EFT (global) analysis of dibosons

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The big picture

- **Build large colliders $\rightarrow$ go to high energy $\rightarrow$ discover new particles!**

- Higgs and nothing else?

- What's next?
  - Build an even larger collider (~ 100 TeV)?
  - No guaranteed discovery!

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- **Build large colliders** $\rightarrow$ go to high energy $\rightarrow$ discover new particles!

  $\searrow$

  do precision measurements $\rightarrow$ **discover new physics indirectly!**

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  - **Higgs factory!** (HL-LHC or a future lepton collider.)
  - **SMEFT** (model independent approach)

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  - **SMEFT** (model independent approach)

- **Diboson is an important part of the precision measurement program!**

Diboson

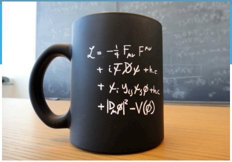
- Disclaimer: I will focus on non-resonant, SM(-like) diboson processes.

- 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: $pp \to WW/WZ$
  - many studies...

The Standard Model Effective Field Theory

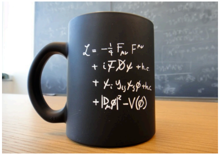


- $[\mathcal{L}_{\rm sm}] \leq 4$. Why?
  - ~~Bad things happen when we have non-renormalizable operators!~~
  - Everything is fine as long as we are happy with finite precision in perturbative calculation.
- **d=5:** $\frac{c}{\Lambda} LLHH \sim \frac{cv^2}{\Lambda}\nu\nu$, Majorana neutrino mass.
- Assuming Baryon and Lepton numbers are conserved,

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_i \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_j \frac{c_j^{(8)}}{\Lambda^4}\mathcal{O}_j^{(8)} + \cdots .$$

- If $\Lambda \gg v, E$, then **SM + dimension-6 operators** are sufficient to parameterize the physics around the electroweak scale.

The Standard Model Effective Field Theory



+

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar{l}_p e_r \varphi)$
$Q_{\widetilde{G}}$	$f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p u_r \widetilde{\varphi})$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p d_r \varphi)$
$Q_{\widetilde{W}}$	$\varepsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				

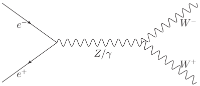
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r)\tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{l}_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde{G}}$	$\varphi^\dagger\varphi\, \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I \varphi)(\bar{l}_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r)\widetilde{\varphi}\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{e}_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde{W}}$	$\varphi^\dagger\varphi\, \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\tau^I \widetilde{\varphi}\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{q}_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\widetilde{\varphi}\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I \varphi)(\bar{q}_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde{B}}$	$\varphi^\dagger\varphi\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{u}_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger \tau^I \varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{d}_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde{W}B}$	$\varphi^\dagger \tau^I \varphi\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde{\varphi}^\dagger D_\mu \varphi)(\bar{u}_p \gamma^\mu d_r)$

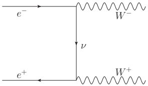
$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
Q_{ll}	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$	Q_{ee}	$(\bar{e}_p \gamma_\mu e_r)(\bar{e}_s \gamma^\mu e_t)$	Q_{le}	$(\bar{l}_p \gamma_\mu l_r)(\bar{e}_s \gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)$	Q_{uu}	$(\bar{u}_p \gamma_\mu u_r)(\bar{u}_s \gamma^\mu u_t)$	Q_{lu}	$(\bar{l}_p \gamma_\mu l_r)(\bar{u}_s \gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p \gamma_\mu \tau^I q_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$	Q_{dd}	$(\bar{d}_p \gamma_\mu d_r)(\bar{d}_s \gamma^\mu d_t)$	Q_{ld}	$(\bar{l}_p \gamma_\mu l_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$	Q_{eu}	$(\bar{e}_p \gamma_\mu e_r)(\bar{u}_s \gamma^\mu u_t)$	Q_{qe}	$(\bar{q}_p \gamma_\mu q_r)(\bar{e}_s \gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p \gamma_\mu \tau^I l_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$	Q_{ed}	$(\bar{e}_p \gamma_\mu e_r)(\bar{d}_s \gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{u}_s \gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p \gamma_\mu u_r)(\bar{d}_s \gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{u}_s \gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p \gamma_\mu T^A u_r)(\bar{d}_s \gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{d}_s \gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{d}_s \gamma^\mu T^A d_t)$

$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$	$Q_{qqq}^{(1)}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	$Q_{qqq}^{(3)}$	$\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$

- Write down all D6 operators, **eliminate redundant ones** via field redefinition, integration by parts, equations of motion...
- 59 operators (76 parameters) for 1 generation, or 2499 parameters for 3 generations. [arXiv:1008.4884] Grzadkowski, Iskrzyński, Misiak, Rosiek, [arXiv:1312.2014] Alonso, Jenkins, Manohar, Trott.
- A **global global fit** with all measurements to all operator coefficients? (Not there yet!)
  - Here we focus on Higgs and electroweak measurements with $\sim 20\text{-}30$ parameters.

