Natural SUSY: Interplay of LHC & Dark Matter direct detection

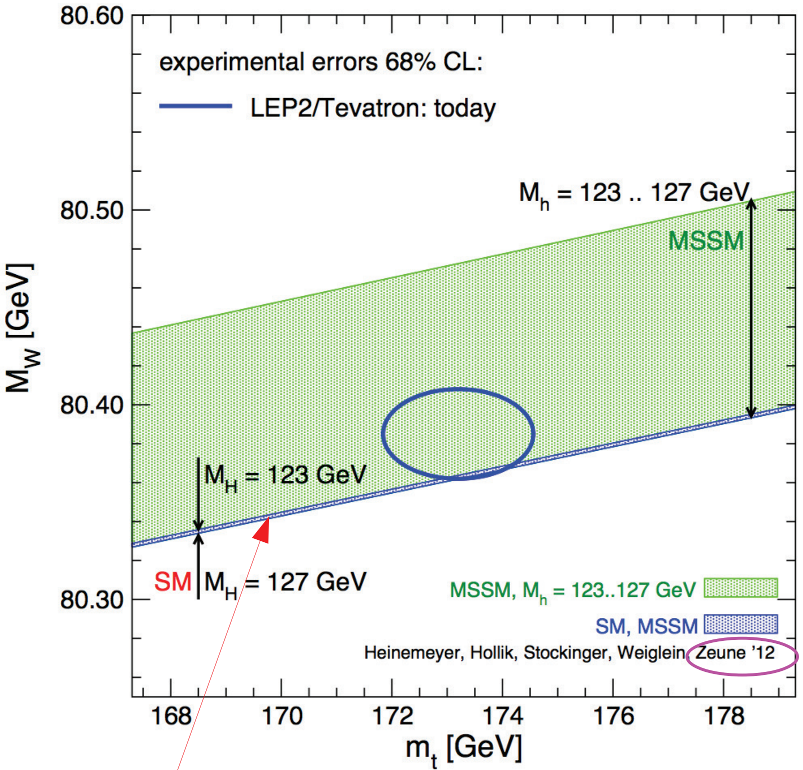
Werner Porod

Universität Würzburg

Content

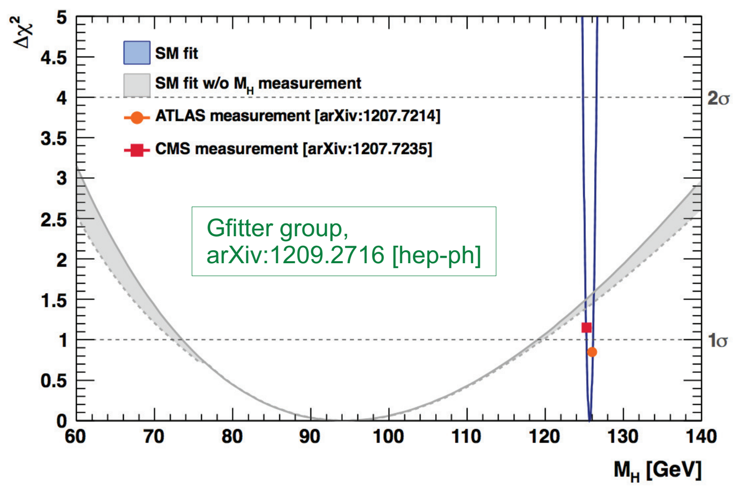
- Why extending the SM at all, why supersymmetry
- Higgs discovery and LHC BSM results: implications
- ‘Natural’ MSSM, a challenge
- ‘Natural’ SUSY and extended gauge groups

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:



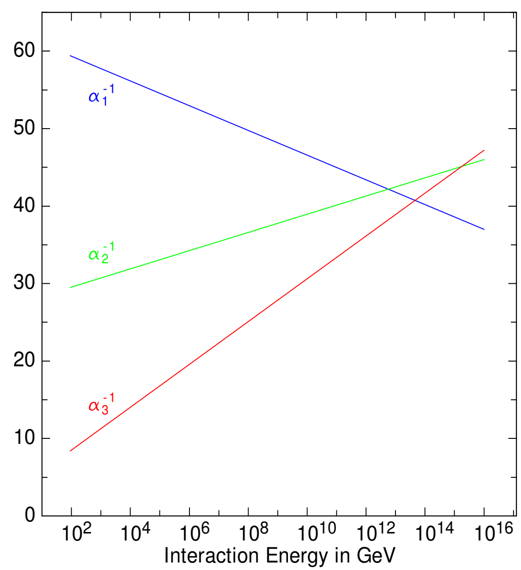
Consistent at the 1.3 σ level.

Why do we want to extend the SM

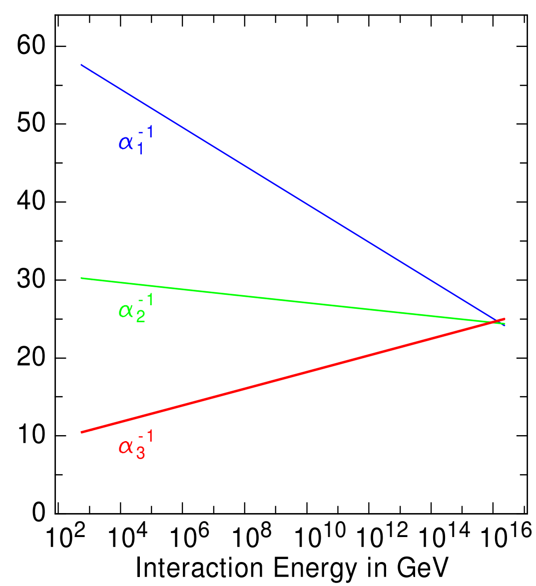
- How to combine gravity with the SM?
  $\Rightarrow$ local Supersymmetry (SUSY) implies gravity
- SM particles can be put in multiplets of larger gauge groups
  - in $SU(5)$: $1 = \nu^c_R$, $5 = (d^c_{\alpha,R}, \nu_{l,L}, l_L)$, $10 = (u_{\alpha,L}, u^c_{\alpha,R}, d_{\alpha,L}, l_R)$
  - in $SO(10)$: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

  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

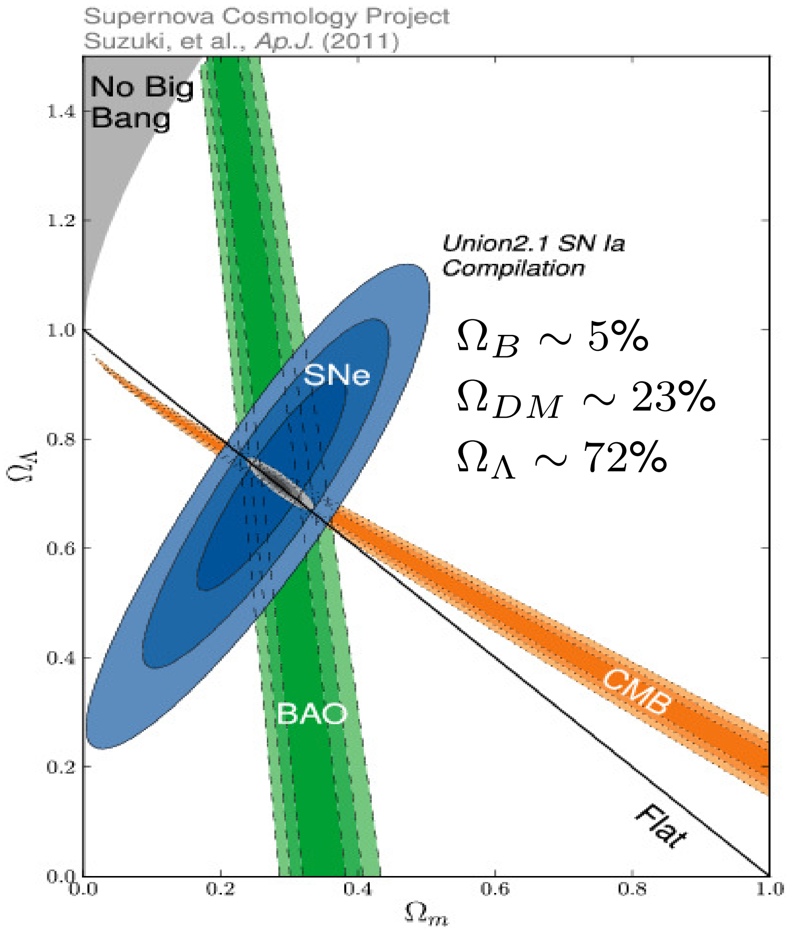


MSSM

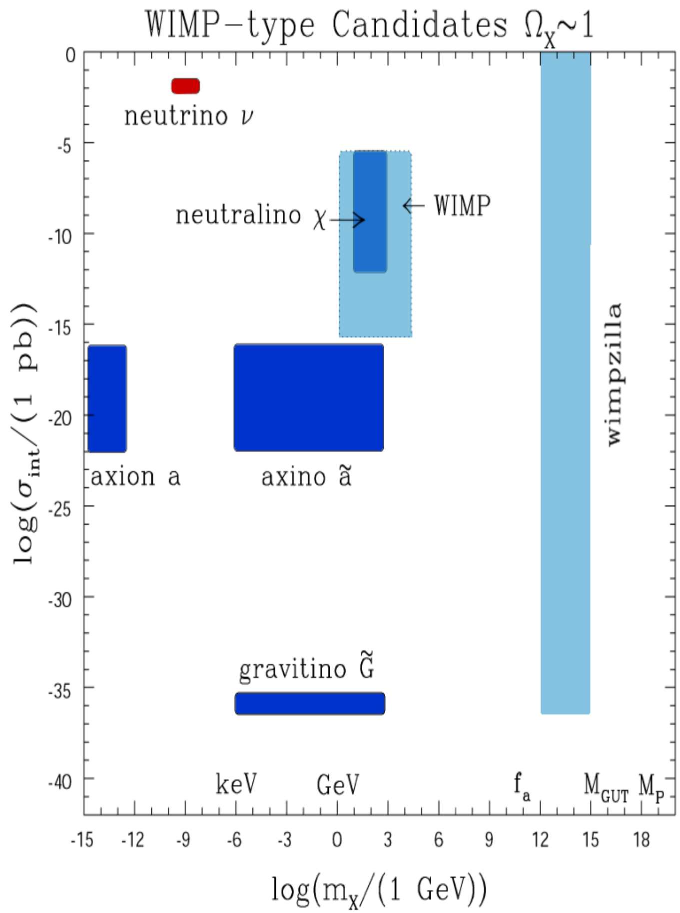


Why do we want to extend the SM

- What is the nature of dark matter ?



$$\Omega_B \sim 5\%$$
$$\Omega_{DM} \sim 23\%$$
$$\Omega_\Lambda \sim 72\%$$

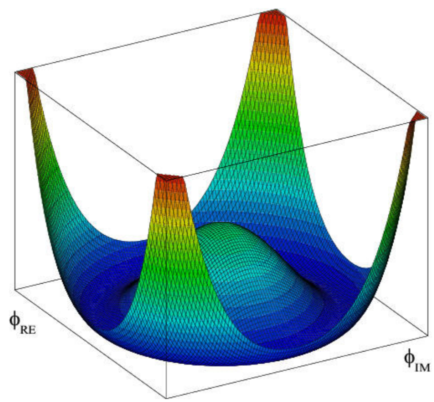


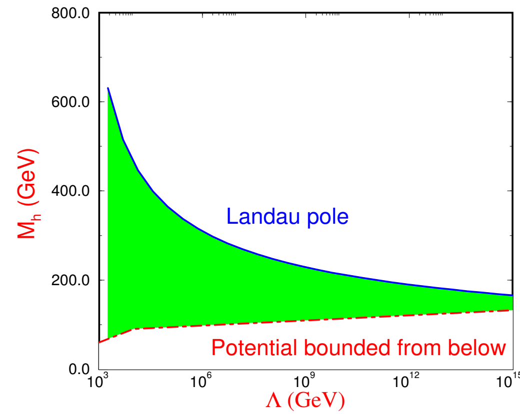
L. Roszkowski, astro-ph/0404052

- What is the origin of the observed baryon asymmetry?

