Some Implications of Higgs Diphoton Excess

Based on arXiv:1212.0560 with G. Lee, A. M Thalapillil and C. E. M. Wagner, and on going work

Ran Huo

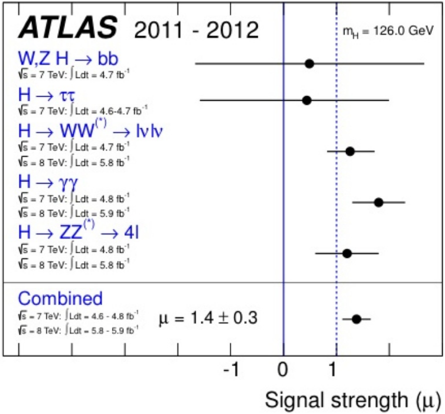
EFI, University of Chicago

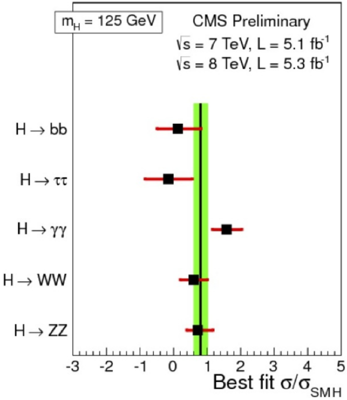
IPMU
March 12, 2013

Outline

- General implication of the diphoton excess to Higgs model building
- An $SU(2) \otimes SU(2)$ gauge extension of the MSSM
- A toy model with naive supersymmetry for EW baryogenesis

The Famous Experimental Diphoton Excess





- New ATLAS result: $\mu_{\gamma\gamma} = 1.65 \pm 0.2$
- New CMS result: *May* kill it in the very near future
- But at least $\bar{\mu}_{\gamma\gamma} \geq 1.32$ for ATLAS and CMS:-)

Systematic Way to Get Higgs Diphoton Branching Ratio

- Low Energy Theorem relates partial width to renormalization and mass matrix

$$\mathcal{L}_{h\gamma\gamma} \simeq \frac{\alpha}{16\pi}\frac{h}{v} b_i Q_i^2 \frac{\partial}{\partial \log v} \log\left(\det \mathcal{M}_i^2\right)$$

- In the SM, dominant amplitude of $h \to \gamma\gamma$ is from $W^\pm$, subdominant amplitude is from top, but they interfere destructively

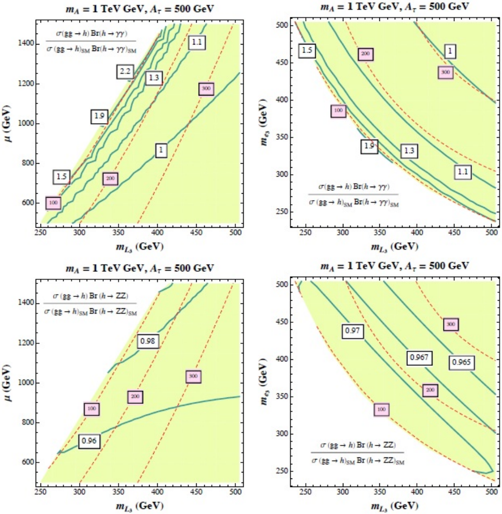
$$\Gamma(h \to \gamma\gamma) = \frac{G_F \alpha^2 m_h^3}{128\sqrt{2}\pi^3}\left| A_1(\tau_W) + \sum_f N_c Q_t^2 A_{1/2}(\tau_t)\right|^2, \qquad \tau_i \equiv \frac{m_h^2}{4m_i^2}.$$

$$A_1(\tau_W) = -8.32_{SM} \to -\frac{22}{3}_{LET}, \qquad N_c Q_t^2 A_{1/2}(\tau_t) = 1.84_{SM} \to \frac{16}{9}_{LET}.$$

- All matter (fermion and scalar) have the same sign b_is with top.
  All the SM particles have trivially positive $\frac{\partial}{\partial \log v} \log\det\mathcal{M}_i^2$.
- However, new physics can flip the sign of $\frac{\partial}{\partial \log v} \log\det\mathcal{M}_i^2$.

