The Higgs in Dirac gaugino and LARGE volume models

Or: Higgs mixing and adjoints

Mark D. Goodsell

CERN / Ecole Polytechnique, Paris

Overview

- Higgs mixing and branching ratios
- The Higgs and Giudice-Masiero term in LARGE volume models
- Dirac gaugino models and the 125 GeV Higgs

Motivation

$$m_H = 125.3 \pm 0.4 \pm 0.5 \text{ GeV (CMS)}, 126.0 \pm 0.4 \pm 0.4 \text{ GeV (ATLAS)}$$

$$\mu_{ii} \equiv \frac{\sigma(pp \to h)BR(h \to ii)}{\sigma_{SM}(pp \to h)BR_{SM}(h \to ii)}$$

	CMS	ATLAS	Tevatron
$\mu_{\gamma\gamma}$	1.6 ± 0.4	1.8 ± 0.5	$3.62^{+2.96}_{-2.54}$
μ_{ZZ}	0.64 ± 0.57(7 TeV)	1.7 ± 1.1(7 TeV)	
	0.79 ± 0.56(8 TeV)	1.3 ± 0.8 (8 TeV)	
μ_{WW}	0.38 ± 0.56 (7 TeV)	0.5 ± 0.6 (7 TeV)	$0.32^{+1.13}_{-0.32}$
	0.98 ± 0.71 (8 TeV)	1.9 ± 0.7 (8 TeV)	
μ_{bb}	0.59 ± 1.17 (7 TeV	0.46 ± 2.18 (7 TeV)	$1.97^{+0.74}_{-0.68}$
	0.41 ± 0.94 (8 TeV)		
$\mu_{\tau\tau}$	0.62 ± 1.17 (7 TeV)	0.45 ± 1.8 (7 TeV)	
	-0.72 ± 0.97 (8 TeV)		

Results are consistent with enhancement in $\gamma\gamma$ channel and possibly suppression in bb, $\tau\tau$ channels.

Challenges

At low energies, there are several challenges:

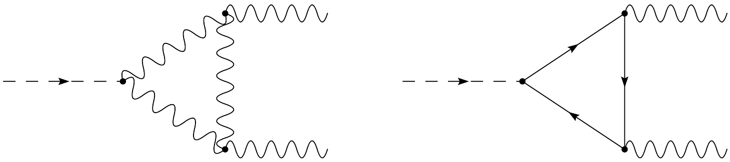
- No detection of superpartners so far $\rightarrow$ natural SUSY or little hierarchy?
- Can we get a heavy enough Higgs?
- Can we enhance $\mu_{\gamma\gamma}$?
- Will this be correlated with a decrease in $\mu_{bb}, \mu_{\tau\tau}$?

Enhancing $\mu_{\gamma\gamma}$

Couplings of Higgs to photons is via top and W loops in standard model:

$$R_{\gamma\gamma} \equiv \frac{BR(h \to \gamma\gamma)}{BR_{SM}(h \to \gamma\gamma)} = \left| \frac{A_{\gamma\gamma}}{A^{SM}_{\gamma\gamma}} \right|^2$$

$$A_{\gamma\gamma} \equiv \frac{v}{2}\left[\frac{g_{hVV}}{m_V^2} Q_V^2 A_1(\tau_V) + \frac{2 g_{hff} N_C Q_f^2}{m_f} A_{1/2}(\tau_f) + \frac{g_{hSS} N_C Q_S^2}{m_S^2} A_0(\tau_S) \right] \quad (1)$$



$A_1^\gamma(\tau_W) = -8.32(\approx -7)$ $\qquad$ $N_c Q_t^2 A_{1/2}^\gamma(\tau_t) = 1.84(\approx \frac{4}{3} \times 3 \times \frac{4}{9})$

So to enhance diphoton decay rate, can consider extra charged particles coupling to Higgs, e.g. staus, charginos or stops.

