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A Reduced basis for CP violation in SMEFT at colliders and its application to Diboson production

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We show that only 10 (17) CP-odd operators of the SMEFT give the leading, i.e. least suppressed by the small fermion masses of the SM, CP-violating contributions once we assume that all fermions are massless but the top (and bottom) quark(s). Since CP-odd operators typically lead to phase space suppressed interferences, we quantify the efficiency to revive the interference for various observables found in the literature but also for new observables in diboson production. Our new observables are found to be more efficient on the whole experimental fiducial phase space and we show the corresponding constraints on the Wilson coefficients depending on the luminosity.

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1. Basis Reduction of SMEFT

The matter-antimatter asymmetry present in our Universe remains a mystery within our best theoretical model so far : the Standard Model (SM) of the fundamental particles. It has been known for decades that Charge-Parity (CP) violation is required to generate such asymmetry from the early Universe [1]. However, the SM has failed to provide an explanation for the modern observations [2].

The Standard Model effective field theory (SMEFT) extends the usual SM with small corrections to already existing interactions but also allows new interactions between SM particles. Some of those consist in new CP-violating interactions which could potentially fix the SM shortcoming. The SMEFT Lagrangian reads

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \sum_{d=5}^{\infty} \frac{1}{\Lambda^{d-4}} \mathcal{L}_d = \mathcal{L}_{SM} + \sum_{d=5}^{\infty} \sum_i \frac{C_i^d}{\Lambda^{d-4}} O_i^d, \tag{1}$$

where the first term $\mathcal{L}_{SM}$ corresponds to the usual SM Lagrangian and the $\mathcal{L}_d$ terms contain the additional operators $\{O_i^d\}_{i,d>4}$ with their corresponding Wilson coefficients $\{C_i^d\}_i$. The index d stands for the dimensional ordering of the operators.

The parameterization in Eq.(1) is independent of the unknown UV-complete theory and remains valid as long as its energy scale Λ sits well above the energies accessible in particle collisions ($\Lambda >> E$). Therefore, the preliminary approximation is to restrict the infinite sum in Eq.(1) to the first term in $1/\Lambda$ that gives a signal at the LHC and includes CP-violating effects,

$$\mathcal{L}_{SMEFT} \sim \mathcal{L}_{SM} + \frac{1}{\Lambda^2} \mathcal{L}_6. \tag{2}$$

In the Warsaw basis [3], the dimension-six Lagrangian $\mathcal{L}_6$ still contains 1349 CP-odd operators with their respective degrees fo freedom, the large majority of them being phases of C_i's [4]. Figure 1 displays the CP-odd dimension-six operators for one generation.

(X^3)		$(\psi^2\phi^3)$		$(\psi^2\phi^2 D)$	
$O_{\tilde{G}GG}$	$f^{ABC}\widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$O_{u\phi}$	$(\phi^\dagger\phi)(\bar{q}u\tilde{\phi})$	$O_{\phi ud}$	$i(\tilde{\phi}^\dagger D_\mu \phi)(\bar{u}\gamma^\mu d)$
$O_{\tilde{W}WW}$	$\epsilon^{IJK}\widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$O_{d\phi}$	$(\phi^\dagger\phi)(\bar{q}d\phi)$		
		$O_{e\phi}$	$(\phi^\dagger\phi)(\bar{l}e\phi)$		
$(X^2\phi^2)$		(ψ^4)		$(X\psi^2\phi)$	
$O_{\phi\tilde{G}}$	$\phi^\dagger\phi\widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$	O_{ledq}	$(\bar{l}^j e)(\bar{d}q^j)$	O_{uG}	$(\bar{q}\sigma^{\mu\nu}T^A u)\tilde{\phi}G_{\mu\nu}^A$
$O_{\phi\tilde{W}}$	$\phi^\dagger\phi\widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$	$O_{lequ}^{(1)}$	$(\bar{l}^j e)\epsilon_{jk}(\bar{q}^k u)$	O_{uW}	$(\bar{q}\sigma^{\mu\nu}u)\tau^I\tilde{\phi}W_{\mu\nu}^I$
$O_{\phi\tilde{B}}$	$\phi^\dagger\phi\widetilde{B}_{\mu\nu}B^{\mu\nu}$	$O_{lequ}^{(3)}$	$(\bar{l}^j\sigma^{\mu\nu}e)\epsilon_{jk}(\bar{q}^k\sigma_{\mu\nu}u)$	O_{uB}	$(\bar{q}\sigma^{\mu\nu}u)\tilde{\phi}B_{\mu\nu}$
$O_{\phi\tilde{W}B}$	$\phi^\dagger\tau^I\phi\widetilde{W}_{\mu\nu}^I B^{\mu\nu}$	$O_{quqd}^{(1)}$	$(\bar{q}^j u)\epsilon_{jk}(\bar{q}^k d)$	O_{dG}	$(\bar{q}\sigma^{\mu\nu}T^A d)\phi G_{\mu\nu}^A$
		$O_{quqd}^{(8)}$	$(\bar{q}^j T^A u)\epsilon_{jk}(\bar{q}^k T^A d)$	O_{dW}	$(\bar{q}\sigma^{\mu\nu}d)\tau^I\phi W_{\mu\nu}^I$
				O_{dB}	$(\bar{q}\sigma^{\mu\nu}d)\phi B_{\mu\nu}$
				O_{eW}	$(\bar{l}\sigma^{\mu\nu}e)\tau^I\phi W_{\mu\nu}^I$
				O_{eB}	$(\bar{l}\sigma^{\mu\nu}e)\phi B_{\mu\nu}$

