Effective field theory, electric dipole moments and electroweak baryogenesis

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4th International Workshop on
Dark Matter, Dark Energy and Matter-Antimatter Asymmetry

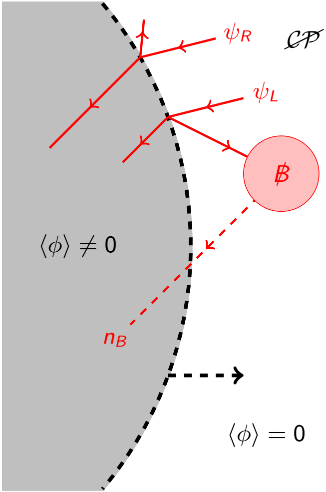
based on: work with C. Balazs (Monash U)
and
G. White (Monash U)

hep-ph/1612.01270

Outline

1. Electroweak baryogenesis
2. Bridge between BAU and EDM
3. Lifting degeneracies due to EoM
4. Example with two operators

Electroweak Baryogenesis



- Many papers to explain[a]

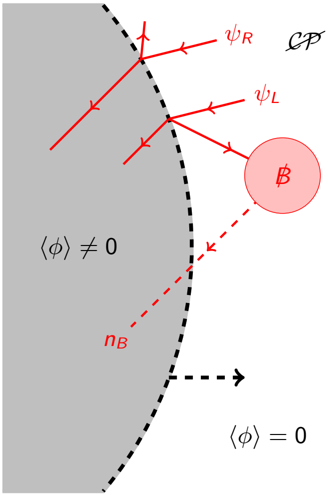
$$\frac{n_B}{s} = (8.59 \pm 0.11) \times 10^{-11} (Planck)$$

- Baryogenesis at the electroweak phase transition[b]

[a] P. A. R. Ade *et al.* [Planck Collaboration], Astron. Astrophys. **571** (2014) A16

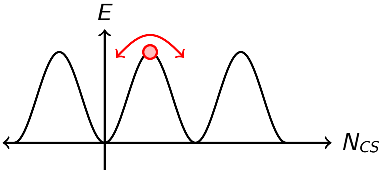
[b] V. A. Kuzmin *et al.*, Phys. Lett. B **155** (1985) 36;
G. R. Farrar and M. E. Shaposhnikov, Phys. Rev. Lett. **70** (1993) 2833;
P. B. Arnold and O. Espinosa, Phys. Rev. D **47** (1993) 3546;
G. W. Anderson and L. J. Hall, Phys. Rev. D **45** (1992) 2685.

Electroweak Baryogenesis



- $\not{B}$ must occur via non-perturbative effects

$$\partial_\mu j_B^\mu = \partial_\mu j_L^\mu = n_f \left(\frac{g_2^2}{32\pi^2} \mathrm{Tr}\, \mathbf{W}_{\mu\nu} \tilde{\mathbf{W}}^{\mu\nu} \right)$$

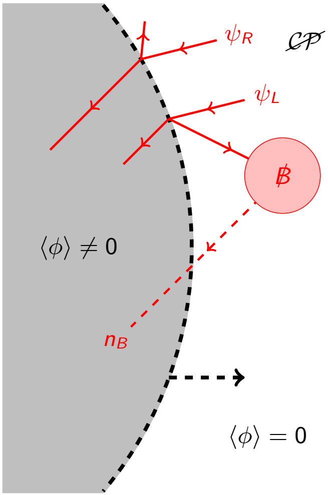


$$N_{CS}(t) := \frac{g_2}{32\pi^2} \int d^3x\ \epsilon^{ijk} \mathrm{Tr} \left(\mathbf{W}_i \partial_j \mathbf{W}_k + \frac{2i}{3} \mathbf{W}_i \mathbf{W}_j \mathbf{W}_k \right)$$

- Instanton suppression lifted by thermal effects

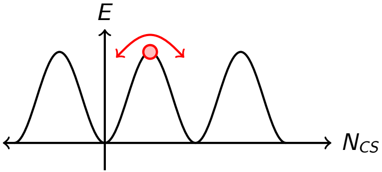
$$E_{sph}(T = 0) \sim (5\ \mathrm{TeV}) B \left(\frac{\lambda}{g_2^2} \right)$$

Electroweak Baryogenesis



- $\not{B}$ must occur via non-perturbative effects

$$\Delta_B = \Delta_L = n_f(N_{CS}(t_f) - (N_{CS}(t_i))$$



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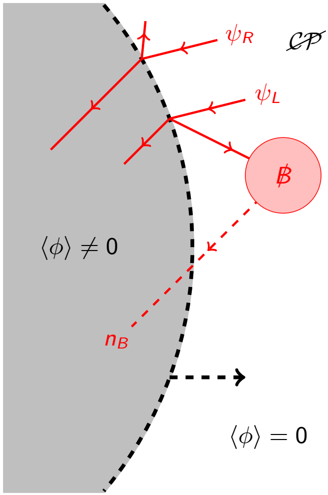
Electroweak Baryogenesis



