CoEPP

Effective field theory, electric dipole moments and electroweak baryogenesis [arXiv:1612.01270]

April 6, 2017

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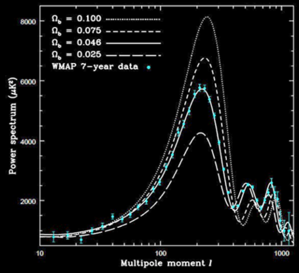
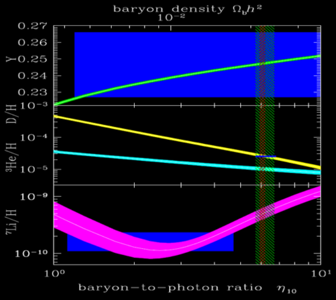
Electroweak Baryogenesis

Baryon abundance

$$\Omega_B = 0.0486 \pm 0.0011$$

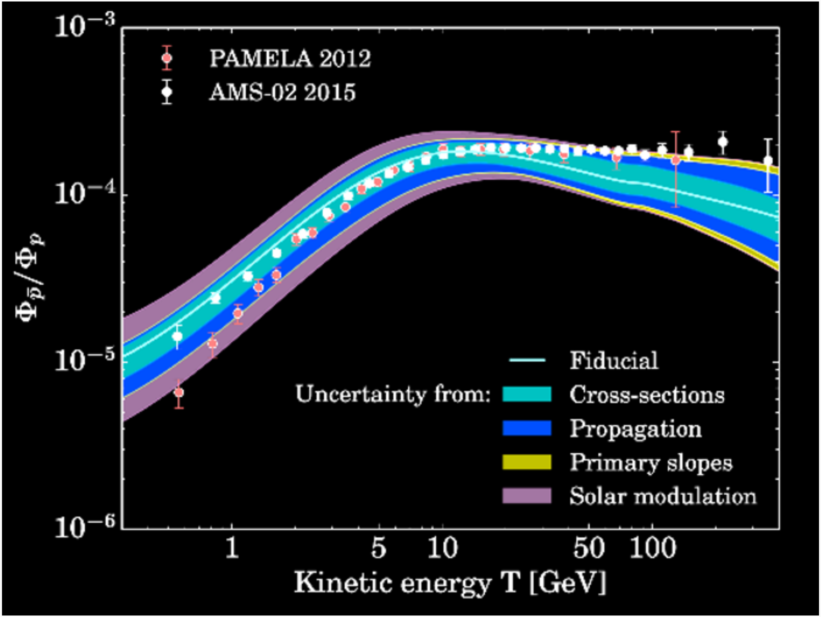


Garrett, Duda 2006



PDG 2014

Anti baryon abundance



Baryon asymmetry of the Universe

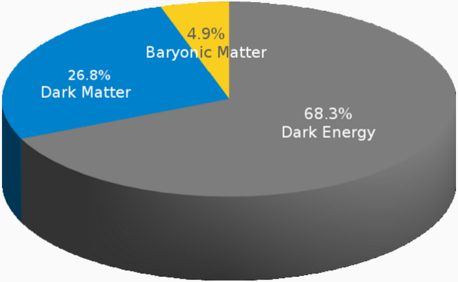
$$Y_B \approx \frac{n_B}{s} = 8.8 \times 10^{-11} >> 10^{-20} \quad (1)$$

Can it be an initial condition?

- Assume inflation occurs
- Assume constant entropy and planckian energy density before inflation
- inflation dilutes the BAU such that the maximum BAU after inflation is

$$Y_B^{\text{Max}} \approx 10^{-15} \tag{2}$$

Energy Budget of the Universe



- From a particle physics point of view understand a mere 4.9% of the Universe
- From a cosmology point of view we understand 0% of the Universe

Sakharov conditions

- B violation
- C and CP violation (CPV)
- Departure from equilibrium

Electroweak baryogenesis

- B violation $\longrightarrow$ Electroweak sphalerons
- C and CP violation $\longrightarrow$ Electroweak sphalerons convert P violation to C, CP violation occurs in CP violating phases.
- Departure from equilibrium $\longrightarrow$ Strongly first order electroweak phase transition (SFOEWPT)

