Reviving the interference: framework and proof-of-principle for the anomalous gluon self-interactions in the SMEFT

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Outline

The SMEFT extends the SM by adding higher-dimensional operators

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \sum_i \frac{C_i}{\Lambda^{d-4}} O_i^d$$

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar{l}_p e_r \varphi)$
$Q_{\widetilde{G}}$	$f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p u_r \widetilde{\varphi})$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p d_r \varphi)$
$Q_{\widetilde{W}}$	$\varepsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar{l}_p\sigma^{\mu\nu}e_r)\tau^I\varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{l}_p\gamma^\mu l_r)$
$Q_{\varphi\widetilde{G}}$	$\varphi^\dagger\varphi\, \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar{l}_p\sigma^{\mu\nu}e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar{l}_p\tau^I\gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar{q}_p\sigma^{\mu\nu}T^A u_r)\widetilde{\varphi}\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{e}_p\gamma^\mu e_r)$
$Q_{\varphi\widetilde{W}}$	$\varphi^\dagger\varphi\, \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\tau^I\widetilde{\varphi}\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{q}_p\gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu}B^{\mu\nu}$	Q_{uB}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\widetilde{\varphi}\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar{q}_p\tau^I\gamma^\mu q_r)$
$Q_{\varphi\widetilde{B}}$	$\varphi^\dagger\varphi\, \widetilde{B}_{\mu\nu}B^{\mu\nu}$	Q_{dG}	$(\bar{q}_p\sigma^{\mu\nu}T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{u}_p\gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\tau^I\varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{d}_p\gamma^\mu d_r)$
$Q_{\varphi\widetilde{W}B}$	$\varphi^\dagger\tau^I\varphi\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde{\varphi}^\dagger D_\mu\varphi)(\bar{u}_p\gamma^\mu d_r)$

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$	Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$	Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$	Q_{qqq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j\sigma_{\mu\nu}e_r)\varepsilon_{jk}(\bar{q}_s^k\sigma^{\mu\nu}u_t)$		

The interference can be small even if it is non-zero everywhere

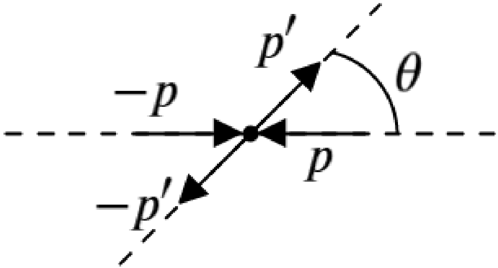
$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \sum_i \frac{C_i}{\Lambda^{d-4}} O_i^d$$

- We truncate the amplitude at $\mathcal{O}(1/\Lambda^2)$

$$\begin{aligned} \sigma &= \sigma^{SM} + \frac{C_i}{\Lambda^2}\,\sigma^{1/\Lambda^2} + \left(\frac{C_i}{\Lambda^2}\right)^2\,\sigma^{1/\Lambda^4} + \ldots \\ &= \int d\Phi\,\left[|\mathcal{M}_{SM}|^2 + 2\mathrm{Re}\Big(\mathcal{M}_{SM}\mathcal{M}^*_{1/\Lambda^2}\Big) + |\mathcal{M}_{1/\Lambda^2}|^2 + \ldots\right] \end{aligned}$$

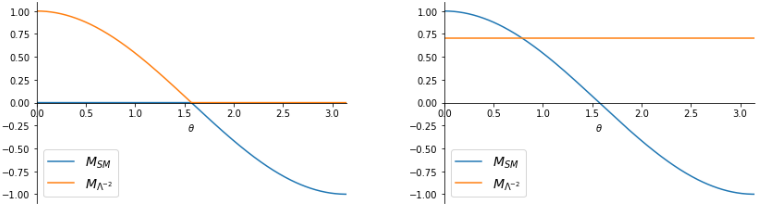
The interference can be small even if it is non-zero everywhere

$$\sigma = \sigma^{SM} + \frac{C_i}{\Lambda^2}\,\sigma^{1/\Lambda^2} + \left(\frac{C_i}{\Lambda^2}\right)^2\,\sigma^{1/\Lambda^4} + \dots$$
$$= \int d\Phi\,\left[|\mathcal{M}_{SM}|^2 + 2\mathrm{Re}\Big(\mathcal{M}_{SM}\mathcal{M}^*_{1/\Lambda^2}\Big) + |\mathcal{M}_{1/\Lambda^2}|^2 + \dots\right]$$



