Higgs to diphoton rate in SO(10) Yukawa Unification

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work with M. Olechowski and S. Pokorski

Preliminary results

Brief remarks on the status of a Higgs

The discovery of a Higgs is firmly established with the mass around 125 GeV which is within the range predicted by MSSM

The Higgs branching ratios converge towards the SM but quite slowly and still some room for deviations of order few $\times$ 10%

Updated CMS Higgs results in the $\gamma\gamma$ channel no longer show excess over the SM but in ATLAS it is still there.

Combination of ATLAS and CMS in $\gamma\gamma$ channel:

$$\mu_{\gamma\gamma} = 1.2 \pm 0.2 \quad \text{(CMS MVA analysis)}$$

$$\mu_{\gamma\gamma} = 1.4 \pm 0.2 \quad \text{(CMS cut-based analysis)}$$

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No strong hints for new physics but enhanced $\gamma\gamma$ rate remains an interesting and valid possibility

Outline

1. Effects of staus on the Higgs $\gamma\gamma$ rate in MSSM
2. Necessary conditions for top-bottom-tau Yukawa unification
   - non-universalities in the soft masses
   - the sign of μ
3. Yukawa unification and the Higgs $\gamma\gamma$ rate enhancement

Enhancing $h \to \gamma\gamma$ rate in the MSSM

There are two ways to enhance $\sigma(gg \to h) \times \text{BR}(h \to \gamma\gamma)$:

1. the b-quark coupling reduced (with respect to the SM) $\Rightarrow$ the Higgs decay rates to gauge bosons enhanced

   However, in the MSSM at tree level $g_{hb\bar{b}}^{\text{MSSM}} \geqslant g_{hb\bar{b}}^{\text{SM}}$.

   At loop level, reduced $g_{hb\bar{b}}^{\text{MSSM}}$ is possible but only for a rather small m_A and large $\tan\beta$ which is strongly constrained by the LHC searches for A in the $\tau\bar{\tau}$ channel

2. SUSY particles with e-m charge and large couplings to the Higgs may enhance $\Gamma(h \to \gamma\gamma)$
   - Strongly mixed stops and sbottoms enhance $\Gamma(h \to \gamma\gamma)$ but suppress $\sigma(gg \to h)$ even more
   - Strongly mixed staus enhance $\Gamma(h \to \gamma\gamma)$ without affecting $\sigma(gg \to h)$

Light staus with strong left-right mixing are the most promising to enhance the $\gamma\gamma$ rate.

Stau effects on $\Gamma(h \to \gamma\gamma)$ and m_h

$$\frac{\Gamma(h \to \gamma\gamma)}{\Gamma(h \to \gamma\gamma)_{\rm SM}} \approx \left(1 + 0.05 \frac{m_\tau^2 X_\tau^2}{m_{\tilde{\tau}_1}^2 m_{\tilde{\tau}_2}^2}\right)^2$$

but strongly-mixed light staus give also negative contribution to the Higgs mass:

$$m_h^2 \approx M_Z^2 \cos^2 2\beta + \frac{3 g^2 m_t^4}{8\pi^2 m_W^2}\left[\ln\left(\frac{M_{\rm SUSY}^2}{m_t^2}\right) + \frac{X_t^2}{M_{\rm SUSY}^2}\left(1 - \frac{X_t^2}{12 M_{\rm SUSY}^2}\right)\right] + \\ - \frac{g^2}{8\pi^2 m_W^2}\frac{m_\tau^4 X_\tau^4}{12 m_{\tilde{\tau}_1}^2 m_{\tilde{\tau}_2}^2}$$

Still, enhancement of $\Gamma(h \to \gamma\gamma)$ up to 50% can be obtained consistently with the 125 GeV Higgs but only if:

Carena et al. '12

1. The lightest stau mass is around 100 GeV
2. Strong left-right mixing i.e. $X_\tau = A_\tau - \mu \tan\beta \gtrsim \mathcal{O}(20~\text{TeV})$

Enhanced $\gamma\gamma$ rate from light staus

It has not been demonstrated so far that the low-energy MSSM spectrum with strongly-mixed light staus can be obtained from a well-motivated high-energy model

