# Diboson measurements at future $e^+e^-$ colliders

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First ECFA Workshop on $e^+e^-$ Higgs/EW/Top Factories
October 6, 2022

# Diboson

- Why do we study it?
  - Why not? (*e.g.* free by-product of a Higgs factory)
  - An important part of the global SMEFT analysis.
  - Connected to the Higgs couplings (in the SMEFT framework).
- Diboson is an old subject! (LEP II era)
  - Probing the Weak Boson Sector in $e^+e^- \to W^+W^-$, Hagiwara, Peccei, Zeppenfeld, Hikasa (Nucl.Phys.B 282 (1987) 253-307)
  - Triple gauge boson couplings, G. Gounaris *et al.*, 1996
  - Electroweak Measurements in Electron-Positron Collisions at W-Boson-Pair Energies at LEP, S. Schael et al., [1302.3415] (LEP summary paper, 2013)
- LHC: $pp \to WW/WZ$ (see the next talk)

# (EFT) Parameterizaiton

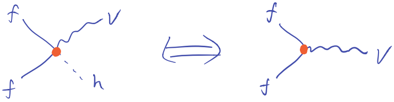

- $e^+e^- \to WW$ at lepton colliders
- Focusing on tree-level CP-even dimension-6 contributions:
  - $e^+e^- \to WW$ can be parameterized by

$$\delta g_{1,Z},\ \ \delta\kappa_\gamma,\ \ \lambda_Z,\ \ \delta g^{ee}_{Z,L},\ \ \delta g^{ee}_{Z,R},\ \ \delta g^{e\nu}_{W},\ \ \delta m_W$$

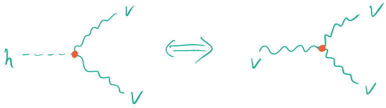
  - $m_W$ is usually much better constrained.
  - $W$ branching ratios can be modified by additional operators (but only affect the total rates).
  - Ignore $\delta Vff$ type couplings $\Rightarrow$ **3 aTGCs!**
    Not necessarily a good approximation! (See [1610.01618] Zhengkang Zhang)

# You can't really separate Higgs from the EW gauge bosons!

- $\mathcal{O}_{H\ell} = iH^\dagger \overleftrightarrow{D}_\mu H \bar{\ell}_L \gamma^\mu \ell_L$,
  $\mathcal{O}'_{H\ell} = iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H \bar{\ell}_L \sigma^a \gamma^\mu \ell_L$,
  $\mathcal{O}_{He} = iH^\dagger \overleftrightarrow{D}_\mu H \bar{e}_R \gamma^\mu e_R$
  - modifies gauge couplings of fermions,
  - also generates $hVff$ type contact interaction.



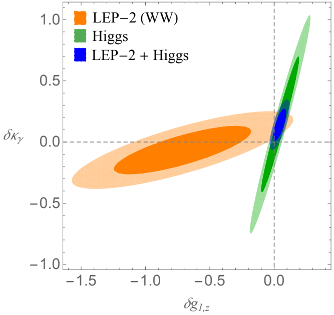

- $\mathcal{O}_{HW} = ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$,
  $\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$
  - generate **aTGCs** $\delta g_{1,Z}$ and $\delta\kappa_\gamma$,
  - also generates $HVV$ **anomalous couplings** such as $hZ_\mu \partial_\nu Z^{\mu\nu}$.



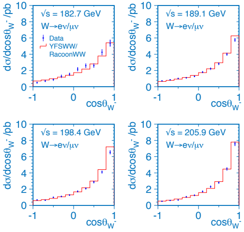
# Impacts on EFT fits, LHC + LEP

- Higgs better measured ⇒ Higgs helps diboson;
- Diboson better measured ⇒ diboson helps Higgs. (usually the case)

[arXiv:1508.00581] Falkowski *et al.*




[arXiv:1302.3415] LEP *WW* paper




- Note: LEP bounds should have been better!
  - The LEP summary paper did not provide global-fit results for the 3 aTGCs.
  - The distributions of *W* decay angles were not provided.

