Supersymmetric models in the light of the first LHC run

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supported by BAYLAT

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- MSSM
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  - general MSSM, ‘natural SUSY’
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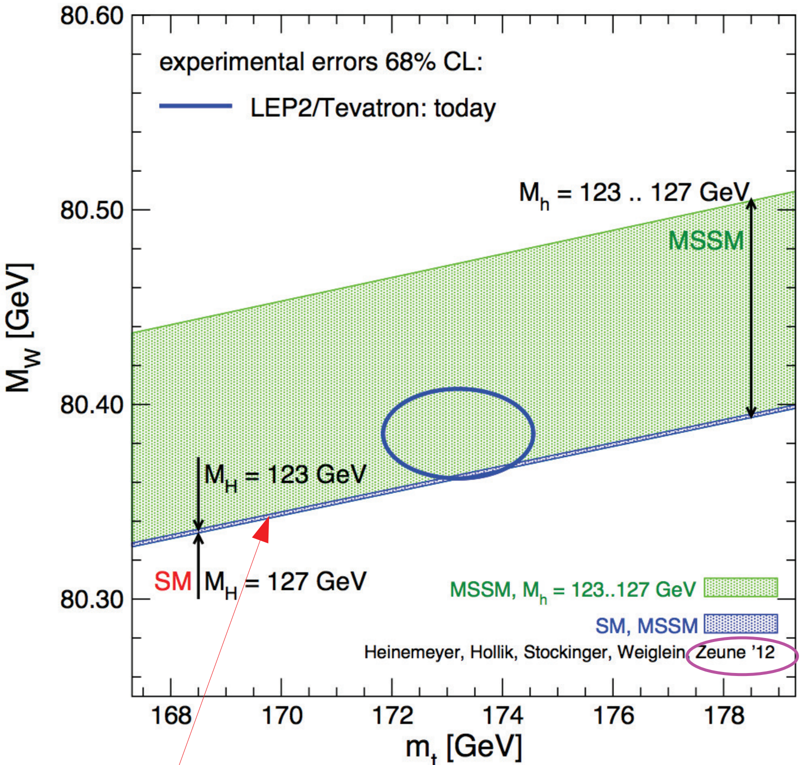
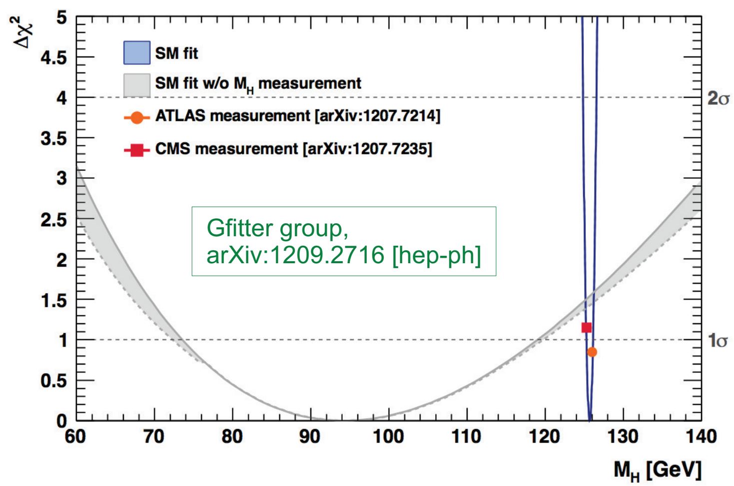
  - implications for SUSY cascade decays
  - Z' physics

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:



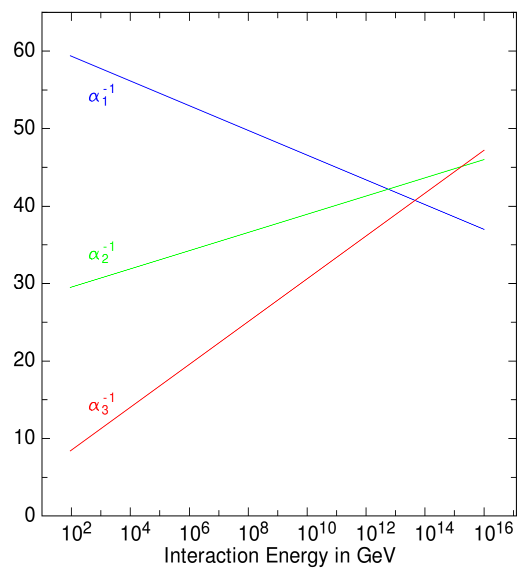
Consistent at the 1.3 σ level.

Why do we want to extend the SM

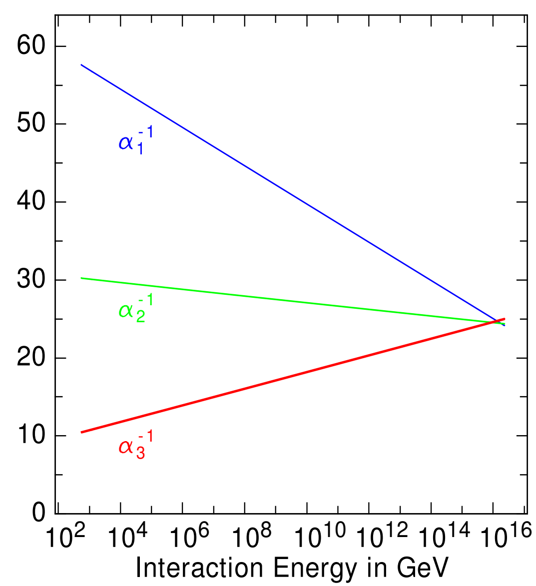
- How to combine gravity with the SM?
  $\Rightarrow$ local Supersymmetry (SUSY) implies gravity
- SM particles can be put in multiplets of larger gauge groups
  - in $SU(5)$: $1 = \nu^c_R$, $5 = (d^c_{\alpha,R}, \nu_{l,L}, l_L)$, $10 = (u_{\alpha,L}, u^c_{\alpha,R}, d_{\alpha,L}, l_R)$
  - in $SO(10)$: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

  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

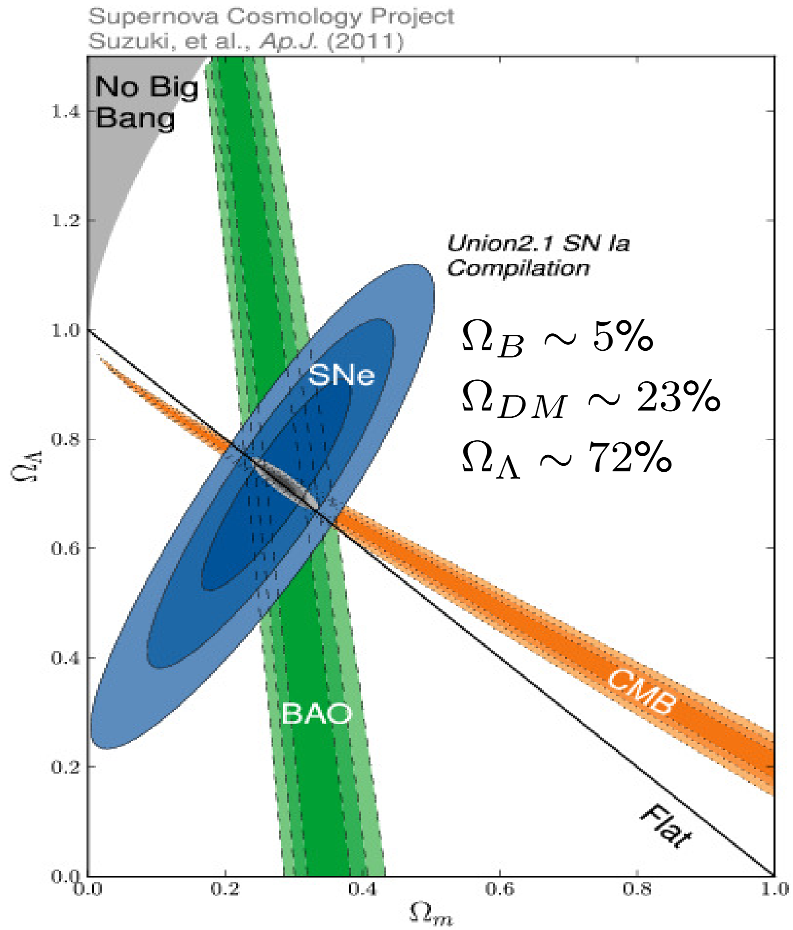


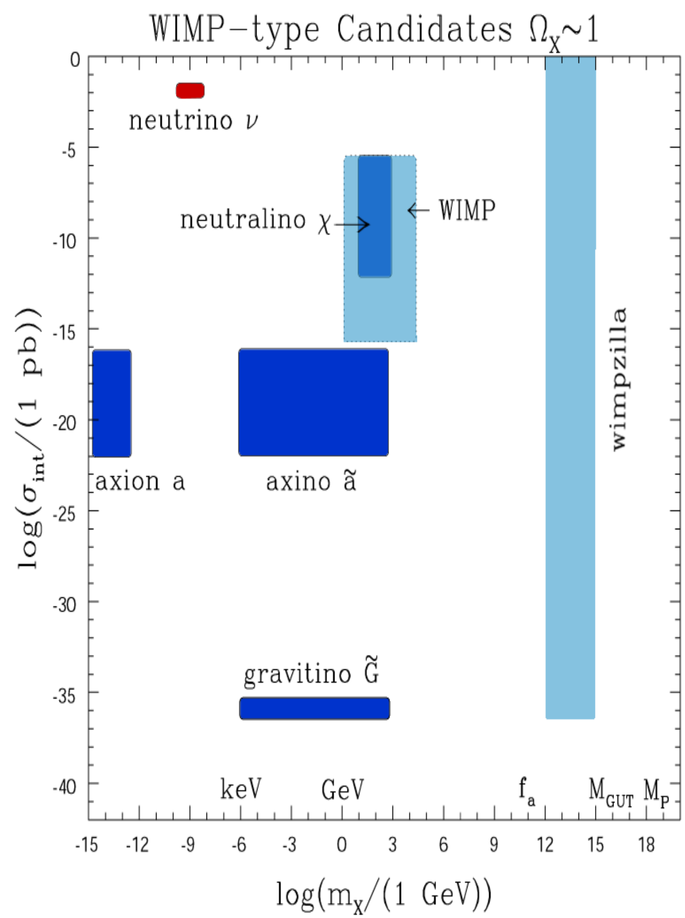
MSSM



Why do we want to extend the SM

- What is the nature of dark matter ?



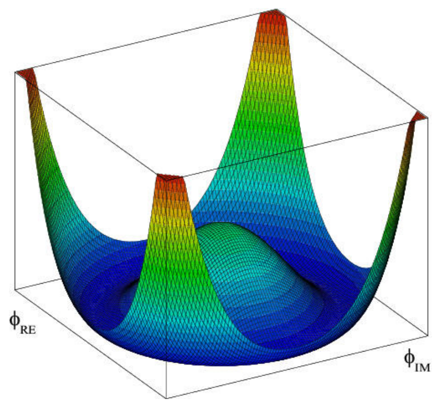


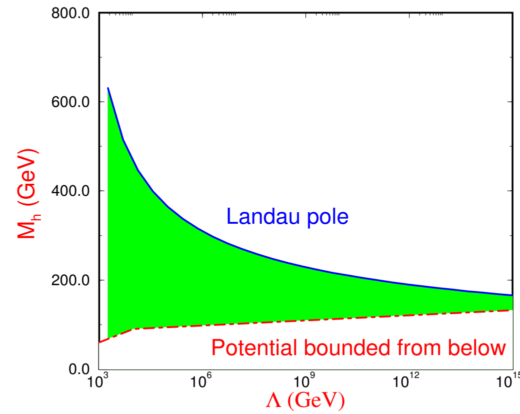
L. Roszkowski, astro-ph/0404052

- What is the origin of the observed baryon asymmetry?

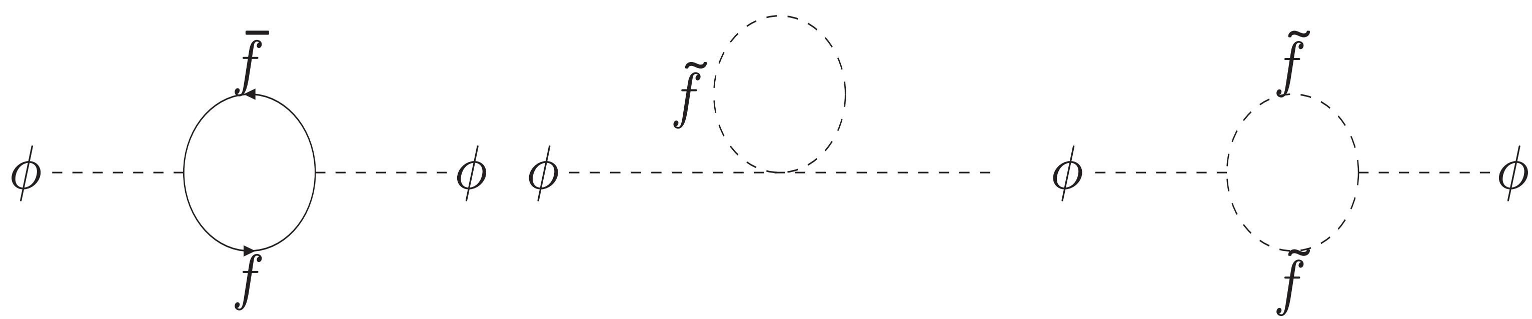
Why do we want to extend the SM

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

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

MSSM, generalities

$$
\begin{aligned}
W_{MSSM} &= -\mu \hat{H}_d \hat{H}_u + \hat{H}_d \hat{L} Y_e \hat{E}^c + \hat{H}_d \hat{Q} Y_d \hat{D}^c - \hat{H}_u \hat{Q} Y_u \hat{U}^c \\
W_{\not{L}} &= \epsilon_i \hat{L}_i \hat{H}_u^b + \lambda_{ijk} \hat{L}_i \hat{L}_j \hat{E}_k^c + \lambda'_{ijk} \hat{L}_i \hat{Q}_j \hat{D}_k \\
W_{\not{B}} &= \lambda''_{ijk} \hat{U}_i^c \hat{D}_j^c \hat{D}_k^c
\end{aligned}
$$

