

# Theoretical Prospects on Higgs CP Mixture

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Based on Jing Shu, YZ, arXiv:1304.0773

# Higgs Couplings

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

- Beyond SM general parametrization:

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

- Effective interactions (d=5)

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

# Higgs production/decay

- Higgs production and decay at LHC

$$\Gamma(h \rightarrow f\bar{f}) \sim |c_f|^2 + |\tilde{c}_f|^2 \quad \text{incoherent contributions}$$

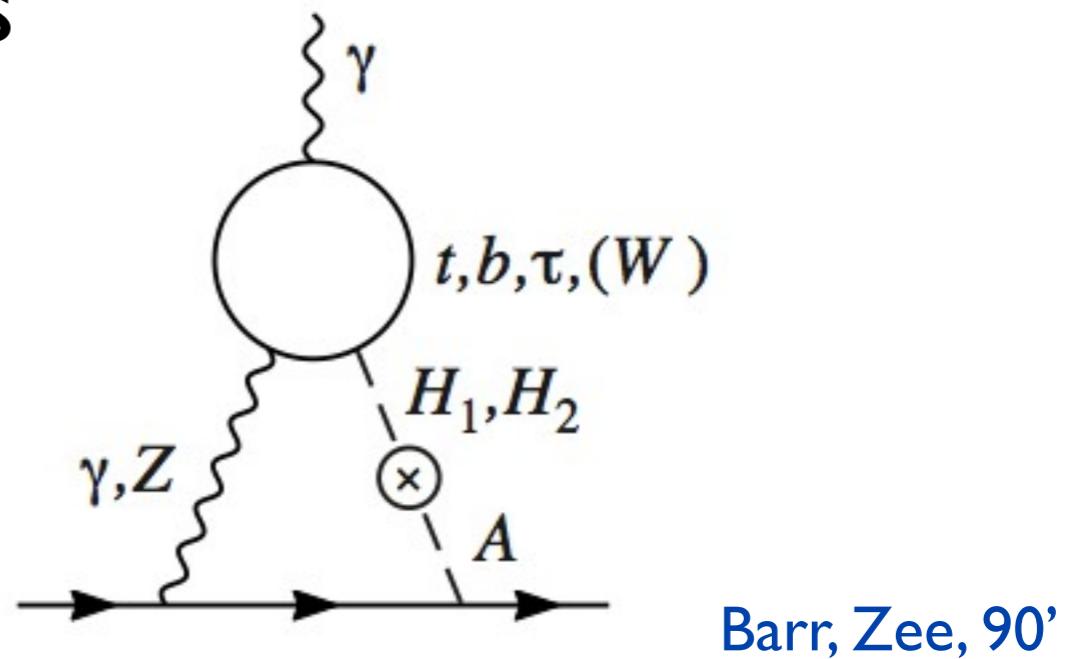
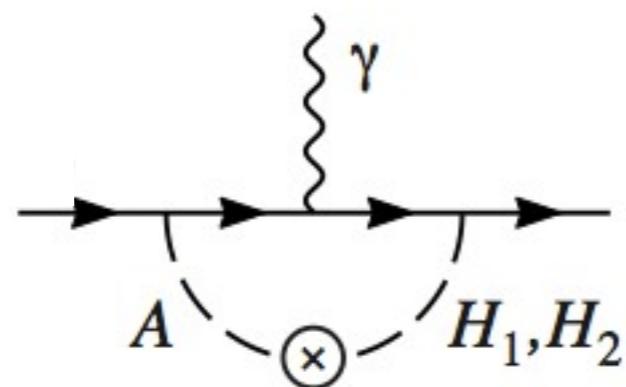
$$\Gamma(h \rightarrow \gamma\gamma) \sim |c_\gamma|^2 + |\tilde{c}_\gamma(\tilde{c}_f)|^2$$

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

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

# Electric Dipole moment

- Electric dipole moments



Barr, Zee, 90'

- One-loop suppressed by light fermion mass  $m^3$ ,
- Light fermions: two-loop dominates.