Electroweak baryogenesis

- B violation $\longrightarrow$ Electroweak sphalerons
- C and CP violation $\longrightarrow$ Electroweak sphalerons convert P violation to C, CP violation occurs in CP violating phases.
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See my book for more details

G. A. White, "A Pedagogical Introduction to Electroweak Baryogenesis,

Electric Dipole moments

- Experimental test of CP violation
- Strongest experimental constraints on electroweak baryogenesis
- Precision is improving by orders of magnitude in a short period of time

Status of EWBG in standard model

Ruled out:

- EWPT is not SFO for $m_H \gtrsim 40$ GeV
- CP violation too feeble


THEORIES
PROOFS
S. Harris

Big Question

EFT has the powerful advantage of turning experimental data into model independent constraints.

Big question: *Is it possible to systematically apply EDM constraints to the EWBG paradigm?*

We will try this first with EFTs with some success.

Big picture

Standard model does not fulfil 2 Sakharov conditions:

- lack of CP violation
- No SFOEWPT

Assume Lagrangian of the form

$$L = L_{\mathrm{SM}} + \frac{1}{\Lambda_{\mathrm{CPV}}^2}\mathcal{O}^{\mathrm{CPV}} + \sum_{n,m}\frac{1}{\Lambda_m^n}\mathcal{O}_{n,m}^{\mathrm{SFOEWPT}} \tag{3}$$

Big picture

Standard model is inadequate in two ways:

- Lack of CP violation $\longrightarrow \mathcal{O}^{\rm CPV}$
- No SFOEWPT $\longrightarrow \mathcal{O}^{\rm SFOEWPT}$

To build a direct bridge between EDM constrains and EWBG

- sweep details of $\mathcal{O}^{\rm SFOEWPT}$ under rug
- assume a SFOEWPT where the Higgs profile has the form

$$h(z) = \frac{v(T)}{2} \tanh\left[\frac{z}{L_w}\right] \,. \tag{4}$$

- result is new physics responsible for SFOEWPT parametrized by nuisance parameters $L_w, v(T)$

A short tutorial on formalism

Reminder about CTP formalism

Recall equilibrium density matrix

$$\rho(0) = \frac{e^{-\beta H}}{\mathrm{Tr} e^{-\beta H}} \tag{5}$$

To evolve it in time

$$\rho(t) = U(t,0)\rho(0)U(t,0) \tag{6}$$

Note explicit form of U

$$U(t,t') = T\left[e^{-\int_{t'}^{t} dt'' H(t'')}\right] \tag{7}$$

Reminder about CTP formalism

Equilibrium density matrix can be written in terms of time evolution operators

$$\rho(0) = \frac{U(T - i\beta, T)}{\mathrm{Tr}U(T - i\beta, T)} \tag{8}$$

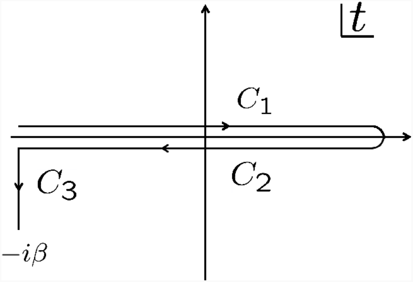
Time dependent expectation value is then

$$\begin{aligned} \langle A(t) \rangle &= \frac{\mathrm{Tr}U(t,0)U(T - i\beta, T)U(0,t)A}{\mathrm{Tr}U(T - i\beta, T)} \\ &= \frac{U(T - i\beta, T)U(T, T')U(T', t)AU(t, T)}{\mathrm{Tr}U(T - i\beta, T)U(T, T')U(T', T)} \end{aligned} \tag{9}$$

Reminder about CTP formalism

Partition function:

$$Z[\beta, \mathcal{J}_C] = \mathrm{Tr} U_{\mathcal{J}_C}(-\infty - i\beta, -\infty) U_{\mathcal{J}_C}(-\infty, T') U_{\mathcal{J}_C}(T', -\infty) \tag{10}$$