(EFT) Parameterizaiton





- $e^+e^- \to WW$ (lepton colliders) or $pp \to WW/WZ$ (hadron colliders)
- Focusing on tree-level CP-even dimension-6 contributions:
  - $e^+e^- \to WW$ can be parameterized by

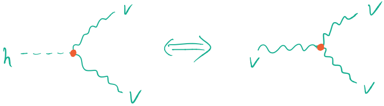
$$\delta g_{1,Z}, \quad \delta\kappa_\gamma, \quad \lambda_Z, \quad \delta g^{ee}_{Z,L}, \quad \delta g^{ee}_{Z,R}, \quad \delta g^{e\nu}_{W}, \quad \delta m_W$$

  - m_W is usually much better constrained.
  - W branching ratios can be modified by additional operators (but only affect the total rates).
  - Ignore δVff type couplings $\Rightarrow$ **3 aTGCs!** Not necessarily a good approximation! (See [1610.01618] Zhengkang Zhang)
- See other talks for neutral diboson analysis.
  - Leading BSM effects are from dimension-8 operators if we ignore the dim-6 corrections to $Zf\bar{f}$ couplings.

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

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

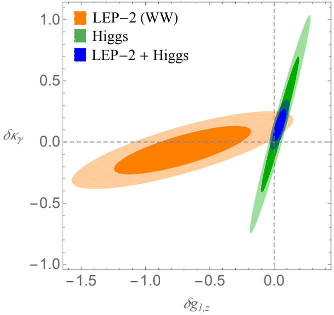
- $\mathcal{O}_{HW} = ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu},$
  $\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$
  - generate **aTGCs** $\delta g_{1,Z}$ and $\delta\kappa_\gamma$,
  - also generates HVV **anomalous couplings** such as $hZ_\mu \partial_\nu Z^{\mu\nu}$.



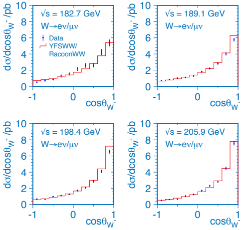
Impacts on EFT fits, LHC + LEP

- 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 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 $|H|^2 \mathcal{O}_{\rm SM}$.

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

  - 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, ...

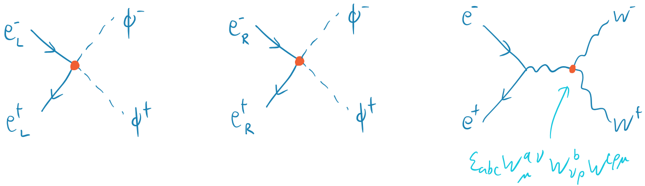
Important properties of the diboson processes

- **Energy enhancement**
  - leading dim-6 effects at high energy $\sim \frac{E^2}{\Lambda^2}$
  - energy *vs.* precision

- **Angular distribution**
  - The diboson angular distributions are sensitive to the dim-6 effects.
  - Just measuring the rates is not enough!
  - How can we efficiently extract information from the distributions?

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
$q_{L,R}\bar{q}_{L,R} \to V_L V_L(h)$	~ 1	$\sim E^2/M^2$
$q_{L,R}\bar{q}_{L,R} \to V_\pm V_L(h)$	$\sim m_W/E$	$\sim m_W E/M^2$
$q_{L,R}\bar{q}_{L,R} \to V_\pm V_\pm$	$\sim m_W^2/E^2$	$\sim E^2/M^2$
$q_{L,R}\bar{q}_{L,R} \to V_\pm V_\mp$	~ 1	~ 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 ~ 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...
- Precision and Energy
  - High energy lepton collider (muon collider)
    See *e.g.* [2012.11555] Buttazzo *et al.*

