New Physics in Diboson Channels at High Invariant Mass

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Burssels

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

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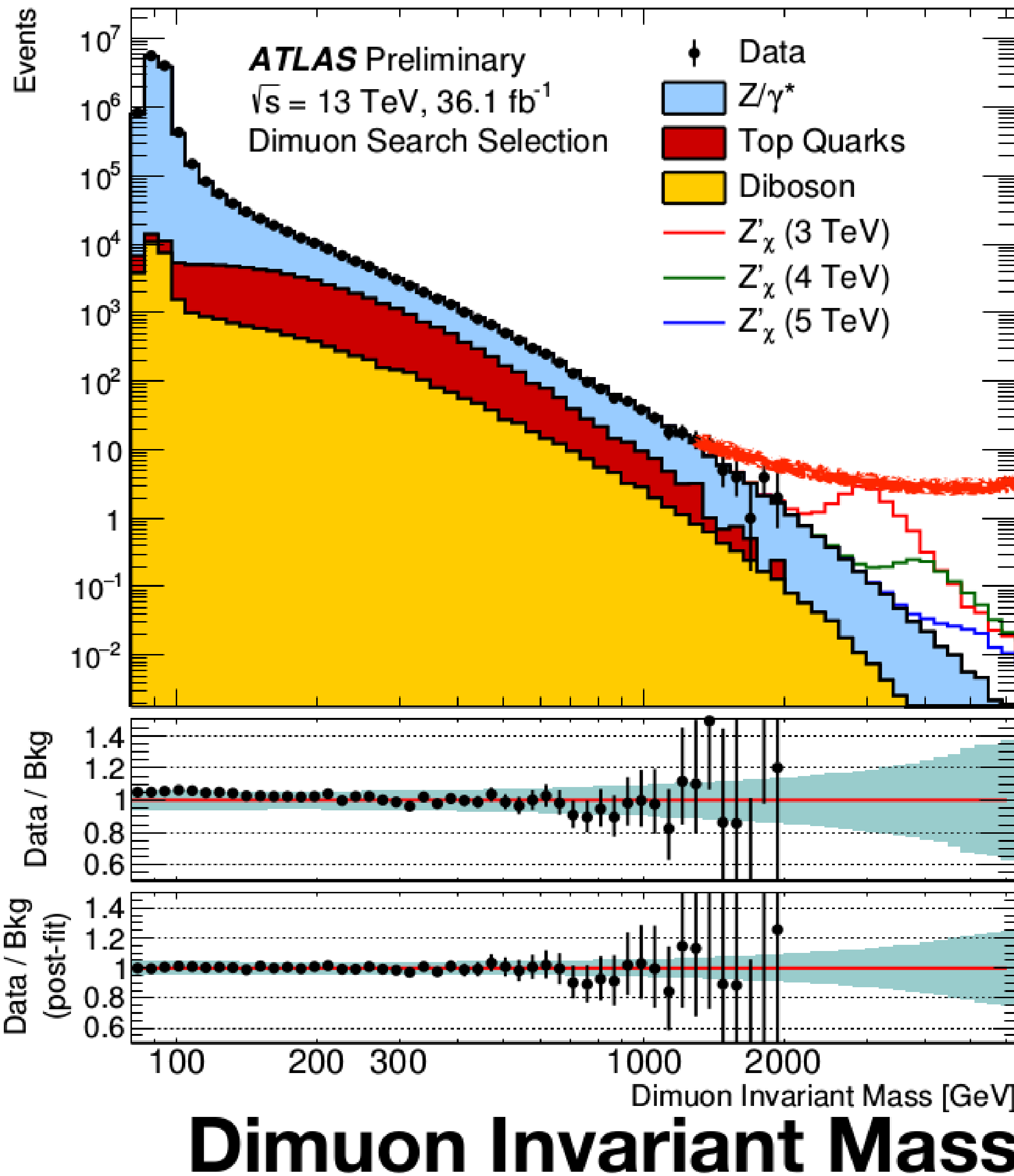
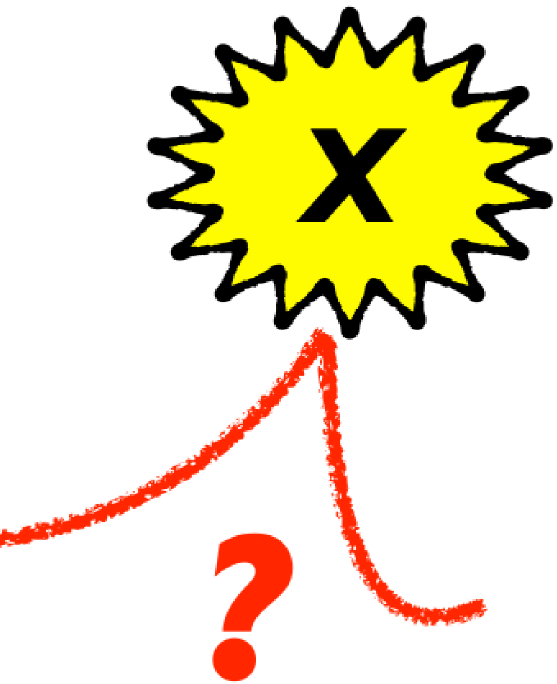
DESY.

