Precision diboson measurements

Aleksandr Azatov

SISSA and INFN Trieste

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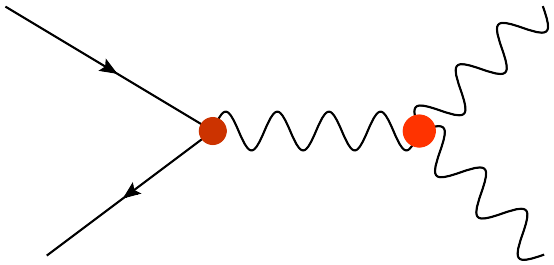
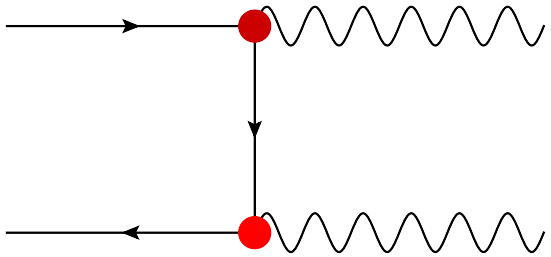
New Physics on the Low-Energy Precision Frontier
CERN

Testing SM interactions in diboson production





- New interactions can modify $\psi\psi V$, VVV vertices
- EFT presents a perfect framework for parametrizing deviations from the SM

Anomalous TGC

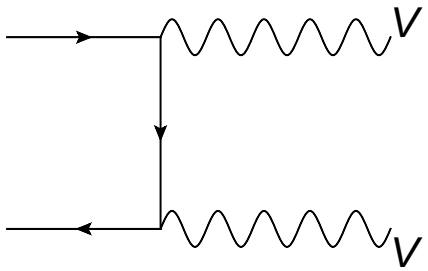
- In SM interactions of the vector bosons are fixed by the gauge symmetry
$$ig\, W^{+\,\mu\nu} W^-_\mu W^3_\nu + ig\, W^{3\,\mu\nu} W^+_\mu W^-_\nu$$
- Three possible deformations are allowed at the level of dimension six operators:
$$\boxed{igc_\theta \delta g_{1,Z}\, Z_\nu W^{+\,\mu\nu} W^-_\mu + h.c.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

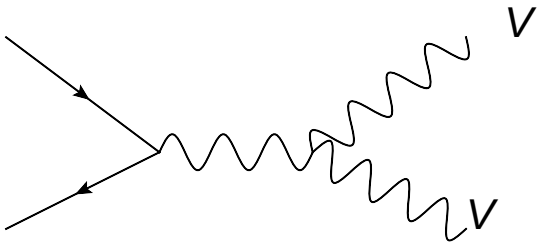
These interactions are bounded at LEP-2 at % level

$$\boxed{\lambda_Z \in [-0.059, 0.017],\ \delta g_{1,Z} \in [-0.054, 0.021],\ \delta\kappa_Z \in [-0.074, 0.051]}$$

Testing anomalous TGC @LHC

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

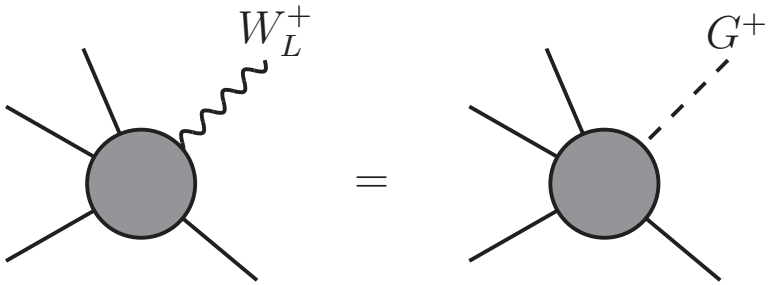




- We want to exploit large collision energy of LHC to put stricter bounds.

SM expectations

- We can use the Goldstone equivalence theorem to easily predict the leading energy growth of the amplitudes.



$$\times \left(1 + \mathcal{O}(m_W^2/E^2)\right)$$

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

$$\Downarrow$$

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

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

Anomalous TGC energy scaling

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

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

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

(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 $\boxed{H \Rightarrow W_L, Z_L}$

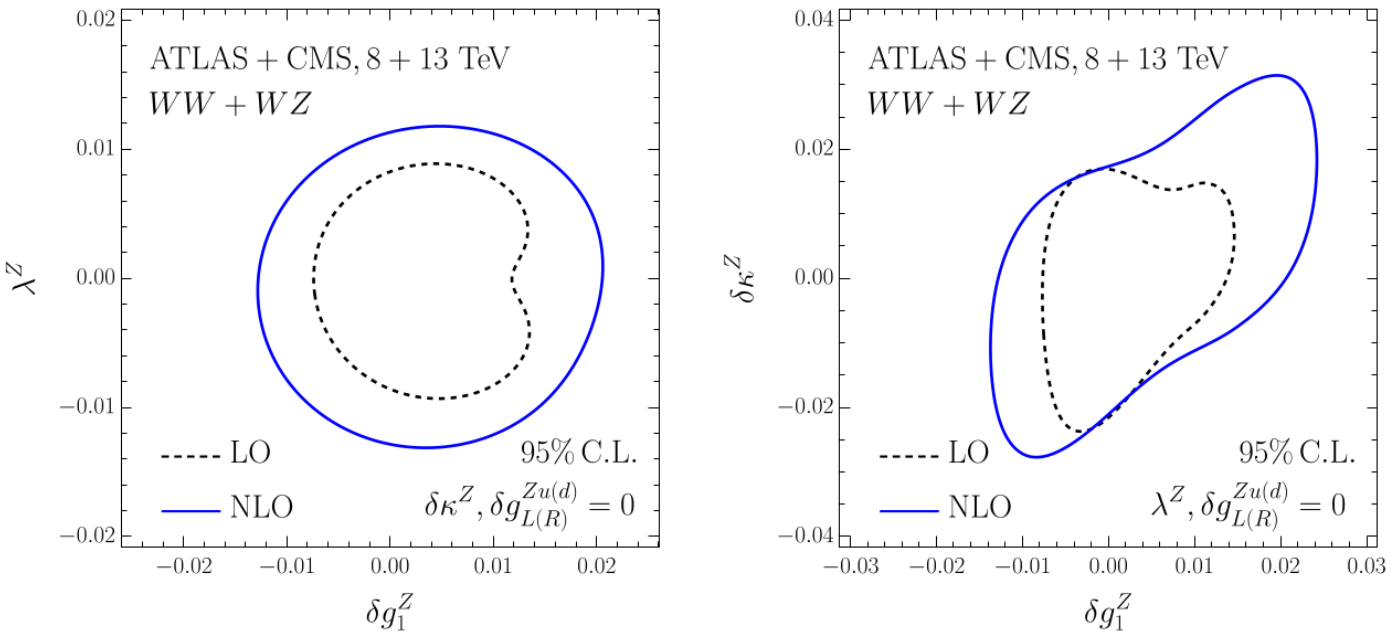
$$\begin{aligned}
O_{HB} &\supset \partial W_L \partial Z_T \partial W_L + v W_T \partial Z_T \partial W_L + v^2 W_T \partial Z_T W_T + \dots \\
O_{HW} &\supset \partial V_L \partial V_T \partial V_L + v V_T \partial V_T \partial V_L + v^2 V_T \partial V_T V_T + \dots \\
O_{3W} &\supset \partial V_T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

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

$$\mathcal{M}\left(q\bar{q} \to W_L^- W_L^+\right) \sim E^2/\Lambda^2\ c_{HB} + E^2/\Lambda^2\ c_{HW} \sim E^2/m_W^2\ \delta g_{1,Z} + E^2/m_W^2\ \delta\kappa_Z$$
$$\mathcal{M}\left(q\bar{q} \to Z_L W_L^+\right) \sim E^2/\Lambda^2\ c_{HW} = E^2/m_Z^2\ \delta g_{1,Z}\ ,$$
$$\mathcal{M}\left(q\bar{q} \to V_T W_T^+\right) \sim E^2/\Lambda^2\ c_{3W} = E^2/m_W^2\ \lambda_Z$$

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

Current constraints from LHC



Baglio et al 1909.11576

LEP-2 % bounds

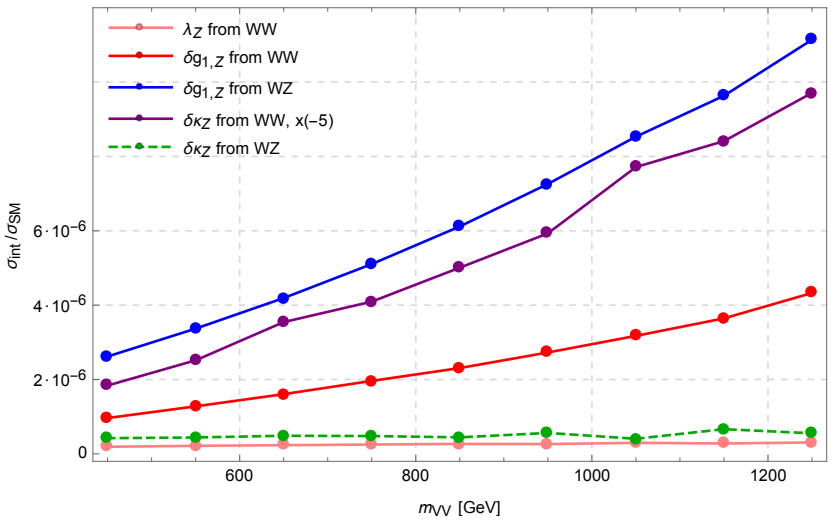
$\lambda_Z \in [-0.059, 0.017], \ \delta g_{1,Z} \in [-0.054, 0.021], \ \delta\kappa_Z \in [-0.074, 0.051]$

SM and BSM amplitudes with more details

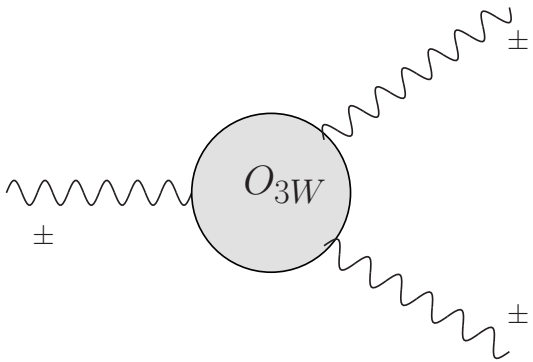
$$\mathcal{M}\left(q\bar{q} \to W_L^- W_L^+\right) \sim E^2/\Lambda^2\ c_{HB} + E^2/\Lambda^2\ c_{HW} \sim E^2/m_W^2\ \delta g_{1,Z} + E^2/m_W^2\ \delta\kappa_Z$$

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

$$\mathcal{M}\left(\mathbf{q\bar{q} \to V_T W_T^+}\right) \sim \mathbf{E^2/\Lambda^2\ c_{3W} = E^2/m_W^2}\ \lambda_Z$$ does not interfere with SM!



$$\epsilon_{abc} W_\mu^{a\,\nu} W_\nu^{b\,\rho} W_\rho^{c,\mu}$$



External vectors have the same polarizations

SM and BSM amplitudes with more details

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

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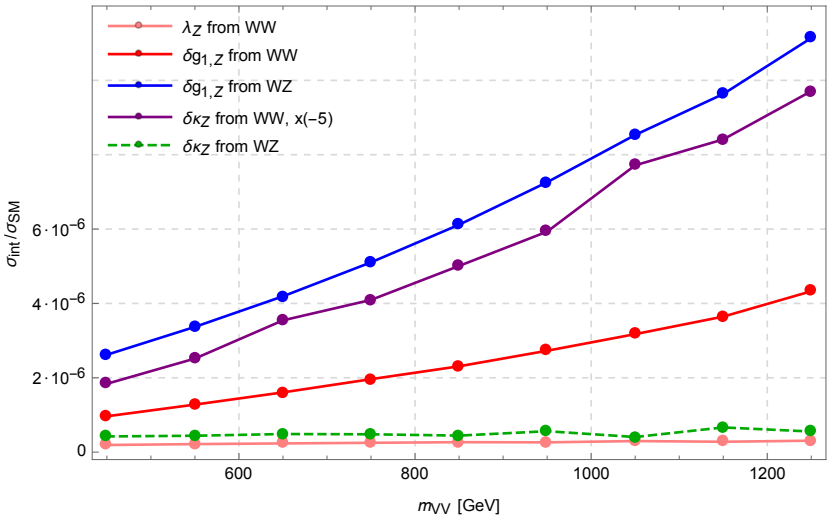


Helicity selction rule for O_{3W}

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.

in SM the vectors will have opposite helicities

General interference/non-interference pattern

In high energy limit we can treat all the SM particles as massless, the spinor-helicity formalism becomes very useful!

In SM all the amplitudes for $2 \to 2$ processes follow the helicity selction rule:

$$A(V^+V^+V^+V^+) = A(V^+V^+V^+V^-) = A(V^+V^+\psi^+\psi^-)$$
$$= A(V^+V^+\phi\phi) = A(V^+\psi^+\psi^+\phi) = 0.$$

The total helicity is always zero, except for the four fermion amplitudes mediated by the Higgs exchange.

