EW Baryogenesis beyond the High T Expansion

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Outline

- Review of the SM and MSSM EW Baryogenesis.
- Entropy release mechanism as new source of EW Baryogenesis.
- A model designed for diphoton enhancement.
- The vector-like supersymmetric model.

- Genesis = Creation of cosmic matter antimatter asymmetry.
- EW Baryogenesis = Asymmetry creation is associated with electroweak symmetry breaking, or the turning on of the Higgs VEV.

How Sakharov's three conditions are fulfilled

- Baryon number violating process: Nonperturbative anomalous sphaleron.

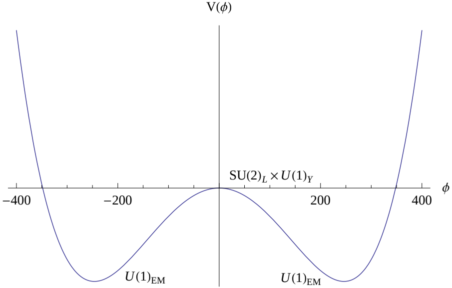
$$\partial_\mu j^\mu_B \equiv \partial_\mu j^\mu_L = n_g \left(\frac{g^2}{2(4\pi)^2} W_{\mu\nu} \tilde{W}^{\mu\nu} - \frac{g'^2}{2(4\pi)^2} B_{\mu\nu} \tilde{B}^{\mu\nu} \right)$$

  Such interaction will create/annihilate $3n_g$ quarks and n_g leptons.
- *CP* violation: Too small in the CKM matrix of the SM, but new physics may have large enough sources. Not Our Focus.
- Deviation from thermal equilibrium: Latent heat in first order phase transition.

EW Symmetry Breaking: $SU(2)_L \times U(1)_Y \to U(1)_{EM}$

- The SM tree level Higgs potential is

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



- The minimum is chosen $\phi = v = \frac{m_h}{\sqrt{2\lambda}} = 246.2$ GeV.
- Masses are given to $W^{\pm}$ and Z^0 gauge boson, only photon associated with electromagnetism remains massless.

Hmm... A Negative Mass Square Term

- We don't know how it comes within the SM.
- In extended model like the MSSM, it can be interpreted as an RGE running effect from high scales.

  At unification scale, it is positive and no EW symmetry breaking.

  This is an example that symmetry should be restored at high scales.
- Within the SM could the symmetry be restored at higher scales? ...Need to compensate the negative mass square.

  Sure!

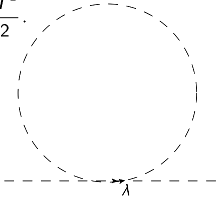
  QFT at finite temperature always provides positive mass square corrections.

In thermal quantum filed theory

- Time: $t \to -i\beta = -\frac{i}{T}$, Energy $E = p^0 \to 2n\pi i T$.
- Thermal propagator: $-\dfrac{i}{(2n\pi T)^2 + \vec{p}^2 + m^2}$.
- Thermal loop: $iT \displaystyle\sum_{n=-\infty}^{\infty} \int \frac{d^3p}{(2\pi)^3} = \frac{i}{\beta} \sum_{n=-\infty}^{\infty} \int \frac{d^3p}{(2\pi)^3}$.

- Example: Higgs loop, contribution at finite T

$$\begin{aligned}
\delta_{m^2} &= -\Pi(T) = -i\int \frac{d^4p}{(2\pi)^4} i\lambda \frac{i}{p^2} \\
&\to T\sum_n \int \frac{d^3p}{(2\pi)^3} i\lambda \frac{-i}{(2n\pi T)^2+\vec{p}^2} = \lambda T\int \frac{d^3p}{(2\pi)^3}\frac{\pi}{2\pi Tp}\coth\frac{\pi p}{2\pi T} \\
&= \frac{1}{2}\lambda\int\frac{p\,dp}{2\pi^2}\left(1+\frac{2e^{-\frac{p}{T}}}{1-e^{-\frac{p}{T}}}\right) = \frac{1}{2}\lambda\int\frac{p\,dp}{2\pi^2}\left(1+2\sum_{n=1}^{\infty}e^{-\frac{np}{T}}\right) \\
&\to \frac{\lambda}{2\pi^2}\sum_{n=1}^{\infty}\int p\,dp\,e^{-\frac{np}{T}} = \frac{\lambda}{2\pi^2}\sum_{n=1}^{\infty}\frac{T^2}{n^2} = \frac{\lambda}{2\pi^2}\frac{\pi^2T^2}{6} = \frac{\lambda T^2}{12}.
\end{aligned}$$



- Mass corrected

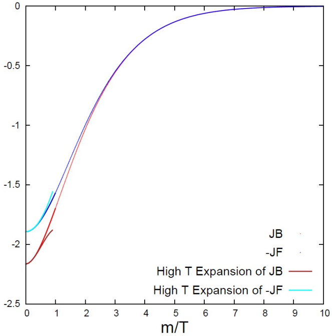
$$-\frac{1}{4}m_h^2\phi^2 + cT^2\phi^2 + \frac{1}{4}\lambda\phi^4 + \cdots$$

At high enough temperature
No Electroweak Symmetry Breaking.

