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Non-standard Higgs decays in U(1) extensions of the MSSM

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Aim

Normal U(1) extended SUSY models have a very rigid structure

Is there a mechanism to avoid this rigid structure?

New signature associated with this mechanism?

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- Background and motivation
- Simple idea
- E6 inspired model
- Higgs masses and decay to pseudoscalars
- Results
- Conclusions

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The μ problem and singlet extensions

- The μ problem

Need $\mu \approx 0.1 - 1$ TeV

$$W_{MSSM} = Y_u \hat{\bar{Q}}_L \hat{H}_u \hat{u}_R - Y_d \hat{\bar{Q}}_L \cdot \hat{H}_d \hat{d}_R - Y_e \hat{\bar{E}} \cdot \hat{H}_d \hat{d}_R - \mu \hat{H}_u \hat{H}_d$$

- Add SM-gauge singlet

$$\mathcal{W} = Y_u \bar{Q}_L H_u u_R - Y_d \bar{Q}_L \cdot H_d d_R - Y_e \bar{E} \cdot H_d d_R - \lambda S H_u H_d$$

effective μ–term

Superfield	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_{PQ}$
$\hat{Q}_i$	$\mathbf{3}$	$\mathbf{2}$	$\frac{1}{6}$	-1
$\overline{u}_i$	$\overline{\mathbf{3}}$	$\mathbf{1}$	$-\frac{2}{3}$	0
$\overline{d}_i$	$\overline{\mathbf{3}}$	$\mathbf{1}$	$\frac{1}{3}$	0
$\hat{L}_i$	$\mathbf{1}$	$\mathbf{2}$	$-\frac{1}{2}$	-1
$\overline{e}_i$	$\mathbf{1}$	$\mathbf{1}$	1	0
$\hat{H}_u$	$\mathbf{1}$	$\mathbf{2}$	$+\frac{1}{2}$	1
$\hat{H}_d$	$\mathbf{1}$	$\mathbf{2}$	$-\frac{1}{2}$	1
$\hat{S}$	$\mathbf{1}$	$\mathbf{1}$	0	-2

Global Peccei-Quinn symmetry

$$\hat{\Psi}_i \to e^{iQ_i^{PQ}\theta} \hat{\Psi}_i$$

$$S \to \langle S \rangle \Rightarrow \mu_{eff} H_u H_d \ .$$

and breaks $U(1)_{PQ}$

massless axion!

U(1) extensions of the MSSM

- Add SM-gauge singlet and extra gauged U(1)

$$\lambda S H_u H_d \longrightarrow \lambda < S > H_u H_d = \mu_{\text{eff}} H_u H_d$$

$$\Rightarrow \cancel{U(1)'} \Rightarrow \text{Massive gauge boson: } \; Z'$$

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U(1) extended SUSY models

- USSM
- E_6SSM

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U(1) extended SUSY models

- USSM
- E_6SSM

Many papers on such models already, e.g.

Suematsu, Yamagishi, Int.J.Phys.A 10, 4521; Cvetic, Langaclker PRD 54, 3570,; de Carlos, Espinosa PLB 407, 12 Cvetic, Demir, Espinosa, Everett, Langacker, PRD 56 2861; Demir, Pak PRD 57 6609; Langacker, Wang PRD 58 115010,Erler, Langacker, Li, PRD 66, 015002, Choi, Habe, Kalinowski, Zerwas NPB 778, 85; Langacker Rev.Mod.Phys 81, 119; Ham, Hur, Ko, Oh, JPG 35, 095007, Kalinowski, King, Roberts, JHEP 0901066 King, Moretti, Nevzorov, PRD 73, 0305009; PLB 634, 278, PLB 650, 57; PA, King, Miller, Moretti, Nevzorov, PLB 681, 448, PRD 80, 035009; PRD 84, 055006; PRD 86, 095003; PA, Stoeckinger,Voigt, PA, King, Binjonaid PRD N.11, 115023; Rizzo, PRD 85, 055010, Braam, Knochel, Rueter JHEP 1006, 013