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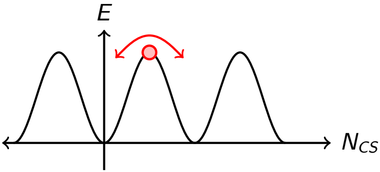

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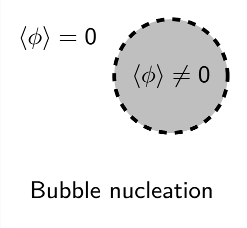
- Sphaleron decoupling in Higgs phase

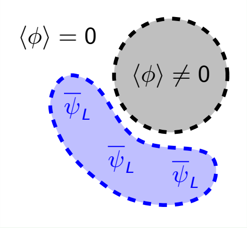
$$\Gamma(T_c) = e^{-\frac{E_{sph}(T_c)}{T_c}} < 1.66 \frac{\sqrt{g_*(T)}}{M_P} T_c^2 = H(T_c)$$

Electroweak Baryogenesis

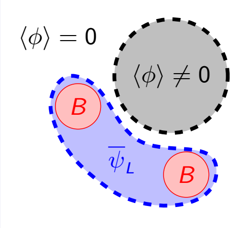
First order phase transition



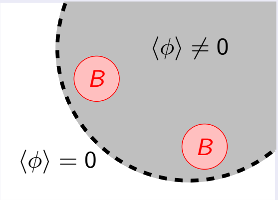
$\mathcal{CP}$ and $\mathcal{C}$ violation



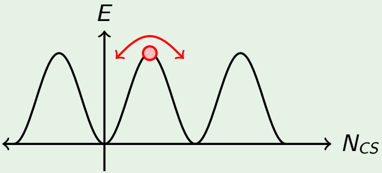
B asymmetry



Bubble expansion



$B + L$ violation with EW Sphaleron

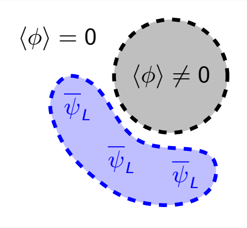


Electroweak Baryogenesis

First order phase transition

$m_h < 72$ GeV

$\mathcal{CP}$ and $\mathcal{C}$ violation



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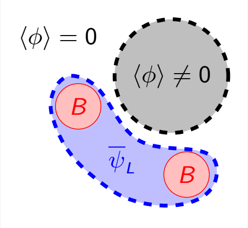

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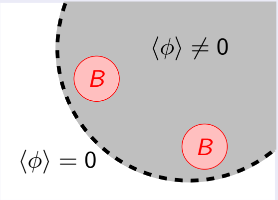

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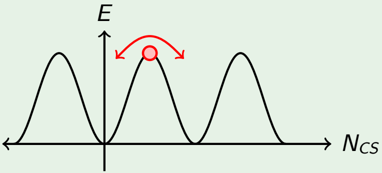

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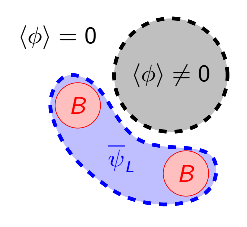
$\mathcal{CP}$ and $\mathcal{C}$ violation

Insufficient CKM

B asymmetry



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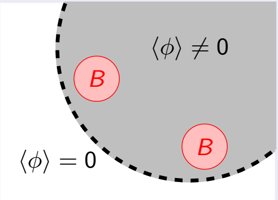

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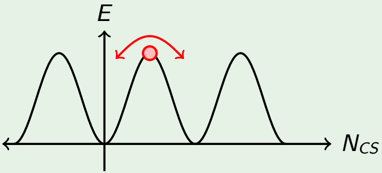

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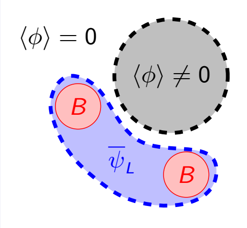

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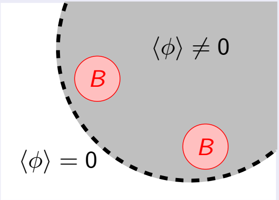


$B + L$ violation with EW Sphaleron

$$\frac{v(T_c)}{T_c} \gtrsim 1.1$$

$$m_h \lesssim 35 \text{ GeV}$$

EDM and EFT

SM Effective Field Theory

- Using higher dimensional operators

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{c_{CPV}}{\Lambda^2_{CPV}}\mathcal{O}_{D=6,\rm CPV} + \frac{c_{SFOPT}}{\Lambda^2_{SFOPT}}\mathcal{O}_{D=6,\rm SFOPT} + \ldots$$

- Enhance strength of the 1st order phase transition[a,b] ($\Lambda < 800$ GeV)

$$\mathcal{O}_6 = \frac{1}{\Lambda^2}(H^\dagger H)^3$$

- $\mathcal{CP}$-violation[b,c]

$$\mathcal{O}_{t\bar{t}h} = \frac{1}{\Lambda^2}(H^\dagger H)\overline{Q}_L H t_R$$

