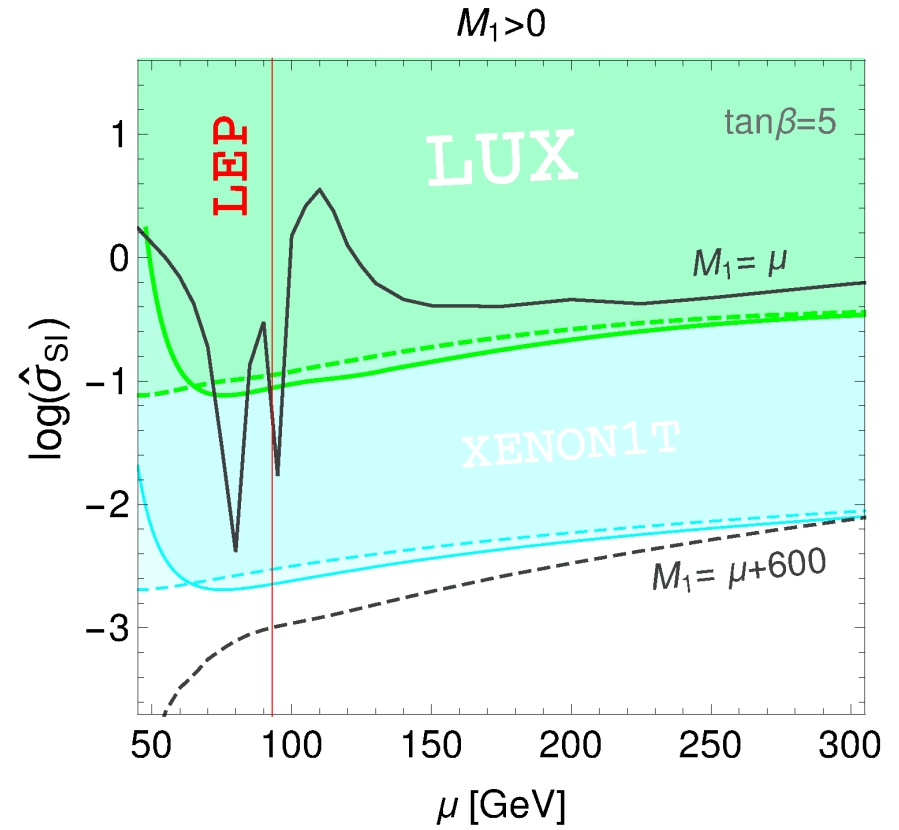
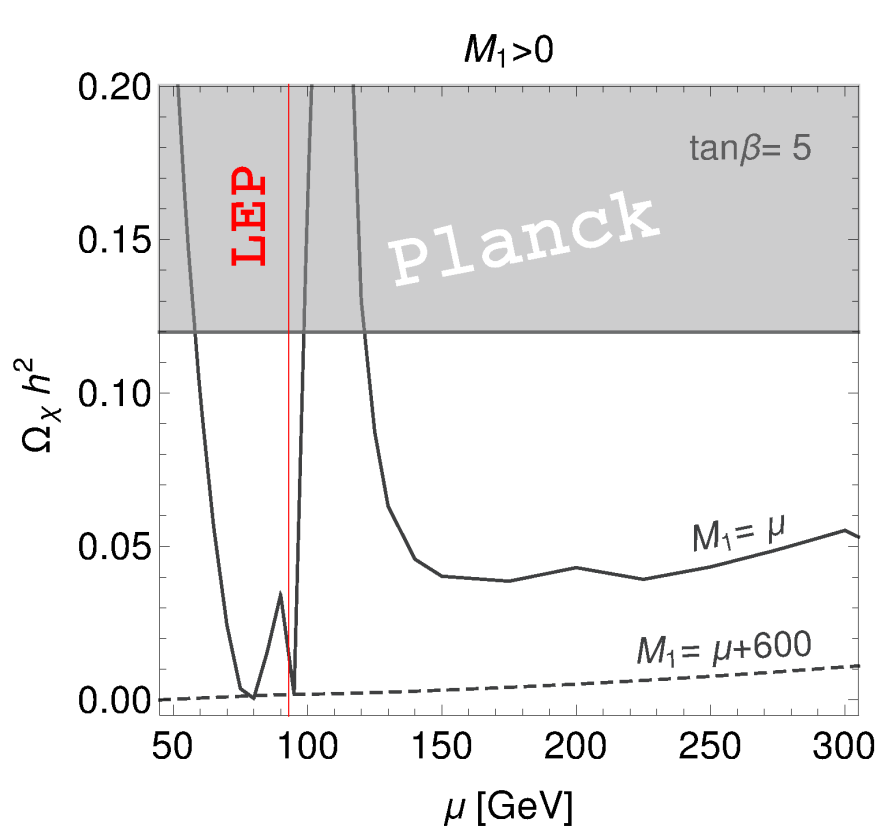
$$\frac{d}{dt} \begin{pmatrix} m_{H_u}^2 \\ m_{\tilde{t}_R}^2 \\ m_{\tilde{Q}_L^3}^2 \end{pmatrix} = -\frac{8\alpha_s}{3\pi} M_3^2 \begin{pmatrix} 0 \\ 1 \\ 1 \end{pmatrix} + \frac{Y_t^2}{8\pi^2} \left(m_{\tilde{Q}_L^3}^2 + m_{\tilde{t}_R}^2 + m_{H_u}^2 + A_t^2 \right) \begin{pmatrix} 3 \\ 2 \\ 1 \end{pmatrix}$$

