Natural Supersymmetry
Dark Matter, Neutrinos & LHC

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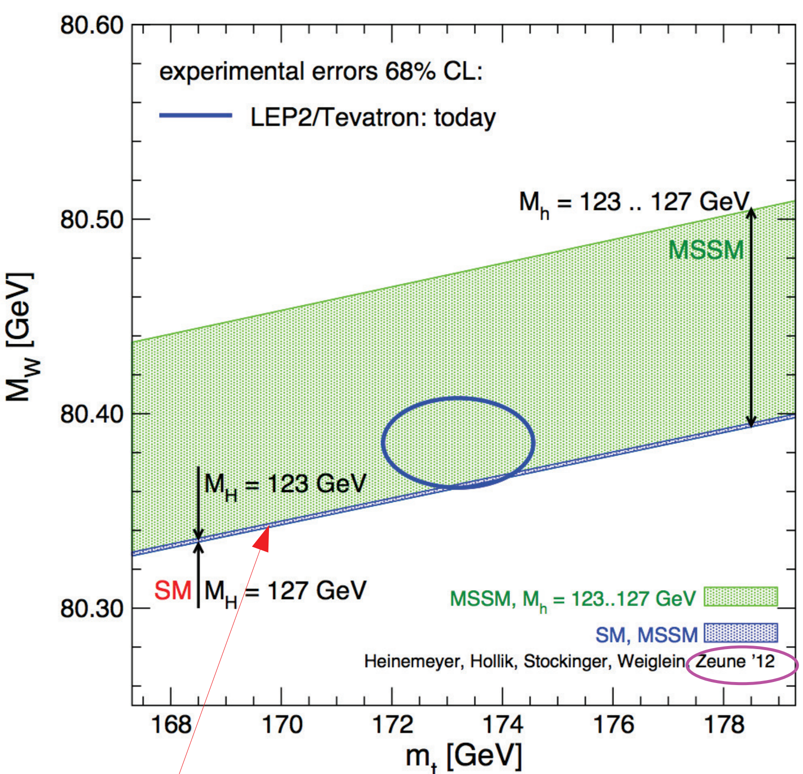
Content

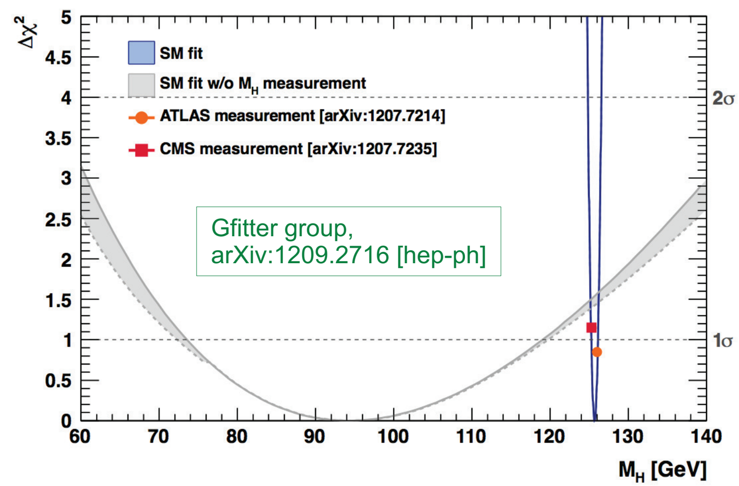
- Why extending the SM at all, why supersymmetry
- MSSM
  - Higgs mass: consequences for GMSB & CMSSM
  - general MSSM, ‘natural SUSY’
  - dark matter
- SUSY and extended gauge groups
  - implications for SUSY cascade decays
  - Z' physics
  - ‘Natural SUSY’ and $\tilde{\nu}_R$-LSP

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:



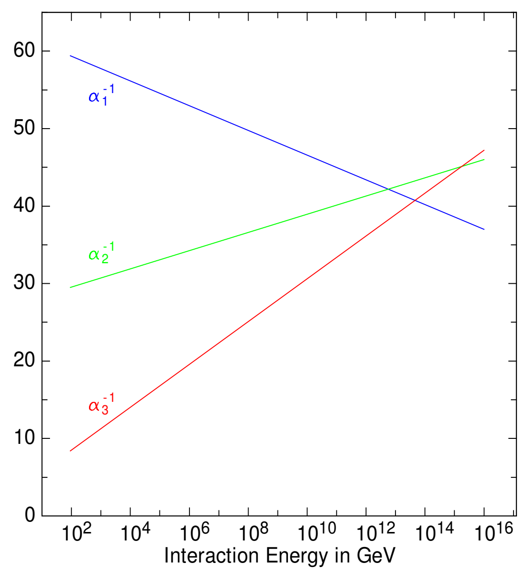
Consistent at the 1.3 σ level.

Why do we want to extend the SM

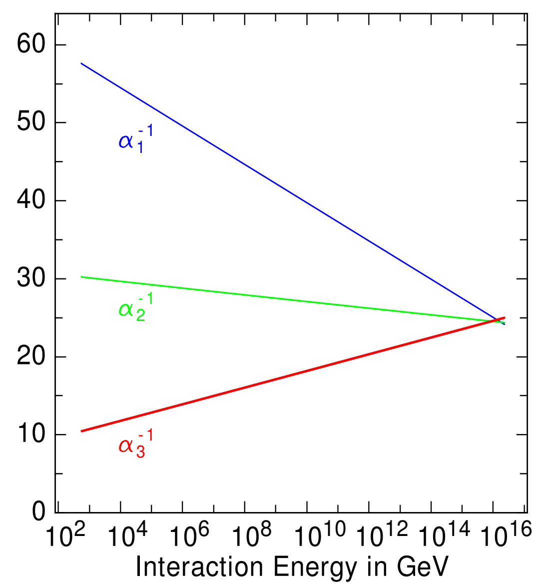
- How to combine gravity with the SM?
  $\Rightarrow$ local Supersymmetry (SUSY) implies gravity
- SM particles can be put in multiplets of larger gauge groups
  - in $SU(5)$: $1 = \nu^c_R$, $5 = (d^c_{\alpha,R}, \nu_{l,L}, l_L)$, $10 = (u_{\alpha,L}, u^c_{\alpha,R}, d_{\alpha,L}, l_R)$
  - in $SO(10)$: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

  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

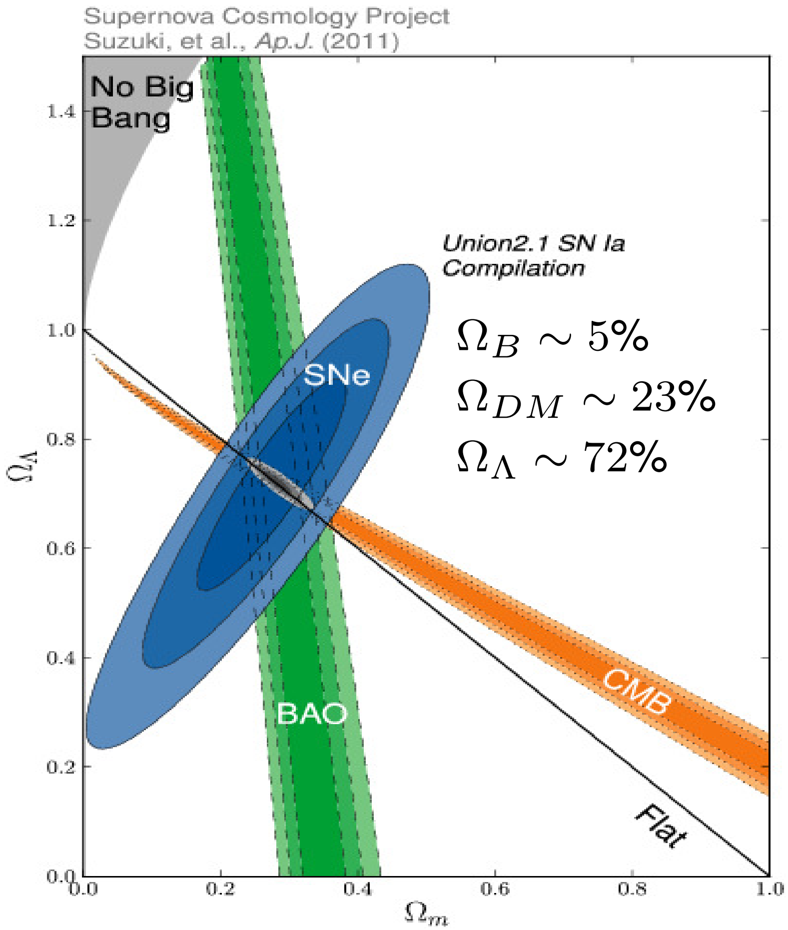


MSSM

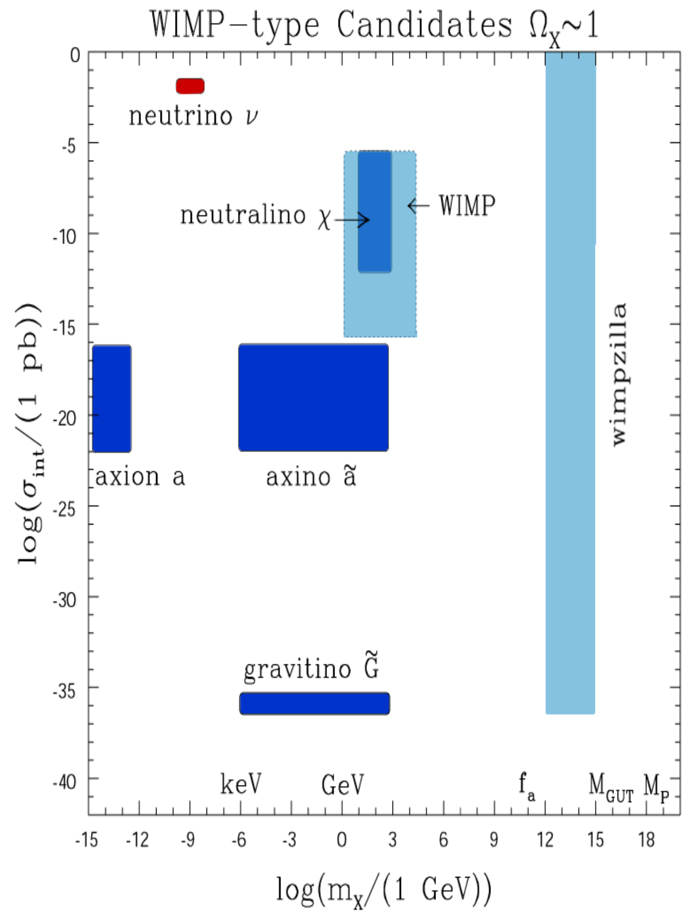


Why do we want to extend the SM

- What is the nature of dark matter ?



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

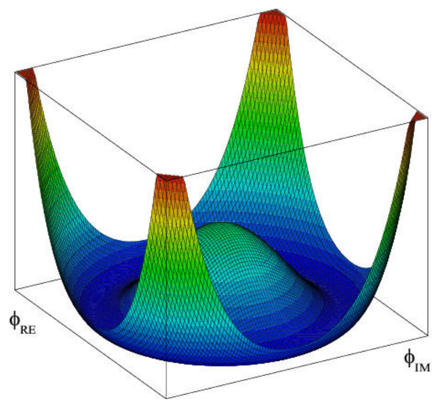


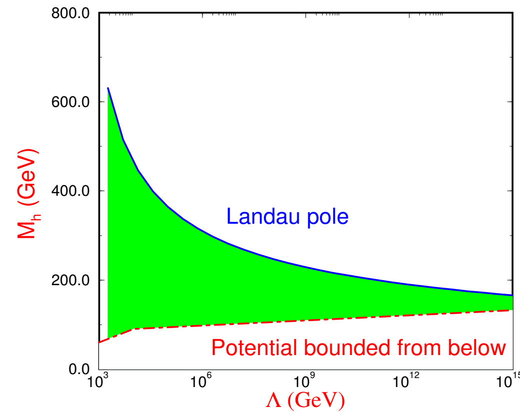
L. Roszkowski, astro-ph/0404052

- What is the origin of the observed baryon asymmetry?

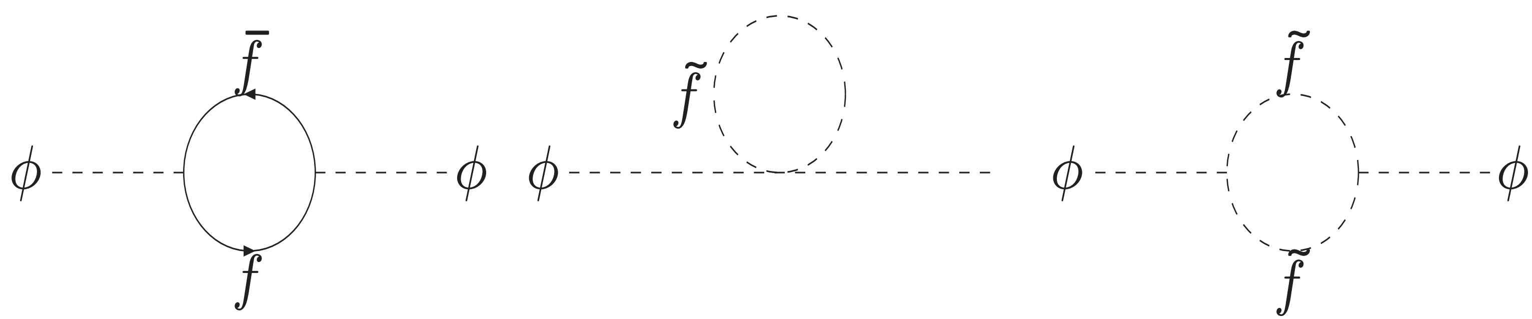
Why do we want to extend the SM

- 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	$\Leftrightarrow$	$\tilde{e}$ $\tilde{d}$ $\tilde{d}$ $\tilde{d}$
	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: $(-1)^{(3(B-L)+2s)}$

$(\tilde{\gamma}, \tilde{z}^0, \tilde{h}^0_d, \tilde{h}^0_u) \rightarrow \tilde{\chi}^0_i$, $(\tilde{w}^\pm, \tilde{h}^\pm) \rightarrow \tilde{\chi}^\pm_j$

MSSM, generalities

$$W_{MSSM} = -\mu \hat{H}_d \hat{H}_u + \hat{H}_d \hat{L} Y_e \hat{E}^c + \hat{H}_d \hat{Q} Y_d \hat{D}^c - \hat{H}_u \hat{Q} Y_u \hat{U}^c$$

$$W_{\not{L}} = \epsilon_i \hat{L}_i \hat{H}_u^b + \lambda_{ijk} \hat{L}_i \hat{L}_j \hat{E}_k^c + \lambda'_{ijk} \hat{L}_i \hat{Q}_j \hat{D}_k$$

$$W_{\not{B}} = \lambda''_{ijk} \hat{U}_i^c \hat{D}_j^c \hat{D}_k^c$$

$W_{\not{L}} + W_{\not{B}} \Rightarrow$ 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, $x = \Lambda/M$, $\Lambda = O(100 TeV) < M$

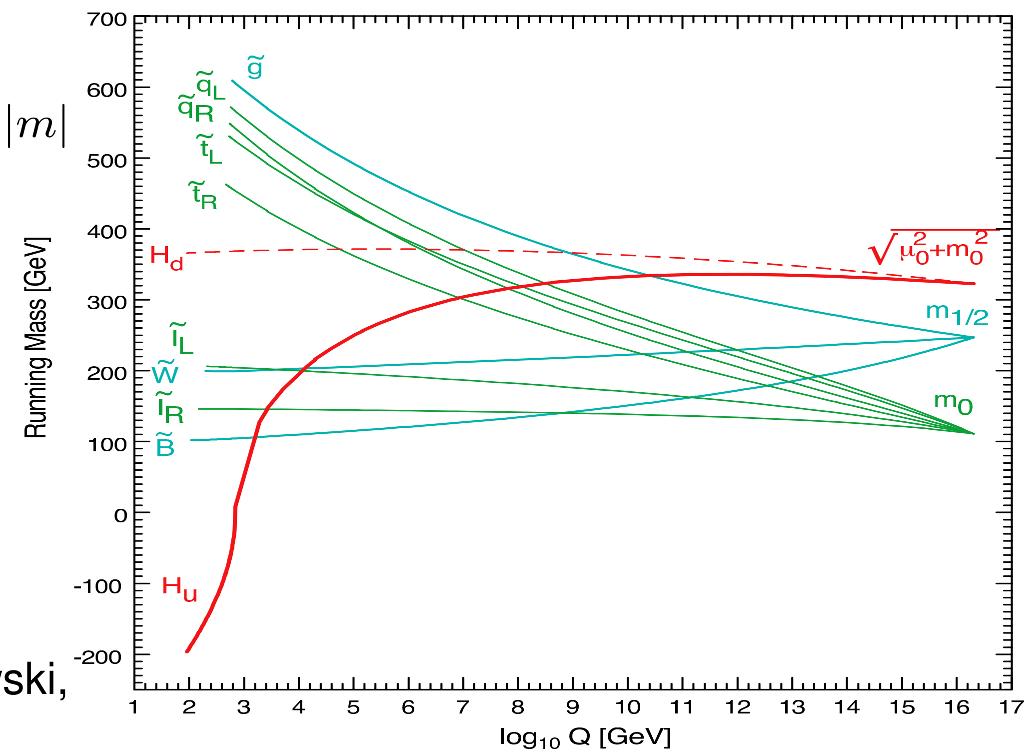
MSSM, generalities

radiative electroweak symmetry breaking

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

with $t = \ln Q/m_Z$

sign$(m^2)|m|$



G. Kane, C. Kolda, L. Roszkowski, J. Wells, PRD 1994

MSSM, Higgs sector

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

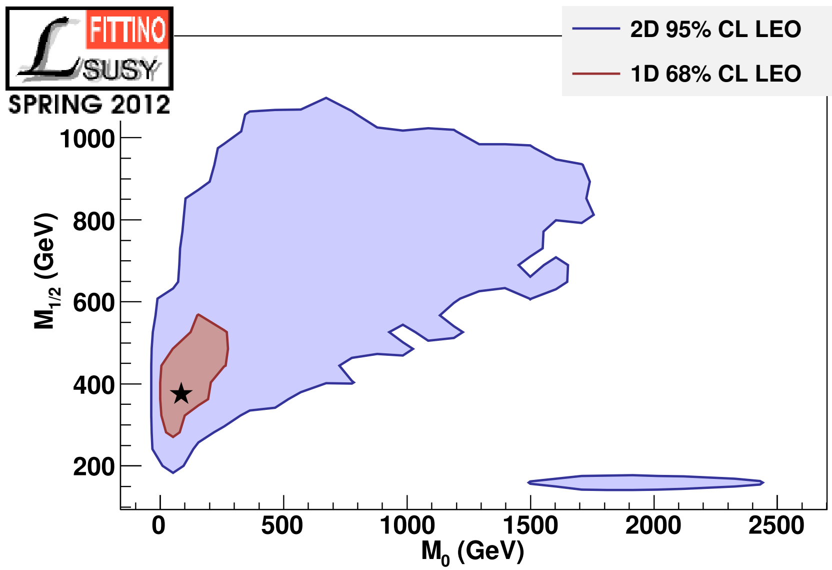
  at higher order:

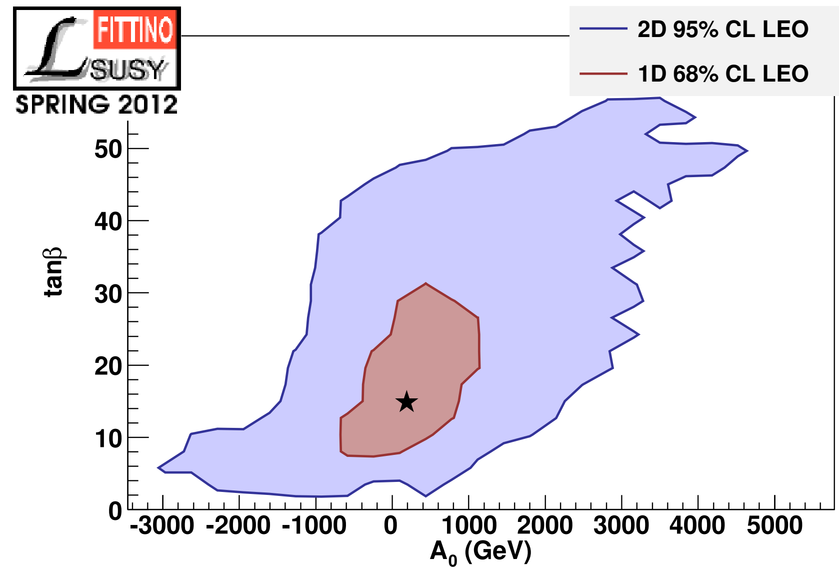
Ellis et al; Okada et al; Haber,Hempfling; Hoang et al; Carena et al; Heinemeyer et al; Zhang et al; Brignole et al; Harlander et al; Kant,Harlander,Mihaila,Steinhauser;. . .

