Title: Electroweak Cogenesis and a CP Violating Higgs Boson

Date: Sep 24, 2013 01:00 PM

URL: http://pirsa.org/13090077

Abstract: We propose a simple renormalizable model of baryogenesis and asymmetric dark matter generation at the electroweak phase transition. Our setup utilizes the two Higgs doublet model plus two complex gauge singlets, the lighter of which is stable dark matter. The dark matter is charged under a global symmetry that is broken in the early universe but restored during the electroweak phase transition. Because the ratio of baryon and dark matter asymmetries is controlled by model parameters, the dark matter need not be light. Thus, new force carriers are unnecessary and the symmetric dark matter abundance can be eliminated via Higgs portal interactions alone. The dark matter mass is also constrained within a window around the weak scale. One of the main predictions of this model is CP violating Higgs signals at the LHC and future colliders.

Electroweak Cogenesis and a CP Violating Higgs Boson

Yue Zhang (Caltech)

Seminar at Perimeter Institute, 24 September 2013

with Clifford Cheung (1306.4321,JHEP),
Jing Shu (1304.0773, PRL)


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Outline

- An asymmetric DM model.
  - Cogenesis of baryon and DM asymmetries during the electroweak phase transition -- the Minimal model.
- A CP violating Higgs boson from a 2HDM.
  - Connects EW baryogenesis with phenomena at LHC and low energy.

Origin of dark matter

- Observation: $\Omega_{\rm B} \sim \Omega_{\rm DM}$.
- Our universe contains a baryon number asymmetry. In the SM, baryon number is an approximate global symmetry $U(1)_{\rm B}$.
- Asymmetric Dark Matter (ADM): also has an asymmetry in today's number density, defined by another global symmetry $U(1)_{\rm DM}$.

ADM

- Connect the dynamics of baryon asymmetry generation to that of dark matter.
- Many models.. what usually expected
  - GeV scale DM: similar chemical potential, equilibrium
  - Light force mediator: get rid of symmetric relic density
- Interesting phenomena, but not simple enough, and has nothing to do with the origin of asymmetry.


ADM
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The Minimal ADM

- Our motivation: how concise can the minimal and renormalizable ADM model be?
- We shall show, in a simple setup, ADM mass lies at weak scale, no need of light force mediators.
- Simple setup, yet rich dynamics.
- This minimal model has interesting predictions in direct detection, Higgs physics, and at low energy.

Cheung, YZ, arXiv:1306.4321, JHEP

Issues to address

- Symmetries
  - restorations at low temperature
- CP violations.
- Connection between DM and baryon
  - mainly about common origins, not why numbers are what they are.

History of symmetries

- Baryon number side:
- EW baryogenesis: minimal framework, 2HDM.
- SM gauge structure, $U(1)_{\mathrm{B+L}}$ broken by sphaleron
  - generate B+L in presence of CP violation
  - erase B+L when CPV disappears (inverse process).
- A first order electroweak phase transition:
  - CPV originates from top quark-bubble wall interaction.
  - B+L quickly restored by turning on Higgs VEV.

History of symmetries

- Dark matter side:
- To generate the asymmetry with a $U(1)_{\rm DM}$ number, must also break it. Also must avoid dangerous washout processes.
- Without gauge structure: restore the symmetry quickly enough, use first order phase transition.
- Simply turn off a scalar field VEV charged under the $U(1)_{\rm DM}$ - need symmetry restoration at low temperature.

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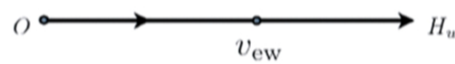
Combine two histories

Cheung, YZ, arXiv:1306.4321, JHEP

- Can restore two symmetries in a single phase transition?