The interference term can be small even if it is non-zero everywhere

$$\sigma = \sigma^{SM} + \frac{C_i}{\Lambda^2}\,\sigma^{1/\Lambda^2} + \left(\frac{C_i}{\Lambda^2}\right)^2 \sigma^{1/\Lambda^4} + \ldots$$
$$= \int d\Phi\ \left[|\mathcal{M}_{SM}|^2 + 2\mathrm{Re}\Big(\mathcal{M}_{SM}\mathcal{M}^*_{1/\Lambda^2}\Big) + |\mathcal{M}_{1/\Lambda^2}|^2 + \ldots\right]$$



- The interference term is divided by Λ^2, the new physics term by Λ^4
- The interference term is sensitive to the sign of the coefficient C_i

The O_G operator presents interference suppression

$$O_G = g_s f_{abc}\, G_{\nu}^{a,\mu} G_{\rho}^{b,\nu} G_{\mu}^{c,\rho}$$

- The best bounds so far come from the $\mathcal{O}(1/\Lambda^4)$ term, for $\Lambda = 1$ TeV at 95% CL

$$S_T = \sum_{j=1}^{N_{jets}} E_{T,j} + (\not{E}_T \; > \; 50 \text{ GeV}) \quad \Rightarrow \quad \frac{C_G}{\Lambda^2} < 0.037 \text{ TeV}^{-2}$$

$$\chi_{dijet} = e^{|y_1 - y_2|} \quad \Rightarrow \quad \frac{C_G}{\Lambda^2} < 0.032 \text{ TeV}^{-2}$$

F. Krauss, S. Kuttimalai, T. Plenh, *LHC multijet events as a probe for anomalous dimension-six gluon interactions*, [1611.00767v3] (2017)

R. Goldouzian, M.D. Hildreth, *LHC dijet angular distributions as a probe for the dimension-six triple gluon vertex*, [2001.02736v1] (2020)

Three-jet production shows the best interference cancellation

$$O_G = g_s f_{abc}\, G_\nu^{a,\mu} G_\rho^{b,\nu} G_\mu^{c,\rho}$$

- The cancellation over the phase space is efficient if the integrals of the interference where its matrix element is positive and negative are almost equal, in absolute value
- $pp\ >\ jj$ shows $\sigma^{1/\Lambda^2} = 0$

	$p_T[j] > 50$ GeV		$p_T[j] > 200$ GeV		$p_T[j] > 1000$ GeV	
process	σ^{1/Λ^2} [pb]	wgt>0	σ^{1/Λ^2} [pb]	wgt>0	σ^{1/Λ^2} [pb]	wgt>0
$pp\ >\ t\bar{t}$	1.388	85.0%	1.384	85.2%	1.384	85.1%
$pp\ >\ t\bar{t}j$	$5.20{\cdot}10^{-1}$	62.4%	$1.13{\cdot}10^{-1}$	60.4%	$1.37{\cdot}10^{-3}$	62.0%
$pp\ >\ jjj$	$2.98{\cdot}10^{1}$	51.6%	$5.90{\cdot}10^{-1}$	52.4%	$4.91{\cdot}10^{-4}$	61.2%
$pp\ >\ jjjj$	$-2.89{\cdot}10^{1}$	45.4%	$-2.50{\cdot}10^{-1}$	44.2%	$-4.12{\cdot}10^{-6}$	38.8%

The measurable cross-section quantifies the interference suppression

- The cancellation over the phase space is efficient if the integrals of the interference where its matrix element is positive and negative are almost equal, in absolute value
- The integral of absolute-valued interference differential cross-section quantifies the total suppression

$$\sigma^{|int|} = \int d\Phi \left| \frac{d}{d\Phi} \sigma^{1/\Lambda^2} \right|$$

- Measurable absolute-valued cross-section

$$\begin{aligned}\sigma^{|meas|} &= \int d\Phi_{meas} \left| \sum_{\{um\}} \frac{d}{d\Phi} \sigma^{1/\Lambda^2} \right| \\ &= \lim_{N\to\infty} \sum_{i=1}^{N} w_i \times \text{sign}\left(\sum_{\{um\}} \text{ME}(\overrightarrow{p}_i, \{um\}) \right)\end{aligned}$$