[a] C. Grojean *et al.*, Phys. Rev. D **71** (2005) 036001; S. W. Ham and S. K. Oh, Phys. Rev. D **70** (2004) 093007; C. Delaunay, C. Grojean and J. D. Wells, JHEP **0804** (2008) 029; P. Huang *et al.*, Phys. Rev. D **93** 055049 (2016)

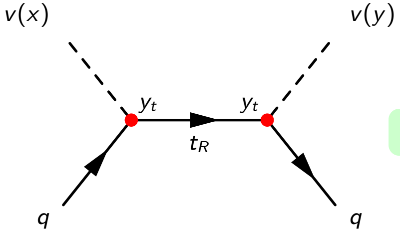
[b] D. Bodeker *et al.*, JHEP **0502** (2005) 026; L. Fromme and S. J. Huber, JHEP **0703** (2007) 049; T. Konstandin, Phys. Usp. **56** (2013) 747,S. J. Huber, M. Pospelov and A. Ritz, Phys. Rev. D **75** (2007) 036006; F. P. Huang *et al.* Phys. Rev. D **93** 103515 (2016)

[c] J. Shu and Y. Zhang, Phys. Rev. Lett. **111** (2013) 9, 091801

CPV sources in BAU

- most important — species strongly coupled to the SM Higgs i.e. gauge bosons, top quark

- Focus attention to top-Higgs interactions with vev insertion approximation[a]



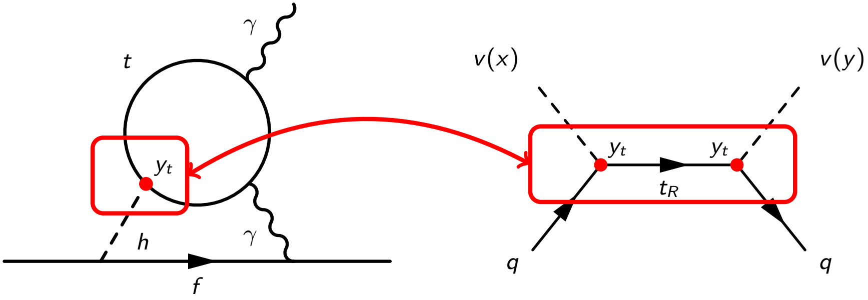
$$\mathcal{L} \supset y_t \overline{Q}_L \tilde{H} t_R, \qquad y_t \in \mathbb{C}$$

$$\partial^\mu_X j_{\psi,\mu} = \int d^3\mathbf{z} \int_{-\infty}^{T} dz^0 \mathrm{Tr}\left[\Sigma^>_\psi(X,z) G^<_\psi(z,X) - G^<_\psi(z,X)\Sigma^>_\psi(X,z) + (X \leftrightarrow z)\right]$$

[a] A. Riotto, Nucl. Phys. B **518** (1998) 339; A. Riotto, Phys. Rev. D **58** (1998) 095009

Direct connection between EDM and CPV-source for BAU[a]

$$\mathcal{L}_{\text{EDM}} = -i d_f \bar{f} \gamma^5 \sigma^{\mu\nu} f F_{\mu\nu}.$$



[a] K. Fuyuto, J. Hisano and E. Senaha, Phys. Lett. B **755** (2016) 491 ; S. J. Huber, M. Pospelov and A. Ritz, Phys. Rev. D **75** (2007) 036006; J. Shu and Y. Zhang, Phys. Rev. Lett. **111** (2013) 091801; X. Zhang and B. L. Young, Phys. Rev. D **49** (1994) 563

EDM constraints

- Current Limits

Type	Molecule/Atom	90% C.L. Bounds
Paramagnetic	^{205}Tl	$\lvert d_{\mathrm{Tl}}\rvert < 1.6 \times 10^{-27}$ e cm[a]
Diamagnetic	^{199}Hg	$\lvert d_{\mathrm{Hg}}\rvert < 6.2 \times 10^{-30}$ e cm[b]
Neutron	n	$\lvert d_n\rvert < 3.0 \times 10^{-26}$ e cm[c]
Electron (ThO)	e	$\lvert d_e\rvert < 8.7 \times 10^{-29}$ e cm[d]

[a] B. C. Regan *et al.*, PRL **88** (2002) 071805

[b] W. C. Griffith *et al.*, PRL **102** (2009) 101601

[c] C. A. Baker *et al.*, PRL **97** (2006) 131801; J. .M. Pendlebury *et al.*, Phys. Rev. D **92** (2015) 092003

