Novel measurements of anomalous triple gauge couplings for the LHC

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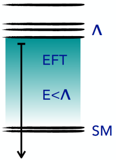
1707.08060 with A.Azatov, J.Elias-Miro, Y.Reyimuaji
In progress with G.Panico, F.Riva, A.Wulzer, A.Azatov, D.Barducci

- Search for new resonances → High energy
- **Precision tests of SM → High luminosity**

EFT: Parametrization at $E < \Lambda$ of NP with $M \geq \Lambda$
($E \sim$ EW scale, $\Lambda \sim$ BSM scale)



- Integration out of heavy fields (Assuming lepton number conservation):

$$\mathcal{L}^{BSM} \to \mathcal{L}^{SM}_{EFT} = \mathcal{L}^{SM} + \sum_{n=6}^{\infty} \sum_{i} \frac{c_i^n}{\Lambda^{n-4}} \mathcal{O}_i^n$$

- Observables:

$$\sigma_{EFT} = \sigma^{SM} + \sum_i \frac{(c_i \sigma_i^{6xSM} + h.c.)}{\Lambda^2} + \sum_{i,j} \frac{c_i c_j^*}{\Lambda^4} \sigma_{ij}^{6x6} + + \sum_i \frac{(c_i \sigma_i^{8xSM} + h.c.)}{\Lambda^4} + \mathcal{O}\left(\frac{1}{\Lambda^4}\right)$$

Naively $\frac{\sigma_i^{6xSM}}{\Lambda^2 \sigma^{SM}} \sim \frac{E^2}{\Lambda^2}$ $\frac{\sigma_{ij}^{6x6}}{\Lambda^4 \sigma^{SM}} \sim \frac{E^4}{\Lambda^4}$

Energy region with EFT validity and BSM sensitivity

$$\frac{E^2}{\Lambda^2} \gg 0 \wedge \frac{E^2}{\Lambda^2} \gg \frac{E^4}{\Lambda^4}$$

Focus : D=6 - SM interference

- Naively LARGER for ENERGIES $E \ll \Lambda$ (EFT validity)
- Possible enlargement of the E-region with D=6 TRUNCATION validity
- Information about the SIGN of the Wilson coefficients

NP Sensitivity of Diboson (VV) production → Focus on a(nomalous)TGCs

$$\mathcal{L}_{TGC}^{SM} = ig\left[\left(W^{+,\mu\nu}W_\mu^- + W^{-,\mu\nu}W_\mu^+\right)W_\nu^3 + W^{3,\mu\nu}W_\mu^+W_\nu^-\right], \quad W_\mu^3 = c_\theta Z_\mu + s_\theta A_\mu$$

$\boldsymbol{\Delta\mathcal{L}_{TGC}}$ (CP-even):

1. $$ig(W^{+,\mu\nu}W_\mu^- + W^{-,\mu\nu}W_\mu^+)(\delta g_{1,z}c_\theta Z_\nu + \delta g_{1,\gamma}s_\theta A_\nu) +$$
$$+ig(\delta\kappa_z c_\theta Z^{\mu\nu} + \delta\kappa_\gamma s_\theta A^{\mu\nu})W_\mu^+W_\nu^- +$$
2. $$+\lambda_z c_\theta \frac{ig}{m_W^2}W^{+,\mu\nu}W_{\nu\rho}^-Z_\mu^\rho + \lambda_\gamma s_\theta \frac{ig}{m_W^2}W^{+,\mu\nu}W_{\nu\rho}^-A_\mu^\rho$$

$\mathbf{U(1)_\gamma}$ invariance $\Rightarrow \delta g_{1,\gamma} = 0$

LEP-II BOUNDS

$\lambda_z \in [-0.059; 0.017]$ $\quad \delta g_{1,z} \in [-0.054; 0.021]$ $\quad \delta\kappa_z \in [-0.074; 0.051]$

NP Sensitivity of Diboson (VV) production → Focus on a(nomalous)TGCs

$$\mathcal{L}_{TGC}^{SM} = ig\left[\left(W^{+,\mu\nu}W_\mu^- + W^{-,\mu\nu}W_\mu^+\right)W_\nu^3 + W^{3,\mu\nu}W_\mu^+W_\nu^-\right], \quad W_\mu^3 = c_\theta Z_\mu + s_\theta A_\mu$$

$\boldsymbol{\Delta}\mathcal{L}_{\mathbf{TGC}}\,|_{\mathbf{D=6}}$ (CP-even) [For example SILH basis]:

1. $\mathbf{ig(D_\mu H)^\dagger \hat{W}^{\mu\nu} D_\nu H} = \mathcal{O}_{HW}$ $\quad \mathbf{ig'(D_\mu H)^\dagger B^{\mu\nu} D_\nu H} = \mathcal{O}_{HB} \to_{\mathbf{EW\text{-}SSB}}$
   $\to ig(W^{+,\mu\nu}W_\mu^- + W^{-,\mu\nu}W_\mu^+)(\delta g_{1,z} c_\theta Z_\nu + \delta g_{1,\gamma} s_\theta A_\nu) +$
   $+ig(\delta\kappa_z c_\theta Z^{\mu\nu} + \delta\kappa_\gamma s_\theta A^{\mu\nu})W_\mu^+ W_\nu^-$

$\mathbf{U(1)_\gamma}$ **invariance** $\Rightarrow \delta\mathbf{g_{1,\gamma} = 0},\qquad$ **D=6 EFT:** $\delta\kappa_{\mathbf{z}} = \delta\mathbf{g_{1,z}} - \frac{\mathbf{s}_\theta^2}{\mathbf{c}_\theta^2}\delta\kappa_\gamma$

$$\delta g_{1,z} = \frac{m_Z^2}{\Lambda^2} c_{HW}\ , \quad \delta\kappa_Z = \frac{m_W^2}{\Lambda^2}\left(c_{HW} - \tan^2\theta\, c_{HB}\right)$$

NP Sensitivity of Diboson (VV) production → Focus on a(nomalous)TGC

$$\mathcal{L}_{TGC}^{SM} = ig\left[\left(W^{+,\mu\nu}W_\mu^- + W^{-,\mu\nu}W_\mu^+\right)W_\nu^3 + W^{3,\mu\nu}W_\mu^+W_\nu^-\right], \quad W_\mu^3 = c_\theta Z_\mu + s_\theta A_\mu$$

$\mathbf{\Delta\mathcal{L}_{TGC}}\,|_{\mathbf{D=6}}$ (CP-even) [For example SILH basis]:

2. $\frac{\mathbf{g}}{\mathbf{3!}}\epsilon^{\mathbf{abc}}\mathbf{W}^{\mathbf{a},\mu\nu}\mathbf{W}^{\mathbf{b}}_{\nu\rho}\mathbf{W}^{\mathbf{c},\rho}_{\mu} = \mathcal{O}_{3W}$ → **New TGC**: $\lambda_z \frac{ig}{m_W^2} W^{+,\mu\nu}W^-_{\nu\rho}W^{3,\rho}_\mu$

D=6 EFT : $\lambda_z = \lambda_\gamma \qquad \lambda_Z = \frac{m_W^2}{\Lambda^2}c_{3W}$

3 aTGC: $\delta g_{1,z}$, $\delta\kappa_\gamma$, λ_z
LEP-I bounds ⇒ 3 independent parameters in VV production: 3 aTGCs

Using Goldstone Equivalence formalism $\mathbf{H} \supset \mathbf{V_L}$ $(V = W, Z)$

- SM : $\quad \mathrm{tr} W_{\mu\nu} W^{\mu\nu} \supset \partial V_T V_T V_T, \quad (D_\mu H)^\dagger D^\mu H \supset \partial V_L V_T V_L + v V_T V_T V_L$

  Leading energy scaling of SM helicity amplitudes

$$\mathcal{M}\left(q\bar{q} \to V_T W_T^+, V_L W_L^+\right) \sim E^0, \quad \mathcal{M}\left(q\bar{q} \to V_T W_L^+ / V_L W_T^+\right) \sim \frac{v}{E}$$

- D=6 EFT

$$\mathcal{O}_{HB} = ig'(D_\mu H)^\dagger B^{\mu\nu} D_\nu H \supset \partial W_L \partial Z_T \partial W_L + v W_T \partial Z_T \partial W_L + v^2 W_T \partial Z_T W_T + \dots$$

$$\mathcal{O}_{HW} = ig(D_\mu H)^\dagger \hat{W}^{\mu\nu} D_\nu H \supset \partial V_L \partial V_T \partial V_L + v V_T \partial V_T \partial V_L + v^2 V_T \partial V_T V_T + \dots$$

$$\mathcal{O}_{3W} = \frac{g}{3!} \epsilon^{abc} W^{a,\mu\nu} W^b_{\nu\rho} W^{c,\rho}_\mu \supset \partial V_T \partial V_T \partial V_T + \dots$$

Leading energy scaling of helicity amplitudes with D=6 operators:

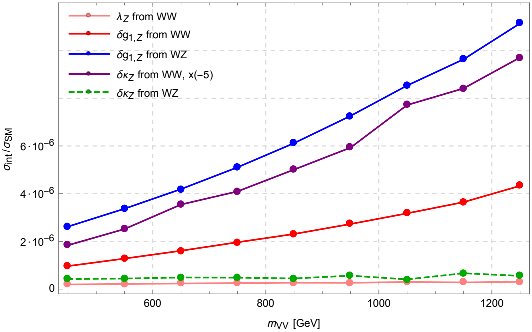
$$\mathcal{M}\left(q\bar{q} \to W_L^- W_L^+\right) \sim E^2/\Lambda^2\, c_{HB} + E^2/\Lambda^2\, c_{HW} \sim E^2/m_W^2\, \delta g_{1,Z} + E^2/m_W^2\, \delta\kappa_Z$$

$$\mathcal{M}\left(q\bar{q} \to Z_L W_L^+\right) \sim E^2/\Lambda^2\, c_{HW} = E^2/m_Z^2\, \delta g_{1,Z}$$

$$\mathcal{M}\left(q\bar{q} \to V_T W_T^+\right) \sim E^2/\Lambda^2\, c_{3W} = E^2/m_W^2\, \lambda_Z$$

Naively expected E^2 enhancement with respect to SM

Interference and interference suppression



- $\delta \mathbf{g_{1,z}}$: $\quad$ **SM** $\times\, \mathcal{O}_{\mathbf{HW}} \sim E^2$ in $q\bar{q} \to V_L V_L$
- $\delta \kappa_{\mathbf{z}}$: $\quad$ **SM** $\times\, \mathcal{O}_{\mathbf{HB}} \sim E^2$ in $q\bar{q} \to W_L W_L$

  $\sim E^0$ in $q\bar{q} \to W_{L,T} Z_T$ (**Interference suppression**)
- $\lambda_{\mathbf{Z}}$: $\quad$ **SM** $\times\, \mathcal{O}_{\mathbf{3W}}$: more information needed
  - **SM**: $q\bar{q} \to V_{T\pm} V_{T\mp}$
    (Helicity selection rule; Azatov, Contino, Machado, Riva [arXiv:1607.05236])
  - $\mathcal{O}_{\mathbf{3W}}$: $q\bar{q} \to V_{T\pm} V_{T\pm}$ $(O_{3W} \propto w_\alpha{}^\beta w_\beta{}^\gamma w_\gamma{}^\alpha + \bar{w}_{\dot\alpha}{}^{\dot\beta} \bar{w}_{\dot\beta}{}^{\dot\gamma} \bar{w}_{\dot\gamma}{}^{\dot\alpha}) \Rightarrow$

    $\Rightarrow SM \times \mathcal{O}_{3W} \sim E^0 \sim m_V^2 \to$ **Interference suppression**

Goal:

Overcome suppression of $SM \times \mathcal{O}_{3W}$ interference

$$\sigma(q\bar{q} \to V_T V_T) \sim \frac{g_{SM}^4}{E^2}\left[1 + c_{3W}\frac{m_V^2}{\Lambda^2} + c_{3W}^2\frac{E^4}{\Lambda^4}\right]$$

- **Relaxation of the condition for dimension 6 truncation validity**

$$\max\left(c_{3W}\frac{m_V^2}{\Lambda^2}, c_{3W}^2\frac{E^4}{\Lambda^4}\right) > \max\left(c_8\frac{E^4}{\Lambda^4}, c_8^2\frac{E^8}{\Lambda^8}\right) \to$$

$$\to \max\left(c_{3W}\frac{E^2}{\Lambda^2}, c_{3W}^2\frac{E^4}{\Lambda^4}\right) > \max\left(c_8\frac{E^4}{\Lambda^4}, c_8^2\frac{E^8}{\Lambda^8}\right)$$

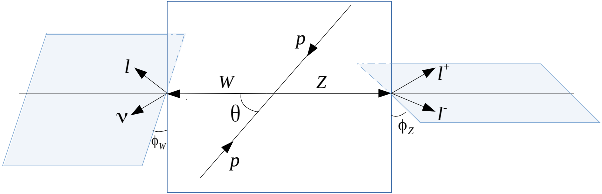
- **Sensitivity to the sign of c_{3W}**

Not $2 \to 2$ **BUT** $2 \to 2 \to 4$

Not helicity selection rule BUT NOT INTERFERENCE:

non trivial distribution in the azimuthal angles of final fermions

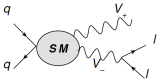
Duncan,Kane,Repko 85

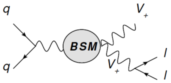


- **BSM$_{\mathrm{TT}}$ $\times$ SM$_{\mathrm{TT}}$** interference

  $2 \to 3: q\bar{q} \to W_{T_+} Z_i$ and $Z \to l^+ l^-$, $i = \pm$ (Neglecting $V_T V_L \sim \frac{v}{E}$ in SM)

$$\frac{d\sigma(q\bar{q} \to W_{T_+} l_- \bar{l}_+)}{dLIPS} \supset$$





$$\supset \frac{\pi}{2s} \frac{\delta(s - m_Z^2)}{\Gamma_Z m_Z} \mathcal{M}^{\mathrm{SM}}_{q\bar{q} \to W_{T_+} Z_{T_-}} \left(\mathcal{M}^{\mathrm{BSM}}_{q\bar{q} \to W_{T_+} Z_{T_+}} \right)^* \mathcal{M}_{Z_{T_-} \to l_- \bar{l}_+} \mathcal{M}^*_{Z_{T_+} \to l_- \bar{l}_+}$$

$$\to \frac{d\sigma_{\mathrm{int}}(q\bar{q} \to W_+ l_- \bar{l}_+)}{d\phi_Z} \propto \frac{E^2}{\Lambda^2} \cos(2\phi_Z)$$