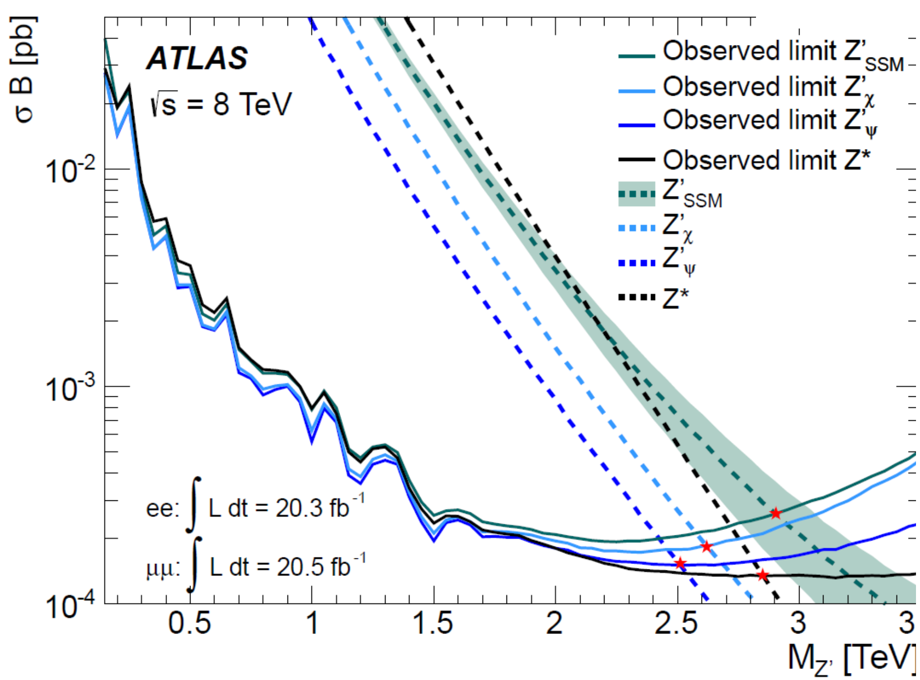
Z’ mass limits

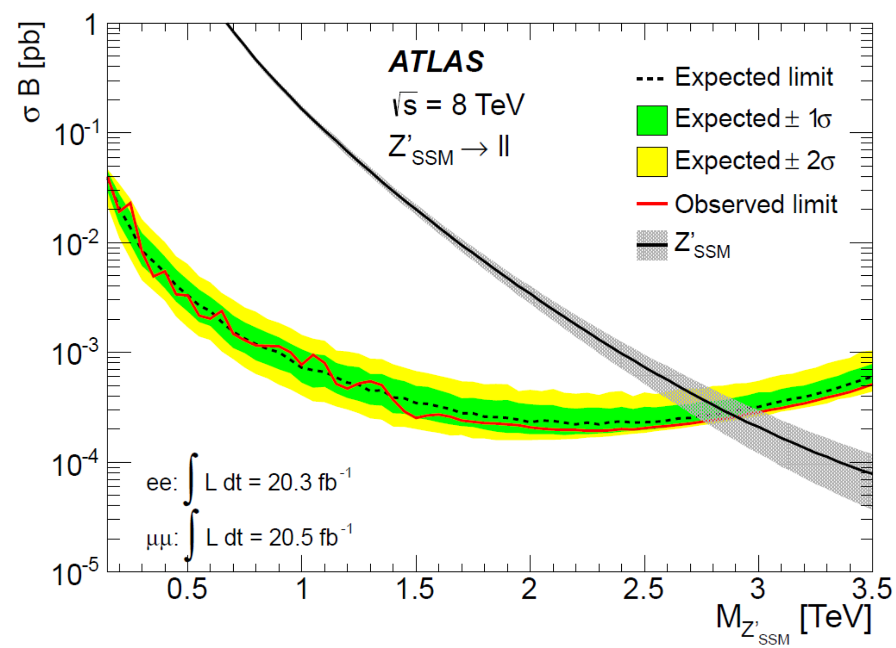
Already have strong limits on the Z’ mass, e.g.

[ATLAS Collaboration] arXiv:1405.4123 [hep-ex]

TABLE VII. Observed and expected lower mass limits for Z' and Z^* bosons, using the corresponding signal template for a given model.

Model	Width [%]	Observed Limit [TeV]	Expected Limit [TeV]
Z'_{SSM}	3.0	2.90	2.87
Z'_χ	1.2	2.62	2.60
Z'_ψ	0.5	2.51	2.46
Z^*	3.4	2.85	2.82





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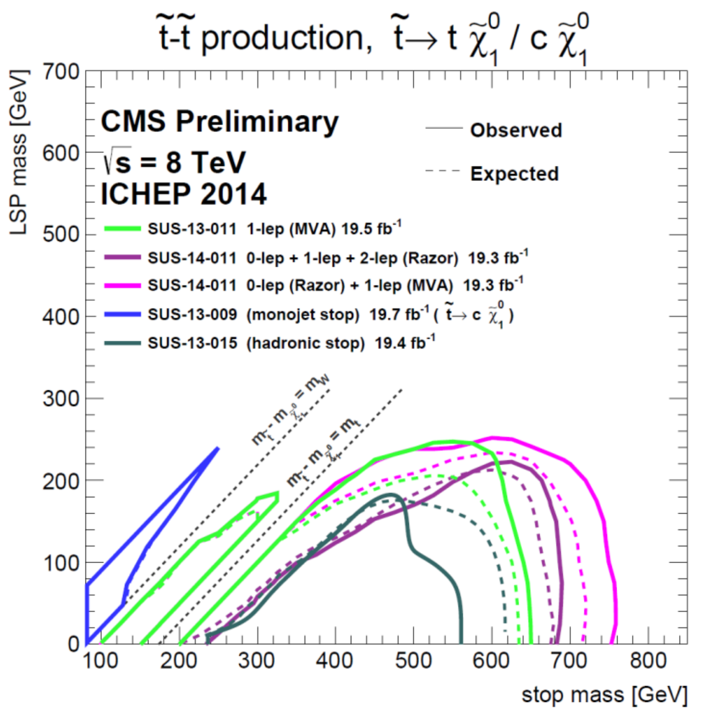
Stop limits

e.g. [CMS collaboration] PAS-SUS-14-011

Still less severe:



Rigid structure

U(1) models link SUSY and EWSB scales with Z' mass

$$V_S \sim m_S^2 S^2 + g_1' Q_S^2 S^4$$

$$M_{Z'} \sim < S > \quad \langle S \rangle \sim |m_S|$$

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<u>Impact on Mass Spectra</u>

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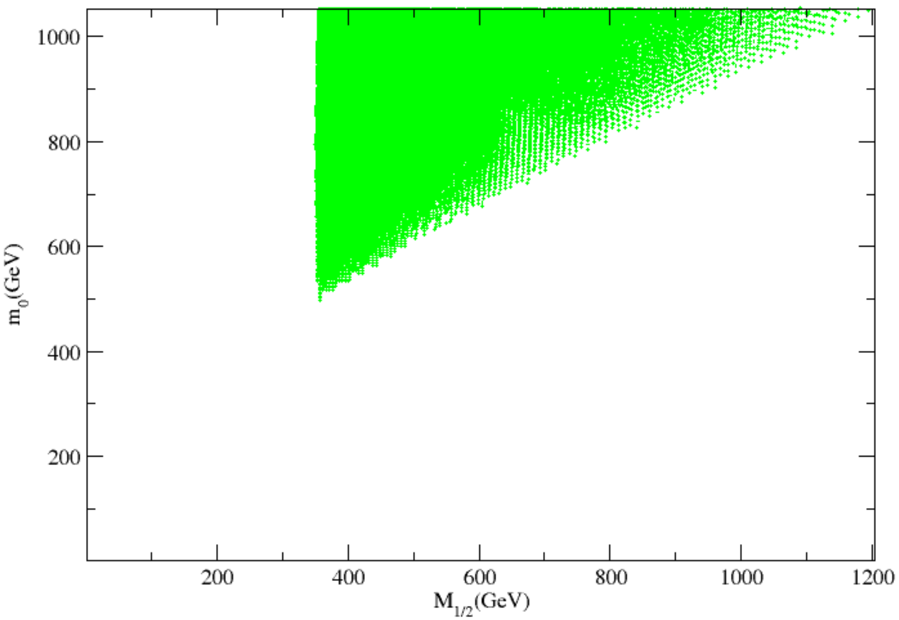

[PA, SFK, DJM, SM, RN, PRD 80, 035009 (2009)]

<u>Impact on Mass Spectra</u>

- Altered EWSB
  (see figure)

