Enhanced SU(2) D-term and Higgs Diphoton BR

Based on work in progress with Gabriel Lee, Arun M Thalapillil and Carlos E. M. Wagner

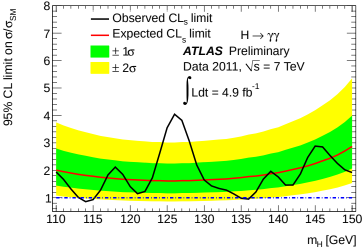
Ran Huo

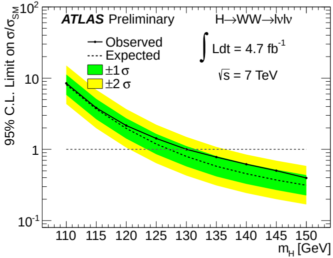
University of Chicago

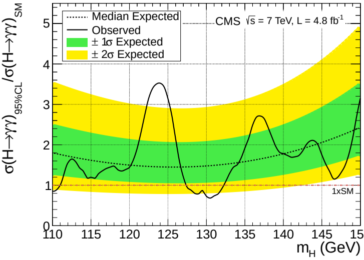
Pheno 2012
May 7, 2012

Motivation: Experimental Results

- LHC and Tevatron Experiments are starting to test the SM Higgs above the LEP limit.
- Excess is seen in the conventional diphoton channel as expected, at both ATLAS and CMS.
- However, in other channels the signal is not so pronounced as suggested by diphoton channel.







A Hint of New Physics?

Although the statistics is still low, we will take the following points of view:

- We do have discovered the Higgs boson with a mass of about 125 GeV.
- The Higgs is different from the SM prediction, as data suggests tentatively, in

  $$\sigma \times \mathrm{Br}(pp \to h \to X_{SM}) = \sigma(pp \to h)\frac{\Gamma(h \to X_{SM})}{\Gamma_t},$$

  which is directly measured.
- $\sigma(pp \to h)$ is not boosted compared to SM, otherwise we should see effects in all the other channels.
- The Higgs diphoton decay branching ratio is enhanced.

Sign of the Loop Amplitude

- The Higgs diphoton decay is loop induced.

In the SM

$$\Gamma(h \to \gamma\gamma) = \frac{G_F \alpha^2 m_h^3}{128\sqrt{2}\pi^3} \left| A_1(\tau_W) + \sum_f N_c Q_f^2 A_{1/2}(\tau_f) \right|^2, \qquad \tau_i \equiv \frac{m_h^2}{4 m_i^2}.$$

- The dominant contribution is from the $W^\pm$ loop term $A_1(\tau_W)$, which is -8.32 for a 125 GeV Higgs.
- The fermions have the opposite sign contribution, $\sum_f N_c Q_f^2 A_{1/2}(\tau_f) = 1.84$ which is dominated by top.

In the decoupling limit of the MSSM, there are sfermion contribution and chargino contribution as well.

- The chargino contribution has the same sign with $W^\pm$ loop.

A Systematical Way to Enhance Higgs Diphoton Branching Ratio

- Higgs always comes with Higgs potential vev, in terms of $v + h = v(1 + \frac{h}{v})$. In the form of $m(1 + \frac{h}{v})$, doing derivative with m leads to the usual Higgs low energy theorem.

$$\lim_{p\to 0} \mathcal{M}(Xh) = g \sum_{i=f,V} \frac{1}{v} \frac{\partial}{\partial \ln m_i} \mathcal{M}(X).$$

- On the other hand, if the mass term is not completely but partially given by Yukawa coupling with v, instead we should do derivative with v, in the form of $yv(1 + \frac{h}{v})$.

$$\lim_{p\to 0} \mathcal{M}(Xh) = g \sum_{i=f,V} \frac{1}{v} \frac{\partial}{\partial \ln v} \mathcal{M}(X).$$

- In loop induced Higgs diphoton decay, in the large loop mass limit it is

$$\mathcal{L}_{h\gamma\gamma} = -\frac{\alpha}{16\pi} h \left[\sum_i \frac{\partial}{\partial v} \ln m_i^{2b_i} \right] F_{\mu\nu} F^{\mu\nu}.$$

J. R. Ellis. *et al*, Nucl. Phys. B **106**, 292 (1976). A. Falkowski, Phys. Rev. D **77**, 055018 (2008)

where the amplitude is given by the vacuum polarization. b_i is their separate contribution to β function.

- If the mass comes in matrix form and there is mixing, $\ln m_i^2 \to \ln \det M_i^\dagger M_i$.

A Systematical Way to Enhance Higgs Diphoton Branching Ratio - Cont'd

In MSSM and various other models, Higgs Yukawa term only gives small contribution to mass (matrix). We only need to make its contribution negative in sign to the dominant contribution.