- Thermal masses:



$$m_h^2(T) \sim -\mu_h^2 + 3\lambda h^2 + \frac{T^2}{12}(\lambda + g^2 + y_t^2 + \cdots)$$
$$m_s^2(T) \sim -\mu_s^2 + 3\lambda_s s^2 + \frac{T^2}{12}(\lambda_s + \cdots)$$

- Both directions can be tachyonic at the PhT.

- Doublet has more gauge/Yukawa interactions, so the transition can happen in correct direction.

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Cheung, YZ, arXiv:1306.4321, JHEP

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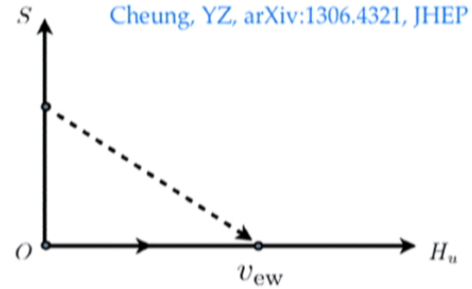

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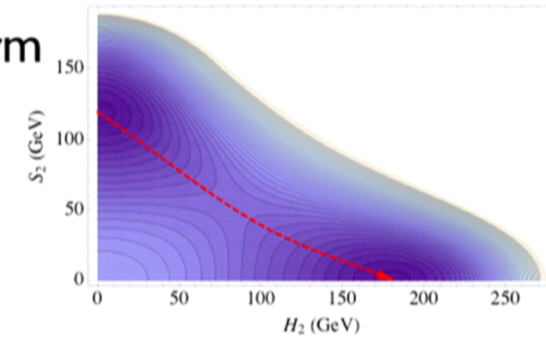
Barrier

- A tree-level barrier term is required

$$\alpha |H_u|^2 |S|^2 > 0$$

$$\alpha \gtrsim 0.5$$



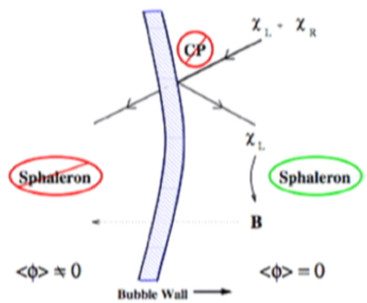
- The coupling α seems too large for the singlet to be DM - additional particle from dark sector.

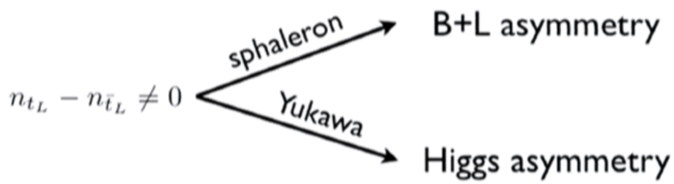
- Hint so far: modify EW baryogenesis framework to generate the DM asymmetry at same time.

Cheung, YZ, arXiv:1306.4321, JHEP

Common CPV source

- We are interested in renormalizable couplings, only possible when couple DM to Higgs fields.
- Asymmetry in the Higgs doublet fields?
- During EW baryogenesis, top quark scatters on the wall and picks up a chiral charge asymmetry.





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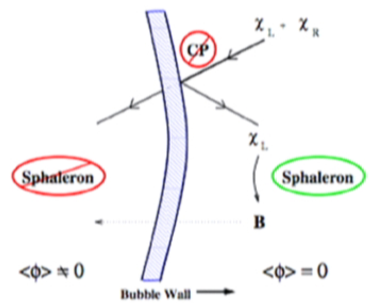

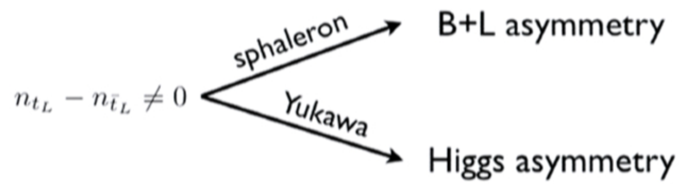

Cheung, YZ, arXiv:1306.4321, JHEP

Transfer operator

- Symmetry restoration: L invariant under $U(1)_{\rm DM}$
- $O_H S^\dagger S$ does not work.
- Simplest nontrivial operator

$$\epsilon H_u H_d S_1 S_2$$

- Introduce two oppositely charged singlets.
- If S_2 is in charge of the phase transition, the lighter state S_1 will be the dark matter candidate.