Thermal Potential Correction

Resuming Higgs two point function, for each complex degree of freedom ($+$ for boson, $-$ for fermion)

$$
\begin{aligned}
V_{1l \text{ Finite T}} &= \pm \frac{T}{2} \sum_n \int \frac{d^3p}{(2\pi)^3} \ln\left((2n\pi T)^2 + \vec{p}^2 + m^2 + \Pi_T\right) \\
&= \cdots \\
&= \pm \int \frac{d^3p}{(2\pi)^3} \left(\frac{\sqrt{\vec{p}^2 + m^2}}{2} + T \ln\left(1 \mp e^{-\frac{\sqrt{\vec{p}^2+m^2+\Pi_T}}{T}}\right)\right) \\
&= \pm \frac{1}{64\pi^2} (m^2)^2 \left(\ln \frac{m^2}{\Lambda^2} - \frac{3}{2} \Big| \frac{1}{2} \right) \qquad = V_{1(T=0)} \\
&+ \quad \pm \int \frac{d^3p}{(2\pi)^3} T \ln\left(1 \mp e^{-\frac{\sqrt{\vec{p}^2+m^2+\Pi_T}}{T}}\right) \qquad = V_{1T}\left(\frac{m}{T}\right) \\
V_{1T}\left(\frac{m}{T}\right) &\equiv \pm \int \frac{d^3p}{(2\pi)^3} T \ln\left(1 \mp e^{-\frac{\sqrt{\vec{p}^2+m^2}}{T}}\right) \equiv \pm \frac{T^4}{2\pi^2} J_{B/F}\left(\frac{m}{T}\right)
\end{aligned}
$$

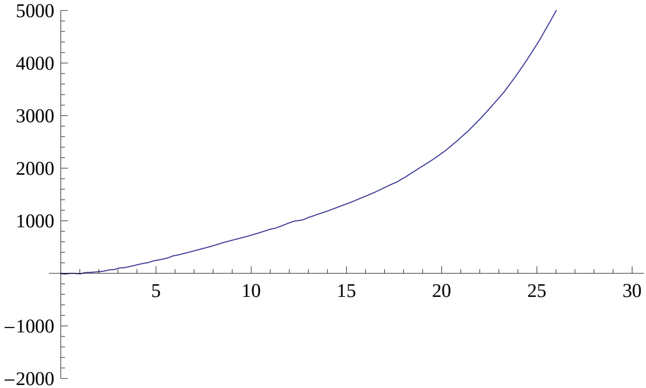


Quirós, hep-ph/9901312.

The SM as an Example

With $m_h = 125$ GeV,

- What happens near $T \simeq 170$ GeV



- Higgs VEV tunnels through the barrier from the $\phi = 0$ to nonzero values during the last several frames.
- During which every SM particle turns on mass (Not the masses measured today).

In the real universe at the phase transition

- 1st order phase transition is described by bubble nucleation process.
- Bubble with $\phi \neq 0$ expands into the $\phi = 0$ region near the speed of light.
- Latent heat on the bubble wall makes departure from thermal equilibrium.
- Nucleation temperature T_n: For a bubble to expand into the whole universe

$$\frac{S_E}{T_n} \simeq 140.$$

- Critical temperature T_c: when a $\phi \neq 0$ local minimum satisfies $V(\phi) = V(0)$.
- Usually phase transition is right after passing the critical temperature, then $T_n \simeq T_c$.

Successful EW Baryogenesis

- = To preserve the matter/antimatter asymmetry from being washed out.
- = To freeze sphaleron process quickly after phase transition, by Boltzmann suppression

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

$$E_s \equiv \frac{8\pi m_W(\phi)}{g^2} B(\frac{\lambda}{g^2}), \qquad B(\frac{\lambda}{g^2}) \simeq 1.96, \qquad \frac{E_s}{T_c} = 37.8 \frac{\langle \phi(T_c) \rangle}{T_c}.$$

- = Phase transition strength

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

M.E. Shaposhnikov, Nucl. Phys. B 287 (1987) 757.

