No channel left behind

Revisiting Vh at LHC, HL-LHC and FCC-hh

Higgs Conference 2022
8 November 2022
Pisa, Italy

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University of Manchester

With F. Bishara, S. De Curtis, L. Delle Rose, P. Englert, C. Grojean, M. Montull, G. Panico.
Mostly: arXiv 2208.11134
arXiv 2004.06122 (JHEP 07 (2020) 075)
arXiv 2011.13941 (JHEP 04 (2021) 154)

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A trick of the tail

Precision with hadron colliders? Yes!

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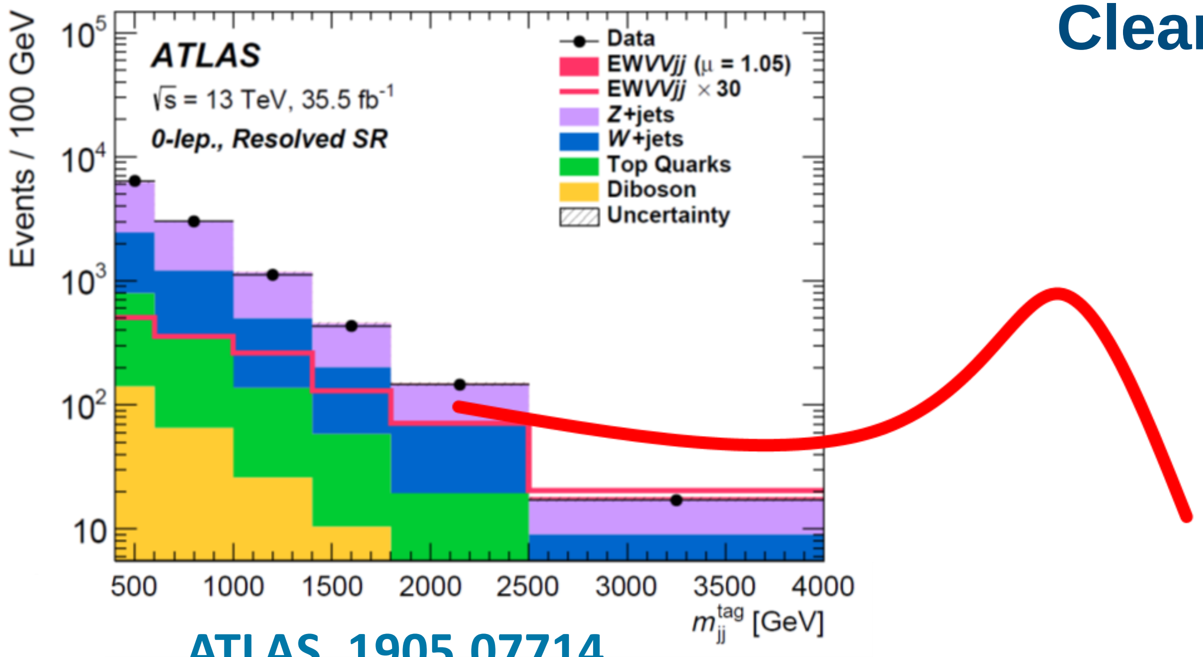

ATLAS, 1905.07714

Clean channels + NP effects that grow with E

Tail hunting!

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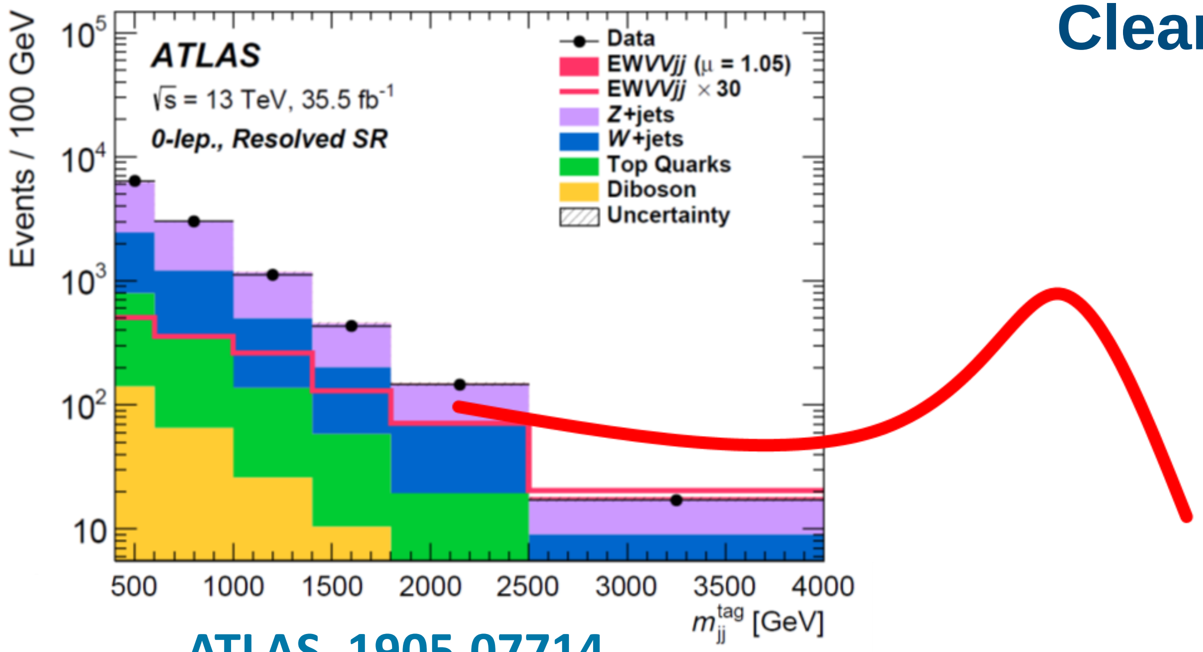

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Heavy New Physics

Effective Field Theories

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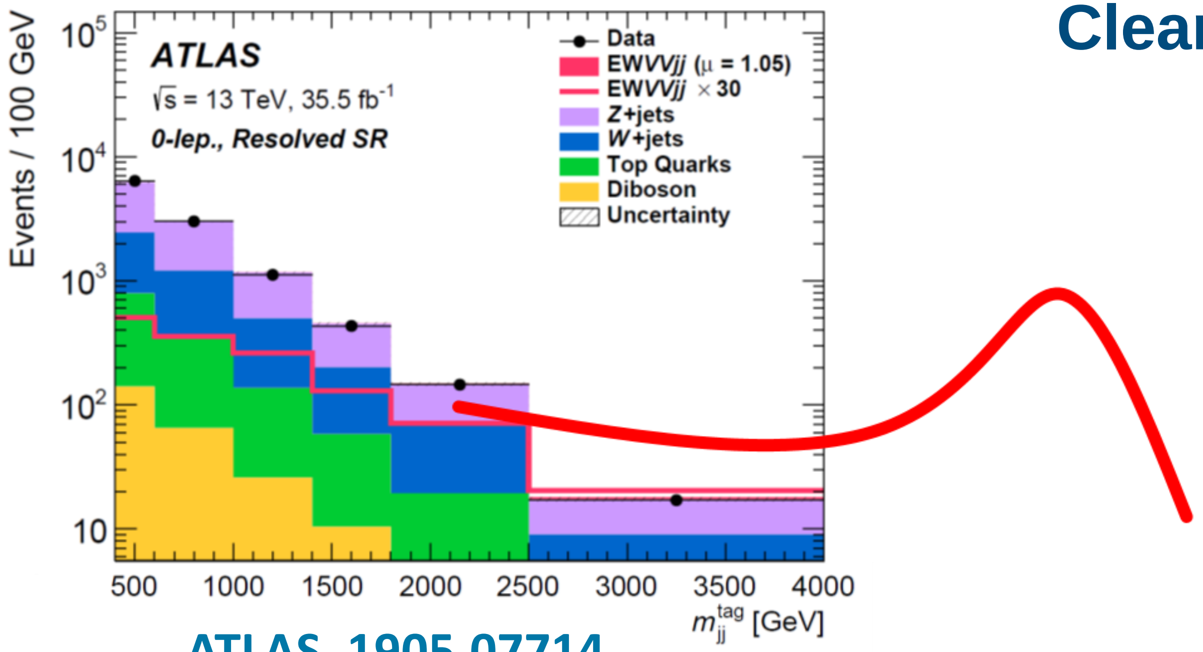

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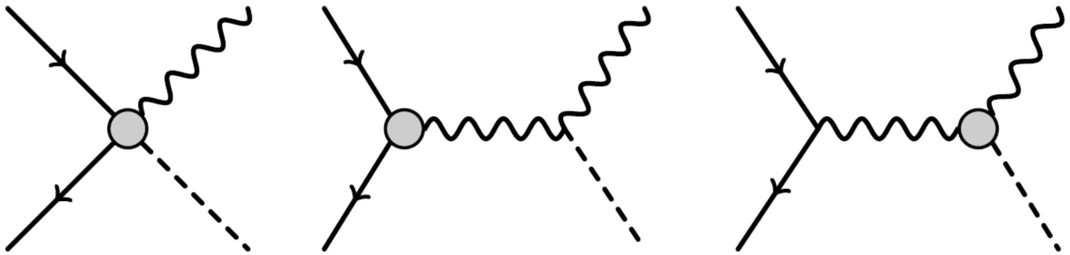
Tail hunting!

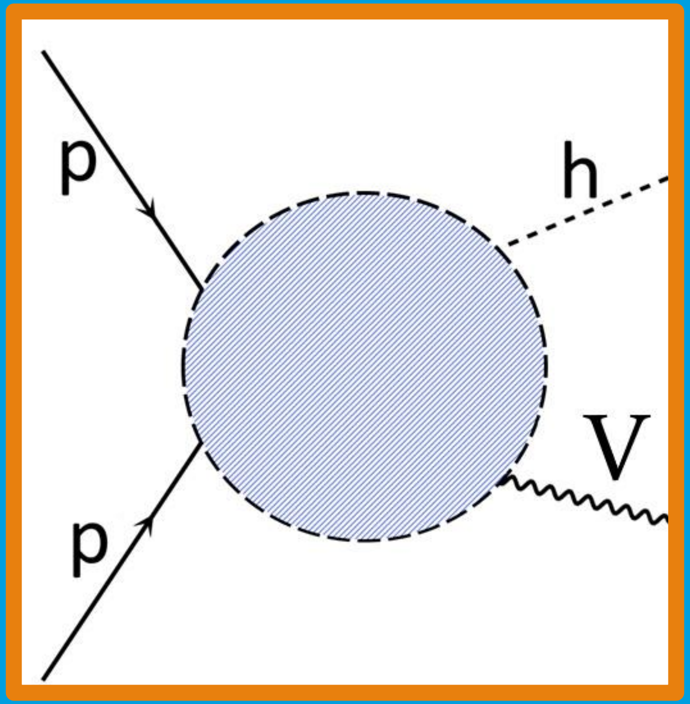
Heavy New Physics

Effective Field Theories

Diboson processes offer a window into EW and Higgs dynamics.



The process of interest.



$$pp \to Vh$$

Vh. What New Physics can we probe?

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

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

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

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High energy behavior

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

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$$Zh \leftarrow \left\{ \begin{array}{l} \frac{c_{\varphi q}^{(1)}}{\Lambda^2} \left(\overline{Q}_L \gamma^\mu Q_L\right) \left(iH^\dagger \overleftrightarrow{D}_\mu H\right) \\ \frac{c_{\varphi u}}{\Lambda^2} \left(\overline{u}_R \gamma^\mu u_R\right) \left(iH^\dagger \overleftrightarrow{D}_\mu H\right) \\ \frac{c_{\varphi d}}{\Lambda^2} \left(\overline{d}_R \gamma^\mu d_R\right) \left(iH^\dagger \overleftrightarrow{D}_\mu H\right) \\ \frac{c_{\varphi q}^{(3)}}{\Lambda^2} \left(\overline{Q}_L \sigma^a \gamma^\mu Q_L\right) \left(iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H\right) \end{array} \right\} \rightarrow \frac{\mathcal{A}_{BSM}}{\mathcal{A}_{SM}} \sim \hat{s} = E_{CM}^2$$

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All four operators → Zh; the $c_{\varphi q}^{(3)}$ operator → $W^\pm h$

All four operators → $$\frac{\mathcal{A}_{BSM}}{\mathcal{A}_{SM}} \sim \hat{s} = E_{CM}^2$$

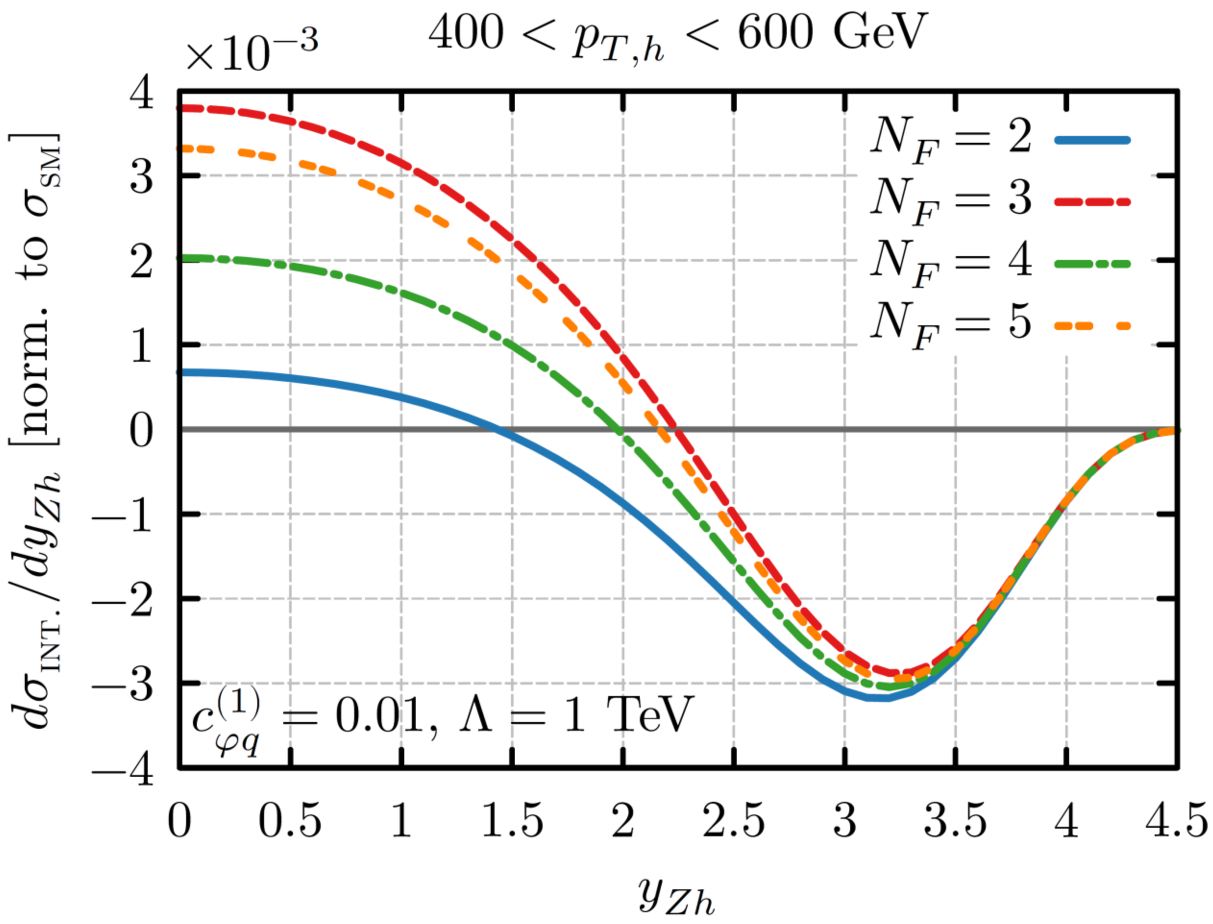
Zh.