Higgs production

Since no significant excess in W or Z production, expect Higgs production to not be much enhanced. Higgs production is almost entirely by gluon fusion at 8 TeV and 125.0 GeV Higgs:

$$\begin{aligned} \sigma_{SM}(pp \to h) =& 19.5^{+14.7\%}_{-14.7\%}\text{pb} \quad \text{gluon fusion} \\ &+ 1.578^{+2.8\%}_{-3\%}\text{pb} \quad \text{vector boson fusion} \\ &+ 0.6966^{+3.7\%}_{-4.1\%}\text{pb} \quad \text{WH process} \\ &+ 0.3943^{+5.0\%}_{-5.1\%}\text{pb} \quad \text{ZH process} \\ &+ 0.1302^{+11.6\%}_{-17.1\%}\text{pb} \quad \text{ttH process} \end{aligned}$$

Hence

$$R_{gg} \equiv \frac{BR(h \to gg)}{BR_{SM}(h \to gg)}$$

dominates the Higgs production ratio to a good approximation.
Light stops either increase or decrease the gluon fusion rate depending on the sign of the coupling (NB coupling is given by $\frac{\partial \log m^2_{\tilde{t}}}{\log v}$): an enhancement requires large mixing, and would lead to a "natural SUSY" correlation between the couplings [Espinoza, Grojean, Sanz, Trott '12].

Higgs Mixing

- What if we can't accept large stop mixing as "natural" - what if we have an extra singlet, such as in the NMSSM?
- Turns out we have new ways to enhance $\mu_{\gamma\gamma}$!
- If the singlet couples to some charged particles (e.g. light higgsinos) these do the job.

Allow

$$\begin{pmatrix} h \\ H \\ s \end{pmatrix} = R \begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix}$$

then

$$\begin{aligned}
\Gamma(gg \to h_1) \sim ht\bar{t} &\propto |R_{11} + R_{21} \cot\beta|^2 \\
\Gamma(h_1 \to \bar{b}b, \bar{\tau}\tau) &\propto |R_{11} - R_{21} \tan\beta|^2 \\
\Gamma(h_1 \to gg) \propto ht\bar{t} &\propto |R_{11} + R_{21} \cot\beta|^2 \\
\Gamma(h_1 \to W^+W^-) &\propto |R_{11}|^2 \\
\Gamma(h_1 \to ZZ) &\propto |R_{11}|^2
\end{aligned}$$

Higgs mixing with extra particles

Get expressions like

$$\mu_{WW} \simeq F(R_{11}, R_{12}) \times |R_{11}|^2$$

$$F(R_{11}, R_{12}) \equiv \frac{|R_{11} + R_{21}\cot\beta|^2}{(0.577+0.063)|R_{11} - R_{21}\tan\beta|^2 + (0.215+0.026)|R_{11}|^2 + (0.086+0.0291)|R_{11} + R_{21}\cot\beta|^2}$$

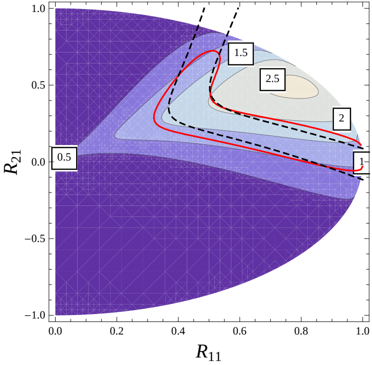
For the $\gamma - \gamma$ rate, we can add the new couplings to obtain

$$\mu_{\gamma\gamma} \simeq F(R_{11}, R_{12}) \times \left| R_{11} - 0.28\cot\beta\, R_{21} - 0.15 N_C Q_f^2 \frac{v\lambda_f}{m_f} R_{31} \right|^2$$

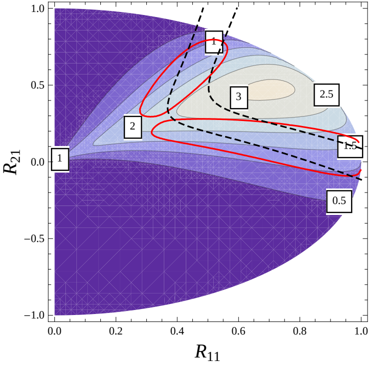
where λ_f is the coupling of the singlet to a Dirac fermion f. For Higgsinos in the NMSSM we have $\lambda_f = \lambda_S$.