- = The high T expansion, namely the $\frac{m(\phi)}{T} \to 0$ limit, in which

$$V_{1T} = \frac{T^4}{2\pi^2} J_{B/F}\left(\frac{m}{T}\right) = \frac{T^4}{2\pi^2} \begin{cases} -\frac{\pi^4}{45} + \frac{\pi^2}{12}\frac{m^2}{T^2} - \frac{\pi}{6}\left(\frac{m^2}{T^2}\right)^{\frac{3}{2}} + \mathcal{O}\left(\frac{m^4}{T^4}\right) & \text{Boson} \\ -\frac{7\pi^4}{360} + \frac{\pi^2}{24}\frac{m^2}{T^2} + \mathcal{O}\left(\frac{m^4}{T^4}\right) & \text{Fermion} \end{cases}.$$

- = "The ϕ^2, ϕ^3, ϕ^4 system".

$$V(\phi, T) = D(T^2 - T_0^2)\phi^2 - ET\phi^3 + \frac{1}{4}\lambda\phi^4.$$

At T_c and ϕ_c we have

$$\begin{aligned} \text{Degenerated} \quad V(\phi_c, T_c) &= D(T_c^2 - T_0^2)\phi_c^2 - ET_c\phi_c^3 + \frac{1}{4}\lambda\phi_c^4 = 0, \\ \text{Minimum} \quad \frac{\partial}{\partial\phi}V(\phi, T_c)\Big|_{\phi=\phi_c} &= 2D(T_c^2 - T_0^2)\phi_c - 3ET_c\phi_c^2 + \lambda\phi_c^3 = 0. \end{aligned}$$

Canceling the ϕ^2 term, we get

$$\frac{\phi_c}{T_c} = \frac{2E}{\lambda}.$$

- $=$ A counting game of ϕ^3 term contribution.
- ϕ^4 coefficient λ also receives small correction but not significant.
- In the SM only $W^{\pm}$ and Z^0 contribute (ignoring Higgs)

$$E = \frac{1}{12\pi}\left(4\left(\frac{1}{2}g\right)^3 + 2\left(\frac{1}{2}\sqrt{g^2+g'^2}\right)^3\right) = 6.4\times 10^{-3} \ll \lambda = 0.13$$

  Note that only transverse DOF contributes.
- In light stop scenario of the MSSM extra contribution comes from light unmixed right hand stop ($m_{\tilde{t}_1} \simeq \frac{1}{\sqrt{2}}y_t\phi_u$)

$$E = \frac{1}{12\pi}\left(4\left(\frac{1}{2}g\right)^3 + 2\left(\frac{1}{2}\sqrt{g^2+g'^2}\right)^3 + 6\left(\frac{1}{\sqrt{2}}y_t \sin\beta\right)^3\right) = 0.054 \simeq \frac{1}{2}\lambda$$

  But it will raise problems such as in gluon fusion.

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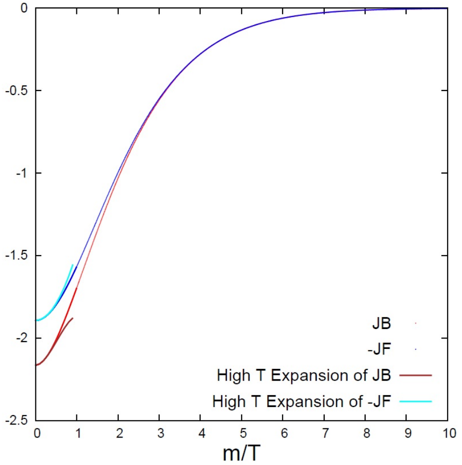

The Boltzmann suppression is not that significant as one just imagine

$$V_{1T}\left(\frac{m}{T}\right) = \pm \int \frac{d^3p}{(2\pi)^3} T \ln\left(1 \mp e^{-\frac{\sqrt{\vec{p}^2+m^2}}{T}}\right) \equiv \pm \frac{T^4}{2\pi^2} J_{B/F}\left(\frac{m}{T}\right)$$

- Traditional EW baryogenesis always induces too light a new particle which may already be excluded.
- New physics may introduce mass terms which are not related to Higgs VEV:

  SUSY soft breaking masses, other vector-like masses, *etc.*

  Currently the bounds are a few hundred GeVs.
- Naive estimation: $\phi_c \lesssim 246.2$ GeV, order one Yukawa, then the Yukawa mass is comparable to the soft/vector-like mass.
- With $T_c \sim 200$ GeV, the $m(\phi)/T$ may have order one change, which induce significant change on $J_{B/F}$ even from start point of a few (not from zero of the traditional case).

First Effort: Fermions Contribute as Good as Bosons

Carena, Megevand, Quirós and Wagner, Nucl. Phys. B 716 (2005) 319.

- The special case of the neutralino/chargino mass matrices with $M_1 = M_2 = -\mu$, $\tan\beta = 1$, arbitrary $SU(2)$ gauge coupling h and $U(1)$ gauge coupling $h' = 0$.
- Chargino/Neutralino mass square eigenstates $m^2(\phi) = M^2 + h^2\phi^2$, a total of 12 DOF.