Propagators in CTP

Propagators now have 4 types

$$\Delta^T = \Delta^{++} = \frac{1}{p^2 - M^2 + i\epsilon} + \Delta_{\mathrm{FT}}^{++} \quad (11)$$

$$\Delta^{\bar{T}} = \Delta^{--} = -\frac{1}{p^2 - M^2 - i\epsilon} + \Delta_{\mathrm{FT}}^{--} \quad (12)$$

$$\Delta^{>} = \Delta^{-+} = \Delta_{\mathrm{FT}}^{-+} \quad (13)$$

$$\Delta^{<} = \Delta^{+-} = \Delta_{\mathrm{FT}}^{+-} \quad (14)$$

$$S^T = S^{++} = \frac{\not{p} + M}{p^2 - M^2 + i\epsilon} + S_{\mathrm{FT}}^{++} \quad (15)$$

$$S^{\bar{T}} = S^{--} = \frac{\not{p} + M}{p^2 - M^2 - i\epsilon} + S_{\mathrm{FT}}^{--} \quad (16)$$

$$S^{>} = S^{-+} = S_{\mathrm{FT}}^{-+} \quad (17)$$

$$S^{<} = S^{+-} = S_{\mathrm{FT}}^{+-} \quad (18)$$

Deriving transport equations

Take the Dyson-Schwinger equations

$$\begin{aligned}\tilde{G}(x,z) &= \tilde{G}^0(x,z) + \int d^4w d^y \tilde{G}(x,w)\tilde{\Sigma}(w,y)G^0(y,z) \quad (19)\\ \tilde{G}(x,z) &= \tilde{G}^0(x,z) + \int d^4w d^y \tilde{G}^0(x,w)\tilde{\Sigma}(w,y)G(y,z) \quad (20)\end{aligned}$$

Recipe:

- Act on first equation with $\Box_x + m^2$
- Act on second equation ith $\Box_z + m^2$
- Take the difference and the limit of $z = x$

Deriving transport equations

Take the Dyson-Schwinger equations

$$\tilde{G}(x,z) = \tilde{G}^0(x,z) + \int d^4w d^y \tilde{G}(x,w)\tilde{\Sigma}(w,y)G^0(y,z) \quad (21)$$

$$\tilde{G}(x,z) = \tilde{G}^0(x,z) + \int d^4w d^y \tilde{G}^0(x,w)\tilde{\Sigma}(w,y)G(y,z) \quad (22)$$

Result

- LHS is just $\partial_\mu J^\mu$
- Right hand side is just a function of the self energies

Transport equations: general form

$$\partial_\mu J_i^\mu = -\sum_j \Gamma^{ij}\mu_i + S_i^{CP} \ . \tag{23}$$

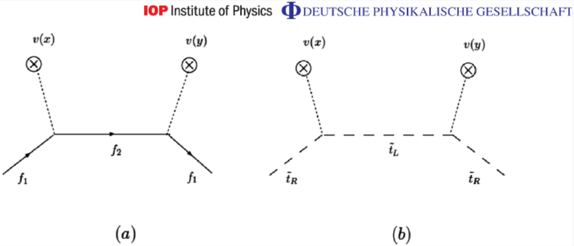
For the LHS use Ficks Law:

$$\partial_\mu J^\mu = v_w n' - D n'' \tag{24}$$

For the right hand side use

$$\mu_i \sim \frac{n}{k} \tag{25}$$

Mass term example



Self energy for stop example

$$\Sigma^{\lambda}(x,z) = -y_t^2\left(A_t v_u(x) - \mu^* v_d(x)\right)\left(A_t^* v_u(z) - \mu v_d(z)\right) S^{\lambda}(x,z) \quad (26)$$

Vev insertion approximation

"The VIA assumes that the particle-antiparticle asymmetry generation is dominated by the region near the phase boundary, where the vevs are small compared to both T and the difference $|m_{11}^2 - m_{22}^2|^{1/2}$."

S. Inoue, G. Ovanesyan and M. J. Ramsey-Musolf, Phys. Rev. D **93**, 015013 (2016) doi:10.1103/PhysRevD.93.015013 [arXiv:1508.05404 [hep-ph]].

