

# Unveiling the Higgs at FCC-hh

With new diboson precision measurements

Higgs 2021

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arXiv 2004.06122 (JHEP 07 (2020) 075)

arXiv 2011.13941 (JHEP 04 (2021) 154)



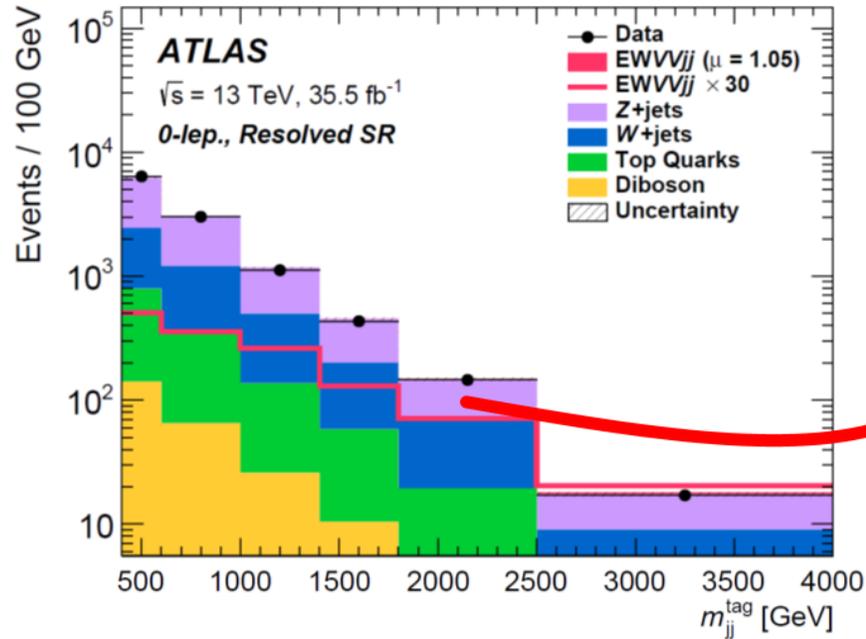
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# Precision with hadron colliders



Clean channels + NP effects that grow with E



Tail hunting!

Heavy New Physics

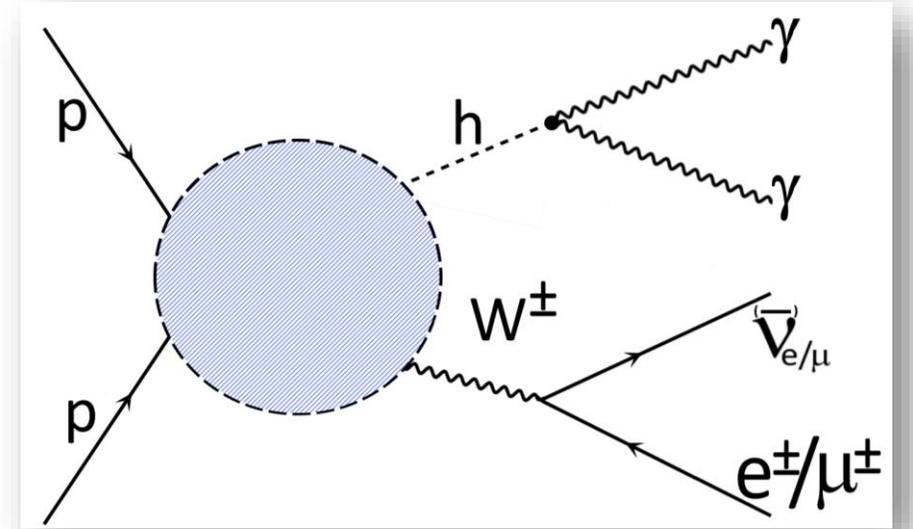


Effective Field Theories

# Leptonic diphoton $Vh$ .

$$pp \rightarrow W^\pm h \rightarrow l^\pm \nu (\gamma\gamma)$$

$$pp \rightarrow Zh \rightarrow l^+ l^- (\nu\bar{\nu}) (\gamma\gamma)$$



What can we gain at FCC-hh?

Probed six dim.-6 SMEFT operators:

$$\mathcal{O}_{\varphi q}^{(1)}$$

$$\mathcal{O}_{\varphi q}^{(3)}$$

$$\mathcal{O}_{\varphi u}$$

$$\mathcal{O}_{\varphi d}$$

$$\mathcal{O}_{\varphi W}$$

$$\mathcal{O}_{\varphi \tilde{W}}$$

# Conclusions

- **New diboson channels to do precision measurements at FCC-hh, like  $Wh$  and  $Zh$  with  $h \rightarrow \gamma\gamma$ .**
- **With a simple  $p_T$  binning, they offer competitive sensitivity to  $\mathcal{O}_{\varphi q}^{(3)}$ .**
- **A second binning in angles or rapidity improves the sensitivity to other operators, even to the interference of a CP-odd one.**
- **$Wh$  and  $Zh$  with  $h \rightarrow \gamma\gamma$  are not exploration channels, but important to probe different directions.**

# Thank you for your attention

## Contact



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<http://www.hep.man.ac.uk/>

# Appendix.

For even more details, read our papers.

# What New Physics can we probe?

- Assumptions: SMEFT + Dim. 6 op. in Warsaw basis + MFV.

High energy behavior

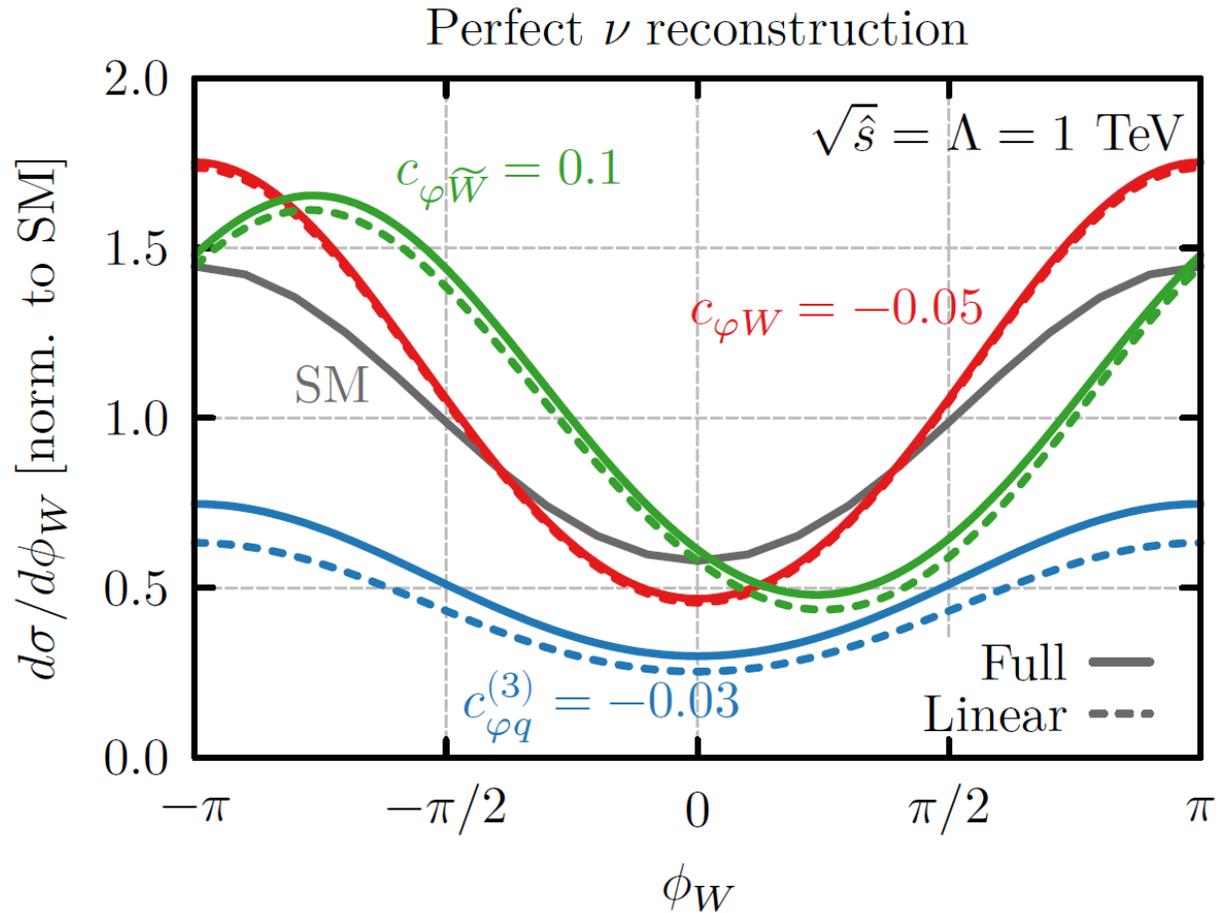
$$\frac{c_{\varphi q}^{(3)}}{\Lambda^2} (\bar{Q}_L \sigma^a \gamma^\mu Q_L) \left( i H^\dagger \sigma^a \overleftrightarrow{D}_\mu H \right) \longrightarrow \frac{\mathcal{A}_{BSM}}{\mathcal{A}_{SM}} \sim \hat{s}$$

$$\left. \begin{aligned} & \frac{c_{\varphi W}}{\Lambda^2} H^\dagger H W^{a,\mu\nu} W_{\mu\nu}^a \\ & \frac{c_{\varphi \widetilde{W}}}{\Lambda^2} H^\dagger H W^{a,\mu\nu} \widetilde{W}_{\mu\nu}^a \end{aligned} \right\} \longrightarrow \frac{\mathcal{A}_{BSM}}{\mathcal{A}_{SM}} \sim \sqrt{\hat{s}}$$

$$\widetilde{W}^{a,\mu\nu} \equiv \frac{1}{2} \epsilon^{\mu\nu\rho\sigma} W_{\rho\sigma}^a$$



# Interference patterns



Differential in  $p_T^h$  and  $\phi_W$

$$\sigma_{\mathcal{O}_{\varphi q}^{(3)}}^{int} \sim \frac{\hat{s}}{\Lambda^2}$$

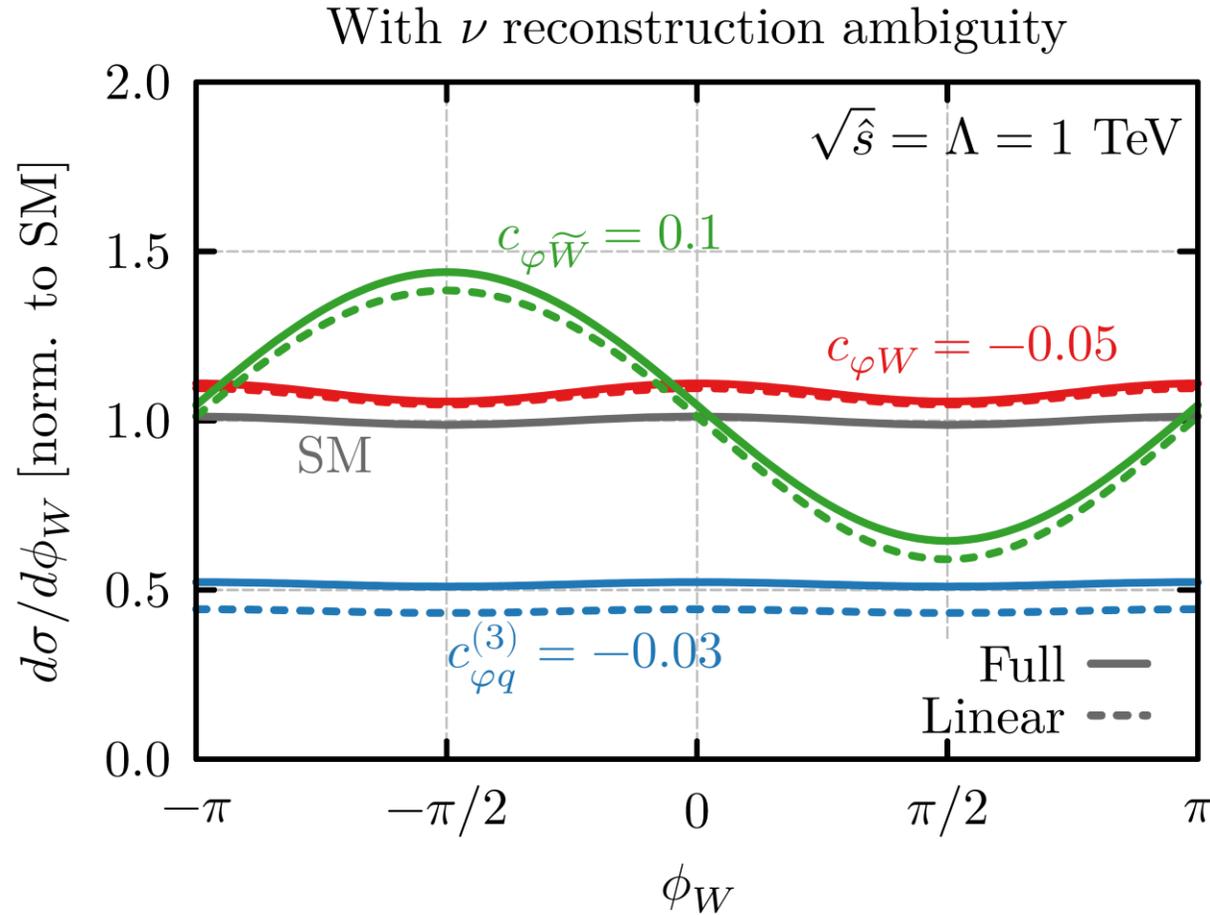
$$\sigma_{\mathcal{O}_{\varphi W}}^{int} \sim \frac{\sqrt{\hat{s}} M_W}{\Lambda^2} \cos(\phi_W)$$