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



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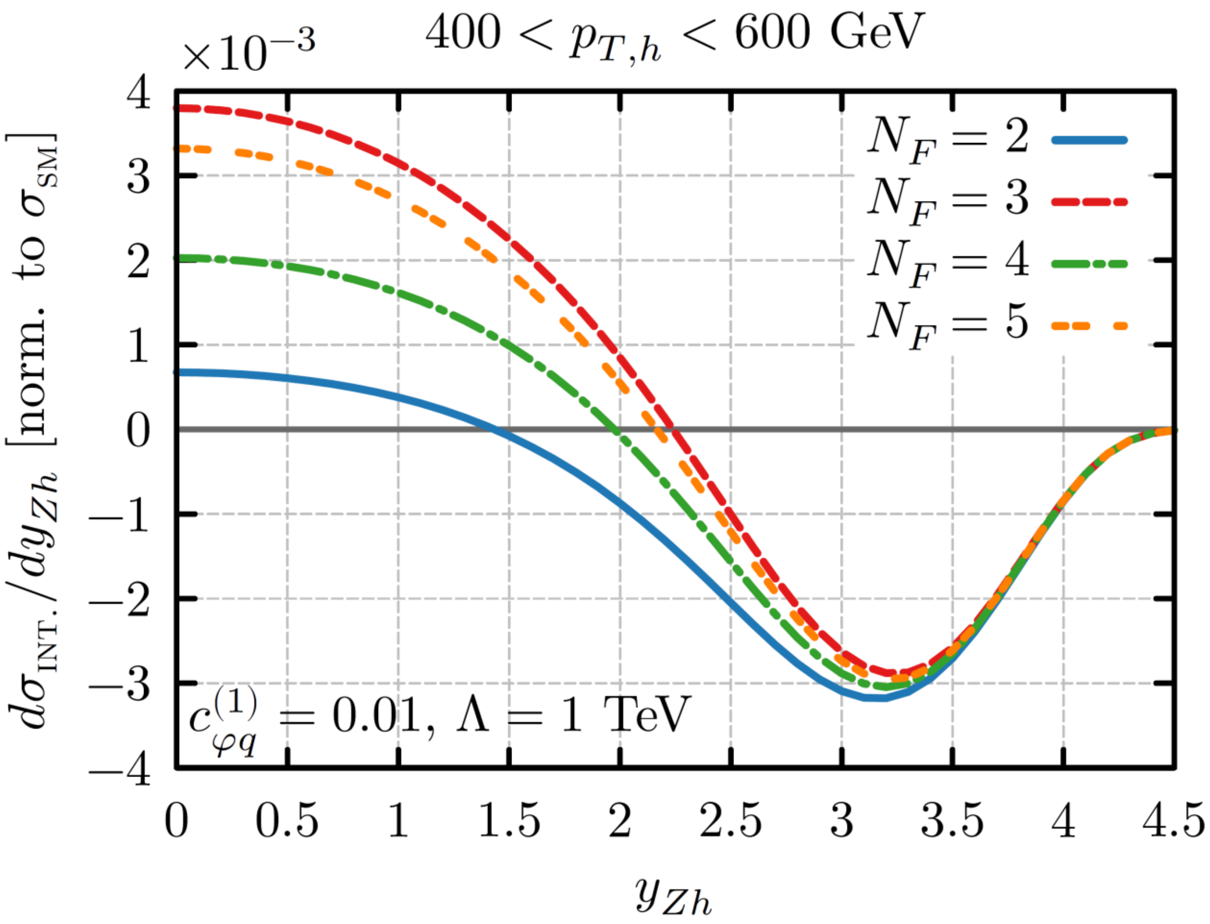

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Cancellation of up and down contributions

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 $Z \to \nu\bar{\nu}$)

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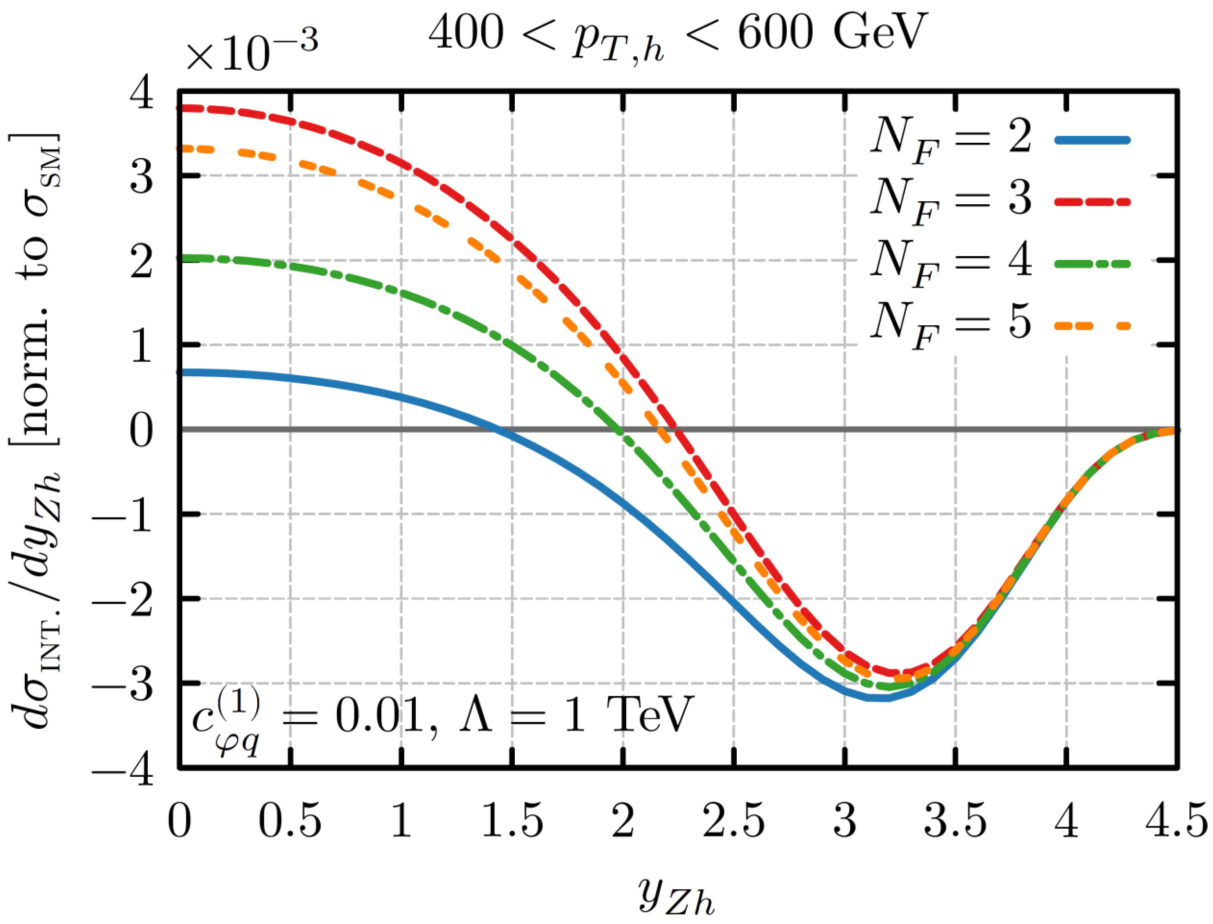

$$\sigma^{int}_{\mathcal{O}^{(1)}_{\varphi q}} \propto s_W^2 Q - T_3$$

Cancellation of up and down contributions

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

Suppression by SM coupling

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New collider, new possibilities

For $p_T^h > 550$ GeV:

$$p\,p \to W^{\pm}\,h$$

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

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

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

Watch my talk at Higgs 2021

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

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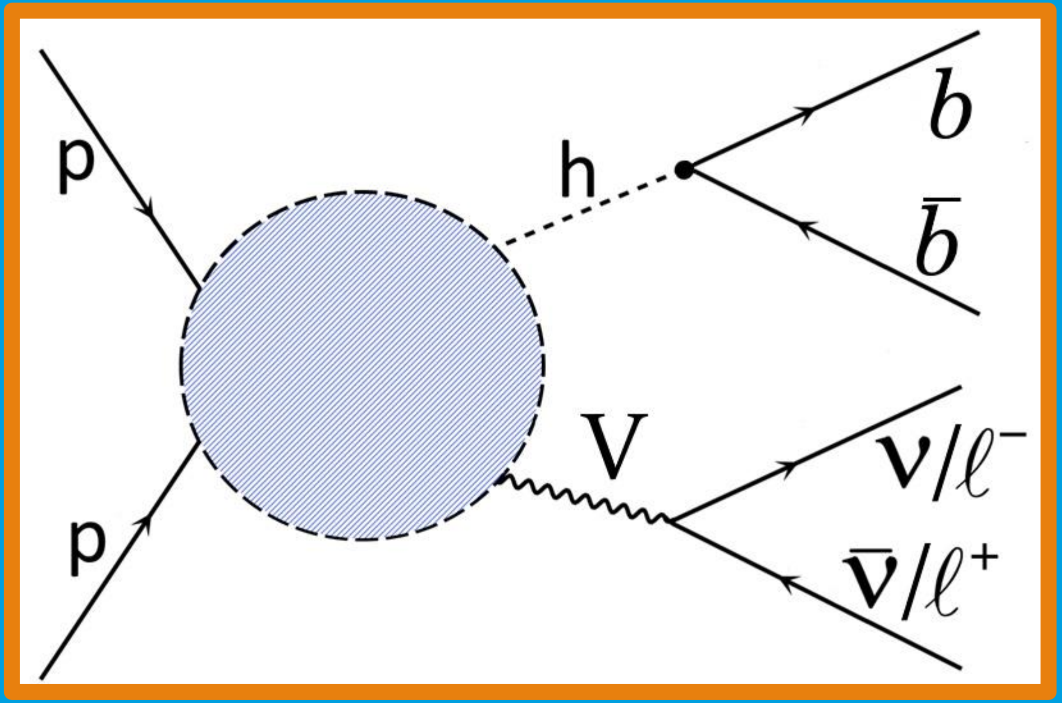
How will the known channels evolve from LHC to FCC-hh?

How will they compare with the new ones?

Let them be quarks, Vh.

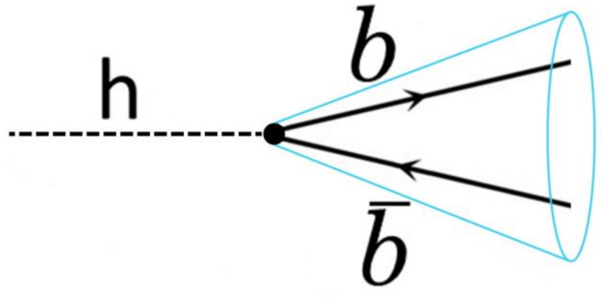
arXiv 2208.11134



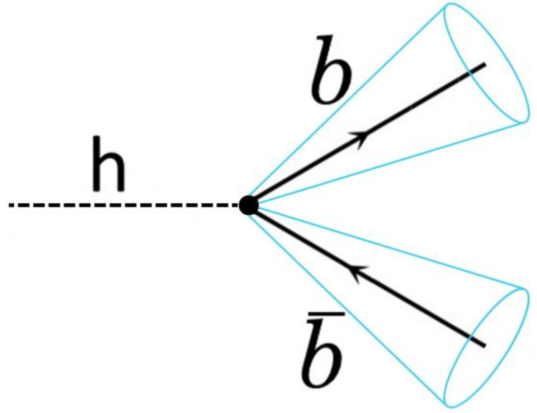
$$pp \to Vh \to \ell(\nu)\ell(\nu)b\bar{b}$$

Combining regimes

Boosted



Resolved



Vh. Combining regimes

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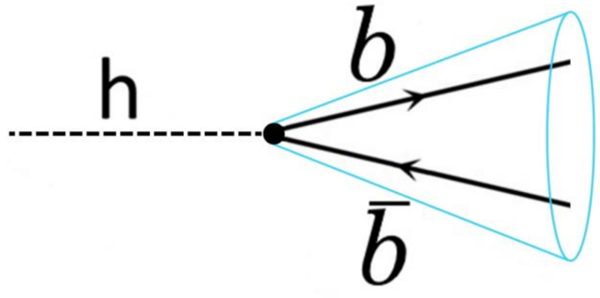


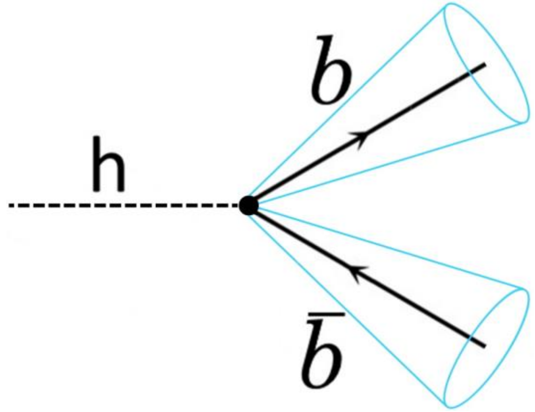
ATLAS, 2008.02508

DOI: 10.1016/j.physletb.2021.136204 28th April 2021

Measurement of the associated production of a Higgs boson decaying into b-quarks with a vector boson at high transverse momentum in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector

The ATLAS Collaboration

Resolved



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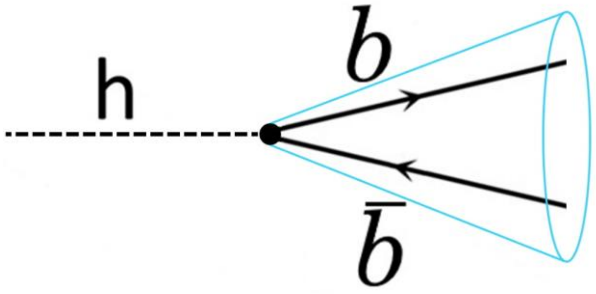

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Scale-invariant tagging

Gouzevitch et al, 1303.6636
Bishara et al, 1611.03860

With use of Mass-drop tagging

Butterworth et al, 0802.2470

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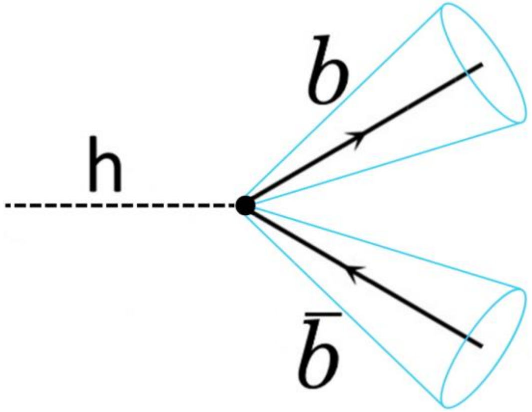

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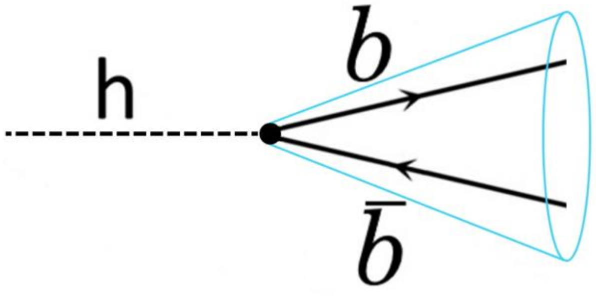

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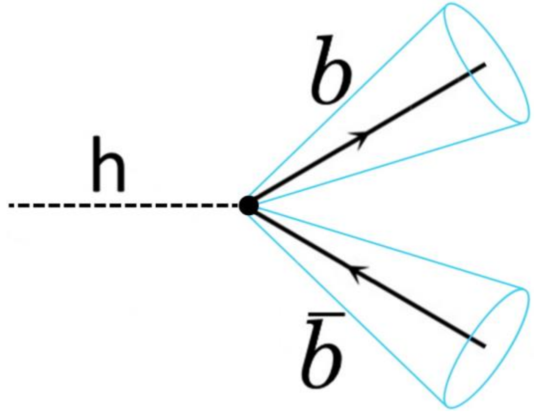

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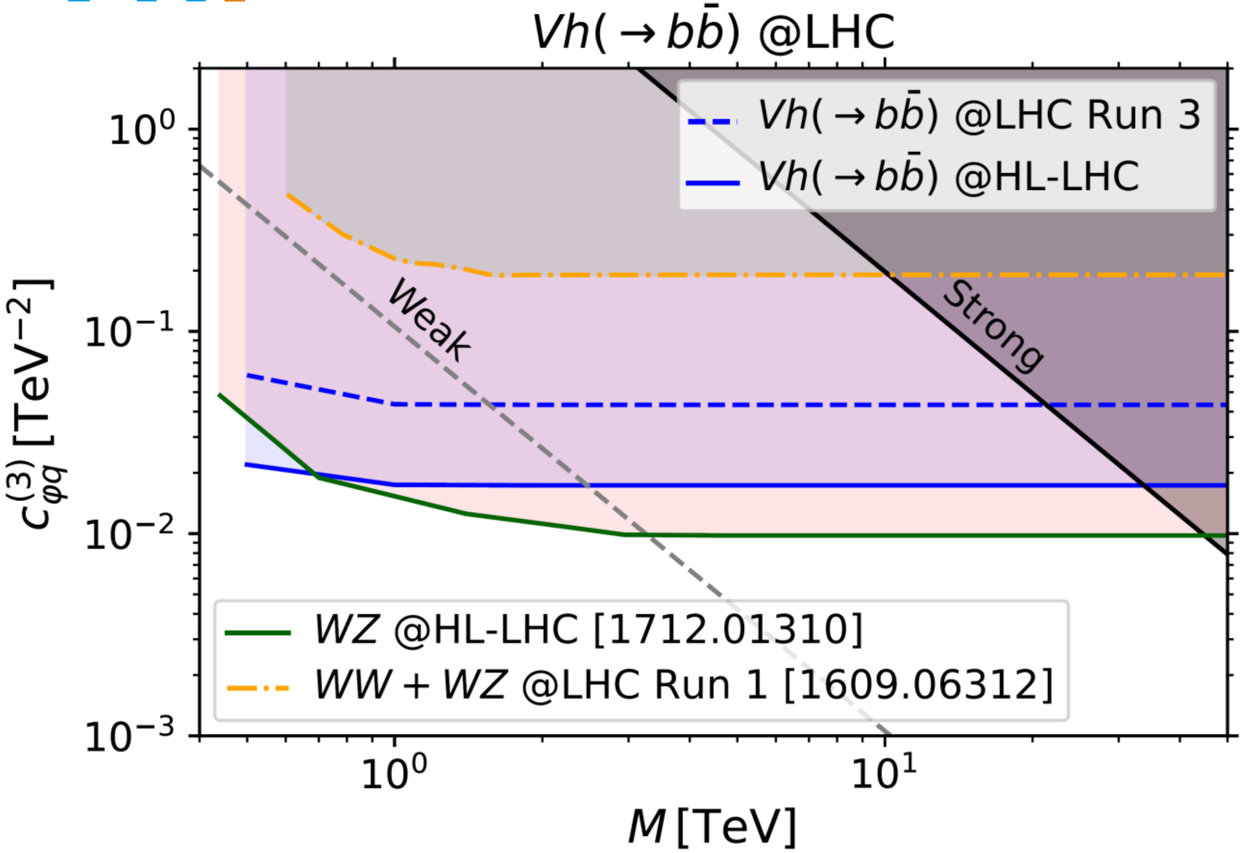
Adding Resolved category: 10-17% improvement at LHC.