Most challenging case: only higgsinos accessible but nothing else
and ΔM too 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

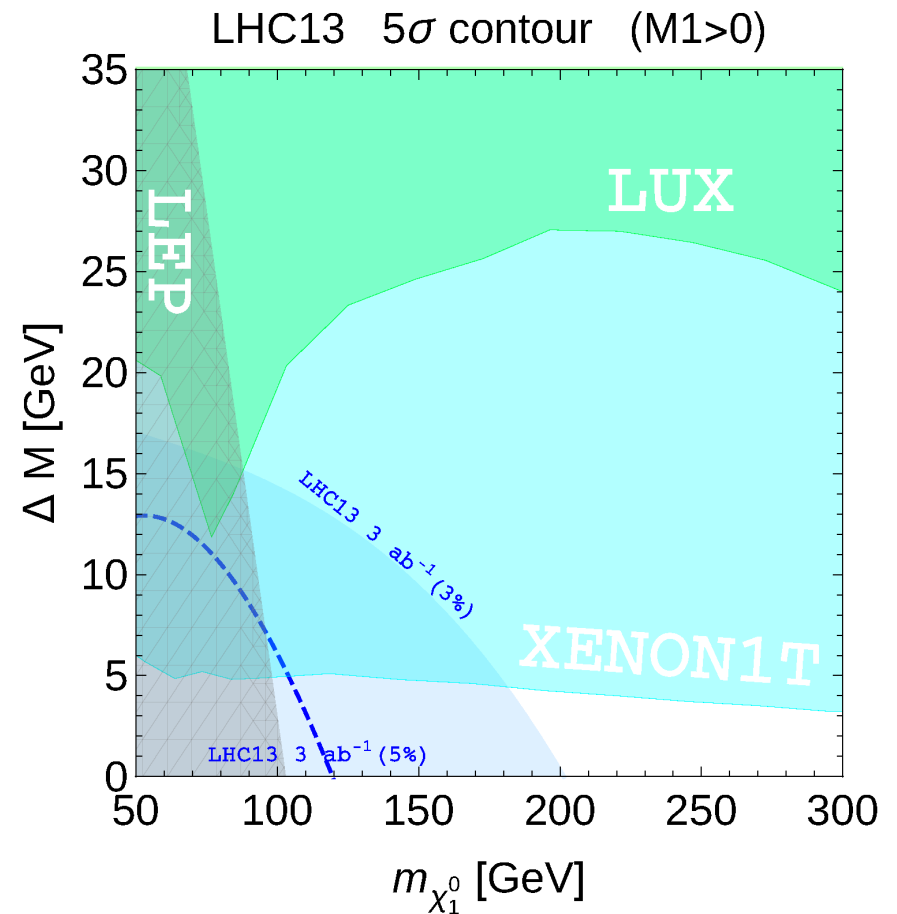
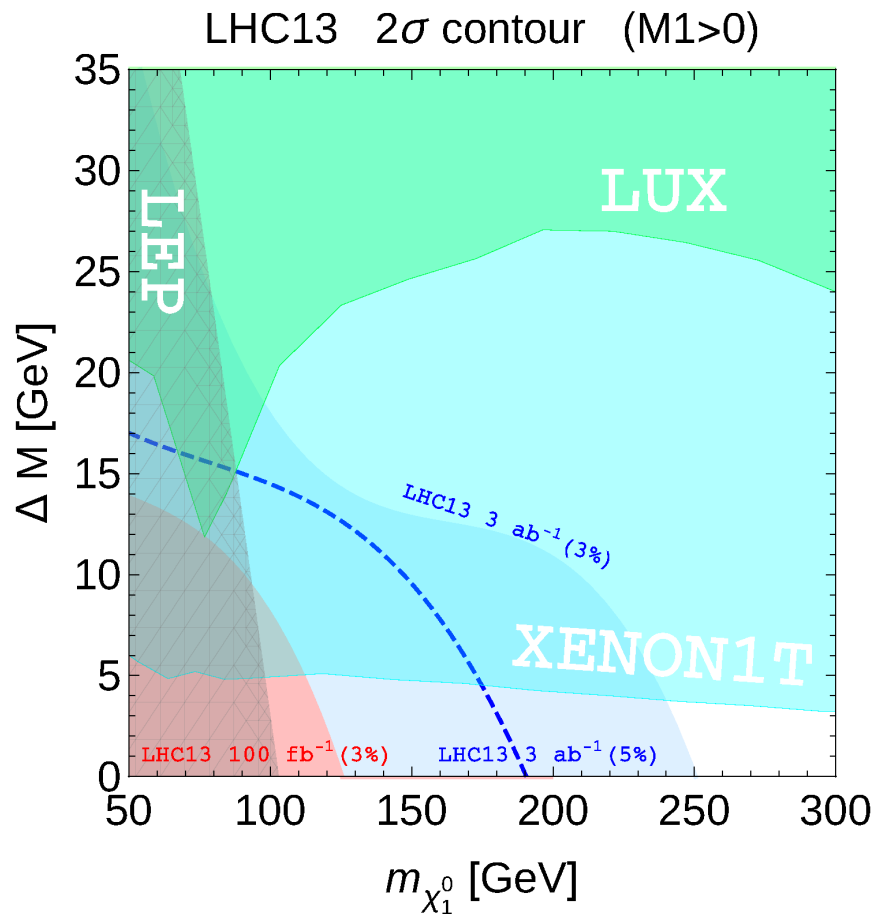


- relic density too low because higgsinos couple 'strongly' to W and Z
- DD cross section rescaled with relic density \rightarrow chance for LHC?