# Connection to Genesis

- Effective coupling

$$m_f \bar{f} \left[ v + c_f \frac{h}{v} + \left( \xi + \tilde{c}_f \frac{h}{v} \right) i\gamma_5 \right] f$$

- Up to linear terms in  $h$  and  $\xi$

$$m_f e^{i(\xi + \tilde{c}_f \frac{h}{v})} \bar{f}_L \left[ v + c_f \frac{h}{v} \right] f_R + \text{h.c.}$$

- Integrate out  $f_L$ , which is charged under SU(2)

$$\sim \left( \xi + \tilde{c}_f \frac{h}{v} \right) F \tilde{F}$$

High T, B violation

$$(\partial_t \xi) \cdot n_B$$

Zero T  
 $h \rightarrow \gamma\gamma$  (CPV)  
 $\tilde{c}_t(\xi)$

# Simplest Example: Type-II 2HDM

- Yukawa  $\mathcal{L}_Y = \bar{Q}Y_U(i\tau_2)\phi_2^*U + \bar{Q}Y_d\phi_1D$

- General Higgs potential

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

- Choose a basis  $\lambda_5$  real  $m_{12}^2$  complex, 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

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

# CP-even-odd mixing

- Mass eigenstates

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

- Higgs couplings, room for CPV

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

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

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

Pay attention to the case

$$\tan \beta \approx 1, \quad \alpha \approx \beta - \pi/2$$

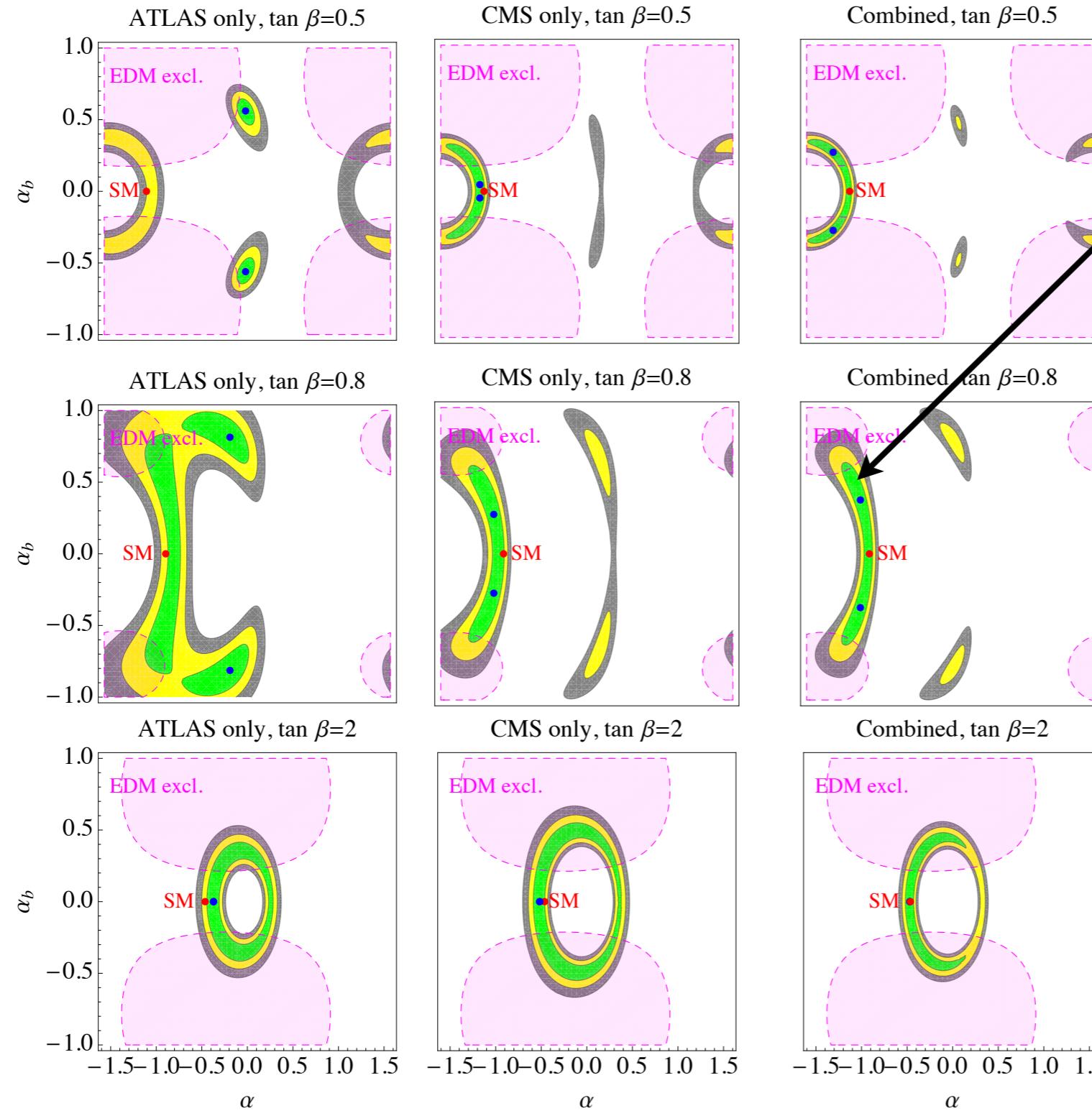
$$\chi^2(\cos^2 \alpha_b, \sin^2 \alpha_b)$$

