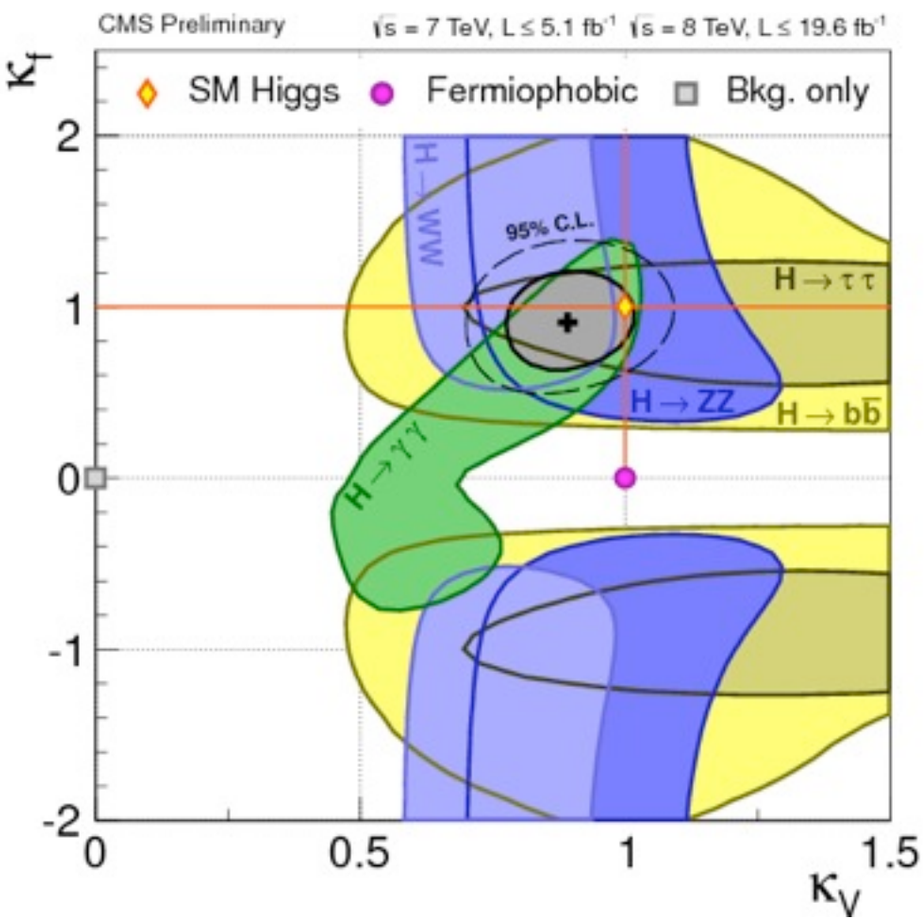
Impact of a CP violating Higgs: LHC, EDMs and Cogenesis

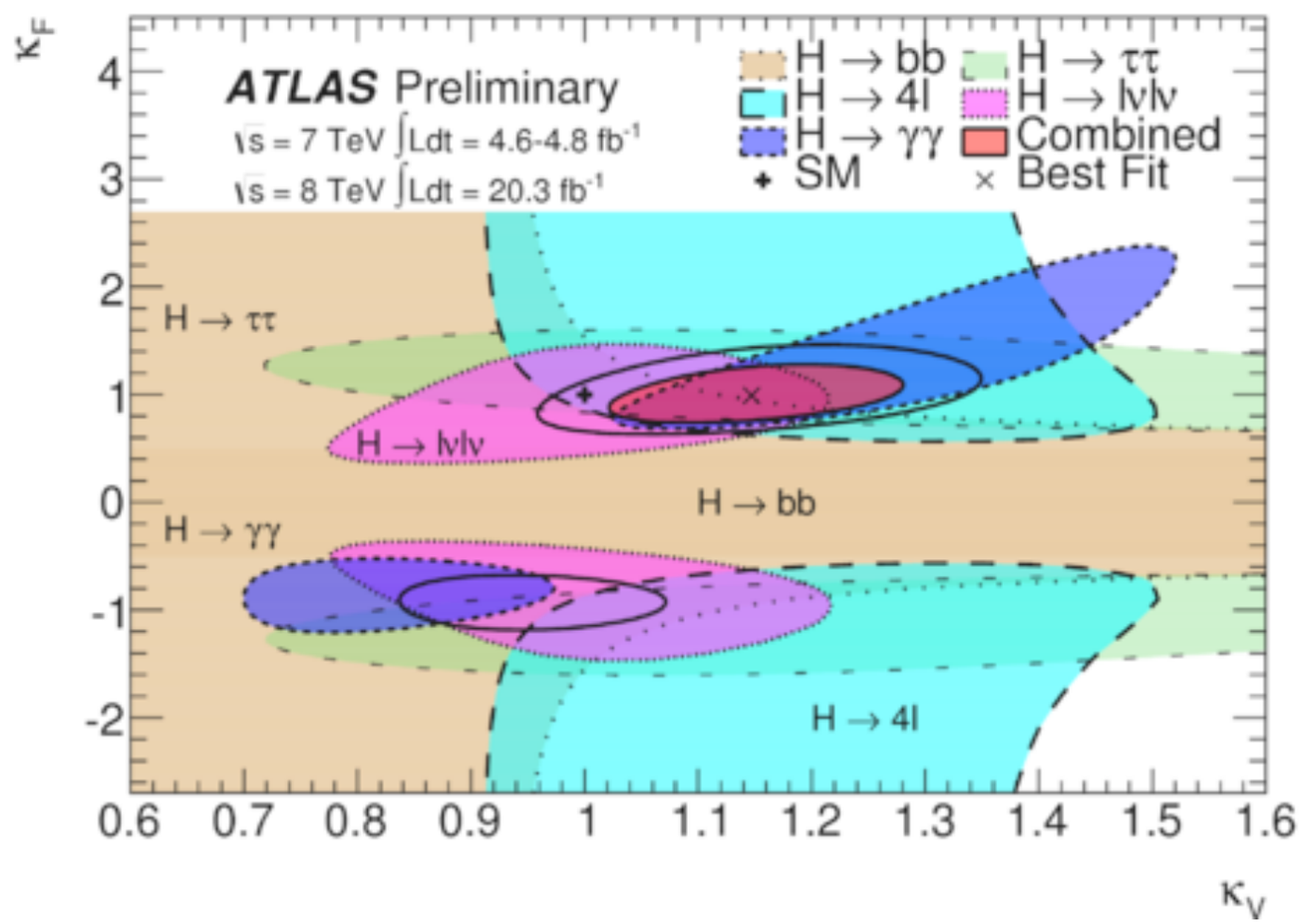
Yue Zhang (Caltech)

Santa Fe summer workshop, 3 July 2014

C. Cheung, **YZ**, 1306.4321
J. Shu, **YZ**, 1304.0773
S. Inoue, M. Ramsey-Musolf, **YZ**, 1403.4257

Higgs Boson Properties





- 125 GeV, looks like SM Higgs - Great triumph.
- New physics behind EW symmetry breaking?

CPV Higgs Scenario

- Higgs boson may be a CP even-odd mixture.
- Experimental constraints still allow sizable CPV.
  - LHC Higgs search: rates, direct ...
  - Electric dipole moments.
- New source of CP violation beyond SM.
- Well motivated: may account for origin of baryon asymmetry (and dark matter) in the universe
  - Electroweak baryogenesis / Electroweak Cogenesis.

Higgs Couplings

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

- Beyond SM, renormalizable model

CP odd

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

- Calculable effective interactions (d=5)

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

Higgs Couplings

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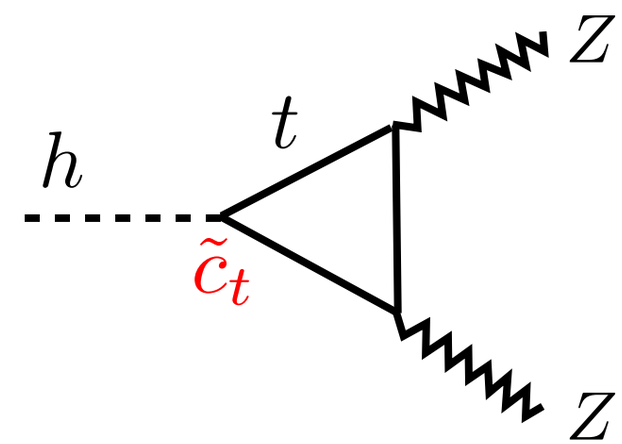
loop

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

Search in golden channel

- Parametrize the amplitude



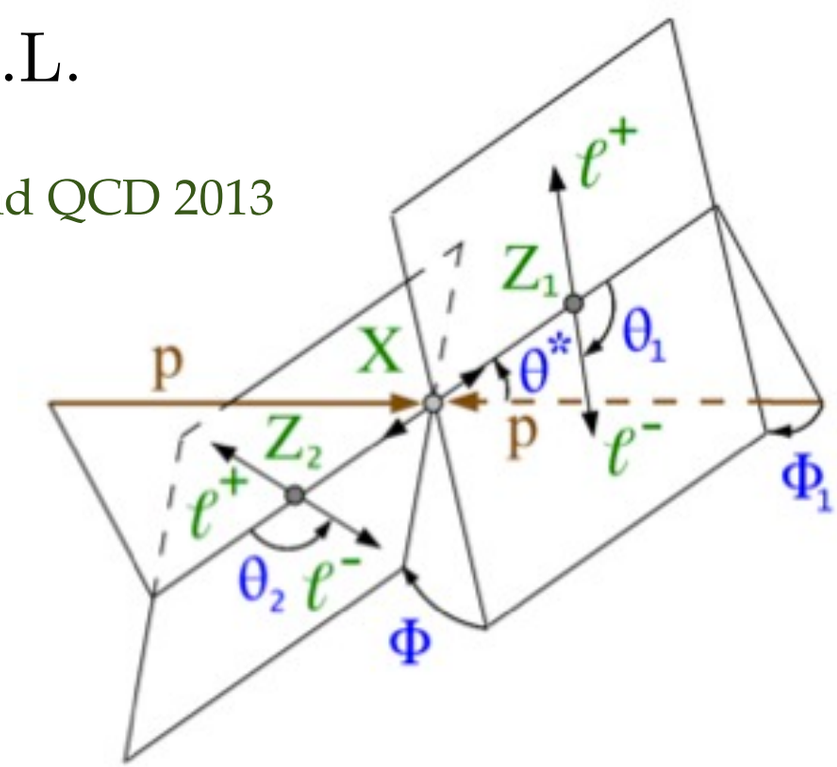
$$A(h \to ZZ) = v^{-1} \epsilon_1^{*\mu} \epsilon_2^{*\nu} \left(a_1 g_{\mu\nu} M_Z^2 + a_3 \epsilon_{\mu\nu\alpha\beta} q_1^\alpha q_2^\beta \right)$$

- So far only a rather weak bound.

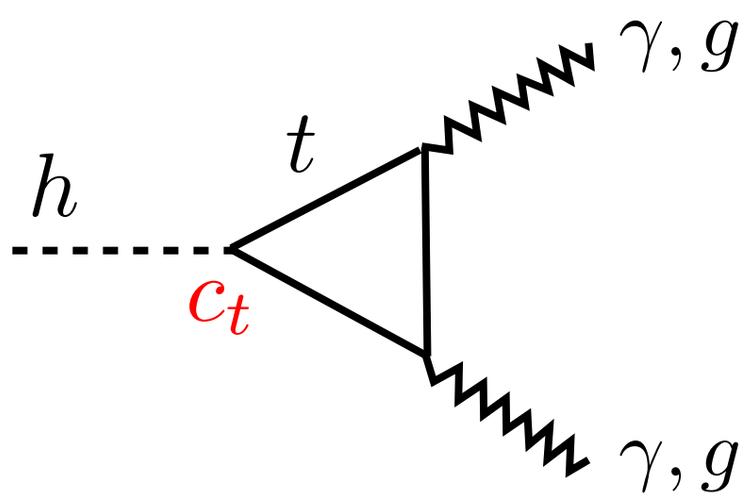
$$f_{a3} = \frac{|a_3|^2}{|a_1|^2 + |a_3|^2} < 0.58 \text{ @ } 95\%\text{C.L.}$$

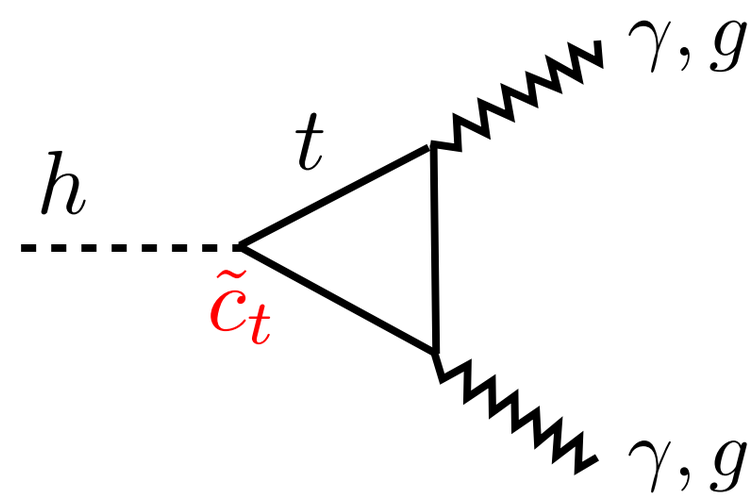
Whitbeck, Moriond QCD 2013

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



Indirect measurement





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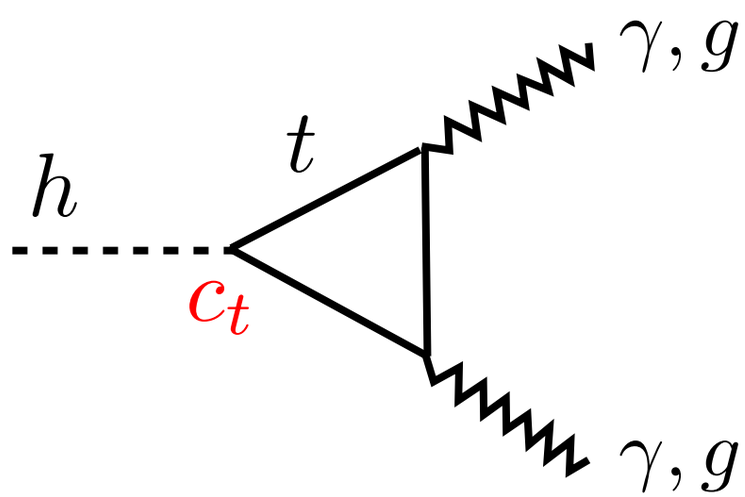
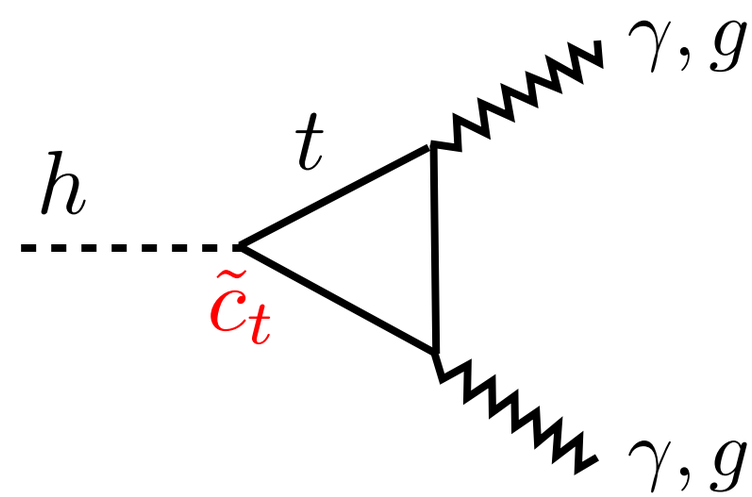