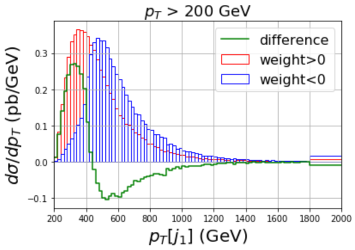
The measurable cross-section quantifies the interference suppression

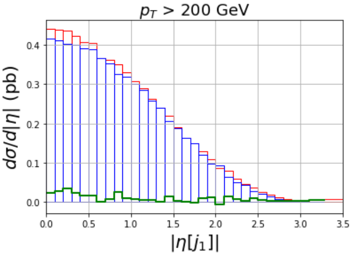
$$\sigma^{|int|} = \int d\Phi \left| \frac{d}{d\Phi} \sigma^{1/\Lambda^2} \right|$$

$$\sigma^{|meas|} = \lim_{N\to\infty} \sum_{i=1}^{N} w_i \times \text{sign}\left(\sum_{\{um\}} \text{ME}(\vec{p}_i, \{um\}) \right)$$

Three-jet production						
	SM	$\mathcal{O}(1/\Lambda^2)$				$\mathcal{O}(1/\Lambda^4)$
$p_{T,min}$ [GeV]	σ [pb]	σ [pb]	wgt>0	$\sigma^{\|meas\|}$ [pb]	$\sigma^{\|int\|}$ [pb]	σ [pb]
50	$9.70 \cdot 10^5$	4.08	50.4%	$7.83 \cdot 10^2$	$1.05 \cdot 10^3$	$3.93 \cdot 10^1$
200	$8.96 \cdot 10^2$	$2.92 \cdot 10^{-1}$	51.4%	$3.5 \cdot 10^1$	$5.02 \cdot 10^1$	2.73
500	3.10	$1.69 \cdot 10^{-2}$	54.0%	$6.04 \cdot 10^{-1}$	$8.96 \cdot 10^{-1}$	$1.48 \cdot 10^{-1}$
1000	$9.08 \cdot 10^{-3}$	$4.56 \cdot 10^{-4}$	60.1%	$1.46 \cdot 10^{-3}$	$2.29 \cdot 10^{-3}$	$3.05 \cdot 10^{-3}$

We focus on variables which separate the cross-section contributions with different sign



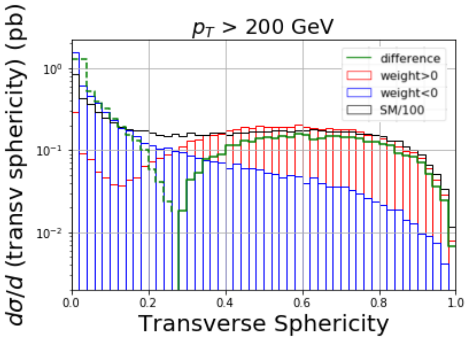


The transverse sphericity presents the best efficiency

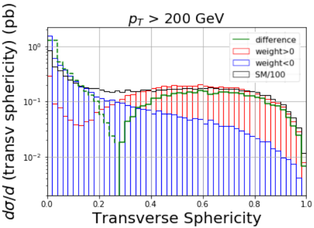
$p_T[j] > 200$ GeV		
Distribution	Cut	% of $\sigma^{\|meas\|}$
Sph_T	0.27	83.54
Thr_T	0.10	48.29
$p_T[j_1]$	440 GeV	43.09
$\Delta R[j_2 j_3]$	1.80	36.68
$\eta[j_1]$	1.2	6.29
σ^{1/Λ^2}	-	2.40

The transverse sphericity presents the best efficiency

$$M_{xy} = \sum_{i=1}^{N_{jets}} \begin{pmatrix} p_{x,i}^2 & p_{x,i}p_{y,i} \\ p_{y,i}p_{x,i} & p_{y,i}^2 \end{pmatrix} \Rightarrow Sph_T = \frac{2\lambda_2}{\lambda_2 + \lambda_1}$$