Sizable  $\alpha_b$  allowed.

- $\alpha_b$  depends on vev

$$\tan \alpha_b \approx \frac{-\lambda_5 \sin 2\xi v^2}{m_{h^+}^2 + (\lambda_4 - \lambda_5 \cos 2\xi)v^2/2} \lesssim \xi$$

# Global Fit to Higgs data



When away from SM:

- 1) enhance  $h \rightarrow \gamma\gamma$
- 2) suppress  $h \rightarrow V b\bar{b}$
- 3) slightly suppressed Higgs total width.

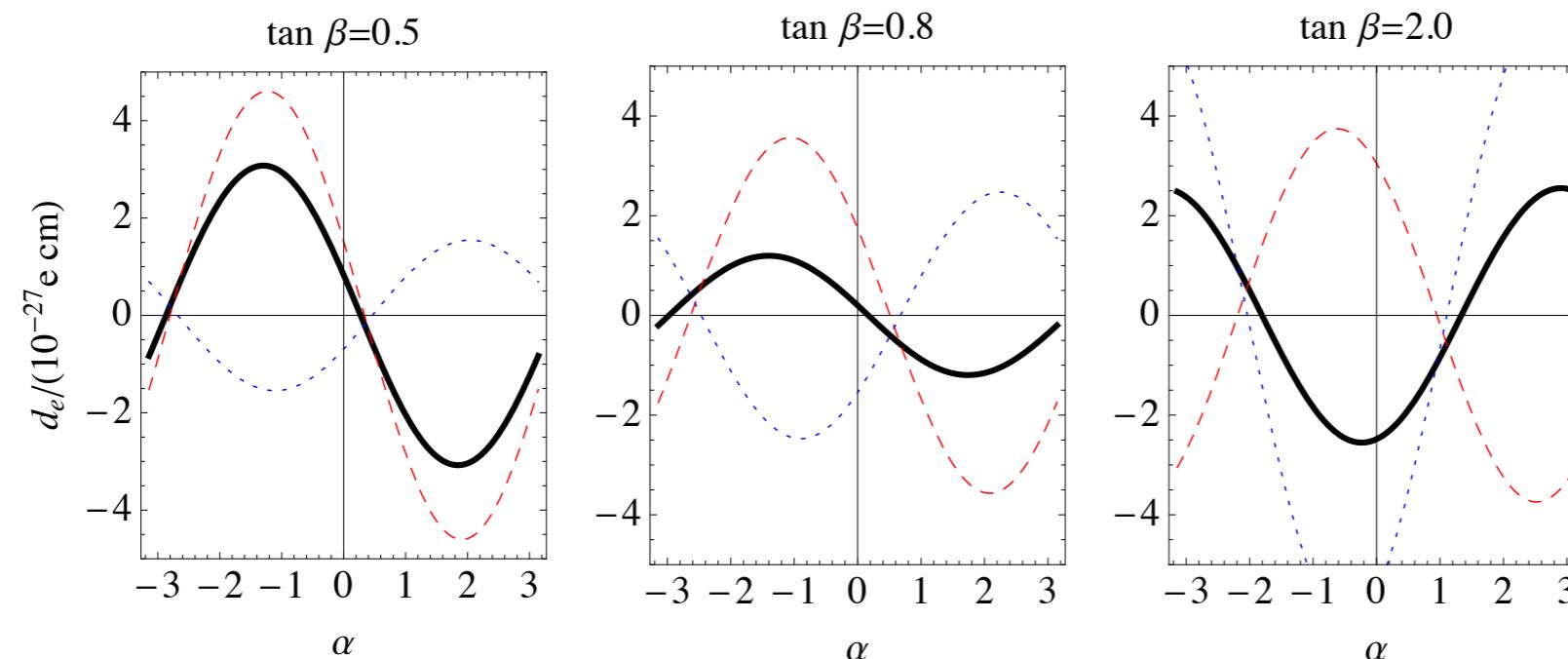
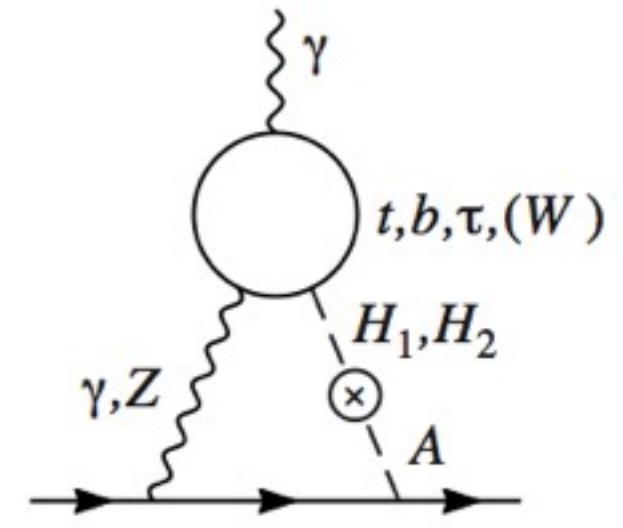
# Electron EDM

$$\tan^2 \beta \text{Im} Z_2 = -\tilde{c}_b c_t ,$$