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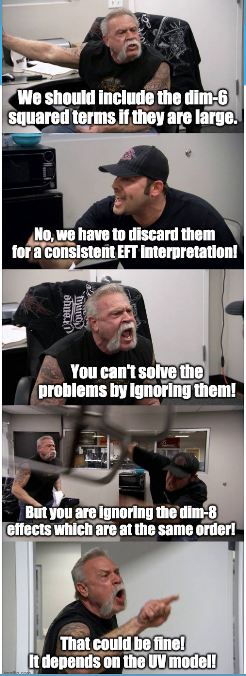
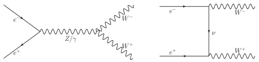
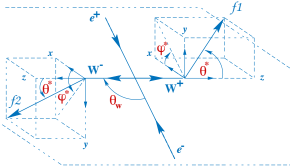


$e^+e^- \to WW$ with Optimal Observables

- 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.



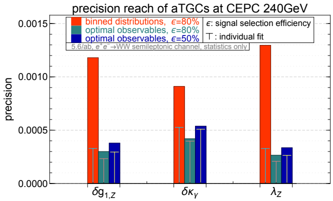


- What are optimal observables?

  (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!

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

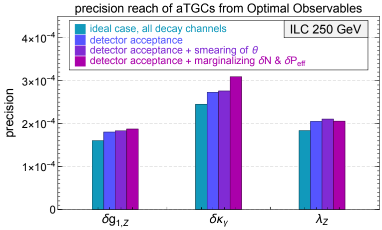
- The optimal observables are given by $\mathcal{O}_i = \frac{S_{1,i}}{S_0}$, and are functions of the 5 angles.

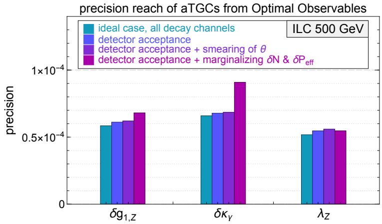


[arXiv:1907.04311] de Blas, Durieux, Grojean, JG, Paul

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 (δN) and effective beam polarization (δP_{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.





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

- 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.
- (See also R.-Q. Xiao's talk tomorrow on applications in netrual diboson.)

[arXiv:1712.01310] Franceschini *et al.*

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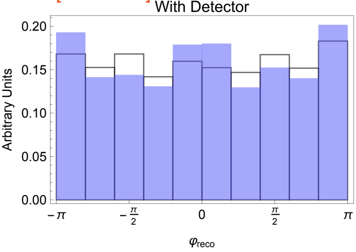
$q_{L,R}\bar{q}_{L,R} \to V_\pm V_\pm$	$\sim m_W^2/E^2$	$\sim E^2/M^2$
$q_{L,R}\bar{q}_{L,R} \to V_\pm V_\mp$	~ 1	~ 1

[1708.07823] Panico *et al.*



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

Higgs + EW SMEFT Global fit

- Global fit
  - Z-pole, diboson and Higgs processes are all connected in the SMEFT framework.
  - Usually ~ 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...)

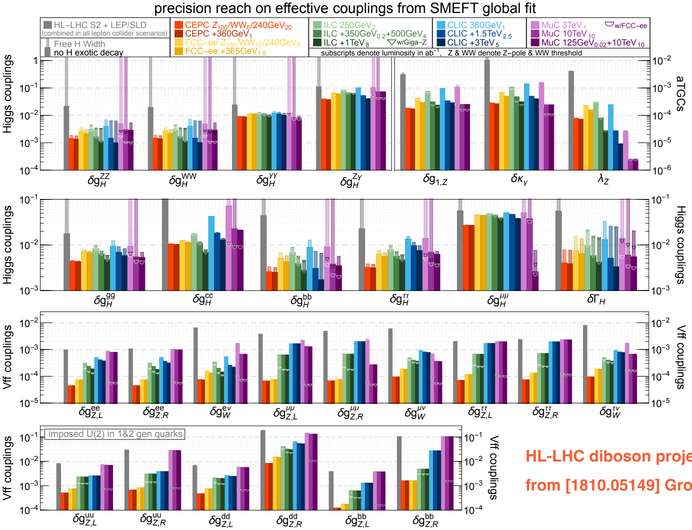
- Limits on all the $\frac{c_i^{(6)}}{\Lambda^2}$
  - Results depend on operator bases, conventions, ...