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Chemical potentials

- VEV structure: $\langle H_d \rangle = v_1 e^{i\theta_1(x,T)}, \quad \langle H_u \rangle = v_2 e^{i\theta_2(x,T)}$
- Spontaneous baryogenesis language:

$$\mu_{\rm B} \sim \mu_{t_L} \sim \dot{\theta}_2 \qquad \mu_{S_1} = -\mu_{S_2} \sim \dot{\theta}_1 + \dot{\theta}_2$$

- Final asymmetries depends on chemical potential and the interaction rates.

$$n_{\rm B} \sim \Delta\theta_2 \Gamma_{\rm sph} \qquad n_{S_{1,2}} \sim \Delta(\theta_1 + \theta_2)\Gamma_{H_u H_d \to S_1 S_2}$$

- Notice, $\Gamma_{H_u H_d \to S_1 S_2} \sim |\epsilon|^2$. We only explain the common the origin. DM mass constrained by pheno. An example, $\epsilon = 10^{-3} \Rightarrow m_{S_1} \sim 100\,{\rm GeV}$

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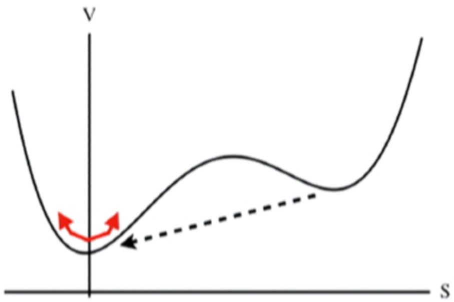
Dynamics after PhT

- Worry about S_2 decay. If $n_{S_2} = -n_{S_1}$ and all decays into S_1^*, may cancel the final asymmetry in S_1 .
- After the phase transition, $\langle S_2 \rangle$ cannot settle down to zero immediately, will oscillate and damp - cause the consumption of S_2 asymmetry.
- Oscillation is much faster than damping, or the evaporation rate.
- Only the S_1 asymmetry stays.



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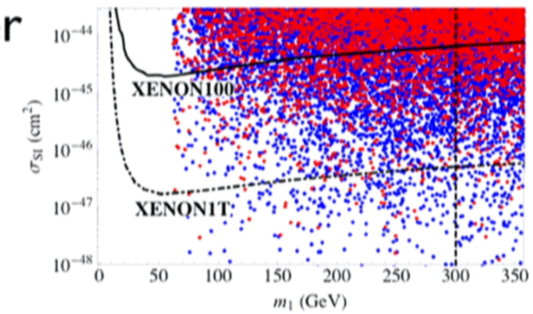
Annihilation

- ADM must annihilate faster than WIMP.
- In this picture, enough annihilate via Higgs portal.



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- Invisible decay: heavier than half of the Higgs mass.

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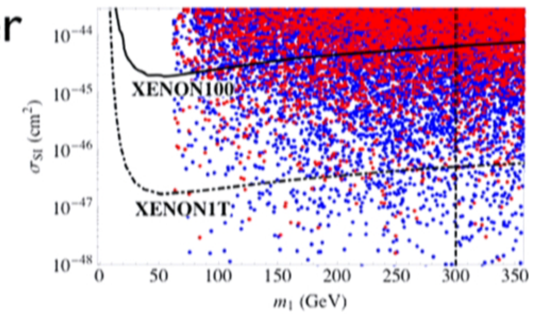