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

exclusion reach

discovery reach

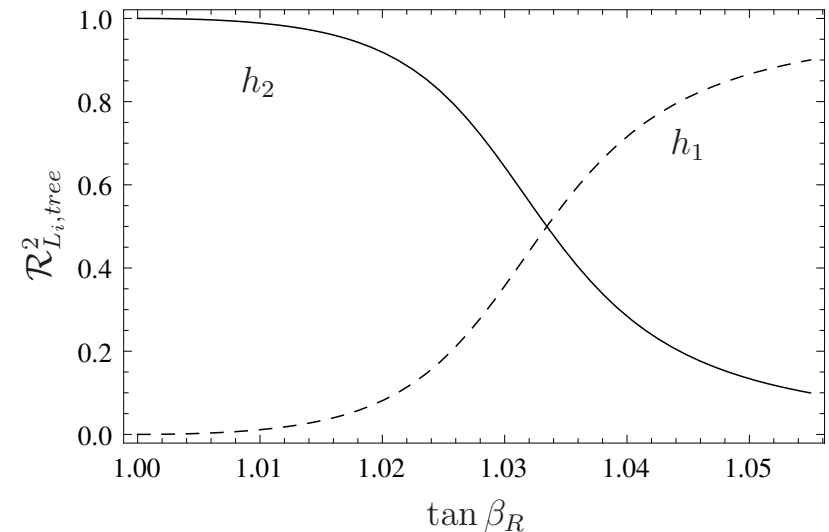
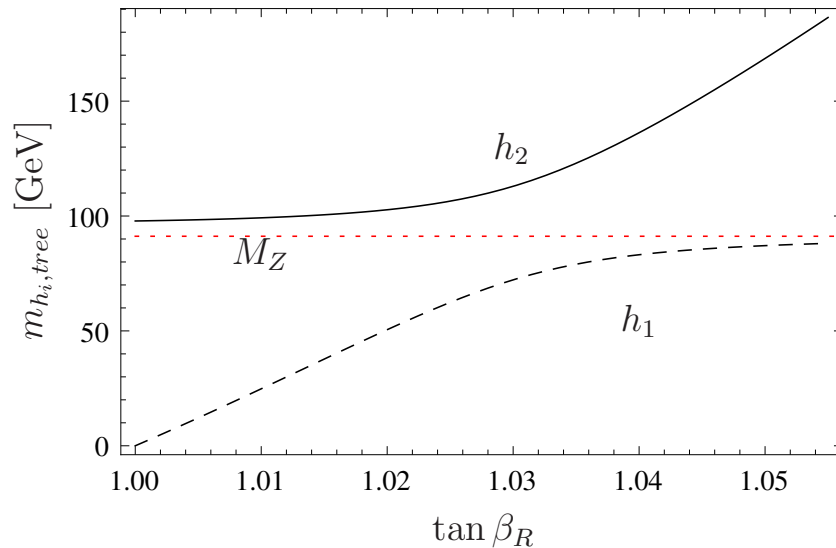


D. Barducci, A. Belyaev, A. Bharucha, WP, V. Sanz, arXiv:1504.02472

- additional D-term contributions to m_h at tree-level
- Origin of R -parity $R_P = (-1)^{2s+3(B-L)}$
 - $\Rightarrow SO(10) \rightarrow SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$
 - $\rightarrow SU(3)_C \times SU(2)_L \times U(1)_R \times U(1)_{B-L}$
 - $\cong SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_X$
 - or $E(8) \times E(8) \rightarrow SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$
- Neutrino masses
 - $B - L$ anomaly free $\Rightarrow \nu_R$
 - usual seesaw, inverse seesaw

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

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



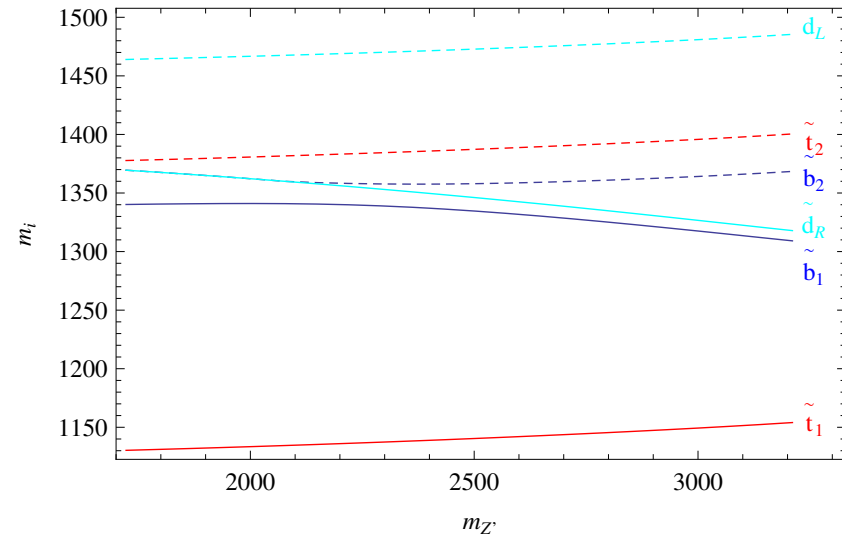
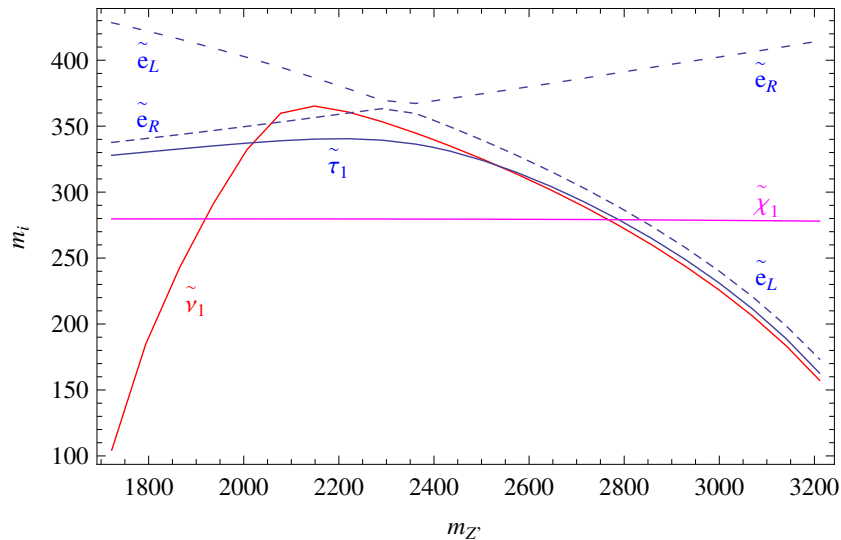
$n = 1$, $\Lambda = 5 \cdot 10^5$ GeV, $M = 10^{11}$ GeV, $\tan \beta = 30$, $\text{sign}(\mu_R) = -$, $\text{diag}(Y_S) = (0.7, 0.6, 0.6)$, $Y_\nu^{ii} = 0.01$, $v_R = 7$ TeV