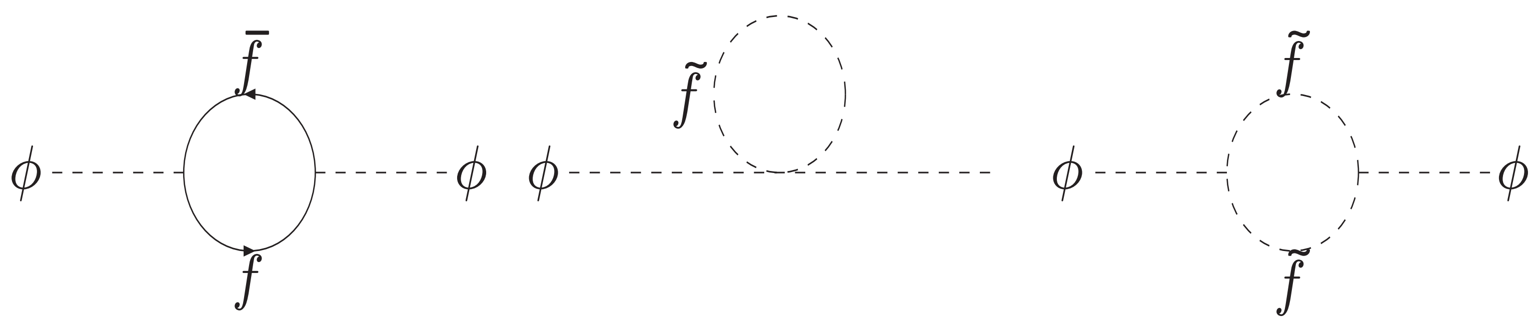
Why do we want to extend the SM

- 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

Supersymmetry, MSSM

	Standard Model		MSSM
matter:	e, d, d, d ν_e, u, u, u	$\Leftrightarrow$	$\tilde{e}$, $\tilde{d}$, $\tilde{d}$, $\tilde{d}$ $\tilde{\nu}_e$, $\tilde{u}$, $\tilde{u}$, $\tilde{u}$
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, Higgs sector

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

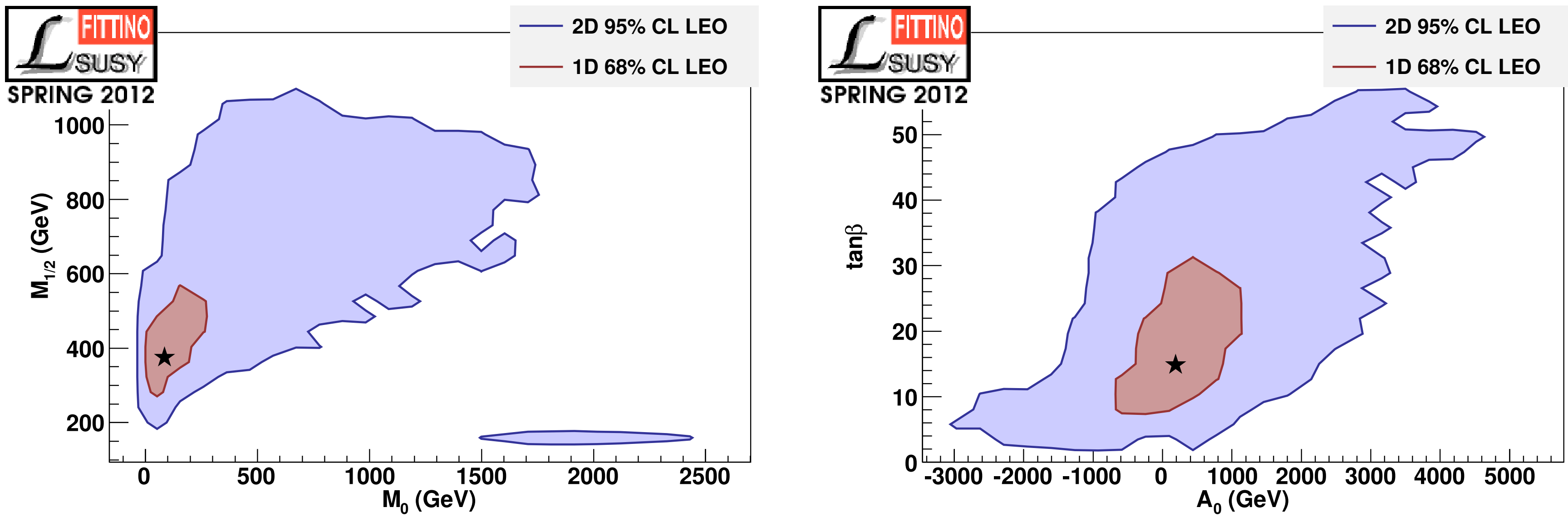
  at higher order:

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;...

$$
\begin{aligned}
m_h^2 &\simeq m_Z^2 \cos^2(2\beta) + \frac{3m_t^4}{4\pi^2 v^2}\left[\ln\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12 M_S^2}\right)\right] \\
M_S^2 &= m_{\tilde t_1} m_{\tilde t_2} \quad , \quad X_t = A_t - \mu\cot\beta \\
m_H, m_A, m_{H+} &: \quad O(v)\ldots O(TeV) \\
m_{H+}^2 &= m_A^2 + m_W^2 \\
v^2 &= v_u^2 + v_d^2 = 4 m_W^2/g^2
\end{aligned}
$$

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

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

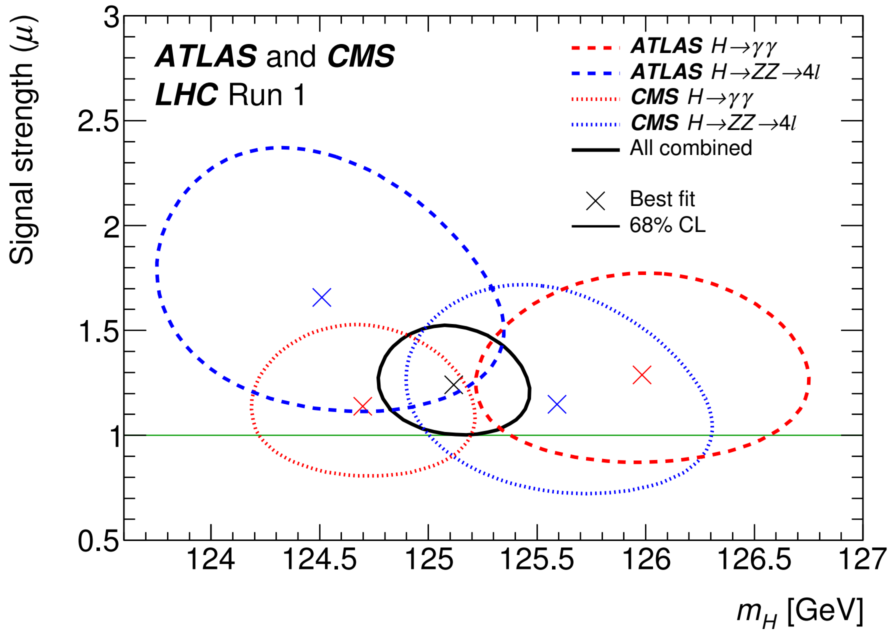
$\Rightarrow M_0 = 84^{+145}_{-28}$ GeV, $M_{1/2} = 375^{+175}_{-88}$ GeV,
$\tan\beta = 15^{+17}_{-7}$ $A_0 = 186^{+831}_{-844}$ GeV,
$\chi^2/ndf = 10.3/8$

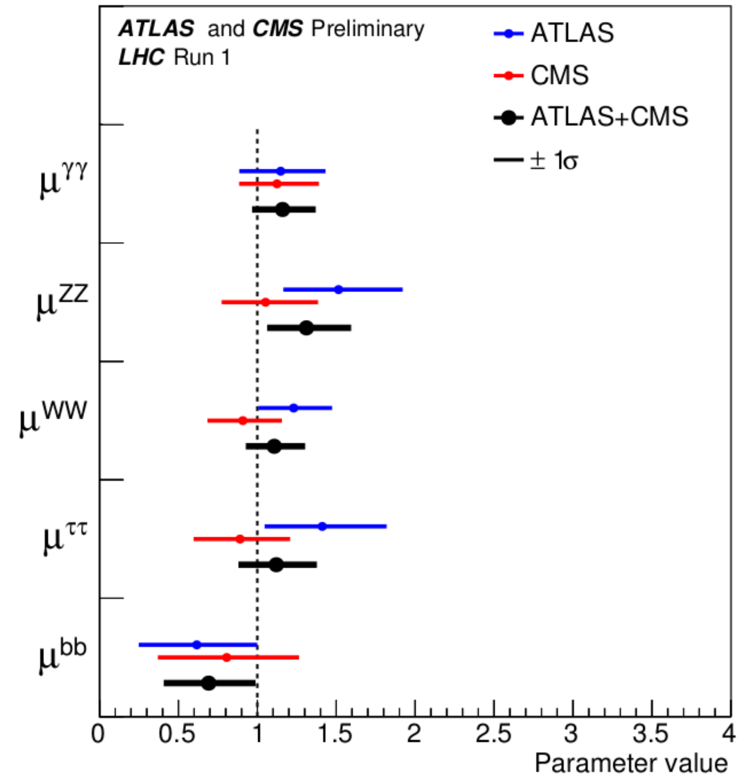
$\Rightarrow m_h = 116$ GeV

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, status 2015





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

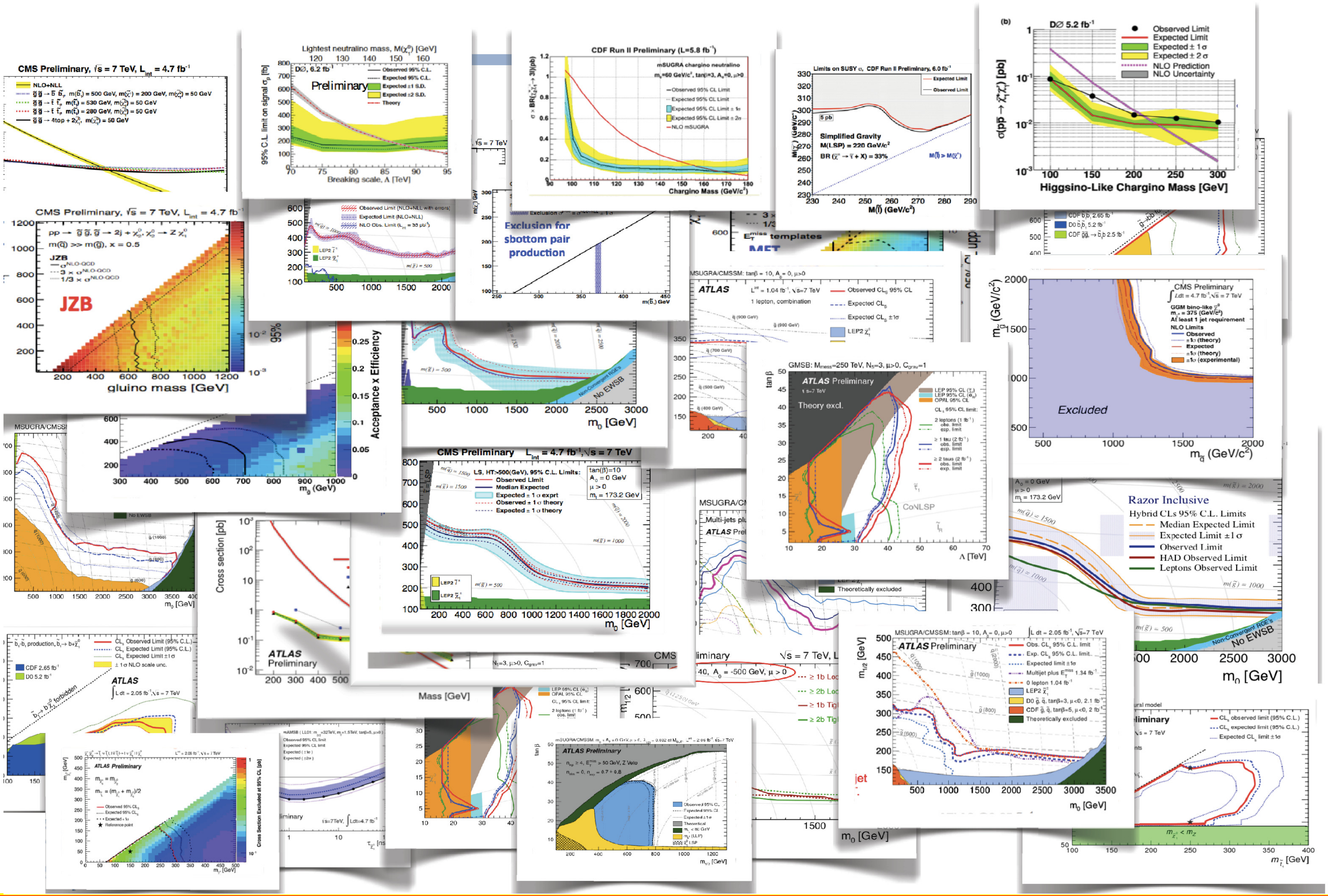
PRL **114** (2015) 191803

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

BSM searches, so far hardly anything . . .



