SUSY models in the light of m_h=125 GeV: Implications for LHC and astrophysics

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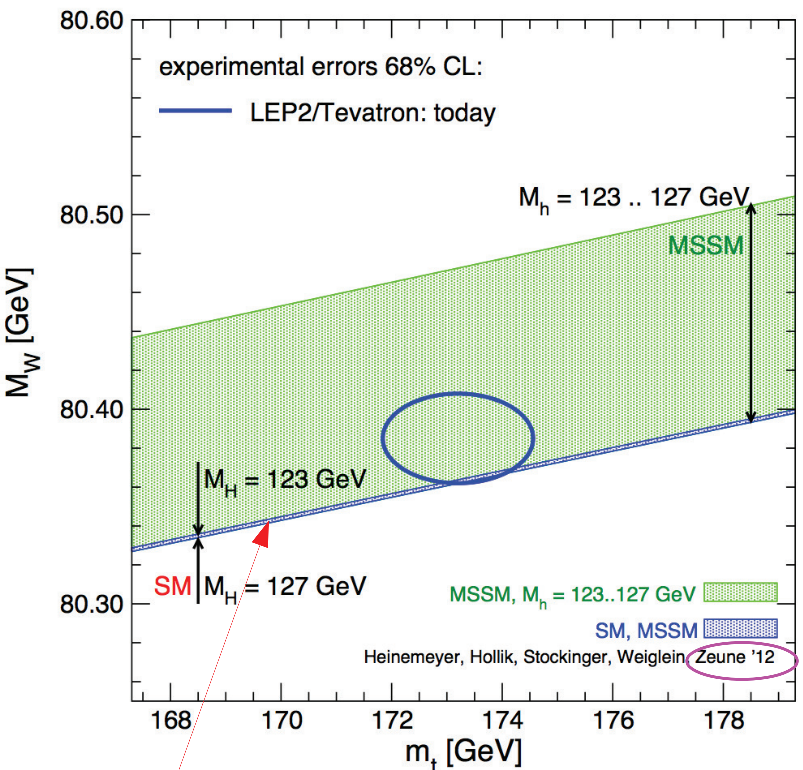
Content

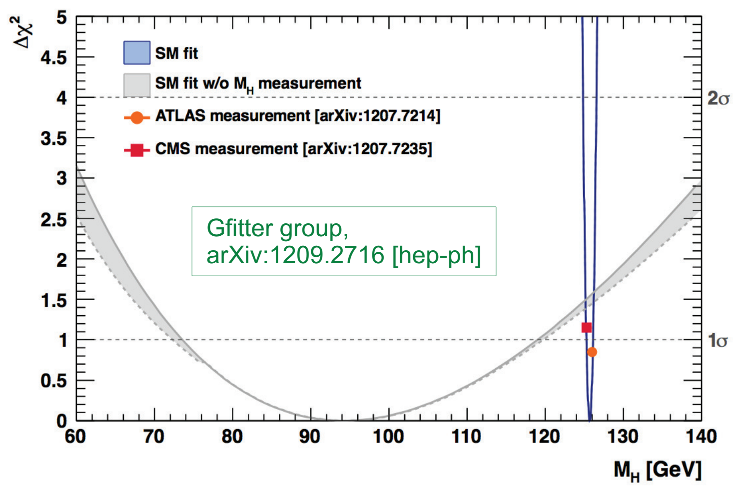
- Why extending the SM at all, why supersymmetry
- Higgs and MSSM
  - consequences for GMSB & CMSSM
  - general MSSM, ‘natural SUSY’
  - dark matter
- NMSSM
- SUSY and extended gauge groups
  - implications for SUSY cascade decays
  - Z' physics

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:

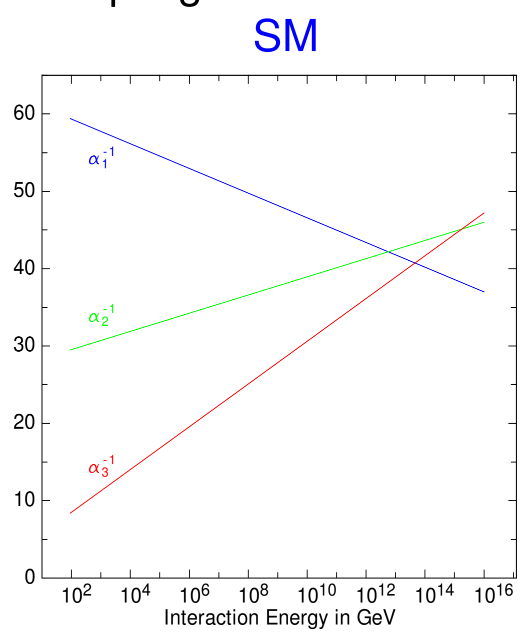


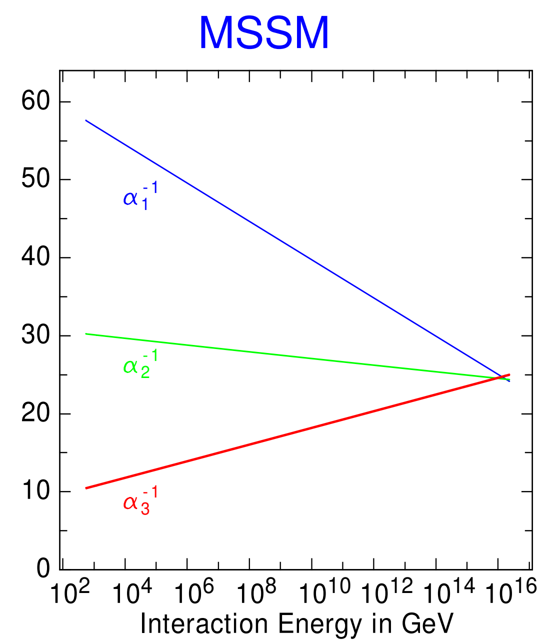
Consistent at the 1.3 σ level.

Why do we want to extend the SM

- How to combine gravity with the SM?
  ⇒ 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 $SO(10)$: $16 = (u_{\alpha,L}, u^c_{\alpha,R}, d_{\alpha,L}, d^c_{\alpha,R}, l_L, l_R, \nu_{l,L}, \nu^c_R)$

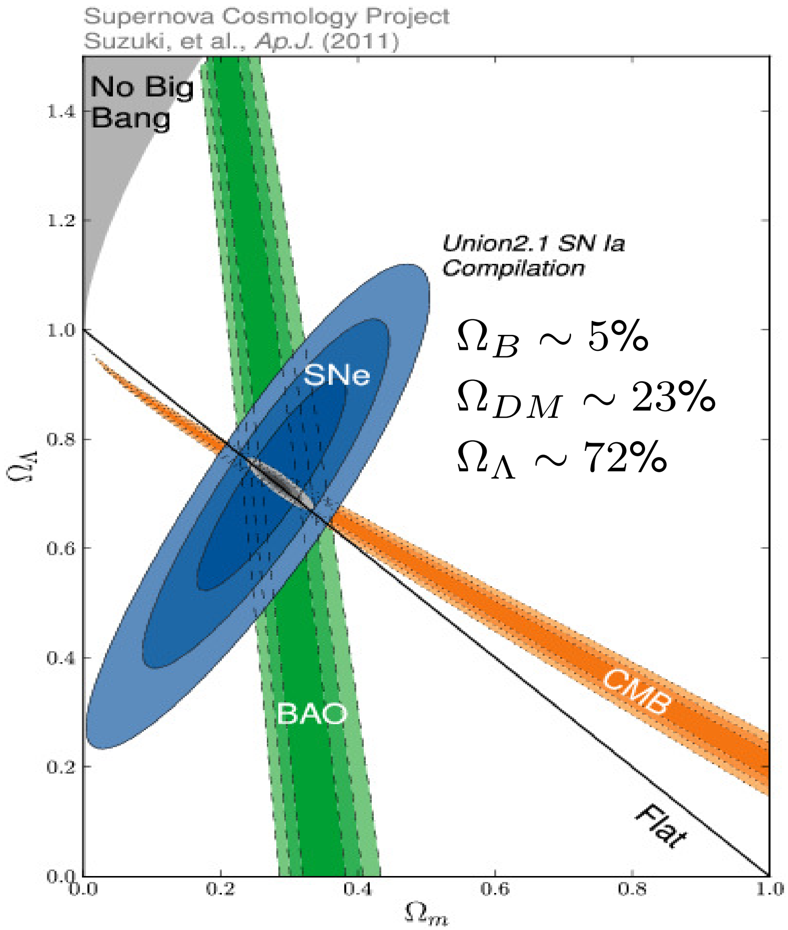
  However there are two problems in the SM but not in SUSY:
  - proton decay (also in SUSY $SU(5)$ a problem)
  - gauge coupling unification

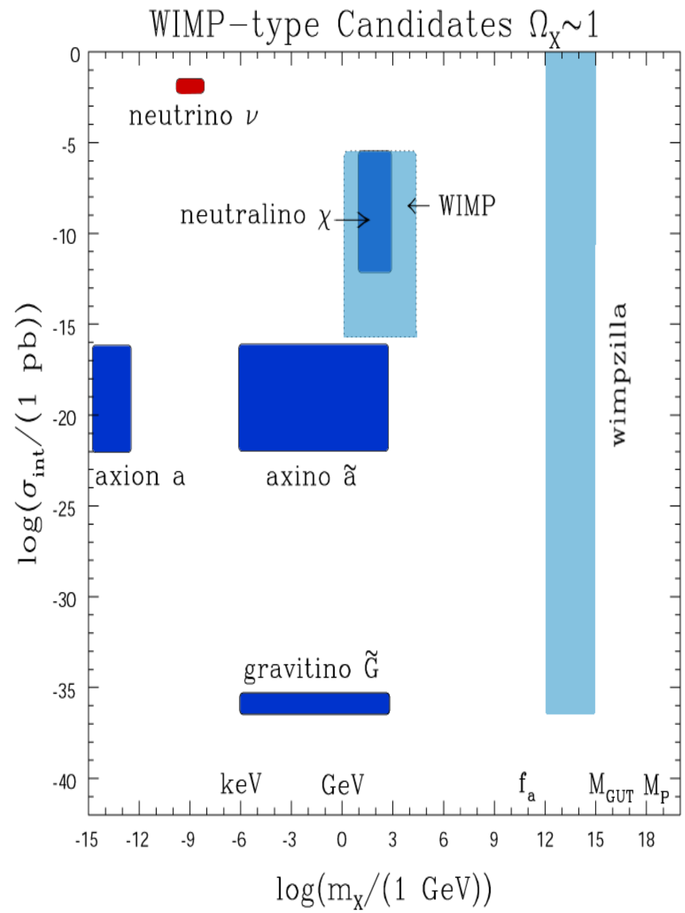




Why do we want to extend the SM

- What is the nature of dark matter ?



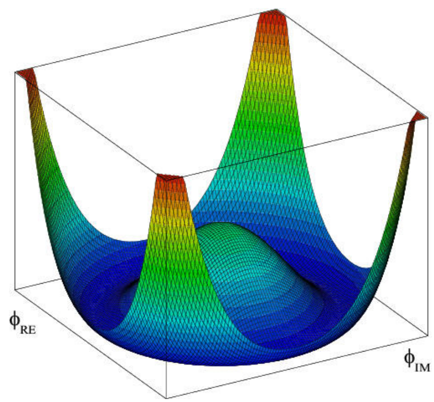


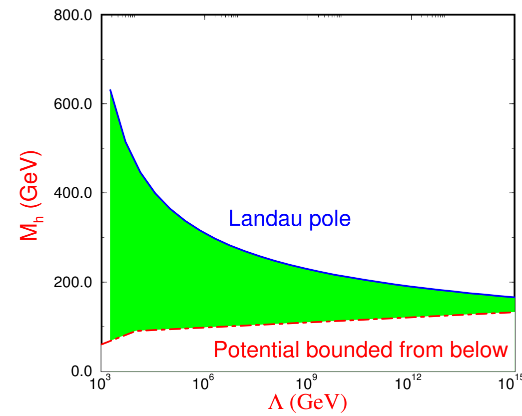
L. Roszkowski, astro-ph/0404052

- What is the origin of the observed baryon asymmetry?