$$\sigma_{\mathcal{O}_{\varphi\tilde{W}}}^{int} \sim \frac{\sqrt{\hat{s}} M_W}{\Lambda^2} \sin(\phi_W)$$

$$p_T^h \in \{200, 400, 600, 800, 1000, \infty\} \text{ GeV}$$

$$\phi_W \in [-\pi, 0], [0, \pi]$$

# Interference patterns



## Differential in $p_T^h$ and $\phi_W$

$$\sigma_{\mathcal{O}_{\phi q}^{(3)}}^{int} \sim \frac{\hat{s}}{\Lambda^2} \quad \nu \text{ reconstruction}$$

$$(\phi_W \rightarrow \pi - \phi_W)$$

$$\sigma_{\mathcal{O}_{\phi W}}^{int} \sim \frac{\sqrt{\hat{s}} M_W}{\Lambda^2} \cos(\phi_W)$$

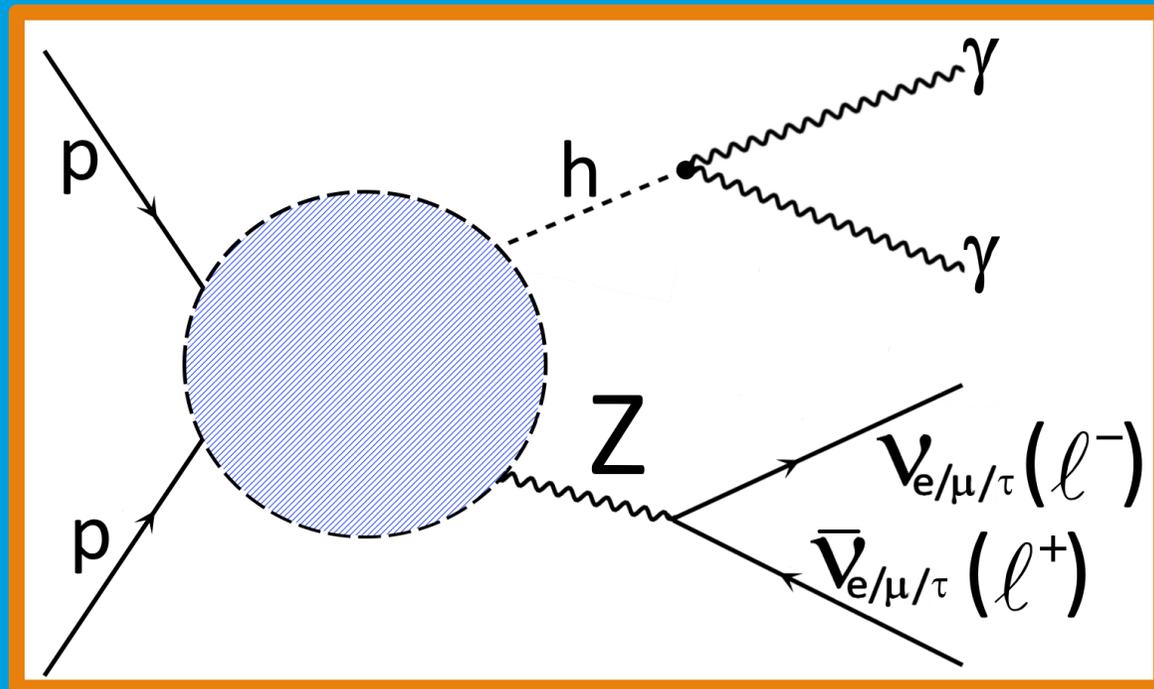
$$\sigma_{\mathcal{O}_{\phi\tilde{W}}}^{int} \sim \frac{\sqrt{\hat{s}} M_W}{\Lambda^2} \sin(\phi_W)$$

$$p_T^h \in \{200, 400, 600, 800, 1000, \infty\} \text{ GeV}$$

$$\phi_W \in [-\pi, 0], [0, \pi]$$

# Diphoton Zh.

arXiv 2011.13941 (JHEP 04 (2021) 154)



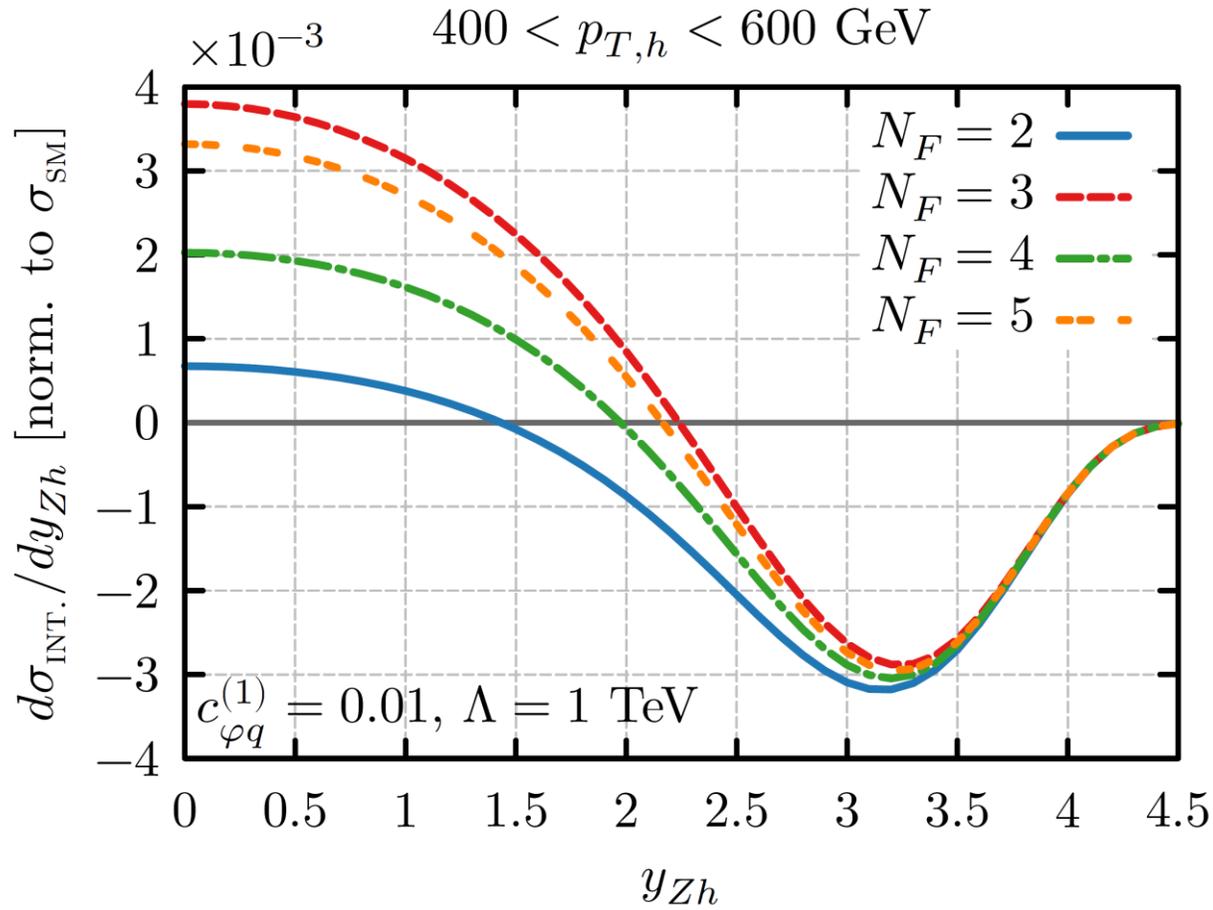
$$pp \rightarrow Zh \rightarrow l^+ l^- (\nu \bar{\nu}) \gamma \gamma$$

# What New Physics can we probe?

- Assumptions: SMEFT + Dim. 6 op. in Warsaw basis + Flav. Univ.

$$\begin{aligned}
 & \frac{c_{\varphi q}^{(3)}}{\Lambda^2} \left( \bar{Q}_L \sigma^a \gamma^\mu Q_L \right) \left( i H^\dagger \sigma^a \overleftrightarrow{D}_\mu H \right) \\
 & \frac{c_{\varphi q}^{(1)}}{\Lambda^2} \left( \bar{Q}_L \gamma^\mu Q_L \right) \left( i H^\dagger \overleftrightarrow{D}_\mu H \right) \\
 & \frac{c_{\varphi u}}{\Lambda^2} \left( \bar{u}_R \gamma^\mu u_R \right) \left( i H^\dagger \overleftrightarrow{D}_\mu H \right) \\
 & \frac{c_{\varphi d}}{\Lambda^2} \left( \bar{d}_R \gamma^\mu d_R \right) \left( i H^\dagger \overleftrightarrow{D}_\mu H \right)
 \end{aligned}
 \left. \vphantom{\begin{aligned} \dots \\ \dots \\ \dots \\ \dots \end{aligned}} \right\} \text{High energy behavior} \rightarrow \frac{\mathcal{A}_{BSM}}{\mathcal{A}_{SM}} \sim \hat{s}$$