LHC data, in particular m_h, high scale models

$m_h = 125.1$ GeV ⇒ large loop contributions

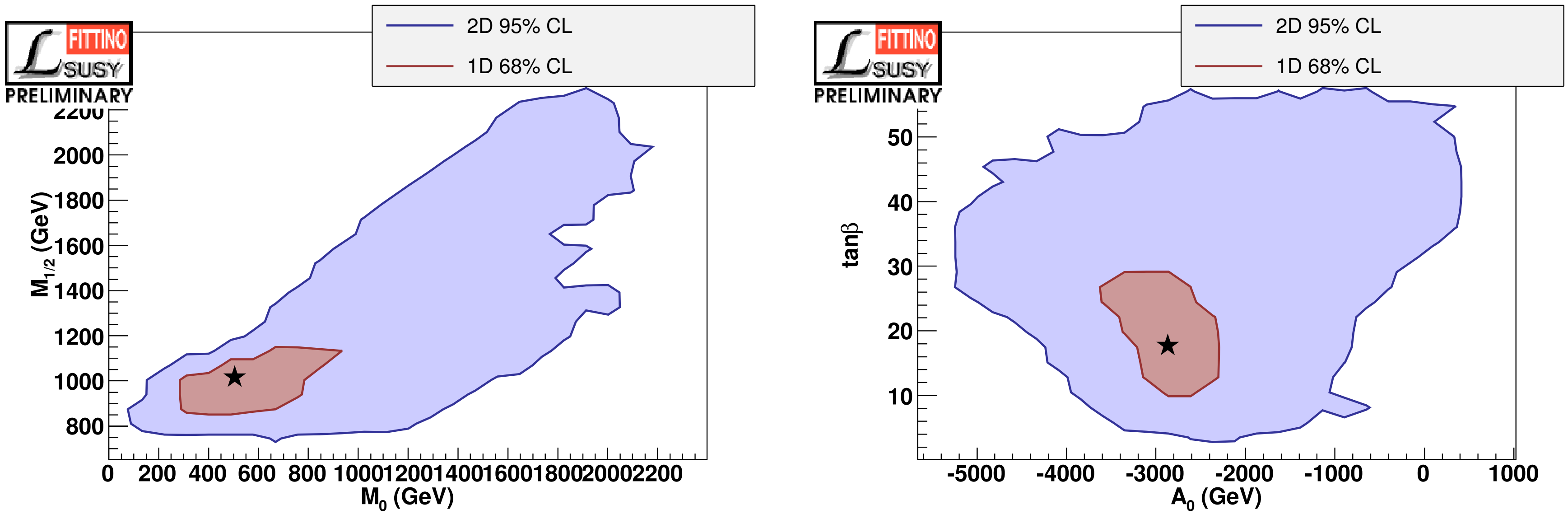
⇒ heavy stops and/or large left-right mixing for stops

- 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, choice not well motivated ⇒ 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: $A_0 \simeq -(1-3)\max(M_{1/2}, m_{Q_3,GUT}, m_{U_3,GUT})$
  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

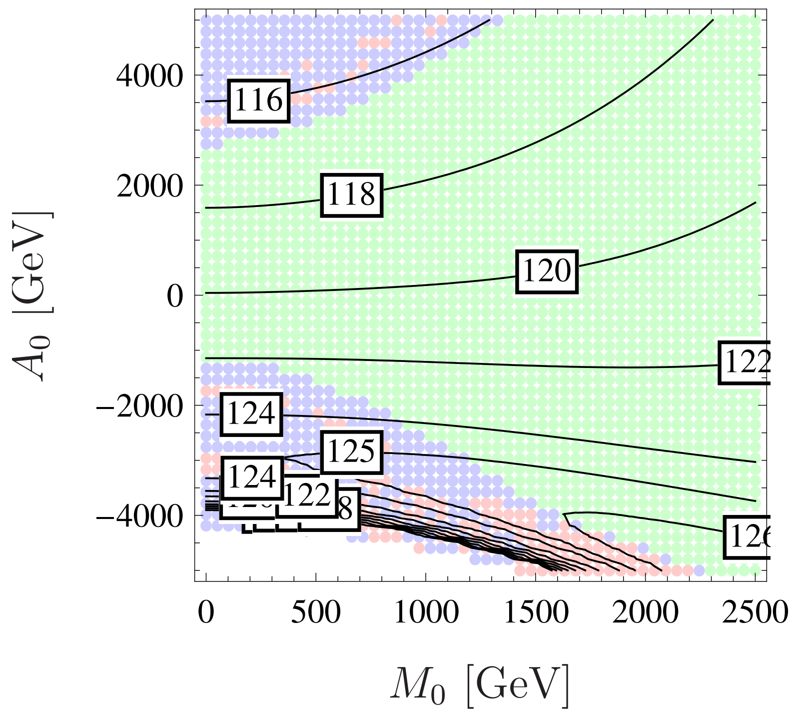
implications for LHC: $m_{\tilde{g}}, m_{\tilde{q}} \gtrsim 2$ TeV, $m_{\tilde{l}_R} \simeq 600$ GeV, $m_{\tilde{\chi}_1^0} \simeq 450$ GeV

can be tested at LHC 13 TeV [14 TeV]

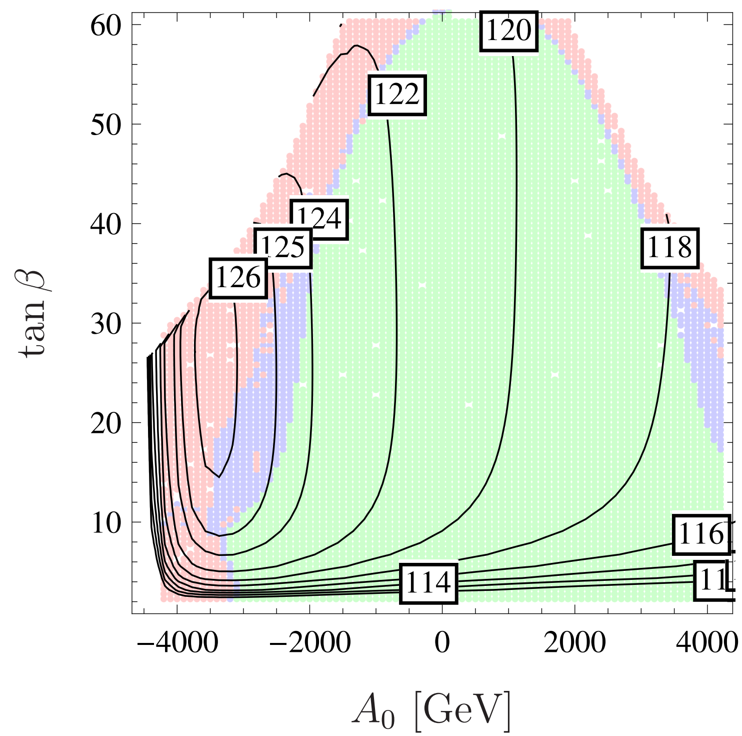
so far so good, but . . .

mSUGRA/CMSSM, charge/color breaking minima

- SUSY models contain many scalars $\Rightarrow$ 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

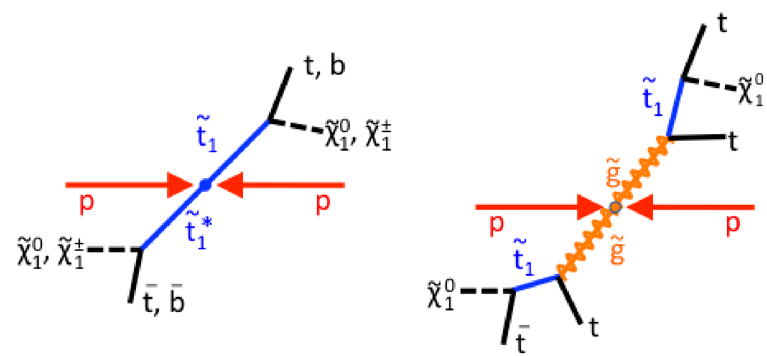
J.E. Camargo-Molina, B. O'Leary, W.P., F. Staub, arXiv:1309.7212

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': $\tilde{t}_1$, $\tilde{b}_1$, $\tilde{g}$, $\tilde{h}^{+,0,-}$
  $\Rightarrow$ 100 MeV $\lesssim m_{\tilde{\chi}_1^+} - m_{\tilde{\chi}_1^0} \simeq m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} \lesssim 5 - 10$ 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 $\tilde{b}_1$

The electroweak measure of fine-tuning

$$\mathcal{L}_{MSSM} = \mu \tilde{H}_u \tilde{H}_d + \text{ h.c. } + (m^2_{H_u} + |\mu|^2)|H^2_u|^2 + (m^2_{H_d} + |\mu|^2)|H^2_d|^2 + \dots$$

basic idea: contributions to m_Z should not contain large cancellations among each other

$$\frac{m_Z^2}{2} = \frac{m^2_{H_d} + \Sigma_d - (m^2_{H_u} + \Sigma_u)\tan^2\beta}{\tan^2\beta - 1} - |\mu|^2 \simeq -(m^2_{H_u} + \Sigma_u) - |\mu|^2$$

'standard fine-tuning measure'†

$$\Delta_{FT} = \max[c_i]\ , \quad c_i = \left|\frac{\partial \ln m_Z^2}{\partial \ln p_i}\right| = \left|\frac{p_i}{m_Z^2}\frac{\partial m_Z^2}{\partial p_i}\right|$$

requireing at most a tuning at the per-cent level one finds

$$|\mu|^2 \simeq m_Z^2 \simeq |m^2_{H_u}|\ , \quad m_{\tilde{t}_1} \lesssim \text{ 1 TeV }, \quad m_{\tilde{g}} \lesssim \text{ 1-2 TeV}$$

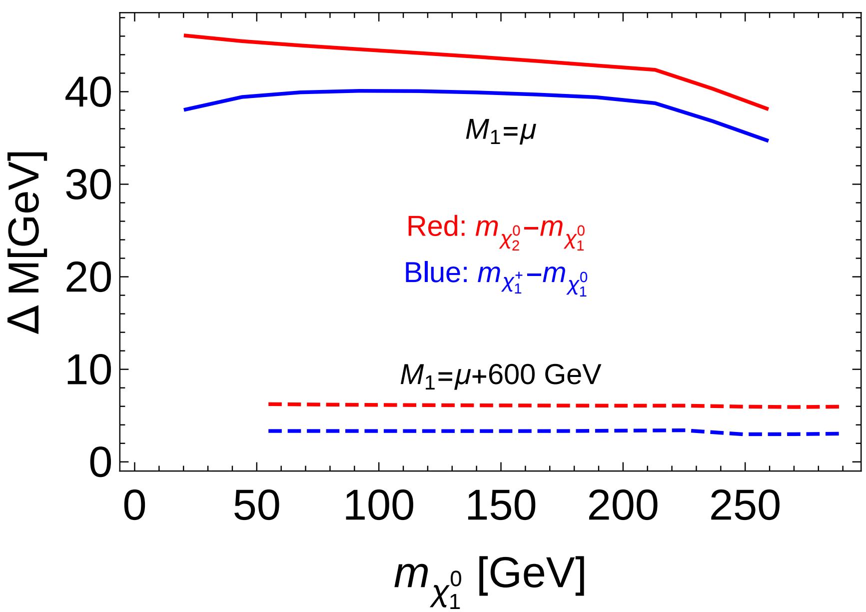
† Ellis, Enqvist, Nanopoulos, Zwirner 1986; Barbieri, Guidice 1988

