Université catholique de Louvain

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A reduced basis for CP violation in SMEFT at colliders and its application to diboson production

based on 2110.02993

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Outline

- Motivation
- 2 Reduced bases
- WZ and $W\gamma$ production
  - Cross-sections
  - Observables
- Comparison of constraints

Motivation

$$\mathcal{L}_{SM} \longrightarrow \frac{\eta_{exp}}{\eta_{SM}(J_4)} \sim 10^{10}$$

Solution : Inject "CP violation" by increasing the number of CP-odd complex phases <u>invariant under unphysical phase redefinitions</u>.

$$\mathcal{L}_{SMEFT} \sim \mathcal{L}_{SM} + \sum_i^N \frac{C_i}{\Lambda^2}\mathcal{O}_i^6 \longrightarrow \frac{\eta_{exp}}{\eta_{SMEFT}(J_4, ...)} < 10^{10}.$$

Goal : Limit the $\not{C}\not{P}$ d.o.f. by selecting dominant contributions.
Problem : In the Warsaw basis, there are still 1149 CP-odd operators.

[1008.4884,1312.2014]

Warsaw Basis : CP-odd operators[1]

(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}	$(\bar{l}\sigma^{\mu\nu}e)\phi B_{\mu\nu}$

[1] **only 1 generation.**

Basis Reduction

Is there a way to further reduce the number of operators ?
For the dimension-six operator to be sizeable :

$$\frac{\left[\mathcal{O}_i^6\right]}{\left[\mathcal{O}_{SM}\right]} \sim \frac{E^2}{\Lambda^2} \leqslant 1 \quad \rightarrow \quad E \leq \Lambda$$

$\rightarrow$ Contributions with a ratio of $\frac{m_f^2}{\Lambda^2}$ are irrelevant if m_f is small.

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$\rightarrow$ Contributions with a ratio of $\frac{m_f^2}{\Lambda^2}$ are irrelevant if m_f is small.

Our strategy is to impose $U(1)^{14}$ symmetry on massive fermionic fields.

- Light fermions become massless.
- Top quark remains massive.
- Bosons unaffected.

- SM is unaffected except in the mass terms.
- CP-odd $\mathcal{O}_i^6$ in :
  - $\{X^3, X^2\phi^2\}$ remain.
  - $\{\psi^2\phi^3, \psi^4, \psi^2\phi^2 D, X\psi^2\phi\}$ disappear unless t_R.

Reduced Basis under $U(1)^{14}$

Impose $U(1)^{14}$ symmetry on massive fermionic fields.

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

Reduced Basis under $U(1)^{13}$

Impose $U(1)^{13}$ symmetry on massive fermionic fields.

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

Amplitude Level

- Neglect $\mathcal{O}\left(\Lambda^{-3}\right)$ at the amplitude level (as operator level)

$$\mathcal{M}_{tot} = \mathcal{M}_{SM} + \frac{C_i}{\Lambda^2}\mathcal{M}_i + \mathcal{O}\left(\Lambda^{-3}\right).$$

$$\left|\mathcal{M}_{tot}\right|^2 = \left|\mathcal{M}_{SM}\right|^2 + 2Re\left\{\frac{C_i}{\Lambda^2}\mathcal{M}_i \times \mathcal{M}_{SM}^*\right\} + \mathcal{O}\left(\Lambda^{-3}\right).$$

- Leading CP-violating SMEFT contribution is the interference :

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

where $\mathcal{M}_i$ comes from one insertion of a CP-odd $\mathcal{O}_i^6$ from the reduced basis.