- 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

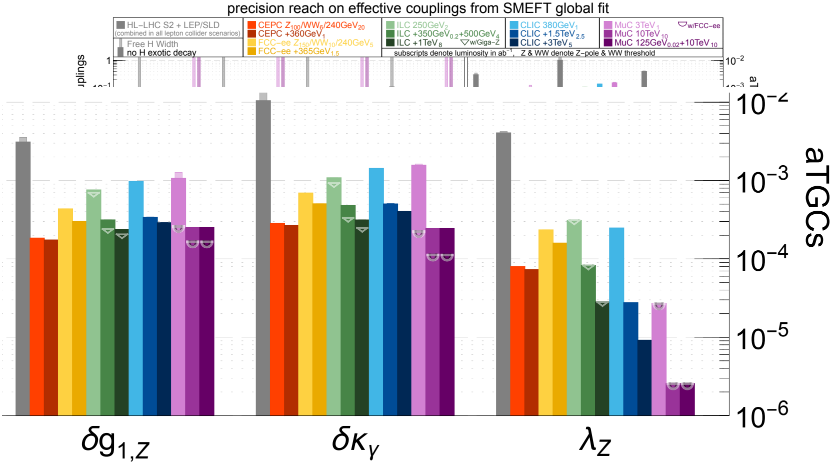
[2206.08326] de Blas, Du, Grojean, JG, Miralles, Peskin, Tian, Vos, Vryonidou

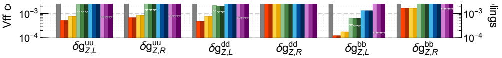


HL-LHC diboson projection taken from [1810.05149] Grojean *et al.*

Results from the recent snowmass study

[2206.08326] de Blas, Du, Grojean, JG, Miralles, Peskin, Tian, Vos, Vryonidou



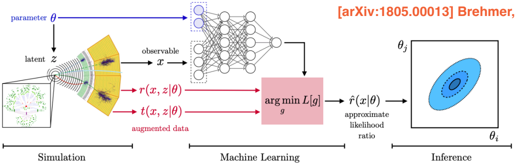


n

from [1810.05149] Grojean *et al.*

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.

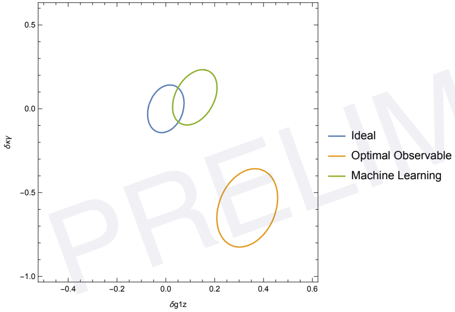


[arXiv:1805.00013] Brehmer, Cranmer, Louppe, Pavez

- 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.

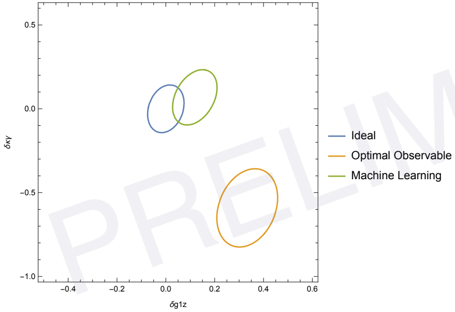
Machine Learning

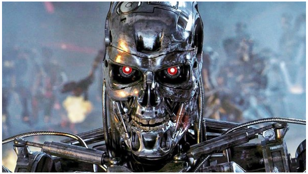
(preliminary results, Shengdu Chai, JG, Lingfeng Li)



- Scale (size of the ellipses) is arbitrary.
- Semileptonic channel, jet smearing + ISR
  - Naively applying truth-level optimal observables could lead to a large bias!
  - Machine learning can give better results (current bias mainly due to limited sample size)!

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



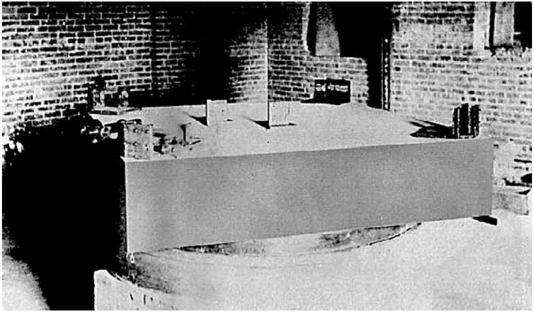


- Scale (size of the ellipses) is arbitrary.
- Semileptonic channel, jet smearing + ISR
  - Naively applying truth-level optimal observables could lead to a large bias!
  - Machine learning can give better results (current bias mainly due to limited sample size)!
- **When will Machine take over?**

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

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

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

- 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. δ_{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