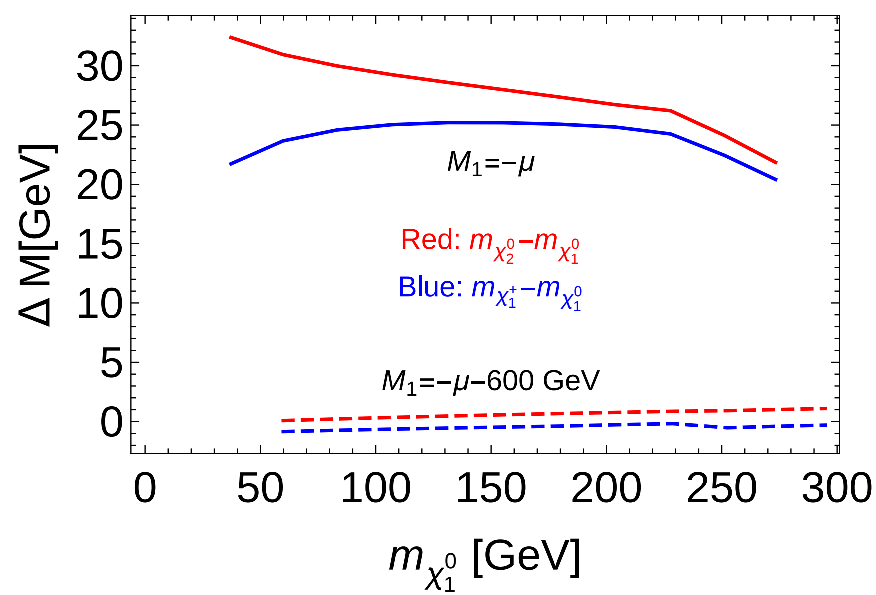
Higgsino LSP: spectrum

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

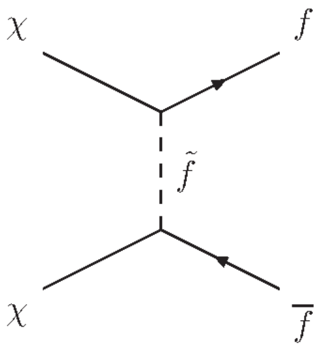
$$\Delta m_0 = m_{\tilde\chi^0_2} - m_{\tilde\chi^0_1} \simeq m_Z^2 \left(\frac{s_\omega^2}{M_1} + \frac{c_\omega^2}{M_2} \right)$$

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



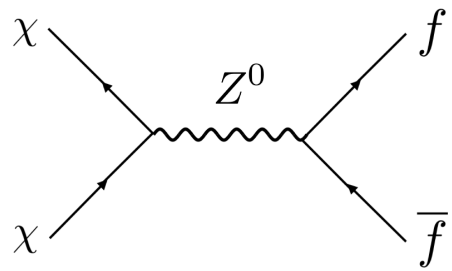


Dark matter, annihilation processes



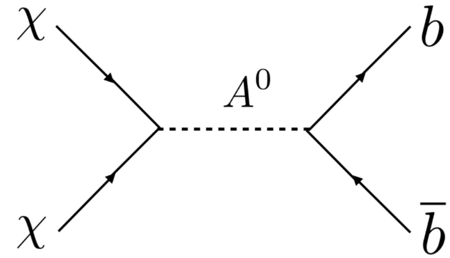
bino

bulk region

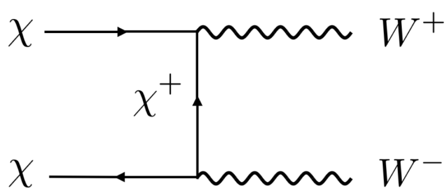


wino, higgsino

focus-point region



funnel region



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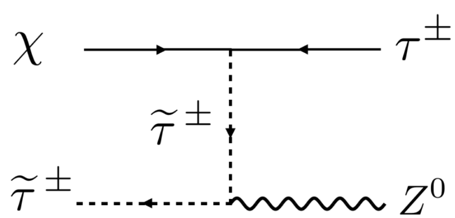
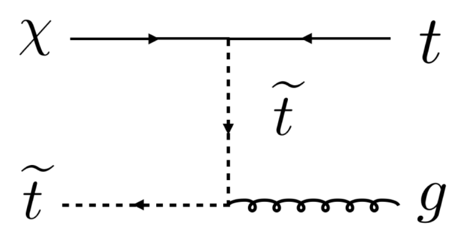
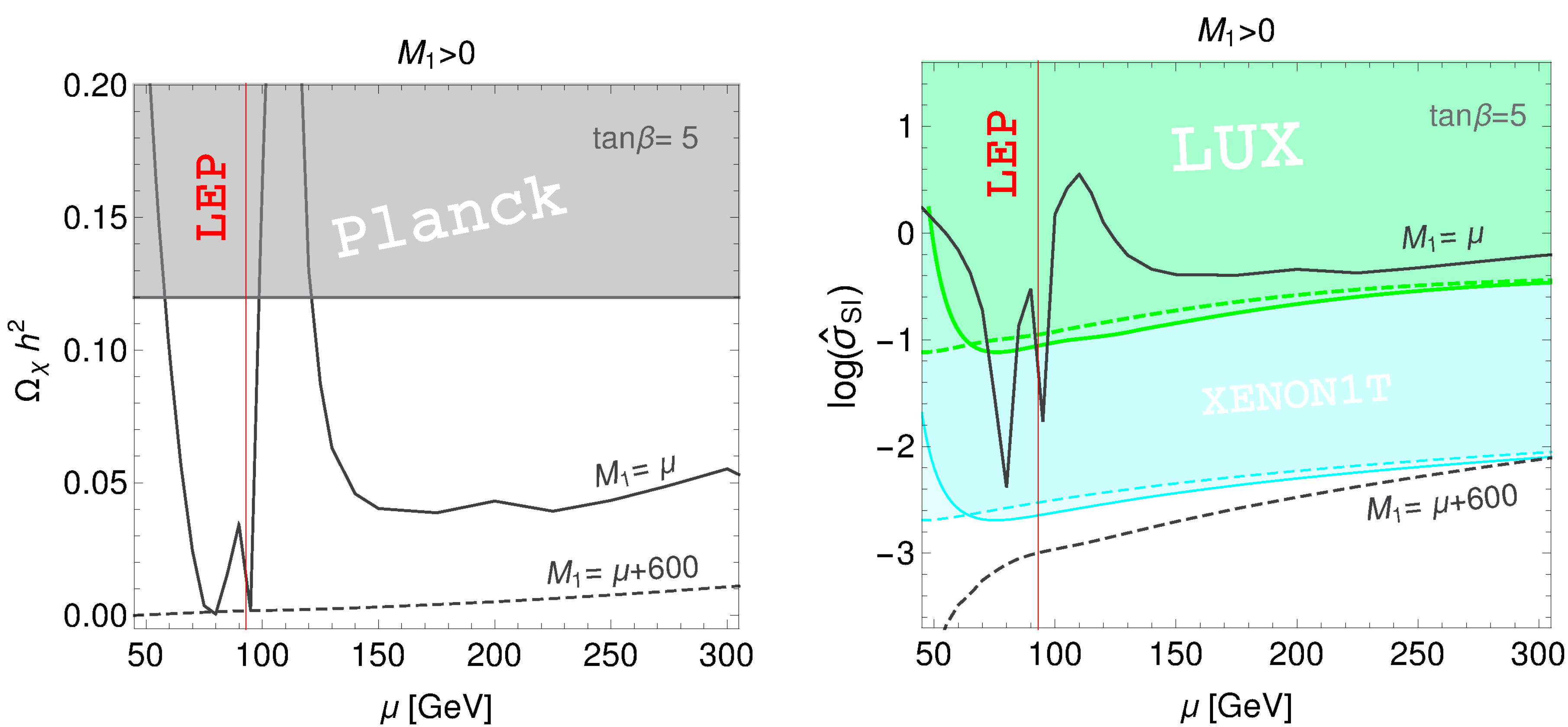


stau co-annihilation



stop co-annihilation

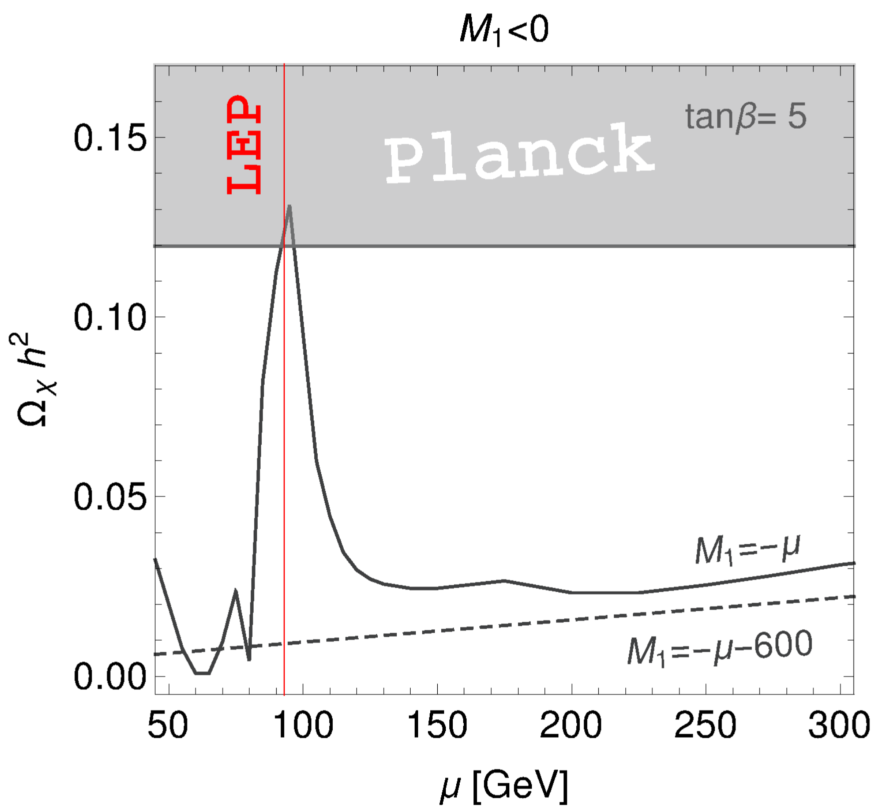
DM relic density and direct detection

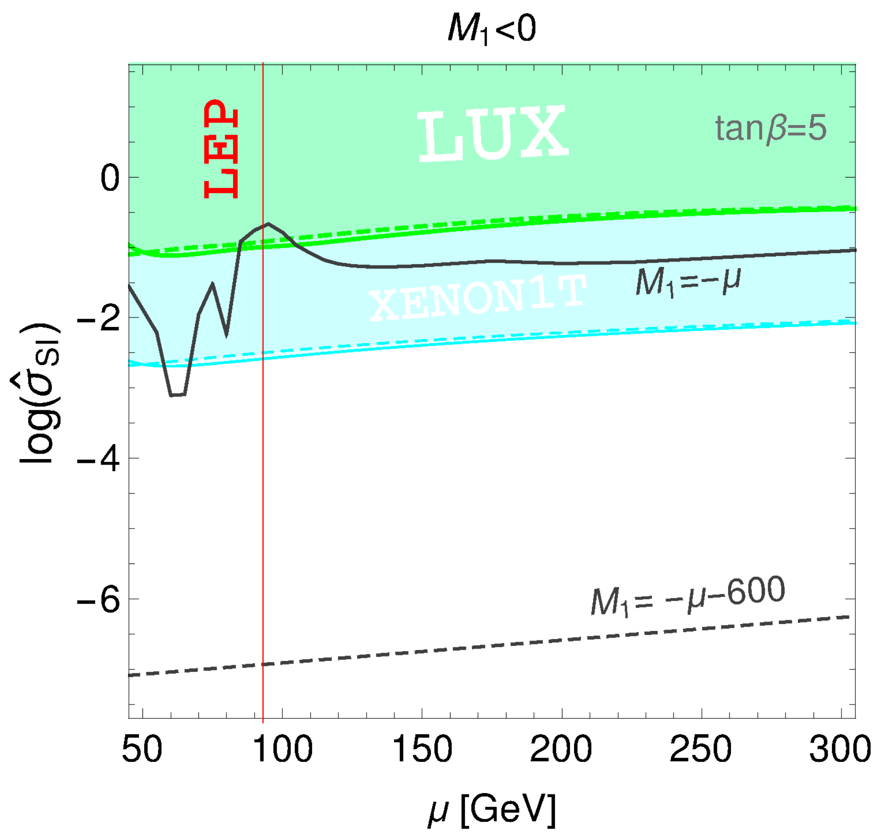


- relic density too low because higgsinos couple 'strongly' to W and Z
- DD cross section rescaled with relic density $\rightarrow$ chance for LHC?