Why do we want to extend the SM

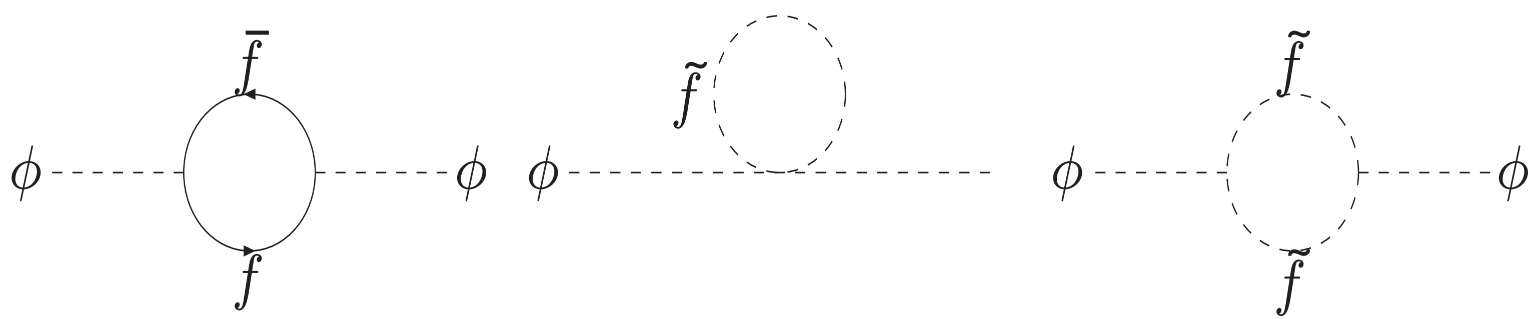
- SM & $m_h = 125.5$ GeV: potentially meta-stable (G. Degrassi *et al.*, arXiv:1205.6497)





- "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

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

R-Parity: $(-1)^{(3(B-L)+2s)}$

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

MSSM, generalities

$$
\begin{aligned}
W_{MSSM} &= -\varepsilon_{ab}\mu \hat{H}_d^a \hat{H}_u^b + \varepsilon_{ab}\left(\hat{H}_d^a \hat{L}^b Y_e \hat{E}^c + \hat{H}_d^a \hat{Q}^b Y_d \hat{D}^c + \hat{H}_u^b \hat{Q}^a Y_u \hat{U}^c\right) \\
W_{\not{L}} &= \varepsilon_{ab}\left(\epsilon \hat{L}^a \hat{H}_u^b + \lambda \hat{L}^a \hat{L}^b \hat{E}^c + \lambda' \hat{L}^a \hat{Q}^b \hat{D}^c\right) \\
W_{\not{B}} &= \varepsilon_{xyz}\lambda'' \hat{U}^{c,x} \hat{D}^{c,y} \hat{D}^{c,z}
\end{aligned}
$$

$W_{\not{L}} + W_{\not{B}} \Rightarrow$ proton decay $\Rightarrow$ R-parity

$$
R \equiv (-1)^{3(B-L)+2s} \quad \text{or} \quad (-1)^{3B+L+2s}
$$

soft SUSY breaking terms

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

MSSM, generalities

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

- mSUGRA/CMSSM: M_{GUT}

$$
\begin{aligned}
M_{1/2} &= M_1 = M_2 = M_3 \\
m_0^2 &= m_{H_d}^2 = m_{H_u}^2 \ , \ m_0^2 \not{1}_3 = m_{\tilde{Q}}^2 = m_{\tilde{U}}^2 = m_{\tilde{D}}^2 = m_{\tilde{L}}^2 = m_{\tilde{E}}^2 \\
T_f &= A_0 Y_f \ (f = u, d, e)
\end{aligned}
$$

- GMSB, $M \gtrsim 100$ TeV

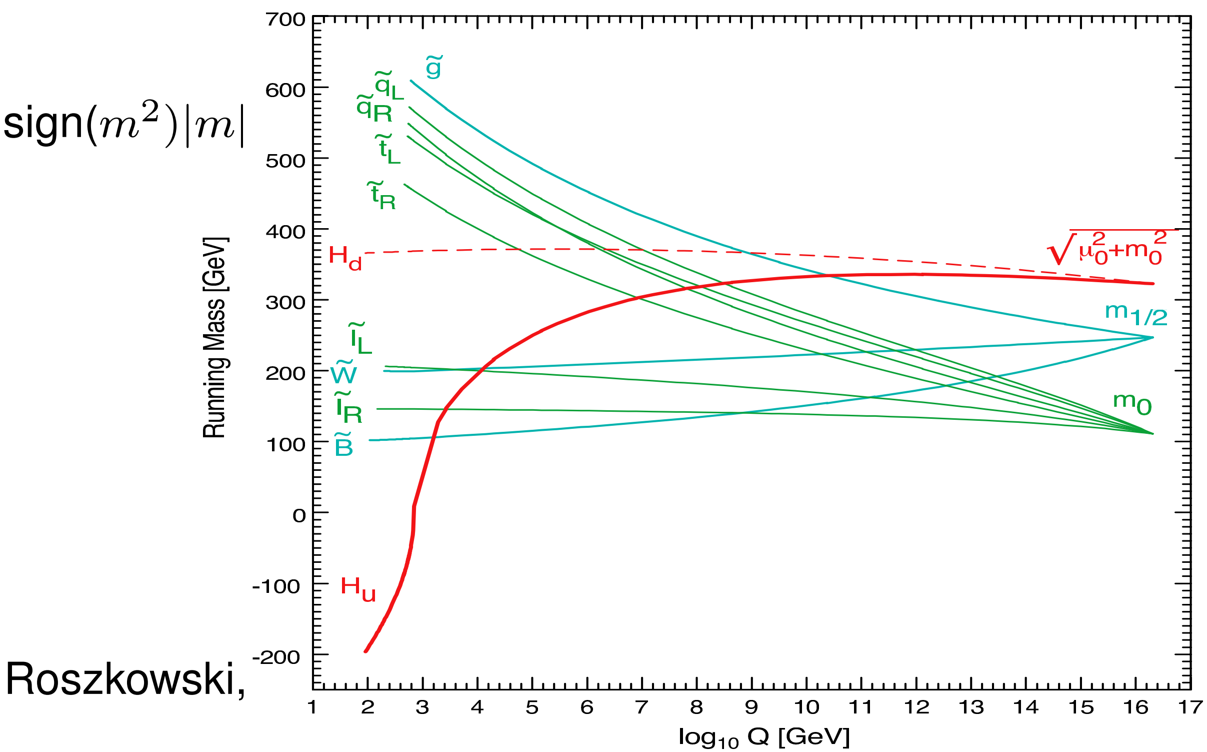
$$
\begin{aligned}
M_i &= g(x,n)\alpha_i \Lambda \\
m_{\tilde{F}}^2 &= f(x,n) \sum_i C_2(R) \alpha_i^2 \Lambda^2 \not{1}_3 \\
T_f &\simeq 0
\end{aligned}
$$

n # of messenger fields, $x = \Lambda/M$, $\Lambda = O(100 TeV) < M$

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 $t = \ln Q/m_Z$



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

MSSM, Higgs sector

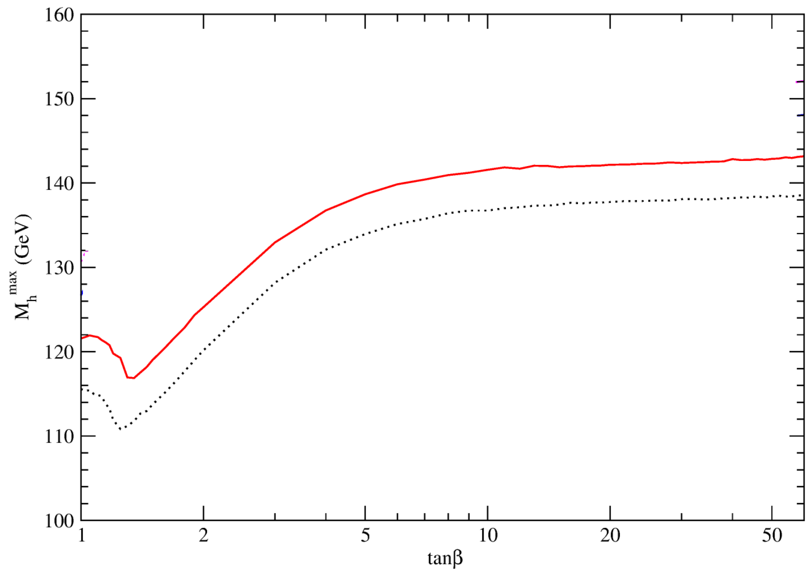
- after EWSB:
  neutral CP-even: h, H neutral CP-odd: A charged: H^+, H^-
- Higgs masses:
  at tree level
  $m_A, \tan\beta = v_u/v_d$
  $m_h \leq m_Z$
  at higher order:

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;. . .

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

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

MSSM, Higgs sector

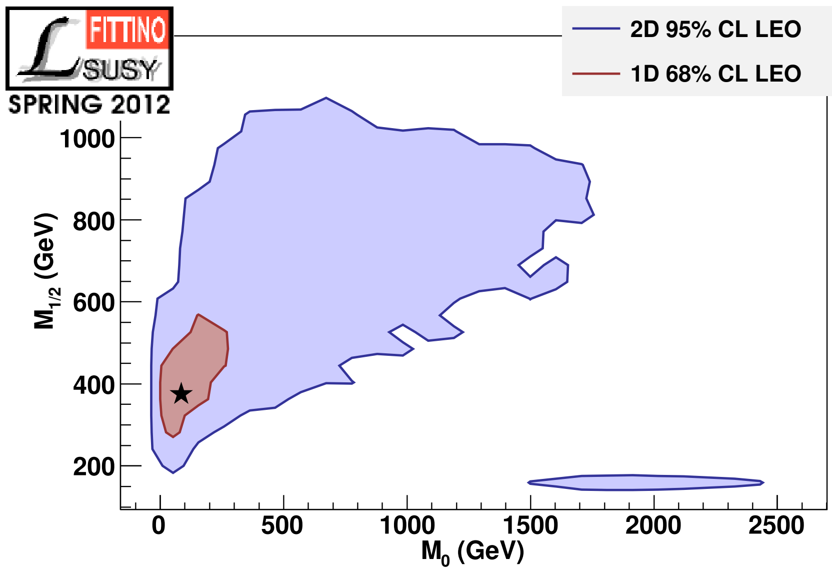


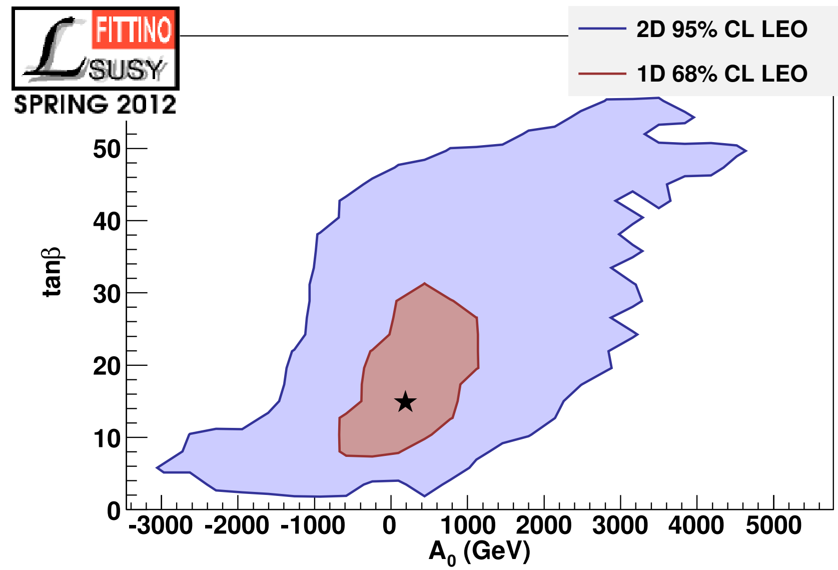
- modified couplings with respect to SM ($\rightarrow$ decoupling limit)

Φ	$g_{\Phi uu}$	$g_{\Phi dd}$	$g_{\Phi VV}$
h	$\cos\alpha/\sin\beta \rightarrow 1$	$-\sin\alpha/\cos\beta \rightarrow 1$	$\sin(\beta-\alpha) \rightarrow 1$
H	$\sin\alpha/\sin\beta \rightarrow 1/\tan\beta$	$\cos\alpha/\cos\beta \rightarrow \tan\beta$	$\cos(\beta-\alpha) \rightarrow 0$
A	$1/\tan\beta$	$\tan\beta$	0