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

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

soft SUSY breaking terms

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

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, $x = \Lambda/M$, $\Lambda = O(100TeV) < M$

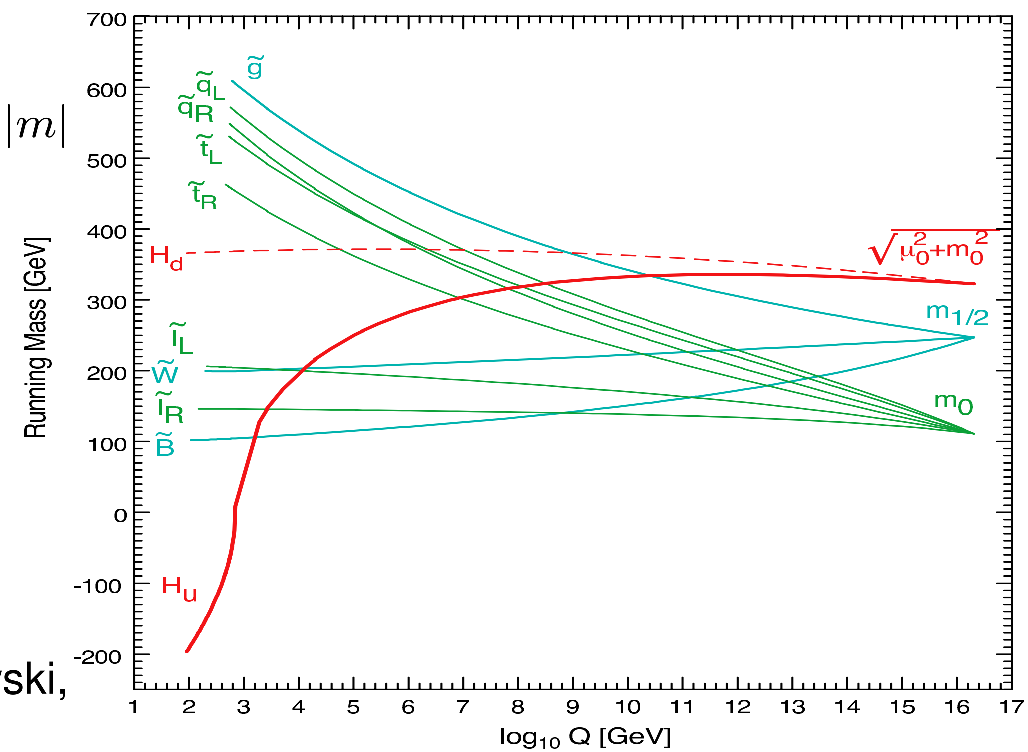
MSSM, generalities

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
  $m_A, \tan\beta = v_u/v_d$
  $m_h \leq m_Z$

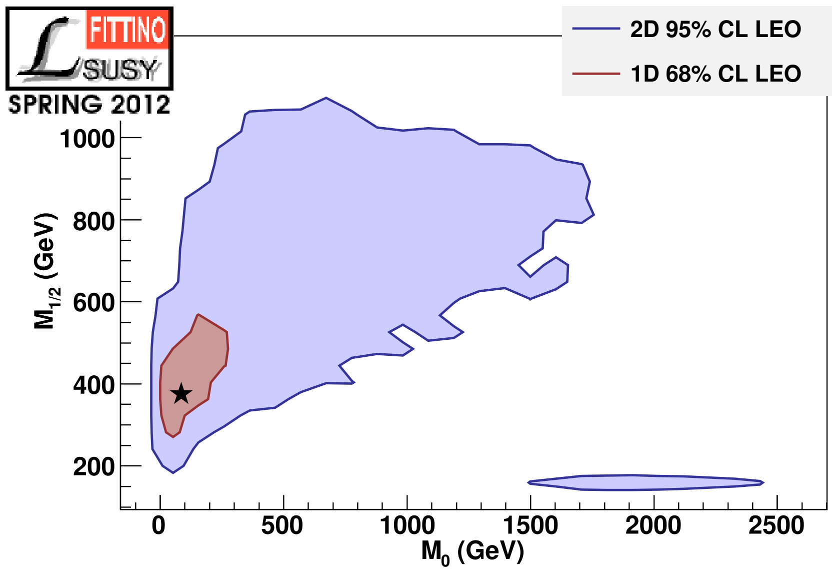
  Ellis et al; Okada et al; Haber,Hempfling; Hoang et al; Carena et al; Heinemeyer et al; Zhang et al; Brignole et al; Harlander et al; Kant,Harlander,Mihaila,Steinhauser;...

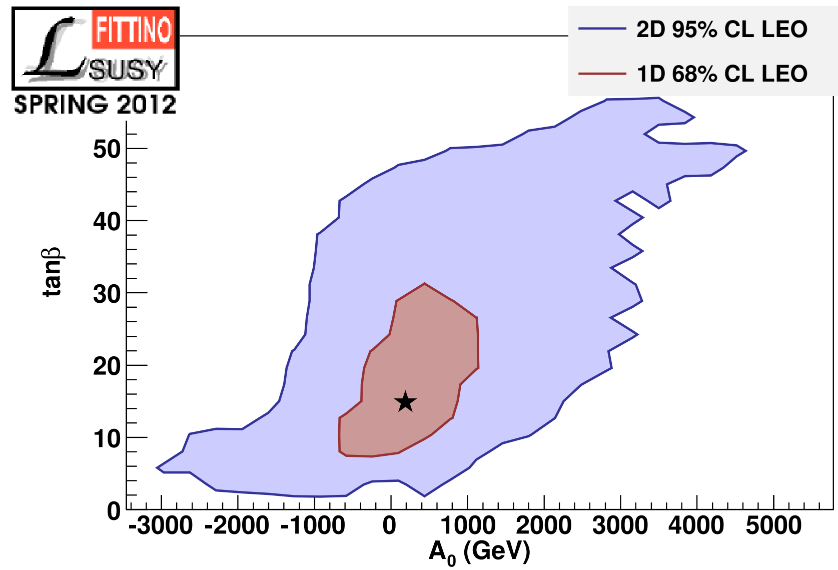
  at higher order:

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

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

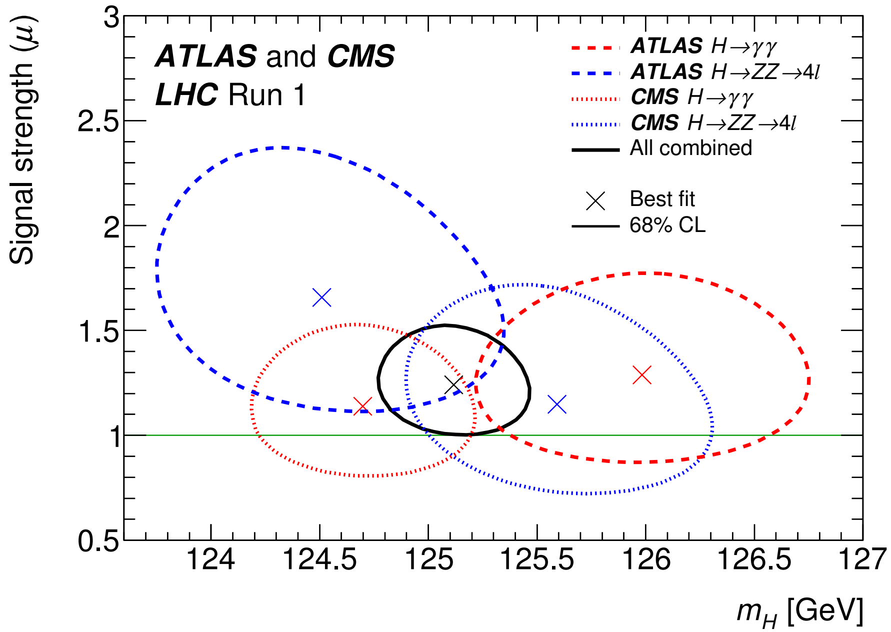
$\Rightarrow M_0 = 84^{+145}_{-28}$ GeV, $M_{1/2} = 375^{+175}_{-88}$ GeV,
$\tan\beta = 15^{+17}_{-7}$ $A_0 = 186^{+831}_{-844}$ GeV,
$\chi^2/ndf = 10.3/8$

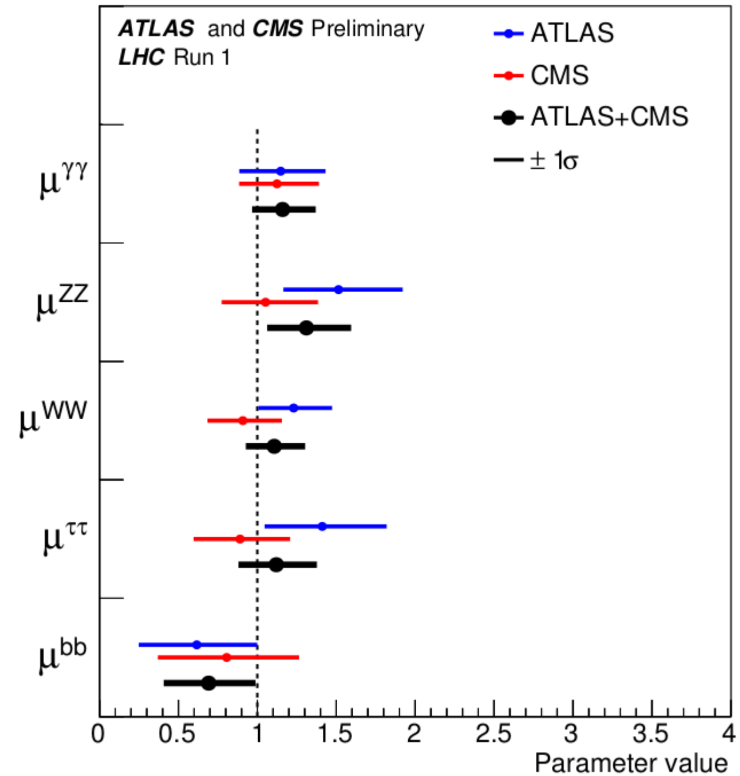
$\Rightarrow m_h = 116$ GeV

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

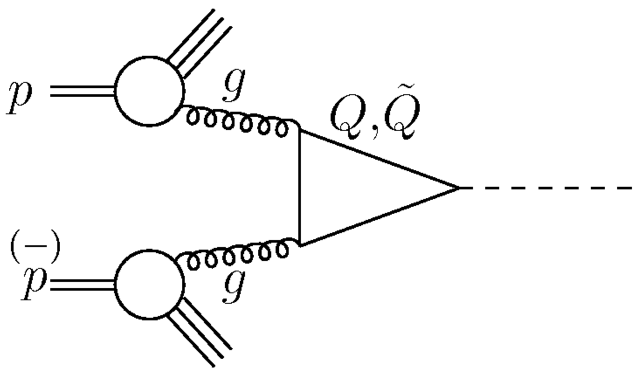
PRL **114** (2015) 191803

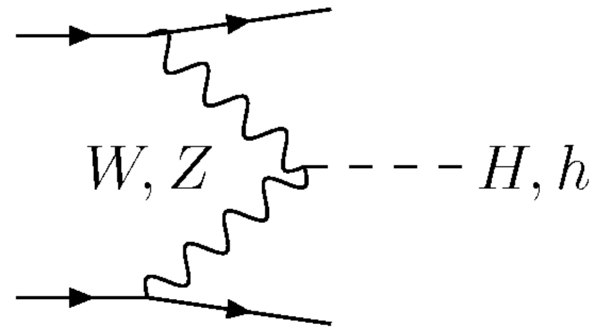
ATLAS-CONF-2015-044

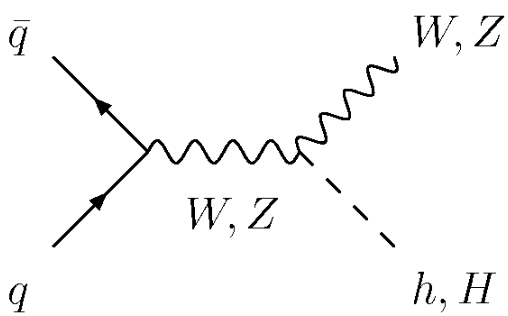
CMS-PAS-HIG-15-002

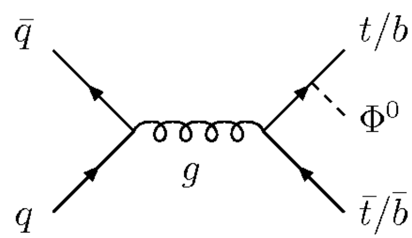
$(125 \text{ GeV})^2 \simeq m_Z^2 + (86 \text{ GeV})^2 \Rightarrow$ large corrections within MSSM