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

DM relic density and direct detection





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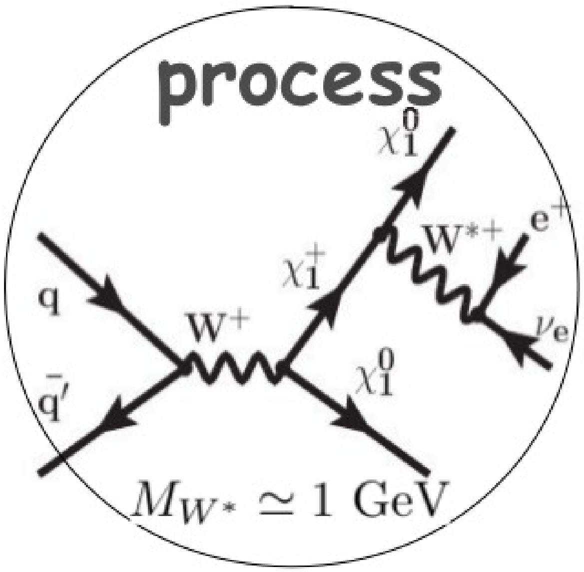
Higgsino LSP: Challenge for LHC

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



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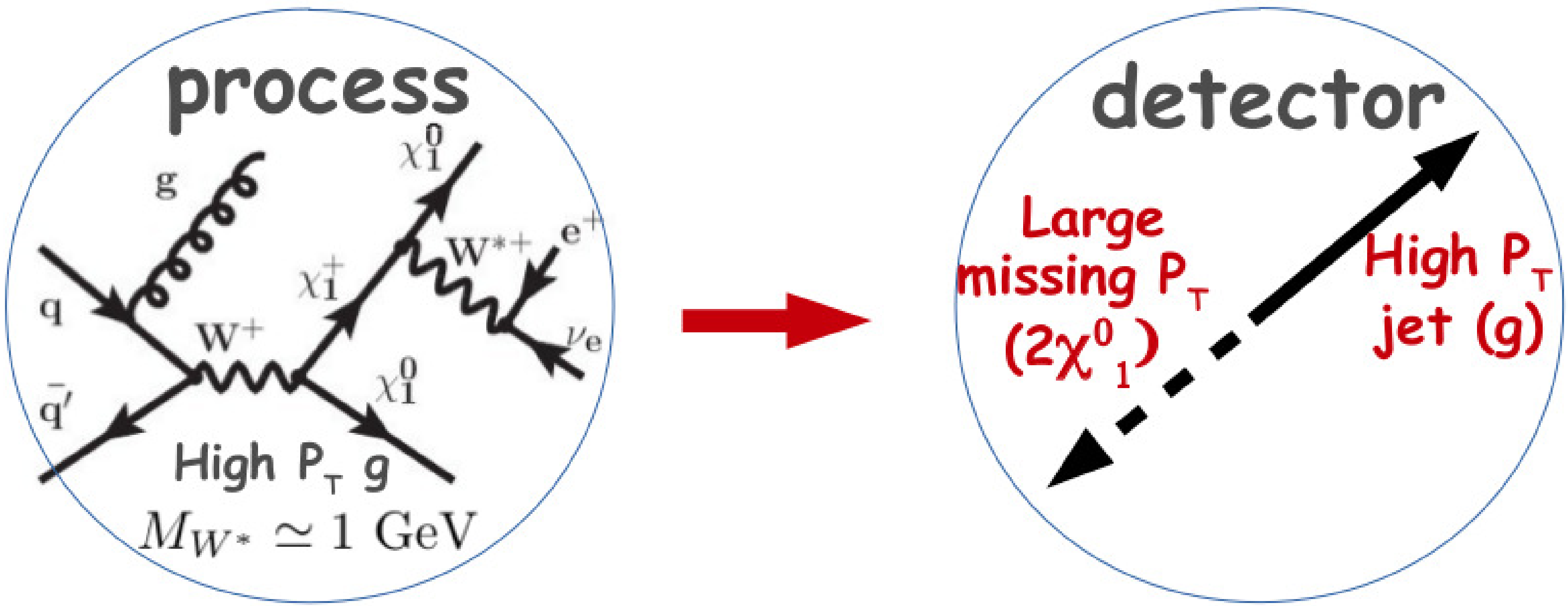


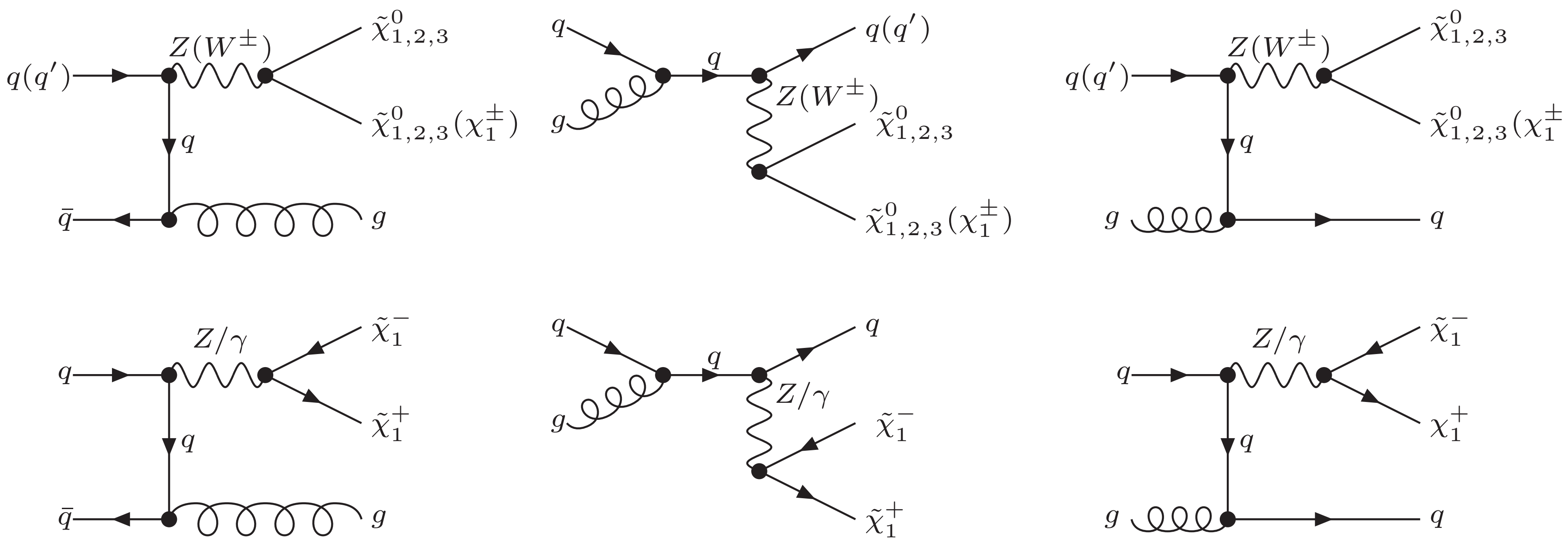
The only way to probe compressed higgsinos is a mono-jet signature:
'Where the Sidewalk Ends? . . .' Alves, Izaguirre,Wacker 2011

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

Higgsino LSP: Challenge for LHC

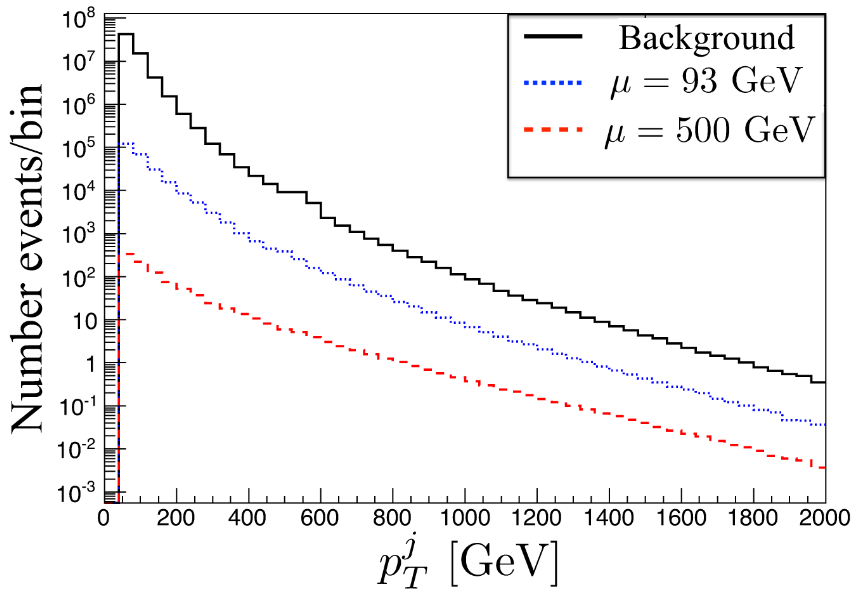
What is the potential of LHC to probe this parameter space through

$$pp \to \tilde{\chi}\tilde{\chi}j \;, \quad \tilde{\chi} = \tilde{\chi}^0_{1,2}, \tilde{\chi}^\pm_1 \qquad ?$$

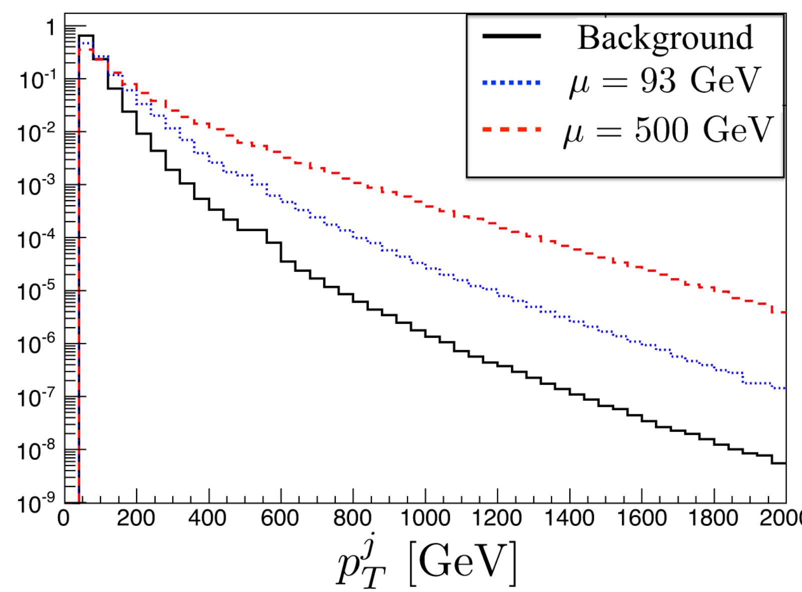


LHC @ 13 TeV: signal versus background

differences in rates: depressing



but differences in shape is encouraging



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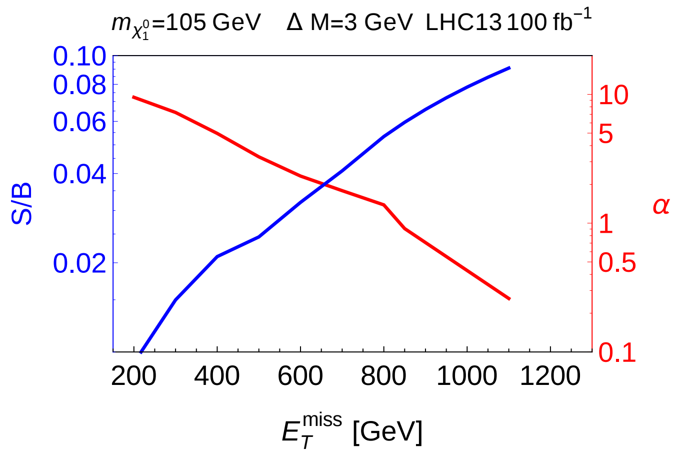
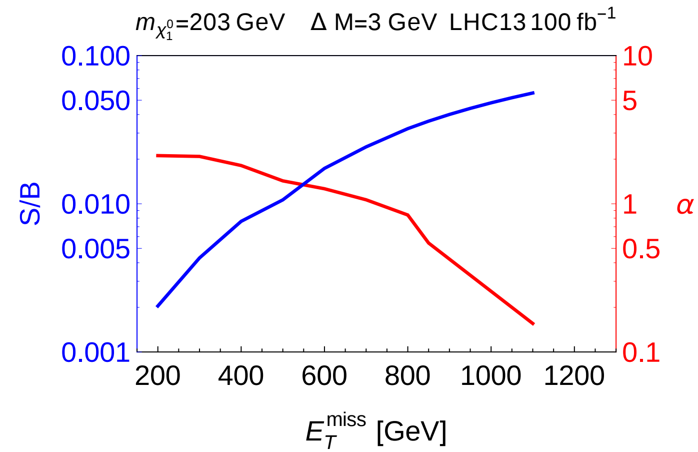
S/B versus signal significance α