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

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

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

neglecting gauge kinetic effects; similarly for squarks



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

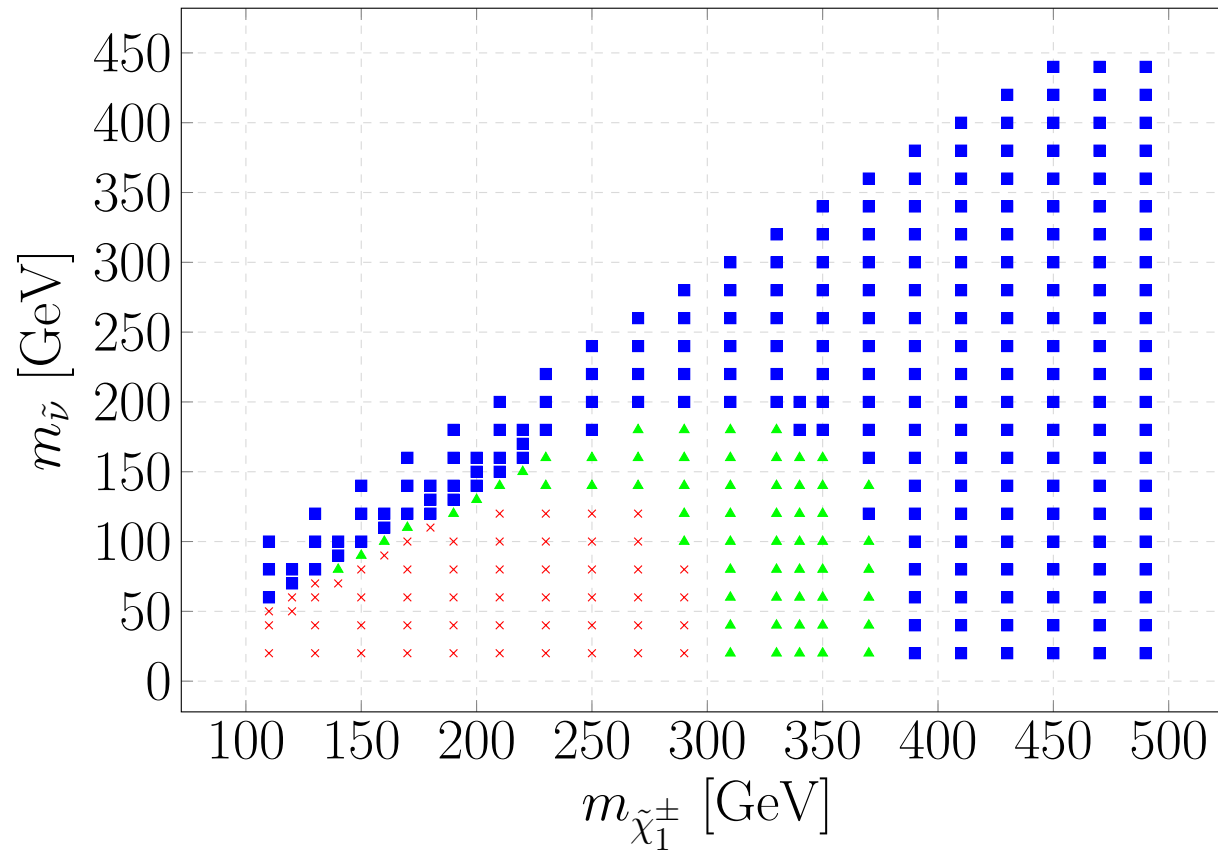
$$\tan \beta_R = 0.94, m_{A_R} = 2 \text{ TeV}, \mu_R = -800 \text{ GeV}$$

