Measurements of anomalous TGC at LHC

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08/05/2018
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1707.08060 with J.Elias-Miro, Y.Reyimuaji, E.Venturini & in progress with G.Panico, F.Riva, A.Wulzer, E.Venturini, D.Barducci

Searching for new physics indirectly

Generically we can search for new physics either **directly** through the new resonance production or **indirectly** by measuring precisely the SM interactions.

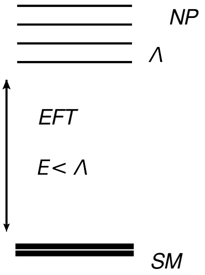
Generically indirect searches can test new physics interactions even if it is hard to observe directly at collider (new states are too heavy or have complicated decay final state) ☺

Of course indirect searches depend on our knowledge of the precision SM prediction ☹

How to parametrize new physics effects?

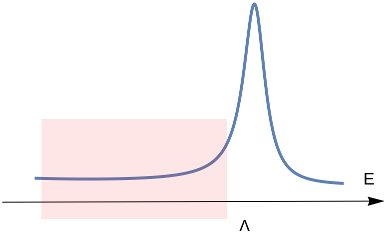
EFT provides a consistent framework for the parametrization of the new physics effects.

- If new physics states are heavier than the SM states and the typical mass scale of the process $\Lambda > E$.
- We can integrate these states out and parametrize their effects in terms of the higher dimensional operators.
- The effects of new physics will appear as corrections in the $\left(\frac{E}{\Lambda}\right)$ series.



Bounding EFT @ LHC

- EFT expansion is valid only below the mass of the new heavy resonance
- We are testing the deviations from the SM in the tails of the Breight -Wigner resonances.
- EFT analysis becomes important if the new resonances are too heavy to be directly produced at the collider.



- At LHC the collision energy is not fixed
- Deviations from SM are bigger at large energies, at the same time we are closer to the boundary of the EFT validity.
- The searches which are performed on the mass peak of the SM particle (Higgs coupling) are safe, but we loose information from the tails

Out of 2499 operators present at the dimension six level we will focus only on the ones that change the interactions between three gauge bosons, anomalous Triple Gauge Couplings (aTGC)

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

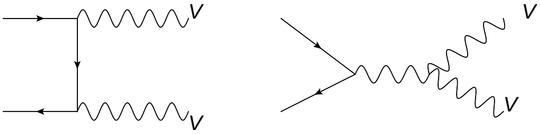
$$\lambda_Z \frac{ig}{m_W^2} W^{+\,\mu_2}_{\mu_1} W^{-\,\mu_3}_{\mu_2} W^{3\,\mu_1}_{\mu_3}$$

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

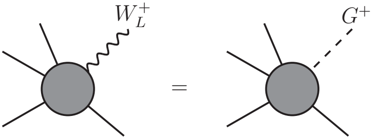
- At LHC these couplings are constrained mainly from the $qq \to VV$ process.



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

SM expectations

- We can use the Goldstone 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.

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

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

(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

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

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

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

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

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

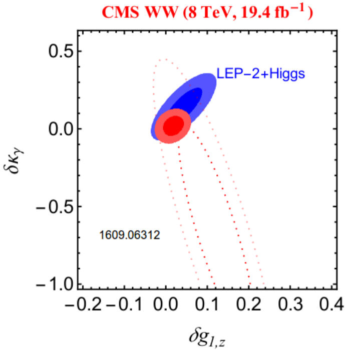
$$\mathcal{M}\left(q\bar{q} \to W^-_L W^+_L\right) \sim E^2/\Lambda^2\ c_{HB} + E^2/\Lambda^2\ c_{HW} \sim E^2/m^2_W\ \delta g_{1,Z} + E^2/m^2_W\ \delta\kappa_Z$$

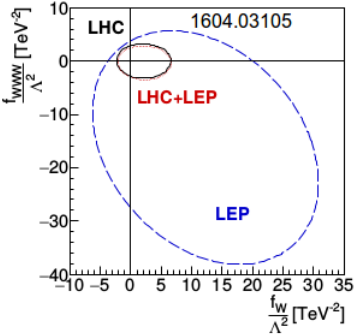
$$\mathcal{M}\left(q\bar{q} \to Z_L W^+_L\right) \sim E^2/\Lambda^2\ c_{HW} = E^2/m^2_Z\ \delta g_{1,Z}\ ,$$