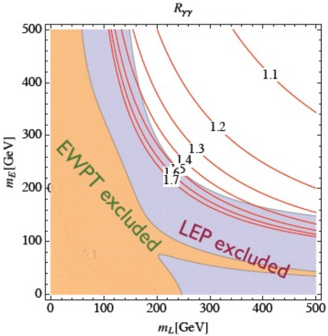
- $M_{\tilde\tau}^2 = \begin{pmatrix} M_\ell^2 + y_\tau^2 {v_d}^2 + \Delta_{\tilde e L} & y_\tau v_d (A_e - \mu \tan\beta) \\ y_\tau v_d (A_{eij}^* - \mu^* \tan\beta) & M_e^2 + y_\tau^2 {v_d}^2 + \Delta_{\tilde e R} \end{pmatrix},$
- $\frac{\partial \ln \det M_{\tilde\tau}^2}{\partial \ln v} \simeq -\frac{2 y_\tau^2 |A_e - \mu \tan\beta|^2 v_d^2}{M_\ell^2 M_e^2}.$
- For scalar $b = \frac{1}{3}$,
- $A_e - \mu \tan\beta$ can be relatively large, so the enhancement is sufficient.
- Stau is near the LEP bound of 82 GeV

Carena, Gori, Shah and Wagner, arXiv:1112.3336



- $M_\ell = \begin{pmatrix} Y'_c v & m_l \\ m_e & Y''_c v \end{pmatrix}$
- $\frac{\partial \ln \det M_{\tilde{\tau}}^2}{\partial \ln v} \simeq -\frac{2 Y'_c Y''_c v^2}{m_l m_e}$
- For chiral fermion $b = \frac{2}{3}$,
- Stability problem
- New lepton is near the LEP bound of 100 GeV

Joglekar, Schwaller and Wagner, arXiv:1207.4235



Model 3: Strong Chargino Extension of MSSM

- Chargino has the "correct" sign contribution

$$M_{ij}^{\pm} = \begin{pmatrix} M_2 & \frac{1}{\sqrt{2}} gv \sin\beta \\ \frac{1}{\sqrt{2}} gv \cos\beta & \mu \end{pmatrix}, \qquad \frac{\partial}{\partial \log v} \log \det M_{ij}^{\pm} \simeq -\frac{g^2 v^2 \sin 2\beta}{2 M_2 \mu}.$$

- But it is still insufficient for the observed diphoton excess. Can be interpreted as the gauge coupling is still small.
- We will talk about the gauge extension later in detail.

Problems and Constraints

- Collider: mass bound vs. being light for diphoton enhancement
- Fermionic Stability: bounded from below $\rightarrow$ SUSY help
- Scalar Stability: not yet tunnel to charge and color breaking minimum
- Electroweak Precision Measurement

What Is Generically Needed

Fermionic diphoton model classification

Arkani-Hamed *et al*, arXiv:1207.4482.

- Charged fermion mass mixing matrix

$$\mathcal{M}_{F^\pm} = \begin{pmatrix} m_\psi & \frac{1}{\sqrt{2}} y\phi \\ \frac{1}{\sqrt{2}} y\phi & m_\chi \end{pmatrix}$$

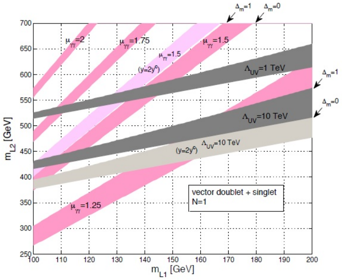
- Higgs is charged under $SU(2)_L \times U(1)_Y \to$ new ψ and χ are charged
- Leptonic: $\psi \sim (1,2)_{-\frac{1}{2}}$ and $\chi \sim (1,1)_{-1}$

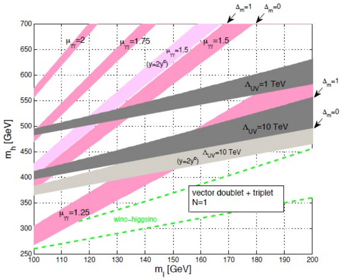
$$\mathcal{L} \supset -y\psi^\dagger H\chi - y\chi^\dagger H^\dagger \psi - m_\psi \psi^\dagger \psi - m_\chi \chi^\dagger \chi$$

- Wino-Higgsino like: $\psi \sim (1,2)_{\frac{1}{2}}$ and $\chi \sim (1,3)_0$

$$\mathcal{L} \supset -\sqrt{2} y\psi^\dagger \chi H - \sqrt{2} y H^\dagger \chi\psi - m_\psi \psi^\dagger \psi - \frac{1}{2} m_\chi \chi\chi$$

- Collider: $M_{l'} \geq 102.6$ GeV vs. $M_{\tilde{\chi}_1^\pm} \geq 103.5$, the same
- Fermionic Stability: Leptonic model is more efficient because all degree of freedom contributing to the quartic coupling RGE are charged and contributing to diphoton enhancement, while wino-Higgsino like model has extra neutral (neutralino) degree of freedom which worsen the stability problem.