- Higgs production and decay rates at LHC

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

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

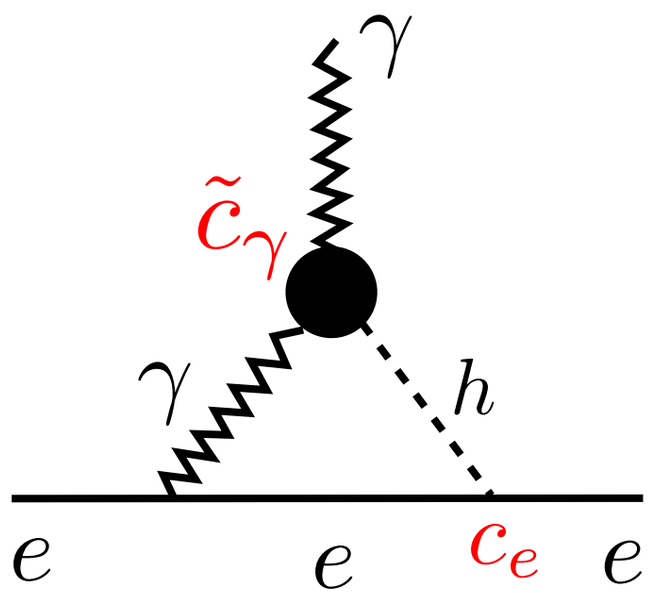
$$\sigma(gg \to h) \sim \Gamma(h \to gg) \sim |c_g(c_f)|^2 + |\tilde{c}_g(\tilde{c}_f)|^2$$

All incoherent contributions

Electric dipole moment

- Strong constraint on CPV Higgs-photon coupling.

McKeen, Pospelov, Ritz, arXiv: 1208.4597



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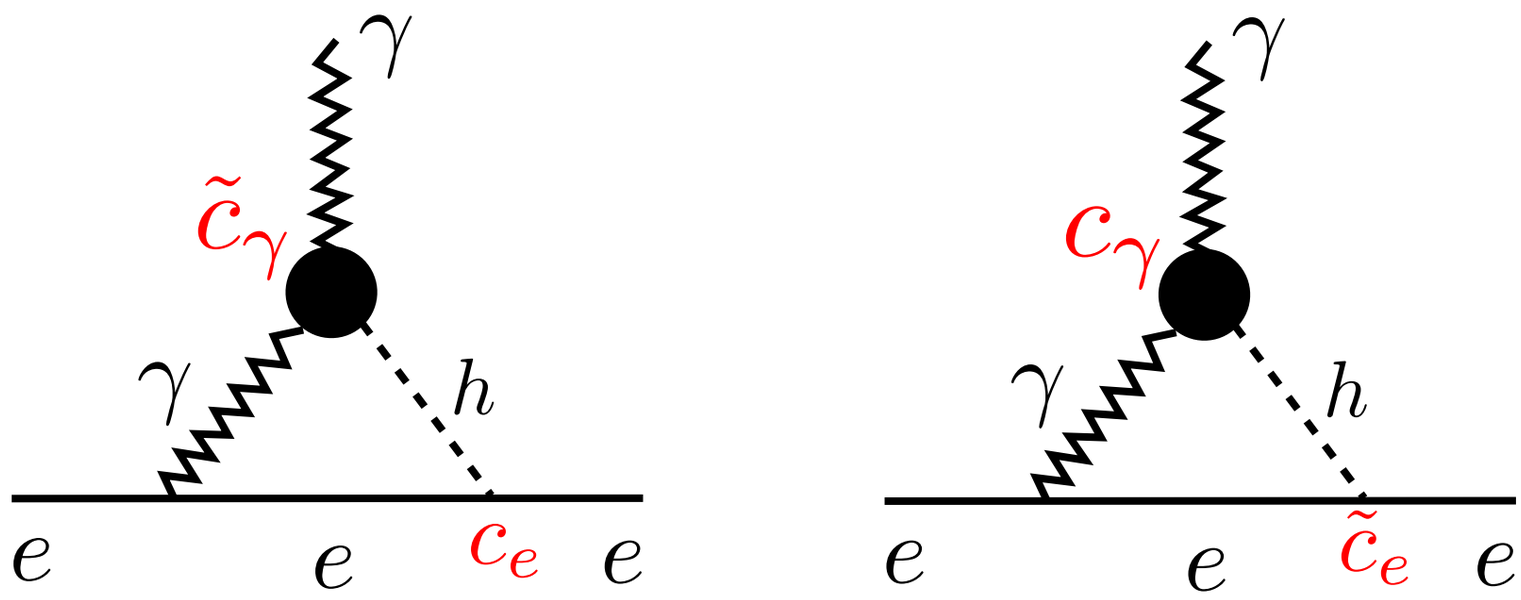

- I will show an example where cancelations can naturally happen among the two parts.

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

Baryogenesis

- 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

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

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

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

Chemical potential for B number

$(\partial_t \xi) \cdot n_B$

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

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

Zero T

Type-II 2HDM

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

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

- Natural flavor conservation, an approximate Z_2

Type-II 2HDM

- Yukawa $\mathcal{L}_Y = \bar{Q} Y_U (i\tau_2)\phi_2^* U + \bar{Q} Y_d \phi_1 D$
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$$V = \frac{\lambda_1}{2}(\phi_1^\dagger\phi_1)^2 + \frac{\lambda_2}{2}(\phi_2^\dagger\phi_2)^2 + \lambda_3(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2) + \lambda_4(\phi_1^\dagger\phi_2)(\phi_2^\dagger\phi_1)$$
$$+\frac{1}{2}\left[\lambda_5(\phi_1^\dagger\phi_2)^2 + \cancel{\lambda_6(\phi_1^\dagger\phi_2)(\phi_1^\dagger\phi_1)} + \cancel{\lambda_7(\phi_1^\dagger\phi_2)(\phi_2^\dagger\phi_2)} + \text{h.c.}\right]$$
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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: $\langle\phi_1\rangle = \begin{pmatrix} 0 \\ v\cos\beta/\sqrt{2} \end{pmatrix}, \quad \langle\phi_2\rangle = \begin{pmatrix} 0 \\ v\sin\beta e^{i\xi}/\sqrt{2} \end{pmatrix}$

relevant for genesis

- Mass eigenstates

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

relevant for Higgs couplings

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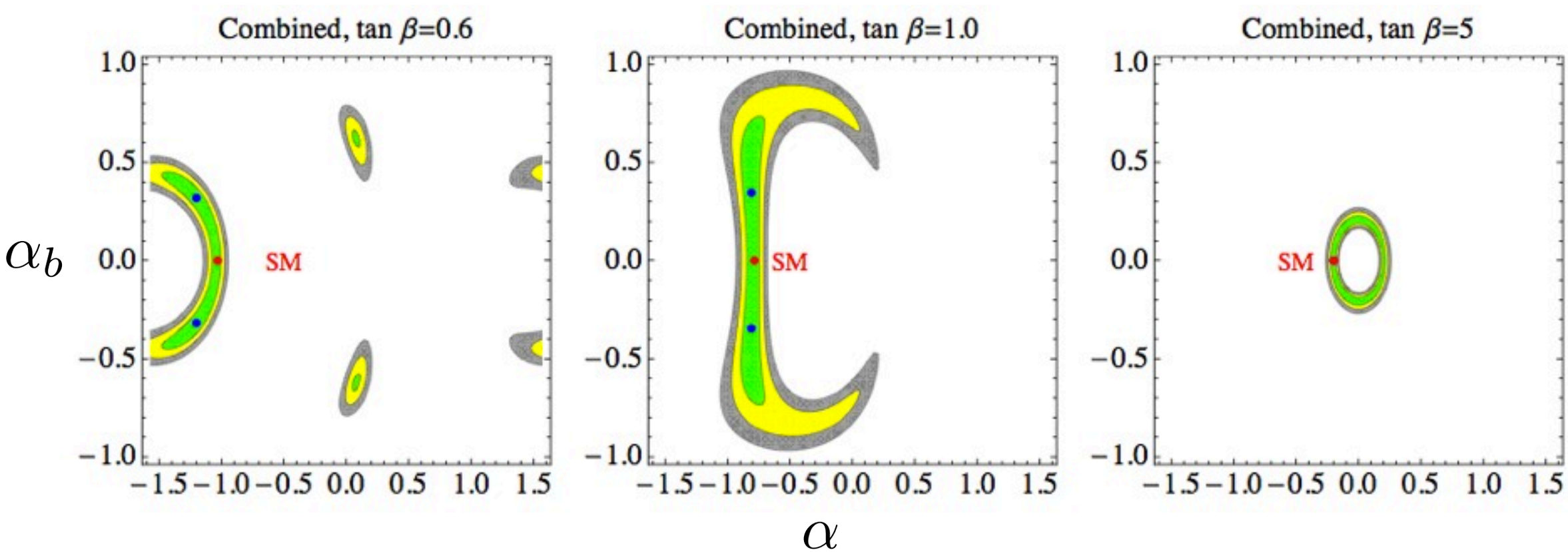
relevant for Higgs couplings

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

Global Fit to Higgs data



- Strong constraint on: $\alpha \approx \beta - \pi/2$ (alignment)
- Apparent flat in the CPV direction, especially when $\tan\beta \approx 1$.

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

A special direction

- CPV in the alignment limit $\alpha \to \beta - \pi/2$ $\quad \alpha_b \neq 0$ $\quad \alpha_c \neq 0$
- When $\tan\beta \approx 1$, Higgs couplings become

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

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- Higgs rates at LHC.

$$\Gamma = \Gamma_{\rm SM}\cos^2\alpha_b + \Gamma_{\rm odd}\sin^2\alpha_b$$

Incoherent sum of CPC, CPV parts

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

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- Higgs rates at LHC.

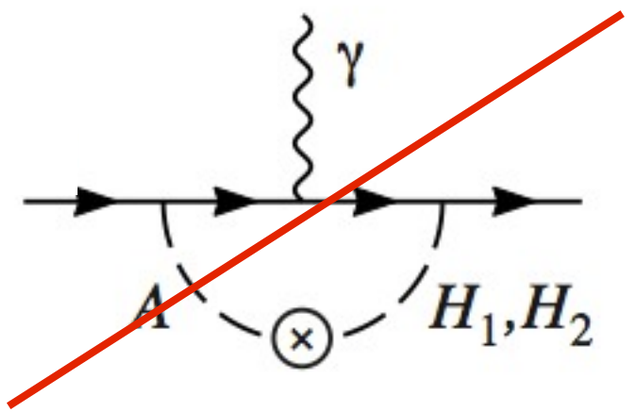
$$\Gamma = \Gamma_{\rm SM}\cos^2\alpha_b + \Gamma_{\rm odd}\sin^2\alpha_b$$

Incoherent sum of CPC, CPV parts

- Not real decoupling limit, second doublet mass goes to infinity: $\alpha_b, \alpha_c \to 0,\ \alpha \to \beta - \pi/2$