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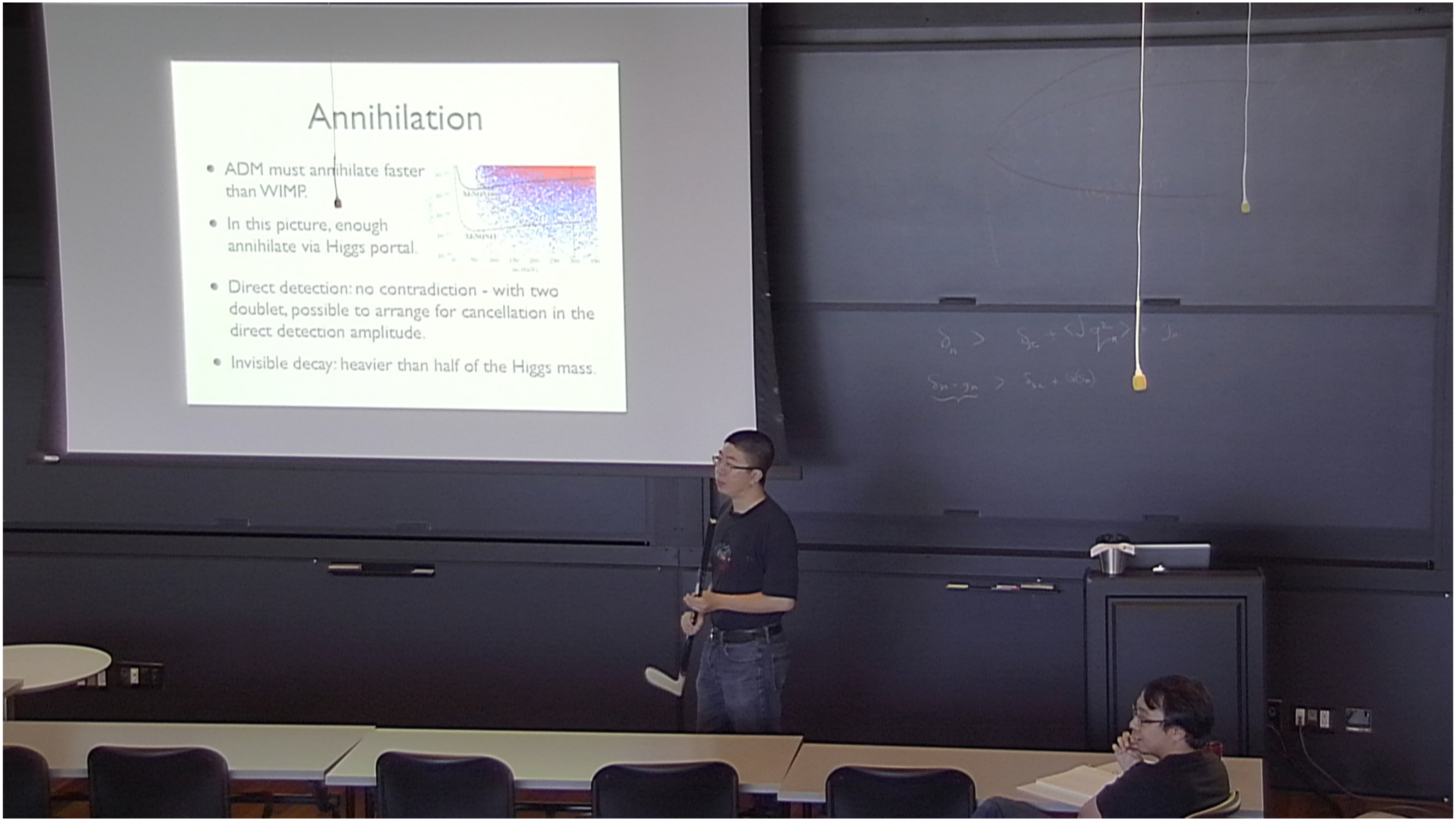
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Predictions about Higgs

- So far only discussed the relative asymmetry between DM and baryon.
- Need to examine the consequences in a model where baryogenesis works.
- A CP violating Higgs sector (2HDM): the lightest Higgs boson is essentially a mixture of CP even and odd eigenstates.
- It is possible to observe CP violating nature of the Higgs boson couplings at LHC, also in EDM.