Figure 1: All CP-odd dimension-six operators for one generation from the complete Warsaw basis in [3].

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(X^3)		$(\psi^2\phi^3)$		$(\psi^2\phi^2 D)$	
$O_{\tilde{G}GG}$	$f^{ABC}\widetilde{G}_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	$O_{t\phi}$	$(\phi^\dagger\phi)(\overline{q}_r t_r\tilde{\phi})$	//	/////
$O_{\widetilde{W}WW}$	$\epsilon^{IJK}\widetilde{W}_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$				
$(X^2\phi^2)$		(ψ^4)		$(X\psi^2\phi)$	
$O_{\phi\tilde{G}}$	$\phi^\dagger\phi\widetilde{G}^A_{\mu\nu}G^{A\mu\nu}$	//	/////	O_{tG}	$(\overline{q}_3\sigma^{\mu\nu}T^A t)\tilde{\phi}G^A_{\mu\nu}$
$O_{\phi\tilde{W}}$	$\phi^\dagger\phi\widetilde{W}^I_{\mu\nu}W^{I\mu\nu}$			O_{tW}	$(\overline{q}_3\sigma^{\mu\nu}t)\tau^I\tilde{\phi}W^I_{\mu\nu}$
$O_{\phi\tilde{B}}$	$\phi^\dagger\phi\widetilde{B}_{\mu\nu}B^{\mu\nu}$			O_{tB}	$(\overline{q}_3\sigma^{\mu\nu}t)\tilde{\phi}B_{\mu\nu}$
$O_{\phi\tilde{W}B}$	$\phi^\dagger\tau^I\phi\widetilde{W}^I_{\mu\nu}B^{\mu\nu}$				

Figure 2: The 10 CP-odd dimension-six operators remaining after applying the reduction of the Warsaw basis with the 14 $U(1)$ flavour symmetries.

A naive dimensional analysis (NDA) shows that leading SMEFT contributions to the amplitude compared to purely SM amplitudes should scale as $O\left(E^2/\Lambda^2\right)$, with E sufficiently large to lead to deviations in observables but small enough to maintain the perturbativity of the SMEFT expansion. If that is the case, then any contribution of the order $O\left(m_i^2/\Lambda^2\right)$, with m_i the mass of a light fermion (all fermions besides the top quark), becomes negligible and masses of light fermions can be discarded. With that endeavour in mind, we impose 14 $U(1)$ flavour symmetries onto the light SM degrees of freedom. As a result, the Yukawa part of the SM Lagrangian is reduced to the top Yukawa

$$\mathcal{L}_{Yuk.} \to y_t\left(\bar{t}_R\tilde{\phi}t_L\right), \tag{3}$$

readily rendering all light fermions massless. Consequently, we are now allowed to rephase all light fermion fields indenpendently and it reduces even further the number of additional operators, from 1349 to 10, by absorbing the CP-odd phases of Wilson coefficients in particle field definitions. The 10 operators are displayed in Figure 2.

