Impact of a CP violating Higgs: LHC, EDMs and Cogenesis

Yue Zhang (Caltech)

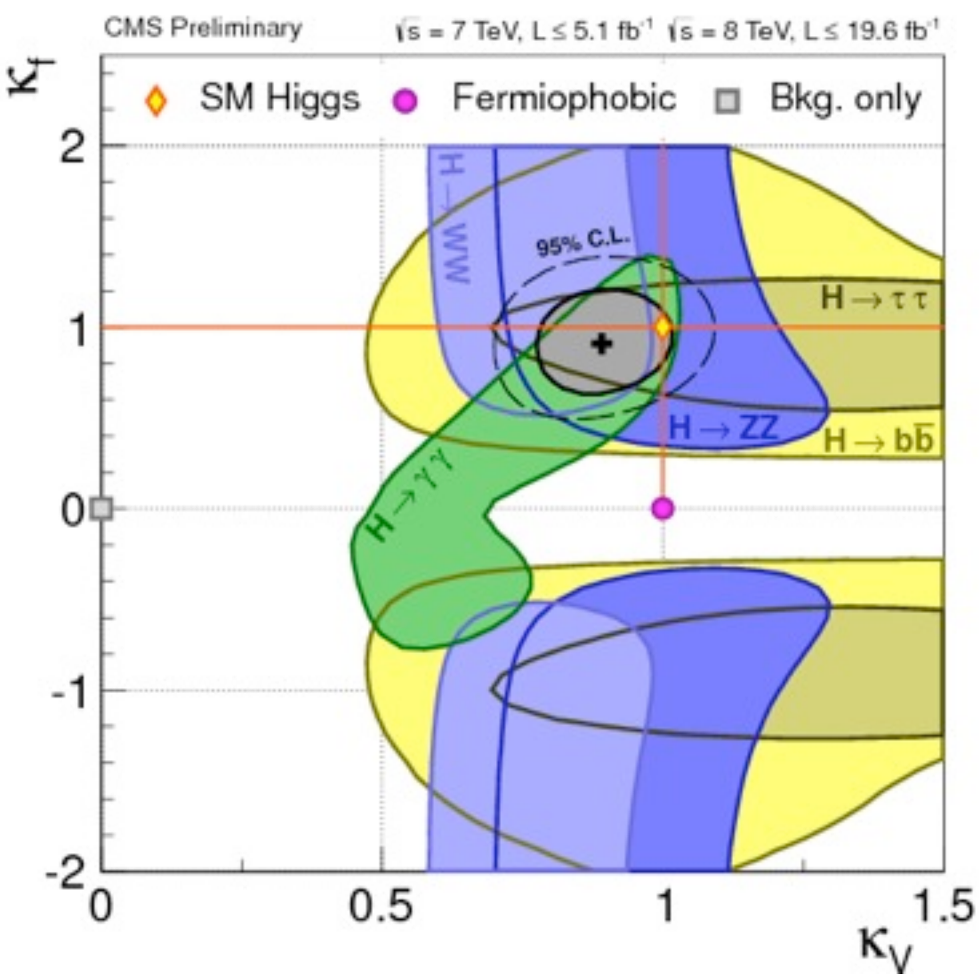
KITP workshop on *particlegenesis*, 22 May 2014

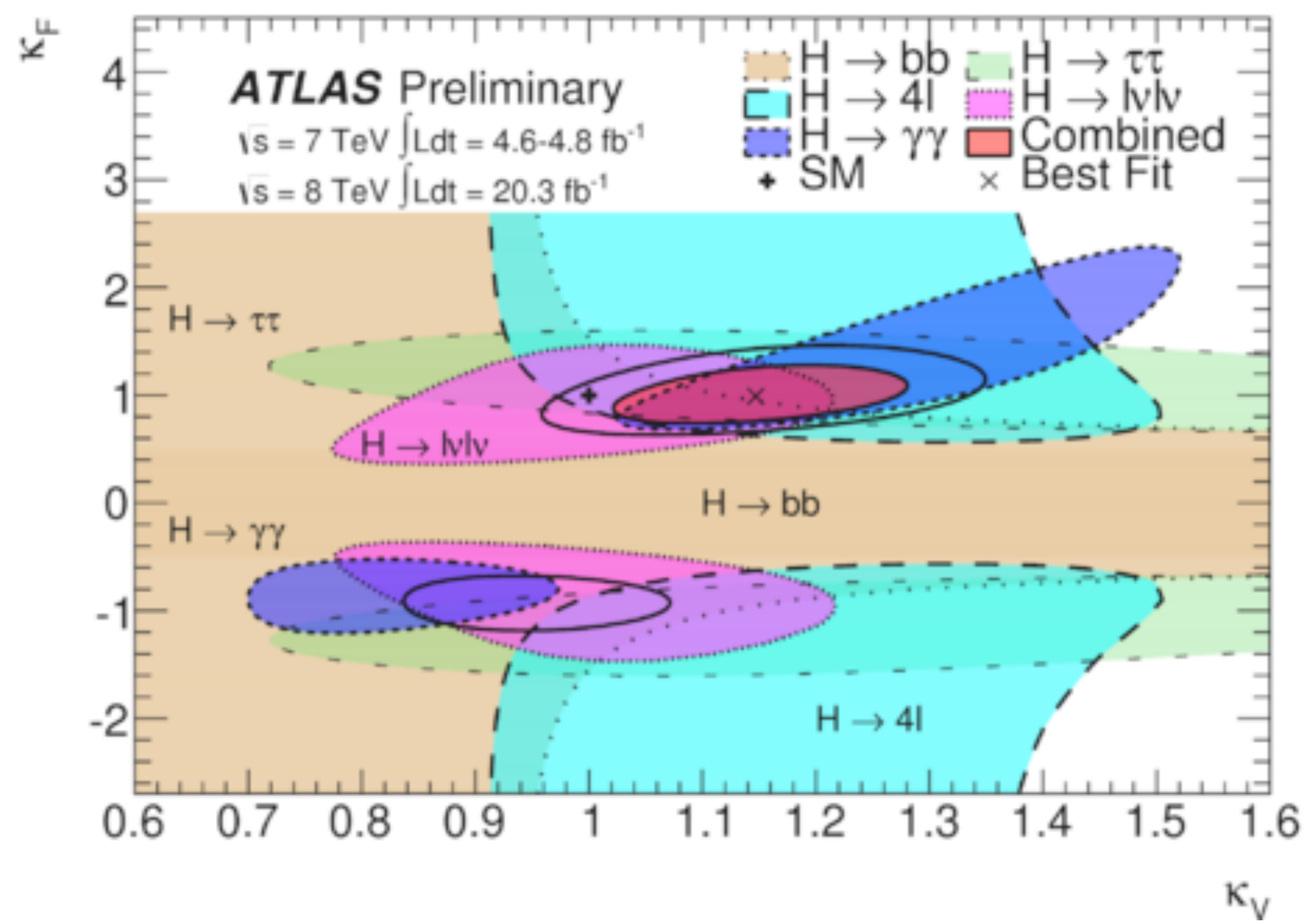
Jing Shu, YZ, 1304.0773

Clifford Cheung, YZ, 1306.4321

Satoru Inoue, Michael Ramsey-Musolf, YZ, 1403.4257

Higgs Boson Properties





- 125 GeV, looks like SM Higgs - Great triumph.
- Where to look next?

Motivations for CPV

- Higgs boson may be a CP even-odd mixture.
- Well motivated: may account for origin of baryon asymmetry (and dark matter) in the universe.
  - Electroweak baryogenesis / Electroweak Cogenesis.
- Constraints from experimental data.
  - LHC Higgs search: rates, direct ...
  - Electric dipole moments.

Higgs Couplings

- SM, one Higgs doublet theory always $\mathcal{L} \sim (v+h)^n$

- Beyond SM, renormalizable model

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

- Calculable effective interactions (d=5)

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

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CP odd

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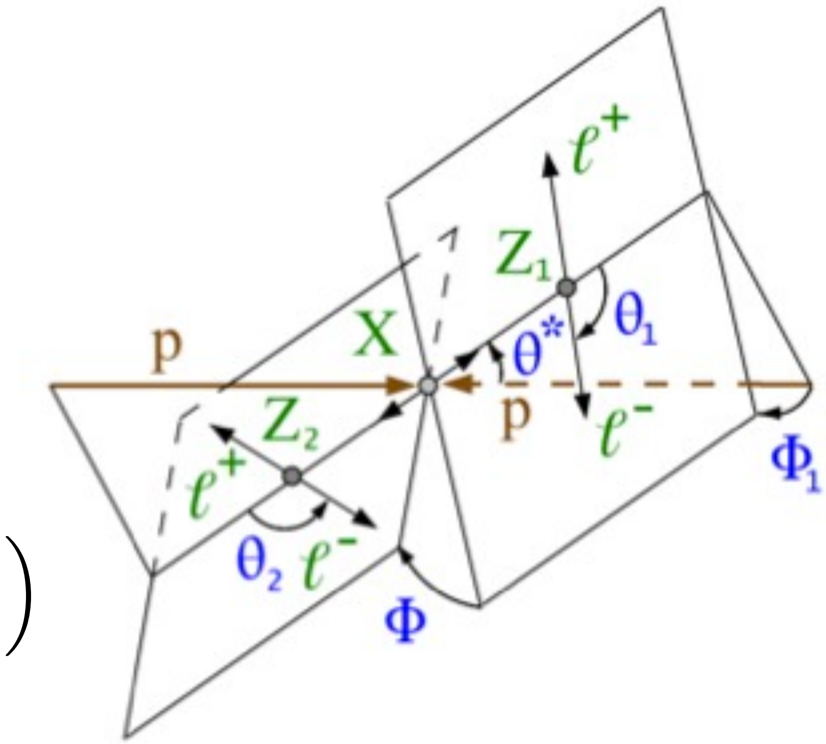
loop

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

Search in golden channel



- Parametrize the amplitude

$$A(h \to ZZ) = v^{-1} \epsilon_1^{*\mu} \epsilon_2^{*\nu} \left(a_1 g_{\mu\nu} M_Z^2 + a_3 \epsilon_{\mu\nu\alpha\beta} q_1^\alpha q_2^\beta \right)$$

- So far only a rather weak bound.

$$f_{a3} = \frac{|a_3|^2}{|a_1|^2 + |a_3|^2} < 0.58 \text{ @ } 95\%\text{C.L.}$$

- a_3 from dimension 6 operator $H^\dagger H Z_{\mu\nu} \tilde{Z}^{\mu\nu} / \Lambda^2$, loop suppressed in renormalizable models.

Indirect measurement

- Higgs production and decay rates at LHC

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

incoherent contributions

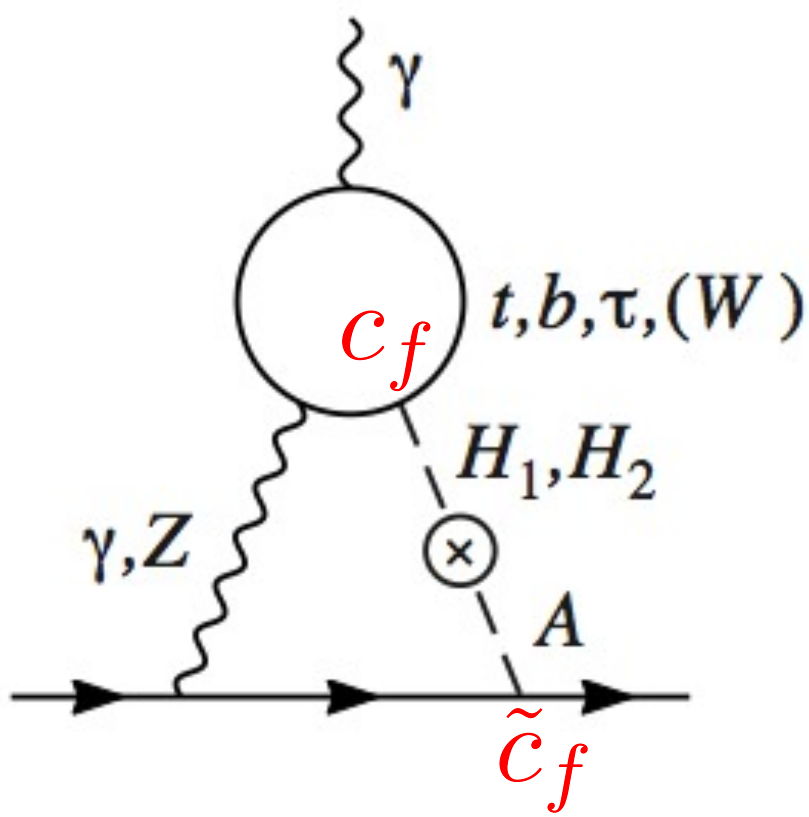
$$\Gamma(h \to \gamma\gamma) \sim |c_\gamma(c_f, a)|^2 + |\tilde{c}_\gamma(\tilde{c}_f)|^2$$

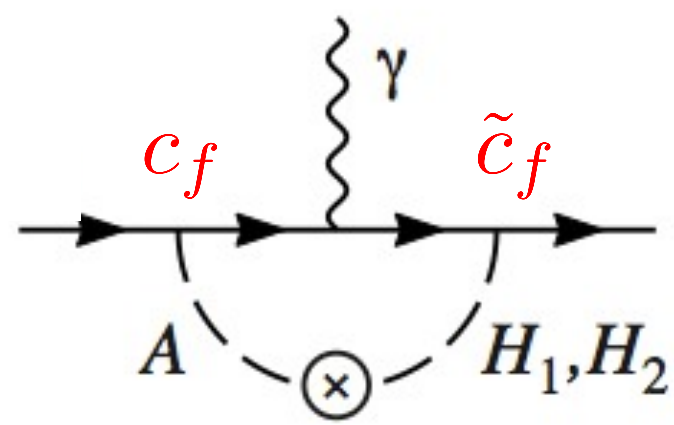
$$\sigma(gg \to h) \sim \Gamma(h \to gg) \sim |c_g(c_f)|^2 + |\tilde{c}_g(\tilde{c}_f)|^2$$

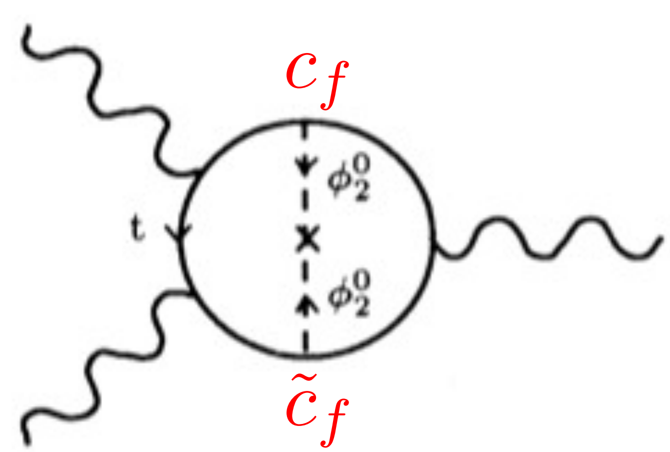
- Sizable CPV effects from EW scale fermion, *e.g.*, top quark, etc.