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$$|\mathcal{M}_{tot}|^2 = |\mathcal{M}_{SM}|^2 + 2Re\left\{\frac{C_i}{\Lambda^2}\mathcal{M}_i \times \mathcal{M}_{SM}^*\right\} + \mathcal{O}\left(\Lambda^{-3}\right).$$

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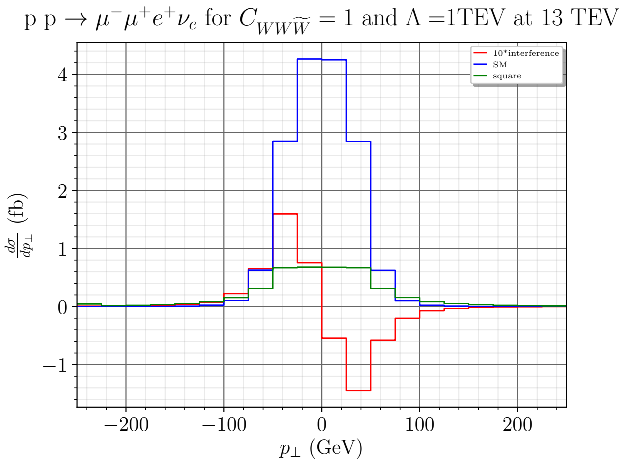
Sign of the Interference : Illustration



Sign of the Interference

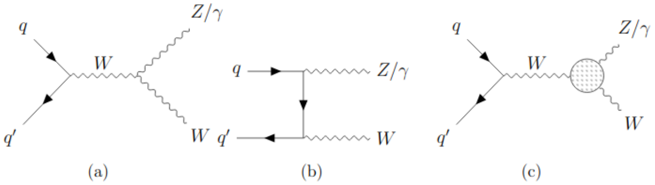
$$\mathcal{M}_{int,i} \equiv 2Re\left\{\frac{C_i}{\Lambda^2}\mathcal{M}_i \times \mathcal{M}^*_{SM}\right\}.$$

- $\mathcal{M}_{int,i}$ is not positive-definite over the phase space but fluctuates.
- Positive and negative contributions perfectly compensates in CP-even observables of a C-even processes. Two suppression mechanisms : Λ^r and sign of $\mathcal{M}_{int}$.
- Ineffectiveness of the cross section and poor constraints on CP-odd operators.

$\Longrightarrow$ Use asymmetries to build CP-odd observables !

Diboson production in ATLAS

First application of the model : $pp \to WZ/\gamma$



- Large cross section
- Good reconstruction in the dileptonic channels $(W \to e\nu_e, Z \to \mu^-\mu^+)$
- Almost CP-even processes
- $\mathcal{O}_{\widetilde{W}WW}, \mathcal{O}_{\phi\widetilde{W}B}$
- Cuts from ATLAS

1606.04017,1205.2531

$\mathcal{O}_{\widetilde{W}WW}$ in $pp \to W^+Z$

- All analyses presented are limited to the partonic level and at LO.
- $C_{\widetilde{W}WW} = 1$ and $\Lambda = 1$TeV.

Process	W^+Z
$\sigma(SM)$	15.74(2) fb
δ_{PDF}	3.45%
$\sigma(\mathcal{O}_{\widetilde{W}WW})$	0.047(4) fb
$\sigma_{\Lambda^{-4}}(\mathcal{O}_{W\widetilde{W}W})$	4.133(5) fb
Schwartz Bound	16.13 fb

Theoretical asymmetry

Full absolute interference contribution (without cancellation by the phase space) :

$$\sigma^{[int]} \equiv \int d\Phi \left| \frac{d\sigma}{d\Phi}(\mathcal{O}_i) \right|$$

Process	W^+Z
$\sigma(SM)$	15.74(2) fb
δ_{PDF}	3.45%
$\sigma(\mathcal{O}_{\widetilde{W}WW})$	0.047(4) fb
$\sigma_{\Lambda^{-4}}\left(\mathcal{O}_{W\widetilde{W}W}\right)$	4.133(5) fb
Schwartz Bound	16.13 fb
$\sigma^{\lvert int \rvert}(\mathcal{O}_{\widetilde{W}WW})$	3.302(4) fb