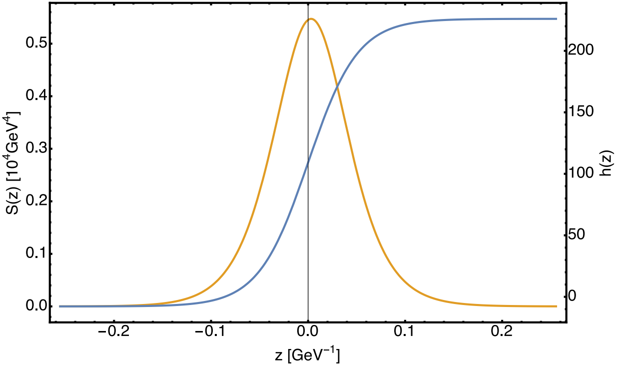
[d] J. Baron *et al.* [AMCE collaboration] Science **343** (2014) 269

Effective description of Strongly First Ordered EWPT

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \frac{c_{CPV}}{\Lambda^2_{CPV}} \mathcal{O}_{D=6,\text{CPV}} + \sum_{n,m \in \mathbb{N}} \frac{c_{n,m}}{\Lambda^n_m} \mathcal{O}^{(m)}_{\Delta V, D=4+n}$$

- Paramaterise SFOPT by v_w , L_w and $\frac{v_t(T_c)}{T_c}$ with Higgs profile:

$$h(z) = v_f + \frac{v_t - v_f}{2} \left[1 + \tanh\left(\frac{z}{L_w}\right)\right]$$



Lifting EoM degeneracies in EFTs

- Use a reduced basis[a] using equations of motion

$$\mathcal{O}_{DD} = \overline{Q}_L t_R \boxed{D^\mu D_\mu \tilde{H}}$$

- CP-violating source

$$S^{\not{CP}}_{\mathcal{O}_{DD}} \sim \frac{1}{\Lambda^2}\left[v(x)\partial_t\left(\boxed{\partial_\mu\partial^\mu v(x)}\right) - \partial_t v(x)\left(\boxed{\partial_\mu\partial^\mu v(x)}\right)\right]$$

[a] B. Grzadkowski *et al.*, JHEP **1010** (2013) 085; J. M. Yang and B. L. Young, Phys. Rev. D **56** (1997) 5907; K. Whisnant *et al.* Phys. Rev. D **56** (1997) 467; J. A. Aguilar-Saavedra, Nucl. Phys. B **821** (2009) 215

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$$\left[-\frac{\partial \mathcal{L}_{\rm SM}}{\partial H^\dagger} + \sum_{n,m} \frac{c_{n,m}}{\Lambda_m^n} \mathcal{O}^{(m)}_{\Delta V, D=4+n} \right]$$

$$H\left(\mu^2 - \lambda H^\dagger H\right) - \epsilon\left(\overline{L} Y_e e_R\right) - \epsilon\left(\overline{u}_R Y_u^\dagger Q\right) - \epsilon\left(\overline{Q}_i Y_d^\dagger d_R\right) + \mathcal{O}\left(\Lambda^{-2}\right) .$$

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$$\left. \frac{\partial V_{\rm SM}}{\partial H} \right|_{v(x)}$$

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- CP-violating source may have important contribution from $\mathcal{O}(\Lambda^{-2})$ terms

$$S^{\not{CP}}_{\mathcal{O}_{DD}} \sim \frac{1}{\Lambda^2}\left[v(x)\partial_t\left(\partial_\mu\partial^\mu v(x)\right) - \partial_t v(x)\left(\partial_\mu \partial^\mu v(x)\right)\right] + \mathcal{O}(\Lambda^{-2})$$

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Operators

- Higher derivative classes[a]

H^6, H^4D^2, H^2D^4, FH^2D^2, ψ^2H^3, F^2H^2, ψ^2H^2D, ψ^2HD^2, ψ^2HF, F^2D^2, ψ^4, ψ^2DF, F^3.

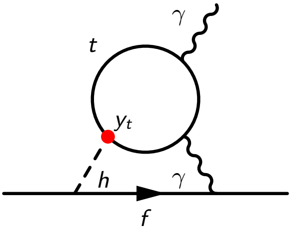
- Concentrate on the top-Higgs sector

ψ^2H^3		ψ^2H^2D		ψ^2HD^2	
$\mathcal{O}_{t1}$	$\left(H^\dagger H\right)\left(\overline{Q}_L\tilde{H}t_R\right)$	$\mathcal{O}_{Hq}^{(1)}$	$\left(H^\dagger i\overleftrightarrow{D}_\mu H\right)\left(\overline{Q}_L\gamma^\mu Q_L\right)$	$\mathcal{O}_{\sigma DD}$	$\left(\overline{Q}_L\sigma^{\mu\nu}t_R\right)D_\mu D_\nu\tilde{H}$
		$\mathcal{O}_{Hq}^{(3)}$	$\left(H^\dagger i\overleftrightarrow{D}^i_\mu H\right)\left(\overline{Q}_L\gamma^\mu\tau^i Q_L\right)$	$\mathcal{O}_{\sigma DD}$	$\left(\overline{Q}_L\sigma^{\mu\nu}\overleftrightarrow{D}_\mu t_R\right)D_\nu\tilde{H}$
		$\mathcal{O}_{Ht}$	$\left(H^\dagger i\overleftrightarrow{D}_\mu H\right)\left(\overline{t}_R\gamma^\mu t_R\right)$	$\mathcal{O}_{DD}$	$\left(\overline{Q}_L t_R\right)D^\mu D_\mu\tilde{H}$
				$\mathcal{O}_{DtDH}$	$\left(\overline{Q}_L\overleftrightarrow{D}_\mu t_R\right)D^\mu\tilde{H}$