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

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

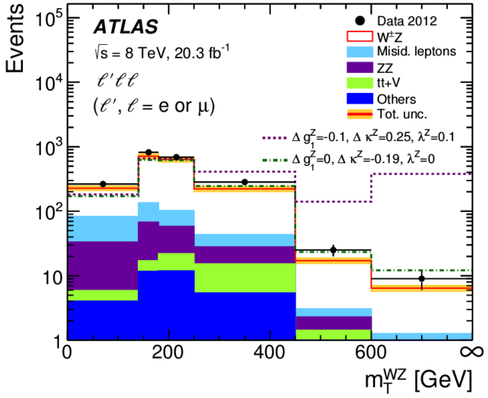
EFT bounds @ LHC





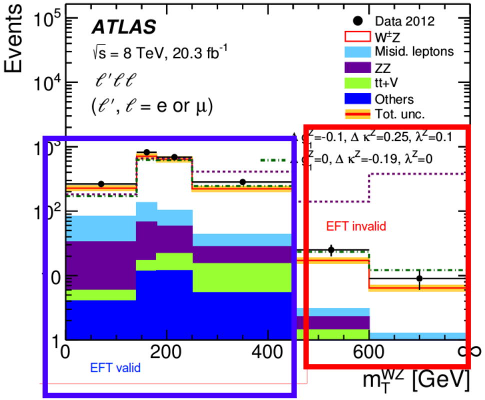
Precision of the LHC searches naively has already surpassed the precision of LEP

EFT bounds @ LHC



sensitivity comes from the tails of the distributions where the EFT description can fail!

EFT bounds @ LHC



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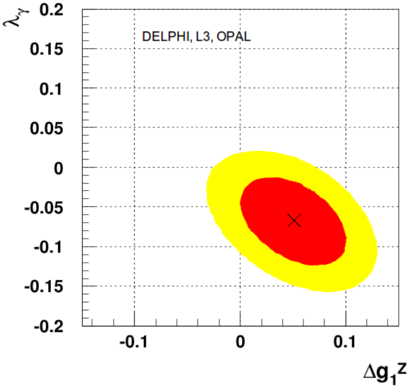
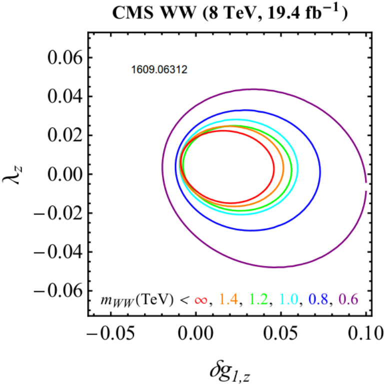




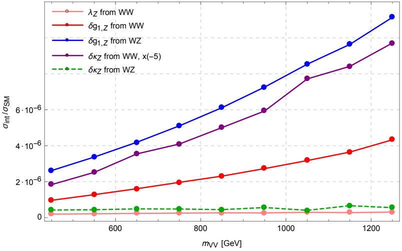
looking only at low energy categories bounds at LEP are still a bit stronger!

SM and BSM amplitudes with more details

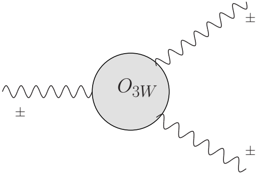
$$\mathcal{M}\left(q\bar{q} \to W_L^- W_L^+\right) \sim E^2/\Lambda^2 \; c_{HB} + E^2/\Lambda^2 \; c_{HW} \sim E^2/m_W^2 \; \delta g_{1,Z} + E^2/m_W^2 \; \delta\kappa_Z$$

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

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

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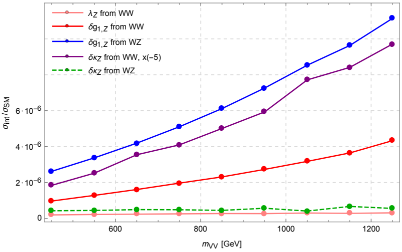

Helicity selction rule for O_{3W}

Lorentz symmetry and the dimensional analysis fixes three point amplitudes to satisfy:

$$\sum h = 1 - [g] = 3$$

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!