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

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

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

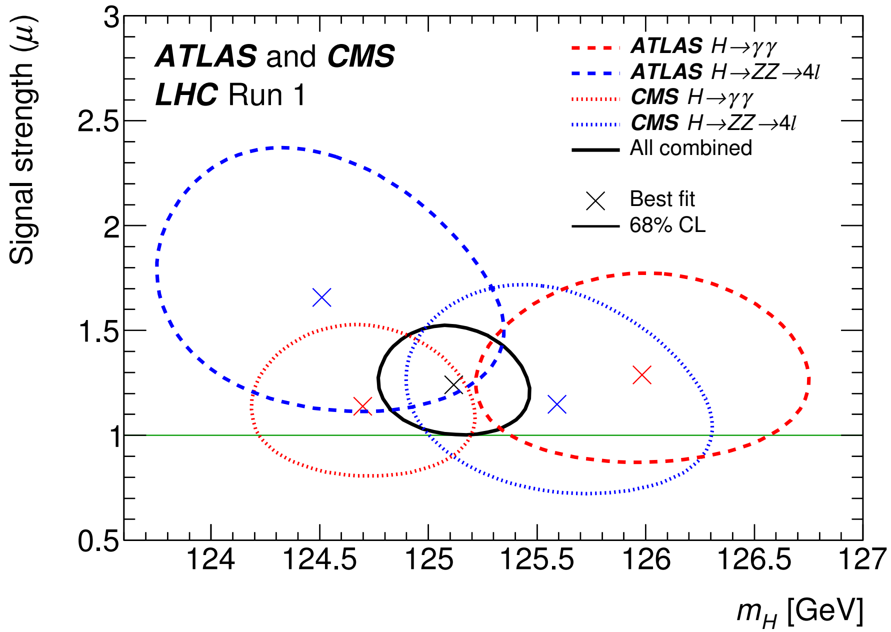
$\Rightarrow M_0 = 84^{+145}_{-28}$ GeV, $M_{1/2} = 375^{+175}_{-88}$ GeV,
$\tan\beta = 15^{+17}_{-7}$ $A_0 = 186^{+831}_{-844}$ GeV,
$\chi^2/ndf = 10.3/8$

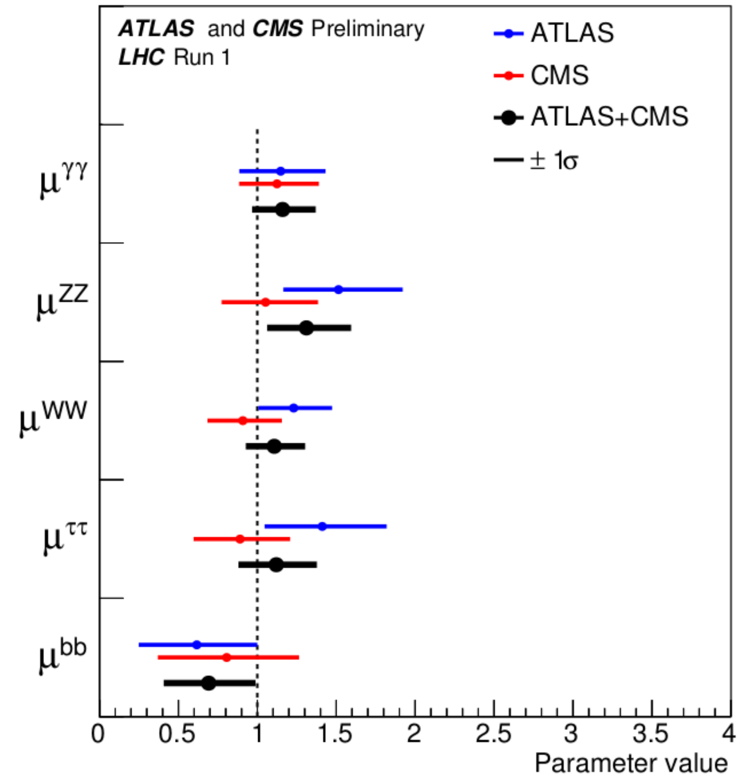
$\Rightarrow m_h = 116$ GeV

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 2015/16





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

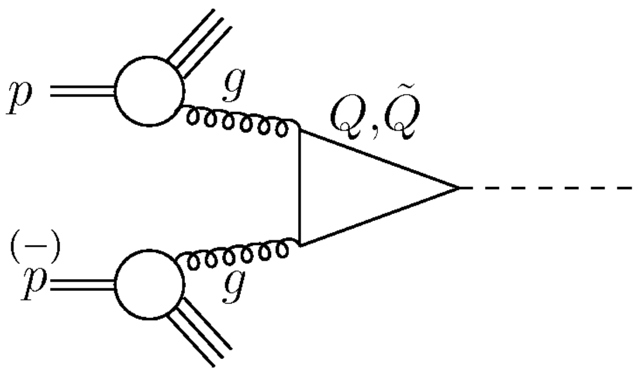
PRL **114** (2015) 191803

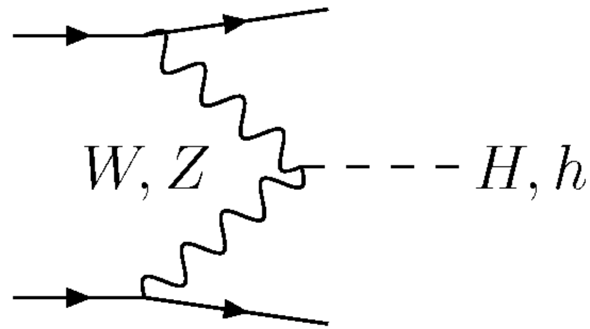
ATLAS-CONF-2015-044

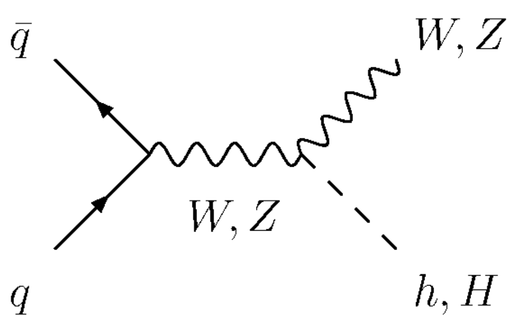
CMS-PAS-HIG-15-002

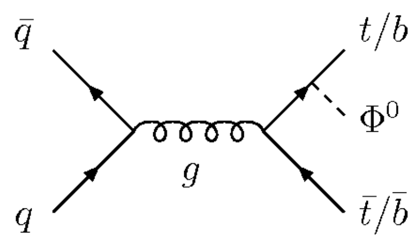
$(125$ GeV$)^2 \simeq m_Z^2 + (86$ GeV$)^2 \Rightarrow$ large corrections within MSSM

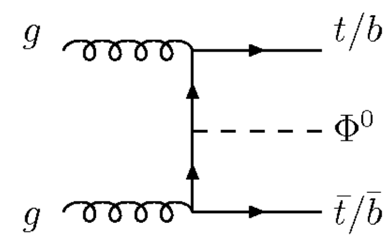
production at hadron colliders



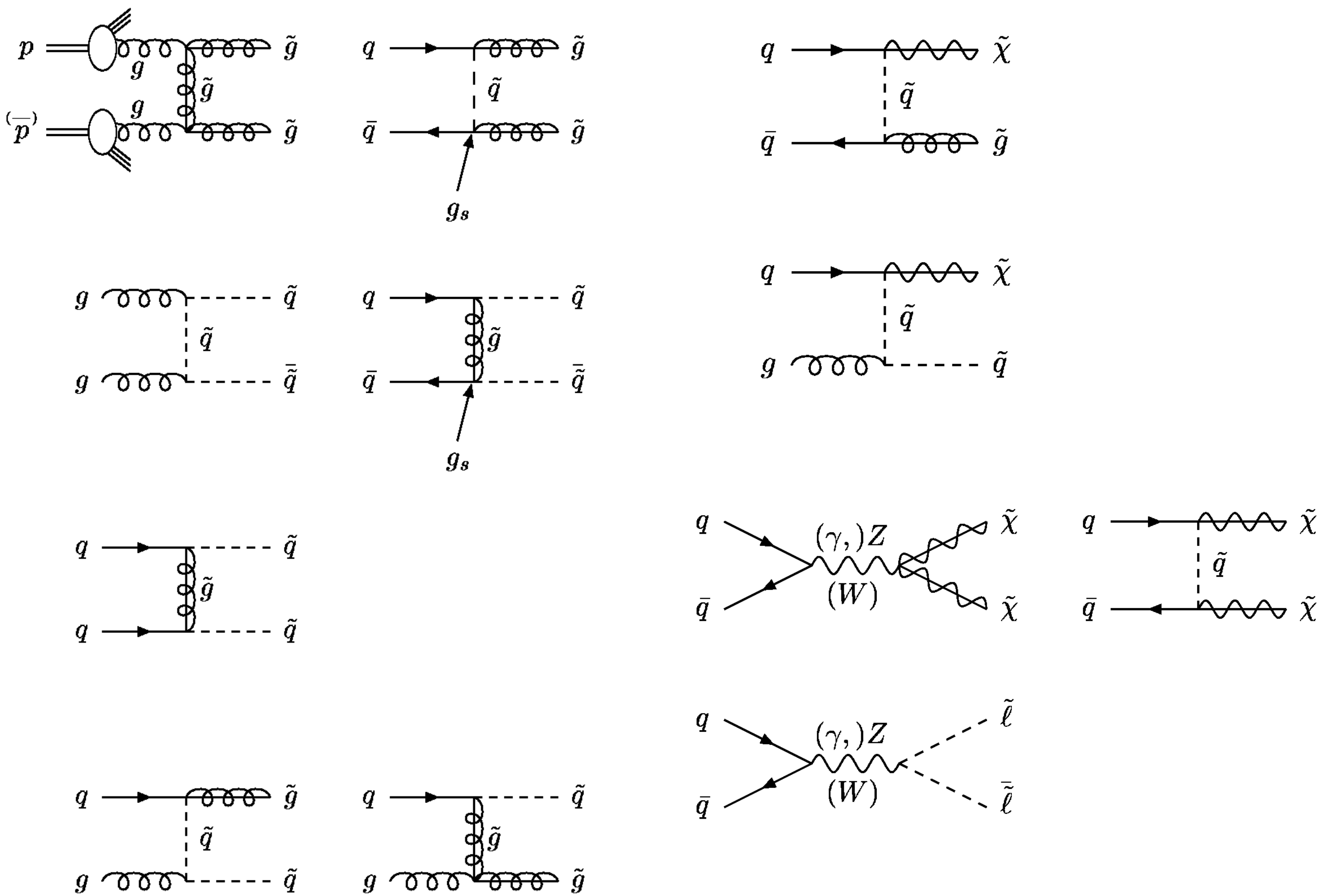






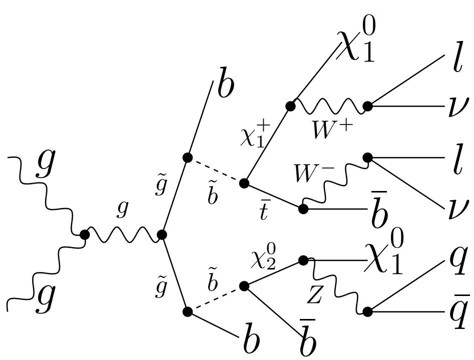


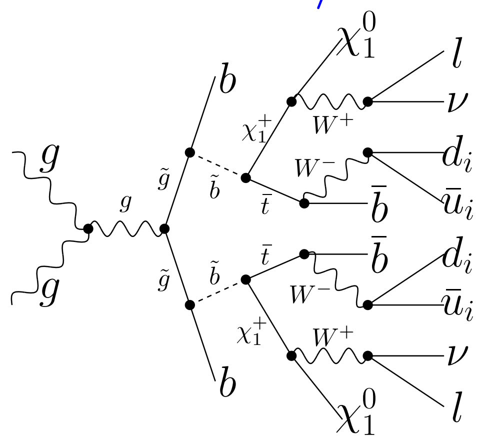
$$\Phi^0 = h, H, A$$

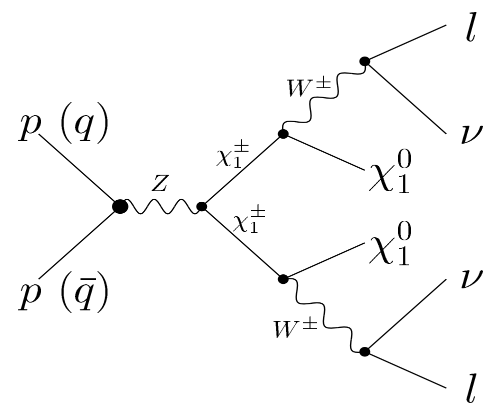

p
$\overset{(-)}{p}$
g
$\tilde{g}$
q
$\bar{q}$
$\tilde{q}$
g_s
$\tilde{\chi}$
$(\gamma,)Z$
(W)
$\tilde{\ell}$
$\bar{\tilde{\ell}}$