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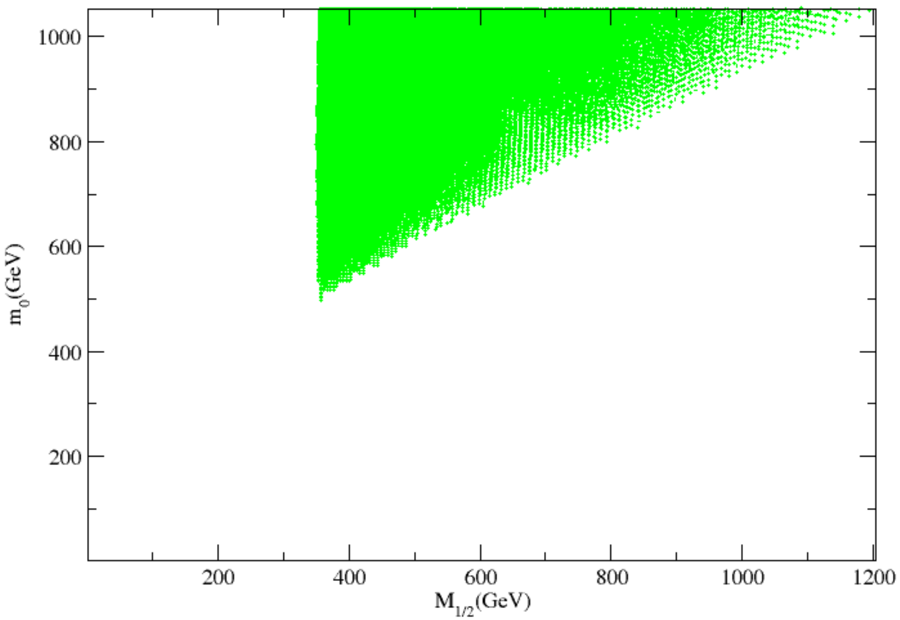

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- D-terms in sfermion masses $m_{\tilde{f}_i}^2 \approx m_i^2 + m_{f_i}^2 + \triangle_i + \text{mixing}$

Soft mass

fermion mass

Aux. D term contribution

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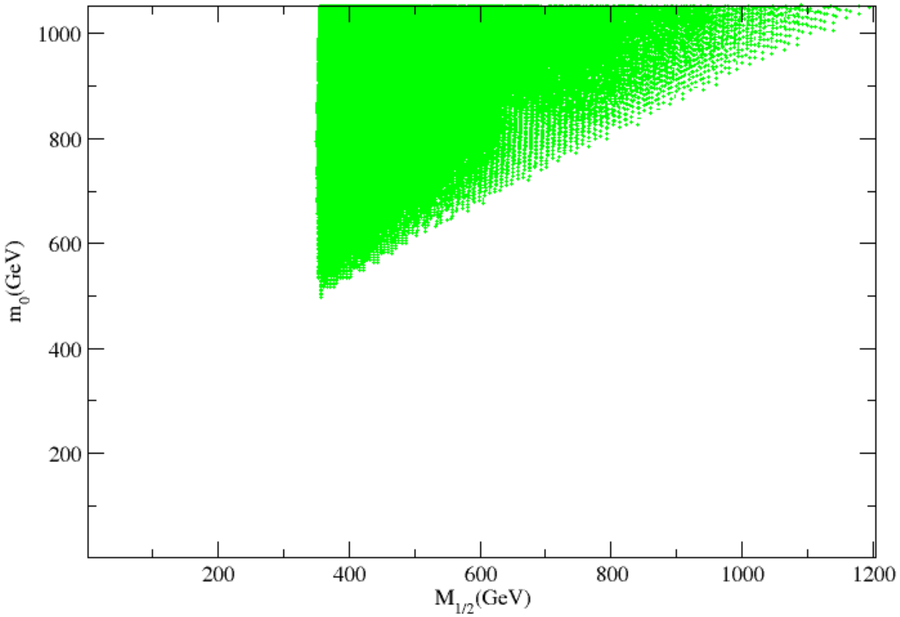

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(with exotic matter)

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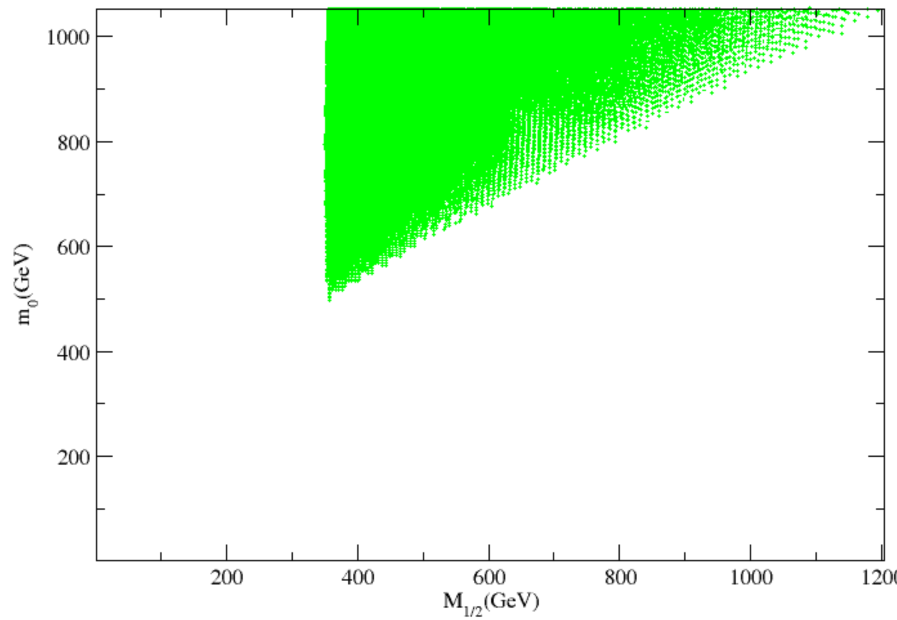

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$$V_S \sim m_S^2 S^2 + g_1' Q_S^2 S^4$$

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gives large fine tuning

[PA, King, Binjonaid PRD No.11, 115023]

see also talk by Dylan Harries

Impact on Mass Spectra

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[PA, SFK, DJM, SM, RN, PRD 80, 035009 (2009)]

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A simple idea

Can we avoid this rigid structure in U(1) extensions?