[a] Momentum dependent non-renormalisable operators may be constrained by oblique parameters (cf. P. Huang *et al.*, Phys. Rev. D **93** (2016) 055049)

$\mathcal{O}_{t1}$

EDM bounds for $\mathcal{O}_{t1}$

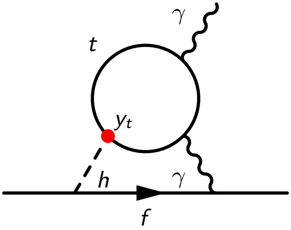


- Barr-Zee diagram[a]

$$\frac{d_e}{e} = \frac{16}{3}\frac{\alpha}{(4\pi)^3}\frac{m_e}{y_t^{SM}y_e^{SM}v^2}\times \left[y_e^S y_t^P f_1\left(\frac{m_t^2}{m_h^2}\right) + y_e^P y_t^S f_2\left(\frac{m_t^2}{m_h^2}\right)\right]$$

[a] C. Y. Chen *et al.*, JHEP **1506** (2015) 056; J. Brod *et al.*, JHEP **1311** (2013) 180; S. J. Huber *et al.*, Phys. Rev. D **75** (2007) 036006; K. Cheung *et al.*, JHEP **1406** (2014) 149; C. Lee, J. Phys. Conf. Ser. **69** (2007) 012036; S. Khatibi and M. M. Najafabadi, Phys. Rev. D **90** (2014) 7, 074014

EDM bounds for $\mathcal{O}_{t1}$



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- Extracting $y_t^{S,P}$ from $\mathcal{O}_{t1}$

$$\mathcal{L} \supset -\left(\alpha + \frac{c_{t1}}{\Lambda^2} H^\dagger H\right)\overline{Q}_L \tilde{H} t_R + h.c.$$

$$= -\underbrace{\frac{1}{\sqrt{2}}\left(\alpha + c_{t1}\frac{v^2}{\Lambda^2}\right)}_{m_t e^{i\xi_m}} v\,\bar{t}_L t_R - \underbrace{\left(\alpha + 3c_{t1}\frac{v^2}{\Lambda^2}\right)}_{y_t e^{i\xi_t}}\frac{h}{\sqrt{2}}\bar{t}_L t_R + h.c.$$

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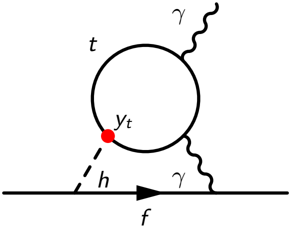

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- Rephase

$$y_t^S = y_t \cos\left(\xi_t - \xi_m\right)$$
$$y_t^P = y_t \sin\left(\xi_t - \xi_m\right)$$

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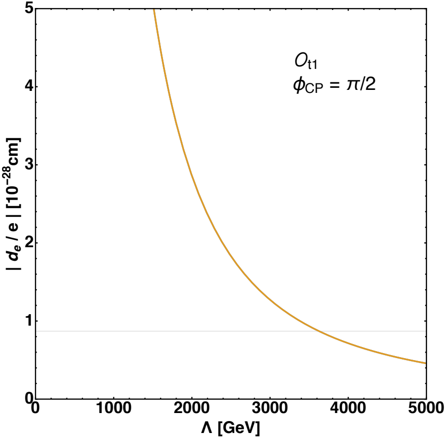
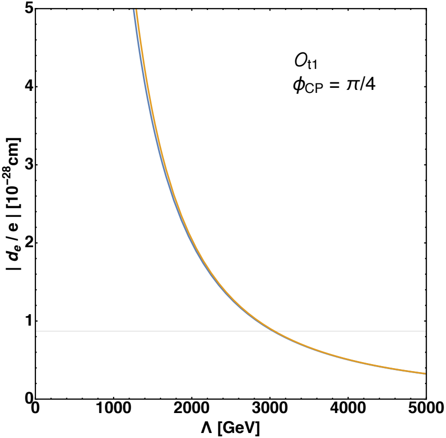
[a] C. Y. Chen *et al.*, JHEP **1506** (2015) 056; J. Brod *et al.*, JHEP **1311** (2013) 180; S. J. Huber *et al.*, Phys. Rev. D **75** (2007) 036006; K. Cheung *et al.*, JHEP **1406** (2014) 149; C. Lee, J. Phys. Conf. Ser. **69** (2007) 012036; S. Khatibi and M. M. Najafabadi, Phys. Rev. D **90** (2014) 7, 074014

