# *CP* violation in gauged $U(1)_B$


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# New *CP*-violating signal

- ATLAS observed a new *CP*-odd effect in the *Zjj* channel
- It can be interpreted by a dim-6 *CP*-violating op. in SMEFT

$$\mathcal{L}_{\rm SMEFT}^{CPV} \ni \frac{C_{H\widetilde{W}B}}{\Lambda^2} O_{H\widetilde{W}B} \qquad \frac{C_{H\widetilde{W}B}}{\Lambda^2} \in [0.23, 2.34]\,\mathrm{TeV}^{-2}$$

[2006.15458 (EPJC), ATLAS collaboration]

- Might be a new CPV signal beyond the KM phase in the SM
- Renormalizable model introducing vector-like leptons (VLLs)

| Fields | $\Psi_{L,R}$ | $E_{L,R}$ | $N_{L,R}$ | $H$ |
|---|---|---|---|---|
| $SU(2)_L$ | $\mathbf{2}$ | $\mathbf{1}$ | $\mathbf{1}$ | $\mathbf{2}$ |
| $U(1)_Y$ | $\mathcal{Y}$ | $\mathcal{Y}-1/2$ | $\mathcal{Y}+1/2$ | $1/2$ |

  - $C_{H\widetilde{W}B}$ can be written by Yukawa interactions of VLLs

[2009.13394 (PRD), S. Bakshi, J. Chakrabortty , C. Englert, M. Spannowsky, P. Stylianou]

# EW baryogenesis

- Solves baryon asymmetry of the Universe
- Our extension to satisfy the Sakharov conditions
  1. $\Delta B \neq 0$ ← assign the baryon number to VLLs
  2. $CP$-violation ← $CP$ phases in interactions of VLLs
  3. Out-of-equilibrium (1st order PT @EW scale) ← multi-Higgs extension
- We propose a model with gauged $U(1)_B$ symmetry

| Fields | $\Psi_L$ | $\Psi_R$ | $E_L$ | $E_R$ | $N_L$ | $N_R$ | $H_1$ | $H_2$ | $\varphi$ |
|---|---|---|---|---|---|---|---|---|---|
| $SU(2)_L$ | **2** | **2** | **1** | **1** | **1** | **1** | **2** | **2** | **1** |
| $U(1)_Y$ | $-1/2$ | $-1/2$ | $-1$ | $-1$ | $0$ | $0$ | $1/2$ | $1/2$ | $0$ |
| $U(1)_B$ | $B_1$ | $B_2$ | $B_2$ | $B_1$ | $B_2$ | $B_1$ | $-(B_1+B_2)\neq 0$ | $0$ | $(B_1-B_2)=-3$ |

$$\frac{\langle H_2\rangle}{\langle H_1\rangle} \equiv \tan\beta \qquad \langle\varphi\rangle \equiv v_\varphi/\sqrt{2}$$

  - To avoid FCNC, $f_{SM}$ only couples to $H_2$ by $U(1)_B$; type-I 2HDM w/o extra $Z_2$
  - Anomaly cancellation $B_1 - B_2 = -3$
  - To obtain $m_{12}^2 H_1^\dagger H_2$, $(B_1, B_2) = (-3, 0)$ is chosen: $\Delta V = \frac{\mu}{\sqrt{2}} H_2^\dagger H_1 \varphi \longrightarrow m_A^2 \propto \mu\, v_\varphi \propto m_{12}^2$

# Model parameters

- Neutral Gauge bosons: $(m_Z, m_{Z'}, \epsilon)$ $\epsilon \ll 1$
- Scalar bosons: $(m_{H^\pm}, m_A, m_H, m_h, m_S; \tan\beta, \sin(\beta-\alpha), \alpha_1, \alpha_2)$ [2HDM+S]
- Fermions: $$-\mathcal{L}_{\mathcal{Y}_{\rm new}} = (y_{\Psi N}\overline{\Psi}_L N_R + \widetilde{y}_{\Psi N}\overline{\Psi}_R N_L)\,\widetilde{H}_2 + (y^c_{\Psi N}\overline{\Psi^c_L} N_L + \widetilde{y}^c_{\Psi N}\overline{\Psi^c_R} N_R)\,\widetilde{H}^*_1 \\ + (y_{\Psi E}\overline{\Psi}_L E_R + \widetilde{y}_{\Psi E}\overline{\Psi}_R E_L)\,H_2 \\ + y_\Psi \overline{\Psi}_L \Psi_R\,\varphi + (y_{N_{LR}}\overline{N}_L N_R + y_E \overline{E}_L E_R)\,\varphi^* + \frac{1}{2} m_N \overline{N_L} N^c_L + \text{h.c.}\,,$$
    - Complex Yukawa's (9*2)+Majorana mass (1)
    - We can remove phases of $(y_\Psi, y_E, y_{N_{LR}}, m_N)$
    - 3 dof are taken independently among remained 6 complex phases
    - Charged fermion: 2 mass $m_{\psi^\pm_{1,2}}$ + 1 mixing angle + 1 *CP*-phase $\theta_{\Psi E}$
    - Neutral fermion: 4 mass $m_{\psi^0_{1,2,3,4}}$ + 6 mixing angle + 2 *CP*-phase $(\widetilde{\theta}_{\Psi N}, \widetilde{\theta}^c_{\Psi N})$