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Pure gauge singlet

Simple mechanism: keep $\lambda S H_u H_d$ but add $\phi, \overline{S}$

SM singlet

U(1)' charge $= -Q_S$

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$$\Rightarrow V_S = m_S^2|S|^2 + m_{\overline{S}}^2|\overline{S}|^2 + m_\phi^2|\phi|^2$$

$$+\frac{Q_S^2 {g_1'}^2}{2}\left(|S|^2 - |\overline{S}|^2\right)^2 \longrightarrow$$

Runaway D-flat direction

$$(m_S^2 + m_{\overline{S}}^2) < 0 \longrightarrow \langle S \rangle = \langle \overline{S} \rangle \to \infty$$

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But F-terms from $W_S = \sigma \phi S \overline{S}$ stabalise the potential

$$\longrightarrow \langle \phi \rangle \sim \langle S \rangle \simeq \langle \overline{S} \rangle \sim \frac{1}{\sigma}\sqrt{|m_S^2 + m_{\overline{S}}^2|}$$

$$\text{small } \sigma \Rightarrow M_{Z'} \gg M_{SUSY}$$

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$$\longrightarrow \quad W_{singlets} = \lambda S(H_u H_d) - \sigma \phi S \overline{S} + \frac{\kappa}{3}\phi^3 + \frac{\mu}{2}\phi^2 + \Lambda \phi$$

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$\longrightarrow$ As in the NMSSM small breaking of the PQ symmetry

$\longrightarrow$ Very light pseudoscalar

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PQ -symmetric PQ - breaking

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$\Rightarrow$ non-standard Higgs decays $h \rightarrow a_1 a_1$

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Signature can appear with Higgsino LSP

USSM Chiral Superfield Content

[M. Cvetic, D.A. Demir, J.R. Espinosa, L. Everett, P. Langacker]

Supermultiplet	spin 0	spin 1/2	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)'$
$\hat{Q}_i$	$(\widetilde{u}_L \ \ \widetilde{d}_L)_i$	$(u_L \ \ d_L)_i$	$\mathbf{3}$	$\mathbf{2}$	$\frac{1}{6}$	Q'_Q
$\overline{u}_i$	$\widetilde{u}^*_{R\,i}$	$u^\dagger_{R\,i}$	$\overline{\mathbf{3}}$	$\mathbf{1}$	$-\frac{2}{3}$	Q'_u
$\overline{d}_i$	$\widetilde{d}^*_{R\,i}$	$d^\dagger_{R\,i}$	$\overline{\mathbf{3}}$	$\mathbf{1}$	$\frac{1}{3}$	Q'_d
$\hat{L}_i$	$(\widetilde{\nu} \ \widetilde{e}_L)_i$	$(\nu \ \ e_L)_i$	$\mathbf{1}$	$\mathbf{2}$	$-\frac{1}{2}$	Q'_L
$\overline{e}_i$	$\widetilde{e}^*_{R\,i}$	$e^\dagger_{R\,i}$	$\mathbf{1}$	$\mathbf{1}$	1	Q'_e
$\hat{H}_u$	$(H_u^+ \ \ H_u^0)$	$(\widetilde{H}_u^+ \ \ \widetilde{H}_u^0)$	$\mathbf{1}$	$\mathbf{2}$	$+\frac{1}{2}$	Q'_{H_u}
$\hat{H}_d$	$(H_d^0 \ \ H_d^-)$	$(\widetilde{H}_d^0 \ \ \widetilde{H}_d^-)$	$\mathbf{1}$	$\mathbf{2}$	$-\frac{1}{2}$	Q'_{H_d}
$\hat{S}$	S	$\widetilde{S}$	$\mathbf{1}$	$\mathbf{1}$	0	Q'_S

$$\mathcal{W}_{USSM} = Y_u \bar{Q}_L H_u u_R - Y_d \bar{Q}_L \cdot H_d d_R - Y_e \bar{E} \cdot H_d d_R - \lambda S H_u H_d$$

μ_{eff}

Problem: to avoid gauge anomalies $\sum_i Q_i^{U(1)} = 0$ etc

Charges not specified in the definition of the USSM

E_6 inpsired models Chiral Superfield Content

[King, Moretti, Nevzorov, PRD 73, 0305009]

Supermultiplet	spin 0	spin 1/2	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_N$
$\hat{Q}_i$	$(\widetilde{u}_L \;\; \widetilde{d}_L)_i$	$(u_L \;\; d_L)_i$	$\mathbf{3}$	$\mathbf{2}$	$\frac{1}{6}$	1
$\overline{u}_i$	$\widetilde{u}^*_{R\,i}$	$u^\dagger_{R\,i}$	$\overline{\mathbf{3}}$	$\mathbf{1}$	$-\frac{2}{3}$	1
$\overline{d}_i$	$\widetilde{d}^*_{R\,i}$	$d^\dagger_{R\,i}$	$\overline{\mathbf{3}}$	$\mathbf{1}$	$\frac{1}{3}$	2
$\hat{L}_i$	$(\widetilde{\nu} \;\; \widetilde{e}_L)_i$	$(\nu \;\; e_L)_i$	$\mathbf{1}$	$\mathbf{2}$	$-\frac{1}{2}$	2
$\overline{e}_i$	$\widetilde{e}^*_{R\,i}$	$e^\dagger_{R\,i}$	$\mathbf{1}$	$\mathbf{1}$	1	1
$\overline{N}_i$	$\widetilde{N}^*_{R\,i}$	$N^\dagger_{R\,i}$	$\mathbf{1}$	$\mathbf{1}$	0	0
$\hat{H}_{2\,i}$	$(H^+_{2\,i} \;\; H^0_{2\,i})$	$(\widetilde{H}^+_{2\,i} \;\; \widetilde{H}^0_{2\,i})$	$\mathbf{1}$	$\mathbf{2}$	$+\frac{1}{2}$	-2
$\hat{H}_{1\,i}$	$(H^0_d \;\; H^-_{1\,i})$	$(\widetilde{H}^0_{1\,i} \;\; \widetilde{H}^-_d)$	$\mathbf{1}$	$\mathbf{2}$	$-\frac{1}{2}$	-3
$\hat{S}_i$	S_i	$\widetilde{S}_i$	$\mathbf{1}$	$\mathbf{1}$	0	5
$\hat{D}_i$	$\widetilde{D}_i$	D_i	$\mathbf{3}$	$\mathbf{1}$	$-\frac{1}{3}$	-2
$\hat{\overline{D}}_i$	$\widetilde{\overline{D}}_i$	$\overline{D}_i$	$\overline{\mathbf{3}}$	$\mathbf{1}$	$\frac{1}{3}$	-3

Complete E6 multiplets of matter

$\Rightarrow$ anomalies are automatically cancelled!