Electric dipole moment

- Electric dipole moments (calculable parts)







and more..

Early universe

- 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 ξ

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

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

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

Chemical potential for B number

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

$$h \to \gamma\gamma \ (\mathrm{CPV})$$

Zero T

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

Type-II 2HDM

- Yukawa
- Higgs potential

$$\mathcal{L}_Y = \bar{Q} Y_U (i\tau_2) \phi_2^* U + \bar{Q} Y_d \phi_1 D$$
$$+ \bar{Q} Y'_U \phi_1 U + \bar{Q} Y'_d (i\tau_2) \phi_2^* D$$

$$\begin{aligned} V = & \frac{\lambda_1}{2}(\phi_1^\dagger \phi_1)^2 + \frac{\lambda_2}{2}(\phi_2^\dagger \phi_2)^2 + \lambda_3 (\phi_1^\dagger \phi_1)(\phi_2^\dagger \phi_2) \\ & + \lambda_4 (\phi_1^\dagger \phi_2)(\phi_2^\dagger \phi_1) + \frac{1}{2}\left[\lambda_5 (\phi_1^\dagger \phi_2)^2 + \lambda_6 (\phi_1^\dagger \phi_2)(\phi_1^\dagger \phi_1) + \lambda_7 (\phi_1^\dagger \phi_2)(\phi_2^\dagger \phi_2) + \mathrm{h.c.}\right] \\ & - \frac{1}{2}\left\{ m_{11}^2 (\phi_1^\dagger \phi_1) + \left[m_{12}^2 (\phi_1^\dagger \phi_2) + \mathrm{h.c.}\right] + m_{22}^2 (\phi_2^\dagger \phi_2) \right\}, \end{aligned}$$

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- Yukawa
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- Higgs potential

$$V = \frac{\lambda_1}{2}(\phi_1^\dagger\phi_1)^2 + \frac{\lambda_2}{2}(\phi_2^\dagger\phi_2)^2 + \lambda_3(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2)$$
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- Natural flavor conservation, an approximate Z_2

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- Natural flavor conservation, an approximate Z_2
- Complex parameters $\lambda_5,\ m_{12}^2$

$\Rightarrow$ only one CP violating phase

Only one CPV source

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

- Mass eigenstates

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

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- Both ξ and $\alpha_b,\ \alpha_c$ depends on the only CPV source - the phase mismatch $\mathrm{Im}\left[\lambda_5^*(m_{12}^2)^2\right]$

Higgs couplings

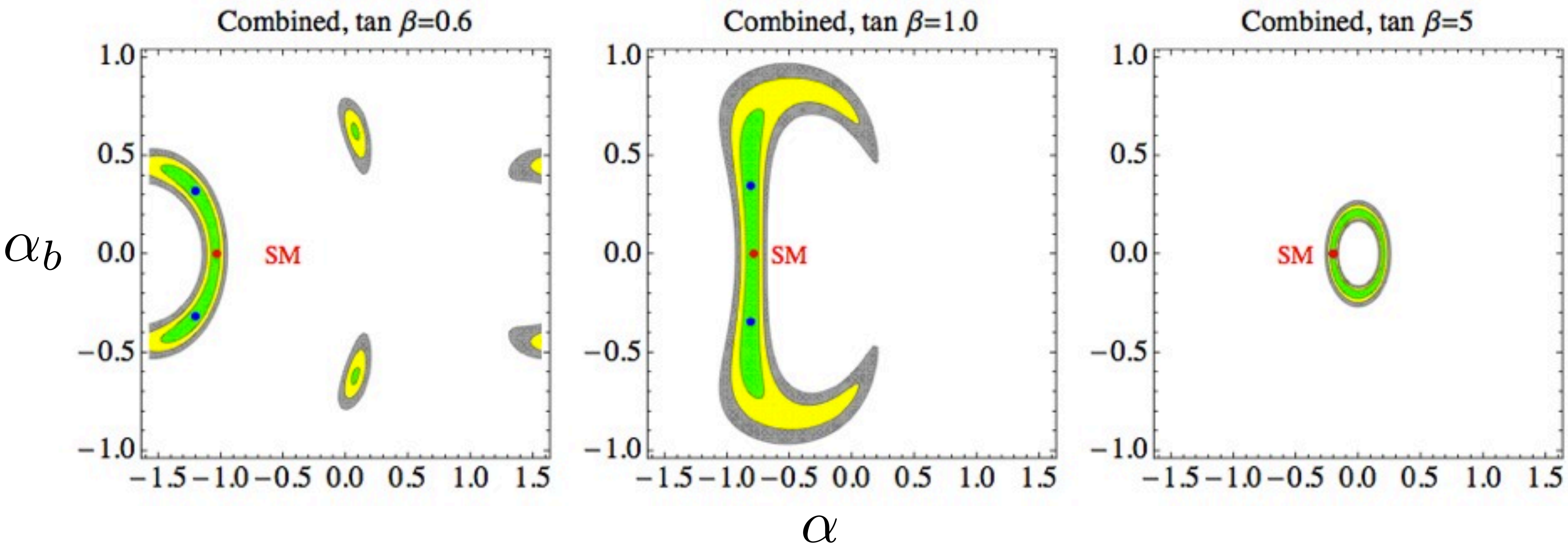
- Type II 2HDM with CPV

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

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

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

Global Fit to Higgs data



- Strong constraint on CPC angle: $\alpha \approx \beta - \pi/2$
- For $\tan\beta \lesssim 1$, non-zero CPV angle $\alpha_b \neq 0$ can give better fit.

Jing Shu, **Y.Z.**, arXiv: 1304.0773, Phys. Rev. Lett.

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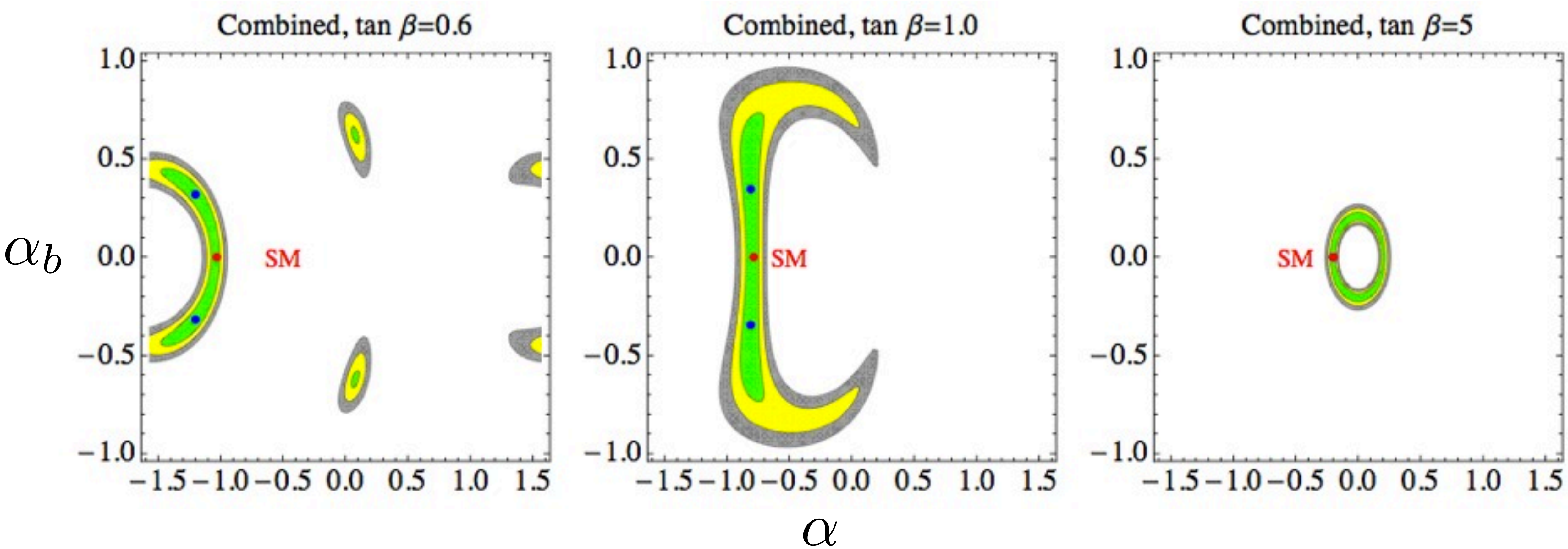

- CPV can give: relatively enhanced $h \to \gamma\gamma$ rate, suppressed $h \to Vb\bar{b}$

Jing Shu, **Y.Z.**, arXiv: 1304.0773, Phys. Rev. Lett.

A special direction

- An interesting case: $\alpha \to \beta - \pi/2$ with non-zero α_b, α_c
- When $\tan\beta \approx 1$, couplings become

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

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- Real decoupling limit, second doublet mass goes to infinity: $\alpha_b, \alpha_c \to 0,\ \alpha \to \beta - \pi/2$

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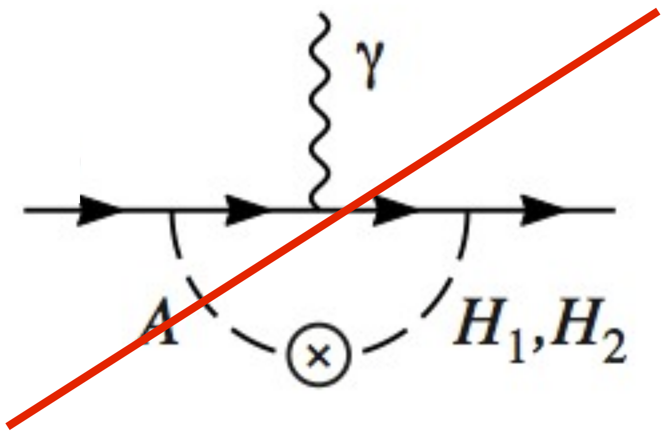
Electron EDM



less important

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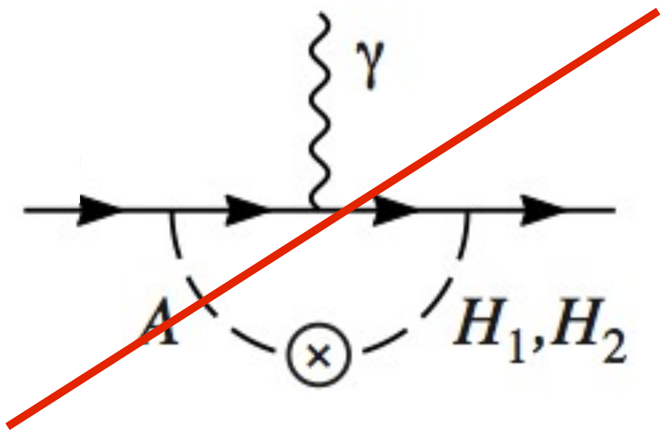

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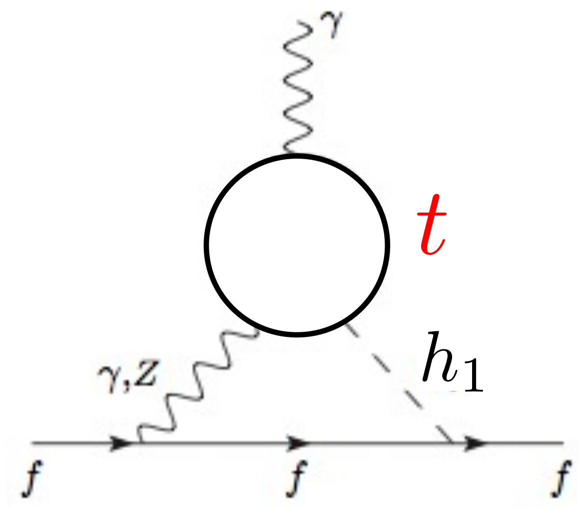

