No channel left behind

Precision with Vh at LHC and FCC-hh

Planck Conference 2022

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Paris, France

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With F. Bishara, S. De Curtis, L. Delle Rose, P. Englert, C. Grojean, M. Montull, G. Panico.

arXiv 2004.06122 (JHEP 07 (2020) 075)

arXiv 2011.13941 (JHEP 04 (2021) 154)

arXiv 22XX.YYYYY

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A trick of the tail

Precision with hadron colliders? Yes!

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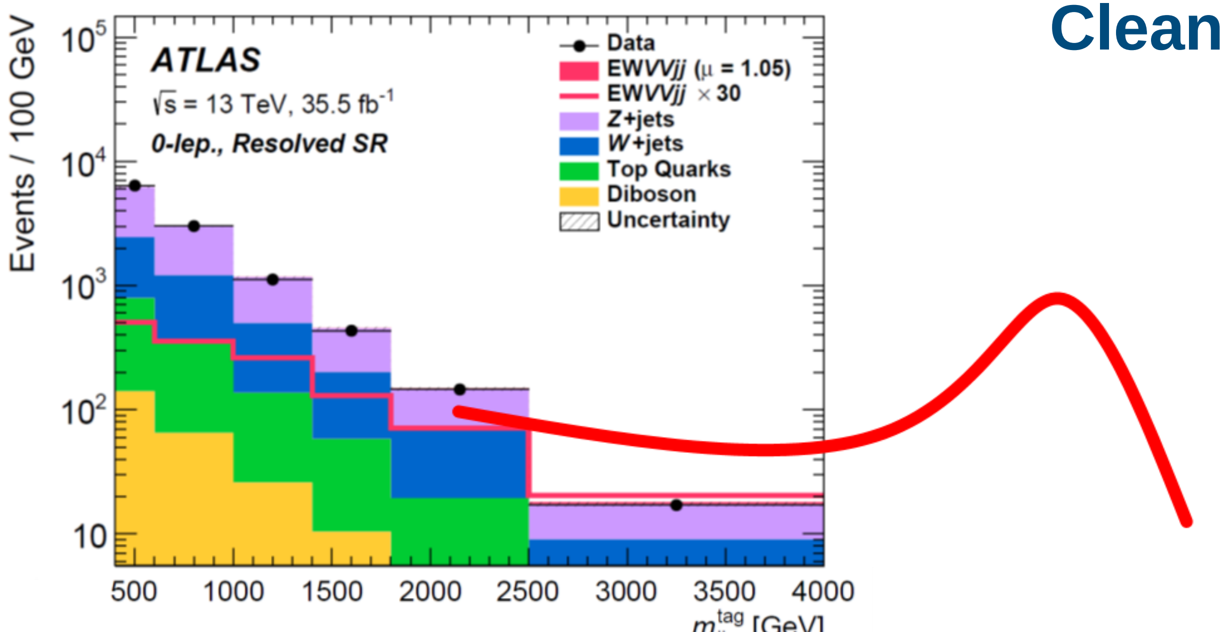

ATLAS, 1905.07714

Clean channels + NP effects that grow with E

Tail hunting!

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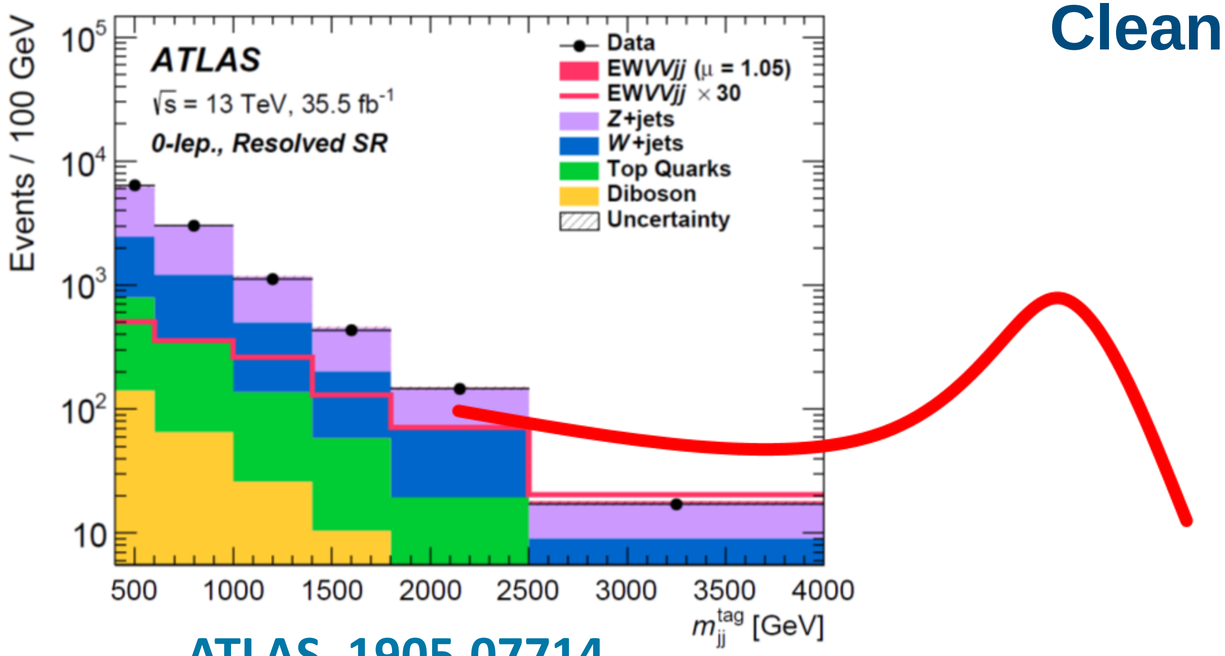

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Heavy New Physics

Effective Field Theories

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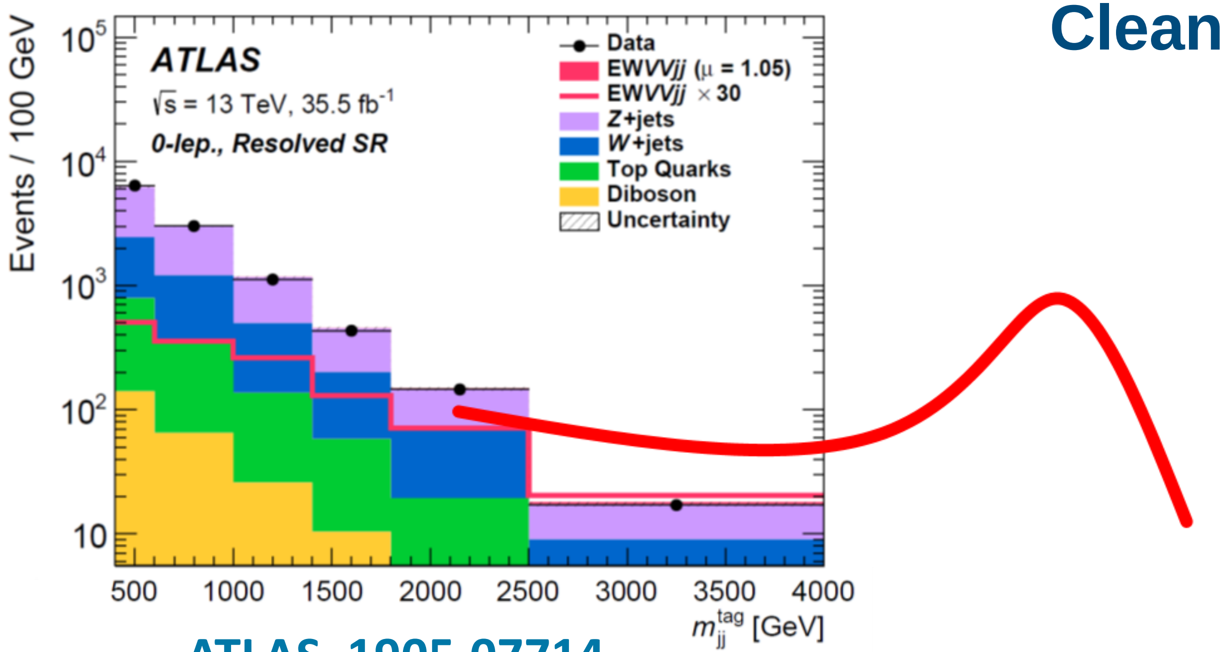


ATLAS, 1905.07714

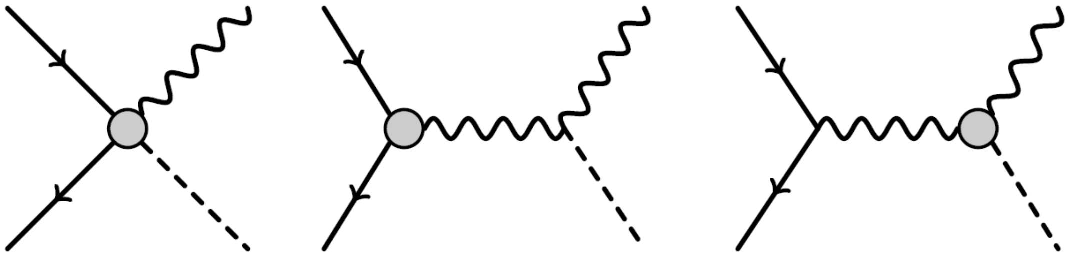
Clean channels + NP effects that grow with E

Tail hunting!

Heavy New Physics

Effective Field Theories

Diboson processes offer a window into EW and Higgs dynamics.



New collider, new possibilities

For $p_T^h > 550$ GeV:

$$pp \to W^{\pm} h$$

Higgs decay	Higgs BR	n_{HL-LHC}	n_{HE-LHC}	n_{FCC-hh}
$\bar{b}b$	$6 \cdot 10^{-1}$	10^3	10^4	10^5
$\tau\tau$	$6 \cdot 10^{-2}$	10^2	10^3	10^4
$\gamma\gamma$	$2 \cdot 10^{-3}$	10^0	10^2	10^3
$4l$	$2 \cdot 10^{-3}$	10^0	10^2	10^3
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$$\frac{s}{\sqrt{s+b}} \ll 1$$

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$$\frac{s}{\sqrt{s+b}} \ll 1$$

$$\frac{s}{\sqrt{s+b}} \approx 1$$

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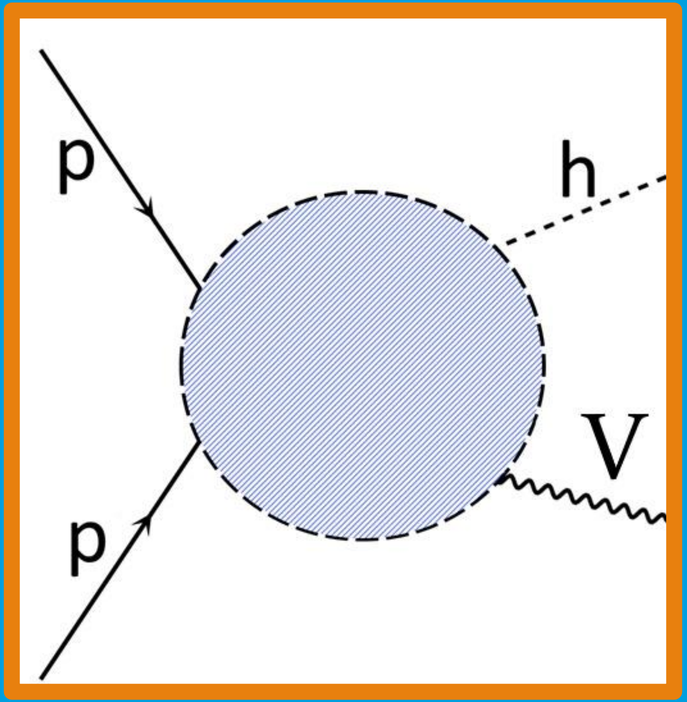
$\bar{b}b$: $\frac{s}{\sqrt{s+b}} \ll 1$

$\gamma\gamma$: $\frac{s}{\sqrt{s+b}} \approx 1$

FCC-hh will open new channels. How will they compare with the known ones?

The process of interest.



$$pp \to Vh$$

What New Physics can we probe?

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

$$\frac{c^{(1)}_{\varphi q}}{\Lambda^2}\left(\overline{Q}_L\gamma^\mu Q_L\right)\left(iH^\dagger \overleftrightarrow{D}_\mu H\right)$$

$$\frac{c_{\varphi u}}{\Lambda^2}\left(\overline{u}_R\gamma^\mu u_R\right)\left(iH^\dagger \overleftrightarrow{D}_\mu H\right)$$

$$\frac{c_{\varphi d}}{\Lambda^2}\left(\overline{d}_R\gamma^\mu d_R\right)\left(iH^\dagger \overleftrightarrow{D}_\mu H\right)$$

$$\frac{c^{(3)}_{\varphi q}}{\Lambda^2}\left(\overline{Q}_L\sigma^a\gamma^\mu Q_L\right)\left(iH^\dagger\sigma^a \overleftrightarrow{D}_\mu H\right)$$

$$\frac{c_{\varphi \mathrm{W}}}{\Lambda^2} H^\dagger H\, W^{a,\mu\nu}W^a_{\mu\nu}$$

$$\frac{c_{\varphi \widetilde{\mathrm{W}}}}{\Lambda^2} H^\dagger H\, W^{a,\mu\nu}\widetilde{W}^a_{\mu\nu}$$

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

Vh. What New Physics can we probe?

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

Zh ←

$$\frac{c_{\varphi q}^{(1)}}{\Lambda^2}\left(\overline{Q}_L\gamma^\mu Q_L\right)\left(iH^\dagger\overleftrightarrow{D}_\mu H\right)$$

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$W^\pm h$ ←

$$\frac{c_{\varphi \mathrm{W}}}{\Lambda^2}H^\dagger H\, W^{a,\mu\nu}W^a_{\mu\nu}$$

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Vh. What New Physics can we probe?