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

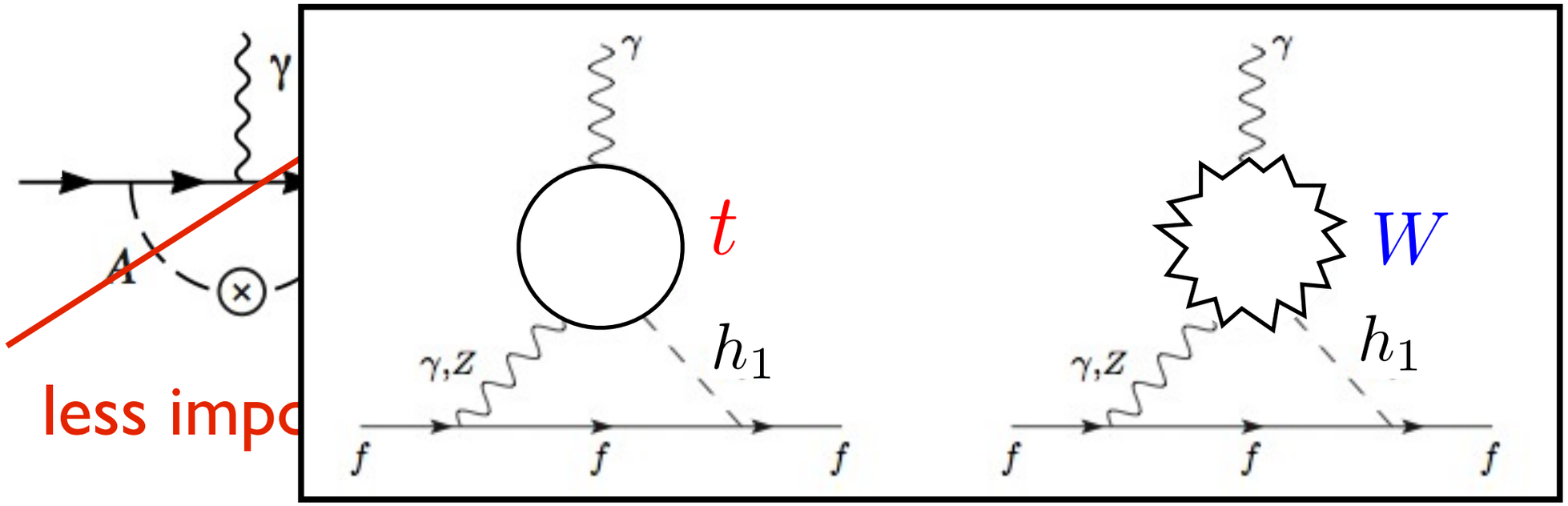
Electron EDM



less important

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

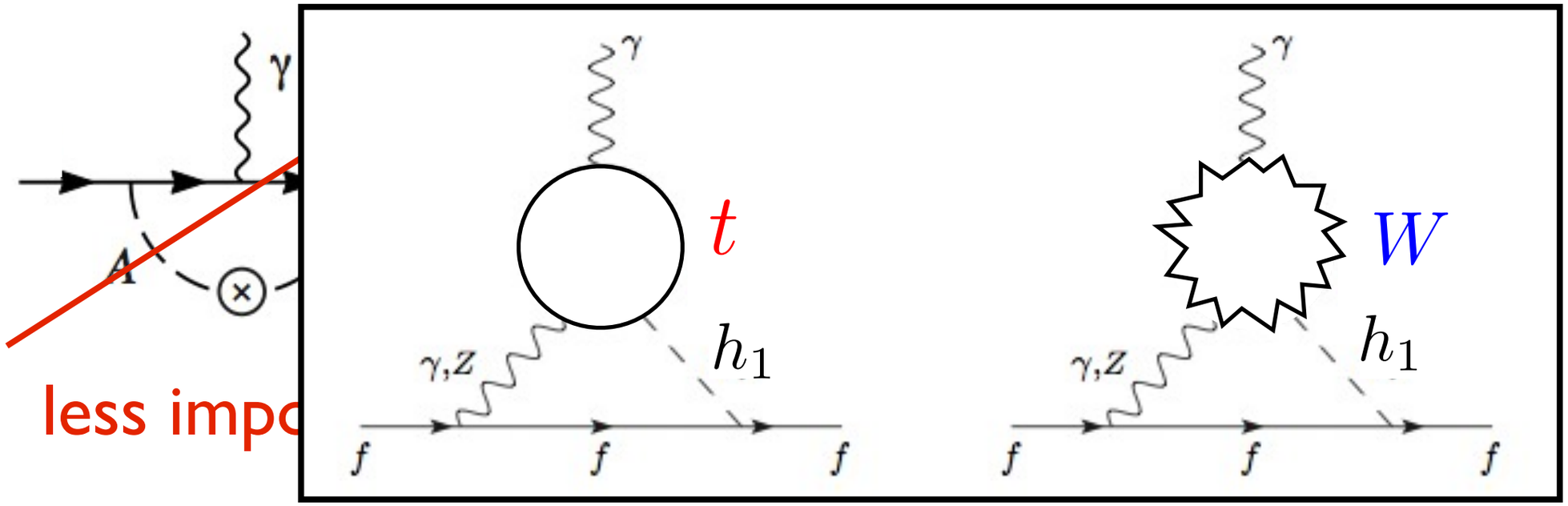
Electron EDM



$$d_e \simeq 10^{-27} e\,\mathrm{cm}\left(2.6 c_t \tilde{c}_e + 3.8 c_e \tilde{c}_t - 6.1 a \tilde{c}_e\right)$$

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

Electron EDM



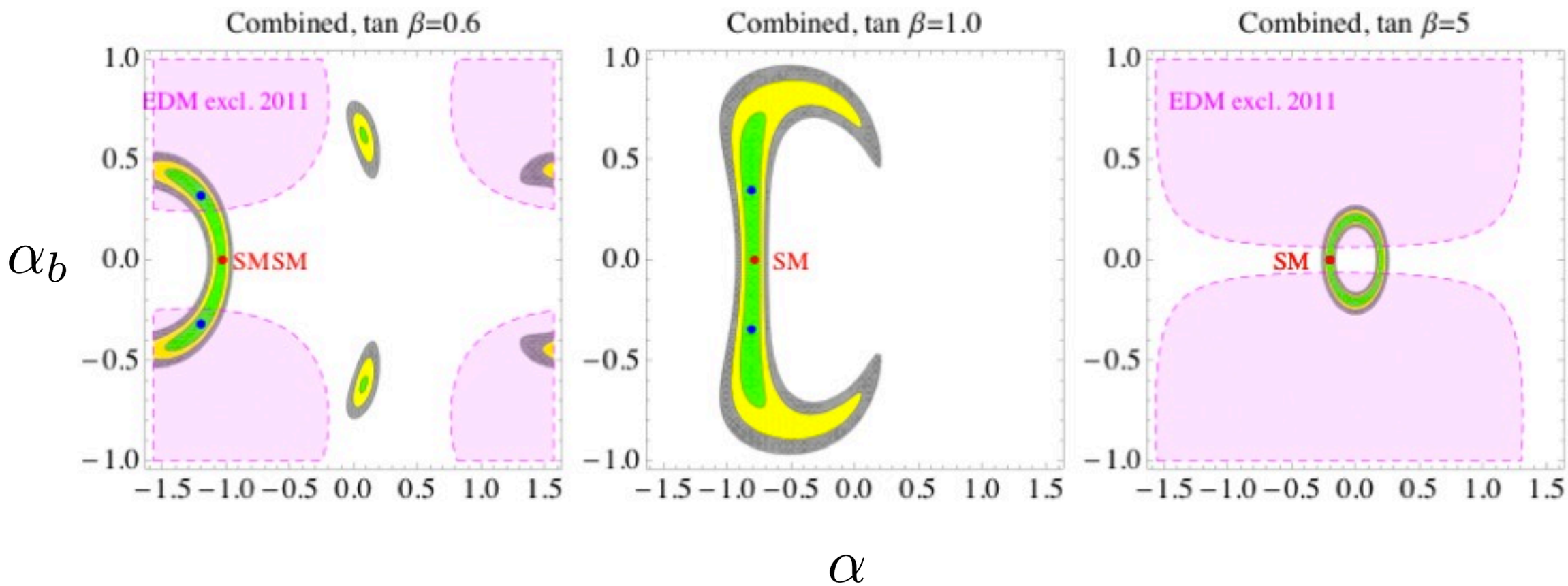
$$d_e \simeq 10^{-27} e\,\mathrm{cm}\left(2.6 c_t \tilde{c}_e + 3.8 c_e \tilde{c}_t - 6.1 a \tilde{c}_e\right)$$

$h \to \gamma\gamma$ $\quad \sim \mathcal{A}_{SM}$ $\quad \mathcal{A}_{odd}$ at low energy

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

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

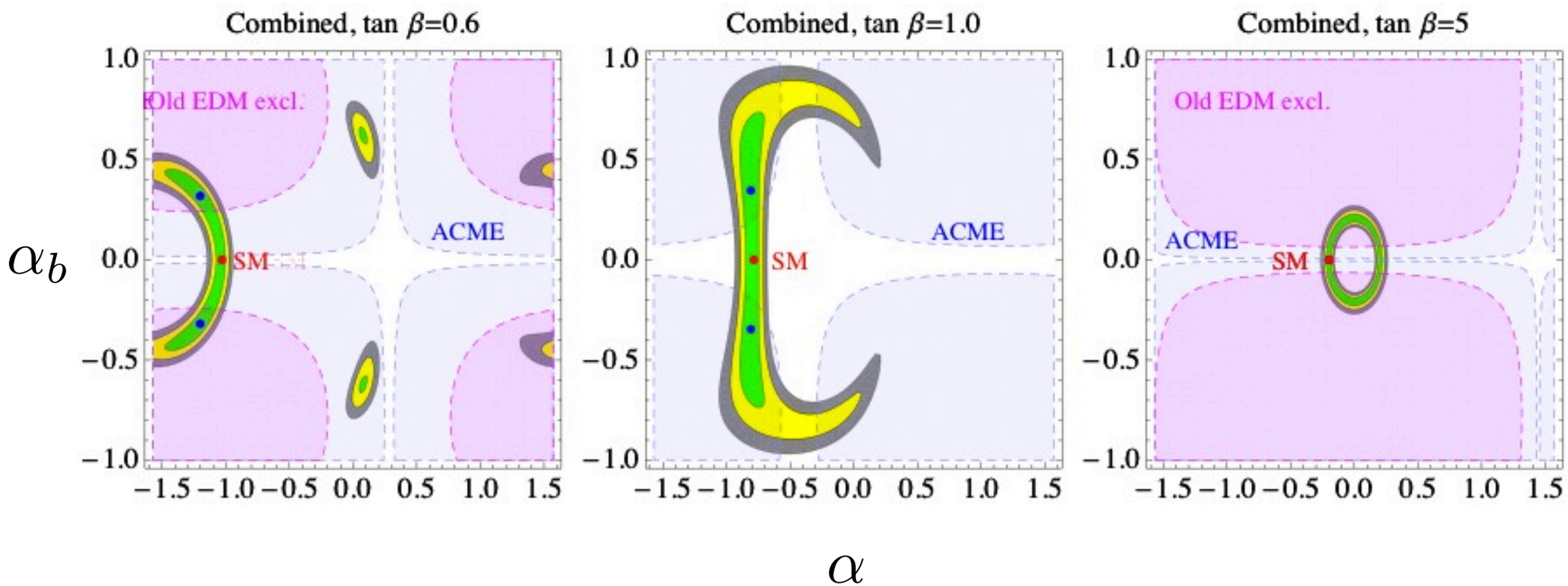
eEDM vs Higgs Fit



- 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

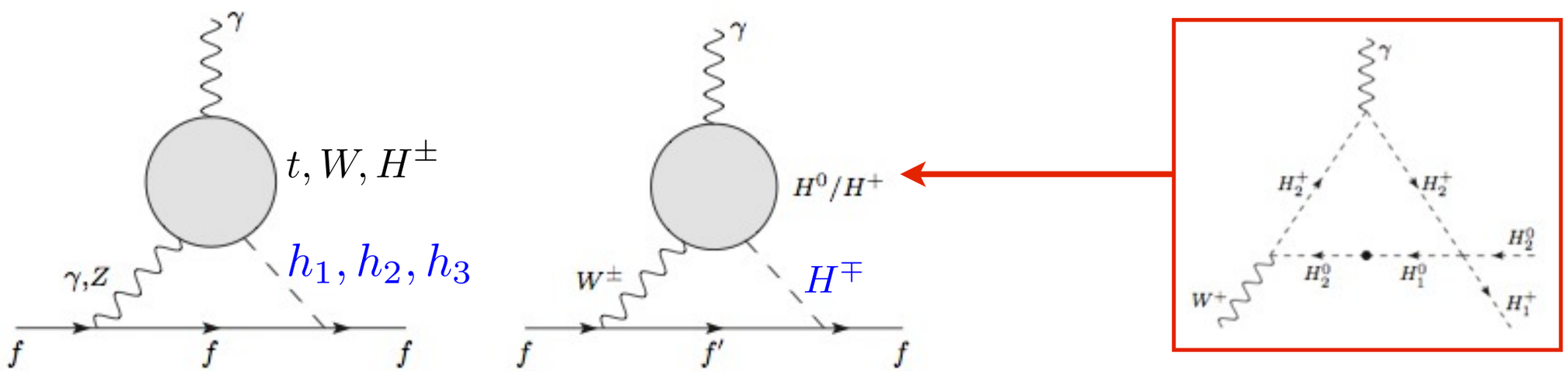


- ACME result: $d_e < 1.025 \times 10^{-28} e\,\mathrm{cm}$ @ 95% C.L.
- Higgs data and EDMs are complementary.

ACME Collaboration, 1310.7534

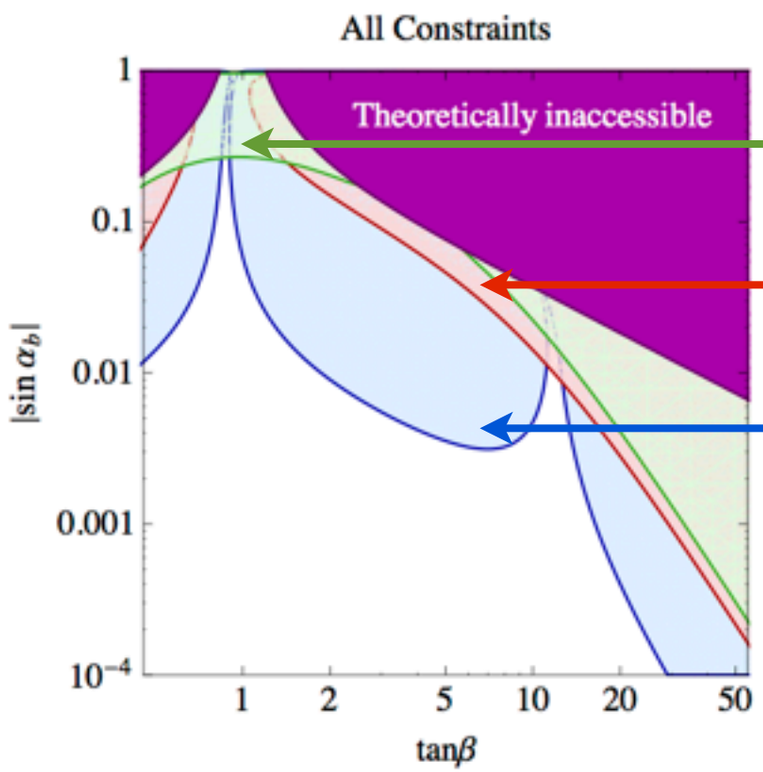
Beyond lightest Higgs

- Lightest Higgs only theory can be misleading.
- Should include heavier scalar contributions - cannot decouple them.



