Precision from Diboson Processes at FCC-hh.

Based on arxiv:2004.06122 and arxiv:2011.13941

in collaboration with: F. Bishara, S. De Curtis, L. Delle Rose, C. Grojean, M. Montull, G. Panico and A. N. Rossia

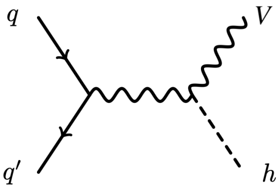
Philipp Englert

Future Colliders @ DESY

Hamburg, 21 October 2021

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:



Motivation

- high energy tail of the Higgs decay channels at different colliders for *Wh* (similar orders of magnitude for *Zh*):

Higgs decay	Higgs BR	$n_{\text{HL-LHC}}$	$n_{\text{HE-LHC}}$	$n_{\text{FCC-hh}}$
$\bar{b}b$	0.6	600	$1 \cdot 10^4$	$2 \cdot 10^5$
$\tau\tau$	$6 \cdot 10^{-2}$	60	$1 \cdot 10^3$	$2 \cdot 10^4$
$\gamma\gamma$	$2 \cdot 10^{-3}$	2	40	700
$\mu\mu$	$2 \cdot 10^{-4}$	0.2	4	70
4ℓ	$1 \cdot 10^{-4}$	0.1	2	40

Table 1. Number of $Wh \to \ell\nu XX$ events predicted by the SM at LO for different Higgs decay channels and with a cut $p_T^h > 550\,\text{GeV}$. The results correspond to $3\,\text{ab}^{-1}$, $|\eta| < 2.5$ for the HL-LHC, $15\,\text{ab}^{-1}$, $|\eta| < 6$ for the HE-LHC and $30\,\text{ab}^{-1}$, $|\eta| < 6$ for the FCC-hh.

- $\bar{b}b$: many events but difficult $\to$ work in progress
- $\gamma\gamma$: easy reconstruction, low backgrounds, not enough events at HL/HE-LHC . . . but: FCC-hh!
(e.g. 700 events for *Wh* $\to$ NP at 5-10% level)

Theory

The framework

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

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

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

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

Theory

The framework

- 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 ***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*

How does the energy growth look like?

- helicity of the V boson plays a big role in the HE behaviour of the amplitudes
- HE-behaviour of the helicity amplitudes of the different contributions to $pp \to Wh$:

W polarization	SM	$\mathcal{O}_{\varphi q}^{(3)}$	$\mathcal{O}_{\varphi \mathrm{W}}$	$\mathcal{O}_{\varphi \widetilde{\mathrm{W}}}$
$\lambda = 0$	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 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 ...

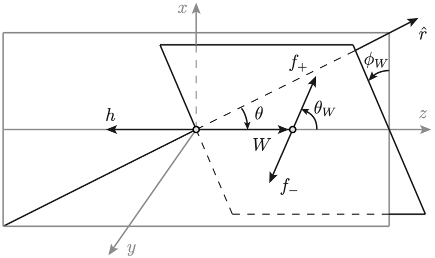
- $\mathrm{Re}\,\mathcal{M}_{SM}\,\mathcal{M}^*_{\varphi\widetilde{\mathrm{W}}} = 0$ because $\mathcal{O}_{\varphi\widetilde{W}}$ is CP-odd
- $\mathrm{Re}\,\mathcal{M}_{SM}\,\mathcal{M}^*_{\varphi\mathrm{W}}$: only amplitudes with the same W-polarization interfere in the HE region $\rightarrow$ leading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

Theory - *Wh*

Energy growth completely restored? Sadly not.

- $\not{E}_T$ & $p_\ell \xrightarrow{\text{reco}} p_\nu$ **only** up to $\phi_W \leftrightarrow \pi - \phi_W$
  $\Rightarrow$ terms $\propto \cos\phi_W$ vanish
- energy growth of $\mathrm{Re}\,\mathcal{M}_{SM}\,\mathcal{M}^*_{\varphi\mathrm{W}}$ effectively vanishes
  $\Rightarrow$ leading term is constant w.r.t. $\hat{s}$
- the leading terms of $|\mathcal{M}_{SM}|^2$, $\mathrm{Re}\,\mathcal{M}_{SM}\,\mathcal{M}^{(3)\,*}_{\varphi q}$ and $\mathrm{Re}\,\mathcal{M}_{SM}\,\mathcal{M}^*_{\varphi\widetilde{\mathrm{W}}}$ are unaffected

- additional side effect of ambiguity: cannot reconstruct $\sqrt{\hat{s}}$
  $\rightarrow$ need to bin in correlated p_T^h

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

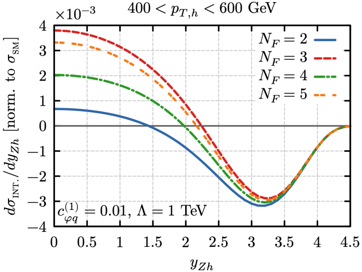
$\rightarrow$ opposite sign for up- and down-type quarks
$\rightarrow$ suppression of the interference term
$\rightarrow$ sensitivity to $\mathcal{O}^{(1)}_{\varphi q}$ is degraded and dominated by terms quadratic in the WC's