BAU for $\mathcal{O}_{t1}$

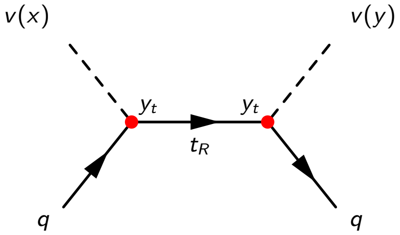




Some more on the CPV source

- Propagator[a] for fermions

$$\partial_X^\mu j_{\psi,\mu} = \int d^3\mathbf{z} \int_{-\infty}^{T} dz^0 \mathrm{Tr}\left[\Sigma_\psi^>(X,z)G_\psi^<(z,X) - G_\psi^<(z,X)\Sigma_\psi^>(X,z) + (X \leftrightarrow z)\right]$$



$$\Sigma_\psi(x,y) = \left(y_t v(x) + \frac{c_i}{\Lambda^2} v(x)^3\right)\left(y_t^* v(y) + \frac{c_i^*}{\Lambda^2} v(y)^3\right) \boxed{G_{t_R}(x,y)}$$

[a] G. A. White, *A Pedagogical Introduction to Electroweak Baryogenesis*, Morgan & Claypool Publishers (2016) IOP Concise Physics

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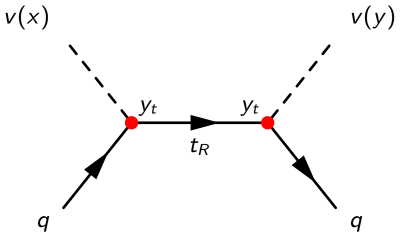

complicatedintegral$(m_{t_L}, m_{t_R}, \Gamma_{t_R}, \Gamma_{t_L}, \Lambda)$

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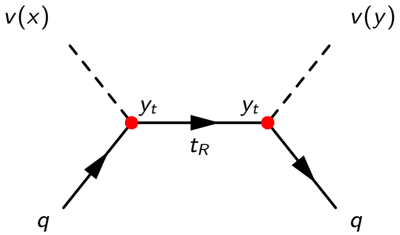
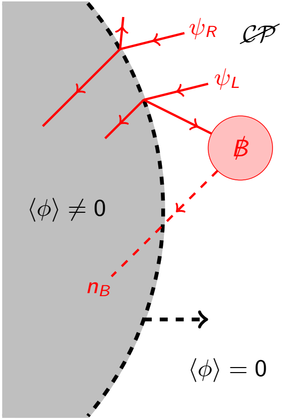


complicated[2] integral$(m_{t_L}, m_{t_R}, \Gamma_{t_R}, \Gamma_{t_L}, \Lambda)$

$$S_{\mathcal{O}_{t1}}^{\not{CP}} = 2\frac{v_w N_C}{\pi^2}\ \mathrm{Im}\left[\frac{c_i y_t^*}{\Lambda^2}\right] v(x)^3 v'(x)\, \mathcal{I}\left[m_{t_L}, m_{t_R}, \Gamma_{t_R}, \Gamma_{t_L}, \Lambda\right]$$

[a] G. A. White, *A Pedagogical Introduction to Electroweak Baryogenesis*, Morgan & Claypool Publishers (2016) IOP Concise Physics

Transport scenario



- Baryogenesis at the electroweak phase transition[a]

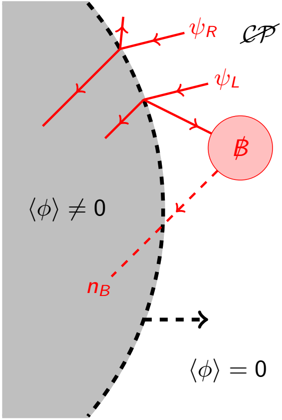
$$
\begin{aligned}
\partial_\mu Q^\mu &= \Gamma_M \left(\frac{T}{k_T} - \frac{Q}{k_Q}\right) + \Gamma_Y \left(\frac{T}{k_T} - \frac{Q}{k_Q} - \frac{H}{k_H}\right) \\
&\quad - 2\Gamma_{SS}\left(\frac{2Q}{k_Q} - \frac{T}{k_T} + \frac{9(Q+T)}{k_B}\right) - S^{\not{C}\not{P}}_{\mathcal{O}_{t1}}, \\
\partial_\mu T^\mu &= -\Gamma_M \left(\frac{T}{k_T} - \frac{Q}{k_Q}\right) - \Gamma_Y \left(\frac{T}{k_T} - \frac{Q}{k_Q} - \frac{H}{k_H}\right) \\
&\quad + \Gamma_{SS}\left(\frac{2Q}{k_Q} - \frac{T}{k_T} + \frac{9(Q+T)}{k_B}\right) + S^{\not{C}\not{P}}_{\mathcal{O}_{t1}}, \\
\partial_\mu H^\mu &= \Gamma_Y \left(\frac{T}{k_T} - \frac{Q}{k_Q} - \frac{H}{k_H}\right),
\end{aligned}
$$