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High energy behavior

Zh

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$$\frac{c^{(3)}_{\varphi q}}{\Lambda^2}\left(\overline{Q}_L\sigma^a\gamma^\mu Q_L\right)\left(iH^\dagger \sigma^a\overleftrightarrow{D}_\mu H\right)$$

$$\longrightarrow \frac{\mathcal{A}_{BSM}}{\mathcal{A}_{SM}} \sim \hat{s} = E^2_{CM}$$

$W^\pm h$

$$\frac{c_{\varphi \mathrm{W}}}{\Lambda^2} H^\dagger H\, W^{a,\mu\nu}W^a_{\mu\nu}$$

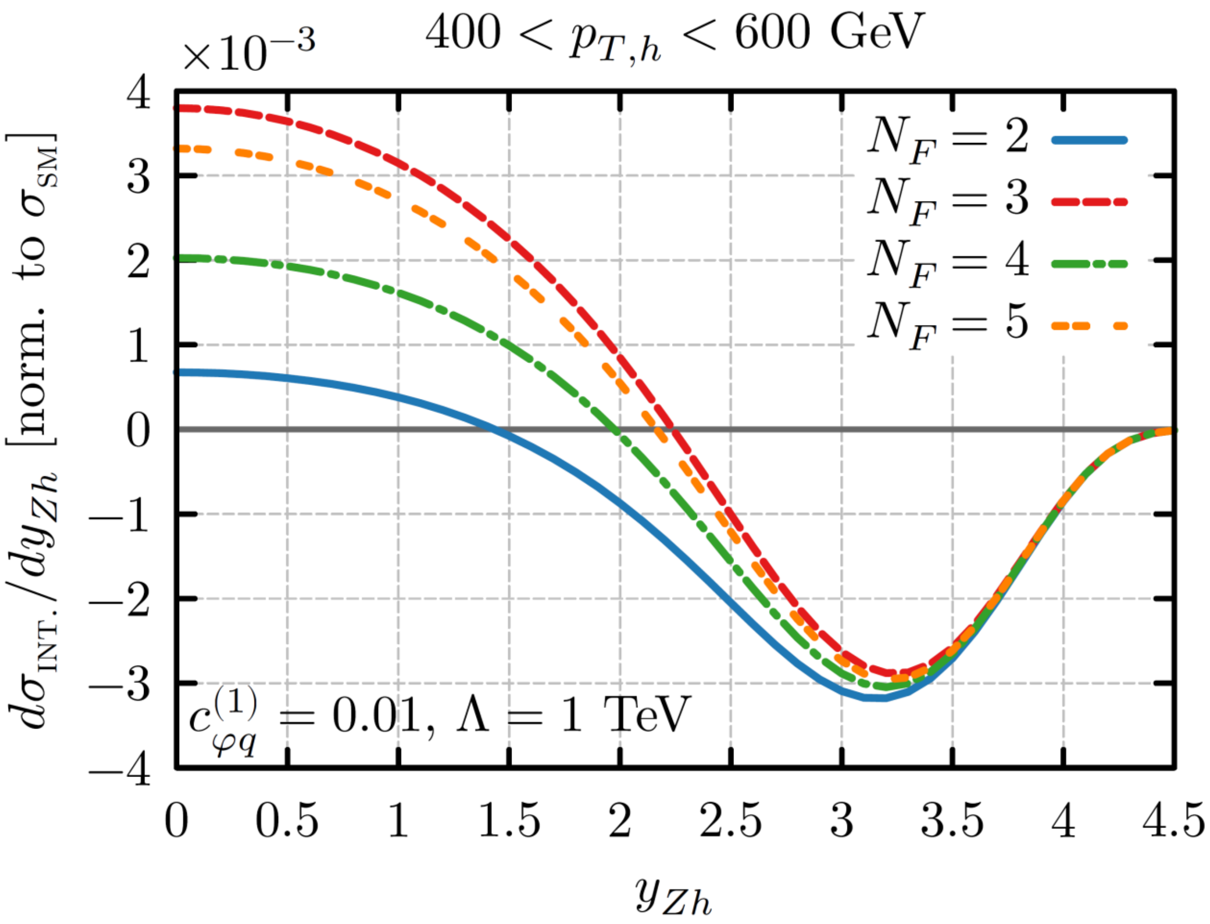
$$\frac{c_{\varphi \widetilde{\mathrm{W}}}}{\Lambda^2} H^\dagger H\, W^{a,\mu\nu}\widetilde{W}^a_{\mu\nu}$$

$$\longrightarrow \frac{\mathcal{A}_{BSM}}{\mathcal{A}_{SM}} \sim \sqrt{\hat{s}} = E_{CM}$$

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

Double binning for the win

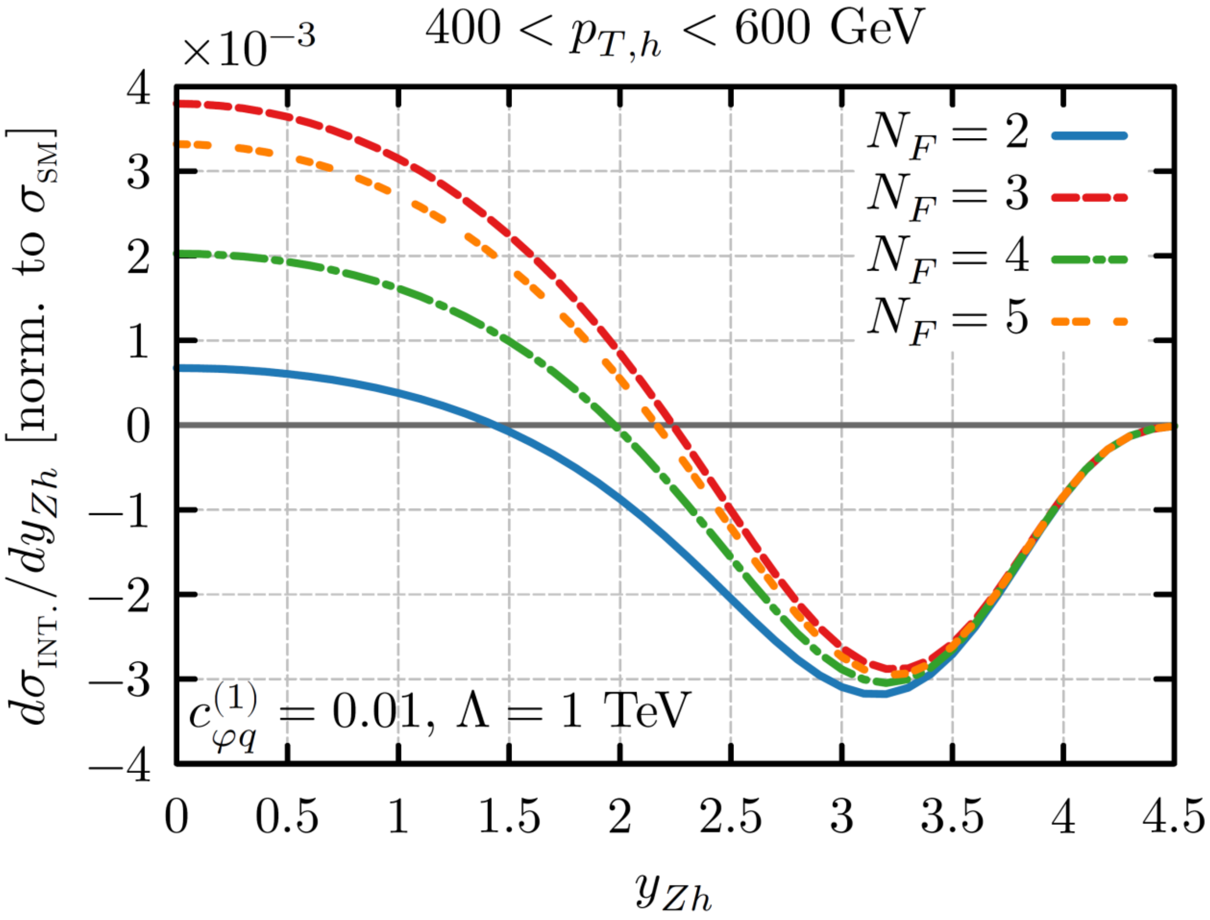
Zh. Double binning for the win



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

Cancellation of up and down contributions

Zh. Double binning for the win



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

Cancellation of up and down contributions

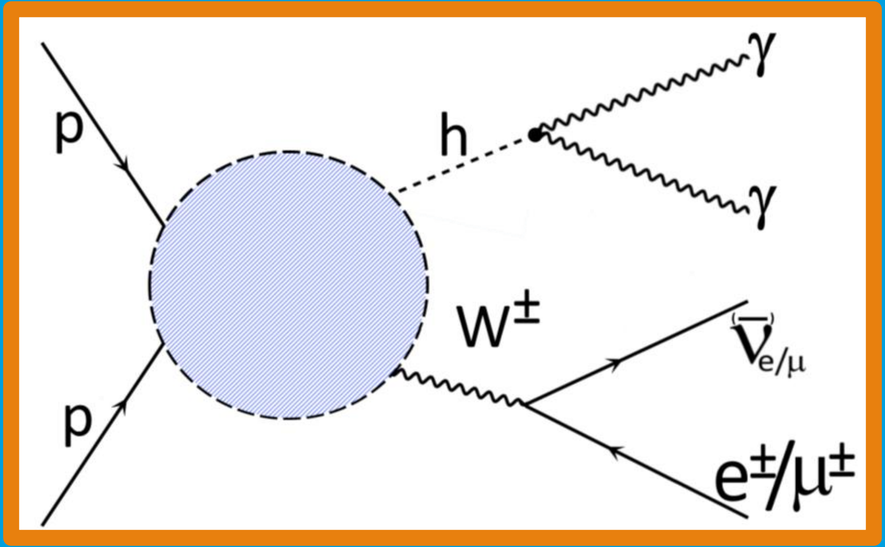
Differential in p_T and rapidity (only FCC-hh)

$$\text{Min}\{p_T^h, p_T^Z\} \in \{200, 400, 600, 800, 1000, \infty\} \text{ GeV} \qquad |y_{Zh}| \in [0, 2),\ [2, 6]$$

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

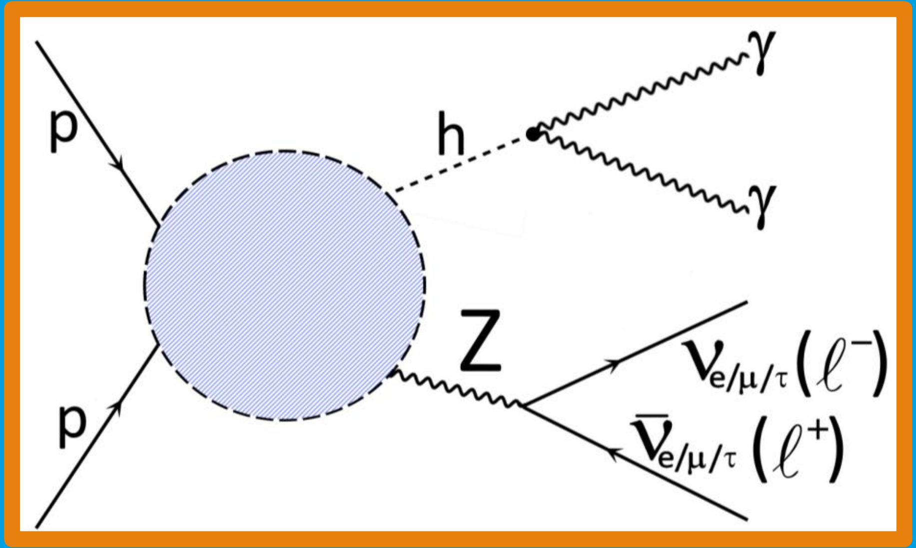
Diphotonic Vh, a summary.

arXiv 2004.06122 (JHEP 07 (2020) 075)



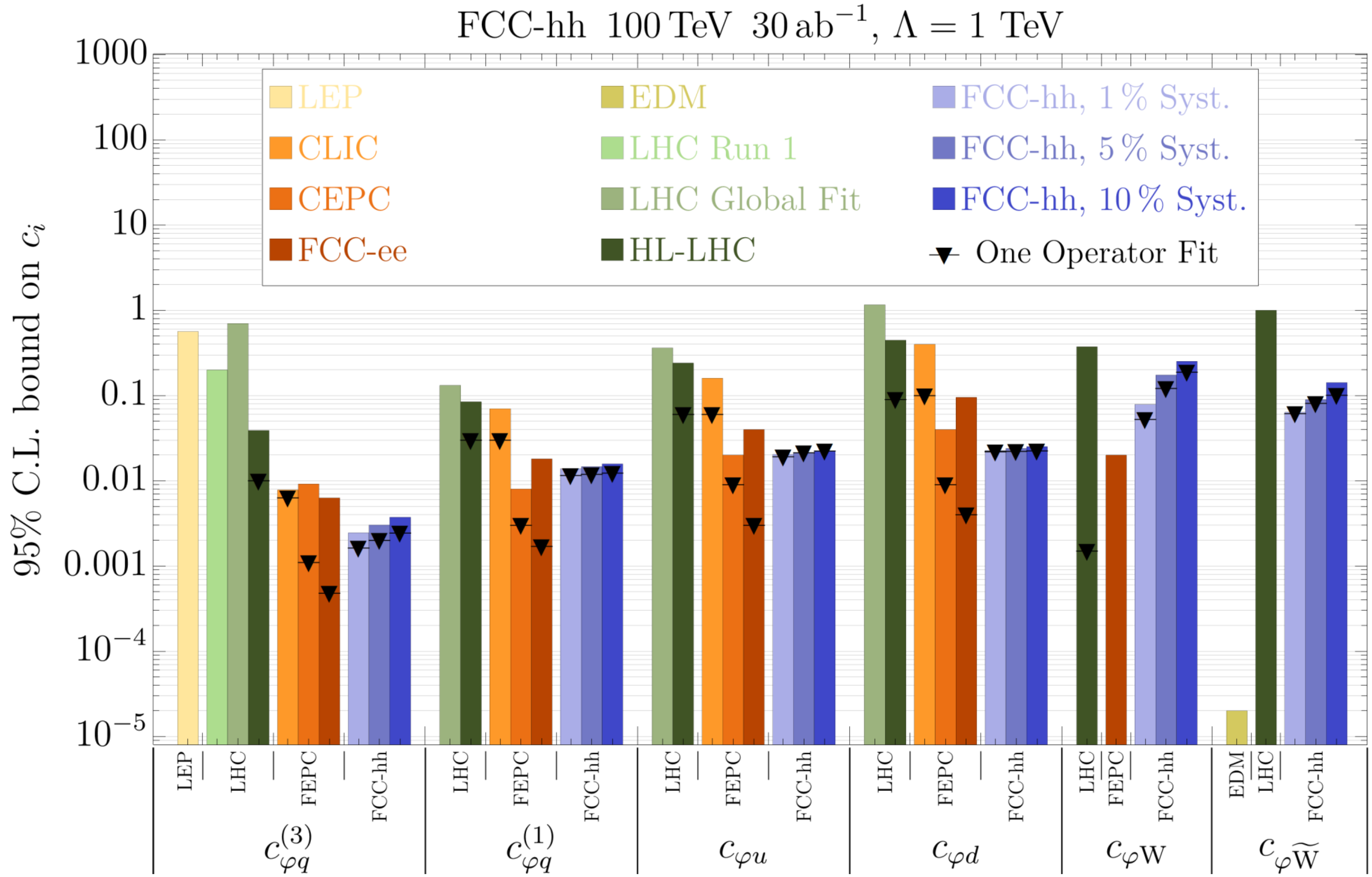
$$pp \to W^{\pm}h \to l^{\pm}\nu\,\gamma\gamma$$

arXiv 2011.13941 (JHEP 04 (2021) 154)



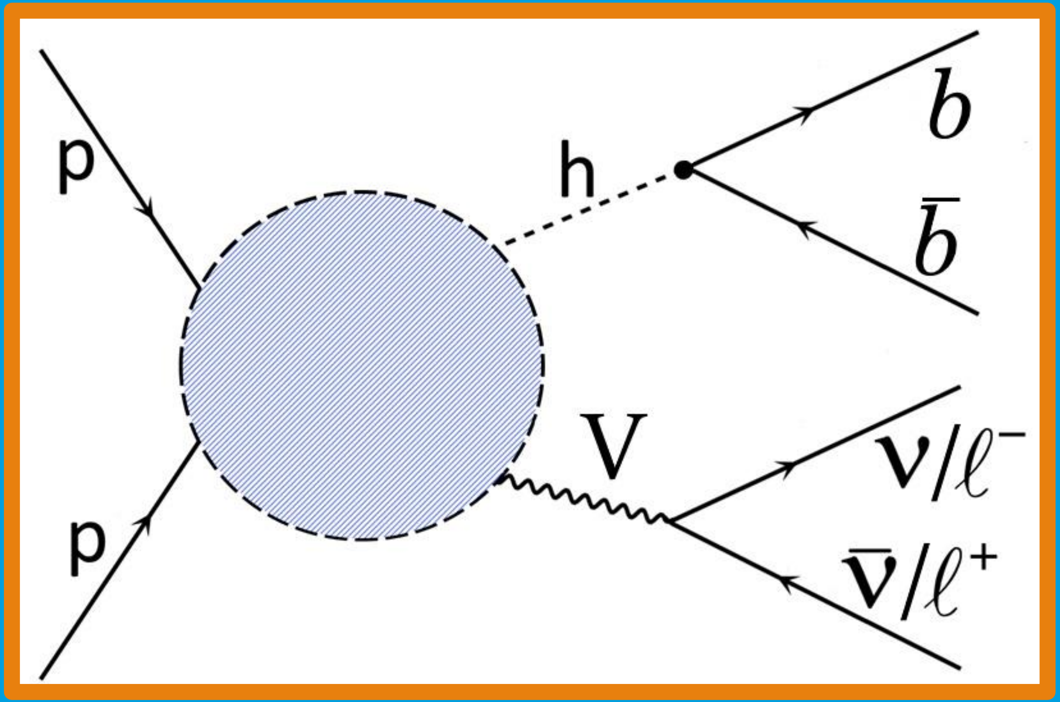
$$pp \to Zh \to l^{+}l^{-}\ (\nu\bar{\nu})\,\gamma\gamma$$