Shu, YZ, arXiv:1304.0773, PRL

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Higgs Couplings

- SM Higgs: always $\mathcal{L} \sim (v+h)^n$

- Beyond SM:

$$\mathcal{L} = \frac{m_f}{v}\bar{f}(v + c_f h + \tilde{c}_f i\gamma_5 h)f + \frac{M_W^2}{v}(v + 2ah)W_\mu W^\mu$$

- Effective interactions (d=5)

$$\begin{aligned}\mathcal{L}_{\text{eff}} &= c_g h G^{a\mu\nu} G^a_{\mu\nu} + \tilde{c}_g h G^{a\mu\nu}\tilde{G}^a_{\mu\nu} \\ &+ c_\gamma h F^{a\mu\nu} F^a_{\mu\nu} + \tilde{c}_\gamma h F^{a\mu\nu}\tilde{F}^a_{\mu\nu}\end{aligned}$$

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Type-II 2HDM

- Yukawa $\mathcal{L}_Y = \bar{Q}Y_U(i\tau_2)\phi_2^* U + \bar{Q}Y_d\phi_1 D$
- General Higgs potential

$$V(\phi_1,\phi_2) = \cdots + m_{12}^2(\phi_1^\dagger\phi_2) + \lambda_5(\phi_1^\dagger\phi_2)^2$$

- Complex couplings λ_5, m_{12}^2, and complex vevs

$$\langle\phi_1\rangle = \begin{pmatrix} 0 \\ v\cos\beta/\sqrt{2} \end{pmatrix}, \quad \langle\phi_2\rangle = \begin{pmatrix} 0 \\ v\sin\beta e^{i\xi}/\sqrt{2} \end{pmatrix}$$

- Minimization condition, only one CP phase

$$\mathrm{Im}(m_{12}^2 e^{i\xi}) = (\lambda_5 \sin 2\xi)v^2 \sin\beta\cos\beta \ ,$$

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CP-even-odd mixing

- Mass eigenstates

125 GeV $$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = \begin{pmatrix} -s_\alpha c_{\alpha_b} & c_\alpha c_{\alpha_b} & s_{\alpha_b} \\ \hline s_\alpha s_{\alpha_b} s_{\alpha_c} - c_\alpha c_{\alpha_c} & -s_\alpha c_{\alpha_c} - c_\alpha s_{\alpha_b} s_{\alpha_c} & c_{\alpha_b} s_{\alpha_c} \\ s_\alpha s_{\alpha_b} c_{\alpha_c} + c_\alpha s_{\alpha_c} & s_\alpha s_{\alpha_c} - c_\alpha s_{\alpha_b} c_{\alpha_c} & c_{\alpha_b} c_{\alpha_c} \end{pmatrix} \begin{pmatrix} H_1 \\ H_2 \\ A \end{pmatrix}$$

- Higgs couplings, room for CPV

$$c_t = \frac{\cos\alpha\cos\alpha_b}{\sin\beta}, \quad c_b = -\frac{\sin\alpha\cos\alpha_b}{\cos\beta}$$

$$\tilde{c}_t = -\cot\beta\sin\alpha_b, \quad \tilde{c}_b = -\tan\beta\sin\alpha_b$$

$$a = \cos\alpha_b\sin(\beta-\alpha)$$

- α_b depends on vev $\tan\alpha_b \approx \dfrac{-\lambda_5\sin 2\xi\, v^2}{m_{h^+}^2 + (\lambda_4 - \lambda_5\cos 2\xi)v^2/2} \lesssim \xi$