In BSM for the processes we never get total helicity zero if there is at least one transverse vector boson. arXiv:1607.05236 AA R.Contino, C.Machado, F.Riva

No interference between SM and BSM in the presence of the transverse vector bosons!

$$pp \to V_L V_L$$

Longitudinal vector boson production

- At the level of dimension six there are also contact operators between fermions contributing to the same process

$$\bar{\psi}\gamma^{\mu}\psi(H^{\dagger}\overleftrightarrow{D}_{\mu}H)$$

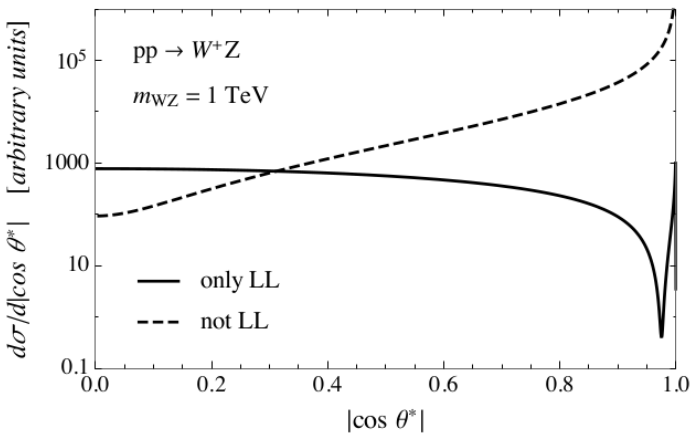
- If are looking at the $qq \to VV$ process all of the amplitudes (in high energy limit) can be parametrized in terms of only 4 parameters

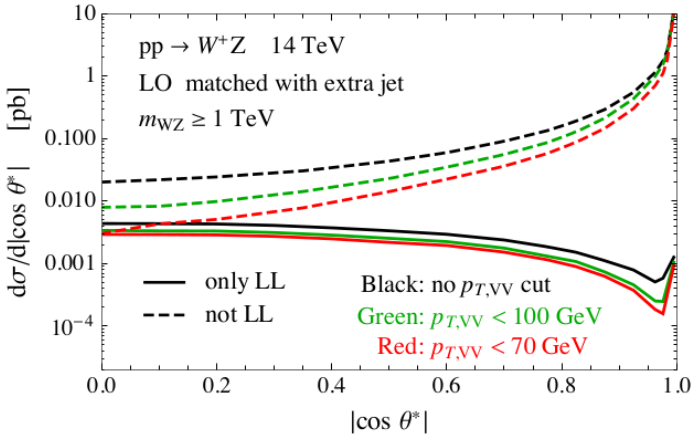
Amplitude	High-energy primaries	Low-energy primaries
$\bar{u}_L d_L \to W_L Z_L, W_L h$	$\sqrt{2}a_q^{(3)}$	$\sqrt{2}\frac{g^2}{m_W^2}\left[c_{\theta_W}(\delta g_{uL}^Z - \delta g_{dL}^Z)/g - c_{\theta_W}^2 \delta g_1^Z\right]$
$\bar{u}_L u_L \to W_L W_L$ $\bar{d}_L d_L \to Z_L h$	$a_q^{(1)} + a_q^{(3)}$	$-\frac{2g^2}{m_W^2}\left[Y_L t_{\theta_W}^2 \delta\kappa_\gamma + T_Z^{u_L}\delta g_1^Z + c_{\theta_W}\delta g_{dL}^Z/g\right]$
$\bar{d}_L d_L \to W_L W_L$ $\bar{u}_L u_L \to Z_L h$	$a_q^{(1)} - a_q^{(3)}$	$-\frac{2g^2}{m_W^2}\left[Y_L t_{\theta_W}^2 \delta\kappa_\gamma + T_Z^{d_L}\delta g_1^Z + c_{\theta_W}\delta g_{uL}^Z/g\right]$
$\bar{f}_R f_R \to W_L W_L, Z_L h$	a_f	$-\frac{2g^2}{m_W^2}\left[Y_{f_R} t_{\theta_W}^2 \delta\kappa_\gamma + T_Z^{f_R}\delta g_1^Z + c_{\theta_W}\delta g_{fR}^Z/g\right]$

1609.06312, Falkowski et al; 1712.01310, Franceschini et al

Improving the LHC reach

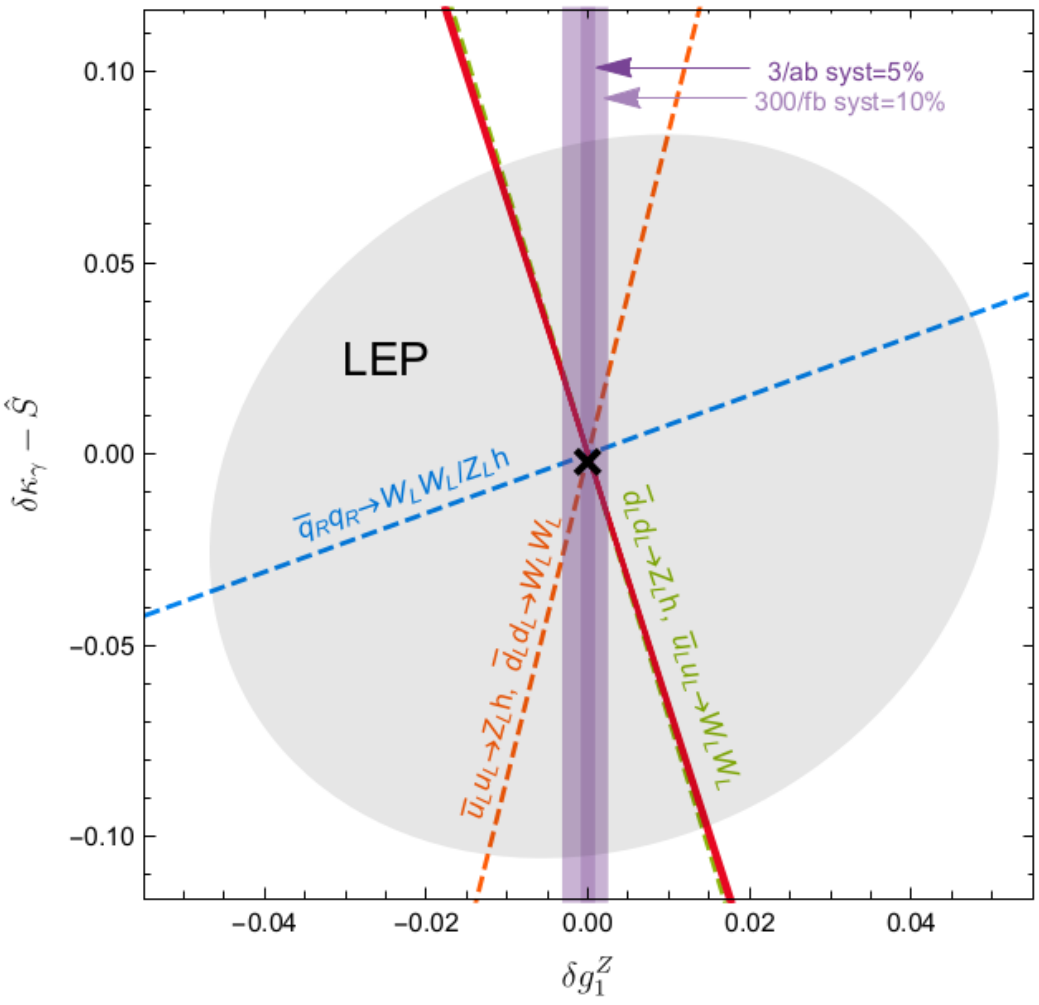
- SM contribution is domianted by the transverse modes $\gtrsim 93\%$
- Luckily the transverse contribution can be suppressed by cutting away W bosons at small angles





1712.01310, Franceschini et al

Results for $pp \to V_L V_L$



1712.01310 Franceschini et al

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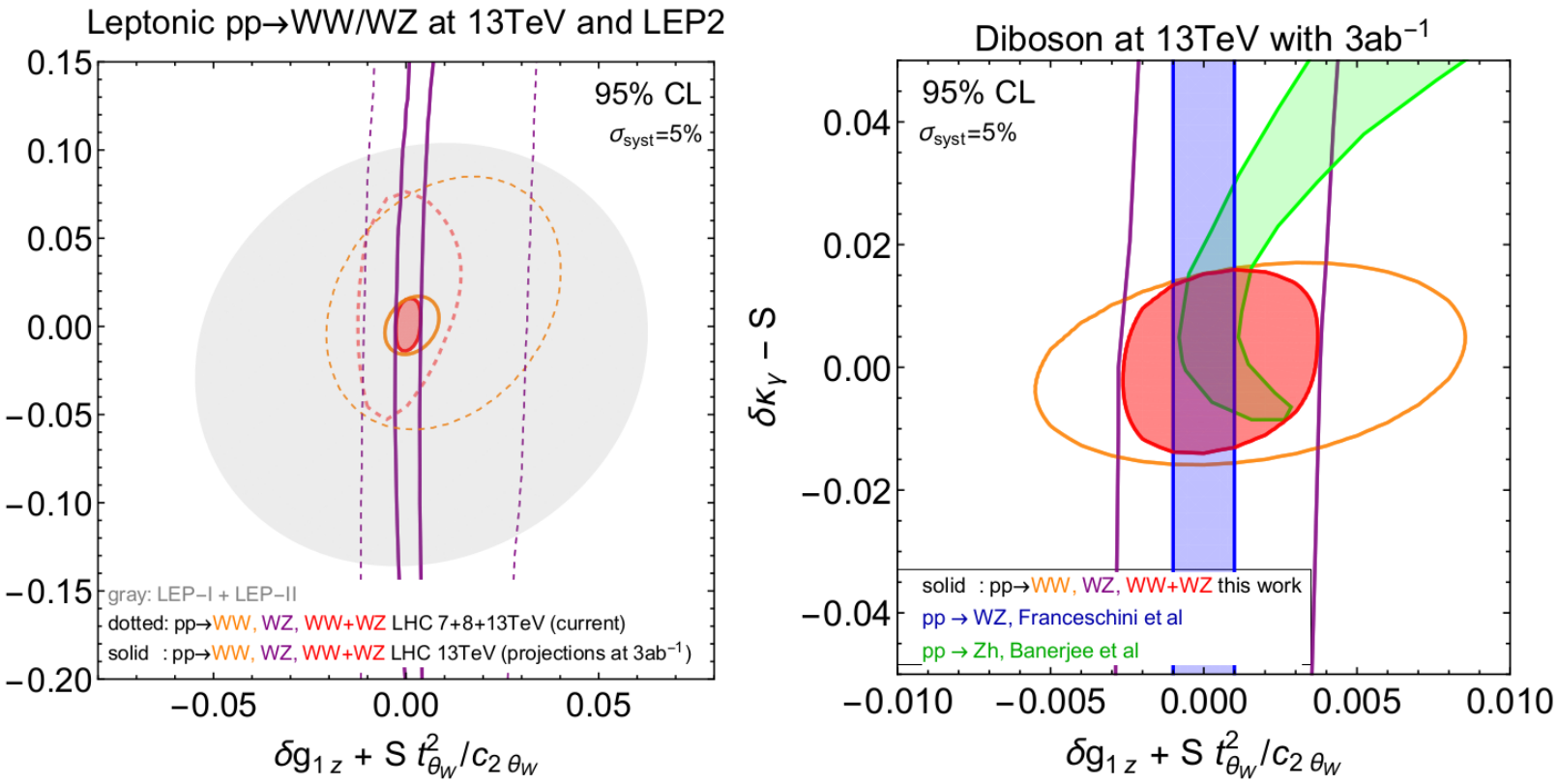
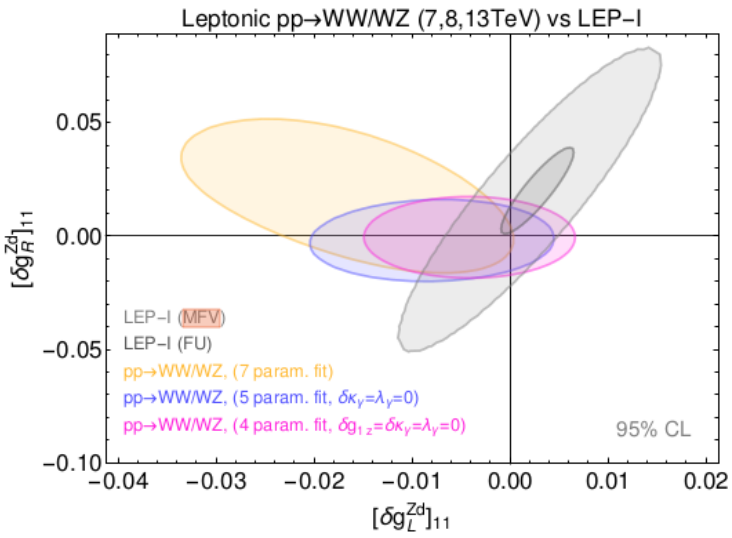
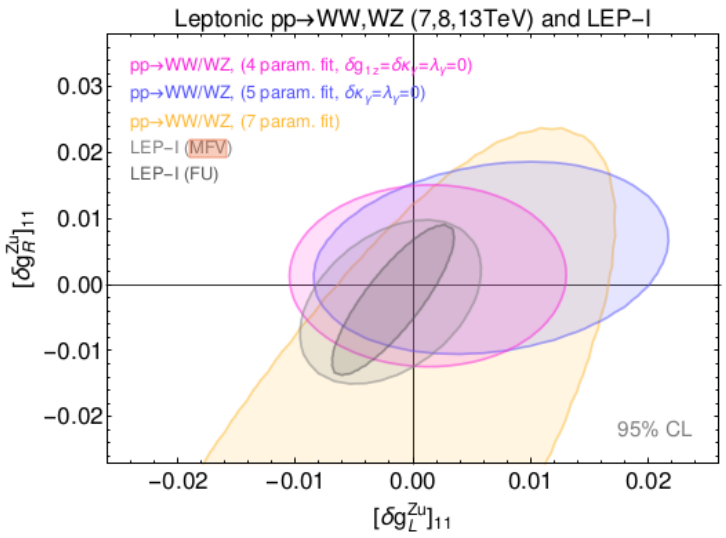


1810.05149 Grojean et al; 1807.01796 Banerjee et al

LHC vs Z pole observables at LEP-1

$\bar{\psi}\gamma^\mu\psi(H^\dagger \overleftrightarrow{D}_\mu H)$ will effect the Z pole observables strongly constrained by LEP-1





1810.05149 Grojean et al

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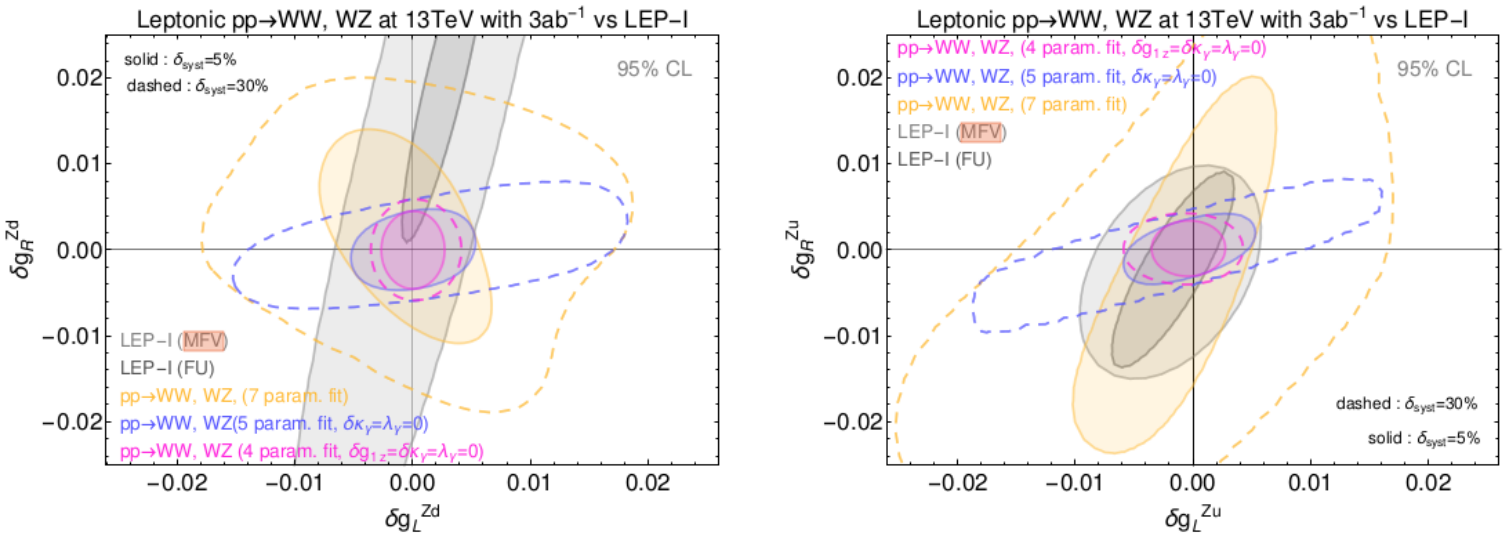

1810.05149 Grojean et al

$pp \to V_T V_T$

$W_{\mu\nu} W^{\nu\lambda} W^{\mu}_{\lambda}, \quad \tilde{W}_{\mu\nu} W^{\nu\lambda} W^{\mu}_{\lambda}$ aTGC give a contribution growing as E^2 but not interfering with SM

$$SM : qq \to V^{\pm} V^{\mp}$$
$$BSM : qq \to V^{\pm} V^{\pm}$$

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 ($qq \to V_T V_T$)

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

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?