Vh. Diphotonic channel in perspective



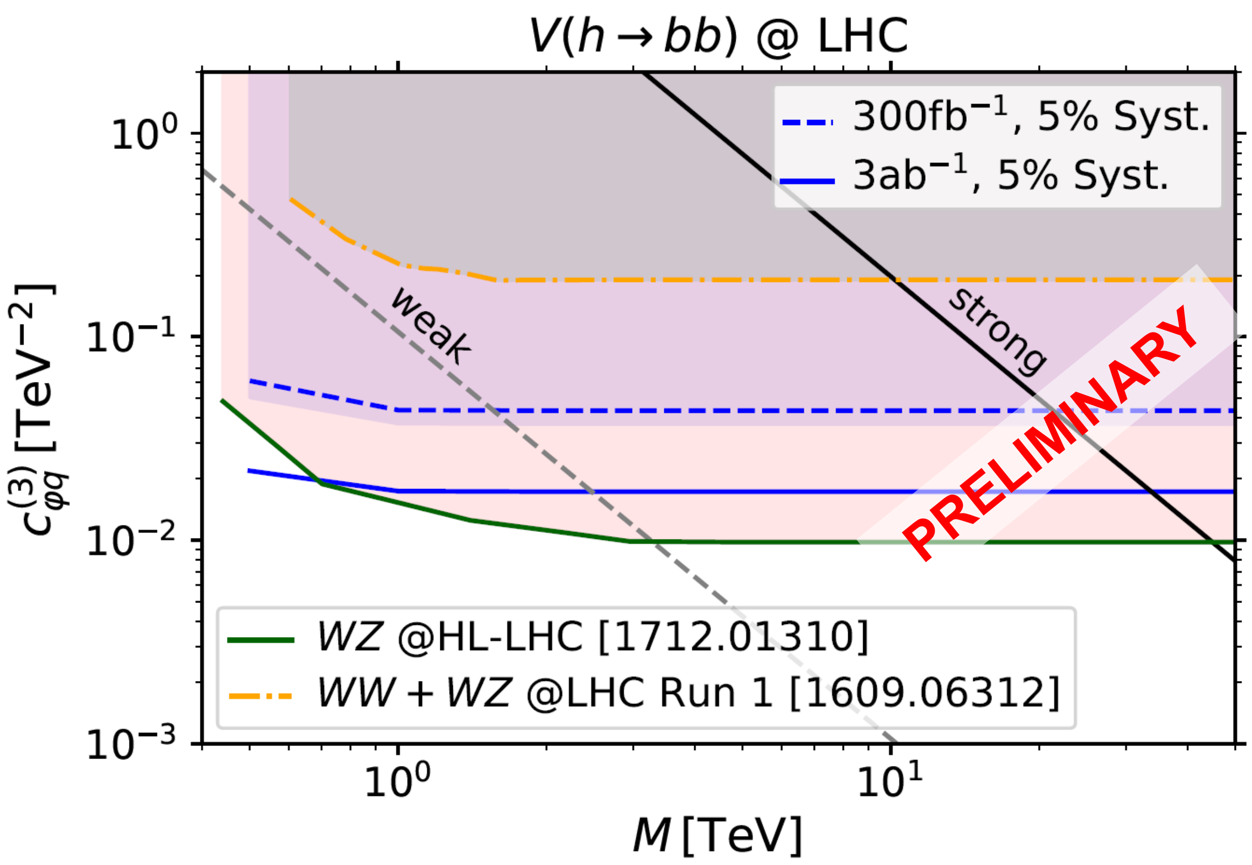
Let them be quarks, Vh.

arXiv 22XX.YYYZZ



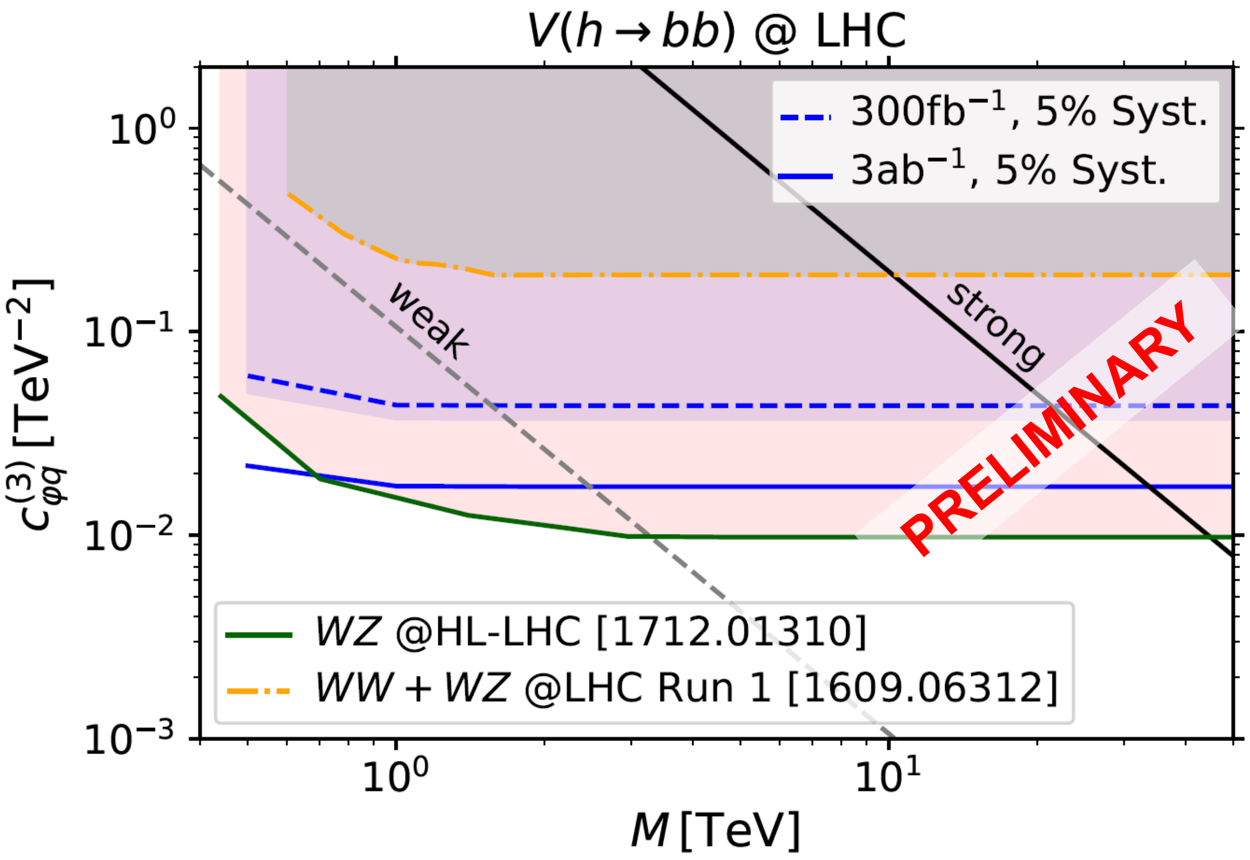
$$pp \to Vh \to \ell(\nu)\ell(\nu)b\bar{b}$$

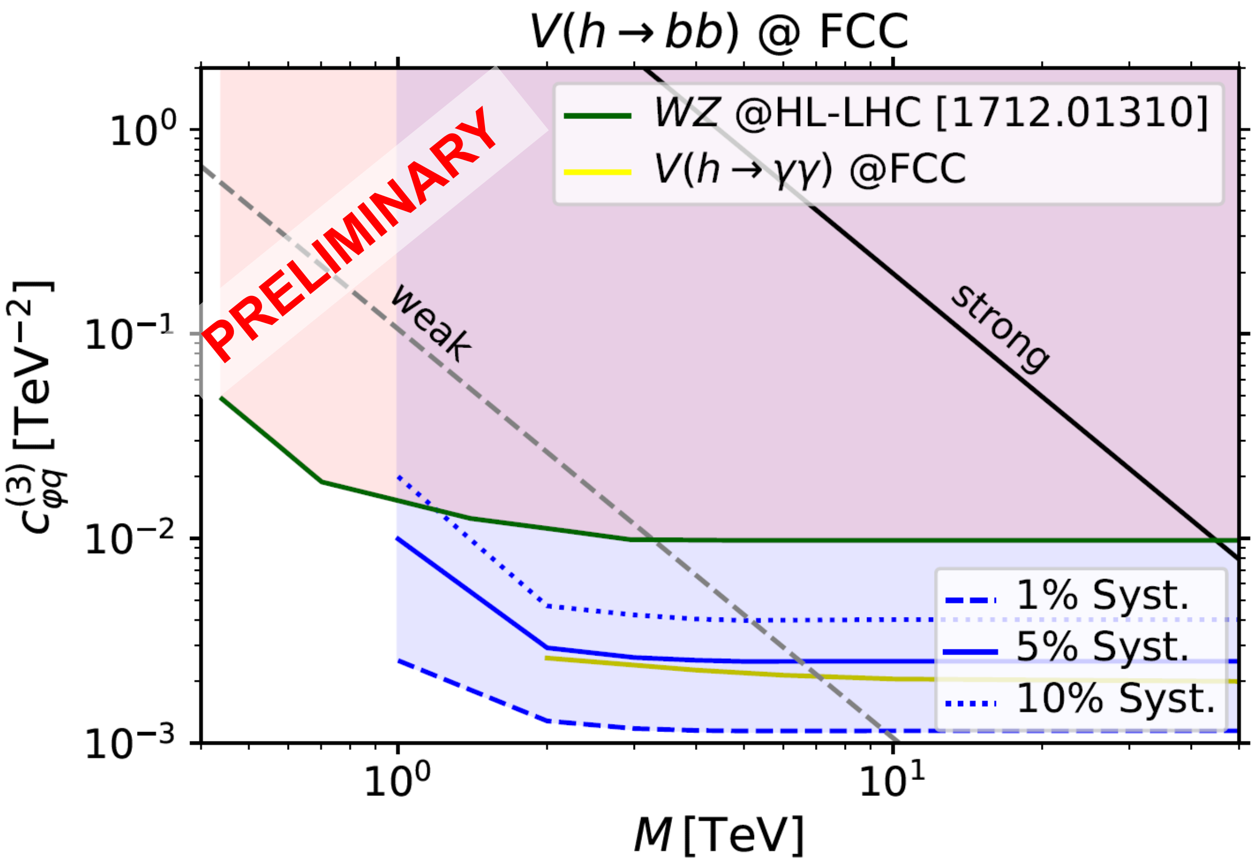
95% C.L. on $c_{\varphi q}^{(3)}$ with $h \to b\bar{b}$



Vh.

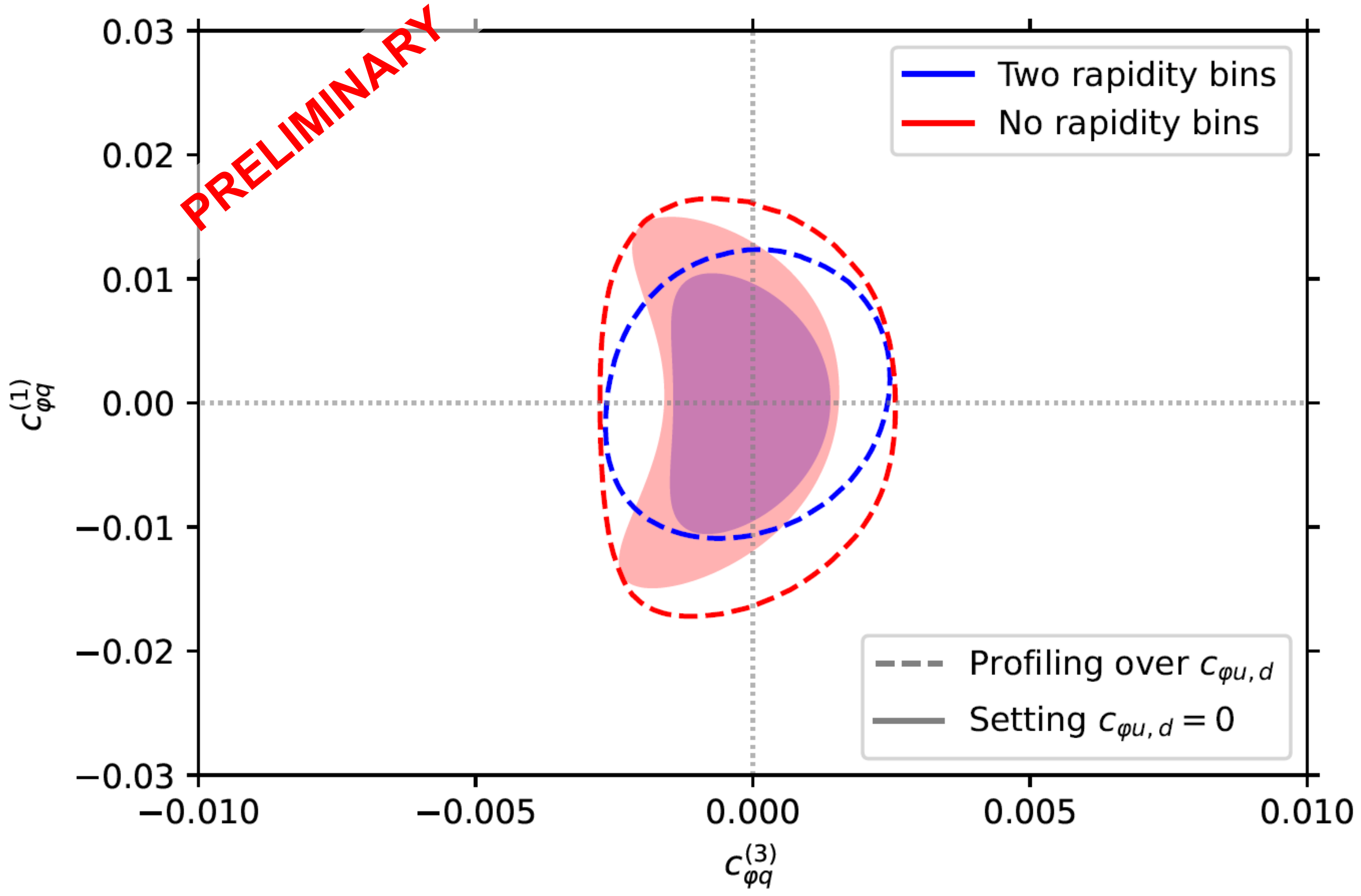
95% C.L. on $c_{\varphi q}^{(3)}$ with $h \to b\bar{b}$