$6j + 2\ell + \not{E}_T$

$8j + 2\ell + \not{E}_T$

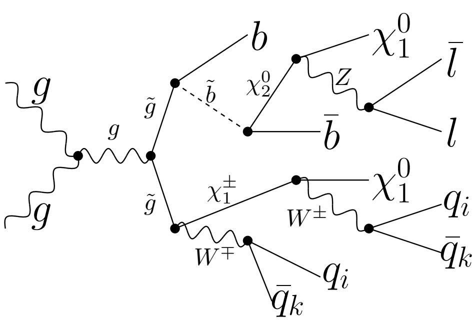


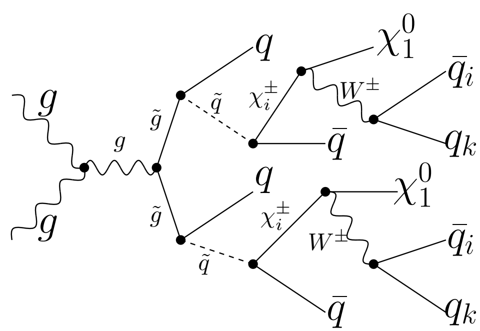


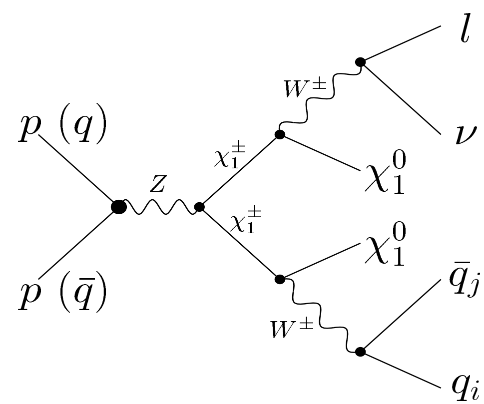


2ℓ

$\not{E}_T$



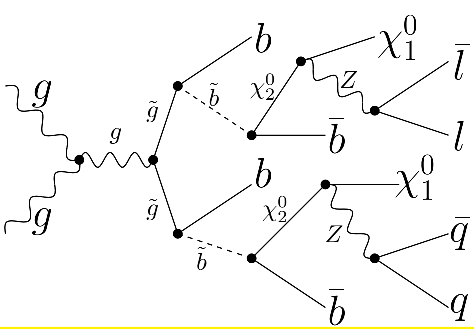


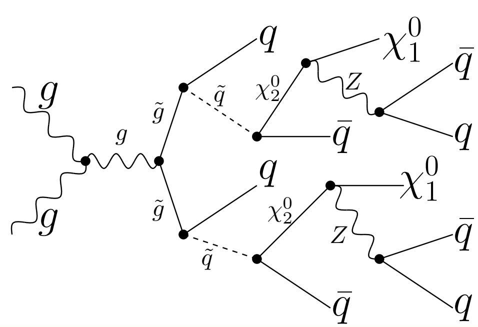


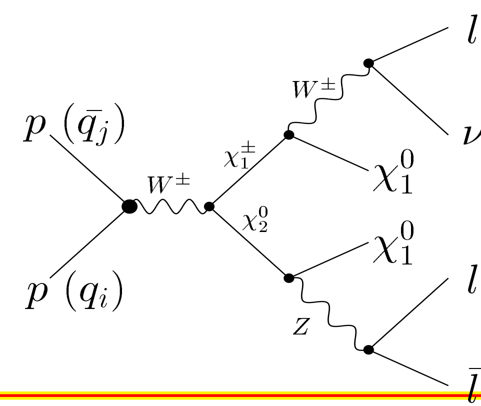
ℓ

$2j$

$\not{E}_T$



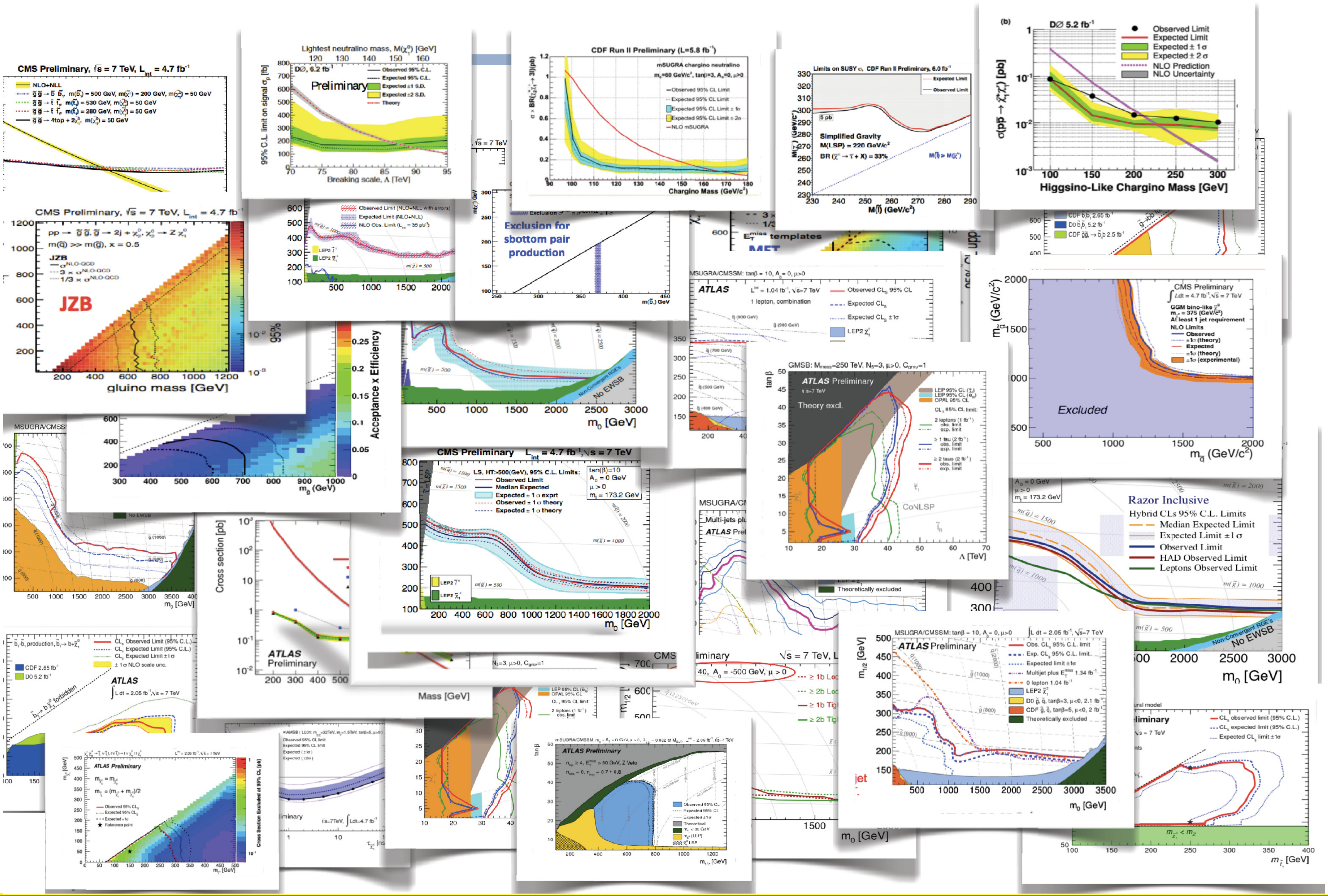




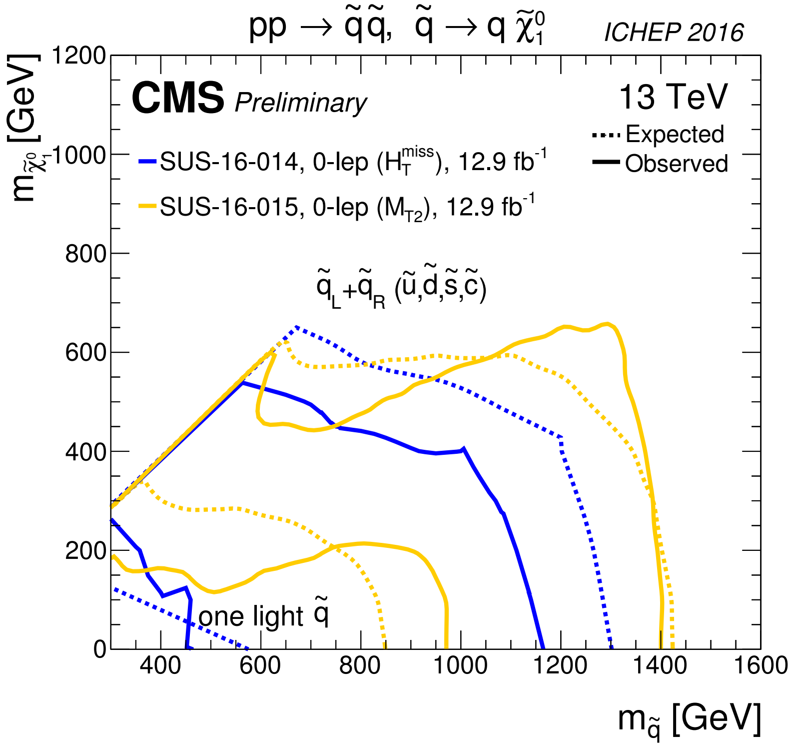
3ℓ

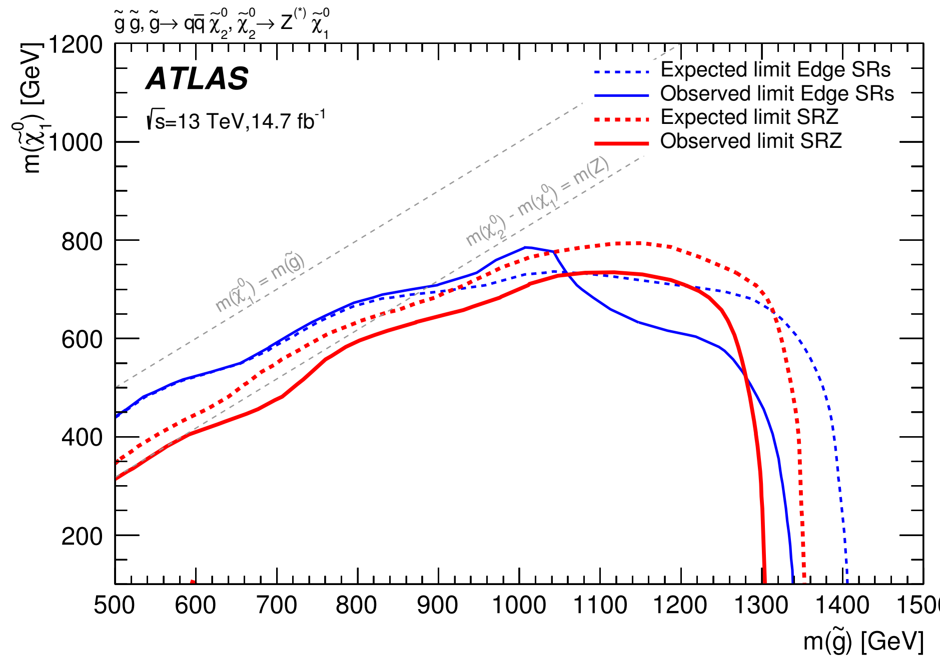
$\not{E}_T$

BSM searches, so far hardly anything . . .



Examples for SUSY searches 13 TeV data





LHC data, in particular m_h, high scale models

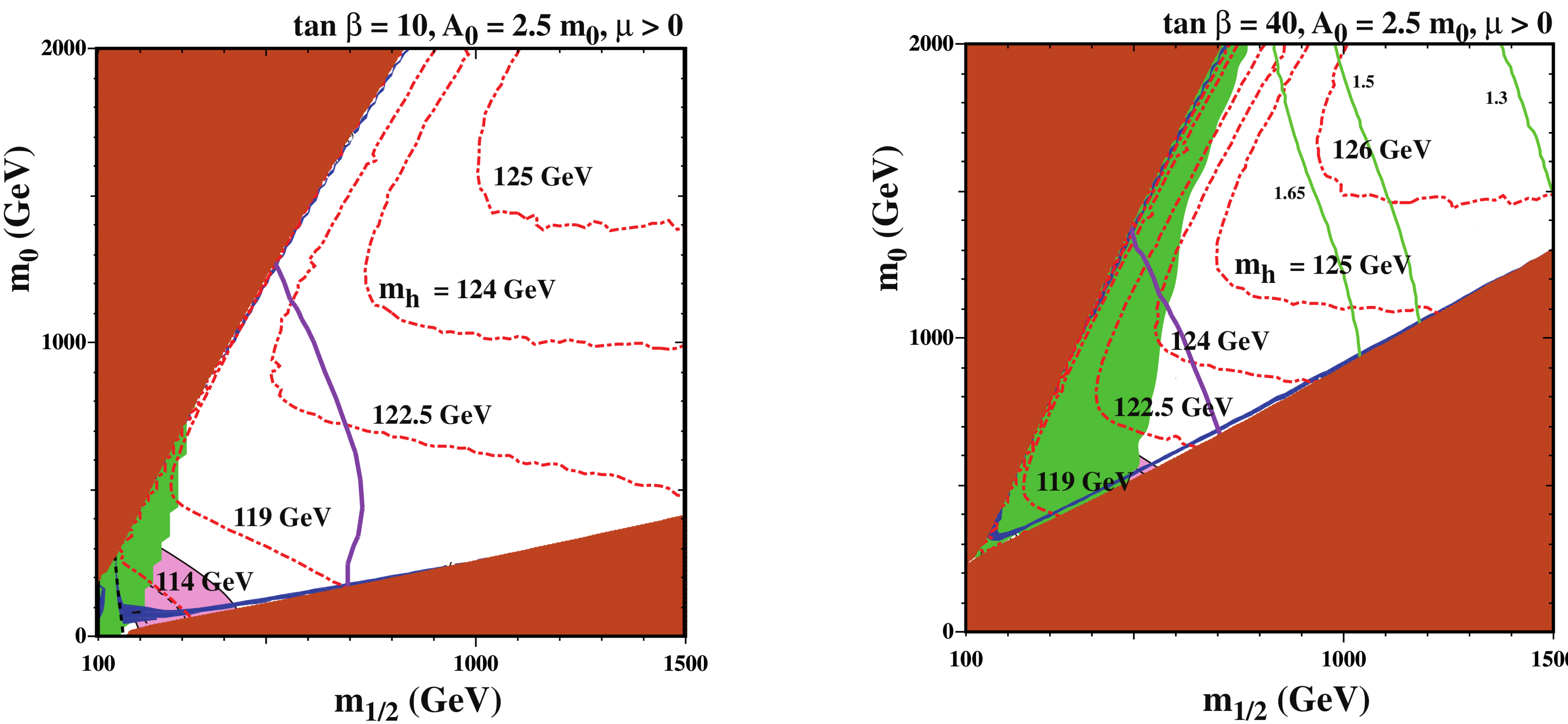
$m_h = 125.1$ GeV $\Rightarrow$ large loop contributions

$\Rightarrow$ 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

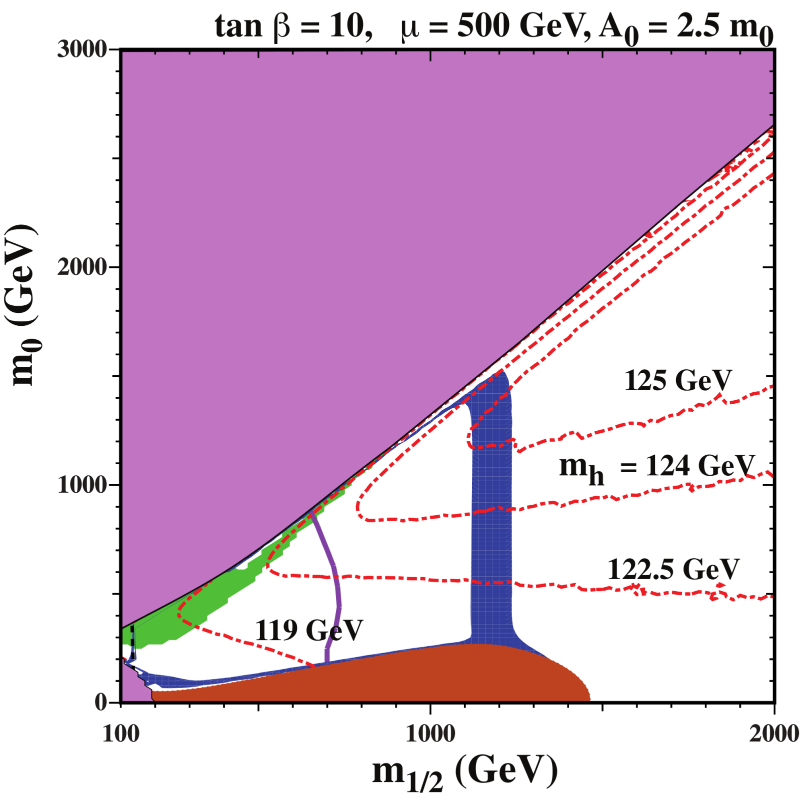
  more complicated models based on P. Meade, N. Seiberg and D. Shih, arXiv:0801.3278 $\Rightarrow$ allow additional terms, choice not well motivated $\Rightarrow$ generic MSSM
- CMSSM, NUHM models: $|A_0| \simeq 2m_0$,
  H. Baer, V. Barger and A. Mustafayev, arXiv:1112.3017; M. Kadastik *et al.*, arXiv:1112.3647; 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: $A_0 \simeq -(1-3)\max(M_{1/2}, m_{Q_3,GUT}, m_{U_3,GUT})$
  among other cases, details in F. Brümmer, S. Kraml and S. Kulkarni, arXiv:1204.5977

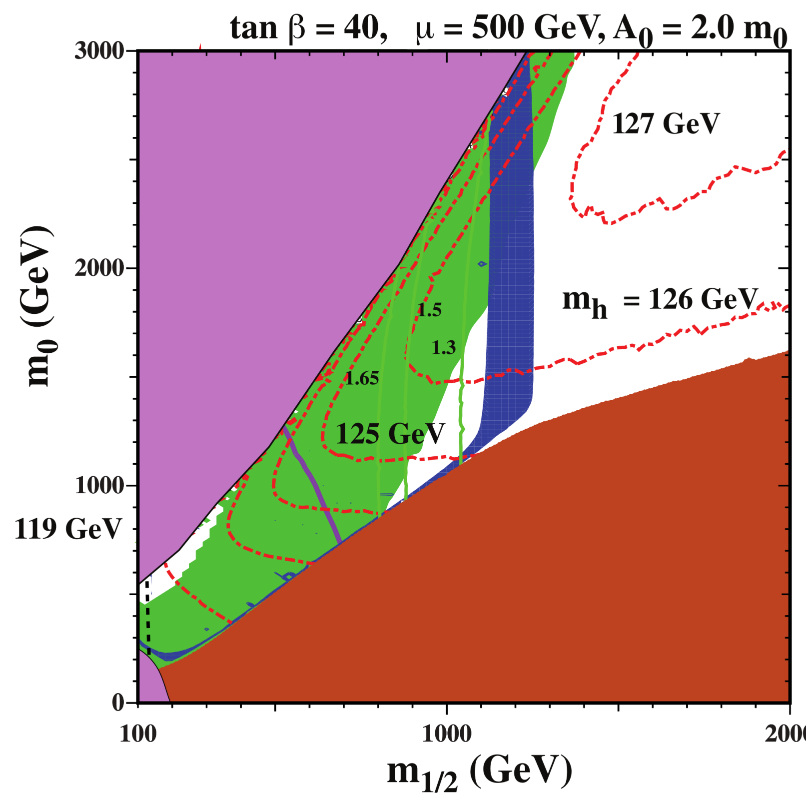
Dark matter, mSUGRA



J. Ellis, F. Luo, K. Olive, P. Sandick, arXiv:1212.4476; $m_t = 173.2$ GeV

$m^2_{H_u} \neq m^2_0 \Rightarrow \mu$ free parameter

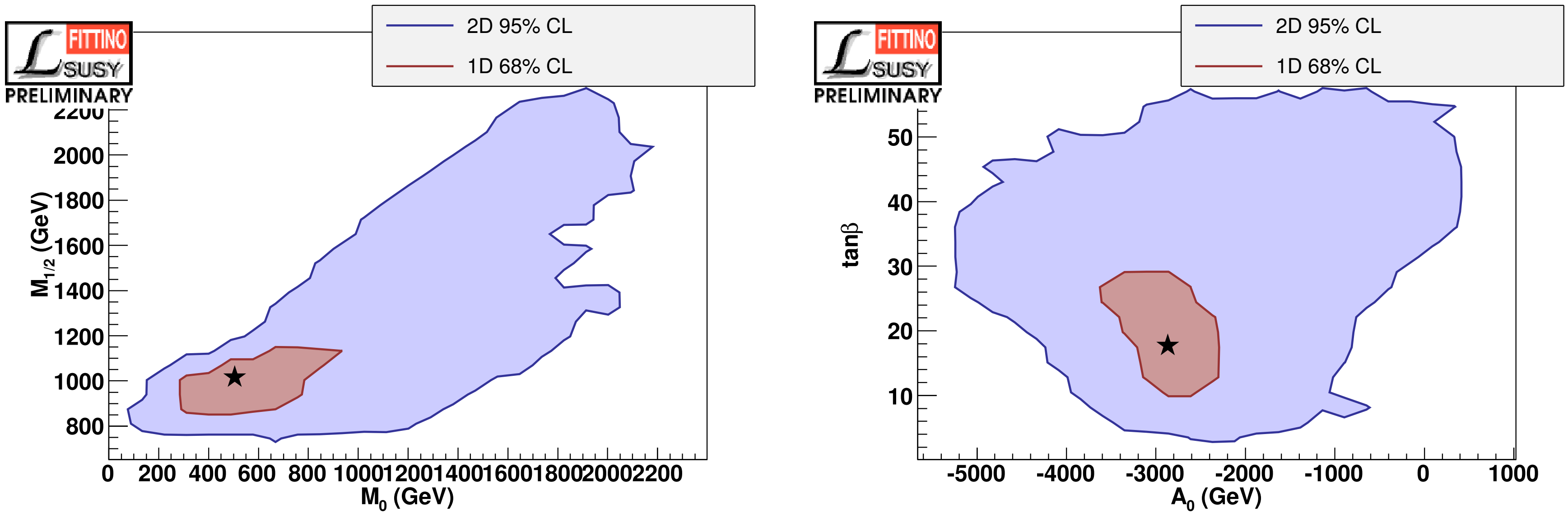




J. Ellis, F. Luo, K. Olive, P. Sandick, arXiv:1212.4476; $m_t = 173.2$ GeV

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

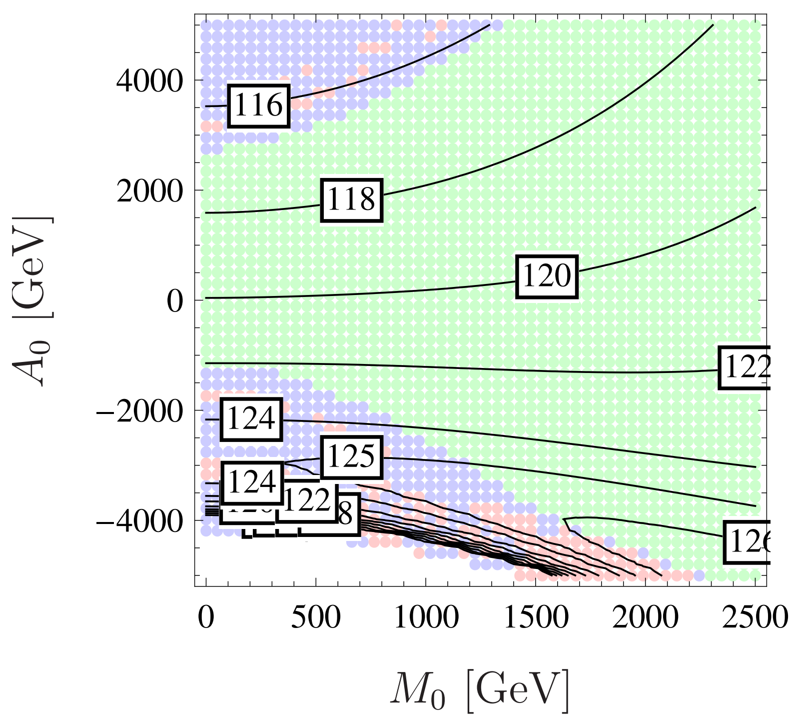
implications for LHC: $m_{\tilde{g}}, m_{\tilde{q}} \gtrsim 2$ TeV, $m_{\tilde{l}_R} \simeq 600$ GeV, $m_{\tilde{\chi}_1^0} \simeq 450$ GeV

can be tested at LHC 13 TeV [14 TeV]