$$\cot^2 \beta \text{Im} Z_1 = \tilde{c}_t c_b ,$$

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

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



J.Shu,YZ, I304.0773

- Detailed analysis on EDM of neutron and atoms.

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

# CPV for Genesis

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

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

Turok, Zadrozny, 90'

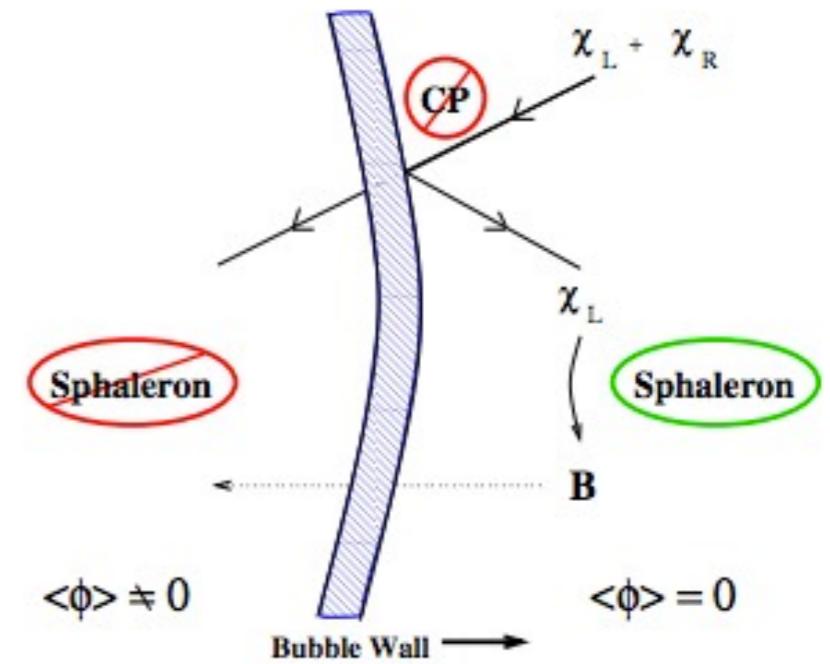
- Include both vev and excitation, again exact up to linear term in  $h$ ,