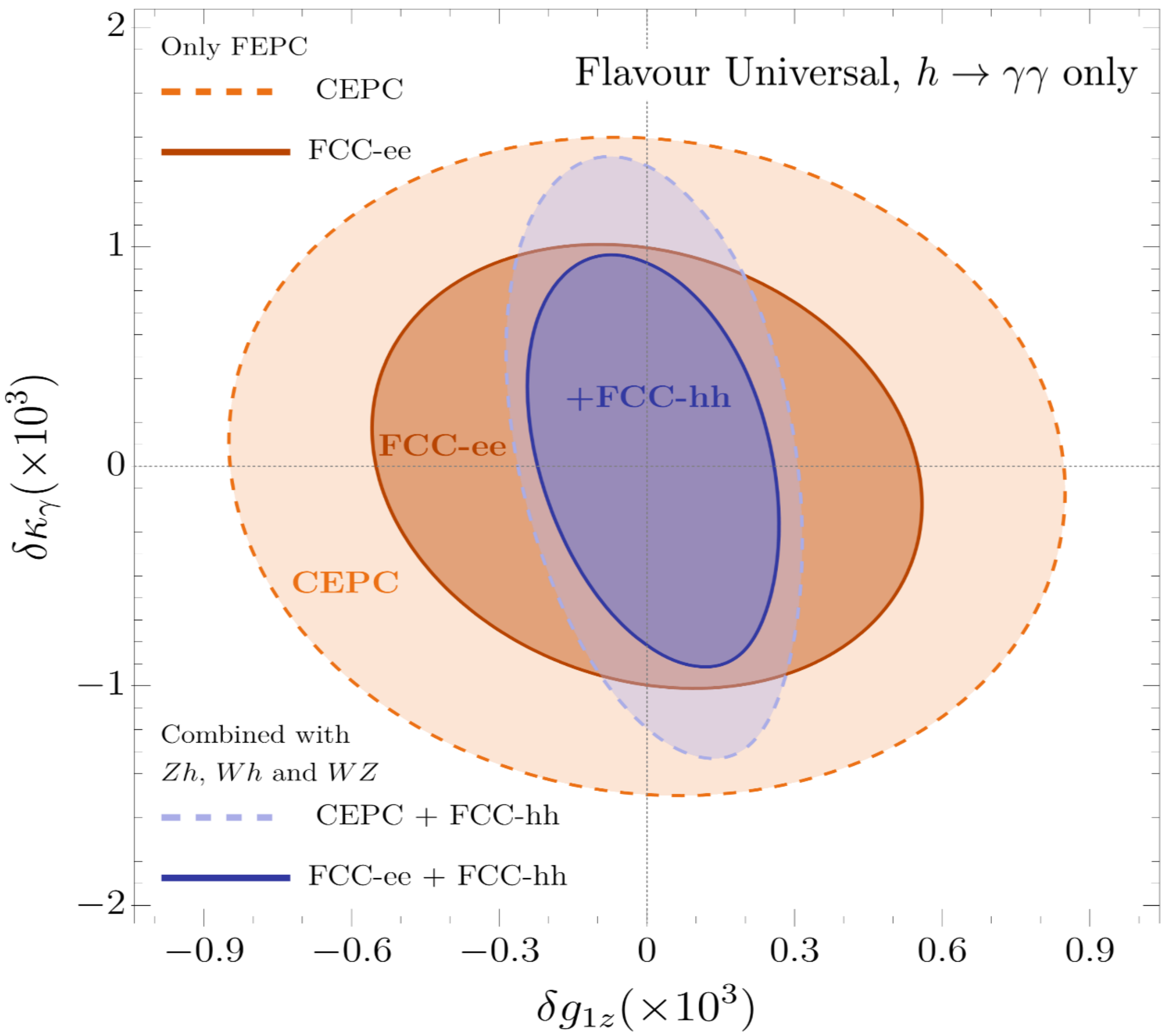
Rapidity binning effects

Zh at FCC-hh 100 TeV, 30 ab^{-1}, 1% syst.



Sizeable impact on aTGC bounds

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



$$c_{\varphi q}^{(3)} = +\frac{\Lambda^2}{4m_W^2} g^2 \left(\delta g_L^{Zu} - \delta g_L^{Zd} - c_{\mathrm{W}}^2\, \delta g_{1z}\right)$$

$$c_{\varphi q}^{(1)} = -\frac{\Lambda^2}{4m_W^2} g^2 \left(\delta g_L^{Zu} + \delta g_L^{Zd} + \frac{1}{3}\left(t_{\mathrm{W}}^2 \delta\kappa_\gamma - s_{\mathrm{W}}^2 \delta g_{1z}\right)\right)$$

$$c_{\varphi u} = -\frac{\Lambda^2}{2m_W^2} g^2 \left(\delta g_R^{Zu} + \frac{2}{3}\left(t_{\mathrm{W}}^2 \delta\kappa_\gamma - s_{\mathrm{W}}^2 \delta g_{1z}\right)\right)$$

$$c_{\varphi d} = -\frac{\Lambda^2}{2m_W^2} g^2 \left(\delta g_R^{Zd} - \frac{1}{3}\left(t_{\mathrm{W}}^2 \delta\kappa_\gamma - s_{\mathrm{W}}^2 \delta g_{1z}\right)\right)$$

Conclusions

- At FCC-hh, there will be new diboson channels to do precision measurements, such as $(W,Z)\,h$ with $h \to \gamma\gamma$.
- With a simple p_T binning, they offer competitive sensitivity to $\mathcal{O}_{\varphi q}^{(3)}$.
- In Zh, a binning in rapidity improves the sensitivity to $\mathcal{O}_{\varphi q}^{(1)}$.
- $h \to b\bar{b}$ allows to perform these studies at (HL-)LHC, but with limitations.
- $h \to \gamma\gamma$ and $h \to b\bar{b}$ at FCC-hh achieve similar results in different ways.
- Wh and Zh with $h \to \gamma\gamma$ are not exploration channels, but important to probe different directions.

Thank you for your attention

Contact

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Appendix.

For even more details, read our papers or contact us.

Diboson in the present

$(W/Z)h$ @ LHC

- ATLAS, *Eur. Phys. J. C 81 (2021) 2, 178*, ArXiv: 2007.02873
- ATLAS, *Phys. Lett. B 816 (2021) 136204*, ArXiv: 2008.02508
- CMS, *JHEP07 (2021) 027*, ArXiv: 2103.06956

What will change in the future?

LHC $\xrightarrow{e^{-i\hat{H}t}}$ FCC-hh

	HL-LHC	FCC-hh
C.o.M. energy	14 TeV	100 TeV
Int. Luminosity	3 ab^{-1}	30 ab^{-1}

FCC-hh: The LHC of the future

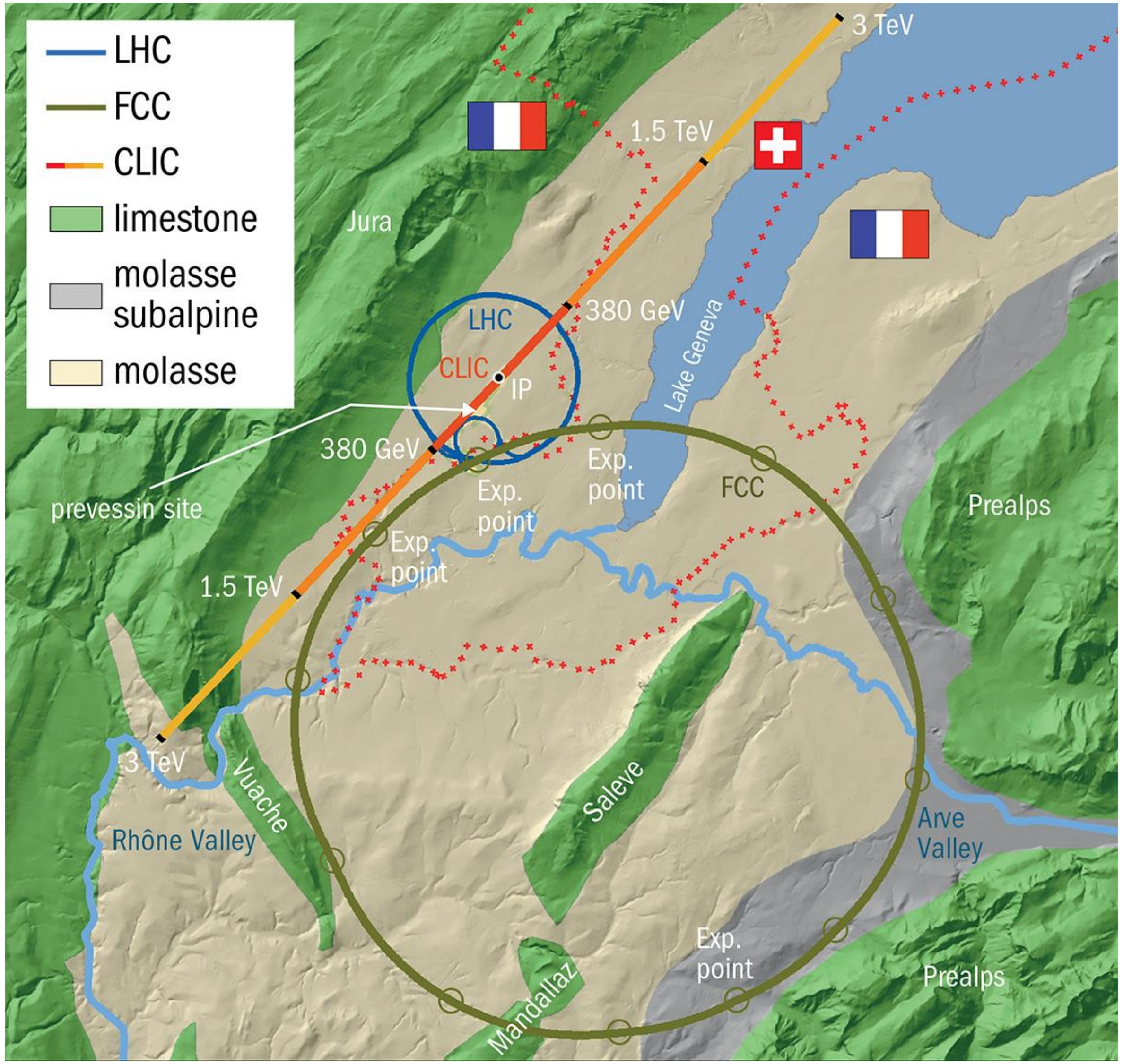
$e^{-i\hat{H}t}$

2021-2025 → **Feasibility study**

2030-2045 → **Construction**

2045-2060 → **FCC-ee operation**

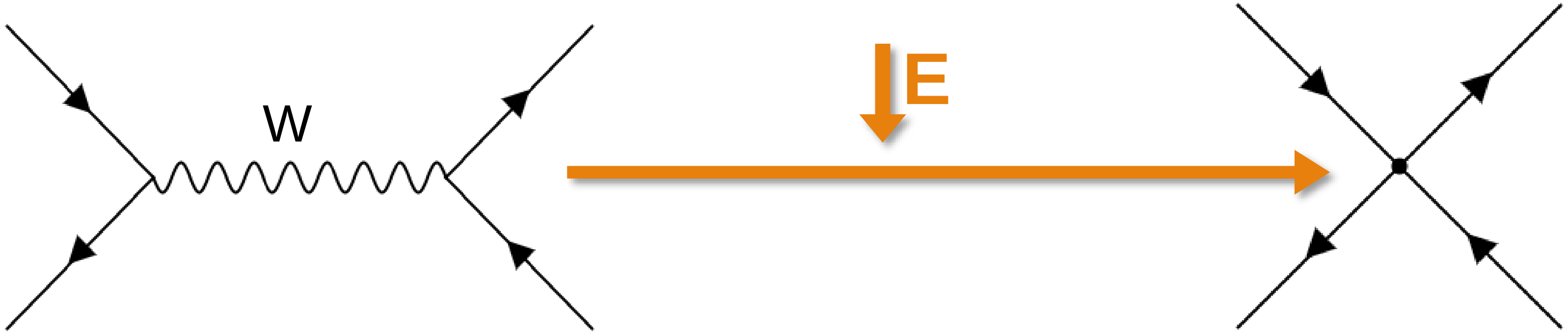
2070-2095 → **FCC-hh operation**



Timeline from talk by M. Benedikt (CERN) at FCC Workshop 2022

Why Effective Field Theories?

- **The main idea behind EFTs is in all fields of Physics.**
- **NP at a higher scale affect the interactions seen at a lower scale.**



$$g\ \bar{q}_L\gamma^\mu W_\mu q_L$$

$$\frac{g^2}{m_W^2}\ \bar{q}_L\gamma^\mu q_L \bar{l}_L\gamma_\mu l_L$$

- **Operators with dimension>4 encode the NP effects in the EFT.**
- **Offer a more model-independent way of searching for NP.**

Standard Model EFT (SMEFT) and Interference

- **Field content and gauge symmetries of the SM and linearly realized EW sym.**
- **Add gauge invariant operators with dimension bigger than 4.**

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_i \frac{c_i^{(8)}}{\Lambda^4}\mathcal{O}_i^{(8)} + \dots$$

- **Leading deviations from the SM appear at dimension 6.**

$$\sigma = |\mathcal{M}_{SM}|^2 + 2\mathrm{Re}\left(\mathcal{M}_{SM}\mathcal{M}^*_{BSM}\right) + |\mathcal{M}_{BSM}|^2$$

$\propto \mathcal{C}_i^{(6)}/\Lambda^2$

$\propto \left(\mathcal{C}_i^{(6)}/\Lambda^2\right)^2$

Interference

Interference patterns

High energy behaviour

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

$V = W,\, Z$

$$\mathcal{O}_{\varphi f} = \mathcal{O}_{\varphi q}^{(3)},\, \mathcal{O}_{\varphi q}^{(1)},\, \mathcal{O}_{\varphi u},\, \mathcal{O}_{\varphi d}$$