Helicities of BSM amplitudes

$\mathcal{O}_i$	$\#\text{legs}_{min}$	helicity_{min}
F^3	3	3
$F^2\phi^2$, $F\psi^2\phi$, ψ^4	4	2
$\psi^2\bar{\psi}^2$, $\psi\bar{\psi}\phi^2 D$, $\phi^4 D^2$	4	0
$\psi^2\phi^3$	5	1
ϕ^6	6	0

$$F_{\mu\nu}\sigma^{\mu}_{\alpha\dot{\alpha}}\sigma^{\nu}_{\beta\dot{\beta}} \equiv F_{\alpha\beta}\bar{\epsilon}_{\dot{\alpha}\dot{\beta}} + \bar{F}_{\dot{\alpha}\dot{\beta}}\epsilon_{\alpha\beta}$$

Adding extra legs can change the helicity only by ± 1

BSM noninterference for $2 \to 2$ processes

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

For which operators the non-interference is important?

- F^3 - **anomalous triple gauge coupling**
- $\psi\psi F\phi$ -dipole operators- constrained much stronger by low energy measurements.
- $F^2\phi^2$ - relevant for the diboson production in VBF, however most of the operators are already strongly constrained by the EWPT and Higgs physics.

Why the interference term is important?

- Generically in the presence of new physics

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

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

- 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**

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

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

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

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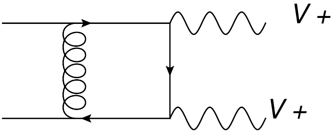
We are getting sensitivity to the sign of the Wilson coefficient, otherwise hidden from the measurements!

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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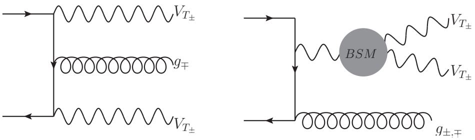


- $(W)^3$ vertex always emits same helicity W bosons, however the helicity of the gluon is not restricted!
- For SM amplitudes gluons are carrying away the needed opposite helicity.

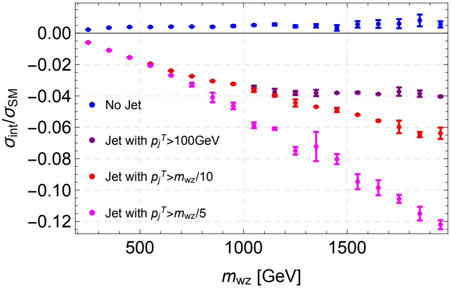
We can use a tag for jet to suppress the background as well, no need to pay $\frac{\alpha_s}{4\pi}$ for the signal to background ratio.

$qq \to VV + j$

- Indeed the interference grows 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 $q(\bar{q}) \to q(\bar{q})g$.

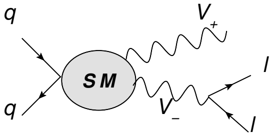


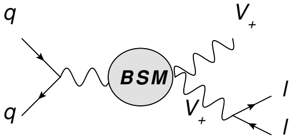
Jet needs to be hard otherwise the signal will be hidden inside the SM background which grows quickly in the soft and colinerar regimes.

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:





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

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

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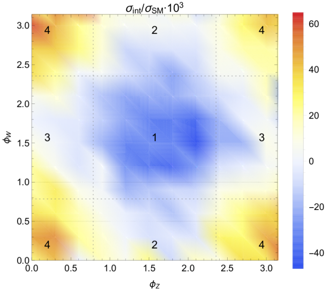
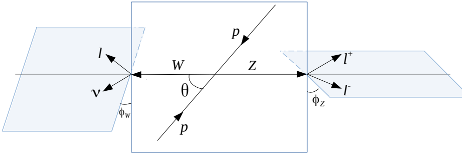
The interference is non-zero but modulated with azimuthal angle of the Z decay products plane. As expected from the $2\to 2$ results the integrated interference is zero again.

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

Azimuthal angle modulation

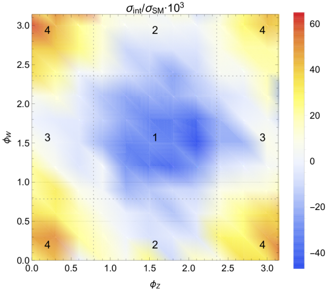


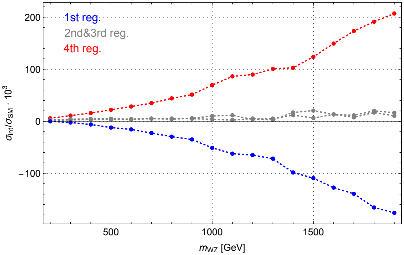


$$\frac{d\sigma_{\text{int}}(q\bar{q} \to WZ \to 4\psi)}{d\phi_Z\, d\phi_W} \propto \cos(2\phi_Z) + \cos(2\phi_W)$$

- 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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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.