- $n_L \to n_B$ conversion

$$
D_Q \rho_B'' - v_w \rho_B' - \Theta(-z)\frac{15}{4}\Gamma_{ws}\rho_B = \Theta(-z)\frac{n_F}{2}\Gamma_{ws} n_L
$$

[a] G. A. White, Phys. Rev. D **93** (2016) 043504

Transport scenario



- Baryogenesis at the electroweak phase transition[a]

$$X(z) = \begin{cases} \sum_{i=1}^{6} x_1 A_{X,b}(\alpha_i) e^{-\alpha_i z} \times \\ \quad \left(\int_0^z \mathrm{d}y \; e^{-\alpha_i y} S_{\mathcal{O}_{t1}}^{\not{C}\not{P}}(y) \right), & z > 0 \\ \sum_{i=1}^{6} y_1 A_{X,s}(\gamma_i) e^{\gamma_i z}, & z < 0 \end{cases}$$

- $n_L \to n_B$ conversion

$$D_Q \rho_B'' - v_w \rho_B' - \Theta(-z) \frac{15}{4} \Gamma_{ws} \rho_B = \Theta(-z) \frac{n_F}{2} \Gamma_{ws} n_L$$

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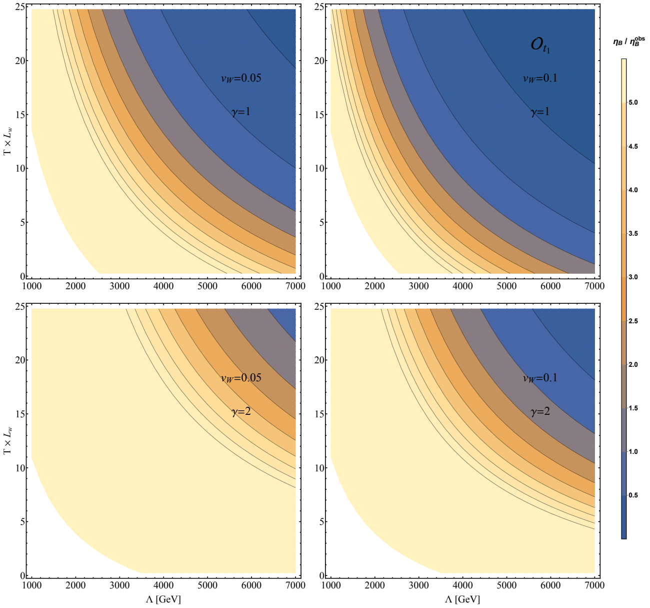
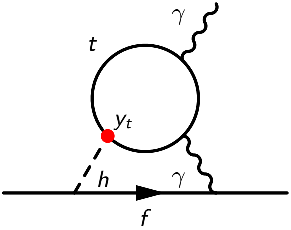
BAU for $\mathcal{O}_{t1}$



$\mathcal{O}_{DD}$

EDM bounds for $\mathcal{O}_{DD}$



- EOM at our disposal[a]:

$$\mathcal{O}_{DD} = \boxed{\overline{Q}_L \tilde{H} t_R \left(\mu^2 - \lambda H^\dagger H\right)} - \left(\overline{Q}_L t_R\right)_i \epsilon^{ij} \left(\overline{L} Y_e e_R + \overline{u}_R Y_u^\dagger Q_L + \overline{Q}_L Y_d^\dagger d_R\right)_j + \mathcal{O}\left(\Lambda^{-2}\right) .$$

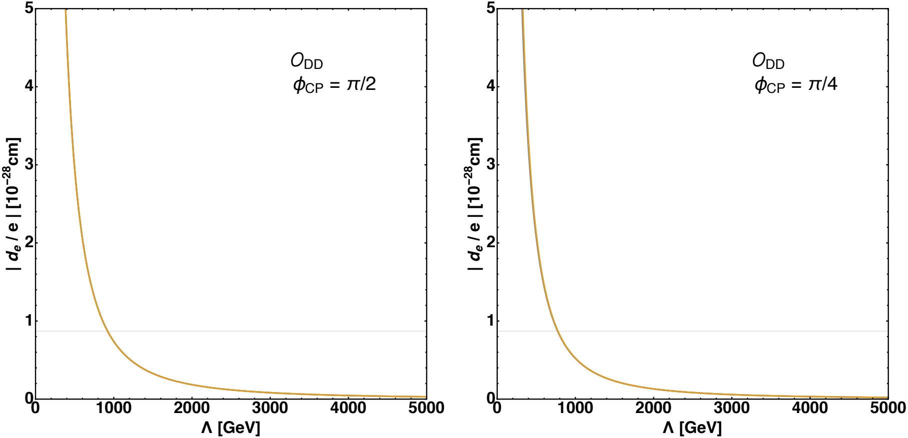
- Extracting $y_t^{S,P}$ from $\mathcal{O}_{t1}$