Motivation

- Habemus Higgs; are we done? Note even close! The SM does not say anything about, e.g., dark matter, the origin of neutrino masses, baryon asymmetry, ...
- However, the LHC hasn't discovered any new states so far. What if NP is too heavy? Even for FCC? Can still lean something from EFTs.
- Why diboson? Some NP amplitudes grow with energy, good handle at high invariant mass.

To illustrate the point...





Artwork by Admir Greljo

Drell-Yan: $pp \to \ell\ell$

Effects in the tail ($\Rightarrow$ EFT), well below the resonance

EFT validity $\leftrightarrow$ $E, p_T \ll M_X$

Getting a bound on the Wilson coefs

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_i \frac{\mathcal{C}_i^{(6)}}{\Lambda^2} Q_i^{(6)} + \sum_i \frac{\mathcal{C}_i^{(8)}}{\Lambda^4} Q_i^{(8)} + \cdots$$

$$\sigma_{\rm BSM} = \sigma_{\rm SM} + \delta\sigma$$

$$\delta\sigma = \hat{\sigma} \cdot f$$

$$\chi^2 \sim \left(\frac{\delta\sigma}{\sigma_{\rm SM}}\right)^2 \cdot \frac{1}{\Delta^2}$$

STAT + SYST

$$\Delta^2 = \left(\frac{1}{\sqrt{N}}\right)^2 + \sum_i \epsilon_i^2$$

$$\Rightarrow \delta\sigma \sim \Delta\, \sigma_{\rm sm}$$

The form of the BSM cross-section

These terms are well behaved by definition $\because \Lambda \gg M_W$

$$f = a_1\, \mathcal{C}\, \frac{M_W^2}{\Lambda^2} + a_2\, \mathcal{C}^2\, \frac{M_W^4}{\Lambda^4} + \text{dim. } 8 + \cdots +$$

$$b_1\, \mathcal{C}\, \frac{E^2}{\Lambda^2} + b_2\, \mathcal{C}^2\, \frac{E^4}{\Lambda^4} + \ldots$$

Linear terms arise from Interference with the SM amplitudes

Must ensure EFT validity with these terms, i.e., enforce $E < \Lambda$

Two cases

① Interference but no growth with energy

$$\delta\sigma = \Delta\,\sigma_{\rm SM} \Rightarrow \mathcal{C}\frac{M_W^2}{\Lambda^2} = 0.1 \times \mathcal{O}(1) \Rightarrow \mathcal{C} = 0.1 \times \frac{\Lambda^2}{M_W^2}$$