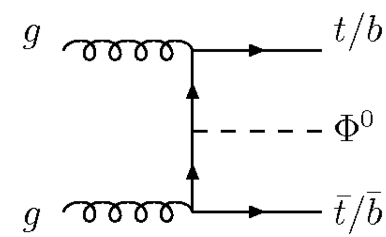
production at hadron colliders





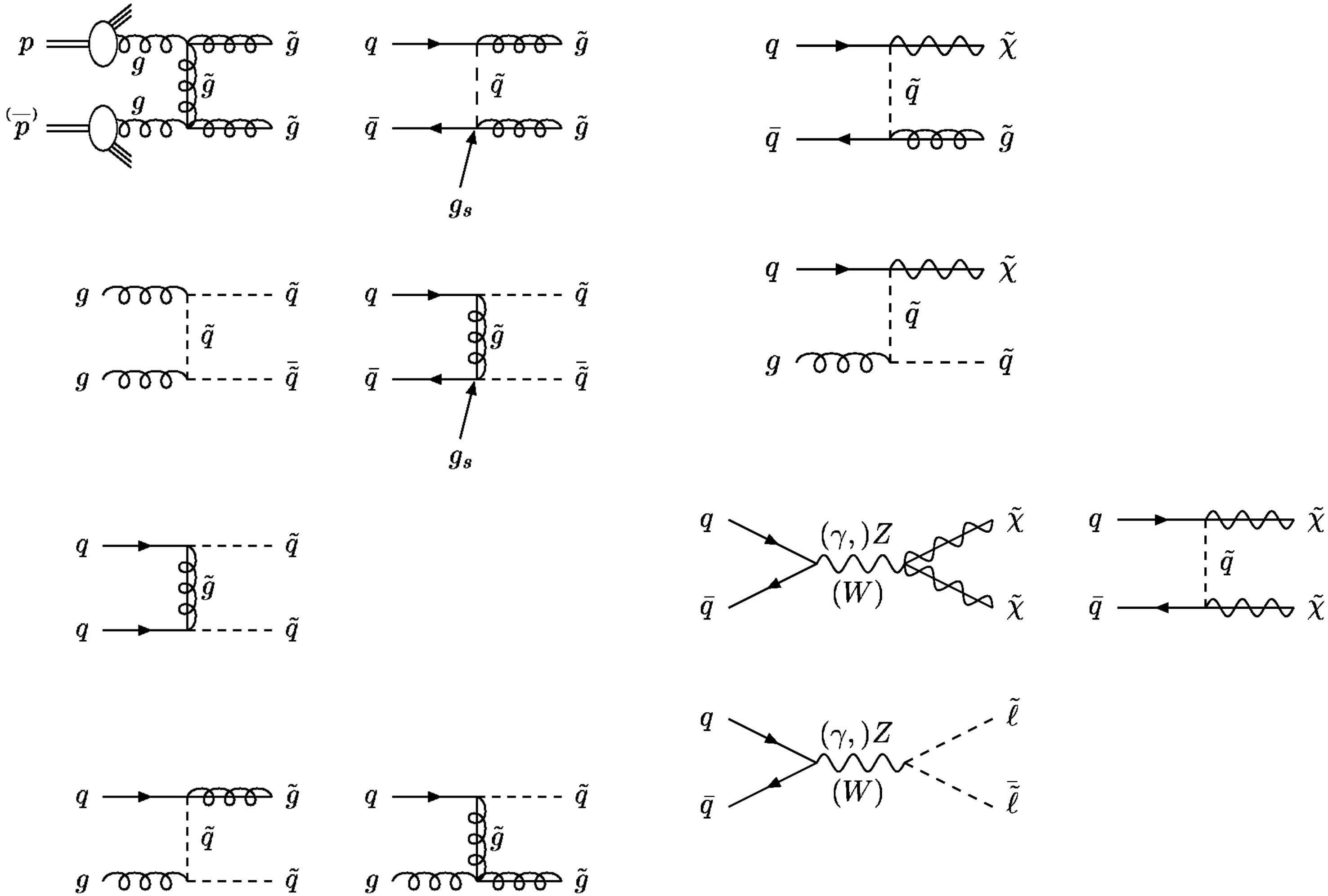




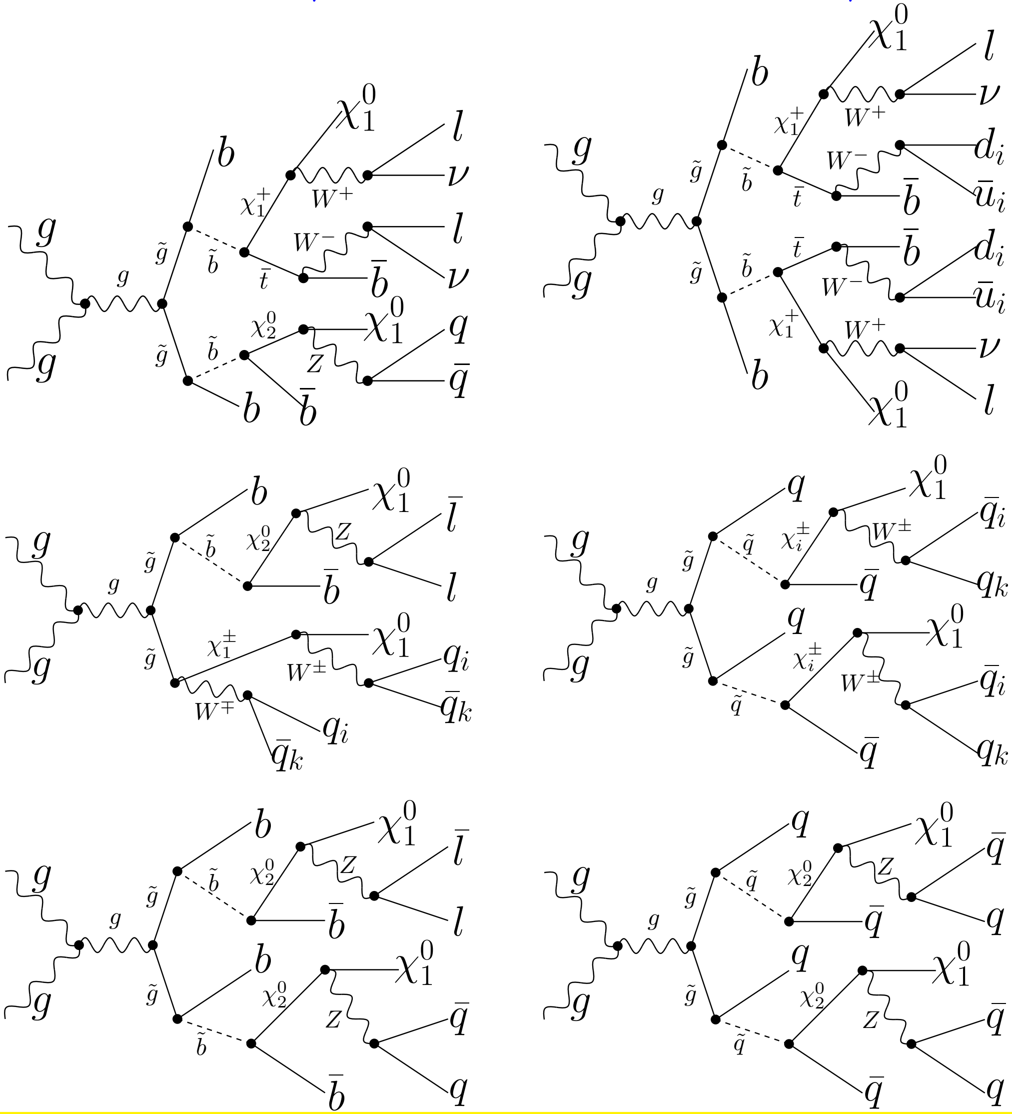


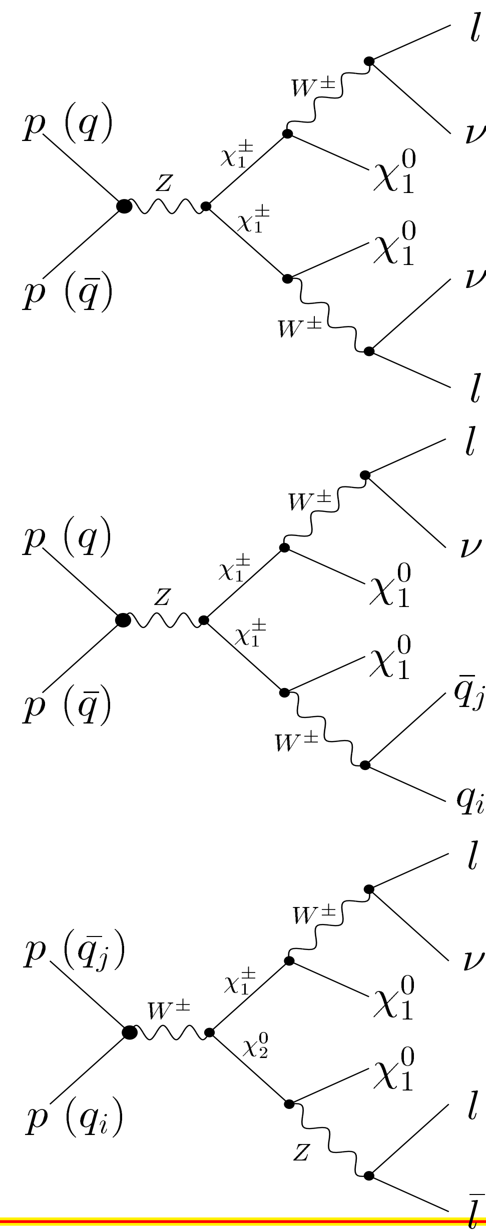
$$\Phi^0 = h, H, A$$

SUSY @ LHC


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

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



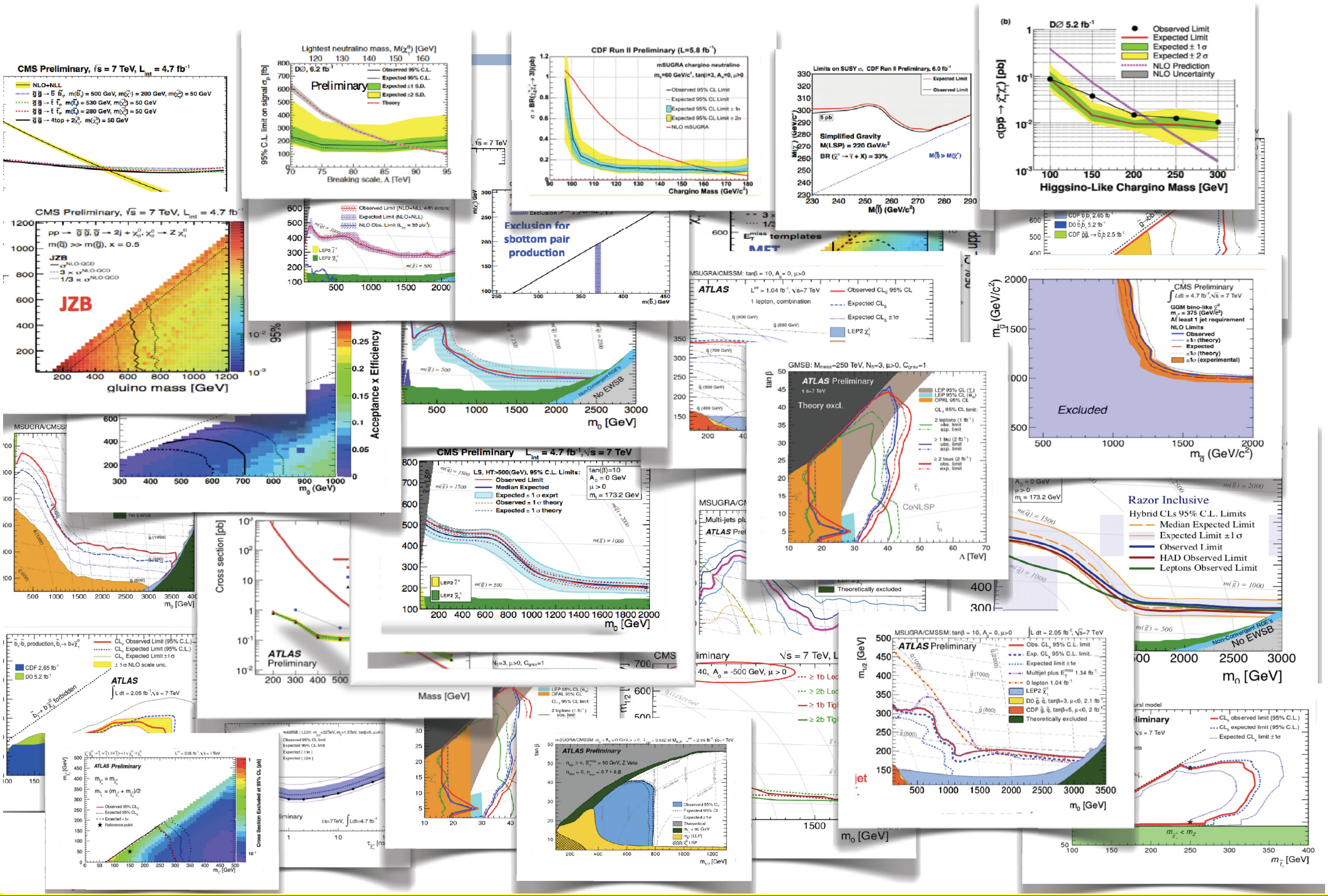


2ℓ
$\not{E}_T$

ℓ
$2j$
$\not{E}_T$

3ℓ
$\not{E}_T$

BSM searches, so far hardly anything ...



LHC data, in particular m_h, high scale models

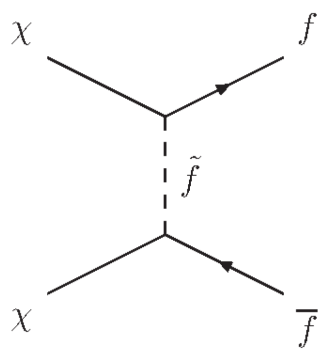
$m_h = 125.1$ GeV ⇒ large loop contributions

⇒ 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

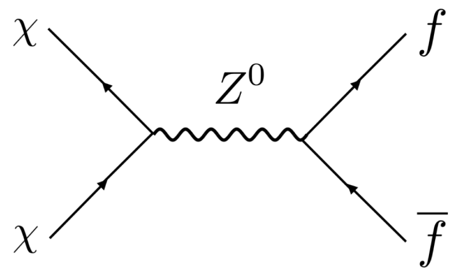
  more complicated models based on P. Meade, N. Seiberg and D. Shih, arXiv:0801.3278 ⇒ allow additional terms, choice not well motivated ⇒ generic MSSM
- CMSSM, NUHM models: $|A_0| \simeq 2m_0$,
  H. Baer, V. Barger and A. Mustafayev, arXiv:1112.3017; M. Kadastik *et al.*, arXiv:1112.3647; O. Buchmueller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