# You also have to measure the Higgs!

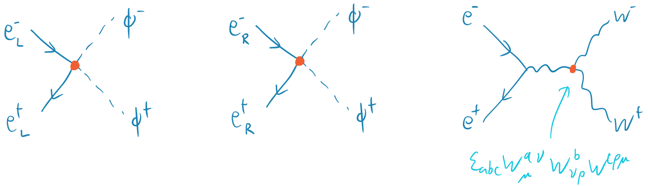
- Some operators can only be probed with the **Higgs particle**.
- $|H|^2 W_{\mu\nu} W^{\mu\nu}$ and $|H|^2 B_{\mu\nu} B^{\mu\nu}$
  - $H \to v/\sqrt{2}$, corrections to gauge couplings?
  - Can be absorbed by field redefinition! This applies to any operators in the form $|H|^2 \mathcal{O}_{\rm SM}$.

$$
\begin{aligned}
c_{\rm SM}\mathcal{O}_{\rm SM} \quad vs. \quad & c_{\rm SM}\mathcal{O}_{\rm SM} + \frac{c}{\Lambda^2}|H|^2\mathcal{O}_{\rm SM} \\
&= (c_{\rm SM} + \frac{c\,v^2}{2\,\Lambda^2})\mathcal{O}_{\rm SM} + \text{terms with } h \\
&= c'_{\rm SM}\mathcal{O}_{\rm SM} + \text{terms with } h
\end{aligned}
$$

  - probed by measurements of the $h\gamma\gamma$ and $hZ\gamma$ couplings, or the $hWW$ and $hZZ$ anomalous couplings.
  - or Higgs in the loop (different story...)
- Yukawa couplings, Higgs self couplings, ...

# Energy enhancement

- **Goldstone equivalence:** At very high energy, the longitudinal modes should be viewed as the goldstones!




**[arXiv:1712.01310] Franceschini** *et al.* (sign denotes helicity)

| | SM | BSM |
|---|---|---|
| $q_{L,R}\bar{q}_{L,R} \to V_L V_L(h)$ | $\sim 1$ | $\sim E^2/M^2$ |
| $q_{L,R}\bar{q}_{L,R} \to V_\pm V_L(h)$ | $\sim m_W/E$ | $\sim m_W E/M^2$ |
| $q_{L,R}\bar{q}_{L,R} \to V_\pm V_\pm$ | $\sim m_W^2/E^2$ | $\sim E^2/M^2$ |
| $q_{L,R}\bar{q}_{L,R} \to V_\pm V_\mp$ | $\sim 1$ | $\sim 1$ |

- Leading BSM amplitude $\sim \frac{E^2}{M^2}$.
- $W^+W^-$ and $hZ$ are related (especially at high energy).

# Energy *vs.* Precision

- Precision
  - Lepton colliders at $\sim 240$ GeV, large statistics, clean environment.
  - High precision $\Rightarrow$ $E \ll \Lambda$
    **Ideal for EFT studies!**
- Energy
  - High energy tails are very sensitive to new physics effects,
  - but are usually poorly measured.
  - This lead to problems in the interpretation of EFT...

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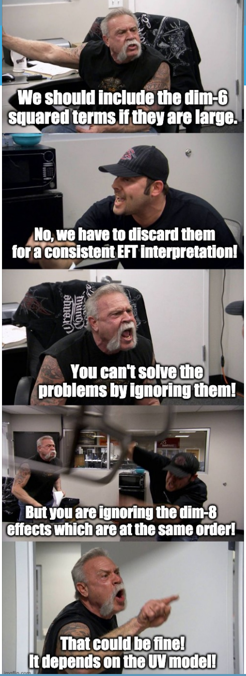
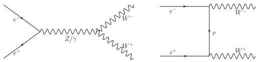
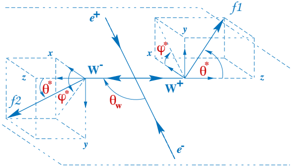


# $e^+e^- \to WW$ with Optimal Observables

- TGCs (and additional EFT parameters) are sensitive to the differential distributions!
  - One could do a fit to the binned distributions of all angles.
  - Not the most efficient way of extracting information.
  - Correlations among angles are sometimes ignored.



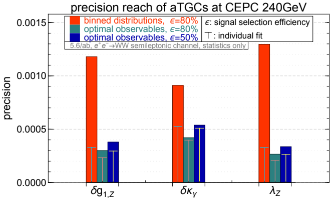




- What are optimal observables?