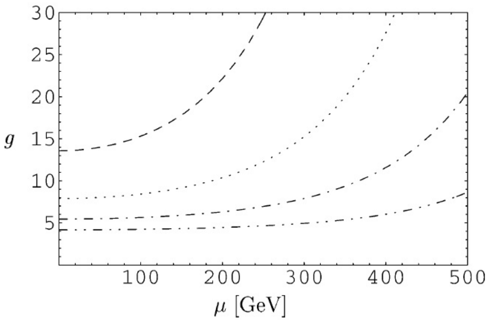

Fig. 1. Curves of constant $\phi_c/T_c = 1$ and $m_H = 120$ GeV, for a fermion with mass $m^2 = \mu^2 + h^2\phi^2$ and g degrees of freedom. From top to bottom the curves correspond to $h = 1.5, 2, 2.5$, and 3.

Entropy Release, or just Jump on $J_{B/F}$

- They call this effect as entropy release, since the $m(\phi)/T \to 0$ limit is just the relativistic limit, in which the leading terms $V_{1T} = -\frac{\pi^2}{90}T^4$ or $-\frac{7}{8}\frac{\pi^2}{90}T^4$ are nothing but the relativistic energy density for each bosonic and fermionic DOF. So they are related to entropy. We are to set free this entropy by turning on Higgs VEV and departing from the relativistic limit.
- However, I think it is nothing but merely (and more intuitively) an upward jump on the $J_{B/F}$ curve, associated with the Higgs VEV turning on.
- We can go deep into the region where $m(\phi)/T$ is a few.
- We can consider multiple jumps, only the net contribution counts.

Some Common Features 1: Mass Matrix

- The new particle mass (square) matrix usually have diagonal soft/vector-like mass terms and off-diagonal Yukawa mass terms.
- Eigenvalues are solutions to a quadratic equation, usually with plus and minus square roots

$$m_{\pm}(\phi) = \sqrt{M^2 + a\phi^2} \pm b\phi, \quad \text{or} \quad m_{\pm}^2(\phi) = M^2 + a\phi^2 \pm \sqrt{b\phi^4 + c\phi^2}, \quad \text{or} \quad \cdots$$

- The physical constraint is that sum of two $\frac{d}{d\phi} m_{\pm}(\phi)\Big|_{\phi=0}$ vanishes, or the $\phi = 0$ is always a solution to the minimization $\frac{d}{d\phi} J_{B/F}(\frac{m(\phi)}{T}) = \frac{J'_{B/F}}{T} \frac{d}{d\phi} m(\phi)$ condition.
- If a term in mass is making $m(\phi)$ overall heavier when the Higgs VEV is turned on, it contributes to EW baryogenesis.
- If a term in mass is making $m(\phi)$ split when the Higgs VEV is turned on, it does not (or even oppositely) contribute to EW baryogenesis.

Some Common Features 2: To Protect 125 and 246

- Zero temperature one loop potential $V_{1(T=0)}$ are renormalized in a way that the SM Higgs mass and Higgs VEV are not shifted ($\frac{d^2V_{1(T=0)}}{d\phi^2} = 0|_{\phi=v}$ and $\frac{dV_{1(T=0)}}{d\phi} = 0|_{\phi=v}$).
- If the mass square is $m^2(\phi) = a + b\phi^2$, then the usual renormalized one loop potential is fine

$$V_{1,i(T=0)} = \pm\frac{g_i}{64\pi^2}\left(\left(m_i^2(\phi)\right)^2\left(\ln\frac{m_i^2(\phi)}{m_i^2(v)} - \frac{3}{2}\right) + 2m_i^2(\phi)m_i^2(v)\right).$$

- In extended models the solution are

$$\begin{aligned} V_{1,i(T=0)} &= \pm\frac{g_i}{64\pi^2}\left(\left(m_i^2(\phi)\right)^2\ln m_i^2(\phi) + \alpha\phi^2 + \beta\phi^4\right) \\ \alpha &= \frac{1}{2}\left(\left(-3\frac{\omega\omega'}{v} + \omega'^2 + \omega\omega''\right)\ln\omega - \frac{3}{2}\frac{\omega\omega'}{v} + \frac{3}{2}\omega'^2 + \frac{1}{2}\omega\omega''\right) \\ \beta &= \frac{1}{4v^2}\left(\left(\frac{\omega\omega'}{v} - \omega'^2 - \omega\omega''\right)\ln\omega + \frac{1}{2}\frac{\omega\omega'}{v} - \frac{3}{2}\omega'^2 - \frac{1}{2}\omega\omega''\right) \end{aligned}$$

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

- In the 2HDM of MSSM I find the simple extension is not adequate to fix every counter term.

Some Common Features 3: Supersymmetry for Quartic Coupling

- Usually we need large Yukawa for a significant jump on $J_P B/F$.
- However, it will induce large radiative corrections to the quartic coupling.
    - For extra fermions it may render quartic coupling negative at high scales.
    - For extra scalars it may develop other vacuum with lower zero point energy than our EWSB one.
- To avoid large corrections the trick for model building is to introduce nearly unbroken supersymmetry.
- Interestingly both bosonic and fermionic DOF contribute additively to phase transition, but they cancel with each other on the quartic coupling RGE.