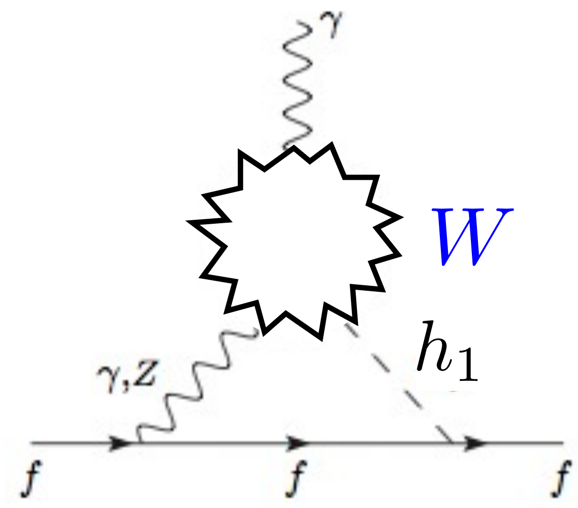

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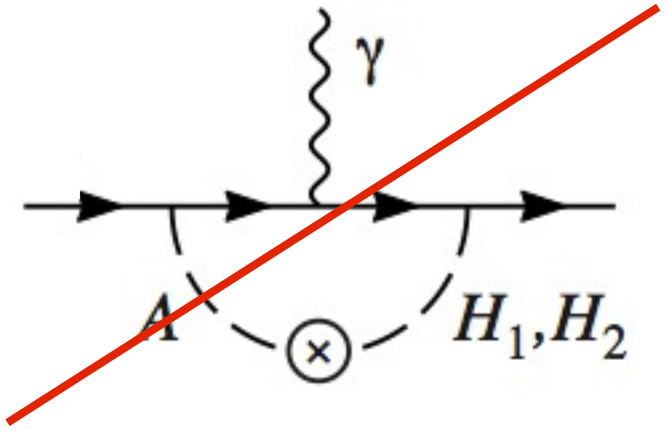
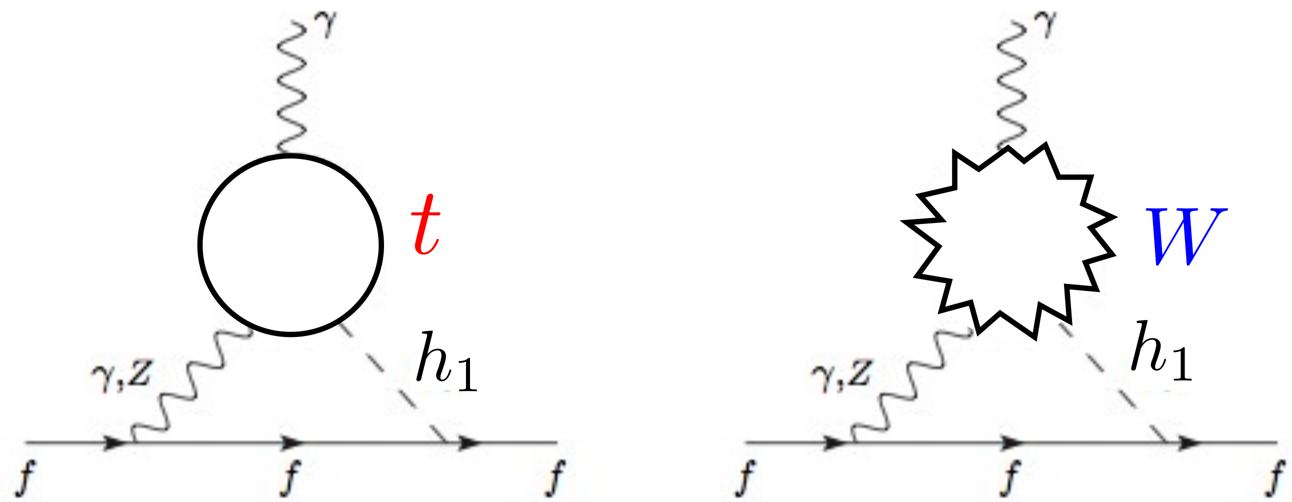
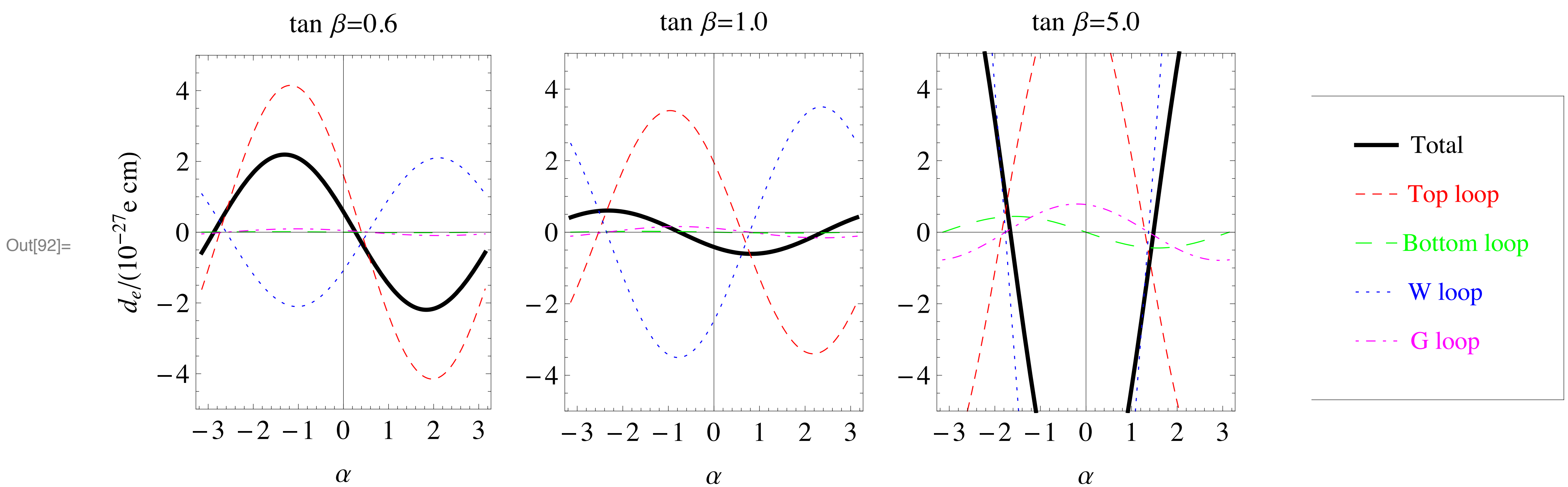




- Strongest cancellation around $\tan\beta \sim 1$



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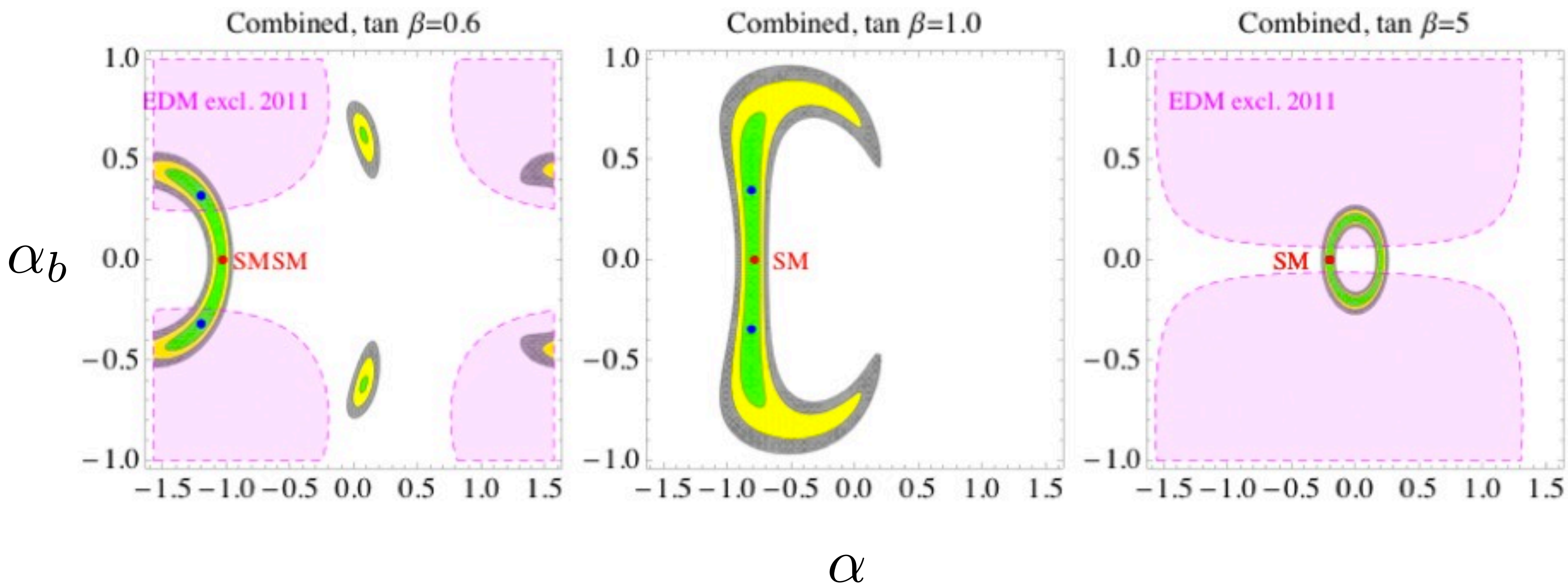
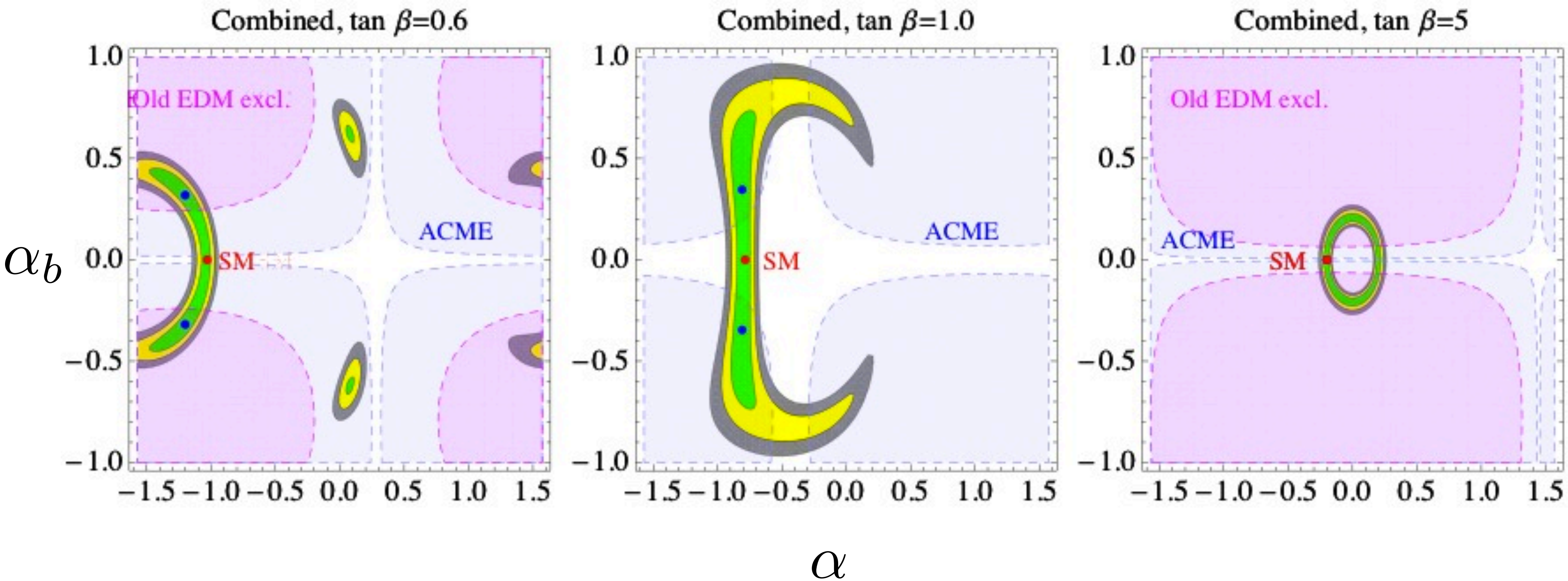
eEDM vs Higgs Fit



- Before ACME result $d_e < 1.25 \times 10^{-27} e\,\mathrm{cm}$ @ 95% C.L.

Hudson et al, Nature 473, 493 (2011)

eEDM vs Higgs Fit

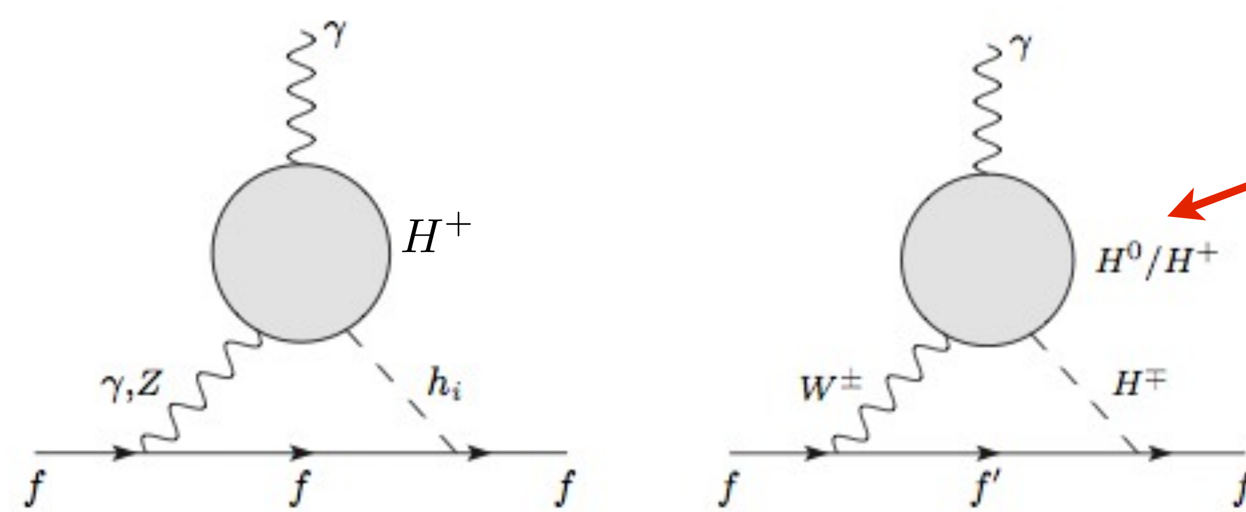


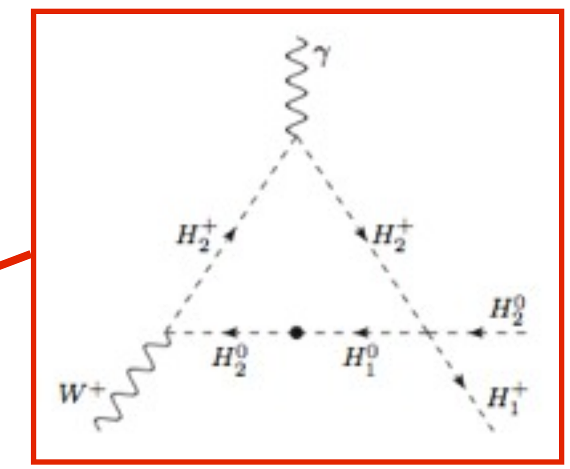
- ACME result: $d_e < 1.025 \times 10^{-28} e\,\mathrm{cm}$ @ 95% C.L.
- Higgs data and EDMs are complementary.

ACME Collaboration, 1310.7534

Beyond lightest Higgs

- They also contribute to EDMs via CPV in the scalar sector.