- Electroweak Precision Measurement: Both can be satisfied.

Outline

- General implication of the diphoton excess to Higgs model building
- An $SU(2) \otimes SU(2)$ gauge extension of the MSSM
- A toy model with naive supersymmetry for EW baryogenesis

Our $SU(2) \otimes SU(2) \rightarrow SU(2)_L$ Model

- Our extended gauge group is $SU(2)_1 \otimes SU(2)_2$.

Batra,Delgado, Kaplan and Tait, 2004.

- The first two generation are charged under $SU(2)_1$, the third generation and the Higgs are charged under $SU(2)_2$.

Yukawa hierarchy between the 1st 2nd generations and the 3rd generation

- A bidoublet Σ transforming as $(\mathbf{2}, \bar{\mathbf{2}})$ induce spontaneously symmetry breaking $SU(2) \otimes SU(2) \rightarrow SU(2)_L$.
- Gauge coupling $g_1 < g_2$ and $1/g^2 = 1/g_1^2 + 1/g_2^2$. $SU(2)_2$ chargino has larger coupling $g_2 > g_{SM}$

$$\frac{\partial}{\partial \log v} \log \det M_{ij}^{\pm} \simeq -\frac{g_2^2 v^2 \sin 2\beta}{2 M_2' \mu}$$

Large enough

- Breaking pattern is $\langle \Sigma \rangle = u\mathbf{1}$.
- New W' mix with W. $M_{W'} = \sqrt{\frac{1}{2}(g_1^2 + g_2^2)}u$ is effectively the scale for supersymmetry restoration.
- Extended chargino mixing matrix

$$M_{ij}^{\pm} = \begin{pmatrix} M_{\tilde{W}_1} & 0 & 0 & \frac{1}{\sqrt{2}} g_1 u \\ 0 & M_{\tilde{W}_2} & \frac{1}{\sqrt{2}} g_2 v \sin\beta & -\frac{1}{\sqrt{2}} g_2 u \\ 0 & \frac{1}{\sqrt{2}} g_2 v \cos\beta & \mu & 0 \\ \frac{1}{\sqrt{2}} g_1 u & -\frac{1}{\sqrt{2}} g_2 u & 0 & M_{\tilde{\Sigma}} \end{pmatrix},$$

Two light charginos after decoupling two heavy ones $M_{\tilde{W}_1}$ and $M_{\tilde{\Sigma}}$

$$M_{ij}^{\pm,\mathrm{eff}} = \begin{pmatrix} M_{\tilde{W}_2} - \frac{1}{2}\frac{g_2^2 u^2}{M_{\tilde{\Sigma}}} - \frac{g_1^2 g_2^2}{4}\frac{u^4}{M_{\tilde{\Sigma}}^2 M_{\tilde{W}_1}} & \frac{1}{\sqrt{2}} g_2 v \sin\beta \\ \frac{1}{\sqrt{2}} g_2 v \cos\beta & \mu \end{pmatrix}.$$

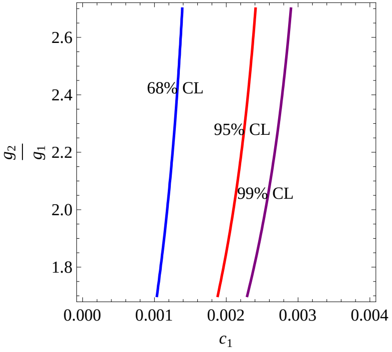
- Similar 6×6 neutralino mixing matrix.

- $$\left.\frac{d\,\lambda}{d\ln Q}\right|_{\tilde{\chi}} = -\frac{1}{(4\pi)^2}\left[4g_2^4 + (g_2^2 + g'^2)^2\right].$$