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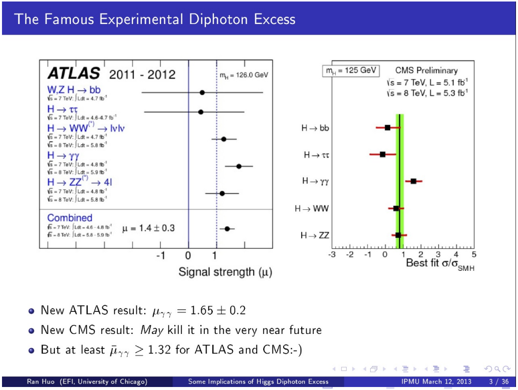
- ATLAS 2012.7 result: $\mu_{\gamma\gamma} = 1.9 \pm 0.5$,
- ATLAS 2013.3 result: $\mu_{\gamma\gamma} = 1.65 \pm 0.2$,

- CMS 2012.7 result: $\mu_{\gamma\gamma} = 1.56 \pm 0.43$,
- CMS 2013.3 result: $\mu_{\gamma\gamma} = 0.78^{+0.28}_{-0.26}\Big|_{\text{MVA}} \quad (1.11^{+0.32}_{-0.30})\Big|_{\text{Cut Based}}$.

Practice is even worse than I can expect last time.



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

- Charged fermion mass mixing matrix

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

- Mirror Leptonic: $\psi_{L,R} \sim (1,2)_{-\frac{1}{2}}$ and $\chi_{L,R} \sim (1,1)_{-1}$,

$$\mathcal{L} \supset -y\psi_L^c \phi \chi_R - y\chi_L^c \phi^c \psi_R - m_\psi \psi_L^c \psi_R - m_\chi \chi_L^c \chi_R + h.c..$$

  Neutral fermion is ψ^0.

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

$$\mathcal{L} \supset -\sqrt{2} y \psi_1^c \chi \varepsilon \phi - \sqrt{2} y \phi^c \varepsilon \chi \psi_1 - \sqrt{2} y \psi_2^c \chi \phi - \sqrt{2} y \phi^c \chi \psi - m_\psi (\psi_1 \varepsilon \psi_2 + \psi_2 \varepsilon \psi_1) - m_\chi \chi \chi.$$

  Induced neutral fermionic mixing

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

The Supersymmetric Extension

- Naive supersymmetry: same coupling, same degree of freedom, different "soft" mass. No mixing in the bosonic component, the simplest boson mass square

$$M_S^2 = m_s^2 + \frac{1}{2}y^2\phi^2.$$

- The model is just the SM plus a SUSY sector.
- Step function beta coefficient

$$\frac{1}{\sqrt{2}}y\psi^{\mp(0)}\phi\chi^{\pm(0)} + \frac{1}{\sqrt{2}}y\chi^{\mp(0)}\phi\psi^{\pm(0)} = -\frac{1}{\sqrt{2}}y\sin 2\theta F_1^{\mp(0)}\phi F_1^{\pm(0)} + \text{interaction with } F_2^{\mp(0)}.$$

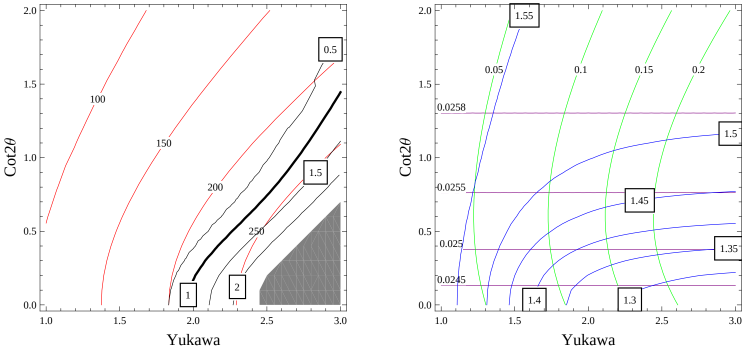
By combinatorics, the 4 $F_1^{\pm}$ leg diagram, or the quartic RGE running from $M_{F_1^{\pm}}$ to $M_{F_2^{\pm}}$, is suppressed by $\sin^4 2\theta(\varphi)$

- Scalar "soft" mass can be solved with how much the quartic coupling runs

$$\Delta\lambda = -\frac{n_{\pm}}{64\pi^2}y^4\left(\frac{\sin^4 2\theta}{2}\ln\frac{M_S^2}{M_{F_1^{\pm}}^2} + \frac{2-\sin^4 2\theta}{2}\ln\frac{M_S^2}{M_{F_2^{\pm}}^2}\right) - \frac{n_0}{64\pi^2}y^4\left(\frac{\sin^4 2\theta}{2}\ln\frac{M_S^2}{M_{F_2^0}^2} + \frac{2-\sin^4 2\theta}{2}\ln\frac{M_S^2}{M_{F_3^0}^2}\right).$$