Linking EDMs and EWBG with EFTs

Applying EFT to out of equilibrium QFT

Assume the correspondence

	Equilibrium	Non-equilibrium
Boson propagator	$\frac{1}{\Lambda^2} + \frac{\partial_\mu \partial^\mu}{\Lambda^4} + \cdots$	$\frac{1}{\Lambda^2} + \frac{\partial_\mu \partial^\mu}{\Lambda^4} + \cdots$
Fermion propagator	$\frac{1}{\Lambda} + \frac{\not{\partial}}{\Lambda^2} + \cdots$	$\frac{1}{\Lambda} + \frac{\not{\partial}}{\Lambda^2} + \cdots$
Loops	Λ^n	Λ^n
Expand around vev	v insertions	$v(z)$ insertions

Counting operators

Prerequisites

- Must involve only particles that have large SM couplings
  - Higgs
  - Top
  - Gauge bosons
- Must involve the Higgs for *resonant* CP violating sources

Counting operators

Types of operators

$$H^4D^2, \quad H^2D^4, \quad \psi^2H^3, \quad FH^2D^2, \quad F^2H^2, \\ \psi^2H^2D, \quad \psi^2HD^2, \quad \psi^2HF. \tag{27}$$

34 operators in total.

EFT and CPV sources

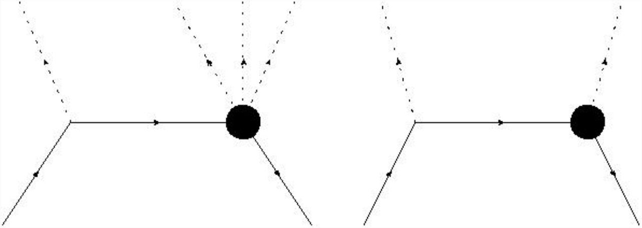
Consider two operators that fulfil our criteria but are normally degenerate

$$\mathcal{O}_{t1} = \left(H^\dagger H\right)\left(\bar{Q}_L \tilde{H} t_R\right) \quad (28)$$

$$\mathcal{O}_{DD} = \left(\bar{Q} t_R\right)\left(D_\mu D^\mu \tilde{H}\right) \quad (29)$$

EFT and CPV sources

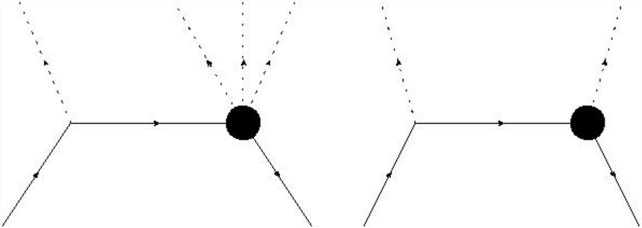
For $\mathcal{O}_{t1}$ and $\mathcal{O}_{DD}$ respectively



Interference with top-vev insertion diagram

EFT and CPV sources

For $\mathcal{O}_{t1}$ and $\mathcal{O}_{DD}$ respectively



Following our recipe for out of equilibrium EFT gives

$$\Sigma_{\mathcal{O}_{t1}} = \left(y_t v(x) + \frac{c_i}{\Lambda^2} v(x)^3\right)\left(y_t^* v(z) + \frac{c_i^*}{\Lambda^2} v(z)^3\right) S(x,z)$$

$$\Sigma_{\mathcal{O}_{DD}} = \left(y_t v(x) + \frac{c_i}{\Lambda^2} \partial_\mu \partial^\mu v(x)\right)\left(y_t^* v(z) + \frac{c_i^*}{\Lambda^2} \partial_\mu \partial^\mu v(z)\right) S_{t_R}(x,y)$$