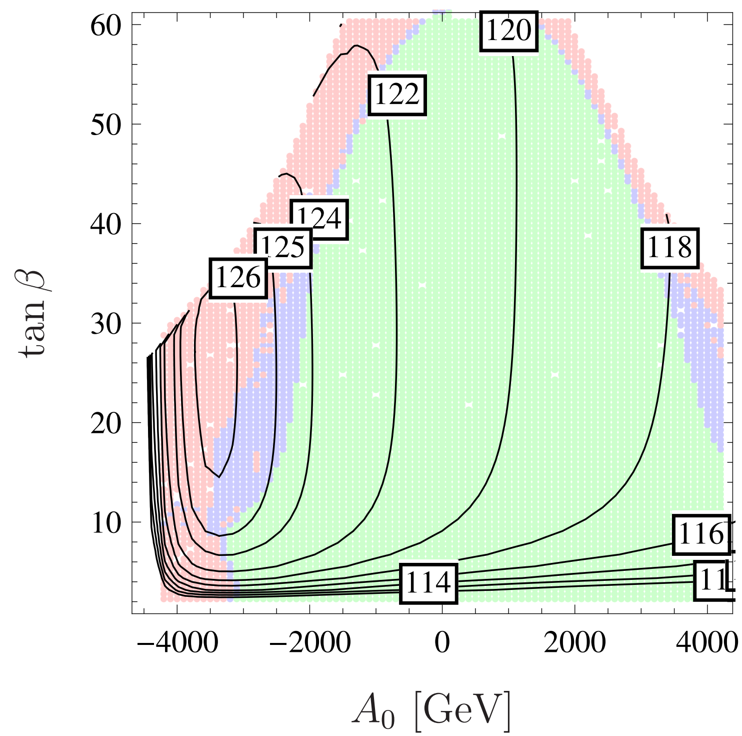
so far so good, but . . .

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

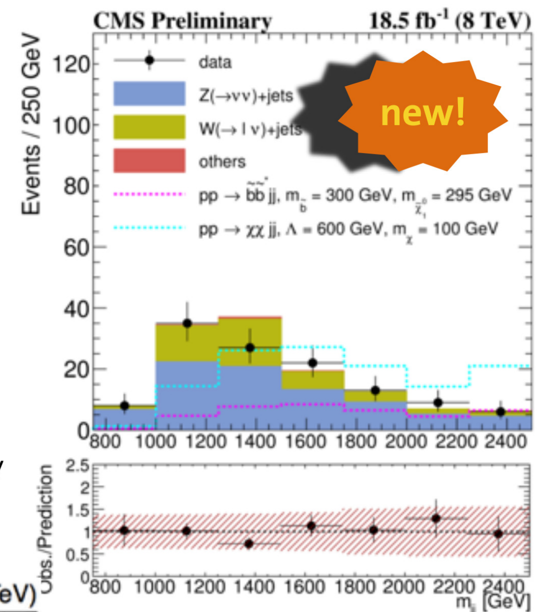
VBF + MET: Compressed SUSY / DM

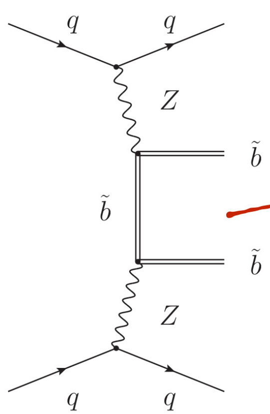
Trigger: MET65+VBFDiJet35

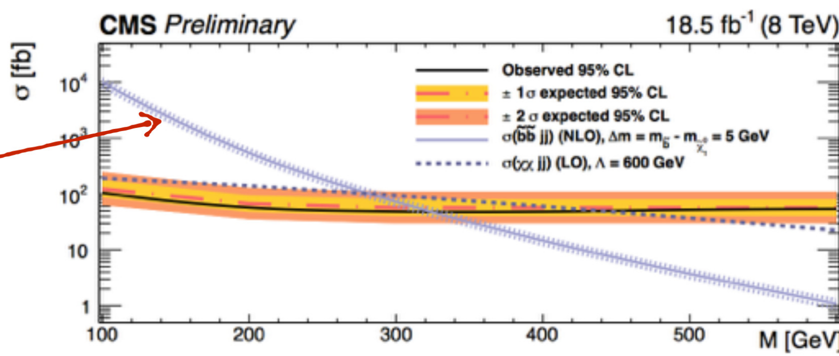
Selection: Two jets (p_T>50 GeV with $\eta_1\eta_2$<0; large rapidity gap $|\eta_1$-$\eta_2|$>4.2 and invariant mass m_{12}>750 GeV; no b-tag); MET>250 GeV; veto further jets (p_T>30 GeV)

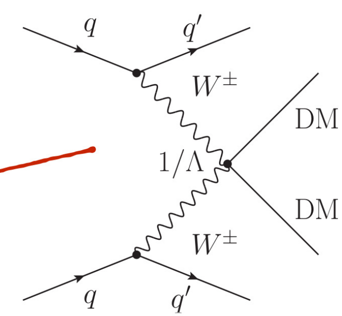
Dominant bgs: $(Z \to \nu\nu) + \text{jets}$ & $(W^\pm \to l^\pm \nu) + \text{jets}$ estimated from data

Interpretation in models with DM production via contact interaction and $\tilde{b}\tilde{b}\tilde{\chi}_1^0\tilde{\chi}_1^0$ production with $m_{\tilde{b}} - m_{\tilde{\chi}_1^0} = 5$ GeV









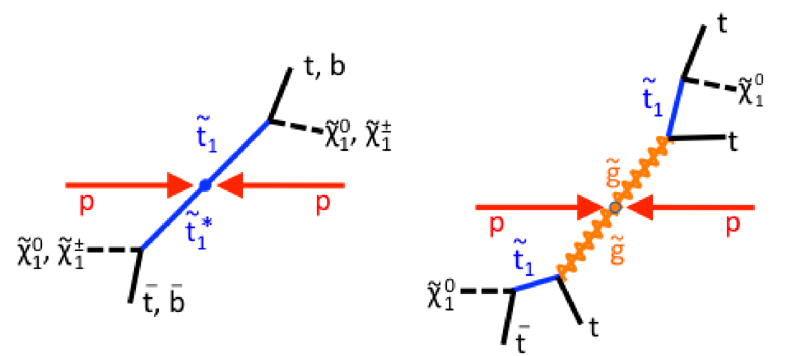
SUS-14-019

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

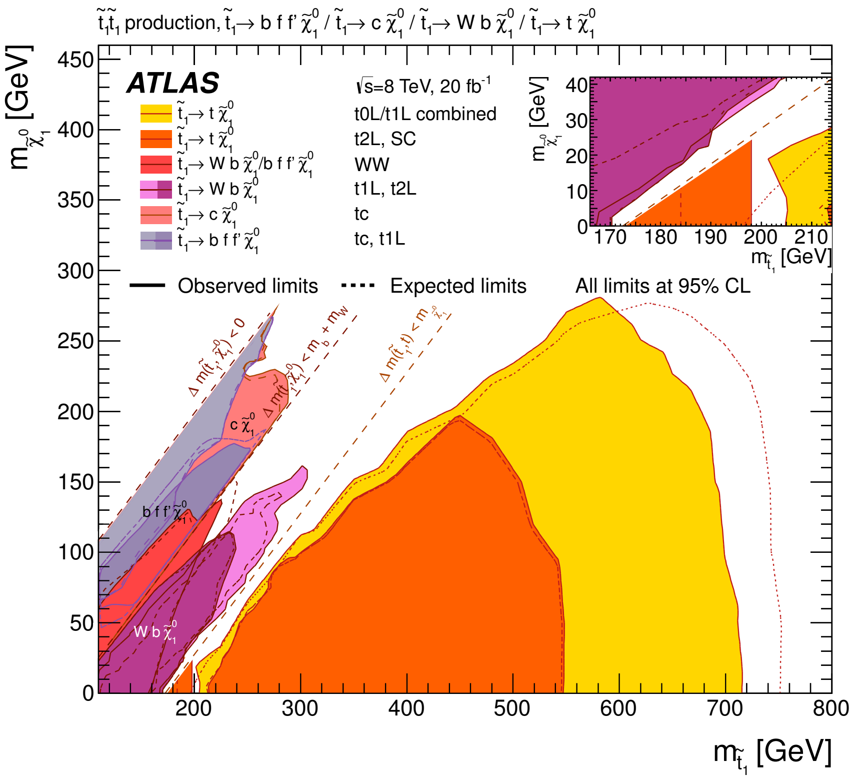
- generic signatures are well known: multi-lepton, multi-jets + missing E_T
- interesting feature of the 'Heavy Higgs case'
  production of h^0 via SUSY cascade decays, e.g. $\tilde\chi^0_2 \to h \tilde\chi^0_1$
- sub-class of general MSSM: 'natural SUSY' (see e.g. H. Baer, V. Barger, P. Huang, A. Mustafayev, X. Tata, arXiv:1207.3343; M. Papucci, J. T. Ruderman and A. Weiler, arXiv:1110.6926)
  keep only SUSY particles light needed for 'natural Higgs': $\tilde t_1$, $\tilde b_1$, $\tilde g$, $\tilde h^{+,0,-}$
  $\Rightarrow$ 100 MeV $\lesssim m_{\tilde\chi^+_1} - m_{\tilde\chi^0_1} \simeq m_{\tilde\chi^0_2} - m_{\tilde\chi^0_1} \lesssim 5 - 10$ GeV

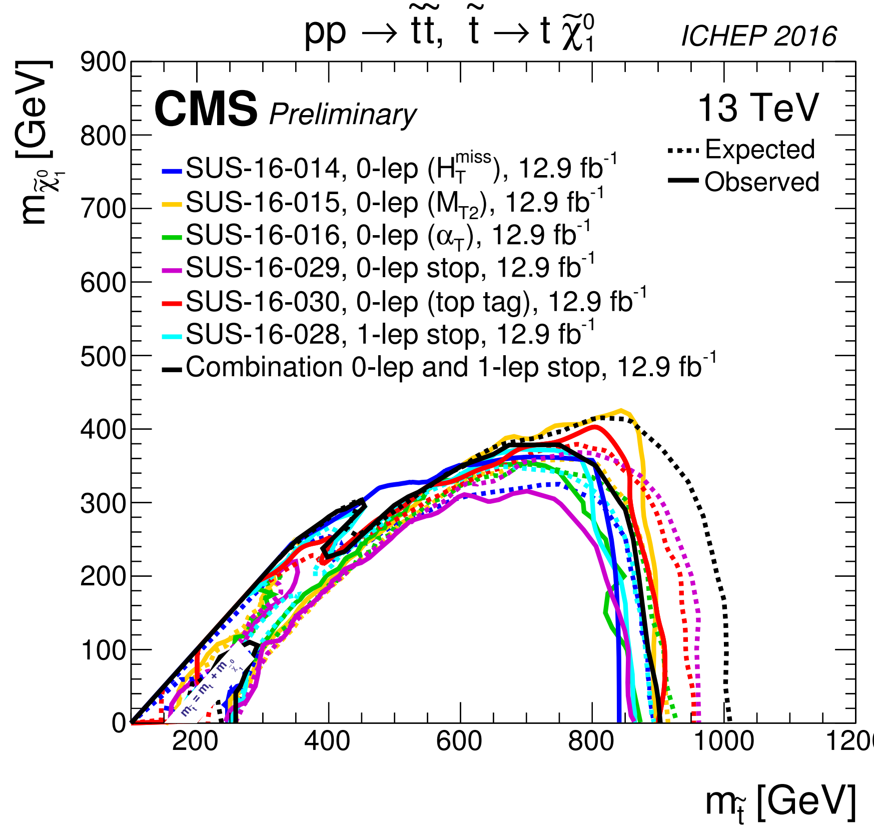
$$
\begin{aligned}
\tilde g &\to \tilde t_1 t, \tilde b_1 b \\
\tilde t_1 &\to t\tilde\chi^0_{1,2}, b\tilde\chi^+_1, W^+ \tilde b_1 \\
\tilde b_1 &\to b\tilde\chi^0_{1,2}, t\tilde\chi^-_1, W^- \tilde t_1
\end{aligned}
$$



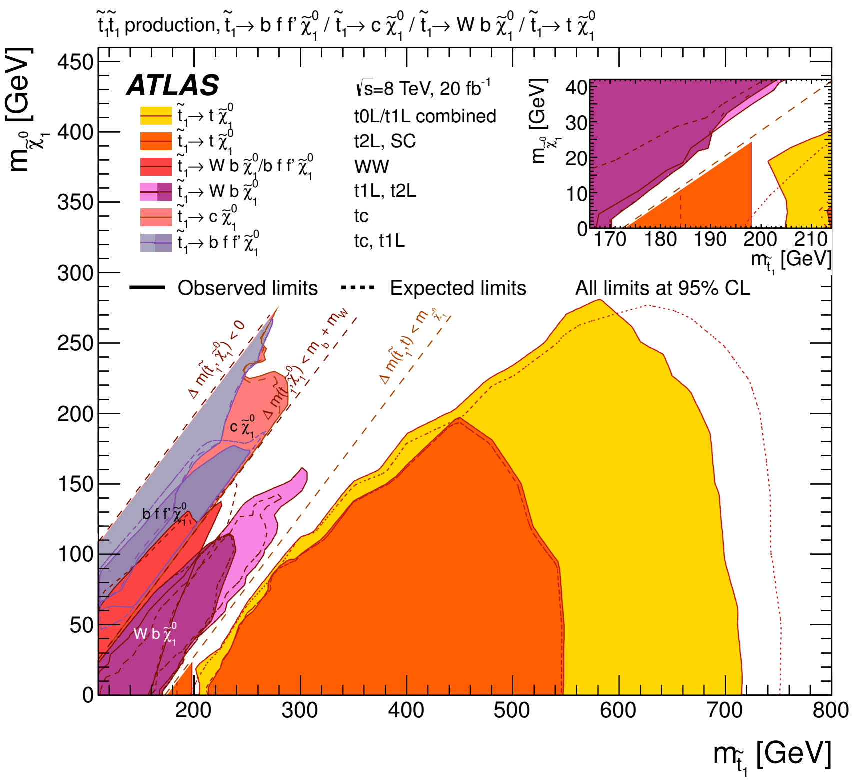
BRs depend on the nature of $\tilde t_1$ and $\tilde b_1$