RH, arXiv:1305.1973

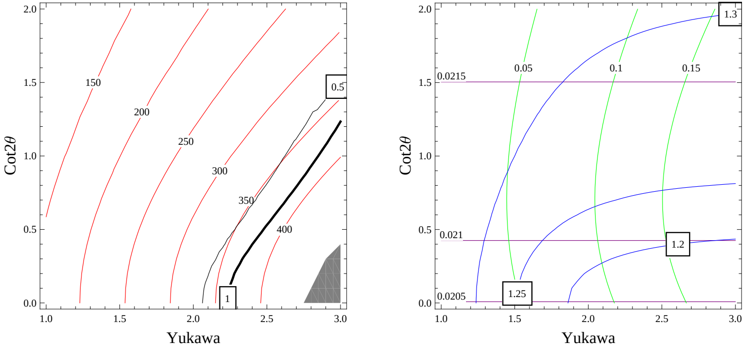
With $\Delta\mathcal{M}_F = 0.25$ and $\Delta\lambda = -0.5\lambda_{SM}$



- Black: phase transition strength $\frac{\langle\phi(T_c)\rangle}{T_c}$;
- Red: Lightest fermion mass;
- Grey Shaded: Excluded by $T_c < 0$;
- Blue: Diphoton signal strength $\mu_{\gamma\gamma}$;
- Green: Peskin - Takeuchi T parameter;
- Purple: Peskin - Takeuchi S parameter.

Leptonic Model Benchmark 2

With $\Delta \mathcal{M}_F = 0.15$ and $\Delta\lambda = -0.5\lambda_{SM}$



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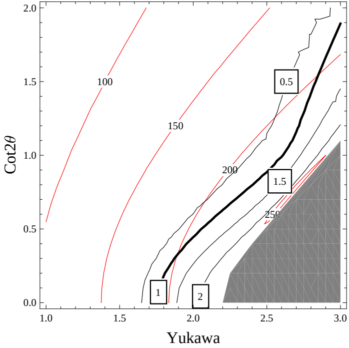

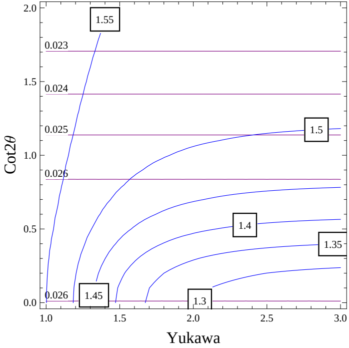

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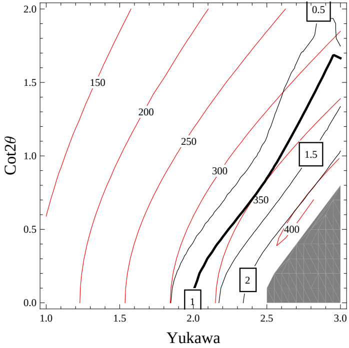
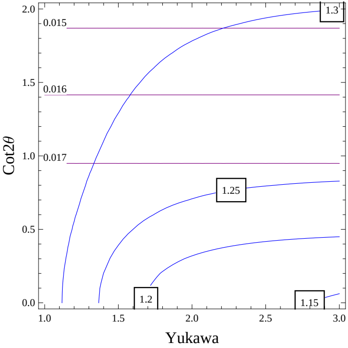
Wino - Higgsino Model Benchmark 2

With $\Delta\mathcal{M}_F = 0.15$ and $\Delta\lambda = -0.5\lambda_{SM}$





- Black: phase transition strength $\frac{\langle \phi(T_c) \rangle}{T_c}$;
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- Purple: Peskin - Takeuchi S parameter.

Discussion

- Typical values: $m_s = 391$ GeV, $m_\psi = m_\chi = 566$ GeV, $M_S = 524$ GeV, $M_{F_1} = 218$ GeV, $M_{F_2} = 915$ GeV.
- Wino-Higgsino is equivalent to $\tan\beta = 1$, with custodial symmetry new physics have no T parameter contribution.
- Bosonic DOF: Mass just get overall heavier when the Higgs VEV is turned on. Useful for phase transition, bad for diphoton excess.
- Fermionic DOF: Mass just get split when the Higgs VEV is turned on. Useful for diphoton excess, bad for phase transition.

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Motivation

- Two new generations of the SM fermions with vector-like masses mixing.
- With supersymmetry (so that their sparticles):
  - The gauge coupling RGE are modified in a way that they can still get unified at around the GUT scale.
  - The new contribution to quartic coupling can raise the SM Higgs mass.
  - The vector-like Yukawa couplings are bounded by infrared fixed point, of order one.
- However, for EW Baryogenesis we are doing dirty.