  (See *e.g.* Z.Phys. C62 (1994) 397-412 Diehl & Nachtmann)
  - In the limit of large statistics (everything is Gaussian) and small parameters (linear contribution dominates), the best possible reaches can be derived analytically!

$$\frac{d\sigma}{d\Omega} = S_0 + \sum_i S_{1,i}\, g_i \,, \qquad c_{ij}^{-1} = \int d\Omega \frac{S_{1,i} S_{1,j}}{S_0} \cdot \mathcal{L} \,,$$

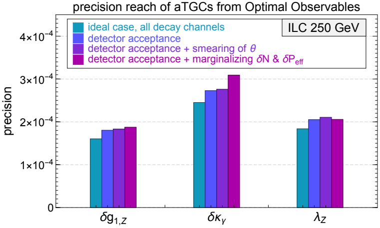
- The optimal observables are given by $\mathcal{O}_i = \frac{S_{1,i}}{S_0}$, and are functions of the 5 angles.

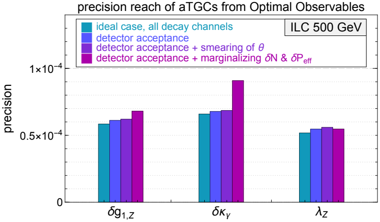



[arXiv:1907.04311] de Blas, Durieux, Grojean, JG, Paul

# Updates on the *WW* analysis with Optimal Observables

- How well can we do it in practice?
  - detector acceptance, measurement uncertainties, ...
- What we have done (in the snowmass study)
  - detector acceptance ($|\cos\theta| < 0.9$ for jets, $< 0.95$ for leptons)
  - some smearing (production polar angle only, $\Delta = 0.1$)
  - ILC: marginalizing over total rate ($\delta N$) and effective beam polarization ($\delta P_{eff}$)
- Constructing full EFT likelihood and feed it to the global fit. (For illustration, only showing the 3-aTGC fit results here.)
- Further verifications (by experimentalists) are needed.



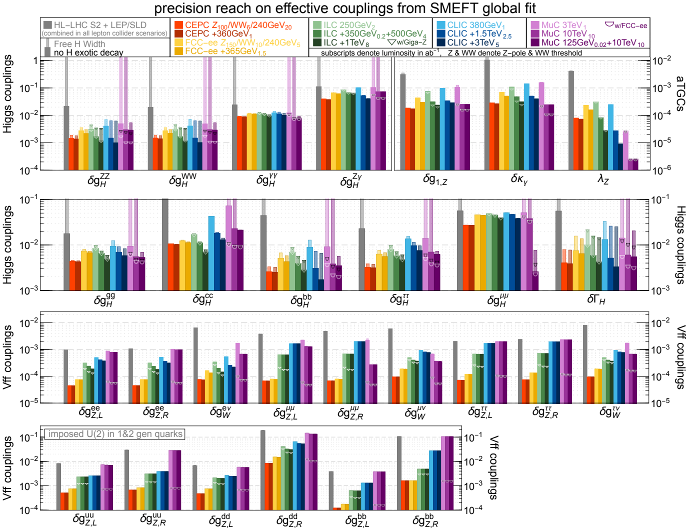



# Higgs + EW SMEFT Global fit (see Victor's talk yesterday)

- Global fit
  - Z-pole, diboson and Higgs processes are all connected in the SMEFT framework.
  - Usually $\sim 20$-$30$ parameters (instead of 2499) if we focus on CP-even effects in Higgs and electroweak measurements.
  - Of course we can add more (*e.g.* top operators)! (but not in this talk...)
- Limits on all the $\frac{c_i^{(6)}}{\Lambda^2}$
  - Results depend on operator bases, conventions, ...
- Present the results in terms of effective couplings ([arXiv:1708.08912], [arXiv:1708.09079], Peskin *et al.*)
  - $g(hZZ)$, $g(hWW)$ couplings have multiple contributions: $hZ^\mu Z_\mu$, $hZ^{\mu\nu}Z_{\mu\nu}$ ... defined as: $g(hZZ) \propto \sqrt{\Gamma(h \to ZZ)}$, $g(hWW) \propto \sqrt{\Gamma(h \to WW)}$.
- Present the results with some fancy bar plots!

# Results from the recent snowmass study

[2206.08326] de Blas, Du, Grojean, JG, Miralles, Peskin, Tian, Vos, Vryonidou (see Victor's talk yesterday)