Note: $g^{MSSM}_{\Phi VV} \lesssim g^{SM}_{\Phi VV}$

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,
$\chi^2/ndf = 10.3/8$

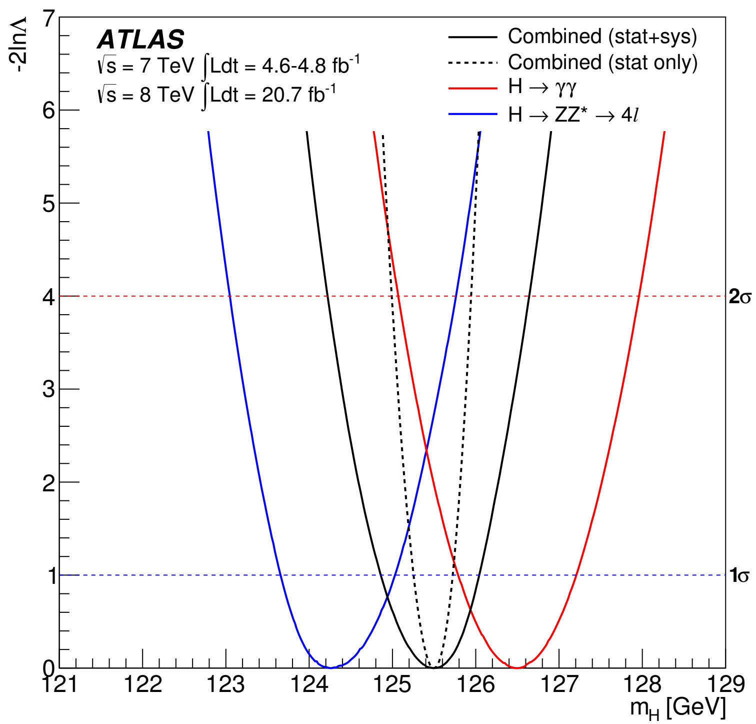
$\Rightarrow m_h = 116$ GeV

P. Bechtle et al., arXiv:1204.4199

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

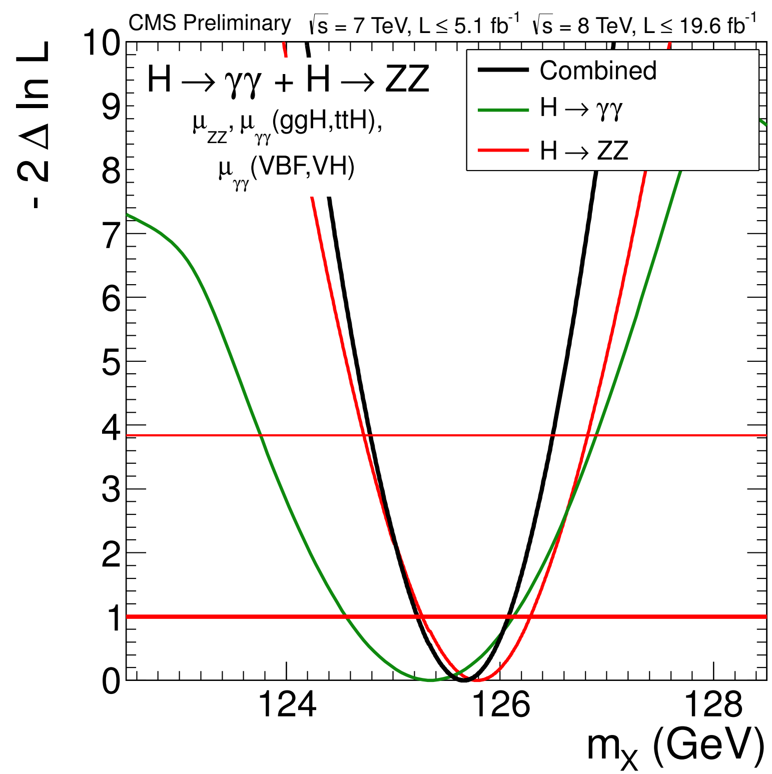
Higgs results in a nut-shell, I

ATLAS, arXiv:1307.1427



$M_H = 125.5 \pm 0.2_{\text{stat}} \pm 0.6_{\text{sys}}$ GeV

CMS, CMS-PAS-HIG-13-005

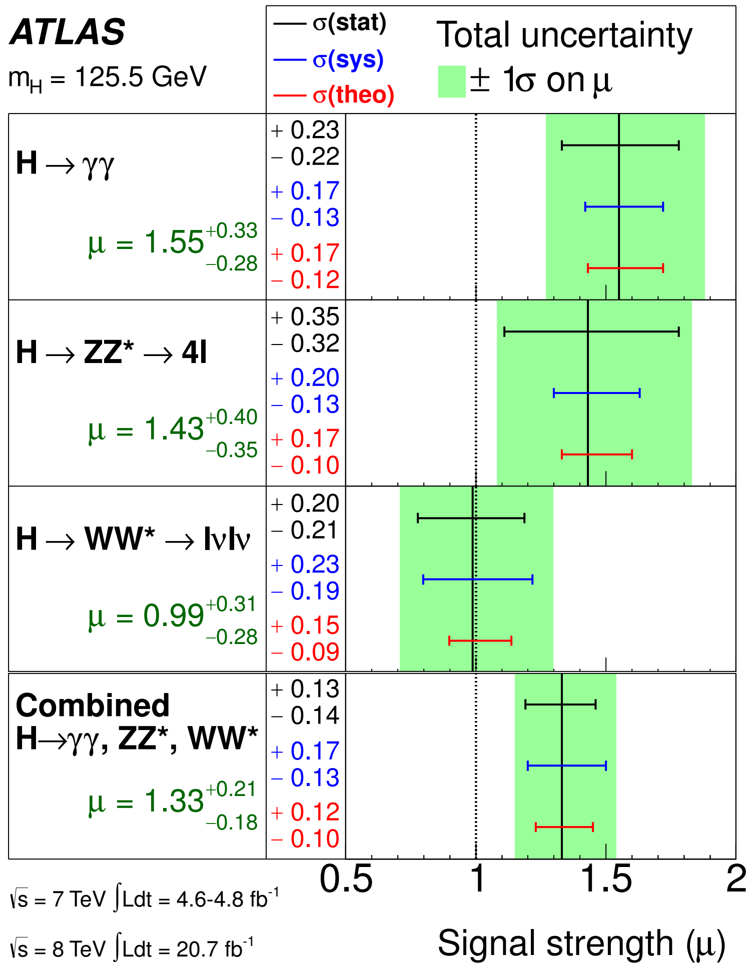


$M_H = 125.7 \pm 0.3_{\text{stat}} \pm 0.3_{\text{sys}}$ GeV

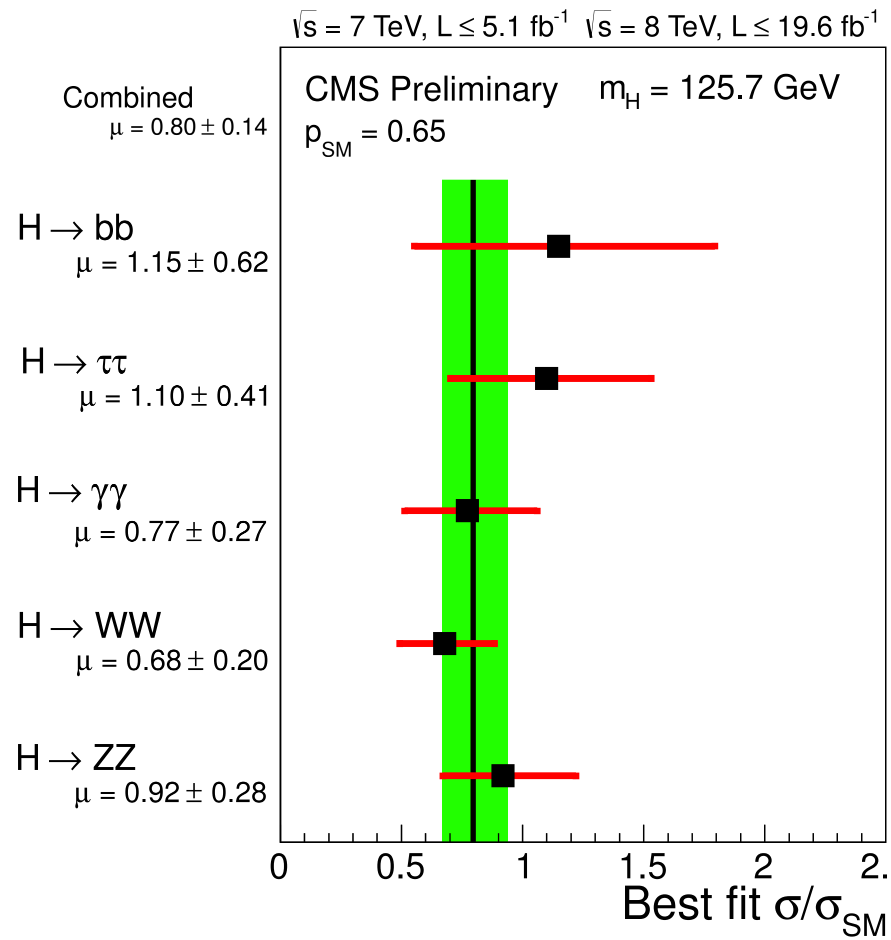
$(126\ \text{GeV})^2 \simeq m_Z^2 + (87\ \text{GeV})^2 \Rightarrow$ large corrections within MSSM

