Novel measurements of anomalous triple gauge couplings

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JHEP 1710 (2017) 027 with J.Elias-Miro, Y. Reyimuaji, E.Venturini, and in progress with + D.Barducci,F.Riva, G.Panico,A.Wulzer

Transverse dibosons in the final state

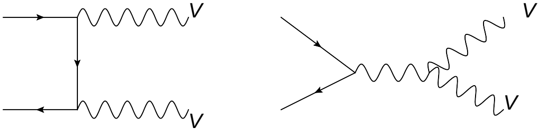
Anomalous TGC

- In SM interactions of the vector bosons are fixed by the gauge symmetry
$$ig\, W^{+\,\mu\nu} W^-_\mu W^3_\nu + ig\, W^{3\,\mu\nu} W^+_\mu W^-_\nu$$
- Two possible deformations are allowed at the level of six derivatives
$$igc_\theta \delta g_{1,Z}\, Z_\nu W^{+\,\mu\nu} W^-_\mu + h.c. + ig(c_\theta\, \delta\kappa_Z\, Z^{\mu\nu} + s_\theta \delta\kappa_\gamma A^{\mu\nu}) W^+_\mu W^-_\nu$$
and
$$\lambda_Z \frac{ig}{m_W^2} W^{+\,\mu_2}_{\mu_1} W^{-\,\mu_3}_{\mu_2} W^{3\,\mu_1}_{\mu_3}$$

These interactions are bounded at LEP-2 at % level
$$\lambda_Z \in [-0.059, 0.017],\ \delta g_{1,Z} \in [-0.054, 0.021],\ \delta\kappa_Z \in [-0.074, 0.051]$$

Testing anomalous TGC @LHC

- At LHC these couplings are constrained mainly from the $qq \to VV$ process.



- We want to exploit large collision energy of LHC to put stricter bounds.

Anomalous TGC energy scaling

All of the aTGC interactions appear at the level of the dimension six operators.

- It is useful to think about TGC in terms of the EFT operators before EWSB.

$$O_{HB} = ig'(D^\mu H)^\dagger D^\nu H B_{\mu\nu}, O_{HW} = ig(D^\mu H)^\dagger \sigma^a D^\nu H W^a_{\mu\nu}$$
$$O_{3W} = \tfrac{g}{3!}\epsilon_{abc} W^{a\,\nu}_{\mu} W^{b\,\rho}_{\nu} W^{c,\mu}_{\rho}$$

$$\lambda_Z = \frac{m_W^2}{\Lambda^2} c_{3W}, \delta g_{1,Z} = \frac{m_Z^2}{\Lambda^2} c_{HW}, \delta\kappa_Z = \frac{m_W^2}{\Lambda^2}\left(c_{HW} - \tan^2\theta c_{HB}\right)$$

(not a unique map)

- We can use the Goldstone boson equivalence theorem to estimate the leading energy scaling of the new contributions.

Energy growth of the BSM amplitudes

We start with dimension six operators

$$O_{HB} = ig'(D^\mu H)^\dagger D^\nu H B_{\mu\nu}, O_{HW} = ig(D^\mu H)^\dagger \sigma^a D^\nu H W^a_{\mu\nu}$$

$$O_{3W} = \frac{g}{3!}\epsilon_{abc} W^{a\,\nu}_{\mu} W^{b\,\rho}_{\nu} W^{c,\mu}_{\rho}$$

Goldstone equivalence theorem relates $H \Rightarrow W_L, Z_L$

$$\begin{aligned} O_{HB} &\supset \partial W_L \partial Z_T \partial W_L + v W_T \partial Z_T \partial W_L + v^2 W_T \partial Z_T W_T + \ldots \\ O_{HW} &\supset \partial V_L \partial V_T \partial V_L + v V_T \partial V_T \partial V_L + v^2 V_T \partial V_T V_T + \ldots \\ O_{3W} &\supset \partial V_T \partial V_T \partial V_T + \ldots \end{aligned}$$