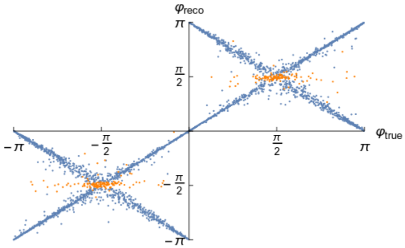
  $$\phi_Z \to \phi_Z + \pi \mod 2\pi$$

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

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

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

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

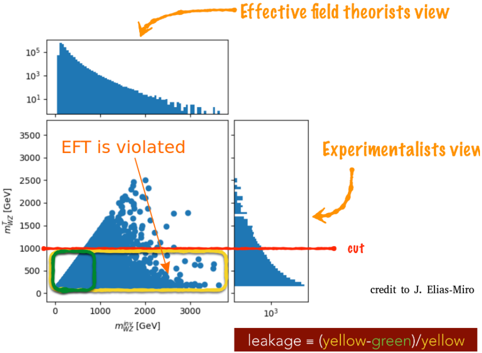
These ambiguities make harder to observe the interference between $(+-)$ and LL final states(δg_1^Z coupling).

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

(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?



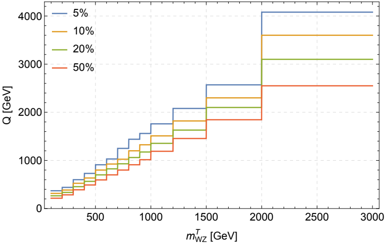
Leakage

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

$$m_{WZ}^T = \sqrt{(E_T^W + E_T^Z)^2 - (p_x^W + p_x^Z)^2 - (p_y^W + p_y^Z)^2}$$

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

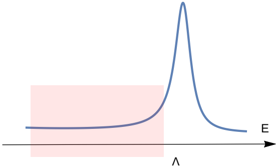
$$\text{Leakage} = \frac{N_i(m_{VW} > Q)}{N_i} \times 100\%$$



then once we know the precision of the measurements we can find the function $Q = Q(m_{WZ}^T)$.

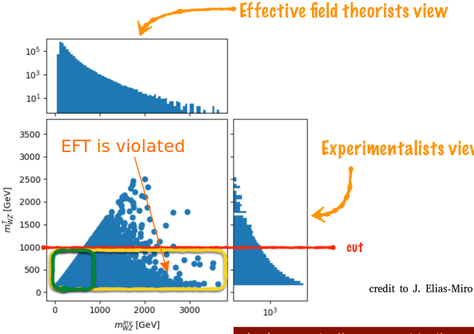
Note that to calculate leakage we need to assume something about the signal, not completely model-independent.

Leakage



- Leakage can become problematic if we have a sharp resonance peak, we can overpopulate the region where EFT is violated.
- leakage will be underestimated $\Rightarrow$ we will overestimate the Wilson coefficient.

However if we discover a sharp resonance who cares about EFT...



credit to J. Elias-Miro

leakage ≡ (yellow-green)/yellow

Bounding EFT consistently

- Experimental collaborations use form-factor procedure
$$N_{th} \to \widetilde{N}_{\rm th} = n_{\rm SM} + \hat{n}_1 c_{3W} + \hat{n}_2 c_{3W}^2$$
- where the $\hat{n}_i$ values are calculated assuming
$$c_{3W} \to c_{3W} \times \frac{1}{(1+\hat{s}/\Lambda^2)^2}$$
- **if the sensitivity comes from the events with energy $> \Lambda$, EFT interpretation is not clear.**

Bounding EFT consistently

Another possibility would be to restrict the generated event phase space to be only within EFT validity (1609.06312)*(proposed for DM in 1502.04701)*

$$N_{th} \to \widetilde{N}_{\rm th} = n_{\rm SM} + n_1|_{(m_{inv}<\Lambda_{\rm MC})} c_{3W} + n_2|_{(m_{inv}<\Lambda_{\rm MC})} c_{3W}^2$$

The the bound is conservative if only

$$\text{sign}(\Delta\sigma_{\rm BSM})|_{m_{inv}>\Lambda_{MC}} = \text{sign}(\Delta\sigma_{\rm BSM})|_{m_{inv}<\Lambda_{MC}}$$

can become problematic if interference term is big.

similar to the previous method with step-function "form-factor"

$$\frac{1}{(1+\hat{s}/\Lambda^2)^2} \to \theta(\Lambda - \sqrt{\hat{s}})$$

all of the methods trivially coincide once $\Lambda \to \infty$. For the values of $\Lambda \sim O($few TeV$)$ the difference can be of $O(20\%)$

all of the methods trivially coincide once $\Lambda \to \infty$. For the values of $\Lambda \sim O($few TeV$)$ the difference can be of $O(20\%)$

For W, Z production the problem can be partially resolved once the neutrino momentum is reconstructed.