This reduction is applicable as long as one is interested in the squared amplitudes up to the $1/\Lambda^2$ order because only one dimension-six operator can appear and the phase of its Wilson coefficient can be absorbed. If more than one operator are present, the CP-odd phase can be passed to another Wilson coefficient which could still contribute to the amplitude.

If one is interested in maintaining the bottom quark massive as well, then 13 $U(1)$ flavour symmetries can be imposed. The Yukawa part of the SM Lagrangian is reduced to the top and bottom Yukawa parts and, in this case, 17 dimension-six operators are kept. The latter are displayed in Figure 3.

2. Sign of interference

The 10 operators in Figure 2 now provides new Feynman diagrams creating new amplitudes, $\left\{\frac{C_i}{\Lambda^2}\mathcal{M}_i\right\}_i$, which interfere with conventional ones drawn from the SM, $\mathcal{M}_{SM}$. One of the most interesting characteristics of the interference amplitudes $\mathcal{M}_{int,i}$, defined as

$$\mathcal{M}_{int,i} = 2Re\left\{\frac{C_i}{\Lambda^2}\mathcal{M}_i.\mathcal{M}^*_{SM}\right\}, \tag{4}$$

is that they are not always positive-definite over the phase-space but actually fluctuate. This behaviour can be seen in the red line in Figure 4. The interference occurs with the inclusion of the operator $O_{\widetilde{W}WW}$ in the dileptonic decay of the WZ production. The SM contribution to the cross section σ and the square of the purely dimension-six amplitude, respectively in blue and green, are symmetric over the CP-odd observable $p_\perp$ whereas the interference between the SM and the operator $O_{\widetilde{W}WW}$ is asymmetric. The considered triple product $p_\perp$ here is defined as

$$p_\perp\left(\vec{p}_e, \vec{p}_Z, \vec{p}^{\,z}_{\Sigma}\right) = \vec{p}_e.\frac{\left(\vec{p}_Z \times \vec{p}^{\,z}_{\Sigma}\right)}{|\vec{p}_Z \times \vec{p}^{\,z}_{\Sigma}|}, \tag{5}$$

with $\vec{p}_e$, $\vec{p}_Z$ and $\vec{p}^{\,z}_{\Sigma}$ being respectively the electron 3-momentum, the Z boson 3-momentum and the 3-vector with its third component which corresponds to the third component of the sum of visible particle $\vec{p}_{\Sigma}$ in final space.

In general, the usual procedure to estimate the effect of the interferences is to look at deviations to the cross section compared to the SM or in differential cross sections, especially in the distribution tails. This kind of counting measurement actually takes into account the sum of these positive and negative contributions of the interferences leading to large cancellations between them. This is called the "phase-space suppression" and aggravates the suppression by Λ in the perturbative expansion. Moreover, the statistical uncertainty in tails is usually large.

The method around the phase-space suppression of CP-odd contributions is to consider new kind of P- or CP-odd observables that do not consider the sum of positive and negative values of the interference but rather their difference : asymmetries. These asymmetries will naturally be minimising the CP-even contributions and makes us particularly sensitive to the CP-odd part of relevant Wilson coefficients.

3. Asymmetries

We have chosen to test the use of asymmetries in WZ and $W\gamma$ production because they are clean channels observed at the LHC with little confusion on the observations of the two bosons