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 $Z(h \rightarrow bb)$

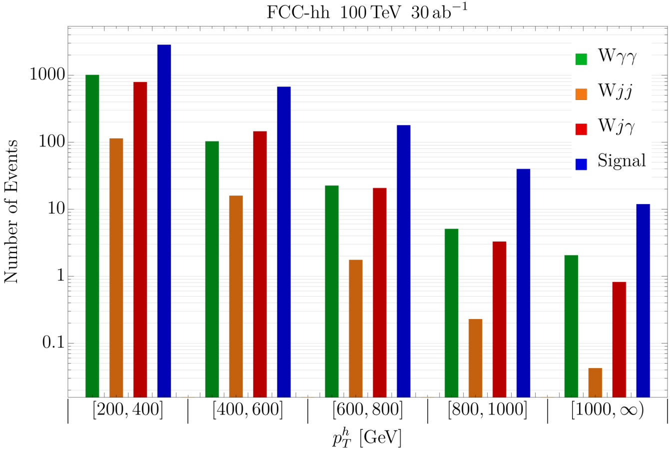
Event Generation and Analysis

The gory details

```
************************************************************
*                                                          *
*                     W E L C O M E  to                    *
*              M A D G R A P H 5 _ a M C @ N L O           *
*                                                          *
*                                                          *
*                 *                       *                *
*                   *        * *        *                  *
*                     * * * * 5 * * * *                    *
*                   *        * *        *                  *
*                 *                       *                *
*                                                          *
*         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   *
*    Type 'tutorial MadLoop' to learn how MadLoop works    *
*                                                          *
************************************************************
```

Event Generation and Analysis

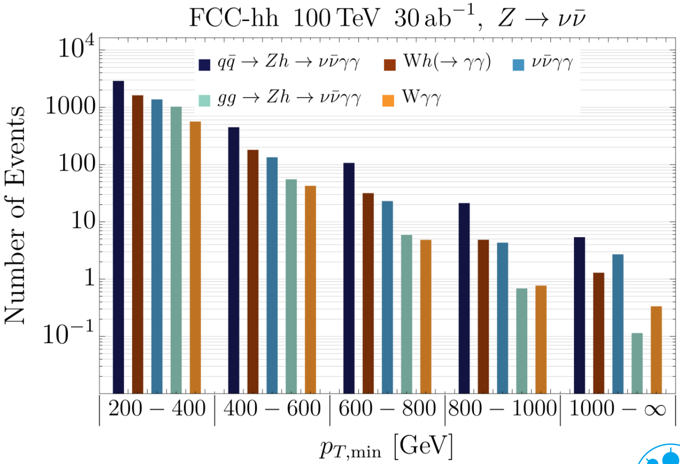
Wh signal vs. backgrounds after the cuts:



$\rightarrow$ the *Wjj* background is negligible

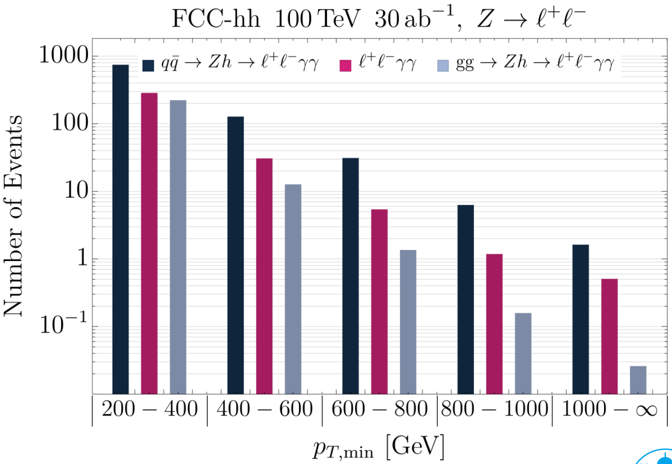
Event Generation and Analysis

$Z(\to \nu\nu)h$ signal vs. backgrounds after the cuts:



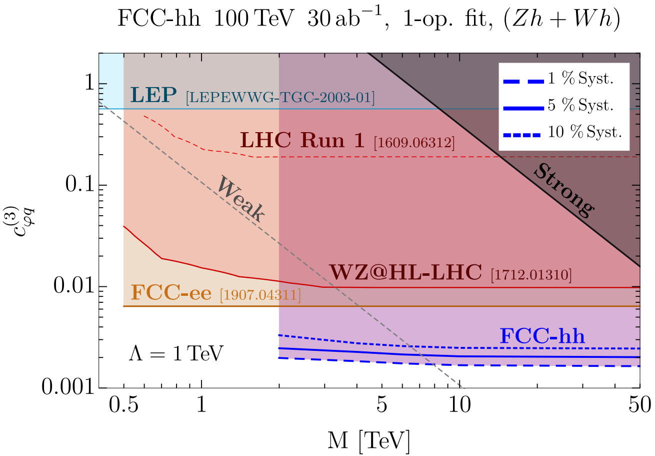
Event Generation and Analysis

$Z(\to \ell^+\ell^-)h$ signal vs. backgrounds after the cuts:



Results

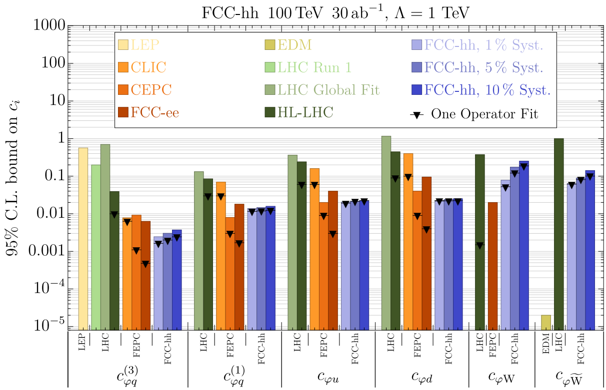
Single operator analysis of $\mathcal{O}_{\varphi q}^{(3)}$
95% C.L. bounds depending on EFT cut-off



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!