$$\mathcal{L} \supset -\left[\alpha + \frac{c_{DD}}{\Lambda^2}(\mu^2 - \lambda H^\dagger H)\right] \overline{Q}_L \tilde{H} t_R + h.c.$$

$$= -\underbrace{\frac{1}{\sqrt{2}}\left(\alpha + \frac{c_{DD}}{\Lambda^2}\left(\mu^2 - \frac{1}{2}\lambda v^2\right)\right)}_{m_t e^{i\xi_m}} v\, \overline{t}_L t_R - \underbrace{\left[\alpha + \frac{c_{DD}}{\Lambda^2}\left(\mu^2 - \frac{3}{2}\lambda v^2\right)\right]}_{y_t e^{i\xi_t}} \frac{h}{\sqrt{2}} \overline{t}_L t_R + h.c.$$

[a] Four-fermion operators to do not lead to sensitive observables, cf. V. Cirigliano *et al.* Phys. Rev. D **94** (2016) 034031

EDM constraints for $\mathcal{O}_{DD}$



CPV source for $\mathcal{O}_{DD}$

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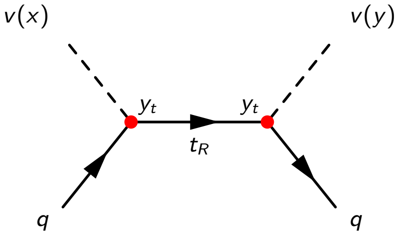

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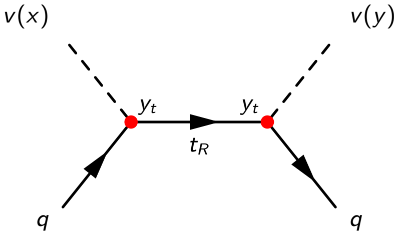

$$S_{\mathcal{O}_{DD}}^{\not{CP}} = \frac{v_w N_C}{\pi^2}\ \mathrm{Im}\left[\frac{c_i y_t^*}{\Lambda^2}\right]\left[v'''(x)v(x) - v''(x)v'(x)\right]\mathcal{I}\left[m_{t_L}, m_{t_R}, \Gamma_{t_R}, \Gamma_{t_L}, \Lambda\right]$$

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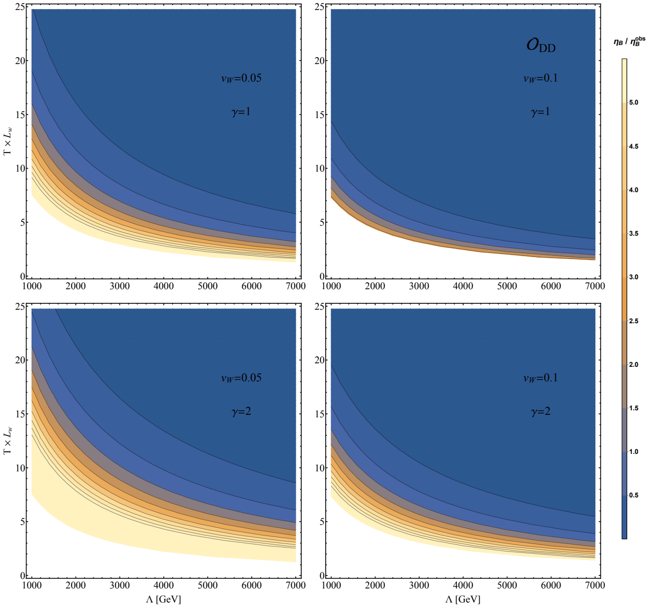
BAU for $\mathcal{O}_{DD}$



Future directions and speculations

- other derivative operators
- If heavy particle (which is integrated out) has parts of its mass coming from EWSB

$$\frac{1}{\Lambda^2} \to \frac{1}{\Lambda_0^2(T) + \Delta\Lambda^2(x)} \stackrel{!}{=} \frac{\lambda(x)}{\Lambda_0^2(T) + g^2 v^2(x)}$$

- Limit $\Lambda_0^{-1}(T) \to 0$ — no boost in BAU
- What about the other limit?

$$S_{\mathcal{O}_{t1}}^{\not{CP}} \sim v^2(x)\dot{\lambda}(x)\mathrm{Im}[y_t c_i^*]\mathcal{I}\,(m_{t_L}, m_{t_R}, \Gamma_{t_L}, \Gamma_{t_R}, \Lambda(x_i))$$

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!! take with a grain of salt

$$S_{2HDM}^{\not{CP}} \sim v^2(x)\dot{\beta}(x)\mathrm{Im}[y_{t_1} y_{t_2}^*]\mathcal{I}\,(m_{t_L}, m_{t_R}, \Gamma_{t_L}, \Gamma_{t_R}, \Lambda(x_i))$$

Conclusions

- EDMs are becoming more important in constraining CPV interactions
- Try to make direct bridge in the EFT framework
- Degeneracies due to EOMs broken by strongly 1st order PT when making such bridge

Thank you!