In this talk: $\gamma\gamma$ rate enhancement can be realized in a SO(10) model with top-bottom-tau Yukawa unification

Minimal SO(10) and Yukawa Unification

- For a given generation all matter fermions, including ν_R, sit in one **16** dim. representation of SO(10)
- Both MSSM Higgs doublets are in the **10** dim. representation of SO(10)
- Yukawa interactions are given by

$$W = h\,\mathbf{16}\,\mathbf{10}\,\mathbf{16}$$

which imply unification of Yukawa couplings at $M_{\rm GUT}$:

$$h = h_t = h_b = h_\tau$$

- Yukawa unification predicts large values of $\tan\beta \sim 50$

Yukawa Unification and REWSB

At large $\tan\beta$ proper REWSB requires $m_{H_d}^2 - m_{H_u}^2 \gtrsim M_Z^2$

For universal soft terms at the GUT scale:

- RG evolution results in positive (negative) contribution to $m_{H_d}^2 - m_{H_u}^2$ proportional to $M_{1/2}^2$ (m_0^2)
- REWSB possible only if $M_{1/2} > m_0$
- μ^2 strongly correlated with $M_{1/2}^2$
  $\Rightarrow$ too large SUSY threshold correction to the bottom mass for $b-\tau$ Yukawa unification

Carena, Olechowski, Pokorski, Wagner '1994

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Carena, Olechowski, Pokorski, Wagner '1994

proper REWSB requires e.g. Higgs splitting at M_{GUT}: $m_{H_u} < m_{H_d}$

Olechowski, Pokorski '1994

Non-universal scalar masses in SO(10)

All sfermions in **16**-dim rep. of SO(10) while Higgses in **10**-dim rep.
$\Rightarrow$ Pattern of soft scalar masses restricted by SO(10) gauge symmetry:

$$m_{H_d,H_u} = m_{10}$$
$$m_{Q,U,D,L,E} = m_{16}$$

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D-term contribution

Rank of SO(10) is larger than the rank of SM gauge group
⇒ in the effective theory below the GUT scale soft scalar masses acquire new contribution proportional to D-term and charges of the broken U(1):

Kawamura, Murayama, Yamaguchi '1994

$$m_{H_d}^2 = m_{10}^2 + 2D$$
$$m_{H_u}^2 = m_{10}^2 - 2D$$
$$m_{Q,U,E}^2 = m_{16}^2 + D$$
$$m_{D,L}^2 = m_{16}^2 - 3D$$

$D > 0$ may allow for proper REWSB

Murayama, Olechowski, Pokorski '1995

Yukawa Unification and the Sign of μ

$b-\tau$ Yukawa unification leads to tree level bottom mass bigger than the observed mass

SUSY loop correction to the bottom mass must be negative with the magnitude between 10 to 20%:

$$\left(\frac{\delta m_b}{m_b}\right) \approx \frac{g_3^2}{6\pi^2}\mu m_{\tilde{g}} \tan\beta\, I(m_{\tilde{b}_1}^2, m_{\tilde{b}_2}^2, m_{\tilde{g}}^2) + \frac{h_t^2}{16\pi^2}\mu A_t \tan\beta\, I(m_{\tilde{t}_1}^2, m_{\tilde{t}_2}^2, \mu^2)$$

For $\mu > 0$

- The gluino-sbottom contribution has wrong sign so has to be suppressed $\Rightarrow$ squarks above 10 TeV & light gluino (almost excluded by the LHC)
- The chargino-stop contribution must dominate $\Rightarrow$ A_t negative and very large to account for the observed bottom mass
- does not work with D-term splitting $\Rightarrow$ ad-hoc Higgs splitting is used

Baer et al. '2008,2012

For $\mu < 0$

- The gluino-sbottom contribution has correct sign
  $\Rightarrow$ more flexibility in the spectrum e.g. squark masses may be smaller