The Model

- New vector-like superfields

$$
\begin{array}{ccccc}
Q(3,2,\frac{1}{3}), & U(3,1,\frac{4}{3}), & D(3,1,-\frac{2}{3}), & L(1,2,-1), & E(1,1,-2), \\
\overline{Q}(\bar{3},2,-\frac{1}{3}), & \overline{U}(\bar{3},1,-\frac{4}{3}), & \overline{D}(\bar{3},1,\frac{2}{3}), & \overline{L}(1,2,1), & \overline{E}(1,1,2).
\end{array}
$$

- New superpotential

$$
\begin{aligned}
W \quad = \quad & W_{\text{MSSM}} + M_Q\overline{Q}Q + M_U\overline{U}U + M_D\overline{D}D + M_L\overline{L}L + M_E\overline{E}E \\
& + k_u H_u Q\overline{U} + k_d H_u \overline{Q}D + k_\ell H_u \overline{L}E - h_u H_d \overline{Q}U - h_d H_d Q\overline{D} - h_\ell H_d L\overline{E} \ .
\end{aligned}
$$

- Supersymmetry breaking term

$$
\begin{aligned}
-\mathcal{L}_{\text{soft}} \quad = \quad & m_Q^2|\tilde{Q}|^2 + m_{\bar{Q}}^2|\tilde{\bar{Q}}|^2 + m_U^2|\tilde{U}|^2 + m_{\bar{U}}^2|\tilde{\bar{U}}|^2 + m_D^2|\tilde{D}|^2 + m_{\bar{D}}^2|\tilde{\bar{D}}|^2 \\
& + m_L^2|\tilde{L}|^2 + m_{\bar{L}}^2|\tilde{\bar{L}}|^2 + m_E^2|\tilde{E}|^2 + m_{\bar{E}}^2|\tilde{\bar{E}}|^2 + (B_Q M_Q \tilde{Q}\tilde{\bar{Q}} + B_U M_U \tilde{U}\tilde{\bar{U}} \\
& + B_D M_D \tilde{D}\tilde{\bar{D}} + B_L M_L \tilde{L}\tilde{\bar{L}} + B_E M_E \tilde{E}\tilde{\bar{E}} + A_{k_u} k_u H_u \tilde{Q}\tilde{\bar{U}} + A_{k_d} k_d H_u \tilde{\bar{Q}}\tilde{D} \\
& - A_{h_u} h_u H_d \tilde{\bar{Q}}\tilde{U} - A_{h_d} h_d H_d \tilde{Q}\tilde{\bar{D}} - A_{h_\ell} h_\ell H_d \tilde{L}\tilde{\bar{E}} + \text{c.c.})
\end{aligned}
$$

The Mass Matrices

- The fermion mass matrices in a basis where the left vectors are F_L, F_R rather than $\bar{F}_L, \bar{F}_R$ are

$$\mathcal{M}_U = \begin{pmatrix} M_Q & \frac{1}{\sqrt{2}} k_u \phi_u \\ \frac{1}{\sqrt{2}} h_u \phi_d & M_U \end{pmatrix} \quad \mathcal{M}_D = \begin{pmatrix} M_Q & \frac{1}{\sqrt{2}} h_d \phi_d \\ \frac{1}{\sqrt{2}} k_d \phi_u & M_D \end{pmatrix} \quad \mathcal{M}_L = \begin{pmatrix} M_L & \frac{1}{\sqrt{2}} h_\ell \phi_d \\ \frac{1}{\sqrt{2}} k_\ell \phi_u & M_E \end{pmatrix}$$

The mass eigenstates are get from matrix

$$\mathcal{M}_F^2 = \begin{pmatrix} \mathcal{M}_F \mathcal{M}_F^\dagger & 0 \\ 0 & \mathcal{M}_F^\dagger \mathcal{M}_F \end{pmatrix}$$

- The scalar mass matrices are

$$\mathcal{M}_S^2 = \mathcal{M}_F^2 + \begin{pmatrix} m_{F_L}^2 + \Delta_{F_L} & 0 & B_{F_L}^* M_{F_L}^* & k_f^* (A_{k_f}^* - \mu^* \cot\beta) \\ 0 & m_{F_R}^2 + \Delta_{F_R} & h_f^* (A_{h_f}^* - \mu^* \tan\beta) & B_{F_R}^* M_{F_R}^* \\ B_{F_L} M_{F_L} & h_f (A_{h_f} - \mu \tan\beta) & m_{\bar{F}_L}^2 + \Delta_{\bar{F}_L} & 0 \\ k_f (A_{k_f} - \mu \cot\beta) & B_{F_R} M_{F_R} & 0 & m_{\bar{F}_R}^2 + \Delta_{\bar{F}_R} \end{pmatrix}$$