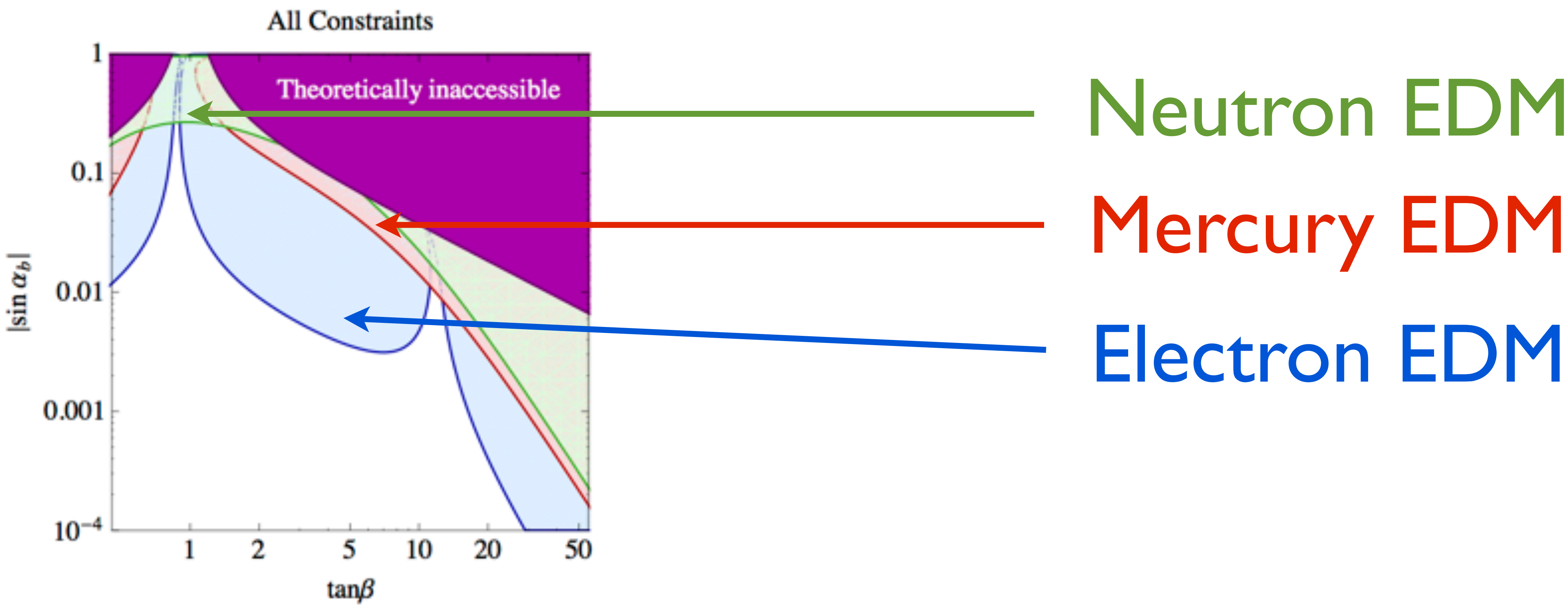


$$\sim \mathrm{Im}[\lambda_5^*(m_{12}^2)^2]$$

- Remember there is only one CPV phase.
- Heavy Higgs are more important at large $\tan\beta$

Satoru Inoue, Michael Ramsey-Musolf, **Y.Z.**, arXiv:1403.4257

The role of heavy Higgs



- The cancelation near $\tan\beta \sim 1$ persists.
- New cancelation regime at $\tan\beta \sim 10 - 20$.
- Beware of uncertainties in neutron/atomic EDM.

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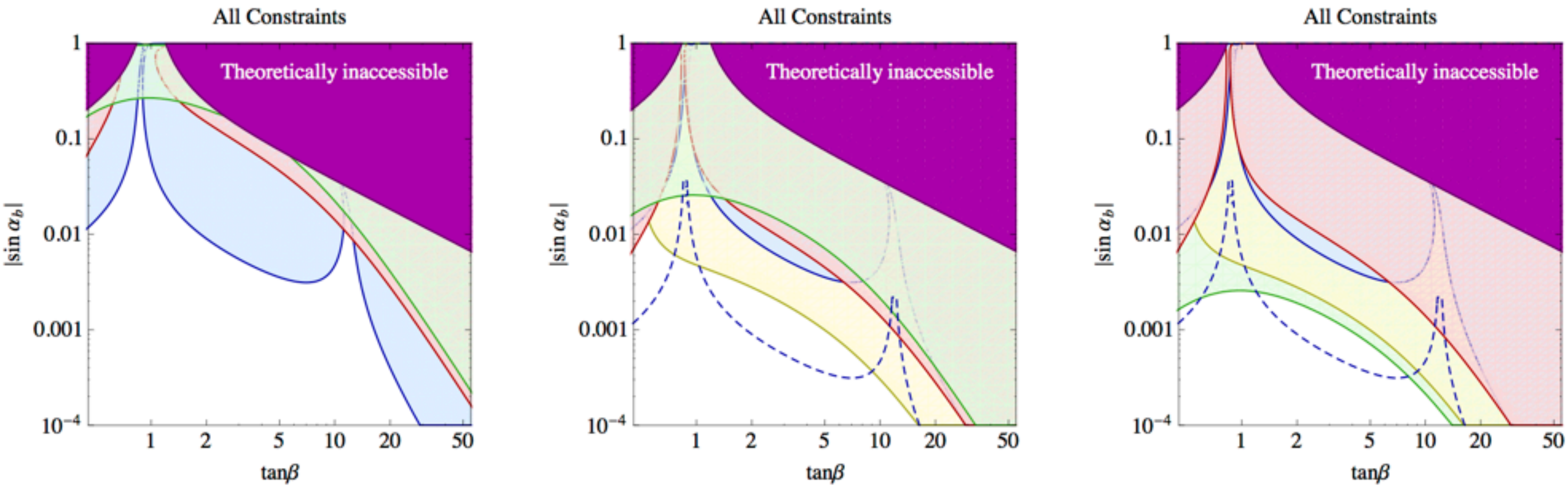
The role of heavy Higgs



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Baryon generation

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

Chemical potential
for B number

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

$$h \to \gamma\gamma \ (\text{CPV})$$

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

Dorsch, Huber, No, 1305.6610
Fromme, Huber, Seniuch, hep-ph/0605242

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$$h \to \gamma\gamma \text{ (CPV)}$$

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

- Still need B violating process: sphaleron process.
- If in equilibrium, all $\Gamma \gg H$, final asymmetry is determined by $\mu = \partial_t \xi \sim t^{-1} \ll 10^{-10} T$
- First order EW phase transition, possible in 2HDM.

Dorsch, Huber, No, 1305.6610
Fromme, Huber, Seniuch, hep-ph/0605242

CPV for Baryogenesis

CP violation $\mathcal{L} \sim \lambda_q \, h e^{i\xi} \, \bar{q}_R q_L + \text{c.c.}$

$$P_{q_L \to q_R} - P_{q_R^c \to q_L^c} \propto h \frac{d\xi}{dt}$$

Redistribute particle numbers

Cheung, **Y.Z.**, arXiv:1306.4321, JHEP

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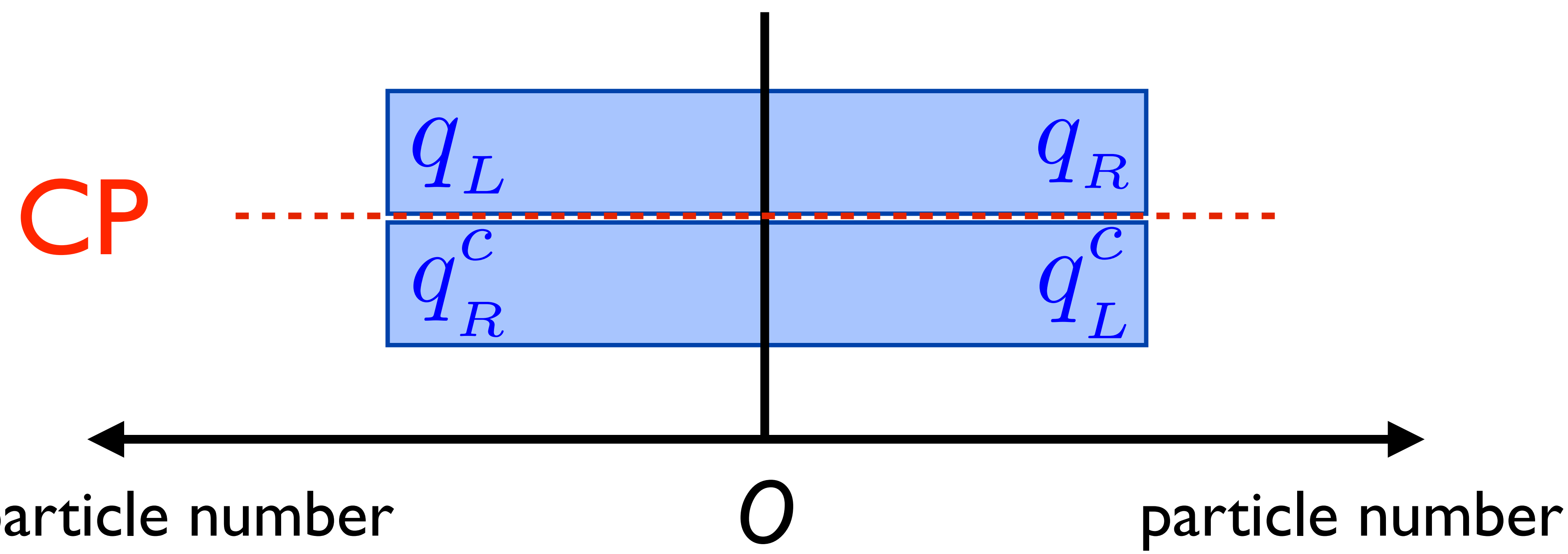

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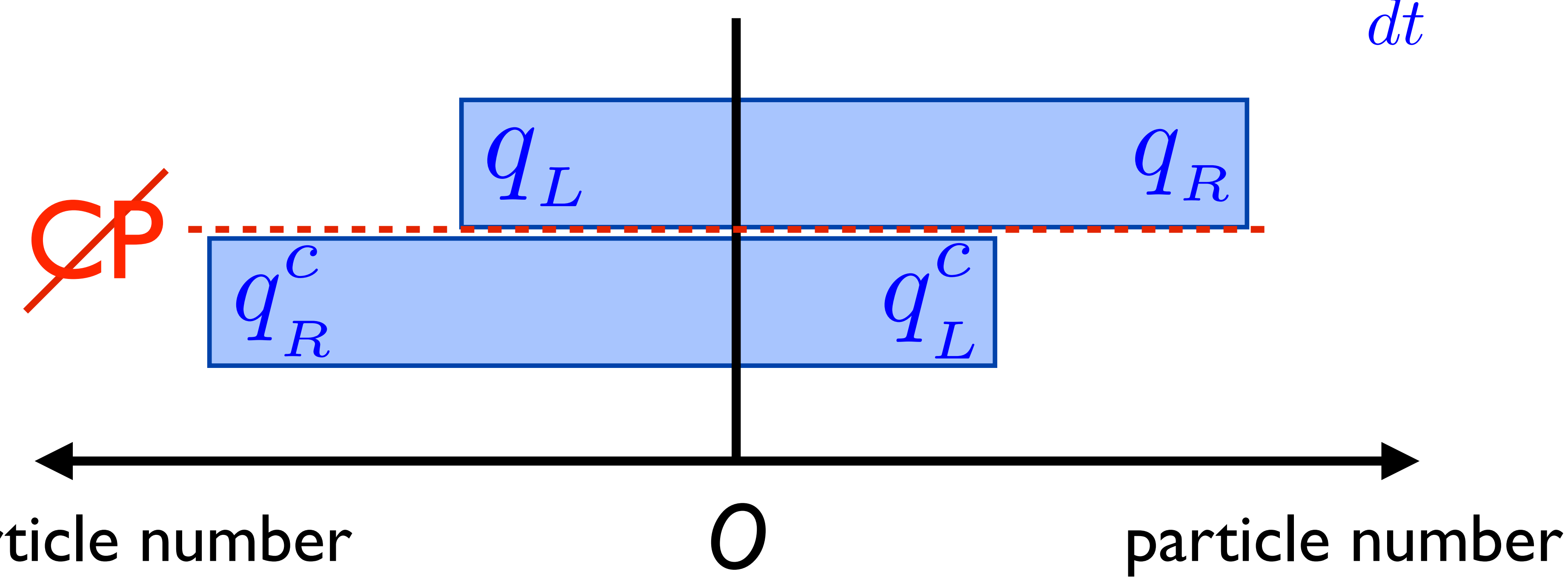
Redistribute particle numbers

$$\text{Shift} \propto h \frac{d\xi}{dt}$$



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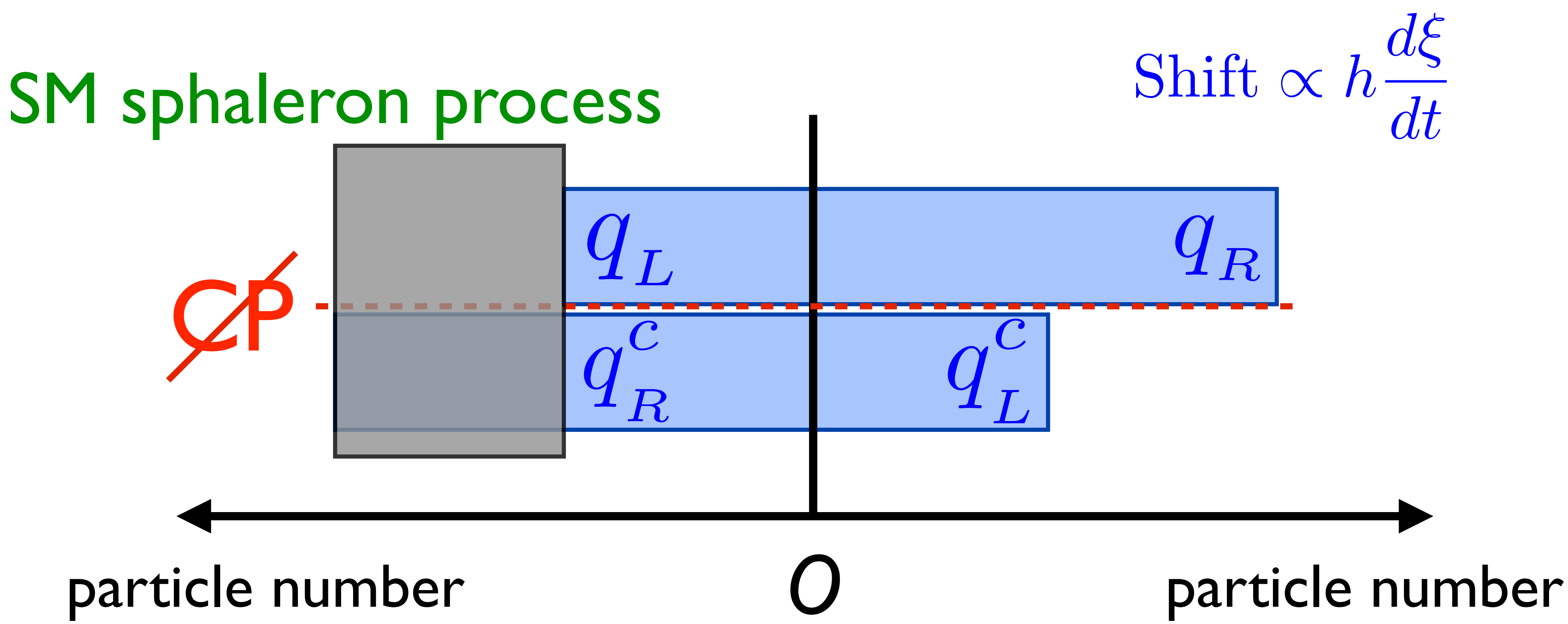
Baryon number violation