Measurable asymmetry

Visible interference contribution without cancellation by the phase space

$$\sigma^{[meas]} \equiv \int d\Phi_{meas} \left| \sum_{\{um\}} \frac{d\sigma}{d\Phi}(\mathcal{O}_i) \right|$$

- Direction of quarks
- Quarks flavours and momenta in PDFs
- Unpolarized matrix elements
- Integrate over possible p^z's for neutrino

Process	W^+Z
$\sigma(SM)$	15.74(2) fb
δ_{PDF}	3.45%
$\sigma(\mathcal{O}_{\widetilde{W}WW})$	0.047(4) fb
$\sigma_{\Lambda^{-4}}(\mathcal{O}_{\widetilde{W}WW})$	4.133(5) fb
Schwartz Bound	16.13 fb
$\sigma^{\lvert int \rvert}(\mathcal{O}_{\widetilde{W}WW})$	3.302(4) fb
$\sigma^{\lvert meas \rvert}(\mathcal{O}_{\widetilde{W}WW})$	1.084(4) fb

Asymmetries

- Differential cross section with respect to a CP-odd observable X after a CP-odd $\mathcal{O}_i^6$ insertion is

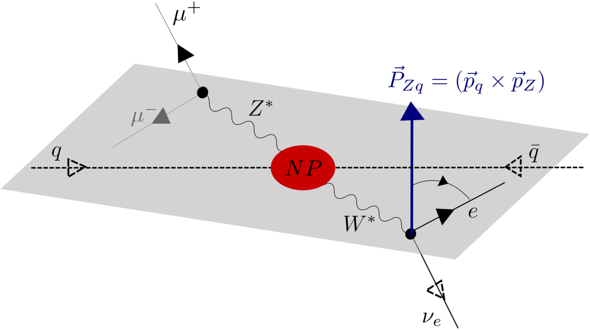
$$\frac{d\sigma}{dX} = \frac{d\sigma(SM)}{dX} + \frac{C_i}{\Lambda^2}\frac{d\sigma(\mathcal{O}_i)}{dX} + \mathcal{O}\left(\Lambda^{-3}\right).$$

- We define the asymmetry in X as

$$\Delta X = \sigma_{X>0} - \sigma_{X<0} \approx \Delta\sigma_X(SM) + \frac{C_i}{\Lambda^2}\Delta\sigma_X(\mathcal{O}_i),$$

with $\sigma_{X>0} = \int_0^{b_+} \frac{d\sigma}{dX}\, dX$ and $\sigma_{X<0} = \int_{b_-}^0 \frac{d\sigma}{dX}\, dX$.
$b_\pm$ are the upper and lower bounds of integration of X.

Triple product



- Definition :

$$p_\perp(p_e, p_q) = \vec{p}_e.(\vec{p}_Z \times \vec{p}_q)$$

Combinations

$p_\perp(p_e, p_q) = \vec{p}_e.\left(\vec{p}_{Z/\gamma} \times \vec{p}_q\right)$

- Different possibilities for the lepton in WZ.
- Explore substitutes of $\vec{p}_{Z/\gamma}$.
- Need to find a surrogate to the unobservable $\vec{p}_q$:
  - $\hat{z}$-axis : $[0, 0, 1]$,
  - lepton : $[0, 0, p^z_l]$,
  - neutral boson Z/γ : $[0, 0, p^z_{Z/\gamma}]$,
  - sum of visible particles : $[0, 0, p^z_{\sum}]$.