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



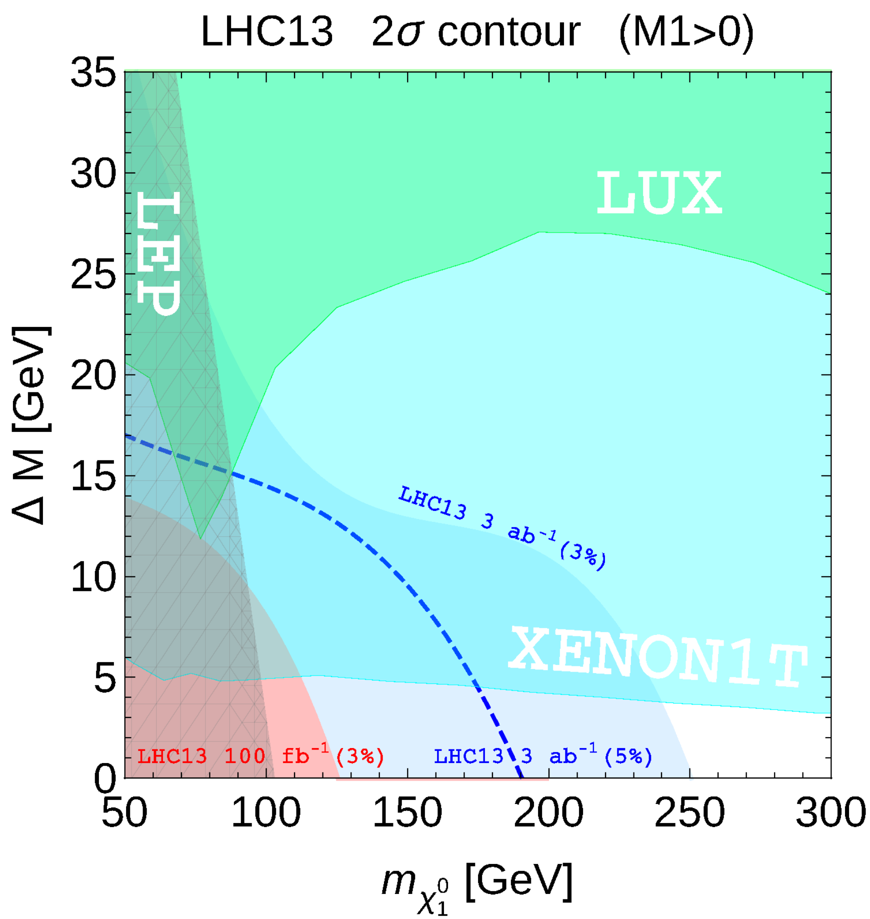


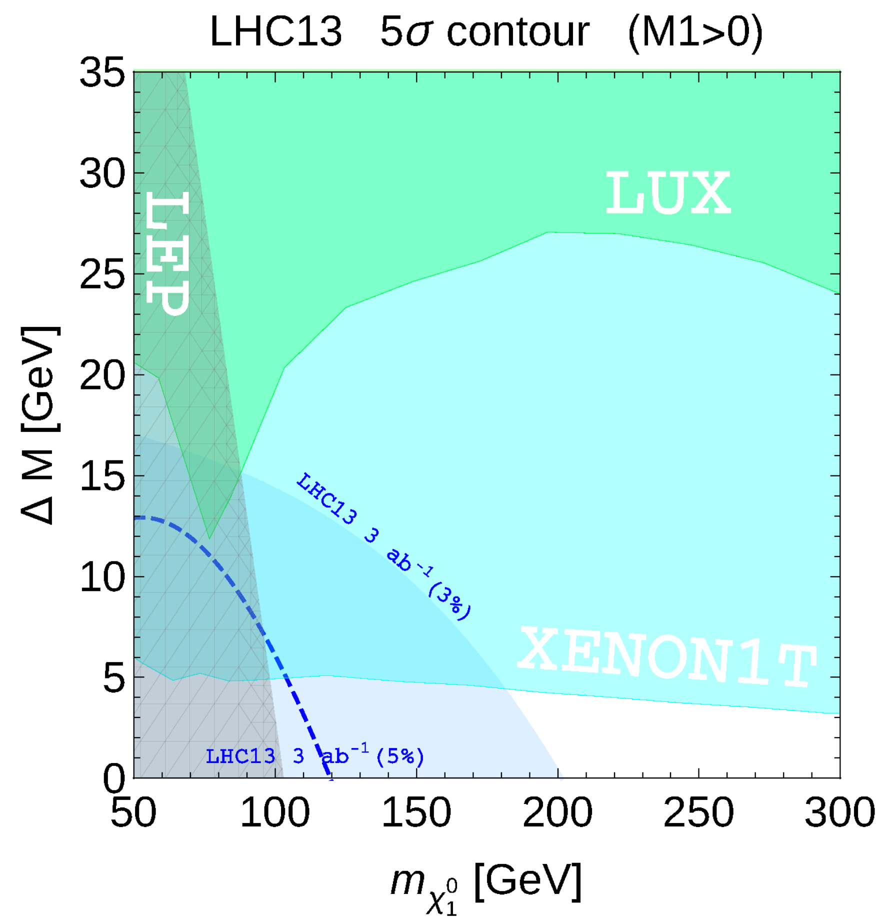
	$Z(\nu\bar{\nu})j$	$W(l\nu)j$	$\mu = 100$ GeV	$\mu = 200$ GeV
Initial # of events	$3.15 \cdot 10^6$	$1.25 \cdot 10^7$	$3.63 \cdot 10^5$	$6.45 \cdot 10^3$
$p_T^j > 200$ GeV $\|\eta^j\| < 2.4$	$1.05 \cdot 10^6$	$4.11 \cdot 10^6$	$1.73 \cdot 10^5$	3528
Jet veto ($n \geq 3$)	$8.7 \cdot 10^5$	$3.13 \cdot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

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

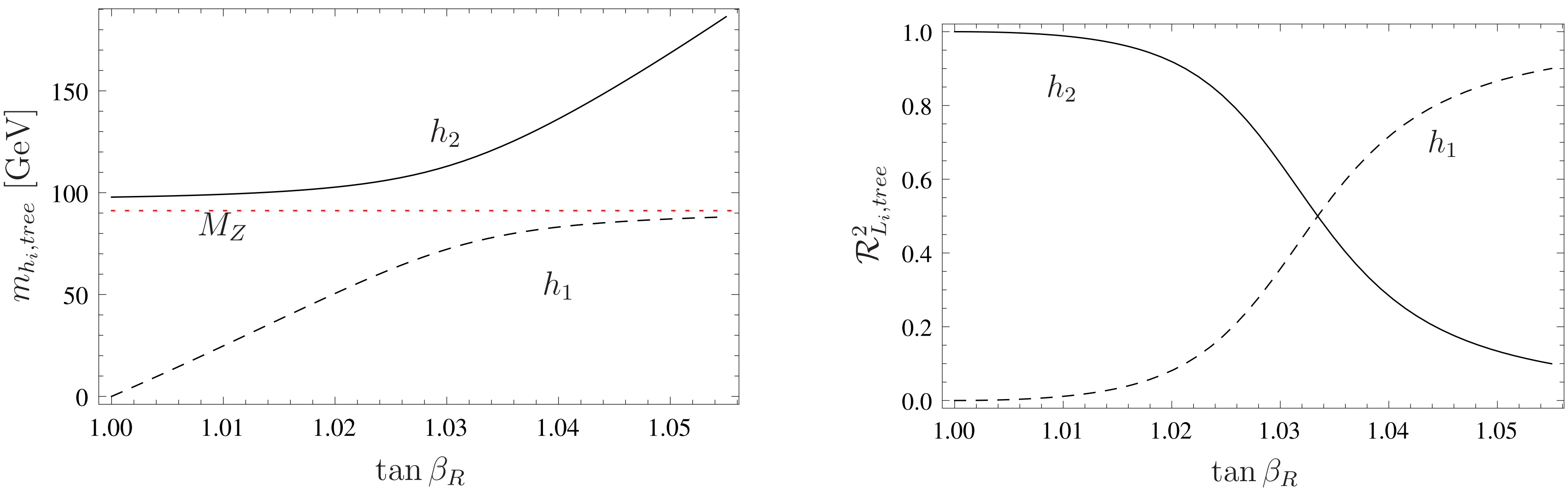
  $\Rightarrow SO(10) \rightarrow SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$
  $\rightarrow SU(3)_C \times SU(2)_L \times U(1)_R \times U(1)_{B-L}$
  $\cong SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_\chi$
  or $E(8) \times E(8) \rightarrow SU(3)_C \times SU(2)_L \times U(1)_Y \times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

- 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: $m^2_{h,tree} \leq m^2_Z + \frac{1}{4} g^2_\chi v^2$

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

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):

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

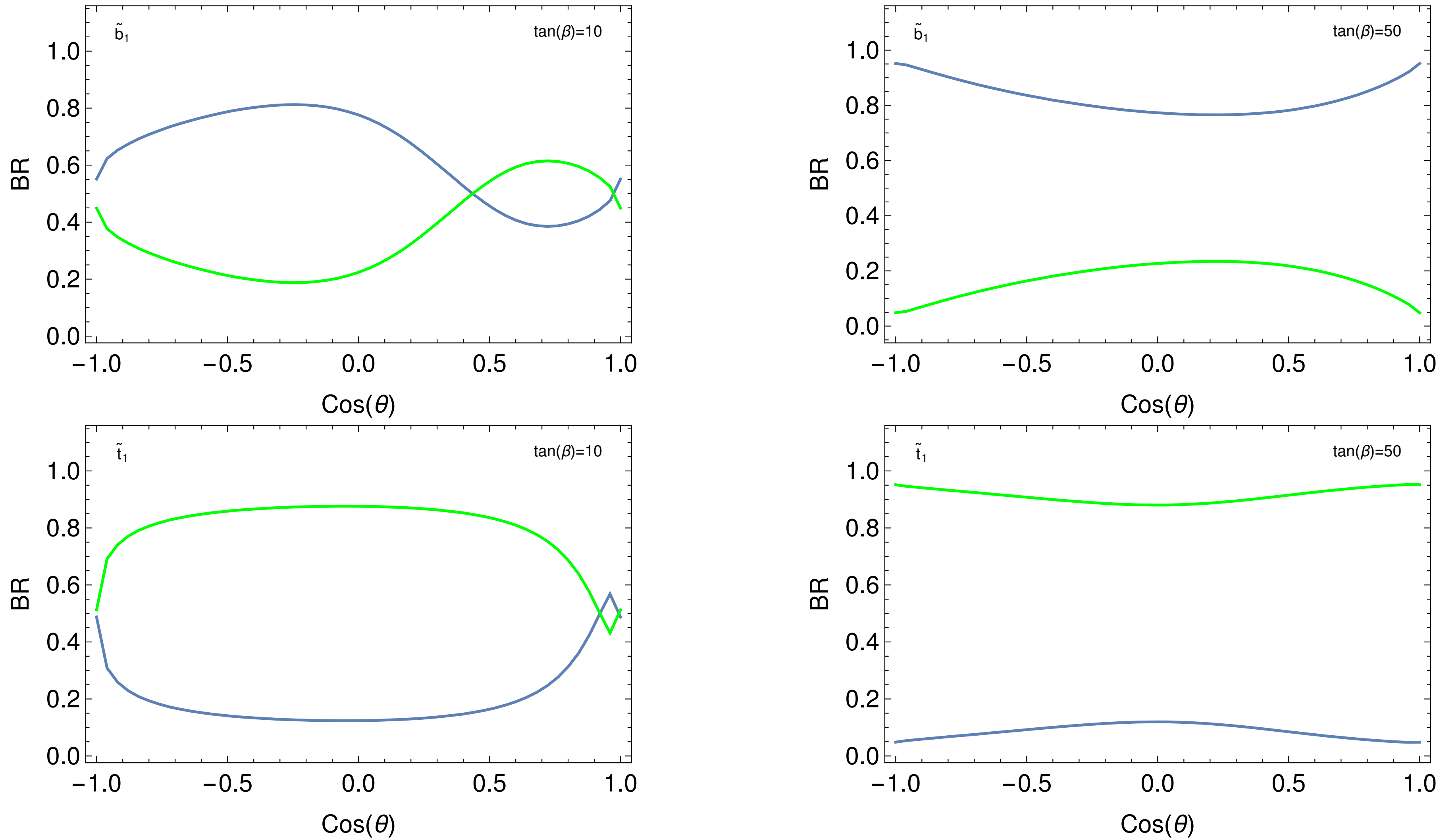
$\Rightarrow$ expect lightest ‘sneutrino’ as LSP, either cascade decays