(X^3)		$(\psi^2\phi^3)$		$(\psi^2\phi^2 D)$	
$O_{\tilde{G}GG}$	$f^{ABC}\widetilde{G}^{A\nu}_{\mu}G^{B\rho}_{\nu}G^{C\mu}_{\rho}$	$O_{t\phi}$	$(\phi^\dagger\phi)(\overline{q}_3 t\tilde{\phi})$	$O_{\phi tb}$	$i(\tilde{\phi}^\dagger D_\mu\phi)(\bar{t}\gamma^\mu b)$
$O_{\widetilde{W}WW}$	$\epsilon^{IJK}\widetilde{W}^{I\nu}_{\mu}W^{J\rho}_{\nu}W^{K\mu}_{\rho}$	$O_{b\phi}$	$(\phi^\dagger\phi)(\overline{q}_3 b\phi)$		
$(X^2\phi^2)$		(ψ^4)		$(X\psi^2\phi)$	
$O_{\phi\tilde{G}}$	$\phi^\dagger\phi\widetilde{G}^A_{\mu\nu}G^{A\mu\nu}$	$O^{(1)}_{qtqb}$	$(\bar{q}^j_3 t)\epsilon_{jk}(\bar{q}^k_3 b)$	O_{tG}	$(\overline{q}_3\sigma^{\mu\nu}T^A t)\tilde{\phi}G^A_{\mu\nu}$
$O_{\phi\tilde{W}}$	$\phi^\dagger\phi\widetilde{W}^I_{\mu\nu}W^{I\mu\nu}$	$O^{(8)}_{qtqb}$	$(\bar{q}^j_3 T_A t)\epsilon_{jk}(\bar{q}^k_3 T_A b)$	O_{tW}	$(\overline{q}_3\sigma^{\mu\nu}t)\tau^I\tilde{\phi}W^I_{\mu\nu}$
$O_{\phi\tilde{B}}$	$\phi^\dagger\phi\widetilde{B}_{\mu\nu}B^{\mu\nu}$			O_{tB}	$(\overline{q}_3\sigma^{\mu\nu}t)\tilde{\phi}B_{\mu\nu}$
$O_{\phi\tilde{W}B}$	$\phi^\dagger\tau^I\phi\widetilde{W}^I_{\mu\nu}B^{\mu\nu}$			O_{bG}	$(\overline{q}_3\sigma^{\mu\nu}T^A b)\phi G^A_{\mu\nu}$
				O_{bW}	$(\overline{q}_3\sigma^{\mu\nu}b)\tau^I\phi W^I_{\mu\nu}$
				O_{bB}	$(\overline{q}_3\sigma^{\mu\nu}b)\phi B_{\mu\nu}$

Figure 3: The 17 CP-odd dimension-six operators remaining after applying the reduction of the Warsaw basis with the 13 $U(1)$ flavour symmetries.

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and the small backgrounds. Two operators in Figure 2, $O_{\widetilde{W}WW}$ and $O_{\phi\widetilde{W}B}$, are relevant in the two processes. They introduce a new WWZ/γ interaction which will interfere with the SM.

In the first place, we study the best theoretical asymmetry $\sigma^{|int|}$,

$$\sigma^{|int|} \equiv \int d\Phi \left| \frac{d\sigma}{d\Phi}(O_i) \right|, \tag{6}$$

which disentagle perfectly the different regions of the phase space using the matrix element with all informations on the particles involved. Then, we turn to the measurable asymmetry $\sigma^{|meas|}$

$$\sigma^{|meas|} \equiv \int d\Phi_{meas} \left| \sum_{\text{det. eff.}} \frac{d\sigma}{d\Phi}(O_i) \right|, \tag{7}$$

which takes into account several experimental limitations (invisibility of initial state and of the neutrino, no information on the helicity, particle distribution functions) [5]. The latter is, in principle, the best asymmetry one can access in the considered collider but is time-consuming to evaluate, and model dependent.

Then, we turn to asymmetries of observables. We propose simpler triple products $p_\perp$ between different sets of 3-momenta and we also compare the asymmetries to already existing observables in the literature. In particular, the signed azimuthal angle difference from [6]

$$\Delta\phi_{pp'} = \phi_{p'} - \phi_p \text{ if } \eta_{p'} > \eta_p, \tag{8}$$