- We use the complete gauge invariant calculation of Barr-Zee recently done in J. Hisano, et al, arXiv:1311.4704

The role of heavy Higgs



Neutron EDM

Mercury EDM

Electron EDM

fix $\alpha = \beta - \pi/2$

and $m_{h_2,h_3,H^\pm} \sim 300 - 400\,\mathrm{GeV}$

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

S. Inoue, M. Ramsey-Musolf, **Y.Z.**, arXiv:1403.4257

Baryon generation

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

Chemical potential
for B number

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

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

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

Baryon generation

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

Chemical potential for B number

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

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

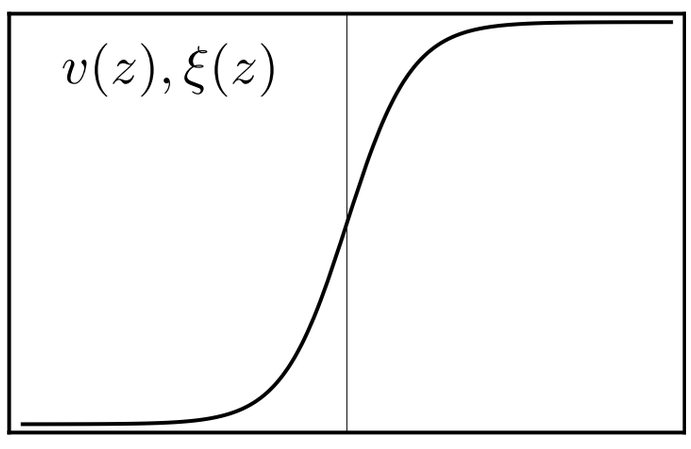
$$\tilde{c}_t(\xi)$$

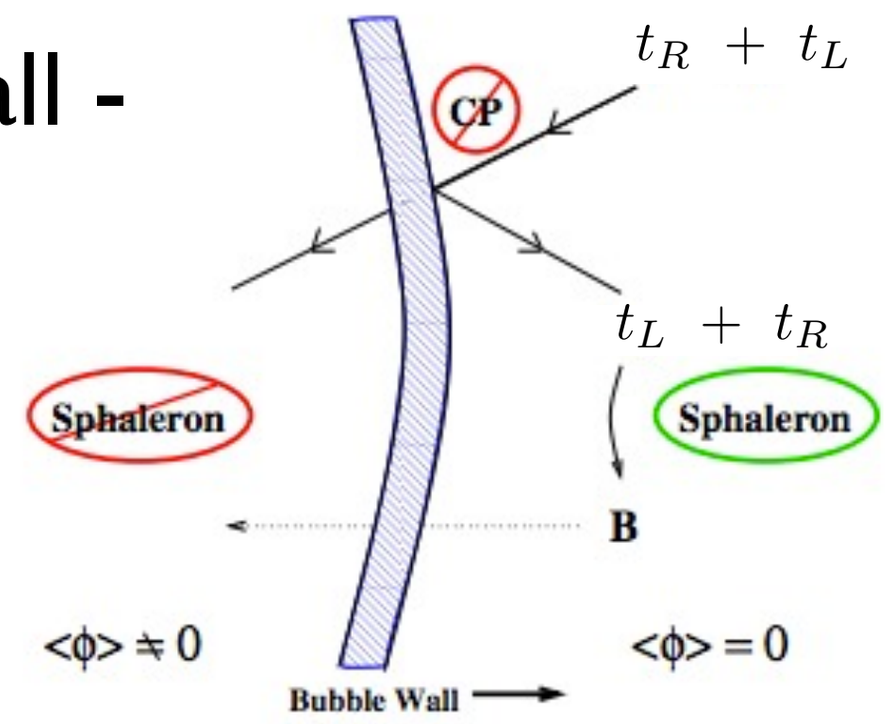
- Still need B violating process: sphaleron process.
- If in equilibrium, all $\Gamma \gg H$, final asymmetry is determined by $\mu = \partial_t \xi \sim t^{-1} \ll 10^{-10} T$
- In need of a first order EW phase transition.

EW baryogenesis

- Fast moving wall- all processes out of equilibrium.
- Chemical potential → CPV source
- Top quark scatters on the wall - interference.

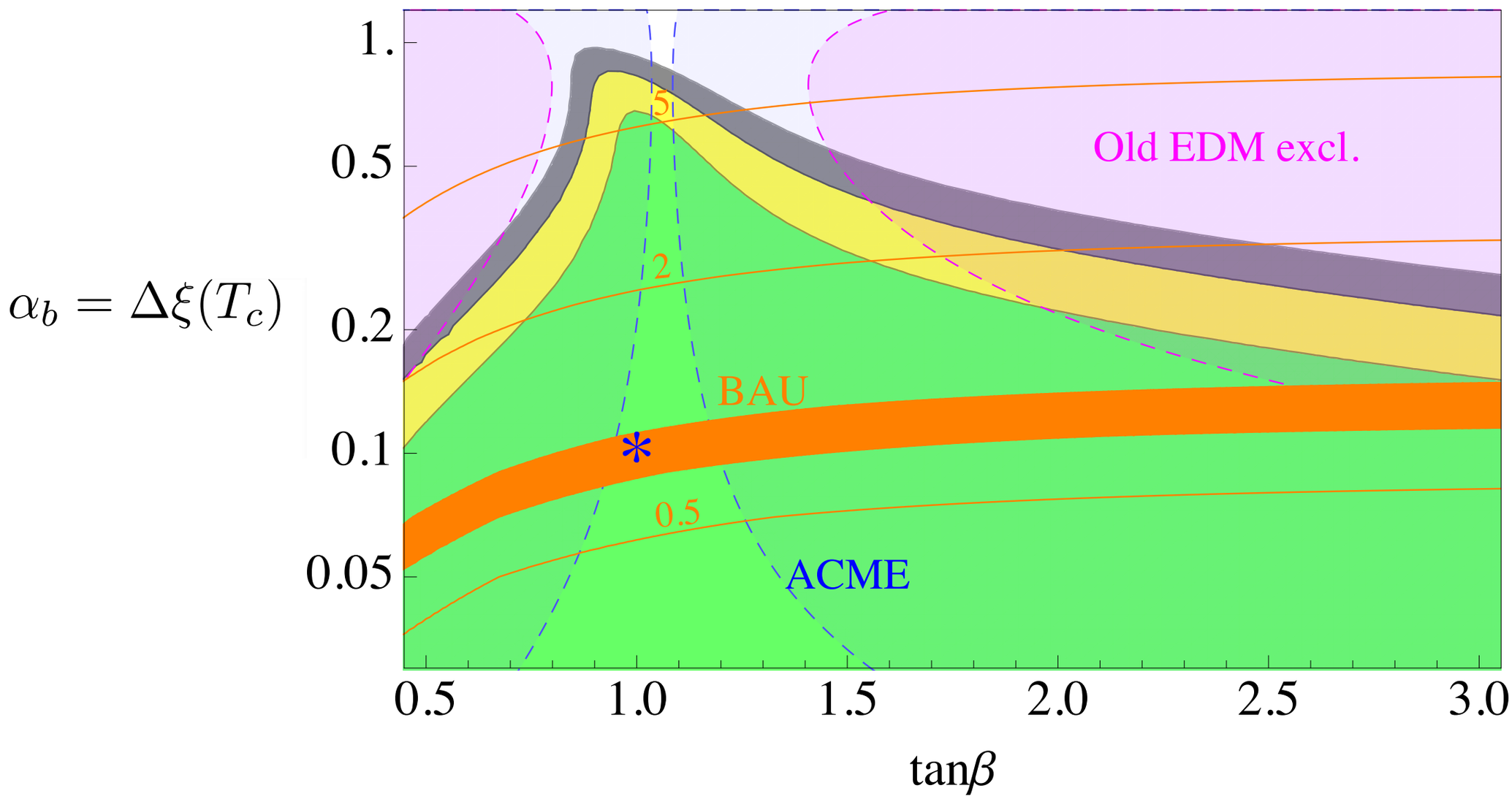
$$\mathrm{Im}[m_t(z)^* m_t(z')] \sim |m_t(z)|^2 \partial_t \xi$$





P. Huet, A. Nelson, PRD, 53, 4578, (1996)
J. Cline, et al, PRD, 54, 2451, (1996)
C. Lee, V. Cirigliano, M. Ramsey-Musolf, PRD, 71 (2005) 075010

Connections



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

Future tests

- Direct CPV: azimuthal phase shift:
  - Higgs decays (also the 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

$$h \to \gamma\gamma \quad \text{convert to } 4e$$

Bishara, Grossman, Harnik, Robinson, Shu, Zupan, 1312.2955

  - Production with two forward jets

$$pp \to h + 2j$$

Klamke, Zeppenfeld, '07

- Virtual Higgs effects
  - $t\bar{t}$ production and leptonic decay: energy distributions of charge leptons.

Schmidt, Peskin '92

Cogenesis

- Observation: $\Omega_{\rm B} \sim \Omega_{\rm DM}$.
  - Baryon asymmetry of the universe- approximate global symmetry $U(1)_{\rm B}$.
  - If dark matter relic density is also due to an asymmetry- require another approximate global symmetry $U(1)_{\rm DM}$.
- Electroweak Cogenesis
  - Same origin of asymmetries - from a CPV Higgs!

Order parameters

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

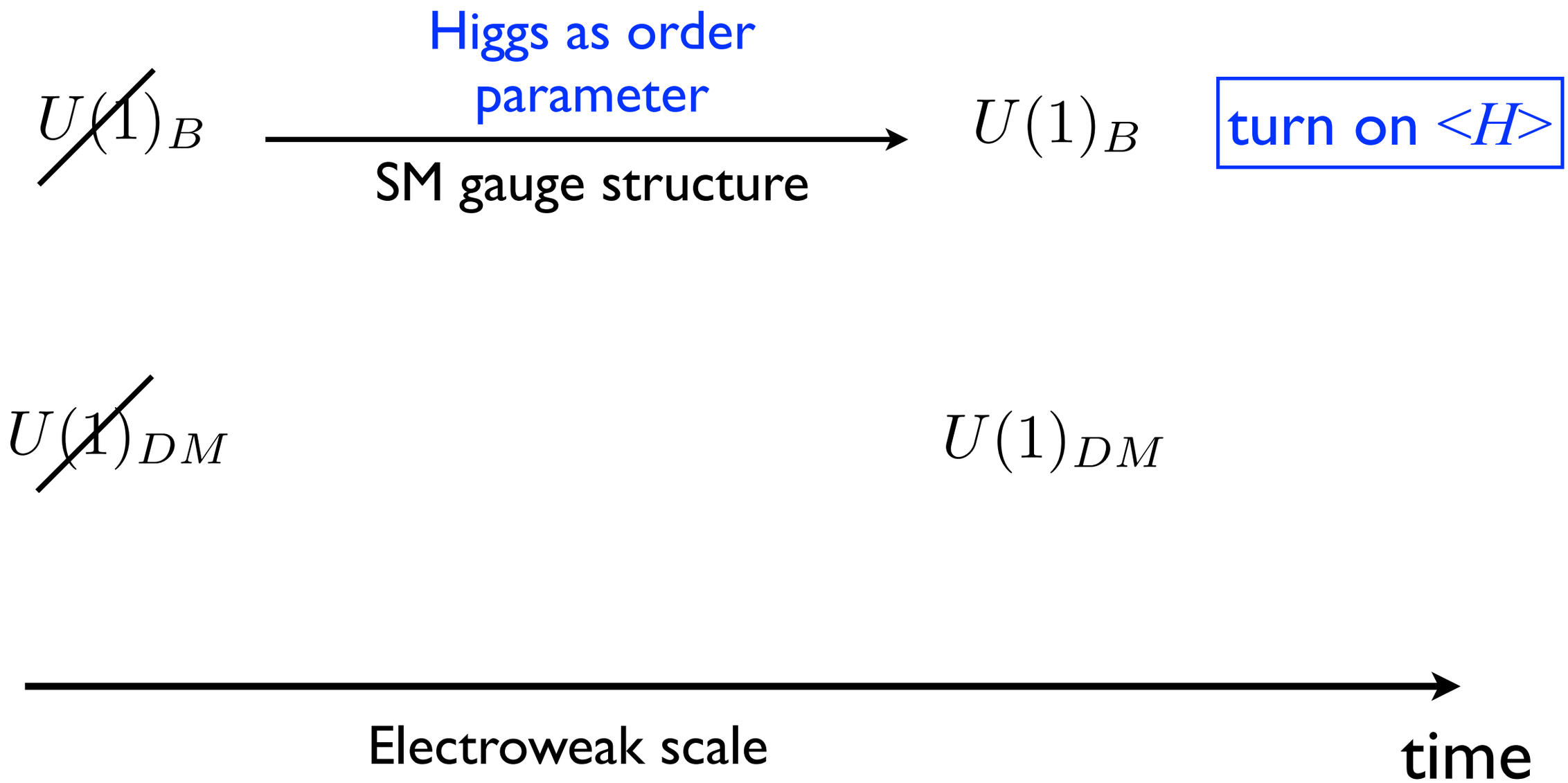
$\cancel{U(1)_{DM}}$ $U(1)_{DM}$

Electroweak scale

time

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

Order parameters



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

Order parameters

$\cancel{U(1)}_B$ —— Higgs as order parameter ——→ $U(1)_B$ $\boxed{\text{turn on } \langle H \rangle}$

SM gauge structure

$\cancel{U(1)}_{DM}$ —— New order parameter ——→ $U(1)_{DM}$ $\boxed{\text{turn off } \langle S \rangle}$