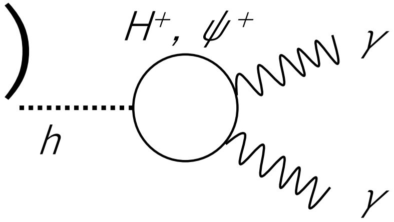
# Outline

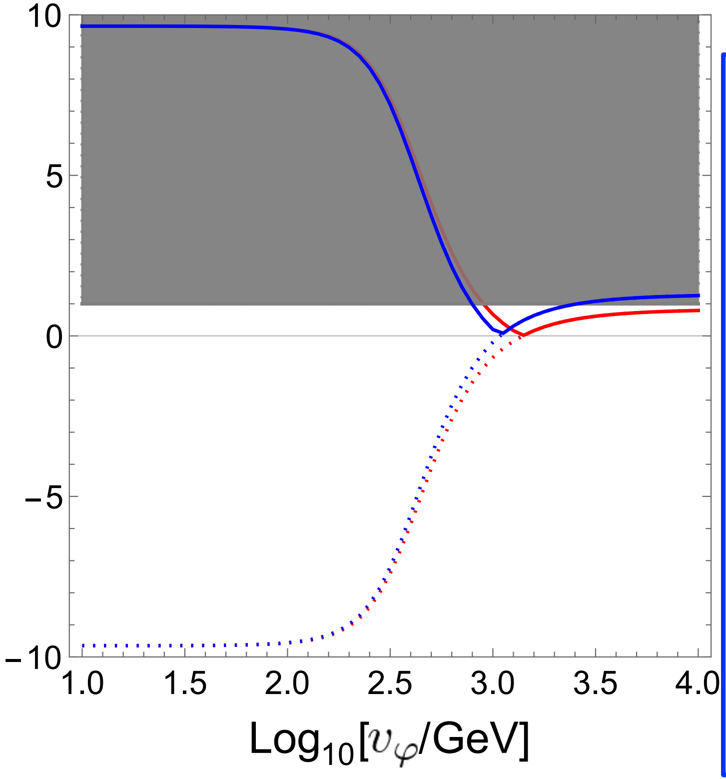
- Signal strength $(gg \to h \to \gamma\gamma) \to v_\varphi$
- Scalar mass constraints → $m_A$ & $m_{H^\pm}$
- Higgs coupling measurement $(\kappa_V, \kappa_f) \to \tan\beta$ & $\sin(\beta - \alpha)$
- Predictions
  - EW-ino searches → $m_{\psi^0}$ & $m_{\psi^\pm}$
  - Rho parameter → $m_{Z'}$
  - Electric Dipole Moment
  - *CP*-violating signal at ATLAS

  } $(\widetilde{\theta}_{\Psi N}, \widetilde{\theta}^c_{\Psi N}, \theta_{\Psi E})$

  3-independent *CP*-phases
- Discussion
- Conclusion

# Signal strength ($gg \to h \to \gamma\gamma$)




- Charged fermion contribution

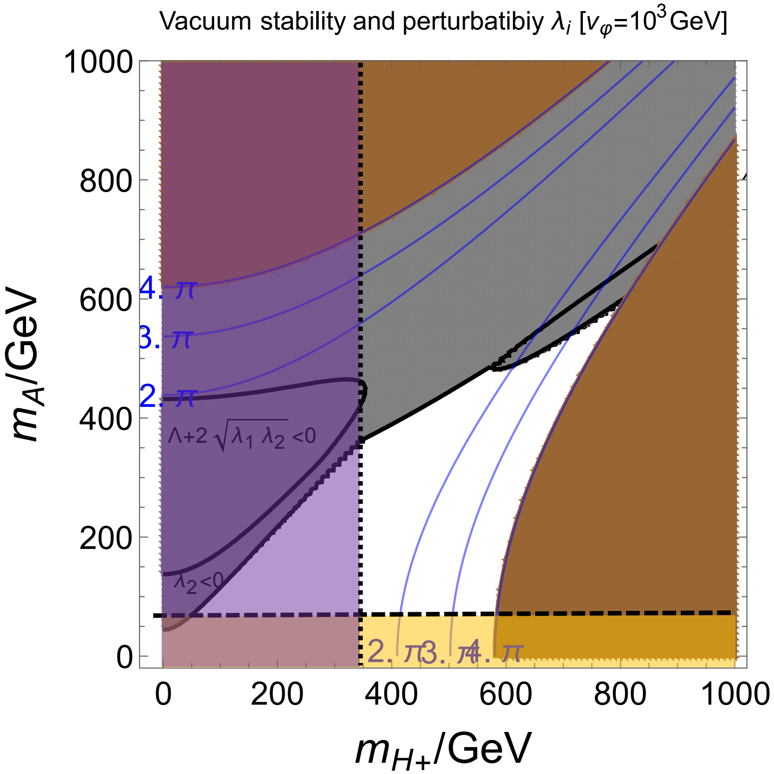
  $v_\varphi \gtrsim 800\,\mathrm{GeV}$

- Charged scalar contribution
  - $\lambda_{hH+H-} \propto m_{H\pm}^2 - M^2$ $\quad M \propto m_A$
  - Small $m_A \to$ non-decoupling limit (blue)