# Interference patterns



$$\sigma_{\mathcal{O}_{\varphi q}}^{\text{int} (1)} \propto s_W^2 Q - T_3$$

**Cancellation of up and down contributions**

$$\sigma_{\mathcal{O}_{\varphi u(d)}}^{\text{int}} \propto g_R^{Zu(d)}$$

**Suppression by SM coupling**

**Differential in  $p_T$  and rapidity**

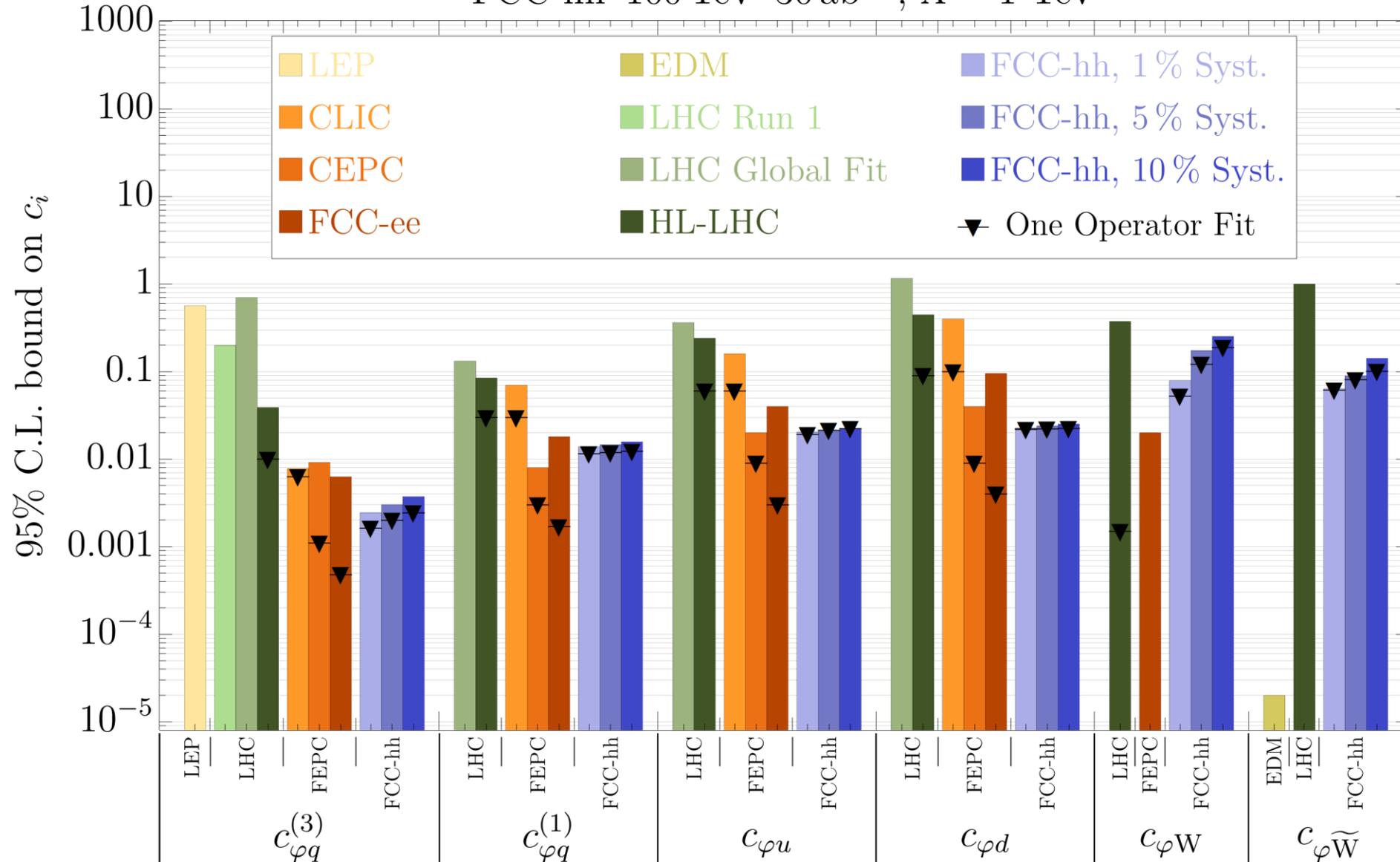
$$\text{Min}\{p_T^h, p_T^Z\} \in \{200, 400, 600, 800, 1000, \infty\} \text{ GeV}$$

$$|y_{Zh}| \in [0, 2), [2, 6]$$

(Slightly different rapidity binning for  $Z \rightarrow \nu\bar{\nu}$ )

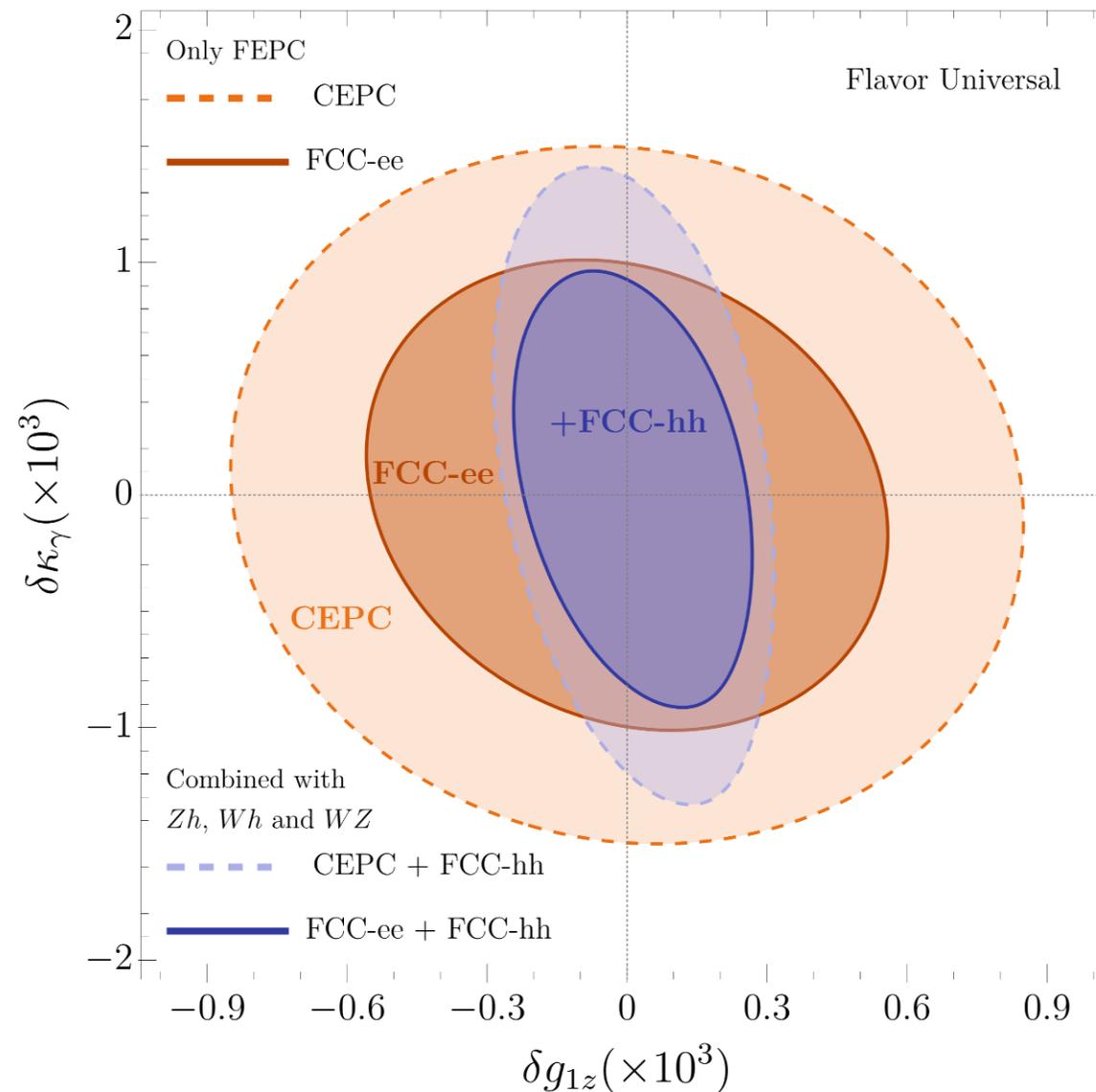
# Very competitive bounds for $c_{\varphi q}^{(3)}$ ( $Zh + Wh$ comb.)

FCC-hh 100 TeV 30  $\text{ab}^{-1}$ ,  $\Lambda = 1$  TeV



# Sizeable impact on aTGC bounds

FCC-hh 100 TeV 30  $\text{ab}^{-1}$ , 95% C.L., 5% Syst.



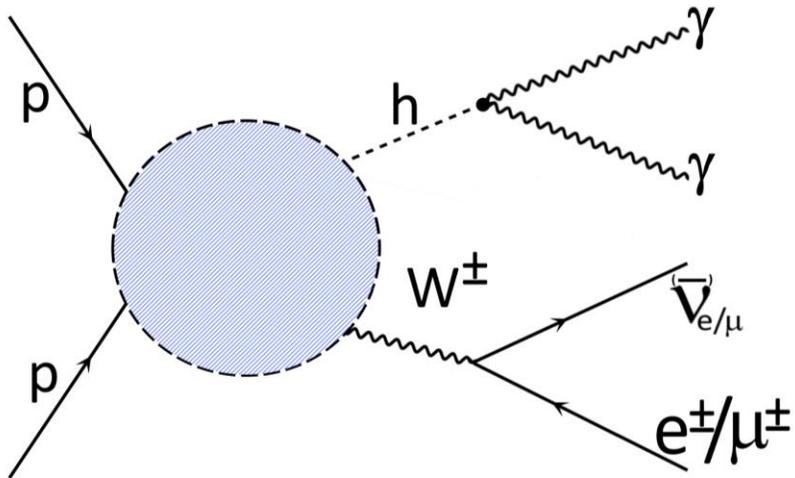
# Interference patterns

## Helicity amplitudes: High energy behavior

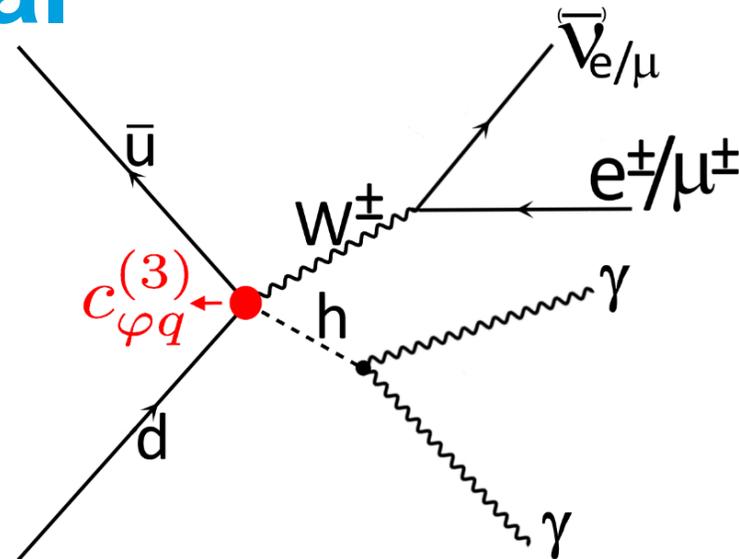
$W$ polarization	SM	$\mathcal{O}_{\varphi q}^{(3)}$	$\mathcal{O}_{\varphi W}$	$\mathcal{O}_{\varphi \tilde{W}}$
$\lambda = 0$	1	$\frac{\hat{s}}{\Lambda^2}$	$\frac{M_W^2}{\Lambda^2}$	0
$\lambda = \pm$	$\frac{M_W}{\sqrt{\hat{s}}}$	$\frac{\sqrt{\hat{s}} M_W}{\Lambda^2}$	$\frac{\sqrt{\hat{s}} M_W}{\Lambda^2}$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

# Wh.

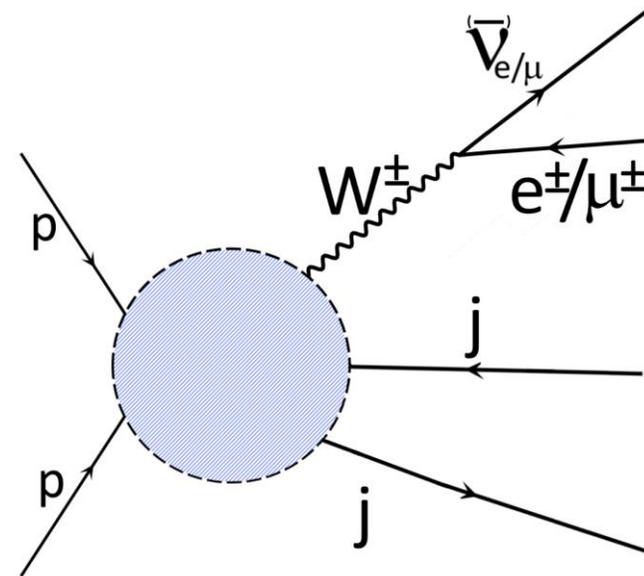
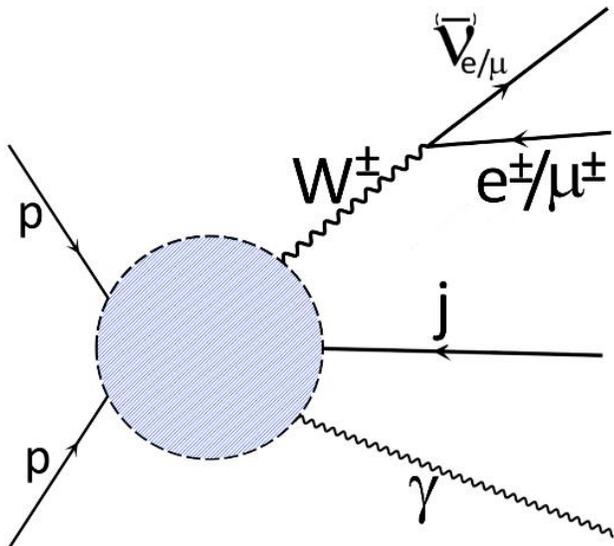
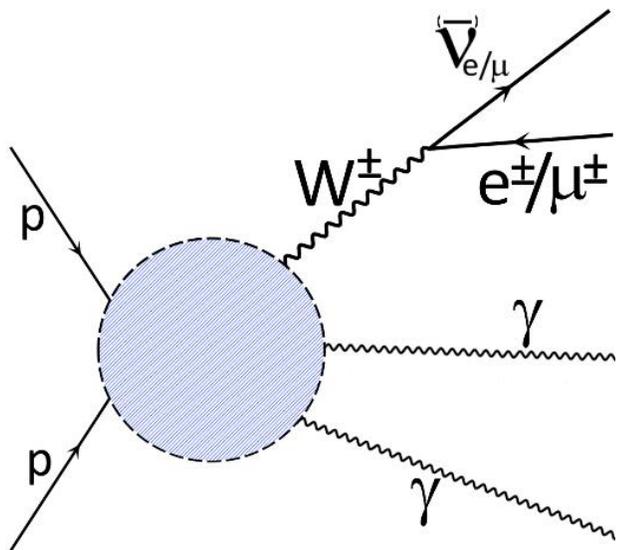
## Signal