A scalar S carrying DM charge

——→ time

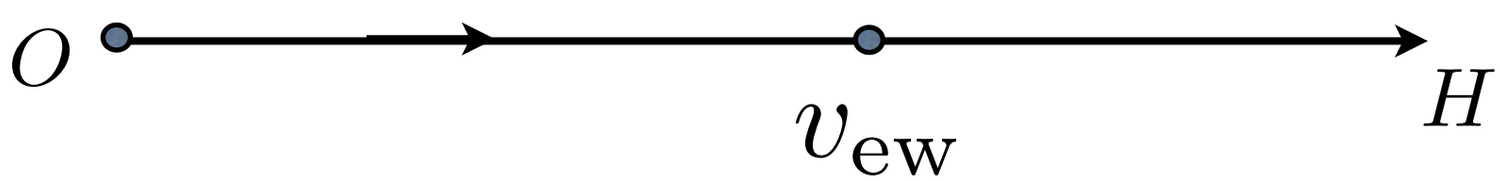
Electroweak scale

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

Restore two symmetries

In a single step

Electroweak phase transition

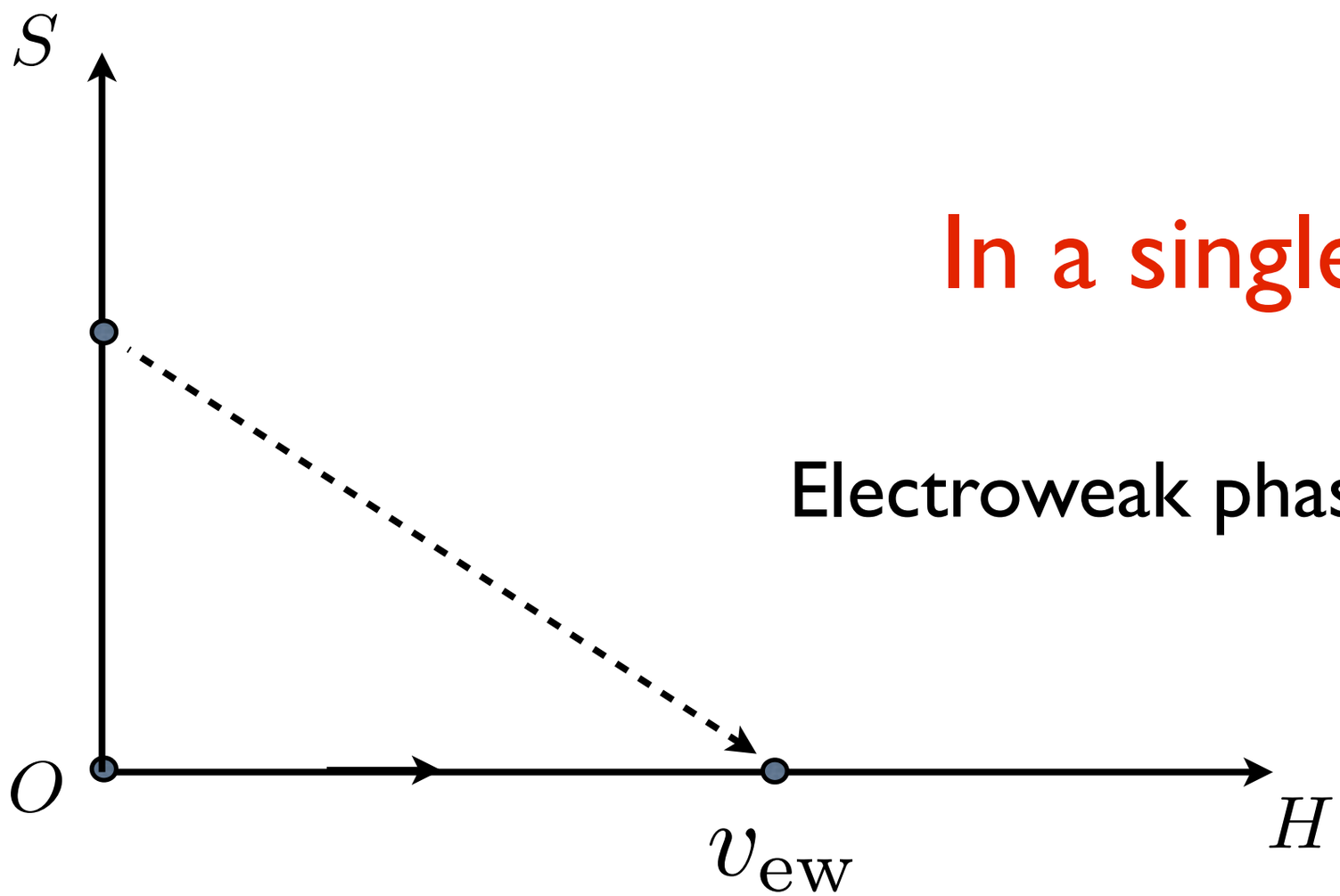


$$m_h^2(T) \sim -\mu_h^2 + 3\lambda h^2 + \frac{T^2}{12}(\lambda + g^2 + y_t^2 + \cdots)$$

$$m_s^2(T) \sim -\mu_s^2 + 3\lambda_s s^2 + \frac{T^2}{12}(\lambda_s + \cdots)$$

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

Restore two symmetries



In a single step

Electroweak phase transition

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

$$m_s^2(T) \sim -\mu_s^2 + 3\lambda_s s^2 + \frac{T^2}{12}(\lambda_s + \cdots)$$

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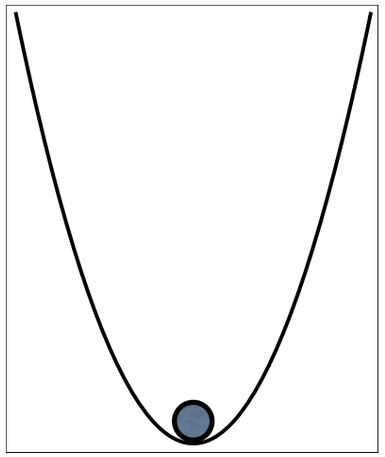
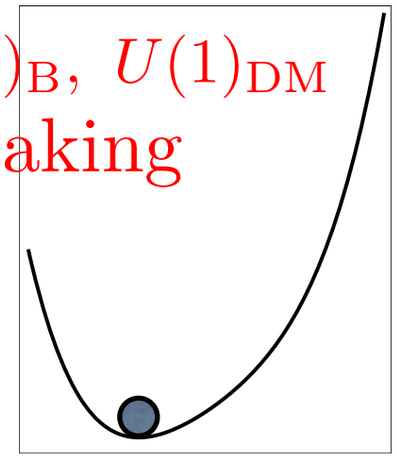
History of symmetries



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



$\langle S \rangle \neq 0$

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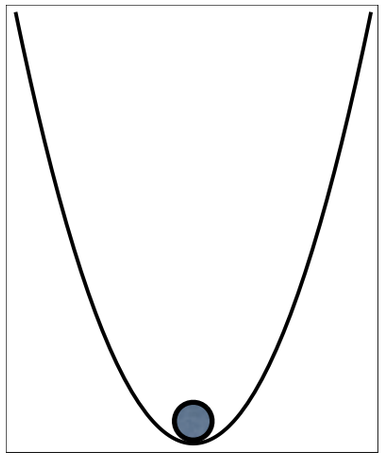
History of symmetries



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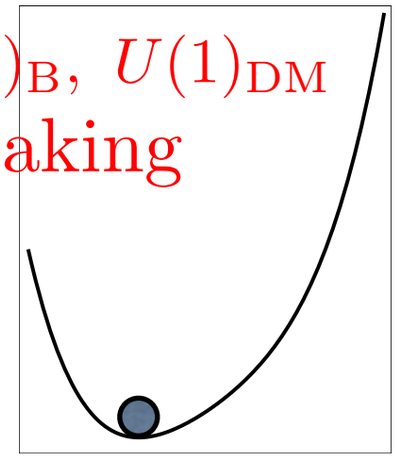
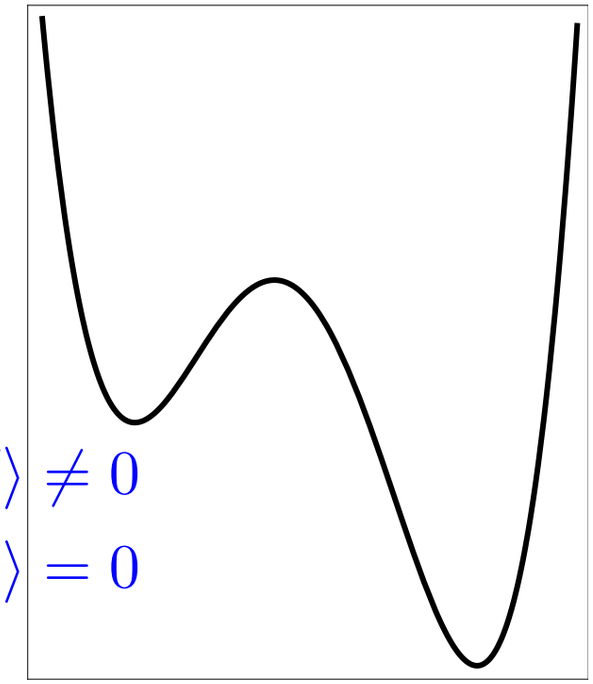


$U(1)_{\rm B},\ U(1)_{\rm DM}$ breaking

$\langle S \rangle \neq 0$

$\langle H \rangle = 0$



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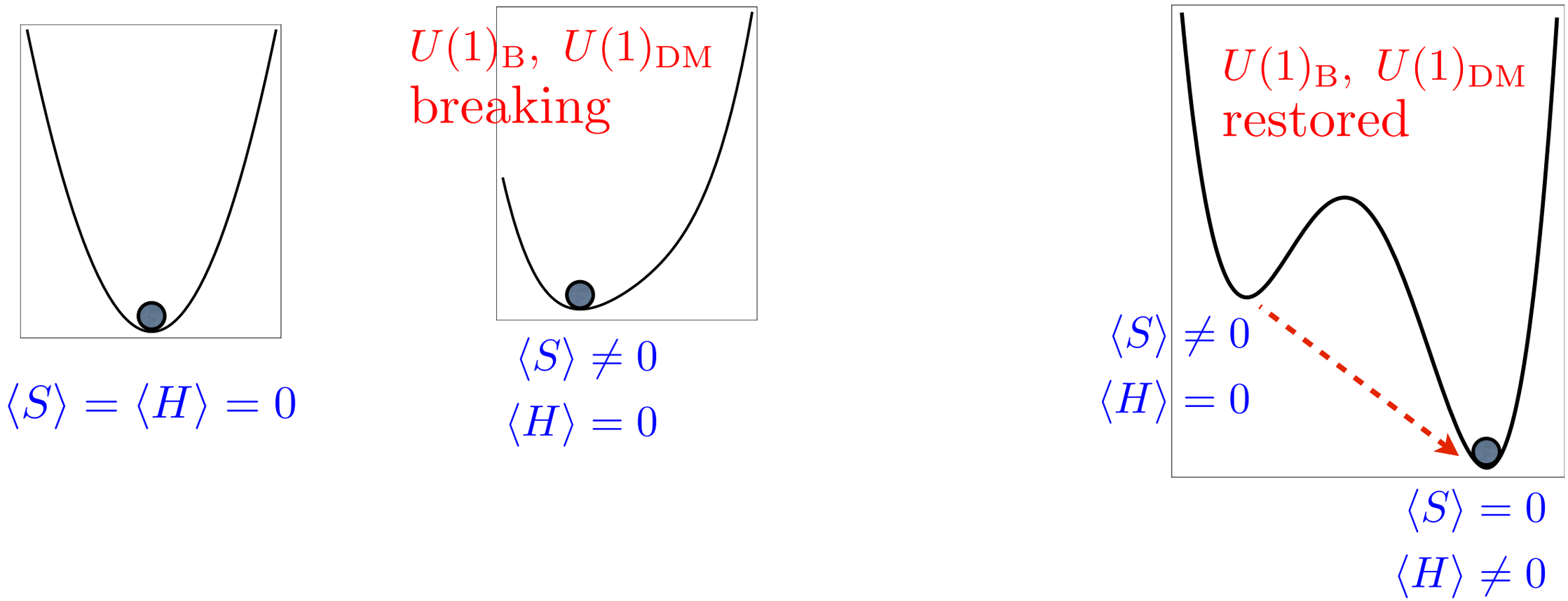