    $v_\varphi \lesssim \mathcal{O}(1)\,\mathrm{TeV}$

  - Large $m_A \to$ decoupling limit (red)

# Scalar mass constraints




Vacuum stability

$$\min\left\{\lambda_{1,2,\varphi},\quad a+2\sqrt{bc},\quad 4\Lambda\lambda_\varphi - 2\lambda_{1\varphi}\lambda_{2\varphi} + \sqrt{(\lambda_{1\varphi}^2 - 4\lambda_1\lambda_\varphi)(\lambda_{2\varphi}^2 - 4\lambda_2\lambda_\varphi)}\right\} > 0,$$

where $\quad (a,b,c) = (\Lambda,\lambda_1,\lambda_2),(\lambda_{1\varphi},\lambda_1,\lambda_\varphi),(\lambda_{2\varphi},\lambda_2,\lambda_\varphi);\ \Lambda \equiv \lambda_3 + \min(0,\lambda_4).$

$$m_A \lesssim 364\,\mathrm{GeV} \quad (m_{H^\pm} = 350\,\mathrm{GeV})$$

Perturbativity $\quad \lambda_i < 4\,\pi$

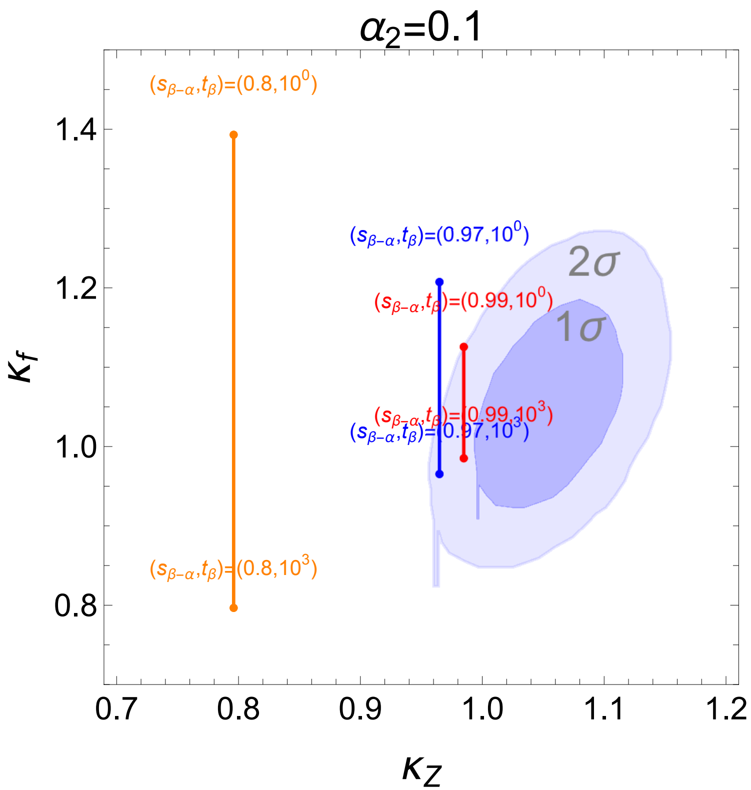
$$m_{H^\pm} \lesssim 600\,\mathrm{GeV}$$

$h \to AA$ is avoided by $m_A \gtrsim m_h/2$

Flavor experiments : it would be safe if

$$m_{H^\pm} \gtrsim 350\,\mathrm{GeV}, \quad \tan\beta \gtrsim 2$$

# Higgs coupling measurement




$$\kappa_X \equiv \frac{c_{hXX}}{c_{hXX}^{\rm SM}}$$

$$\kappa_f = c_{\alpha_2}\left(s_{\beta-\alpha} + \frac{c_{\beta-\alpha}}{t_\beta}\right)$$