Analysis

- 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 two categories
  $\phi_Z \in [\pi/4, 3/4\pi] \quad \text{and} \quad \phi_Z \in [0, \pi/4] \cup [3\pi/4, \pi]$.

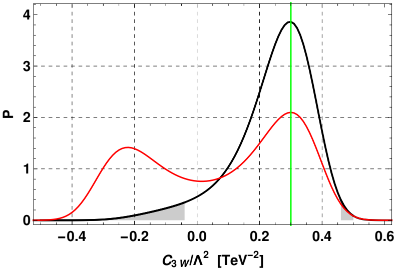
Results

	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]	

$$\lambda_Z \in [-0.0014, 0.0016] \quad ([-0.003, 0.0034])$$

Sensitivity to linear terms is strongly improved!

Results



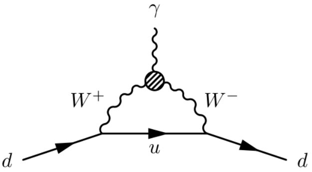
We are sensitive to the sign of the Wilson coefficient, can resolve possible degeneracies in the fit!

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

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

Adding CP odd operator to the fit

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

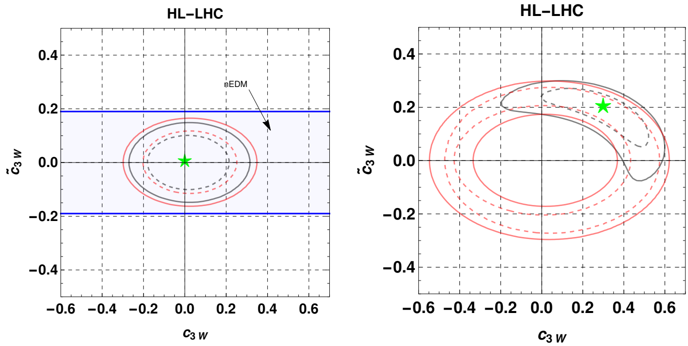


Wilson coefficient is strongly bound neutron EDM

$$|\lambda_{\gamma,Z}| < 1.2\times 10^{-3}, \quad |\tilde{c}_{3W}| < 0.19 \text{ at } 90\ \%\text{CL}$$

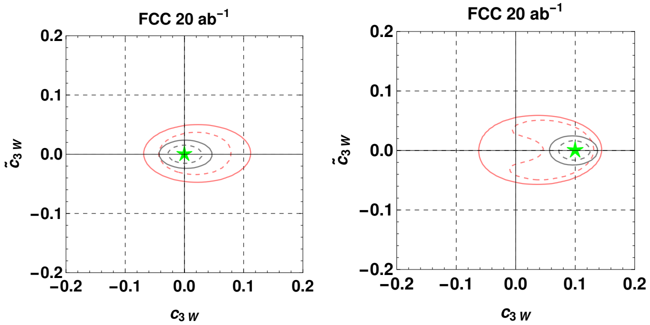
from *1309.7822*

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
- HL-LHC sensitivity becomes comparable to the neutron EDM cosntraints on the CP odd operator.

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*

Outlook

Differential distributions improve the sentivity to the New Physics. In particular for the O_{3W} operator the improvement is not only quantitative but qualitative. We are able to test the interference between SM and BSM $\Rightarrow$ better behaved EFT expansion, measure the sign of the new couplings.

Similar azimuthal modulation effect should happen always when there are different helicity intermediate states:

- applications to the other operators?different final states?
- improvements of the global fit with all the TGCs?