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

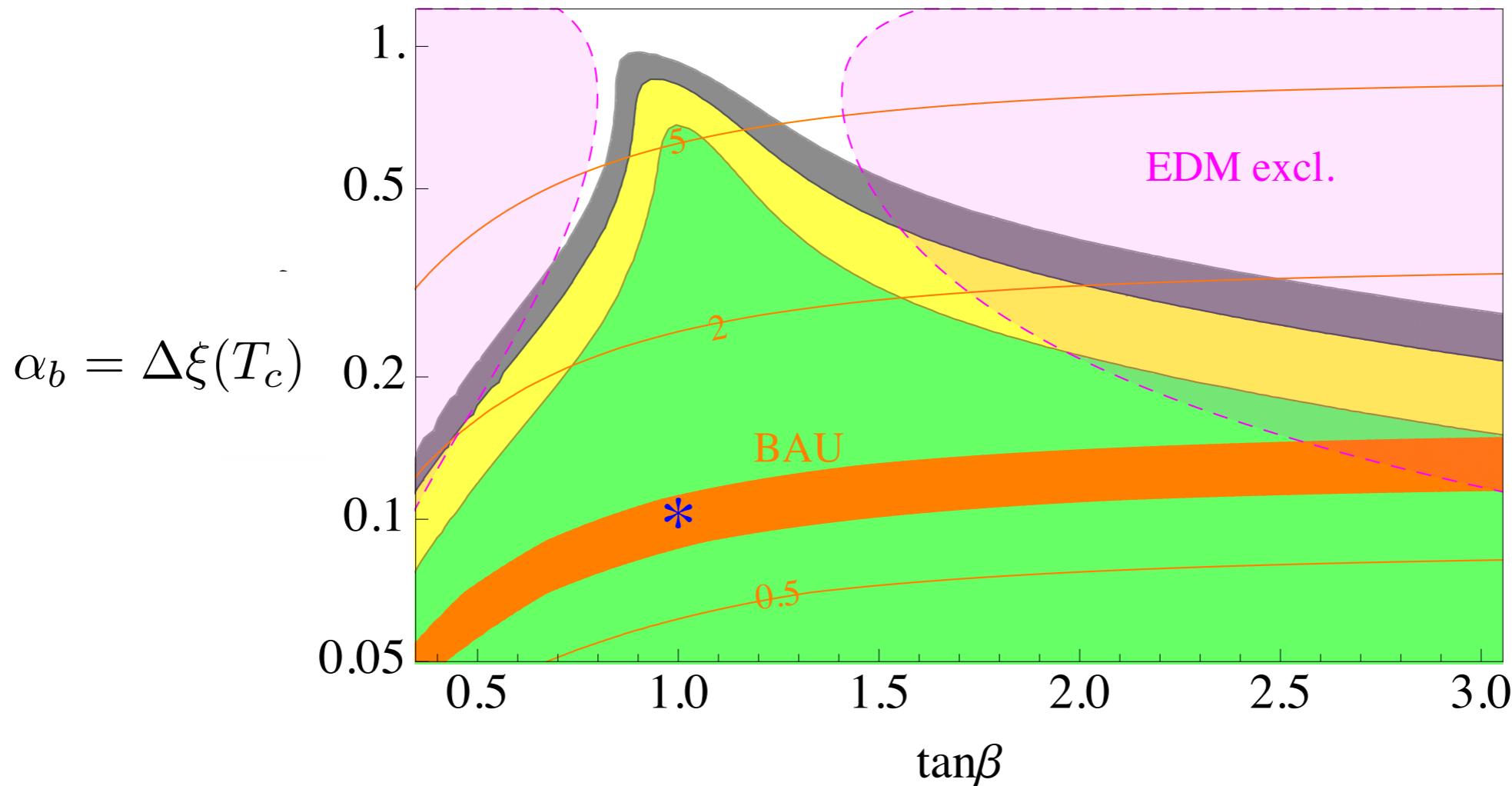
$$\mathcal{L}_{\text{eff}} = \frac{g^2}{24\pi^2} \frac{\xi + (h/v)(\tilde{c}_t + \tilde{c}_b)}{|\phi_1^\dagger \phi_2|} F^{a\mu\nu} \tilde{F}_{\mu\nu}^a$$