$$\kappa_Z \simeq \kappa_W = c_{\alpha_2}\, s_{\beta-\alpha}$$

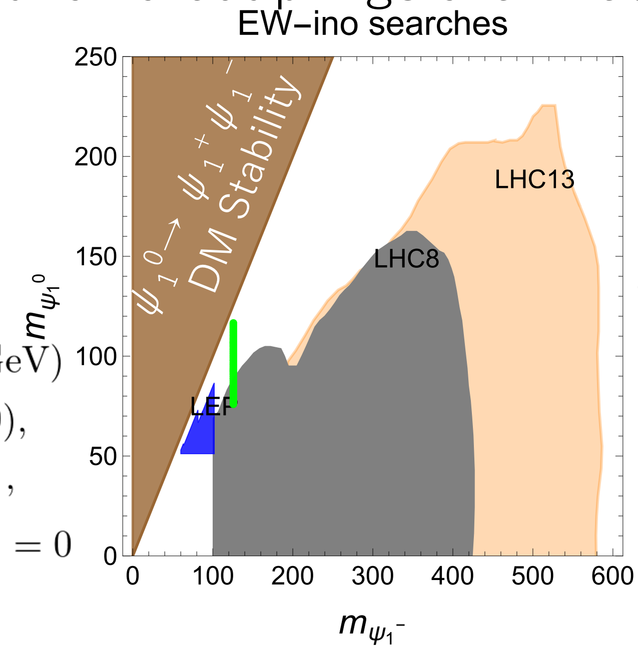
$$\frac{m_{Z'}}{m_Z} \ll 1$$

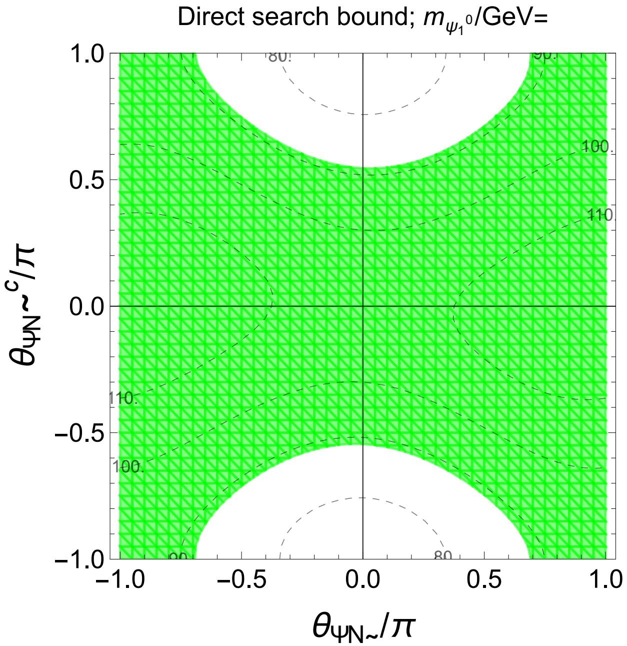
$$\sin(\beta-\alpha) \gtrsim 0.99 \quad \text{if} \quad \tan\beta = \mathcal{O}(1)$$

# ① EW-ino searches

- Two *CP* phases for neutral fermions are scanned
  - Absolute value of Yukawa couplings are fixed
  - Input parameter:

$$(m_{H^\pm}, m_H, m_A, m_S; m_{Z'})$$
$$= (350, 350, 100, 96; 0.1)\,\mathrm{GeV},$$
$$(v_\varphi/\mathrm{GeV}; t_\beta, s_{\beta-\alpha}, \alpha_1, \alpha_2; \epsilon)$$
$$= (800, 2, 0.99, 0, 0.1; -10^{-3}),$$
$$(y_{\Psi N}, y^c_{\Psi N}, y_{\Psi E}, y_\Psi, y_{N_{LR}}, y_{\Psi E}, m_N/\mathrm{GeV})$$
$$= (0.15, 0.15, 0.60, 0.20, 0.30, 1.00, 500),$$
$$\widetilde{y}_{\Psi N} = y_{\Psi N}\ , \widetilde{y}^c_{\Psi N} = y^c_{\Psi N}\ , \widetilde{y}_{\Psi E} = y_{\Psi E}\ ,$$
$$\theta_{\Psi N} = \theta^c_{\Psi N} = \widetilde{\theta}_{\Psi E} = \theta_E = \theta_\Psi = \theta_{N_{LR}} = 0$$



# ② rho parameter

- $\rho_{1\text{-loop}} = 1 - (\Delta\rho_{\text{tree}} + \Delta\rho_{\text{gauge}}) + \alpha_{\text{em}}(T_{\text{scalar}} + T_{\text{fermion}})$
- $\rho_{\text{exp}} \equiv 1.00039 \pm 0.00019 \quad (1\sigma)$

(*1) (*2)

(*1)

$\rho_{\text{tree}} \neq 1$

Independent parameters

$(g, g', v, v_\varphi)$

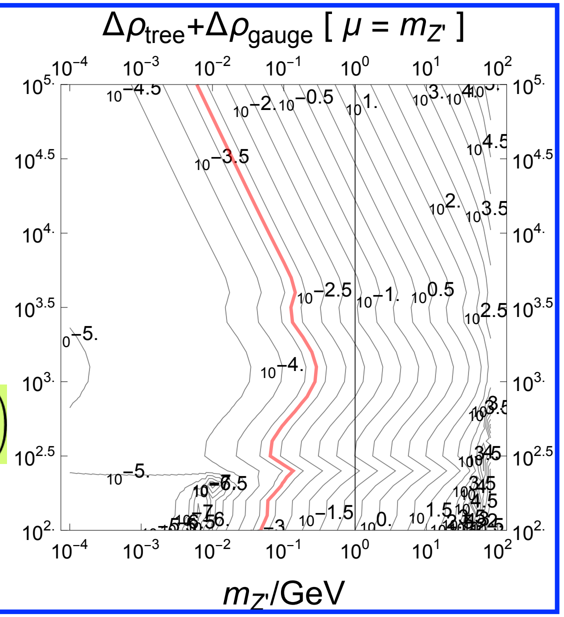
$\updownarrow$

$(\alpha_{\text{em}}, G_F, m_Z, \rho_{\text{tree}})$

$\Delta\rho_{\text{gauge}} = \xi^2_{\text{1-loop}}\left(1 - \frac{m^2_{Z'}}{m^2_Z}\right)$

*Z*-*Z'* mixing at 1-loop

$m_{Z'} \lesssim 0.1\,\text{GeV}$




(*2)