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

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

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is this important?

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

Importance of interference, breaking the flat directions

$$\sigma = \sigma_0 + \sigma^{\mathrm{int}} c_{3W} + \tilde{\sigma}^{\mathrm{int}} \tilde{c}_{3W} + \sigma^{\mathrm{BSM}_1} c_{3W}^2 + \sigma^{\mathrm{BSM}_2} \tilde{c}_{3W}^2 + \sigma^{\mathrm{BSM}_3} c_{3W} \tilde{c}_{3W}.$$

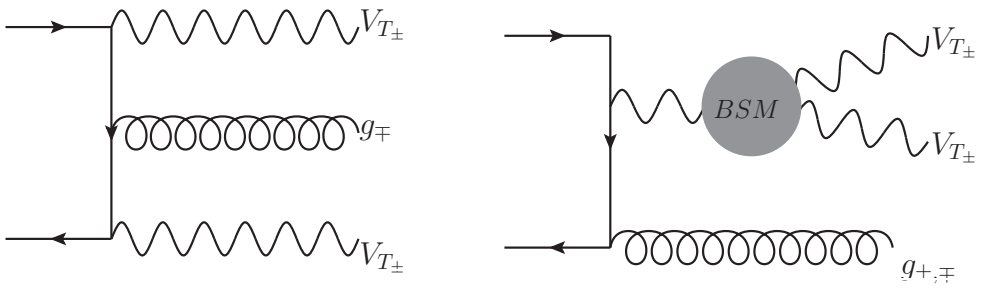
Only interference can distinguish the contributions of the $O_{3W}, O_{3\tilde{w}}$ operators.

The only way to measure the sign of the Wilson coefficients!

Overcoming the non-interference obstruction: 1st method

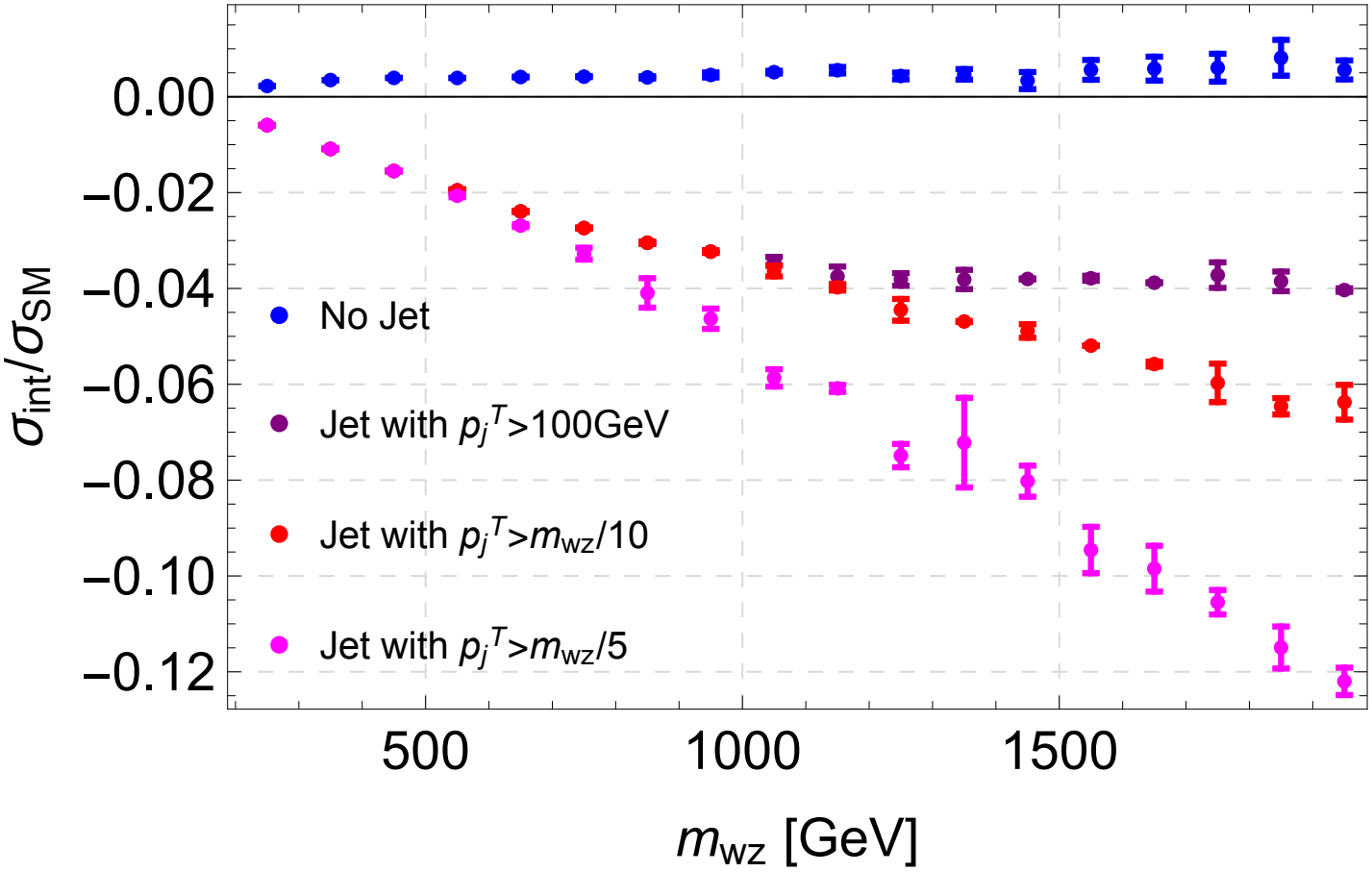
Dixon, Shadmi 94

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



- $(W)^3$ 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.
- at one loop level helicity selection rules are not valid any more.

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.

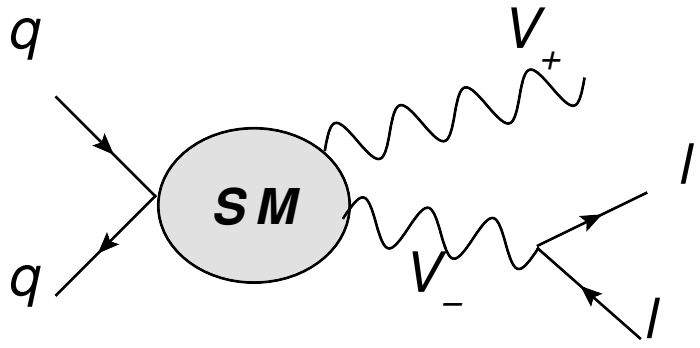

0.00
−0.02
−0.04
−0.06
−0.08
−0.10
−0.12
σ_{int}/σ_{SM}
No Jet
Jet with p_j^T>100GeV
Jet with p_j^T>m_{WZ}/10
Jet with p_j^T>m_{WZ}/5
500
1000
1500
m_{WZ} [GeV]

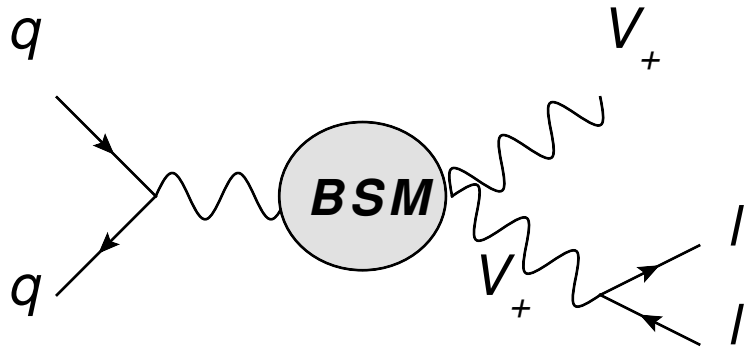
1707.08060

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:





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

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

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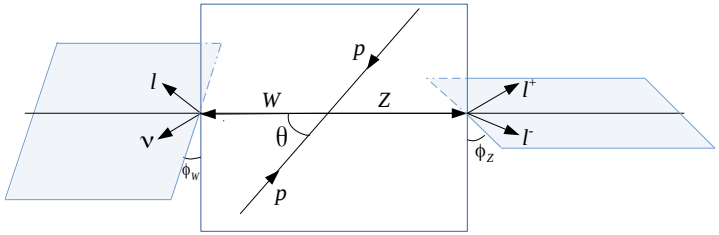

$$\frac{\pi}{2s}\frac{\delta(s-m_Z^2)}{\Gamma_Z m_Z}\mathcal{M}^{\rm SM}_{q\bar{q}\to W_{T_+}Z_{T_-}}\left(\mathcal{M}^{\rm BSM}_{q\bar{q}\to W_{T_+}Z_{T_+}}\right)^*\mathcal{M}_{Z_{T_-}\to l_-\bar{l}_+}\mathcal{M}^*_{Z_{T_+}\to l_-\bar{l}_+}\Rightarrow$$

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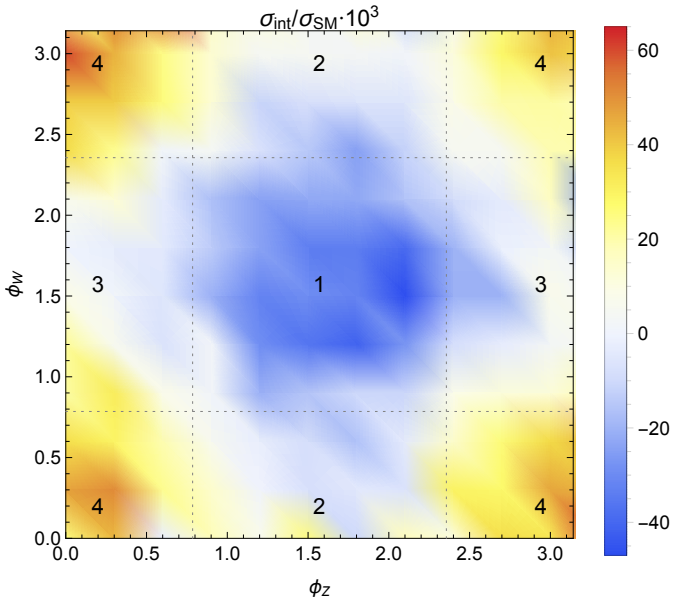
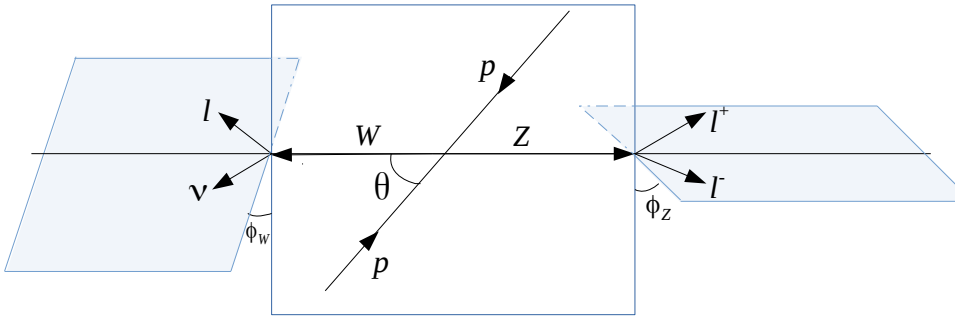
1707.08060

Azimuthal angle modulation

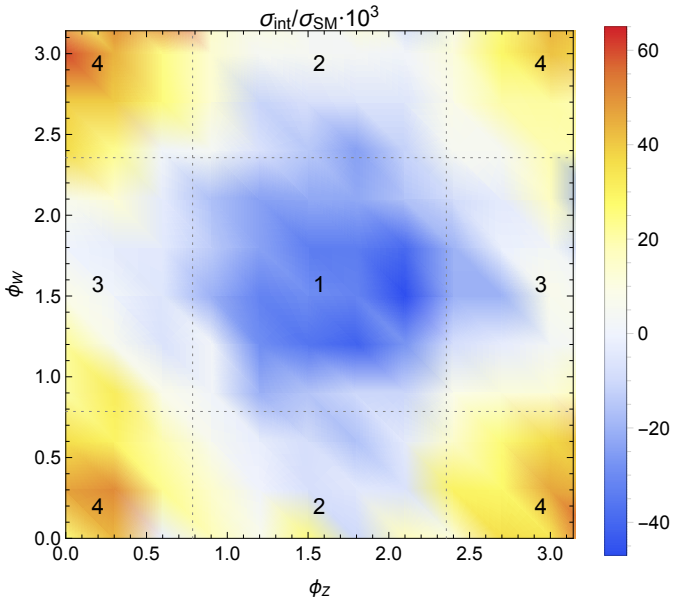


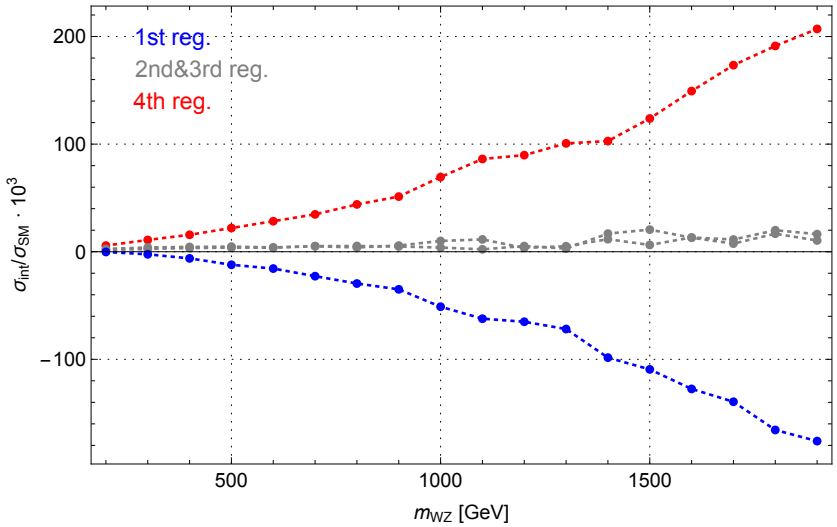


$$\frac{d\sigma_{\text{int}}(q\bar{q} \to WZ \to 4\psi)}{d\phi_Z\, d\phi_W} \propto \cos(2\phi_Z) + \cos(2\phi_W)$$

- 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





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

- 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.