Naively expected energy growth

ϕ_Z: Azimuthal angle of LH (or RH) lepton from Z w.r.t. $\vec{p}_z$

Modulated and non zero interference; zero after integration ($2 \to 2$)

BUT

- In $Z \to l^+ l^-$ the helicity of l^- (or l^+) is not fixed and observed
- Observable: ϕ_Z^c for l^- (or l^+) with fixed charge $\to \phi_Z^c = \phi_Z \vee \phi_Z^c = \phi_Z + \pi$

  Ambiguity, BUT $\cos(2\phi_Z)$ **modulation is not affected**

- **BSM$_{\mathbf{TT}}$ $\times$ SM$_{\mathbf{TT}}$** interference

$$q\bar{q} \rightarrow W_i Z_j \text{ and } W \rightarrow \nu l \ Z \rightarrow l^+ l^-, \ i,j = \pm$$

$$\frac{d\sigma_{\text{int}}(q\bar{q} \rightarrow WZ \rightarrow 4\psi)}{d\phi_Z \, d\phi_W} \propto \frac{E^2}{\Lambda^2} \left(\cos(2\phi_Z) + \cos(2\phi_W)\right)$$

Modulated non zero $\sim$ E^2 interference even integrating over ϕ_Z or ϕ_W

BUT Ambiguity also on ϕ_W

- In $W \rightarrow \nu l$ $\vec{p}_\nu$ is not observed
- $\vec{p}_\nu$ and ϕ_W reconstruction $\rightarrow \phi_W^{rec} = \phi_W \vee \phi_W^{rec} = \pi - \phi_W$ [1]

  Ambiguity, BUT $\cos(2\phi_W)$ **modulation is not affected**

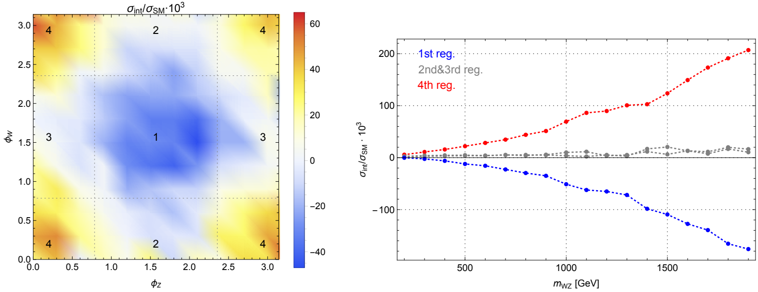
- **BSM$_{\mathbf{TT}}$ $\times$ SM$_{\mathbf{LL}}$** interference

$$\frac{d\sigma_{\text{int}}(q\bar{q} \rightarrow WZ \rightarrow 4\psi)}{d\phi_Z \, d\phi_W} \propto \frac{E^2}{\Lambda^2} \cos(\phi_Z + \phi_W)$$

Hard to be observed due to ϕ_Z helicity-charge (or ϕ_W) ambiguity

$$\cos(\phi_Z + \phi_W) \sim g_L^2 \cos(\phi_Z^c + \phi_W) + g_R^2 \cos(\phi_Z^c + \pi + \phi_W) =$$
$$= (g_L^2 - g_R^2) \cos(\phi_Z^c + \phi_W) \sim 0 \quad [g_L \sim -0.28, g_R \sim -0.22]$$

[1] Panico, Riva, Wulzer [arXiv: 1708.07823]



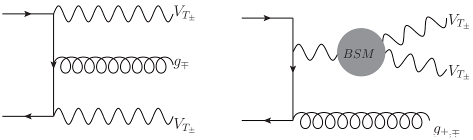
Left: Differential interference cross section over SM one as a function the azimuthal angles ϕ_W and ϕ_Z (In $[0, \pi]$) for the events with $W - Z$ invariant mass $m_{WZ} \in [700, 800] GeV$.
Right: same quantity as a function of the m_{WZ} binned in 2 bins of ϕ_Z and 2 bins of ϕ_W $(\cos(2\phi) \geq 0, < 0)$.