Dark matter, annihilation processes



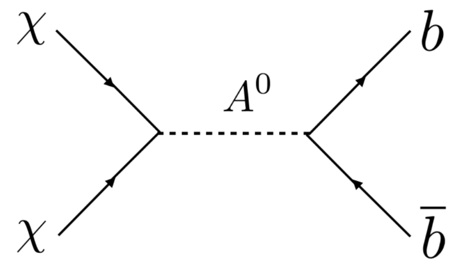
bino

bulk region

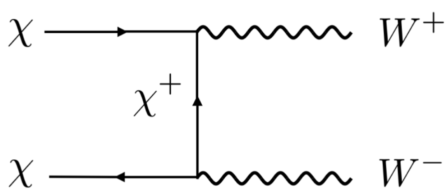


wino, higgsino

focus-point region

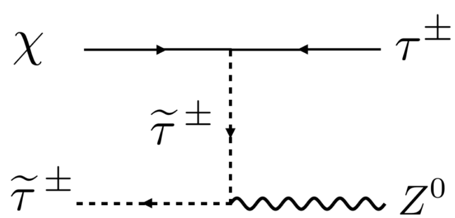


funnel region

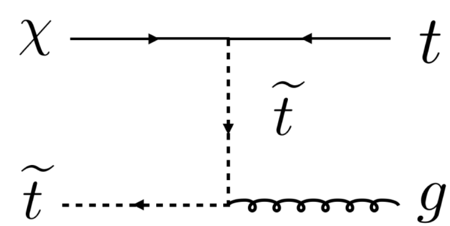


wino, higgsino

focus-point region

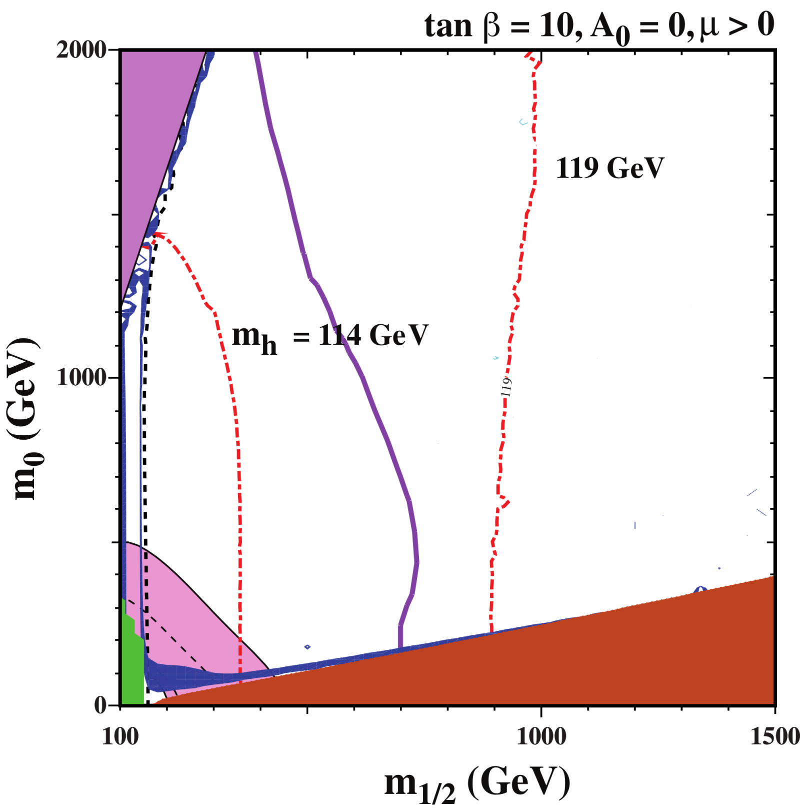


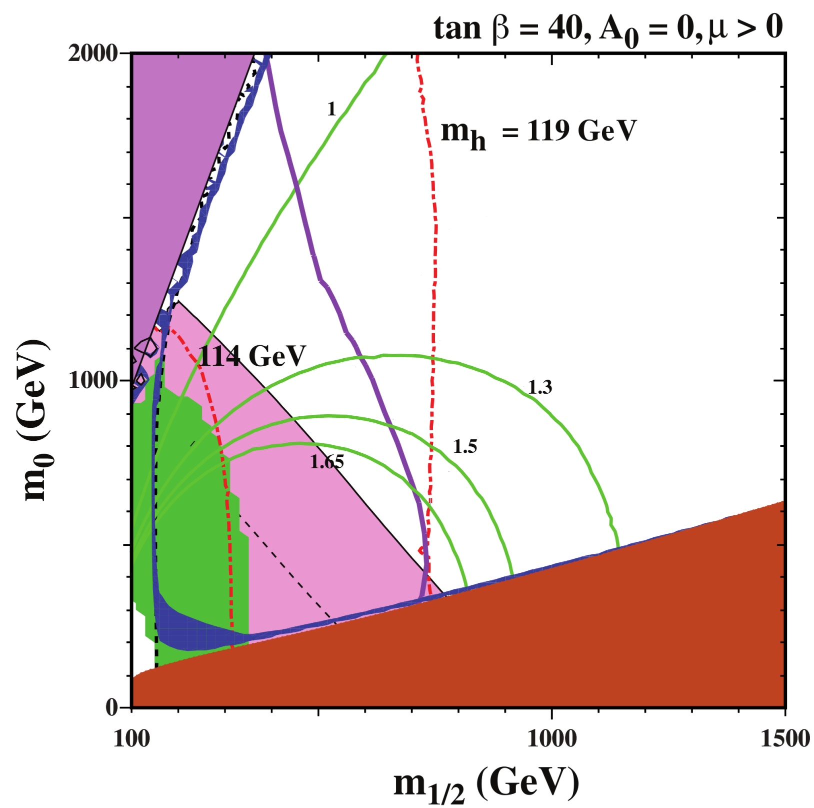
stau co-annihilation



stop co-annihilation

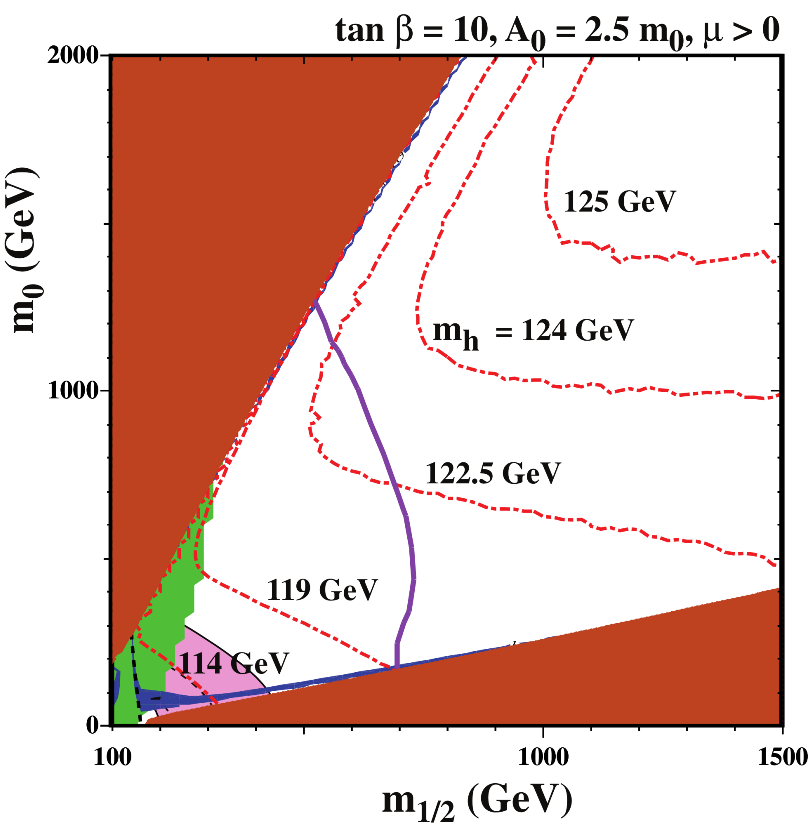
Dark matter, mSUGRA

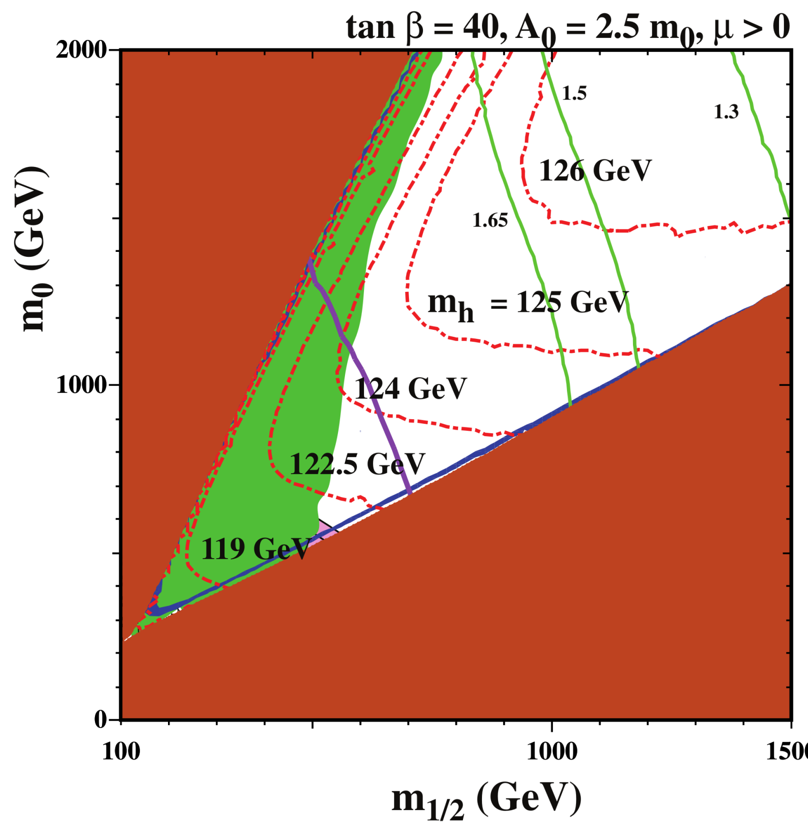




J. Ellis, F. Luo, K. Olive, P. Sandick, arXiv:1212.4476; $m_t = 173.2$ GeV

Dark matter, mSUGRA

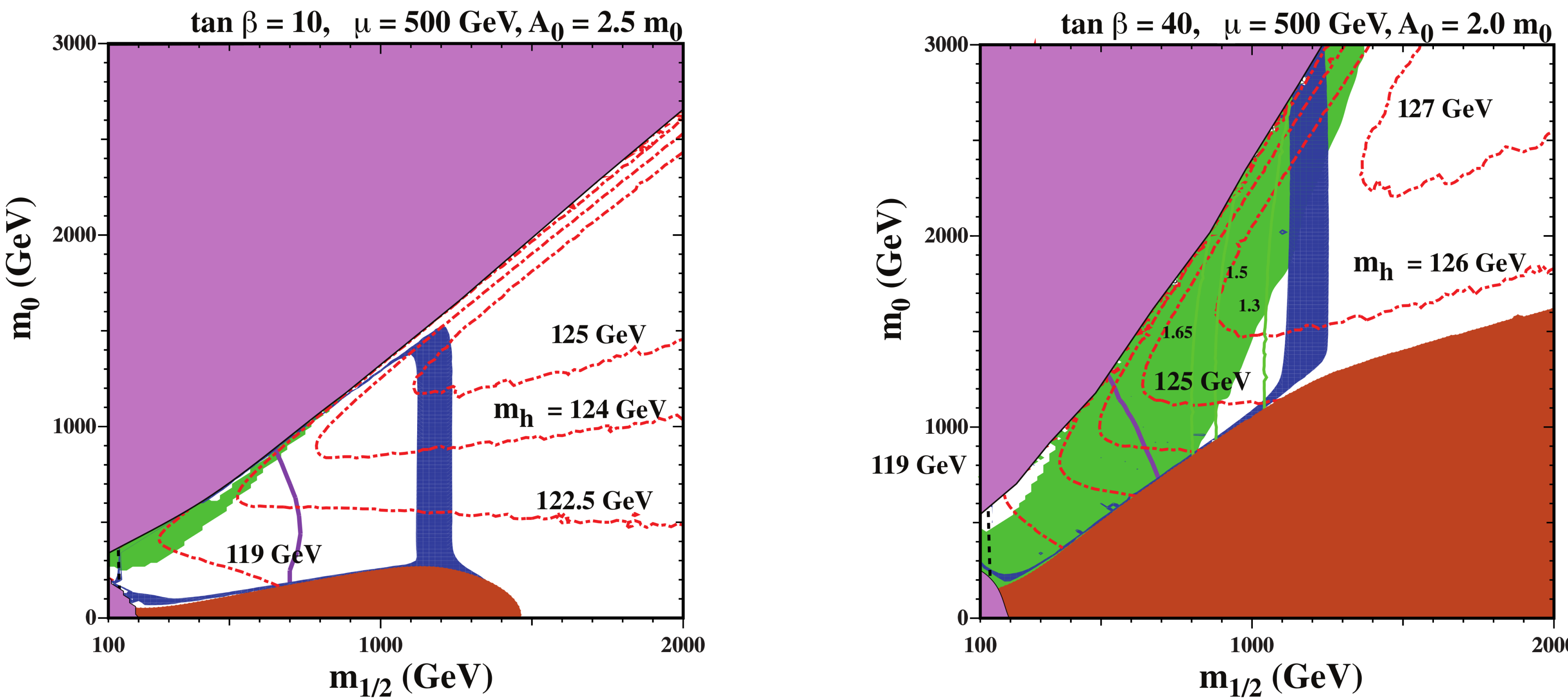




J. Ellis, F. Luo, K. Olive, P. Sandick, arXiv:1212.4476; $m_t = 173.2$ GeV

Dark matter, NUHM1

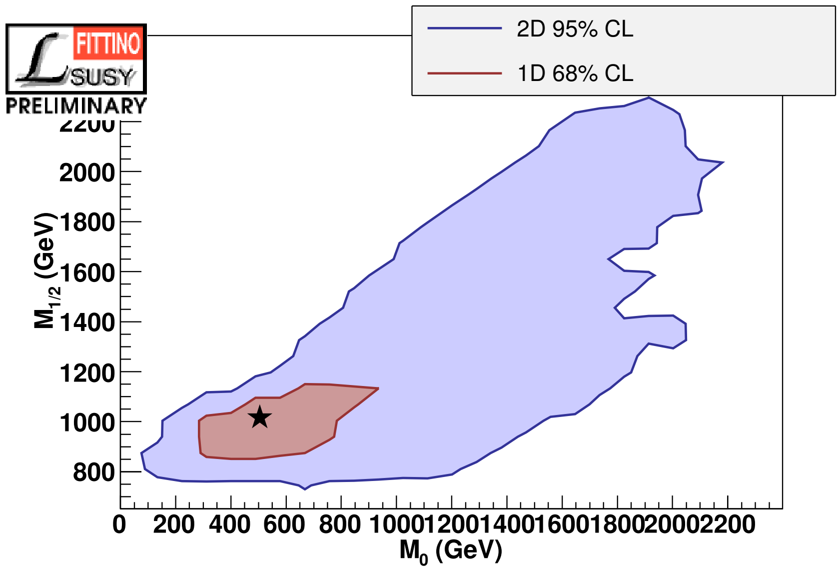
$m_{H_u}^2 \neq m_0^2 \Rightarrow \mu$ free parameter