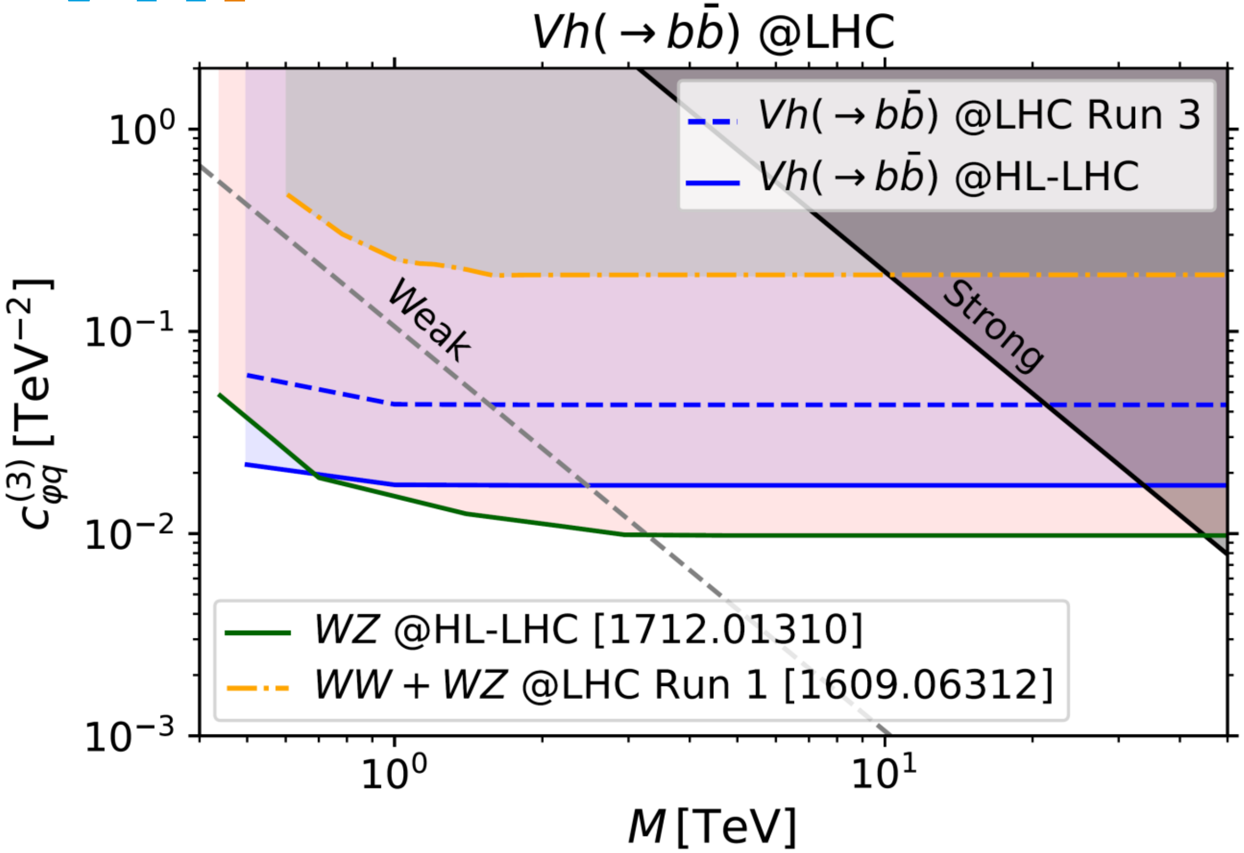
+Projections for FCC-hh based on CDR

Vh. Direct comparison LHC vs FCC-hh



LHC Run 3

Vh. Direct comparison LHC vs FCC-hh



LHC Run 3 → **HL-LHC**

~2x

LHC Run 3 is limited by statistics

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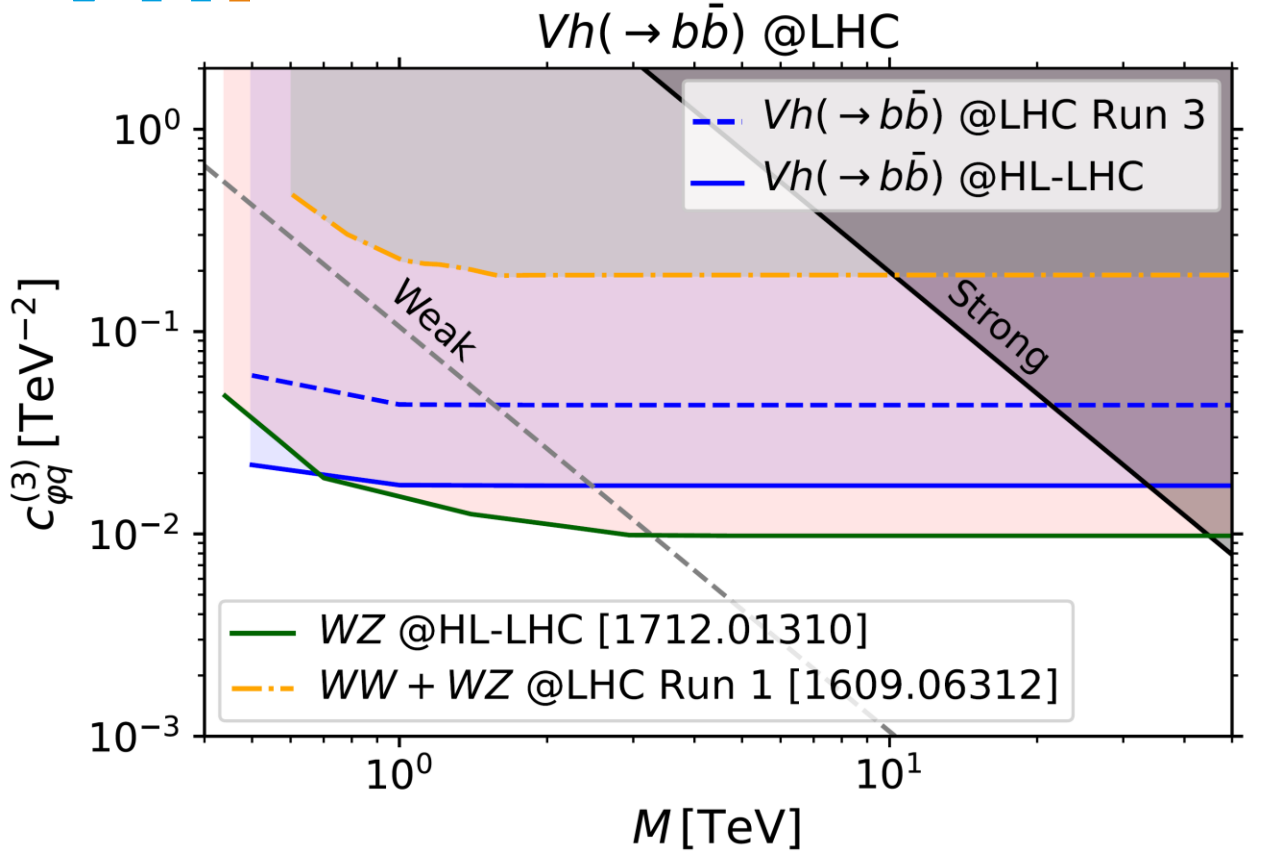
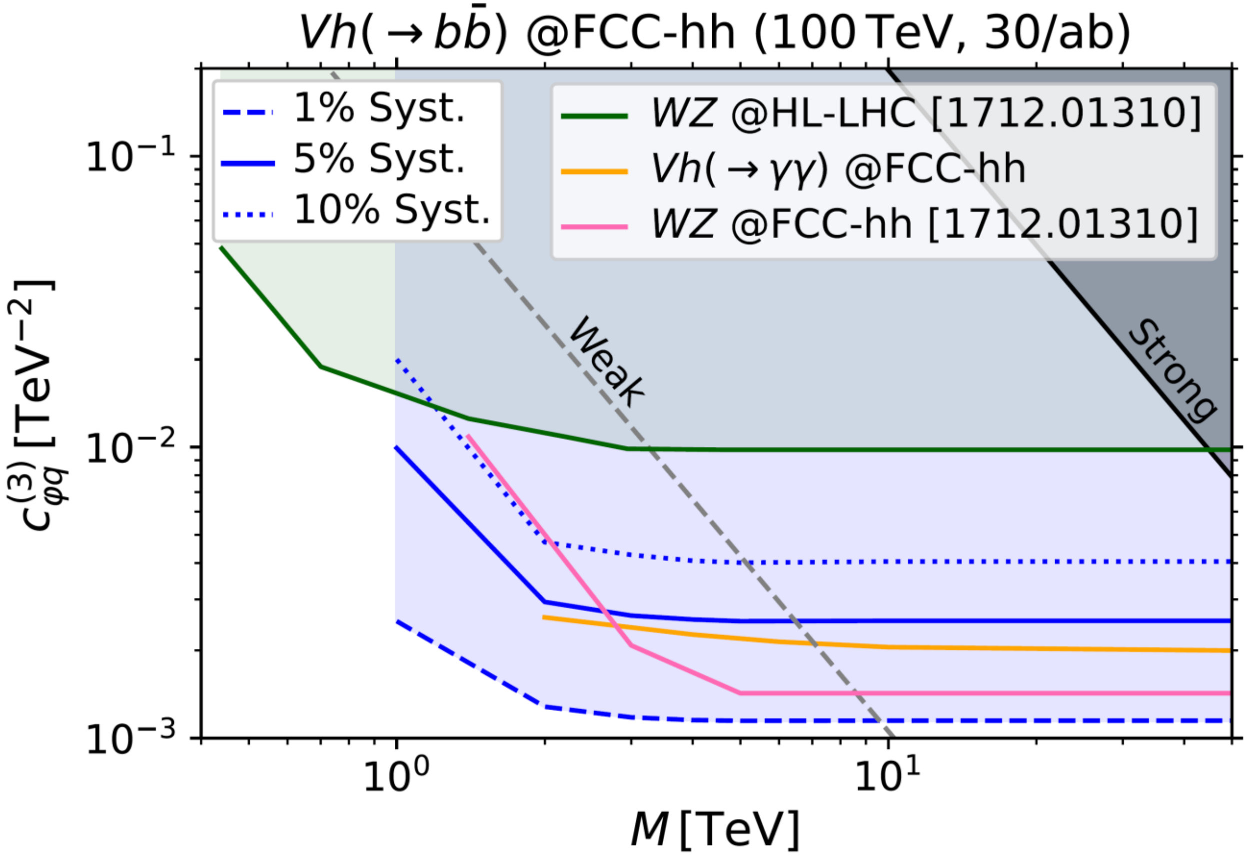


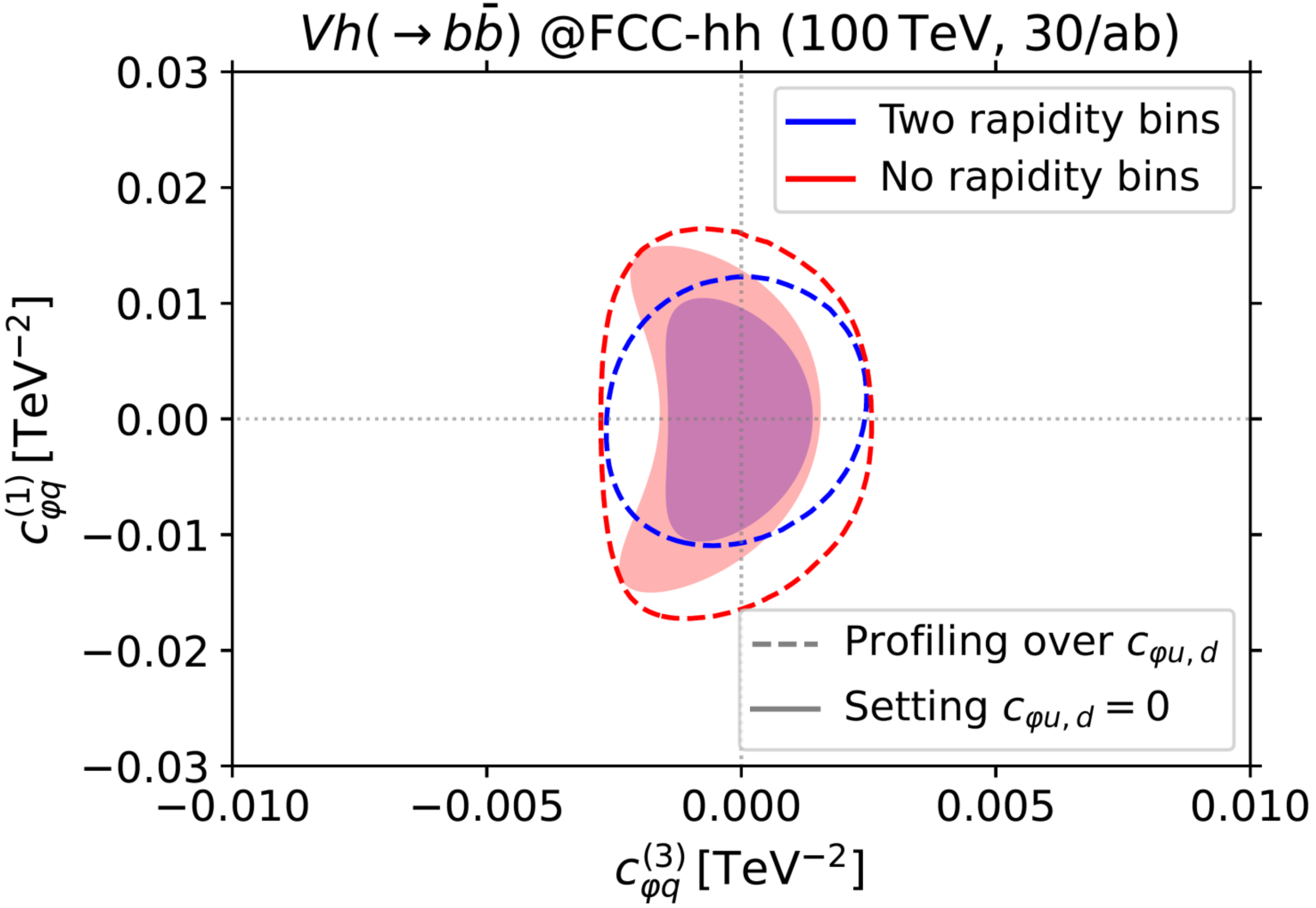


LHC Run 3 → (~2x) → **HL-LHC** → (~5x) → **FCC-hh**

LHC Run 3 is limited by statistics

$(h \to)\ \gamma\gamma \approx b\bar{b}$ **@FCC-hh**

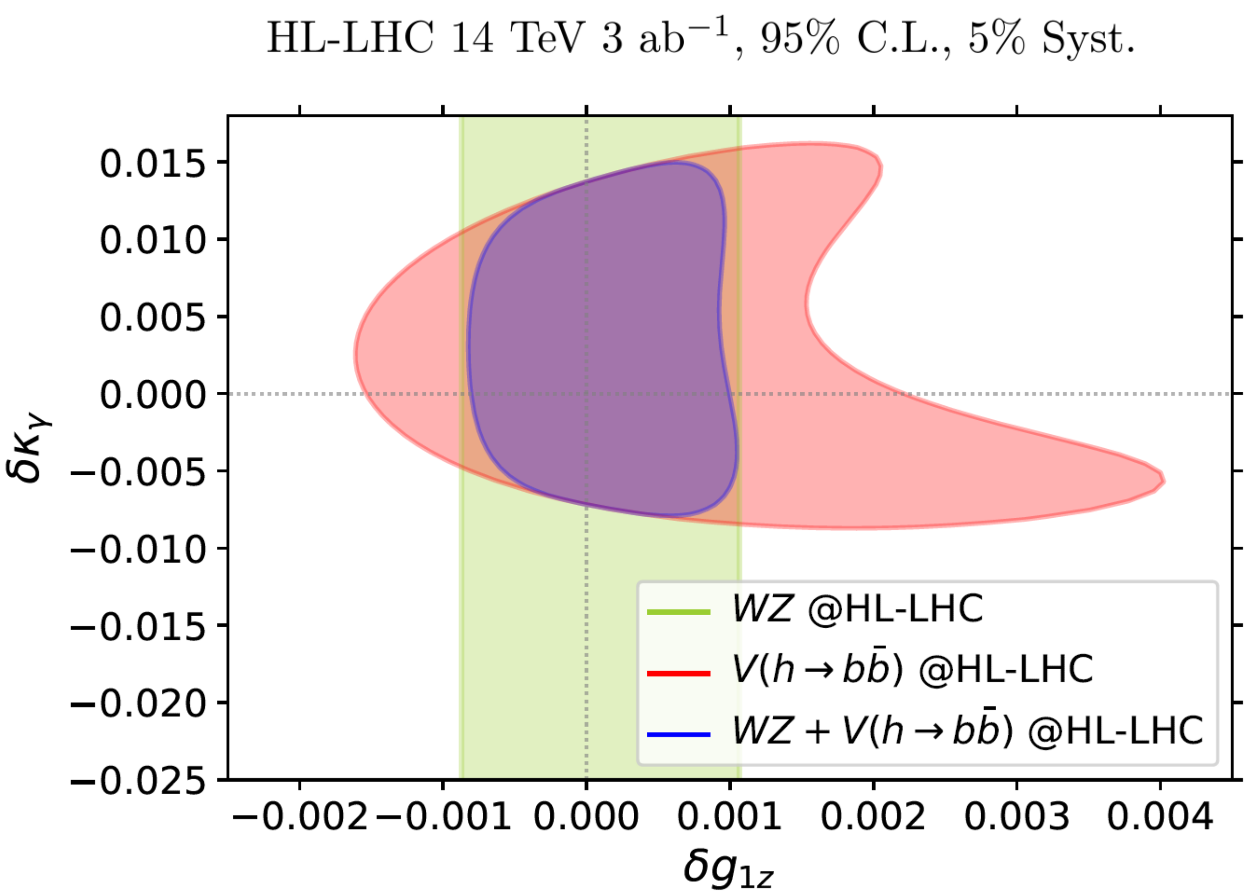
Rapidity binning effects.



Significant impact on $\mathcal{O}_{\varphi q}^{(1)}$ due to the lift of the cancellation.