- Staus in MSSM

$$M_{\tilde{\tau}}^2 = \begin{pmatrix} M_{\ell}^2 + y_\tau^2 {v_d}^2 + \Delta_{\tilde{e}L} & y_\tau v_d (A_e - \mu \tan\beta) \\ y_\tau v_d (A_{eij}^* - \mu^* \tan\beta) & M_e^2 + y_\tau^2 {v_d}^2 + \Delta_{\tilde{e}R} \end{pmatrix},$$

$$\frac{\partial \ln \det M_{\tilde{\tau}}^2}{\partial v} \simeq -\frac{2y_\tau^2 |A_e - \mu \tan\beta|^2 v_d}{M_\ell^2 M_e^2}.$$

M. Carena, S. Gori, N. Shah, C. Wagner, arXiv: 1112.3336

- A fourth generation leptons and its mirror, see Pedro's talk

$$M_\ell = \begin{pmatrix} Y_c' v & M_L \\ M_E & Y_c'' v \end{pmatrix},$$

$$\frac{\partial \ln \det M_{\tilde{\ell}}}{\partial v} \simeq -\frac{2y_c' y_c'' v}{M_L M_E}.$$

A. Joglekar, P. Schwaller, C. Wagner, 2012

Another Chargino Sector with Enhanced Coupling

- As mentioned before, the MSSM chargino has the same mass matrix structure and the same sign amplitude with $W^{\pm}$

$$M_{\tilde{\chi}^{\pm}} = \begin{pmatrix} M_2 & \frac{1}{\sqrt{2}} g v \sin\beta \\ \frac{1}{\sqrt{2}} g v \cos\beta & \mu \end{pmatrix}.$$

- However the MSSM chargino itself is insufficient for the required enhancement, because the coupling g_2 is too small.

private communication with Tao Liu.

- We replace the MSSM $SU(2)_L$ by $SU(2)_1 \times SU(2)_2$, where the $SU(2)_1$ only couples to the first two generations with coupling constant g_1, and the $SU(2)_2$ couples to the third generation and two Higgs doublets with coupling constant g_2.

P. Batra, A. Delgado, D. E. Kaplan and T. M. P. Tait, JHEP **0402**, 043 (2004).

  The $SU(2)_2$ is strongly coupled, which is expected to give sufficient enhancement of the diphoton BR.

- We introduce a bidoublet superfield Σ as $(2, \bar{2})$ under the two $SU(2)$s, which spontaneously breaks $SU(2)_1 \times SU(2)_2 \to SU(2)_L$.

Breaking of $SU(2)_1 \times SU(2)_2$ to $SU(2)_L$

- The superpotential is $W = \lambda S(\frac{1}{2}\Sigma\Sigma - \omega^2)$, where S is a singlet superfield. The induced potential is

  $$V_\Sigma = -\frac{1}{2}\lambda^2\omega^2\Sigma\Sigma + \text{h.c.} + \frac{1}{4}\lambda^2|\Sigma\Sigma|^2 + m_s^2|\Sigma|^2,$$

  where m_s is the soft mass parameter.
- For $m_s^2 - \lambda^2\omega^2 < 0$ the symmetry is spontaneously breaking. Scalar Σ field acquires a vev $\langle\Sigma\rangle = u\mathbf{1}_{2\times 2}$.
- The Σ vev breaks $SU(2)_1 \times SU(2)_2$ gauge boson W_1 and W_2 to massless SM like $W = (g_1 W_2 + g_2 W_1)/\bar{g}$ and a new $W' = (g_1 W_1 - g_2 W_2)/\bar{g}$, where $\bar{g} = \sqrt{g_1^2 + g_2^2}$.
- If the W is required to have a SM weak coupling $g_{SM} = \frac{g_1 g_2}{\bar{g}}$, then the W' have a coupling of $-\frac{g_2}{g_1} g_{SM}$ to Higgs and third generation, and $\frac{g_1}{g_2} g_{SM}$ to the first two generations.

Byproduct - Rise of Higgs Mass

- The relevant quartic Higgs potential before $SU(2)_1 \times SU(2)_2$ breaking is

$$V_{h+\Sigma} = \frac{1}{8}g_2^2(\mathrm{Tr}\Sigma^\dagger\sigma^i\Sigma + H_u^\dagger\sigma^i H_u + H_d^\dagger\sigma^i H_d)^2 + \frac{1}{8}g_1^2(\mathrm{Tr}\Sigma\sigma^i\Sigma^\dagger)^2 + \frac{1}{8}g'^2(H_u^\dagger H_u - H_d^\dagger H_d)^2.$$

- Integrating out Σ field leads to the quartic potential

$$V_h = \frac{1}{8}g_{SM}^2\Delta(H_u^\dagger\sigma^i H_u + H_d^\dagger\sigma^i H_d)^2 + \frac{1}{8}g'^2(H_u^\dagger H_u - H_d^\dagger H_d)^2,$$

which is the conventional Higgs quartic potential except for the factor

$$\Delta = \frac{1 + \frac{2m_s^2}{u^2}\frac{1}{g_1^2}}{1 + \frac{2m_s^2}{u^2}\frac{1}{g_1^2+g_2^2}} > 1.$$

P. Batra, A. Delgado, D. E. Kaplan and T. M. P. Tait, JHEP **0402**, 043 (2004).

- The tree level CP even neutral Higgs mass matrix is $M_{H^0}^2 =$

$$\begin{pmatrix} m_A^2\sin^2\beta + \frac{1}{4}(g_{SM}^2\Delta + g'^2)v^2\cos^2\beta & -(m_A^2 + \frac{1}{4}(g_{SM}^2\Delta + g'^2)v^2)\sin\beta\cos\beta \\ -(m_A^2 + \frac{1}{4}(g_{SM}^2\Delta + g'^2)v^2)\sin\beta\cos\beta & m_A^2\cos^2\beta + \frac{1}{4}(g_{SM}^2\Delta + g'^2)v^2\sin^2\beta \end{pmatrix}.$$

- With relatively small $\tan\beta$ and stop mixing parameter we can achieve a 125 GeV Higgs, which is desirable in our model.