$$\tilde{t}_i \to t\tilde{\chi}^0_{1/2} \ , \ b\tilde{\chi}^+_1$$
$$\tilde{b}_i \to b\tilde{\chi}^0_{1/2} \ , \ t\tilde{\chi}^-_1$$
$$\tilde{t}_1 \to W^+\tilde{b}_i \, , \quad \tilde{b}_i \to W^-\tilde{t}_1$$
$$\tilde{\chi}^+_1 \to \tilde{\nu}_{Ri}\ell^+_i$$
$$\tilde{\chi}^0_{1/2} \to \tilde{\nu}_{Ri}\nu_i$$

or three-body decays

$$\tilde{t}_1 \to bl^+\tilde{\nu}_{Ri} \quad , \quad \tilde{t}_1 \to t\nu_i\tilde{\nu}_{Ri} \quad ,$$
$$\tilde{b}_1 \to tl^-\tilde{\nu}_{Ri} \quad , \quad \tilde{b}_1 \to b\nu_i\tilde{\nu}_{Ri} \quad .$$

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

Set-up of analysis

based on CheckMATE

compares number of events passing each signal region of every considered analysis with the observed $S95$ limit using

$$r^c_{exp/obs} = \frac{S - 1.96 \cdot \Delta S}{S^{95}_{exp/obs}}$$

S . . . event number of the considered signal region

ΔS . . . MC error

$S^{95}_{exp/obs}$ . . . expected or experimentally observed 95% confidence limit on the signal

following Drees et al. (2015):

- $r^c_{obs} < \frac{2}{3}$: ‘strictly allowed’
- $\frac{2}{3} < r^c_{obs} < 1.5$: ‘inconclusive’ or ‘ambiguous’
- $r^c_{obs} > 1.5$: ‘strictly excluded’

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

Parameters considered

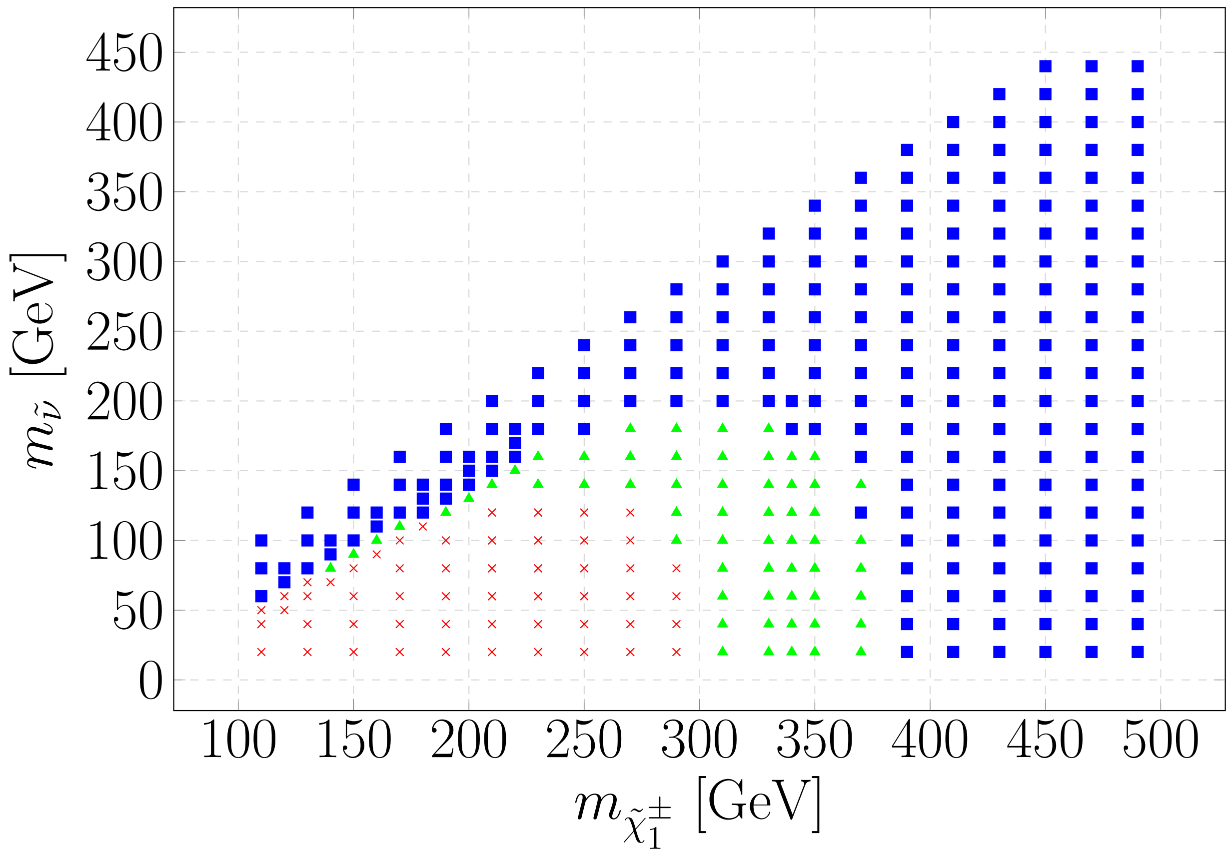
- $m_{\tilde{t}_1}$ in GeV: 300, 400, 500, 600, 700, 800, 900, 1000
- $m_{\tilde{b}_1}$ in GeV: 300, 400, 500, 600, 700, 800, 900, 1000
- $m_{\tilde{\nu}_R}$ in GeV : 60, 100, 200, 300, 400, 500
- μ in GeV: 110, 190, 290, 390, 490, 590 and require $m_{\tilde{\nu}_R} < \mu$
- $\tan\beta$: 10, 50
- $\theta_{\tilde{t}}$: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

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

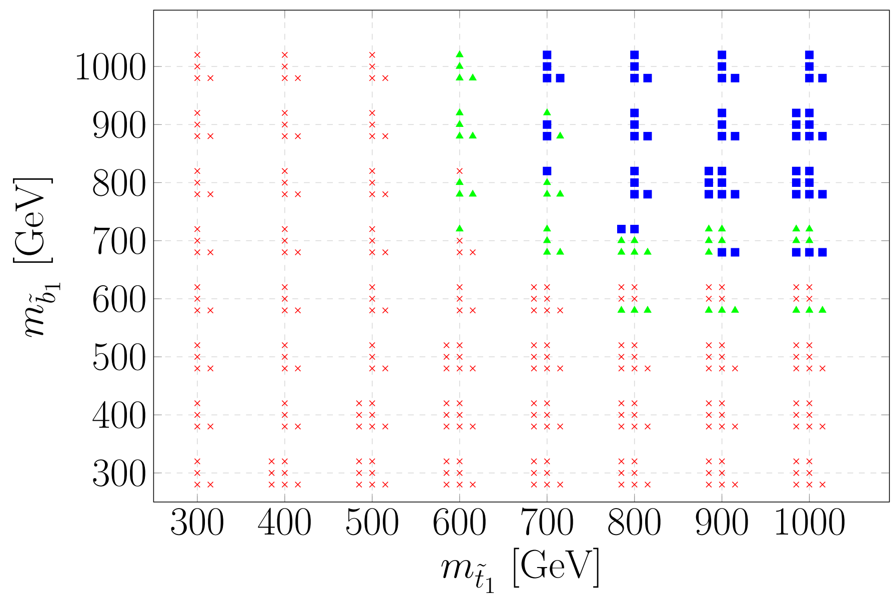


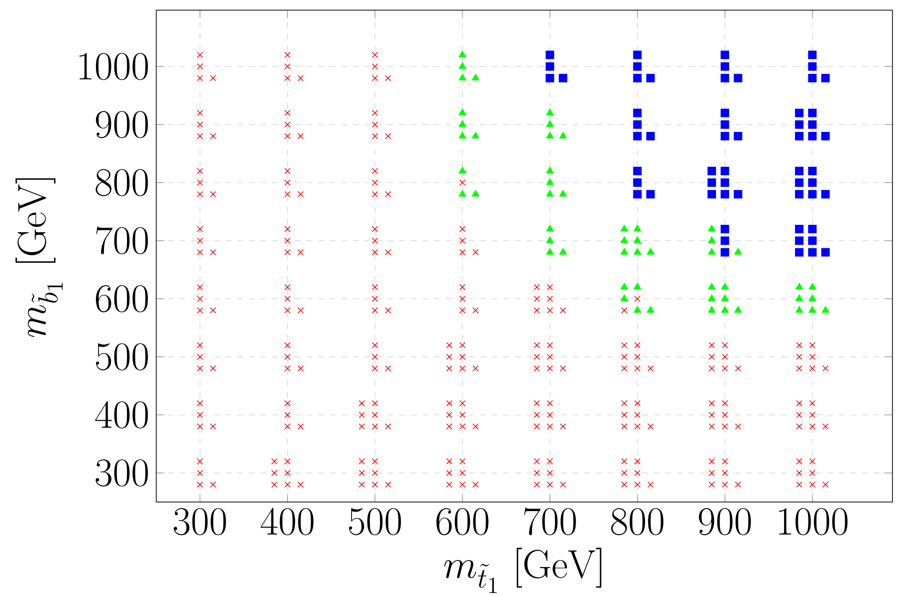
× excluded, ▲ ambigous, ■ allowed

L. Mitzka, WP arXiv:1603.06130

Detailed results, I

	$\theta_{\tilde t} = 0^\circ$	$\theta_{\tilde t} = 45^\circ$	$\theta_{\tilde t} = 90^\circ$
$\theta_{\tilde b} = 0^\circ$	$\tilde b_1 = \tilde b_L$ $\tilde t_1 = \tilde t_L$	$\tilde b_1 = \tilde b_L$ $\tilde t_1 = \tilde t_{LR}$	
$\theta_{\tilde b} = 45^\circ$	$\tilde b_1 = \tilde b_{LR}$ $\tilde t_1 = \tilde t_L$	$\tilde b_1 = \tilde b_{LR}$ $\tilde t_1 = \tilde t_{LR}$	
$\theta_{\tilde b} = 90^\circ$	$\tilde b_1 = \tilde b_R$ $\tilde t_1 = \tilde t_L$	$\tilde b_1 = \tilde b_R$ $\tilde t_1 = \tilde t_{LR}$	$\tilde b_1 = \tilde b_R$ $\tilde t_1 = \tilde t_R$