EFT and CPV sources

Grinding through the algebra gives

$$S^{CP}_{\mathcal{O}_{t1}} = 2\frac{v_w N_C}{\pi^2}\text{Im}\left[\frac{c_i y_t^*}{\Lambda^2}\right] v(x)^3 v'(x) I\left[m_{t_L}, m_{t_R}, \Gamma_{t_R}, \Gamma_{t_L}, \Lambda\right] \ , \tag{30}$$

$$S^{CP}_{\mathcal{O}_{DD}} = \frac{v_w N_C}{\pi^2}\text{Im}\left[\frac{c_i y_t^*}{\Lambda^2}\right]\left[v'''(x)v(x) - v''(x)v'(x)\right] \times I\left[m_{t_L}, m_{t_R}, \Gamma_{t_R}, \Gamma_{t_L}, \Lambda\right] \ . \tag{31}$$

Degeneracy of operators

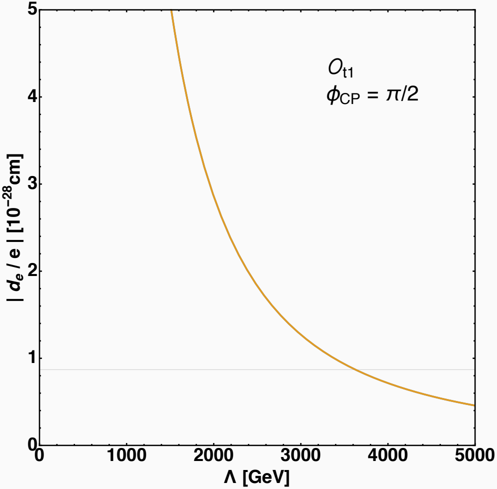
Two supposedly degenerate operators have qualitatively different dependency on

- Wall width (L_w)
- Phase transition strength ($v(T)/T$)

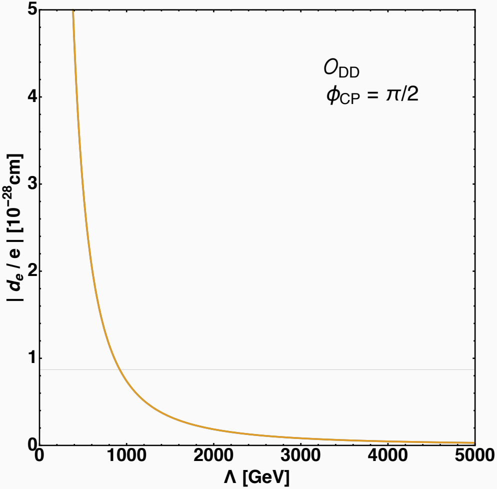
Something has to give either:

- Operator degeneracies involving Higgs fields are lifted during the electroweak phase transition
- There is something incorrect about the recipe of how to apply EFTs during a phase transition