Higgs mixing

Can plot contours of $\mu_{\gamma\gamma}$, e.g. $\tan\beta = 1.2$:



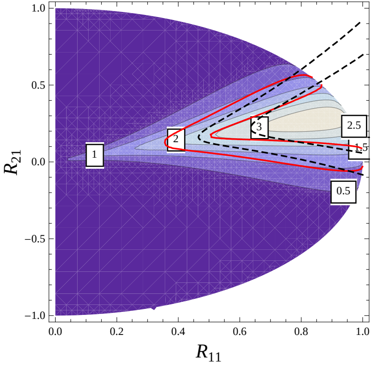
$v\lambda_f/m_f = 2$



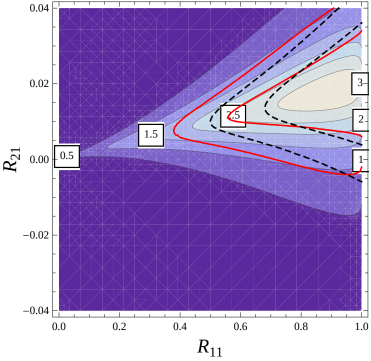
$v\lambda_f/m_f = 3$

Changing $\tan\beta$

Changing $\tan\beta$ has a large effect, e.g. for $v\lambda_f/m_f = 3$:



$\tan\beta = 3$



$\tan\beta = 50$

The Higgs in LARGE volume models

with A. Hebecker and T. Weigand

LARGE volume scenario very well developed in terms of moduli stabilisation. Only now are real strides towards concrete model building being made.

Some questions:

- Model building in geometric regime or quiver locus?
- How does the Higgs appear? Is it a true non-chiral pair?
- If not $\rightarrow$ μ-term forbidden by e.g. $U(1)$s, can we have a Giudice-Masiero term? How big is it?
- If it is non-chiral, is the term there? Do we have a shift-symmetric form of the Kähler potential?

Shall assume that the Higgs is a true non-chiral pair.

GM term in brane models

- Can calculate these terms on toroidal orbifolds $\rightarrow$ probe quiver locus
- Intersecting brane worlds $\rightarrow$ probe geometric regime
- In both cases need $N = 2$ sector to realise the "Higgs" pair
- Calculate the term $K \supset K_0 + H(U + \overline{U}, T + \overline{T}) H_u \cdot H_d$ via four-point diagram; note that Lagrangian contains

$$\mathcal{L} \supset H' \partial_\mu L (\partial^\mu H_u \cdot H_d + H_u \cdot \partial^\mu H_d)$$

so

$$\langle H_u H_d L L \rangle = 2is(H'' - K_0' K_0^{-1} H')$$

where $L = \frac{1}{\sqrt{2}}(T + \overline{T}), \frac{1}{\sqrt{2}}(U + \overline{U})$ is prop. to real part of the superfield.

D3 branes at singularities

- Know that adjoints from Wilson lines enjoy a shift symmetry
- In toroidal models have shift symmetry from translation around tori
- $\mathcal{N} = 2$ sectors of orbifolds with D3 branes at singularities are toy model for Higgs pairs at quiver locus on general background.
- In principle calculate Kähler metric from explicit four-point calculation $\rightarrow$ looks exactly like adjoints on other branes.

Outline CFT calculation

- Take model with $N = 2$ sector, e.g. $\mathbb{Z}_4$ orbifold, take twist vector $v = (1/4, 1/4, -1/2)$.
- N=2 pair of states have same vertex operator $V^{-1} = e^{-\phi} e^{ik\cdot X}\Psi^3$.
- Known Kähler metric of matter fields is $K_{i\bar{j}} = \frac{1}{(U_3+\overline{U}_3)(T_3+\overline{T}_3)}$.
- Doubling trick on disk relates $\Psi \leftrightarrow \tilde{\Psi}$.
- Can calculate three-point function with $\overline{U}_3$-modulus $V^{-1,-1} = e^{-\phi} e^{-\tilde{\phi}} e^{ik\cdot X}\overline{\Psi}^3\overline{\tilde{\Psi}}^3 \to$ get U_3-dependence of H.
- Calculate four-point function of

$$\frac{\partial_T \partial_U H}{K_H\sqrt{K_{T\overline{T}}K_{U\overline{U}}}} = \langle V^{0,0}(U_3)V^{0,0}(T_3)V^{-1}(H_u)V^{-1}(H_d)\rangle \neq 0$$