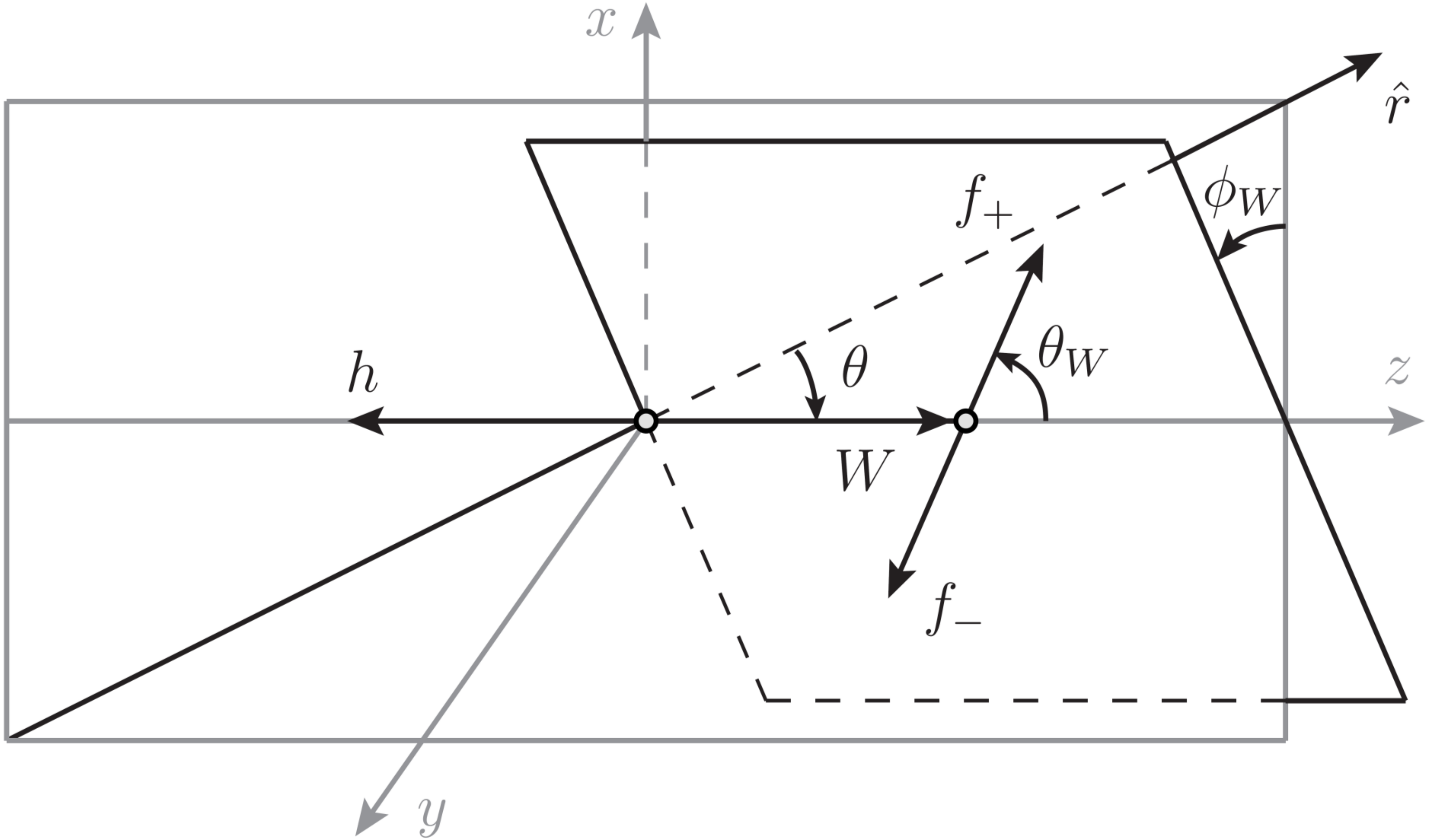
Differential in p_T

↓

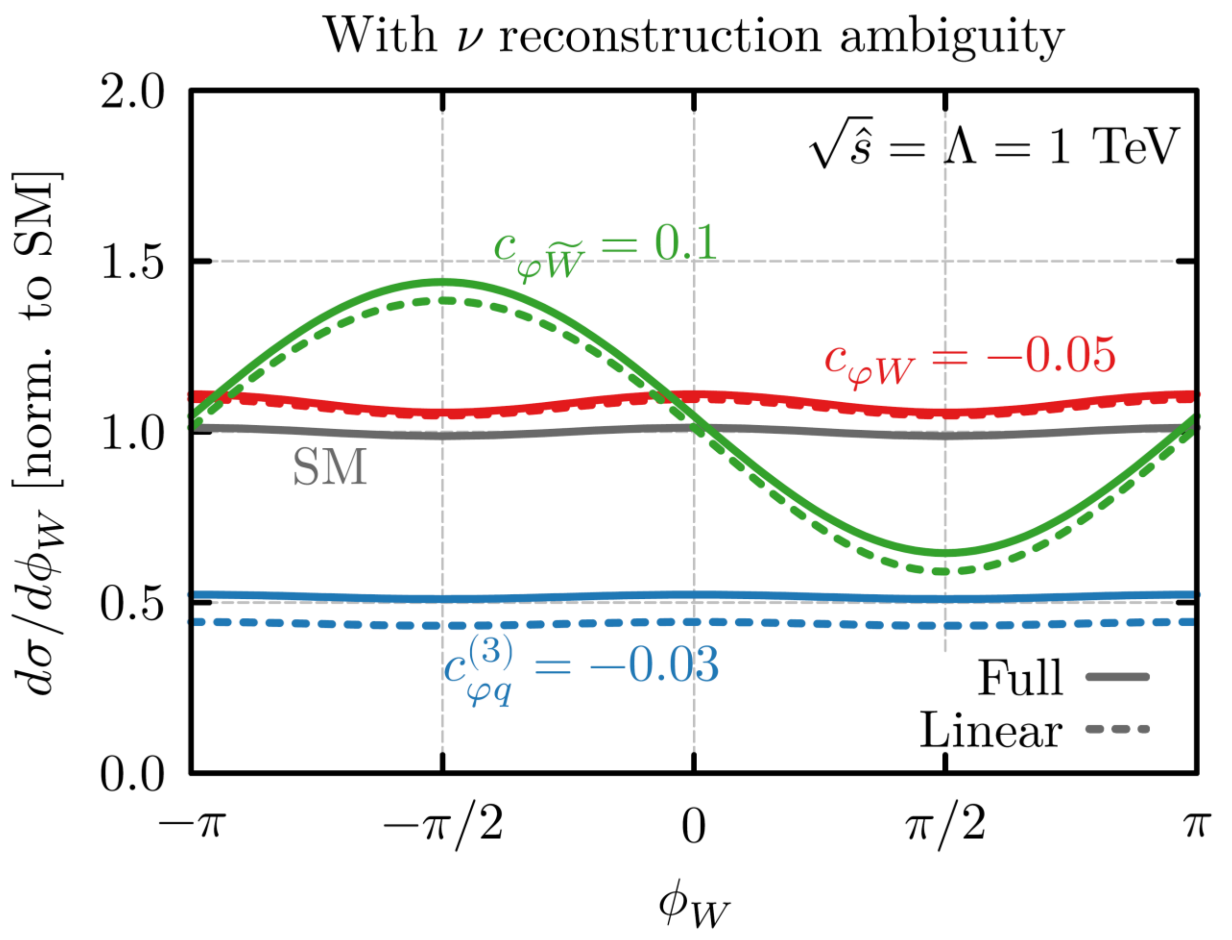
Interference between same polarisation

Interference patterns

Measuring angles resurrects interference



Wh. Interference patterns



Differential in p_T^h and ϕ_W

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

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

ν **reconstruction**
$(\phi_W \to \pi - \phi_W)$

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

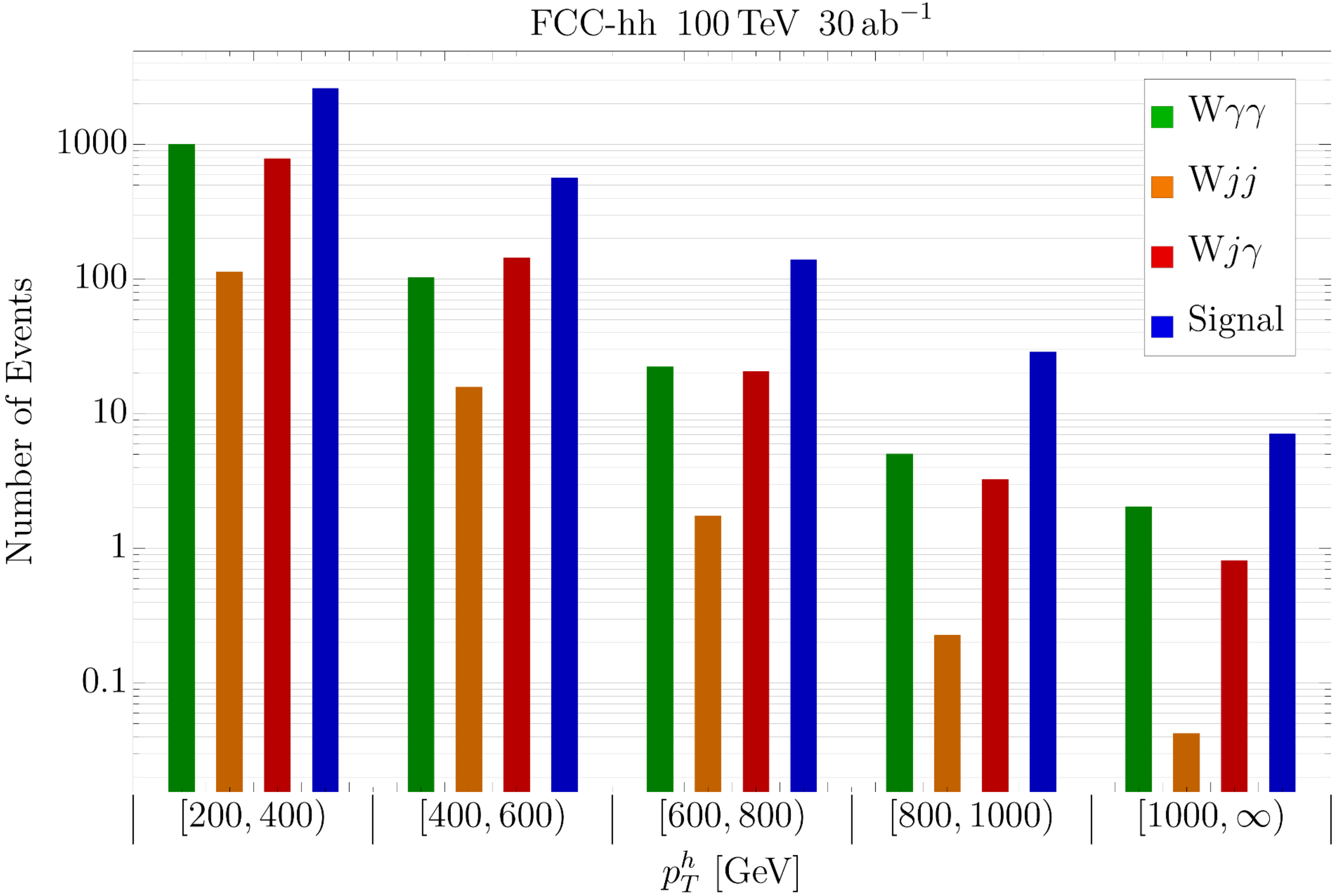
$$p_T^h \in \{200, 400, 600, 800, 1000, \infty\}\ \text{GeV} \qquad \phi_W \in [-\pi, 0],\ [0, \pi]$$

Binning in $h \to b\bar{b}$

Categories		Variable	(HL-)LHC	FCC-hh
0-lepton	boosted	$p_{T,\text{min}}$ [GeV]	$\{0, 300, 350, \infty\}$	$\{0, 200, 400, 600, 800, \infty\}$
	resolved		$\{0, 160, 200, 250, \infty\}$	$\{0, 200, 400, 600, 800, \infty\}$
1-lepton	boosted	p_T^h [GeV]	$\{0, 175, 250, 300, \infty\}$	$\{0, 200, 400, 600, 800, \infty\}$
	resolved		$\{0, 175, 250, \infty\}$	$\{0, 200, 400, 600, \infty\}$
2-lepton	boosted	$p_{T,\text{min}}$ [GeV]	$\{250, \infty\}$	$\{0, 200, 400, 600, \infty\}$
	resolved		$\{175, 200, \infty\}$	$\{0, 200, 400, 600, \infty\}$

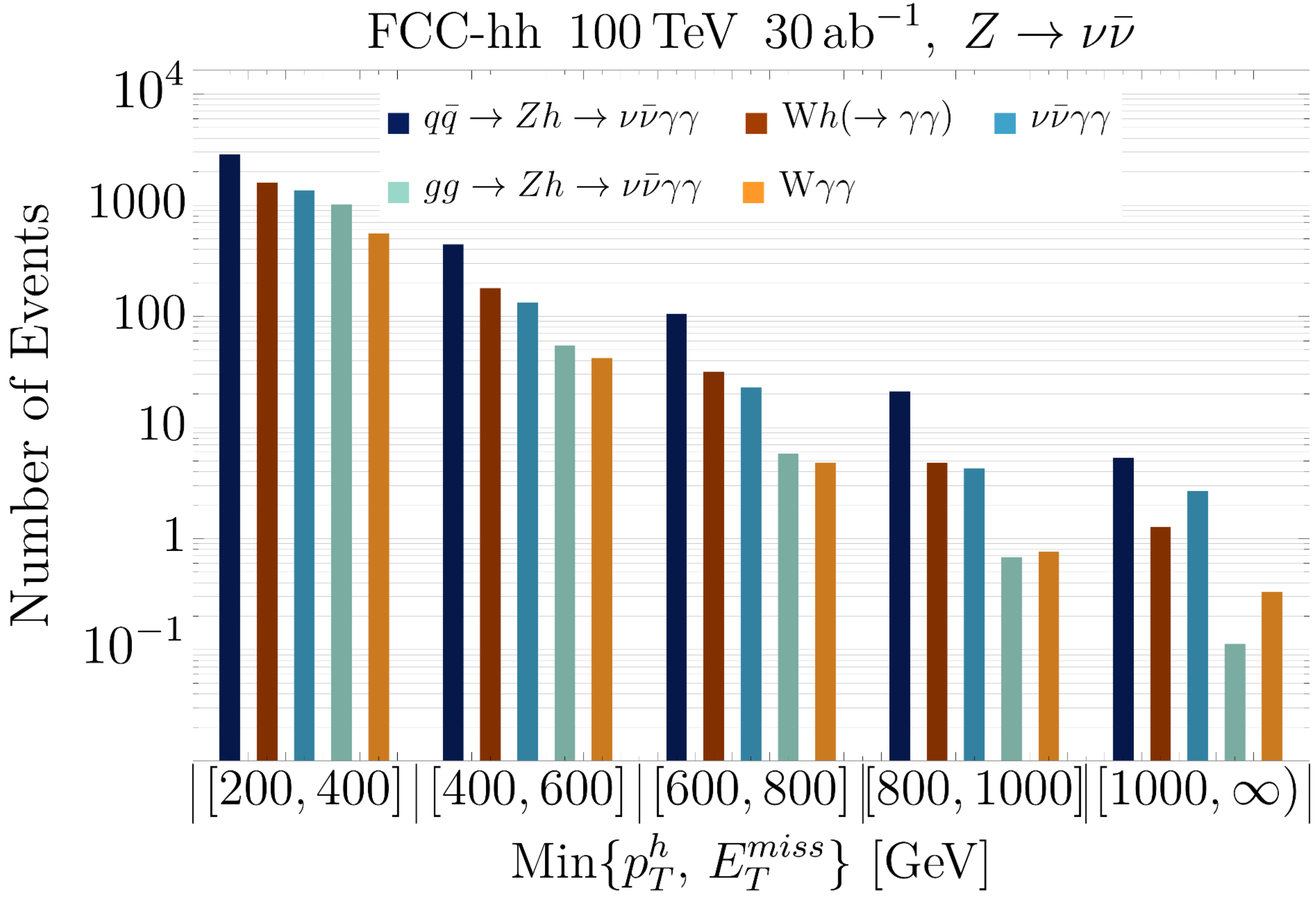
Wh. How big is the background?