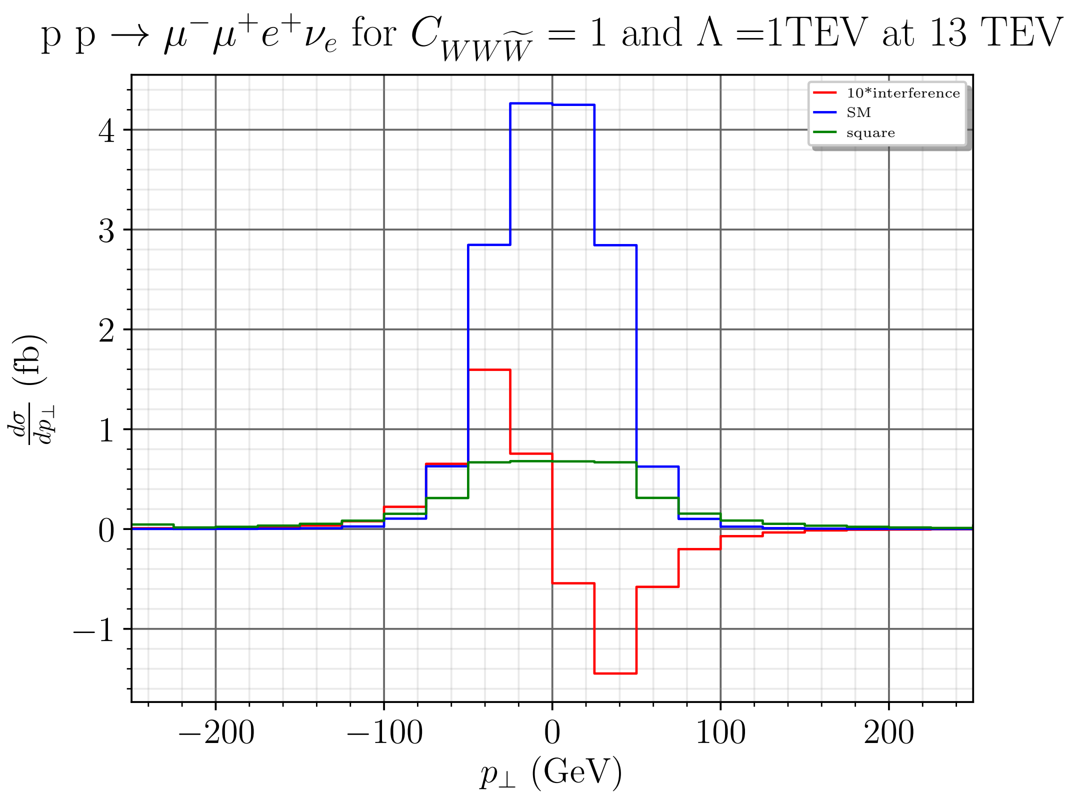

Figure 4: Modulation of the interference over the phase-space with respect to $p_\perp$ displayed in red. The SM and square

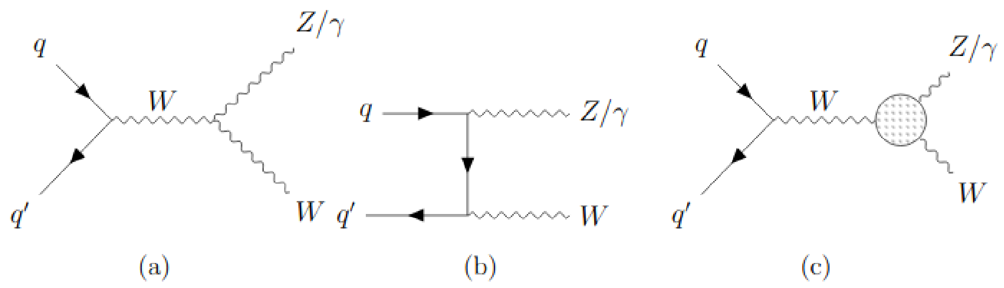

Figure 5: Feynamn diagrams relevant for WZ and $W\gamma$ production. The first two arise from the SM and the amplitude on the right is drawn from $O_{\widetilde{W}WW}$ and $O_{\phi\widetilde{W}B}$.

and the sine of twice the angle between the decay and scattering planes from [7]

$$\begin{cases} \sin\phi_{WZ} \equiv \sin 2\phi_Z + \sin 2\phi_W, \\ \sin\phi_{W\gamma} \equiv \sin 2\phi_W, \end{cases} \tag{9}$$

where

$$\phi_i = sign\left[\left(\hat{n}^i_{scat.} \times \hat{n}^i_{decay}\right).\vec{p}_{V^i}\right] \arccos\left(\hat{n}^i_{scat.}.\hat{n}^i_{decay}\right).$$

The normal vectors to the decay plan and the scattering planes of the heavy boson V, respectively $\hat{n}^i_{decay}$ and $\hat{n}^i_{scat.}$, are defined as

$$\hat{n}^i_{decay} = \frac{\vec{p}_{l^i,+} \times \vec{p}_{l^i,-}}{|\vec{p}_{l^i,+} \times \vec{p}_{l^i,-}|} \ \& \ \hat{n}^i_{scat.} = \frac{\hat{z}_{lab.} \times \vec{p}_{V^i}}{|\hat{z}_{lab.} \times \vec{p}_{V^i}|}.$$

As an example, we present the results of $O_{\widetilde{W}WW}$ in W^+Z and $W^+\gamma$ production in the ATLAS detector in Table 1 using the cuts from [8, 9]. Full results are available in [10] for both operators in dileptonic decays of $W^\pm Z$ and $W^\pm\gamma$. Plots of differential cross sections and differential asymmetries with respect to the center-of-mass energy are available as well.