- $m_{\tilde{t}_1}$ 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

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

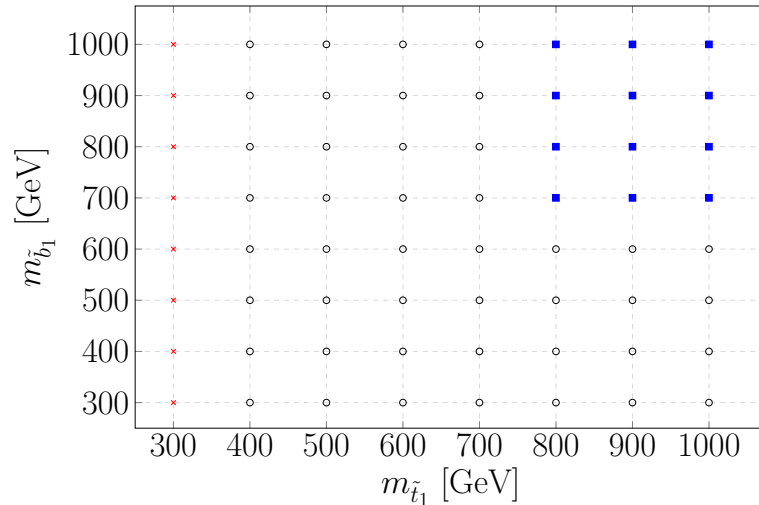


× excluded, ▲ ambiguous, ■ allowed

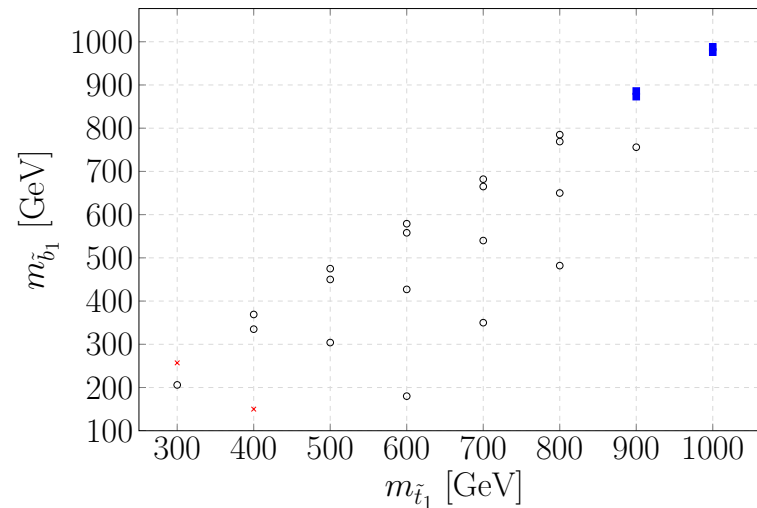
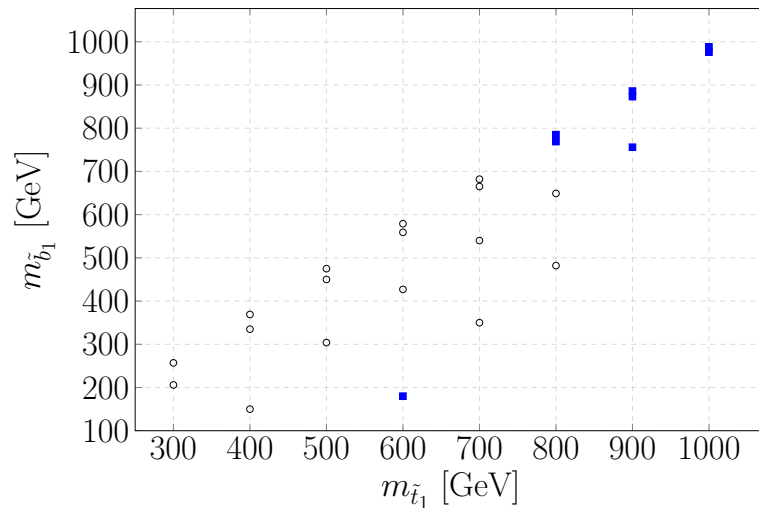
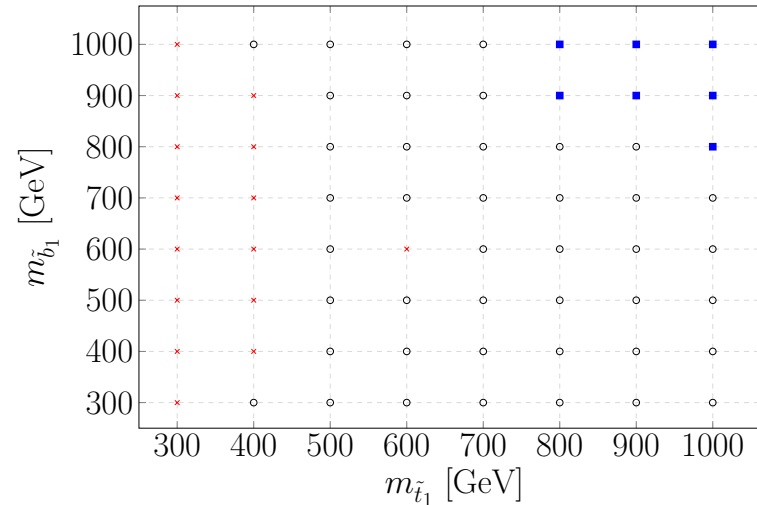
using CheckMATE

L. Mitzka, WP arXiv:1603.06130

ambiguous as allowed



ambiguous as forbidden



× excluded for all parameters, ○ exclusion depends on parameters, ■ allowed for all parameters