C.I. on $|\mathcal{C}| = 250$ ✖

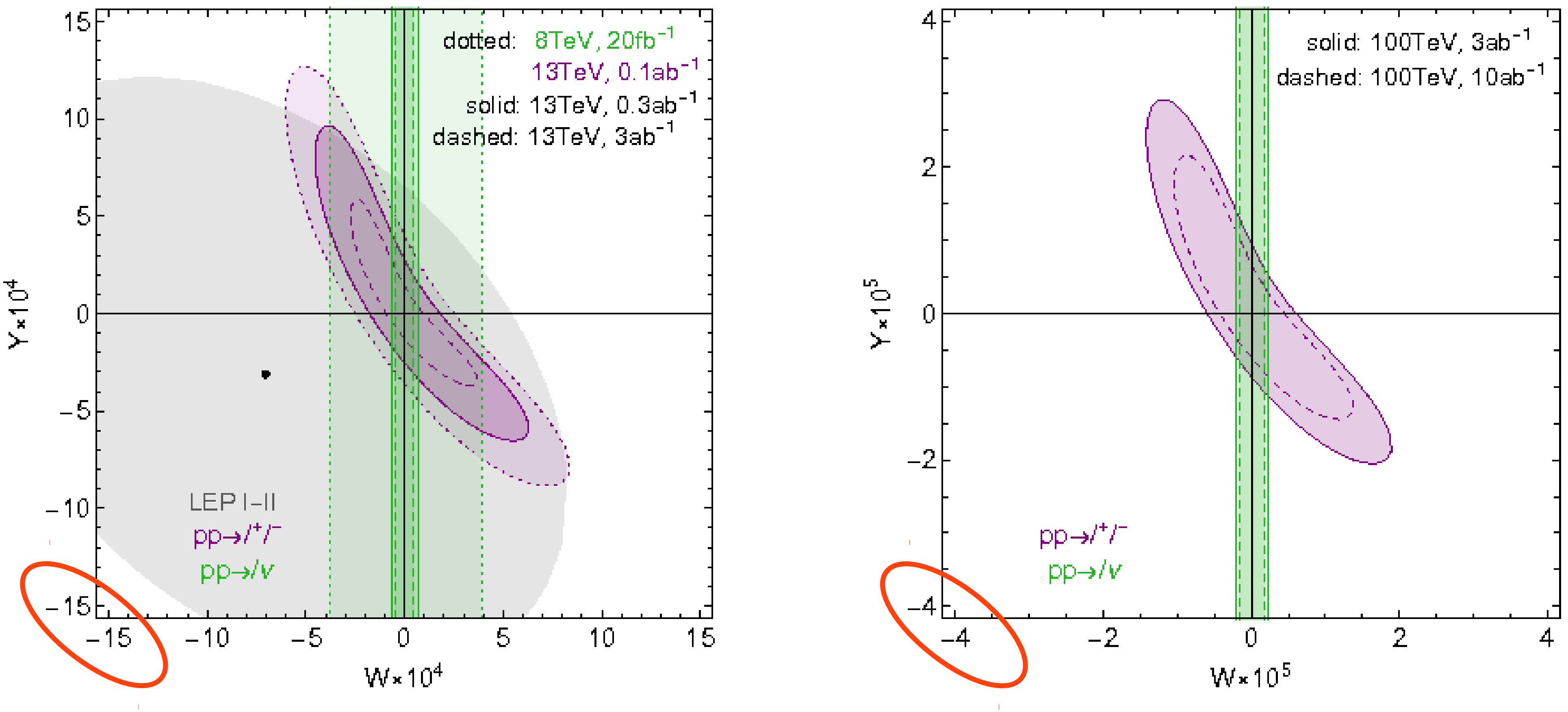
② Interference but with growth with enregy