We see that the SM cross section is 3 orders of magnitude larger than the interference cross section for W^+Z and 2 orders for $W^+\gamma$. This was expected due to the $1/\Lambda$ expansion in the SMEFT and the phase-space suppression discussed previously. The importance of the phase-space suppression is further highlighted by the value of $\sigma^{|int|}$ which is only 1 order of magnitude smaller than $\sigma(SM)$. Realistically, in W^+Z, only a third of the theoritical best asymmetry can be achieved through $\sigma^{|meas|}$ but is almost of the same order as $\sigma(SM)$. On the other hand, $\sigma^{|meas|}$ is only a fifth of $\sigma^{|int|}$ in W^+Z.

Aiming to get as close as possible to $\sigma^{|meas|}$ with our observable asymmetries, we see that no observable totally recover the sensitivity but taht it can be approached. In W^+Z, the best asymmetry is obtained with the triple product $p_\perp(p_e, p_Z, p^z_\Sigma)$ by almost 60%. The SM contributions, being mostly CP-even, are naturally small and compatible with statistical fluctuations. The observable $\Delta\phi$, already available in the literature, draws the best asymmetry for $W^+\gamma$ with more than 90% of $\sigma^{|meas|}$. Its drawback is a non-negligible contribution from the SM, whereas $p_\perp(p_e, p_{Z/\gamma}, p^z_{Z/\gamma})$ performs quite well with a rather small SM background and an interference contribution larger than 90% of $\sigma^{|meas|}$ as well.

Process	$W^+Z \to \mu^-\mu^+e^+\nu_e$	$W^+\gamma \to e^+\nu_e\gamma$
$\sigma(SM)$	15.74(2) fb	715.1(8) fb
$\sigma(O_{\widetilde{W}WW})$	0.047(4) fb	-2.07(4) fb
$\sigma^{\|int\|}(O_{\widetilde{W}WW})$	3.302(4) fb	33.83(4) fb
$\sigma^{\|meas\|}(O_{\widetilde{W}WW})$	1.084(4) fb	6.07(4) fb
$\Delta p_\perp(p_e, p_{Z/\gamma}, p^z_\Sigma)(SM)$	-0.02(2) fb	0.8(8) fb
$\Delta p_\perp(p_e, p_{Z/\gamma}, p^z_\Sigma)(O_{\widetilde{W}WW})$	-0.628(4) fb	-4.60(4) fb
$\Delta p_\perp(p_e, p_{Z/\gamma}, p^z_{Z/\gamma})(SM)$	-0.01(2) fb	-0.527(4) fb
$\Delta p_\perp(p_e, p_{Z/\gamma}, p^z_{Z/\gamma})(O_{\widetilde{W}WW})$	0.5(8) fb	-5.62(4) fb
$\Delta\left(\Delta\phi_{eZ/\gamma}\right)(SM)$	0.07(2) fb	-4.5(8) fb
$\Delta\left(\Delta\phi_{eZ/\gamma}\right)(O_{\widetilde{W}WW})$	0.196(4) fb	-5.85(4) fb
$\Delta \sin\phi_{WZ/\gamma}(SM)$	-0.03(2) fb	-0.1(8) fb
$\Delta \sin\phi_{WZ/\gamma}(O_{\widetilde{W}WW})$	-0.321(4) fb	-0.31(4) fb

Table 1: Cross section and asymmetries for ATLAS at $\sqrt{s}$ = 13TeV, the Wilson coefficient $C_{\widetilde{W}WW}$ has been set to 1 and Λ at 1 TeV. The statistical errors are displayed in brackets.

