Precision from Diboson Processes at FCC-hh.

Based on arxiv:2004.06122 and arxiv:2011.13941

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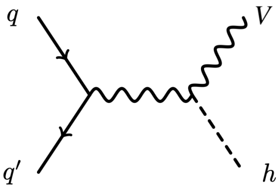
Motivation

- Precision physics @ hadron colliders: difficult
- exceptions: e.g. Drell-Yan, diboson production channels
- heavy new physics tends to grow with energy
- cleanliness of leptonic decay channels of the V-bosons
- here: $pp \to Vh$; tree level SM diagram:



Theory

The framework

- SMEFT: parametrize heavy new physics in terms of effective operators

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \sum_{d>4} \mathcal{L}^{(d)} \qquad \text{with} \qquad \mathcal{L}^{(d)} \equiv \sum_i \frac{c_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}$$

- leading contributions (dim 6) to energy growth in ***Wh***, with the constraint of MFV in the Warsaw basis (see e.g. [1712.01310]):

$$\mathcal{O}_{\varphi q}^{(3)} = \left(\bar{Q}_L \sigma^a \gamma^\mu Q_L\right) \left(i H^\dagger \sigma^a \overleftrightarrow{D}_\mu H\right)$$
$$\mathcal{O}_{\varphi W} = H^\dagger H W^{a,\mu\nu} W^a_{\mu\nu}$$
$$\mathcal{O}_{\varphi \widetilde{W}} = H^\dagger H W^{a,\mu\nu} \widetilde{W}^a_{\mu\nu}$$

Theory

The framework

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- leading contributions (dim 6) to energy growth in ***Zh***, with the constraint of MFV in the Warsaw basis (see e.g. [1712.01310]):

$$\mathcal{O}_{\varphi q}^{(1)} = (\overline{Q}_L \gamma^\mu Q_L) \left(i H^\dagger \overleftrightarrow{D}_\mu H \right), \qquad \mathcal{O}_{\varphi u} = (\overline{u}_R \gamma^\mu u_R) \left(i H^\dagger \overleftrightarrow{D}_\mu H \right)$$

$$\mathcal{O}_{\varphi q}^{(3)} = (\overline{Q}_L \sigma^a \gamma^\mu Q_L) \left(i H^\dagger \sigma^a \overleftrightarrow{D}_\mu \right), \quad \mathcal{O}_{\varphi d} = (\overline{d}_R \gamma^\mu d_R) \left(i H^\dagger \overleftrightarrow{D}_\mu H \right)$$

Theory

How to best exploit the energy growth of heavy NP effects?

- squared matrix element:

$$\mathcal{M}^2 = |\mathcal{M}_{\mathsf{SM}}|^2 + \underbrace{2\mathrm{Re}\mathcal{M}_{\mathsf{SM}}\mathcal{M}^*_{\mathsf{BSM}}}_{\propto \frac{c}{\Lambda^2}} + \underbrace{|\mathcal{M}_{\mathsf{BSM}}|^2}_{\propto \frac{c^2}{\Lambda^4}}$$

- optimize sensitivity to interference terms because:
  - lower power of $1/\Lambda \rightarrow$ Wilson-coefficient/energy does not need to be so large
  - if $|\mathcal{M}_{\mathsf{BSM}}|^2$ contribute sizeably: dim-8 operators could be of relevance $\rightarrow$ more model dependent results if neglected

The story of *Wh*

Theory - *Wh*

Let's analyze the HE-behaviour in the interference terms!

- Naive expectation: Bin in $\sqrt{\hat{s}}$, observe the energy growth and enjoy life
- Reality:

$$|\mathcal{M}_{\mathsf{SM}}|^2 \sim \sin^2\theta \qquad \mathrm{Re}\,\mathcal{M}_{\mathsf{SM}}\mathcal{M}^*_{\varphi \mathrm{W}} \sim \frac{M_W^2}{\Lambda^2}$$

$$\mathrm{Re}\,\mathcal{M}_{\mathsf{SM}}\,\mathcal{M}^{(3)\,*}_{\varphi q} \sim \frac{\hat{s}}{\Lambda^2}\sin^2\theta \qquad \mathrm{Re}\,\mathcal{M}_{\mathsf{SM}}\,\mathcal{M}^*_{\varphi \widetilde{\mathrm{W}}} = 0$$

$\rightarrow$ analysis differential in $\sqrt{\hat{s}}$ could provide good sensitivity to $\mathcal{O}^{(3)}_{\varphi q}$ but not to the other two operators

Theory - *Wh*

Why?