$\supset$



## Background



# Simulation details

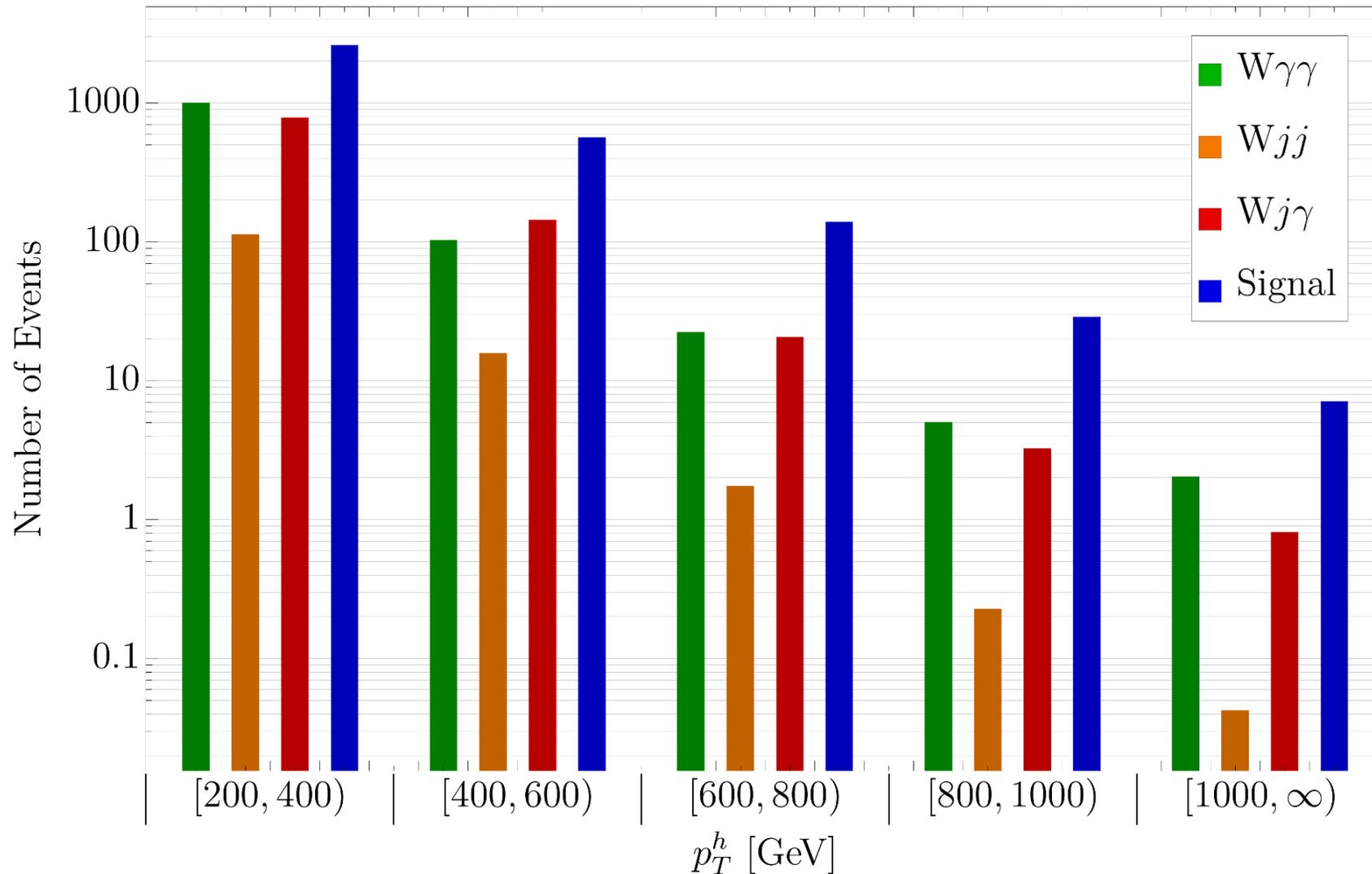
- Montecarlo generation: Madgraph5\_aMC@NLO v.2.6.5; showering: Pythia 8.2; detector simulation: Delphes v.3.4.1 with FCC-hh card.
- Signal and  $W\gamma\gamma$  simulated at FO, the rest simulated at LO. QED k-factor for the signal.
- Parton level generation cuts:

	$Wh$	$W\gamma\gamma$	$Wj\gamma$ and $Wjj$
$p_{T,\min}^\ell$ [GeV]		30	(all samples)
$p_{T,\min}^{\gamma,j}$ [GeV]		50	(all samples)
$\cancel{E}_{T,\min}$ [GeV]		100	(all samples)
$ \eta_{\max}^{j,\ell} $		6.1	(all samples)
$\Delta R_{\min}^{\gamma\gamma,\gamma j,\gamma\ell}$	–	0.01	0.01
$\Delta R_{\max}^{\gamma\gamma,\gamma j,jj}$	–	2.5	2
$m^{\gamma\gamma,\gamma j,jj}$ [GeV]	–	[50,300]	[50,250]
$p_{T,\min}^{h,\gamma\gamma}$ [GeV]	{150,350,550,750}	{100,300,500,700}	–
$p_{T,\min}^{\ell\nu}$ [GeV]	–	–	{100,300,500,700}

- Selection cuts and cutflow in the third  $p_T^h$  bin:

Selection cuts		Selection cuts / efficiency	$\xi_{h \rightarrow \gamma\gamma}^{(3)}$	$\xi_{\gamma\gamma}^{(3)}$	$\xi_{j\gamma}^{(3)}$	$\xi_{jj}^{(3)}$
$p_{T,\min}^\ell$ [GeV]	30	$\geq 1\ell^\pm$ with $p_T > 30$ GeV	0.86	0.46	0.94	0.94
$p_{T,\min}^\gamma$ [GeV]	50	$\geq 2\gamma$ each with $p_T > 50$ GeV	0.50	0.18	$5.7 \cdot 10^{-3}$	$8.7 \cdot 10^{-7}$
$\cancel{E}_T$ , min [GeV]	100	$\cancel{E}_T > 100$ GeV	0.49	0.16	$5.1 \cdot 10^{-3}$	$8.5 \cdot 10^{-7}$
$m_{\gamma\gamma}$ [GeV]	[120, 130]	$120 \text{ GeV} < m_{\gamma\gamma} < 130 \text{ GeV}$	0.46	$6 \cdot 10^{-3}$	$2 \cdot 10^{-4}$	$8.2 \cdot 10^{-8}$
$\Delta R_{\max}^{\gamma\gamma}$	{1.3, 0.9, 0.75, 0.6, 0.6}	$\Delta R^{\gamma\gamma} < \Delta R_{\max}$	0.45	$4 \cdot 10^{-3}$	$3.1 \cdot 10^{-5}$	$6.4 \cdot 10^{-8}$
$p_{T,\max}^{Wh}$ [GeV]	{300, 500, 700, 900, 900}	$p_T^{Wh} < p_{T,\max}^{Wh}$	0.41	$7 \cdot 10^{-4}$	$1.1 \cdot 10^{-5}$	$4.7 \cdot 10^{-8}$

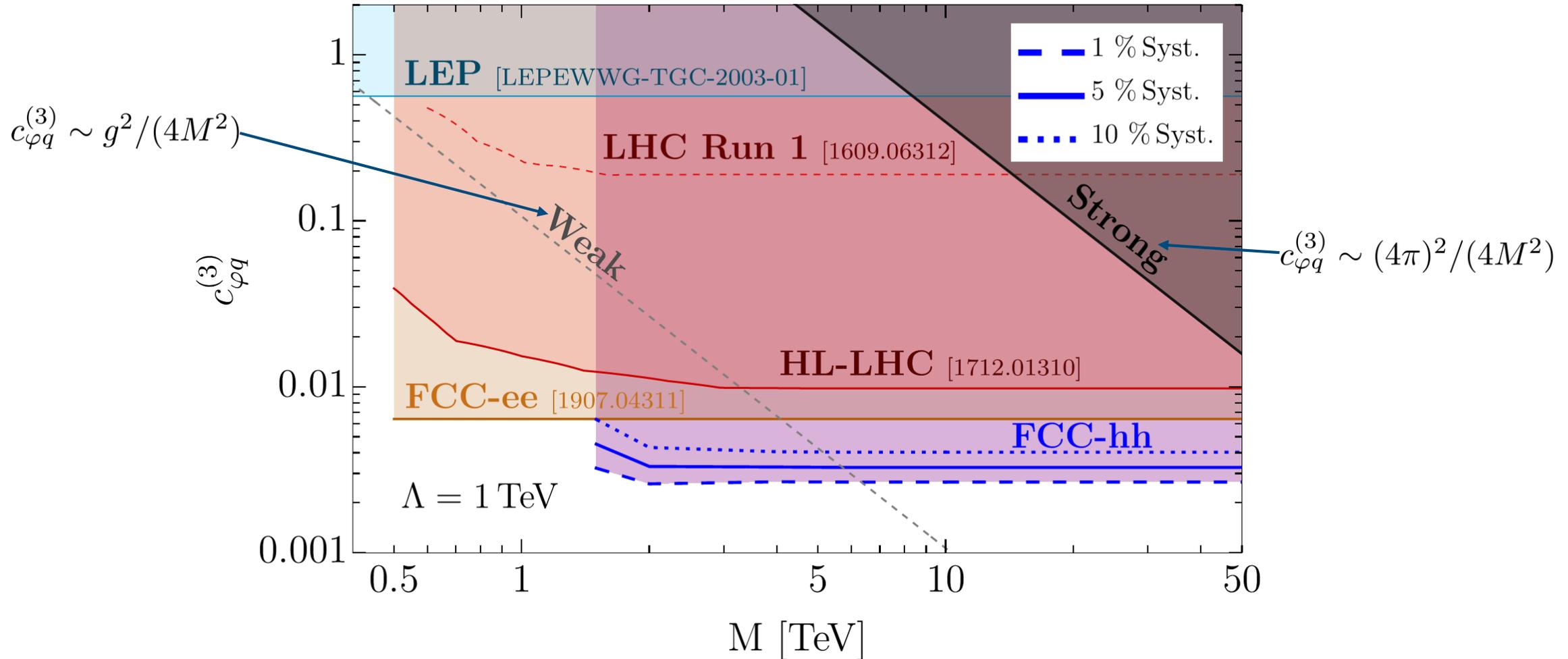
- Events per bin for the relevant processes