  Cured by supersymmetry, which fix the high scale bound.
- In top down running with fixed UV value, λ and Higgs mass will be too high (> 125 GeV).
- The RGE beta coefficient is a step function with the chargino/neutralino mass. Only when the 2nd strongly coupled light chargino comes in, the running is significant.
- We also minimize tree level Higgs mass source by $\tan\beta \simeq 1$.
- Then the SM Higgs mass is completely radiatively generated

$$M_h^2 \simeq \frac{v^2}{16\pi^2}\left(2g_2^4 + (g_2^2 + g'^2)^2\right)\log\frac{M_{W'}}{M_{\tilde{\chi}^\pm}} + \frac{3v^2}{4\pi^2}y_t^4\left(\log\frac{M_{\rm SUSY}}{M_t} + \frac{\tilde{A}_t^2}{2M_{\rm SUSY}^2}\left(1 - \frac{\tilde{A}_t^2}{12M_{\rm SUSY}^2}\right)\right),$$

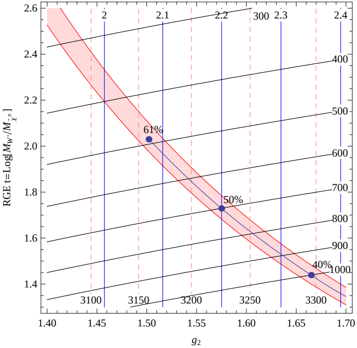
- Tree level mixing of SM W with heavy gauge bosons W', going beyond of the oblique corrections.
- Flavor/generation non-universal, more severely constrained.
- Oblique correction from chargino/neutralino sector.
- We perform a global fit with 25 measurements.



Observable	$SU(2)_1 \times SU(2)_2$ value
Γ_Z	$(\Gamma_Z)_{SM}(1 - 0.557c_1 - 0.338d_1 - 0.00385S + 0.0106T)$
R_e	$(R_e)_{SM}(1 - 0.503c_1 + 0.585d_1 - 0.00301S + 0.00214T)$
R_μ	$(R_\mu)_{SM}(1 - 0.503c_1 + 0.585d_1 - 0.00301S + 0.00214T)$
R_τ	$(R_\tau)_{SM}(1 - 1.554c_1 + 1.637d_1 - 0.00301S + 0.00214T)$
σ_h	$(\sigma_h)_{SM}(1 - 0.611c_1 + 0.629d_1 + 0.000665 - 0.000700T)$
R_b	$(R_b)_{SM}(1 - 1.786c_1 + 1.767d_1 + 0.000985S - 0.000472T)$
R_c	$(R_c)_{SM}(1 + 0.503c_1 - 0.468d_1 - 0.00129S + 0.000913T)$
A_{FB}^e	$(A_{FB}^e)_{SM} + 0.173d_1 - 0.00632S + 0.00449T$
A_{FB}^μ	$(A_{FB}^\mu)_{SM} + 0.173d_1 - 0.00632S + 0.00449T$
A_{FB}^τ	$(A_{FB}^\tau)_{SM} - 0.201c_1 + 0.374d_1 - 0.00632S + 0.00449T$
$A_\tau(P_\tau)$	$(A_\tau(P_\tau))_{SM} - 1.817c_1 + 2.597d_1 - 0.0286S + 0.0203T$
$A_e(P_\tau)$	$(A_e(P_\tau))_{SM} + 0.780d_1 - 0.0286S + 0.0203T$
A_{FB}^b	$(A_{FB}^b)_{SM} - 0.015c_1 + 0.530d_1 - 0.0189S + 0.0134T$
A_{FB}^c	$(A_{FB}^c)_{SM} + 0.399d_1 - 0.0146S + 0.0104T$
M_W^2	$(M_W^2)_{SM}(1 + 0.430d_1 - 0.00727S + 0.112T + 0.00846U)$
$g_L^2(\nu N \to \nu X)$	$(g_L^2(\nu N \to \nu X))_{SM} + 0.246d_1 - 0.00269S + 0.00663T$
$g_R^2(\nu N \to \nu X)$	$(g_R^2(\nu N \to \nu X))_{SM} - 0.085d_1 + 0.000937S - 0.000192T$
$g_{eV}(\nu e \to \nu e)$	$(g_{eV}^2(\nu e \to \nu e))_{SM} - 0.661d_1 + 0.00727S - 0.00546T$
$g_{eA}^2(\nu e \to \nu e)$	$(g_{eA}^2(\nu e \to \nu e))_{SM} - 0.00391T$
$Q_W(\mathrm{Cs})$	$(Q_W(\mathrm{Cs}))_{SM} + 72.7d_1 - 0.796S - 0.0113T$

$$c_1 = \frac{1}{2}\left(\frac{g}{g_1}\right)^4\left(\frac{v}{u}\right)^2,\ d_1 = -\frac{1}{2}\left(\frac{g}{g_1}\right)^2\left(\frac{g}{g_2}\right)^2\left(\frac{v}{u}\right)^2.\ T = 0.075,\ S = 0.11.$$