Sizeable impact on aTGC bounds

Universal Theories



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

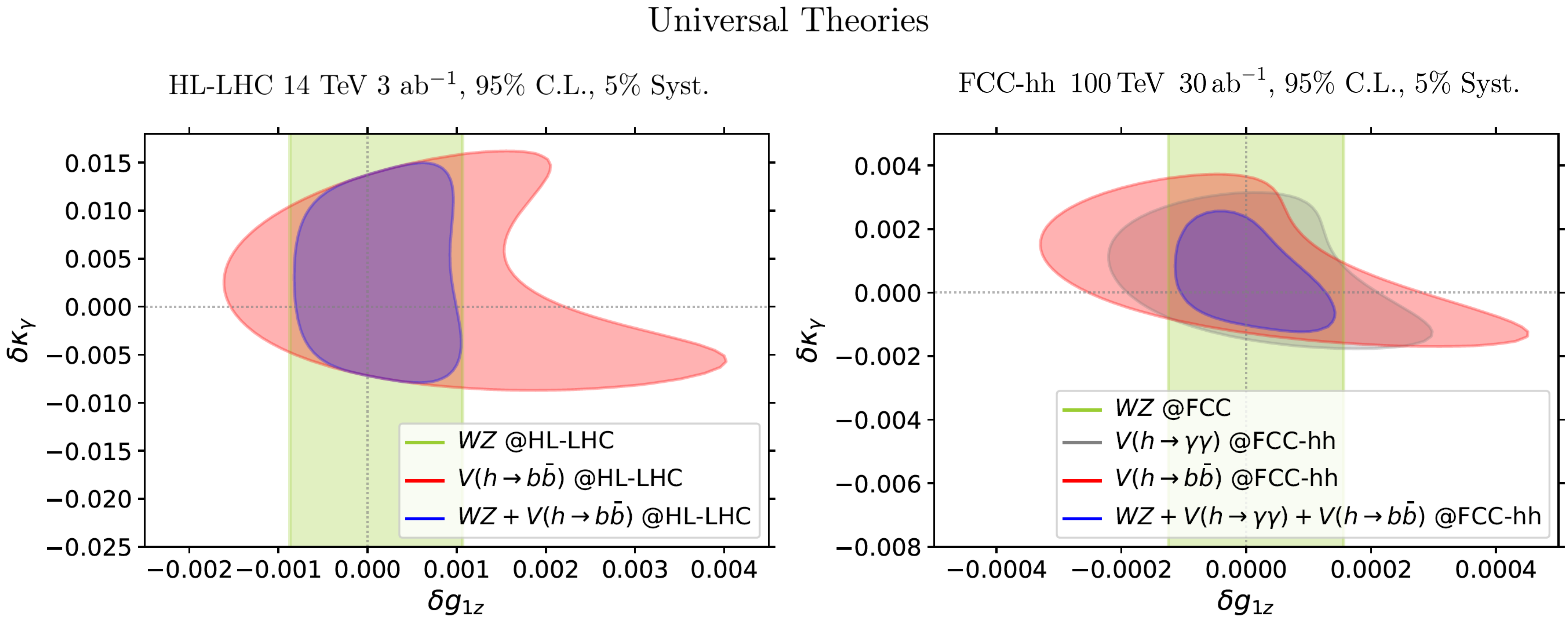
$$c_{\varphi q}^{(1)} = -\frac{\Lambda^2}{4m_W^2} g^2 \left(\delta g_L^{Zu} + \delta g_L^{Zd} + \frac{1}{3}\left(t_{\rm W}^2 \delta\kappa_\gamma - s_{\rm W}^2 \delta g_{1z}\right)\right)$$

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

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

$$\mathcal{L}_{TGC} \supset ie\left(1 + \delta\kappa_\gamma\right) A^{\mu\nu} W_\mu^+ W_\nu^- + ig\, c_W \left(1 + \delta g_{1z}\right)\left(W_{\mu\nu}^+ W^{-,\mu} - W_{\mu\nu}^- W^{+,\mu}\right) Z^\nu$$

Vh. Sizeable impact on aTGC bounds



Clear complementarity among diboson channels

Conclusions

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- Wh and Zh with are not exploration channels, but important to probe different directions.

Thank you for your attention

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

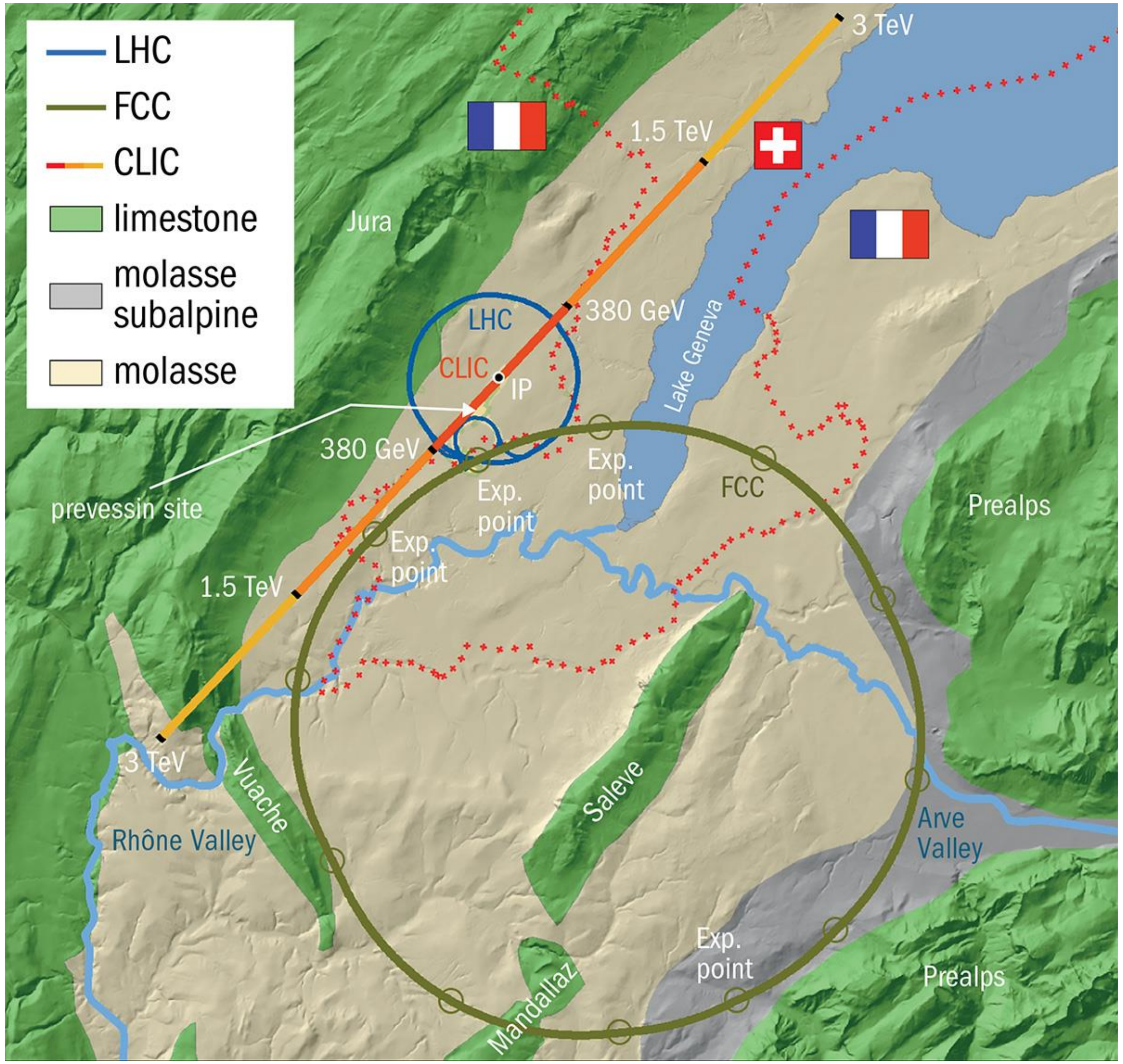
Appendix.

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

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

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.**

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

(The dimension-8 term is crossed out.)

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

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

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

Interference

Wh. 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
$\lambda = \pm$	$\frac{M_W}{\sqrt{\hat{s}}}$	$\frac{\sqrt{\hat{s}}\, M_W}{\Lambda^2}$	$\frac{\sqrt{\hat{s}}\, M_W}{\Lambda^2}$	$\frac{\sqrt{\hat{s}}\, M_W}{\Lambda^2}$

$V = W,\ Z$

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

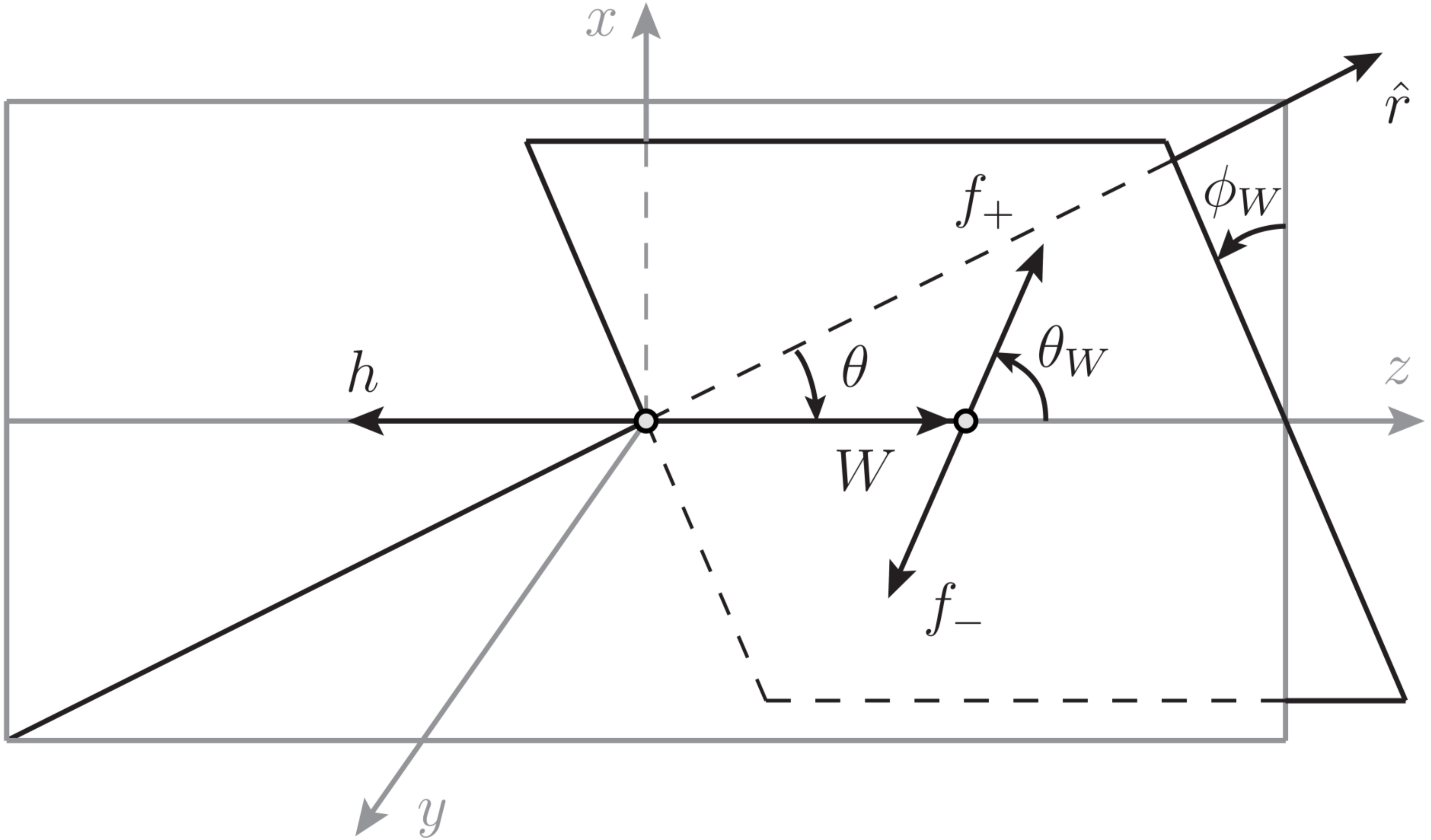
Differential in p_T

↓

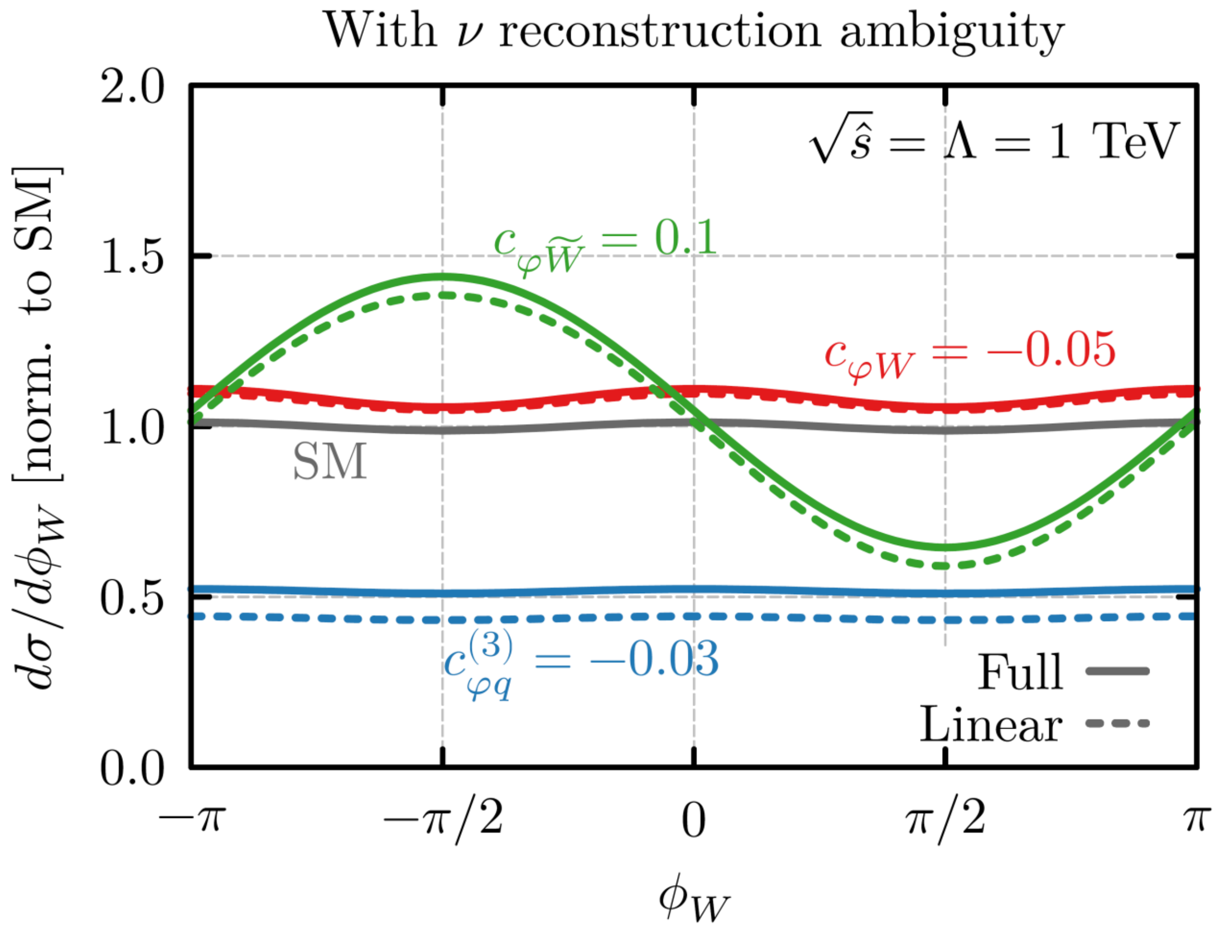
Interference between same polarisation

Interference patterns

Measuring angles resurrects interference



Wh. Interference patterns



Differential in p_T^h and ϕ_W

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

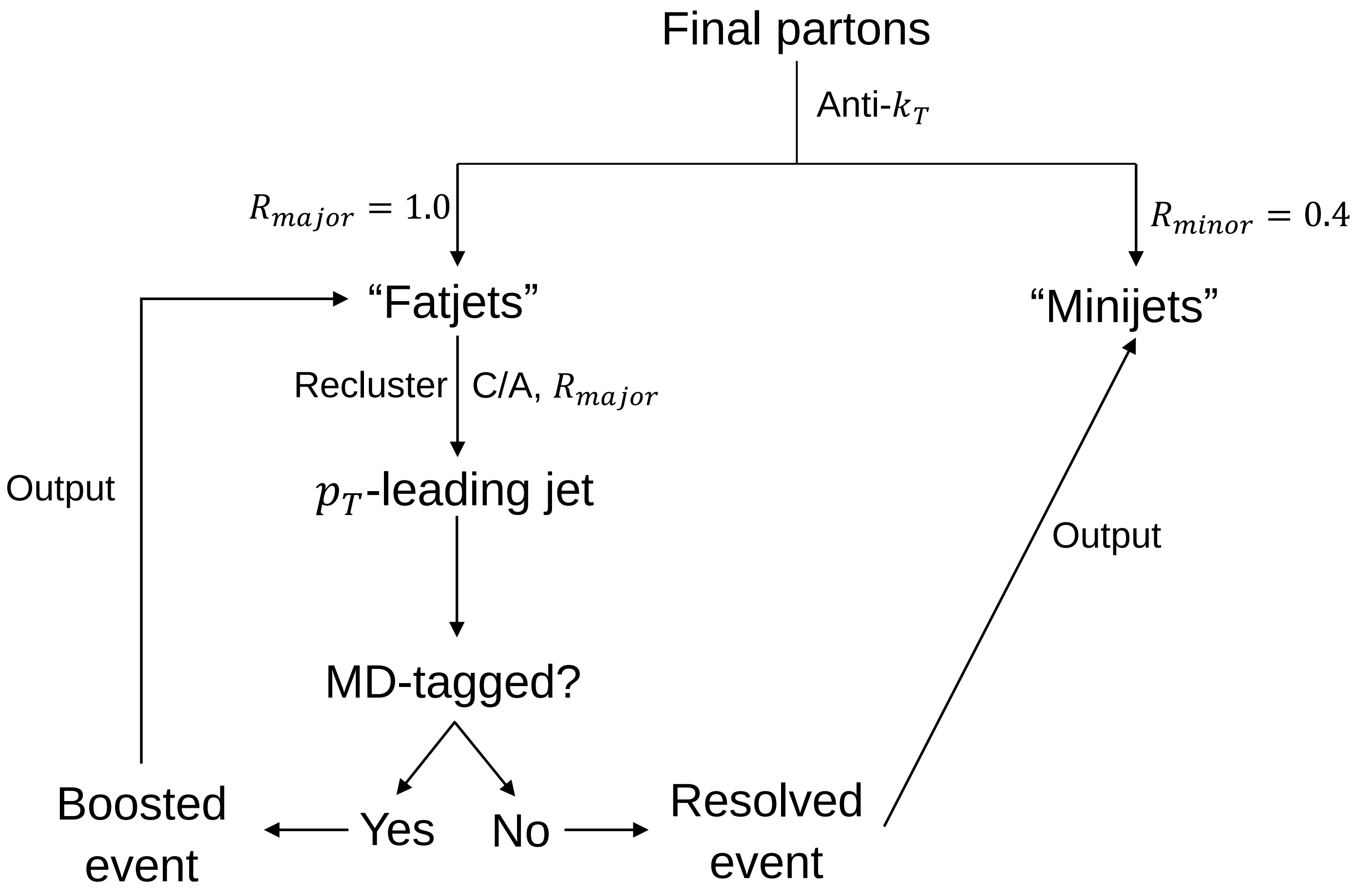
ν reconstruction $(\phi_W \to \pi - \phi_W)$