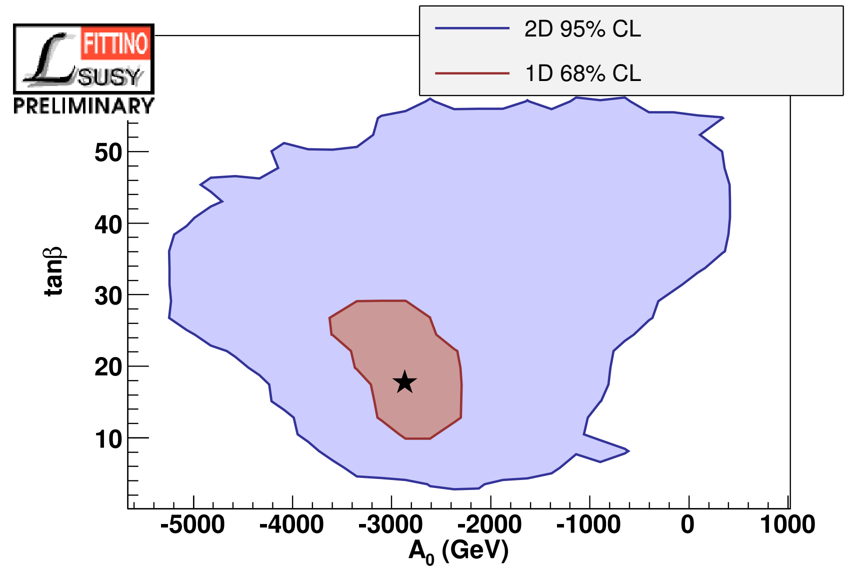


J. Ellis, F. Luo, K. Olive, P. Sandick, arXiv:1212.4476; $m_t = 173.2$ GeV

mSUGRA/CMSSM including LHC bounds & m_h

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





P. Bechtle et al., arXiv:1508.05951

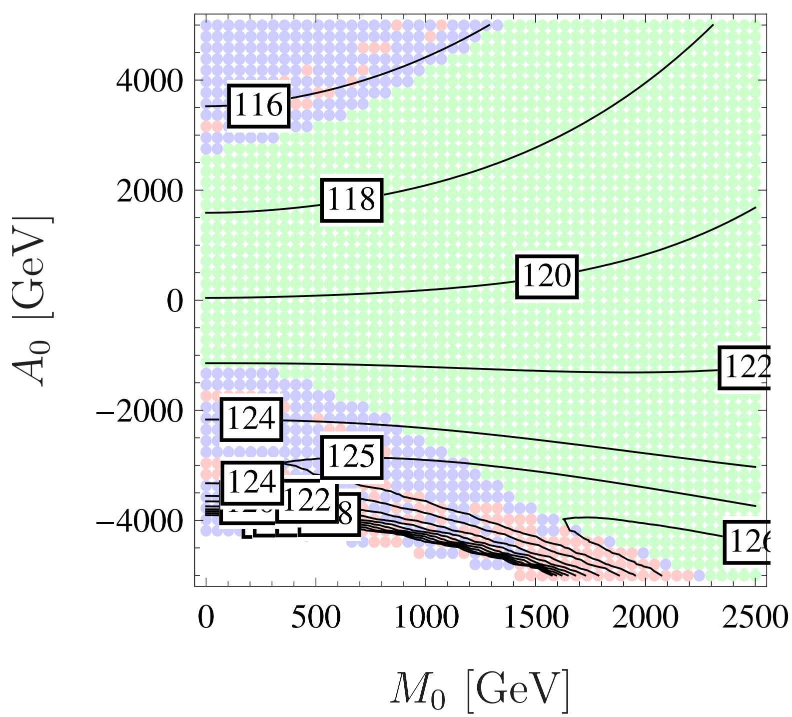
implications for LHC: $m_{\tilde{g}}, m_{\tilde{q}} \gtrsim 2$ TeV, $m_{\tilde{l}_R} \simeq 600$ GeV, $m_{\tilde{\chi}_1^0} \simeq 450$ GeV

can be tested at LHC 13 TeV [14 TeV]

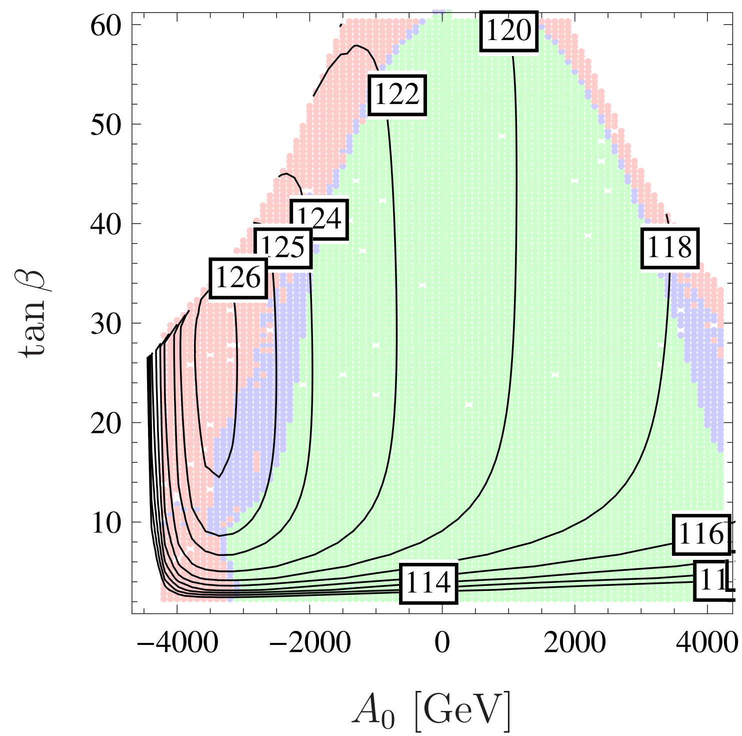
so far so good, but . . .

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

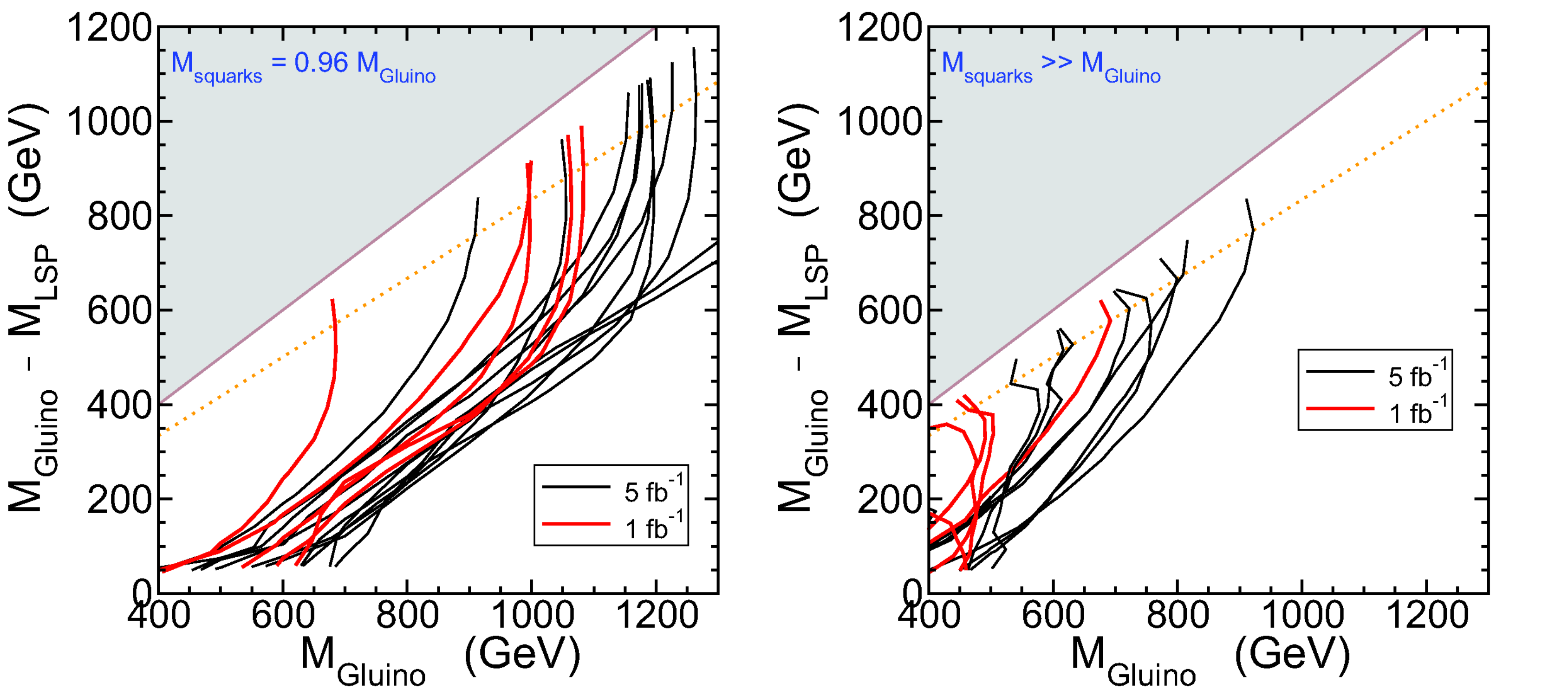
J.E. Camargo-Molina, B. O'Leary, W.P., F. Staub, arXiv:1309.7212

How to soften bounds on masses of SUSY particles from LHC

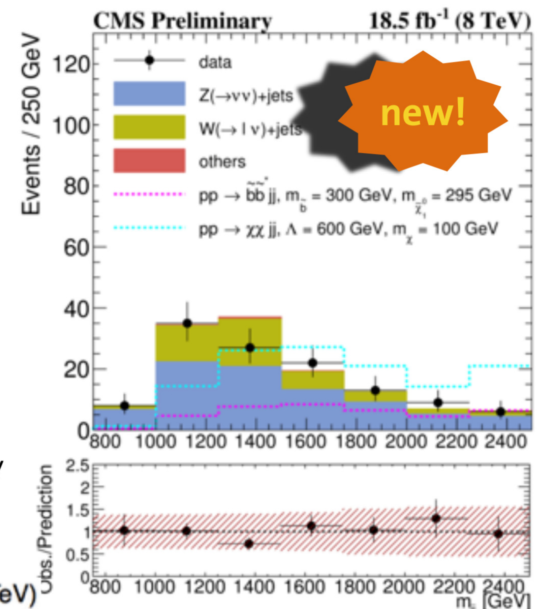
GMSB, AMSB, CMSSM, . . . : hierarchical spectrum $\Rightarrow$ hard jets, hard leptons, $\not{E}_T$

in general MSSM: complete different hierarchies possible
$\Rightarrow$ 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



VBF + MET: Compressed SUSY / DM

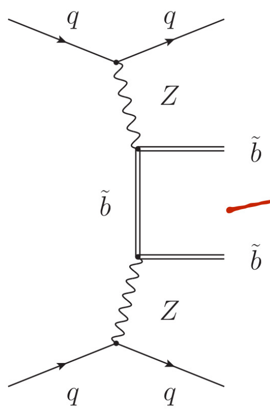


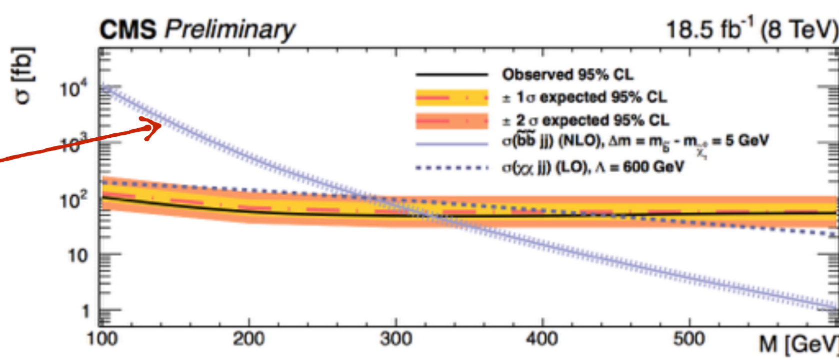
Trigger: MET65+VBFDiJet35

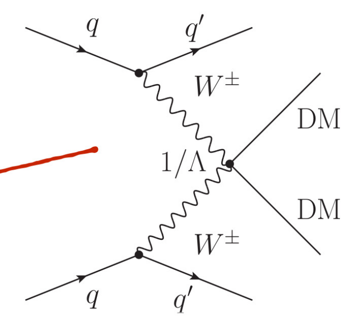
Selection: Two jets (p_T>50 GeV with $\eta_1\eta_2$<0; large rapidity gap $|\eta_1$-$\eta_2|$>4.2 and invariant mass m_{12}>750 GeV; no b-tag); MET>250 GeV; veto further jets (p_T>30 GeV)

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 $\tilde{b}\tilde{b}\tilde{\chi}^0_1\tilde{\chi}^0_1$ production with $m_{\tilde{b}} - m_{\tilde{\chi}^0_1} = 5$ GeV