Higgs results in a nut-shell, II

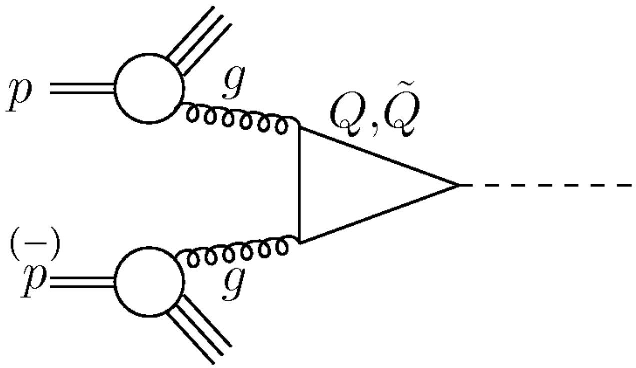
ATLAS, arXiv:1307.1427

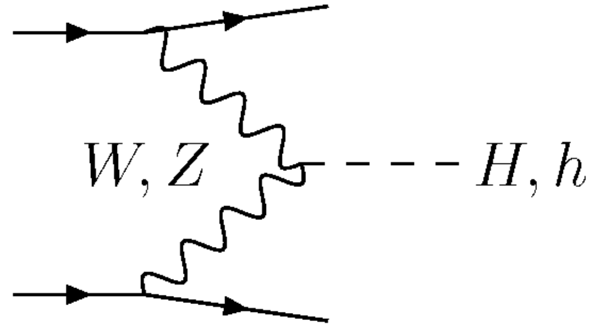


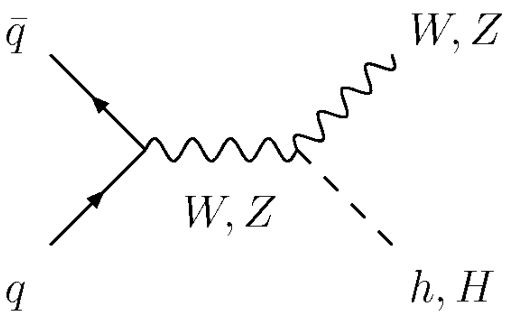
CMS, CMS-PAS-HIG-13-005

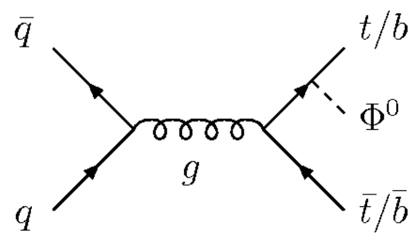


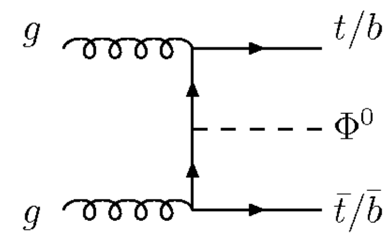
production at hadron colliders

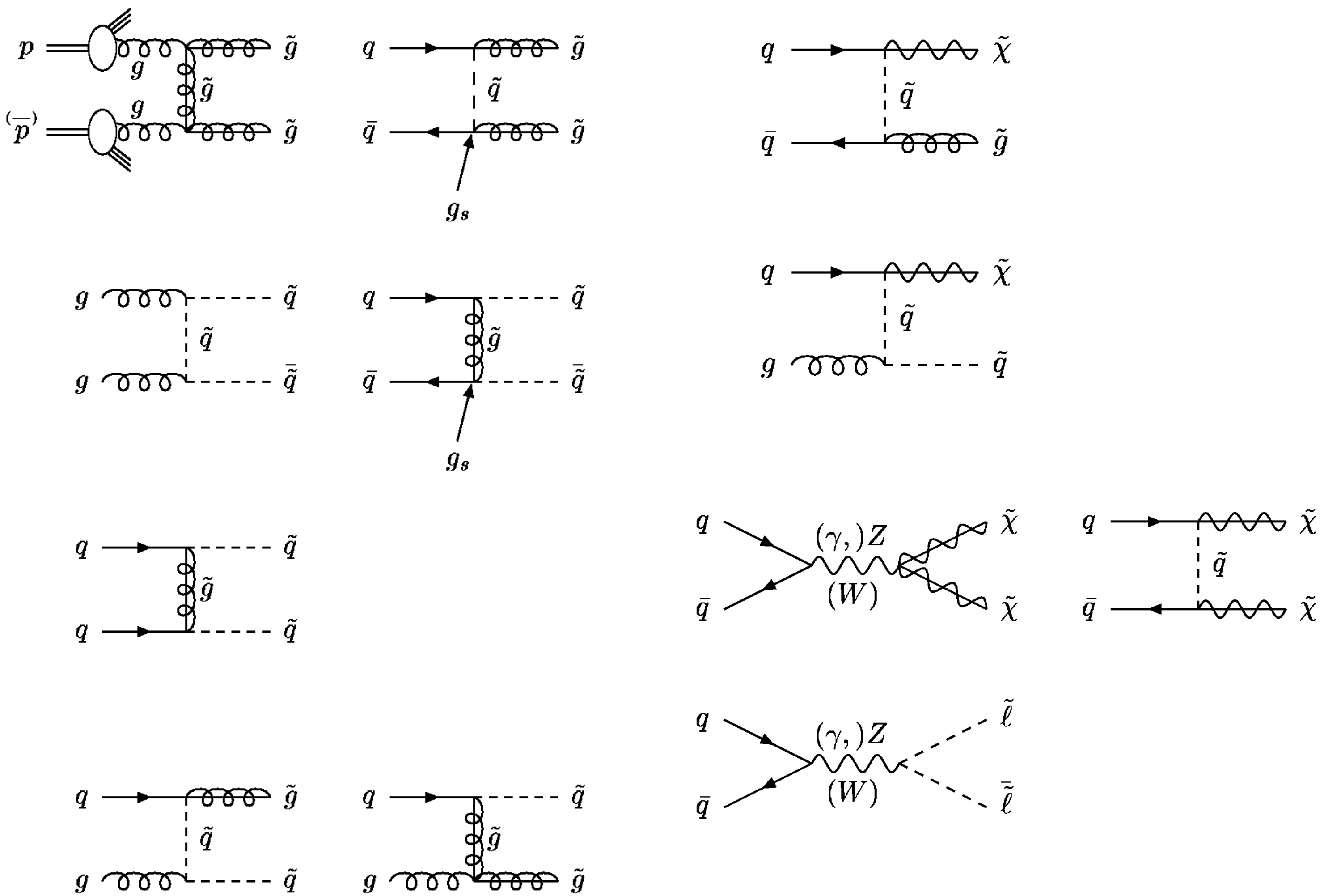




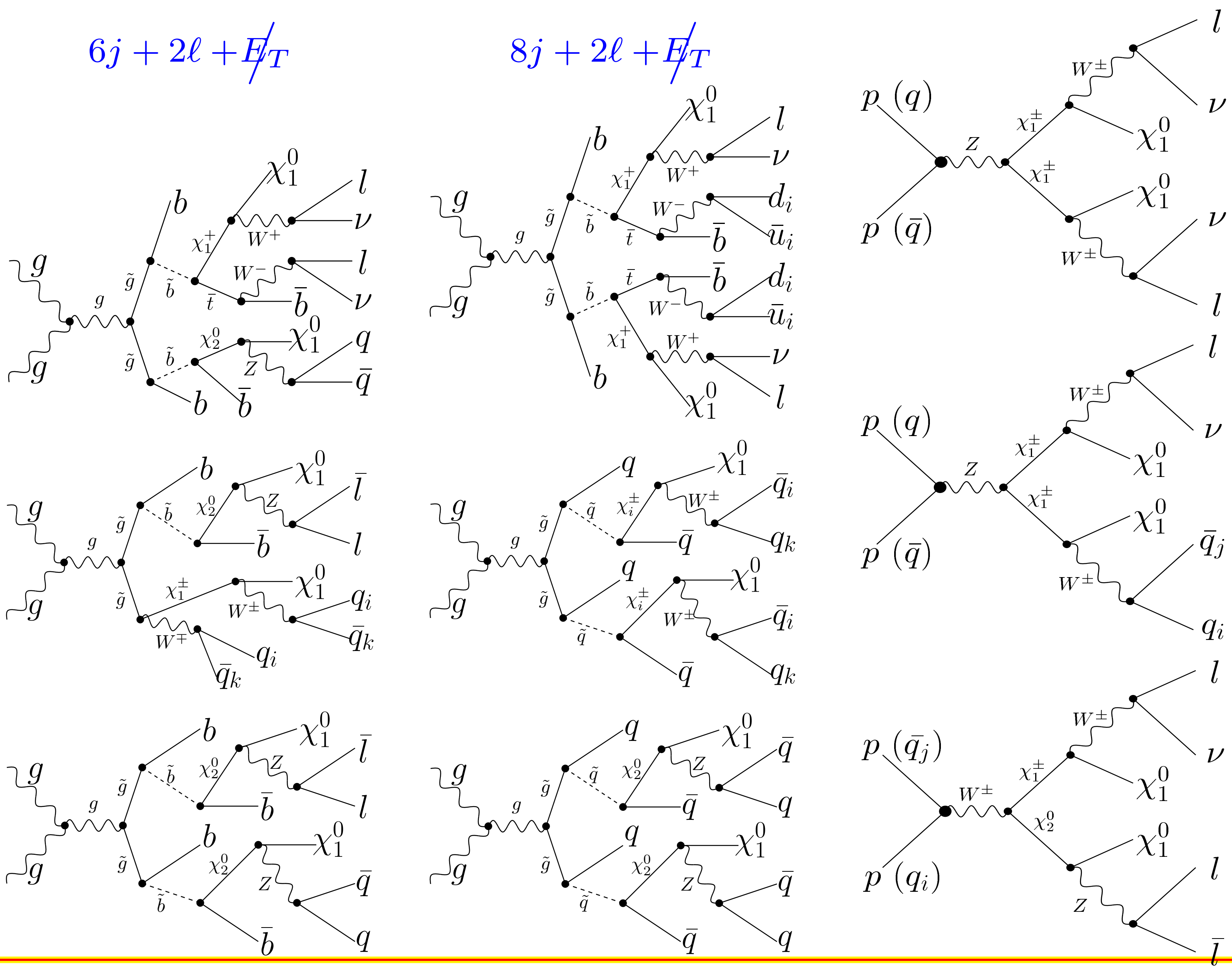







p
g
g̃
q
q̄
q̃
g_s
χ̃
(γ,)Z
(W)
ℓ̃

$6j + 2\ell + \not{E}_T$ $8j + 2\ell + \not{E}_T$

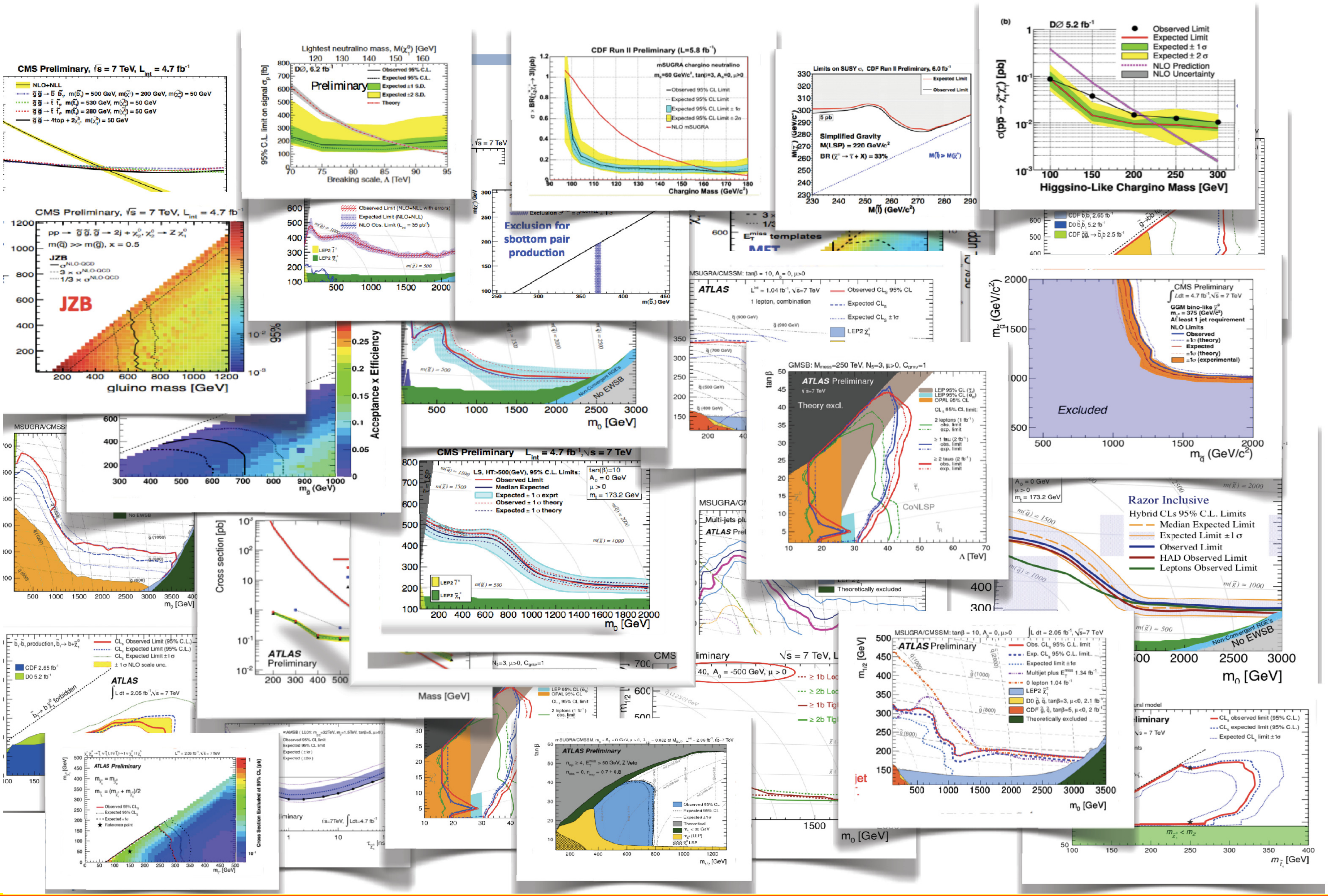


2ℓ
$\not{E}_T$

ℓ
$2j$
$\not{E}_T$

3ℓ
$\not{E}_T$

BSM searches, so far nothing . . .



LHC data, in particular m_h, high scale models

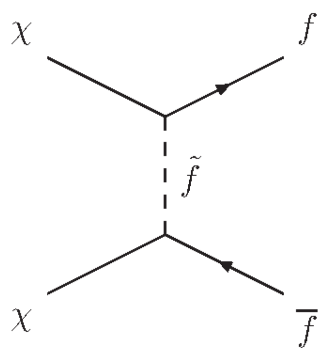
$m_h = 125.5$ GeV $\Rightarrow$ large loop contributions

$\Rightarrow$ 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

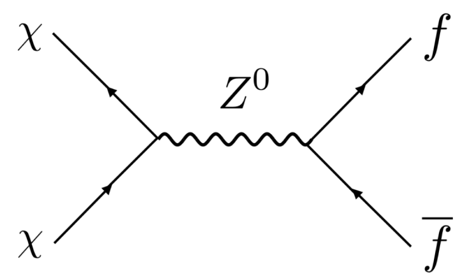
  more complicated models based on P. Meade, N. Seiberg and D. Shih, arXiv:0801.3278 $\Rightarrow$ allow additional terms, choice not well motivated $\Rightarrow$ generic MSSM
- CMSSM, NUHM models: $|A_0| \simeq 2m_0$,
  H. Baer, V. Barger and A. Mustafayev, arXiv:1112.3017; M. Kadastik *et al.*, arXiv:1112.3647; 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, annihilation processes