Can repeat a similar argument for the CP odd operator

$$\boxed{O_{3\tilde{W}} = -\frac{1}{\Lambda^2}\frac{g}{3!}\epsilon_{abc}\tilde{W}^{a,\mu\nu}W^{b}_{\nu\lambda}W^{c\lambda}{}_{\mu}}$$

we are getting the interference scales as

$$\boxed{\frac{d\sigma^{3\tilde{W}}_{\text{int}}(q\bar{q} \to WZ \to 4\psi)}{d\phi_Z\, d\phi_W} \propto \sin(2\phi_Z) + \sin(2\phi_W)}$$

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

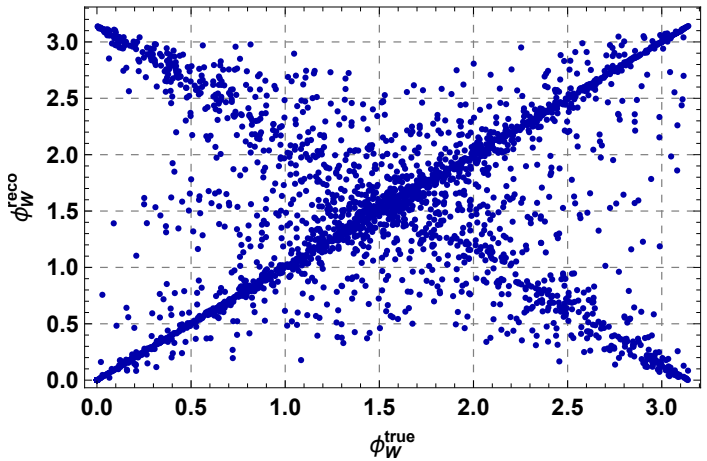
- In experiment we measure only the charges of the leptons, not their helicities
- Angualr modulation is fixed by the helicities of the decay products, so we have an ambiguity in determining the plane of the Z decay ϕ_Z.

  $\boxed{\phi_Z \to \phi_Z + \pi \quad \text{mod } 2\pi}$
- irrelevant for the $O_{3W}, O_{3\tilde{W}}$ operators since the modulation is $\boxed{\propto \cos 2\phi_Z, \sin 2\phi_Z}$

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

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



- $O_{3W} \propto \cos 2\phi$ **OK**
- $O_{3\tilde{W}} \propto \sin 2\phi$ **NO**

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

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

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

$$\frac{g}{3!}\epsilon^{abc} \tilde{W}_{\mu\nu}^{a} W^{b,\nu\rho} W_\rho^{c,\mu} \propto \sin 2\phi_Z + \cancel{\sin 2\phi_W}$$

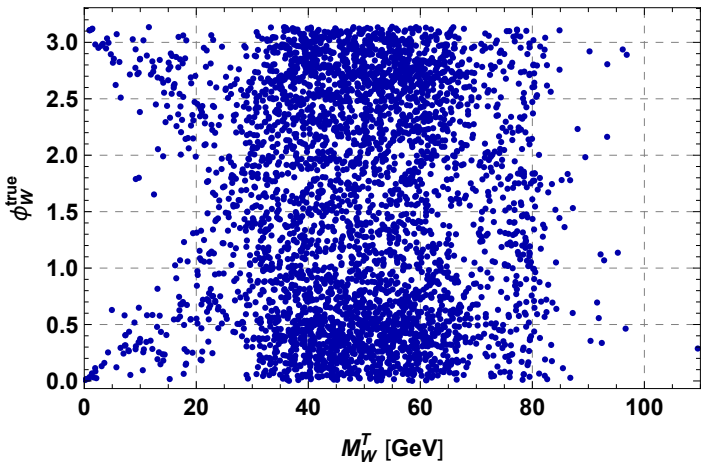
Precision studies at LHC *1901.04821*

- Higher order QCD effects are know to be important (*1703.09065, Grazzini et al*)
- In our case we know that NLO QCD effects can change qualitatively interference effects
- MadGraph5 aMCNLO using (HELatNLOUFO model)+PYTHIA8
- NLO+j events with Fx Fx merging are simulated to understand the importance of the NNLO effects
- We have checked the results for the SM signal and we are able to reproduce identically the NLO results known in the literature
- The analysis is done for the $WZ \to lll\nu$ and $W\gamma \to l\nu\gamma$ final state following very closely experimental studies (*ATLAS-CONF-2018-034 (2018), CMS Collaboration, Phys. Rev. D89 (2014)*).

Modulations from cuts ($W\gamma$ case) *1901.04821*

- So far we have been completely ignoring the kinematic acceptance cuts needed to suppress the background.
- In order to suppress the background without genuine missing $\not{E}_T$ cut on M_T^W variable is used

$$(M_W^T)^2 = (p_T^e + \not{p}_T)^2 - (\vec{p}_T^e + \vec{\not{p}}_T)^2$$



There is correlation between M_W^T cut and ϕ_W

Modulation from cuts

$M_T^W = 0 \quad \Rightarrow \vec{p}_T^e || \vec{\not{p}}_T || \vec{p}_T^W \Rightarrow \phi_W = 0, \pi$

$M_T^W = M_W \quad \Rightarrow \quad \frac{|\vec{p}_T^e|}{|\vec{p}_T^\nu|} = -\frac{p_z^e}{p_z^\nu}$, if $p_T^W \gg p_z^W \Rightarrow$ then we will have $p_T^{e,\nu} \gg p_z^{e,\nu}$ so that the angles are roughly $\pi/2$.

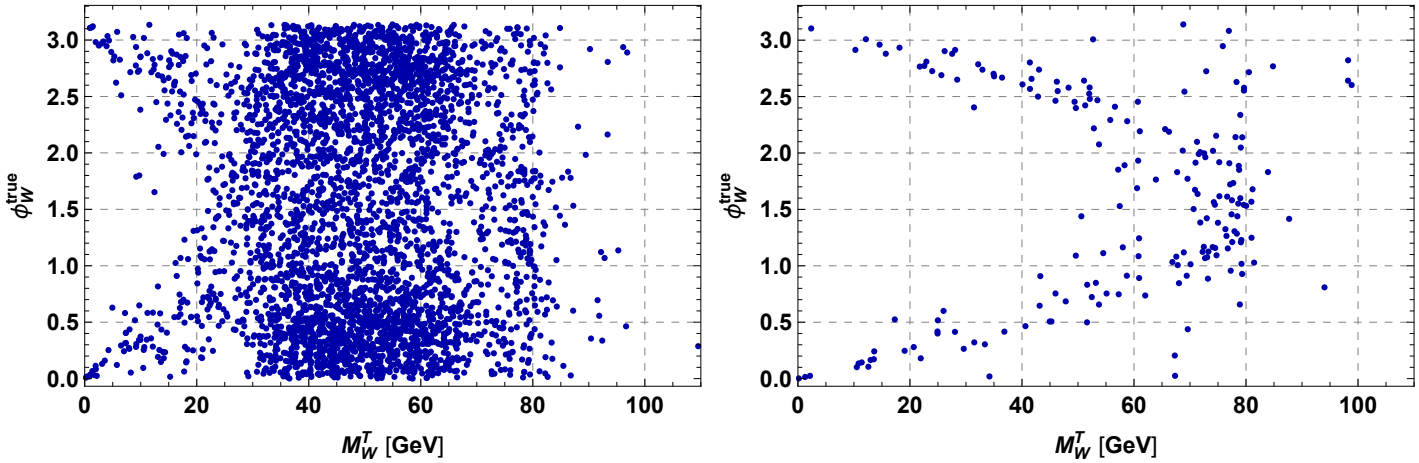
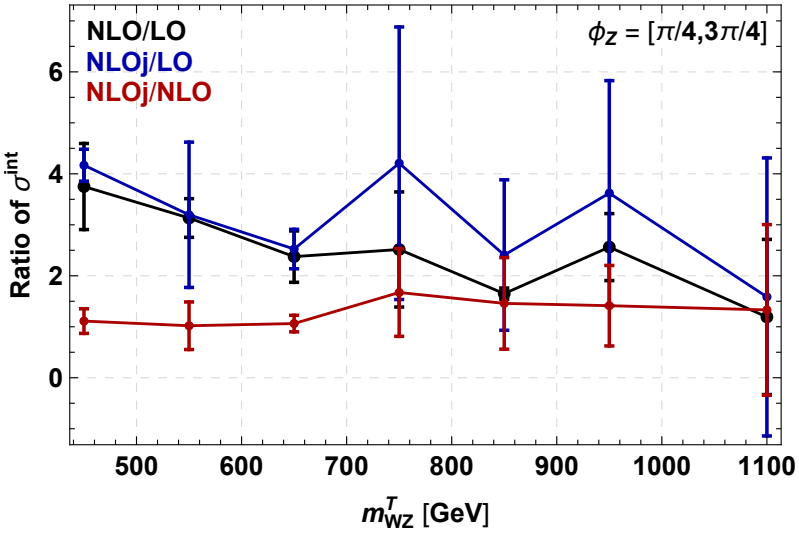
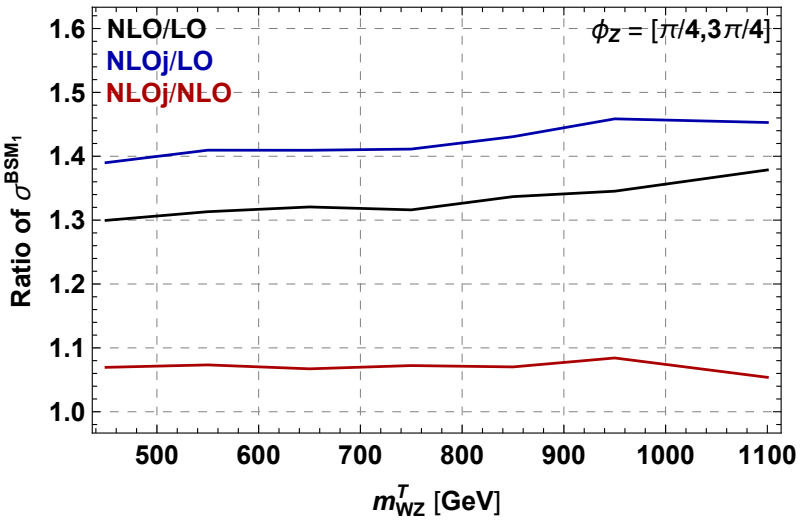


Figure: Left- no cuts, Right- p_T^γ >100 GeV

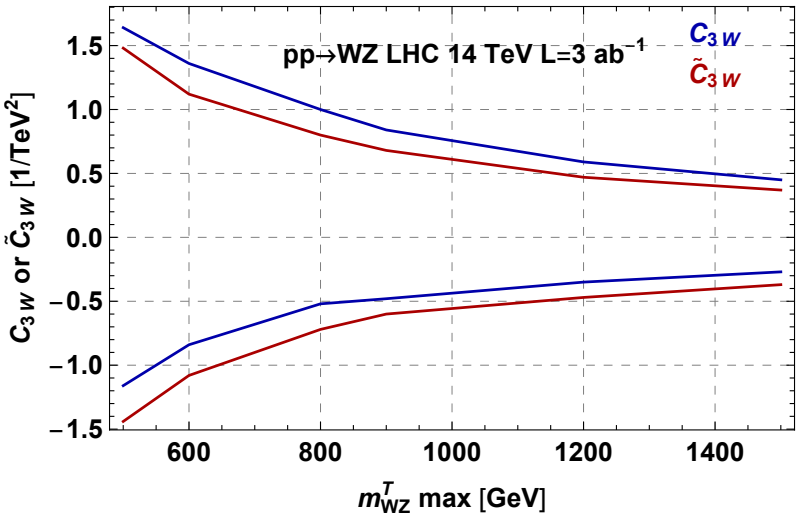
Strong correlation between M_T and azimuthal angles, especially for the boosted particles. Strong cut on M_T selects the bin $\phi \in [\pi/4, 3\pi/4]$ ($\sim \cos 2\phi$ modulation).