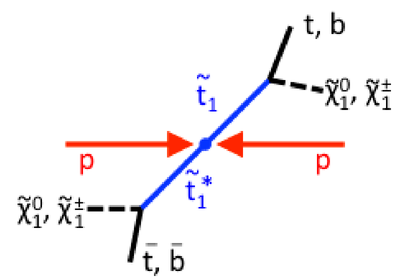
SUS-14-019

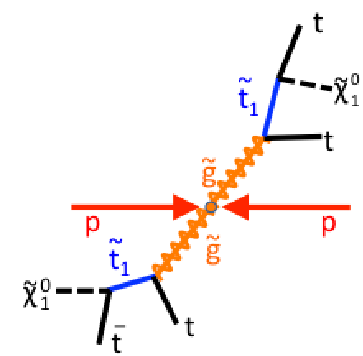
General MSSM

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

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



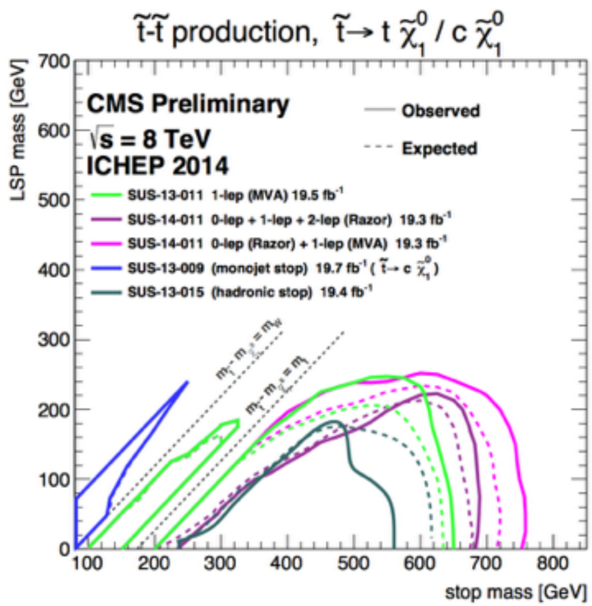


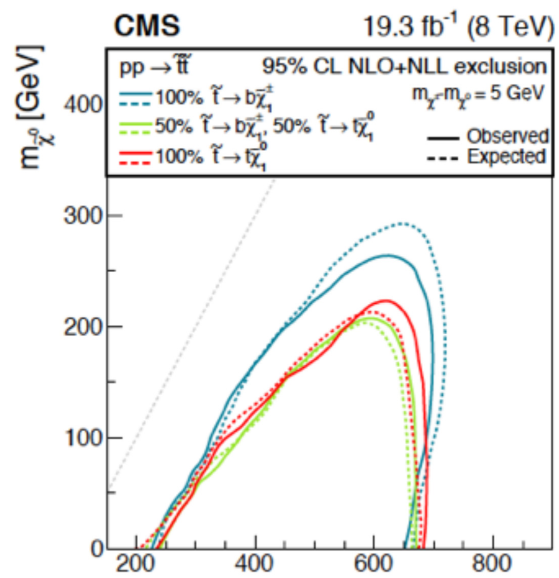
BRs depend on the nature of $\tilde t_1$ and $\tilde b_1$

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 $m_{\tilde{\chi}_1^0} \lesssim 100$ GeV
- Mass limits depend slightly on branching ratios of $\mathrm{Br}(\tilde{t}_1 \to t\tilde{\chi}_1^0)$ and $\mathrm{Br}(\tilde{t}_1 \to b\tilde{\chi}_1^\pm)$





SUS-13-004, PRD

J. Duarte (Mon)

A. Dräger (Fri)

NMSSM in nut-shell

μ-problem of the MSSM $\Rightarrow$ add singlet $\Rightarrow \mu = \lambda\langle S\rangle$

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

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

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]:

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

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

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

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

  $\Rightarrow SO(10) \rightarrow SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

  $\rightarrow SU(3)_C \times SU(2)_L \times U(1)_R \times U(1)_{B-L}$

  $\cong SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_\chi$

  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

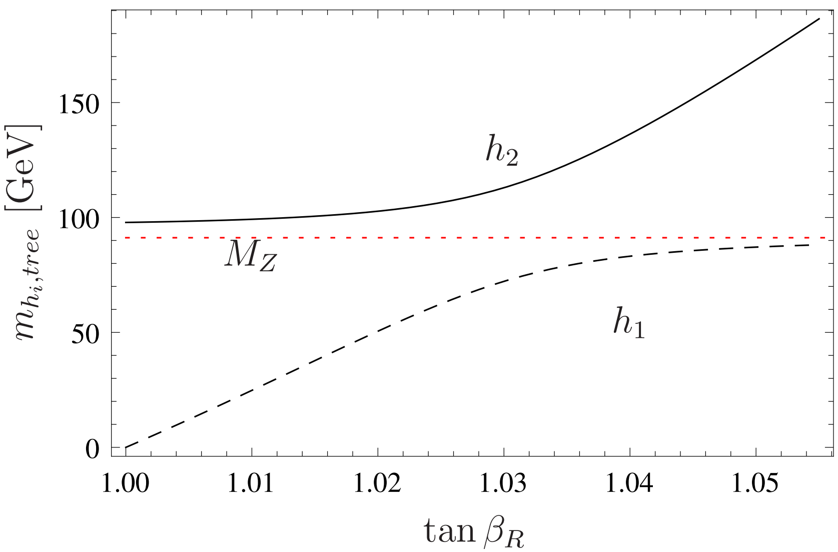
  $B - L$ anomaly free $\Rightarrow \nu_R$

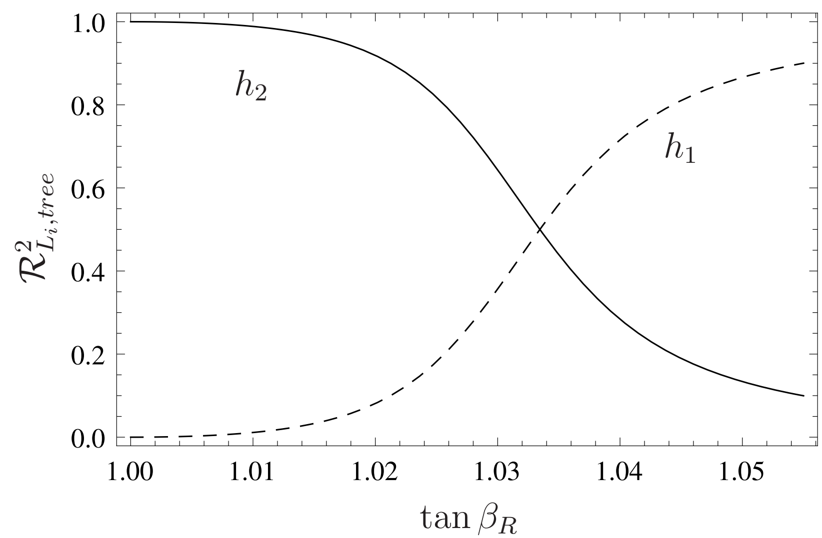
  usual seesaw, inverse seesaw

Higgs sector I

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



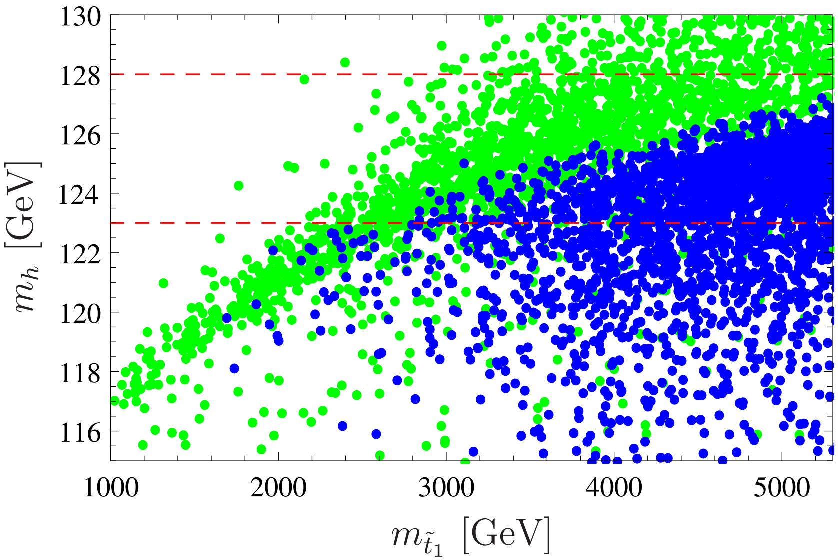


$n = 1,\ \Lambda = 5 \cdot 10^5$ GeV, $M = 10^{11}$ GeV, $\tan\beta = 30$, sign$(\mu_R) = -$, $diag(Y_S) = (0.7, 0.6, 0.6)$, $Y_\nu^{ii} = 0.01$, $v_R = 7$ TeV

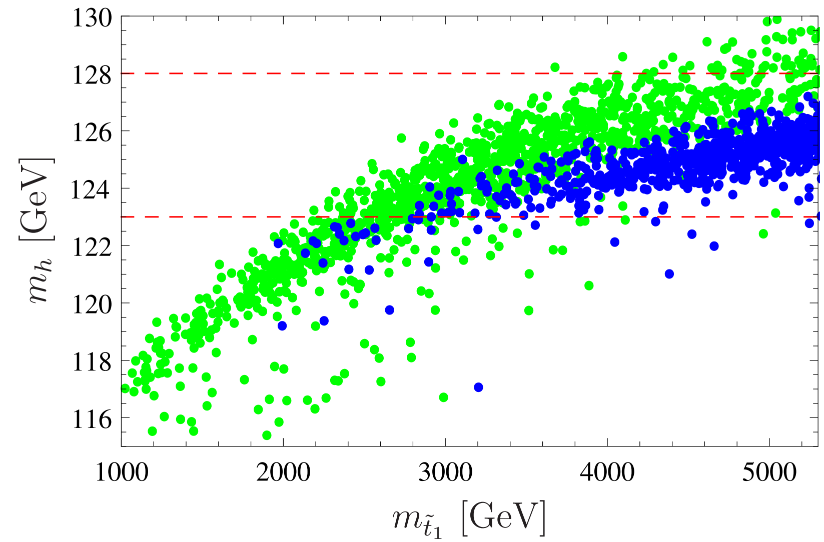
M.E. Krauss, W.P., F. Staub, arXiv:1304.0769

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: $h_2 \simeq h$

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

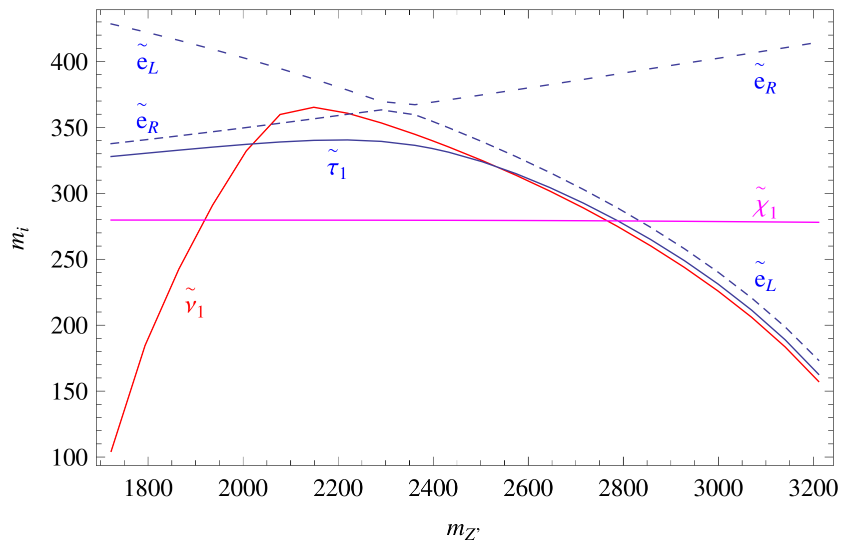
M.E. Krauss, W.P., F. Staub, arXiv:1304.0769

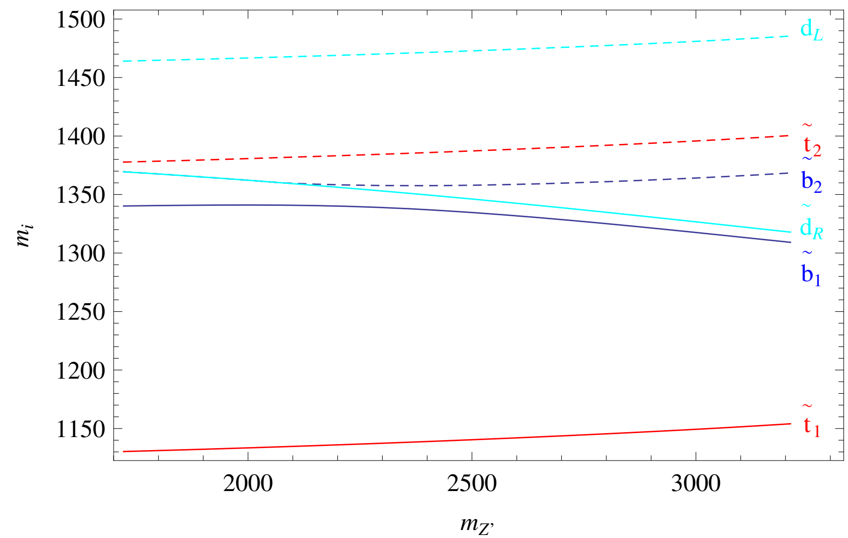
Sfermions

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

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

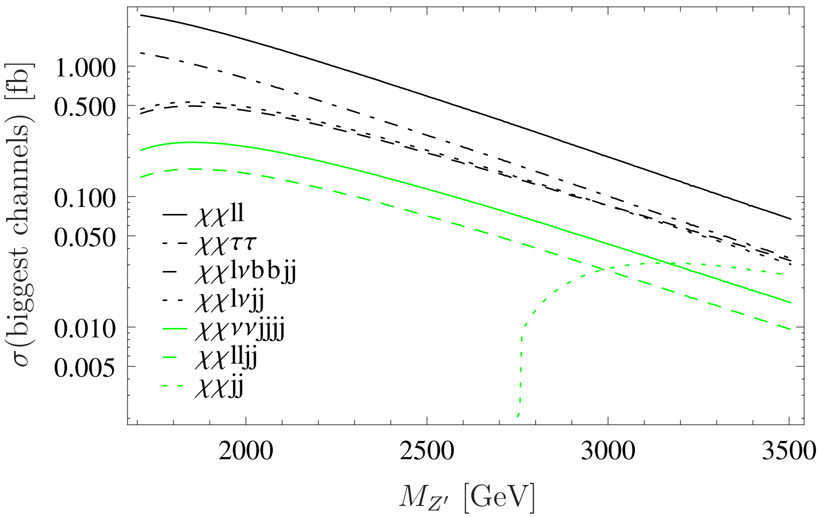
$$\begin{aligned}
\tilde{q}_R &\to q\tilde{\chi}^0_1 \to q\nu_k\tilde{\nu}_1 \to q\nu_j Z\tilde{\nu}_1 \qquad (k=4,\dots,9\,,\ j=1,2,3)\\
\tilde{q}_R &\to q\tilde{\chi}^0_1 \to q\nu_k\tilde{\nu}_1 \to ql^\pm W^\mp\tilde{\nu}_1\\
\tilde{q}_R &\to q\tilde{\chi}^0_1 \to q\nu_k\tilde{\nu}_3 \to ql^\pm W^\mp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