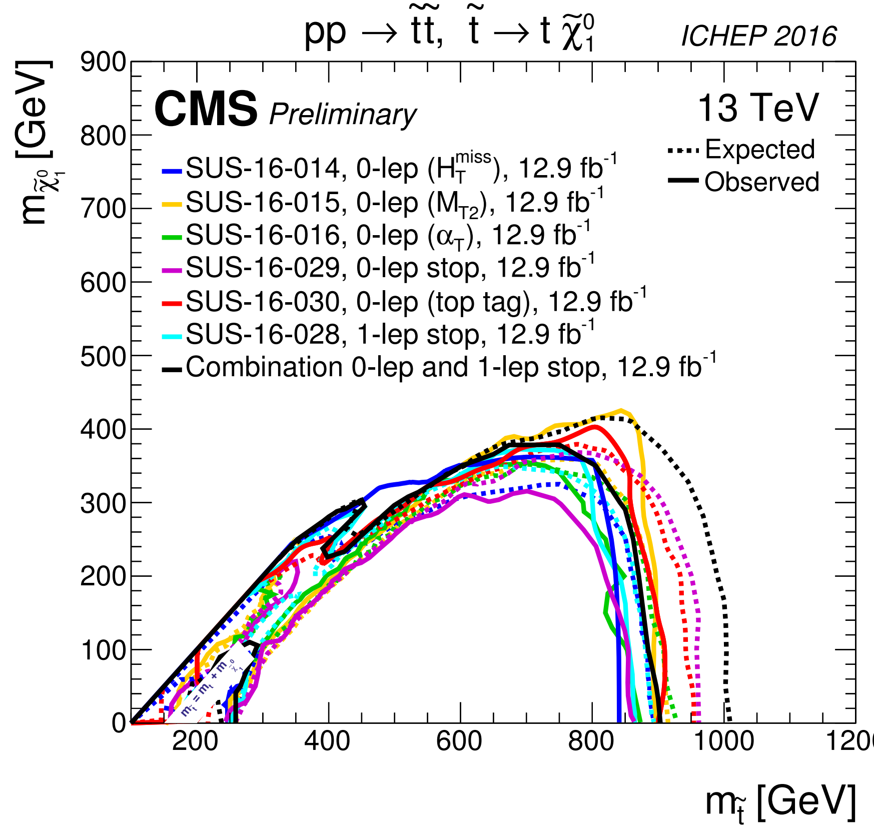
LHC bounds on $\tilde{t}_1$





LHC bounds on $\tilde{t}_1$



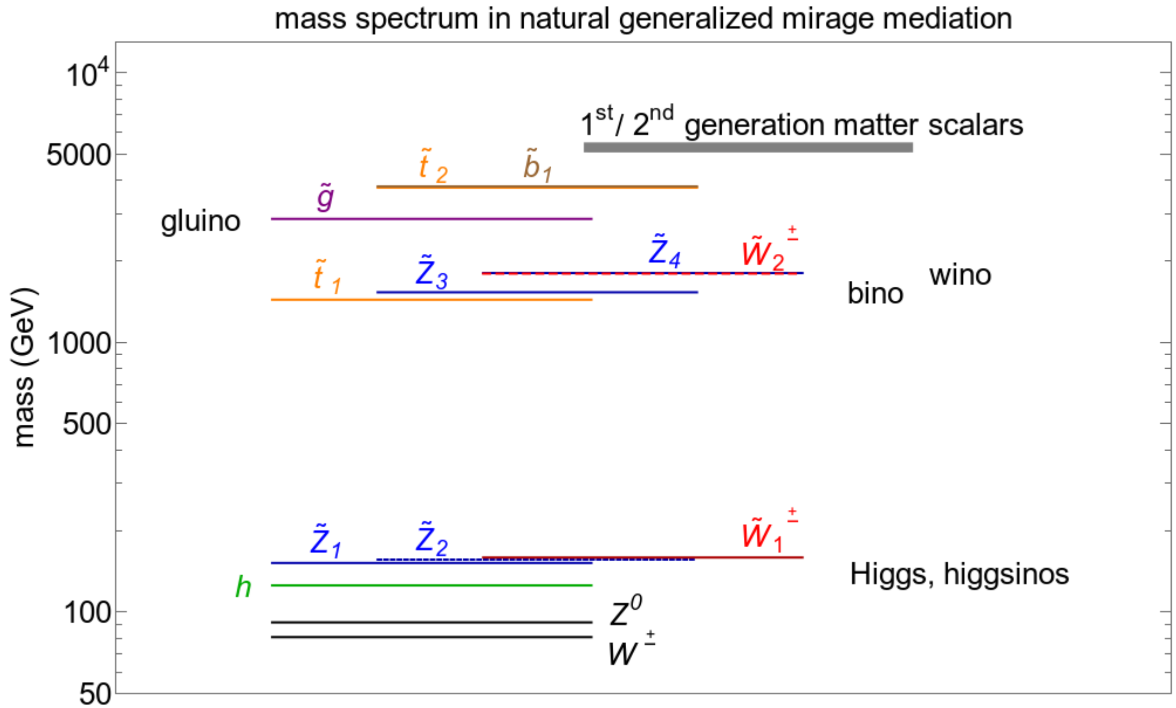


$$\frac{d}{dt}\begin{pmatrix} m^2_{H_u} \\ m^2_{\tilde{t}_R} \\ m^2_{\tilde{Q}^3_L} \end{pmatrix} = -\frac{8\alpha_s}{3\pi} M_3^2 \begin{pmatrix} 0 \\ 1 \\ 1 \end{pmatrix} + \frac{Y_t^2}{8\pi^2}\left(m^2_{\tilde{Q}^3_L} + m^2_{\tilde{t}_R} + m^2_{H_u} + A_t^2\right)\begin{pmatrix} 3 \\ 2 \\ 1 \end{pmatrix}$$

General Mirrage Mediation

Different sources for soft SUSY breaking: moduli & AMSB

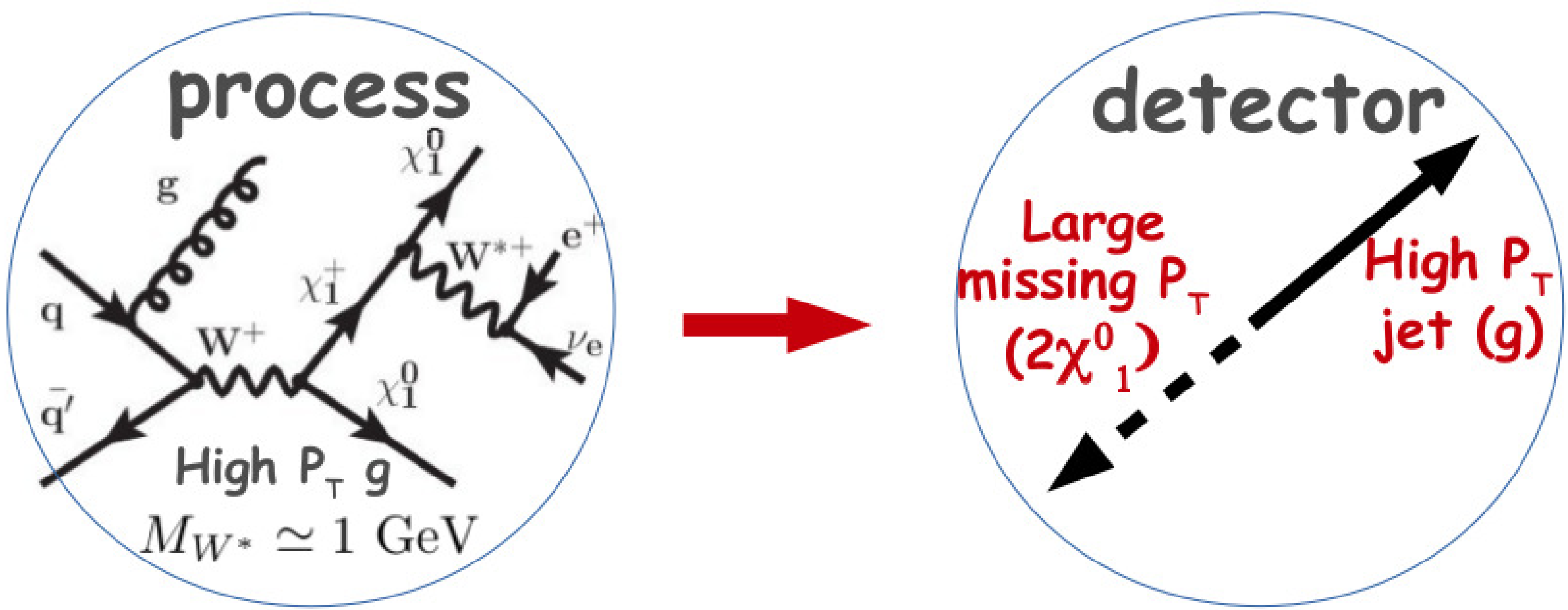
main consequence: gaugino masses unify at a (vastly) different scale then gauge couplings



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

Higgsino LSP: Challenge for LHC

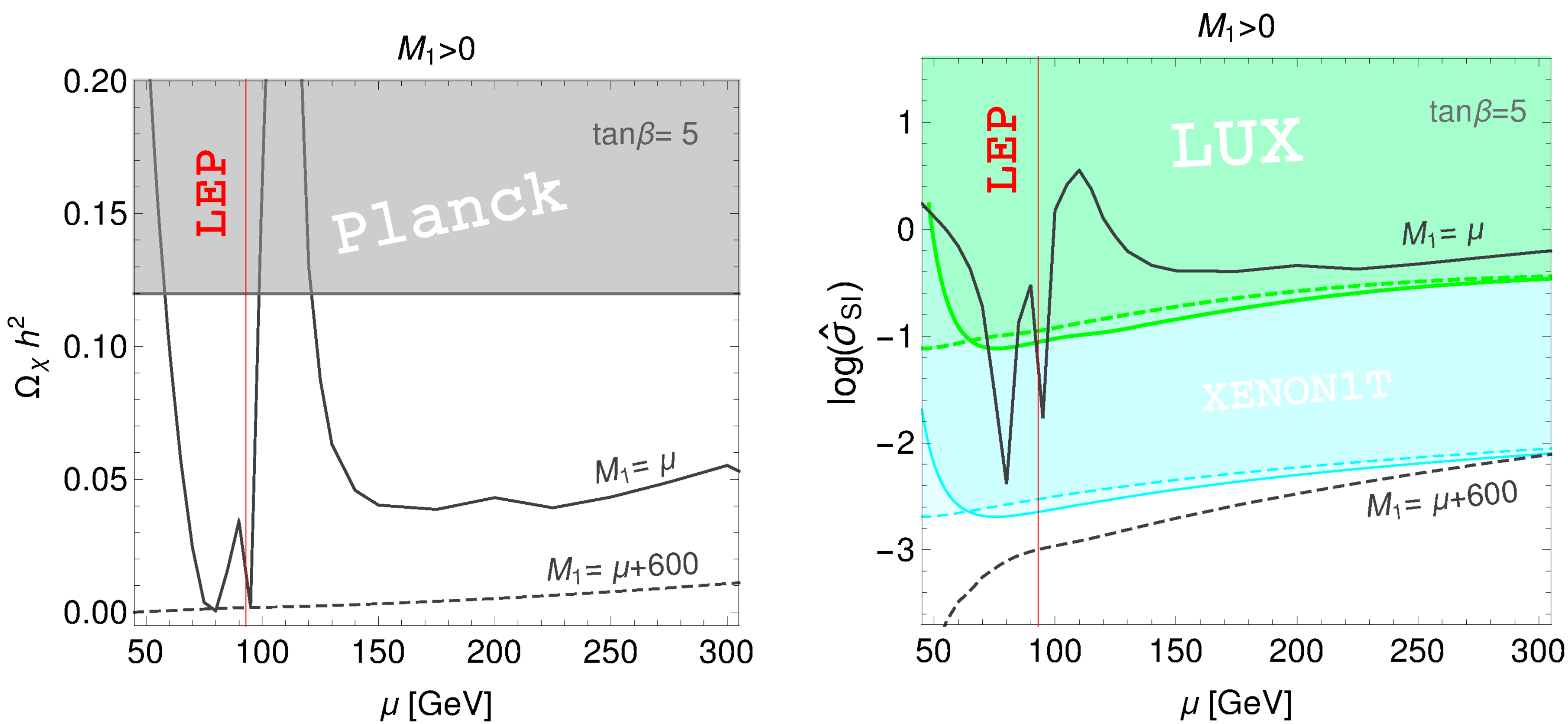
Most challenging case: only higgsinos accessible but nothing else
and ΔM to small for any leptonic signature



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

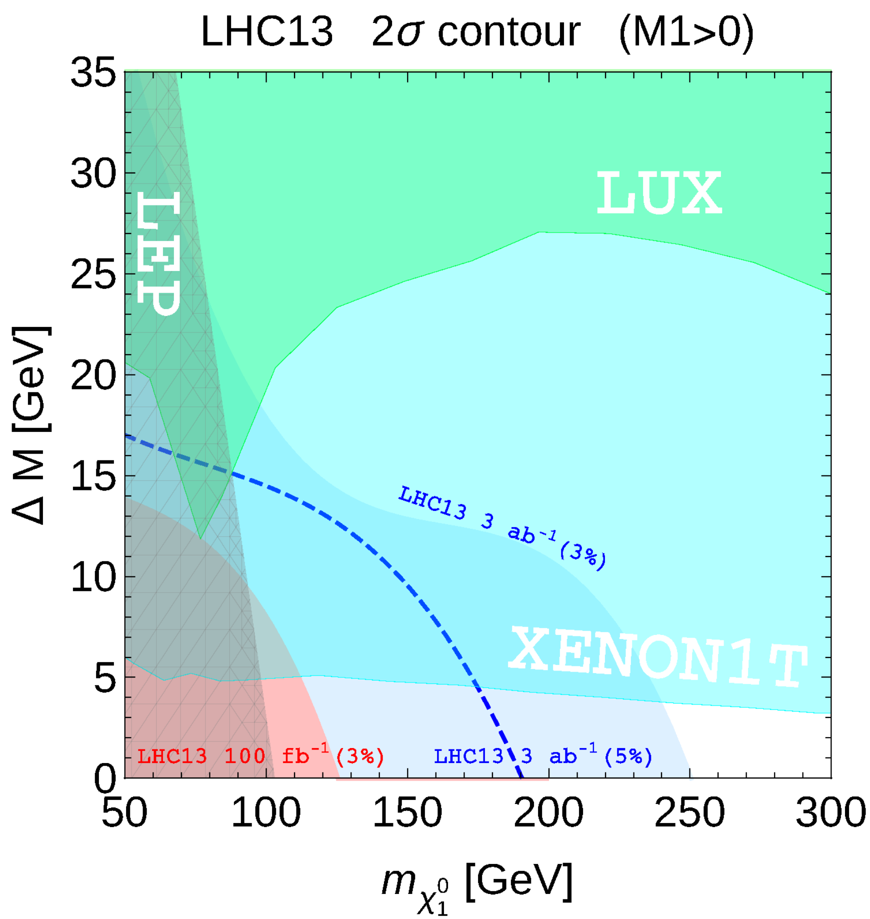
which has been used in studies on compressed SUSY spectra, e.g. Dreiner,Kramer,Tattersall 2012; Han,Kobakhidze,Liu,Saavedra,Wu 2013; Han,Kribs,Martin,Menon 2014

DM relic density and direct detection

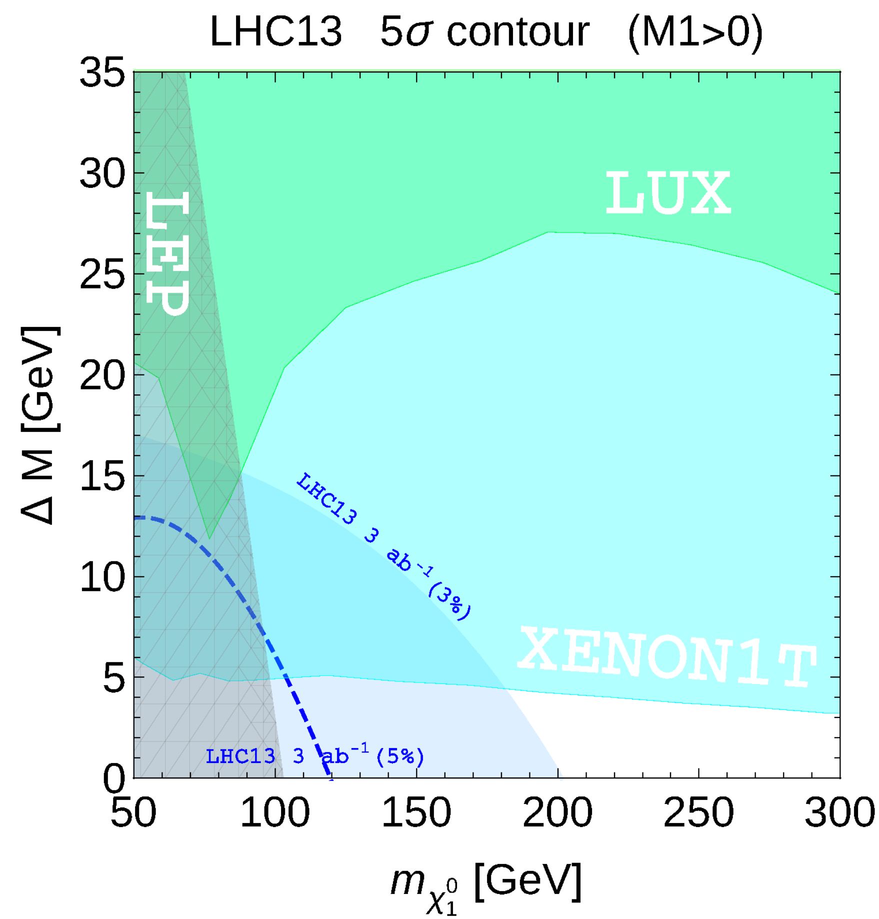


- relic density too low because higgsinos couple 'strongly' to W and Z
- DD cross section rescaled with relic density $\rightarrow$ chance for LHC?

D. Barducci, A. Belyaev, A. Bharucha, WP, V. Sanz, arXiv:1504.02472 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 $R_P = (-1)^{2s+3(B-L)}$

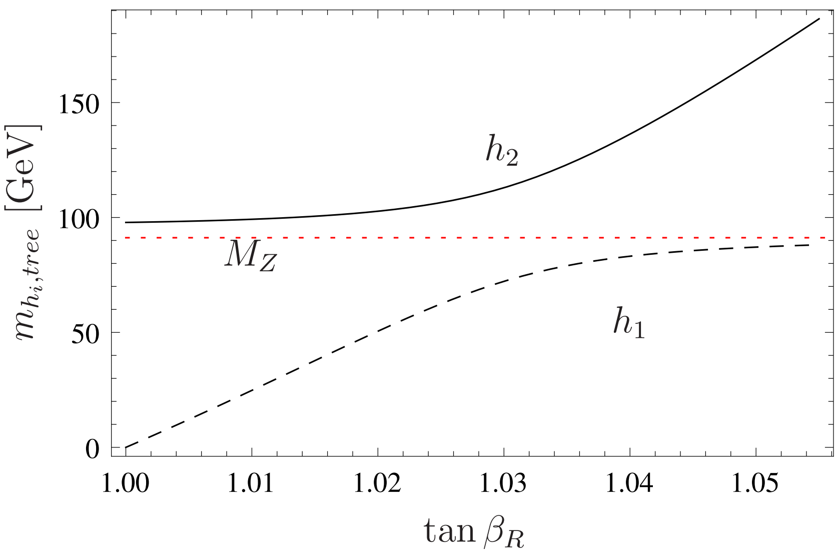
  $\Rightarrow SO(10) \to SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$
  $\to SU(3)_C \times SU(2)_L \times U(1)_R \times U(1)_{B-L}$
  $\cong SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_\chi$
  or $E(8) \times E(8) \to SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$

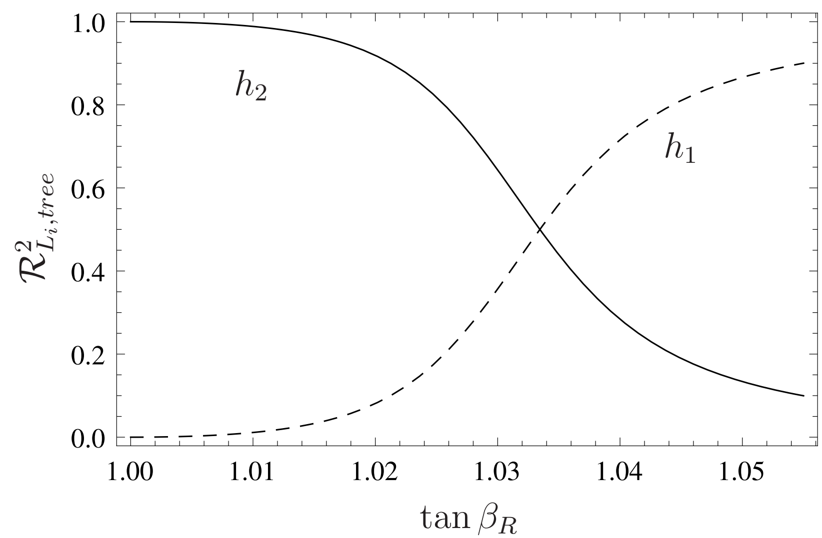
- Neutrino masses

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

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

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



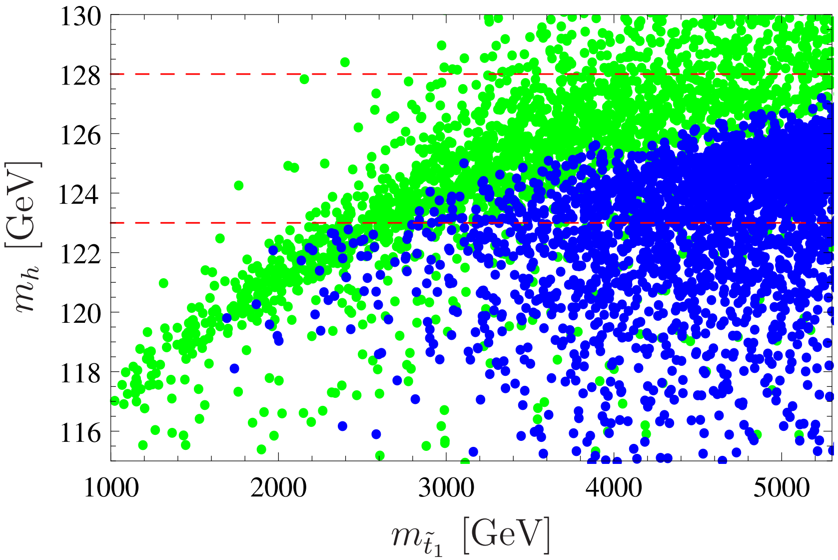


$n = 1,\ \Lambda = 5 \cdot 10^5$ GeV, $M = 10^{11}$ GeV, $\tan\beta = 30$, sign$(\mu_R) = -$, $diag(Y_S) = (0.7, 0.6, 0.6)$, $Y_\nu^{ii} = 0.01$, $v_R = 7$ TeV