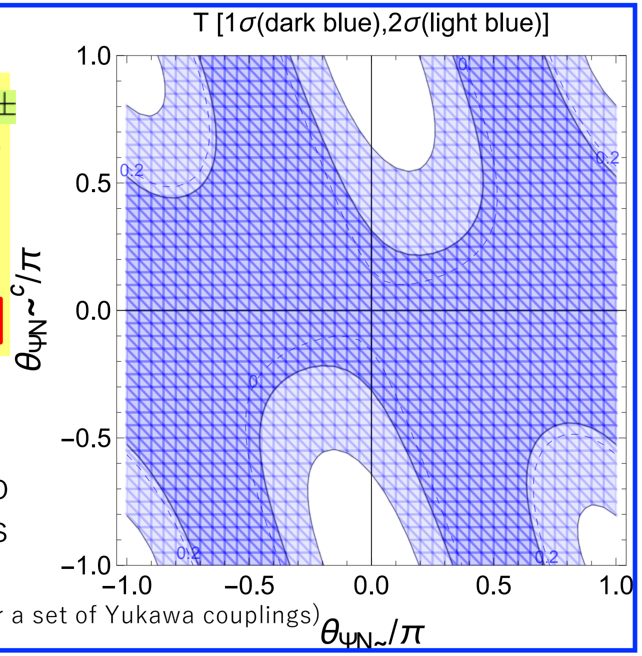
$m_H = m_{H^\pm}$

(custodial symmetry)

$v_\varphi \gg v$

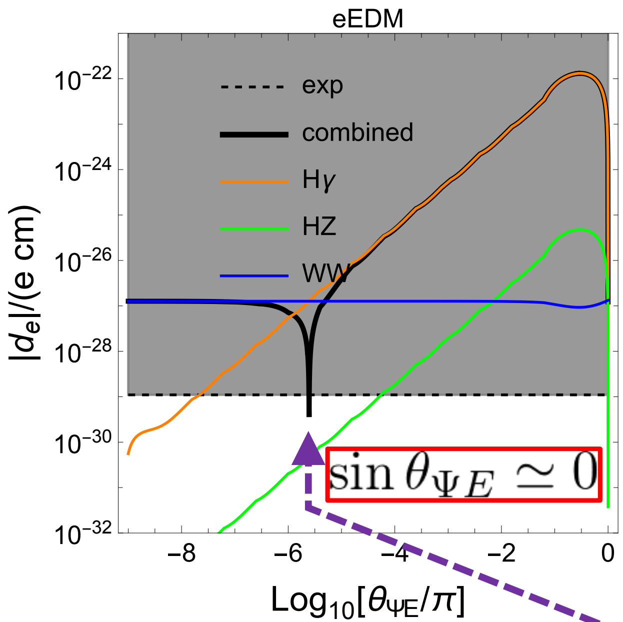
$\Rightarrow$ $T_{\text{scalar}} \simeq 0$

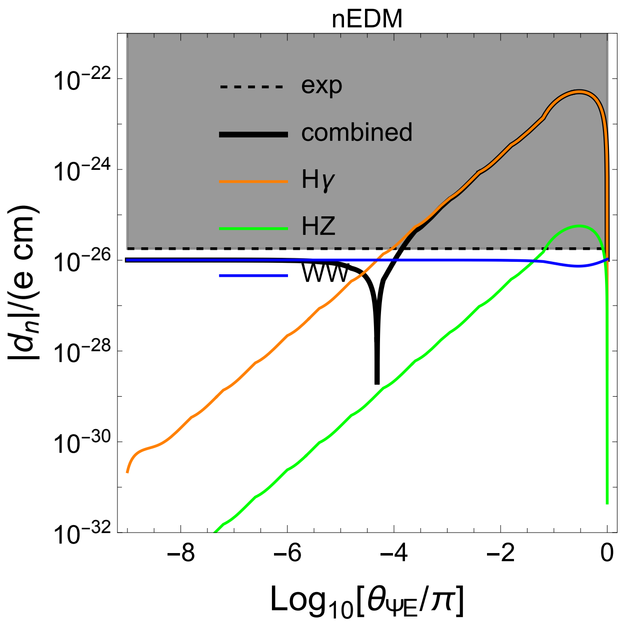
*S* parameter is not sensitive to two *CP*-phases

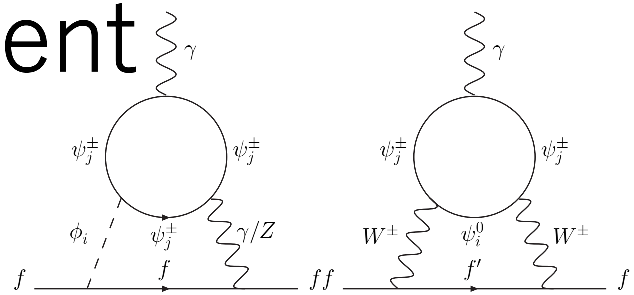


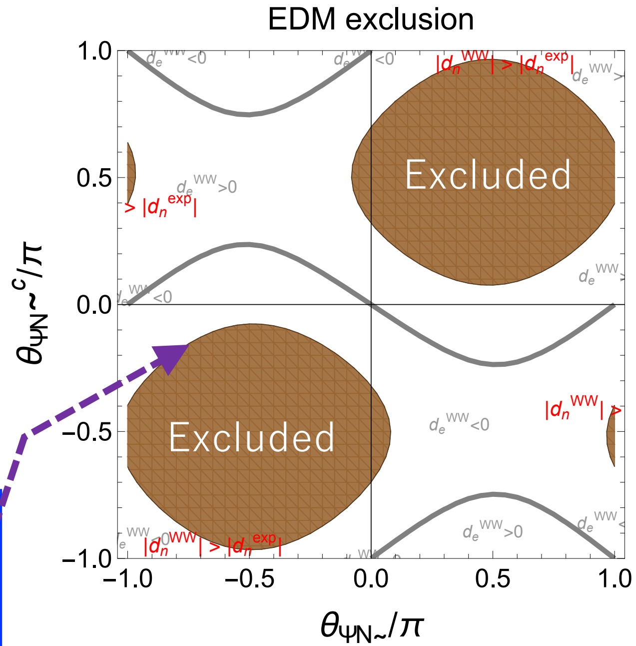

(taken an example for a set of Yukawa couplings)