NLO effects

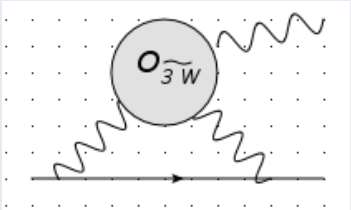

NLO/LO
NLOj/LO
NLOj/NLO
$\phi_Z = [\pi/4, 3\pi/4]$
Ratio of σ^{int}
m_{WZ}^T [GeV]

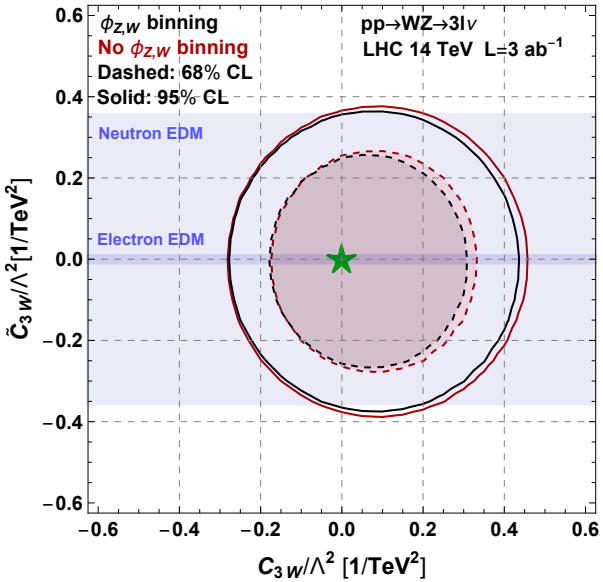

NLO/LO
NLOj/LO
NLOj/NLO
$\phi_Z = [\pi/4, 3\pi/4]$
Ratio of σ^{BSM_1}
m_{WZ}^T [GeV]

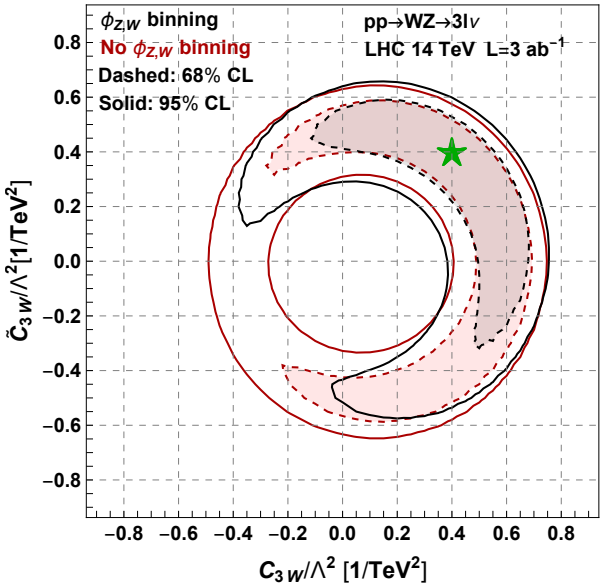
Results : WZ analysis @ 14 TeV



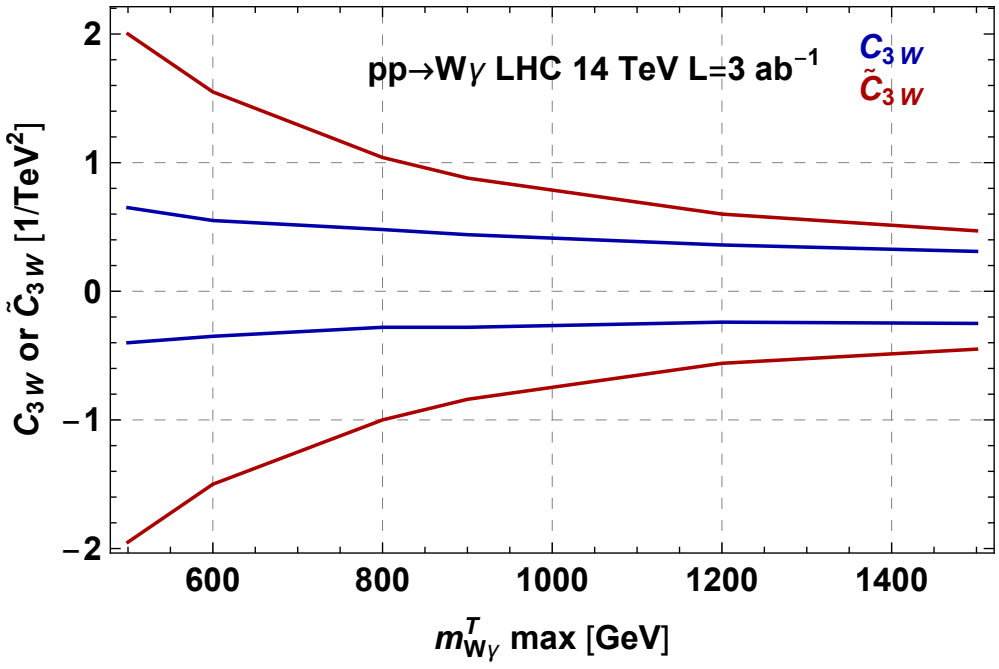
The sensitivity on O_{3W} is comparable to the bounds from neutron EDM's

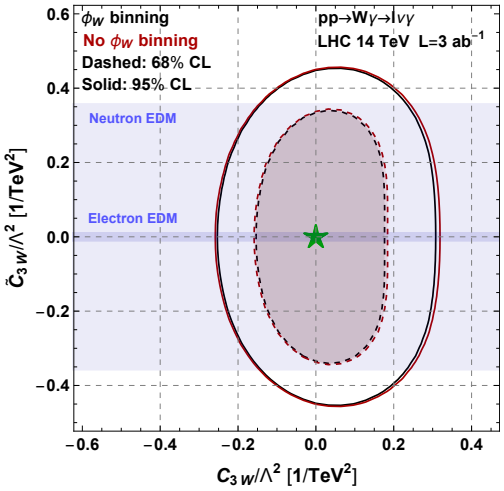


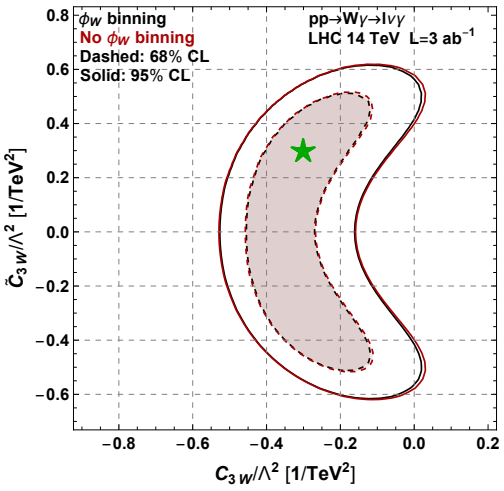




Results : *WA* analysis @ 14 TeV

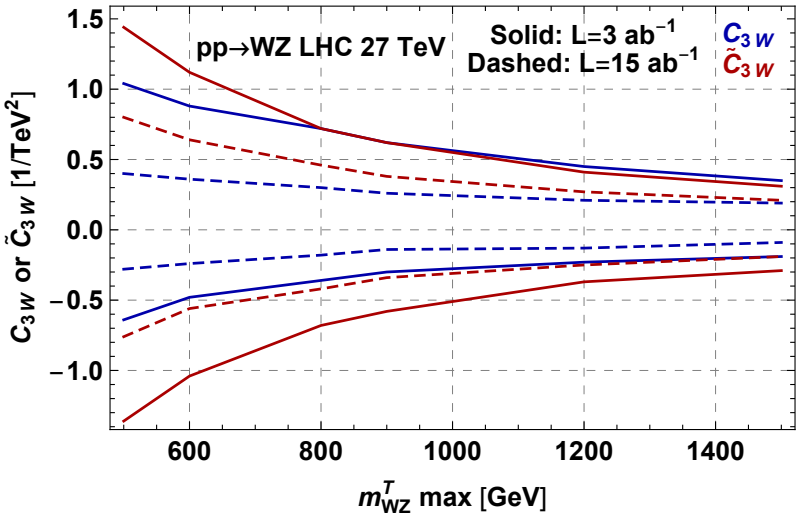


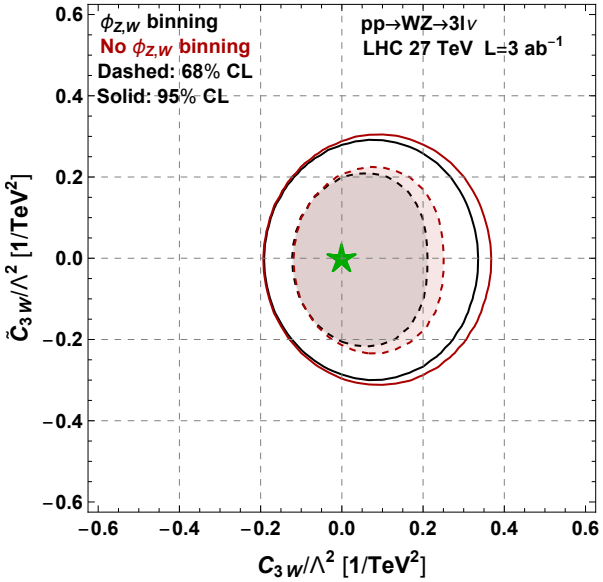


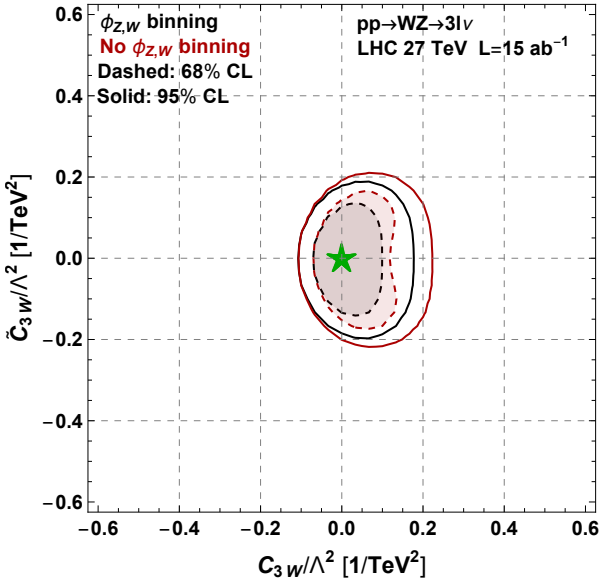


The modulation from cuts mimics the binning in ϕ_W

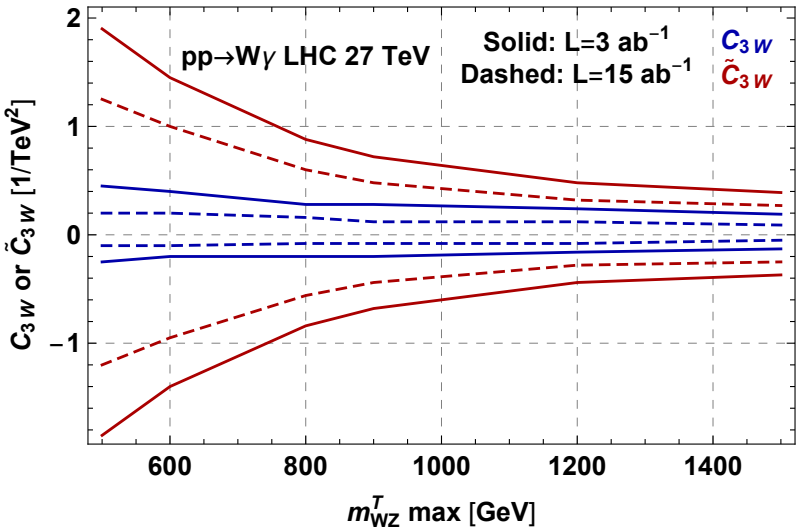
Results : *WZ* analysis @ 27 TeV

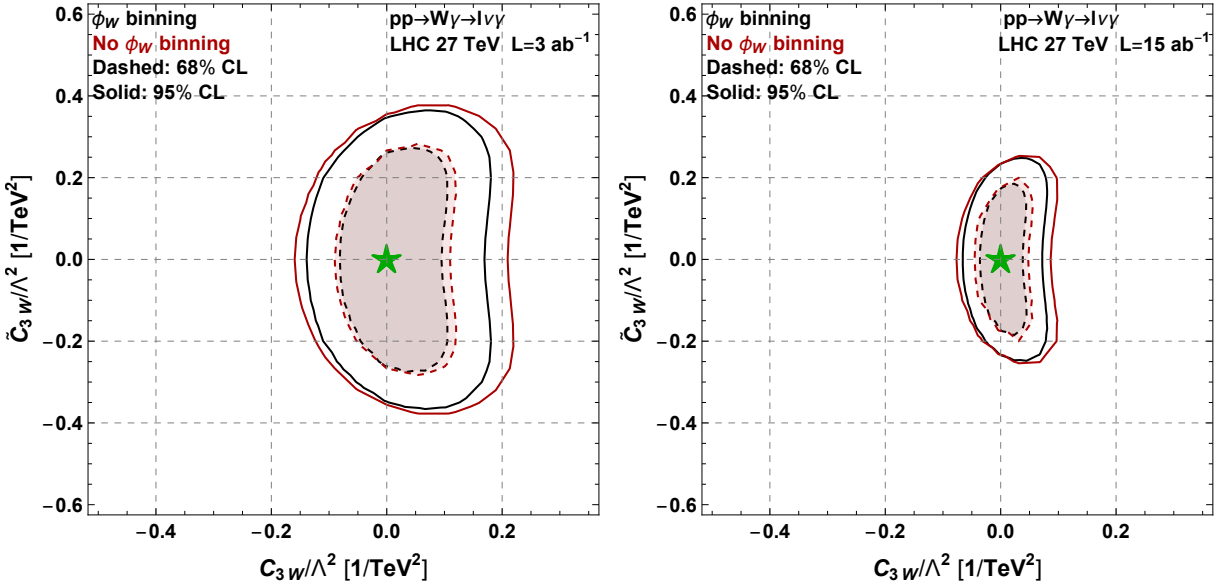






Results : *WA* analysis @ 27 TeV





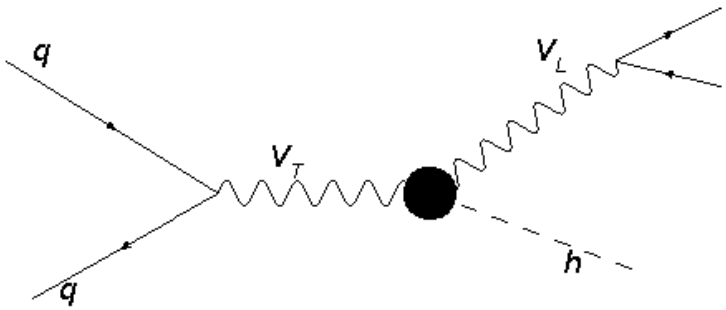
Summary of the bounds

Channel	Energy	Luminosity	λ_Z [$\times 10^{-3}$] 68%	λ_Z [$\times 10^{-3}$] 95%	$\tilde{\lambda}_Z$ [$\times 10^{-3}$] 68%	$\tilde{\lambda}_Z$ [$\times 10^{-3}$] 95%
$\boldsymbol{WZ}$	14 TeV	3 ab^{-1}	[-2.1, 1.2]	[-2.9, 1.7]	[-1.7, 1.7]	[-2.4, 2.4]
	27 TeV	3 ab^{-1}	[-1.4, 0.7]	[-2.2, 1.2]	[-1.5, 1.3]	[-2.0, 1.8]
		15 ab^{-1}	[-0.7, 0.4]	[-1.2, 0.6]	[-0.9, 0.8]	[-1.3, 1.2]
$\boldsymbol{W\gamma}$	14 TeV	3 ab^{-1}	[-1.2, 0.9]	[-2.0, 1.6]	[-2.2, 2.1]	[-3.0, 2.9]
	27 TeV	3 ab^{-1}	[-0.7, 0.4]	[-1.2 0.8]	[-1.8, 1.7]	[-2.5, 2.4]
		15 ab^{-1}	[-0.4, 0.2]	[-0.6, 0.3]	[-1.3, 1.2]	[-1.7, 1.5]

Table 2: Summary of the results for the various channels in terms of the CP-even and CP-odd anomalous triple gauge couplings. Only events with $m^T_{WZ,W\gamma} < 1.5$ TeV are used.