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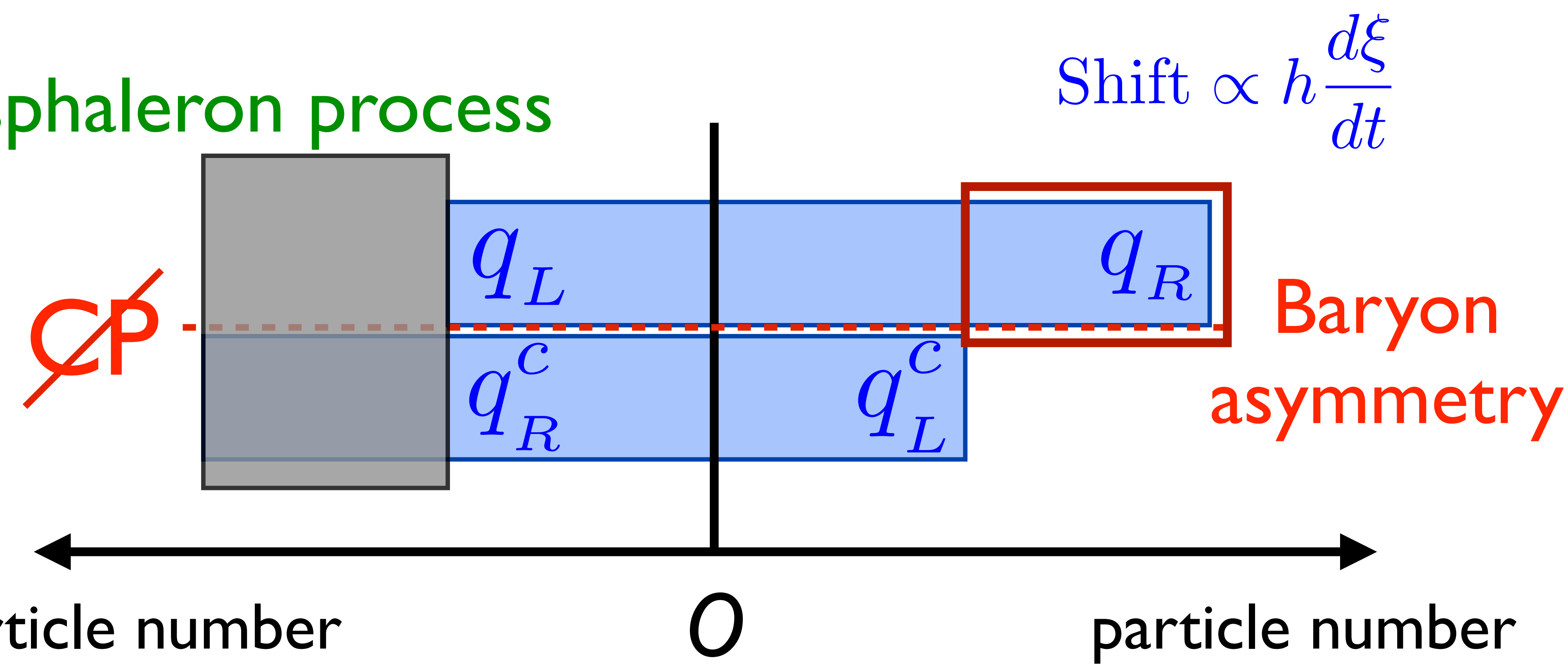

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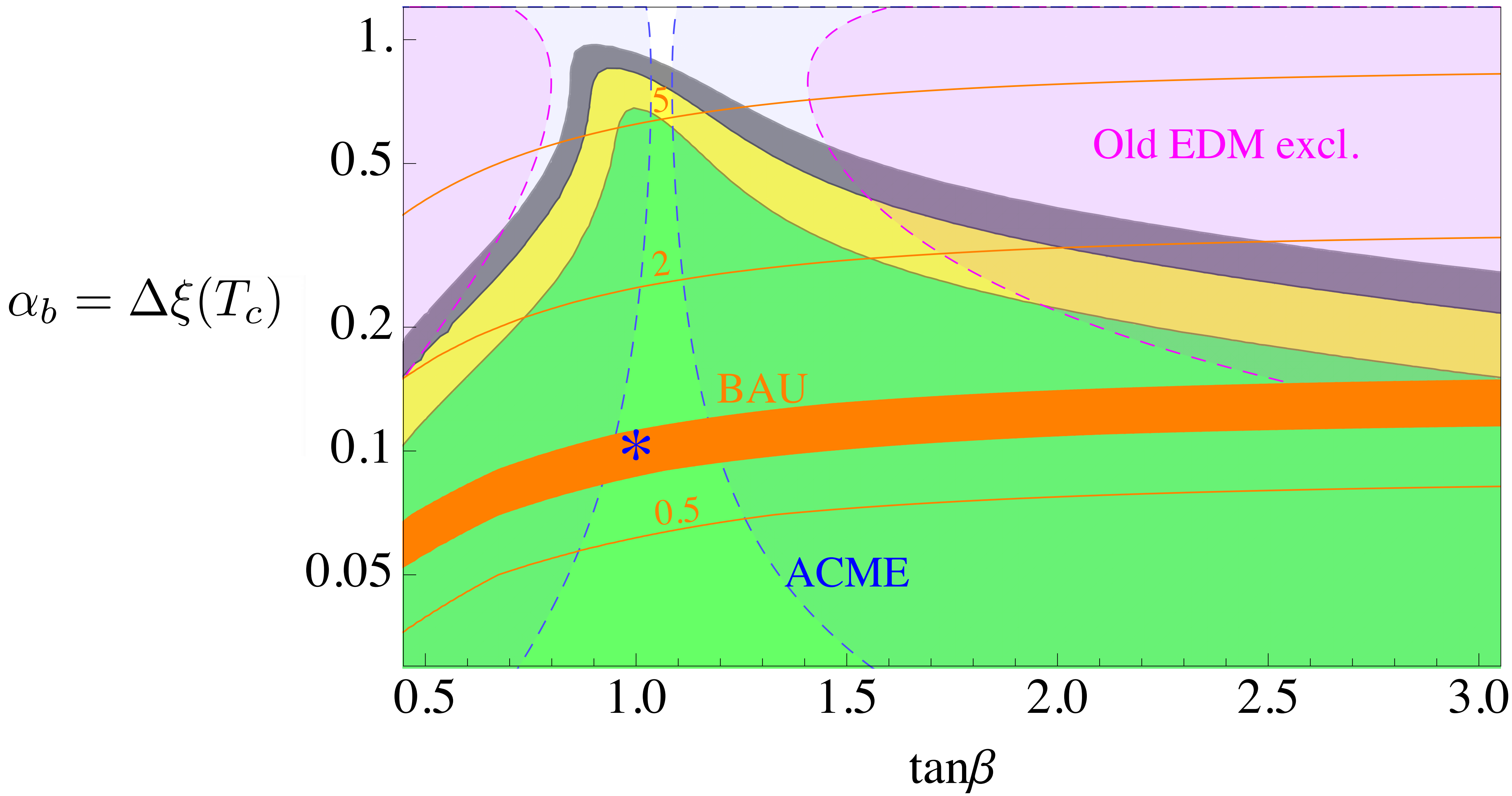
Connections



Jing Shu, **Y.Z.**, arXiv: 1304.0773, Phys. Rev. Lett.

Cogenesis

- Observation: $\Omega_{\rm B} \sim \Omega_{\rm DM}$.
- Today's baryon number in our universe is preserved due to an approximate global symmetry $U(1)_{\rm B}$.
- Dark matter could also has an asymmetry today, defined by another approximate global symmetry $U(1)_{\rm DM}$.
- Same source of CP violation - Higgs!

CPV for DM-genesis

CP violation $\mathcal{L} \sim \lambda_X \, h e^{i\xi} \, S \, X + \mathrm{c.c.}$

DM partner
order parameter

dark matter
(DM) scalar

Cheung, **Y.Z.**, arXiv:1306.4321, JHEP

CPV for DM-genesis

CP violation

$$\mathcal{L} \sim \lambda_X \; h e^{i\xi} \; S \; X + \text{c.c.}$$

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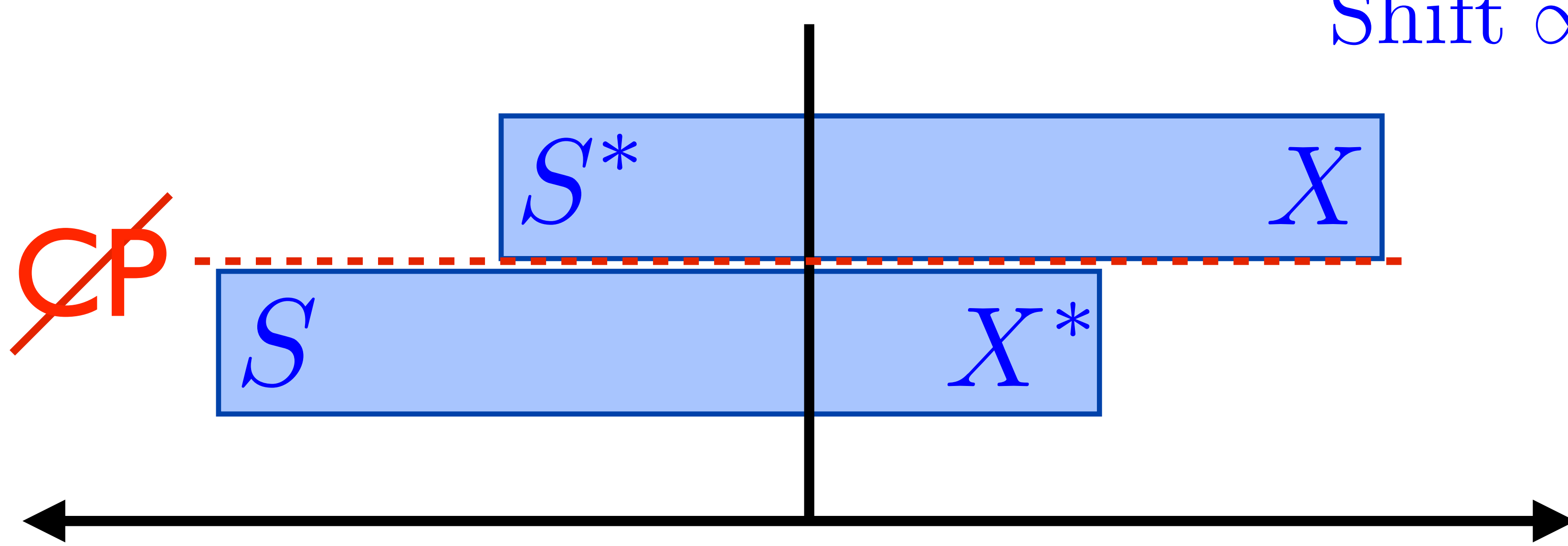
$\text{Shift} \propto h \dfrac{d\xi}{dt}$



particle number   0   particle number

Cheung, **Y.Z.**, arXiv:1306.4321, JHEP

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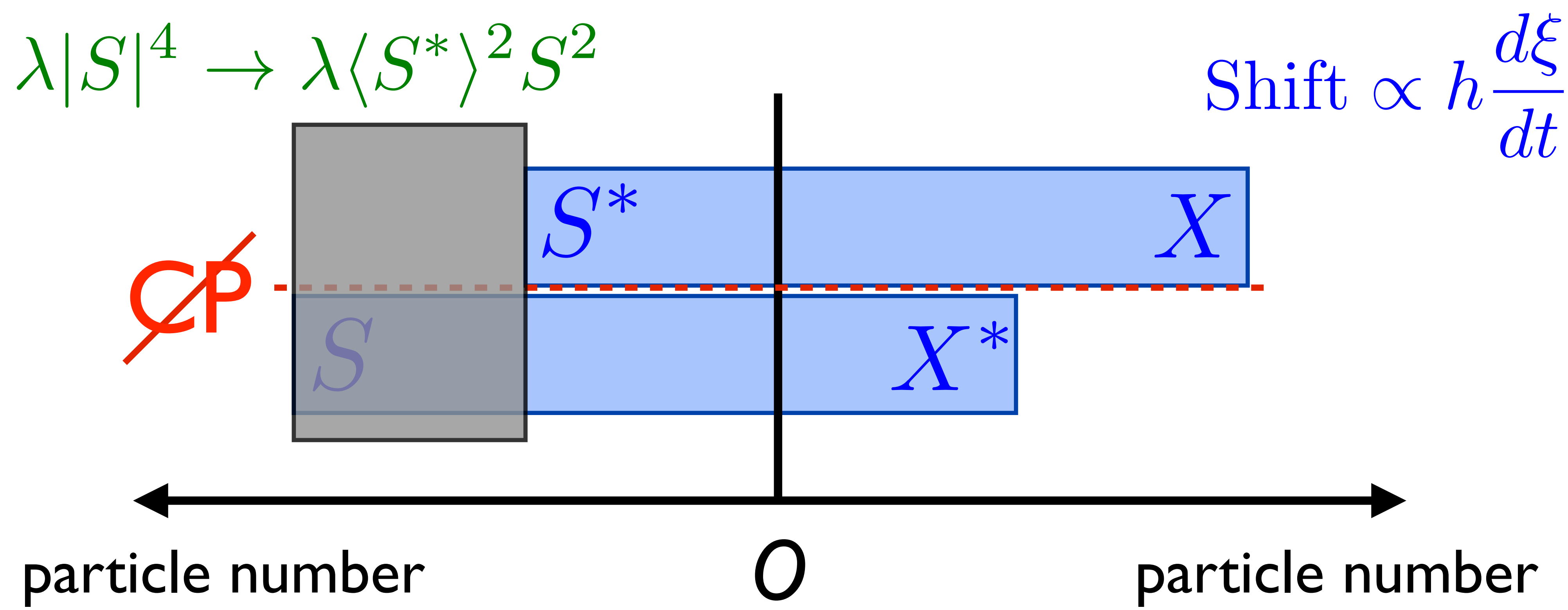