  $\vdots$

Cross-section in the presence of the dimension six operators

- If we assume the lepton number conservation

$$\mathcal{L} = \mathcal{L}^{\mathrm{SM}} + \mathcal{L}^6 + \mathcal{L}^8 + \cdots , \quad \mathcal{L}^D = \sum_i c_i^{(D)} \mathcal{O}_i^{(D)}$$

$$c_i^{(D)} \sim \frac{1}{\Lambda^{D-4}}$$

- Dominant effects come from the dimension six operators!

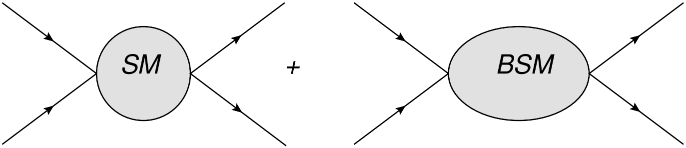
$$\sigma \sim \mathrm{SM}^2 + \frac{SM \times BSM_6}{\Lambda^2} + \frac{BSM_6^2}{\Lambda^4} + \frac{SM \times BSM_8}{\Lambda^4} + \ldots$$

- leading term in $\frac{1}{\Lambda^2}$ comes from the interference between SM and BSM!

What are the properties of the interference term?

$$\boldsymbol{\frac{\mathrm{SM} \times \mathrm{BSM}_6}{\Lambda^2}}$$

Energy dependence of $2 \to 2$ scattering

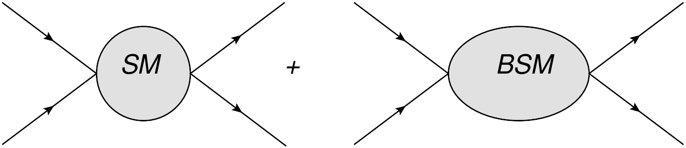


- From dimensional analysis

$$A_{2\to 2} \sim A_{SM} + A_{BSM_6}\left(\frac{m^2}{\Lambda^2} + \frac{\mathbf{E^2}}{\mathbf{\Lambda^2}}\right)$$

- Large energy E region is most sensitive to BSM effects, however we need to be careful to make sure the EFT expansion remains valid.

Energy dependence of $2 \to 2$ scattering



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For simplicity let us start with the massless theory i.e. $E \gg m_W, m_t$

$2 \to 2$ scattering at tree level: the best basis

- There are many basis for dimension six operators, which one is more convenient for understanding the properties of $2 \to 2$ scattering?
- It is easier to calculate the contact diagram, so it is better to reduce the number of the bivalent and trivalent operators to minimum.
- So we need something like Warsaw basis with the following operators:
  $$\mathbf{F^3}, \mathbf{F^2}\phi^\mathbf{2}, \mathbf{F}\psi^\mathbf{2}\phi, \psi^\mathbf{4}, \psi^\mathbf{2}\bar{\psi}^\mathbf{2}, \psi\bar{\psi}\phi^\mathbf{2}\mathbf{D}, \phi^\mathbf{4}\mathbf{D^2}, \psi^\mathbf{2}\phi^\mathbf{3}, \phi^\mathbf{6}$$
- $F \equiv F_{\mu\nu}, D \equiv D_\mu$

Selection rules for $2 \to 2$ scattering in SM

- Amplitudes of the massless gauge theory follow the helicity selection rules (MHV)

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

- helicity of all the SM $2 \to 2$ scattering amplitudes is zero, except for the four fermion amplitudes mediated by the Higgs exchange.

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It is very important to trace the helicity of the BSM amplitudes! very transparent in the helicity-spinor formalism!

Helicity counting rules

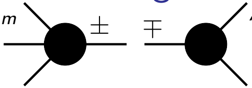
- fermions: Weyl spinors $\psi_\alpha, \bar{\psi}^{\dot{\alpha}}$ transforming as (1/2,0) and (0,1/2) under Lorentz group
- gauge field (1/2,1/2):

$$F_{\mu\nu}\sigma^{\mu}_{\alpha\dot{\alpha}}\sigma^{\nu}_{\beta\dot{\beta}} \equiv F_{\alpha\beta}\bar{\epsilon}_{\dot{\alpha}\dot{\beta}} + \bar{F}_{\dot{\alpha}\dot{\beta}}\epsilon_{\alpha\beta}$$

  where $F, \bar{F}$ are self-dual and anti-self dual parts transforming as (1,0) and (0,1). $F(\bar{F})$ project helicity $+1(-1)$ states.
- Calculation of the helicity of the amplitudes from the 4-valent operators becomes trivial:

$$\boxed{h(\phi^2 F^2) = 2h(\phi) + 2h(F) = 2}$$

Helicity of the non-contact diagrams



- Helicity of the total amplitude will be

$$h(A_n) = h(A_m) + h(A_{m'})$$

- True if there is a pole in the factorization channel, i.e. we have a definite helicity state propagating on the virtual line.
- in SM always true, in EFT the pole of the propagator can be cancelled by the derivatives in the new vertex:
  $\Box\phi/p^2 \sim \phi \Rightarrow$ no pole
- To avoid cancellations between the derivatives in the vertex and the poles it is better to redefine operators to have as less derivatives as possible.