# ③ Electric Dipole Moment






- Electron EDM: Cancellation $d_e^{\rm exp} \geq d_e^{\rm tot} \simeq d_e^{H\gamma} + d_e^{WW}$
- Neutron EDM: Impose a condition $d_n^{\rm exp} \geq d_n^{\rm tot} \simeq d_n^{WW}$

# ④ *CP*-violating signal at ATLAS

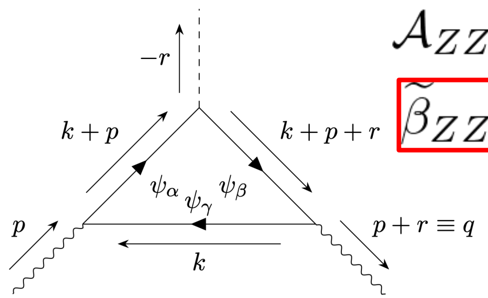
- Dim-6 *CP*-violating op. in SMEFT

$$\frac{C_{H\widetilde{W}B}}{\Lambda^2}(H^\dagger \tau^a H)\widetilde{W}^a_{\mu\nu}B^{\mu\nu} \ni \frac{C_{H\widetilde{W}B}}{\Lambda^2}\left(-\frac{1}{2}(v+h)^2\right)(-c_\xi^2\, s_W\, c_W)\widetilde{Z}_{\mu\nu}Z^{\mu\nu}$$

$$\frac{C_{H\widetilde{W}B}}{\Lambda^2} \in [0.23, 2.34]\,\mathrm{TeV}^{-2}$$

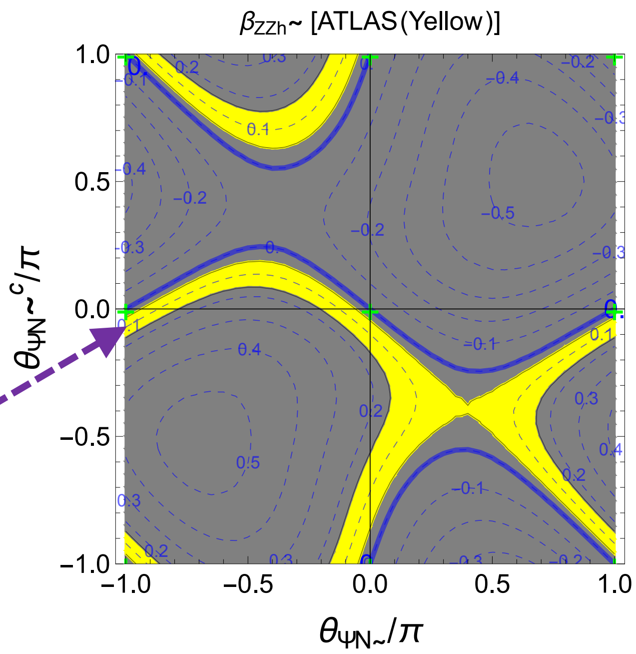
[2006.15458 (EPJC), ATLAS collaboration]

- *ZZh* interaction at 1-loop

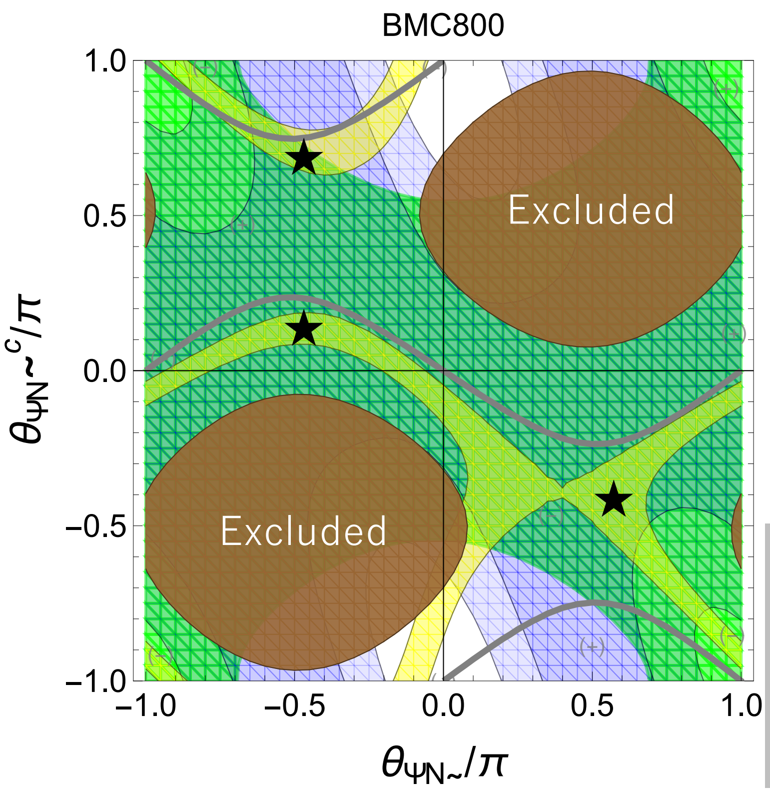



$$\mathcal{A}_{ZZh} \ni \widetilde{\beta}_{ZZh}\, h\, \widetilde{Z}_{\mu\nu}Z^{\mu\nu}$$