Chargino and Neutralino Mixing Matrice

- For chargino which is relevant to loop amplitude, $M^{\pm}_{ij} =$

$$\begin{pmatrix} M_2 & 0 & \sqrt{2} m_W s_\beta & 0 \\ 0 & M_2' & -\frac{g_2}{g_1}\sqrt{2} m_W s_\beta & \sqrt{2}\bar{g}u \\ \sqrt{2} m_W c_\beta & -\frac{g_2}{g_1}\sqrt{2} m_W c_\beta & \mu & 0 \\ 0 & \sqrt{2}\bar{g}u & 0 & M_{\tilde{\Sigma}} \end{pmatrix},$$

  with $(\tilde{\chi}^{-\prime})^T = (\tilde{W}^-, \tilde{W}'^-, \tilde{H}_d^-, \tilde{\Sigma}^-)$ on the left coupling to $\tilde{\chi}^{+\prime} = (\tilde{W}^+, \tilde{W}'^+, \tilde{H}_u^+, \tilde{\Sigma}^+)^T$ on the right.
- For neutralino, $M^0_{ij} =$

$$\begin{pmatrix} M_1 & 0 & 0 & -m_Z s_W c_\beta & m_Z s_W s_\beta & 0 \\ 0 & M_2 & 0 & m_Z c_W c_\beta & -m_Z c_W s_\beta & 0 \\ 0 & 0 & M_2' & -\frac{g_2}{g_1} m_Z c_W c_\beta & \frac{g_2}{g_1} m_Z c_W s_\beta & \sqrt{2}\bar{g}u \\ -m_Z s_W c_\beta & m_Z c_W c_\beta & -\frac{g_2}{g_1} m_Z c_W c_\beta & 0 & -\mu & 0 \\ m_Z s_W s_\beta & -m_Z c_W s_\beta & \frac{g_2}{g_1} m_Z c_W s_\beta & -\mu & 0 & 0 \\ 0 & 0 & \sqrt{2}\bar{g}u & 0 & 0 & M_{\tilde{\Sigma}} \end{pmatrix},$$

  with $\tilde{\chi}^{0\prime} = (\tilde{B}, \tilde{W}^3, \tilde{W}'^3, \tilde{H}_d^0, \tilde{H}_u^0, \tilde{\Sigma}^0)^T$ on both the left and the right.

Desirable Parameter Choice

The sensitive MSSM parameters are $\tan\beta$, M_2 and μ. The relevant new parameters are $\frac{g_2}{g_1}$, M_2', u, m_s and M_Σ.

- $\tan\beta \lesssim 3$ should be small to maximize the $\frac{\partial \ln \det M_{\tilde{\ell}}}{\partial v} \simeq -\frac{g^2 v \sin\beta\cos\beta}{M_2\mu}$ off diagonal effect. Allowed by our model.
- $\frac{g_2}{g_1}$ cannot go too large for the sake of perturbativity. $\frac{g_2}{g_1} \lesssim 2.5$
- M_2' have to be light to maximize the $\tilde{W}'$ contribution. $M_2' \sim$ a few hundred GeV.
- M_Σ should be large to decouple everything with Σ. $m_s \sim$ a few TeV.

Still TENTATIVE!

Preliminary Numerical Results

- A 125 GeV Higgs can be obtained.
- A 30% $\sim$ 100% Higgs diphoton branching ratio enhancement can be obtained.
- Excluded light chargino can be avoided.

One sample parameter point:

$\tan\beta$	1.5
M_2	4000 GeV
μ	200 GeV
$\frac{g_2}{g_1}$	2.5
M_2'	700 GeV
u	500 GeV
m_s	7000 GeV
M_Σ	10000 GeV
m_h	123.07 GeV
$\mathrm{BR}(h \to \gamma\gamma)$	3.6772×10^{-3}
$\mathrm{BR}/\mathrm{BR}^{SM}(h \to \gamma\gamma)$	1.577
$m_{\tilde{\chi}_1^\pm}$	106.8 GeV.

Summary and Future Work

- We have provided a model to explain the Higgs diphoton decay branching ratio enhancement.
- The Higgs mass and diphoton BR can be at the desired value.

A lot of other constraint should be considered:

- Immediately we need to do calculations of the electroweak precision measurement observables, the vacuum stability.
- And perhaps calculation with the gauge coupling unification, the dark matter and so on.