$pp \to vH$ with dimension 6 operators

In SM the process is dominated by the final state with the longitudinal vector boson in the final state.



In BSM we can have corrections both to V_L, V_T final states

$$\Delta\mathcal{L}_6^{hZ\bar{f}f} \supset \delta\hat{g}^h_{ZZ}\frac{2m_Z^2}{v}h\frac{Z^\mu Z_\mu}{2} + \sum_f g^h_{Zf}\frac{h}{v}Z_\mu\bar{f}\gamma^\mu f$$

long

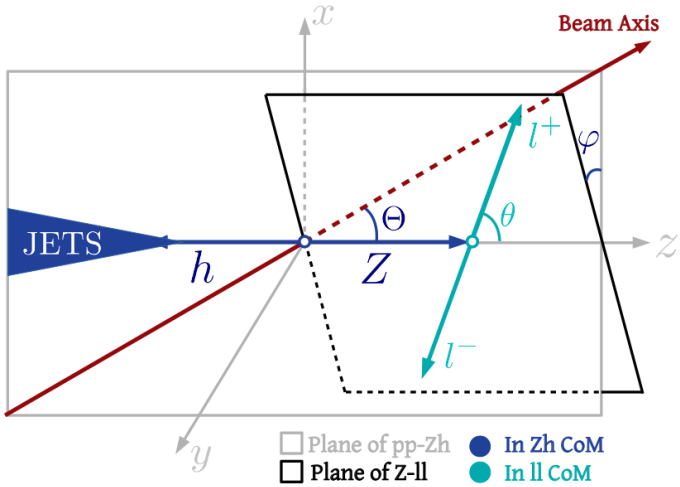
$$+\kappa_{ZZ}\frac{h}{2v}Z^{\mu\nu}Z_{\mu\nu} + \tilde{\kappa}_{ZZ}\frac{h}{2v}Z^{\mu\nu}\tilde{Z}_{\mu\nu}$$

transv.

Sensitivity to $k_{zz}, \tilde{k}_{zz}$ is suppressed

1905.02728, 1912.07628 Banerjee et al

$pp \to Z(ll)H(bb)$



Amplitude becomes a function of Θ, θ, ϕ

$$A_{\kappa_{zz}} \propto \frac{\sqrt{s}}{m_Z} \cos\phi \sin 2\theta \sin 2\Theta$$

$$A_{\tilde{\kappa}_{zz}} \propto \frac{\sqrt{s}}{m_Z} \sin\phi \sin 2\theta \sin 2\Theta$$

Need simultaneously to measure all three angles, otherwise the interference will be washed out due to the chirality ambiguity $(\theta, \phi) \to (\pi - \theta, \pi + \phi)$

$|\kappa, \tilde{\kappa}| < 0.07$ at 3 ab^{-1} *1905.02728, 1912.07628 Banerjee et al*

Summary

HL-LHC precision surpasses the precision of LEP

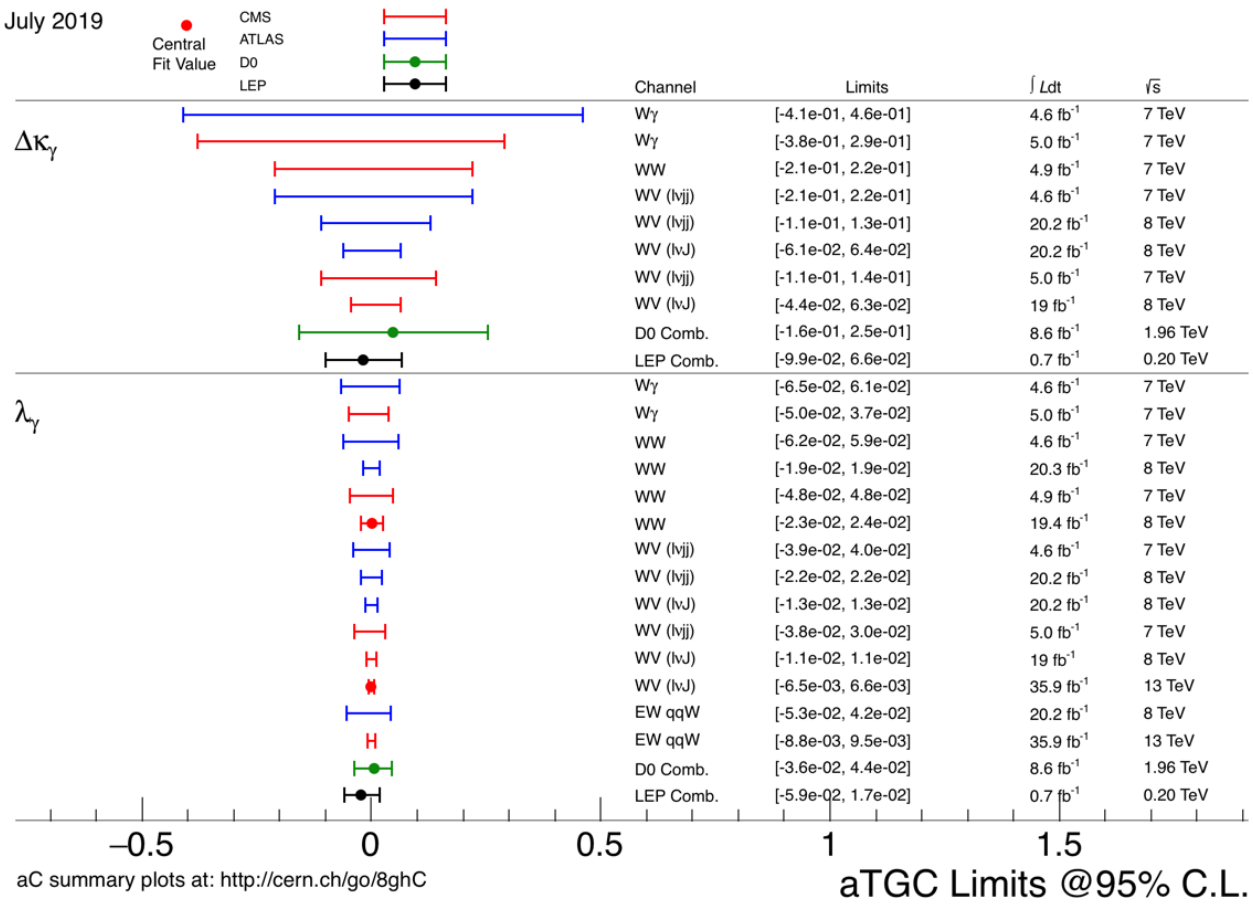
Differential distributions improve the sensitivity to the New Physics: better EFT expansion, additional tool in differentiating the operators, sign measurements.

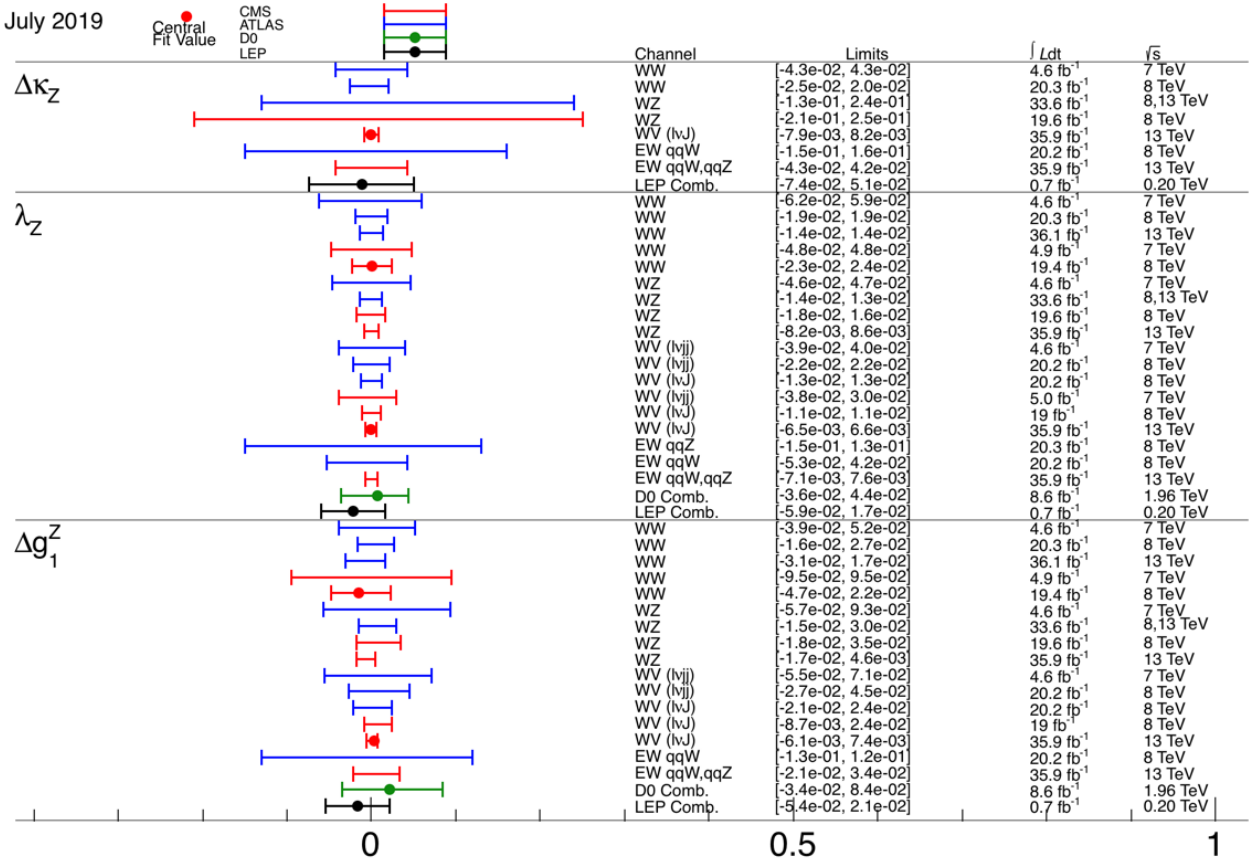
A lot of interesting physics within such simple measurements

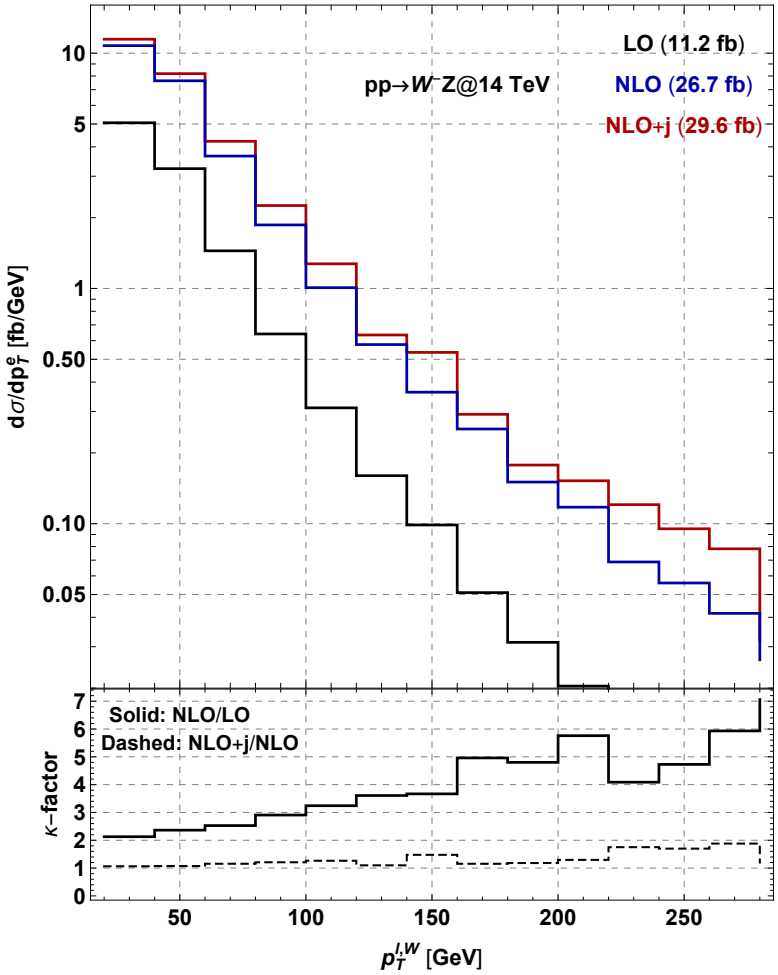
- QCD NLO effects modify qualitatively the predictions
- Some acceptance cuts lead to the automatic selection of the azimuthal angles
- Bounds become comparable with neutron EDM constraints.