Necessary conditions for enhanced $\Gamma(h \to \gamma\gamma)$

Since the lightest stau mass has to be around 100 GeV, the neutralino LSP must be even lighter:

$$\left|M_1^{\rm EW}\right| \text{(or } \left|M_2^{\rm EW}\right|) \lesssim 100 \text{ GeV}$$

while LHC limits on the gluino mass give $\left|M_3^{\rm EW}\right| \gtrsim 1.2 \text{ TeV}$ so:

$$\left|\frac{M_1}{M_3}\right| \lesssim \frac{1}{2} \text{ or } \left|\frac{M_2}{M_3}\right| \lesssim \frac{1}{4} \text{ at the GUT scale}$$

Assumption of universal gaugino masses has to be relaxed

Gaugino Masses from Non-singlet F-terms

Gaugino masses in SUGRA can arise from dimension 5 operator:

$$\mathcal{L} \supset -\frac{F^{ab}}{2M_{\rm Planck}}\lambda^a\lambda^b + \text{c.c.}$$

- $\langle F^{ab}\rangle$ must transform as a singlet under the SM gauge group
- $\langle F^{ab}\rangle$ must belong to the symmetric part of $\mathbf{45}\times\mathbf{45}$
- $\langle F^{ab}\rangle$ can be in a non-singlet representation of SO(10)

$$(\mathbf{45}\times\mathbf{45})_S = \mathbf{1}+\mathbf{54}+\mathbf{210}+\mathbf{770}$$

If $\langle F^{ab}\rangle$ transforms as **24** $\subset$ **54** of SU(5) $\subset$ SO(10), gaugino masses are given by:

Martin, 2009

$$M_1 : M_2 : M_3 = -\frac{1}{2} : -\frac{3}{2} : 1$$

$\left|\frac{M_1}{M_3}\right| \lesssim \frac{1}{2}$ and/or $\left|\frac{M_1}{M_3}\right| \lesssim \frac{1}{4}$ possible if both the singlet and **24** F-terms break SUSY

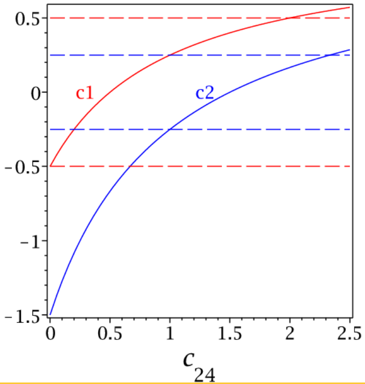
Gaugino Masses from the singlet and **24** F-term

$$M_1 = M_{1/2}^{(1)} - \frac{1}{2}M_{1/2}^{(24)} \equiv \frac{-\frac{1}{2}+c_{24}}{1+c_{24}}M_{1/2} \equiv c_1 M_{1/2}$$

$$M_2 = M_{1/2}^{(1)} - \frac{3}{2}M_{1/2}^{(24)} \equiv \frac{-\frac{3}{2}+c_{24}}{1+c_{24}}M_{1/2} \equiv c_2 M_{1/2}$$

$$M_3 = M_{1/2}^{(1)} + M_{1/2}^{(24)} \equiv M_{1/2}$$

$$c_{24} \equiv M_{1/2}^{(1)}/M_{1/2}^{(24)}$$



Enhanced $\Gamma(h \to \gamma\gamma)$ viable only for:

$$0 \lesssim c_{24} \lesssim 2.3$$

$c_{24} \lesssim 1.2 \to$ bino dominates LSP

$c_{24} \gtrsim 1.2 \to$ wino dominates LSP

The SO(10) model

$$\boxed{\mu < 0}$$

- Non-universal scalar masses:

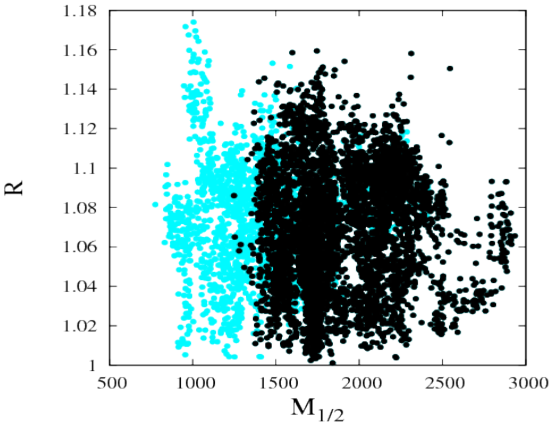
$$\begin{aligned} m_{H_d}^2 &= m_{10}^2 + 2D \\ m_{H_u}^2 &= m_{10}^2 - 2D \\ m_{Q,U,E}^2 &= m_{16}^2 + D \\ m_{D,L}^2 &= m_{16}^2 - 3D \end{aligned}$$