Not $2 \to 2$ LO BUT NLO

Virtual gluon exchange effects with $\frac{\alpha_S}{4\pi}$ suppression:

Focus on $2 \to 3$ with real gluon emission

Dixon, Shadmi 94

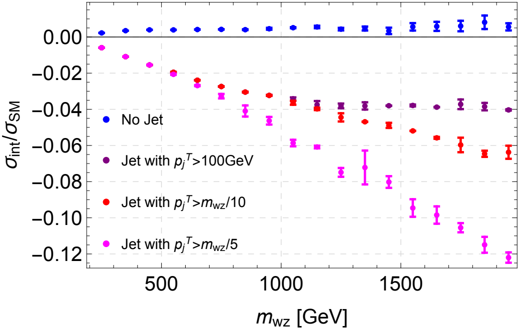


- SM: $q\bar{q} \to V_\pm V_\mp \quad \Longrightarrow q\bar{q} \to V_\pm V_\pm g_\mp$: qualitative change
- Total helicity ± 1 allowed both in SM and in $\mathcal{O}_{3W}$ amplitudes

Interference in $\mathbf{q\bar{q}} \to$ VVj is not forbidden by helicity selection rules

$$\mathbf{q\bar{q} \to VV + j}$$

$$\frac{\sigma_{int}}{\sigma_{SM}} \sim \frac{E^2}{\Lambda^2}$$ In presence of **HARD JET**



Differential distributions $\Rightarrow$

Qualitative change in interference cross section: $\sigma_{int}/\sigma_{SM} \sim E^2/\Lambda^2$

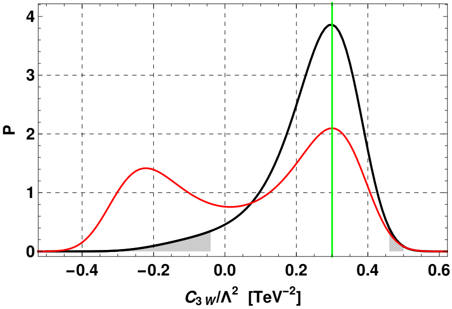
$\Rightarrow$ **Improvement of validity of EFT approach with D=6 truncation**

$\Rightarrow$ **BOUNDS on the WC c_{3W} with possible sensitivity to the SIGN**

	Lumi. 300 fb^{-1}		Lumi. 3000 fb^{-1}		Q [TeV]
	95% CL	68% CL	95% CL	68% CL	
Excl.	[-1.06,1.11]	[-0.59,0.61]	[-0.44,0.45]	[-0.23,0.23]	1
Excl., linear	[-1.50,1.49]	[-0.76,0.76]	[-0.48,0.48]	[-0.24,0.24]	
Incl.	[-1.29,1.27]	[-0.77,0.76]	[-0.69,0.67]	[-0.40,0.39]	
Incl., linear	[-4.27,4.27]	[-2.17,2.17]	[-1.37,1.37]	[-0.70,0.70]	
Excl.	[-0.69,0.78]	[-0.39,0.45]	[-0.31,0.35]	[-0.17,0.18]	1.5
Excl., linear	[-1.22,1.19]	[-0.61,0.61]	[-0.39,0.39]	[-0.20,0.20]	
Incl.	[-0.79,0.85]	[-0.46,0.52]	[-0.41,0.47]	[-0.24,0.29]	
Incl., linear	[-3.97,3.92]	[-2.01,2.00]	[-1.27,1.26]	[-0.64,0.64]	
Excl.	[-0.47,0.54]	[-0.27,0.31]	[-0.22,0.26]	[-0.12,0.14]	2
Excl., linear	[-1.03,0.99]	[-0.52,0.51]	[-0.33,0.32]	[-0.17,0.17]	
Incl.	[-0.52,0.57]	[-0.30,0.34]	[-0.27,0.31]	[-0.15,0.19]	
Incl., linear	[-3.55,3.41]	[-1.79,1.75]	[-1.12,1.11]	[-0.57,0.57]	

$$\lambda_Z \in [-0.0014, 0.0016] \quad ([-0.0029, 0.0034])$$

Large improvement in the sensitivity to interference term (linear in c_{3W}/Λ^2) adding ϕ_Z and p_j^T differential distributions (D=6 EFT validity)



Posterior probability for the inclusive (red) and exclusive (black) analysis after 3 ab^{-1} at LHC, with insertion of a signal with $c_{3W}/\Lambda^2 = 0.3\,TeV^{-2}$.