- $\to$ this turns out to look exactly like calculation for Wilson lines etc, so we know the result.
- $\to$ shift symmetric Kähler metric for non-chiral pairs in $N = 2$ sectors of orbifold singularities
- Relevant in many contexts, e.g. [Hebecker, Knochel, Weigand 12], but also relevant for model-building in sequestered regime and dark radiation [Cicoli, Conlon, Quevedo 12].

Intersecting branes

- Consider intersecting D6-branes, T-dual to IIB branes with fluxes
- Mutually $N = 2$ supersymmetric pairs of branes have angles $(\theta, -\theta, 0)$.
- Vertex operators for chiral states are different now: have

$$V_{H_u}^{-1} = e^{-\phi} e^{ik\cdot X} e^{i\theta H_1} e^{-i\theta H_2}$$
$$V_{H_d}^{-1} = e^{-\phi} e^{ik\cdot X} e^{i(1-\theta)H_1} e^{-i(1-\theta)H_2}$$

- Now by H-charge conservation there is no non-vanishing four-point amplitude with bulk moduli
- $\rightarrow$ NO GM term!
- Relevant for model building in geometric regime?

Rigid branes

- Non-rigid branes may not be a good model for the generic CY case
- Consider fractional D6-branes on $\mathbb{Z}_2 \times \mathbb{Z}_2'$ orbifold

$$\Pi_a^F = \frac{1}{4}\left[\Pi_a^B + \sum \epsilon^{\Theta}\Pi_a^{\Theta}\right]$$

- Now we can have a GM term ...

Dirac gauginos

work with K. Benakli and F. Staub

- If we eventually find gauginos at LHC, we won't know immediately whether they are Majorana ...
- Can we build models with Dirac or mixed masses? How does that affect the Higgs sector?
- To add Dirac masses, we need to add adjoint chiral superfields ($\mathcal{L} \supset -m_D \chi\lambda$). If the NMSSM singlet is an adjoint of a brane stack, then should have these additional gauged adjoints too!
- Dirac mass terms will arise in gravity mediation when we have a non-zero D-term for an anomalous $U(1)$; the "kinetic mixing" between visible groups and the hidden $U(1)$ depends upon the adjoint field, and we have

$$m_D = \left| -\frac{1}{2}\frac{D'}{\sqrt{2}}\frac{gg'}{16\pi^2}\partial_{X^I}\mathrm{tr}\left(Q' R(T^I)\log|\mathcal{M}|^2/\mu^2\right)\right|_{X^I=0}\right|$$

However, shall focus on bottom-up approach: embedding this concretely in LVS is future work ...

Supersymmetric Couplings

Here are the most general renormalisable superpotential couplings:

- SUSY couplings contained in superpotential:
  $W = W_{\mathrm{Yukawa}} + W_{\mathrm{Higgs}} + W_{\mathrm{Adjoint}}$
- No new Yukawas:

$$W_{\mathrm{Yukawa}} = Y_U^{ij}\mathbf{Q_i}\cdot\mathbf{H_u u_j^c} + Y_D^{ij}\mathbf{Q_i}\cdot\mathbf{H_d d_j^c} + Y_E^{ij}\mathbf{L_i}\cdot\mathbf{H_d e_j^c}$$

- Two new Higgs couplings (c.f. NMSSM) which descend from $N = 2$ structure:

$$W_{\mathrm{Higgs}} = \mu\mathbf{H_u}\cdot\mathbf{H_d} + \lambda_S\mathbf{S H_d}\cdot\mathbf{H_u} + 2\lambda_T\mathbf{H_d}\cdot\mathbf{T H_u}$$