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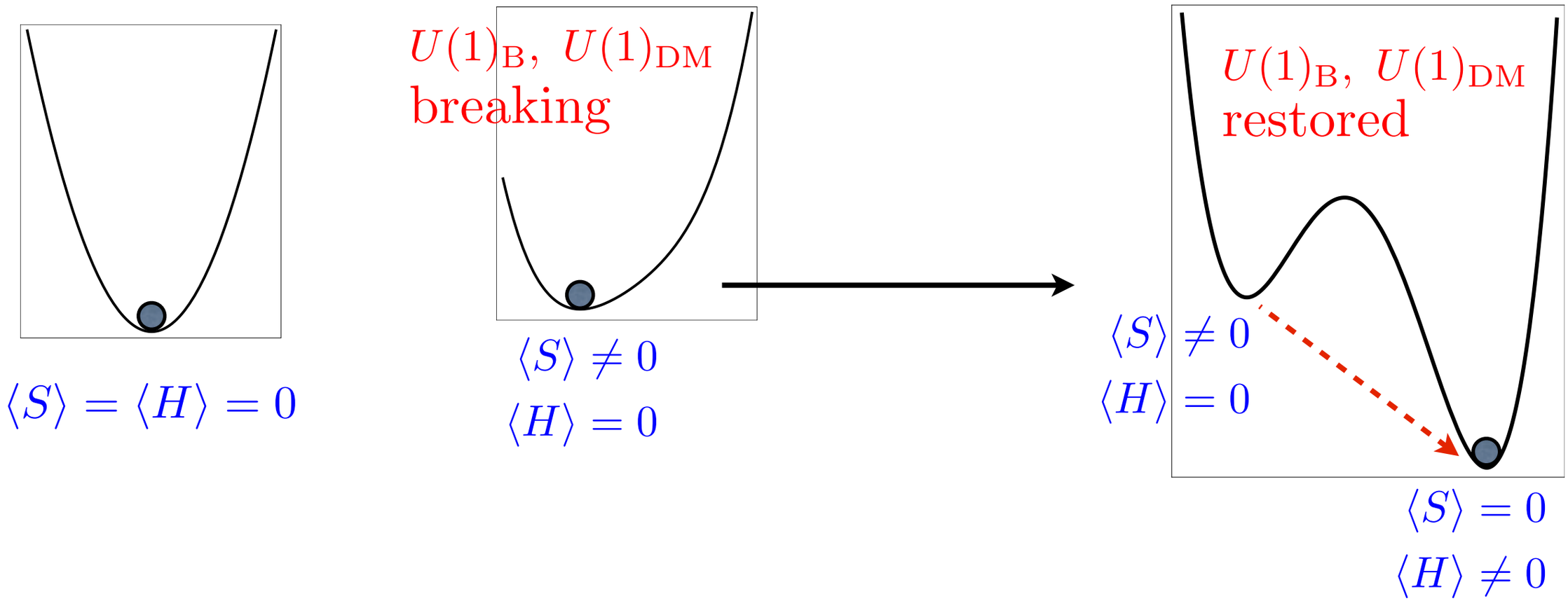
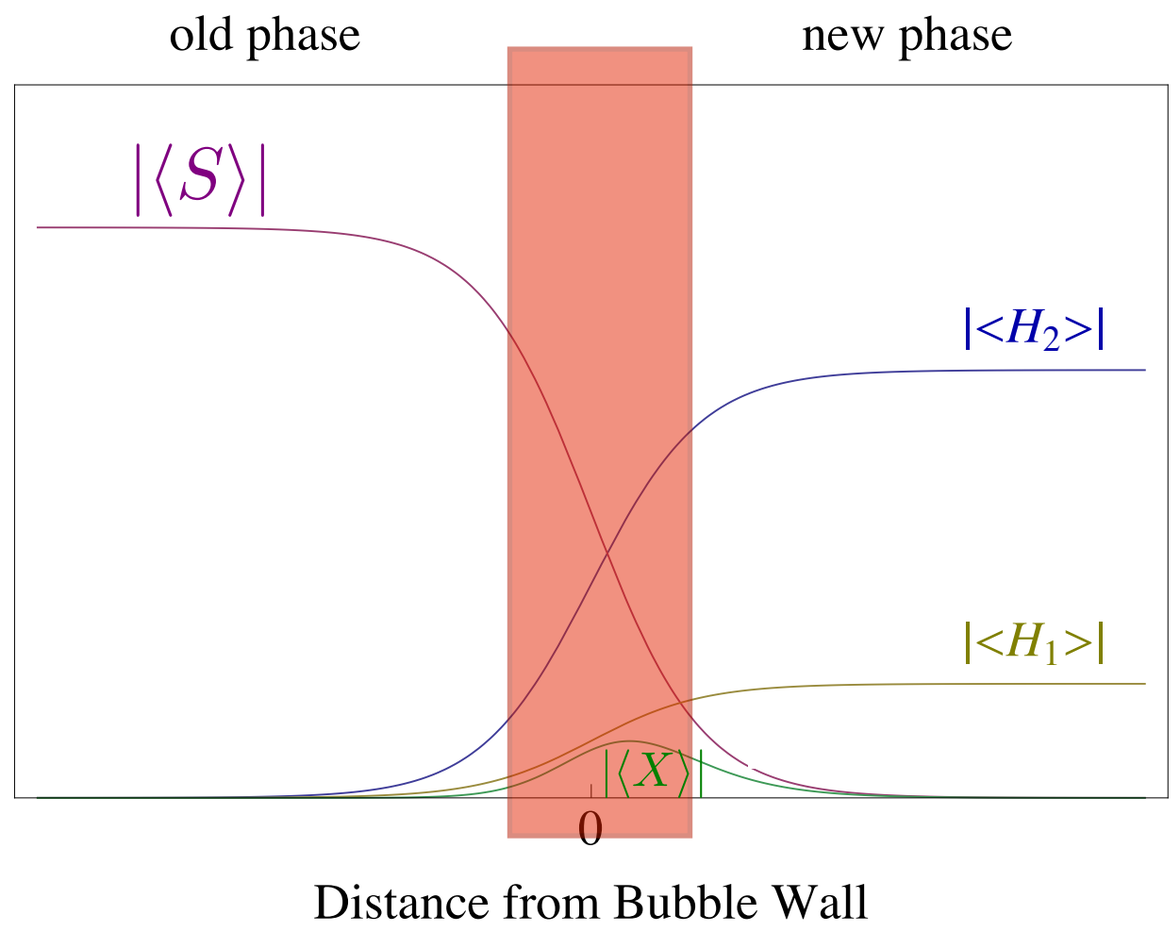


- Dark matter sector helps triggering strong first order EW phase transition.
- No effect on Higgs coupling to fermions/gauge bosons.

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

VEV profiles

- Everybody has a VEV on the bubble wall.
- Both genesis happen on/near the wall.



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

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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Redistribute particle numbers

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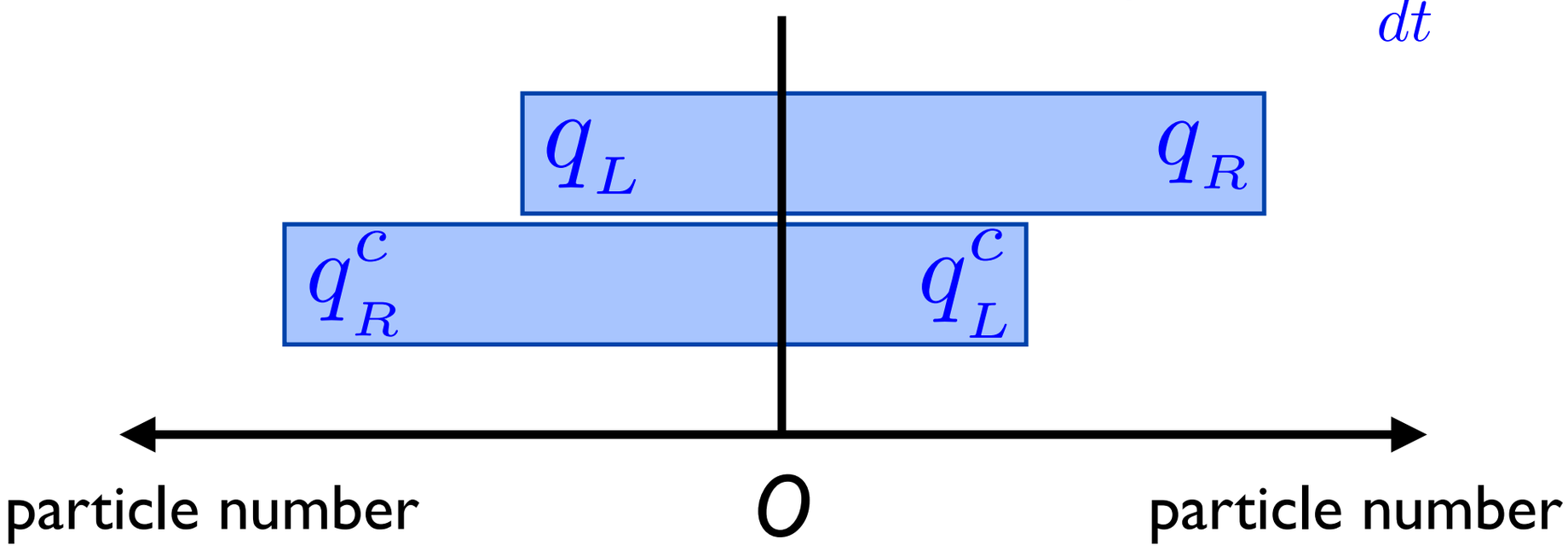

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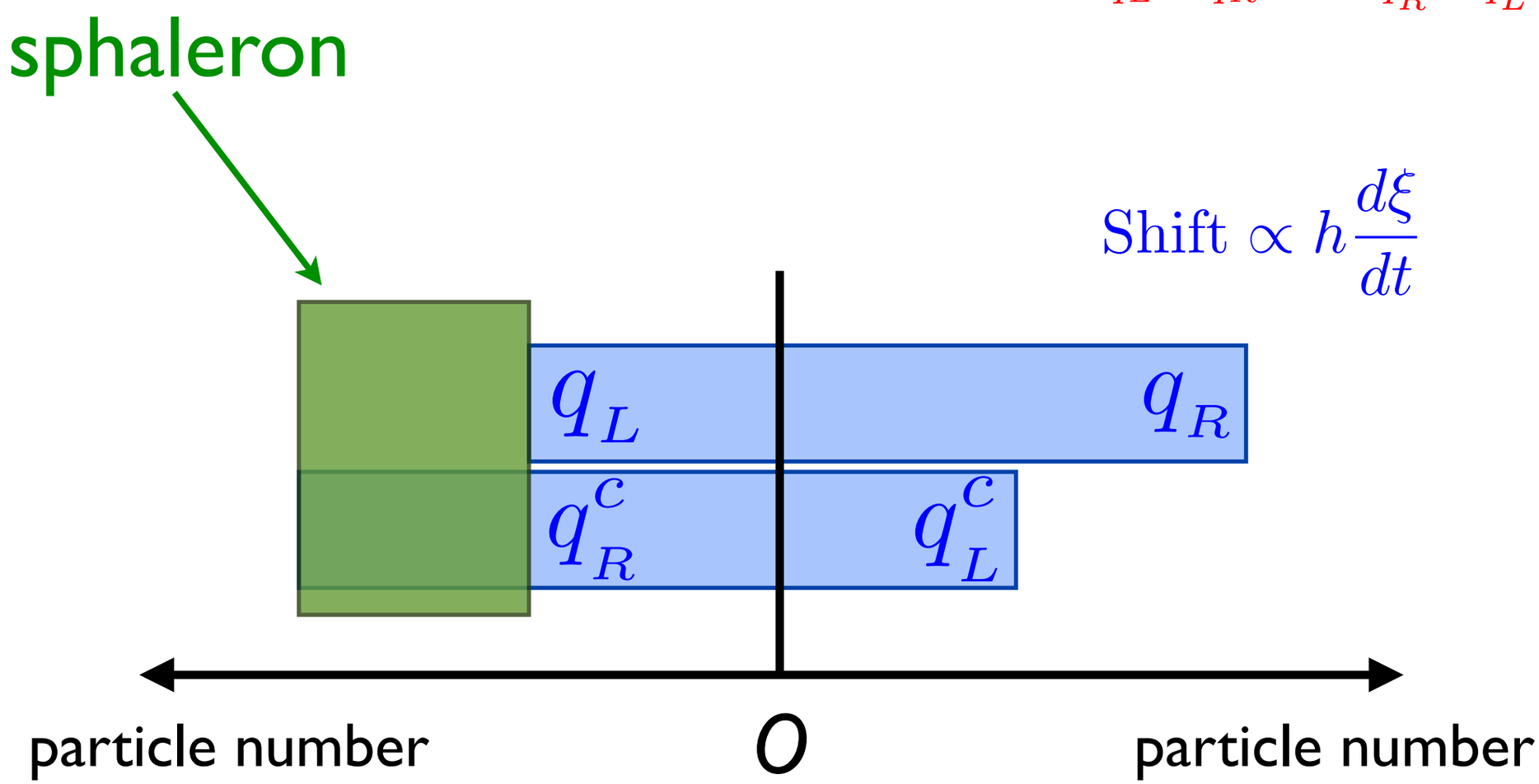

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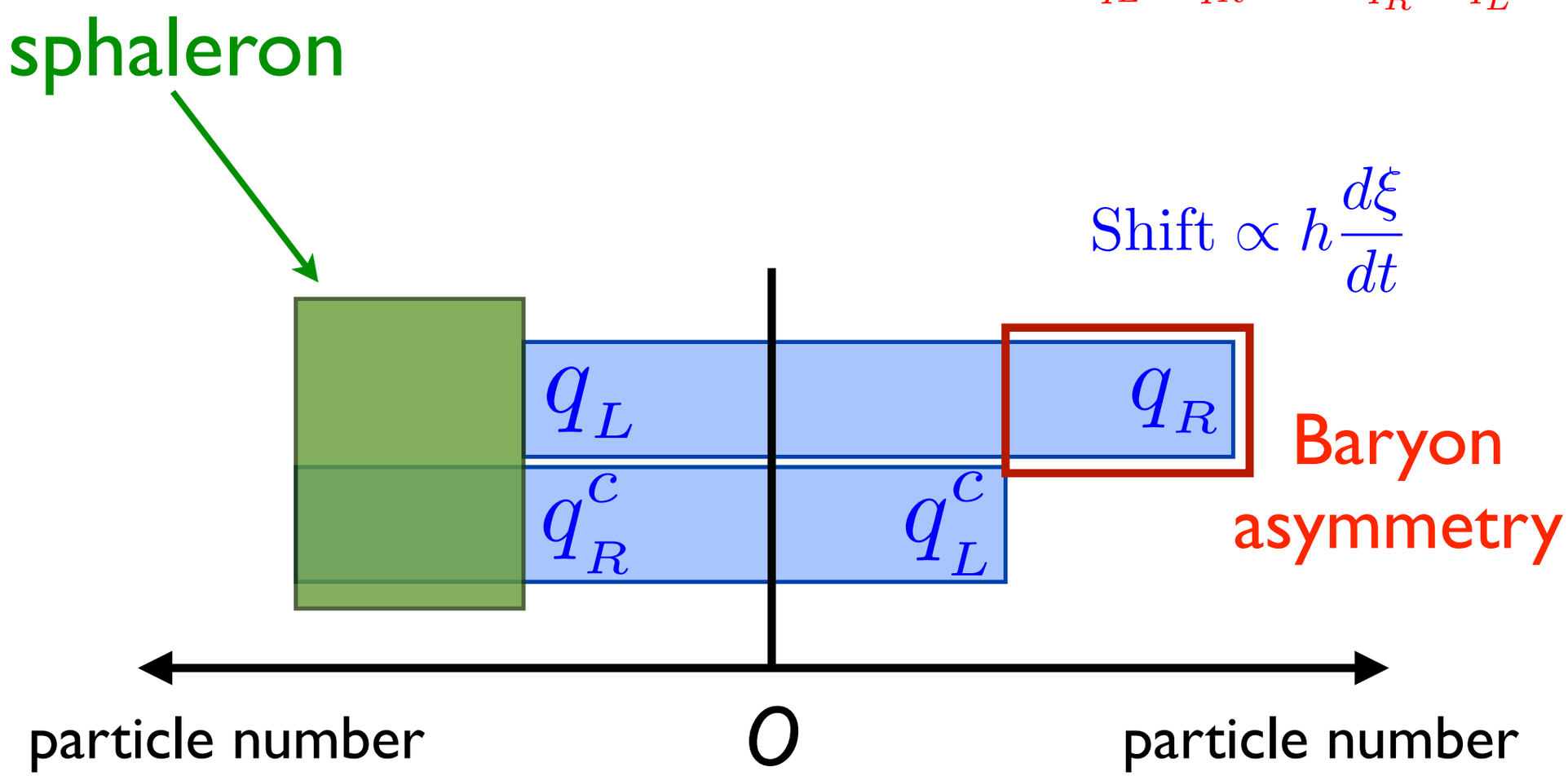