Qualitative difference in the Wilson coefficient probability density:

access to the sign of c_{3W}

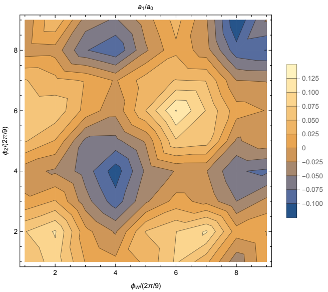
CP - odd

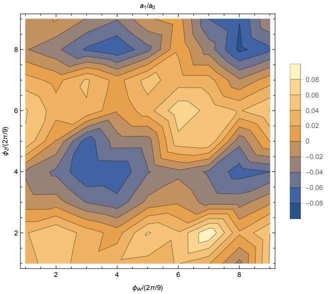
CP - odd $D = 6$ operator: $\tilde{\mathcal{O}}_{3W}\, \frac{\mathbf{g}}{\mathbf{3!}} \epsilon^{\mathbf{abc}} \tilde{\mathbf{W}}^{\mathbf{a},\mu\nu} \mathbf{W}^{\mathbf{b}}_{\nu\rho} \mathbf{W}^{\mathbf{c},\rho}_{\mu}$

Interference resurrection through azimuthal differential distribution

$$\frac{d\sigma_{\text{int}}(q\bar{q} \to WZ \to 4\psi)}{d\phi_Z\, d\phi_W} \propto \frac{E^2}{\Lambda^2} (\sin(2\phi_Z) + \sin(2\phi_W))$$

Different from CP - even case $\Rightarrow$ Discrimination of the 2 operators

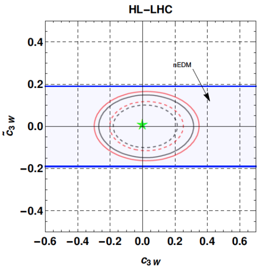


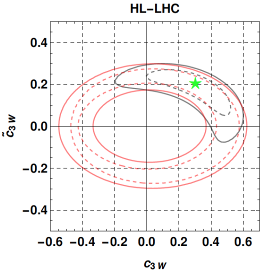


Left: $\sigma_{int}/\sigma_{SM}(\phi_W, \phi_Z)$ **Right:** $\sigma_{int}/\sigma_{SM}(\phi_W^{rec}, \phi_Z)$

In progress with Azatov,Barducci,Panico,Riva,Wulzer

$\mathcal{O}_{3W}$ and $\tilde{\mathcal{O}}_{3W}$ @ 14TeV LHC after 3ab^{-1}





95% confidence regions after 3 ab^{-1} at LHC, without BSM signal (left) and with insertion of a signal with $c_{3W}/\Lambda^2 = 0.3\,TeV^{-2}$ and $\tilde{c}_{3W}/\Lambda^2 = 0.2\,TeV^{-2}$ (right)

In progress with Azatov,Barducci,Panico,Riva,Wulzer

- **Differential distributions improve the sensitivity to BSM effects and the EFT safety**

  For $\mathcal{O}_{3W}$ they qualitatively change the interference term and restore the naively expected energy growth:

  1. Validity of EFT $D = 6$ truncation
  2. Sensitivity to the sign of the Wilson coefficient

- It would be interesting to analyze further these effects

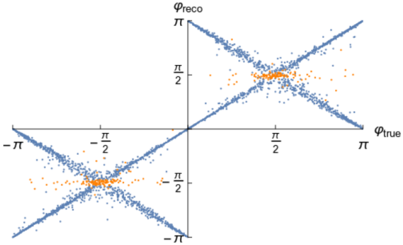
  1. For other TGC operators
  2. At HE-LHC or in future colliders
  3. In $W\gamma$ production

Thanks

In the boosted regime for W

$$\cot\varphi = \frac{1}{\sin[\phi_\nu - \phi_l]}\left[\sinh[\eta_l - \eta_\nu] + \mathcal{O}\left(\frac{m_W^2}{p_{\perp l}p_{\perp\nu}}\right)\right]$$

Ambiguity: $\phi_W \leftrightarrow \pi - \phi_W$



Panico, Riva, Wulzer [arXiv: 1708.07823]

SM interference with CP - even operators

$$I^{V_1 V_2}_{\mathbf{h}\otimes\mathbf{h}'} = T^{V_1 V_2}_{\mathbf{h}\mathbf{h}'} \left[\mathcal{A}^{\rm SM}_{\mathbf{h}} \mathcal{A}^{\rm BSM+}_{\mathbf{h}'} + \mathcal{A}^{\rm BSM+}_{\mathbf{h}} \mathcal{A}^{\rm SM}_{\mathbf{h}'} \right] \cos\left[\mathbf{\Delta h} \cdot \varphi \right]$$

SM interference with CP - odd operators

$$I^{V_1 V_2}_{\mathbf{h}\otimes\mathbf{h}'} = i T^{V_1 V_2}_{\mathbf{h}\mathbf{h}'} \left[\mathcal{A}^{\rm SM}_{\mathbf{h}} \mathcal{A}^{\rm BSM-}_{\mathbf{h}'} - \mathcal{A}^{\rm BSM-}_{\mathbf{h}} \mathcal{A}^{\rm SM}_{\mathbf{h}'} \right] \sin\left[\mathbf{\Delta h} \cdot \varphi \right]$$