L. Mitzka, WP arXiv:1603.06130

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}
- light stop still consistent with data
- extended gauge groups:
 - $\tilde{\nu}_R$ 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 $\cos \theta_{\tilde{t}}$

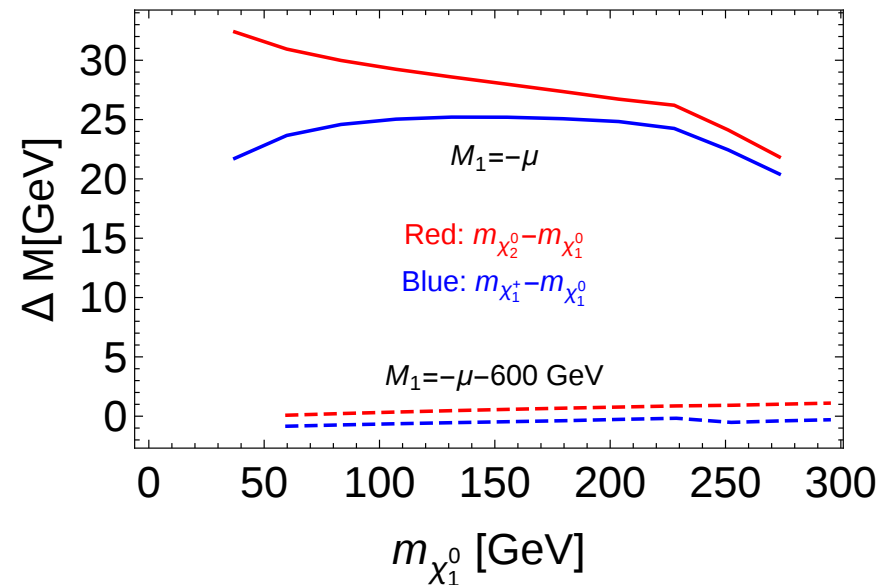
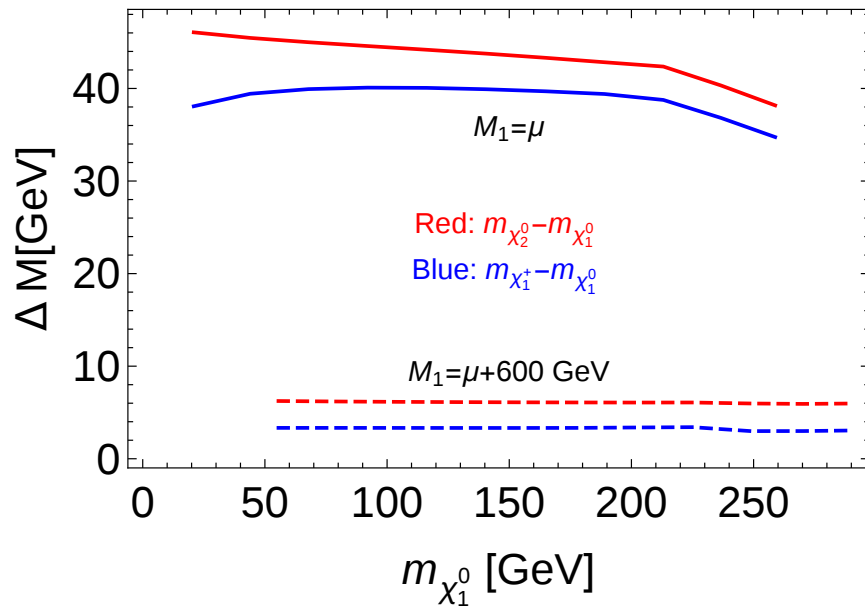
$$M_{\tilde{\chi}_0} = \begin{pmatrix} M_1 & 0 & -M_Z s_\omega c_\beta & M_Z s_\omega s_\beta \\ 0 & M_2 & M_Z c_\omega c_\beta & -M_Z c_\omega s_\beta \\ -M_Z s_\omega c_\beta & M_Z c_\omega c_\beta & -\mu & \\ M_Z s_\omega s_\beta & -M_Z c_\omega s_\beta & -\mu & 0 \end{pmatrix}$$