Leading energy scaling can be estimated by noting that the light quarks couple mostly to transverse gauge bosons:

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

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

$$\mathcal{M}\left(q\bar{q} \to V_T V_T\right) \sim E^2/\Lambda^2 \; c_{3W} = E^2/m^2_W \; \lambda_Z$$

We have an additional E^2 compared to the SM amplitudes, as expected from dimensional analysis

SM and BSM amplitudes

If the BSM is described by the dimension six operators than , for the $qq \to V_T V_T$ process the leading interference term is suppressed due to the helicity selection rules:

	A_{SM}	A_{BSM}
$q\bar{q} \to$ LL	$\propto 1$	$\propto E^2/M^2$
$q\bar{q} \to \pm\mp$	$\propto 1$	$\propto 1$
$q\bar{q} \to \pm\pm$	$\propto M^2/E^2$	$\propto E^2/M^2$

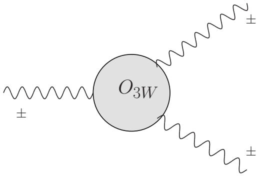
No interference between SM and BSM in the presence of the transverse vector bosons, for $2 \to 2$ processes 1607.05236 AA,R.Contino,C.Machado,F.Riva

$$\sum_i^4 h_i|^{SM} = 0, \quad \sum_i^4 h_i|^{BSM_{dim\ 6}} = 2, 4$$

SM and BSM amplitudes with more details

Helicity selction rule for O_{3W}

Lorentz symmetry and the dimensional analysis fixes three point amplitudes to satisfy: $\boxed{\sum h = 1 - [g] = 3}$ for dimension 6 operators (*Cachazo,Benincasa*) $\Rightarrow$ fields coming from $W_{\mu\nu} W_{\nu\lambda} W_{\lambda_\mu}$ have always the same helicity.



Why the interference term is important?

- Generically in the presence of new physics

$$\mathcal{L} = \mathcal{L}^{\rm SM} + \mathcal{L}^6 + \mathcal{L}^8 + \cdots \,, \quad \mathcal{L}^D = \sum_i c_i^{(D)} \mathcal{O}_i^{(D)}, \quad c_i^{(D)} \sim \frac{1}{\Lambda^{D-4}}$$

$$\boxed{\sigma \sim SM^2 + \frac{SM \times BSM_6}{\Lambda^2} + \frac{BSM_6^2}{\Lambda^4} + \frac{SM \times BSM_8}{\Lambda^4} + \ldots}$$

- leading term in $\frac{1}{\Lambda^2}$ comes from the interference between SM and BSM
- Both $|BSM_8|$ and $|BSM_6|^2$ are suppressed by the Λ^4 scale. Is it consistent to truncate the expansion at the dimension six level?
- **The analysis is consistent if only**

$$\boxed{\textbf{Max}\left[\frac{SM \times BSM_6}{\Lambda^2}, \frac{BSM_6^2}{\Lambda^4}\right] \gg \frac{SM \times BSM_8}{\Lambda^4}}$$

Importance of interference ($qq \to V_T V_T$)

$$\sigma_6 \sim \frac{g_{SM}^4}{E^2}[1 + \overbrace{c_{3W}\frac{m_V^2}{\Lambda^2}}^{\text{BSM}_6\times\text{SM}} + \overbrace{c_{3W}^2\frac{E^4}{\Lambda^4}}^{\text{BSM}_6{}^2}] \quad \sigma_8 \sim \frac{g_{SM}^4}{E^2}[\overbrace{c_8\frac{E^4}{\Lambda^4}}^{\text{BSM}_8\times\text{SM}} + \overbrace{c_8^2\frac{E^8}{\Lambda^8}}^{\text{BSM}_8{}^2}]$$

Then the dimension six truncation is valid if only

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

If we will be able to overcome the interference suppression the condition relaxes to

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

is this important?

