CP violation: to infinity and beyond

Ben Gripaios

Cambridge

April 2018

CP violation: to infinity and beyond

- dimension 6 CPV in EFT ...
- ...and 7,8, ... ∞
- ...and beyond

a sisyphean task!

B. Lightyear, 1995

Outline

- What is *CP*?
- Why *CP* violation?
- How to seek and interpret *CP*V?

What is *CP*?

What is *CP*?!

$C : \phi \in \mathbb{R} \to \pm\phi, \phi \in \mathbb{C} \to \phi^*, \psi \to i\gamma^2\psi^* \ldots$

IMHO this is (a) wrong and (b) misses the point

QM vs relativistic QFT

- In QM, symmetries should preserve probabilities: (anti) linear/ unitary operators U
- In SR, the Minkowski metric is preserved by $x \to \Lambda x + a$
- In QFT, (a central extension of) Poincaré: $\exists U(\Lambda, a)$ s.t. $U(\Lambda', a')U(\Lambda, a) = U(\Lambda'\Lambda, \Lambda' a + a')$
- Connected $\implies \exists H, P^i, J^i, K^i$ s.t. $HP^i = P^i H, HJ^i = J^i H, HK^i \neq K^i H$:-)

Weinberg, Vol. I

Definition of P, T, C

- $U(\Lambda', a')U(\Lambda, a) = U(\Lambda'\Lambda, \Lambda' a + a')$
- Connected: $\det\Lambda = 1$ and $\Lambda^0_0 \geq 1$. Disconnected?
- Definition: $P = U(\Lambda, 0), \Lambda = \mathrm{diag}(+---)$ for which this is still true.
- ditto for T, but with $\Lambda = \mathrm{diag}(-+++)$
- For C, send particles into antiparticles

Rather implicit definition!

1. Does *CP* exist?
2. Is *CP* unique?

Does CP exist?

No!

- Existence $\implies (CP)H = H(CP)$
- Experiment: 1964
- Theory: No CP defined for $U(1)$ extends to $SU(2) \times U(1)$.

CP is an alternative fact, at best a convenient fiction:

A symmetry of QED; an approximate symmetry of SM

Is *CP* unique?

No!

- $\mathbb{R} \ni \phi(t,x) \to \pm\phi(t,x)$
- $\int dt d^3 x m_\phi \phi^2$
- $\mathbb{C} \ni \phi(t,x) \to \eta\phi(t,x), |\eta| = 1$
- $\int dt d^3 x m_\phi |\phi|^2$

Physically inequivalent, in general.

Why is *CP* violation interesting?

- It exists!
- Too big in the SM!
- Too small in the SM!

Why is *CP* violation interesting?

- It exists!
- Too big in the SM! cf EDM of n, e, Tl, Hg
- Too small in the SM! cf baryogenesis

Various measurements - BBN, CMB, ... - agree (roughly) that

$$\frac{n_B - n_{\overline{B}}}{n_\gamma} = 6 \times 10^{-10}$$

which requires (an odd initial condition or)

- *B*-violation
- *C*- and *CP*-violation
- non-thermal equilibrium

(These are necessary but not sufficient, cf. washout.)

- *B*-violation
- *C*- and *CP*-violation
- non-thermal equilibrium

These are all present in the SM, but not enough, given $m_h = 125$ GeV.

We need BSM and especially *CP*V BSM.

Before LEP and LHC & co. visited hubris upon us, we had lots of good ideas for baryogenesis

- SM with $m_h \ll 125$ GeV
- (N)MSSM
- GUT
- Affleck-Dine
- leptogenesis

(At least one of these still is a good idea!)

Now that we know that we don't know, let's return to a more ignorant approach …

How to seek and interpret CPV (in general purpose collider experiments)?

Kübler-Ross: The five stages of grief . . .

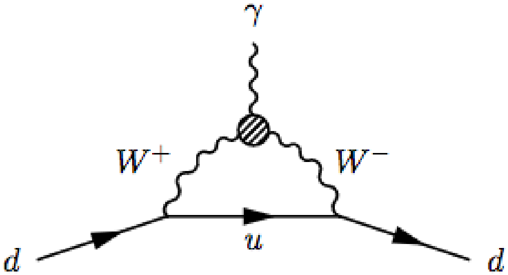
1. Denial

(Or how not to do it.)