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

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

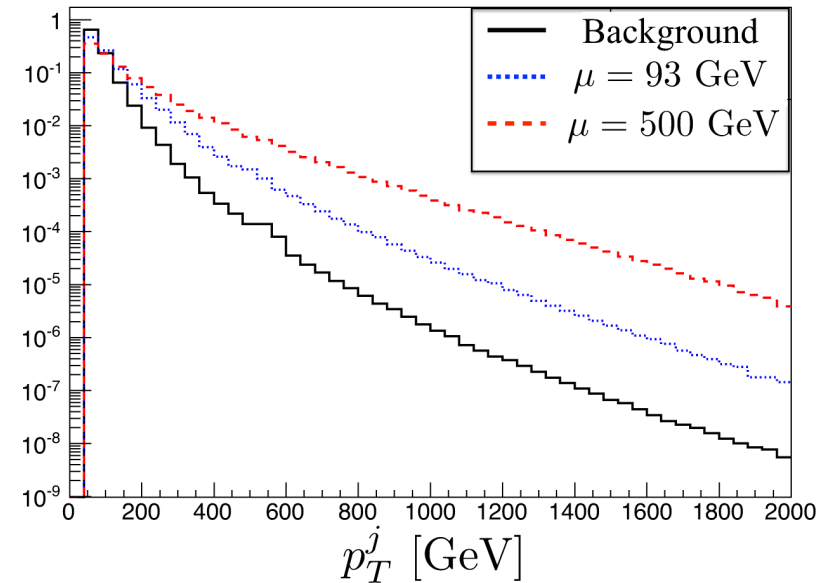
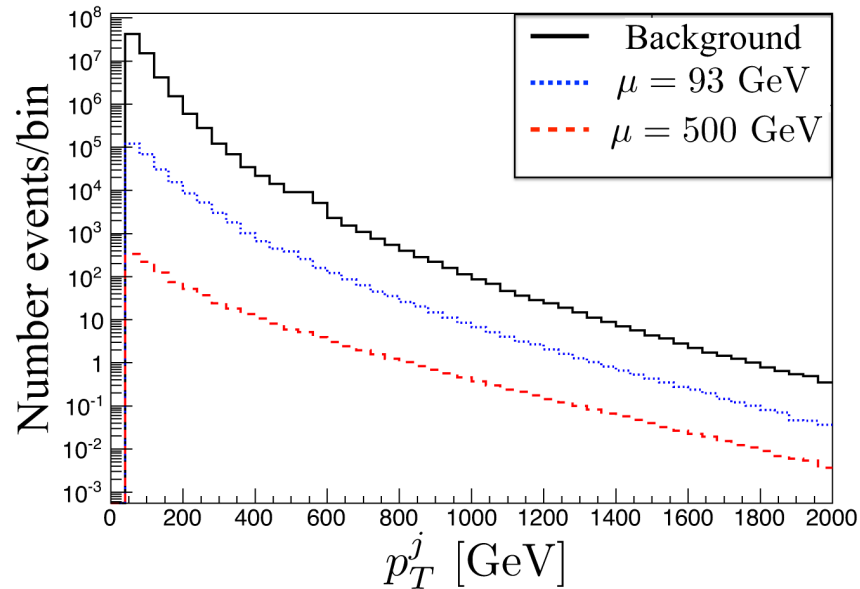
$$\Delta m_0 = m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} \simeq m_Z^2 \left(\frac{s_\omega^2}{M_1} + \frac{c_\omega^2}{M_2} \right)$$

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



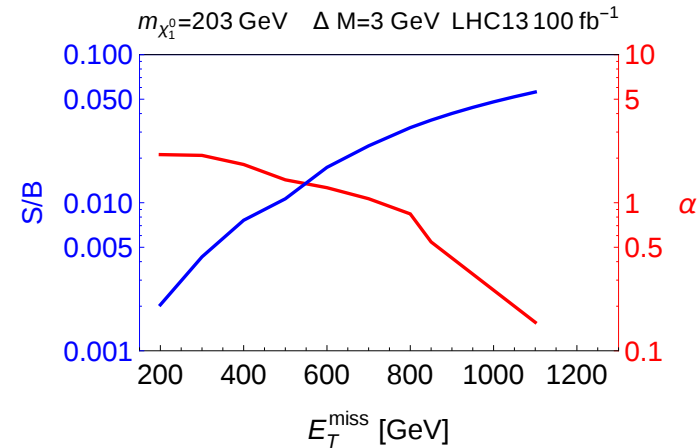
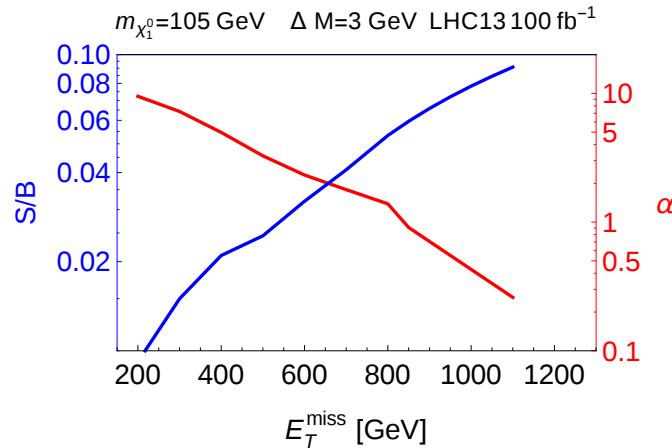
differences in rates: depressing