FCC-hh 100 TeV 30 ab<sup>-1</sup>

# More results

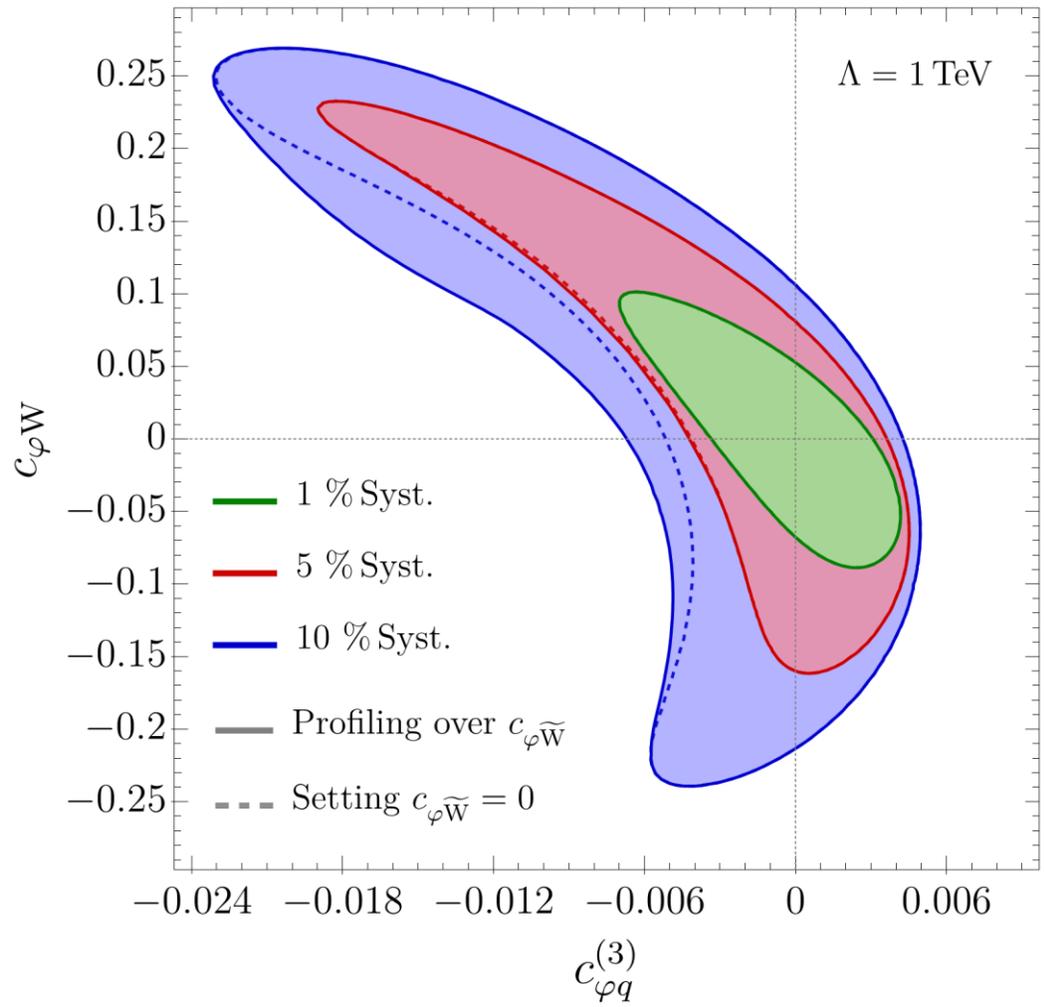
- Bounds on  $\mathcal{O}_{\varphi q}^{(3)}$  with one operator fit as a function of the NP scale  $M$ . See details in JHEP 07 (2020) 075, Fig. 5

FCC-hh 100 TeV 30  $\text{ab}^{-1}$  ( $c_{\varphi W} = c_{\varphi \widetilde{W}} = 0$ )

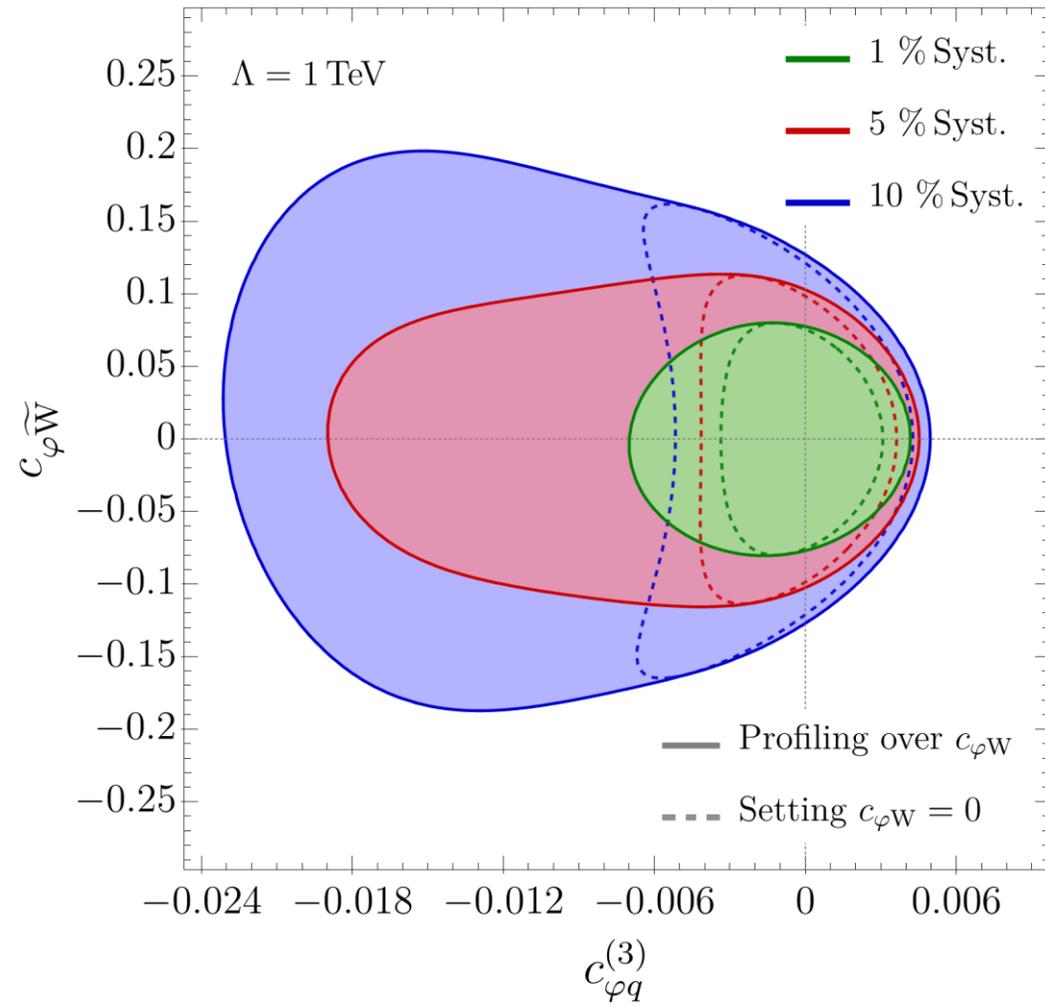


- 95% CL bounds

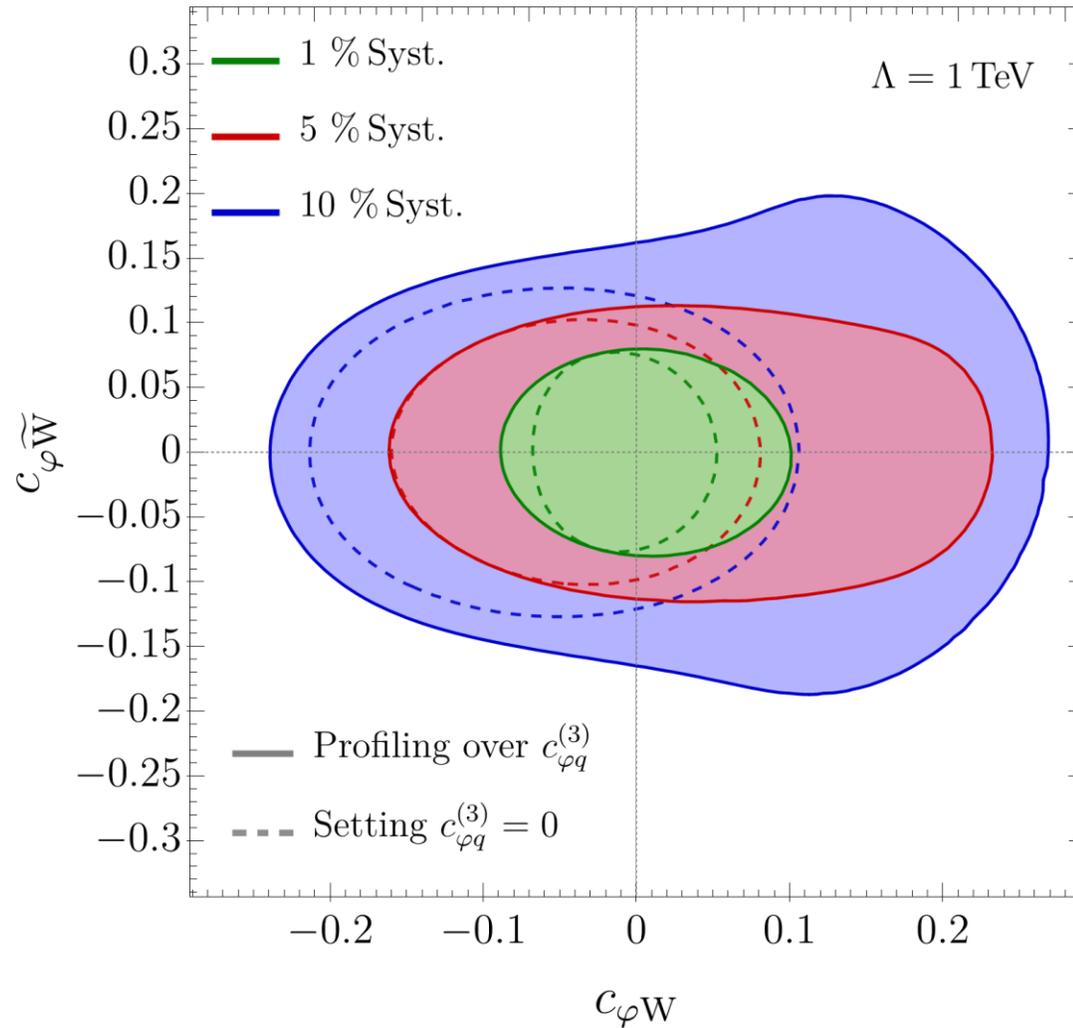
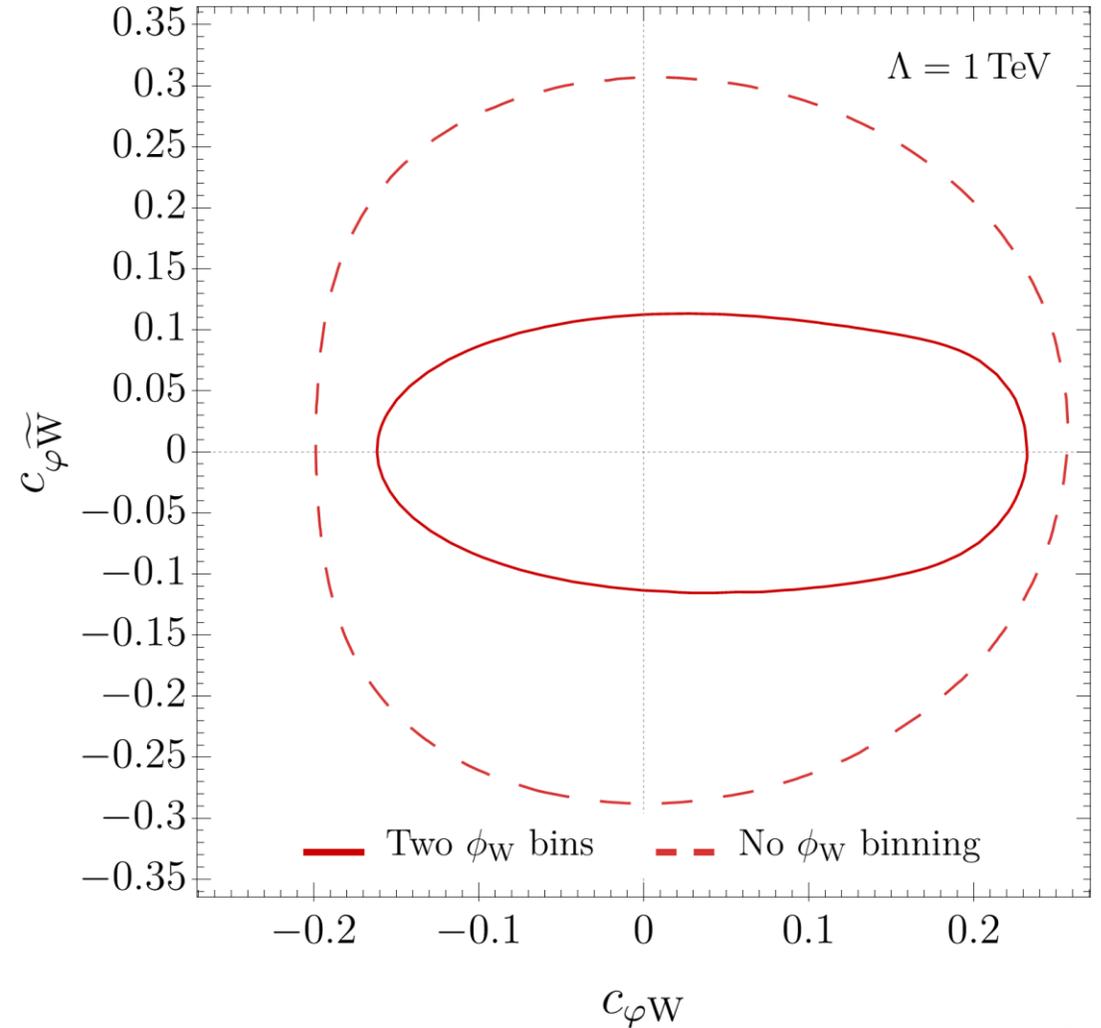
FCC-hh 100 TeV 30 ab<sup>-1</sup>



FCC-hh 100 TeV 30 ab<sup>-1</sup>



- 95% CL bounds

FCC-hh 100 TeV 30 ab<sup>-1</sup>FCC-hh 100 TeV 30 ab<sup>-1</sup>, 5% Syst.