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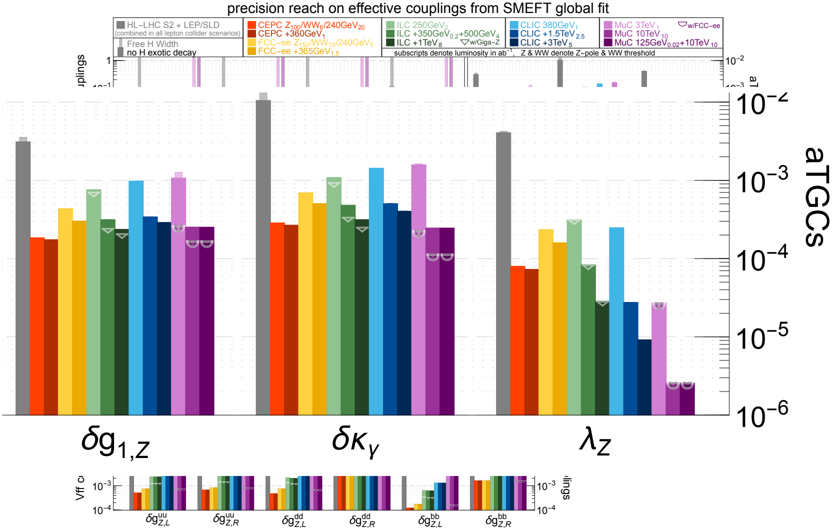
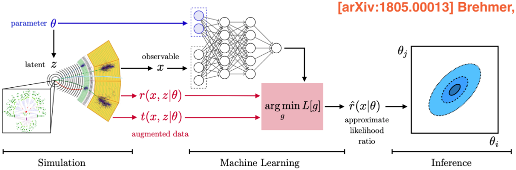


# Machine Learning

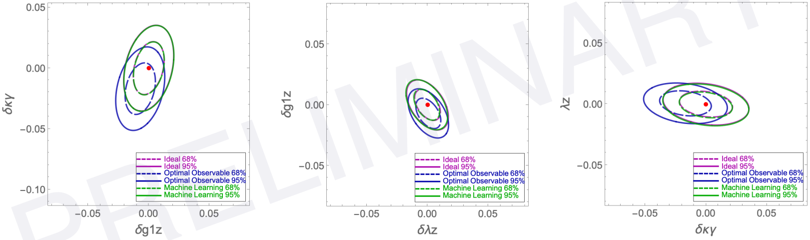
- How well can we measure diboson in practice?
  - detector acceptance, measurement uncertainties, ISR ...
- Analytical methods becomes more difficult and time consuming when we include more realistic effects.

[arXiv:1805.00013] Brehmer, Cranmer, Louppe, Pavez




- Machine Learning is a promising solution for the extraction of information (theory parameters) from complicated collider data.
  - Already implemented in $pp \to ZW$. [2007.10356] Chen, Glioti, Panico, Wulzer
  - Current work with Shengdu Chai, Lingfeng Li on $e^+e^- \to WW$ with machine learning.

# Machine Learning (preliminary results, Shengdu Chai, JG, Lingfeng Li)



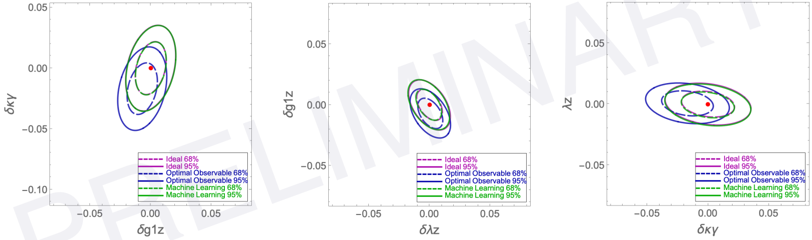



- Scale (size of the ellipses) is arbitrary.
- Semileptonic channel, jet smearing + ISR, 3-aTGC fit
  - Naively applying truth-level optimal observables could lead to a large bias!
  - It’s easier for machine learning to take care of systematics! (Current method is basically a “ML version of optimal observables”.)

# Machine Learning

(preliminary results, Shengdu Chai, JG, Lingfeng Li)



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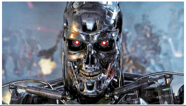
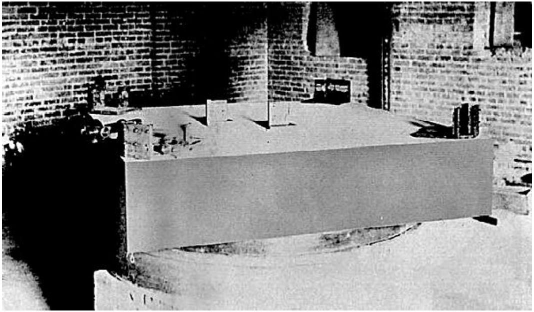
- **When will Machine take over?**



# Conclusion

- **Diboson** is an important measurement!
- **Energy** and **precision** are both important for the diboson measurement!
- **Machine learning** is (likely to be) the future!
- Future directions
  - CP-odd operators?
  - Loop contributions of dim-6 operators?
  - Beyond dim-6?