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

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

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

Tagging algorithm



(b-)Tagging algorithm

$\exists\ (b, c, j)$ final parton within $\Delta R \leq R_{minor}$ of Minijet → b –tag for Minijet with prob. $eff^{LHC/FCC}_{(b,c,j)}$

For Boosted events → +1 b-tag for MDT jet per b-tagged Minijet within $\Delta R \leq 0.2$

Enough for Resolved events

$$\mathrm{eff}_b^{\mathrm{LHC}} = \begin{cases} 0 & \text{if } p_T \leq 20\,\mathrm{GeV} \text{ or } |\eta| > 2.5 \\ 0.8\tanh(0.003 p_T)\frac{30}{1+0.086 p_T} & \text{else} \end{cases}$$

$$\mathrm{eff}_c^{\mathrm{LHC}} = \begin{cases} 0 & \text{if } p_T \leq 20\,\mathrm{GeV} \text{ or } |\eta| > 2.5 \\ 0.2\tanh(0.02 p_T)\frac{1}{1+0.0034 p_T} & \text{else} \end{cases}$$

$$\mathrm{eff}_j^{\mathrm{LHC}} = \begin{cases} 0 & \text{if } p_T \leq 20\,\mathrm{GeV} \text{ or } |\eta| > 2.5 \\ 0.002\tanh(7.3 \cdot 10^{-6} \cdot p_T) & \text{else} \end{cases}$$

$$\mathrm{eff}_b^{\mathrm{FCC}} = \begin{cases} 0 & \text{if } p_T \leq 20\,\mathrm{GeV} \text{ or } |\eta| > 4.5 \\ 0.85 & \text{else} \end{cases}$$

$$\mathrm{eff}_c^{\mathrm{FCC}} = \begin{cases} 0 & \text{if } p_T \leq 20\,\mathrm{GeV} \text{ or } |\eta| > 4.5 \\ 0.05 & \text{else} \end{cases}$$

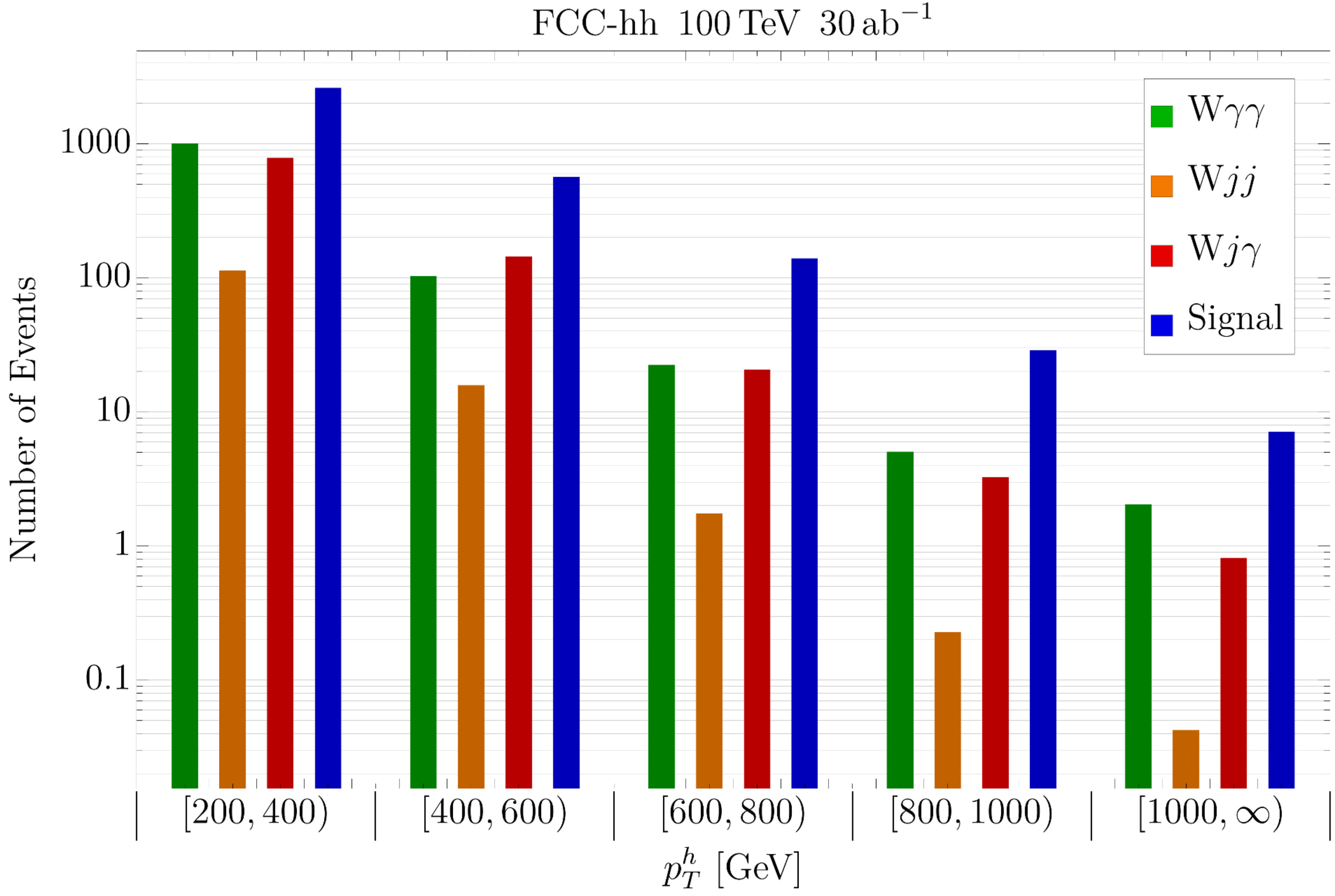
$$\mathrm{eff}_j^{\mathrm{FCC}} = \begin{cases} 0 & \text{if } p_T \leq 20\,\mathrm{GeV} \text{ or } |\eta| > 4.5 \\ 0.01 & \text{else} \end{cases}$$

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

Categories		Variable	(HL-)LHC	FCC-hh
0-lepton	boosted	$p_{T,\min}$ [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	$p_{T,\min}$ [GeV]	$\{250, \infty\}$	$\{0, 200, 400, 600, \infty\}$
	resolved		$\{175, 200, \infty\}$	$\{0, 200, 400, 600, \infty\}$

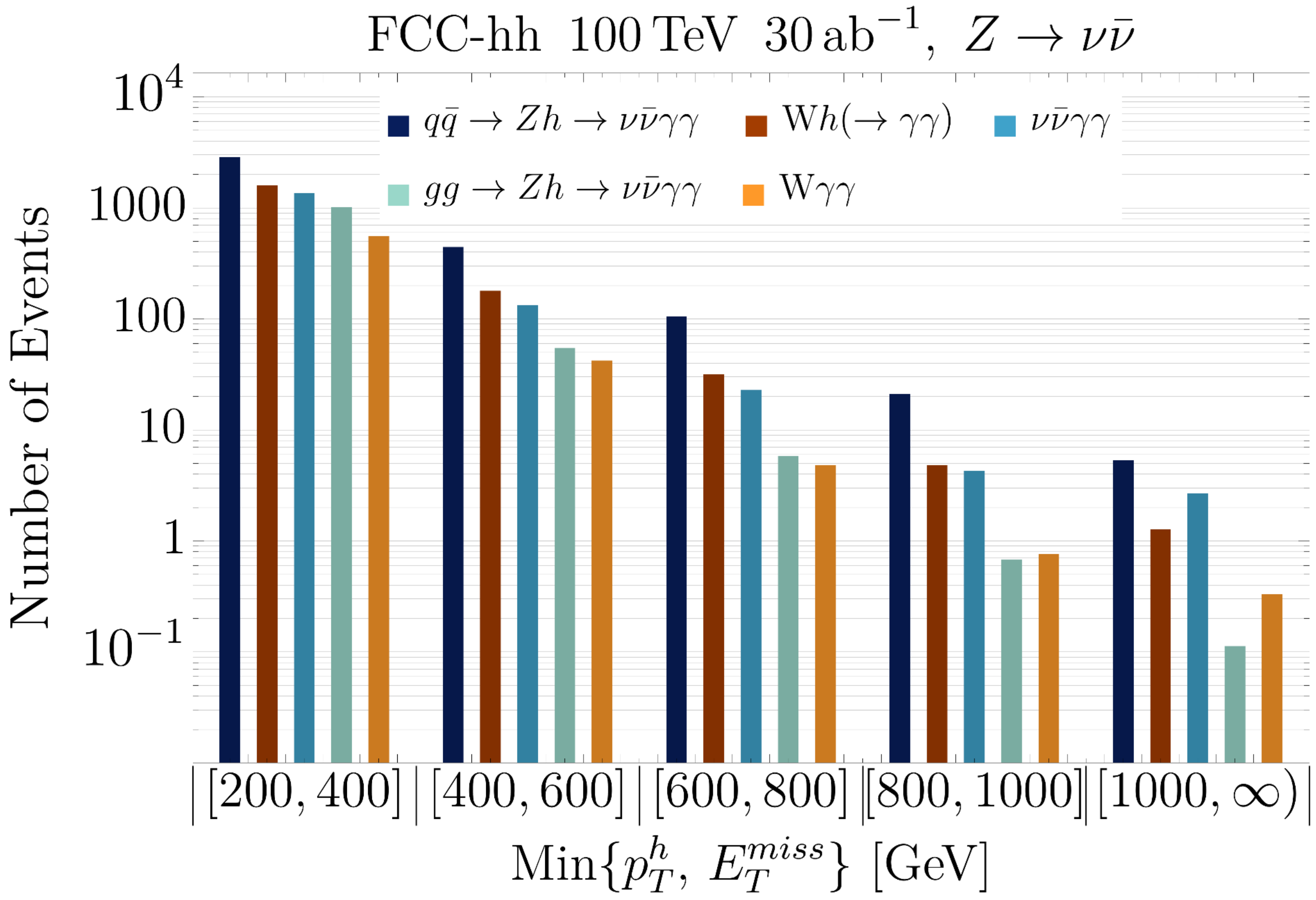
Wh. How big is the background?

- Events per bin for the relevant processes



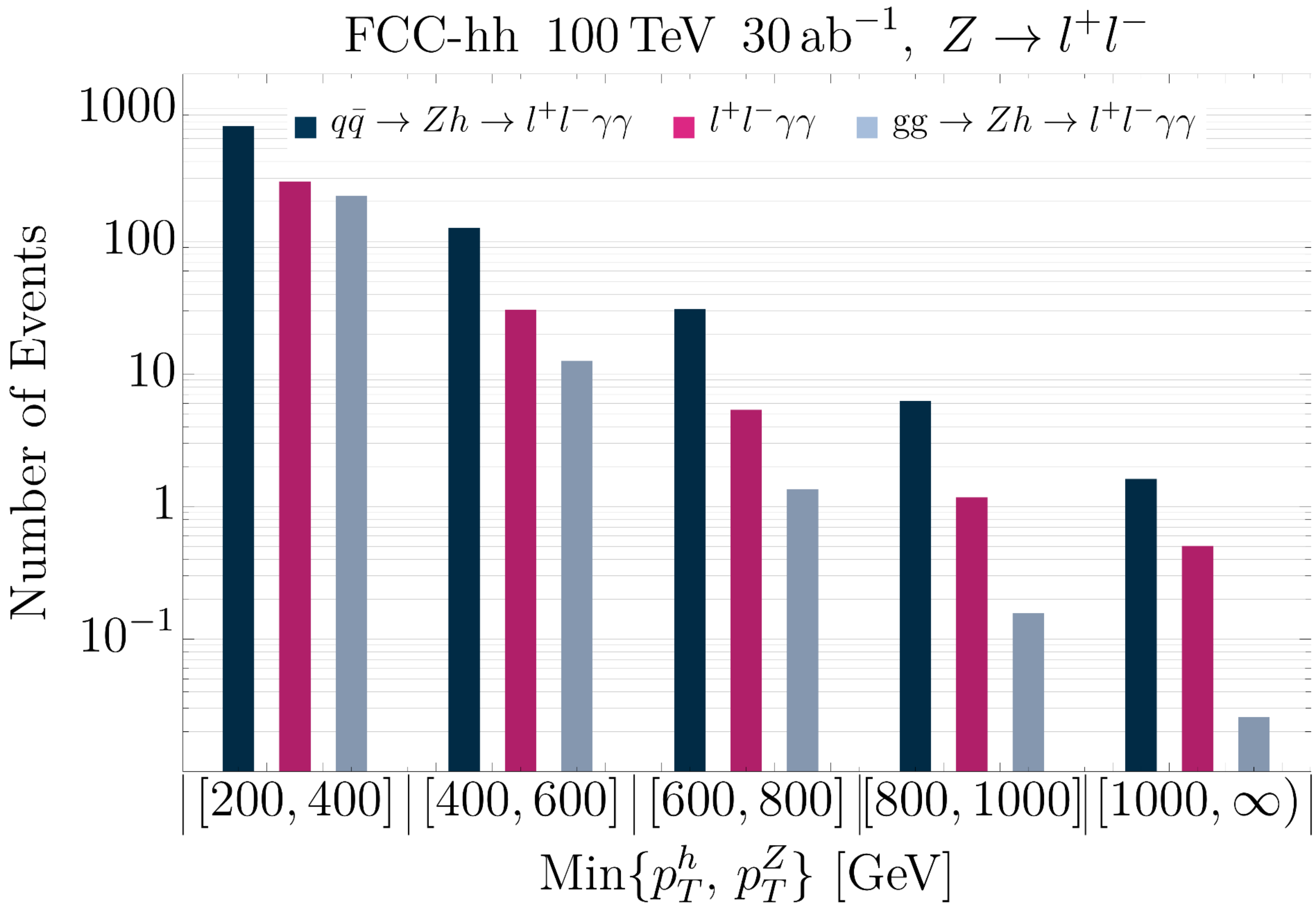
Zh. Signal and background

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



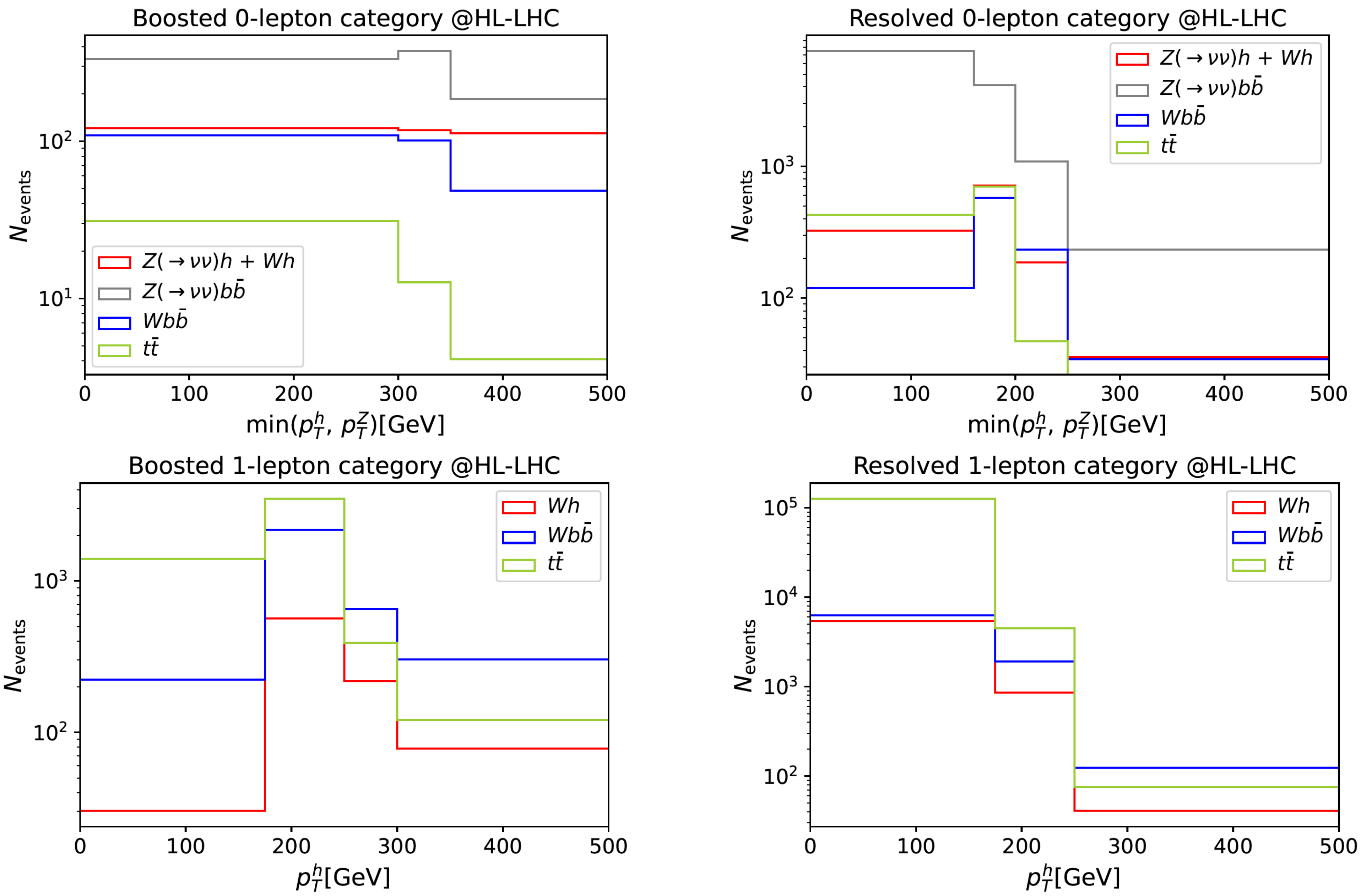
Zh. More results

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



Vh.