E6 inspired model

- Take concrete example:

E6SSM variant with an exact custodial symmetry

[R. Nevzorov PRD 87, 015029]

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- Add extra singlets for mechanism

  Superpotential

$$
\begin{aligned}
W &= \lambda S(H_u H_d) - \sigma \phi S\overline{S} + \frac{\kappa}{3}\phi^3 + \frac{\mu}{2}\phi^2 + \Lambda\phi \\
&\quad + \lambda_{\alpha\beta} S(H^d_\alpha H^u_\beta) + \kappa_{ij} S(D_i \overline{D}_j) + \tilde{f}_{i\alpha} S_i (H^d_\alpha H_u) + f_{i\alpha} S_i (H_d H^u_\alpha) \\
&\quad + g^D_{ij}(Q_i L_4)\overline{D}_j + h^E_{i\alpha} e^c_i (H^d_\alpha L_4) + \mu_L L_4 \overline{L}_4 + \tilde{\sigma}\phi L_4 \overline{L}_4 + W^{(\mu=0)}_{MSSM}
\end{aligned}
$$

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\end{aligned}
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Gauge group

Extra U(1) from E6 breakdown

$$
\begin{aligned}
E_6 &\to SO(10) \times U(1)_\psi \\
&\quad\quad \hookrightarrow SU(5) \times U(1)_\chi \\
&\quad\quad\quad\quad \hookrightarrow SU(3)_C \times SU(2)_W \times U(1)_Y
\end{aligned}
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\end{aligned}
$$

Extra U(1) from E6 breakdown

$$SU(3) \times SU(2) \times U(1)_Y \times U(1)_N$$

$$\tan\theta = \sqrt{15} \qquad U(1)_N = \cos\theta\, U(1)_\chi + \sin\theta\, U(1)_\psi$$

E6 inspired model

At low energies many new states in addition to Z'

- Exotic colored states from SU(3) triplets

  Higgs signature is observed could indicate exotic matter nearby

  Detection of exotic matter helps distinguish from NMSSM

- Extra weakly interacting matter SU(2) states

  Extra Higgs-like and neutralino-like sectors decoupled from the Higgs and neutralino states

  Two dark matter candidates

- Enlarged Higgs and neutralino sectors

  5 EWSB conditions to solve

  5 CP even Higgs states

  3 CP odd Higgs states

  8 neutralinos

Model chosen because it is: very elegant at the GUT scale
extremely well motivated

But many states, masses and mixings at low energies

$\longrightarrow$ complicated expressions even at tree level.

- Five EWSB conditions, e.g.

$$
\begin{aligned}
\frac{\partial V}{\partial v_1} &= m_1^2 v_1 - \frac{\lambda A_\lambda}{\sqrt{2}} s_1 v_2 + \frac{\lambda\sigma}{2} v_2 s_2 \varphi + \frac{\lambda^2}{2}(v_2^2 + s_1^2) v_1 + \frac{\bar{g}^2}{8}\Big(v_1^2 - v_2^2\Big) v_1 + \\
&+ \frac{g_1'^2}{2}\Big(\tilde{Q}_{H_d} v_1^2 + \tilde{Q}_{H_u} v_2^2 + \tilde{Q}_S (s_1^2 - s_2^2)\Big)\tilde{Q}_{H_d} v_1 + \frac{\partial \Delta V}{\partial v_1} = 0\,, \\
\frac{\partial V}{\partial v_2} &= m_2^2 v_2 - \frac{\lambda A_\lambda}{\sqrt{2}} s_1 v_1 + \frac{\lambda\sigma}{2} v_1 s_2 \varphi + \frac{\lambda^2}{2}(v_1^2 + s_1^2) v_2 + \frac{\bar{g}^2}{8}\Big(v_2^2 - v_1^2\Big) v_2 + \\
&\quad + \frac{g_1'^2}{2}\Big(\tilde{Q}_{H_d} v_1^2 + \tilde{Q}_{H_u} v_2^2 + \tilde{Q}_S (s_1^2 - s_2^2)\Big)\tilde{Q}_{H_u} v_2 + \frac{\partial \Delta V}{\partial v_2} = 0\,,
\end{aligned}
$$

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- Tree level expressions found by hand for understanding /intuition

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[PA ,J.H.Park, D.Stöckinger ,A.Voigt , arXiv:1406.2319 [hep-ph], F.Staub CPC 181 1077-1086,;182 808-833, 184 1792-1809,;CPC 185 1773-1790]

(see talk by Alexander Voigt)

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(see talk by Alexander Voigt)

- Full one-loop Self energies and tadpoles obtained with FlexibleSUSY/SARAH

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(see talk by Alexander Voigt)

- Full one-loop Self energies and tadpoles obtained with FlexibleSUSY/SARAH
- Leading two-loop corrections for NMSSM-like CP even and CP odd Higgs states with FlexibleSUSY using files of P. Slavich

[G.Degrassi and P.Slavich, Nucl.Phys.B 825, 119]

Pseudoscalar decay rate

- For our signature we really need:

$$\mathcal{L}_{h_1 A_1 A_1} = -G h_1 A_1 A_1 \qquad \Gamma(h_1 \to A_1 A_1) = \frac{G^2}{8\pi m_{h_1}} \sqrt{1 - \frac{4m_{A_1}^2}{m_{h_1}^2}}\,.$$

The full expression for
coupling G is a page long!