$\mathcal{O}_{T_1}$ EDM constraints

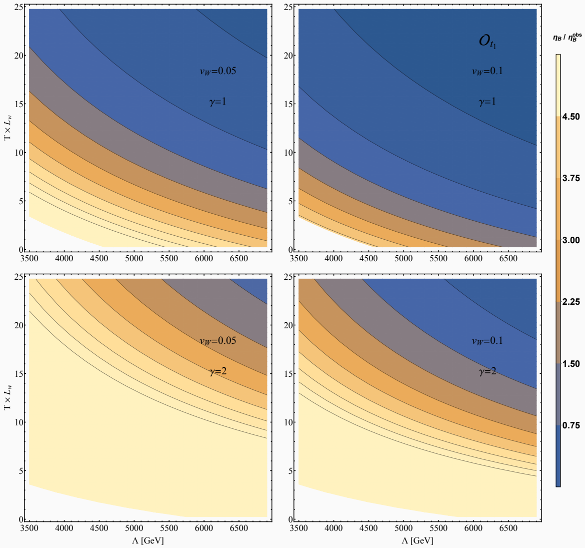


$\mathcal{O}_{DD}$ EDM constraints

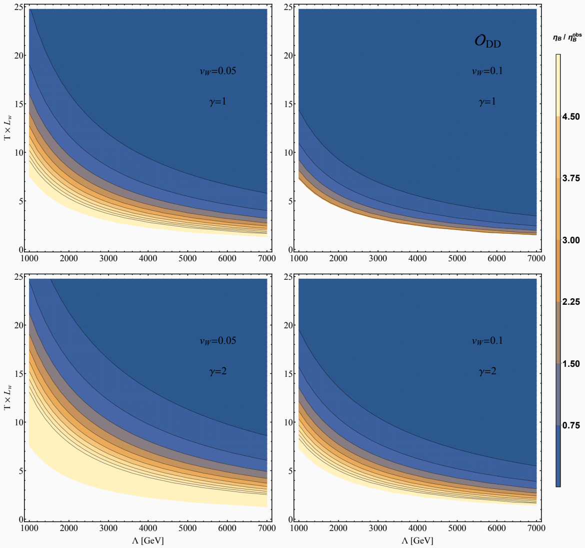


Results

Results for non-derivative operator



Results for derivative operator



Skepticism

Is this real?

- Can the cutoff really be that high?
  - EW phase transition requires new particles at $\lesssim 1$ TeV
  - EWBG usually requires particles involved in CPV sources to be a few hundred GeV at most
  - Boltzmann suppression is the villain in both cases
- What is happening with the degeneracy?

Ease your Skepticism for now

Is this real?

- Can the cutoff really be that high? Yes! Boltzmann suppression only affects FT piece
  - EW phase transition requires new particles at $\lesssim 1$ TeV
  - EWBG usually requires particles involved in CPV sources to be a few hundred GeV at most
  - Boltzmann suppression is the villain in both cases
- What is happening with the degeneracy? Not sure! But there do appear to be UV completions that demonstrate this effect

UV completion

Reminder about propagators of heavy particles

$$\begin{aligned}
\Delta^{++} &\approx \frac{1}{M^2} + \mathcal{O}\left(\exp[-M/T]\right) && (32)\\
\Delta^{--} &\approx -\frac{1}{M^2} + \mathcal{O}\left(\exp[-M/T]\right) && (33)\\
\Delta^{-+} &\approx \mathcal{O}\left(\exp[-M/T]\right) && (34)\\
\Delta^{+-} &\approx \mathcal{O}\left(\exp[-M/T]\right) && (35)\\
S^{++} &\approx \frac{1}{M} + \mathcal{O}\left(M\exp[-M/T]\right) && (36)\\
S^{--} &\approx \frac{1}{M} + \mathcal{O}\left(M\exp[-M/T]\right) && (37)\\
S^{-+} &\approx \mathcal{O}\left(M\exp[-M/T]\right) && (38)\\
S^{+-} &\approx \mathcal{O}\left(M\exp[-M/T]\right) && (39)
\end{aligned}$$

Finite temperature parts are Boltzmann suppressed

Relevance to EW phase transition

Consider ϕ^4 theory. One loop correction to effective potential at finite temperature is

$$\begin{aligned} \frac{\partial \Delta V_1}{\partial m^2(\phi)} &= \frac{1}{2}\int \frac{d^4p}{(2\pi)^2}\Delta^{++}(p) \\ \rightarrow \quad \Delta V_1 &= \Delta_{\text{CW}} + \Delta_{\text{FT}} \, . \end{aligned} \tag{40}$$

- Its difficult to catalyze a SFOEWPT through CW corrections
- Can do it through thermal corrections which are always Boltzmann suppressed
- Can also do it through changing the angle of PT.
  - This becomes more difficult as ancillary particle gets heavy.

Relevance to CP violating sources

Particle current divergences related to self energy

$$\partial_\mu J^\mu(x) = \int d^4y G^{+-}(x,y)\Sigma^{-+}(y,x) + \cdots \tag{41}$$

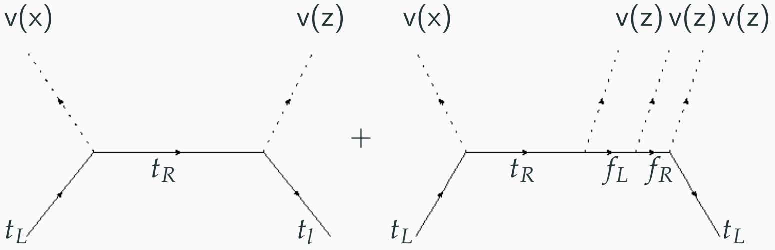
- All propagators and self energies on RHS are either $+-$ or $-+$
- Therefore in state must have a mass $\mathcal{O}(T)$!
- Heavy particles can only contribute to CPV sources if it is in self energy