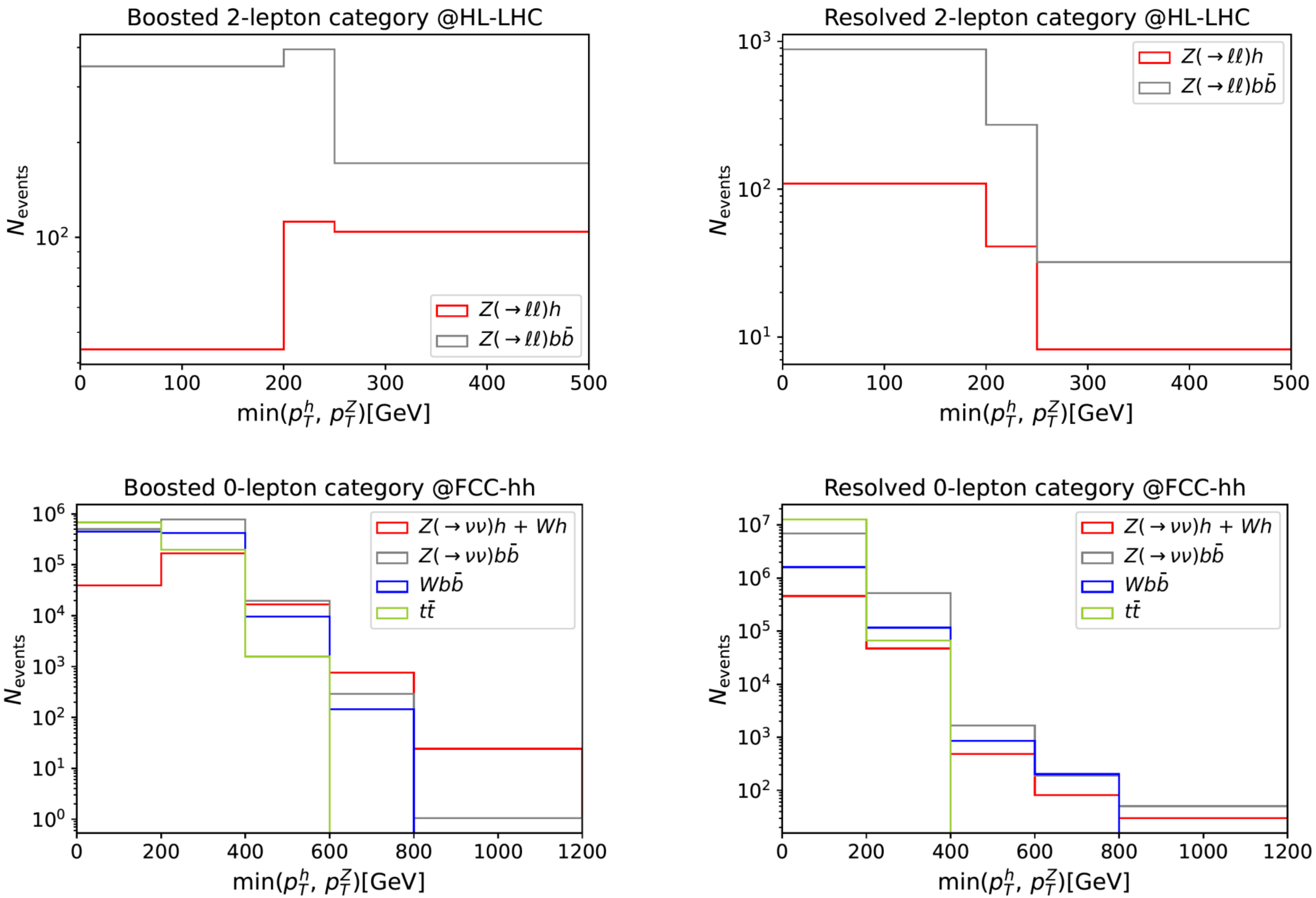
$h \to b\bar{b}$



Boosted 0-lepton category @HL-LHC
N_{events}
$Z(\to\nu\nu)h + Wh$
$Z(\to\nu\nu)b\bar{b}$
$Wb\bar{b}$
$t\bar{t}$
$\min(p_T^h, p_T^Z)$[GeV]
Resolved 0-lepton category @HL-LHC
N_{events}
$Z(\to\nu\nu)h + Wh$
$Z(\to\nu\nu)b\bar{b}$
$Wb\bar{b}$
$t\bar{t}$
$\min(p_T^h, p_T^Z)$[GeV]
Boosted 1-lepton category @HL-LHC
N_{events}
Wh
$Wb\bar{b}$
$t\bar{t}$
p_T^h[GeV]
Resolved 1-lepton category @HL-LHC
N_{events}
Wh
$Wb\bar{b}$
$t\bar{t}$
p_T^h[GeV]

Vh.

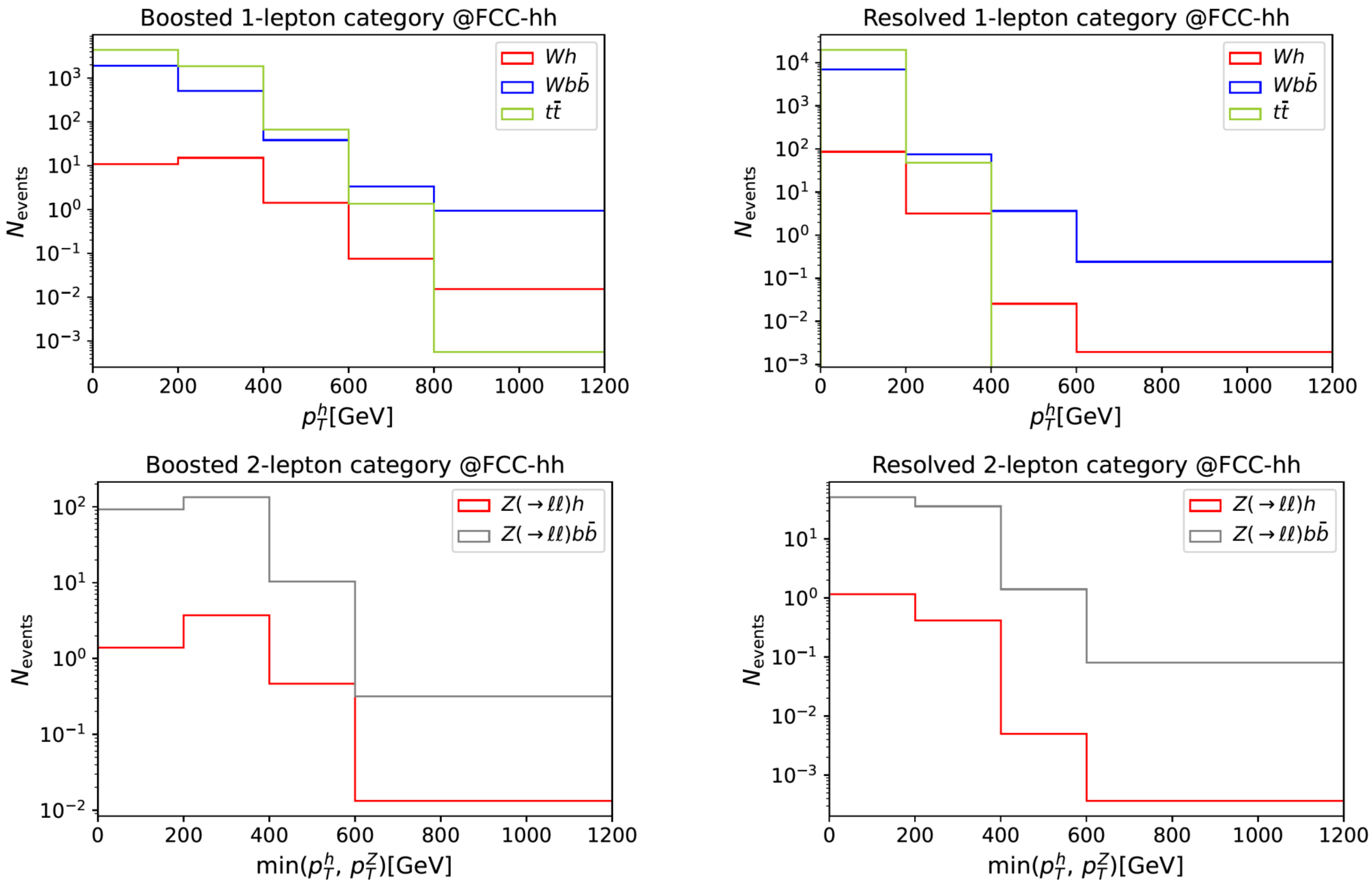
$h \to b\bar{b}$



Boosted 2-lepton category @HL-LHC
Resolved 2-lepton category @HL-LHC
Boosted 0-lepton category @FCC-hh
Resolved 0-lepton category @FCC-hh
N_{events}
$\min(p_T^h,\ p_T^Z)$[GeV]
$Z(\to \ell\ell)h$
$Z(\to \ell\ell)b\bar{b}$
$Z(\to \nu\nu)h$ + Wh
$Z(\to \nu\nu)b\bar{b}$
$Wb\bar{b}$
$t\bar{t}$

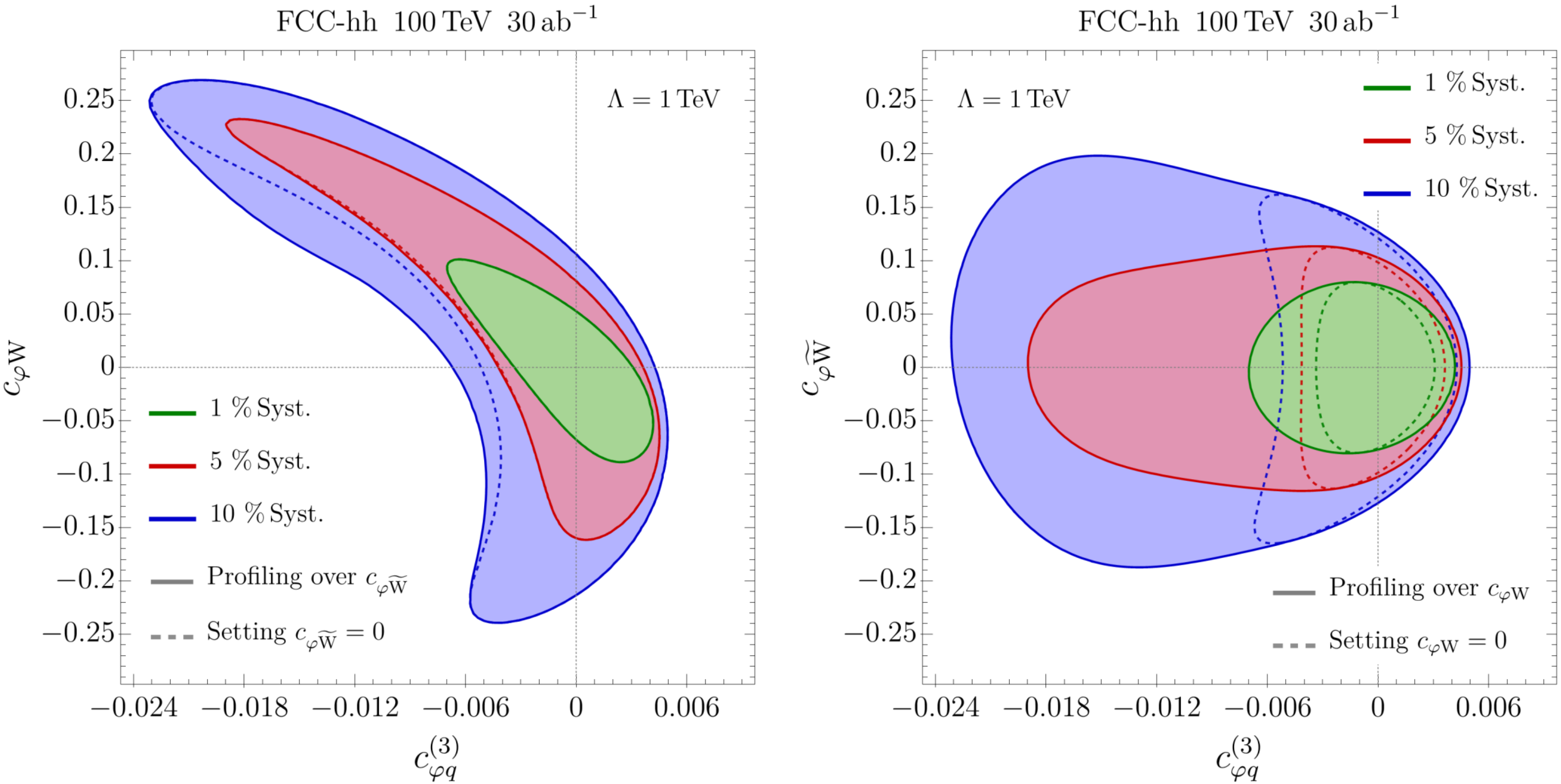
Vh.

$h \to b\bar{b}$

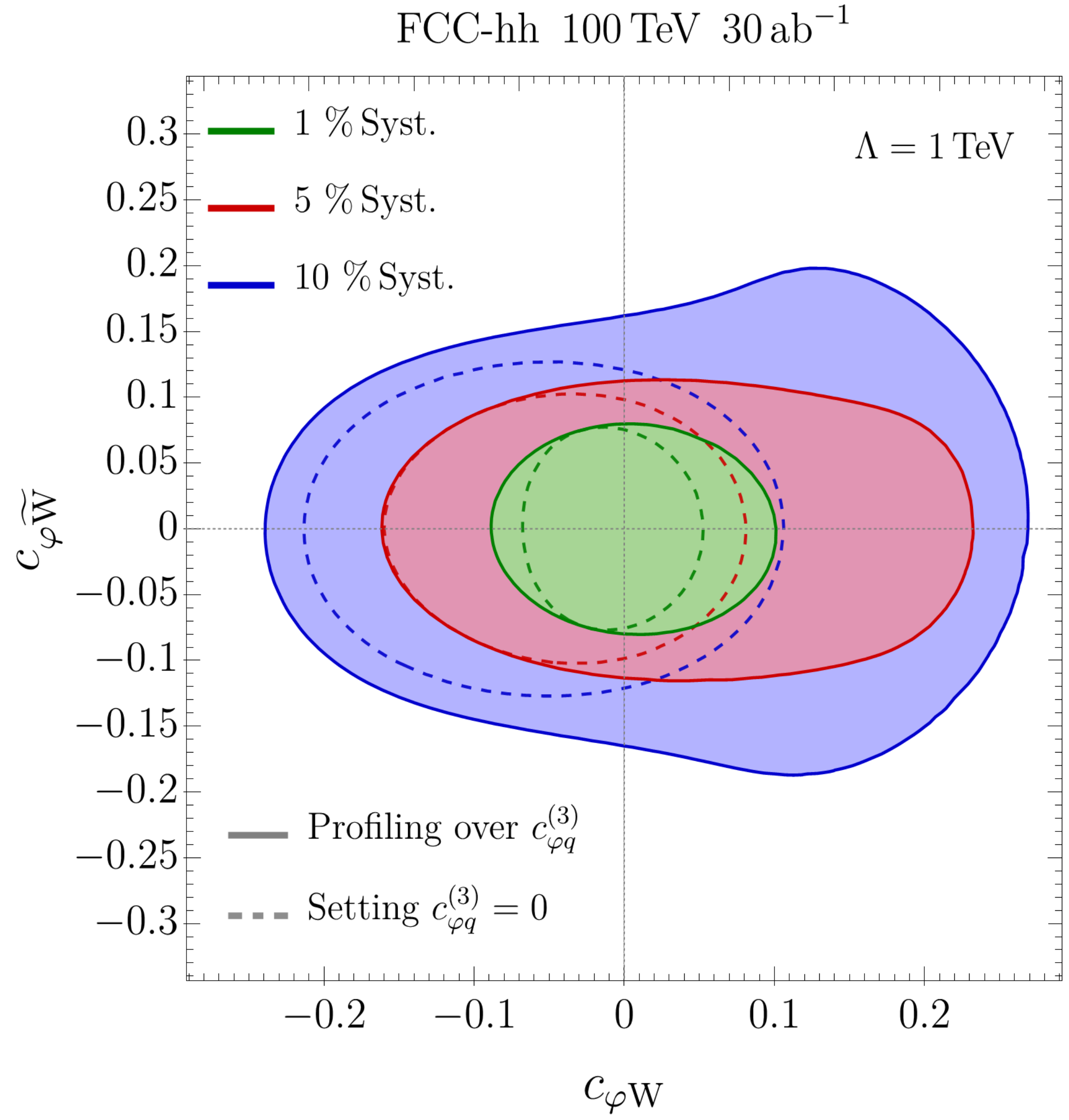

Boosted 1-lepton category @FCC-hh
Wh
Wbb̄
tt̄
N_events
p_T^h [GeV]
Resolved 1-lepton category @FCC-hh
Boosted 2-lepton category @FCC-hh
Z(→ℓℓ)h
Z(→ℓℓ)bb̄
min(p_T^h, p_T^Z)[GeV]
Resolved 2-lepton category @FCC-hh