# A lesson from history



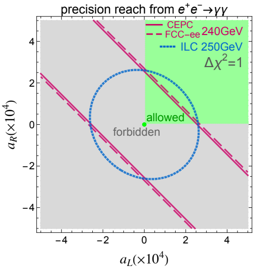
**"Our future discoveries must be looked for in the sixth place of decimals."**

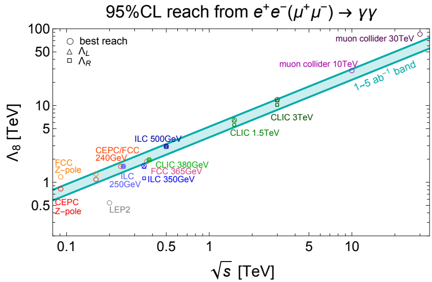
**— Albert A. Michelson**

# backup slides

# Neutral diboson?

- $Z\gamma/ZZ$ measurements can probe neutral aTGCs (generated by dim-8 operators). (See *e.g.* [1902.06631, 2008.04298], Ellis et al. for recent work on it.)
- **Think beyond TGC:** Dim-8 operators also generate contact interactions with $+-$ final state helicities. [1806.09640] Bellazzini, Riva
  - which are subject to positivity bounds!
- The diphoton ($e^+e^- \to \gamma\gamma$) channel offers a clean probe of the positivity bounds! [arXiv:2011.03055] JG, Lian-Tao Wang, Cen Zhang



# $e^+e^- \to WW$ parameterization

$$\begin{aligned}\mathcal{L}_{\rm tgc} = \; & igs_{\theta_W} A^\mu (W^{-\nu} W^+_{\mu\nu} - W^{+\nu} W^-_{\mu\nu}) \\ & + ig(1+\delta g_1^Z) c_{\theta_W} Z^\mu (W^{-\nu} W^+_{\mu\nu} - W^{+\nu} W^-_{\mu\nu}) \\ & + ig \left[ (1+\delta\kappa_Z) c_{\theta_W} Z^{\mu\nu} + (1+\delta\kappa_\gamma) s_{\theta_W} A^{\mu\nu} \right] W^-_\mu W^+_\nu \\ & + \frac{ig}{m_W^2} (\lambda_Z c_{\theta_W} Z^{\mu\nu} + \lambda_\gamma s_{\theta_W} A^{\mu\nu}) W^{-\rho}_v W^+_{\rho\mu} \,, \end{aligned} \tag{1}$$

- Imposing Gauge invariance one obtains $\delta\kappa_Z = \delta g_{1,Z} - t^2_{\theta_W} \delta\kappa_\gamma$ and $\lambda_Z = \lambda_\gamma$.
- "~~Higgs~~ effective coupling basis"
  (+ deviations in W BR. $\delta_{m_W}$ is constrained very well by $W$ mass measurements.)

$$\delta g_{1,Z}, \quad \delta\kappa_\gamma, \quad \lambda_Z, \quad \delta g^{ee}_{Z,L}, \quad \delta g^{ee}_{Z,R}, \quad \delta g^{e\nu}_W, \quad \delta_{m_W}$$