If we integrate over the W decay angles ...

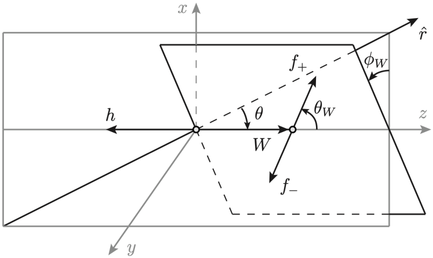
- $\mathrm{Re}\,\mathcal{M}_{SM}\,\mathcal{M}^*_{\varphi\widetilde{\mathrm{W}}} = 0$ because $\mathcal{O}_{\varphi\widetilde{W}}$ is CP-odd
- $\mathrm{Re}\,\mathcal{M}_{SM}\,\mathcal{M}^*_{\varphi\mathrm{W}}$: only amplitudes with the same W-polarization interfere in the HE region $\rightarrow$ leading term $=$ const

W polarization	SM	$\mathcal{O}^{(3)}_{\varphi q}$	$\mathcal{O}_{\varphi\mathrm{W}}$	$\mathcal{O}_{\varphi\widetilde{\mathrm{W}}}$
$\lambda = 0$	1	$\frac{\hat{s}}{\Lambda^2}$	$\frac{M_W^2}{\Lambda^2}$	0
$\lambda = \pm$	$\frac{M_W}{\sqrt{\hat{s}}}$	$\frac{\sqrt{\hat{s}}\,M_W}{\Lambda^2}$	$\frac{\sqrt{\hat{s}}\,M_W}{\Lambda^2}$	$\frac{\sqrt{\hat{s}}\,M_W}{\Lambda^2}$

Theory - *Wh*

Let's not integrate over the W-decay angles then!

- explicit calculation without integration → interference between different helicity channels and different CP-parities restored [1708.07823]
- What are the angles?



Theory - *Wh*

- leading terms in $M_W/\sqrt{\hat{s}}$ expansion:

$$|\mathcal{M}_{SM}|^2 \sim \frac{1}{4}\sin^2\theta\sin^2\theta_W \; + \frac{M_W}{\sqrt{\hat{s}}}\mathcal{F}(\theta,\theta_W)\cos\phi_W$$

$$\mathrm{Re}\,\mathcal{M}_{SM}\,\mathcal{M}^{(3)*}_{\varphi q} \sim \frac{\hat{s}}{\Lambda^2}\left[\frac{1}{4}\sin^2\theta\sin^2\theta_W + \frac{M_W}{\sqrt{\hat{s}}}\mathcal{F}(\theta,\theta_W)\cos\phi_W\right]$$

$$\mathrm{Re}\,\mathcal{M}_{SM}\,\mathcal{M}^{*}_{\varphi \mathrm{W}} \sim \frac{\sqrt{\hat{s}}\,M_W}{\Lambda^2}\mathcal{F}(\theta,\theta_W)\cos\phi_W$$

$$\mathrm{Re}\,\mathcal{M}_{SM}\,\mathcal{M}^{*}_{\varphi \widetilde{\mathrm{W}}} \sim \frac{\sqrt{\hat{s}}\,M_W}{\Lambda^2}\mathcal{F}(\theta,\theta_W)\sin\phi_W$$

- integration over θ_W does not destroy the interference $\rightarrow$ double differential analysis in p_T^h and ϕ_W = the way to go

The story of Zh

Theory - *Zh*

The interference terms in the *Zh*-channel

$$|\mathcal{M}_{\mathrm{SM}}|^2 \sim \sin^2\theta \qquad \mathrm{Re}\,\mathcal{M}_{\mathrm{SM}}\,\mathcal{M}^*_{\mathrm{BSM}} \sim \frac{\hat{s}}{\Lambda^2}\sin^2\theta$$

$\rightarrow$ employ analysis differential in $\sqrt{\hat{s}}$

But:

- interference terms of $\mathcal{O}_{\varphi u}, \mathcal{O}_{\varphi d} \propto$ coupling of Z to RH quarks
  $\rightarrow$ suppressed $\rightarrow$ quadratic BSM effects relevant
- interference term of $\mathcal{O}^{(1)}_{\varphi q} \propto$ SM coupling of Z to quarks