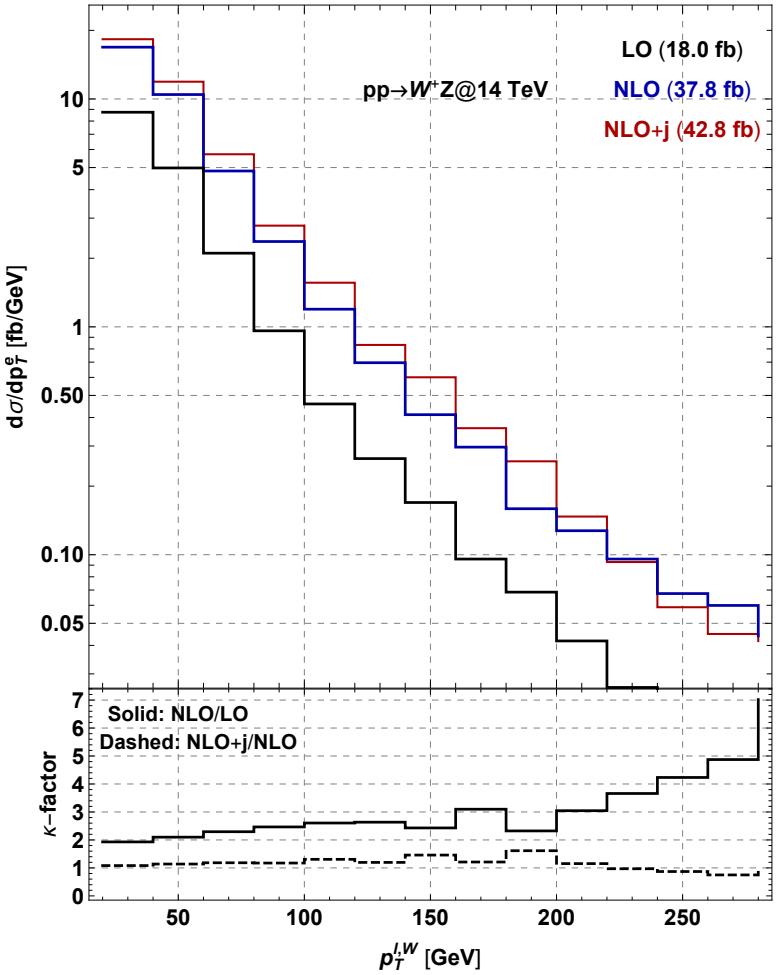
BACK UP

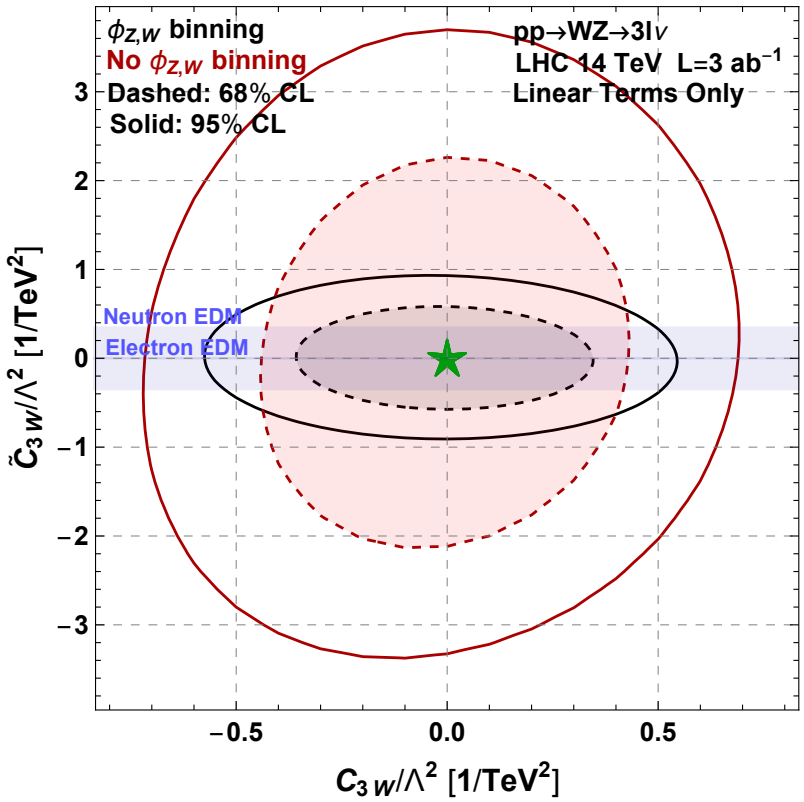
$$
\begin{aligned}
\mathcal{L}_{V\bar{q}q} &= \sqrt{g^2+g'^2}Z_\mu \left[\sum_{f\in u,d} \bar{f}_L \gamma_\mu \left(T_f^3 - s_W^2 Q_f + \delta g_L^{Zf} \right) f_L + \sum_{f\in u,d} \bar{f}_R \gamma_\mu \left(-s_W^2 Q_f + \delta g_R^{Zf} \right) f_R \right] \\
&+ \frac{g}{\sqrt{2}} \left(W_\mu^+ \bar{u}_L \gamma_\mu \left(I_3 + \delta g_L^{Wq} \right) d_L + \text{h.c.} \right) .
\end{aligned}
$$

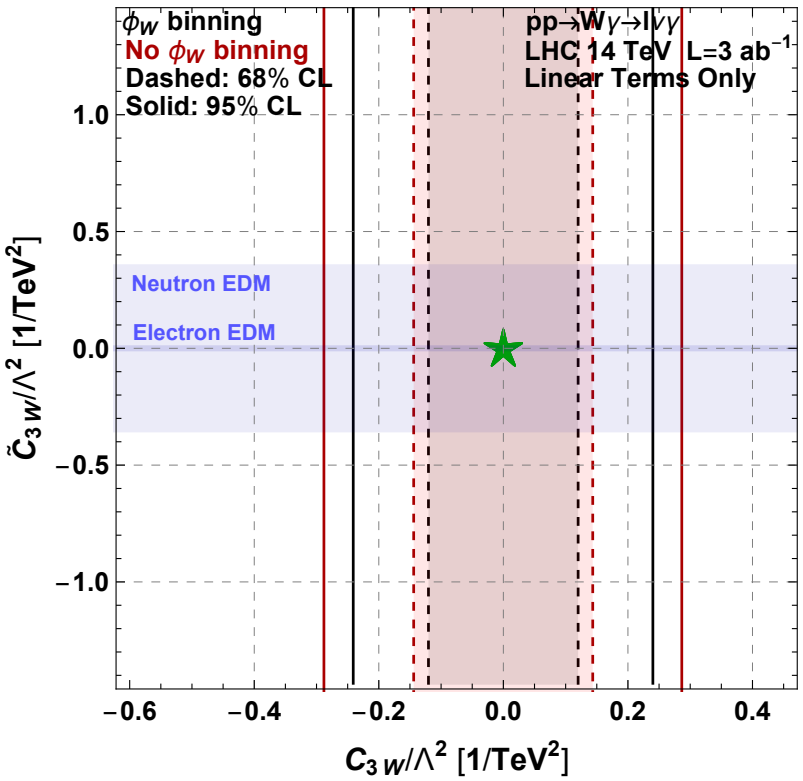

July 2019
Central Fit Value
CMS
ATLAS
D0
LEP
Channel
Limits
∫Ldt
√s
Δκγ
Wγ [-4.1e-01, 4.6e-01] 4.6 fb-1 7 TeV
Wγ [-3.8e-01, 2.9e-01] 5.0 fb-1 7 TeV
WW [-2.1e-01, 2.2e-01] 4.9 fb-1 7 TeV
WV (lνjj) [-2.1e-01, 2.2e-01] 4.6 fb-1 7 TeV
WV (lνjj) [-1.1e-01, 1.3e-01] 20.2 fb-1 8 TeV
WV (lνJ) [-6.1e-02, 6.4e-02] 20.2 fb-1 8 TeV
WV (lνjj) [-1.1e-01, 1.4e-01] 5.0 fb-1 7 TeV
WV (lνJ) [-4.4e-02, 6.3e-02] 19 fb-1 8 TeV
D0 Comb. [-1.6e-01, 2.5e-01] 8.6 fb-1 1.96 TeV
LEP Comb. [-9.9e-02, 6.6e-02] 0.7 fb-1 0.20 TeV
λγ
Wγ [-6.5e-02, 6.1e-02] 4.6 fb-1 7 TeV
Wγ [-5.0e-02, 3.7e-02] 5.0 fb-1 7 TeV
WW [-6.2e-02, 5.9e-02] 4.6 fb-1 7 TeV
WW [-1.9e-02, 1.9e-02] 20.3 fb-1 8 TeV
WW [-4.8e-02, 4.8e-02] 4.9 fb-1 7 TeV
WW [-2.3e-02, 2.4e-02] 19.4 fb-1 8 TeV
WV (lνjj) [-3.9e-02, 4.0e-02] 4.6 fb-1 7 TeV
WV (lνjj) [-2.2e-02, 2.2e-02] 20.2 fb-1 8 TeV
WV (lνJ) [-1.3e-02, 1.3e-02] 20.2 fb-1 8 TeV
WV (lνjj) [-3.8e-02, 3.0e-02] 5.0 fb-1 7 TeV
WV (lνJ) [-1.1e-02, 1.1e-02] 19 fb-1 8 TeV
WV (lνJ) [-6.5e-03, 6.6e-03] 35.9 fb-1 13 TeV
EW qqW [-5.3e-02, 4.2e-02] 20.2 fb-1 8 TeV
EW qqW [-8.8e-03, 9.5e-03] 35.9 fb-1 13 TeV
D0 Comb. [-3.6e-02, 4.4e-02] 8.6 fb-1 1.96 TeV
LEP Comb. [-5.9e-02, 1.7e-02] 0.7 fb-1 0.20 TeV
–0.5
0
0.5
1
1.5
aC summary plots at: http://cern.ch/go/8ghC
aTGC Limits @95% C.L.

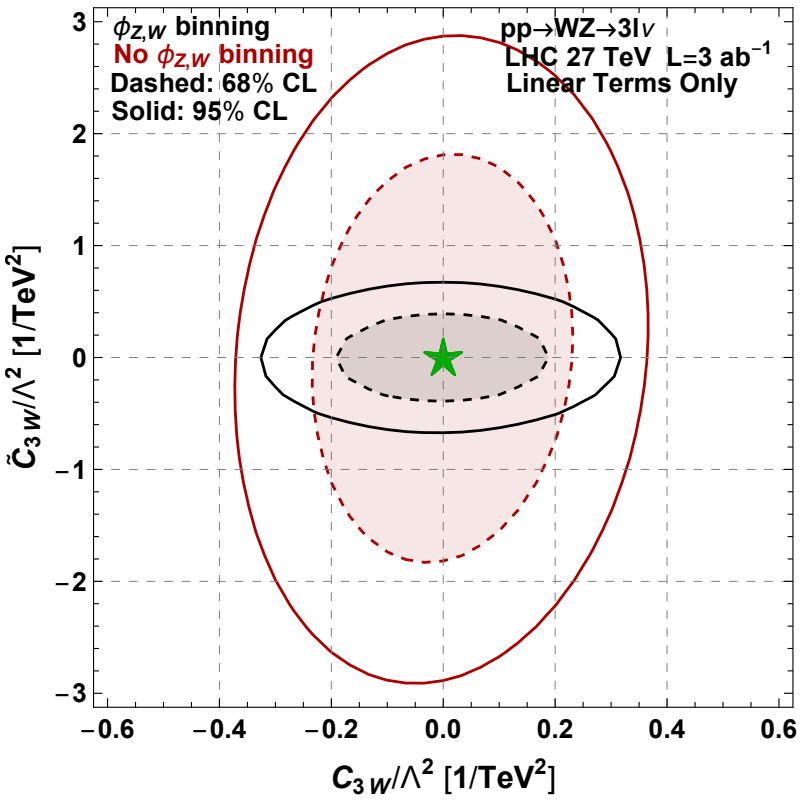

July 2019
Central Fit Value
CMS
ATLAS
D0
LEP
Channel
Limits
∫ Ldt
√s
Δκ_Z
WW [-4.3e-02, 4.3e-02] 4.6 fb^-1 7 TeV
WW [-2.5e-02, 2.0e-02] 20.3 fb^-1 8 TeV
WZ [-1.3e-01, 2.4e-01] 33.6 fb^-1 8,13 TeV
WZ [-2.1e-01, 2.5e-01] 19.6 fb^-1 8 TeV
WV (lνJ) [-7.9e-03, 8.2e-03] 35.9 fb^-1 13 TeV
EW qqW [-1.5e-01, 1.6e-01] 20.2 fb^-1 8 TeV
EW qqW,qqZ [-4.3e-02, 4.2e-02] 35.9 fb^-1 13 TeV
LEP Comb. [-7.4e-02, 5.1e-02] 0.7 fb^-1 0.20 TeV
λ_Z
WW [-6.2e-02, 5.9e-02] 4.6 fb^-1 7 TeV
WW [-1.9e-02, 1.9e-02] 20.3 fb^-1 8 TeV
WW [-1.4e-02, 1.4e-02] 36.1 fb^-1 13 TeV
WW [-4.8e-02, 4.8e-02] 4.9 fb^-1 7 TeV
WW [-2.3e-02, 2.4e-02] 19.4 fb^-1 8 TeV
WZ [-4.6e-02, 4.7e-02] 4.6 fb^-1 7 TeV
WZ [-1.4e-02, 1.3e-02] 33.6 fb^-1 8,13 TeV
WZ [-1.8e-02, 1.6e-02] 19.6 fb^-1 8 TeV
WZ [-8.2e-03, 8.6e-03] 35.9 fb^-1 13 TeV
WV (lνjj) [-3.9e-02, 4.0e-02] 4.6 fb^-1 7 TeV
WV (lνjj) [-2.2e-02, 2.2e-02] 20.2 fb^-1 8 TeV
WV (lνJ) [-1.3e-02, 1.3e-02] 20.2 fb^-1 8 TeV
WV (lνjj) [-3.8e-02, 3.0e-02] 5.0 fb^-1 7 TeV
WV (lνJ) [-1.1e-02, 1.1e-02] 19 fb^-1 8 TeV
WV (lνJ) [-6.5e-03, 6.6e-03] 35.9 fb^-1 13 TeV
EW qqZ [-1.5e-01, 1.3e-01] 20.3 fb^-1 8 TeV
EW qqW [-5.3e-02, 4.2e-02] 20.2 fb^-1 8 TeV
EW qqW,qqZ [-7.1e-03, 7.6e-03] 35.9 fb^-1 13 TeV
D0 Comb. [-3.6e-02, 4.4e-02] 8.6 fb^-1 1.96 TeV
LEP Comb. [-5.9e-02, 1.7e-02] 0.7 fb^-1 0.20 TeV
Δg_1^Z
WW [-3.9e-02, 5.2e-02] 4.6 fb^-1 7 TeV
WW [-1.6e-02, 2.7e-02] 20.3 fb^-1 8 TeV
WW [-3.1e-02, 1.7e-02] 36.1 fb^-1 13 TeV
WW [-9.5e-02, 9.5e-02] 4.9 fb^-1 7 TeV
WW [-4.7e-02, 2.2e-02] 19.4 fb^-1 8 TeV
WZ [-5.7e-02, 9.3e-02] 4.6 fb^-1 7 TeV
WZ [-1.5e-02, 3.0e-02] 33.6 fb^-1 8,13 TeV
WZ [-1.8e-02, 3.5e-02] 19.6 fb^-1 8 TeV
WZ [-1.7e-02, 4.6e-03] 35.9 fb^-1 13 TeV
WV (lνjj) [-5.5e-02, 7.1e-02] 4.6 fb^-1 7 TeV
WV (lνjj) [-2.7e-02, 4.5e-02] 20.2 fb^-1 8 TeV
WV (lνJ) [-2.1e-02, 2.4e-02] 20.2 fb^-1 8 TeV
WV (lνJ) [-8.7e-03, 2.4e-02] 19 fb^-1 8 TeV
WV (lνJ) [-6.1e-03, 7.4e-03] 35.9 fb^-1 13 TeV
EW qqW [-1.3e-01, 1.2e-01] 20.2 fb^-1 8 TeV
EW qqW,qqZ [-2.1e-02, 3.4e-02] 35.9 fb^-1 13 TeV
D0 Comb. [-3.4e-02, 8.4e-02] 8.6 fb^-1 1.96 TeV
LEP Comb. [-5.4e-02, 2.1e-02] 0.7 fb^-1 0.20 TeV
0
0.5
1
aC summary plots at: http://cern.ch/go/8ghC
aTGC Limits @95% C.L.