Triple products configurations	$\mathcal{O}_{\widetilde{W}WW}$	$\mathcal{O}_{\phi\widetilde{W}B}$
$(\vec{p}_q, \vec{p}_Z, \vec{p}_e)$	-1.612(4)	-0.3888(7)
$(\vec{p}_q, \vec{p}_Z, \vec{p}_{\mu^-})$	-0.184(4)	-0.0271(7)
$\left([0,0,p^z_{\sum}], \vec{p}_Z, \vec{p}_e\right)$	-0.628(4)	-0.1207(7)
$(\vec{p}_W, \vec{p}_{\mu^-}, \vec{p}_e)$	0.535(4)	0.0965(7)
$(\vec{p}_W, \vec{p}_{\mu^+}, \vec{p}_e)$	0.511(4)	0.1009(7)
$([0,0,p^z_W], \vec{p}_e, \vec{p}_{\mu^-})$	-0.227(4)	-0.0594(7)
$(\vec{p}_W, \vec{p}_{\mu^-}, \vec{p}_{\mu^+})$	-0.080(4)	-0.0110(7)
$\left([0,0,p^z_{\sum}], \vec{p}_W, \vec{p}_Z\right)$	-0.045(4)	-0.0086(7)
$([0,0,p^z_e], \vec{p}_{\mu^-}, \vec{p}_W)$	0.028(4)	0.0061(7)
$(\vec{p}_e, \vec{p}_{\mu^-}, \vec{p}_{\mu^+})$	-0.025(4)	-0.004(7)
$([0,0,p^z_e], \vec{p}_{\mu^-}, \vec{p}_{\mu^+})$	-0.029(4)	-0.0061(7)
$([0,0,p^z_{\mu^-}], \vec{p}_e, \vec{p}_{\mu^+})$	-0.213(4)	-0.0244(7)
$([0,0,p^z_{\mu^+}], \vec{p}_{\mu^-}, \vec{p}_e)$	0.252(4)	0.0327(7)
$\left([0,0,p^z_{\sum}], \vec{p}_e + \vec{p}_{\mu^-}, \vec{p}_{\mu^+}\right)$	-0.362(4)	-0.0582(7)
$\left([0,0,p^z_{\sum}], \vec{p}_e + \vec{p}_{\mu^+}, \vec{p}_{\mu^-}\right)$	-0.300(4)	-0.0481(7)
$\left([0,0,p^z_{\sum}], \vec{p}_e - \vec{p}_{\mu^-}, \vec{p}_{\mu^+}\right)$	-0.047(4)	-0.0097(7)
$\left([0,0,p^z_{\sum}], \vec{p}_e - \vec{p}_{\mu^+}, \vec{p}_{\mu^-}\right)$	-0.160(4)	-0.0279(7)

Other CP-odd observables in Diboson

"Precision diboson measurements at hadron colliders"

Azatov et al. [1901.04821]

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

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

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

Other CP-odd observables in Diboson

"ATLAS Violating CP Effectively"

Das Bakshi et al. [2009.13394]

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

Examples in diboson production :

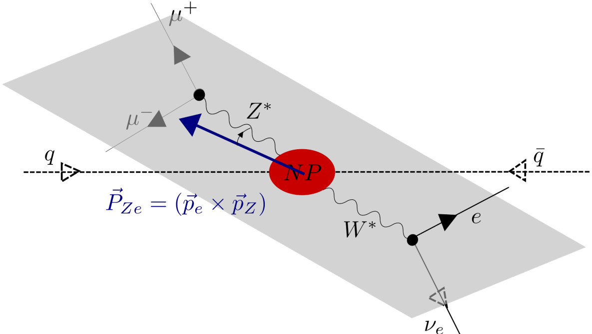
- $WZ \to l^+ l^- l' \nu$ production : $\Delta\phi_{l'Z}$
- $W\gamma \to \gamma l \nu$ production : $\Delta\phi_{l\gamma}$
- $W^+W^- \to l^+ \nu l^- \nu$ production : $\Delta\phi_{l^+l^-}$

Other CP-odd observables in Diboson

"Probing CP-violation at colliders through interference effects in diboson production and decay"

Kumar et al., [0801.2891]

$$\Xi^z_\pm(p_Z, p_l) = sign\,(p^z_Z)\,sign\,[(p_l \times p_Z)^z] = sign([0,0,p^z_Z].\,(\vec{p}_l \times \vec{p}_Z))$$
$$\to \Delta\Xi^z_\pm = \Delta p_\perp(p_e, p^z_Z)$$