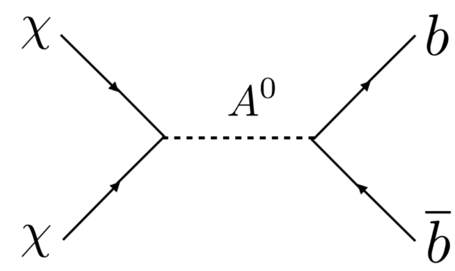
bino

bulk region

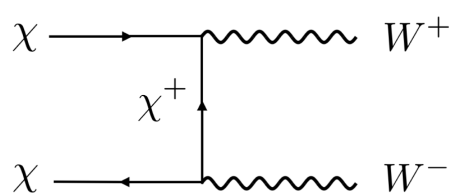


wino, higgsino

focus-point region

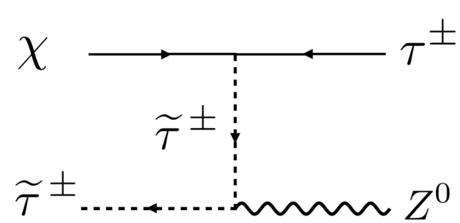


funnel region

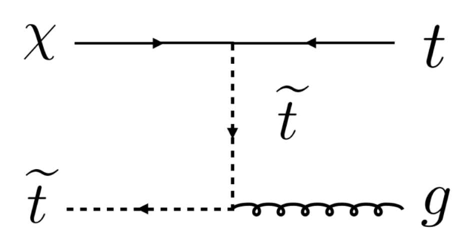


wino, higgsino

focus-point region

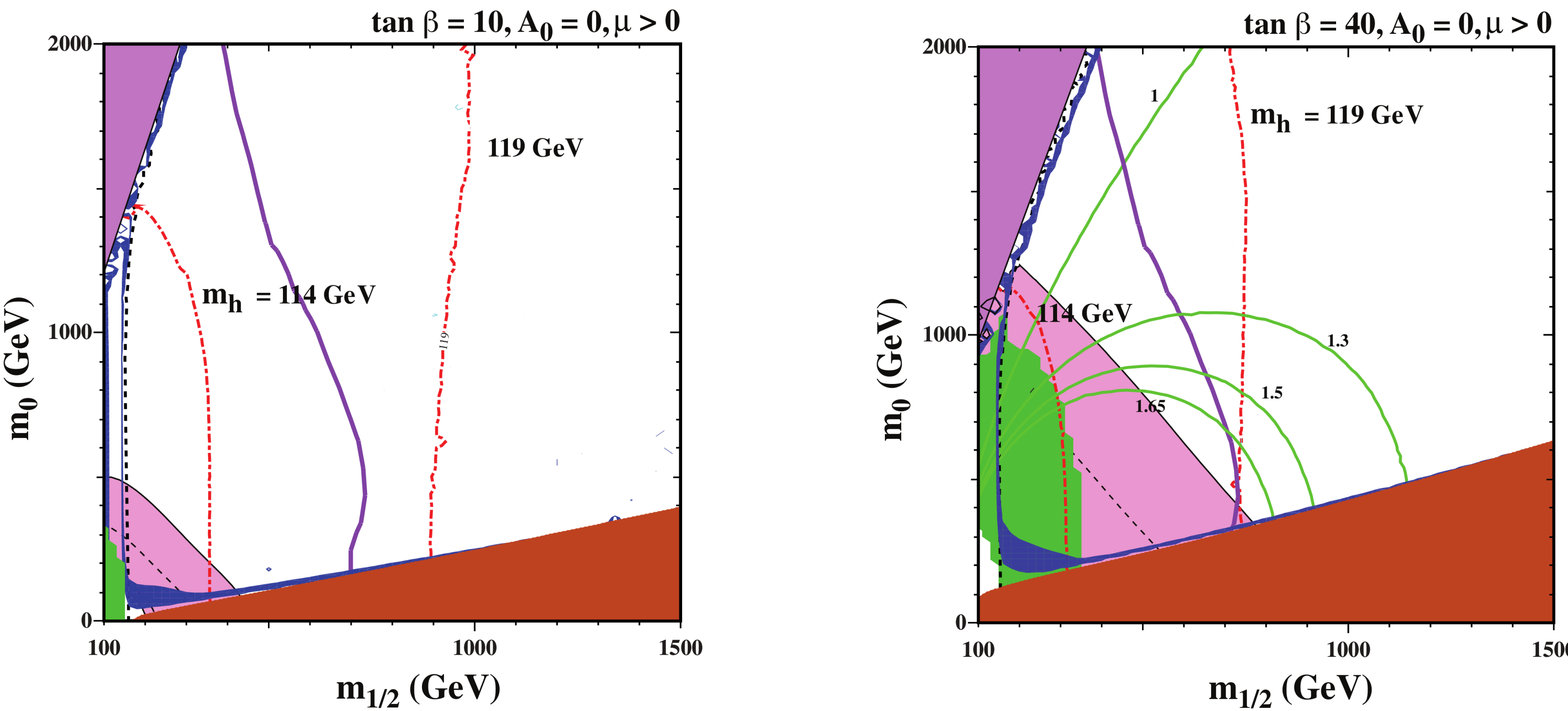


stau co-annihilation



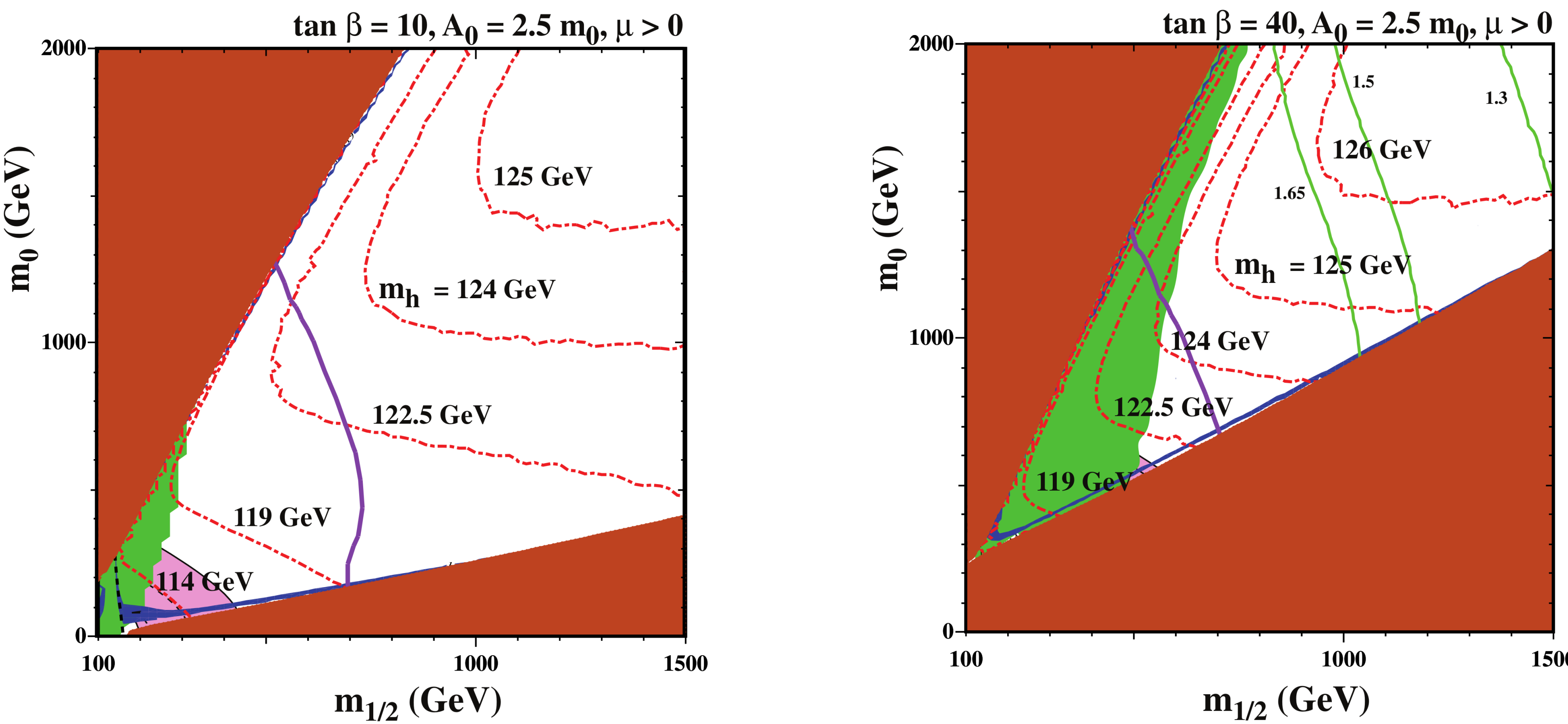
stop co-annihilation

Dark matter, mSUGRA



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

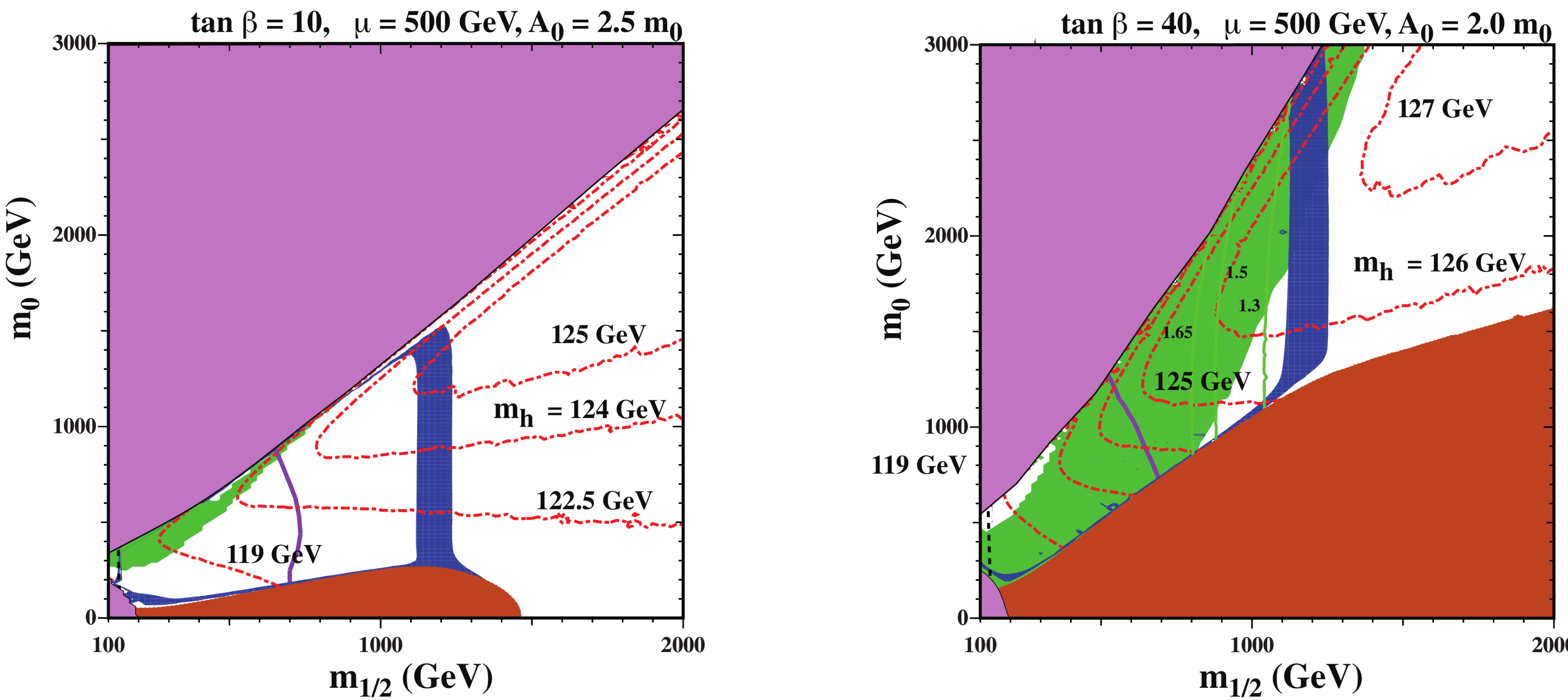
Dark matter, mSUGRA



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

Dark matter, NUHM1

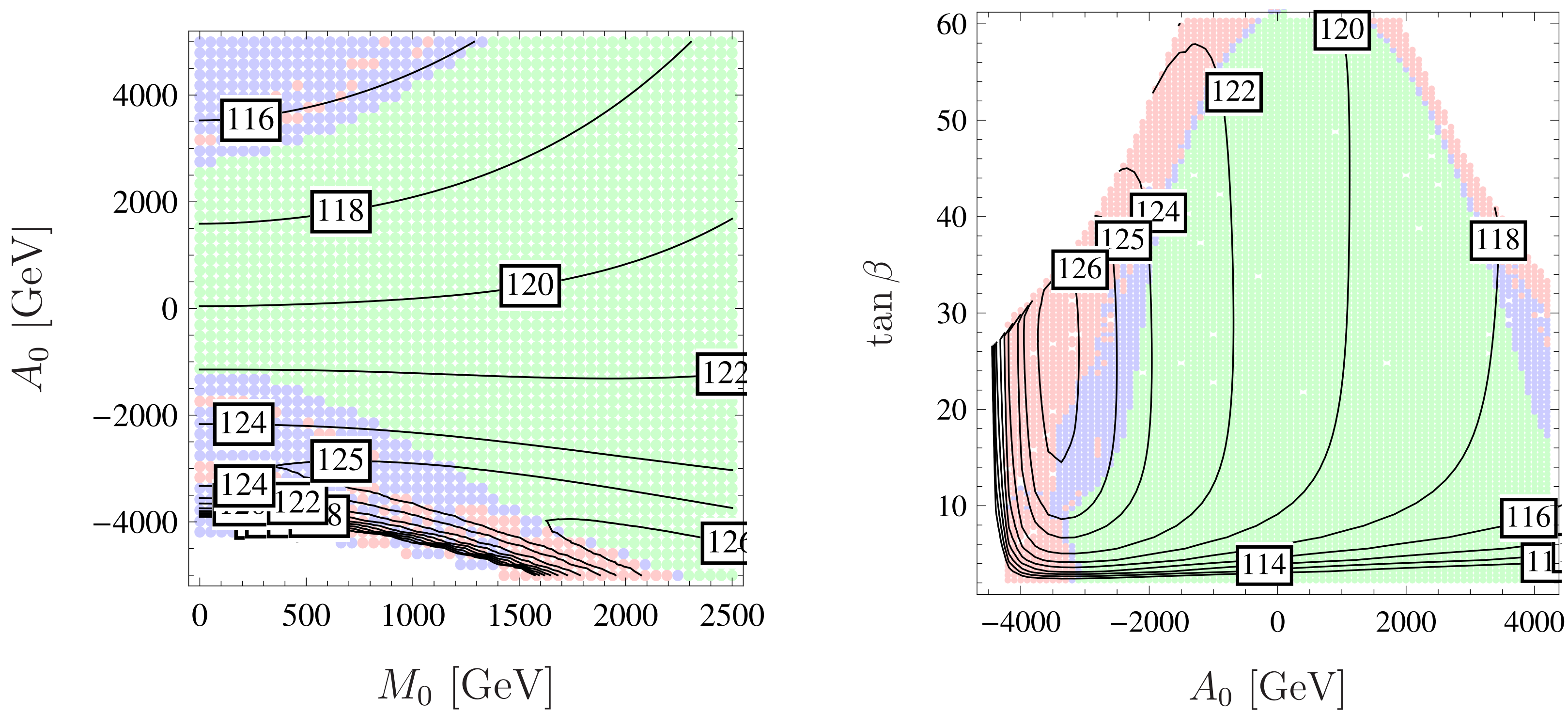
$m_{H_u}^2 \neq m_0^2 \Rightarrow \mu$ free parameter



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

mSUGRA/CMSSM, charge/color breaking minima

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



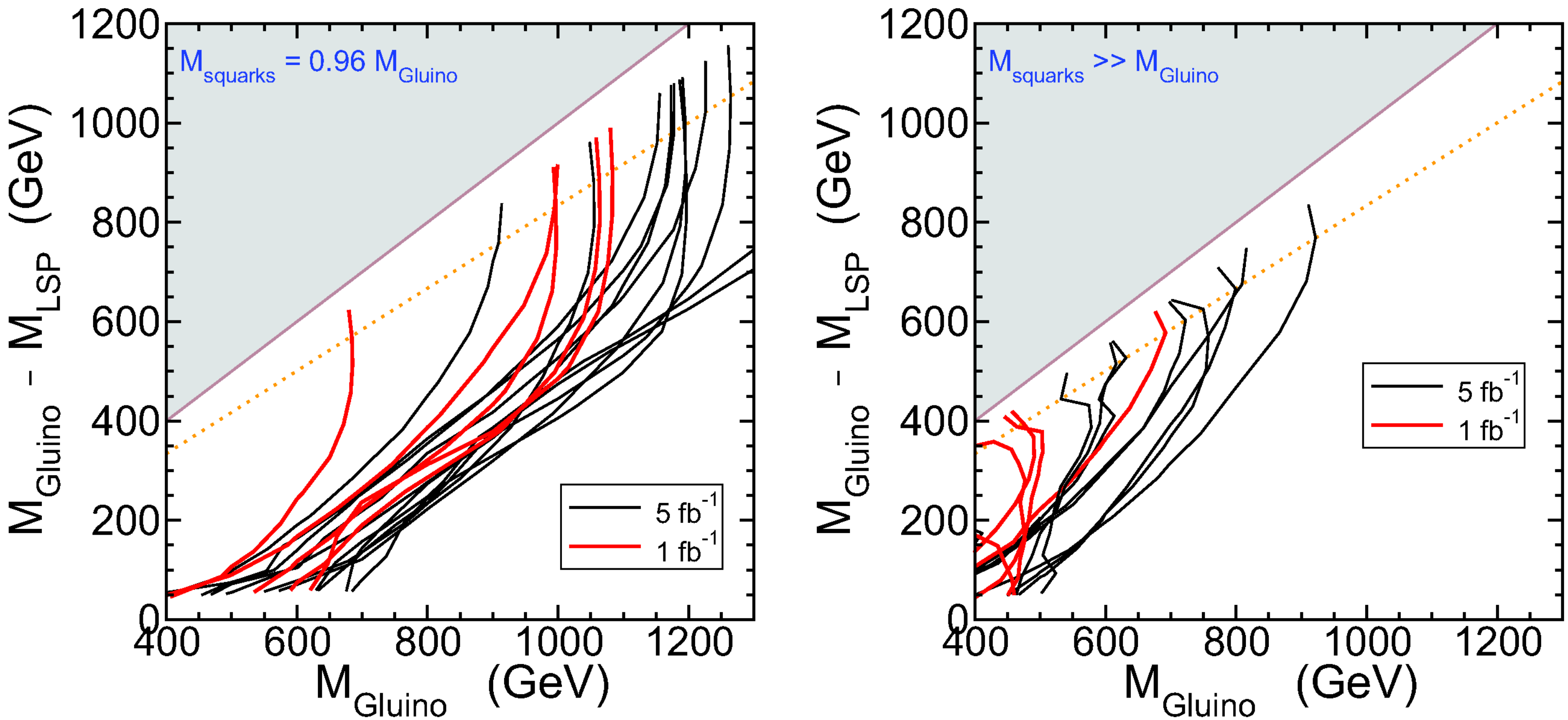
$M_{1/2} = 1$ TeV, $\tan\beta = 10$, $\mu > 0$ $\qquad$ $M_{1/2} = M_0 = 1$ TeV

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

GMSB, AMSB, CMSSM, . . . : hierarchical spectrum ⇒ hard jets, hard leptons, $\not{E}_T$

in general MSSM: complete different hierarchies possible
⇒ compressed spectra with (very) soft jets and leptons

S. Martin, talk at 'Implications of LHC results for TeV-scale physics', CERN, March 29, 2012, update of arXiv:1111.6897



H.K. Dreiner, M. Krämer, and J. Tattersall, arXiv:1211.4981 (using LHC 7 TeV results)
masses between LSP and either $\tilde{g}$ or $\tilde{q}$: 1-100 GeV