We use the best distributions to get bounds on C_G



$$\chi^2 = \sum_i \left(\frac{x_i^{exp} - x_i^{th}}{\Delta_i} \right)^2$$

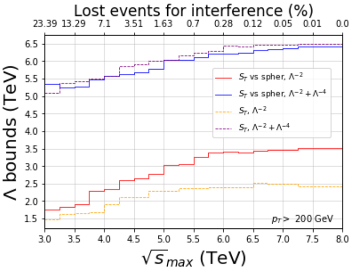
$$= \sum_i \left(\frac{\frac{C_G}{\Lambda^2} \sigma_i^{1/\Lambda^2}}{\Delta_i} \right)^2$$

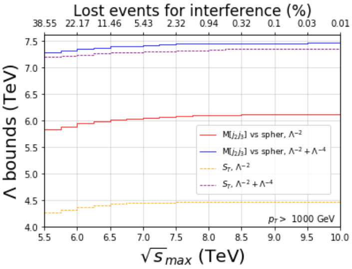
- The LHC data we are interested in is not public yet

The best $\mathcal{O}(1/\Lambda^2)$ bounds are comparable to the $\mathcal{O}(1/\Lambda^4)$ ones

$\Lambda = 1$ TeV, 68% CL					
$p_{T,min}$ [GeV]	Distribution	Sph_T cut	Bins	Upper bound on C_G	Lower bound on C_G
50	$p_T[j_3]$ vs Sph_T	0.23	34	$2.5{\cdot}10^{-1}$ ($1.1{\cdot}10^{-1}$)	$-2.5{\cdot}10^{-1}$ ($-1.2{\cdot}10^{-1}$)
200	S_T vs Sph_T	0.27	34	$7.5{\cdot}10^{-2}$ ($2.3{\cdot}10^{-2}$)	$-7.5{\cdot}10^{-2}$ ($-2.4{\cdot}10^{-2}$)
500	$M[j_2 j_3]$ vs Sph_T	0.31	21	$5.5{\cdot}10^{-2}$ ($5.3{\cdot}10^{-2}$)	$-5.5{\cdot}10^{-2}$ ($-3.5{\cdot}10^{-2}$)
1000	$M[j_2 j_3]$ vs Sph_T	0.35	7	$2.6{\cdot}10^{-2}$ ($1.9{\cdot}10^{-2}$)	$-2.6{\cdot}10^{-2}$ ($-1.8{\cdot}10^{-2}$)

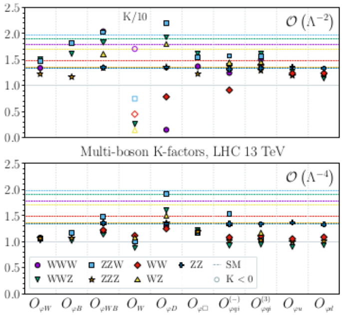
We check the EFT valid by cutting the events energy





- The EFT is valid if $\sqrt{s} < \Lambda$
- Constraints barely change for $\sqrt{s} \gtrsim 6$ TeV
- The bounds from the interference grow faster than the $\mathcal{O}(1/\Lambda^2)$ ones

Large K-factors are predicted when interference suppression occurs



Process	SM	$c_W, \mathcal{O}(1/\Lambda^2)$	$c_W, \mathcal{O}(1/\Lambda^4)$
WW	1.5	-4.5	1.1
WZ	1.7	-1.4	1.1
ZZ	1.3	-	-
WWW	1.8	-17	1.0
WWZ	1.9	2.6	0.9
ZZW	2.0	-7.5	1.0
ZZZ	1.4	-	-

- Positively and negatively contributing regions could have more reasonable but different K-factors, which affect the level of cancellation
- Observables that can separate the two regions can provide stable predictions for the interference

C. Degrande, G. Durieux, F. Maltoni, K. Mimasu, E. Vryonidou, C. Zhang, *Automated one-loop computations in the SMEFT*, [2008.11743] (2020)

Take-aways

- We used the sign of measurable matrix elements to quantify the efficiency of differential distributions to separate phase space regions that contribute with opposite signs to the interference cross-section
- We used these distributions to set, for the first time, bounds on the O_G operator coefficient that are dominated by the leading interference term
- Being sensible to the interference, our observables are also sensitive to the sign of the C_G coefficient
- This approach is fully generic and can be applied to any BSM scenarios where interference suppression occurs, even outside the SMEFT
- Using this approach to lift the cancellation may be important to get stable predictions at NLO
- This method may be used in parallel with Machine Learning techniques:
  - if the EFT is not fully valid
  - to find the best distribution to feed the networks
  - to check the final results