- 95% CL bounds summary

Coefficient	Profiled Fit		One Operator Fit	
$c_{\varphi q}^{(3)}$	$[-5.1, 3.4] \times 10^{-3}$	1% syst.	$[-2.7, 2.5] \times 10^{-3}$	1% syst.
	$[-11.6, 3.8] \times 10^{-3}$	5% syst.	$[-3.3, 2.9] \times 10^{-3}$	5% syst.
	$[-20.6, 4.1] \times 10^{-3}$	10% syst.	$[-4.0, 3.5] \times 10^{-3}$	10% syst.
$c_{\varphi W}$	$[-7.1, 7.9] \times 10^{-2}$	1% syst.	$[-5.3, 4.3] \times 10^{-2}$	1% syst.
	$[-13.0, 17.5] \times 10^{-2}$	5% syst.	$[-12.1, 6.8] \times 10^{-2}$	5% syst.
	$[-20.0, 25.2] \times 10^{-2}$	10% syst.	$[-18.8, 9.0] \times 10^{-2}$	10% syst.
$c_{\varphi \tilde{W}}$	$[-6.4, 6.4] \times 10^{-2}$	1% syst.	$[-6.1, 6.1] \times 10^{-2}$	1% syst.
	$[-9.0, 8.8] \times 10^{-2}$	5% syst.	$[-8.1, 8.1] \times 10^{-2}$	5% syst.
	$[-13.5, 14.2] \times 10^{-2}$	10% syst.	$[-10.1, 10.1] \times 10^{-2}$	10% syst.

- Bound on aTGCs.  $c_{\varphi q}^{(3)}$  is related to aTGCs as follows:

$$c_{\varphi q}^{(3)} = \frac{\Lambda^2}{m_W^2} g^2 (\delta g_L^{Zu} - \delta g_L^{Zd} - c_\theta^2 \delta g_{1z})$$

- For theories where the vertex corrections are small (e.g. universal theories), the bound on  $c_{\varphi q}^{(3)}$  can be recast as a bound on  $\partial g_{1z}$ . For 5% systematics and  $\Lambda = 1$  TeV:

	One operator Fit	Profiled global fit
$\partial g_{1z} \in$	$[-5.0, 4.4] \times 10^{-5}$	$[-17.6, 5.8] \times 10^{-5}$

- Bound from other sources:

	LEP ([1902.00134])	Current LHC ([1810.05149])	WZ@HL-LHC ([1712.01310])	FCC-ee ([1907.04311])
$\partial g_{1z} \in$	$[-1.3, 1.8] \times 10^{-1}$	$[-19, 1] \times 10^{-3}$	$[-1, 1] \times 10^{-3}$	$[-5, 5] \times 10^{-4}$

## Interference patterns

## Helicity amplitudes: High energy behavior

$Z$ polarization	SM	$\mathcal{O}_{\varphi q}^{(3)}$	$\mathcal{O}_{\varphi q}^{(1)}$	$\mathcal{O}_{\varphi u}$	$\mathcal{O}_{\varphi d}$
$\lambda = 0$	1	$\frac{\hat{s}}{\Lambda^2}$	$\frac{\hat{s}}{\Lambda^2}$	$\frac{\hat{s}}{\Lambda^2}$	$\frac{\hat{s}}{\Lambda^2}$
$\lambda = \pm 1$	$\frac{M_Z}{\sqrt{\hat{s}}}$	$\frac{\sqrt{\hat{s}} M_Z}{\Lambda^2}$	$\frac{\sqrt{\hat{s}} M_Z}{\Lambda^2}$	$\frac{\sqrt{\hat{s}} M_Z}{\Lambda^2}$	$\frac{\sqrt{\hat{s}} M_Z}{\Lambda^2}$

# Simulation details

- Montecarlo generation: Madgraph5\_aMC@NLO v.2.7.3; showering: Pythia 8.2; detector simulation: Delphes v.3.4.1 with FCC-hh card. SMEFT@NLO UFO (<http://feynrules.irmp.ucl.ac.be/wiki/SMEFTatNLO>)
- Signal simulated at LO and corrected to (QCD+QED) NLO with k-factors. Gluon initiated processes simulated at LO. The rest simulated at QCD NLO.
- Parton level generation cuts:

Cut	Channel	
	$Z \rightarrow \nu\bar{\nu}$	$Z \rightarrow l^+l^-$
$p_{T,\min}^j$ [GeV]	30	
$p_{T,\min}^\gamma$ [GeV]	50	
$p_{T,\min}^l$	0	30 (only for LO samples)
$ \eta_{max}^{\gamma,j} $	6.1 <sup>1</sup>	
$ \eta_{max}^l $	$\infty$	6.1
$\Delta R^{\ell,\gamma l}$	0.01	
$\Delta R^{\gamma\gamma}$	0.25 (0.01 for LO samples)	
$p_T^{V,j}$	{0, 200, 400, 600, 800, 1200, $\infty$ }	

- Selection cuts and binning:

$Z \rightarrow \nu\bar{\nu}$		$Z \rightarrow l^-l^+$	
Bins of $ y^h $	Bins of $\min\{p_T^h, p_T^Z\}$		Bins of $ y^{Zh} $
[0, 2), [2, 6]	[200, 400)		[0, 2), [2, 6]
	[400, 600)		
[0, 1.5), [1.5, 6]	[600, 800)		
[0, 1), [1, 6]	[800, 1000)		
	[1000, $\infty$ )		

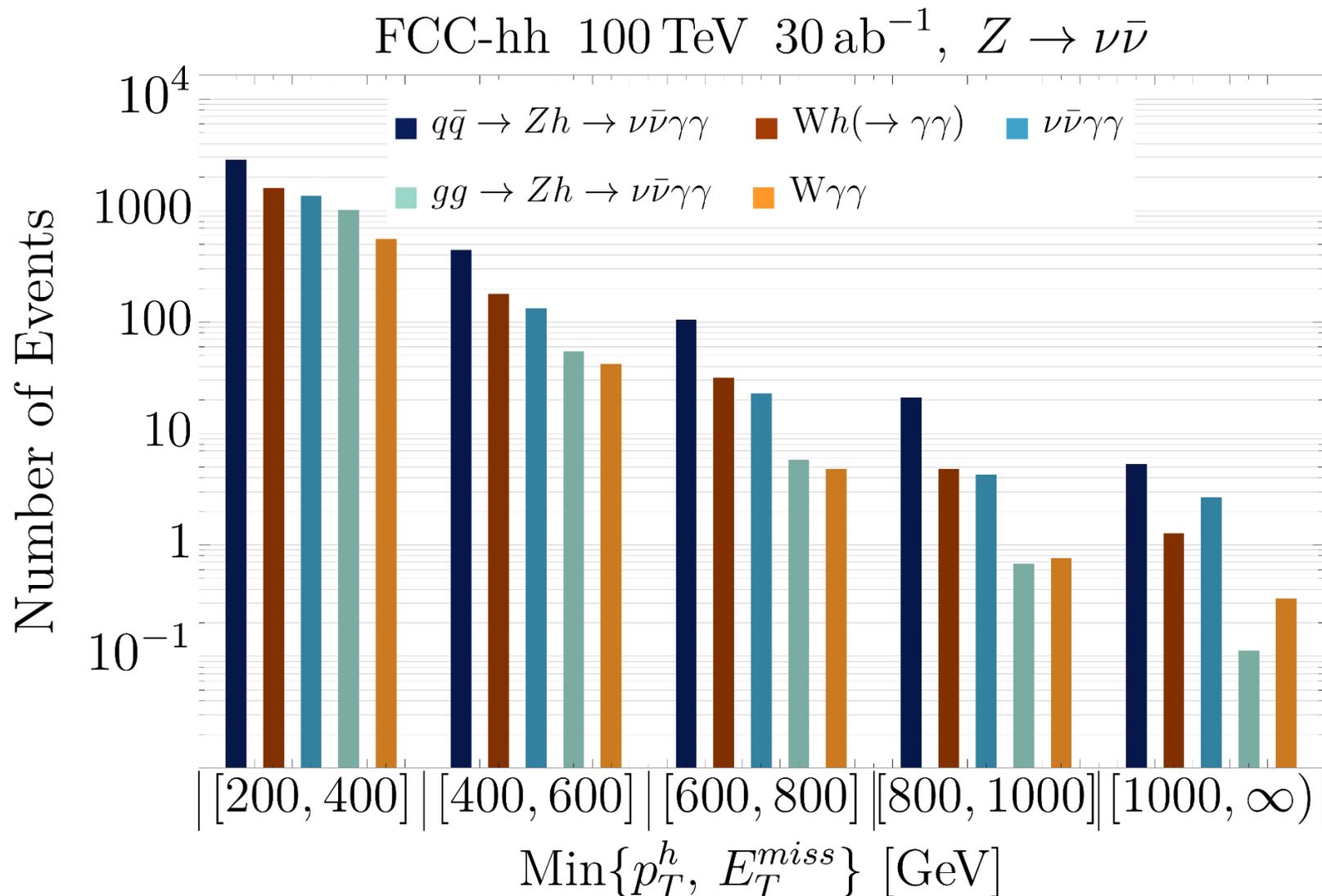
	Selection cuts
$p_{T,\min}^\ell$ [GeV]	30
$p_{T,\min}^\gamma$ [GeV]	50
$m_{\gamma\gamma}$ [GeV]	[120, 130]
$m_{l+l^-}$ [GeV]	[81, 101]
$\Delta R_{\max}^{\gamma\gamma}$	{1.3, 0.9, 0.75, 0.6, 0.6}
$\Delta R_{\max}^{l+l^-}$	{1.2, 0.8, 0.6, 0.5, 0.4}
$p_{T,\max}^{Zh}$ [GeV]	{200, 600, 1100, 1500, 1900}

- K-factors for signal in 1+QCD+QED format

$p_{Tmin}$ bin [GeV]	$Zh \rightarrow ll\gamma\gamma$	$Zh \rightarrow \nu\nu\gamma\gamma$	$Wh \rightarrow \nu l\gamma\gamma$
0 – 200	$1 + 0.59 - 0.07 = 1.52$	$1 + 0.26 - 0.06 = 1.20$	$1 + 0.17 - 0.04 = 1.13$
200 – 400	$1 + 0.52 - 0.09 = 1.43$	$1 + 0.31 - 0.09 = 1.22$	$1 + 0.28 - 0.09 = 1.19$
400 – 600	$1 + 0.64 - 0.14 = 1.50$	$1 + 0.37 - 0.14 = 1.23$	$1 + 0.28 - 0.17 = 1.11$
600 – 800	$1 + 0.69 - 0.18 = 1.51$	$1 + 0.40 - 0.18 = 1.22$	$1 + 0.35 - 0.24 = 1.11$
800 – 1000	$1 + 0.70 - 0.24 = 1.46$	$1 + 0.40 - 0.24 = 1.16$	$1 + 0.39 - 0.32 = 1.07$
1000 – $\infty$	$1 + 0.69 - 0.32 = 1.37$	$1 + 0.40 - 0.32 = 1.08$	$1 + 0.36 - 0.40 = 0.96$