- We see $\gamma, W^{\pm}, Z$.
- '$d = 6$' operators $\tilde{\gamma} W^+ W^-$ and $\tilde{Z} W^+ W^-$
- EDM constrains $\tilde{\gamma} W^+ W^-$, so look for $\tilde{Z} W^+ W^-$.

Kumar, Rajaraman, & Wells, 0801.2891

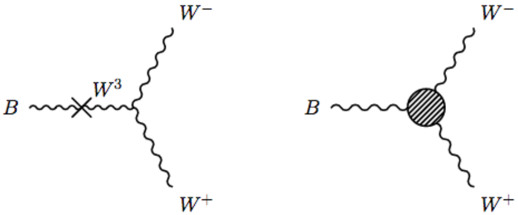
Han & Li, 0911.2933



What is the cut-off of this EFT?

Not Λ, but $(g^2 g' v^2 \Lambda^2)^{\frac{1}{4}} \ll \Lambda$

BMG & Sutherland, 1309.7822



The correct way to do is to acknowledge $SU(2) \times U(1)$:

The invariant $d = 6$ operator WWW forces WWγ/WWZ $= \tan\theta_W$. Departures require a $d = 8$ operator.

Need $\Lambda < 170$ GeV

BMG & Sutherland, 1309.7822

2. Anger

Lesson learned: when seeking CPV at LHC, expts and theorists should take account of what we already know.

3. Bargaining

We'll accept $SU(2) \times U(1)$ and the existence of spin-0 h, if you'll pretend that it isn't the Higgs boson

Now we can play a nice game (i.e. one that we can actually win!):

Pretend that CP exists, so that $h \to \pm h$; which hypothesis does data prefer?

- Study gauge/Higgs processes
- $h \to ZZ \to 4l, h \to WW \to 2l2\nu, h \to Z\gamma, h \to \gamma\gamma, Vh \to Vbb$
- 0^{+} favoured at 99.95%

e.g. ATLAS, 1307.1432

e.g. CMS, 1411.3441

But is it really game over?!

e.g. for $h \to ZZ$ these studies compare a renormalizable SM vertex $vhZ^{\mu}Z_{\mu}$ with the higher-dimension operator $vh\tilde{Z}^{\mu\nu}Z_{\mu\nu}/\Lambda^2$

But there are 4 operators in the ‘gauge/Higgs sector’:

$$\Delta\mathcal{L}_{CP}^{(4)} = \tilde{c}'_{WW}\,\tilde{W}^a_{\mu\nu}W^{\mu\nu\,a}\,\frac{h}{v} + \tilde{c}'_{WB}\,\mathrm{Tr}\left[\Sigma^\dagger\,\tilde{W}^a_{\mu\nu}\sigma^a\,\Sigma\,B_{\mu\nu}\sigma^3\right]\frac{h}{v}$$
$$+\,\tilde{c}'_{BB}\,\tilde{B}_{\mu\nu}B^{\mu\nu}\,\frac{h}{v} + \frac{\tilde{c}_{gg}}{2}\,\tilde{G}^a_{\mu\nu}G^{a\mu\nu}\,\frac{h}{v}\,.$$

Contino & al., 1303.3876

So, is it really game over?!

No, because there is no ‘gauge/Higgs’ sector

- Theory: This is a basis-dependent definition
- Expt: the process is $pp \to 4l$

BMG & Sutherland, to appear

4. Depression

Btw, there is no CP odd/even sector, either

- Classes of d-dimensional operators can be reduced into irreps of symmetries of the lagrangian at lower dimensions

BMG & Sutherland, to appear

- But CP is not a symmetry of the $d = 4$ lagrangian!

5. Acceptance

We accept $SU(2) \times U(1)$ and the existence of the Higgs. And we fit all 80/2500 operators.

We accept $SU(2) \times U(1)$ and the existence of the Higgs. And we fit all 80/2500 operators.

- A game we're getting better at, at least with CP

Ellis & al, 1410.7703

Riva & Falkowski, 1411.0669

- Without CP, the wheels are starting to turn

Dwivedi & al., 1505.05844

Ferreira & al., 1612.01808

Brehmer & al., 1712.02350

There are, no doubt, easier and harder ways of going about this:

- *CP* is a symmetry of the perturbative SM with ≤ 2 families
- *CP* is an approximate symmetry with 3 families
- ‘most’ observables don’t know/care about *CP*V in $d \leq 4$
- some observables are better measured/better sensitive to *CP* than others

Where should we look for CPV?