$$\mathcal{C} = 0.1 \times \frac{\Lambda^2}{E^2}$$

C.I. on $|\mathcal{C}| = 0.3$ ✔

Where we have chosen $\Lambda = 5$ TeV and $E = 3$ TeV; $\mathcal{C} \sim g_*^2$

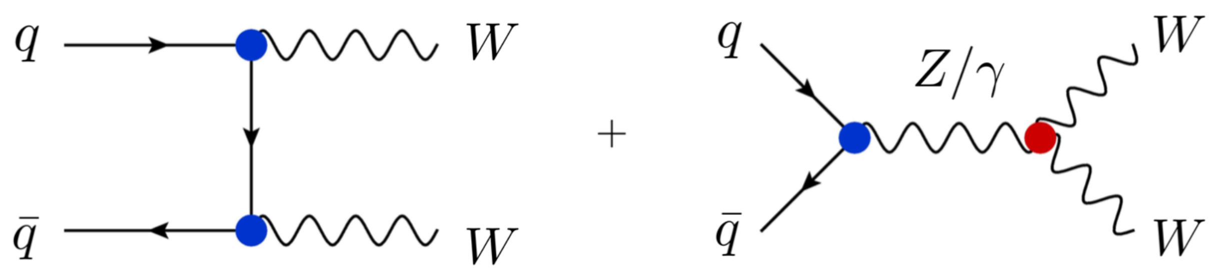
Example: Drell-Yan



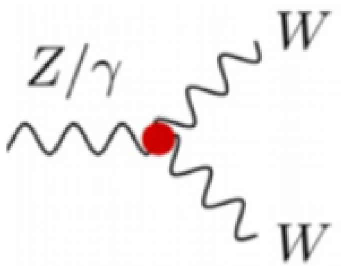
$$-\frac{W}{4m_{\mathrm{W}}^2}\left(D_\rho W^a_{\mu\nu}\right)^2, \qquad -\frac{Y}{4m_{\mathrm{W}}^2}\left(\partial_\rho B_{\mu\nu}\right)^2$$

WW production

[Butter et al.: 1604.03105]
[Azatov et al.: 1707.08060]
[Grojean et al.: 1810.05149]
[+ more]



Improving LEP-2 bounds on
anomalous Triple Gauge Couplings



Bounds on aTGC

Butter et al 1604.03105

	LHC Run I				LEP			
	68 % CL	Correlations			68 % CL	Correlations		
Δg_1^Z	0.010 ± 0.008	1.00	0.19	−0.06	$0.051^{+0.031}_{-0.032}$	1.00	0.23	−0.30
$\Delta\kappa_\gamma$	0.017 ± 0.028	0.19	1.00	−0.01	$-0.067^{+0.061}_{-0.057}$	0.23	1.00	−0.27
λ	0.0029 ± 0.0057	−0.06	−0.01	1.00	$-0.067^{+0.036}_{-0.038}$	−0.30	0.27	1.00

Per mille at LHC !!

Percent at LEP

Diboson channels: WW, WZ, Wh, Zh

[Franceschini et al.: 1712.01310]