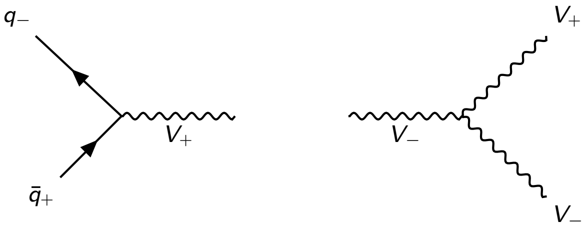
Panico, Riva, Wulzer [arXiv: 1708.07823]

Non interference between A^4_{SM} and $A^4_{O_{3W}}$ in the massless limit

Helicity of 4-point amplitudes in massless limit ($m_W \ll E$) [Only TTT in O_{3W}]

$$\mathbf{h(A^4_{SM}) = 0} \textbf{ [Tree-level, with all outgoing momenta]}$$

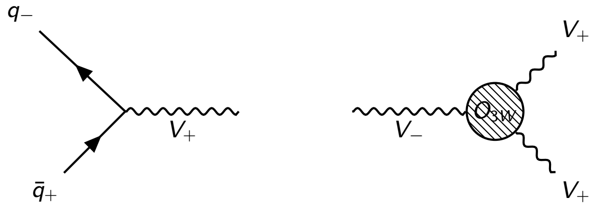
- From helicity of contact 3-point diagrams $|h(A^3_{SM})| = 1$, if factorization is allowed (always the case in SM):
  $h(A^4_{SM}) = h(A^3_{qqV-SM}) + h(A^3_{VVV-SM}) = \pm 2, 0$
- Helicity selection rule in massless gauge theory:
  $A(V^+V^+\psi^+\psi^-) = A(V^-V^-\psi^+\psi^-) = 0$ $(\pm : h = \pm 1)$
  [Also $A(V^+V^+V^+V^-) = A(V^-V^-\phi\phi) = A(V^+\psi^+\psi^+\phi) = 0$]
- s-channel of $A_{SM}(q\bar{q} \to VV)$



Helicity of 4-point amplitudes in massless limit ($m_W \ll E$)

$$\mathbf{h}(\mathbf{A}^4_{\mathbf{O_{3W}}}) = \pm\mathbf{2} \text{ [Tree-level, with all outgoing momenta]}$$

- From helicity of contact 3-point diagrams $|h(A^3_{O_{3W}})| = 3$ (Cheung-Shen prescription) and $|h(A^3_{SM})| = 1$, if factorization is allowed:
  $h(A^4_{SM}) = h(A^3_{qqV-SM}) + h(A^3_{O_{3W}}) = \pm 2(\pm 4)$
- $A_{BSM}(q\bar{q} \to VV)$



Helicity of 4-point amplitudes in massless limit ($m_W \ll E$)

$$\mathbf{h(A^4_{O_{3W}}) = \pm 2 \text{ [Tree-level, with all outgoing momenta]}}$$

- **Factorization is not allowed**: O_{3W} vertex cancels propagator pole
- But same results with analytical computation:
  1. $A_{BSM}(q\bar{q} \to V_+ V_-) = 0$
  2. $A_{BSM}(q\bar{q} \to V^a_+ V^b_+) = i\frac{g c_{3W}}{2\Lambda^2}\epsilon^{abc} T^c \frac{[p_{\bar{q}} p_{V^a}][p_{\bar{q}} p_{V^b}][p_{V^a} p_{V^b}]}{[p_{\bar{q}} p_q]} \neq 0$

Non interference of SM 4-point amplitudes and BSM 4-point amplitudes with D=6 operators, in massless limit ($m_W \ll E$)

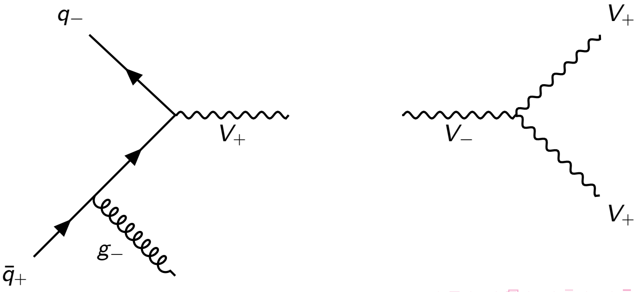
A_4	$\lvert h(A_4^{\mathrm{SM}})\rvert$	$\lvert h(A_4^{\mathrm{BSM}})\rvert$
$VVVV$	0	4,2
$VV\phi\phi$	0	2
$VV\psi\psi$	0	2
$V\psi\psi\phi$	0	2
$\psi\psi\psi\psi$	2,0	2,0
$\psi\psi\phi\phi$	0	0
$\phi\phi\phi\phi$	0	0

Extra hard QCD jet

[Shadmi Dixon 9312363, pioneering analysis within QCD]