Dumb answer: wherever we like!

Some observables are cleaner than others . . .

CPV elsewhere in physics

- Via *CPT*/Kramers: T^2 fermion = - fermion $\implies$ degenerate $\implies$ no EDM in $e, n, Hg, Tl, \ldots$
- How to apply this to LHC?!

CPV elsewhere in physics II

- $[CP, H] = 0 \implies$ no switching eigenstates, cf $K_L \to 2\pi, 3\pi$
- $e^+e^-/p\bar{p}$:-)
- pp :-(; $q\bar{q}$ initial states and invariants
- detectors are biased (though reversing B helps)

CPV elsewhere in physics III

- P: reverses momenta (and adds phases)
- C: switches particles/antiparticles (and adds phases)
- T: reverses momenta, spins, in/out states

n.b.

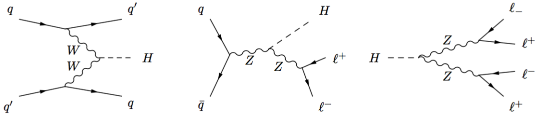
- P rates unchanged by reversing momenta
- C: rates unchanged by switching particles/antiparticles
- T: rates sometimes unchanged by reversing momenta and spins: $S_1 = -S_0 S_1^\dagger S_0$

aka naïve time reversal $\hat{T}$

General Purpose Colliders

How can we use these ideas?

- Can't measure spins, so use momenta
- With $2 \to 3$ processes, 4 independent momenta
- Can form C-even, P, $\hat{T}$-odd $\varepsilon_{\mu\nu\sigma\rho} p_1^\mu p_2^\nu p_3^\sigma p_4^\rho$
- Plus two C-odd, P, $\hat{T}$-even scalar products



Brehmer & al., 1712.02350.pdf

- Quantify (using Fisher info) how much can be got from this
- I guess we'll end up doing it by machine (learning) . . .

And beyond . . .

Is SMEFT enough?

It is hard to get EW baryogenesis with SMEFT

- need big effects $\Longrightarrow$ low cut-off
- danger of invalidating the EFT
- e.g. $|H|^6$ and strongly first-order EWPT

Grojean & al., 0407019

Bodeker & al., 0412366

Grinstein & Trott, 0806.1971

Cirigliano & al., 1603.03049

(6. Hope)

We need effects ‘beyond infinity’ in EFT! Two examples . . .

In the SM (and SMEFT), H is a co-ordinate on $\mathbb{R}^4$

In the minimal composite Higgs model, H is a co-ordinate on $SO(5)/SO(4) \cong S^4$

The extra point makes a difference: there is a topological term in the action that counts how many times spacetime S^4 wraps around $SO(5)/SO(4)$

It violates CP!

It does not appear at any order in the EFT expansion :-)

It is utterly negligible at low energies :-(

But it may be a vestige of interesting physics in a UV completion

Davighi & BMG, 1603.03049 & to appear

A 2nd, more prosaic example, new light degrees of freedom . . .

Scalar singlet

A scalar singlet can have big effects

- The scalar potential can be strongly first order

Espinosa & al, 1107.5441

- The CPV $d = 5$ operator $\eta Q^3 H U^3$ can achieve EWBG

Espinosa, BMG & al, 1110.2876

Scalar singlet II

A nice model is readily available: composite Higgs with $SO(6)/SO(5)$

BMG & al, 0902.1483

but is hardly in the spirit of this meeting!

Scalar singlet III

Just write the EFT up to $d = 5$:

$d = 1 \;\; \phi$

$d = 2 \;\; \phi\phi$

$d = 3 \;\; {H^\dagger}_a H^a \phi \, , \, \phi\phi\phi$

$d = 4 \;\; \epsilon^{\alpha\beta}\epsilon^{\dot\alpha\dot\beta} D_{\alpha\dot\beta}\phi D_{\beta\dot\alpha}\phi, \; {H^\dagger}_a H^a \phi\phi, \; \phi\phi\phi\phi$