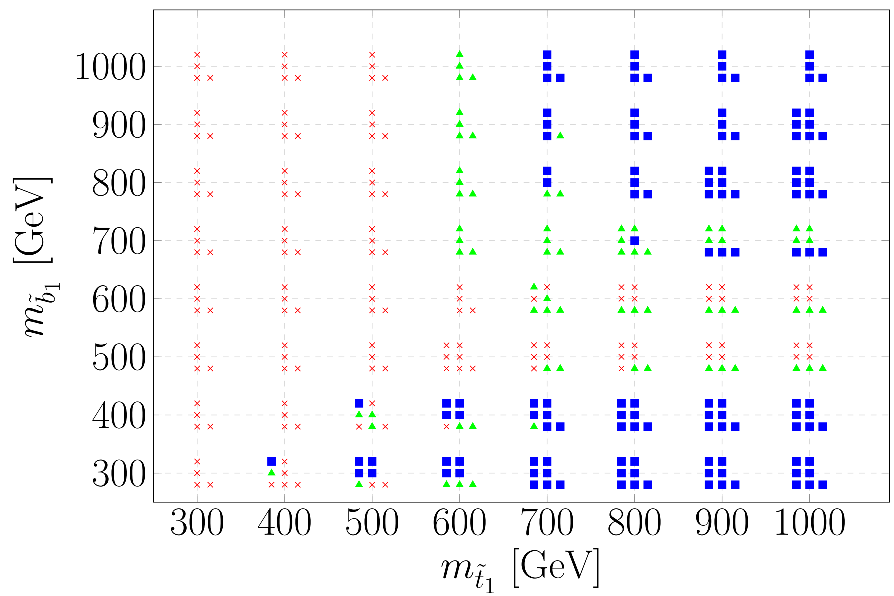


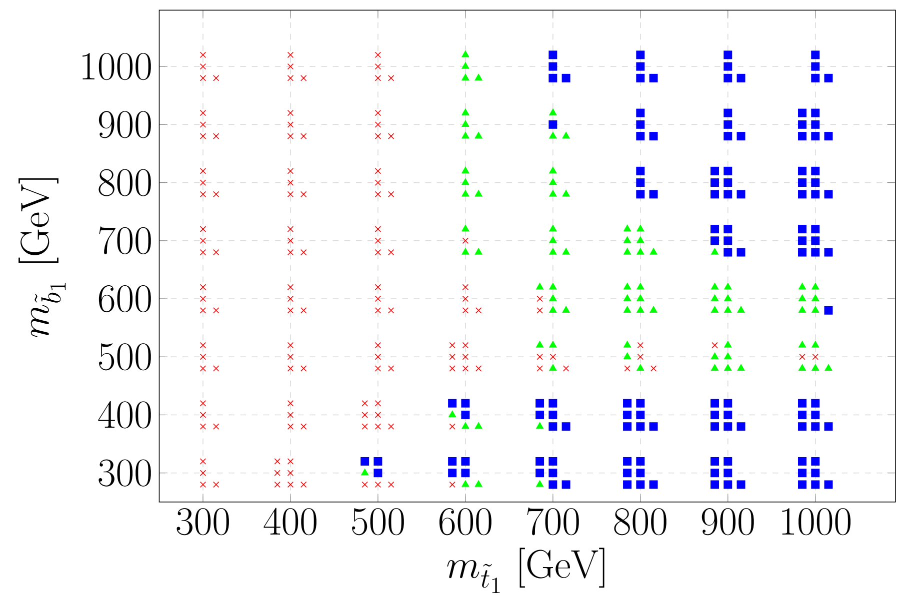
$\mu = 110$ GeV, $m_{\tilde\nu_R} = 60$ GeV, × excluded, ▲ ambigous, ■ allowed

L. Mitzka, WP arXiv:1603.06130

Detailed results, II

	$\theta_{\tilde t} = 0°$	$\theta_{\tilde t} = 45°$	$\theta_{\tilde t} = 90°$
$\theta_{\tilde b} = 0°$	$\tilde b_1 = \tilde b_L$ $\tilde t_1 = \tilde t_L$	$\tilde b_1 = \tilde b_L$ $\tilde t_1 = \tilde t_{LR}$	
$\theta_{\tilde b} = 45°$	$\tilde b_1 = \tilde b_{LR}$ $\tilde t_1 = \tilde t_L$	$\tilde b_1 = \tilde b_{LR}$ $\tilde t_1 = \tilde t_{LR}$	
$\theta_{\tilde b} = 90°$	$\tilde b_1 = \tilde b_R$ $\tilde t_1 = \tilde t_L$	$\tilde b_1 = \tilde b_R$ $\tilde t_1 = \tilde t_{LR}$	$\tilde b_1 = \tilde b_R$ $\tilde t_1 = \tilde t_R$



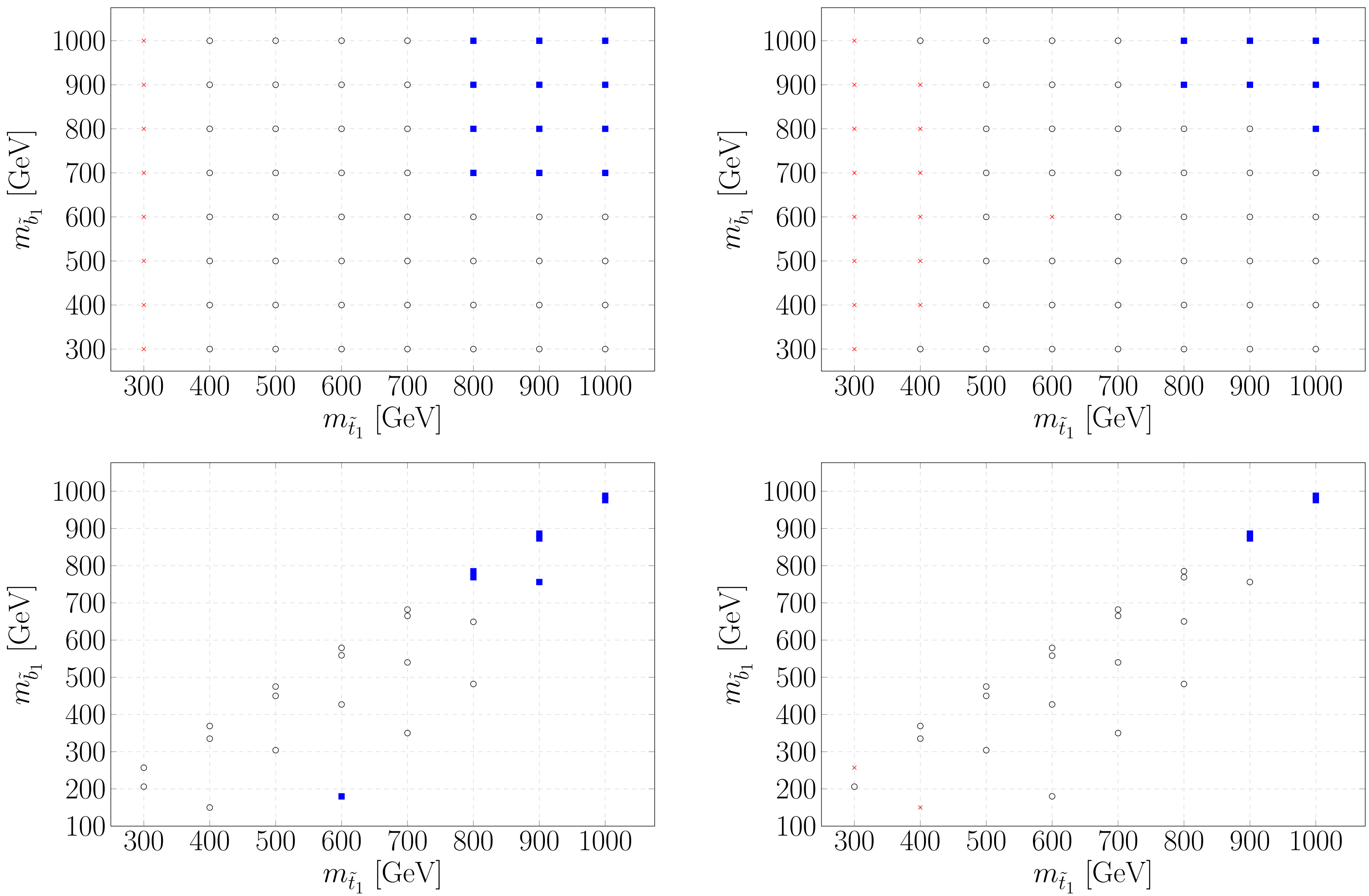


$\mu = 290$ GeV, $m_{\tilde\nu_R} = 200$ GeV, × excluded, ▲ ambigous, ■ allowed

L. Mitzka, WP arXiv:1603.06130

Summary results

ambigous as allowed | ambigous as forbidden



× excluded for all parameters, ○ exclusion parameter dependend, ■ allowed for all parameters

L. Mitzka, WP arXiv:1603.06130

Conclusions

- 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 $|\mu| \simeq 150$ GeV (200 GeV) for $\mathcal{L}$=3 ab^{-1}
- 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, $m_{\tilde{t}_1} \gtrsim 800$ GeV unconstrained,
  - 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

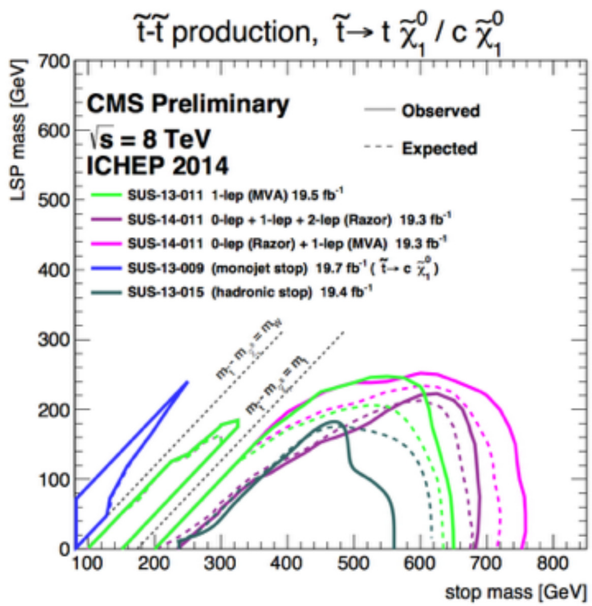
$$M_{\tilde{\chi}_0} = \begin{pmatrix} M_1 & 0 & -M_Z s_\omega c_\beta & M_Z s_\omega s_\beta \\ 0 & M_2 & M_Z c_\omega c_\beta & -M_Z c_\omega s_\beta \\ -M_Z s_\omega c_\beta & M_Z c_\omega c_\beta & & -\mu \\ M_Z s_\omega s_\beta & -M_Z c_\omega s_\beta & -\mu & 0 \end{pmatrix}$$

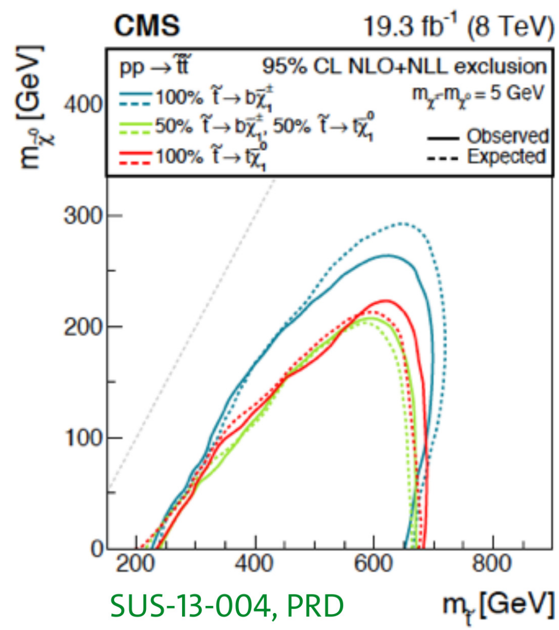
$$M_{\tilde{\chi}_\pm} = \begin{pmatrix} M_2 & \sqrt{2} M_W s_\beta \\ \sqrt{2} M_W c_\beta & \mu \end{pmatrix}$$

Summary: Top-Squarks

So far, no excess observed for any search channel:

- Mass limits in SMS interpretation up to $m_{\tilde{t}_1} < 760$ GeV for $m_{\tilde{\chi}^0_1} \lesssim 100$ GeV
- Mass limits depend slightly on branching ratios of $\mathrm{Br}(\tilde{t}_1 \to t\tilde{\chi}^0_1)$ and $\mathrm{Br}(\tilde{t}_1 \to b\tilde{\chi}^\pm_1)$





J. Duarte (Mon)

A. Dräger (Fri)

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