It is better to use basis where the operators have less number of derivatives and more fields.

Classifying the dimension six operators (Cheung, Shen)

- Define for an arbitrary amplitude holomorphic and anti-holomorphic weights:

$$w(A) = n(A) - h(A), \quad \bar{w}(A) = n(A) + h(A)$$

- We can define the weight of the operator in the following way

$$w(\mathcal{O}) = \min_A \{w(A)\}, \quad \bar{w}(\mathcal{O}) = \min_A \{\bar{w}(A)\}$$

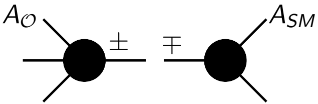
- **note that this definition can be applied in any basis of dim 6 operators.**

Properties of holomorphic weights $(w, \bar{w})$ (Cheung, Shen)

- we need to find

$$w(\mathcal{O}) = \min_A \{w(A)\}\,, \quad \bar{w}(\mathcal{O}) = \min_A \{\bar{w}(A)\}$$

- note that weights are monotonically growing functions of n



$$\Delta w = \Delta n + \Delta h = 1 + h(A_{SM}) \gtrsim 0$$
$$\Delta \bar{w} = \Delta n - \Delta h = 1 - h(A_{SM}) \gtrsim 0$$

- **the weight of the operator is defined by the diagram with less number of legs!**

The weights of the dimension six operators

$\mathcal{O}_i$	n_{min}	h_{min}	$(w, \bar{w})$	c_i
F^3	3	3	(0,6)	g_*/Λ^2
$F^2\phi^2$, $F\psi^2\phi$, ψ^4	4	2	(2,6)	g_*^2/Λ^2
$\psi^2\bar{\psi}^2$, $\psi\bar{\psi}\phi^2 D$, $\phi^4 D^2$	4	0	(4,4)	g_*^2/Λ^2
$\psi^2\phi^3$	5	1	(4,6)	g_*^3/Λ^2
ϕ^6	6	0	(6,6)	g_*^4/Λ^2

The helicity of the amplitude generated by the operator $\mathcal{O}$ will be constrained

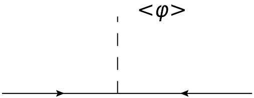
$$\boxed{\bar{w}(\mathcal{O}) - n \leq h(A_n^{\mathcal{O}}) \leq n - w(\mathcal{O})\,.}$$

BSM noninterference for $2 \to 2$ processes

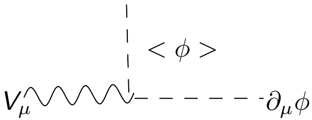
A_4	$\lvert h(A_4^{\mathrm{SM}})\rvert$	$\lvert h(A_4^{\mathrm{BSM}})\rvert$
$VVVV$	0	4,2
$VV\phi\phi$	0	2
$VV\psi\psi$	0	2
$V\psi\psi\phi$	0	2
$\psi\psi\psi\psi$	2,0	2,0
$\psi\psi\phi\phi$	0	0
$\phi\phi\phi\phi$	0	0

no interference for $V^4, V^2\phi^2, V^2\psi^2, V\psi\psi\phi$ processes!!

Classifying the finite mass effects



- insertion of the Higgs vev flips the fermion helicity $\Delta h = 1$, and every helicity flip will cost $\sim \frac{m_\psi}{E}$.



- Insertion of the one scalar vev can transform the transverse component to longitudinal and vice versa $\Delta h = 1 \sim \frac{m_V}{E}$

BSM noninterference for $2 \to 2$ processes

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

For which operators the non-interference is important?

- F^3 - anomalous triple gauge coupling
- $\psi\psi F\phi$ -dipole operators- constrained much stronger by low energy measurements.
- $F^2\phi^2$ - relevant for the diboson production in VBF, however most of the operators are already strongly constrained by the EWPT and Higgs physics.

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