- Several new adjoint couplings, but violate $N = 2$ so shall set to zero:

$$W_{\mathrm{Adjoint}} = \mathbf{L S} + \frac{M_S}{2}\mathbf{S}^2 + \frac{\kappa_S}{3}\mathbf{S}^3 + M_T \mathrm{tr}(\mathbf{TT}) + \lambda_{ST}\mathbf{S}\mathrm{tr}(\mathbf{TT}) + M_O \mathrm{tr}(\mathbf{OO}) + \lambda_{SO}\mathbf{S}\mathrm{tr}(\mathbf{OO}) + \frac{\kappa_O}{3}\mathrm{tr}(\mathbf{OOO}).$$

In string theory, expect the $N = 2$ coupling relationship ($\lambda_S, \lambda_T = \sqrt{2}g$) to only be valid at tree level, and to receive threshold corrections etc.

New D-terms

- For spontaneously broken SUSY, non-standard soft terms actually come from one holomorphic coupling:

$$\int d^2\theta 2\sqrt{2} m_D \theta^\alpha \mathrm{tr}(W_\alpha \Sigma) \supset -m_D(\lambda_a \chi_a) + \sqrt{2} m_D \Sigma_a D_a$$

- This translates into

$$\mathcal{L} \supset -m_{bD}\sqrt{2} g_b \Sigma_a \phi^\dagger R^a_b \phi$$

- i.e. the D-term is shifted. This changes the Higgs potential, masses and also the sfermion masses! Higgs mass matrix in the basis $\{h, H, S_R, T^0_R\}$ is

$$\begin{pmatrix} M_Z^2 + \Delta_h s_{2\beta}^2 & \Delta_h s_{2\beta} c_{2\beta} & \Delta_{hs} & \Delta_{ht} \\ \Delta_h s_{2\beta} c_{2\beta} & M_A^2 - \Delta_h s_{2\beta}^2 & \Delta_{Hs} & \Delta_{Ht} \\ \Delta_{hs} & \Delta_{Hs} & \tilde{m}_S^2 & \lambda_S \lambda_T \frac{v^2}{2} \\ \Delta_{ht} & \Delta_{Ht} & \lambda_S \lambda_T \frac{v^2}{2} & \tilde{m}_T^2 \end{pmatrix}$$

where

$$\begin{aligned} \Delta_h &= \frac{v^2}{2}(\lambda_S^2 + \lambda_T^2) - M_Z^2 \\ \Delta_{hs} &= v[v_S \lambda_S^2 - g' m_{1D} c_{2\beta}] \\ \Delta_{Hs} &= g' m_{1D} v s_{2\beta} \end{aligned}$$

Triplet is naturally heavy, which is good since a large triplet vev would violate the EWPD ... (need $m_T \gtrsim$ few TeV)

Tree level Higgs

Can enhance the Higgs mass naturally! Tree level bound becomes

$$m_h^2 \leqslant M_Z^2 c_{2\beta}^2 + \frac{v^2}{2}(\lambda_S^2 + \lambda_T^2) s_{2\beta}^2 .$$

At small $\tan\beta$, do not need heavy stops or large stop mixing etc ...

Higgs RGEs

NB Higgs finetuning is reduced in these models since the Dirac masses do not enter the RGEs in the same way as Majorana ones.
The soft terms for the Higgs run as

$$
\begin{aligned}
16\pi^2 \frac{d}{dt} m_{H_u}^2 =& 6|y_t|^2 [m_{Q_3}^2 + m_{U_3}^2 + m_{H_u}^2] \\
&+ 2\lambda_S^2 [m_{H_u}^2 + m_S^2 + m_{H_d}^2] + 6\lambda_T^2 [m_{H_u}^2 + m_T^2 + m_{H_d}^2] \\
&+ g_Y^2 Tr(Y m^2) \\
&- 4\lambda_S^2 m_{D1}^2 - 12\lambda_T^2 m_{D2}^2 \\
16\pi^2 \frac{d}{dt} m_{H_d}^2 =& 6|y_b|^2 [m_{Q_3}^2 + m_{D_3}^2 + m_{H_d}^2] \\
&+ 2|y_\tau|^2 [m_{L_3}^2 + m_{E_3}^2 + m_{H_d}^2] \\
&+ 2\lambda_S^2 [m_{H_u}^2 + m_S^2 + m_{H_d}^2] + 6\lambda_T^2 [m_{H_u}^2 + m_T^2 + m_{H_d}^2] \\
&- g_Y^2 Tr(Y m^2) \\
&- 4\lambda_S^2 m_{D1}^2 - 12\lambda_T^2 m_{D2}^2 \\
16\pi^2 \frac{d}{dt} B_\mu =& B_\mu [3|y_t|^2 + 3|y_b|^2 + |y_\tau|^2 - 3g_2^2 - y_Y^2] \\
&+ 2B_\mu \lambda_S^2 + 6B_\mu \lambda_T^2
\end{aligned}
$$