Search	$\mathcal{L}$ (fb^{-1})	Search Region (given in source)	Degeneracy Bound (GeV) Stop	Squark	Gluino	Equal
Monojet						
ATLAS	4.7	SR3/SR4	230	370	520	680
CMS	5.0	$E_T^{\rm miss} > 400$	190	340	480	650
SUSY						
ATLAS MET	4.7	A' med/C med	-	260	450	540
CMS α_T	5.0	Optimised H_T bin	190	330	530	600
CMS MET	5.0	A2	-	300	460	550
CMS M_{T2}	4.7	A/B	-	-	400	500
CMS Razor	4.4	bHad($6_4 + 7_4 + 8_4 + 9_4$)	200	350	530	610

Higgs in the general MSSM

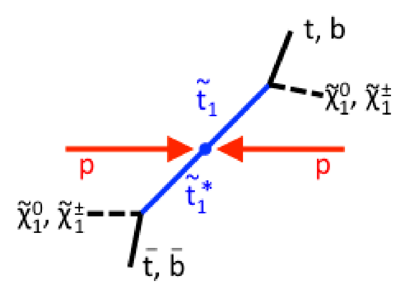
general MSSM: corrections maximised for $|(A_t - \mu/\tan\beta)/\sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}| \simeq 2$,
M. Carena et al., hep-ph/0001002
much more freedom, current data easily explained
see e.g. P. Bechtle et al., arXiv:1211.1955

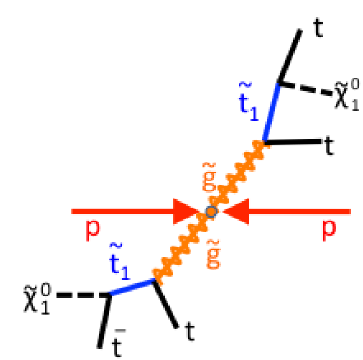
Parameter	Light Higgs case Best fit			Heavy Higgs case Best fit		
m_A [GeV]	300	669	860	120.5	124.2	128.0
$\tan\beta$	15	16.5	26	9.7	9.8	10.8
μ [GeV]	1900	2640	(3000)	1899	2120	2350
$M_{\tilde{Q}_3}$ [GeV]	450	1100	(1500)	580	670	740
$M_{\tilde{L}_3}$ [GeV]	250	285	(1500)	(200)	323	(1500)
A_f [GeV]	1100	2569	3600	1450	1668	1840
M_2 [GeV]	(200)	201	450	(200)	304	370
m_h [GeV]	122.2	126.1	127.1	63.0	65.3	72.0
m_H [GeV]	280	665	860	123.9	125.8	126.4
m_{H^+} [GeV]	310	673	860	136.5	138.8	141.5

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 $\tilde b_1$

NMSSM in nut-shell

μ-problem of the MSSM $\Rightarrow$ add singlet

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

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

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

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

NMSSM phenomenology in a nut-shell

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

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

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

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

- singlino as dark matter[d]

[a] see e.g. U. Ellwanger, J. F. Gunion and C. Hugonie, hep-ph/0503203

[b] see e.g. D. Das, U. Ellwanger and A. M. Teixeira, arXiv:1202.5244

[c] see e.g. U. Ellwanger and C. Hugonie, hep-ph/9712300
S. Hesselbach, F. Franke and H. Fraas, hep-ph/0007310

[d] see e.g. C. Hugonie, G. Belanger and A. Pukhov, arXiv:0707.0628

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 $E(8) \times E(8) \to SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$

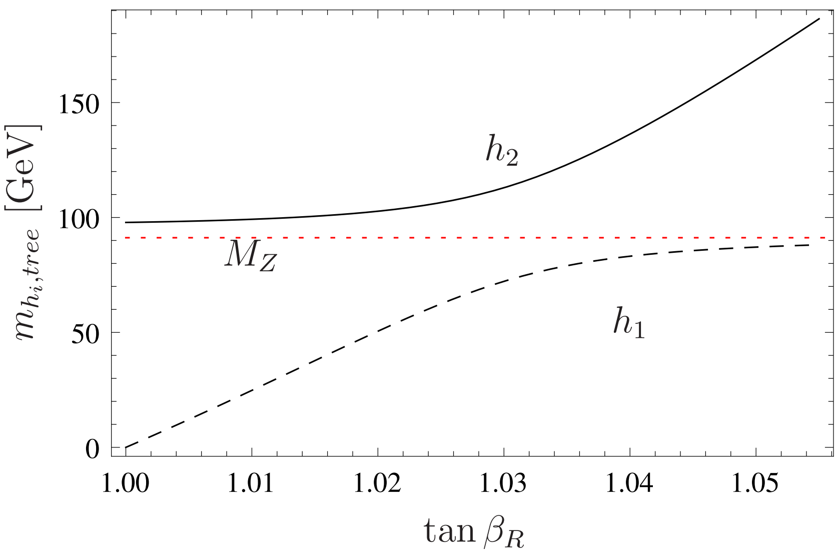
- Neutrino masses

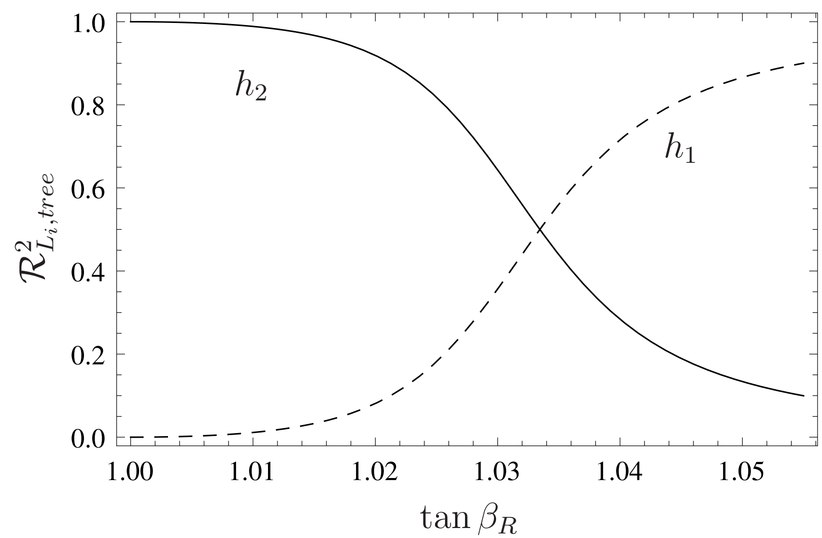
  $B - L$ anomaly free $\Rightarrow \nu_R$
  usual seesaw, inverse seesaw

Higgs sector I

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



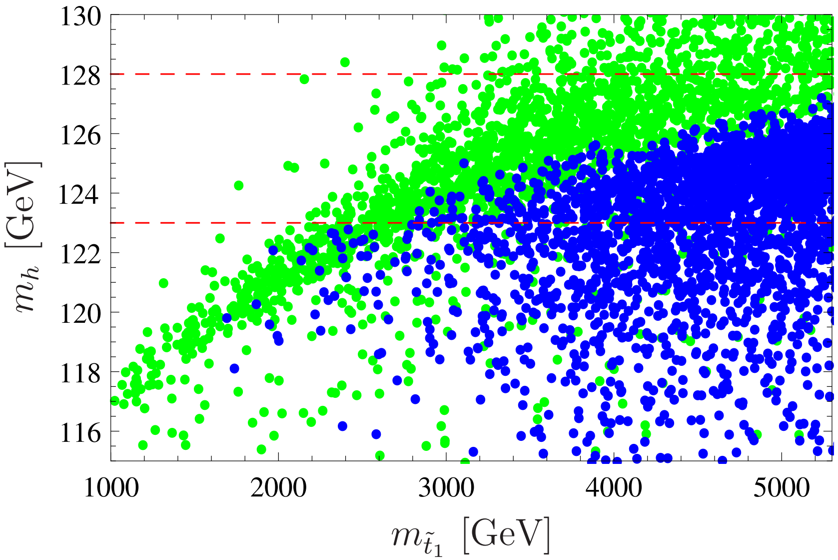


$n = 1,\ \Lambda = 5 \cdot 10^5$ GeV, $M = 10^{11}$ GeV, $\tan\beta = 30$, sign$(\mu_R) = -$, $diag(Y_S) = (0.7, 0.6, 0.6)$, $Y^{ii}_\nu = 0.01$, $v_R = 7$ TeV

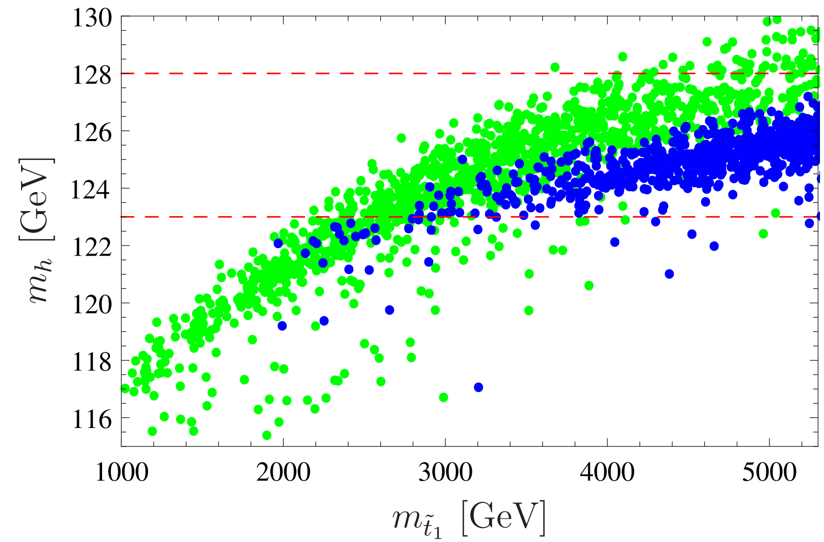
M.E. Krauss, W.P., F. Staub, arXiv:1304.0769

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: $h_2 \simeq h$

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

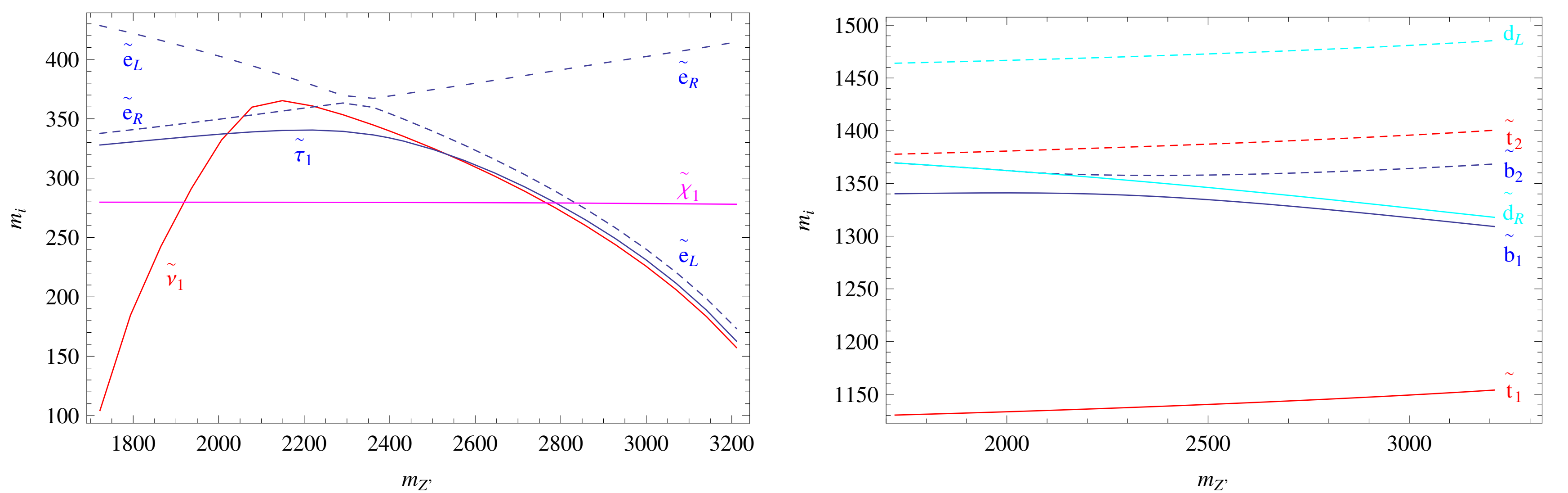
M.E. Krauss, W.P., F. Staub, arXiv:1304.0769

Sfermions

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

$D_L \simeq (-\frac{1}{2} + \sin^2_{\theta_W}) m^2_Z c_{2\beta} - \frac{15}{4} m^2_{Z'} c_{2\beta_R}$ and $D_R \simeq -\sin^2_{\theta_W} m^2_Z c_{2\beta} + \frac{5}{4} m^2_{Z'} c_{2\beta_R}$

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.
$m_{\chi^0_1}$	367.	417.	313.	259. $\tilde{h}_R$	412.
$m_{\chi^0_2}$	718.	780. $\tilde{h}_R$	615.	280.	739. $\tilde{h}_R$
$m_{\chi^0_3}$	1047.	818.	1087.	549.	804.
$m_{\chi^0_5}$	1348. $(\tilde{B}_\perp)$	1866.	1232. $(\tilde{B}_\perp)$	857.	1294.
$m_{\chi^0_6}$	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

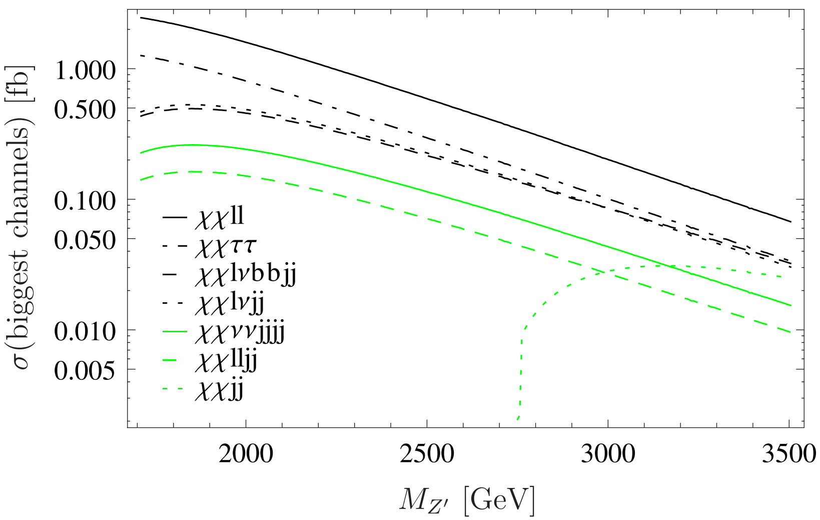
$$\begin{aligned}
\tilde{q}_R &\to q\tilde{\chi}^0_1 \to q\nu_k\tilde{\nu}_1 \to q\nu_j Z\tilde{\nu}_1 \qquad (k = 4,\ldots,9\,,\; j = 1,2,3) \\
\tilde{q}_R &\to q\tilde{\chi}^0_1 \to q\nu_k\tilde{\nu}_1 \to q l^\pm W^\mp\tilde{\nu}_1 \\
\tilde{q}_R &\to q\tilde{\chi}^0_1 \to q\nu_k\tilde{\nu}_3 \to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