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

In the limit $E \gg M_W$ 💡, probe 4 directions in the SMEFT

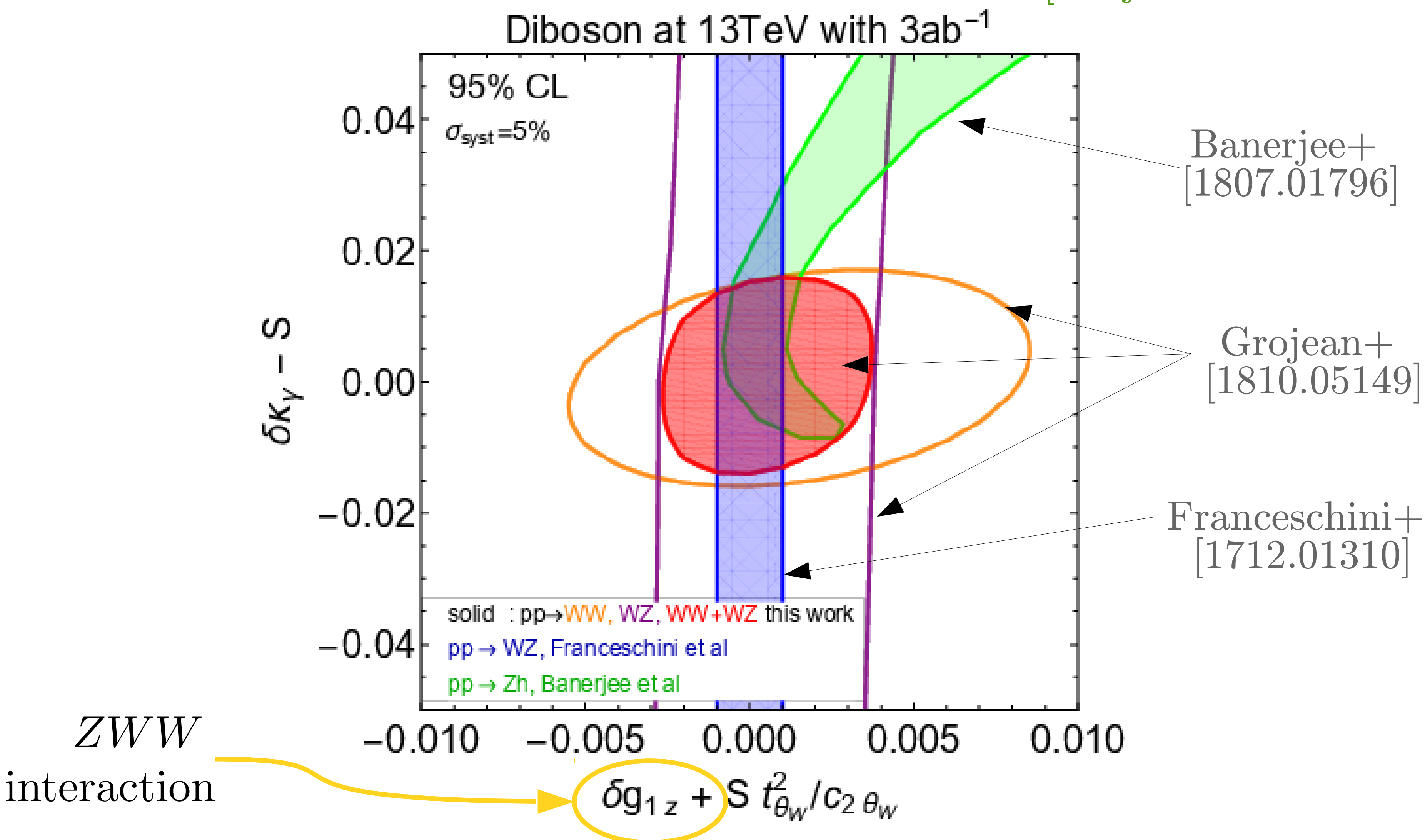
$$a_q^{(3)} \left(\overline{q}_L \sigma^a \gamma^\mu q_L\right)\left(iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H\right), \qquad a_u \left(\overline{u}_R \gamma^\mu u_R\right)\left(iH^\dagger \overleftrightarrow{D}_\mu H\right),$$

$$a_q^{(1)} \left(\overline{q}_L \gamma^\mu q_L\right)\left(iH^\dagger \overleftrightarrow{D}_\mu H\right), \qquad a_d \left(\overline{d}_R \gamma^\mu d_R\right)\left(iH^\dagger \overleftrightarrow{D}_\mu H\right).$$

💡 If $E \sim M_W$, the subleading contributions are of the same size and should be considered, but ...

Diboson results

[Grojean et al.: 1810.05149]



- Bound from LEP fills the plot area!
- Wh is ongoing and shows competitive sensitivty (preliminary)

Summary and outlook

- Hadron colliders can be competitive with LEP in constraining precision EW observables
- Drell-Yan and diboson channels are the most promising due to growth with energy and low systematics (e.g., in leptonic or semi-leptonic) final states
- Work on the Wh channel is ongoing to complete the diboson picture
- More differential distribution, e.g., in azimuthal angle, additionally, can be used to constrain more operators

Thank you!