The new couplings can have a strong effect on driving electroweak symmetry breaking.

Scenarios

Equation for singlet vev is

$$0 = \kappa^2 v_S^3 + \frac{\kappa}{\sqrt{2}}(A_\kappa + 3M_S)v_S^2 + (\tilde{m}_{SR}^2 + \lambda_S(\lambda_S - \kappa s_{2\beta})\frac{v^2}{2})v_S + \sqrt{2}t_S + v_0^3$$

$$v_0 \equiv -\frac{v^2}{2}\left[g' m_{1D} c_{2\beta} - \lambda_S\left(\sqrt{2}\mu - \frac{(A_S + M_S)}{\sqrt{2}} s_{2\beta} + \lambda_T v_T\right)\right].$$

Can have several different scenarios:

- MSSM in disguise: here we shall allow a μ-term, and assume that the only source of R-symmetry violation arises in the supersymmetry-breaking sector, but permit only a B_μ term.
- MSSM without μ term: this is the scenario of [Nelson, Rius, Sanz, Unsal], taking $\mu = 0$.
- Hidden sector R-breaking: take $\mu = 0$ but allow non-zero B_S, leading to a substantial non-zero expectation value for the singlet.
- Visible sector R-breaking: we allow a non-zero κ, breaking R-symmetry in the visible sector, but allowing μ and B_μ to be generated via a non-zero singlet vev.

Charginos

The chargino mass matrix is expanded by new charged states from the triplet: in the basis $(T^+, \tilde{W}^+, H_u^+)/(T^-, \tilde{W}^-, H_d^+)$ it is

$$M_{Ch} = \begin{pmatrix} M_T & m_{2D} + g_2 v_T & \frac{2\lambda_T}{g_2} M_Z c_W c_\beta \\ m_{2D} - g_2 v_T & M_2 & \sqrt{2} M_Z c_W s_\beta \\ -\frac{2\lambda_T}{g_2} M_Z c_W s_\beta & \sqrt{2} M_Z c_W c_\beta & \tilde{\mu} - \sqrt{2}\lambda_T v_T \end{pmatrix}$$

This can change the predictions for the Higgs-gamma-gamma rate if they are light. Find approximately

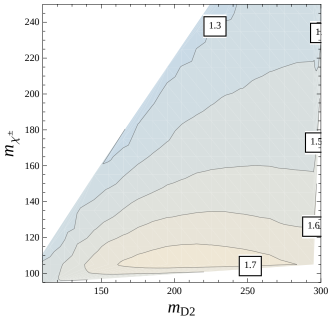
$$A_{\gamma\gamma}^{\text{Charginos}} \simeq \frac{4}{3} \frac{1}{\sqrt{2} m_{D2} \tilde{\mu} - g_2 v^2 \lambda_T c_{2\beta}} \left[2 g_2 \lambda_T v^2 (-c_{2\beta} R_{11} + s_{2\beta} R_{21}) + \lambda_S v m_{D2} R_{31} \right]$$

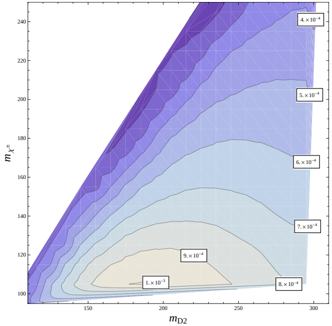
Numerical implementation

- Dirac gauginos are interesting beyond-the-MSSM models, and since they do not have standard soft terms have been hard to implement in standard tools.
- However, they have now been implemented in SARAH by F. Staub (to appear in next release).
- Generates SPheno code, including Higgs properies, full one-loop mass corrections, two-loop RGEs (implementing results of [MDG June 2012]) ...