Results

Process	W^+Z		Process	$W^+\gamma$	
Operators	SM	$\mathcal{O}_{\widetilde{W}WW}$	Operators	SM	$\mathcal{O}_{\widetilde{W}WW}$
$\Delta p_\perp(p_e, p_q)$	-0.04(2)	-1.612(4)	$\Delta p_\perp(p_e, p_q)$	7.7(8)	-13.81(4)
$\Delta p_\perp(p_e, p^z_\sum)$	-0.02(2)	-0.628(4)	$\Delta p_\perp(p_e, p^z_\sum)$	0.8(8)	-4.60(4)
$\Delta p_\perp(p_e, p^z_e)$	0.0(2)	-0.535(4)	$\Delta p_\perp(p_e, p^z_e)$	0.6(8)	1.11(4)
$\Delta p_\perp(p_e, p^z_Z)$	-0.01(2)	-0.527(4)	$\Delta p_\perp(p_e, p^z_\gamma)$	0.5(8)	-5.62(4)
$\Delta \sin\phi_{WZ}$	-0.03(2)	-0.321(4)	$\Delta \sin\phi_{W\gamma}$	-0.1(8)	-0.31(4)
$\Delta(\Delta\phi_{eZ})$	0.07(2)	0.196(4)	$\Delta(\Delta\phi_{e\gamma})$	-4.5(8)	-5.85(4)

Constraints

Operators	$\sigma(pp \to Wjj)$ [2]	$\Delta\phi_{jj}(pp \to Zjj)$[3]	EDMs[4]
$\mathcal{O}_{\widetilde{W}WW}$	[-14, 14] (expected)	[-0.12, 0.12] (expected)	$\leq 1.74\ 10^{-4}$
	[-11, 11] (measured)	[-0.11, 0.14] (measured)	
$\mathcal{O}_{\phi\widetilde{W}B}$	//	[-1.06, 1.06] (expected)	$\leq 5.57\ 10^{-6}$
	//	[-0.23, 2.34] (measured)	

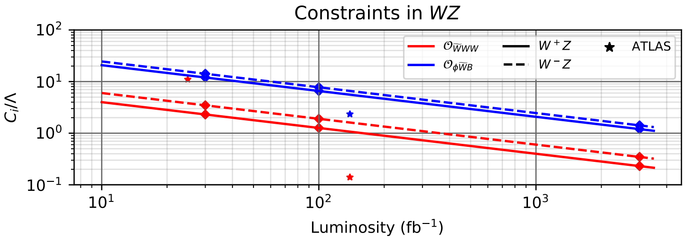
Table: Collection of the constraints on the two dimension-six operators with $\Lambda = 1$TeV at 95% CL.

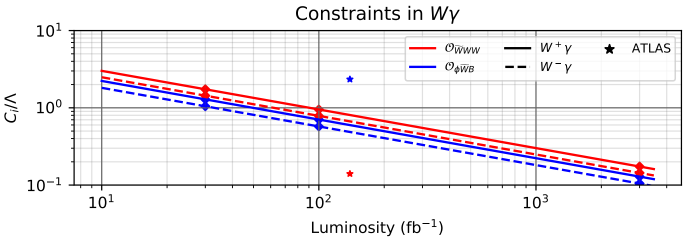
[2] **Eur.Phys.J.C,77(7):474,2017**

[3] **Eur.Phys.J.C 81(2):163,2021**

[4] **JHEP,04:090,2019**

Constraints and Luminosity





Conclusion

- Reducing dim-6 basis with $U(1)$ symmetries
- $\mathcal{M}_{int,i} \equiv 2Re\left\{\frac{C_i}{\Lambda^2}\mathcal{M}_i \times \mathcal{M}^*_{SM}\right\}$ is not positive-definite over phase-space $\rightarrow$ Asymmetries of simple observables
- The most sensitive observables to build asymmetry are
  - for $pp \rightarrow WZ$: $p_\perp(p_e, p^z_\sum)$.
  - for $pp \rightarrow W\gamma$: $\Delta\phi_{e\gamma}$.