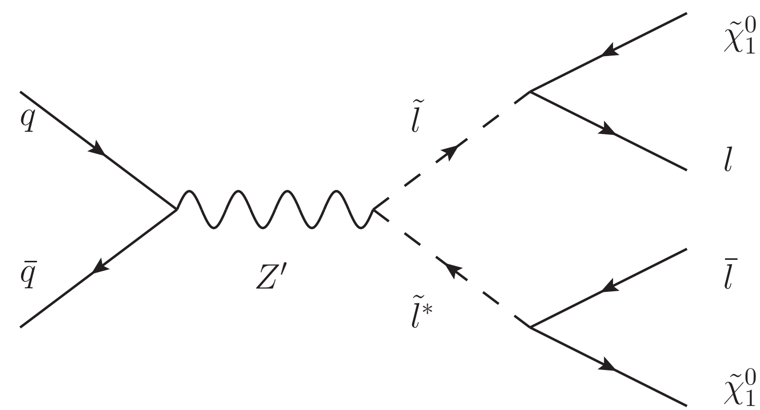
BLRSP3: usual cascades similar to CMSSM, but

$$\begin{aligned}
\tilde{\chi}^0_1 &\to l^\pm\tilde{l}^\mp \to l^\pm W^\mp\tilde{\nu}_1 \qquad (j = 1,2,3\;,\; k = 4,5,6) \\
\tilde{\chi}^0_1 &\to l^\pm\tilde{l}^\mp \to l^\pm W^\mp\tilde{\nu}_{2,3} \to l^\pm W^\mp f\bar{f}\tilde{\nu}_1 \\
\tilde{\chi}^0_1 &\to \nu_j\tilde{\nu}_{2,3} \to \nu_{1,2,3} f\bar{f}\tilde{\nu}_1 \\
\tilde{\chi}^0_1 &\to \nu_j\tilde{\nu}_k \to \nu_j h_{1,2}\tilde{\nu}_1 \\
\tilde{\chi}^0_1 &\to \nu_j\tilde{\nu}_k \to \nu_j h_{1,2} f\bar{f}\tilde{\nu}_1
\end{aligned}$$

$\Rightarrow$ enhanced jet and lepton multiplicities

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





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

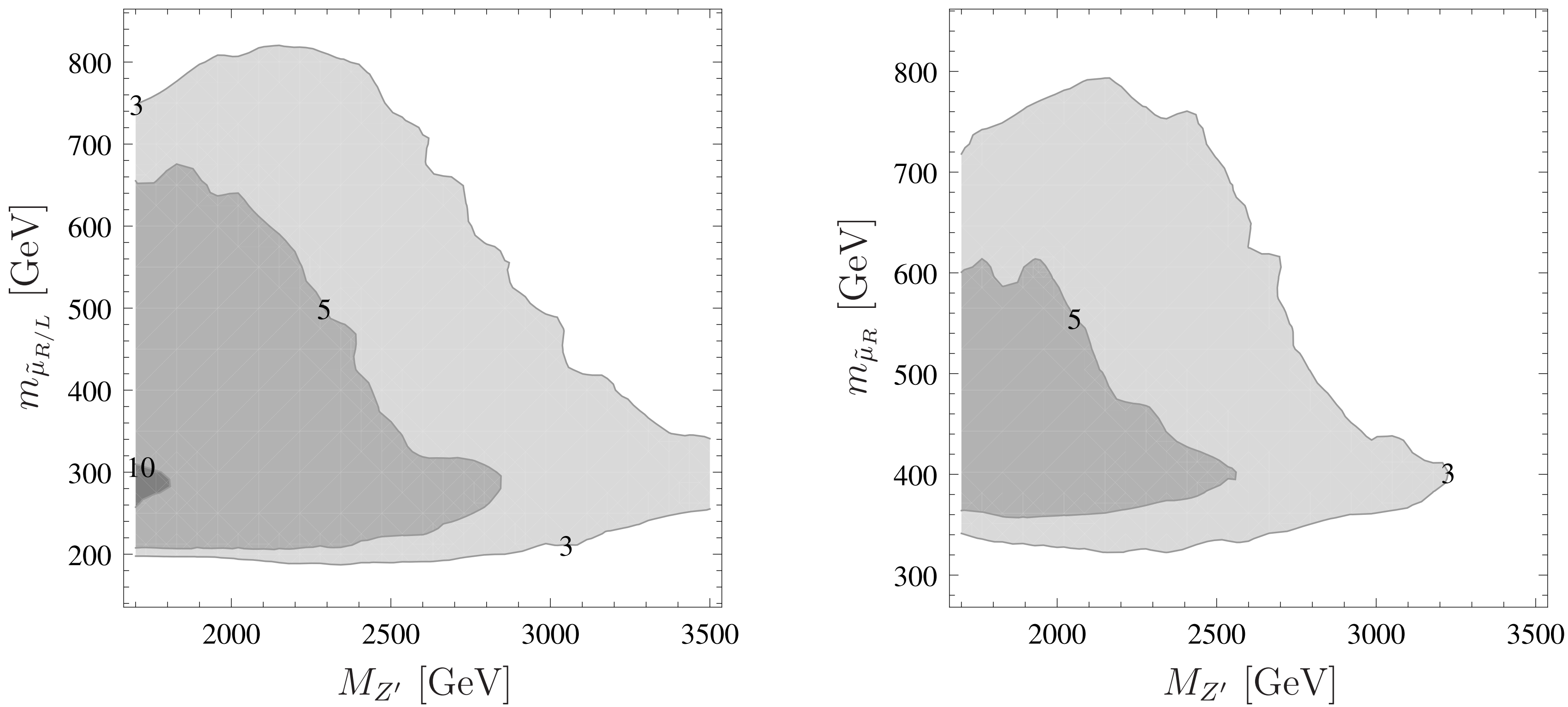
see also: J. Kang and P. Langacker, PRD **71** (2005) 035014; M. Baumgart, T. Hartman, C. Kilic, and L.-T. Wang, JHEP **0711** (2007) 084; C.-F. Chang, K. Cheung, and T.-C. Yuan, JHEP **1109** (2011) 058; G. Corcella and S. Gentile, arXiv:1205.5780

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

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

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

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

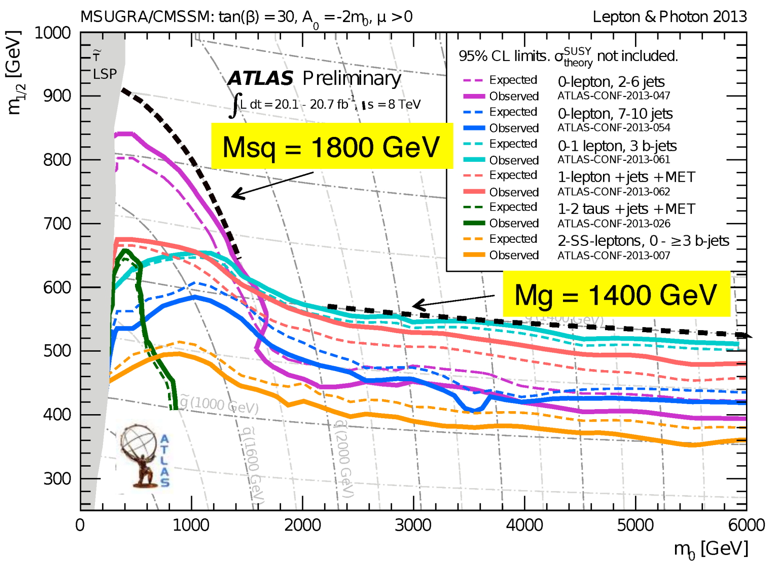


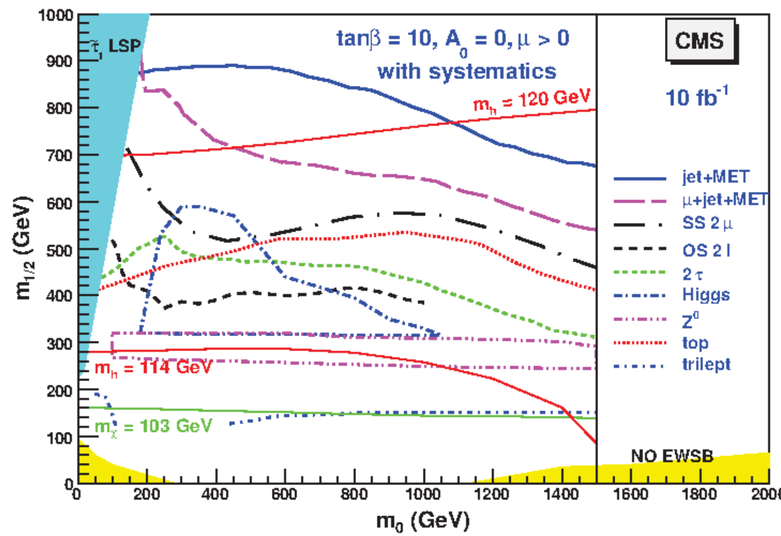
M. Krauss, B. O'Leary, W.P., F. Staub, arXiv:1206.3513

Conclusions

- $m_h = 125.5$ 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
  - natural MSSM: expect t, b, W and $\not{E}_T$ in the final states
  - general MSSM: predictions depend strongly on details
  - models with large A_t, A_b: problems with charge/color breaking minima
- NMSSM particle content: non-standard Higgs decays, displaced vertices at LHC
- models with extended gauge sectors
  - 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
  - Z' might look differently than expected & might even serve as SUSY discovery channel

Conclusions





- I do not expect significant SUSY signals at LHC@14TeV before $L \simeq 10$ fb^{-1} but potentially a Z'
- Even in the CMSSM the parameter range is much larger, let alone the general (N)MSSM or non-minimal realisations

SUSY looks most likely different than CMSSM suggested

Heavy neutrinos

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

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

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

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

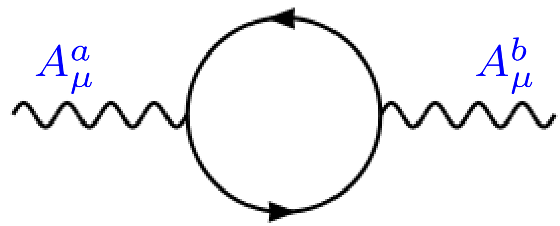
in BLRSP4

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

Gauge kinetic mixing

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

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



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

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

Vector bosons

basis (W^0, B_Y, B_χ)

$$
\begin{aligned}
M^2_{VV} &= \frac{1}{4}\begin{pmatrix} g_2^2 v^2 & -g_2 g' v^2 & g_2 \tilde{g}_\chi v^2 \\ -g_2 g' v^2 & g'^2 v^2 & -g' \tilde{g}_\chi v^2 \\ g_2 \tilde{g}_\chi v^2 & -g' \tilde{g}_\chi v^2 & \frac{25}{4} g_\chi^2 v_R^2 + \tilde{g}_\chi^2 v^2 \end{pmatrix} \\
\tilde{g}_\chi &= g_\chi - g_{Y\chi} \\
v^2 &= v_d^2 + v_u^2 \ , \ v_R^2 = v_{\chi_R}^2 + v_{\bar{\chi}_R}^2
\end{aligned}
$$

expanding in v^2/v_R^2

$$
\begin{aligned}
m_Z^2 &\simeq \frac{1}{4}\left(g'^2 + g_2^2\right) v^2 \left(1 - \frac{4}{25}\left(1 - \frac{g_{Y\chi}}{g_\chi}\right)^2 \frac{v^2}{v_R^2}\right) \\
m_{Z'}^2 &\simeq \left(\frac{5}{4} g_\chi v_R\right)^2
\end{aligned}
$$

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

$$
\begin{aligned}
M^2_{hh} &= \begin{pmatrix} m^2_{LL} & m^2_{LR} \\ m^{2,T}_{LR} & m^2_{RR} \end{pmatrix} \\
m^2_{LL} &= \begin{pmatrix} g^2_\Sigma v^2 c^2_\beta + m^2_A s^2_\beta & -\frac{1}{2}\left(m^2_A + g^2_\Sigma v^2\right) s_{2\beta} \\ -\frac{1}{2}\left(m^2_A + g^2_\Sigma v^2\right) s_{2\beta} & g^2_\Sigma v^2 s^2_\beta + m^2_A c^2_\beta \end{pmatrix} , \\
m^2_{LR} &= \frac{5}{8} g_\chi \tilde{g}_\chi v v_R \begin{pmatrix} c_\beta c_{\beta_R} & -c_\beta s_{\beta_R} \\ -s_\beta c_{\beta_R} & s_\beta s_{\beta_R} \end{pmatrix} , \\
m^2_{RR} &= \begin{pmatrix} g^2_{Z_R} v^2_R c^2_{\beta_R} + m^2_{A_R} s^2_{\beta_R} & -\frac{1}{2}\left(m^2_{A_R} + g^2_{\Sigma_R} v^2_R\right) s_{2\beta_R} \\ -\frac{1}{2}\left(m^2_{A_R} + g^2_{\Sigma_R} v^2_R\right) s_{2\beta_R} & g^2_{\Sigma_R} v^2_R s^2_{\beta_R} + m^2_{A_R} c^2_{\beta_R} \end{pmatrix} \\
v^2_R &= v^2_{\chi_R} + v^2_{\bar{\chi}_R} \; , \; v^2 = v^2_d + v^2_u \; , \; s_x = \sin(x) \; , \; c_x = \cos(x) \\
g^2_\Sigma &= \frac{1}{4}(g^2_2 + g'^2 + \tilde{g}^2_\chi) \; , \; g^2_{\Sigma_R} = \frac{25}{16} g^2_\chi \; , \; \tilde{g}_\chi = g_\chi - g_{Y\chi}
\end{aligned}
$$