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$$\sigma_6 \sim \frac{g_{\rm SM}^4}{E^2}[1 + \overbrace{c_{3W}\frac{m_V^2}{\Lambda^2}}^{\rm BSM_6\times SM} + \overbrace{c_{3W}^2\frac{E^4}{\Lambda^4}}^{\rm BSM_6{}^2}] \qquad \sigma_8 \sim \frac{g_{\rm SM}^4}{E^2}[\overbrace{c_8\frac{E^4}{\Lambda^4}}^{\rm BSM_8\times SM} + \overbrace{c_8^2\frac{E^8}{\Lambda^8}}^{\rm BSM_8{}^2}]$$

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is this important?

Depends on power-counting i.e. types of UV completions we are studying.

Typical size of c_{3W}

In the weakly coupled theories O_{3W} appears at one loop level $c_{3W} \sim \frac{g^2}{16\pi^2}$
$\Rightarrow$ too small to be discovered at LHC independently of weather the interference suppression is present or not (SUSY, Composite Higgs...)

Remedios power counting *(Liu, Riva,Rattazzi,Pomarol)* - $c_{3W} \sim \frac{g_*}{g}$, $c_8 \sim \frac{g_*}{g}$, no improvement in EFT validity reach.

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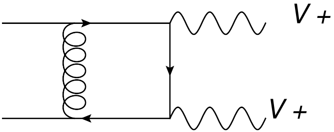
We are getting sensitivity to the sign of the Wilson coefficient, otherwise hidden from the measurements!

Overcoming the non-interference obstruction: 1st method

Dixon, Shadmi 94

- The non-interference selection rule applies only for the $2 \to 2$ processes at tree level. There are violations at NLO!



- Effects are $(\frac{\alpha_s}{4\pi})$ suppressed, what about real emission?

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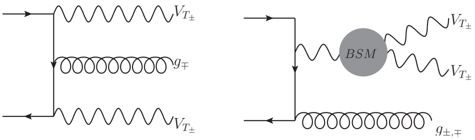


- $(W)^3$ vertex always emits same helicity W bosons, however the helicity of the gluon is not restricted!
- For SM amplitudes gluons are carrying away the needed opposite helicity.

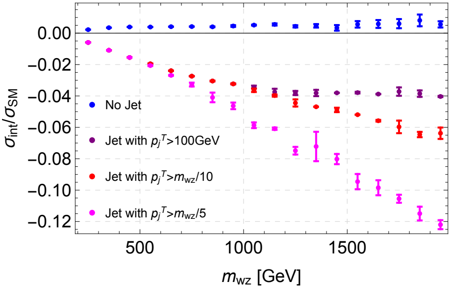
We can use a tag for jet to suppress the background as well, no need to pay $\frac{\alpha_s}{4\pi}$ for the signal to background ratio.

$qq \to VV + j$

- Indeed the interference growth once an additional hard jet is required.
- There are no soft and colinear singularities in the SM amplitude

$$A(q\bar{q} \to V_{T_\pm} V_{T_\pm} g_\mp).$$

since it cannot be generated from $2 \to 2$ by splitting quark(anti-quark) line into $q(\bar{q}) \to q(\bar{q})g$.

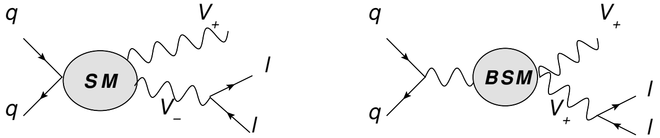


Jet needs to be hard otherwise the signal will be hidden inside the SM background which grows quickly in the soft and colinerar regimes.