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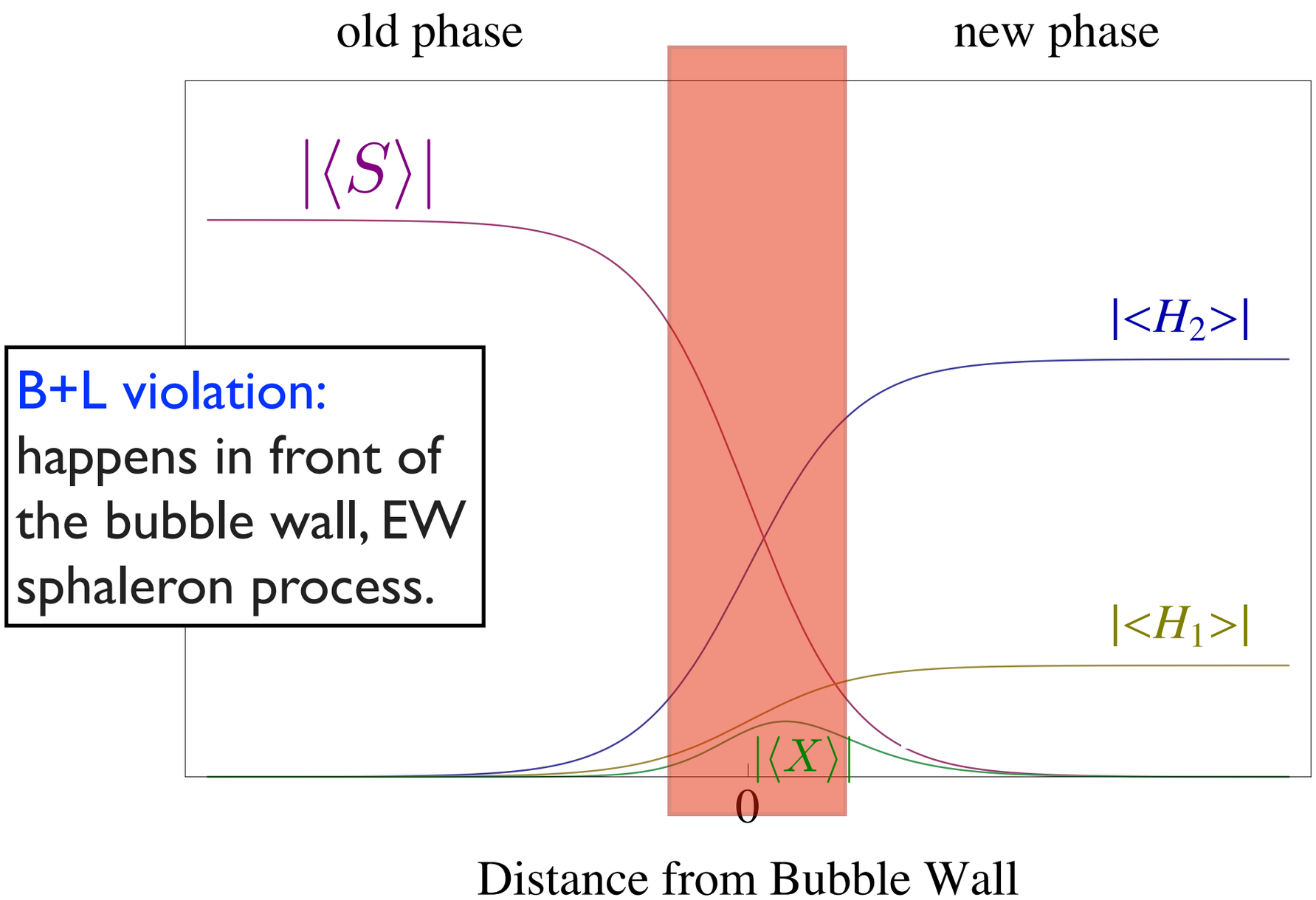
Processes on the wall



B+L violation:
happens in front of the bubble wall, EW sphaleron process.

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

CPV for DM-genesis

CP violation $\mathcal{L} = \lambda H_u H_d S X \sim \lambda\, h e^{i\xi}\, S\, X + \text{c.c.}$

DM partner
order parameter

dark matter
(DM) scalar

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

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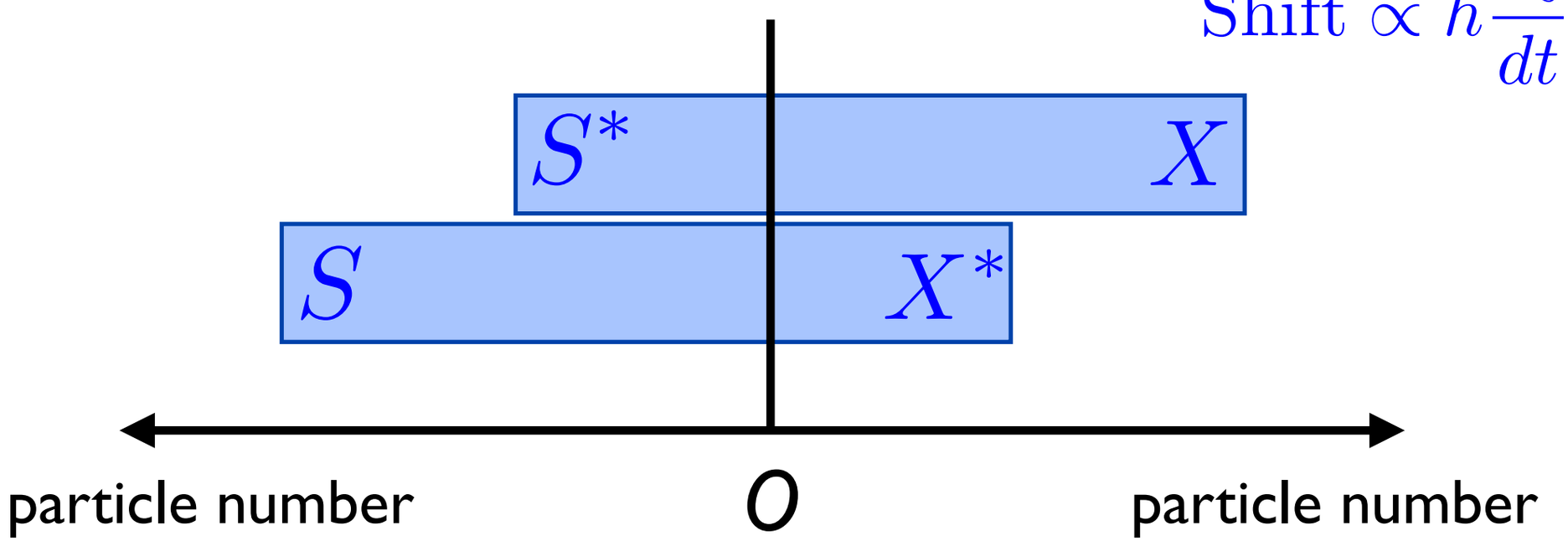

Cheung, **Y.Z.**, arXiv:1306.4321, JHEP

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DM number violation

DM partner order parameter

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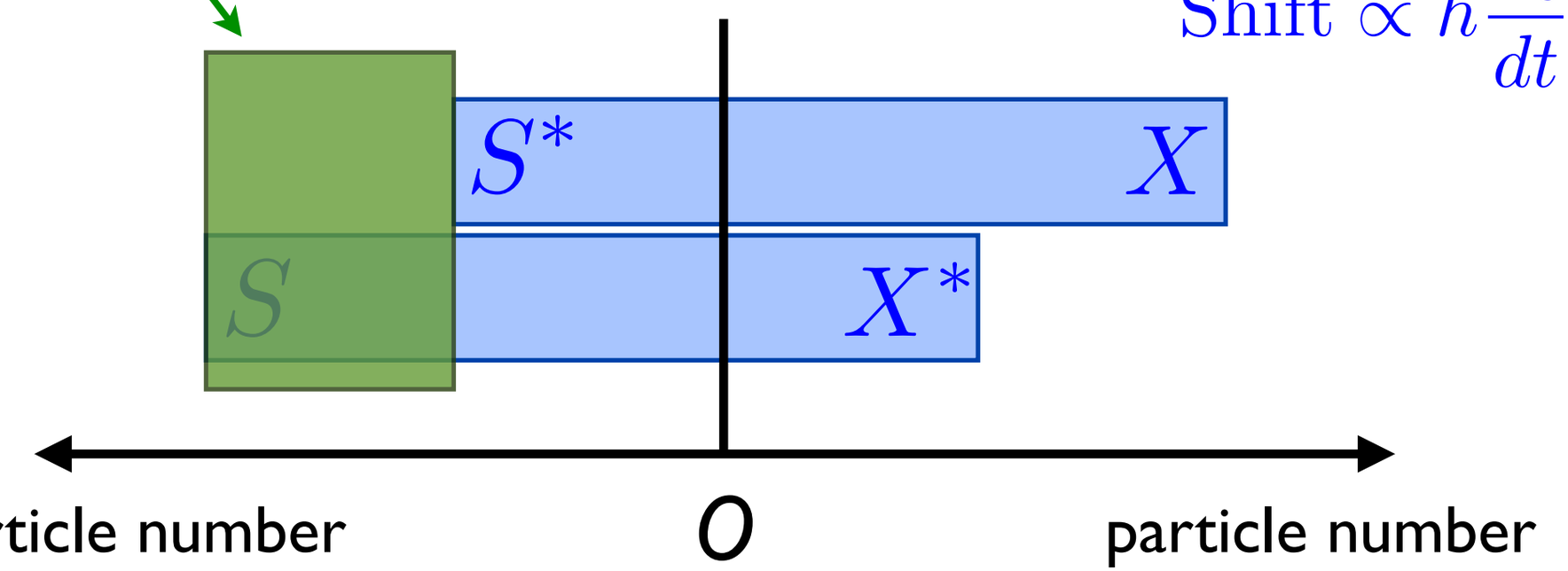

Cheung, **Y.Z.**, arXiv:1306.4321, JHEP

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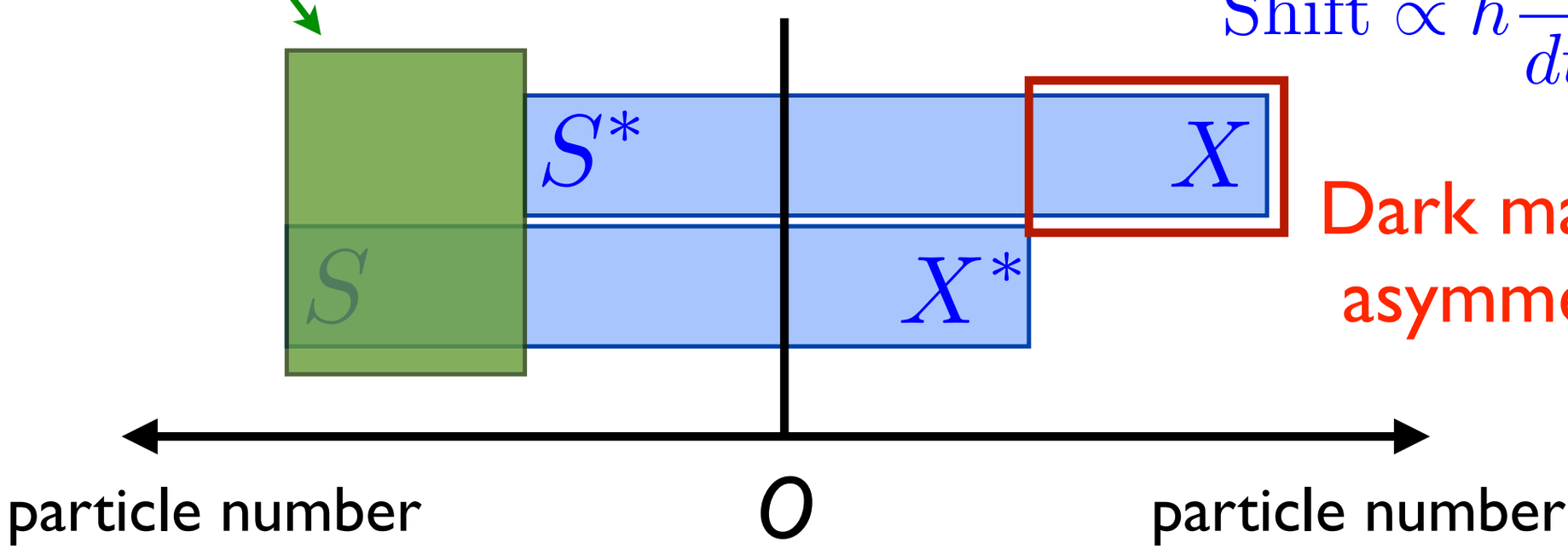
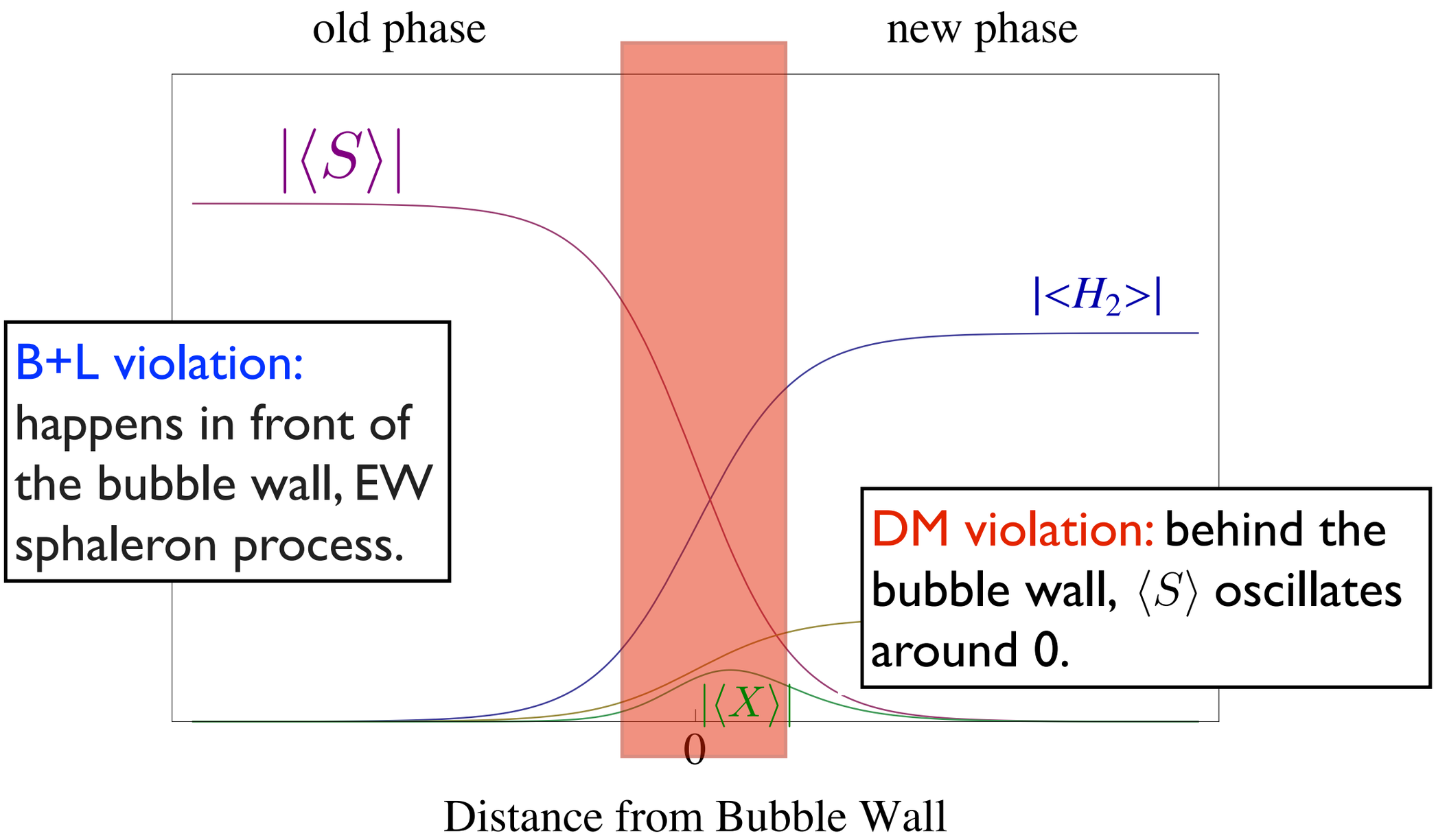