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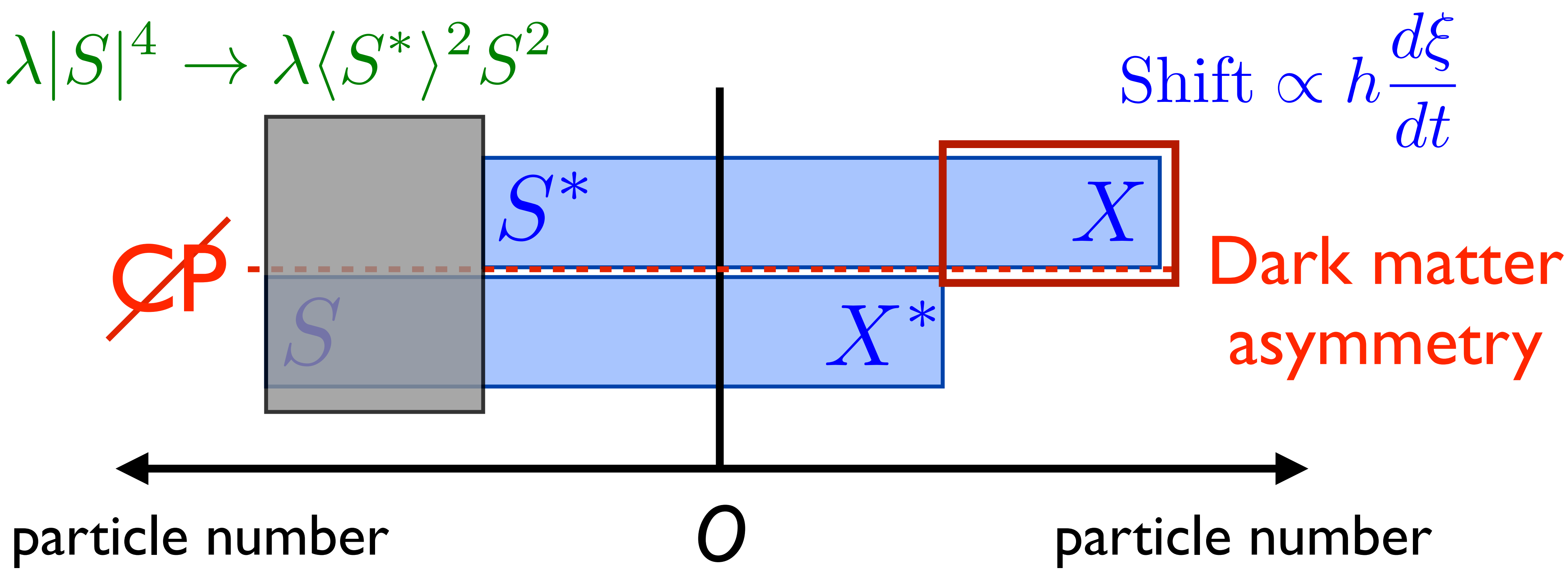


Cheung, **Y.Z.**, arXiv:1306.4321, JHEP

Order parameters

$U\cancel{(1)}_B$ $\qquad\qquad$ $U(1)_B$

$U\cancel{(1)}_{DM}$ $\qquad\qquad$ $U(1)_{DM}$

Electroweak scale

time

Cheung, **Y.Z.**, arXiv:1306.4321, JHEP

Order parameters

$$\cancel{U(1)}_B \xrightarrow[\text{SM gauge structure}]{\text{Higgs as order parameter}} U(1)_B \qquad \boxed{\text{turn on } \langle H \rangle}$$

$$\cancel{U(1)}_{DM} \qquad\qquad\qquad\qquad U(1)_{DM}$$

$$\xrightarrow[\text{Electroweak scale}]{\hspace{10em}} \text{time}$$

Cheung, **Y.Z.**, arXiv:1306.4321, JHEP

Order parameters

Higgs as order parameter

$\cancel{U(1)}_B \xrightarrow{\hspace{3cm}} U(1)_B$ turn on $<H>$

SM gauge structure

New order parameter

$\cancel{U(1)}_{DM} \xrightarrow{\hspace{3cm}} U(1)_{DM}$ turn off $<S>$

A scalar S carrying DM charge

$\xrightarrow{\hspace{8cm}}$

Electroweak scale

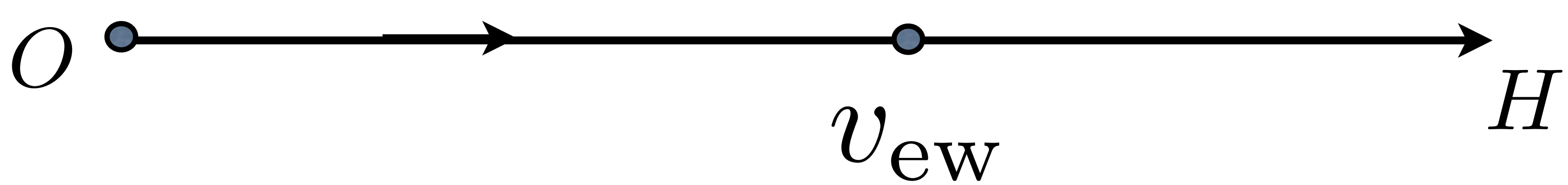
time

Cheung, **Y.Z.**, arXiv:1306.4321, JHEP

Restore two symmetries

In a single step

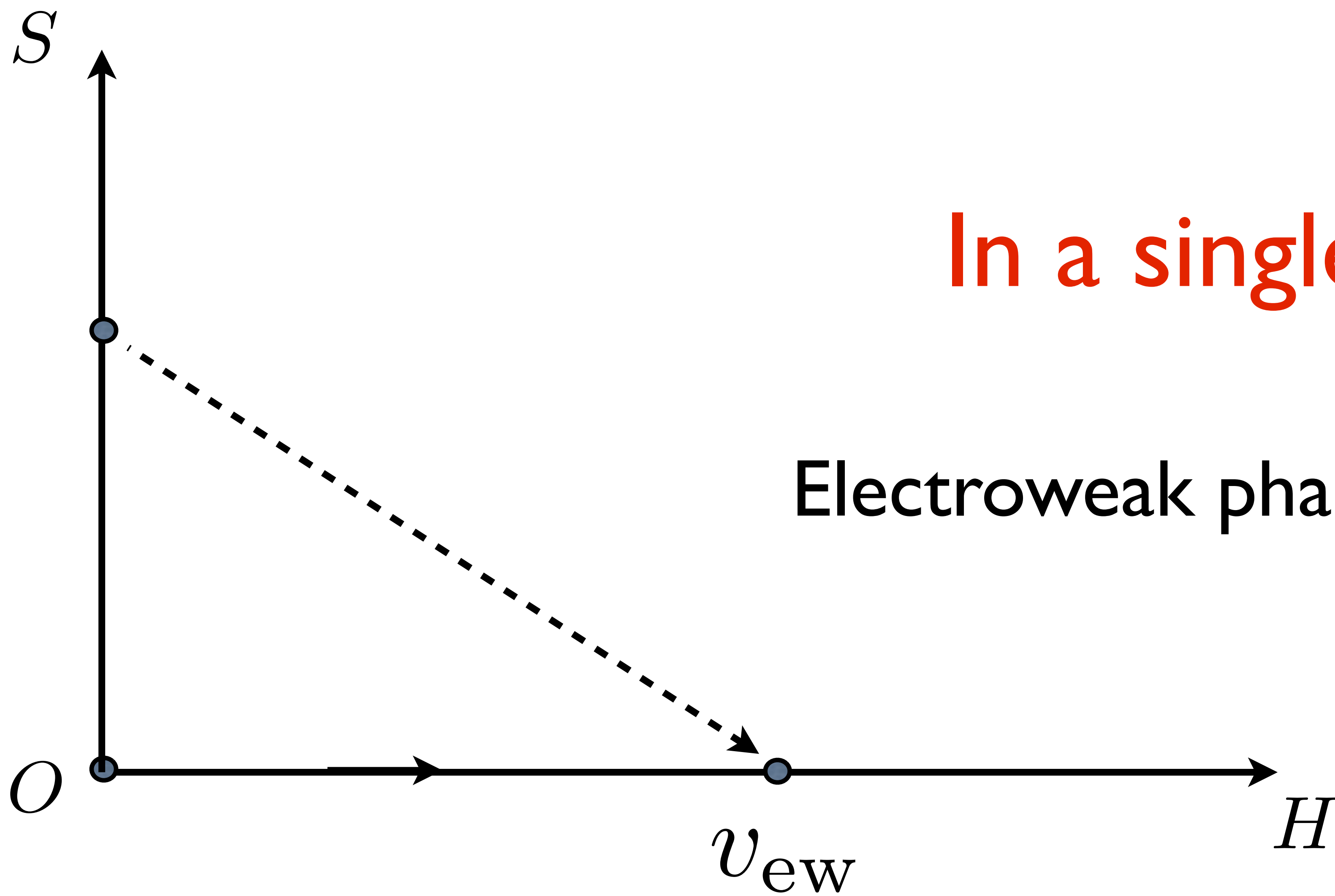
Electroweak phase transition



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

Cheung, **Y.Z.**, arXiv:1306.4321, JHEP

Restore two symmetries



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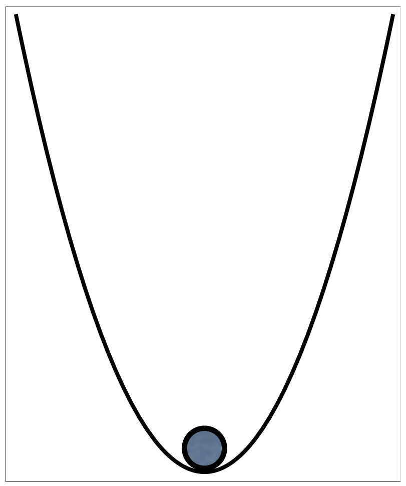
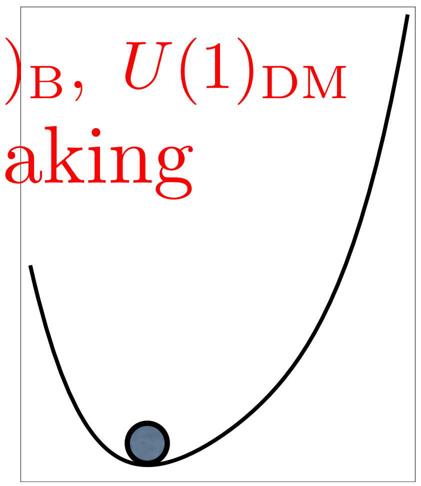
History of symmetries



$\langle S \rangle = \langle H \rangle = 0$

$U(1)_{\mathrm{B}},\ U(1)_{\mathrm{DM}}$ breaking

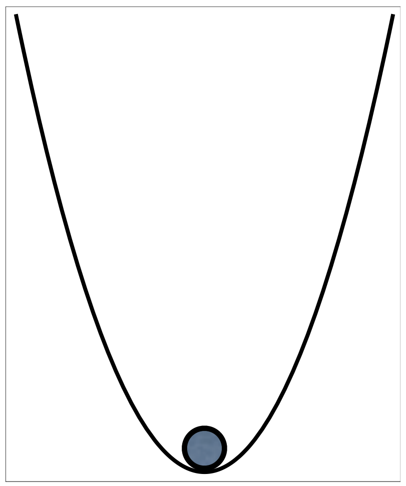


$\langle S \rangle \neq 0$

$\langle H \rangle = 0$

Cheung, **Y.Z.**, arXiv:1306.4321, JHEP

History of symmetries



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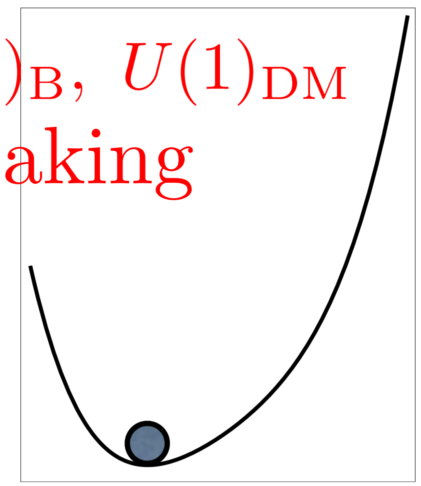

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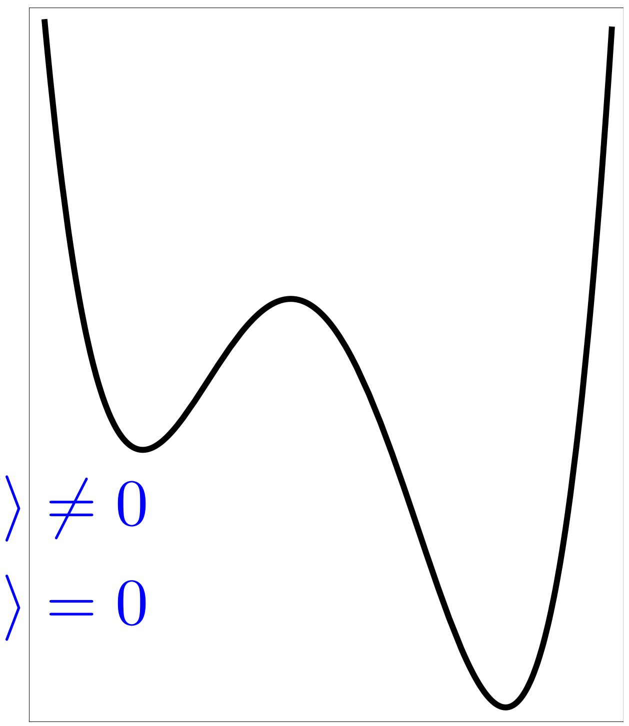