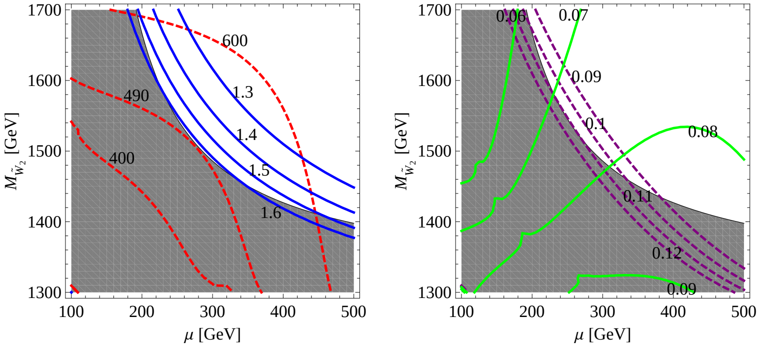
$\tan\beta = 1$, $M_{\tilde{W}_1}$ and $M_{\tilde{\Sigma}}$ decouplingly large. Top/stop sector Higgs mass contribution small.



- Blue vertical: g_2/g_1;
- Pink dashed vertical: u constraint from $\frac{1}{2}(\frac{g}{g_1})^4(\frac{v}{u})^2 \lesssim 2 \times 10^{-3}$, $\rightarrow M_{W'}$ where λ RGE ends;
- Black near horizontal: $M_{\tilde{\chi}^{\pm}}$ where effectively λ RGE starts;
- Pink band: SM Higgs mass 124 - 127 GeV.

Higgs representative line cannot extend because we cannot get consistent chargino mass.

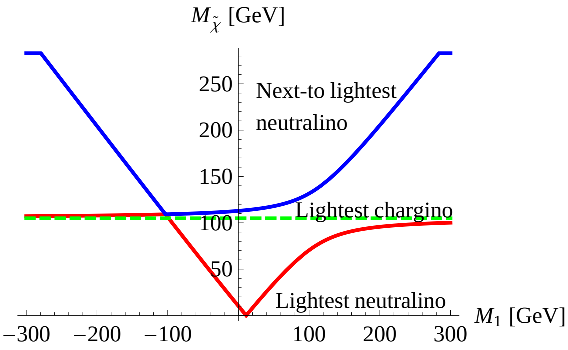
is where the $M_{\tilde{\chi}_1^\pm} = 103.5$ LEP bound curve get just tangent with one effective $M_{\tilde{\chi}^\pm}$ curve.



- Grey region: $M_{\tilde{\chi}_1^\pm} < 103.5$ GeV excluded;
- Blue: diphoton enhancement $\mu_{\gamma\gamma}$; Red dashed: $M_{\tilde{\chi}^\pm}$ where effectively λ RGE starts;
- Green: Oblique parameter T; Purple: Oblique parameter S.

Chargino and Neutralino Collider Phenomenology

For best point



- Left region: $M_{\tilde{\chi}_1^\pm} < M_{\tilde{\chi}_1^0}$, gravitino is the LSP; chargino pairs have the same signal as W pairs.

Inclusive W pair cross section excess noticed by P. Meade

- Except the central region, is allowed by trilepton searches.

Relaxing from the Best Point

- If we relax $\tan\beta = 1$, we get tree level Higgs mass contribution

$$M^2_{h,\text{tree}} = \frac{1}{4}(g^2\Delta + g'^2)v^2\cos^2 2\beta,$$

- The enhancement factor Δ is residue of an exchange of a triplet, which is order a few

$$\Delta = \frac{1 + \frac{4m_\Sigma^2}{u^2}\frac{1}{g_1^2}}{1 + \frac{4m_\Sigma^2}{u^2}\frac{1}{g_1^2+g_2^2}}.$$

Batra,Delgado, Kaplan and Tait, 2004.