- Events per bin for the relevant processes



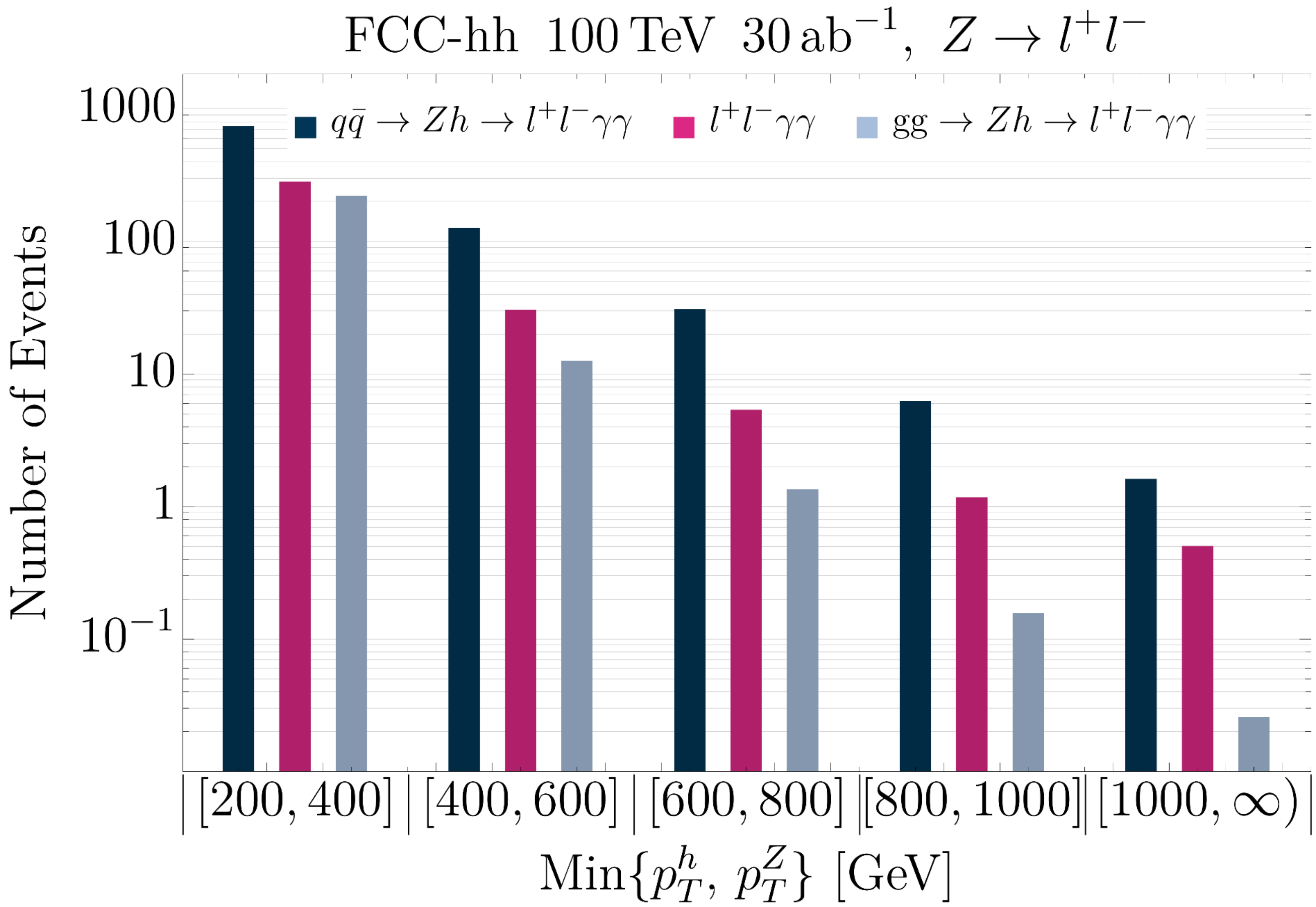
Zh. Signal and background

- Wh is part of the signal because it is affected by $\mathcal{O}_{\varphi q}^{(3)}$.



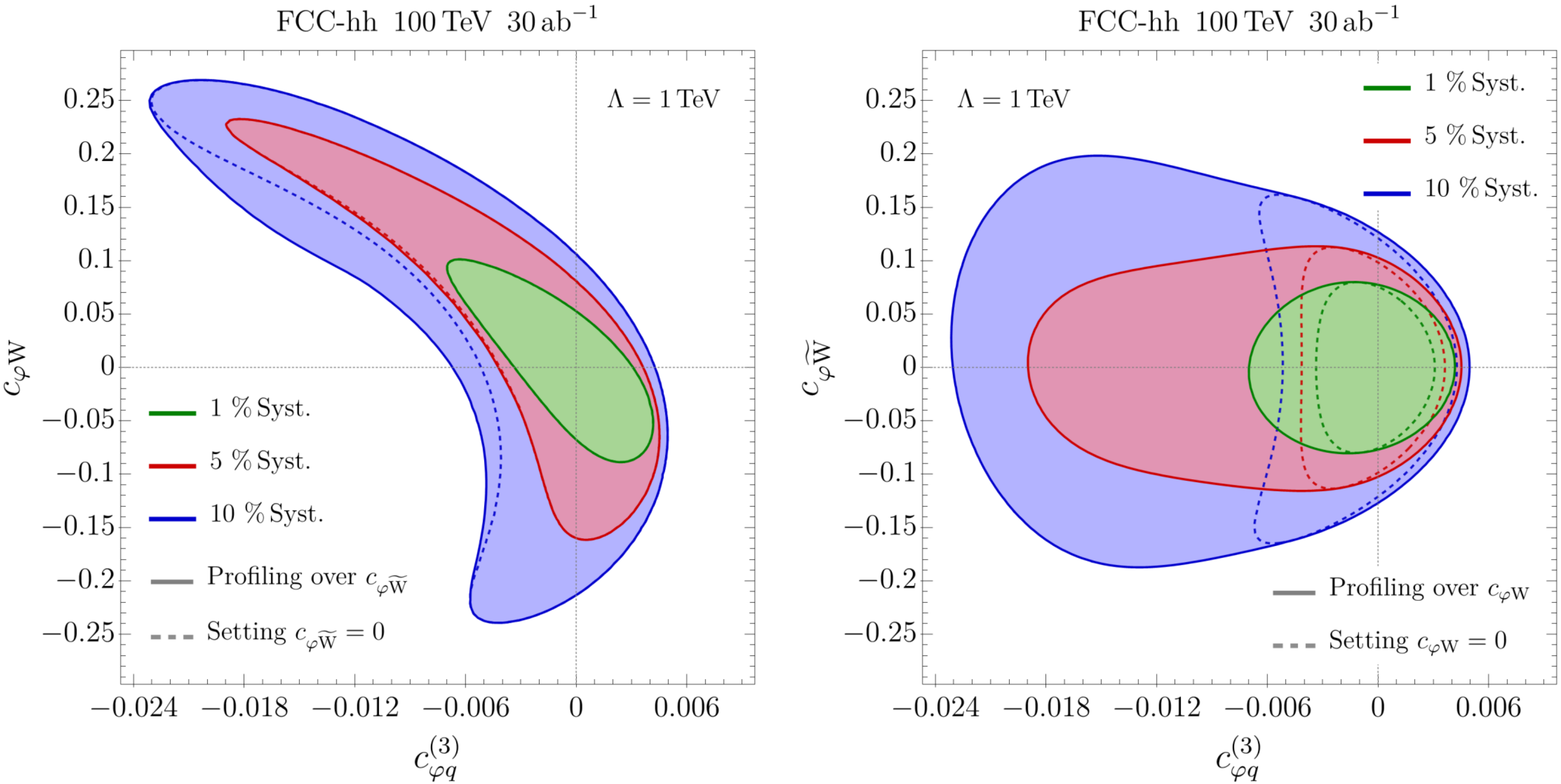
Zh. More results

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

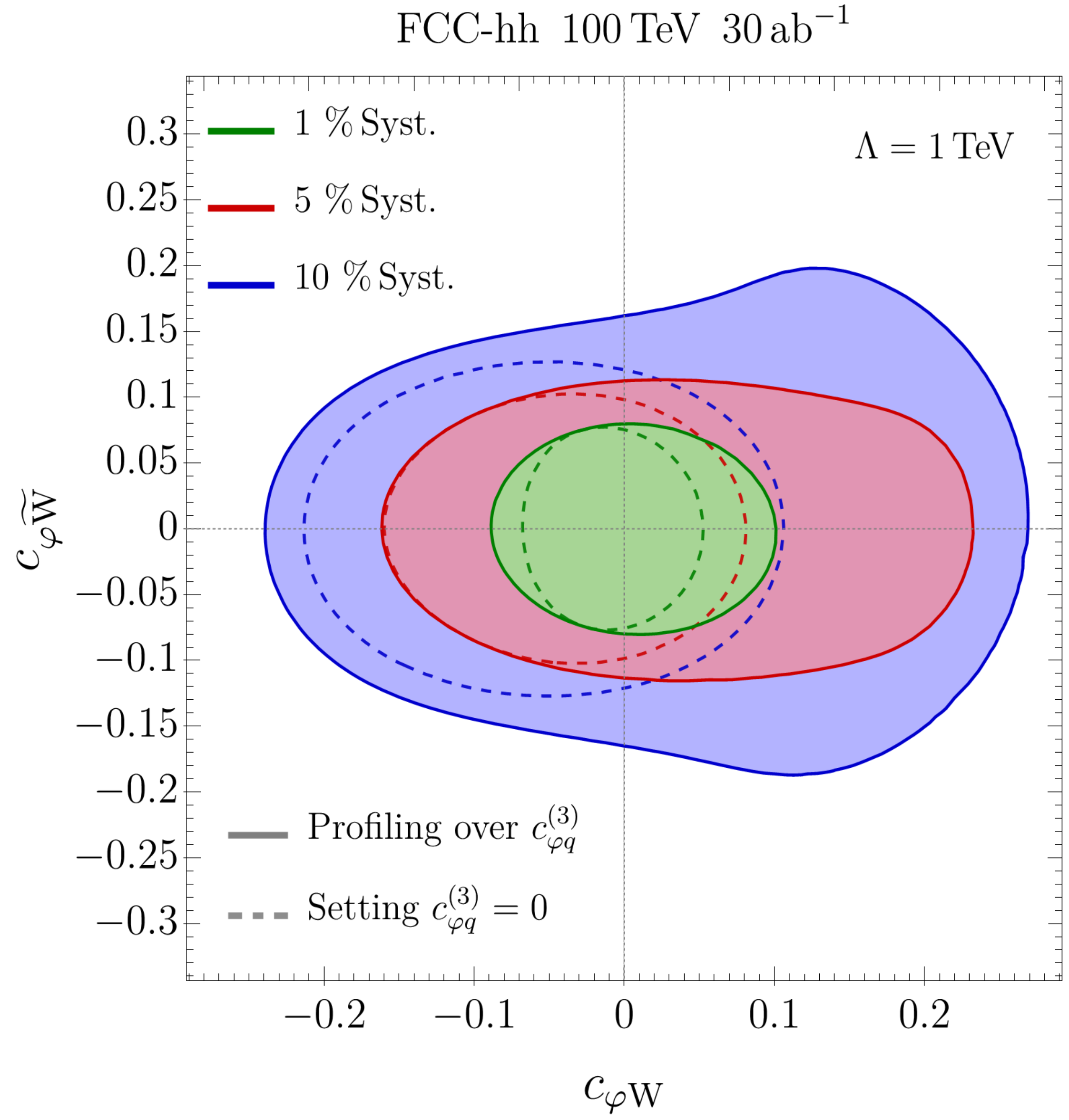


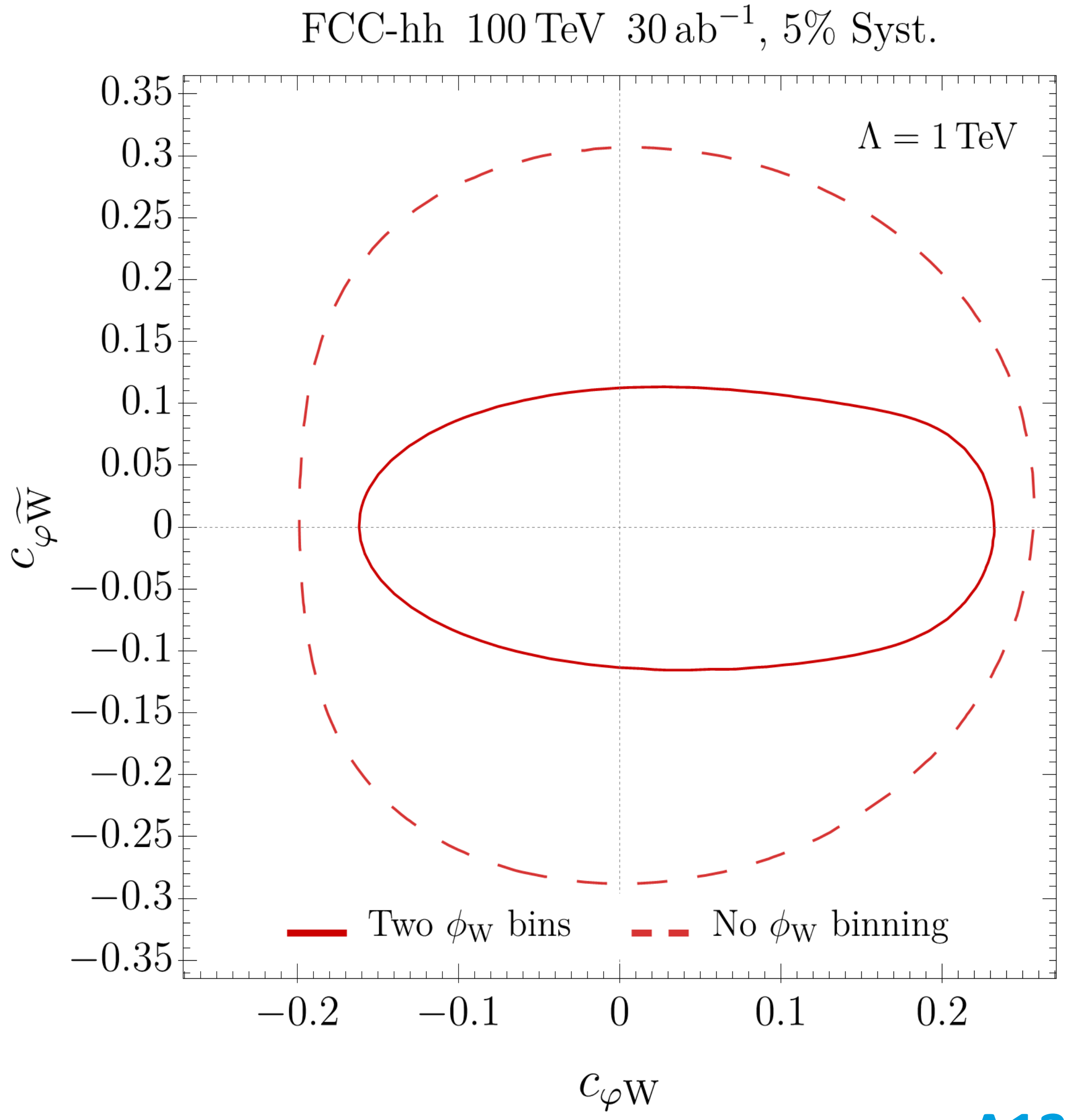
More results

- 95% CL bounds



Wh. 95% C.L. on the bosonic operators





Wh.

More results

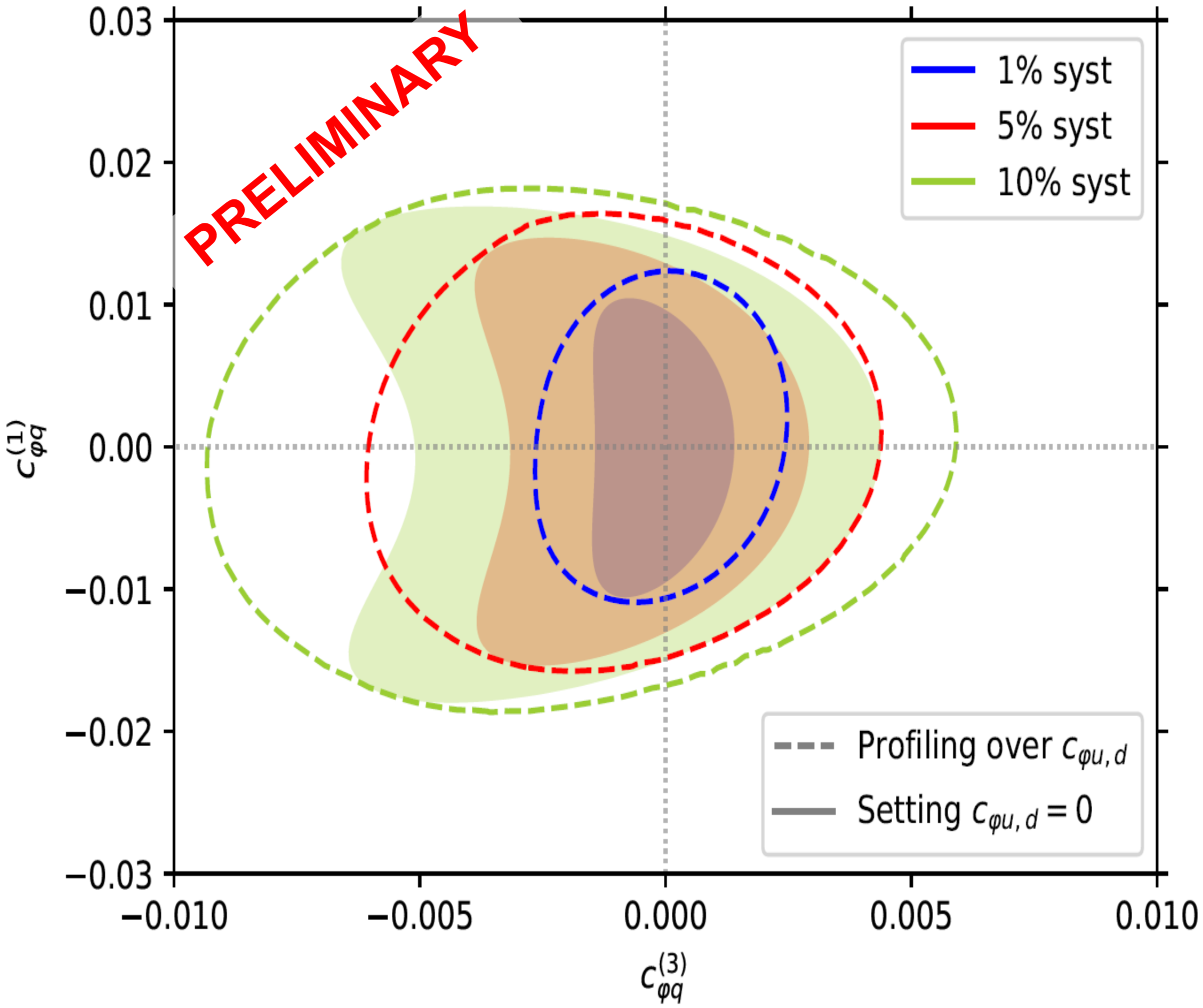
- 95% CL bounds summary

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.
$c_{\varphi \mathrm{W}}$	$[-7.1,\ 7.9] \times 10^{-2}$	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.
$c_{\varphi \widetilde{\mathrm{W}}}$	$[-6.4,\ 6.4] \times 10^{-2}$	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.