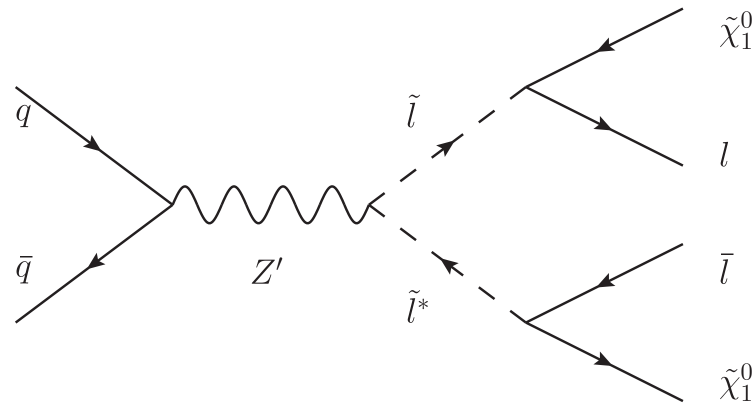
BLRSP3: usual cascades similar to CMSSM, but

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

$\Rightarrow$ 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

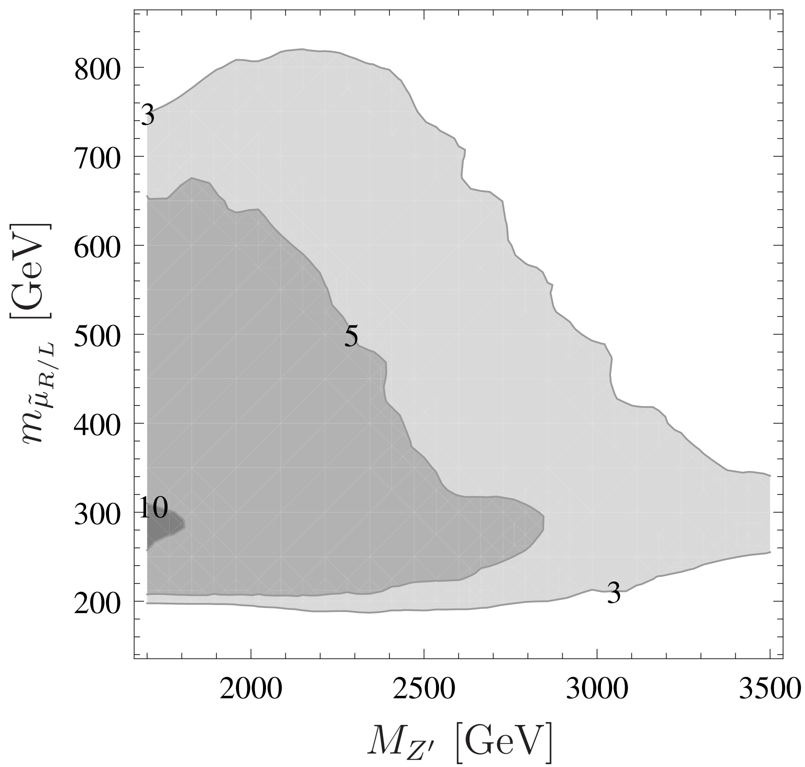
see also: J. Kang and P. Langacker, PRD **71** (2005) 035014; M. Baumgart, T. Hartman, C. Kilic, and L.-T. Wang, JHEP **0711** (2007) 084; C.-F. Chang, K. Cheung, and T.-C. Yuan, JHEP **1109** (2011) 058; G. Corcella and S. Gentile, arXiv:1205.5780

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

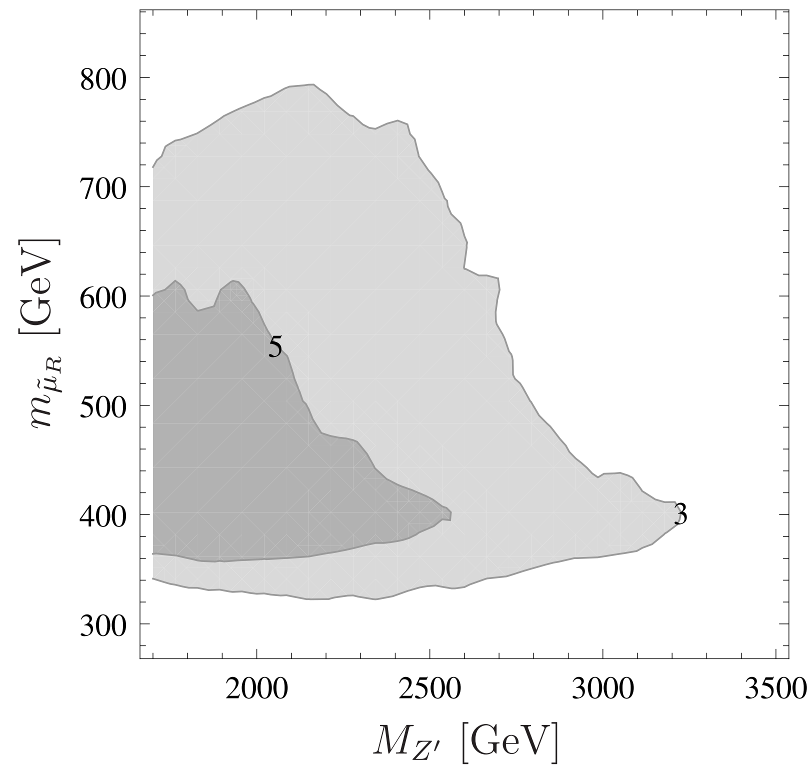
main dependence on masses ⇒ vary $m_{\tilde{l}}$ and $m_{Z'}$, $M_L = 1.2 M_E$

100 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

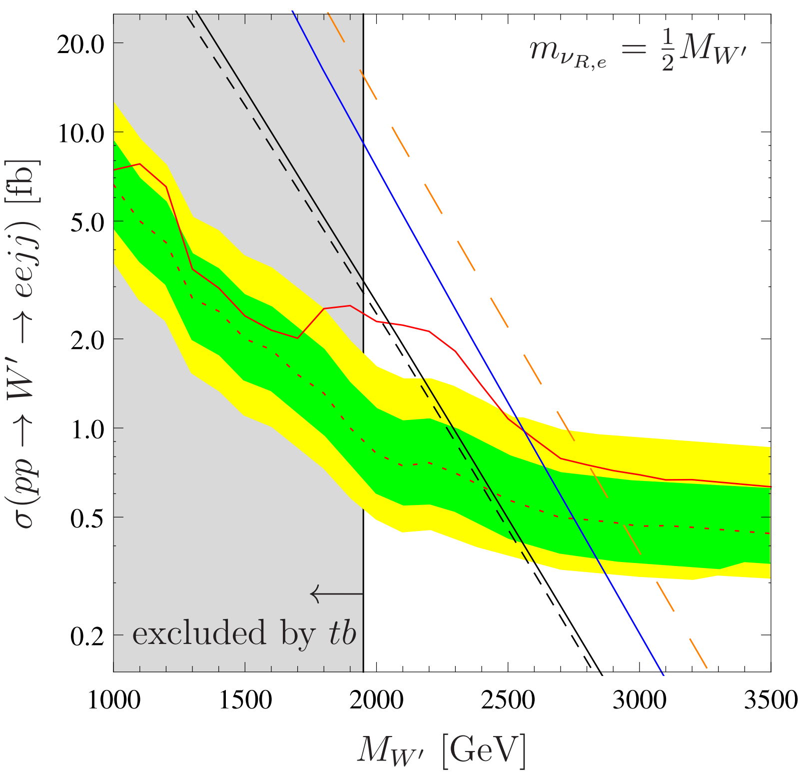
CMS excess for $eejj$, hint for light SUSY?

CMS coll., arXiv:1407.3683

2.8σ excess in search for $pp \to W' \to \nu_R l \to eejj$ final state @ $m_{W'} \simeq 2.2.$ TeV

interpretation in an $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ model,

M. Krauss, W.P., arXiv:1507.04349

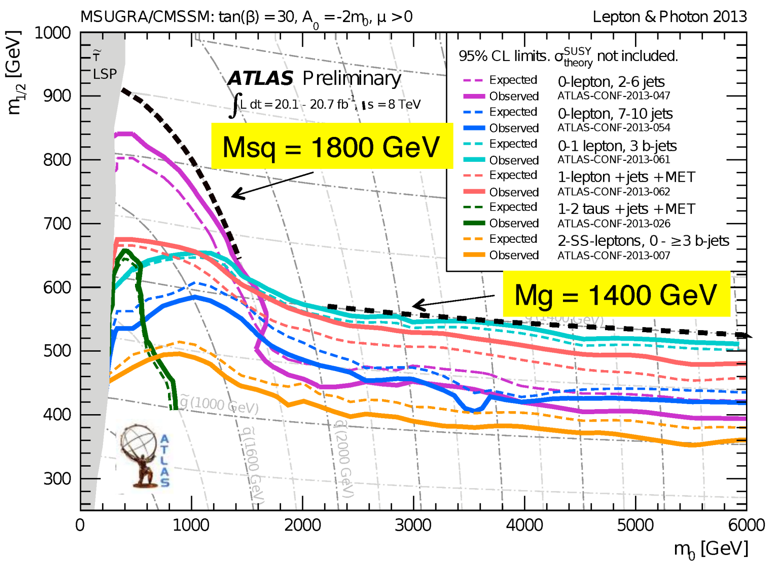


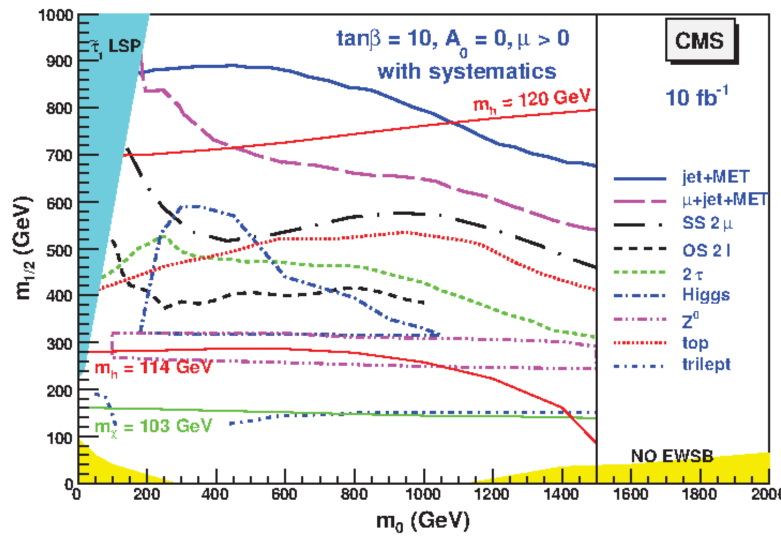
- dashed orange line: minimal model, W' decays only into $q\bar{q}'$ and $\nu_{R,e}e$, $g_L = g_R$, $\nu_R \to W'^* e \to q\bar{q}' e$
- full blue line: allow in addition for decays in SUSY particles: $W' \to \tilde{\chi}^0_1 \tilde{\chi}^\pm_1$ and $\nu_R \to \tilde{\chi}^0_1 \tilde{\chi}^\pm_1 e^\mp$
- black lines: in most part of the parameter space also
  $\nu_R \to H^\pm e^\mp \to tbe$
  $\Rightarrow$ predicts $\nu_{R,\mu}$ with $m_{\nu_{R,\mu}} \lesssim 200$ GeV

Conclusions

- $m_h = 125.1$ 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 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
  - W' and Z' might look differently than expected & might even serve as SUSY discovery channel

Conclusions





- I do not expect significant SUSY signals at LHC@13/14TeV before $L \simeq 10$ fb^{-1} but potentially a Z', W' or another s-channel resonance

SUSY looks most likely different than CMSSM suggested

Heavy neutrinos

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

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

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

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

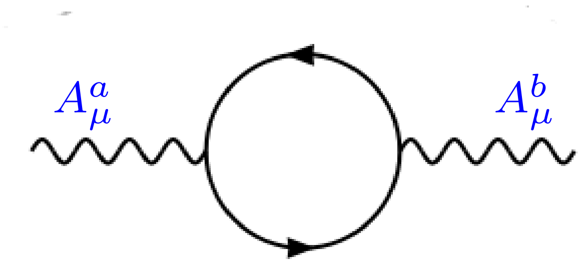
in BLRSP4

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

Gauge kinetic mixing

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

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



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

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)

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

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

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

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

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

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

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

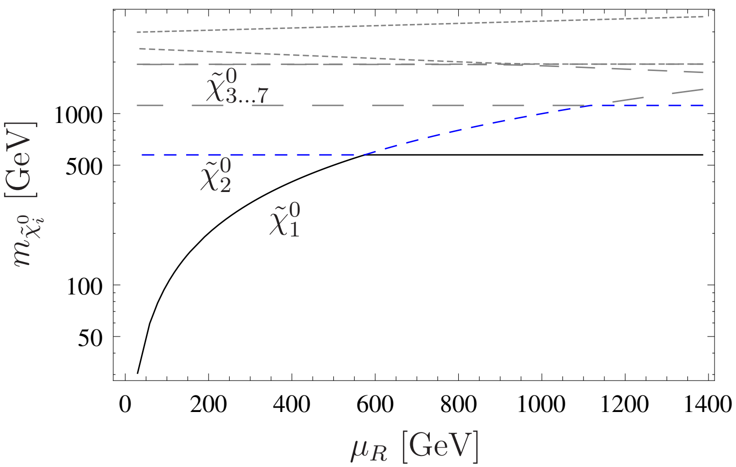
$M_{\tilde{\chi}^0} =$

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

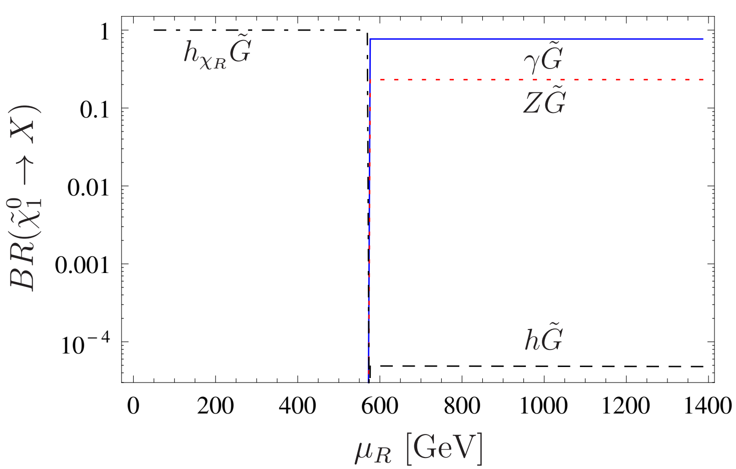
neglecting the mixing between the two sectors and setting $\tan\beta_R = 1$