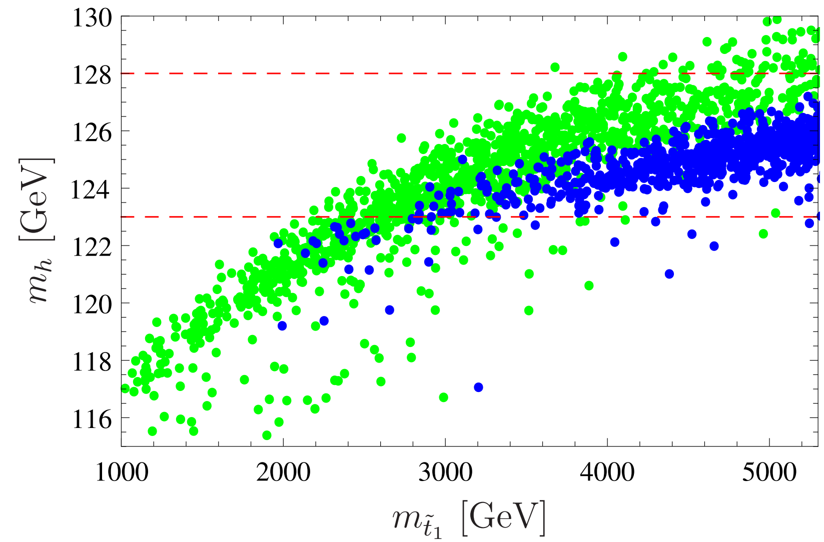
M.E. Krauss, W.P., F. Staub, arXiv:1304.0769

Higgs sector II

$R_{h\to\gamma\gamma} \geq 0.5$



$R_{h\to\gamma\gamma} \geq 0.9$



scan over GMSB parameters: $1 \leq n \leq 4$, $10^5 \leq M \leq 10^{12}$ GeV, $10^5 \leq \sqrt{n}\Lambda \leq 10^6)$ GeV, $1.5 \leq \tan\beta \leq 40$, $1 < \tan\beta_R \leq 1.15$, sign$(\mu_R) \pm 1$, sign$(\mu) = 1$, $6.5 \leq v_R \leq 10$ TeV, $0.01 \leq Y_S^{ii} \leq 0.8$, $10^{-5} \leq Y_\nu^{ii} \leq 0.5$
blue points: $h_1 \simeq h$, green points: $h_2 \simeq h$

$$R_{h\to\gamma\gamma} = \frac{[\sigma(pp \to h) \times BR(h \to \gamma\gamma)]_{BLR}}{[\sigma(pp \to h) \times BR(h \to \gamma\gamma)]_{SM}} \, .$$

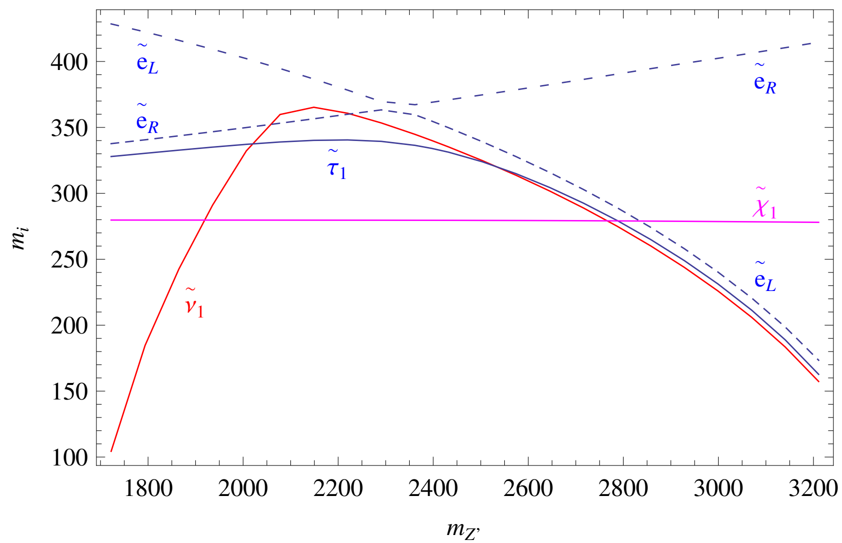
M.E. Krauss, W.P., F. Staub, arXiv:1304.0769

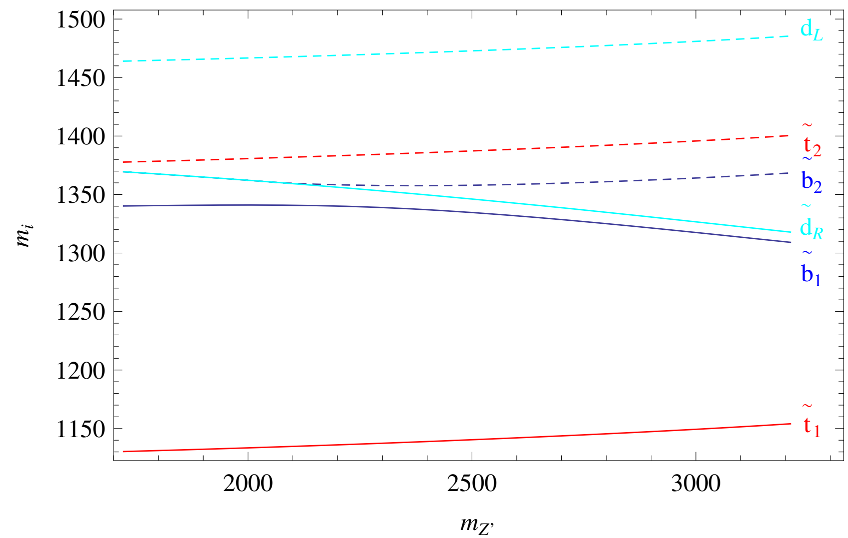
Sfermions

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

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

Example spectra from high scale models

	BLRSP1	BLRSP2	BLRSP3	BLRSP4	BLRSP5
$m_{\tilde{\nu}_1}$	105.0	797.	91.6	542.	921.
$m_{\tilde{\nu}_{2/3}}$	215.0	797.	92.6	542.	924.
$m_{\tilde{\nu}_4}$	604.	1120.	253.	585.	940.
$m_{\tilde{e}_1}$	524.	1014.	255.	263.	693.
$m_{\tilde{e}_{2,3}}$	557.	1055.	266.	271.	706.
$m_{\tilde{u}_1}$	1436.	1185.	1247.	1111.	1545.
$m_{\tilde{u}_2}$	1721.	1852.	1527.	1361.	1905.
$m_{\tilde{u}_{3,4}}$	1799.	2155.	1566.	1392.	2008.
$m_{\chi_1^0}$	367.	417.	313.	259. $\tilde{h}_R$	412.
$m_{\chi_2^0}$	718.	780. $\tilde{h}_R$	615.	280.	739. $\tilde{h}_R$
$m_{\chi_3^0}$	1047.	818.	1087.	549.	804.
$m_{\chi_5^0}$	1348. $(\tilde{B}_\perp)$	1866.	1232. $(\tilde{B}_\perp)$	857.	1294.
$m_{\chi_6^0}$	1802. $\tilde{h}_R$	2018. $(\tilde{B}_\perp)$	1811. $(\tilde{B}_\perp)$	1639. $(\tilde{B}_\perp)$	1688. $(\tilde{B}_\perp)$

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

Changes in SUSY cascades

CMSSM, GMSB: $\tilde{q}_R \to q\tilde{\chi}^0_1$

BLRSP1: $\tilde{\nu}$ LSP, $m_{\nu_h} \simeq 100$ GeV

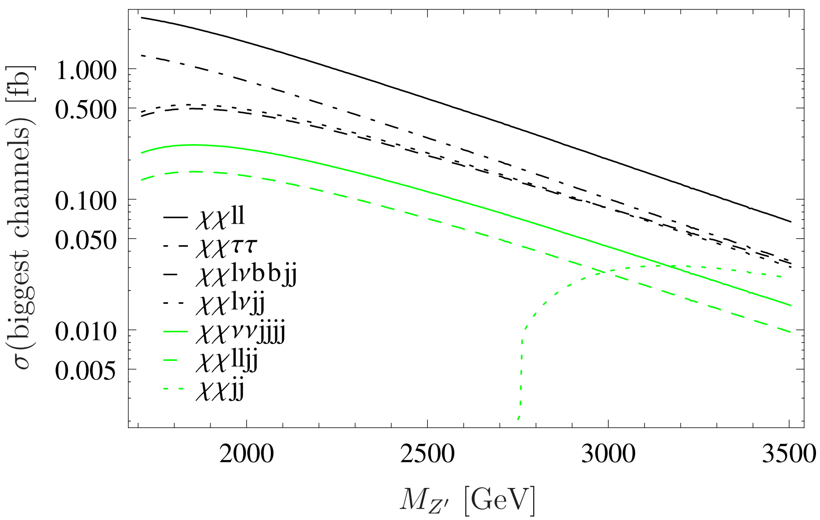
$$
\begin{aligned}
\tilde{q}_R &\to q\tilde{\chi}^0_1 \to q\nu_k\tilde{\nu}_1 \to q\nu_j Z\tilde{\nu}_1 \qquad (k=4,\dots,9\,,\ j=1,2,3)\\
\tilde{q}_R &\to q\tilde{\chi}^0_1 \to q\nu_k\tilde{\nu}_1 \to ql^\pm W^\mp\tilde{\nu}_1\\
\tilde{q}_R &\to q\tilde{\chi}^0_1 \to q\nu_k\tilde{\nu}_3 \to ql^\pm W^\mp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

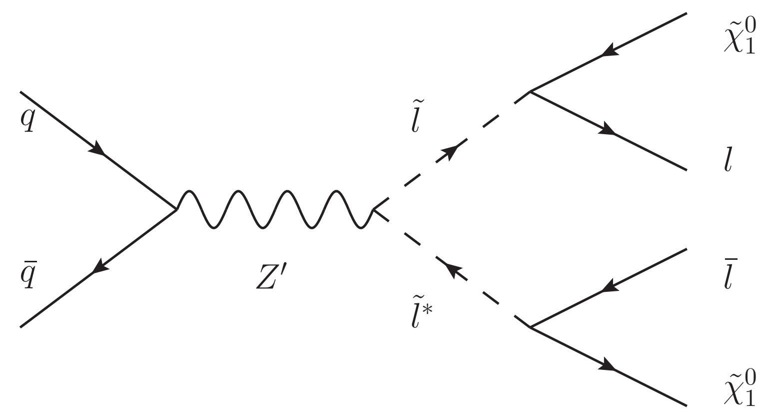
BLRSP3: usual cascades similar to CMSSM, but

$$
\begin{aligned}
\tilde{\chi}^0_1 &\to l^\pm\tilde{l}^\mp \to l^\pm W^\mp\tilde{\nu}_1\\
\tilde{\chi}^0_1 &\to l^\pm\tilde{l}^\mp \to l^\pm W^\mp\tilde{\nu}_{2,3} \to l^\pm W^\mp f\bar{f}\tilde{\nu}_1\\
\tilde{\chi}^0_1 &\to \nu_j\tilde{\nu}_{2,3} \to \nu_{1,2,3} f\bar{f}\tilde{\nu}_1\\
\tilde{\chi}^0_1 &\to \nu_j\tilde{\nu}_k \to \nu_j h_{1,2}\tilde{\nu}_1 \qquad (j,k=1,2,3)\\
\tilde{\chi}^0_1 &\to \nu_j\tilde{\nu}_k \to \nu_j h_{1,2} f\bar{f}\tilde{\nu}_1
\end{aligned}
$$

$\Rightarrow$ enhanced jet and lepton multiplicities, study of ν_R

LHC 14 TeV: Sleptons via Z' in BL1, I





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

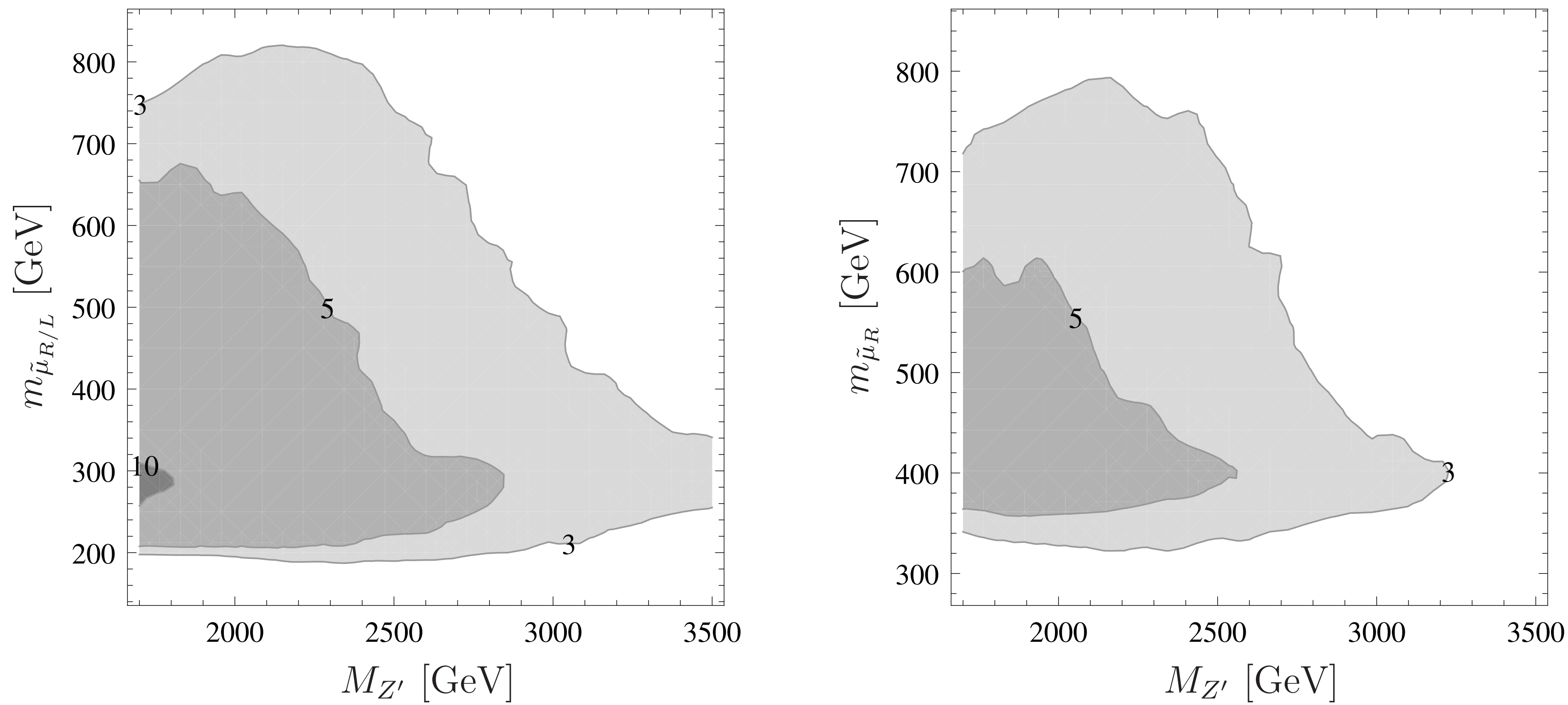
see also: J. Kang and P. Langacker, PRD **71** (2005) 035014; M. Baumgart, T. Hartman, C. Kilic, and L.-T. Wang, JHEP **0711** (2007) 084; C.-F. Chang, K. Cheung, and T.-C. Yuan, JHEP **1109** (2011) 058; G. Corcella and S. Gentile, arXiv:1205.5780

LHC 14 TeV: Sleptons via Z' in 'BL1', II

main dependence on masses $\Rightarrow$ vary $m_{\tilde{l}}$ and $m_{Z'}$, $M_L = 1.2 M_E$