If you know other CP-odd observables relevant for WZ/γ, we will be glad to compare their asymmetries with our results.

Back-up Slides

- Results in all channels
- Plot w.r.t $\sqrt{s}$
- Example of reduction of the basis and limitation
- Cuts

Results WZ

Process	$W^+Z \to \mu^-\mu^+e^+\nu_e$	$W^-Z \to \mu^-\mu^+e^-\tilde{\nu}_e$
$\sigma(SM)$	15.74(2) fb	9.88(1) fb
δ_{PDF}	3.45%	3.78%
$\sigma(\mathcal{O}_{\widetilde{W}WW})$	0.047(4) fb	-0.033(3) fb
$\sigma_{\Lambda^{-4}}(\mathcal{O}_{\widetilde{W}WW})$	4.133(5) fb	1.982(3) fb
Schwartz Bound	16.13 fb	8.85 fb
$\sigma^{\lvert int \rvert}(\mathcal{O}_{\widetilde{W}WW})$	3.302(4) fb	2.028(3) fb
$\sigma^{\lvert meas \rvert}(\mathcal{O}_{\widetilde{W}WW})$	1.084(4) fb	0.634(3) fb
$\sigma(\mathcal{O}_{\phi\widetilde{W}B})$	0.0086(7) fb	-0.0066(4) fb
$\sigma_{\Lambda^{-4}}(\mathcal{O}_{\phi\widetilde{W}B})$	0.0231(3) fb	0.0145(2) fb
Schwartz Bound	1.21 fb	0.76 fb
$\sigma^{\lvert int \rvert}(\mathcal{O}_{\phi\widetilde{W}B})$	0.5467(7) fb	0.3533(4) fb
$\sigma^{\lvert meas \rvert}(\mathcal{O}_{\phi\widetilde{W}B})$	0.1807(7) fb	0.1100(4) fb

Results $W\gamma$

Process	$W^+\gamma \to \gamma e^+ \nu_e$	$W^-\gamma \to \gamma e^- \tilde{\nu}_e$
$\sigma(SM)$	715.1(8) fb	589.1(7) fb
δ_{PDF}	2.99%	3.43%
$\sigma(\mathcal{O}_{\widetilde{W}WW})$	-2.07(4) fb	1.61(6) fb
$\sigma_{\Lambda^{-4}}(\mathcal{O}_{\widetilde{W}WW})$	39.78(5) fb	18.54(6) fb
Schwartz Bound	337.3 fb	209.0 fb
$\sigma^{\lvert int \rvert}(\mathcal{O}_{\widetilde{W}WW})$	33.83(4) fb	24.76(6) fb
$\sigma^{\lvert meas \rvert}(\mathcal{O}_{\widetilde{W}WW})$	6.07(4) fb	6.57(6) fb
$\sigma(\mathcal{O}_{\phi\widetilde{W}B})$	2.75(4) fb	-2.09(3) fb
$\sigma_{\Lambda^{-4}}\left(\mathcal{O}_{\phi\widetilde{W}B}\right)$	3.239(4) fb	2.878(3) fb
Schwartz Bound	96.3 fb	82.4 fb
$\sigma^{\lvert int \rvert}(\mathcal{O}_{\phi\widetilde{W}B})$	34.00(4) fb	26.37(3) fb
$\sigma^{\lvert meas \rvert}(\mathcal{O}_{\phi\widetilde{W}B})$	9.43(4) fb	9.53(3) fb