Example one of EFT and CTP

Toy model*

$$L \sim y_t \bar{t}_L t_R H + g_t \bar{t}_L f_R H + g_H \bar{f}_L f_R H + \cdots \qquad (42)$$

interference with top vev insertion leads to CPV source



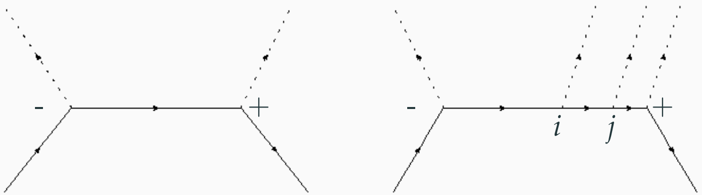
Note: if f_R has SU(2) then a tree level mass term is allowed.

Example one of EFT and CTP

Toy model

$$L \sim y_t \bar{t}_L t_R H + g_t \bar{t}_L f_R H + g_H \bar{f}_L f_R H + \cdots \qquad (43)$$

Lets look just at the propagators. Let $\{i, j\} \in \{\pm\pm\}$

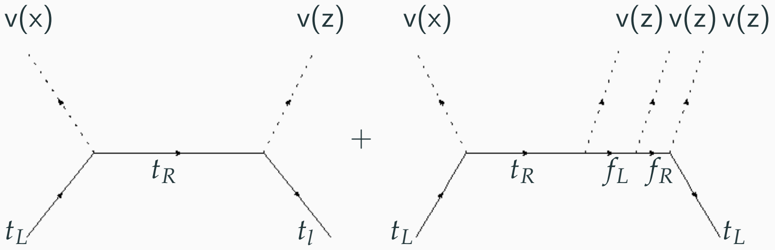


Example one of EFT and CTP

Self energy is

$$\Sigma_1^{-+} = |y_t|^2 v(x)v(z)S_{t_R}^{-+} \tag{44}$$

$$\begin{aligned}\Sigma_2^{-+} &= y_t|g_t|^2 g_H v(x)v(z)^3 \Big[S_{t_R}^{-+}S_{f_L}^{++}S_{f_R}^{++} + S_{t_R}^{--}S_{f_L}^{-+}S_{f_R}^{++} \\ &\quad + S_{t_R}^{--}S_{f_L}^{--}S_{f_R}^{-+} + S_{t_R}^{-+}S_{f_L}^{+-}S_{f_R}^{-+}\Big] \\ &\approx \frac{y_t|g_t|^2 g_H v(x)v(z)^3}{M_H^2}S_{t_R}^{-+} + \cdots \end{aligned} \tag{45}$$



Example one of EFT and CTP

Self energy is

$$\Sigma_1^{-+} = |y_t|^2 v(x) v(z) S_{t_R}^{-+} \tag{46}$$

$$\begin{aligned}\Sigma_2^{-+} &= y_t |g_t|^2 g_H v(x) v(z)^3 \Big[S_{t_R}^{-+} S_{f_L}^{++} S_{f_R}^{++} + S_{t_R}^{--} S_{f_L}^{-+} S_{f_R}^{++} \\ &\quad + S_{t_R}^{--} S_{f_L}^{--} S_{f_R}^{-+} + S_{t_R}^{-+} S_{f_L}^{+-} S_{f_R}^{-+} \Big] \\ &\approx \frac{y_t |g_t|^2 g_H v(x) v(z)^3}{M_H^2} S_{t_R}^{-+} + \cdots \end{aligned} \tag{47}$$