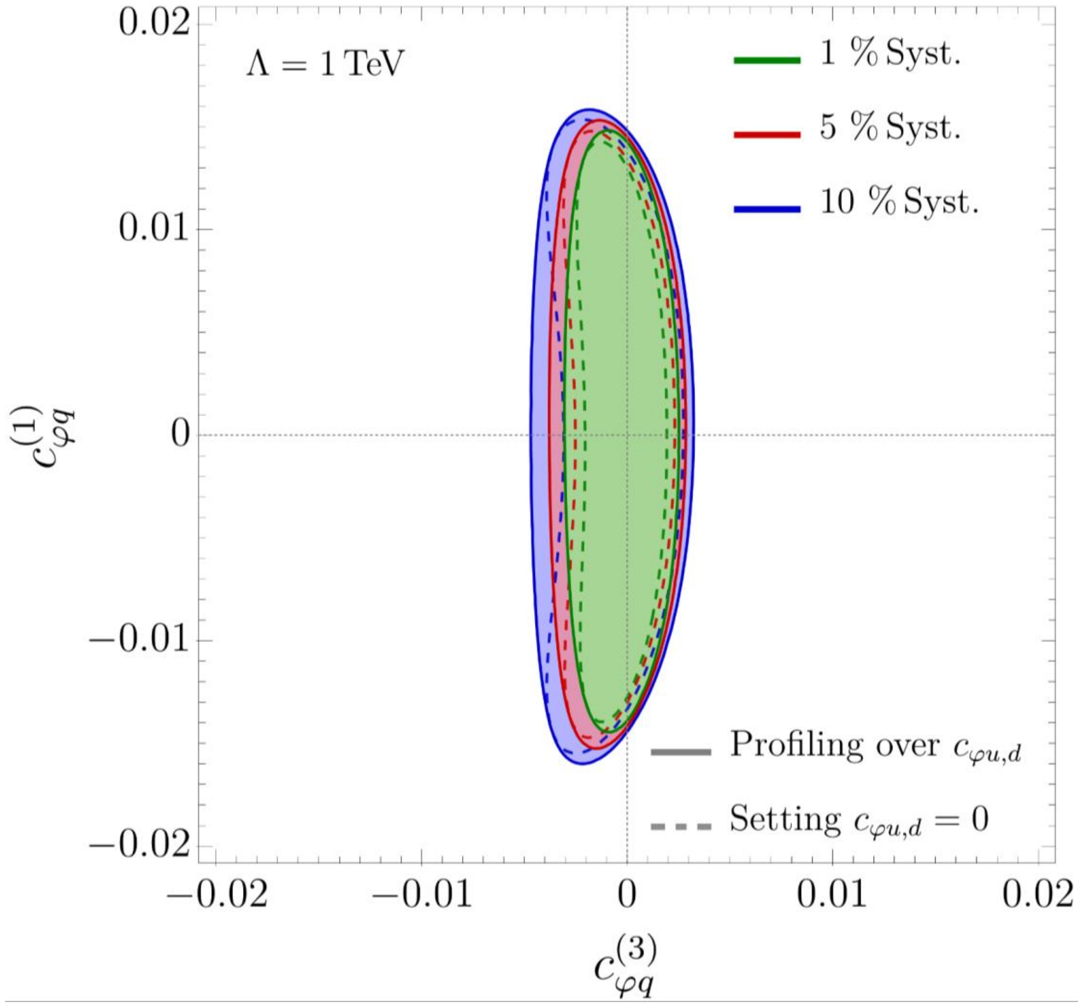
Vh. At FCC-hh, photons or b-quarks?

$\mathrm{FCC\text{-}hh}\ \ 100\,\mathrm{TeV}\ \ 30\,\mathrm{ab}^{-1}\ \ (Zh + Wh)$