but differences in shape is encouraging



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

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



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

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

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

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

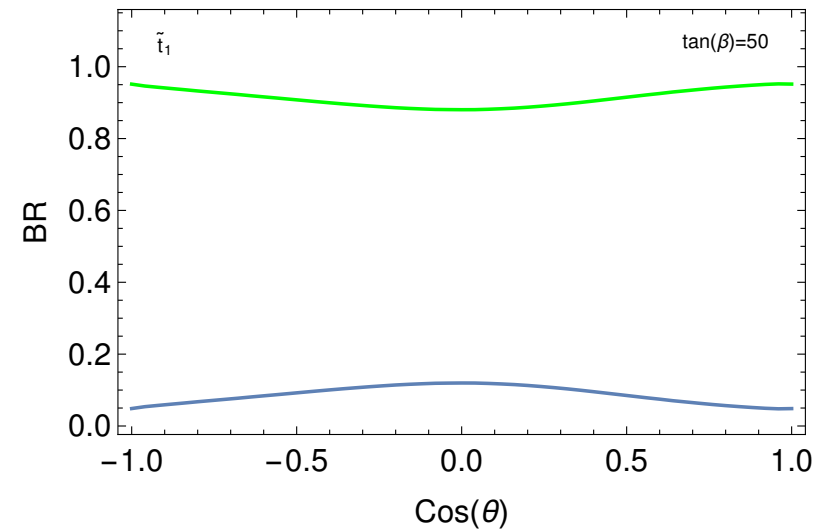
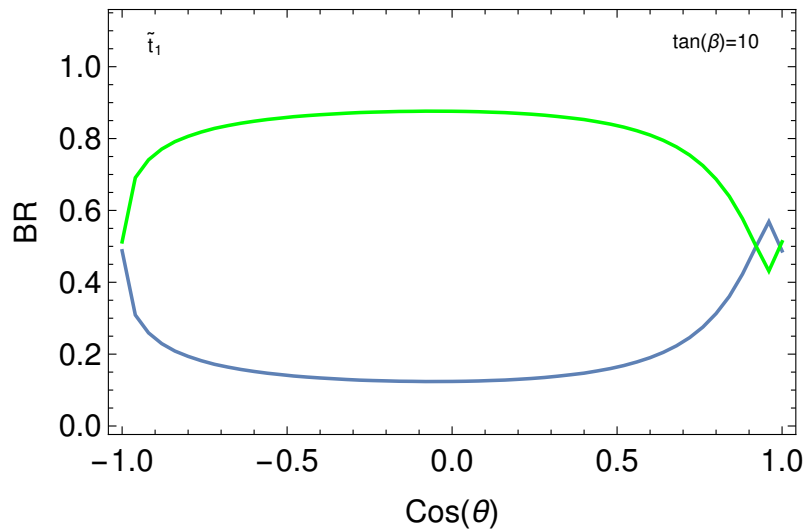
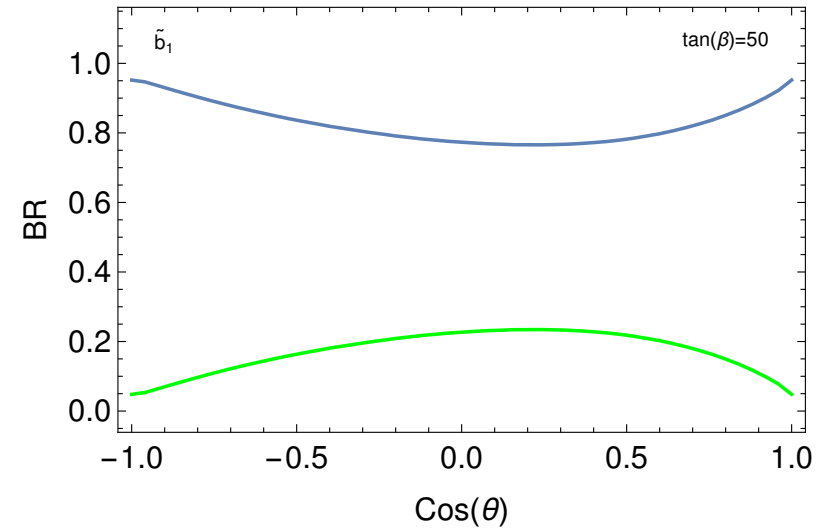
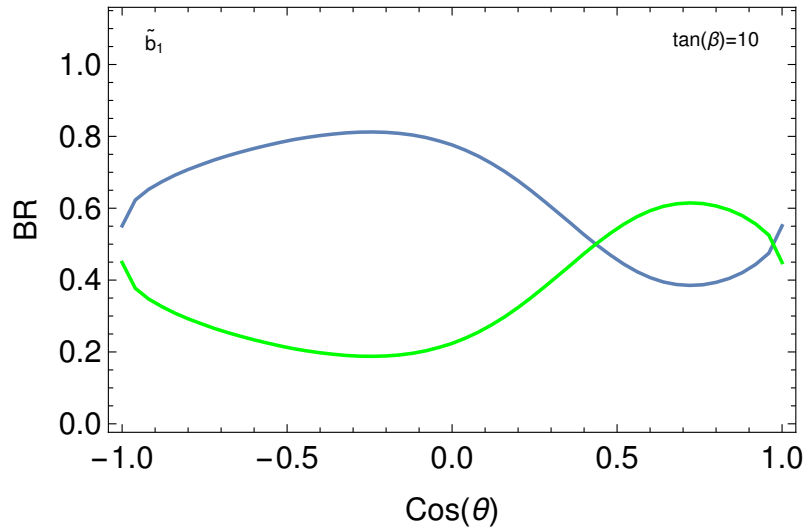
assume $Y_{\nu,k} = Y_\nu$; tree level relation

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

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

$$M_{\nu_R, \tilde{S}}^2 = \begin{pmatrix} |M_k|^2 & B_{M_k} \\ B_{M_k} & |M_k|^2 \end{pmatrix} \Rightarrow m_{1,2}^2 = |M_k|^2 \pm |B_{M_k}|$$

\Rightarrow expect lightest 'sneutrino' as LSP,



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

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^{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^{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 (via τ), E_T^{miss}
atlas_1407_0583	\tilde{t}	1 lepton, jets and E_T^{miss}
atlas_conf_2013_062	\tilde{t}, \tilde{g}	1 lepton, jets and E_T^{miss}
atlas_conf_2013_104	\tilde{t}	1 lepton, jets and E_T^{miss}
atlas_conf_2013_061	\tilde{g}	three b -jets and E_T^{miss}
atlas_1308_2631	\tilde{b}, \tilde{t}	2 b jets and E_T^{miss}
atlas_conf_2013_047	\tilde{q}, \tilde{g}	jets and E_T^{miss}
atlas_conf_2013_024	\tilde{t}	hadronic $t\bar{t}$ final states