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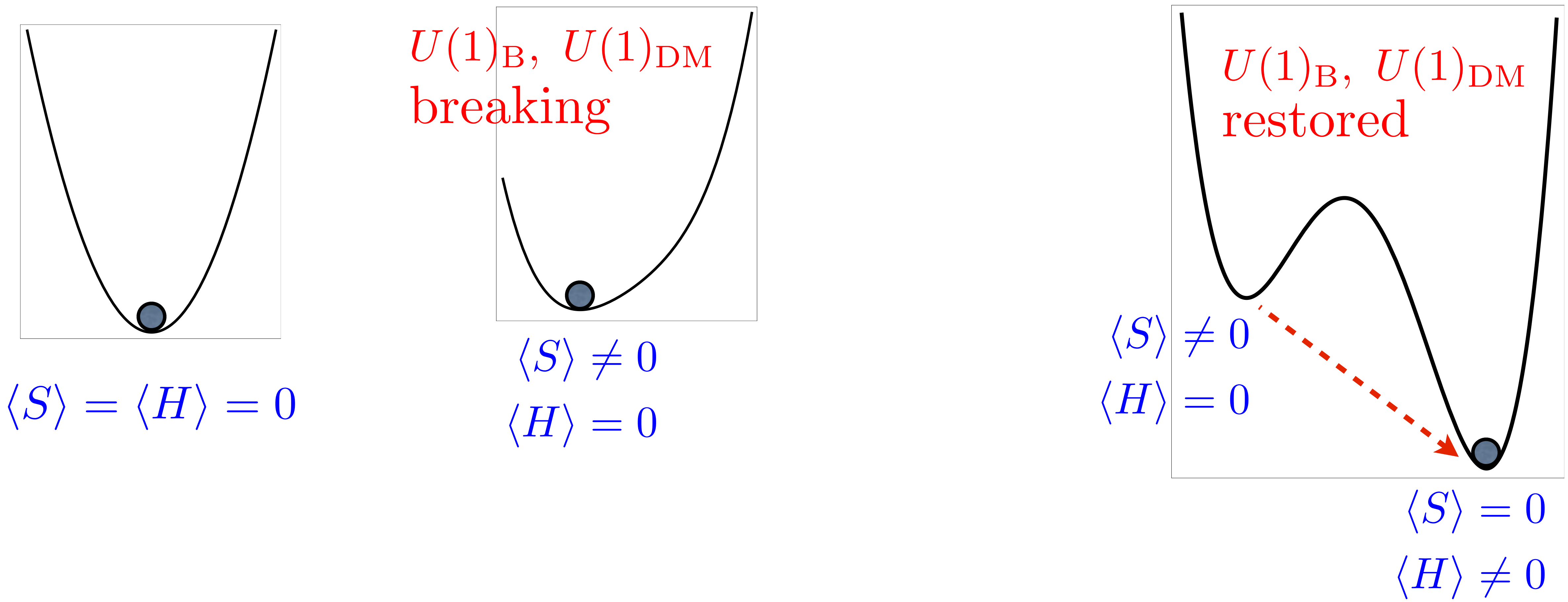
Cheung, **Y.Z.**, arXiv:1306.4321, JHEP

History of symmetries



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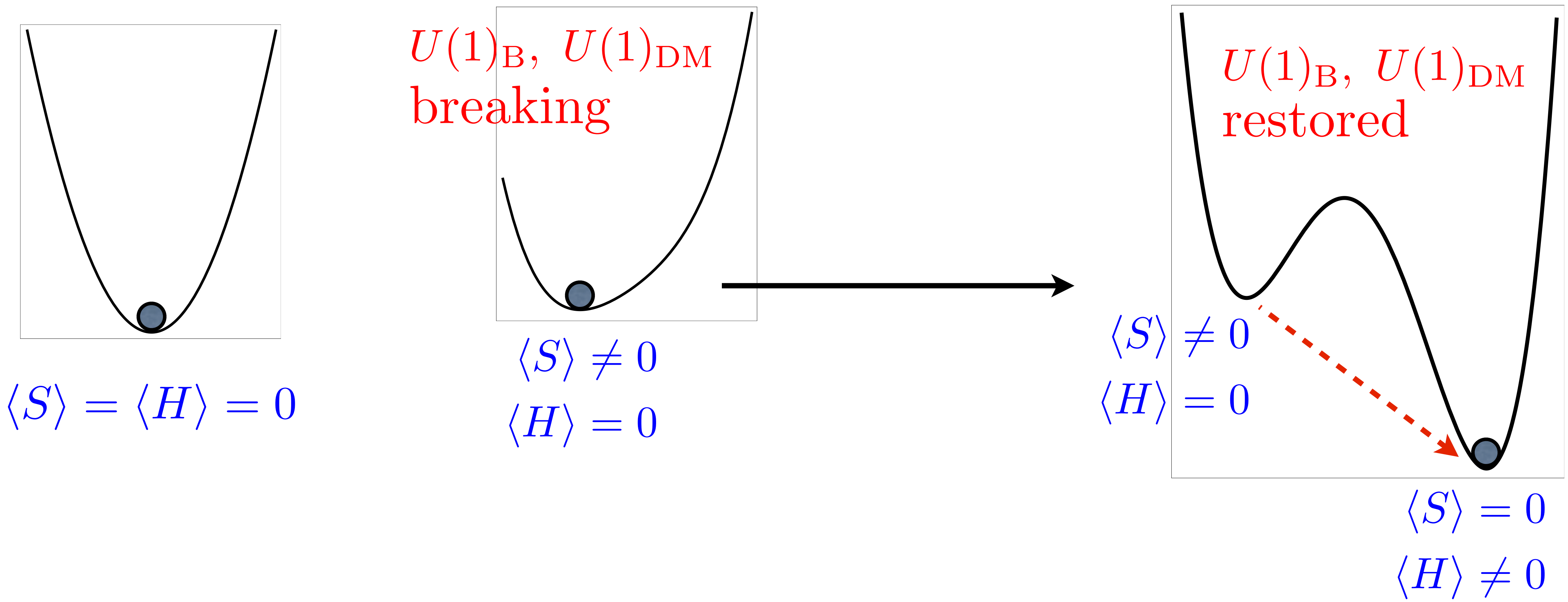
History of symmetries

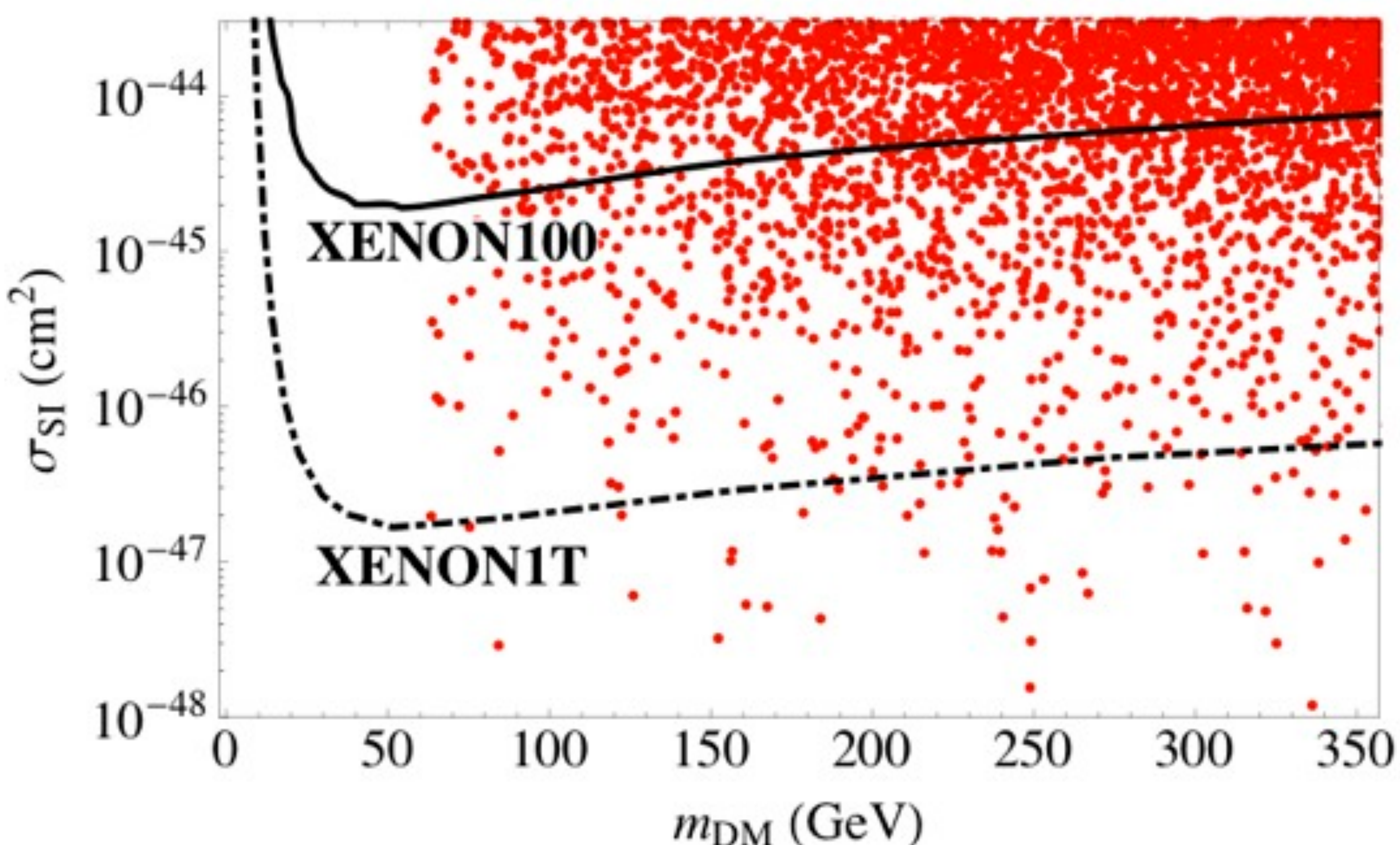


- Dark matter sector helps triggering strong first order EW phase transition.
- No effect on Higgs coupling to fermions/gauge bosons.

Cheung, **Y.Z.**, arXiv:1306.4321, JHEP

Phenomenology

- Eliminate symmetric part of DM via Higgs portal.
- Weak scale ADM candidate, no light mediator.
- To be tested by future direct detection experiments.



Cheung, **Y.Z.**, arXiv:1306.4321, JHEP

More tests

- Direct CPV: azimuthal phase shift:
  - Higgs decays (also heavy Higgs decays)

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

Whitbeck, Moriond QCD 2013

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

Harnik, Martin, Okui, Primolando, Yu, 1308.1094

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

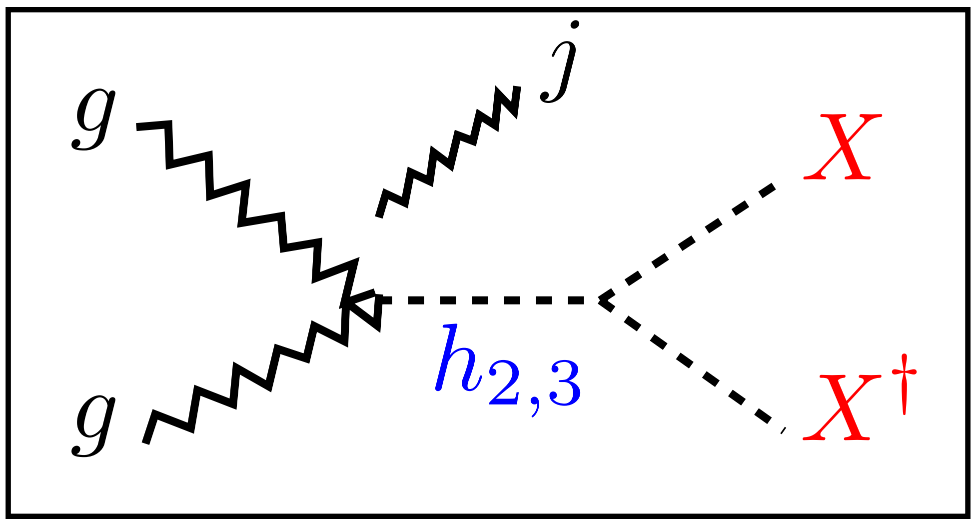
Klamke, Zeppenfeld, '07
Gunion, He, '96

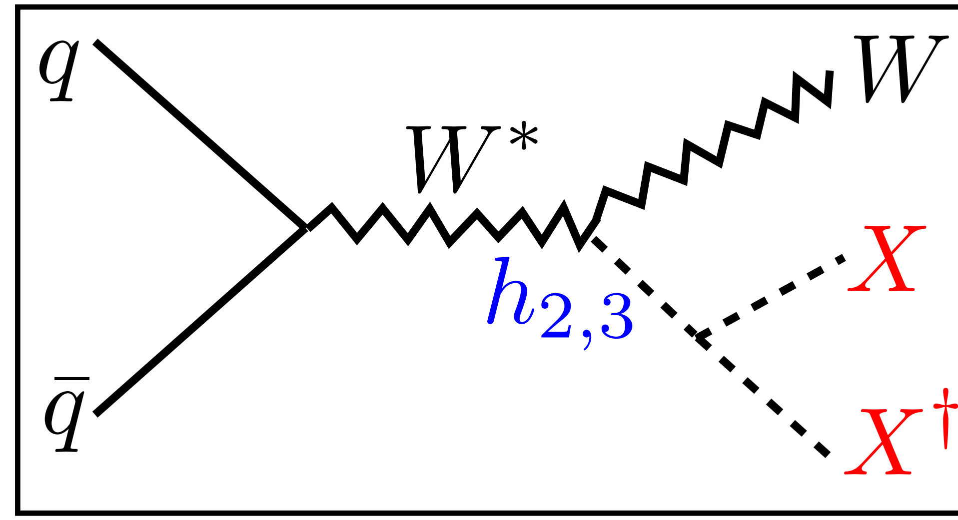
- Virtual Higgs effects
  - $t\bar{t}$ production and leptonic decay: p_T distribution of charge lepton asymmetry.