100 fb^{-1}, $\sqrt{s} = 14$ TeV

$m_{\tilde{\chi}^0_1} = 140$ GeV $\quad$ $m_{\tilde{\chi}^0_1} = 280$ GeV



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

Natural SUSY, $\tilde{\nu}_R$ LSP, Parameters considered

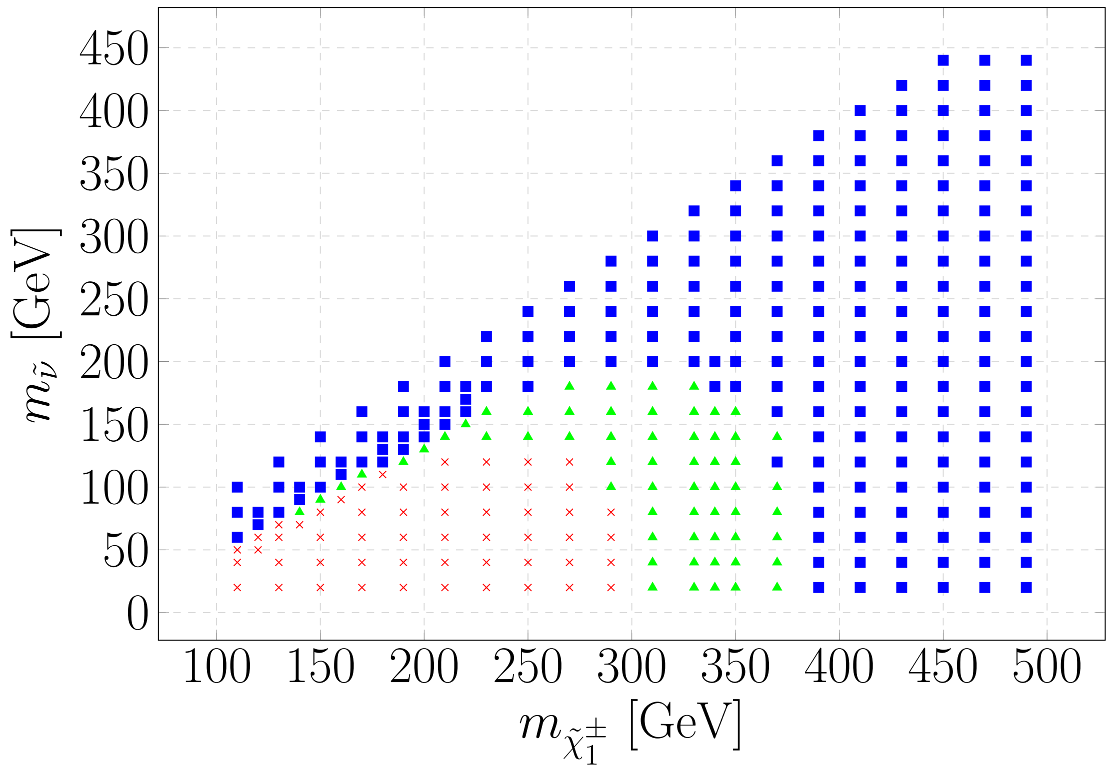
- $m_{\tilde{t}_1}$ in GeV: 300, 400, 500, 600, 700, 800, 900, 1000
- $m_{\tilde{b}_1}$ in GeV: 300, 400, 500, 600, 700, 800, 900, 1000
- $m_{\tilde{\nu}_R}$ in GeV : 60, 100, 200, 300, 400, 500
- μ in GeV: 110, 190, 290, 390, 490, 590 and require $m_{\tilde{\nu}_R} < \mu$
- $\tan\beta$: 10, 50
- $\theta_{\tilde{t}}$: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

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

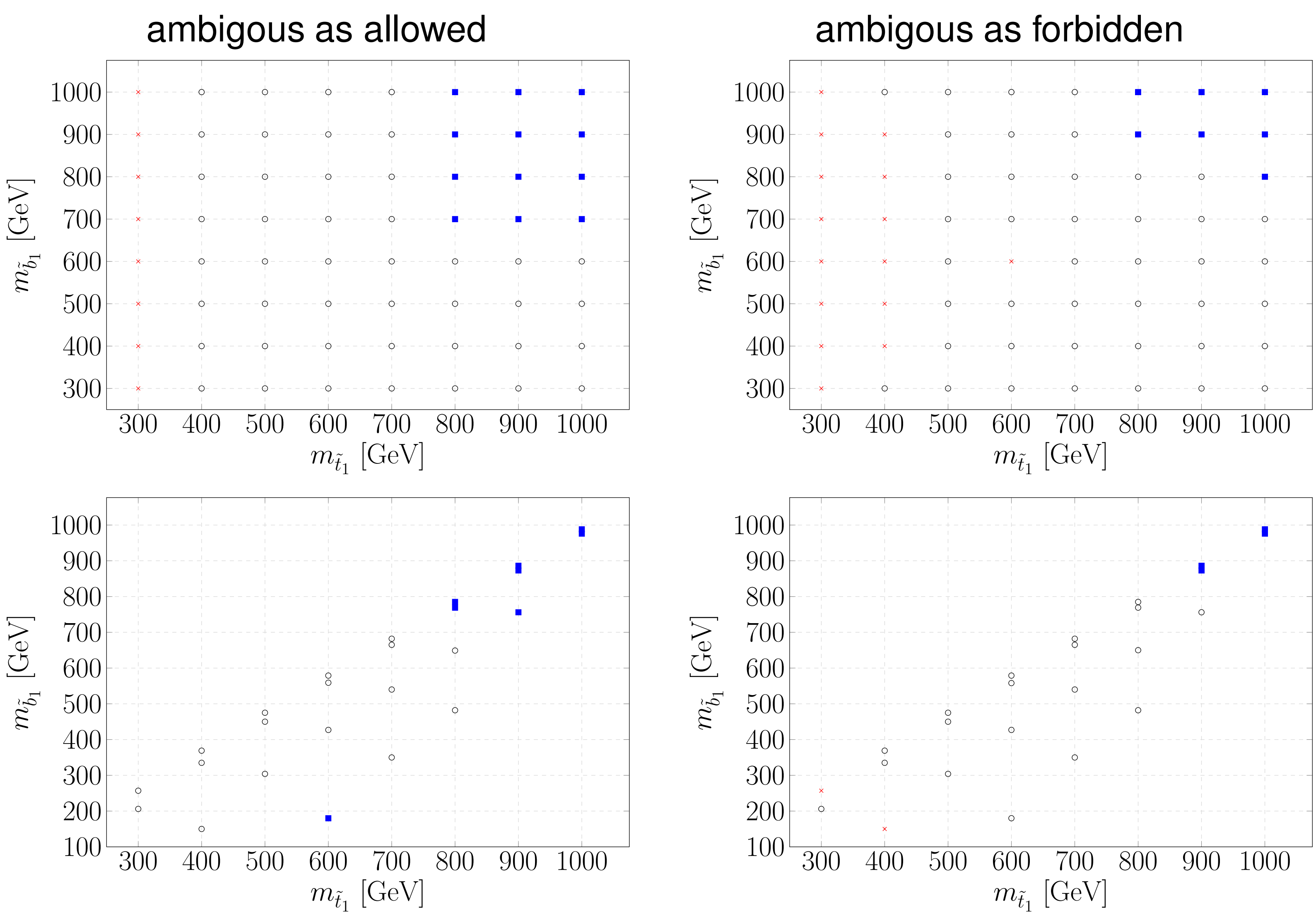


× excluded, ▲ ambigous, ■ allowed

8 TeV data using `CheckMATE` L. Mitzka, WP arXiv:1603.06130

13 TeV update: ongoing work with N. Cerna Velezco, T. Faber, J. Jones

Summary results



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

L. Mitzka, WP arXiv:1603.06130

Conclusions I

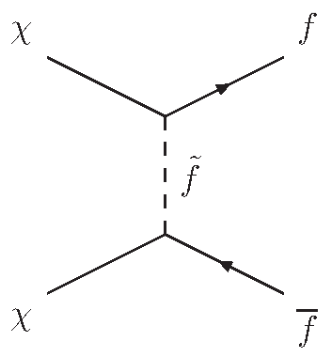
- $m_h = 125.1$ GeV & SUSY: either large radiative corrections or additional tree-level contributions in models beyond MSSM
- MSSM particle content
  - GMSB: beyond LHC reach (minimal version)
  - CMSSM: expect $m_{\tilde{g}}, m_{\tilde{q}} \gtrsim 2$ GeV, excluded with 90% CL if all data combined
  - '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
  - general MSSM: predictions depend strongly on details
  - models with large A_t, A_b: problems with charge/color breaking minima

Conclusions II

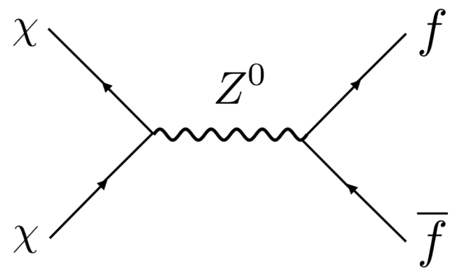
- extended gauge groups
  - also motived by ν-physics $\Rightarrow$ extended (s)neutrino sector
  - GMSB-like realisation: testable at LHC but heavy $\tilde{g}$, $\tilde{q}$
  - CMSSM-like realisation: different spectrum compared to CMSSM
    $\Rightarrow$ substantial changes of cascade decays
  - W' and Z' might look differently than expected & might even serve as SUSY discovery channel
  - potentially indications of SUSY in Z' decays
  - $\tilde{\nu}_R$ LSP: compatible with DM, no direct DM constraint apply
  - findings based on 8 TeV
    - $m_{\tilde{H}^\pm} \lesssim 290$ GeV excluded if $m_{\tilde{H}^\pm} - m_{\tilde{\nu}_R} \gtrsim 150$ GeV
      13 TeV update in coll. with Nhell and Joel
    - 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 $\cos\theta_{\tilde{t}}$

Dark matter, annihilation processes



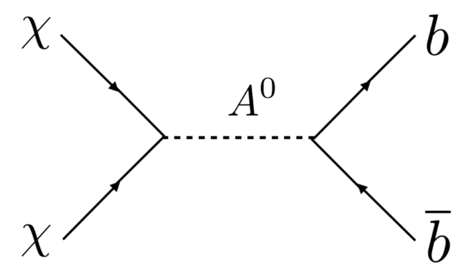
bino

bulk region

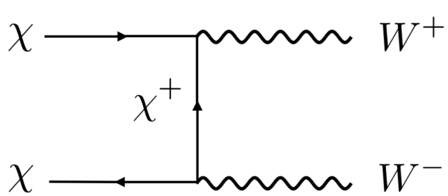


wino, higgsino

focus-point region

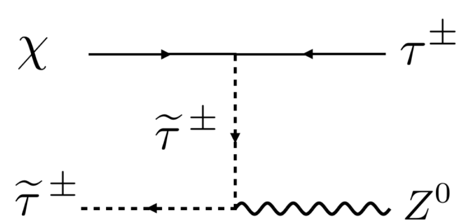


funnel region

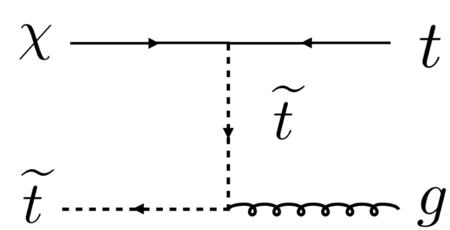


wino, higgsino

focus-point region



stau co-annihilation



stop co-annihilation

Constraints from Z-width: $m_{\nu_h} \gtrsim m_Z$
invisible width

$$\left| 1 - \sum_{ij=1, i\leq j}^{3} \left| \sum_{k=1}^{3} U^{\nu}_{ik} U^{\nu,*}_{jk} \right|^2 \right| < 0.009$$

dominant decays

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

roughly

$$BR(\nu_j \to W^{\pm} l^{\mp}) : BR(\nu_j \to Z\nu_i) : BR(\nu_j \to h_k \nu_i) \simeq 0.5 : 0.25 : 0.25$$

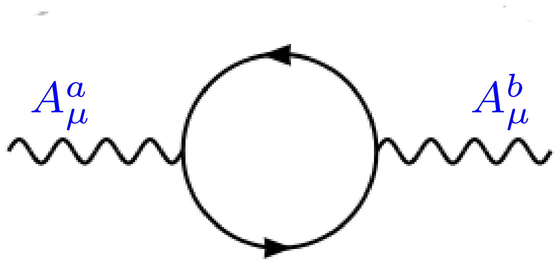
in BLRSP4

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

Gauge kinetic mixing

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

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



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

equivalent

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

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

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

basis (W^0, B_Y, B_χ)

$$M^2_{VV} = \frac{1}{4}\begin{pmatrix} g_2^2 v^2 & -g_2 g' v^2 & g_2 \tilde{g}_\chi v^2 \\ -g_2 g' v^2 & g'^2 v^2 & -g' \tilde{g}_\chi v^2 \\ g_2 \tilde{g}_\chi v^2 & -g' \tilde{g}_\chi v^2 & \frac{25}{4} g_\chi^2 v_R^2 + \tilde{g}_\chi^2 v^2 \end{pmatrix}$$

$$\tilde{g}_\chi = g_\chi - g_{Y\chi}$$

$$v^2 = v_d^2 + v_u^2 \ , \ v_R^2 = v_{\chi_R}^2 + v_{\bar{\chi}_R}^2$$

expanding in v^2/v_R^2

$$m_Z^2 \simeq \frac{1}{4}\left(g'^2 + g_2^2\right) v^2 \left(1 - \frac{4}{25}\left(1 - \frac{g_{Y\chi}}{g_\chi}\right)^2 \frac{v^2}{v_R^2}\right)$$

$$m_{Z'}^2 \simeq \left(\frac{5}{4} g_\chi v_R\right)^2$$

M. Hirsch, W.P., L. Reichert, F. Staub, arXiv:1206:3516;
M.E. Krauss, W.P., F. Staub, arXiv:1304.0769

basis $(\lambda_{BL}, \lambda_L^0, \tilde{h}_d^0, \tilde{h}_u^0, \lambda_R, \tilde{\bar{\chi}}_R, \tilde{\chi}_R)$

$$M_{\tilde{\chi}^0} =$$

$$\begin{pmatrix} M_{BL} & 0 & -\frac{1}{2}g_{RBL}v_d & \frac{1}{2}g_{RBL}v_u & \frac{M_{BLR}}{2} & \frac{1}{2}v_{\bar{\chi}_R}\tilde{g}_{BL} & -\frac{1}{2}v_{\chi_R}\tilde{g}_{BL} \\ 0 & M_2 & \frac{1}{2}g_2 v_d & -\frac{1}{2}g_2 v_u & 0 & 0 & 0 \\ -\frac{1}{2}g_{RBL}v_d & \frac{1}{2}g_2 v_d & 0 & -\mu & -\frac{1}{2}g_R v_d & 0 & 0 \\ \frac{1}{2}g_{RBL}v_u & -\frac{1}{2}g_2 v_u & -\mu & 0 & \frac{1}{2}g_R v_u & 0 & 0 \\ \frac{M_{BLR}}{2} & 0 & -\frac{1}{2}g_R v_d & \frac{1}{2}g_R v_u & M_R & -\frac{1}{2}v_{\bar{\chi}_R}\tilde{g}_R & \frac{1}{2}v_{\chi_R}\tilde{g}_R \\ \frac{1}{2}v_{\bar{\chi}_R}\tilde{g}_{BL} & 0 & 0 & 0 & -\frac{1}{2}v_{\bar{\chi}_R}\tilde{g}_R & 0 & -\mu_R \\ -\frac{1}{2}v_{\chi_R}\tilde{g}_{BL} & 0 & 0 & 0 & \frac{1}{2}v_{\chi_R}\tilde{g}_R & -\mu_R & 0 \end{pmatrix}$$

Higgs sector, I

$$\chi_R = \frac{1}{\sqrt{2}}\left(\sigma_R + i\varphi_R + v_{\chi_R}\right) \;,\; \bar{\chi}_R = \frac{1}{\sqrt{2}}\left(\bar{\sigma}_R + i\bar{\varphi}_R + v_{\bar{\chi}_R}\right)$$

$$H_d^0 = \frac{1}{\sqrt{2}}\left(\sigma_d + i\varphi_d + v_d\right) \;,\quad H_u^0 = \frac{1}{\sqrt{2}}\left(\sigma_u + i\varphi_u + v_u\right)$$

pseudo scalars, basis $(\varphi_d, \varphi_u, \bar{\varphi}_R, \varphi_R)$

$$M^2_{AA} = \begin{pmatrix} M^2_{AA,L} & 0 \\ 0 & M^2_{AA,R} \end{pmatrix}$$

$$M^2_{AA,L} = B_\mu \begin{pmatrix} \tan\beta & 1 \\ 1 & \cot\beta \end{pmatrix} \quad , \quad M^2_{AA,R} = B_{\mu_R} \begin{pmatrix} \tan\beta_R & 1 \\ 1 & \cot\beta_R \end{pmatrix}$$

$\tan\beta = v_u/v_d$ and $\tan\beta_R = v_{\chi_R}/v_{\bar{\chi}_R}$

two physical states

$$m^2_A = B_\mu(\tan\beta + \cot\beta)\,, \qquad m^2_{A_R} = B_{\mu_R}(\tan\beta_R + \cot\beta_R)$$

independent of gauge kinetic mixing!

Higgs sector, II

$$M^2_{hh} = \begin{pmatrix} m^2_{LL} & m^2_{LR} \\ m^{2,T}_{LR} & m^2_{RR} \end{pmatrix}$$

$$m^2_{LL} = \begin{pmatrix} g^2_\Sigma v^2 c^2_\beta + m^2_A s^2_\beta & -\frac{1}{2}\left(m^2_A + g^2_\Sigma v^2\right) s_{2\beta} \\ -\frac{1}{2}\left(m^2_A + g^2_\Sigma v^2\right) s_{2\beta} & g^2_\Sigma v^2 s^2_\beta + m^2_A c^2_\beta \end{pmatrix},$$

$$m^2_{LR} = \frac{5}{8} g_\chi \tilde{g}_\chi v v_R \begin{pmatrix} c_\beta c_{\beta_R} & -c_\beta s_{\beta_R} \\ -s_\beta c_{\beta_R} & s_\beta s_{\beta_R} \end{pmatrix},$$

$$m^2_{RR} = \begin{pmatrix} g^2_{Z_R} v^2_R c^2_{\beta_R} + m^2_{A_R} s^2_{\beta_R} & -\frac{1}{2}\left(m^2_{A_R} + g^2_{\Sigma_R} v^2_R\right) s_{2\beta_R} \\ -\frac{1}{2}\left(m^2_{A_R} + g^2_{\Sigma_R} v^2_R\right) s_{2\beta_R} & g^2_{\Sigma_R} v^2_R s^2_{\beta_R} + m^2_{A_R} c^2_{\beta_R} \end{pmatrix}$$

$$v^2_R = v^2_{\chi_R} + v^2_{\bar{\chi}_R}\ ,\ v^2 = v^2_d + v^2_u\ ,\ s_x = \sin(x)\ ,\ c_x = \cos(x)$$

$$g^2_\Sigma = \frac{1}{4}(g^2_2 + g'^2 + \tilde{g}^2_\chi)\ ,\ g^2_{\Sigma_R} = \frac{25}{16} g^2_\chi\ ,\ \tilde{g}_\chi = g_\chi - g_{Y\chi}$$

$\Rightarrow$ new D-term contributions at tree-level: $m^2_{h^0,tree} \le m^2_Z + \frac{1}{4}\tilde{g}^2_\chi v^2$

H.E. Haber, M. Sher, PRD 35 (1987) 2206; M. Drees, PRD 35 (1987) 2910; M. Cvetic et al., PRD 56 (1997) 2861; E. Ma, arXiv:1108.4029; M. Hirsch et al., arXiv:1110.3037, arXiv:1206:3516 basis $(\lambda_Y, \lambda_{W^3}, \tilde{h}_d^0, \tilde{h}_u^0, \lambda_\chi, \tilde{\bar{\chi}}_R, \tilde{\chi}_R)$