Overcoming the interference obstruction: 2nd method

Duncan,Kane,Repko 85

- Non-interference result is obtained for the $2 \to 2$ processes , in reality we are looking at $2 \to 4$ process since both W,Z decay.
- Let us consider for simplicity $2 \to 3$ process in the narrow width approximation, then the interference with of the amplitudes with opposite intermediate Z helicities will be:



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

$$\frac{d\sigma_{\rm int}(q\bar q\to W_+ l_-\bar l_+)}{d\phi_Z}\propto \mathcal{M}_{Z_{T_-}\to l_-\bar l_+}\mathcal{M}^*_{Z_{T_+}\to l_-\bar l_+}\propto \cos(2\phi_Z)$$

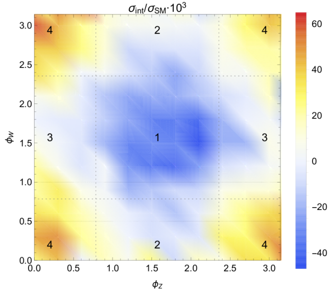
$$\frac{\pi}{2s}\frac{\delta(s-m_Z^2)}{\Gamma_Z m_Z}\mathcal{M}^{\rm SM}_{q\bar{q}\to W_{T_+}Z_{T_-}}\left(\mathcal{M}^{\rm BSM}_{q\bar{q}\to W_{T_+}Z_{T_+}}\right)^* \mathcal{M}_{Z_{T_-}\to l_-\bar{l}_+}\mathcal{M}^*_{Z_{T_+}\to l_-\bar{l}_+} \Rightarrow$$

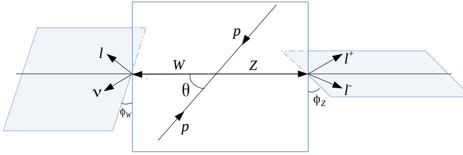
$$\frac{d\sigma_{\rm int}(q\bar{q}\to W_+ l_-\bar{l}_+)}{d\phi_Z} \propto \mathcal{M}_{Z_{T_-}\to l_-\bar{l}_+}\mathcal{M}^*_{Z_{T_+}\to l_-\bar{l}_+} \propto \cos(2\phi_Z)$$

The interference is non-zero but modulated with azimuthal angle of the Z decay products plane. As expected from the $2 \to 2$ results the integrated interference is zero again.

(similar ideas for $W\gamma$ final state 1708.07823)

Azimuthal angle modulation

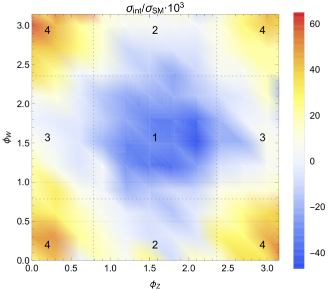


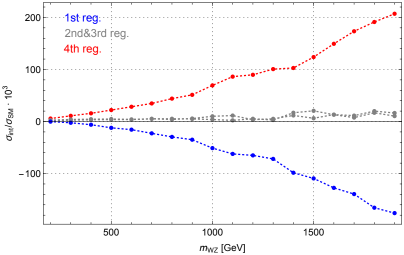


$$\frac{d\sigma_{\text{int}}(q\bar{q} \to WZ \to 4\psi)}{d\phi_Z \, d\phi_W} \propto \cos(2\phi_Z) + \cos(2\phi_W)$$

- The modulation in azimuthal angles will always happen if there are virtual states with the different polarizations
- for the λ_Z deformation, no need to bin in both angles, we can just look at the decays of one gauge boson.

Azimuthal angle modulation





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- for the λ_Z deformation, no need to bin in both angles, we can just look at the decays of one gauge boson.

Ambiguities in angles *(Panico,Riva, Wulzer 1708.07823)*

- In experiment we measure only the charges of the leptons, not their helicities
- Angualr modulation is fixed by the helicities of the decay products, so we have an ambiguity in determining the plane of the Z decay ϕ_Z.