- Non-universal gaugino masses:

$$\begin{aligned} M_1 &= \frac{-\frac{1}{2} + c_{24}}{1 + c_{24}} M_{1/2} \\ M_2 &= \frac{-\frac{3}{2} + c_{24}}{1 + c_{24}} M_{1/2} \\ M_3 &= M_{1/2} \end{aligned}$$

- Universal trilinear couplings: $A_U = A_D = A_E = A_0$

$$R \equiv \left. \frac{\max(h_t, h_b, h_\tau)}{\min(h_t, h_b, h_\tau)} \right|_{\rm GUT} \qquad R_{\gamma\gamma} \equiv \frac{\sigma(gg \to h) \times {\rm BR}(h \to \gamma\gamma)}{\sigma(gg \to h)^{\rm SM} \times {\rm BR}(h \to \gamma\gamma)^{\rm SM}}$$



$m_h > 123$ GeV

$m_{\rm stau} > 90$ GeV

$m_{\rm chargino} > 103.5$ GeV

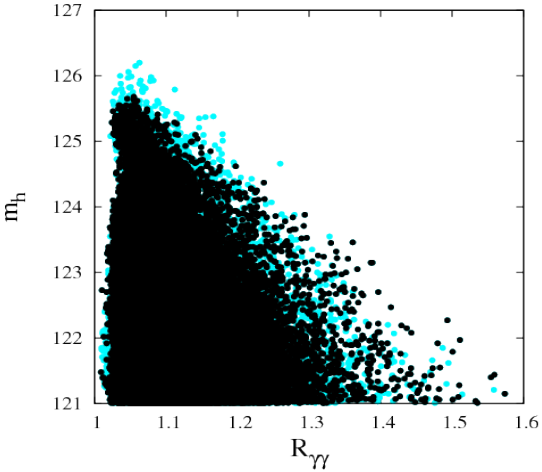
$m_A > 750$ GeV

$R_{\gamma\gamma} > 1.1$

Black points satisfy $b \to s\gamma$, $B_s \to \mu^+\mu^-$, the upper WMAP bound on $\Omega_{\rm LSP}$ and direct limits on sparticles masses.