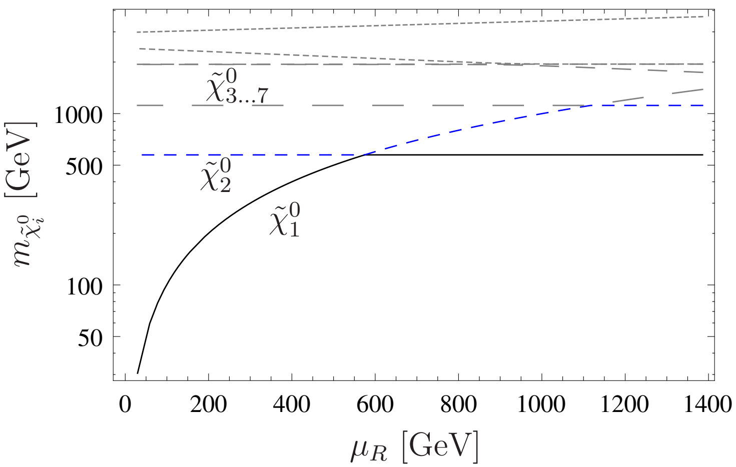
$$M_{\tilde{\chi}^0} =$$

$$\begin{pmatrix} M_1 & 0 & -\frac{g' v_d}{2} & \frac{g' v_u}{2} & \frac{M_{Y\chi}}{2} & 0 & 0 \\ 0 & M_2 & \frac{g_2 v_d}{2} & -\frac{g_2 v_u}{2} & 0 & 0 & 0 \\ -\frac{g' v_d}{2} & \frac{g_2 v_d}{2} & 0 & -\mu & \frac{(g_\chi - g_{Y\chi}) v_d}{2} & 0 & 0 \\ \frac{g' v_u}{2} & -\frac{g_2 v_u}{2} & -\mu & 0 & -\frac{(g_\chi - g_{Y\chi}) v_u}{2} & 0 & 0 \\ \frac{M_{Y\chi}}{2} & 0 & \frac{(g_\chi - g_{Y\chi}) v_d}{2} & -\frac{(g_\chi - g_{Y\chi}) v_u}{2} & M_\chi & \frac{5 g_\chi v_{\bar{\chi}_R}}{4} & -\frac{5 g_\chi v_{\chi_R}}{4} \\ 0 & 0 & 0 & 0 & \frac{5 g_\chi v_{\bar{\chi}_R}}{4} & 0 & -\mu_R \\ 0 & 0 & 0 & 0 & -\frac{5 g_\chi v_{\chi_R}}{4} & -\mu_R & 0 \end{pmatrix}$$

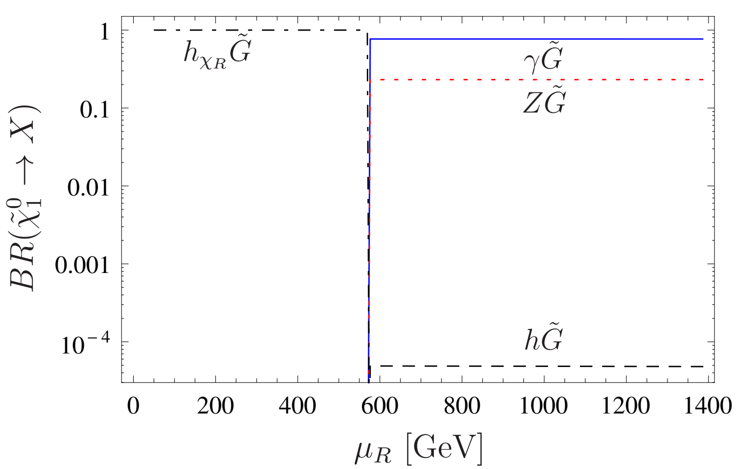
neglecting the mixing between the two sectors and setting $\tan\beta_R = 1$

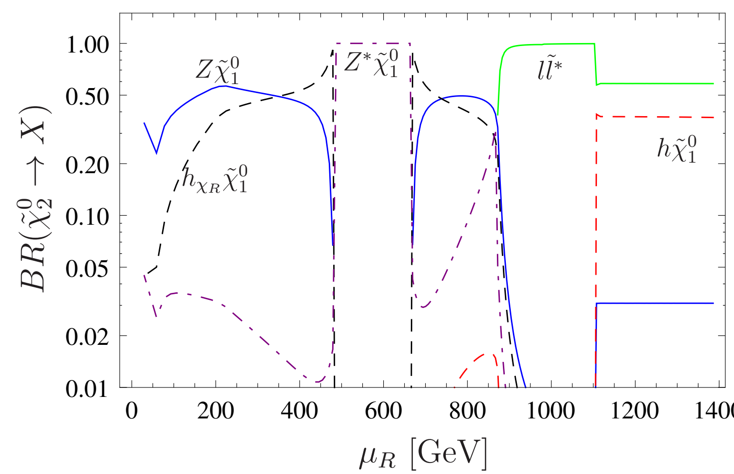
$$m_i : \; \mu_R \, , \quad \frac{1}{2}\left(M_\chi + \mu_R \pm \sqrt{\frac{1}{4} m_{Z'}^2 + (M_\chi - \mu_R)^2} \right)$$

Neutralinos II



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





$n = 1$, $\Lambda = 3.8 \cdot 10^5$ GeV, $M = 9 \cdot 10^{11}$ GeV, $\tan\beta = 30$ $v_R = 6.7$ GeV, $\tan\beta_R$ varied

$$M_\nu = \begin{pmatrix} 0 & \frac{1}{\sqrt{2}} v_u Y_\nu^T & 0 \\ \frac{1}{\sqrt{2}} v_u Y_\nu & 0 & \frac{1}{\sqrt{2}} v_{\chi R} Y_s \\ 0 & \frac{1}{\sqrt{2}} v_{\chi R} Y_s & \mu_S \end{pmatrix} \overset{1\text{gen},\mu_S=0}{\Longrightarrow} m_\nu = \begin{pmatrix} 0 \\ -\sqrt{|Y_\nu|^2 v_u^2 + |Y_s|^2 v_{\chi R}^2} \\ \sqrt{|Y_\nu|^2 v_u^2 + |Y_s|^2 v_{\chi R}^2} \end{pmatrix}$$

setting $\mu_S = 0$ and $B_{\mu_S} = 0$

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

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

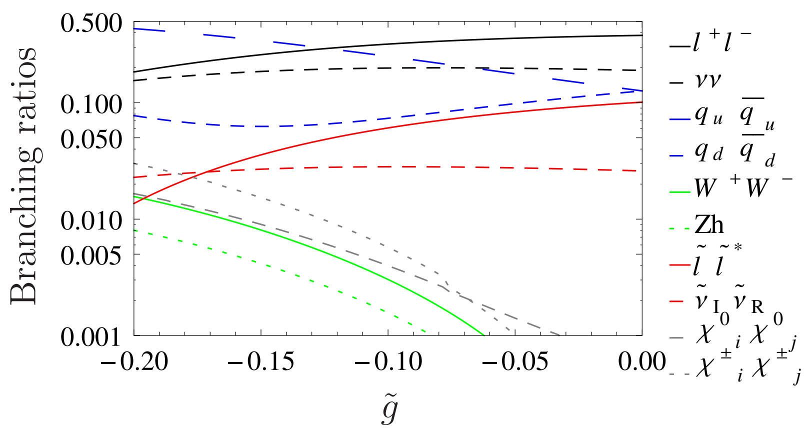
$$D_L = \frac{1}{32}\Big(2\big(-3g_\chi^2 + g_\chi g_{Y\chi} + 2(g_2^2 + g'^2 + g_{Y\chi}^2)\big)v^2 c_{2\beta} - 5g_\chi(3g_\chi + 2g_{Y\chi})v_R^2 c_{2\beta_R}\Big)\mathbf{1}$$

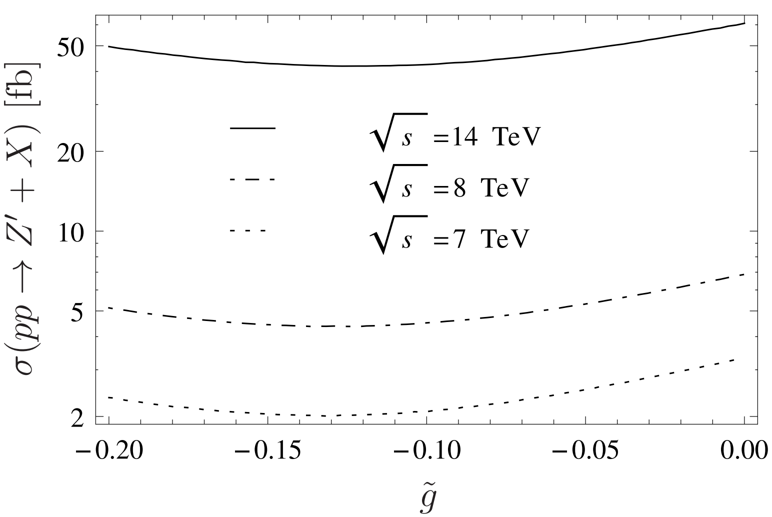
$$D_R = \frac{5g_\chi}{32}\Big(2(g_\chi - g_{Y\chi})v^2 c_{2\beta} + 5g_\chi v_R^2 c_{2\beta_R}\Big)\mathbf{1}$$

Z' physics, effect of gauge kinetic mixing I

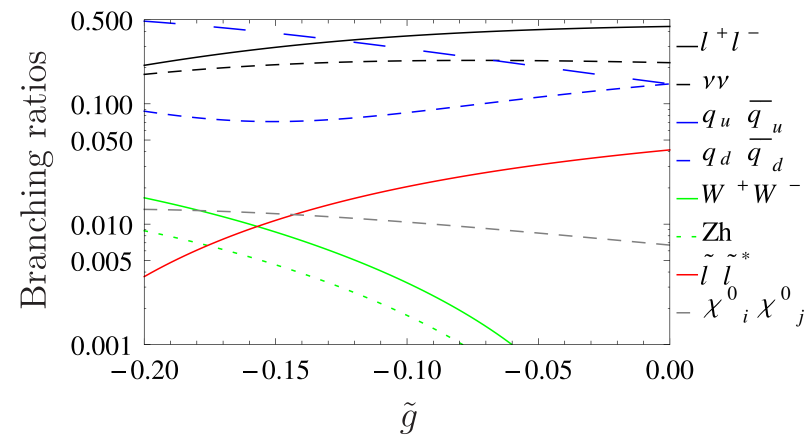
Z' couplings: $Q_{B-L} \cdot g_{B-L} \to Q_{B-L} \cdot g_{B-L} + Q_Y \cdot \tilde{g}$

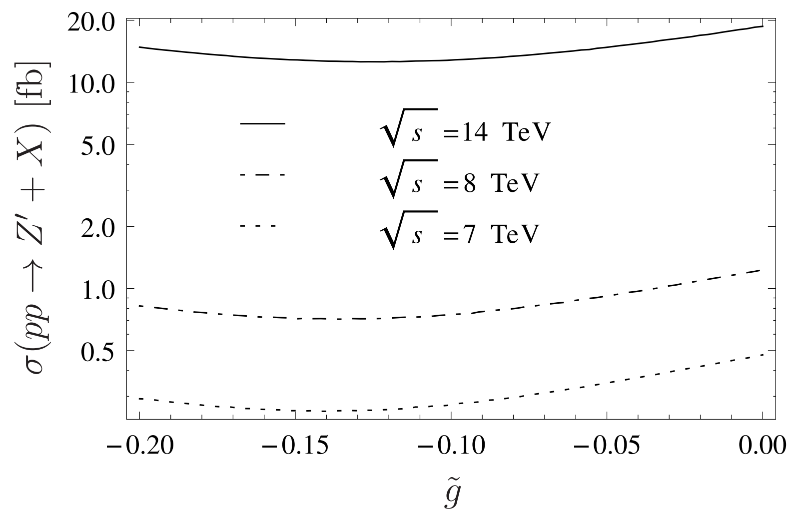
BL1





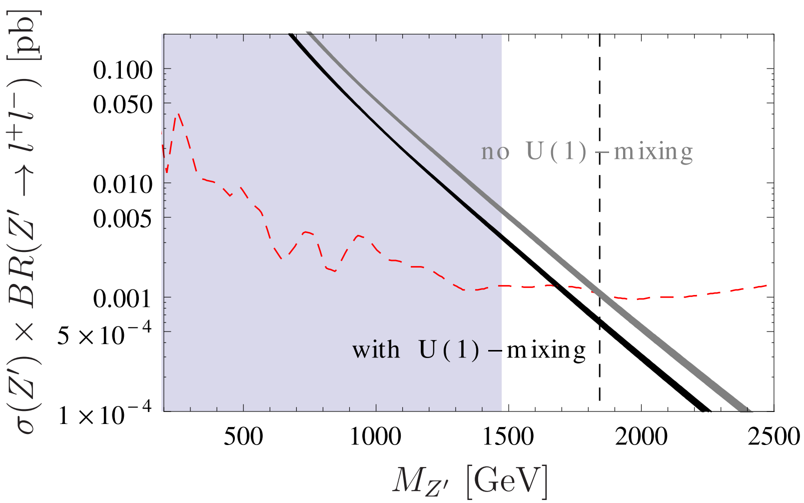
BL2



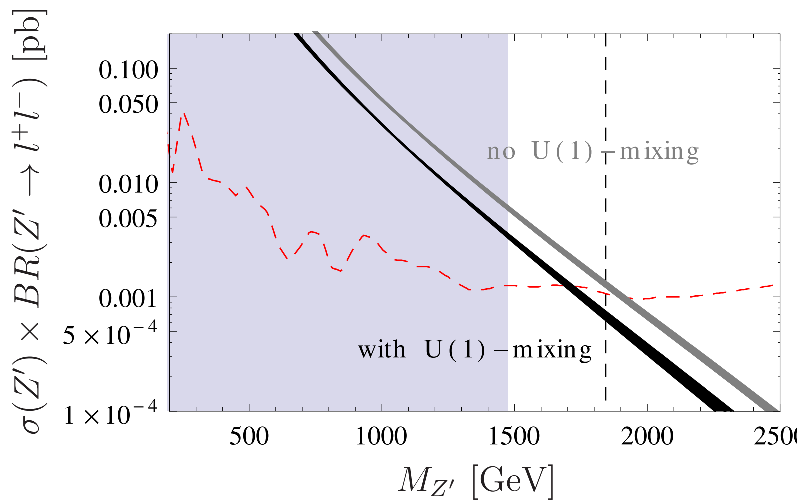


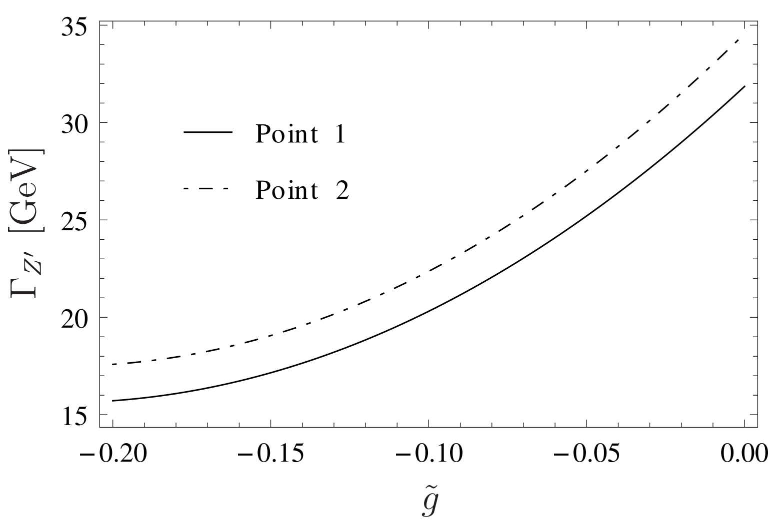
Z' physics, effect of gauge kinetic mixing II

BL1



BL2





Z' couplings:

$$Q_{B-L} \cdot g_{B-L} \to Q_{B-L} \cdot g_{B-L} + Q_Y \cdot \tilde{g}$$

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

LHC 14 TeV: Sleptons via Z' in BL1, III

- invariant mass of the muon pair: $M_{\mu\mu} > 200$ GeV
- missing transverse momentum: $p_T(\not{E}) > 200$ GeV
- transverse cluster mass

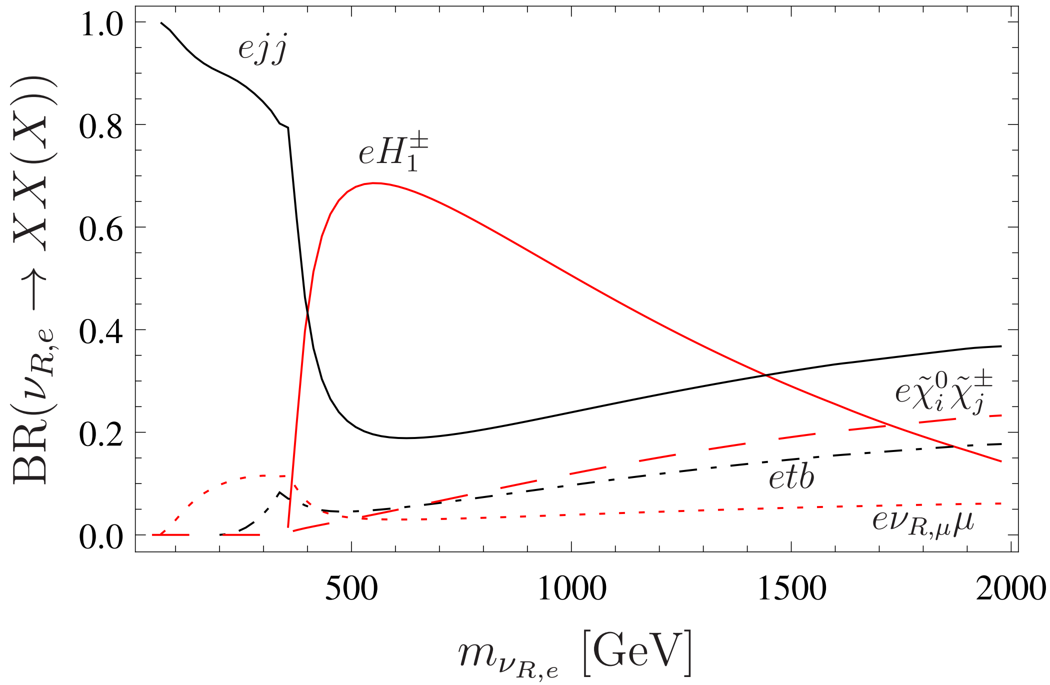
$$M_T = \sqrt{\left(\sqrt{p_T^2(\mu^+\mu^-) + M_{\mu\mu}^2} + p_T(\not{E})\right)^2 - (\vec{p}_T(\mu^+\mu^-) + \vec{p}_T(\not{E}))^2}$$

$$M_T > 800 \text{ GeV}$$

- for $t\bar{t}$ suppresssion and squark/gluino cascade decays:

$$p_{T,\text{hardest jet}} < 40 \text{ GeV}$$

$SU(2)_L \times SU(2)_R \times U(1)_{B-L}$, ν_R decays



$m_{W'} = 2.2$ TeV, $\tan\beta_R = 1.02$ and $\mu_{\text{eff}} = 150$ GeV
M. Krauss, W.P., arXiv:1507.04349