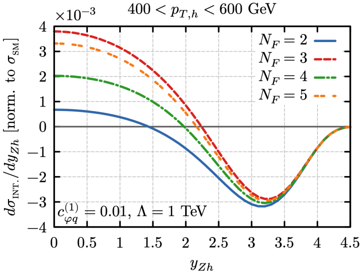
$\rightarrow$ opposite sign for up- and down-type quarks
$\rightarrow$ suppression of the interference term
$\rightarrow$ sensitivity to $\mathcal{O}^{(1)}_{\varphi q}$ is degraded and dominated by terms quadratic in the WC's

Theory - *Zh*

The solution (in principle)

- there are differences in the rapidity distributions of *u*- and *d*-type initiated processes due to the pdf's

$\rightarrow$ alleviate cancellation by a second binning in the *Zh*-rapidity:



- limited statistics in each bin renders the gain small, but: potentially useful for $Z(h \rightarrow bb)$

The gory details

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*                     W E L C O M E  to                    *
*              M A D G R A P H 5 _ a M C @ N L O           *
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*         VERSION 2.7.3                 2020-06-21         *
*                                                          *
*    The MadGraph5_aMC@NLO Development Team - Find us at   *
*    https://server06.fynu.ucl.ac.be/projects/madgraph     *
*                            and                           *
*            http://amcatnlo.web.cern.ch/amcatnlo/         *
*                                                          *
*               Type 'help' for in-line help.              *
*           Type 'tutorial' to learn how MG5 works         *
*    Type 'tutorial aMCatNLO' to learn how aMC@NLO works   *
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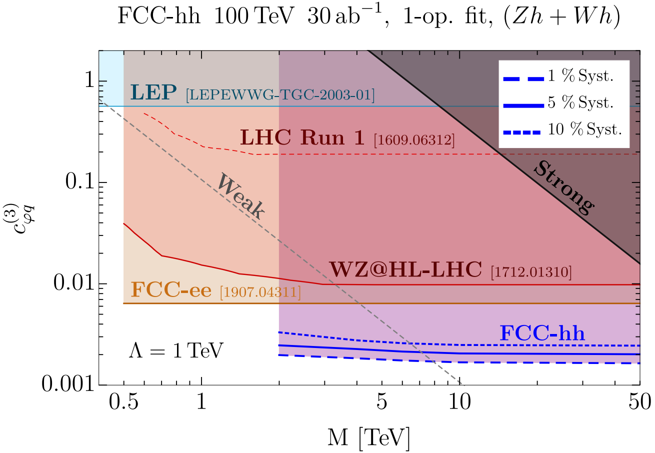
Results

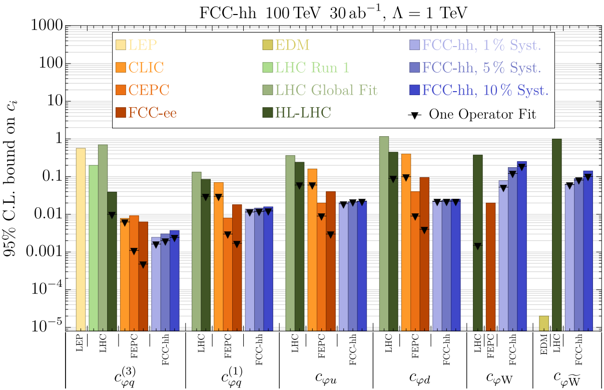
Single operator analysis of $\mathcal{O}_{\varphi q}^{(3)}$
95% C.L. bounds depending on EFT cut-off



weak:
$$c_{\varphi q}^{(3)} = \frac{g^2}{4M^2}$$
strong:
$$c_{\varphi q}^{(3)} = \frac{(4\pi)^2}{4M^2}$$

Results

Comparison to other bounds



Future directions

What's left to do?

- $W(\to \ell\nu)h(\to \bar{b}b)$ (larger cross-section but larger backgrounds)
- $W(\to jj)h(\to \bar{b}b)$ (same problems but potentially more sensitive to $c_{\varphi \mathrm{W}}$)
- $Z(\to \nu\nu/\ell\ell)h(\to \bar{b}b)$
- ...

Thank you!

Thank you for your attention!