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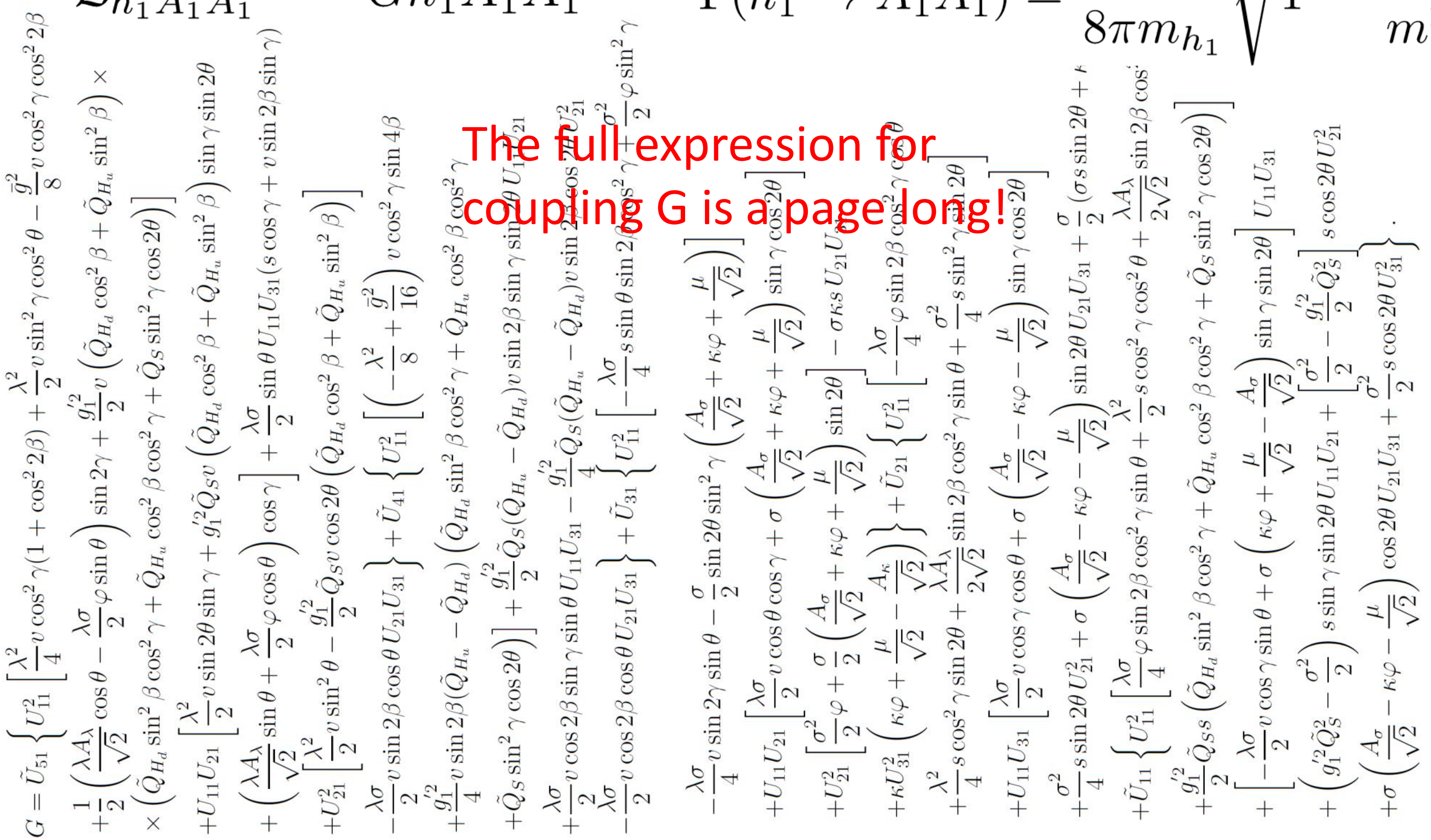
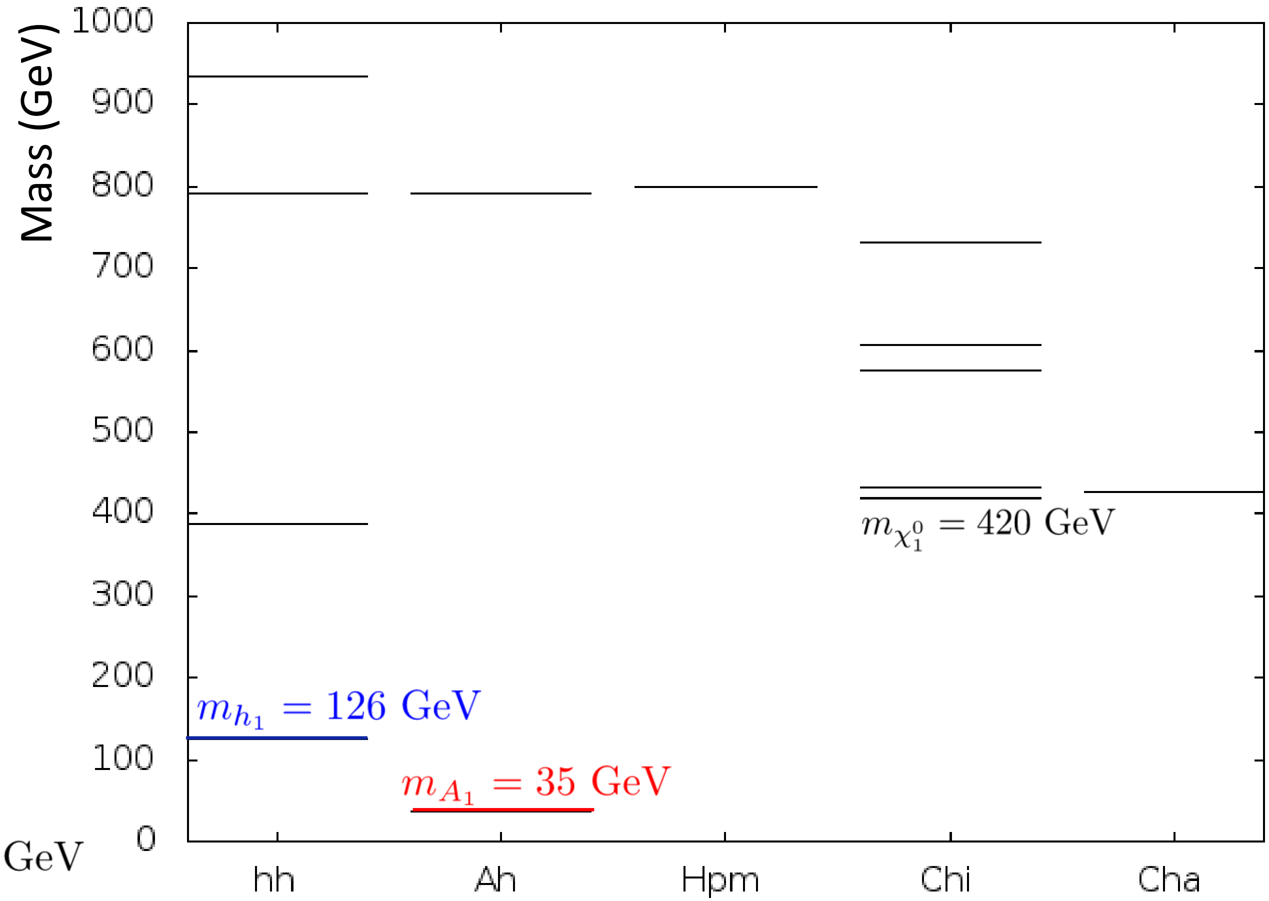


The full expression for coupling G is a page long!