- $\tan\beta = 1.5 \rightarrow \mu_{\gamma\gamma} = 1.42,$
  $\tan\beta = 2 \rightarrow \mu_{\gamma\gamma} = 1.34.$

Other Aspect of the Model

- Low $\tan\beta$, top Yukawa blow up? Further protection from large negative g_2 contribution, fine till GUT
- Small top/stop Higgs mass contribution (~ 4800 GeV^2) $\rightarrow$ light non-mixing stop $\rightarrow$ stop increase gluon fusion by $\sim 10\%$. Based on the same low energy theorem
- Collider search: light chargino and neutralino, but it is the W' to really tell it from the MSSM

Outline

- General implication of the diphoton excess to Higgs model building
- An $SU(2) \otimes SU(2)$ gauge extension of the MSSM
- A toy model with naive supersymmetry for EW baryogenesis

From Higgs to EW Baryogenesis

- If the Higgs potential is understood, the next natural step is the transition itself $\rightarrow$ Electroweak Baryogenesis. (like my advisor)
- Especially, the diphoton excess would implies a new particle strongly couple to Higgs, which just improves the insufficiency of couplings in the SM.

Genesis

Sakharov's condition

	EW Baryogenesis	Leptogenesis
B or L violating process	Sphaleron	B: Sphaleron from L L: No definition
CP violation (with CV in the SM)	Not specified	Majorana ν CP phase
Deviation from equilibrium	Strongly 1st order PT	Out of equilibrium decay

Successful EW Baryogenesis

- = To preserve the CPV or (already generated) matter anti-matter asymmetry from being washed out.
- = To freeze sphaleron process quickly after PT

$$\Gamma \propto \mu \left(\frac{g^2}{4\pi} T\right)^{-3} m_W(T)^7 e^{-\frac{E_s}{T}}$$

$$E_s \equiv \frac{8\pi m_W(\phi)}{g^2} B(\frac{\lambda}{g^2}) \qquad B(\frac{\lambda}{g^2}) \simeq 1.96 \text{ for } m_h = 125 \text{ GeV}$$

$$\frac{E_s}{T_c} = 37.8 \frac{\langle\phi(T_c)\rangle}{T_c}$$

- = At nucleation temperature (right below critical temperature), PT strength $\equiv$

$$\frac{\langle\phi(T_n)\rangle}{T_n} \gtrsim 1 \qquad \text{The Goal}$$

Quirós, hep-ph/9901312.

- To relevant leading order

$$V(\phi, T) = V_0(\phi) + \sum_{i=W,Z,t\cdots} V_{1,i}(\phi) + \sum_{i=W,Z,t\cdots} V_{1,i}(\phi, T)$$

where $V_0(\phi) = -\frac{1}{4}m_h^2\phi^2 + \frac{1}{4}\lambda\phi^4$

- Zero temperature 1 loop $V_{1,i}(\phi)$ need to be renormalized to preserved tree level Higgs minimum and Higgs mass

$$\begin{aligned} V_{1,i}(\phi) &= \pm\frac{g_i}{64\pi^2}\left(m_i^2(\phi)\right)^2\left(\ln\frac{m_i^2(\phi)}{Q^2} - \frac{3}{2} \text{ or } \frac{5}{6}\right) \\ &\to \pm\frac{g_i}{64\pi^2}\left(\left(m_i^2(\phi)\right)^2\left(\ln\frac{m_i^2(\phi)}{m_i^2(v)} - \frac{3}{2}\right) + 2m_i^2(v)m_i^2(\phi)\right) \end{aligned}$$

For $m_i(\phi)^2 = a + b\phi^2$ type mass square.

- Finite temperature 1 loop $V_{1,i}(\phi, T)$

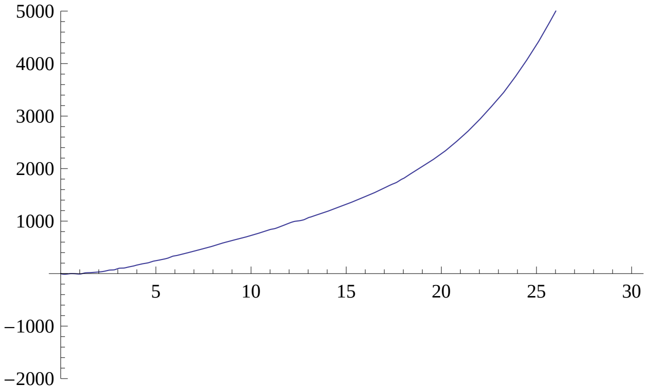
$$V_{1T,i} = \pm g_i\int\frac{d^3p}{(2\pi)^3}T\ln\left(1 \mp e^{-\frac{\sqrt{\vec{p}^2+m^2}}{T}}\right)$$

Need to be calculated numerically generally, although at $T \gg m$ can be expanded.

- Thermal mass $m_i(\phi)^2 = g^2\phi^2 + \mathcal{O}(g^2)T^2$. Daisy resummation.