# D6 operators

| | |
|---|---|
| $\mathcal{O}_H = \frac{1}{2}(\partial_\mu \lvert H^2 \rvert)^2$ | $\mathcal{O}_{GG} = g_s^2 \lvert H \rvert^2 G^A_{\mu\nu} G^{A,\mu\nu}$ |
| $\mathcal{O}_{WW} = g^2 \lvert H \rvert^2 W^a_{\mu\nu} W^{a,\mu\nu}$ | $\mathcal{O}_{y_u} = y_u \lvert H \rvert^2 \bar{q}_L \tilde{H} u_R + \text{h.c.} \quad (u \to t, c)$ |
| $\mathcal{O}_{BB} = g'^2 \lvert H \rvert^2 B_{\mu\nu} B^{\mu\nu}$ | $\mathcal{O}_{y_d} = y_d \lvert H \rvert^2 \bar{q}_L H d_R + \text{h.c.} \quad (d \to b)$ |
| $\mathcal{O}_{HW} = ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$ | $\mathcal{O}_{y_e} = y_e \lvert H \rvert^2 \bar{l}_L H e_R + \text{h.c.} \quad (e \to \tau, \mu)$ |
| $\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$ | $\mathcal{O}_{3W} = \frac{1}{3!} g \epsilon_{abc} W^{a\,\nu}_{\mu} W^b_{\nu\rho} W^{c\,\rho\mu}$ |
| $\mathcal{O}_W = \frac{ig}{2}(H^\dagger \sigma^a \overleftrightarrow{D}_\mu H) D^\nu W^a_{\mu\nu}$ | $\mathcal{O}_B = \frac{ig'}{2}(H^\dagger \overleftrightarrow{D}_\mu H) \partial^\nu B_{\mu\nu}$ |
| $\mathcal{O}_{WB} = gg' H^\dagger \sigma^a H W^a_{\mu\nu} B^{\mu\nu}$ | $\mathcal{O}_{H\ell} = i H^\dagger \overleftrightarrow{D}_\mu H \bar{\ell}_L \gamma^\mu \ell_L$ |
| $\mathcal{O}_T = \frac{1}{2}(H^\dagger \overleftrightarrow{D}_\mu H)^2$ | $\mathcal{O}'_{H\ell} = i H^\dagger \sigma^a \overleftrightarrow{D}_\mu H \bar{\ell}_L \sigma^a \gamma^\mu \ell_L$ |
| $\mathcal{O}_{\ell\ell} = (\bar{\ell}_L \gamma^\mu \ell_L)(\bar{\ell}_L \gamma_\mu \ell_L)$ | $\mathcal{O}_{He} = i H^\dagger \overleftrightarrow{D}_\mu H \bar{e}_R \gamma^\mu e_R$ |
| $\mathcal{O}_{Hq} = i H^\dagger \overleftrightarrow{D}_\mu H \bar{q}_L \gamma^\mu q_L$ | $\mathcal{O}_{Hu} = i H^\dagger \overleftrightarrow{D}_\mu H \bar{u}_R \gamma^\mu u_R$ |
| $\mathcal{O}'_{Hq} = i H^\dagger \sigma^a \overleftrightarrow{D}_\mu H \bar{q}_L \sigma^a \gamma^\mu q_L$ | $\mathcal{O}_{Hd} = i H^\dagger \overleftrightarrow{D}_\mu H \bar{d}_R \gamma^\mu d_R$ |

- SILH' basis (eliminate $\mathcal{O}_{WW}$, $\mathcal{O}_{WB}$, $\mathcal{O}_{H\ell}$ and $\mathcal{O}'_{H\ell}$)
- Modified-SILH' basis (eliminate $\mathcal{O}_W$, $\mathcal{O}_B$, $\mathcal{O}_{H\ell}$ and $\mathcal{O}'_{H\ell}$)
- Warsaw basis (eliminate $\mathcal{O}_W$, $\mathcal{O}_B$, $\mathcal{O}_{HW}$ and $\mathcal{O}_{HB}$)

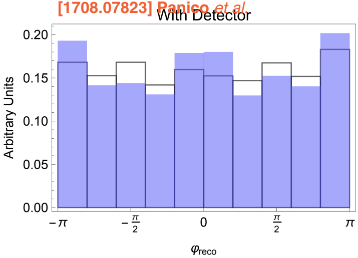
# Diboson Interference Resurrection [1707.08060] Azatov *et al.*, [1708.07823] Panico *et al.*

[arXiv:1712.01310] Franceschini *et al.*

| | SM | BSM |
|---|---|---|
| $q_{L,R}\bar{q}_{L,R} \to V_L V_L(h)$ | $\sim 1$ | $\sim E^2/M^2$ |
| $q_{L,R}\bar{q}_{L,R} \to V_\pm V_L(h)$ | $\sim m_W/E$ | $\sim m_W E/M^2$ |
| $q_{L,R}\bar{q}_{L,R} \to V_\pm V_\pm$ | $\sim m_W^2/E^2$ | $\sim E^2/M^2$ |
| $q_{L,R}\bar{q}_{L,R} \to V_\pm V_\mp$ | $\sim 1$ | $\sim 1$ |

- The interference between SM and dim-6 amplitudes are **suppressed** if they have different helicities.
- The interference is **resurrected** by considering the diboson decays!
  $\mathcal{A}(ffVV) \to \mathcal{A}(6f)$
- These dim-6 effects show up in the **azimuthal angles** of the $W/Z$ decay.

[1708.07823] Panico *et al.*




black line: SM, blue area: $C_{3W} = 0.2\mathrm{TeV}^{-2}$