Pseudoscalar decay rate

BM1 Sub-Tev Higgs and gauginos

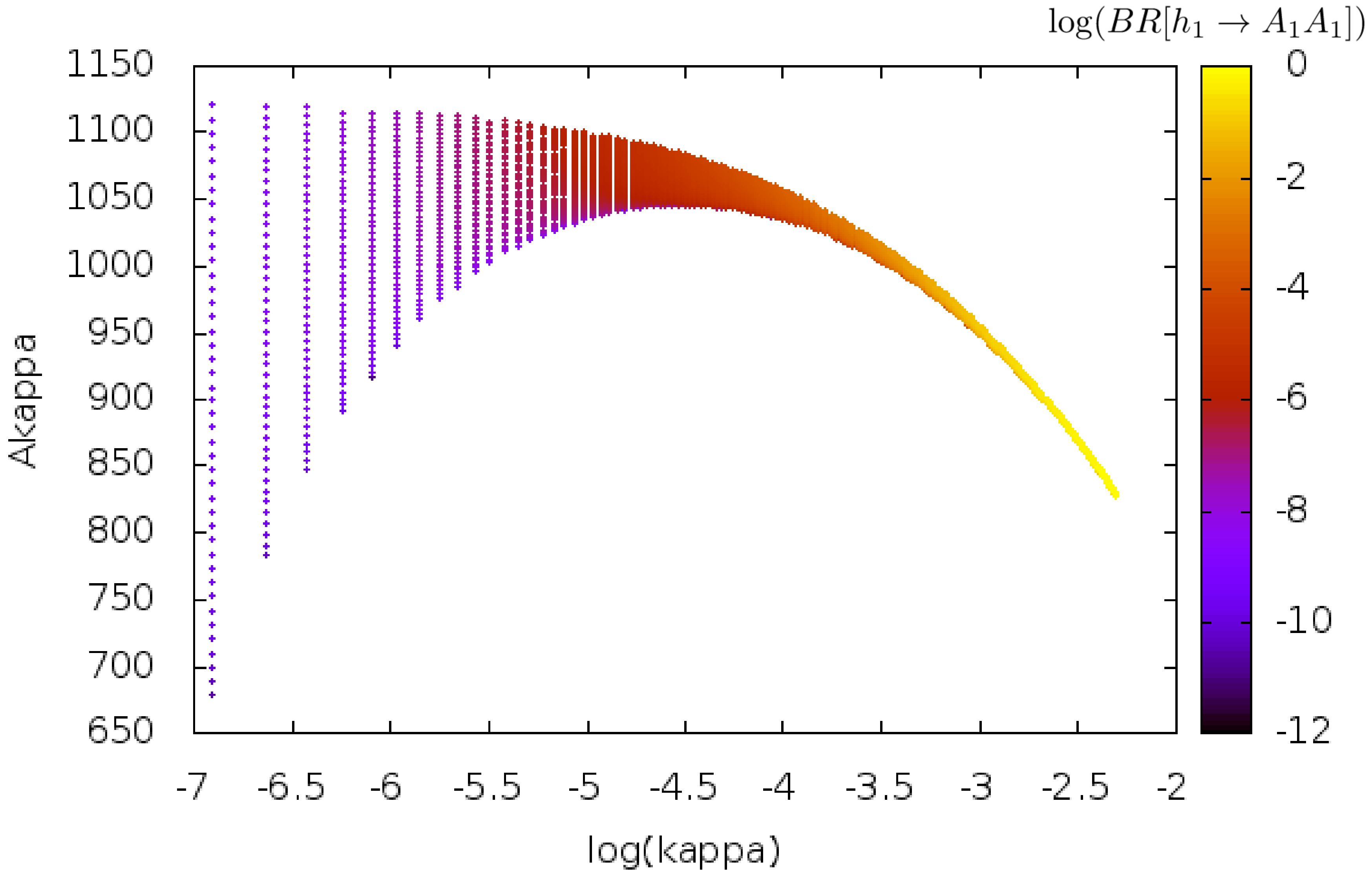
$$\kappa = 0.03$$
$$\sigma = 0.1$$
$$\lambda = 0.1$$
$$A_\kappa = 1013\,\mathrm{GeV}$$
$$A_\sigma = 1200\,\mathrm{GeV}$$
$$A_\lambda = 600\,\mathrm{GeV}$$
$$m'_Z = 2956\,\mathrm{GeV}$$