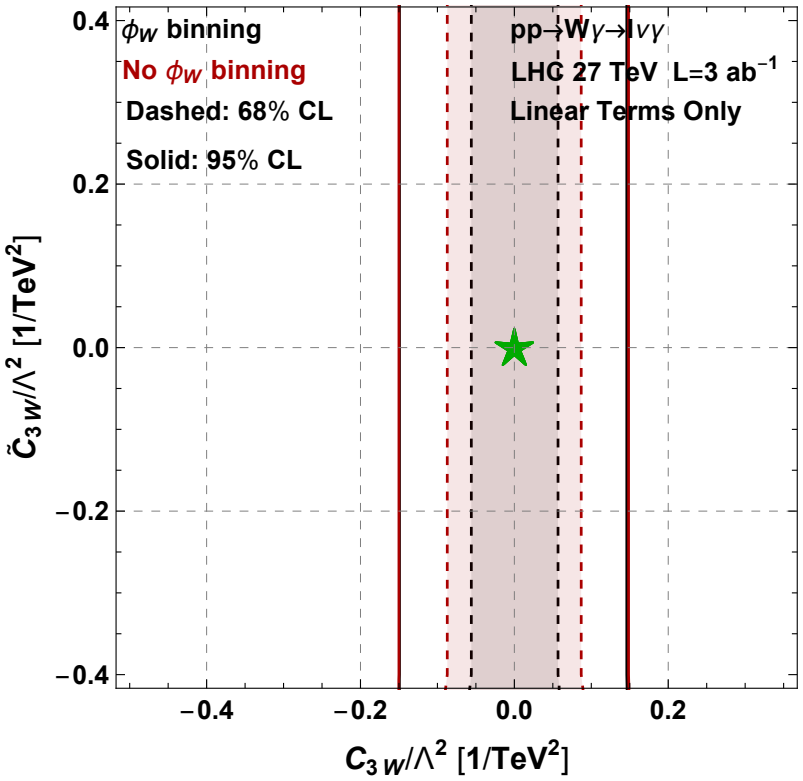

LO (11.2 fb)
pp→W⁻Z@14 TeV
NLO (26.7 fb)
NLO+j (29.6 fb)
dσ/dp_T^ℓ [fb/GeV]
Solid: NLO/LO
Dashed: NLO+j/NLO
κ−factor
p_T^{l,W} [GeV]

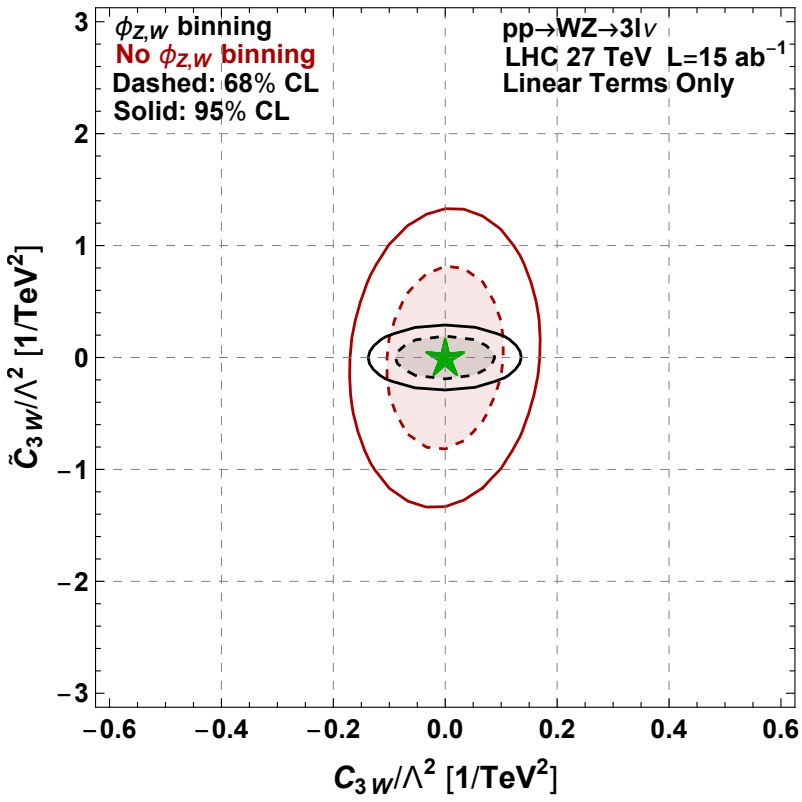

LO (18.0 fb)
pp→W⁺Z@14 TeV
NLO (37.8 fb)
NLO+j (42.8 fb)
dσ/dp_T^ℓ [fb/GeV]
Solid: NLO/LO
Dashed: NLO+j/NLO
κ−factor
p_T^{l,W} [GeV]

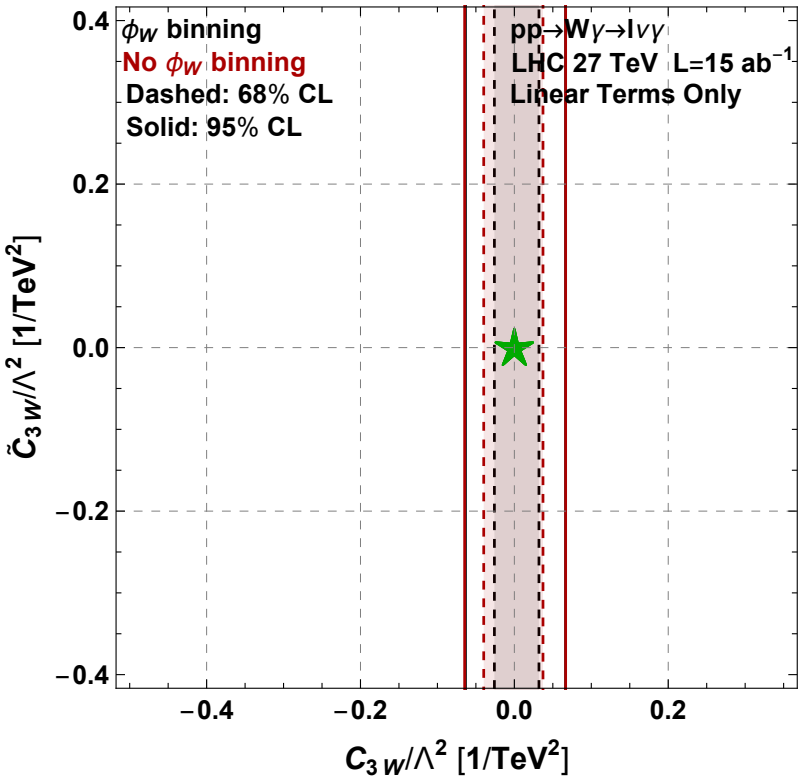

$\phi_{Z,W}$ binning
No $\phi_{Z,W}$ binning
Dashed: 68% CL
Solid: 95% CL
pp→WZ→3lν
LHC 14 TeV L=3 ab^{-1}
Linear Terms Only
Neutron EDM
Electron EDM
$\tilde{C}_{3W}/\Lambda^2$ [1/TeV^2]
C_{3W}/Λ^2 [1/TeV^2]


ϕ_W binning
No ϕ_W binning
Dashed: 68% CL
Solid: 95% CL
pp→Wγ→l$\nu\gamma$
LHC 14 TeV L=3 ab^{-1}
Linear Terms Only
Neutron EDM
Electron EDM
$\tilde{C}_{3W}/\Lambda^2$ [1/TeV^2]
C_{3W}/Λ^2 [1/TeV^2]


$\phi_{Z,W}$ binning
No $\phi_{Z,W}$ binning
Dashed: 68% CL
Solid: 95% CL
pp→WZ→3lν
LHC 27 TeV L=3 ab^{-1}
Linear Terms Only
$\tilde{C}_{3W}/\Lambda^2$ [1/TeV^2]
C_{3W}/Λ^2 [1/TeV^2]


ϕ_W binning
No ϕ_W binning
Dashed: 68% CL
Solid: 95% CL
pp→Wγ→lνγ
LHC 27 TeV L=3 ab^{-1}
Linear Terms Only
$\tilde{C}_{3W}/\Lambda^2$ [1/TeV^2]
C_{3W}/Λ^2 [1/TeV^2]


$\phi_{Z,W}$ binning
No $\phi_{Z,W}$ binning
Dashed: 68% CL
Solid: 95% CL
pp→WZ→3lν
LHC 27 TeV L=15 ab^{-1}
Linear Terms Only
$\tilde{C}_{3W}/\Lambda^2$ [1/TeV^2]
C_{3W}/Λ^2 [1/TeV^2]


ϕ_W binning
No ϕ_W binning
Dashed: 68% CL
Solid: 95% CL
pp→Wγ→lνγ
LHC 27 TeV L=15 ab^{-1}
Linear Terms Only
$\tilde{C}_{3W}/\Lambda^2$ [1/TeV^2]
C_{3W}/Λ^2 [1/TeV^2]

$pp \to vH$ with dimension 6 operators

$\mathcal{O}_{H\Box} = (H^\dagger H)\Box(H^\dagger H)$	$\mathcal{O}_{HL}^{(3)} = iH^\dagger\sigma^a \overleftrightarrow{D}_\mu H \bar{L}\sigma^a\gamma^\mu L$
$\mathcal{O}_{HD} = (H^\dagger D_\mu H)^*(H^\dagger D_\mu H)$	$\mathcal{O}_{HB} = \lvert H\rvert^2 B_{\mu\nu}B^{\mu\nu}$
$\mathcal{O}_{Hu} = iH^\dagger \overleftrightarrow{D}_\mu H \bar{u}_R\gamma^\mu u_R$	$\mathcal{O}_{HWB} = H^\dagger\sigma^a H W^a_{\mu\nu}B^{\mu\nu}$
$\mathcal{O}_{Hd} = iH^\dagger \overleftrightarrow{D}_\mu H \bar{d}_R\gamma^\mu d_R$	$\mathcal{O}_{HW} = \lvert H\rvert^2 W_{\mu\nu}W^{\mu\nu}$
$\mathcal{O}_{He} = iH^\dagger \overleftrightarrow{D}_\mu H \bar{e}_R\gamma^\mu e_R$	$\mathcal{O}_{H\tilde{B}} = \lvert H\rvert^2 B_{\mu\nu}\tilde{B}^{\mu\nu}$
$\mathcal{O}_{HQ}^{(1)} = iH^\dagger \overleftrightarrow{D}_\mu H \bar{Q}\gamma^\mu Q$	$\mathcal{O}_{H\tilde{W}B} = H^\dagger\sigma^a H W^a_{\mu\nu}\tilde{B}^{\mu\nu}$
$\mathcal{O}_{HQ}^{(3)} = iH^\dagger\sigma^a \overleftrightarrow{D}_\mu H \bar{Q}\sigma^a\gamma^\mu Q$	$\mathcal{O}_{H\tilde{W}} = \lvert H\rvert^2 W^a_{\mu\nu}\tilde{W}^{a\mu\nu}$
$\mathcal{O}_{HL}^{(1)} = iH^\dagger \overleftrightarrow{D}_\mu H \bar{L}\gamma^\mu L$	

$\Rightarrow$

$$\Delta\mathcal{L}_6^{hZ\bar{f}f} \supset \delta\hat{g}^h_{ZZ}\frac{2m_Z^2}{v}h\frac{Z^\mu Z_\mu}{2} + \sum_f g^h_{Zf}\frac{h}{v}Z_\mu\bar{f}\gamma^\mu f + \kappa_{ZZ}\frac{h}{2v}Z^{\mu\nu}Z_{\mu\nu} + \tilde{\kappa}_{ZZ}\frac{h}{2v}Z^{\mu\nu}\tilde{Z}_{\mu\nu}$$

long

transv.

amplitudes for $qq \to vH$

$$\mathcal{M}_\sigma^{\lambda=\pm} = \sigma\frac{1+\sigma\lambda\cos\Theta}{\sqrt{2}}\frac{gg_f^Z}{c_{\theta_W}}\frac{m_Z}{\sqrt{\hat{s}}}\left[1+\left(\frac{g^h_{Zf}}{g_f^Z}+\kappa_{ZZ}-i\lambda\tilde{\kappa}_{ZZ}\right)\frac{\hat{s}}{2m_Z^2}\right]$$

$$\mathcal{M}_\sigma^{\lambda=0} = -\sin\Theta\frac{gg_f^Z}{2c_{\theta_W}}\left[1+\delta\hat{g}^h_{ZZ}+2\kappa_{ZZ}+\frac{g^h_{Zf}}{g_f^Z}\left(-\frac{1}{2}+\frac{\hat{s}}{2m_Z^2}\right)\right],$$

1905.02728, 1912.07628 Banerjee et al