A special case

- Pay attention to the case $\tan\beta \approx 1,\ \alpha \approx \beta - \pi/2$
- Couplings become

$$c_t = c_b = a = \cos\alpha_b \qquad \tilde{c}_t = \tilde{c}_b = -\sin\alpha_b$$

- Fit: $\chi^2(\cos^2\alpha_b, \sin^2\alpha_b)$ flat around $\alpha_b \sim 0$
- Sizable α_b is allowed, masses m_{h_2}, m_{h_3} must not go to infinity.
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Impact of CP violation

- Higgs production and decay at LHC

$$\Gamma(h \to f\bar{f}) \sim |c_f|^2 + |\tilde{c}_f|^2$$

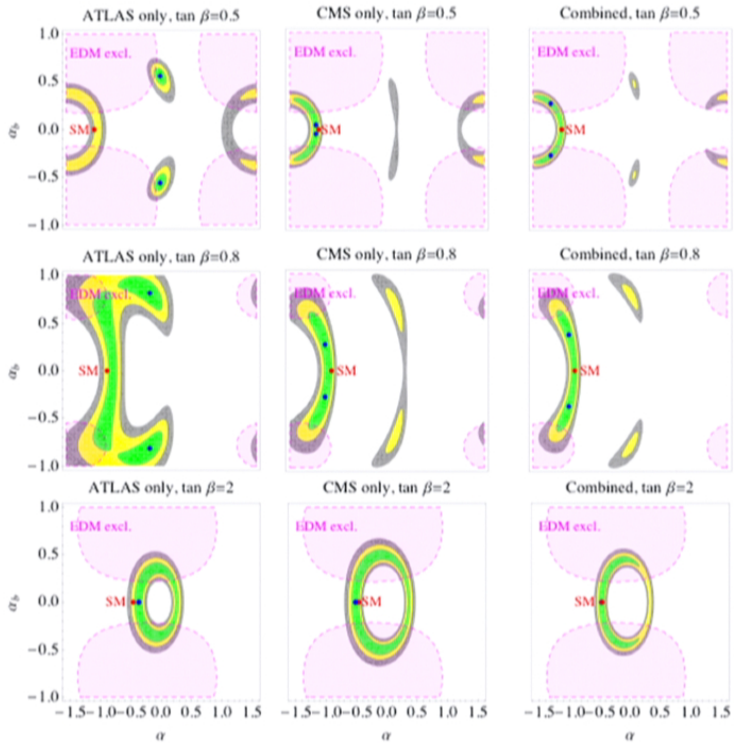
incoherent contributions

$$\Gamma(h \to \gamma\gamma) \sim |c_\gamma|^2 + |\tilde{c}_\gamma(\tilde{c}_f)|^2$$

$$\sigma(gg \to h) \sim \Gamma(h \to gg) \sim |c_g|^2 + |\tilde{c}_g(\tilde{c}_f)|^2$$

- Sizable CPV effects from EW scale fermion.
- In real models, a could also be affect by CPV.