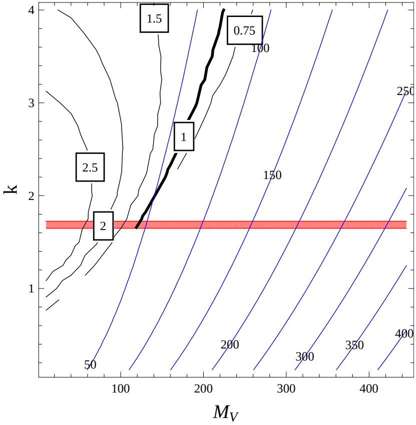
We set all supersymmetric vector like masses equal to M_V, all supersymmetry breaking masses equal to m and $M_S^2 = M_V^2 + m^2$, all up type Yukawa equal to k. Ignore all down type Yukawa h and all $A_{k_f} - \mu\cot\beta$, $A_{h_f} - \mu\tan\beta$, B and Δ terms. Then the mass eigenstates are

$$\begin{aligned} m^2_{f_{1,2}}(\phi_u,\phi_d) &= M_V^2 + \frac{1}{4}k^2\phi_u^2 \mp \frac{1}{4}\sqrt{k^4\phi_u^4 + 8M_V^2k^2\phi_u^2}, \\ m^2_{\tilde{f}_{1,2}}(\phi_u,\phi_d) &= M_S^2 + \frac{1}{4}k^2\phi_u^2 - \frac{1}{4}\sqrt{k^4\phi_u^4 + 8M_V^2k^2\phi_u^2}, \\ m^2_{\tilde{f}_{3,4}}(\phi_u,\phi_d) &= M_S^2 + \frac{1}{4}k^2\phi_u^2 + \frac{1}{4}\sqrt{k^4\phi_u^4 + 8M_V^2k^2\phi_u^2}. \end{aligned}$$

Both becoming overall heavier and split effects.

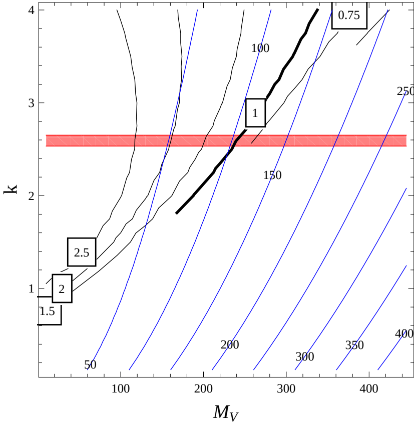
Vector-Like Model Benchmark 1

With $M_S/M_V = 1.5$.



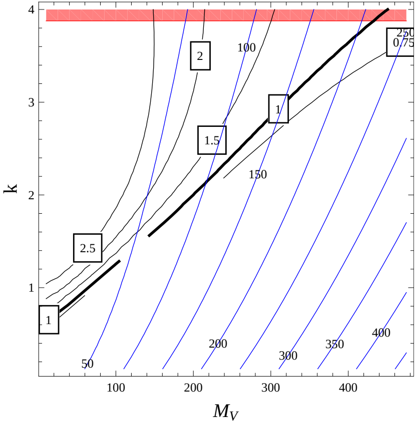
- Black: phase transition strength $\frac{\langle \phi(T_c) \rangle}{T_c}$;
- Blue: Lightest fermion mass;
- Pink band: SM Higgs mass $124 - 127$ GeV.

With $M_S/M_V = 1.1$. The new light fermion is at the light charged lepton mass bound.



- Black: phase transition strength $\frac{\langle\phi(T_c)\rangle}{T_c}$;
- Blue: Lightest fermion mass;
- Pink band: SM Higgs mass $124 - 127$ GeV.

With $M_S/M_V = 1.019$. The vector like Yukawa is at the perturbativity bound.



- Black: phase transition strength $\frac{\langle\phi(T_c)\rangle}{T_c}$;
- Blue: Lightest fermion mass;
- Pink band: SM Higgs mass $124-127$ GeV.

Other Comments to the Model

- We are not respecting the infrared fixed point Yukawa couplings $k \simeq 1.0$ and $h \simeq 1.2$.
- Gluon fusion and Higgs diphoton rate are not changed, with $h = 0$ and $M_S \simeq M_V$.
- EW precision measurement observables are always problems. We get order 30 Peskin-Takeuchi T parameter.
- One can break the degeneracy of the vector-like quarks and leptons, but due to lost of control of large corrections it's not that easy to find solutions in which even the EWSB happens at zero T.

  The model is excluded.

Xue Chang and RH, submitted to PRD

- EW Baryogenesis with soft/vector-like masses beyond high T expansion are interesting scenarios.

  Probably the last hope of EW Baryogenesis.
- Next we can fit the $J_{B/F}$ curve and do a semi-analytical analysis, with arbitrary kinds mass.