An Example

- SM near critical temperature $T \simeq 171.3$ GeV



- Higgs VEV tunnels from the x=0 to nonzero values during the last several frames
- Tunneling condition

$$\frac{S_E}{T} \simeq 140$$

for a bubble to expand to the whole universe.

A Historical Outline

- SM: as shown before
  - Indeed a 1st order PT
  - Using high T expansion, the PT can be analytically calculated

$$\frac{\langle\phi(T_n)\rangle}{T_n} = \frac{2E}{\lambda} \qquad E = \frac{1}{4\pi v^3}(2m_W^2 + m_Z^3) \quad \text{Only boson contributes?}$$

  - Which is insufficient $\frac{\langle\phi(T_n)\rangle}{T_n} \simeq 0.12$
- Light stop: not in our stream
- Strong wino higgsino:
  - First fermionic baryogenesis model
  - Idea of changing effective degree of freedom

Carena, Megevand, Quirós and Wagner, 2005.

- With diphoton motivation:
  - Fermionic contribution with non-trivial mass mixing matrix considered
  - But their benchmark Yukawa coupling is 4! Stability, perturbativity...

Davoudiasl, Lewis and Ponton, arXiv:1211.3449.

Our Naively Supersymmetric Model

- General framework for diphoton excess from fermionic component.

$$\mathcal{M}_{F^\pm} = \begin{pmatrix} m_\psi & \frac{1}{\sqrt{2}} y\phi \\ \frac{1}{\sqrt{2}} y\phi & m_\chi \end{pmatrix}$$

- Arbitrary charged fermionic mixing

$$\tan 2\theta = \frac{\sqrt{2}yv}{m_\chi - m_\psi} \qquad \begin{pmatrix} F_1^\pm \\ F_2^\pm \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \psi^\pm \\ \chi^\pm \end{pmatrix}$$

- Induced neutral fermionic mixing for wino-higgsino case

$$\mathcal{M}_{F^0} = \begin{pmatrix} m_\psi & -\frac{1}{2} y\phi \\ -\frac{1}{2} y\phi & \frac{1}{2} m_\chi \end{pmatrix}$$

$$\tan 2\phi = \frac{yv}{m_\psi - \frac{1}{2} m_\chi} \qquad \begin{pmatrix} F_1^0 \\ F_2^0 \end{pmatrix} = \begin{pmatrix} \cos\phi & -\sin\phi \\ \sin\phi & \cos\phi \end{pmatrix} \begin{pmatrix} \psi^0 \\ \chi^0 \end{pmatrix}$$

- Naive supersymmetry: same coupling, same degree of freedom, different "soft" mass
- No mixing in the bosonic component. $M_s^2 = m_{\text{soft}}^2 + \frac{1}{2} y^2 \phi^2$

Which Ponton make it wrong at first

- Fermionic mass square is not of the form $a + b\phi^2$

$$
\begin{aligned}
M_{F^{\pm}_{1,2}} &= \frac{1}{2}\Big(m_\psi + m_\chi \mp \sqrt{(m_\psi - m_\chi)^2 + 2y^2\phi^2}\Big) \\
M_{F^{0}_{1,2}} &= \frac{1}{2}\Big(m_\psi + \frac{1}{2}m_\chi \mp \sqrt{(m_\psi - \frac{1}{2}m_\chi)^2 + y^2\phi^2}\Big),
\end{aligned}
$$

so the zero temperature $V_1(\phi)$ form cannot be used

- $V_1(\phi)$ for arbitrary mass square

$$
\begin{aligned}
V_{1,i}(\phi) &= \pm\frac{g_i}{64\pi^2}\Big(\big(m_i^2(\phi)\big)^2 \ln m_i^2(\phi) + \alpha\phi^2 + \beta\phi^4\Big) \\
\alpha &= \frac{1}{2}\Big(\big(-3\frac{\omega\omega'}{v} + \omega'^2 + \omega\omega''\big)\ln\omega - \frac{3}{2}\frac{\omega\omega'}{v} + \frac{3}{2}\omega'^2 + \frac{1}{2}\omega\omega''\Big) \\
\beta &= \frac{1}{4v^2}\Big(\big(\frac{\omega\omega'}{v} - \omega'^2 - \omega\omega''\big)\ln\omega + \frac{1}{2}\frac{\omega\omega'}{v} - \frac{3}{2}\omega'^2 - \frac{1}{2}\omega\omega''\Big)
\end{aligned}
$$