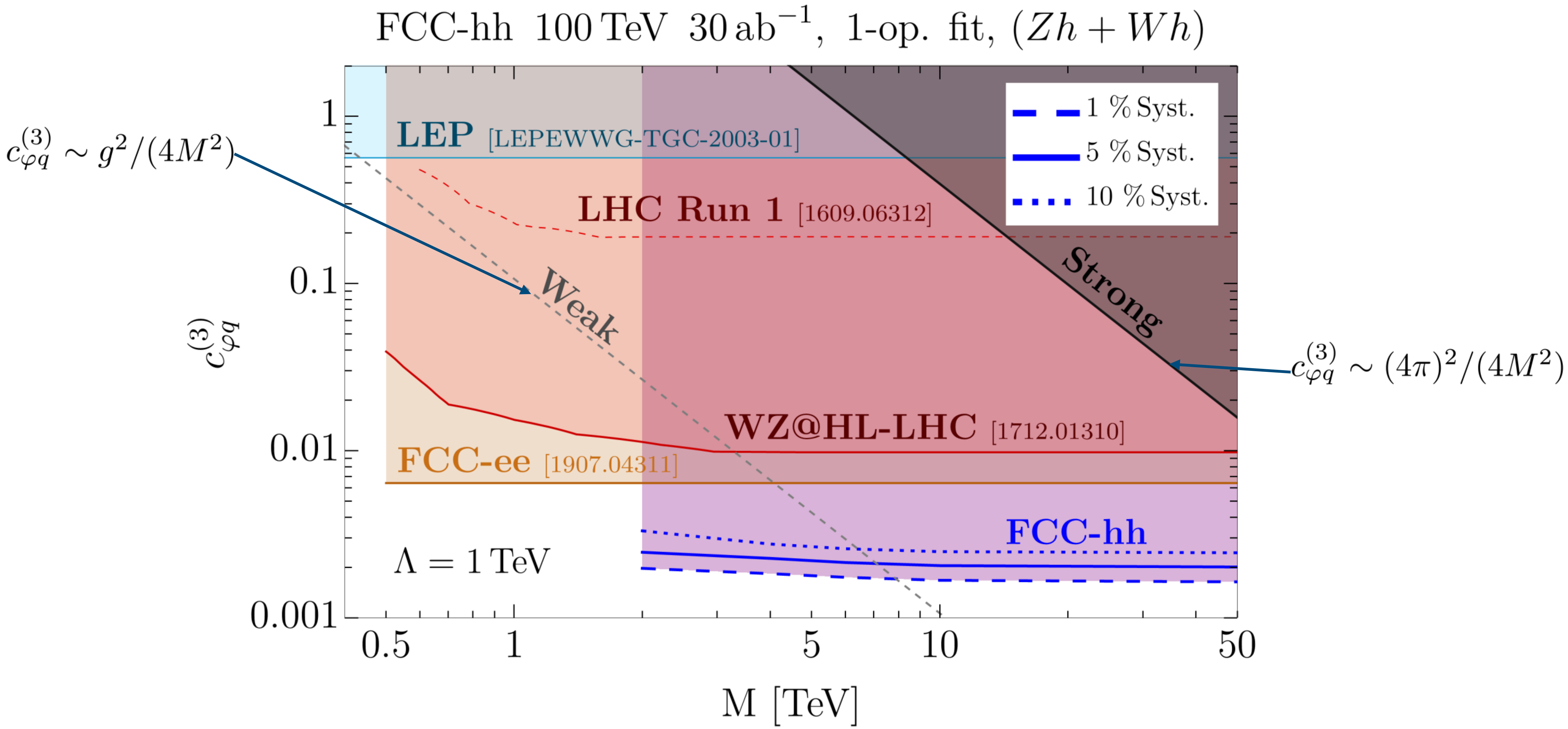
$h \to b\bar{b}$



$h \to \gamma\gamma$

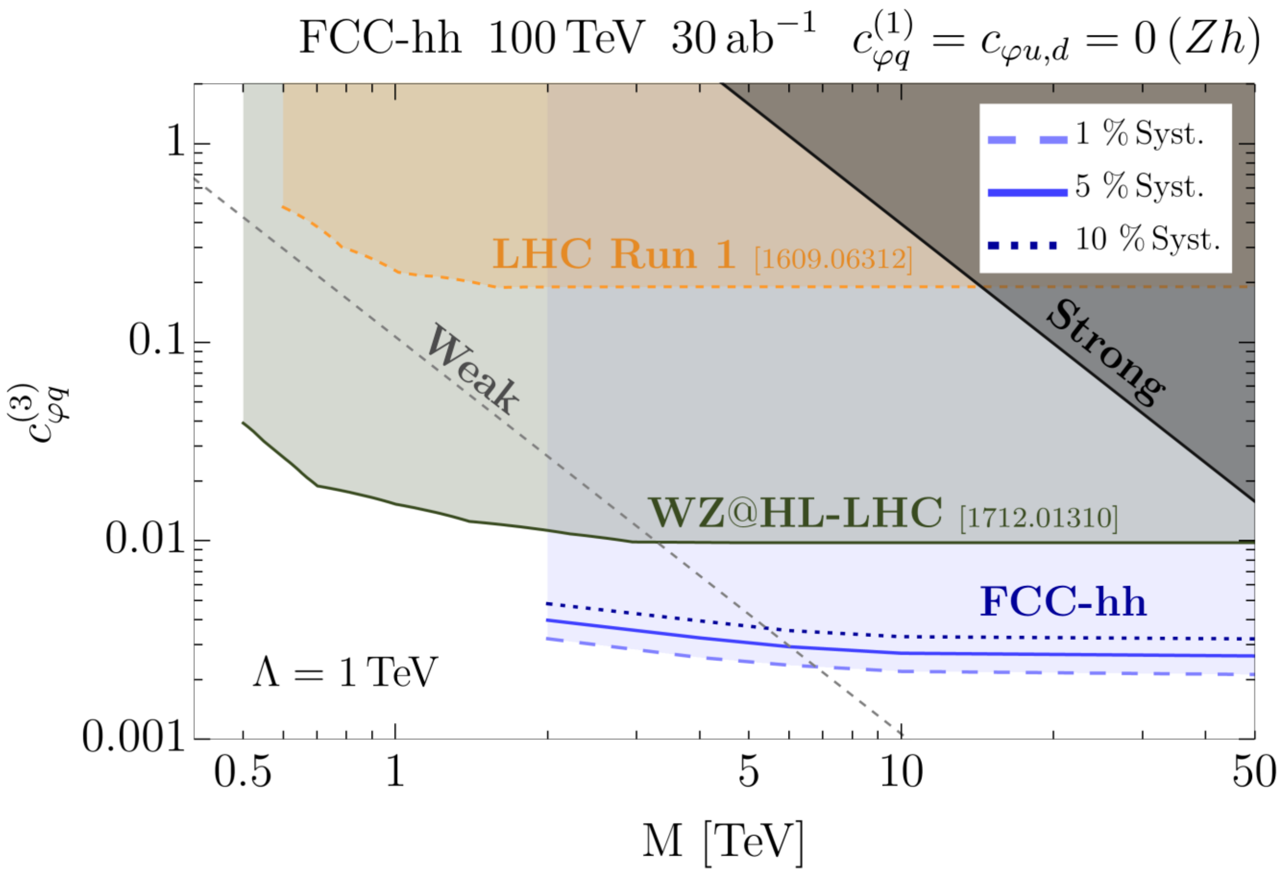


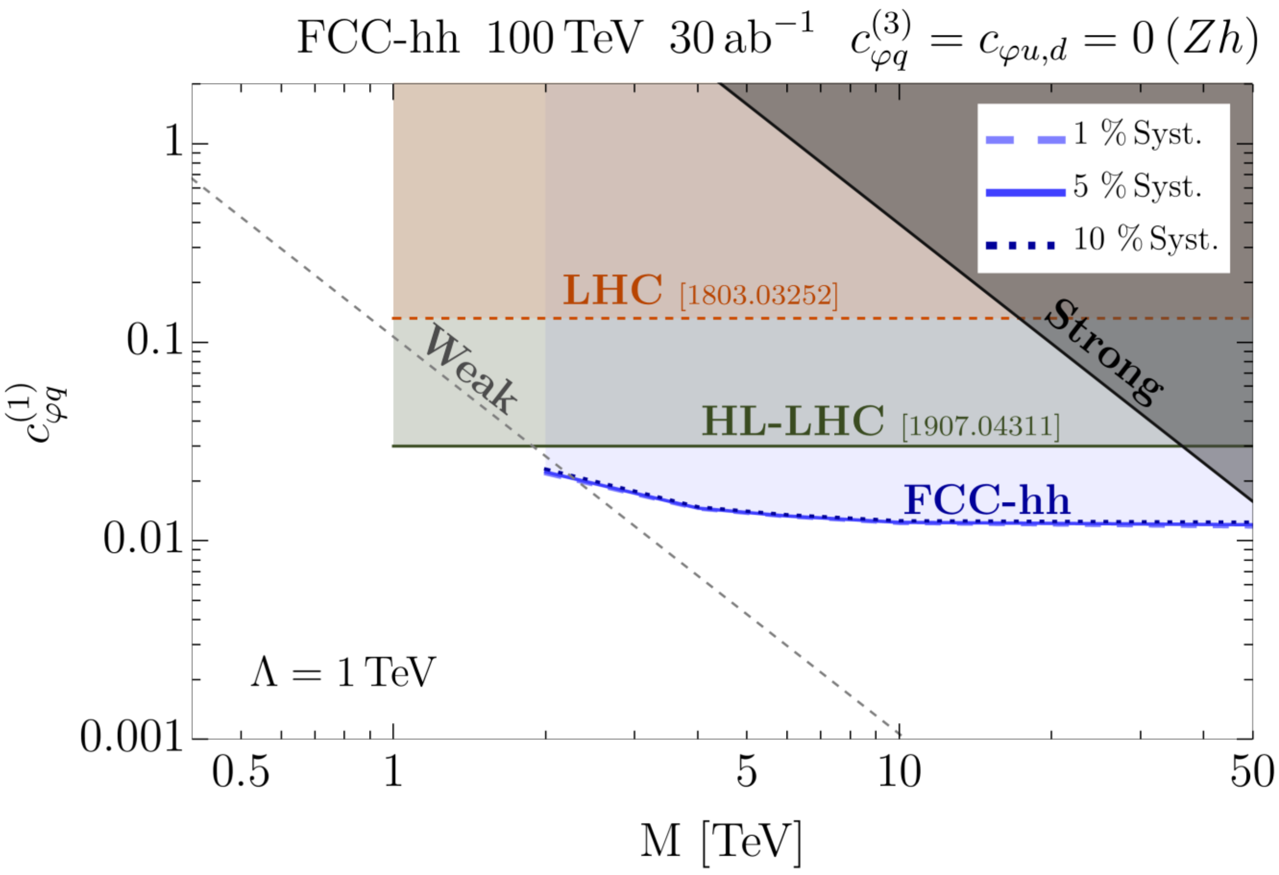
Bounds for $c_{\varphi q}^{(3)}$



Zh. More results

- 95% CL bounds





Zh. More results

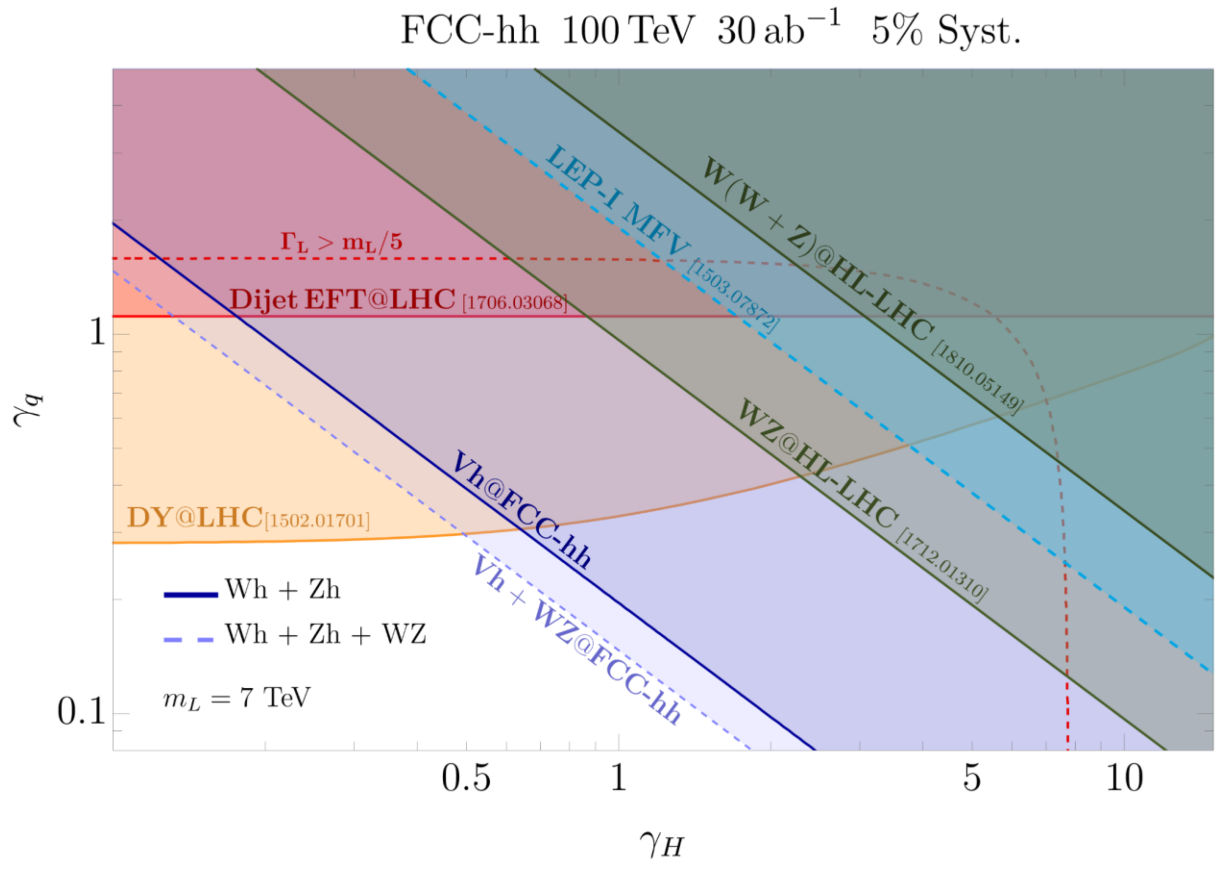
- 95% CL bounds summary

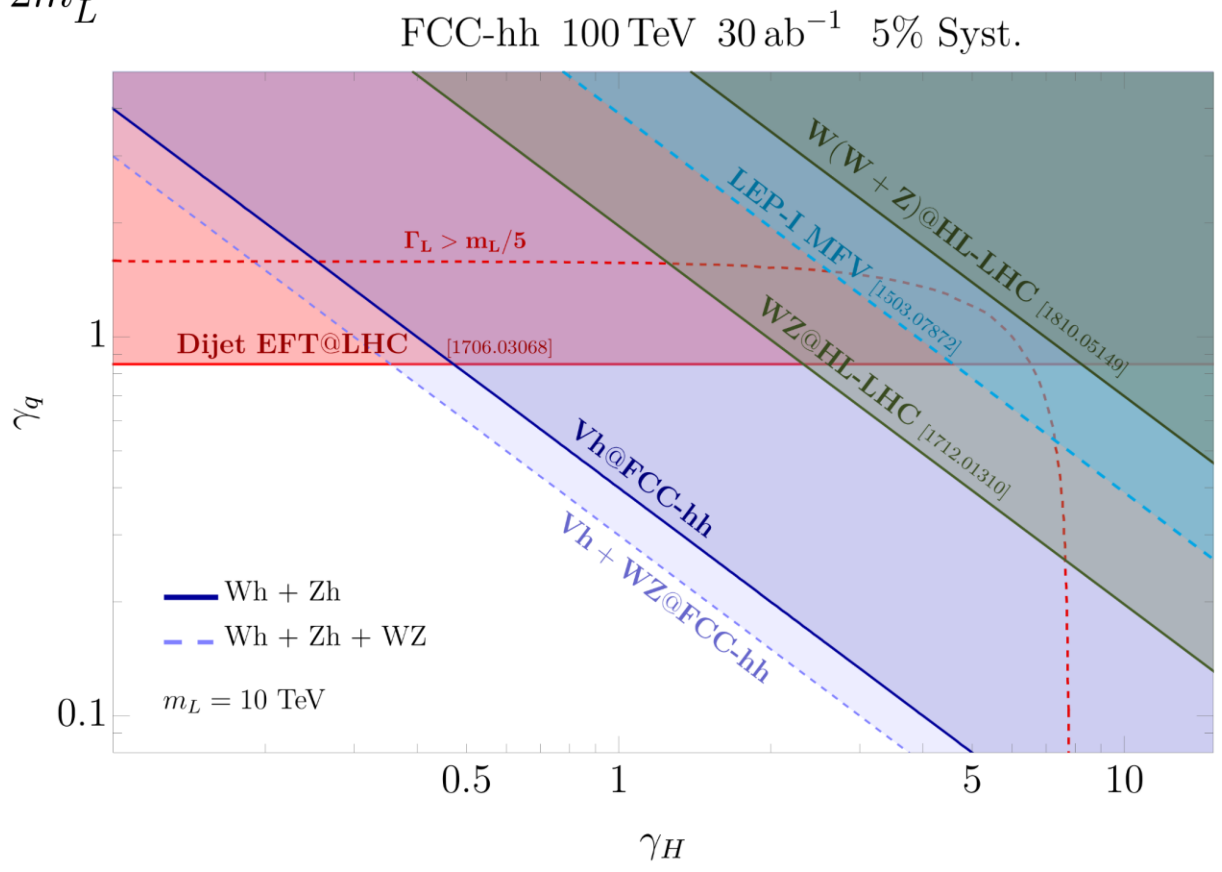
Coefficient	Profiled Fit		One Operator Fit	
$c_{\varphi q}^{(3)}$	$[-5.2, 3.1] \times 10^{-3}$	1% syst.	$[-2.1, 2.0] \times 10^{-3}$	1% syst.
	$[-6.7, 3.3] \times 10^{-3}$	5% syst.	$[-2.6, 2.4] \times 10^{-3}$	5% syst.
	$[-8.2, 3.7] \times 10^{-3}$	10% syst.	$[-3.2, 2.8] \times 10^{-3}$	10% syst.
$c_{\varphi q}^{(3)}$ $(+Wh)$	$[-2.5, 2.1] \times 10^{-3}$	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.

UV models: Spin-1 triplets

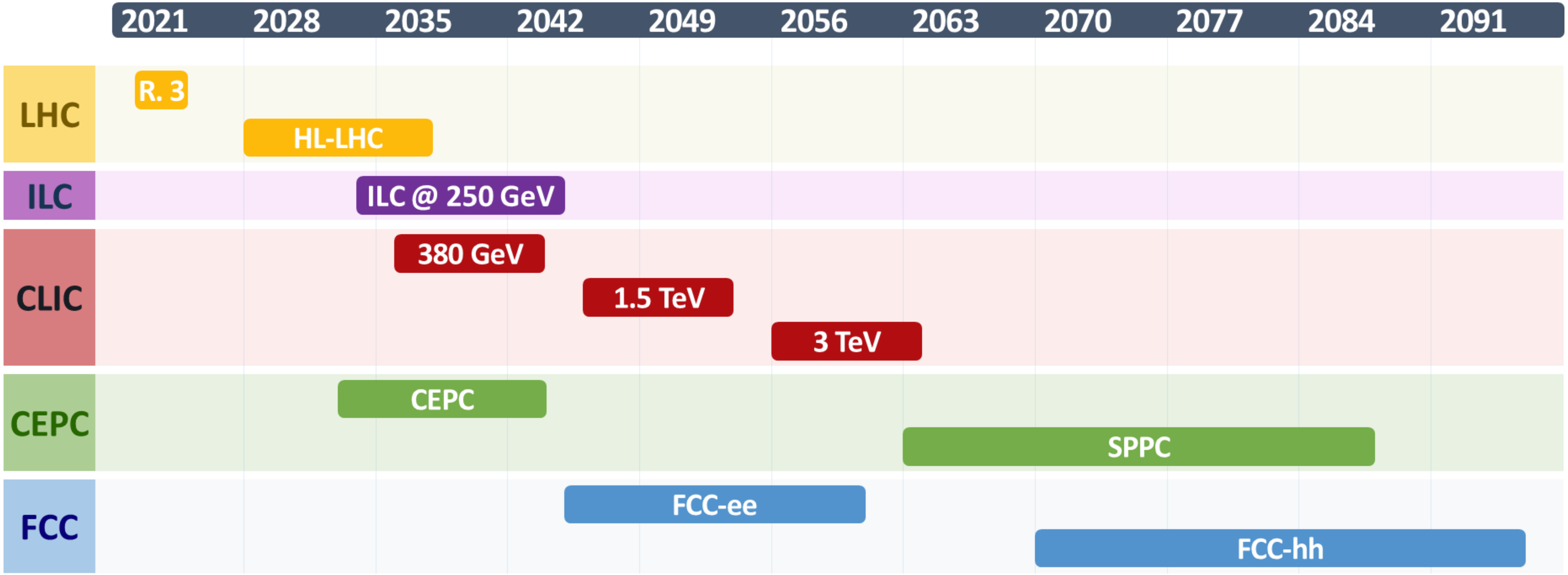
$$L_\mu \sim (1,3)_0 \qquad \mathcal{L}_{BSM} = \frac{1}{4} F^a_{L,\mu\nu} F^{a,\mu\nu}_L + \frac{m_L^2}{2} L_\mu L^\mu + \gamma_H L^a_\mu \frac{i}{2} H^\dagger \sigma^a \overleftrightarrow{D}^\mu H + \sum_f \gamma_f L^a_\mu \bar{f} \gamma^\mu \sigma^a f$$

$$c^{(3)}_{\varphi q} = -\frac{\gamma_H \gamma_q}{2 m_L^2}$$

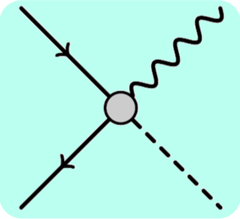
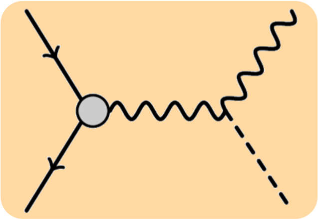
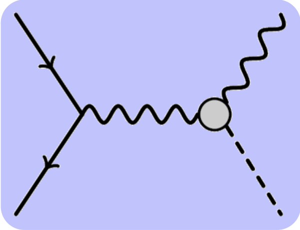
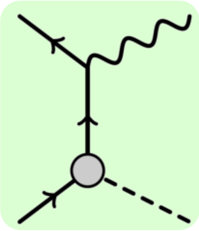




Future experiments timeline



Dimension-6 operators in Vh

$$\mathcal{O}_{\varphi D} = \left(H^\dagger D^\mu H\right)^* \left(H^\dagger D_\mu H\right)$$

$$\mathcal{O}_{\varphi \mathrm{W}} = H^\dagger H\, W^{a,\mu\nu} W^a_{\mu\nu}$$

$$\mathcal{O}_{\varphi \widetilde{\mathrm{W}}} = H^\dagger H\, W^{a,\mu\nu} \widetilde{W}^a_{\mu\nu}$$

$$\mathcal{O}_{\varphi \mathrm{B}} = H^\dagger H\, B^{\mu\nu} B_{\mu\nu}$$

$$\mathcal{O}_{\varphi \widetilde{\mathrm{B}}} = H^\dagger H\, B^{\mu\nu} \widetilde{B}_{\mu\nu}$$

$$\mathcal{O}_{\varphi \mathrm{WB}} = H^\dagger \sigma^a H\, B^{\mu\nu} W^a_{\mu\nu}$$

$$\mathcal{O}_{\varphi \widetilde{\mathrm{W}}\mathrm{B}} = H^\dagger \sigma^a H\, B^{\mu\nu} \widetilde{W}^a_{\mu\nu}$$

$$\mathcal{O}_{u\mathrm{W}} = \left(\bar{q}_L \sigma^{\mu\nu} u_R\right) \tau^I \tilde{H} W^I_{\mu\nu}$$

$$\mathcal{O}_{d\mathrm{W}} = \left(\bar{q}_L \sigma^{\mu\nu} d_R\right) \tau^I H W^I_{\mu\nu}$$

$$\mathcal{O}_{u\mathrm{B}} = \left(\bar{q}_L \sigma^{\mu\nu} u_R\right) \tilde{H} B_{\mu\nu}$$

$$\mathcal{O}_{d\mathrm{B}} = \left(\bar{q}_L \sigma^{\mu\nu} d_R\right) H B_{\mu\nu}$$

$$\mathcal{O}_{\varphi ud} = \left(\bar{u}_R \gamma^\mu d_R\right) \left(i H^\dagger \overleftrightarrow{D}_\mu H\right)$$

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

$$\mathcal{O}^{(1)}_{\varphi q} = \left(\bar{Q}_L \gamma^\mu Q_L\right) \left(i H^\dagger \overleftrightarrow{D}_\mu H\right)$$

$$\mathcal{O}_{\varphi u} = \left(\bar{u}_R \gamma^\mu u_R\right) \left(i H^\dagger \overleftrightarrow{D}_\mu H\right)$$

$$\mathcal{O}_{\varphi d} = \left(\bar{d}_R \gamma^\mu d_R\right) \left(i H^\dagger \overleftrightarrow{D}_\mu H\right)$$

$$\mathcal{O}_{u\varphi} = H^\dagger H \left(\bar{q}_L \tilde{H} u_R\right)$$

$$\mathcal{O}_{d\varphi} = H^\dagger H \left(\bar{q}_L H d_R\right)$$

MFV suppressed — **Sub-leading energy growth** — **No interference with SM for massless quarks**