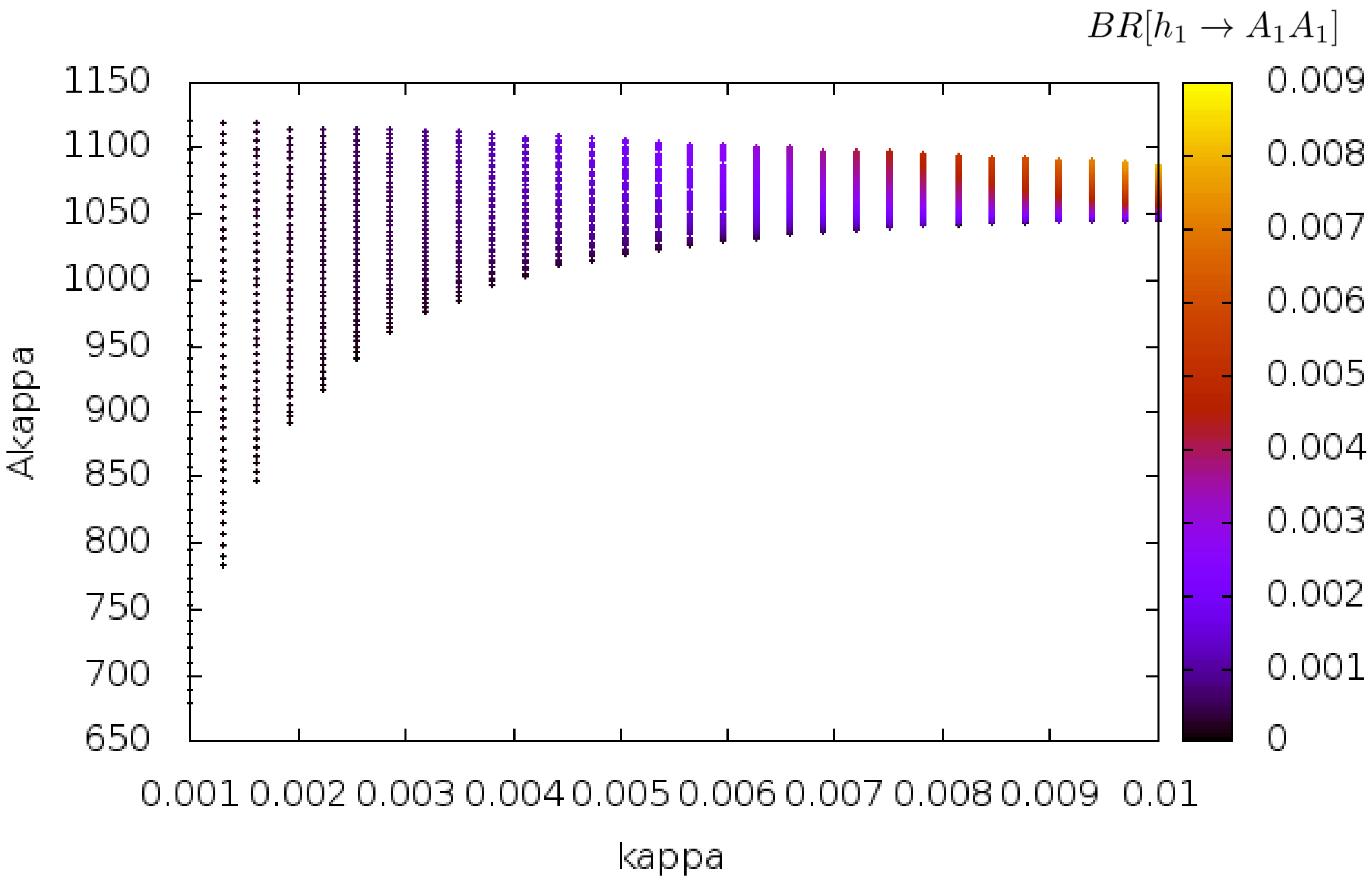
$$G = -1.27\,\mathrm{GeV}$$
$$R_{ZZh_1} = -0.998$$
$$R_{ZA_1h_1} = -0.0002$$
$$BR(h_1 \to A_1A_1) = 0.0935$$
$$\Gamma(h_1 \to A_1A_1) = 0.00042\,\mathrm{GeV}$$
$$\Gamma_{total} = 0.0045\,\mathrm{GeV}$$

$$m_{H_d}^2 = 827000\,(\mathrm{GeV})^2 \quad m_{H_u}^2 = -2.4\cdot 10^6\,(\mathrm{GeV})^2$$
$$m_S^2 = -7\cdot 10^5\,(\mathrm{GeV})^2 \quad m_{\overline{S}}^2 = 1.3\cdot 10^6\,(\mathrm{GeV})^2$$
$$m_\phi^2 = 61500\,(\mathrm{GeV})^2$$

Pseudoscalar decay rate



Pseudoscalar decay rate



Conclusions

- Usual U(1) extended SUSY models have very rigid structure
- Limits on Z' mass imply large fine tuning
- There is a mechanism to split Z' from SUSY breaking scale
- Removes tension between Z' and EW scales (may help with naturalness)
- Adding this mechanism to U(1) extensions allows a new Non-standard Higgs decay: $h \to a_1 a_1$
- Same signature as in NMSSM but with Higgsino LSP
- Observation in Higgs sector may indicate more new physics nearby
- Exotic matter needed to cancel anomalies can distinguish from NMSSM

Back up slides

$$
\begin{aligned}
\frac{\partial V}{\partial s_1} &= m_S^2\, s_1 - \frac{\lambda A_\lambda}{\sqrt{2}} v_1 v_2 - \frac{\sigma A_\sigma}{\sqrt{2}} \varphi s_2 + \left(\frac{\sigma}{2} s_1 s_2 - \frac{\kappa}{2}\varphi^2 - \frac{\mu}{\sqrt{2}}\varphi - \Lambda\right) \sigma s_2 \\
&+ \frac{\sigma^2}{2}\varphi^2 s_1 + \frac{g_1^{'2}}{2}\left(\tilde{Q}_{H_d} v_1^2 + \tilde{Q}_{H_u} v_2^2 + \tilde{Q}_S s_1^2 - \tilde{Q}_S s_2^2\right)\tilde{Q}_S s_1 \\
&+ \frac{\lambda^2}{2}(v_1^2 + v_2^2) s_1 + \frac{\partial \Delta V}{\partial s_1} = 0\,, \\
\frac{\partial V}{\partial s_2} &= m_S^2\, s_2 - \frac{\sigma A_\sigma}{\sqrt{2}} \varphi s_1 + \left(\frac{\sigma}{2} s_1 s_2 - \frac{\kappa}{2}\varphi^2 - \frac{\mu}{\sqrt{2}}\varphi - \Lambda\right) \sigma s_1 \\
&- \frac{g_1^{'2}}{2}\left(\tilde{Q}_{H_d} v_1^2 + \tilde{Q}_{H_u} v_2^2 + \tilde{Q}_S s_1^2 - \tilde{Q}_S s_2^2\right)\tilde{Q}_S s_2 \\
&+ \frac{\lambda\sigma}{2} v_1 v_2 \varphi + \frac{\partial \Delta V}{\partial s_2} = 0\,, \\
\frac{\partial V}{\partial \varphi} &= m_\varphi^2\, \varphi - \frac{\sigma A_\sigma}{\sqrt{2}} s_1 s_2 + B\mu\varphi + \sqrt{2}\xi\Lambda + \frac{\kappa A_\kappa}{\sqrt{2}}\varphi^2 + \frac{\sigma^2}{2}(s_1^2 + s_2^2)\varphi \\
&- 2\left(\frac{\sigma}{2} s_1 s_2 - \frac{\kappa}{2}\varphi^2 - \frac{\mu}{\sqrt{2}}\varphi - \Lambda\right)\left(\kappa\varphi + \frac{\mu}{\sqrt{2}}\right) + \frac{\lambda\sigma}{2} v_1 v_2 s_2 + \frac{\partial \Delta V}{\partial \varphi} = 0\,,
\end{aligned}
$$