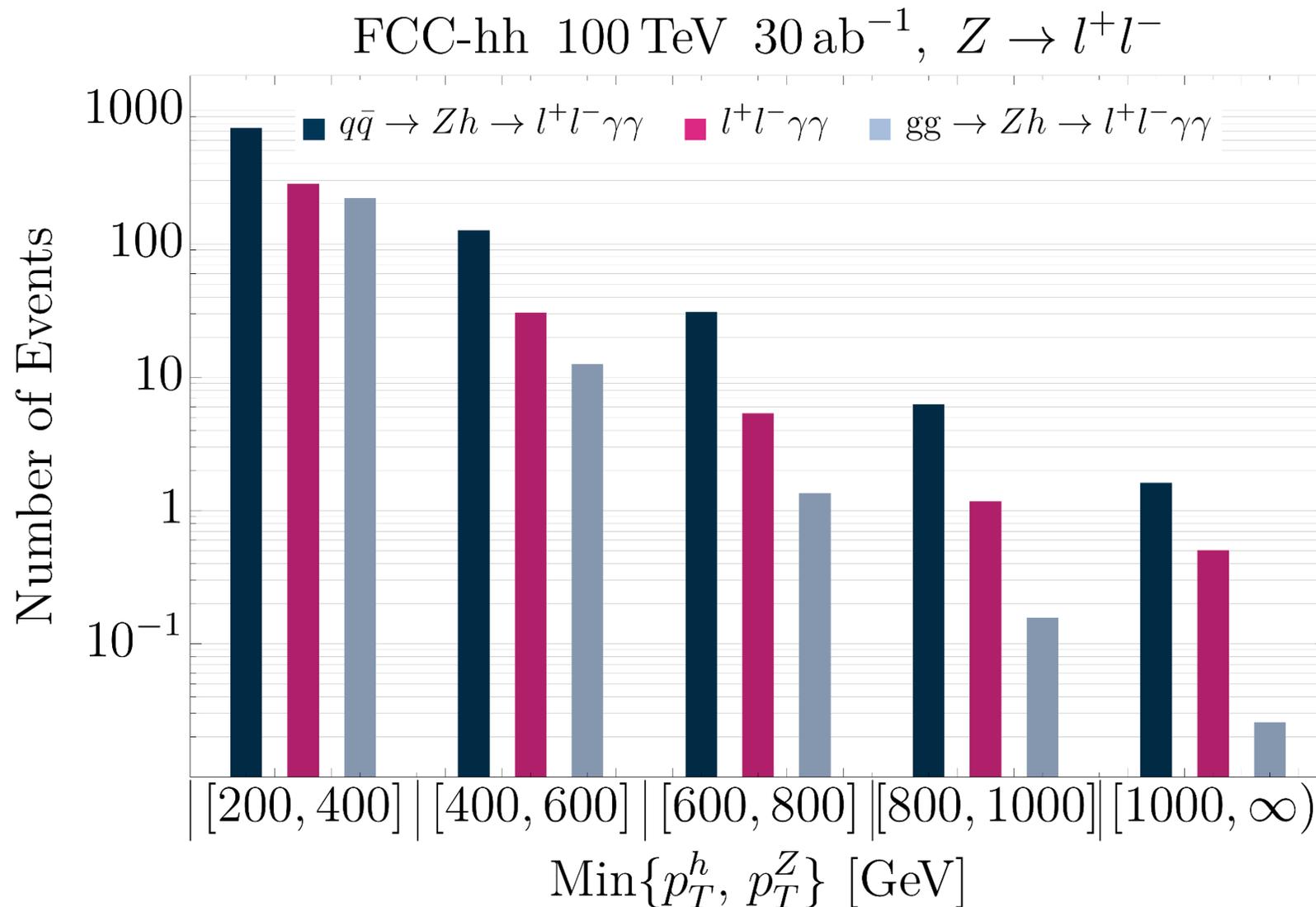
## More results

- Events per bin for the relevant processes in the neutrino channel.  $Wh$  is part of the signal because it is affected by  $\mathcal{O}_{\varphi q}^{(3)}$ .



## More results

- Events per bin for the relevant processes in the leptonic channel.

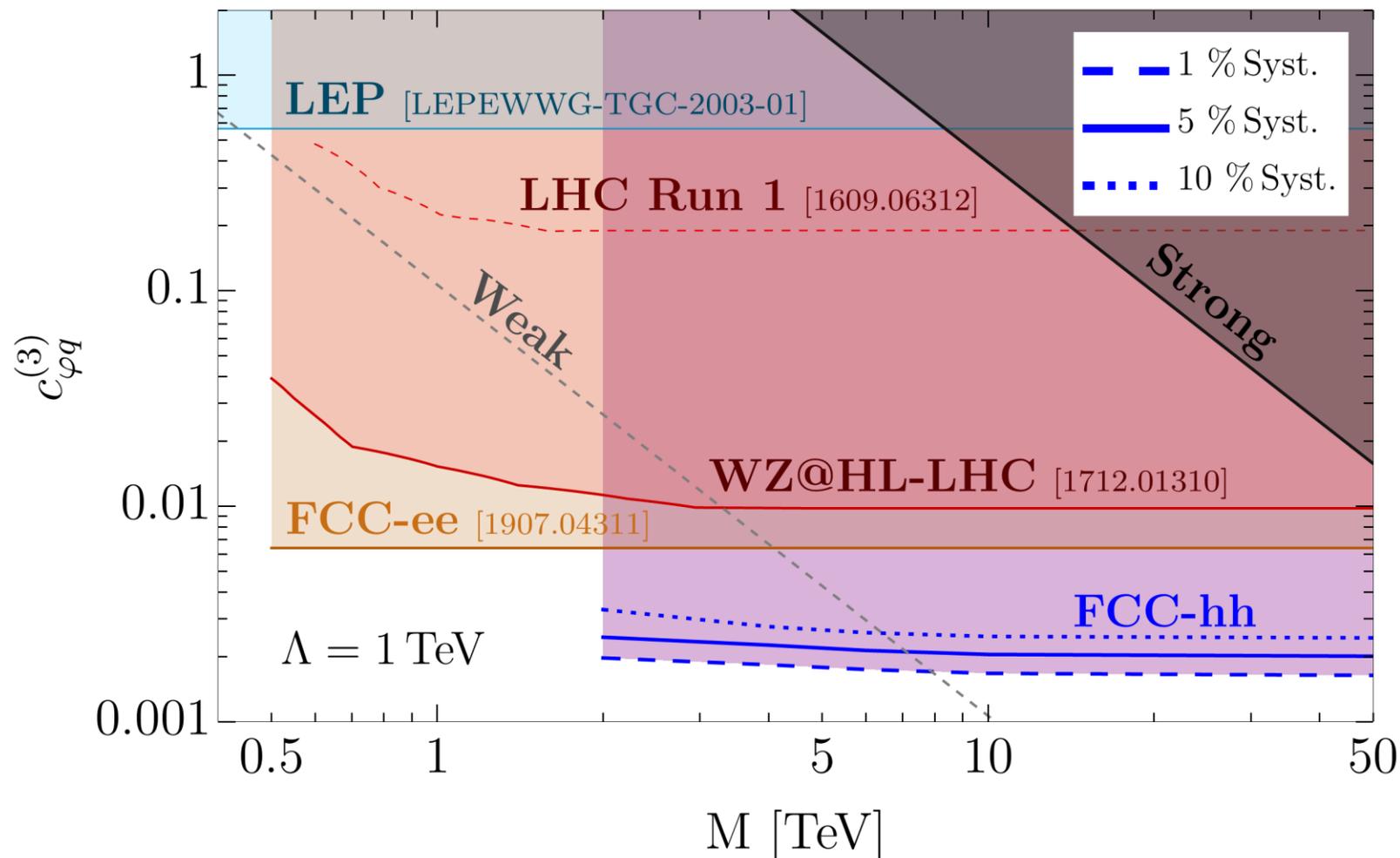


# Zh + Wh

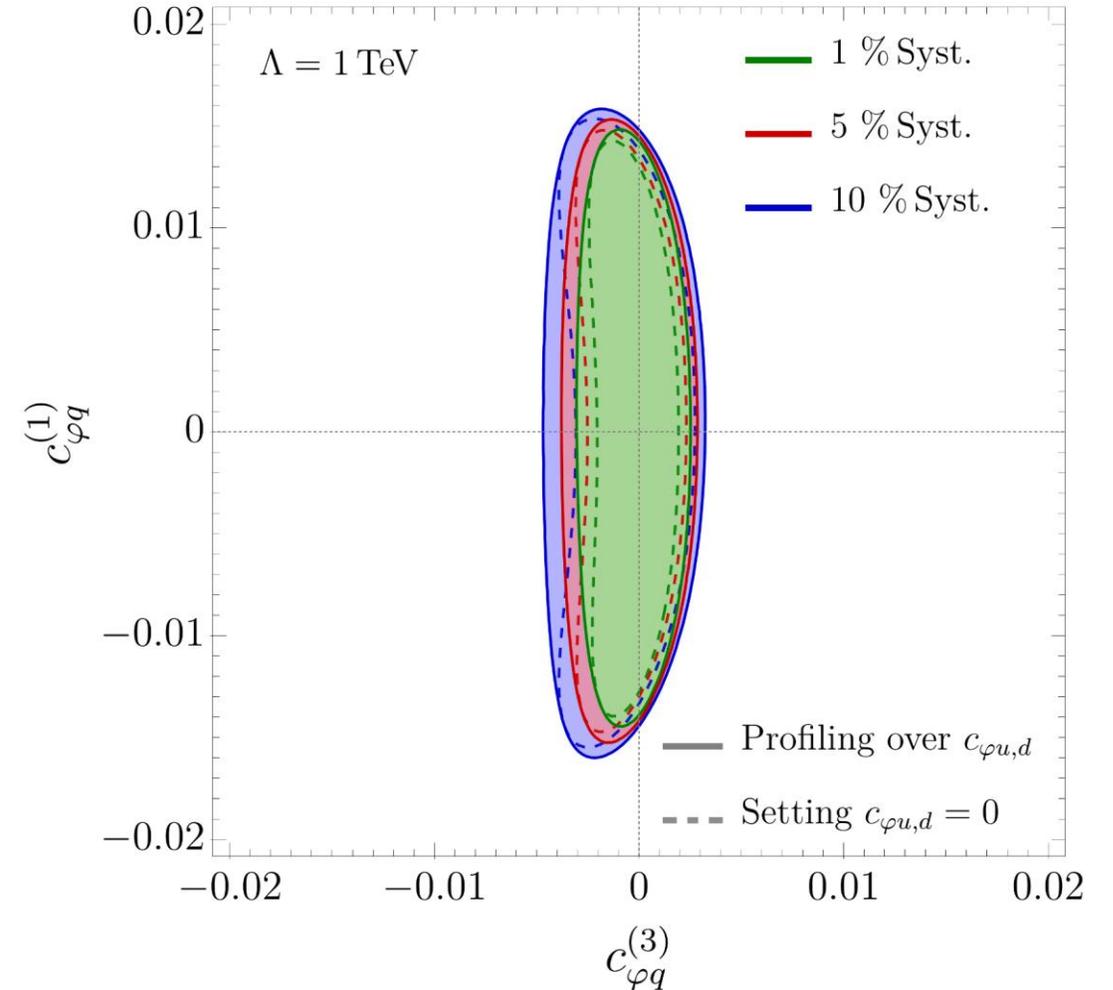
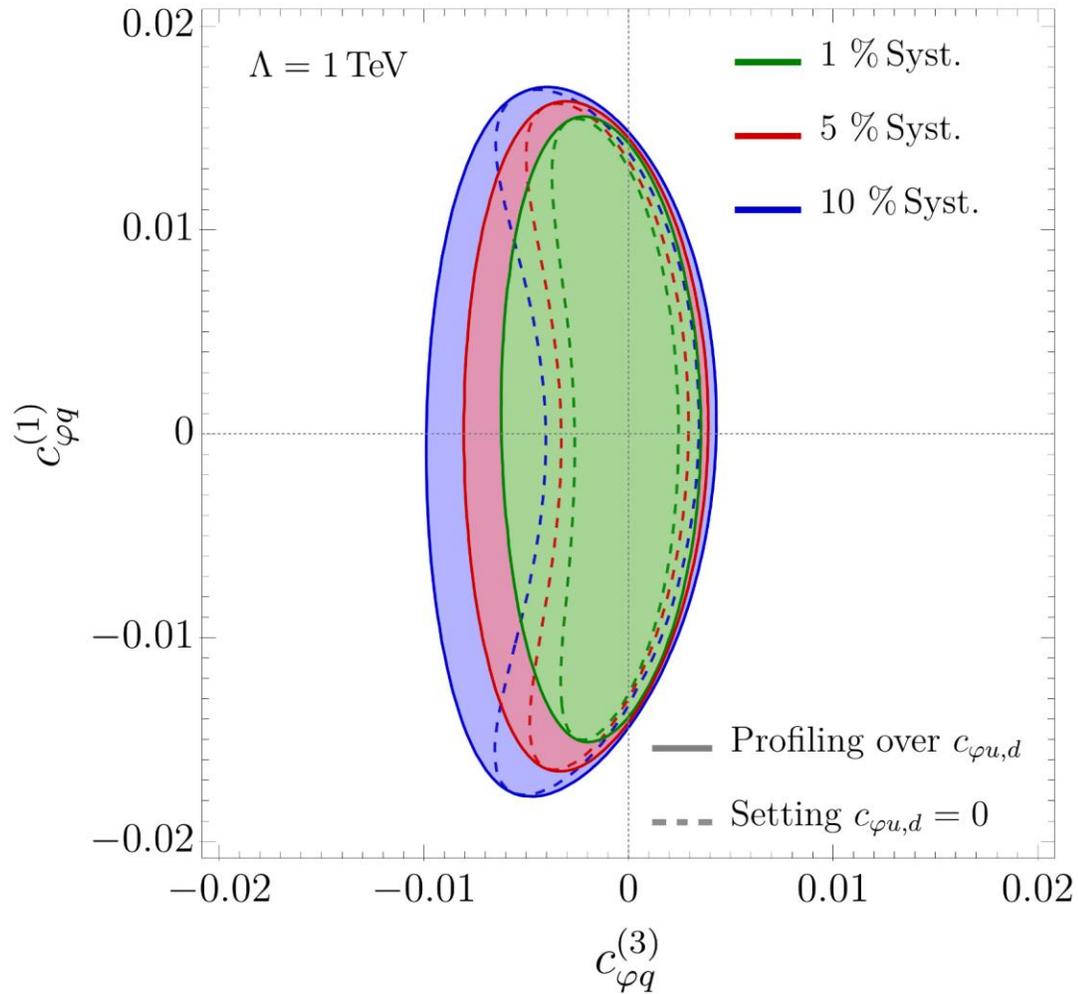
# More results