Results WZ

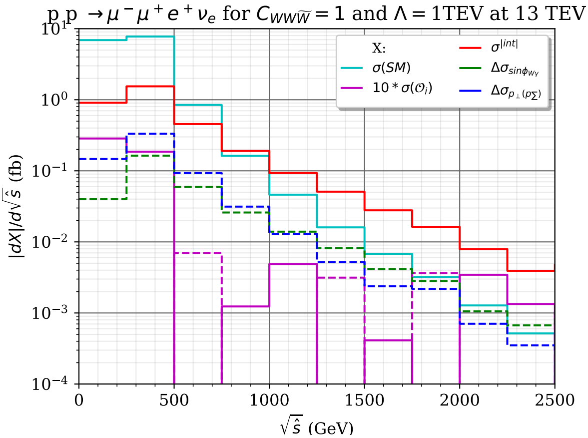
Operators	SM	$\mathcal{O}_{\widetilde{W}WW}$	$\mathcal{O}_{\phi\widetilde{W}B}$
Process	$W^+Z \to \mu^-\mu^+e^+\nu_e$		
$\Delta p_\perp(p_e, p_q)$	-0.04(2)	-1.612(4)	-0.3888(7)
$\Delta p_\perp(p_e, p^z_\sum)$	-0.02(2)	-0.628(4)	-0.1207(7)
$\Delta p_\perp(p_e, p^z_e)$	0.0(2)	-0.535(4)	-0.1173(7)
$\Delta p_\perp(p_e, p^z_Z)$	-0.01(2)	-0.527(4)	-0.0874(7)
$\Delta \sin\phi_{WZ}$	-0.03(2)	-0.321(4)	0.0031(7)
$\Delta(\Delta\phi_{eZ})$	0.07(2)	0.196(4)	0.0688(7)

Process	$W^-Z \to \mu^-\mu^+e^-\tilde{\nu}_e$		
$\Delta p_\perp(p_e, p_q)$	-0.08(1)	1.006(3)	0.2522(4)
$\Delta p_\perp(p_e, p^z_\sum)$	-0.03(1)	-0.331(3)	0.0810(4)
$\Delta p_\perp(p_e, p^z_e)$	-0.01(1)	0.295(3)	0.0514(4)
$\Delta p_\perp(p_e, p^z_Z)$	0.00(1)	0.295(3)	0.0627(4)
$\Delta \sin\phi_{WZ}$	-0.02(1)	-0.190(3)	0.0013(4)
$\Delta(\Delta\phi_{eZ})$	-0.05(1)	0.022(3)	0.0109(4)

Results $W\gamma$

Operators	SM	$\mathcal{O}_{\widetilde{W}WW}$	$\mathcal{O}_{\phi\widetilde{W}B}$
Process	$W^+\gamma \to \gamma e^+ \nu_e$		
$\Delta p_\perp(p_e, p_q)$	7.7(8)	-13.81(4)	22.23(4)
$\Delta p_\perp(p_e, p^z_{\sum})$	0.8(8)	-4.60(4)	5.59(4)
$\Delta p_\perp(p_e, p^z_\gamma)$	0.5(8)	-5.62(4)	7.59(4)
$\Delta p_\perp(p_e, p^z_e)$	0.6(8)	1.11(4)	0.42(4)
$\Delta \sin\phi_{W\gamma}$	-0.1(8)	-0.31(4)	-0.79(4)
$\Delta(\Delta\phi_{e\gamma})$	-4.5(8)	-5.85(4)	7.16(4)
Process	$W^-\gamma \to \gamma e^- \tilde{\nu}_e$		
$\Delta p_\perp(p_e, p_q)$	5.3(7)	10.65(3)	-17.27(3)
$\Delta p_\perp(p_e, p^z_{\sum})$	1.2(7)	2.34(3)	-4.15(3)
$\Delta p_\perp(p_e, p^z_\gamma)$	0.1(7)	-1.68(3)	1.48(3)
$\Delta p_\perp(p_e, p^z_e)$	0.9(7)	5.09(3)	-7.07(3)
$\Delta \sin\phi_{W\gamma}$	-0.4(7)	-1.87(3)	1.22(3)
$\Delta(\Delta\phi_{e\gamma})$	1.2(7)	-6.17(3)	8.46(3)