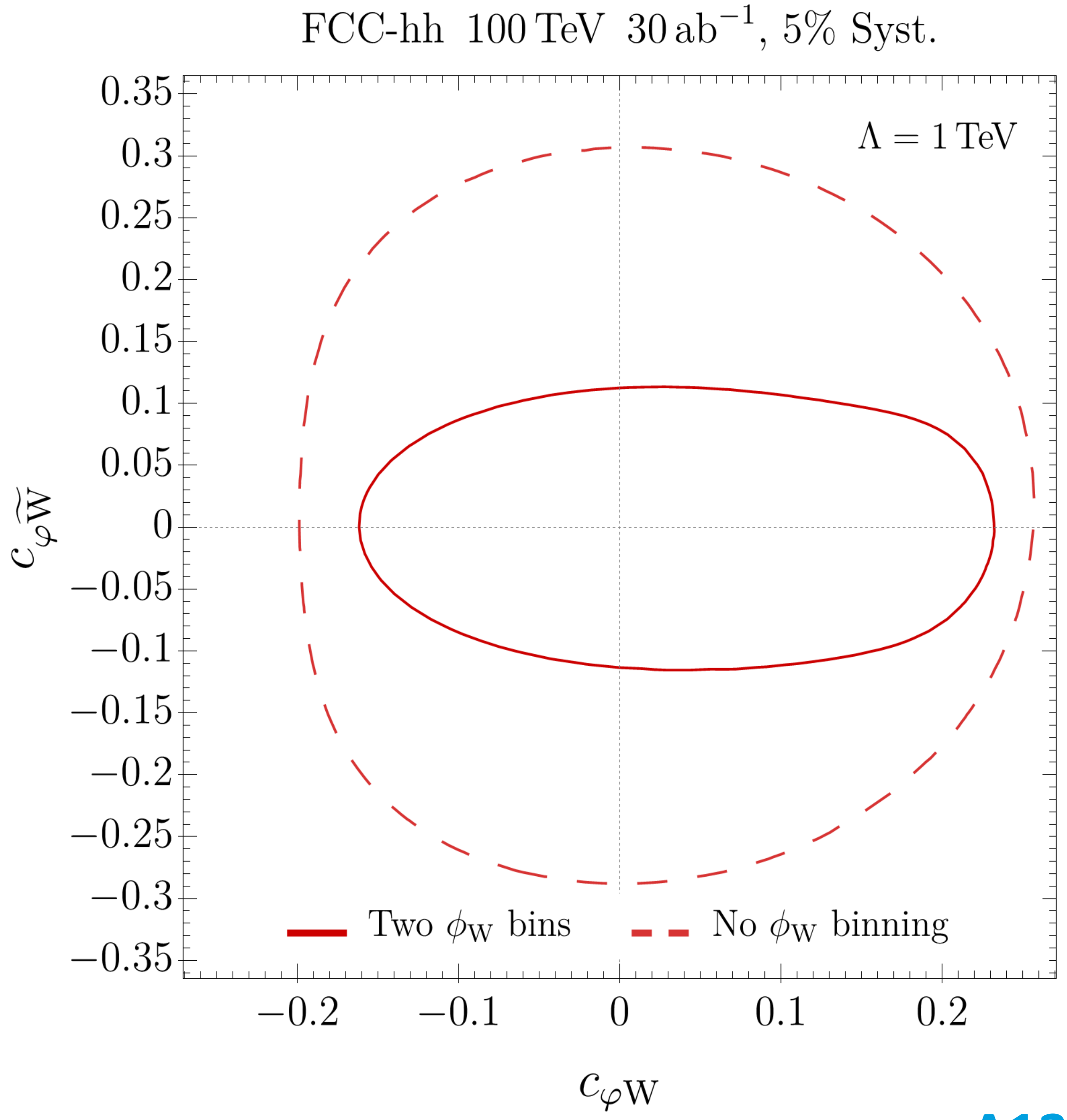
Wh. More results

- 95% CL bounds



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





Wh. More results

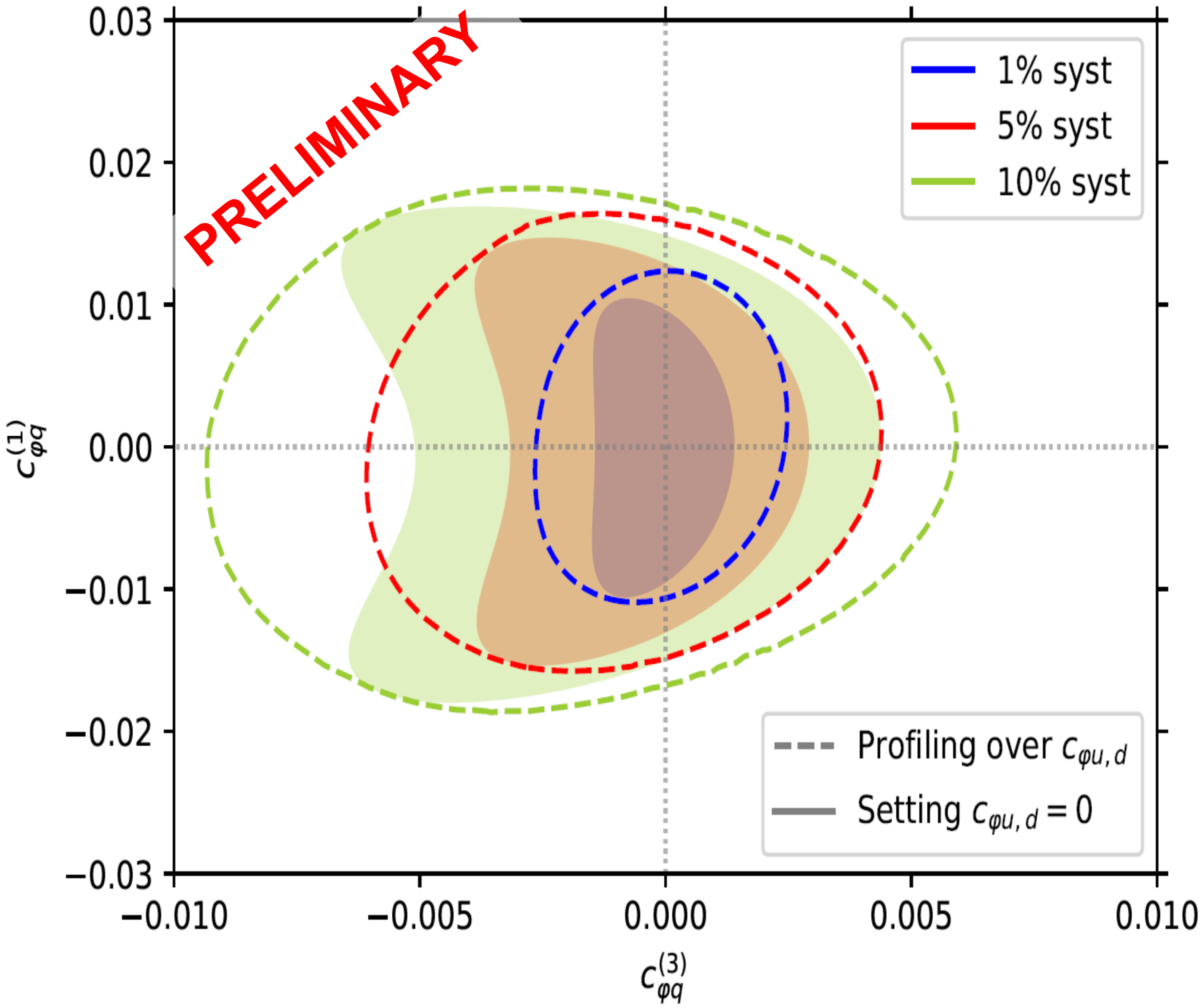
- 95% CL bounds summary

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.

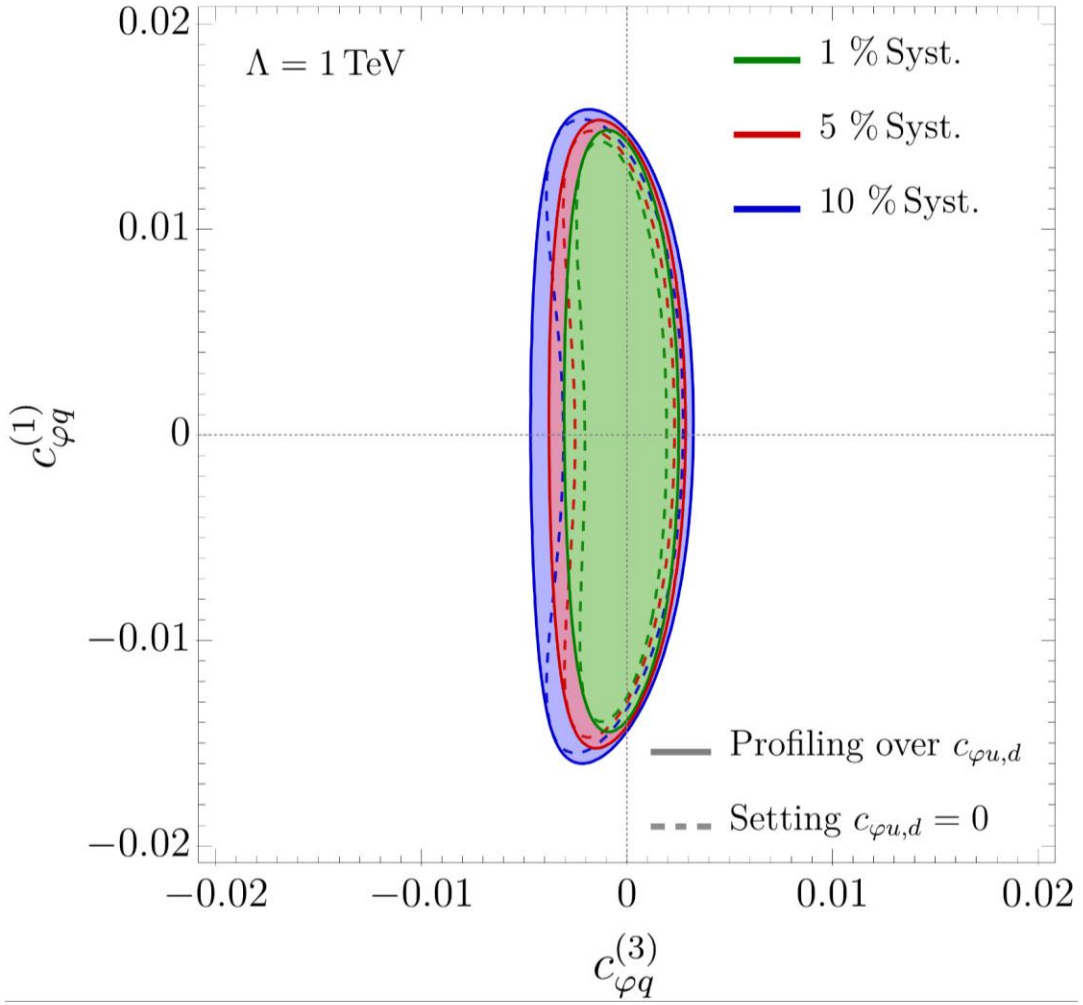
Vh. At FCC-hh, photons or b-quarks?

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

$h \to b\bar{b}$

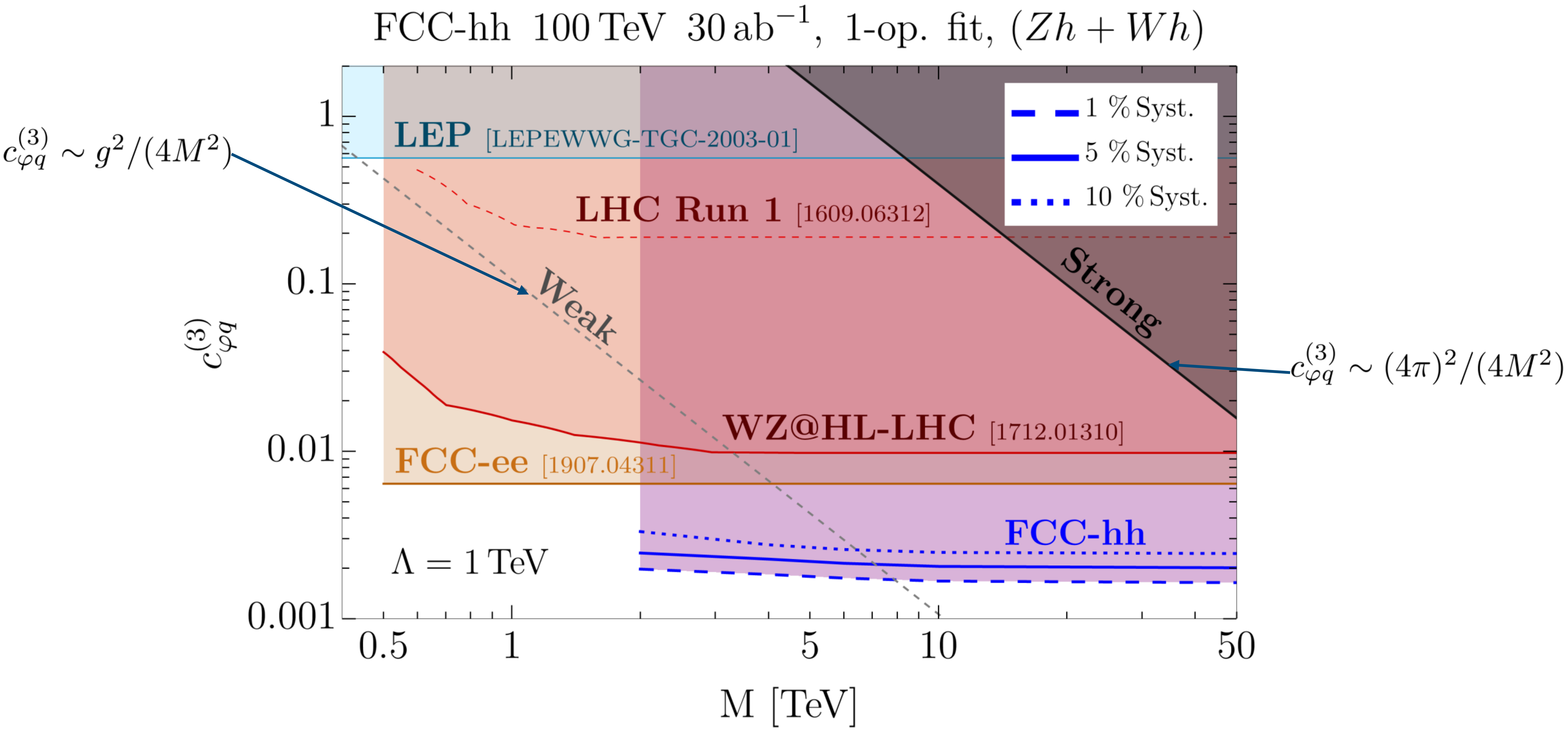


$h \to \gamma\gamma$



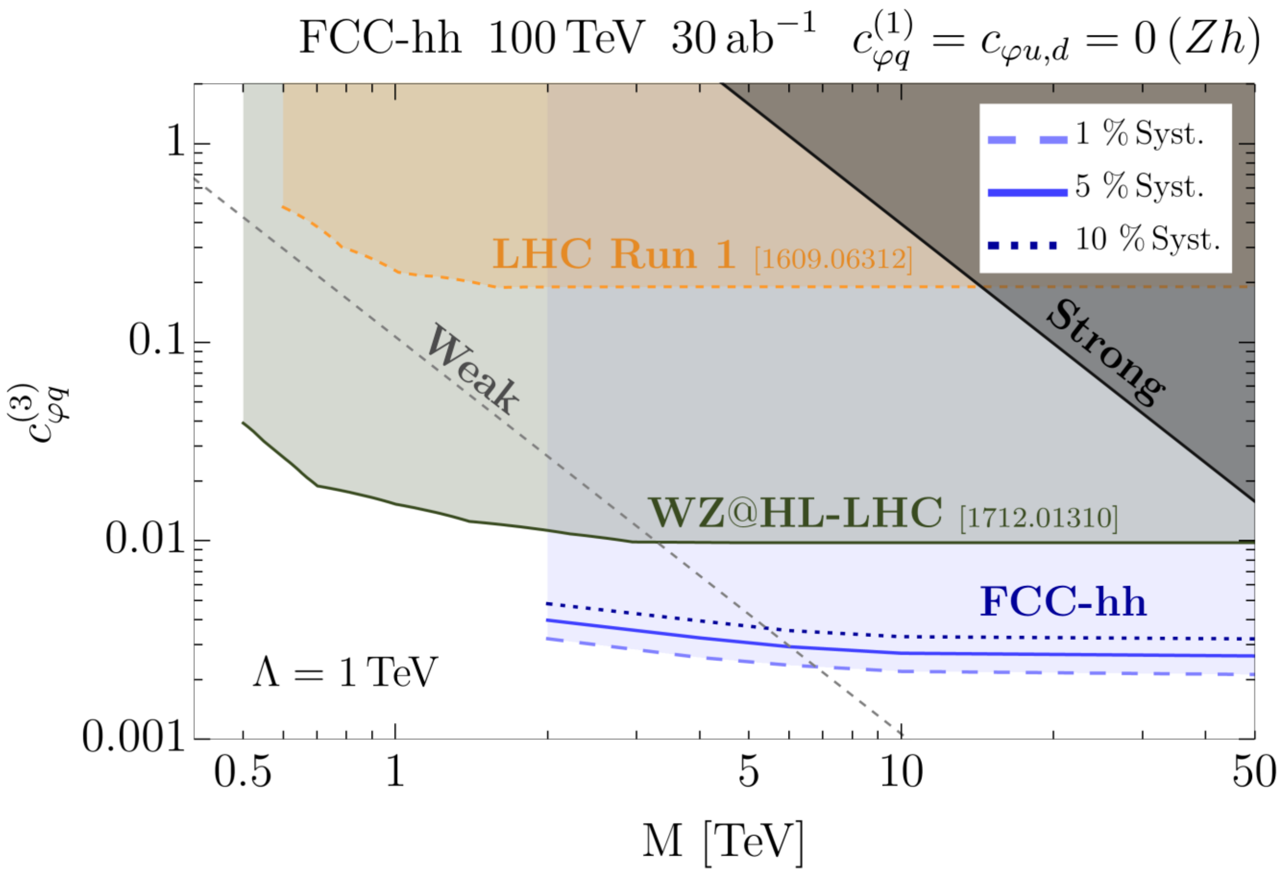
Vh.