Global Fit to Higgs data



Shu, YZ, arXiv:1304.0773, PRL

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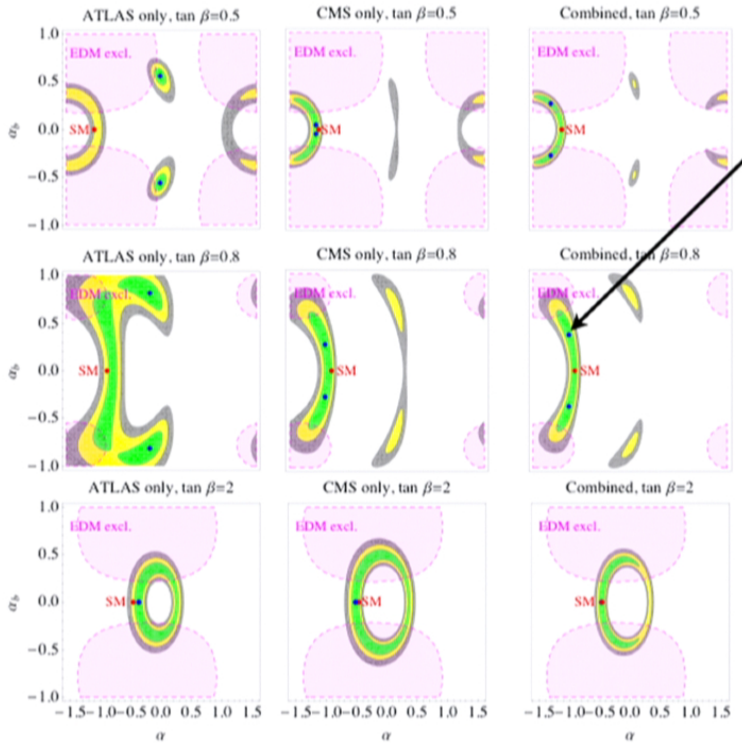


When away from SM:

1) enhance $h \to \gamma\gamma$

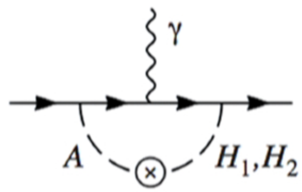
2) suppress $h \to Vb\bar{b}$

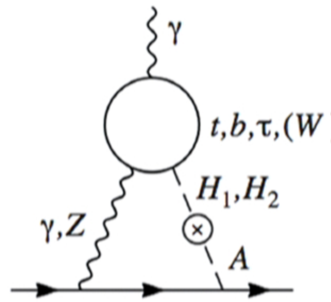
3) slightly suppressed Higgs total width.

Shu, YZ, arXiv:1304.0773, PRL

Impact of CP violation

- Electric dipole moments





Barr, Zee, 90'

One-loop suppressed by m^3, two-loop dominates.

- A useful parametrization

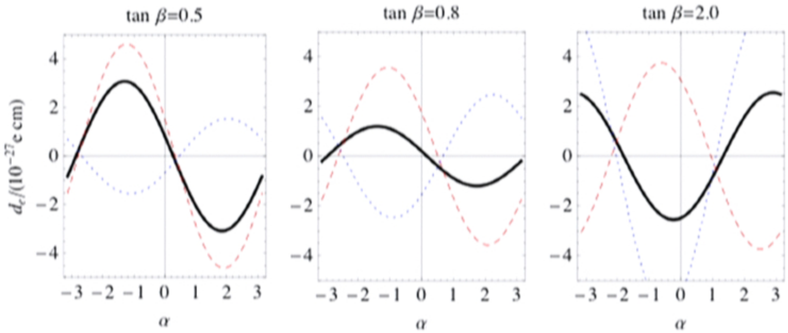
$$\tan^2\beta \mathrm{Im}\, Z_2 = -\tilde{c}_b c_t, \quad \cot^2\beta \mathrm{Im}\, Z_1 = \tilde{c}_t c_b \ ,$$

$$(\sin^2\beta \tan^2\beta \mathrm{Im} Z_2 + \cos^2\beta \mathrm{Im} Z_1) = a\, \tilde{c}_b \ ,$$

Shu, YZ, arXiv:1304.0773, PRL

Electron EDM

- Strongest cancellation $\tan\beta \sim 1$



Shu, YZ, arXiv:1304.0773, PRL

- EDM constraints could be relaxed, also need to examine neutron and atomic EDMs.

H.Guo, M.Ramsey-Musolf, YZ, in progress.