Dark matter asymmetry

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

Processes on the wall



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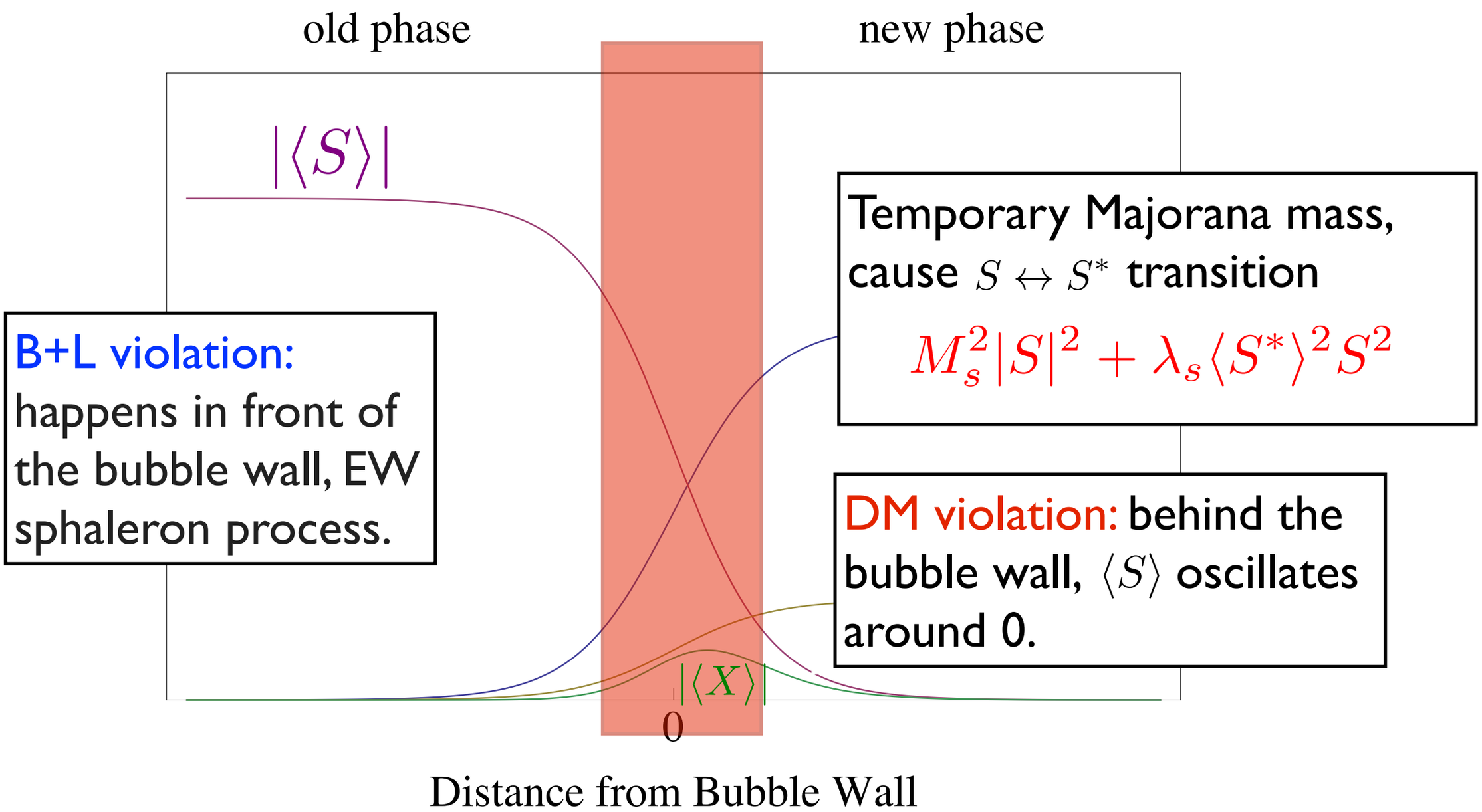

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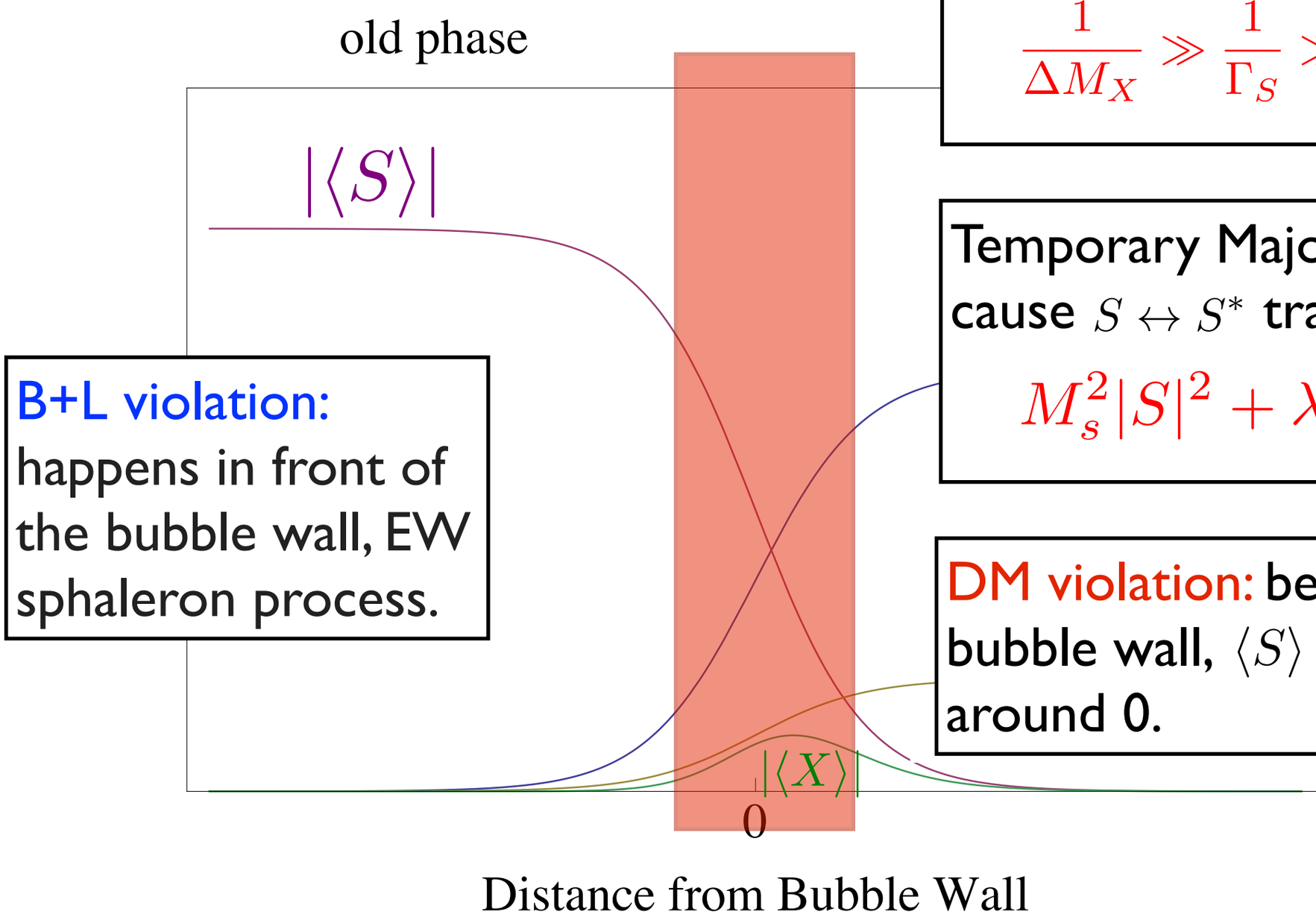
Processes on the wall



Time scales

$$\frac{1}{\Delta M_X} \gg \frac{1}{\Gamma_S} \gg \frac{1}{\Delta M_s}$$

Temporary Majorana mass, cause $S \leftrightarrow S^*$ transition

$$M_s^2|S|^2 + \lambda_s \langle S^*\rangle^2 S^2$$

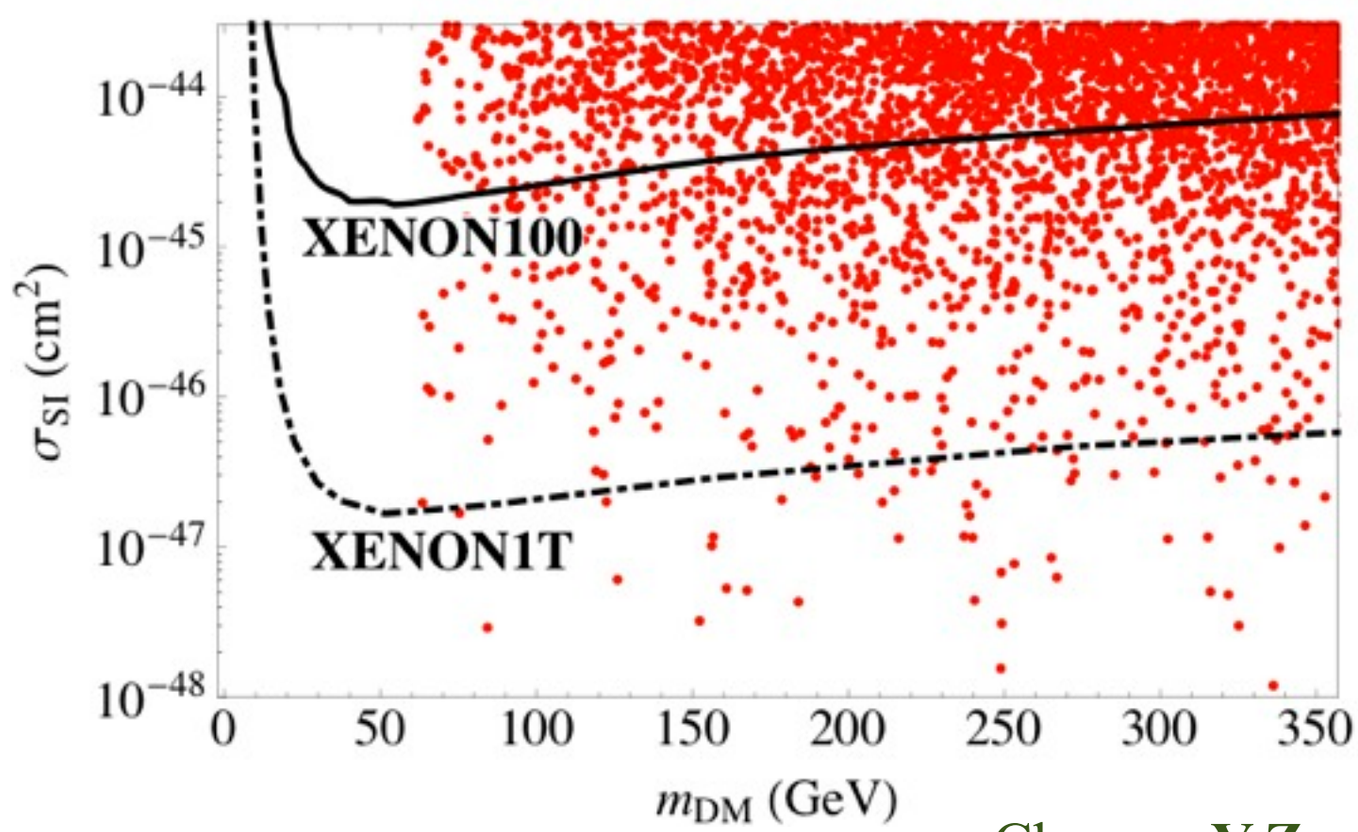
B+L violation: happens in front of the bubble wall, EW sphaleron process.

DM violation: behind the bubble wall, $\langle S\rangle$ oscillates around 0.

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

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 tests at colliders.
- New source of CP violation at electroweak scale.
- We construct a simple model of Electroweak Cogenesis. Make a stronger case for studying CPV associated with the Higgs boson.

Thank you!