4. Constraints and Luminosity

We compare the constraints on the Wilson coefficients with existing analyses from ATLAS [11, 12]. Taking the SM as the only symmetric background and posing a signal-to-background ratio of 2, Figure 6 shows the limit on the value of C_i/Λ^2 with respect to the luminosity acheived at the LHC. The best observables for each operator in each channel were used to draw the constraints. Two analyses from the ATLAS collaboration are marked as stars. In [11], the cross section of the WZ semi-hadronic channel, $\sigma\,(pp \to Wjj)$, is used to extract contraints only on $O_{\widetilde{W}WW}$ and $\Delta\phi_{jj}$ in [12] is applied to both $O_{\widetilde{W}WW}$ and $O_{\phi\widetilde{W}B}$ for the vector boson fusion process $pp \to Zjj$.

Electric dipole moments could have been compared as well but limits from these measurements are so stringent that they would not be visible on the plot.

Our estimated constraints are similar in both processes for $O_{\widetilde{W}WW}$ and lie between the semi-hadronic WZ and VBF measurements by ATLAS. On the contrary, $W\gamma$ gives much better constraints on $O_{\phi\widetilde{W}B}$ than WZ and they are competitive with VBF. As a result, they could be use to confirm or disprove the deviation seen in this process.

5. Conclusion

Searching for leading CP-odd contributions in the SMEFT pointed us to consider the SM light degrees of freedom as massless which permitted us to absorb many CP-odd phases into field redefinitions. The large number of CP-odd parameters was reduced to 10 if only the top quark is massive and 17 if the top and bottom quarks are massive.

We discuss the effect of phase-space suppression suffered by interferences between SM and dimension-six amplitudes. This suppression is further aggravated if one look into CP-even measurements as the cross section. Thus, we advocate for the use of asymmetries to investigate these leading CP-odd effects.

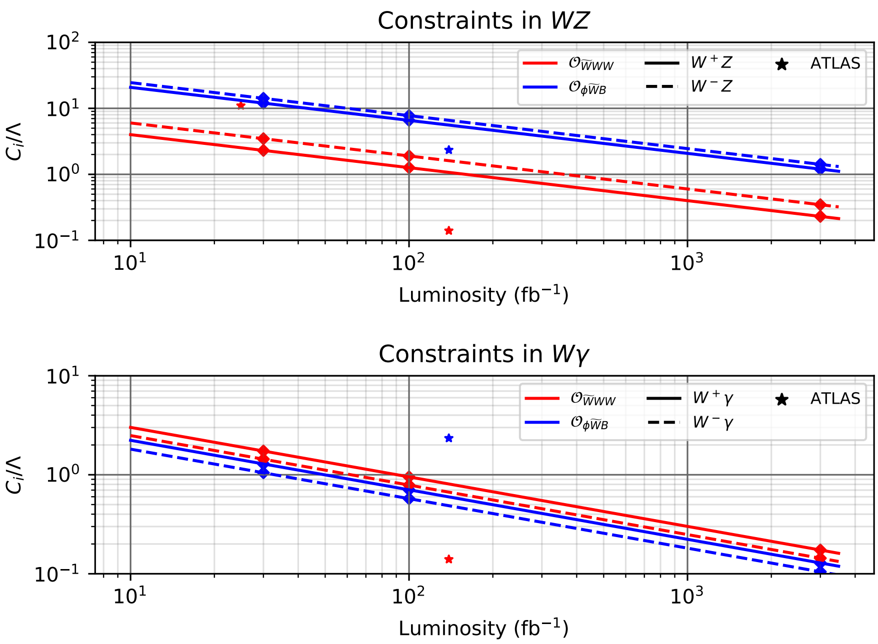

Figure 6: Limits on the value of C_i/Λ^2 as a function of the luminosity in the ATLAS detector. Blue lines correspond to $O_{\phi\widetilde{W}B}$ and red lines to $O_{\widetilde{W}WW}$.

We point to diboson production to test the use of asymmetries and compare our results to existing observables from the literature. $O_{\widetilde{W}WW}$ and $O_{\phi\widetilde{W}B}$ have been inveesitgated in the dileptonic channels of WZ and the leptonic channel of $W\gamma$. The large phase-space suppression is stressed by $\sigma^{|int|}$ compared to the interference cross section and the possibility to realisatically extract CP-odd contributions is expressed by $\sigma^{|meas|}$.

The pair of triple products present in Table 1 performs well compared to the two observables from [6, 7] with small SM contributions and have the potential to constrain the Wilson coefficients of the two operators in ATLAS.

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