Connect low and high T

- 2HDM: integrating out the a whole doublet (t,b)

$$\mathcal{L}_{\rm eff} = \frac{g^2}{24\pi^2}\frac{i\log(\phi_1^\dagger\phi_2)}{|\phi_1^\dagger\phi_2|}F^{a\mu\nu}\tilde{F}^a_{\mu\nu} + h.c.$$

Turok, Zadrozny, 90'

- Include both vev and excitation, again exact up to linear term in h,

$$\langle\phi_1\rangle \sim \begin{pmatrix} 0 \\ v\cos\beta e^{-i\tilde{c}_b h/v}\end{pmatrix}, \quad \langle\phi_2\rangle \sim \begin{pmatrix} 0 \\ v\sin\beta e^{i\xi + i\tilde{c}_t h/v}\end{pmatrix}$$

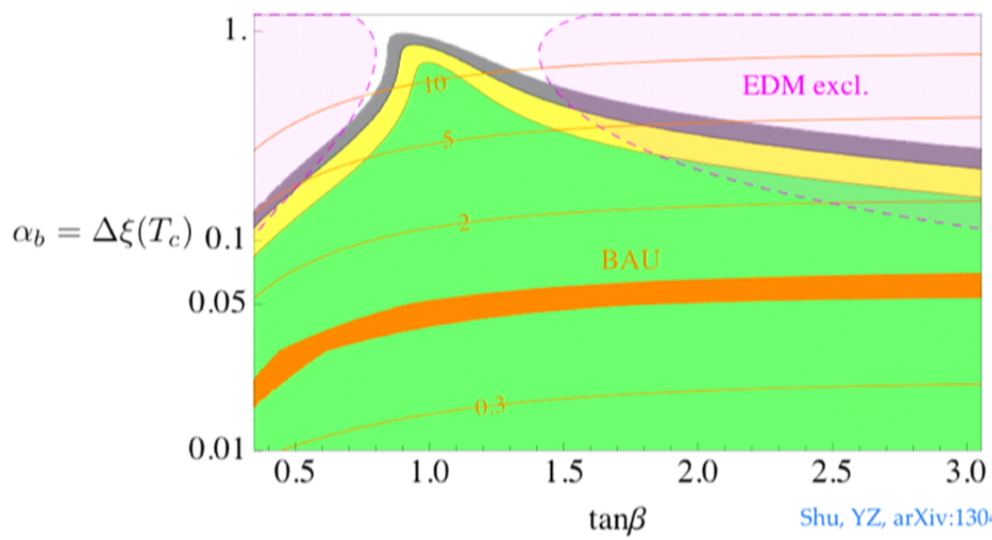
$$\mathcal{L}_{\rm eff} = \frac{g^2}{24\pi^2}\frac{\xi + (h/v)(\tilde{c}_t + \tilde{c}_b)}{|\phi_1^\dagger\phi_2|}F^{a\mu\nu}\tilde{F}^a_{\mu\nu}$$

High T, B violation $(\partial_t\xi)\cdot n_B$

$h \to \gamma\gamma$ (CPV) Zero T

$\tilde{c}_t(\xi)$

Connections



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- If Higgs boson CP violating effect is found at LHC in future, we may be probing the theory for genesis.

Direct measure Higgs CP

- Azimuthal phase shift:
  - Higgs decays

$$h \to ZZ^* \to 2\ell^+ 2\ell^-$$

$a_{F\tilde{F}} < 0.58$ @ 95% CL

Whitbeck, Moriond QCD 2013

$$h \to \tau^+\tau^- \to 2\pi 2\nu, 2\rho 2\nu$$

  - production $pp \to h + 2j, ht\bar{t}$

Klamke, Zeppenfeld, '07
Gunion, He, '96

- Virtual Higgs effects
  - $t\bar{t}$ production and leptonic decay: p_T distribution of charge lepton asymmetry.

Schmidt, Peskin '92

Conclusion

- We construct a simple ADM model with cogenesis
  - global symmetries restored at low energy
  - Common origin for baryon and DM asymmetries, but they never equilibrated with each other.
  - weak scale DM with Higgs portal, no light mediator
- CP violation in Higgs sector still less constrained at LHC, enough room for genesis, future direct measure Higgs CP properties.
  - neutron EDM may do better in foreseeable future.