# EW baryogenesis

- The same fermion that modifies Higgs couplings can also provide necessary CPV source.
- CP violation source  $\sim \xi'(z)$
- Final baryon asymmetry asymmetry  $\frac{\Delta_b}{s} \sim \alpha_w^4 \Delta \xi$
- Provide a lower bound on the size of CPV angle.



# Connections



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

# Direct measure Higgs CP

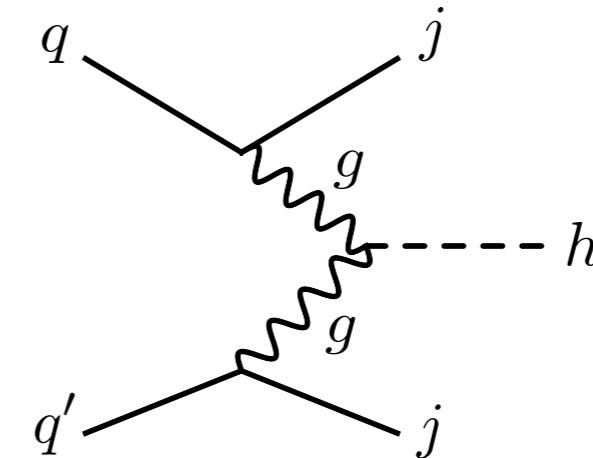
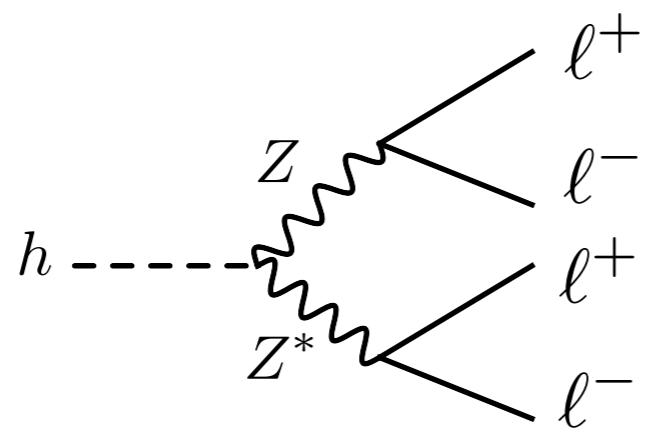
- Decay: “Golden channel”, azimuthal phase shift.

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

Whitbeck, Moriond QCD 2013

- Production in together with two forward jets, similar topology.

Klamke, Zeppenfeld, hep-ph/0703202



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

Schmidt, Peskin, PRL, 1992

# Conclusions

- CP violating Higgs sector with an order one CPV angle is consistent with LHC Higgs data, and electric dipole moment constraints.
- Close connection to baryogenesis in early universe - motivation for studying CPV associated with Higgs boson.
- Can also be directly probed with future LHC data.

Thank you