$\mathbf{h(A^5_{SM}) = \pm 1}$ **[Tree-level, with all outgoing momenta]**

- From helicity of subdiagrams $|h(A^4_{q\bar{q}Vg-SM})| = 0$ and $|h(A^3_{VVV-SM})| = 1$, if factorization is allowed (always the case in SM):
  $h(A^5_{SM}) = h(A^4_{q\bar{q}Vg-SM}) + h(A^3_{VVV-SM}) = \pm 1$
- s-channel of $A_{SM}(q\bar{q} \to gVV)$

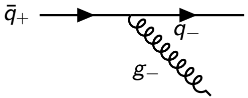


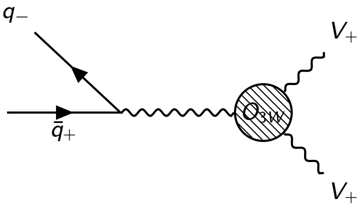
Interference between A^5_{SM} and $A^5_{O_{3W}}$ in the massless limit

Extra hard QCD jet

$$\mathbf{h(A^5_{O_{3W}}) = \pm 1, \pm 3}$$ **[Tree-level, with all outgoing momenta]**

- From helicity of subdiagrams $|h(A^4_{q\bar{q}VV-O_{3W}})| = 0$ and $|h(A^3_{qqg-SM})| = 1$, if factorization is allowed (always the case in SM):
  $h(A^5_{SM}) = h(A^4_{q\bar{q}VV-O_{3W}}) + h(A^3_{qqg-SM}) = \pm 1, \pm 3$
- $A_{O_{3W}}(q\bar{q} \to gVV)$: **Allowed Factorization**





Differential distributions $\Rightarrow$
Qualitative change in interference cross section: $\sigma_{int}/\sigma_{SM} \sim E^2/\Lambda^2$

$\Rightarrow$ **Improvement of validity of EFT approach with D=6 truncation**

BUT

For CONSISTENT EFT analysis **INVARIANT MASS (m_{VV}) CUT** is necessary

PROBLEMS:

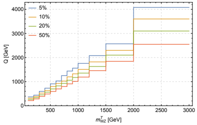
- m_{WZ} and m_{WW} are not observable at LHC
- m^T_{WV} is not in one to one correspondence with m_{WV}: $m^T_{WV} < m_{WV}$

Setting consistent bounds

In the i^{th} bin (of m^T_{WV} and other observables)

$$\text{Leakage}_i = \frac{N_i(m_{VW} > Q)}{N_i} \times 100$$

Estimates of Leakage using $\mathcal{O}_{3W}$-EFT with very large c_{3W} $\rightarrow$
Conservative unless there are very narrow Bright-Wigner resonances



CONSISTENT BOUNDS WITHIN PRECISION P% (5%)

Analysis with all bins having $\text{Leakage}_i < P\%(5\%)$, once fixed $Q = \Lambda$:

$$m^T_{WV} < \tilde{m}^T_{WV}(\Lambda, P\%)$$

Likelihood for i^{th} bin:

$$p(N_{th\,i}|n_{obs\,i}) \propto N_{th_i}^{\,n_{obs\,i}} e^{-N_{th\,i}}, \quad \text{with} \quad N_{th\,i} \text{ in } \mathcal{O}_{3W}\text{-EFT} \quad n_{obs\,i} \sim n_{SM\,i}$$

VV production at ATLAS [1603.02151]
Reproduced with MadGraph simulation at 14TeV

1. Leptonic Decay: electronic and muonic channels
2. $W^{\pm}Z \Rightarrow$ Only one neutrino (E_T^{miss})
   In particular: $W^{\pm}Z \rightarrow e^{\pm}\nu_e\mu^{+}\mu^{-}$

   Binnig in:

   - $m_{WZ}^T = \sqrt{\left(\sqrt{m_W^2 + (p_W^T)^2} + \sqrt{m_Z^2 + (p_Z^T)^2}\right)^2 - ((p_W + p_Z)^T)^2}$
     m_{WZ}^T : $[200; 300; 400; 600; 600; 700; 800; 900; 1000; 1200; 1500; 2000]\,GeV$
   - p_j^T of additional final jet in $ppWZj$
     p_j^T : $[0, 100]\,GeV; [100, 300]\,GeV; [300, 500]\,GeV; > 500\,GeV$
   - ϕ_Z : $[\pi/4, 3\pi/4] \cup [5\pi/4, 7\pi/4]; [0, \pi/4] \cup [3\pi/4, 5\pi/4] \cup [7\pi/4, 2\pi]$
3. ATLAS kinematical cuts

- Consistency for
  $$A_{WZ} = \frac{\sigma(pp \rightarrow WZ)\,|_{\text{selected phase space}}}{\sigma(pp \rightarrow WZ)\,|_{\text{full phase space}}} \quad (\sim 39\% \quad \text{at} \quad 8\text{TeV})$$
- Consistency for bounds on c_{3W} from $pp \rightarrow W^{\pm}Z$ (No Jet)