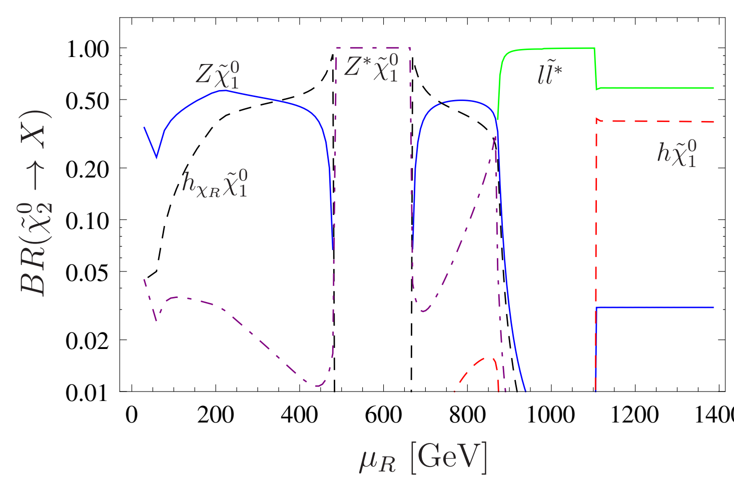
$$m_i : \; \mu_R \, , \quad \frac{1}{2}\left(M_\chi + \mu_R \pm \sqrt{\frac{1}{4} m^2_{Z'} + (M_\chi - \mu_R)^2} \right)$$

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

Neutrinos and sneutrinos

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

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

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

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

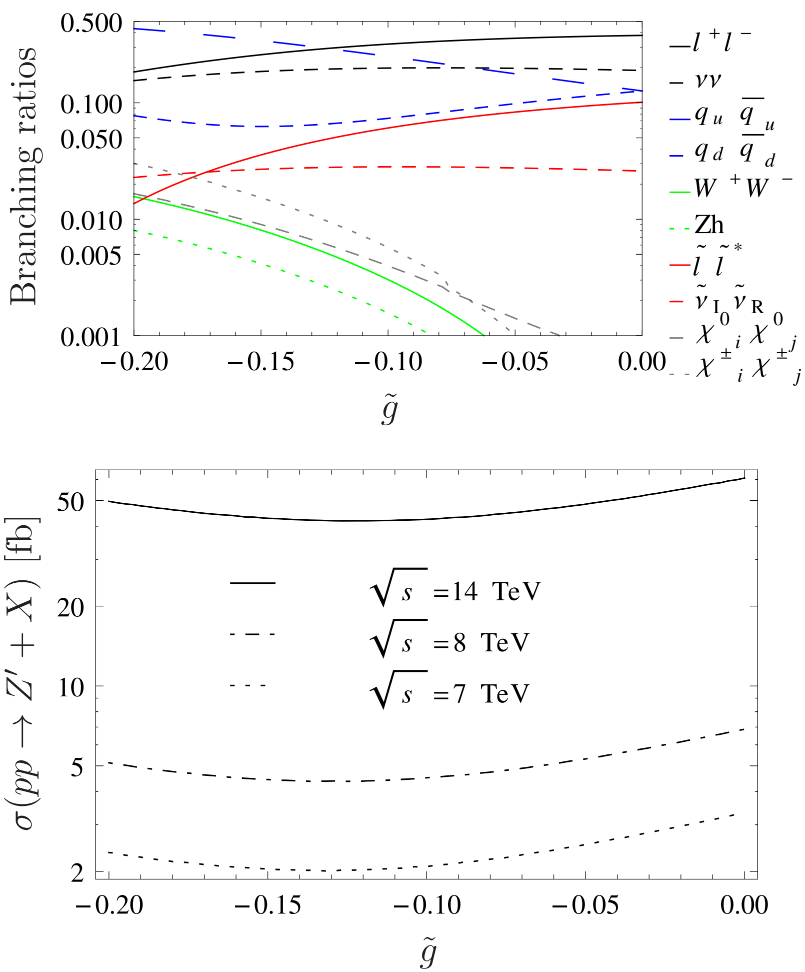
$$D_L = \frac{1}{32}\Big(2\big(-3g_\chi^2 + g_\chi g_{Y\chi} + 2(g_2^2 + g'^2 + g_{Y\chi}^2)\big)v^2 c_{2\beta} - 5 g_\chi (3 g_\chi + 2 g_{Y\chi}) v_R^2 c_{2\beta_R}\Big)\mathbf{1}$$

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

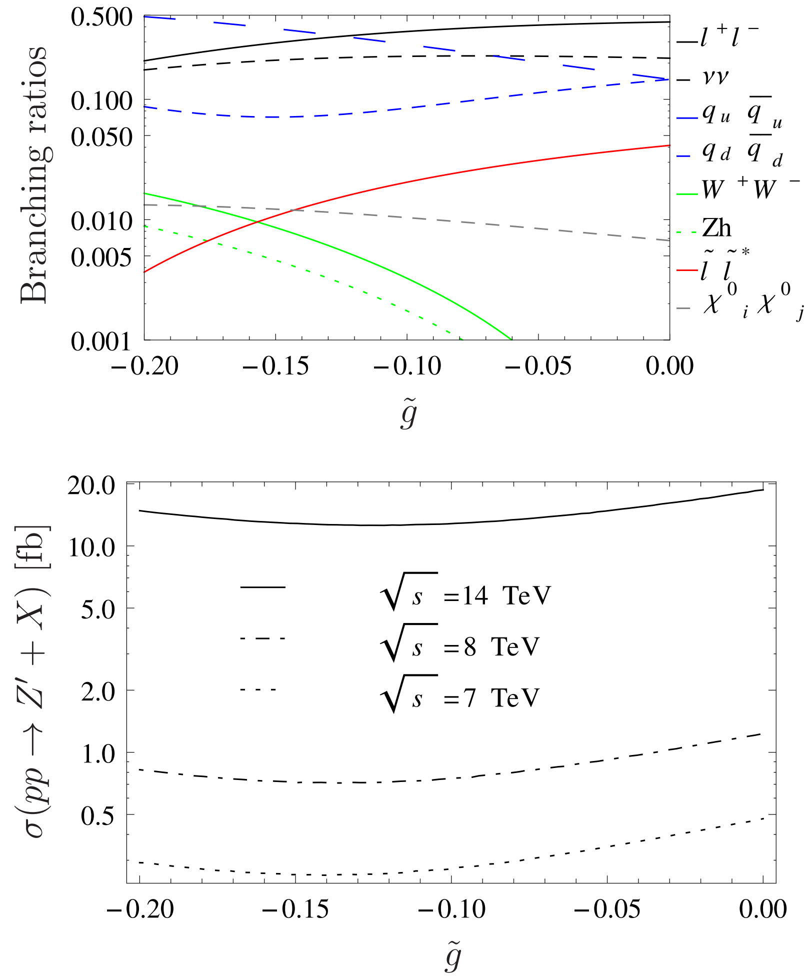
Z' physics, effect of gauge kinetic mixing I

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

BL1

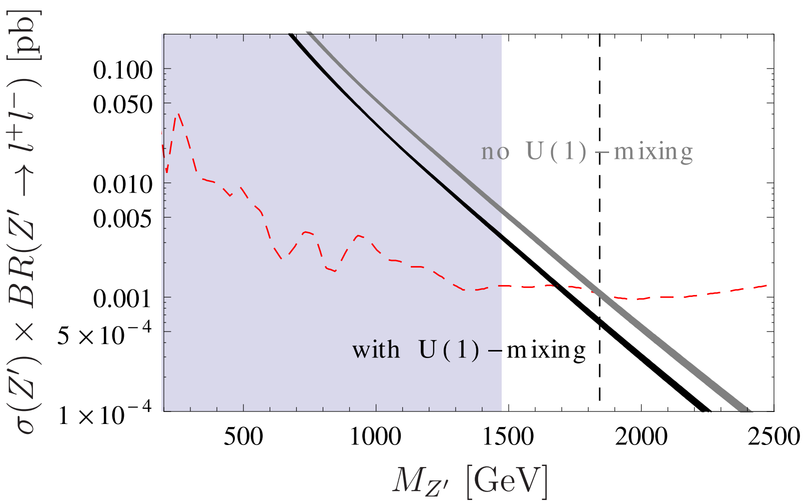


BL2

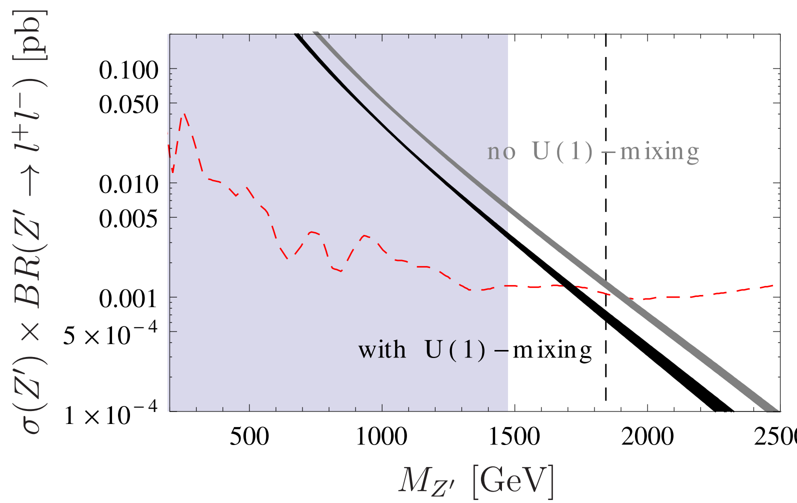


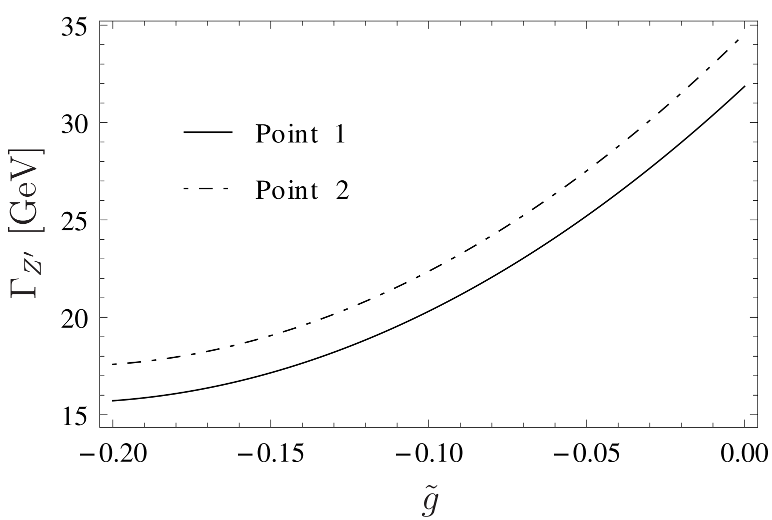
Z' physics, effect of gauge kinetic mixing II

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

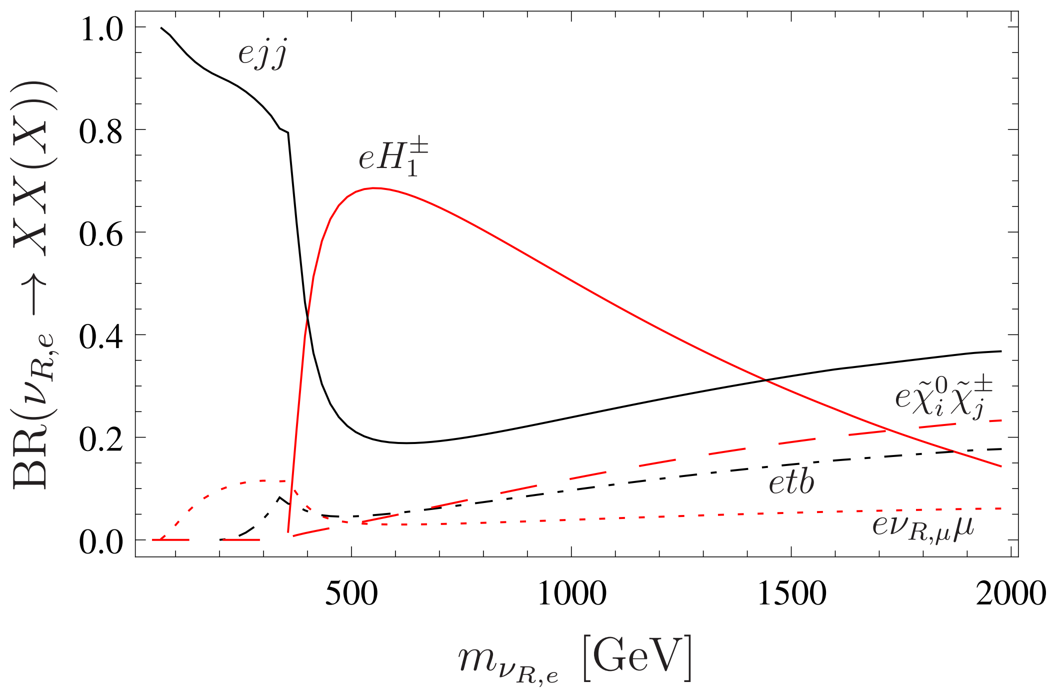
- invariant mass of the muon pair: $M_{\mu\mu} > 200$ GeV
- missing transverse momentum: $p_T(\not{E}) > 200$ GeV
- transverse cluster mass

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

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

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

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



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