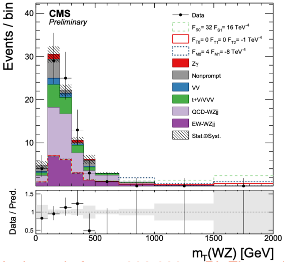
$\mathcal{O}_H = \frac{1}{2}(\partial_\mu \lvert H^2 \rvert)^2$	$\mathcal{O}_{GG} = g_s^2 \lvert H\rvert^2 G^A_{\mu\nu} G^{A,\mu\nu}$
$\mathcal{O}_{WW} = g^2 \lvert H\rvert^2 W^a_{\mu\nu} W^{a,\mu\nu}$	$\mathcal{O}_{y_u} = y_u \lvert H\rvert^2 \bar{q}_L \tilde{H} u_R + \text{h.c.} \quad (u \to t, c)$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

- 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 $\mathcal{O}_{HB}$)

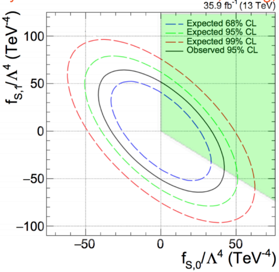
Probing dimension-8 operators?

- The dimension-8 contribution has a large energy enhancement ($\sim E^4/\Lambda^4$)!
- It is difficult for LHC to probe these bounds.
  - Low statistics in the high energy bins.
  - Example: Vector boson scattering.
  - $\Lambda \lesssim \sqrt{s}$, the EFT expansion breaks down!
- Can we separate the dim-8 and dim-6 effects?
  - Precision measurements at several different $\sqrt{s}$?
    (A **very** high energy lepton collider?)
  - Or find some special process where dim-8 gives the leading new physics contribution?

CMS-PAS-SMP-18-001



positivity bounds from 1902.08977 Bi, Zhang, Zhou

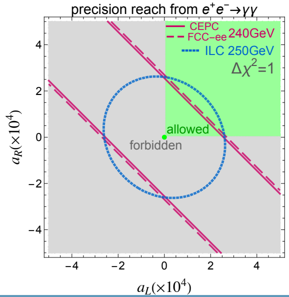


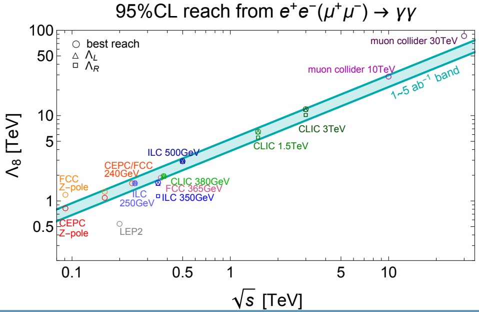
The diphoton channel [arXiv:2011.03055] JG, Lian-Tao Wang, Cen Zhang

- $e^+e^- \to \gamma\gamma$ (or $\mu^+\mu^- \to \gamma\gamma$), SM, non-resonant.
- Leading order contribution: **dimension-8 contact interaction**.
  ($f^+f^- \to \bar{e}_L e_L$ or $e_R \bar{e}_R$)

$$\mathcal{A}(f^+f^-\gamma^+\gamma^-)_{\mathrm{SM+d8}} = 2e^2 \frac{\langle 24\rangle^2}{\langle 13\rangle\langle 23\rangle} + \frac{a}{v^4}[13][23]\langle 24\rangle^2 \,.$$

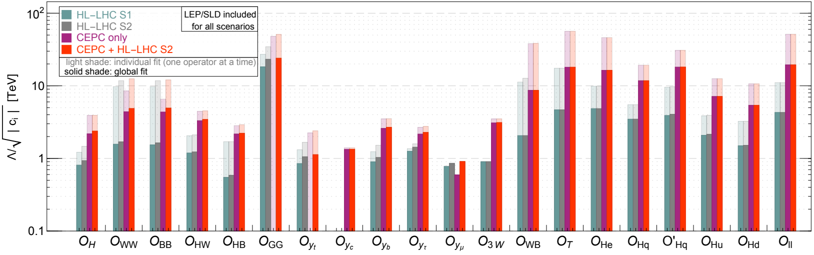
- Can probe dim-8 operators (and their positivity bounds) at a **Higgs factory** (~ 240 GeV)!





Reach on the scale of new physics

95% CL reach from the full EFT fit



- Reach on the scale of new physics Λ.
- Note: reach depends on the couplings c_i!