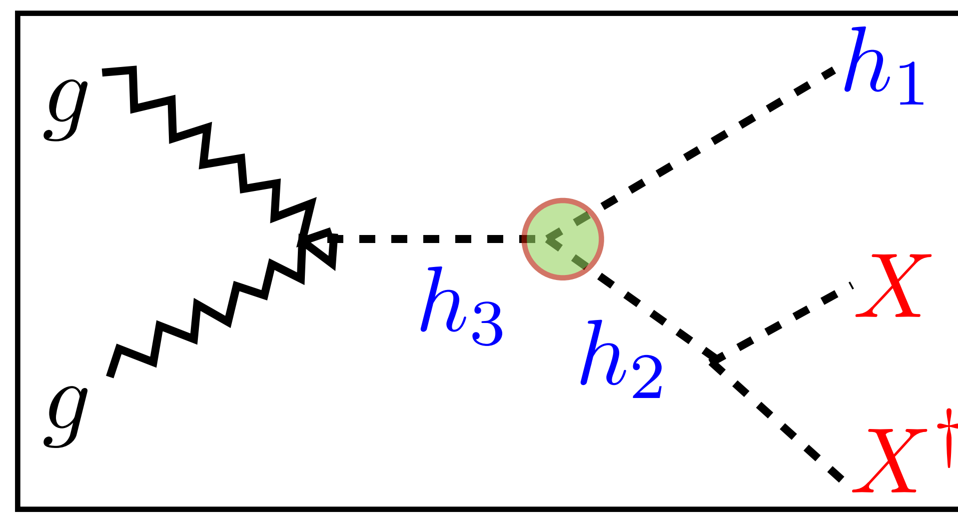
Schmidt, Peskin '92

More tests

- Mono-particle searches







More tests

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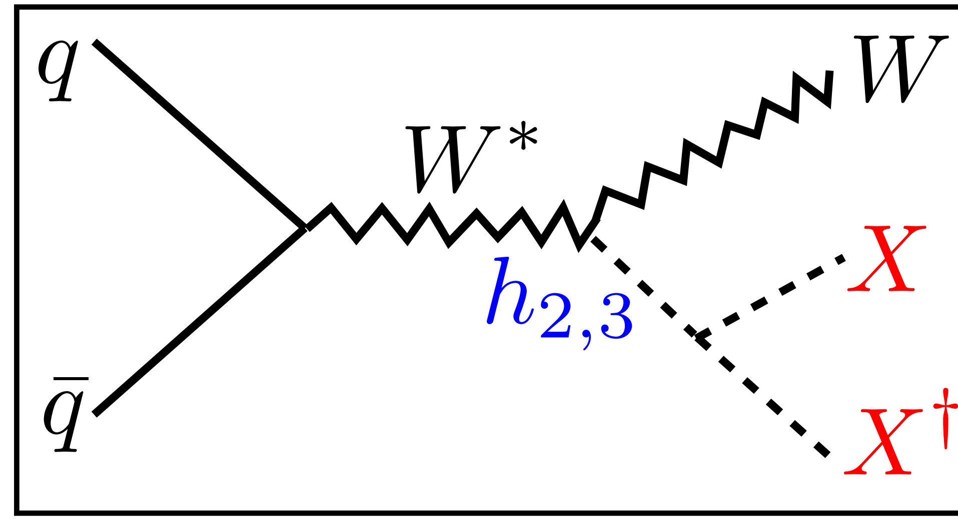
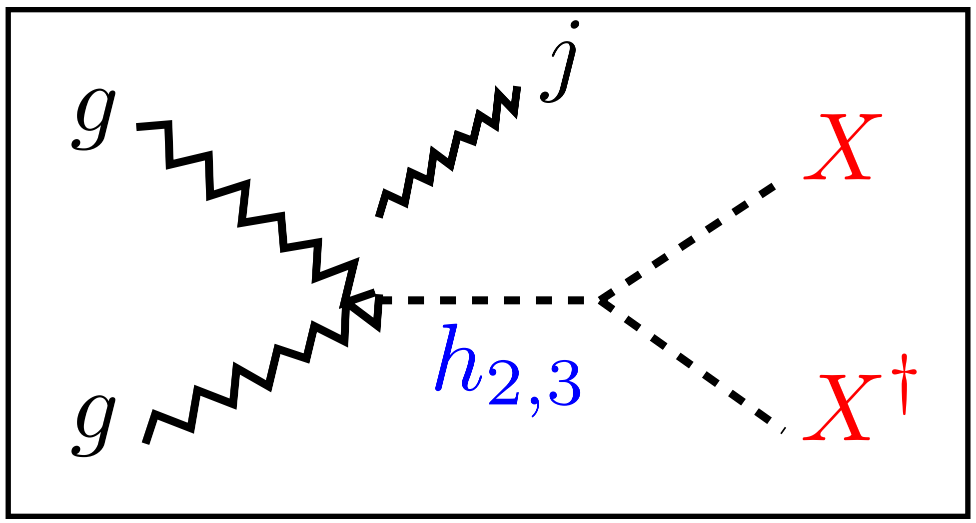
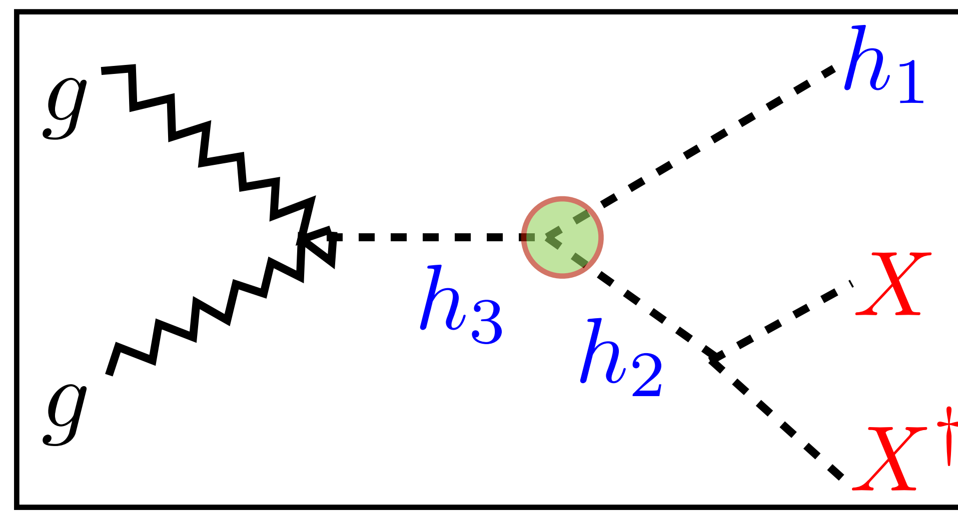
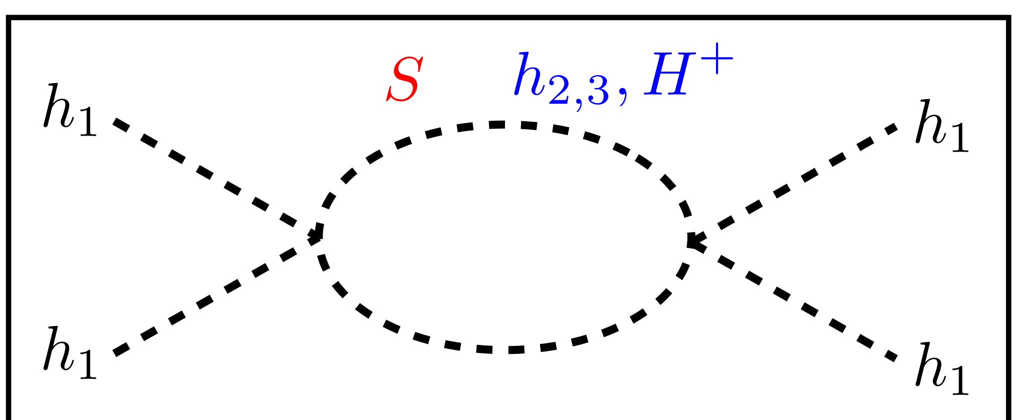






- Higgs self interaction



More tests

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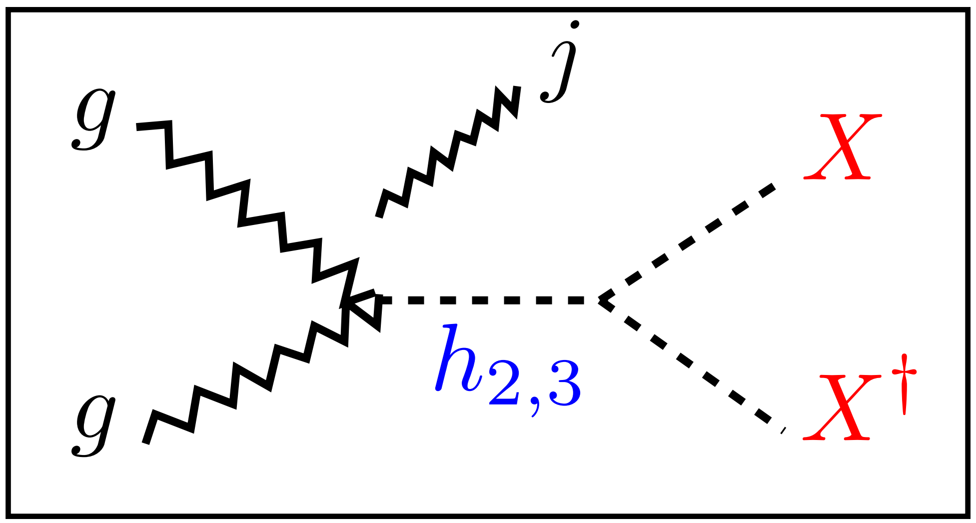

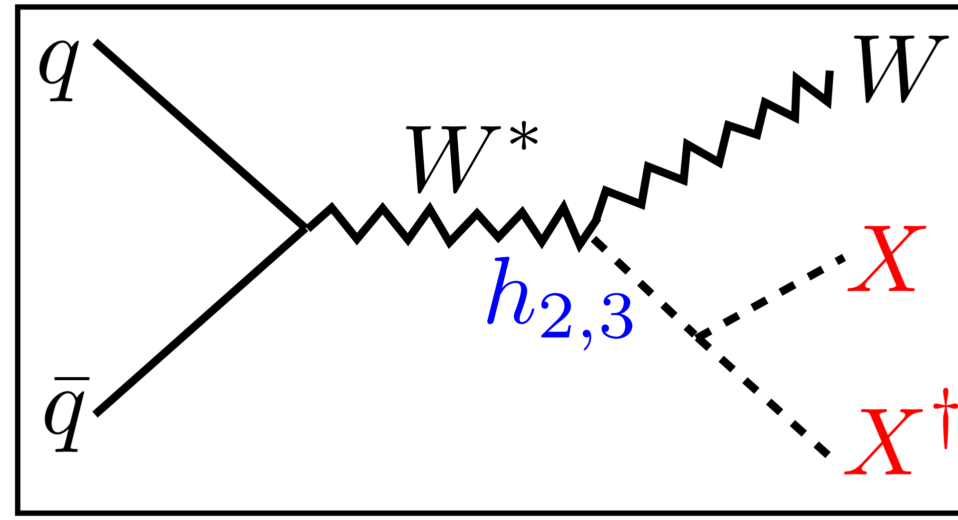

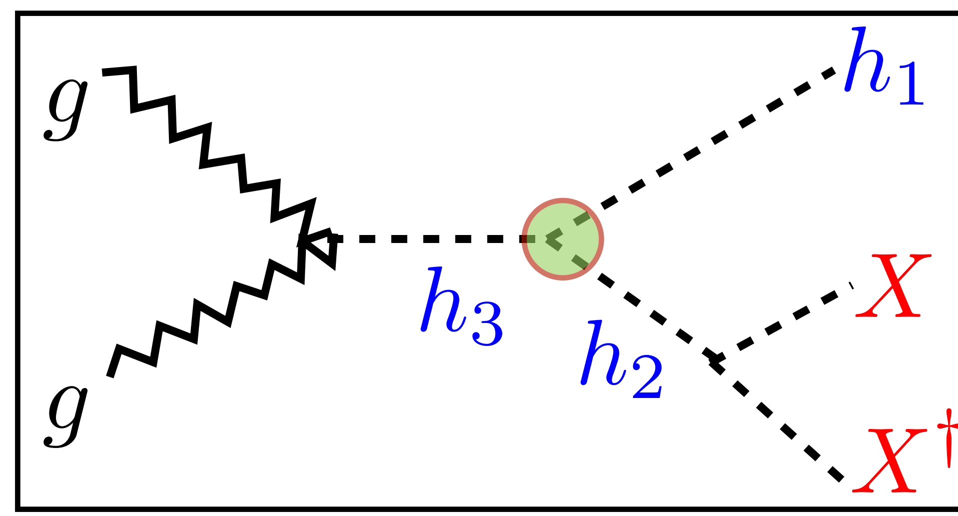

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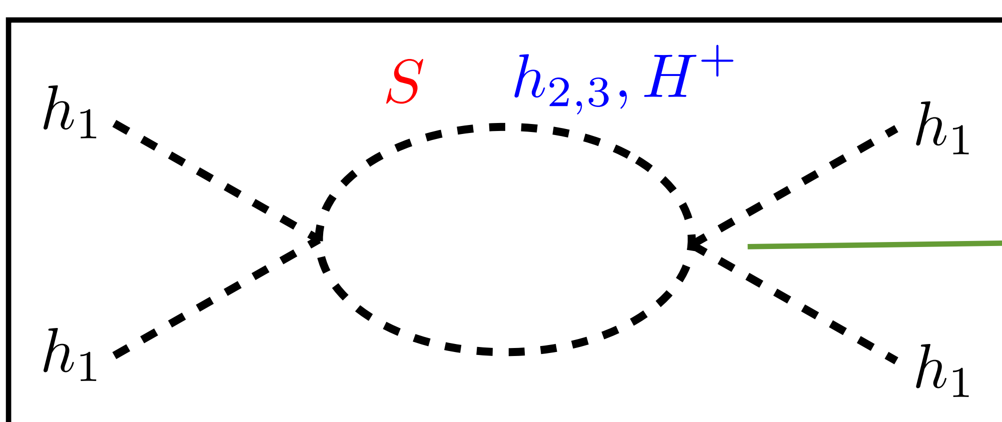

$$\text{ADM, EWphT}: \ \lambda \sim \mathcal{O}(1)$$

$$\text{WIMP}: \ \lambda \sim \mathcal{O}(0.1)$$

Conclusion

- The 125 GeV Higgs boson could be a CP mixture. Currently $\mathcal{O}(1)$ CP phase consistent with data.
  - EDMs are powerful probes, barring uncertainties.
  - Future direct test at colliders.
- We construct a simple model of Electroweak Cogenesis. Make a stronger case for studying CPV associated with the Higgs boson.
  - Also measure the 2HDM portal to ADM.