Chargino contributions

Perform a scan over models using the SPheno code, at large $\tan\beta$ and λ_T to enhance $\mu_{\gamma\gamma}$:





Comparison of numerical code with effective potential

We can write the generic form for the Higgs potential in terms of effective operators as

$$\begin{aligned} V_{eff} = & (m_{H_u}^2 + \mu^2)|H_u|^2 + (m_{H_d}^2 + \mu^2)|H_d|^2 - [m_{12}^2 H_u \cdot H_d + h.c.] \\ & + \frac{1}{2}\Big[\frac{1}{4}(g^2 + g'^2) + \lambda_1\Big](|H_d|^2)^2 + \frac{1}{2}\Big[\frac{1}{4}(g^2 + g'^2) + \lambda_2\Big](|H_u|^2)^2 \\ & + \Big[\frac{1}{4}(g^2 - g'^2) + \lambda_3\Big]|H_d|^2|H_u|^2 + \Big[-\frac{1}{2}g^2 + \lambda_4\Big](H_d \cdot H_u)(H_d^* \cdot H_u^*) \end{aligned}$$

where at tree level

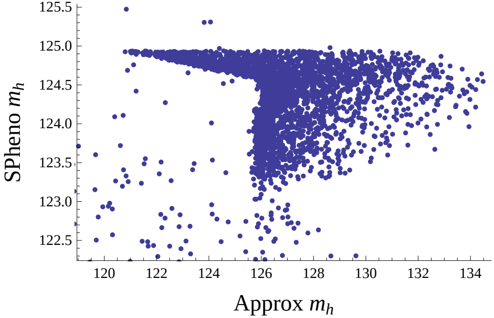
$$\lambda_3 = 2\lambda_T^2, \qquad \lambda_4 = \lambda_S^2 - \lambda_T^2, \qquad \lambda_1 = \lambda_2 = 0$$

Loop corrections to these can be derived and, in large $\tan\beta$ limit, the Higgs mass is approximately

$$m_h^2 \approx M_Z^2 c_{2\beta}^2 + \frac{v^2}{2}(\lambda_S^2 + \lambda_T^2)s_{2\beta}^2 + \lambda_2 v^2.$$

Numerical comparison

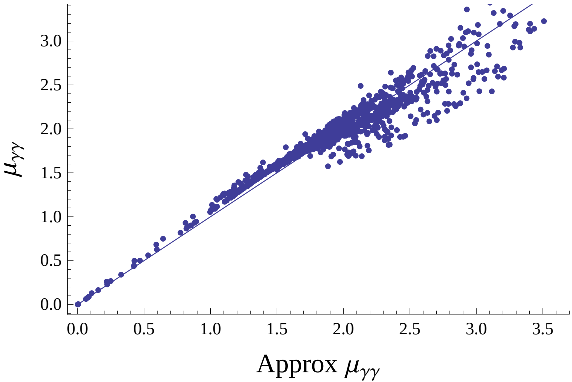
Comparison of effective potential with a SPheno scan over models with heavy singlet and triplet scalars:



Can have light squarks and correct Higgs mass.

Comparison of numerical code with approximations

Finally, we can compare the approximate formulae for $\mu_{\gamma\gamma}$ involving Higgs mixing with large λ_S with SPheno output:



Conclusions

- Currently the data favours an enhanced branching ratio of the Higgs into $\gamma\gamma$, and possibly decreased into fermions. Although it is too early to tell, such a scenario would be nicely explained by Higgs mixing.
- This can be implemented in Dirac gaugino models, which have many other nice features and can now really be explored for the first time as the tools become available.
- Alternatively this could occur in the NMSSM, where the singlet could be an adjoint in a string model; in this case the Higgses would apparently have no GM term - but the singlet would have a shift symmetry at leading order.
- Long program of research into these and other beyond-MSSM theories