$$\widetilde{\beta}_{ZZh} \in [0.049, 0.157]\,\mathrm{TeV}^{-1}$$



# Summary




① EW-ino searches (**green**: allowed)
② $T$ parameter (**blue**: allowed)
③ electric dipole moment (**brown**: excluded)
④ *CP*-violating signal at ATLAS (**yellow**: consistent)
→ **Combined all** (★: predicted)

# Discussion

- EWBG (future work)
  - Strong 1st order phase transition at EW scale & Gravitational waves
  - Estimation of the baryon number
- DM
  - Accidental $Z_2$ after U(1)$_B$ breaking: $\Psi_{L,R} \to -\Psi_{L,R}, \quad N_{L,R} \to -N_{L,R}$
  - The SI cross section for fermion DM with scalar mediator

$$\sigma_{\rm SI} \equiv c^2 \frac{4\mu^2}{\pi} f_N^2 \, , \quad \mu \equiv \frac{m_N m_{\psi_1^0}}{m_N + m_{\psi_1^0}}: \text{ reduced mass}$$

$$c \equiv \sum_{\phi=h,H,S} \frac{c_{\phi\psi_1^0\psi_1^0}\kappa_{\phi ff}}{v(t-m_\phi^2)} \overset{t\to 0}{\simeq} \frac{c_\alpha\, c_{\alpha_2}\, s_{\alpha_2}}{s_\beta v} \frac{m_{\psi_1^0}}{v_\varphi} \left(\frac{1}{m_h^2} - \frac{1}{m_S^2}\right)$$ ($\alpha_1$=0 is taken)

  - Can be suppressed by taking $m_S \sim m_h$.

# Conclusion

- ATLAS observed a new *CP*-odd effect in the *Zjj* channel which can be interpreted by a dim-6 CPV op. in SMEFT $\frac{C_{H\widetilde{W}B}}{\Lambda^2} \in [0.23, 2.34]\,\mathrm{TeV}^{-2}$
- We have proposed a model for EWBG with gauged $U(1)_B$
  - New fermions are assigned $U(1)_B$ charges & generate *CP* phases
  - In scalar sector, $(H_{1,2}, S)$ are introduced & break $U(1)_B$
- We have derived constraints in $v_\varphi$, $(m_{Z'}, m_A, m_{H^\pm})$, $(t_\beta, s_{\beta-\alpha})$
- At fixed Yukawa couplings, we have shown predictions in *CP*-phases considering bounds on (EW-ino searches, *T* parameter, EDMs) which are consistent with CPV signal at ATLAS $\widetilde{\beta}_{ZZh} \in [0.049, 0.157]\,\mathrm{TeV}^{-1}$
- Complete work for successful EWBG is planed as future work

# Backup

# Model

| | $SU(3)_C$ | $SU(2)_L$ | Isospin | $U(1)_Y$ | $U(1)_{EM}$ | $U(1)_B$ | Flavor | $Z_2$ |
|---|---|---|---|---|---|---|---|---|
| Fields | | | $T^3$ | $Q_Y$ | $Q = T^3 + Q_Y$ | $Q_X$ | $i$ | |
| $Q_L^i = (u_L^i \quad d_L^i)^T$ | 3 | 2 | (1/2,−1/2) | 1/6 | (+2/3,−1/3) | 1/3 | 3 | +1 |
| $u_R^i$ | 3 | 1 | 0 | 2/3 | +2/3 | 1/3 | 3 | +1 |
| $d_R^i$ | 3 | 1 | 0 | −1/3 | −1/3 | 1/3 | 3 | +1 |
| $L_L^i = (\nu_L^i \quad e_L^i)^T$ | 1 | 2 | (1/2,−1/2) | −1/2 | (0,−1) | 0 | 3 | +1 |
| $e_R^i$ | 1 | 1 | 0 | −1 | −1 | 0 | 3 | +1 |
| $\Psi_L = (\Psi_L^0 \quad \Psi_L^-)^T$ | 1 | 2 | (1/2,−1/2) | −1/2 | (0,−1) | −3 | 1 | −1 |
| $\Psi_R = (\Psi_R^0 \quad \Psi_R^-)^T$ | 1 | 2 | (1/2,−1/2) | −1/2 | (0,−1) | 0 | 1 | −1 |
| $E_L^-$ | 1 | 1 | 0 | −1 | −1 | 0 | 1 | −1 |
| $E_R^-$ | 1 | 1 | 0 | −1 | −1 | −3 | 1 | −1 |
| $N_L$ | 1 | 1 | 0 | 0 | 0 | 0 | 1 | −1 |
| $N_R$ | 1 | 1 | 0 | 0 | 0 | −3 | 1 | −1 |
| $H_1 = (\phi_1^+ \quad \varphi_1^0)^T$ | 1 | 2 | (1/2,−1/2) | 1/2 | (+1,0) | 3 | 1 | +1 |
| $H_2 = (\phi_2^+ \quad \varphi_2^0)^T$ | 1 | 2 | (1/2,−1/2) | 1/2 | (+1,0) | 0 | 1 | +1 |
| $\varphi$ | 1 | 1 | 0 | 0 | 0 | −3 | 1 | +1 |