Blue points violate $b \to s\gamma$ or $B_s \to \mu^+\mu^-$

$t - b - \tau$ Yukawa unification allows for enhanced $R_{\gamma\gamma}$



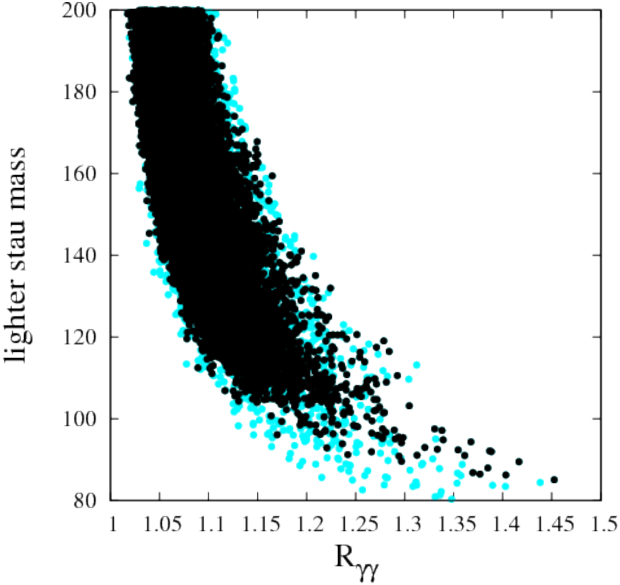
$m_{\rm stau} > 90$ GeV

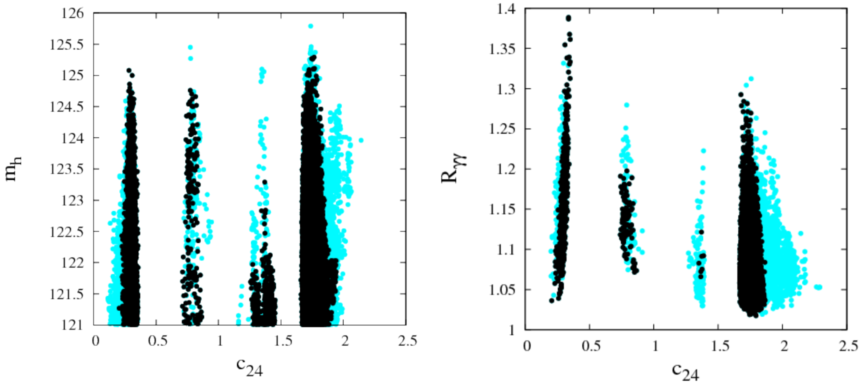
$m_{\rm chargino} > 103.5$ GeV

$m_A > 750$ GeV

$R < 1.1$

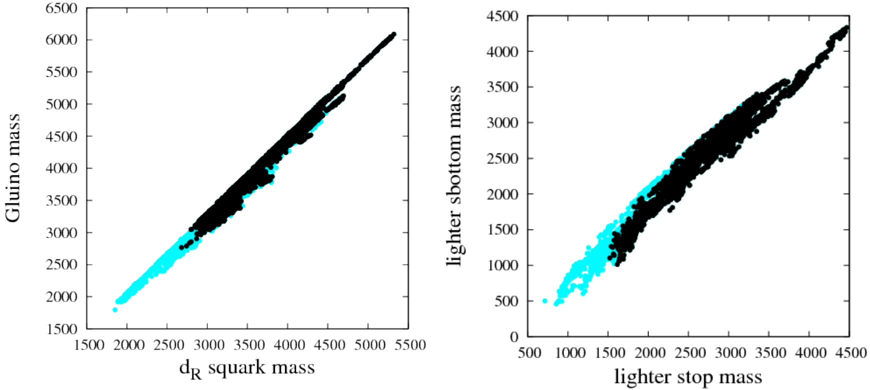
$h \to \gamma\gamma$ **rate can be enhanced up to 40 %**


200
180
160
140
120
100
80
lighter stau mass
1
1.05
1.1
1.15
1.2
1.25
1.3
1.35
1.4
1.45
1.5
$R_{\gamma\gamma}$



$c_{24} < 1 \Rightarrow$ bino-like LSP - WMAP bound saturated due to stau coannihilations

$c_{24} > 1 \Rightarrow$ wino-like LSP - Ω_{LSP} too small



$b \to s\gamma$ and $B_s \to \mu^+\mu^-$ set stronger lower mass limits on sparticle masses than the 125 GeV Higgs

- gluino and 1st gen. squark masses $\gtrsim 2.5$ TeV - might be reached at the 13 TeV LHC (if we are lucky)
- sbottom may be as light as 1 TeV - not far above current limit of about 600 GeV

Conclusions

SO(10) models with $t - b - \tau$ Yukawa coupling unification can accommodate enhanced $h \to \gamma\gamma$ rate

Non-universality of soft terms at $M_{\rm GUT}$ are necessary for proper REWSB and light strongly-mixed staus enhancing $\Gamma(h \to \gamma\gamma)$

Appropriate pattern of non-universalities easily accommodated in SUSY SO(10) GUT:

- $m_{10} - m_{16}$ splitting and D-term contribution to scalar masses
- gaugino masses from a mixture of singlet and non-singlet F-term in **24** of SU(5) $\subset$ SO(10)

Flavour observables push up the gluino and 1st gen. squark masses above 2.5 TeV but sbottom may be light enough to be detected at the LHC

Bino-like LSP can be a good dark matter candidate

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If the experimental results eventually converge to the SM prediction lighter SUSY partners may be possible in the model