$d = 5 \;\; \epsilon^{\alpha\beta}\epsilon^{\gamma\delta} W^a_{\gamma\beta b} W^b_{\alpha\delta a}\phi \, , \, \epsilon^{\dot\alpha\dot\beta}\epsilon^{\dot\gamma\dot\delta} {W^\dagger}^a_{\dot\delta\dot\beta b} {W^\dagger}^b_{\dot\alpha\dot\gamma a}\phi \, , \, \epsilon^{\alpha\beta}\epsilon^{\gamma\delta} G^A_{\gamma\beta B} G^B_{\alpha\delta A}\phi \, , \, \epsilon^{\dot\alpha\dot\beta}\epsilon^{\dot\gamma\dot\delta} {G^\dagger}^A_{\dot\delta\dot\beta B} {G^\dagger}^B_{\dot\alpha\dot\gamma A}\phi$

$\, , \, \epsilon_{\dot\alpha\dot\beta}\epsilon^{ab} {H^\dagger}_a {Q^\dagger_L}^{\dot\beta}_{Ab} {u_R}^{A\dot\alpha}\phi \, , \, \epsilon_{\alpha\beta}\epsilon_{ab} H^a {Q_L}^{\alpha A b} {u^\dagger_R}^{\beta}_{A}\phi \, , \, \epsilon^{\alpha\beta}\epsilon^{\gamma\delta} B_{\gamma\beta} B_{\alpha\delta}\phi \, , \, \epsilon^{\dot\alpha\dot\beta}\epsilon^{\dot\gamma\dot\delta} {B^\dagger}_{\dot\delta\dot\beta} {B^\dagger}_{\dot\alpha\dot\gamma}\phi$

$\, , \, \epsilon_{\dot\alpha\dot\beta} H^a {Q^\dagger_L}^{\dot\beta}_{Aa} {d_R}^{A\dot\alpha}\phi \, , \, \epsilon_{\alpha\beta} {H^\dagger}_a {Q_L}^{\alpha A a} {d^\dagger_R}^{\beta}_{A}\phi \, , \, \epsilon_{\alpha\beta} {H^\dagger}_a {e^\dagger_R}^{\alpha} {L_L}^{\beta a}\phi \, , \, \epsilon_{\dot\alpha\dot\beta} H^a {e_R}^{\dot\beta} {L^\dagger_L}^{\dot\alpha}_{a}\phi$

$\, , \, {H^\dagger}_a {H^\dagger}_b H^a H^b \phi \, , \, {H^\dagger}_a H^a \phi\phi\phi \, , \, \phi\phi\phi\phi\phi$

BMG & Sutherland, 1604.07365

22 operators, ripe for a fit!

DEFT

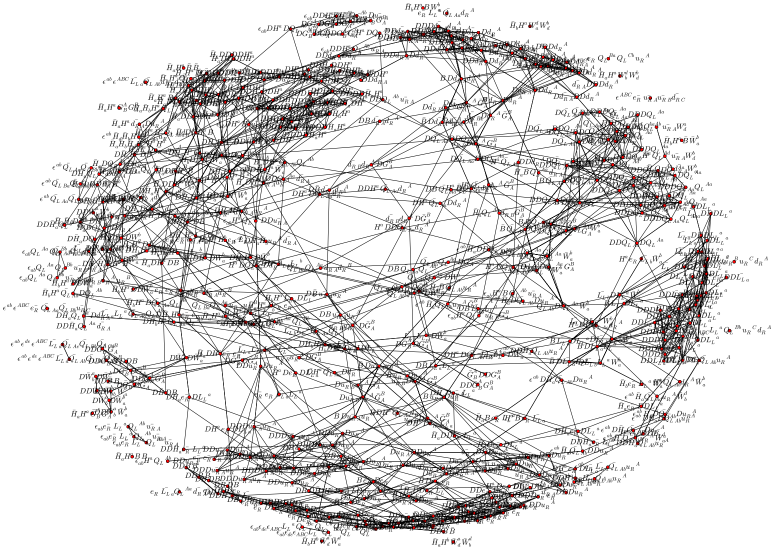
n.b. In the old days this used to be painstakingly done by hand

these days it can be done by machine.

- Poincarè-invariant theories
- $D = 3 + 1$ (smaller D would be easy to do too)
- any gauge group which is a product of $SU(n)$s and $U(1)$s
- any matter field content
- any basis or bases
- includes CP

BMG & Sutherland, to appear

SM $d = 6$



CP violation: to infinity and beyond

- EFT (of course!), at ever higher dimensions . . .
- . . . and beyond, for baryogenesis
- a sisyphean task!

B. Lightyear, 1995