$\mathcal{O}_{\widetilde{W}WW}$ in $pp \to W^+ Z \to \mu^- \mu^+ e^+ \nu_e$



Basis Reduction under $U(1)^{14}$

- SM is unaffected except in the mass terms.
- CP-odd $\mathcal{O}_i^6$ in :
  - $\left\{X^3, X^2\phi^2\right\}$ remain.
  - $\left\{\psi^2\phi^3, \psi^4, \psi^2\phi^2 D, X\psi^2\phi\right\}$ disappear unless t_R.
- Example non-hermitian : $\mathcal{O}_{ledq} = \left(\bar{l}^j e\right)\left(\bar{d} q^j\right)$
  - Extract the phase $C_{ledq} = e^{i\varphi_{ledq}}\left|C_{ledq}\right|$,
  - Fix the gauge $e_r \to e^{-i\varphi_{ledq}} e_r'$,
  - Absorb the phase
    $C_{ledq}\mathcal{O}_{ledq} = e^{i\varphi_{ledq}}|C_{ledq}|(\bar{l}^j e)(\bar{d} q^j) \to |C_{ledq}|(\bar{l}^j e')(\bar{d} q^j)$.

Limitations

Only valid for one operator at a time. Otherwise, phase passed to other operator.

Example of 2 non-hermitian : $\mathcal{O}_{ledq} = \left(\bar{l}^j e\right)\left(\bar{d} q^j\right)$ and $\mathcal{O}_{e\phi}$

- Extract the phase $C_{e\phi} = e^{i\varphi_{e\phi}} |C_{e\phi}|$,
- Absorb the phase
  $C_{ledq}\mathcal{O}_{ledq} = e^{i\varphi_{ledq}}|C_{ledq}|(\bar{l}^j e)(\bar{d} q^j) \rightarrow |C_{ledq}|(\bar{l}^j e')(\bar{d} q^j)$.
- Transfer the phase
  $e^{i\varphi_{e\phi}}|C_{e\phi}|(\phi^\dagger\phi)(\bar{l} e\phi) \rightarrow e^{i(\varphi_{e\phi}-\varphi_{ledq})}|C_{e\phi}|(\phi^\dagger\phi)(\bar{l} e\phi)$.

- The PDF set exploited in the event generation is the NNPDF2.3 in which $\alpha_S(M_Z) = 0.119$.
- We fix the SM parameters at the Z pole mass :

$$m_Z = 91.1876,\ (\alpha_{EM})^{-1} = 127.9,\ G_F = 1.166370^{-5},$$
$$\Gamma_Z = 2.4952,\ \Gamma_W = 2.085.$$

- WZ events:

$$p_T(\mu) > 15\text{GeV}, \quad |\eta(\mu)| < 2.5, \quad p_T(e) > 20\text{GeV}, \quad |\eta(e)| < 2.5,$$
$$\Delta R(\mu^+\mu^-) > 0.2, \quad \Delta R(e\mu^-) > 0.3, \quad \Delta R(e\mu^+) > 0.3,$$
$$|m_{\mu^-\mu^+} - m_Z| < 10\text{GeV}, \quad m_T(e\nu_e) > 30\text{GeV}.$$

- $W\gamma$ events :

$$p_T(e) > 25\text{GeV}, \quad |\eta(e)| < 2.47, \quad E_T(\gamma) > 15\text{GeV}, \quad |\eta(\gamma)| < 2.37,$$
$$E_T^{miss} > 35\text{GeV}, \quad \Delta R(e\gamma) > 0.7, \quad m_T(e\nu_e) > 40\text{GeV},$$
$$|m(e\gamma) - m_Z| > 10\text{GeV}.$$