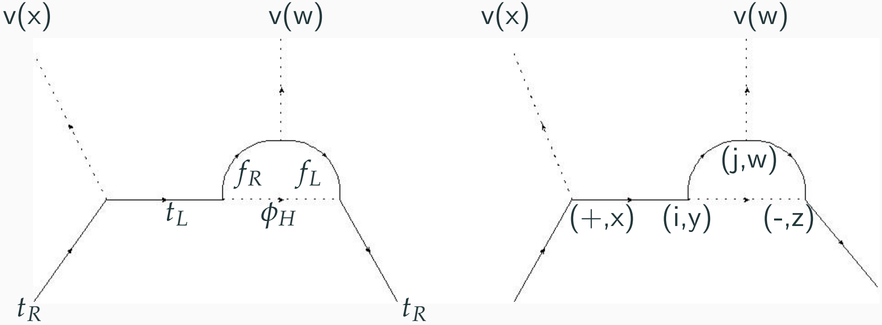
So this looks like the effective operator

$$\mathcal{O}_{t1} = \left(H^\dagger H \right) \left(\overline{Q}_L \tilde{H} t_R \right) \tag{48}$$

Derivative coupling

another toy model*

$$\mathcal{L} \ni y_\phi \phi_H \bar{f}_L t_R + y_H \phi_H \bar{f}_L f_R + \mu_H^2 \phi_H^2 \tag{49}$$



**Comment:* The heavy scalar has SU(2) so it must have a tree level mass ($\mu_H^2 > 0$).

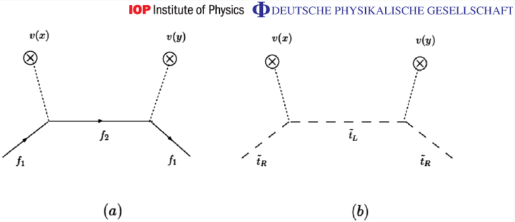
Derivative coupling

The term with $i = +$ is Boltzmann suppressed.
Just have the $i = j = -$ term which can be approximated by $\partial_\mu \partial^\mu / M_\phi^2$ Gives the effective operator

$$\mathcal{O}_{DD} = \bar{t}_L t_R D_\mu D^\mu H \tag{50}$$

Weak scale CP violating sources

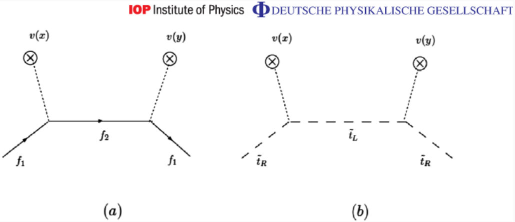
Consider Diagram



- This diagram will produce an effective operator relevant to EDM constraints
- *But!* None of these states can be heavy compared to weak scale if it contributes to EWBG (all propagators are $\pm\mp$)
- In other words there are cases where $\Lambda_{\rm QCD} << \Lambda_{\rm CPV}$ but $\Lambda_{\rm CPV} \sim \Lambda_{\rm EW}$

Weak scale CP violating sources

Consider Diagram



- So EFT-EWBG does not build a direct bridge between EDM constraints on CPV operators and *all* possible UV completions relevent to EWBG
- Actually it captures a class of CP violating sources not usually considered in the literature

Outlook and conclusions

EFT-EWBG Summary

Summary:

1 We found in our paper that the cutoff scale can be pretty high

2 This does not contradict other results that have $\Lambda < 1$ TeV if you understand Boltzmann suppression.

3 It isn't obvious if all operators have a UV completion

4 The in state cannot be a heavy particle and you must produce a $\pm\pm$ heavy particle propagator in the self energy as well as no $\pm\mp$ heavy particle propagators

5 The first and last vertices must be $\pm$ and $\mp$ respectively

6 The effective field theory frame work (obviously) won't cover new weak scale particles

Answering the big question

Is it possible to systematically study EWBG using EDM constraints?

- For EFTs we continue to develop the paradigm starting with UV completion
- Perhaps this can be complimented with classes of simplified models (where you add a single particle to the SM and calculate the EWBG and tie it directly to experiment).

Conclusion

- EFTs seem to be able to link a class of EWBG models to experiment
- The cutoff can be quite high
- There are some technical questions about EFTs out of equilibrium that need to be better understood
- Are simplified models a complimentary approach?