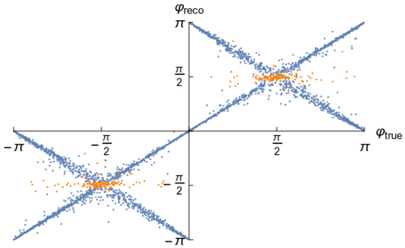
$$\boxed{\phi_Z \to \phi_Z + \pi \mod 2\pi}$$

- irrelevant for the O_{3W} operator since the modulation is $\boxed{\propto \cos 2\phi_Z}$

W decay? *(Panico,Riva, Wulzer 1708.07823)*

- So far we have focused only on the Z decay plane, what about W decay plane?
- We need to reconstruct the neutrino momentum.
- Two-fold ambiguity leads to the degeneracy

$$\phi_W \to \pi - \phi_W \mod 2\pi$$



$\phi_W \to \pi - \phi_W \mod 2\pi$ $\phi_Z \to \phi_Z + \pi \mod 2\pi$

Both O_{3W} and $\tilde{O}_{3W}$ can be measured in spite of these ambiguities

$$\frac{g}{3!}\epsilon_{abc} W_\mu^{a\,\nu} W_\nu^{b\,\rho} W_\rho^{c,\mu} \propto \cos 2\phi_1 + \cos 2\phi_2,$$

$$\frac{g}{3!}\epsilon^{abc} \tilde{W}^a_{\mu\nu} W^{b,\nu\rho} W_\rho^{c,\mu} \propto \sin 2\phi_1 + \sin 2\phi_2$$

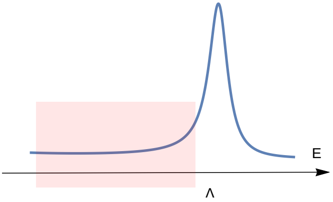
These ambiguities make harder to observe the interference between $(+-)$ and LL final states(δg_1^Z coupling).

$$I^{WZ}_{(00)\otimes(\pm\mp)} = \frac{\pi}{2\sqrt{2}} g^2 \mathcal{A}_{00}^{\mathrm{BSM}+} \sin\varphi_{\mathrm{W}}^{\mathrm{reco}} \sin\varphi_{\mathrm{Z}}^{c}\ d_0(\theta_{\mathrm{Z}}^c)\Big[\mathcal{A}_{+-}^{\mathrm{SM}}\times$$
$$[g_L^2 d_{-1}(\theta_{\mathrm{Z}}^c) - g_R^2 d_{+1}(\theta_{\mathrm{Z}}^c)] + \mathcal{A}_{-+}^{\mathrm{SM}}[g_L^2 d_{+1}(\theta_{\mathrm{Z}}^c) - g_R^2 d_{-1}(\theta_{\mathrm{Z}}^c)]\Big]$$

(Panico,Riva, Wulzer 1708.07823)

Bounding EFT consistently

- Suppose EFT expansion breaks down at the scale Λ.
- Obviously EFT analysis is consistent if only the energy of events is below $E < \Lambda$
- What to do if the energy of event is not fully reconstructed? (often the case when we have neutrinos in the final state)



Possible solution

Calcualte theory prediction only in the phase space region where EFT description is valid if the the NP contribution is always positive the obtained constraints will be always conservative (proposed for DM in 1502.04701).**Not the case if the interference is large.**

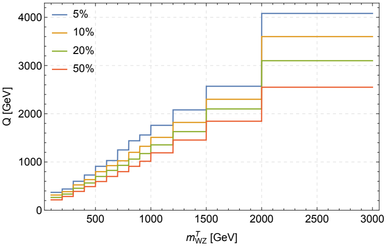
Leakage

- For $3l\nu$ final state the events are binned in

$$m^T_{WZ} = \sqrt{(E^W_T + E^Z_T)^2 - (p^W_x + p^Z_x)^2 - (p^W_y + p^Z_y)^2}$$

- we can find approximate map between the transverse and invariant masses

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



then once we know the precision of the measurements we can find corresponding value of the cut-off.