# Lagrangian

$$\mathcal{L} = \mathcal{L}_{\rm YM} + \mathcal{L}_{\rm gauge} - V + \mathcal{L}_{\rm kin} + \mathcal{L}_{\mathcal{Y}_{\rm SM}} + \mathcal{L}_{\mathcal{Y}_{\rm new}} \ ,$$

where

$$\begin{aligned}
\mathcal{L}_{\rm YM} &= -\frac{1}{4}\mathbf{W}_{\mu\nu}\cdot\mathbf{W}^{\mu\nu} - \frac{1}{4}\hat{B}_{\mu\nu}\hat{B}^{\mu\nu} - \frac{1}{4}\hat{X}_{\mu\nu}\hat{X}^{\mu\nu} + \frac{\epsilon'}{2}\hat{B}^{\mu\nu}\hat{X}_{\mu\nu} \ , \\
\mathcal{L}_{\rm gauge} &= |D_\mu H_1|^2 + |D_\mu H_2|^2 + |D_\mu \varphi|^2 \ , \\
V &= \lambda_1 |H_1|^4 + \lambda_2 |H_2|^4 + \lambda_3 |H_1|^2 |H_2|^2 + \lambda_4 \left| H_1^\dagger H_2 \right|^2 + \lambda_\varphi (\varphi^* \varphi)^2 \\
&\quad + (\lambda_{1\varphi}\varphi^*\varphi + m_1^2)|H_1|^2 + (\lambda_{2\varphi}\varphi^*\varphi + m_2^2)|H_2|^2 + m_\varphi^2 \varphi^*\varphi + \Delta V + \text{h.c.} \ , \\
-i\,\mathcal{L}_{\rm kin} &= \overline{\Psi}_L D \Psi_L + \overline{\Psi}_R D \Psi_R + \overline{E}_L D E_L + \overline{E}_R D E_R + \overline{N}_L D N_L + \overline{N}_R D N_R \ , \\
-\mathcal{L}_{\mathcal{Y}_{\rm SM}} &= y_u\, \overline{Q}_L\, u_R\, \widetilde{H_2} + (y_d\, \overline{Q}_L\, d_R + y_e\, \overline{L}_L\, e_R)\, H_2 + \text{h.c.} \ , \\
-\mathcal{L}_{\mathcal{Y}_{\rm new}} &= (y_{\Psi N}\overline{\Psi}_L N_R + \widetilde{y}_{\Psi N}\overline{\Psi}_R N_L)\, \widetilde{H}_2 + (y^c_{\Psi N}\overline{\Psi^c_L} N_L + \widetilde{y}^c_{\Psi N}\overline{\Psi^c_R} N_R)\, \widetilde{H}_1^* \\
&\quad + (y_{\Psi E}\overline{\Psi}_L E_R + \widetilde{y}_{\Psi E}\overline{\Psi}_R E_L)\, H_2 \\
&\quad + y_\Psi \overline{\Psi}_L \Psi_R\, \varphi + (y_{N_{LR}}\overline{N}_L N_R + y_E \overline{E}_L E_R)\, \varphi^* + \frac{1}{2} m_N \overline{N_L} N_L^c + \text{h.c.} \ ,
\end{aligned}$$

# $CP$ phases

- 3 physical phases

$$\mathrm{Im}\left(y_{\Psi E}\widetilde{y}^{*}_{\Psi E}e^{-i\,(\theta_{y_\Psi}+\theta_{y_E})}\right) = \sin(\theta_{\Psi E} - \widetilde{\theta}_{\Psi E} - \theta_{\Psi} - \theta_{E})\ ,$$

$$\mathrm{Im}\left(\widetilde{y}_{\Psi N}y^{c}_{\Psi N}e^{i\,\theta_{y_\Psi}}\right) = \sin(\widetilde{\theta}_{\Psi N} - \theta^{c}_{\Psi N} + \theta_{\Psi})\ ,$$

$$\mathrm{Im}\left(y_{\Psi N}\widetilde{y}^{c}_{\Psi N}e^{-i\,(\theta_{y_\Psi}+2\,i\,\theta_{N_{LR}})}\right) = \sin(\theta_{\Psi N} - \widetilde{\theta}^{c}_{\Psi N} - \theta_{\Psi} - 2\,\theta_{N_{LR}})$$

- We define 3 independent phases as

$$(\widetilde{\theta}_{\Psi N}\,, \widetilde{\theta}^{c}_{\Psi N}\,, \theta_{\Psi E})$$

taking $\theta_{\Psi N} = \theta^{c}_{\Psi N} = \widetilde{\theta}_{\Psi E} = \theta_{E} = \theta_{\Psi} = \theta_{N_{LR}} = 0$.

# rho parameter at tree / (S, T)$_{scalar}$