- Bounds on  $\mathcal{O}_{\varphi q}^{(3)}$  with one operator fit combining the Wh and Zh processes as a function of the NP scale  $M$ .

FCC-hh 100 TeV 30 ab<sup>-1</sup>, 1-op. fit, (Zh + Wh)



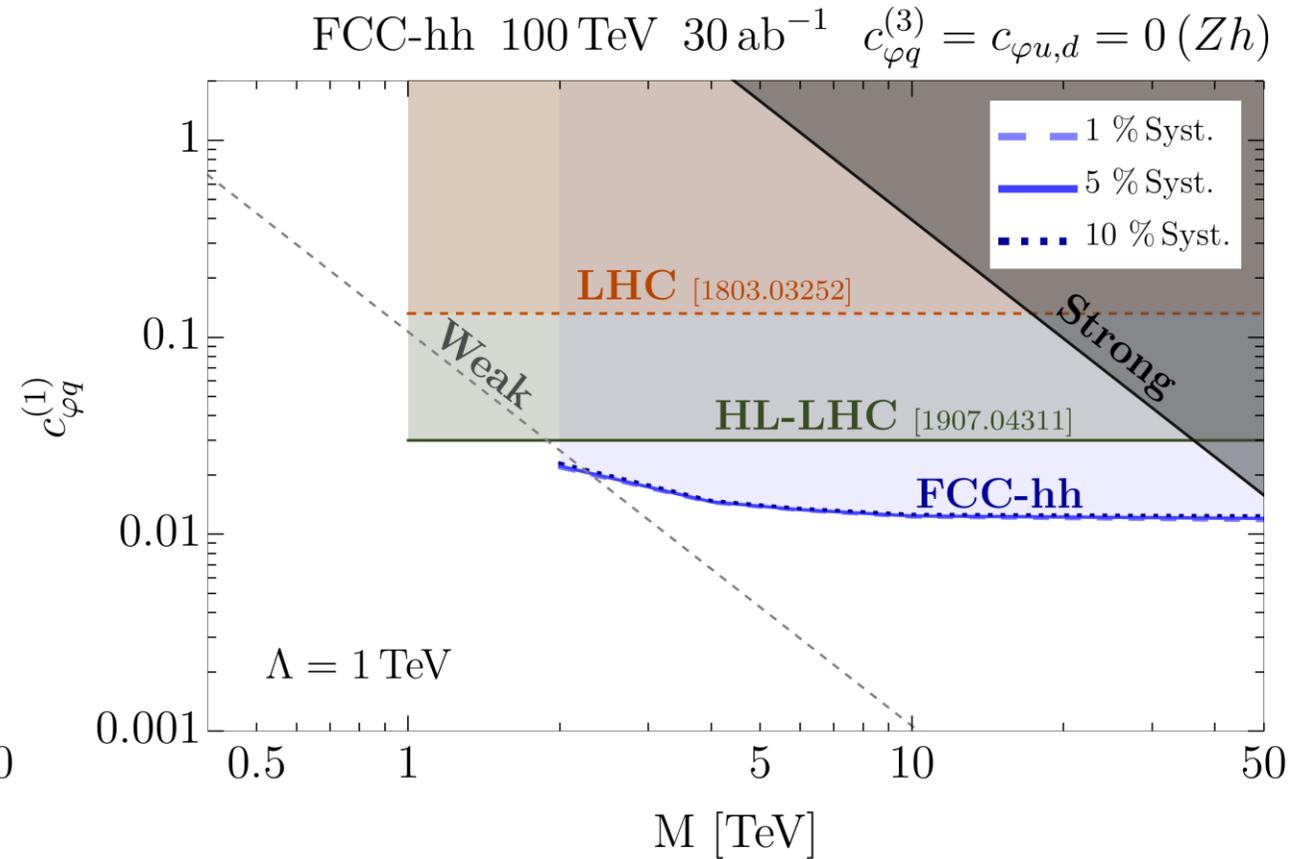
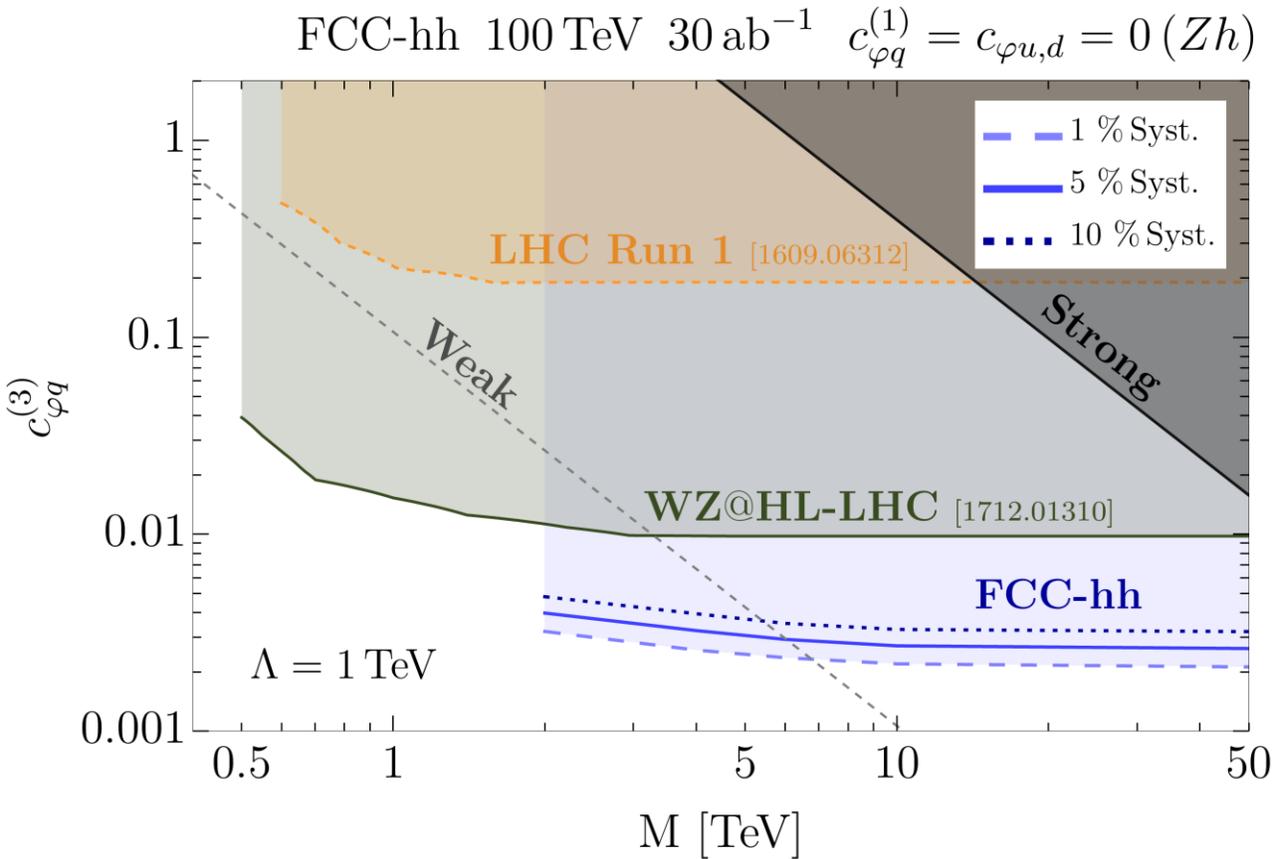
- 95% CL bounds

FCC-hh 100 TeV 30 ab<sup>-1</sup>FCC-hh 100 TeV 30 ab<sup>-1</sup> ( $Zh + Wh$ )

# Zh.

# More results

- 95% CL bounds



- 95% CL bounds summary

Coefficient	Profiled Fit	One Operator Fit
$c_{\varphi q}^{(3)}$	$[-5.2, 3.1] \times 10^{-3}$ 1% syst.	$[-2.1, 2.0] \times 10^{-3}$ 1% syst.
	$[-6.7, 3.3] \times 10^{-3}$ 5% syst.	$[-2.6, 2.4] \times 10^{-3}$ 5% syst.
	$[-8.2, 3.7] \times 10^{-3}$ 10% syst.	$[-3.2, 2.8] \times 10^{-3}$ 10% syst.
$c_{\varphi q}^{(3)}$ (+Wh)	$[-2.5, 2.1] \times 10^{-3}$ 1% syst.	$[-1.6, 1.6] \times 10^{-3}$ 1% syst.
	$[-3.0, 2.4] \times 10^{-3}$ 5% syst.	$[-2.0, 1.9] \times 10^{-3}$ 5% syst.
	$[-3.7, 2.7] \times 10^{-3}$ 10% syst.	$[-2.4, 2.2] \times 10^{-3}$ 10% syst.
$c_{\varphi q}^{(1)}$	$[-1.3, 1.4] \times 10^{-2}$ 1% syst.	$[-1.1, 1.15] \times 10^{-2}$ 1% syst.
	$[-1.5, 1.5] \times 10^{-2}$ 5% syst.	$[-1.1, 1.2] \times 10^{-2}$ 5% syst.
	$[-1.6, 1.5] \times 10^{-2}$ 10% syst.	$[-1.2, 1.2] \times 10^{-2}$ 10% syst.
$c_{\varphi u}$	$[-2.0, 1.6] \times 10^{-2}$ 1% syst.	$[-1.9, 0.89] \times 10^{-2}$ 1% syst.
	$[-2.1, 1.7] \times 10^{-2}$ 5% syst.	$[-2.1, 0.96] \times 10^{-2}$ 5% syst.
	$[-2.2, 1.8] \times 10^{-2}$ 10% syst.	$[-2.2, 1.0] \times 10^{-2}$ 10% syst.
$c_{\varphi d}$	$[-2.1, 2.3] \times 10^{-2}$ 1% syst.	$[-1.4, 2.2] \times 10^{-2}$ 1% syst.
	$[-2.2, 2.4] \times 10^{-2}$ 5% syst.	$[-1.5, 2.2] \times 10^{-2}$ 5% syst.
	$[-2.3, 2.5] \times 10^{-2}$ 10% syst.	$[-1.5, 2.2] \times 10^{-2}$ 10% syst.