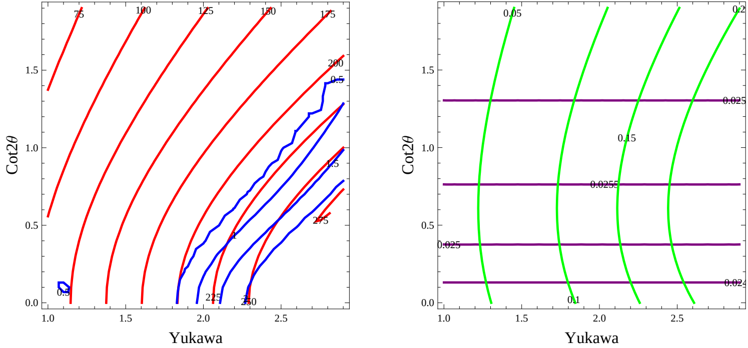
where $\omega = m_i^2(v)$ and $\omega' = \frac{d}{d\phi}m_i^2(\phi)\Big|_{\phi=v}$, and so on

- Again, Supersymmetry protect the potential against instability
- Step function beta coefficient
- $$\frac{1}{\sqrt{2}}y\psi^{\mp(0)}\phi\chi^{\pm(0)}+\frac{1}{\sqrt{2}}y\chi^{\mp(0)}\phi\psi^{\pm(0)}=-\frac{1}{\sqrt{2}}y\sin 2\theta(\varphi)F_1^{\mp(0)}\phi F_1^{\pm(0)}+\text{term with } F_2^{\mp(0)}$$

  By combinatorics, the 4 F_1 leg diagram, or the quartic RGE running from M_{F_1} to M_{F_2}, is suppressed by $\sin^4 2\theta(\varphi)$
- Scalar "soft" mass can be solved with how much the quartic coupling runs
- The heavy bosonic ones are not very separated in scale, also contribute to PT strength

Leptonic Model

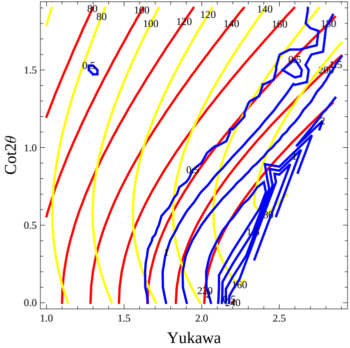
With $\mu_{\gamma\gamma} = 1.5$ and $\Delta\lambda = -0.5\lambda_0$



- Blue: $\frac{\langle\phi(T_n)\rangle}{T_n}$;
- Red: Lightest fermion mass;
- Green: Oblique parameter T;
- Purple: Oblique parameter S.

Wino-Higgsino Like Model

With $\mu_{\gamma\gamma} = 1.5$ and $\Delta\lambda = -0.5\lambda_0$



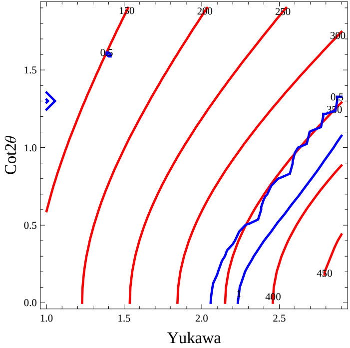
- Blue: $\frac{\langle \phi(T_n) \rangle}{T_n}$;
- Red: Lightest charged fermion mass;
- Yellow: Lightest neutral fermion mass;
- More degree of freedom contributing to Higgs potential $\rightarrow$ better EW baryogenesis

Merit of the Model

- Complete in the minimal sense, no stability problem
- Fermionic and bosonic degree of freedom both contributing, reduce the Yukawa coupling from 4, perturbativity OK
- Not relying on high T expansion
- A generic study of the parameter region of model with vector-like/soft mass

What If Diphoton Really Die?

With $\mu_{\gamma\gamma} = 1.3$ and $\Delta\lambda = -0.5\lambda_0$



- Blue: $\frac{\langle\phi(T_n)\rangle}{T_n}$;
- Red: Lightest fermion mass;
- Green: Oblique parameter T;
- Purple: Oblique parameter S.

Summary

- A series of models can be constructed to fit diphoton data, using systematic low energy theorem approach.
- As shown in our $SU(2) \otimes SU(2)$ model, we can get enhanced diphoton branching ratio, desired Higgs mass with consistent electroweak precision observable and collider constraints.
- Baryogenesis seems fine with all the constraints, in a generic setup.

CMS results for gauge boson production cross sections