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

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 $(\lambda_Y, \lambda_{W^3}, \tilde{h}^0_d, \tilde{h}^0_u, \lambda_\chi, \tilde{\bar{\chi}}_R, \tilde{\chi}_R)$

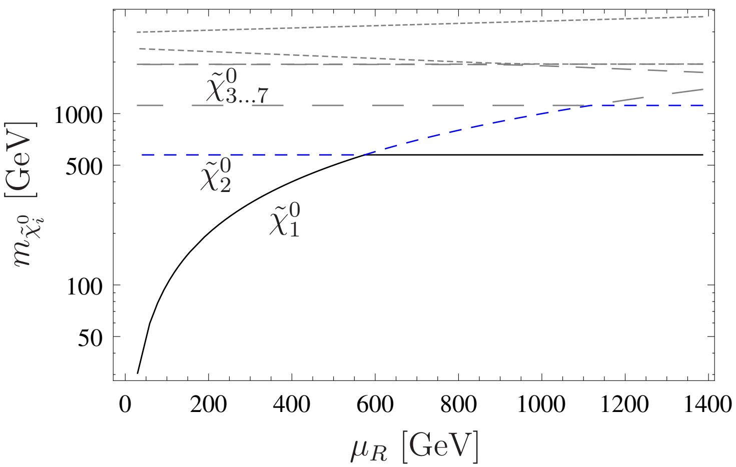
$$M_{\tilde{\chi}^0} =$$

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

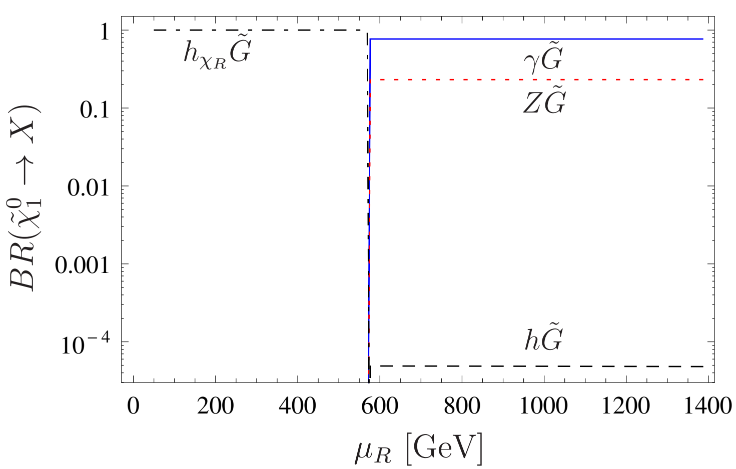
neglecting the mixing between the two sectors and setting $\tan\beta_R = 1$

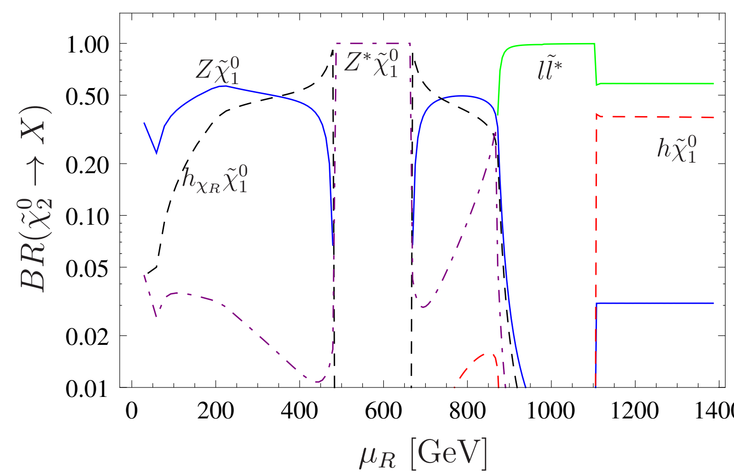
$$m_i : \ \mu_R , \quad \frac{1}{2}\left(M_\chi + \mu_R \pm \sqrt{\frac{1}{4} m^2_{Z'} + (M_\chi - \mu_R)^2} \right)$$

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

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

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

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

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

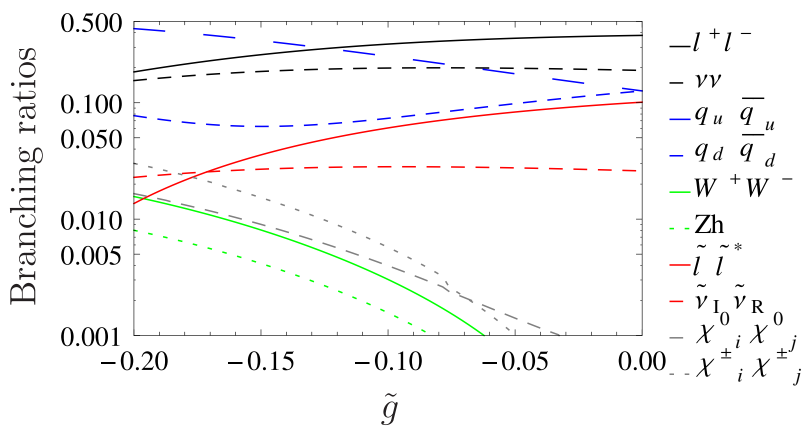
$$D_L = \frac{1}{32}\Big(2\big(-3g_\chi^2 + g_\chi g_{Y\chi} + 2(g_2^2 + g'^2 + g_{Y\chi}^2)\big) v^2 c_{2\beta} - 5 g_\chi (3 g_\chi + 2 g_{Y\chi}) v_R^2 c_{2\beta_R}\Big)\mathbf{1}$$

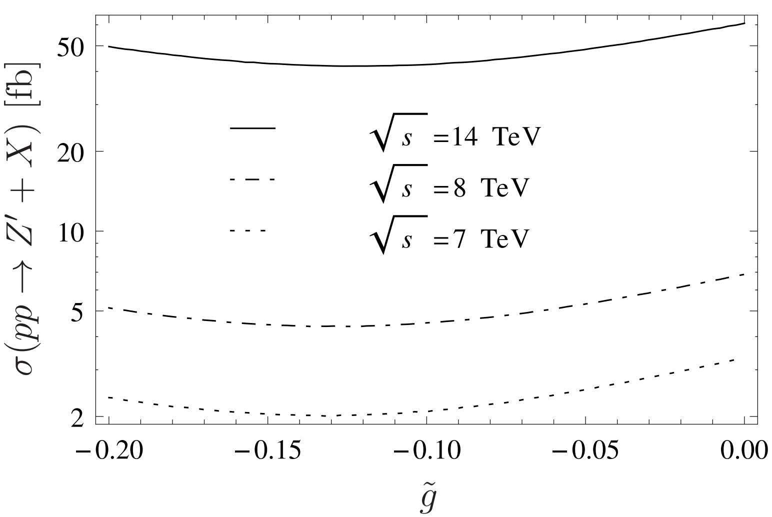
$$D_R = \frac{5 g_\chi}{32}\Big(2(g_\chi - g_{Y\chi}) v^2 c_{2\beta} + 5 g_\chi v_R^2 c_{2\beta_R}\Big)\mathbf{1}$$

Z' physics, effect of gauge kinetic mixing I

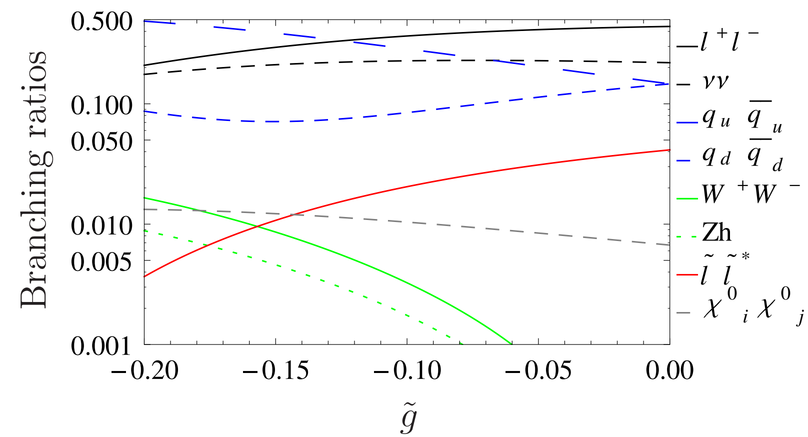
Z' couplings: $Q_{B-L} \cdot g_{B-L} \to Q_{B-L} \cdot g_{B-L} + Q_Y \cdot \tilde{g}$

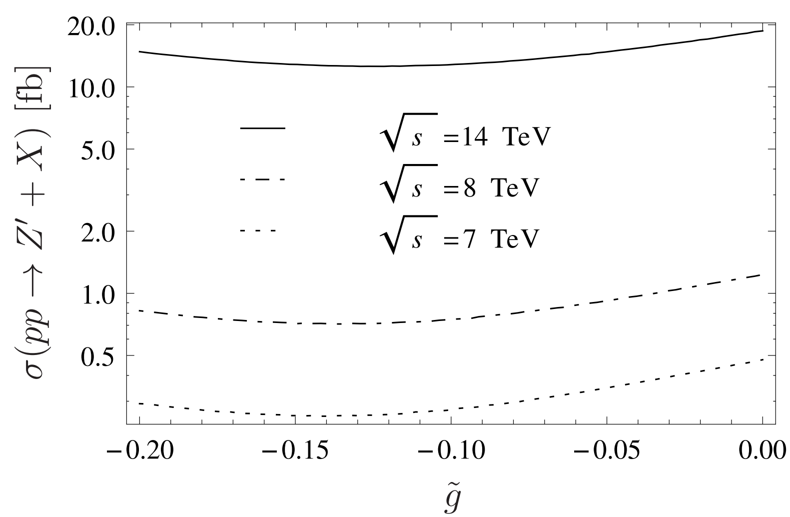
BL1





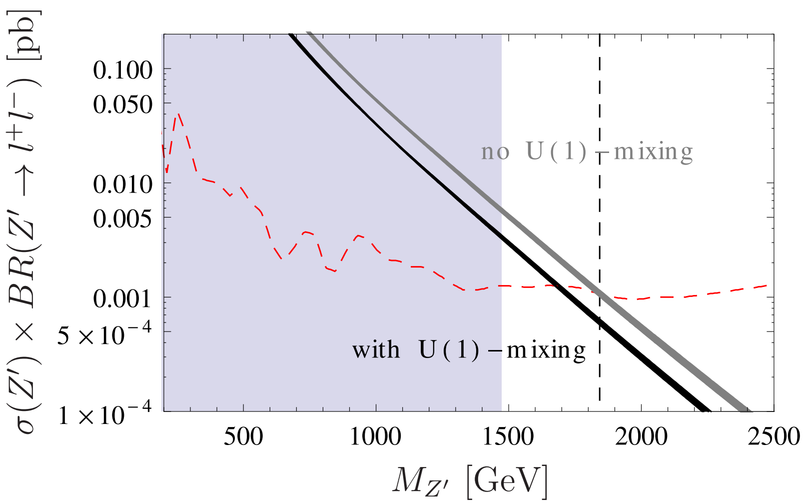
BL2



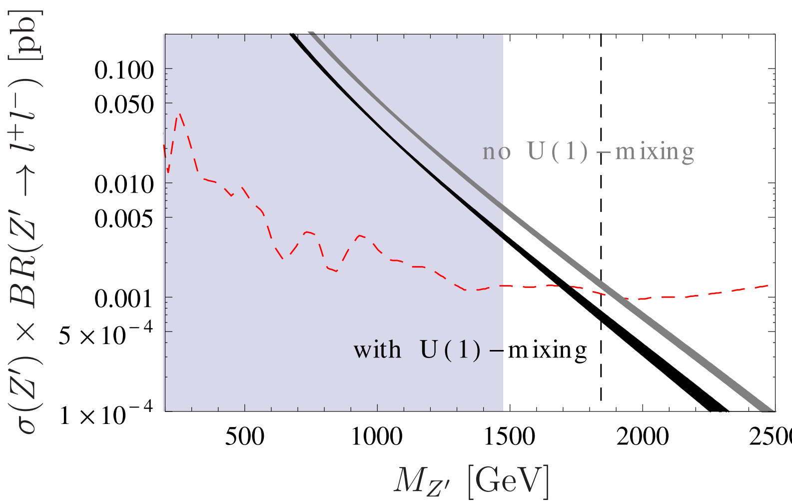


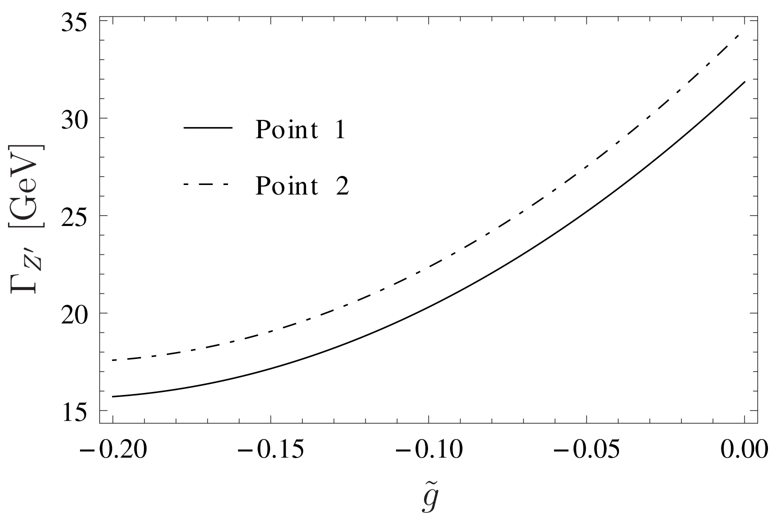
Z' physics, effect of gauge kinetic mixing II

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:

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