Becomes innacurate (in unlikely situation) if there is a narrow new physics peak, so that the majority of the events will have the invariant mass $\sim M_{peak}$

Analysis only O_{3W}

- We look only at $pp \to W^{\pm}Z \to lll\nu$ final state
- All of the events are binned in m_{WZ}^{T} mass $[200, 300, 400, 600, 600, 700, 800, 900, 1000, 1200, 1500, 2000]$ GeV
- We perfomr the binning in p_T of the aditional jet $p_j^T = [0, 100], [100, 300], [300, 500], [500, \infty]$ GeV
- Z decay azimuthal angle is binned in four categories $\phi_Z \in [0, \pi/4, \pi/2/, 3\pi/4, \pi]$

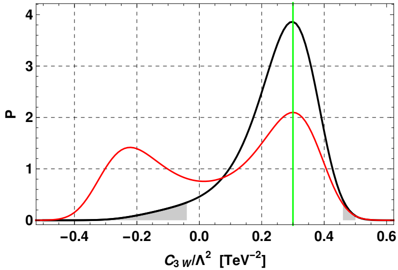
Results

	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]	

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

Sensitivity to linear terms is strongly improved!

Results

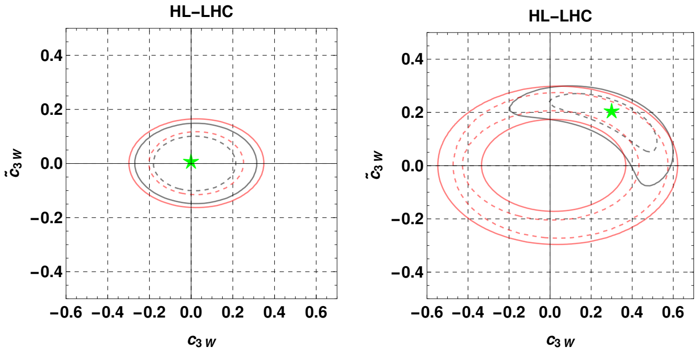


We are sensitive to the sign of the Wilson coefficient, can resolve possible degeneracies in the fit!

$$R_{\phi_Z} = \frac{N_{\phi_Z \in [\pi/4, 3\pi/4]} - N_{\phi_Z \in [0, \pi/4] \cup [3\pi/4, \pi]}}{N_{\phi_Z \in [\pi/4, 3\pi/4]} + N_{\phi_Z \in [0, \pi/4] \cup [3\pi/4, \pi]}}$$

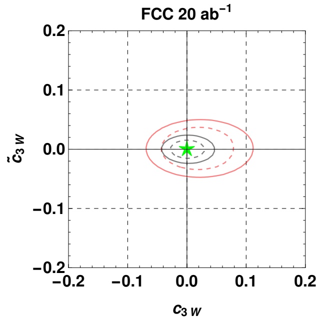
R_{ϕ_Z} asymmetry is particularly sensitive to the interference!

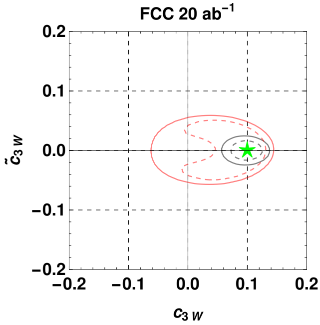
O_{3W} and $\tilde{O}_{3W}$ at $3ab^{-1}$ (*with Barducci, Elias-Miro, Panico, Riva, Venturini, Wulzer*)



Binning in ϕ_Z strongly improves the possibility to differentiate between the CP even and CP odd operators

O_{3W} and $\tilde{O}_{3W}$ at FCC, preliminary results





LEP	HL-LHC	ILC $\times 10^{-4}$	CEPC$\times 10^{-4}$	FCC$\times 10^{-4}$
[-0.059,0.017]	[-0.0014,0.0016]	$\pm 5.1 \times 10^{-4}$	± 3.3	[-2.5,2.2]

ILC & CEPC from *1507.02238, 1306.6352*

Differential distributions improve the sentivity to the New Physics.

In particular for the $O_{3W}, \tilde{O}_{3W}$ operator the improvement is not only quantitative but qualitative.

- We can measure the sign of the Wilson coefficients
- Differentiate between the CP even and CP odd operators

Applicaitons for the other processes?

- δg_1^Z?
- $VV \to VV$?