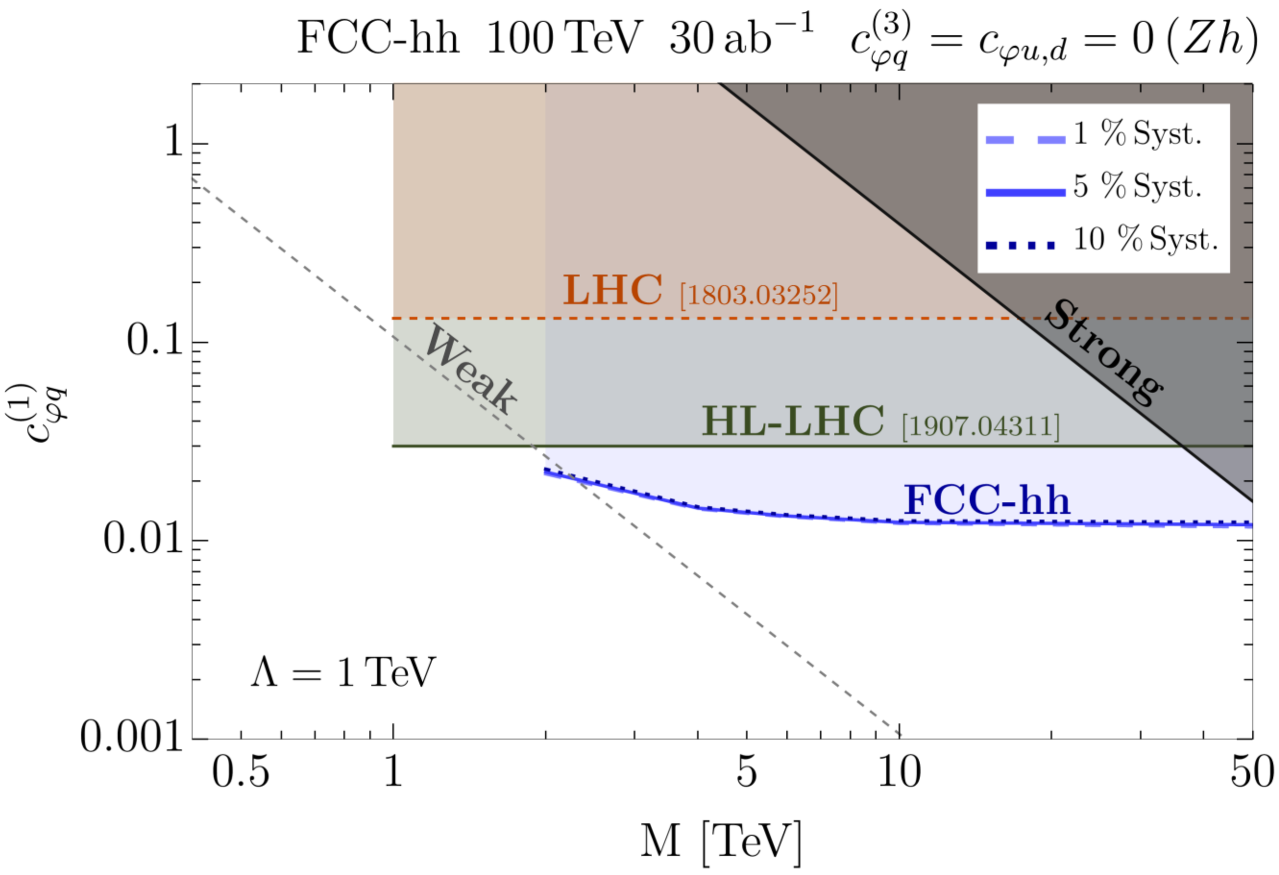
Bounds for $c_{\varphi q}^{(3)}$



Zh. More results

- 95% CL bounds





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.

Vh. Sizeable impact on aTGC bounds

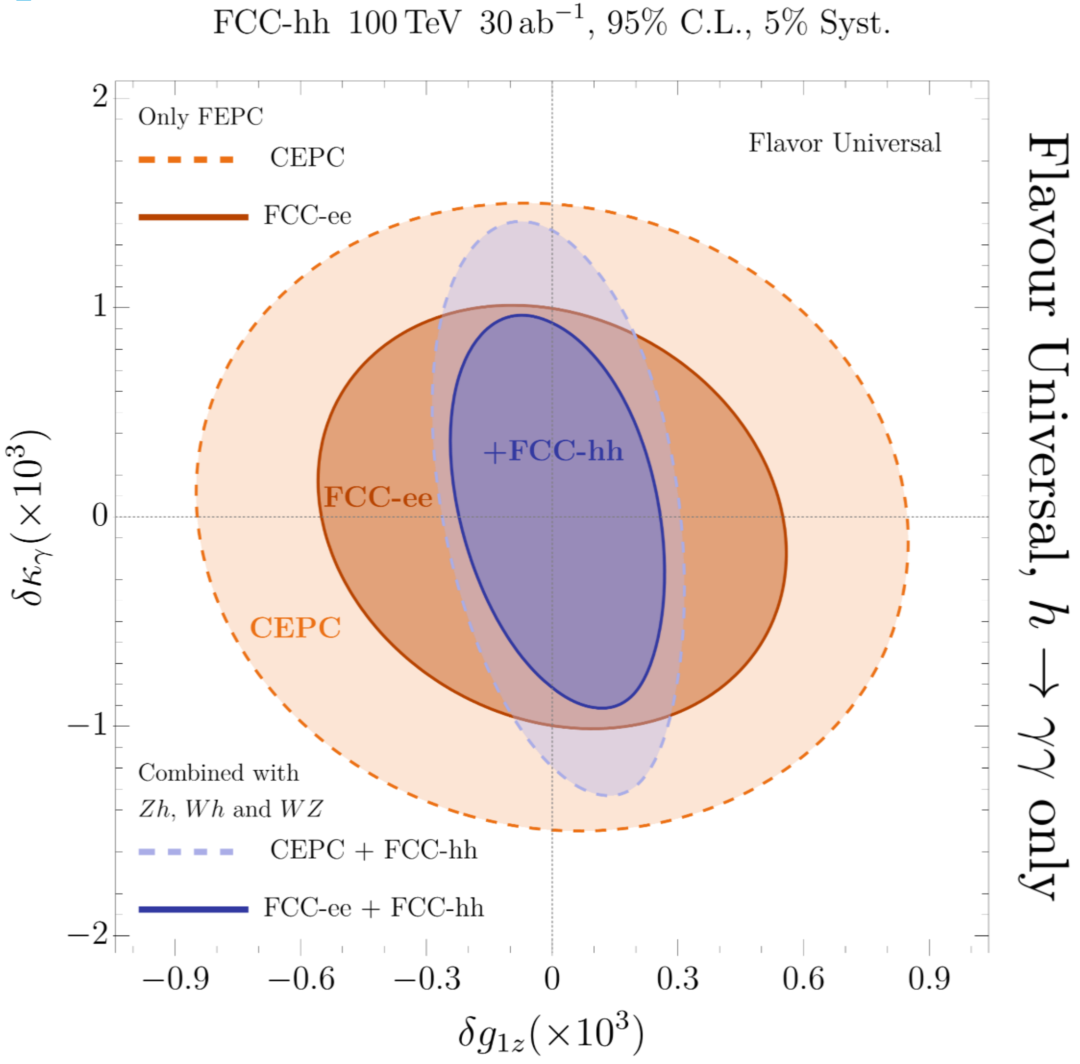
$$c_{\varphi q}^{(3)} = + \frac{\Lambda^2}{4m_W^2} g^2 \left(\delta g_L^{Zu} - \delta g_L^{Zd} - c_{\rm W}^2 \, \delta g_{1z}\right)$$

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

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

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

$$\mathcal{L}_{TGC} \supset ie\left(1 + \delta\kappa_\gamma\right) A^{\mu\nu} W_\mu^+ W_\nu^- + ig\, c_W \left(1 + \delta g_{1z}\right)\left(W_{\mu\nu}^+ W^{-,\mu} - W_{\mu\nu}^- W^{+,\mu}\right) Z^\nu$$

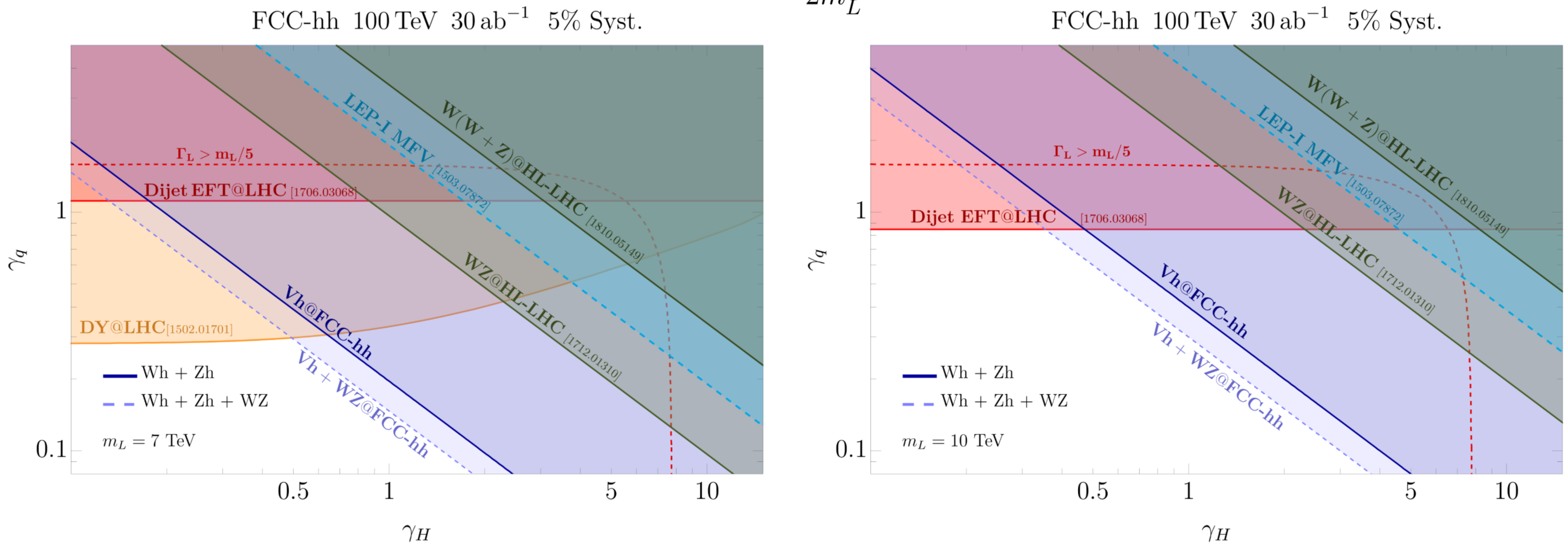


Clear complementarity with future lepton colliders

Vh. UV models: Spin-1 triplets

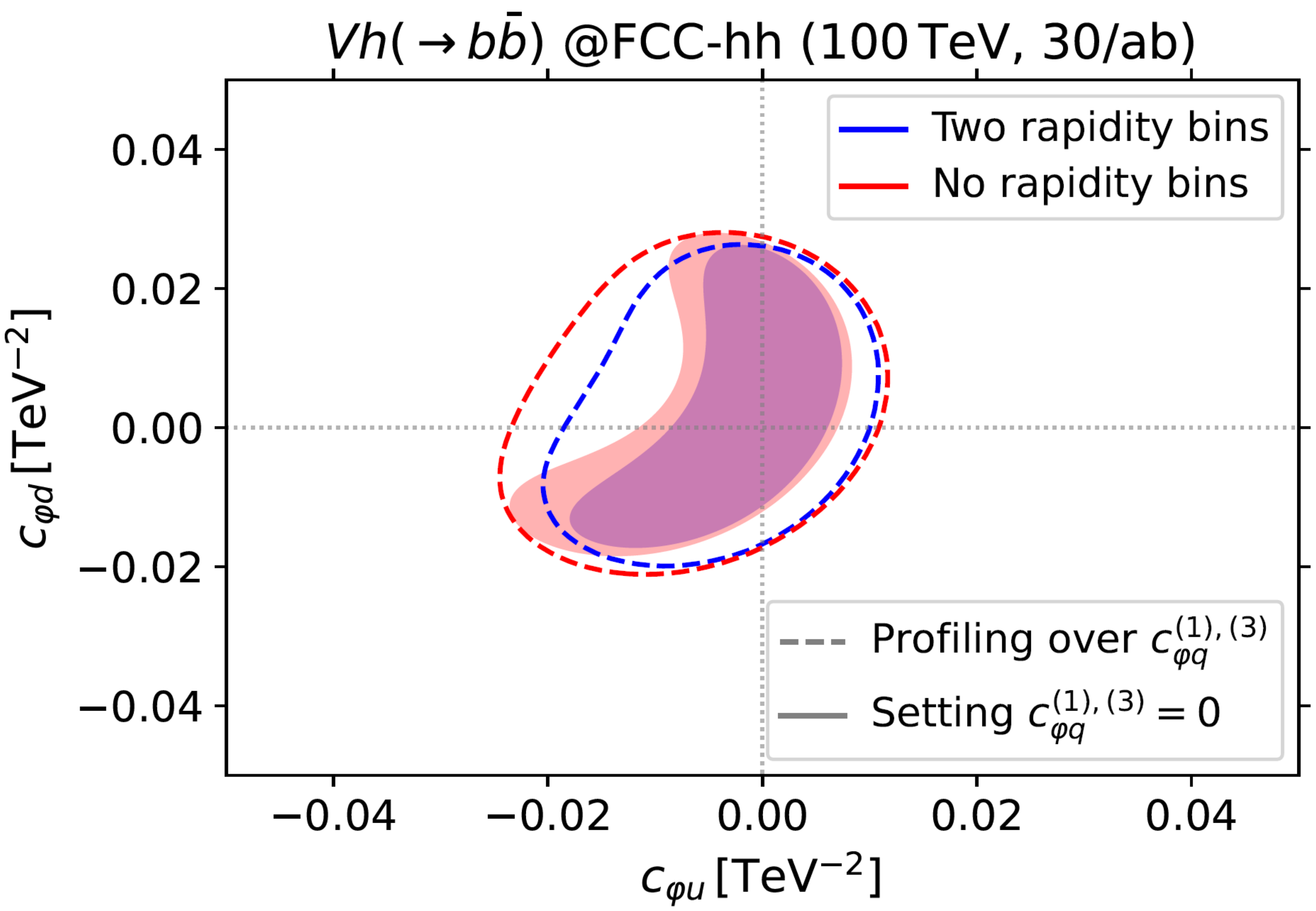
$$L_\mu \sim (1,3)_0 \qquad \mathcal{L}_{BSM} = \frac{1}{4} F^a_{L,\mu\nu} F^{a,\mu\nu}_L + \frac{m_L^2}{2} L_\mu L^\mu + \gamma_H L^a_\mu \frac{i}{2} H^\dagger \sigma^a \overleftrightarrow{D}^\mu H + \sum_f \gamma_f L^a_\mu \overline{f} \gamma^\mu \sigma^a f$$

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



Vh.

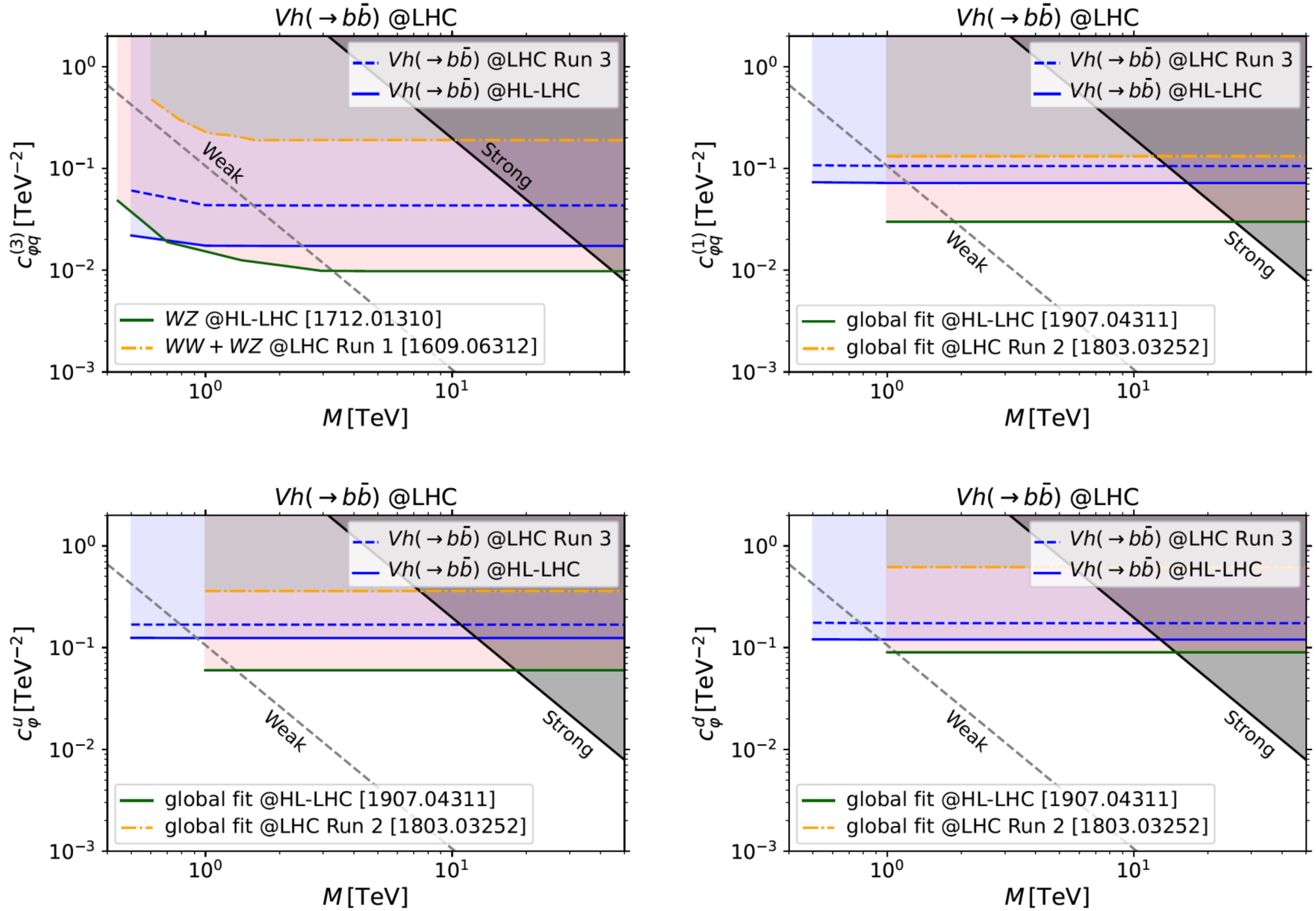
$h \to b\bar{b}$



$Vh(\to b\bar{b})$ @FCC-hh (100 TeV, 30/ab)
Two rapidity bins
No rapidity bins
Profiling over $c_{\varphi q}^{(1),(3)}$
Setting $c_{\varphi q}^{(1),(3)} = 0$
$c_{\varphi d}$ [TeV^{-2}]
$c_{\varphi u}$ [TeV^{-2}]
0.04
0.02
0.00
−0.02
−0.04

Vh.

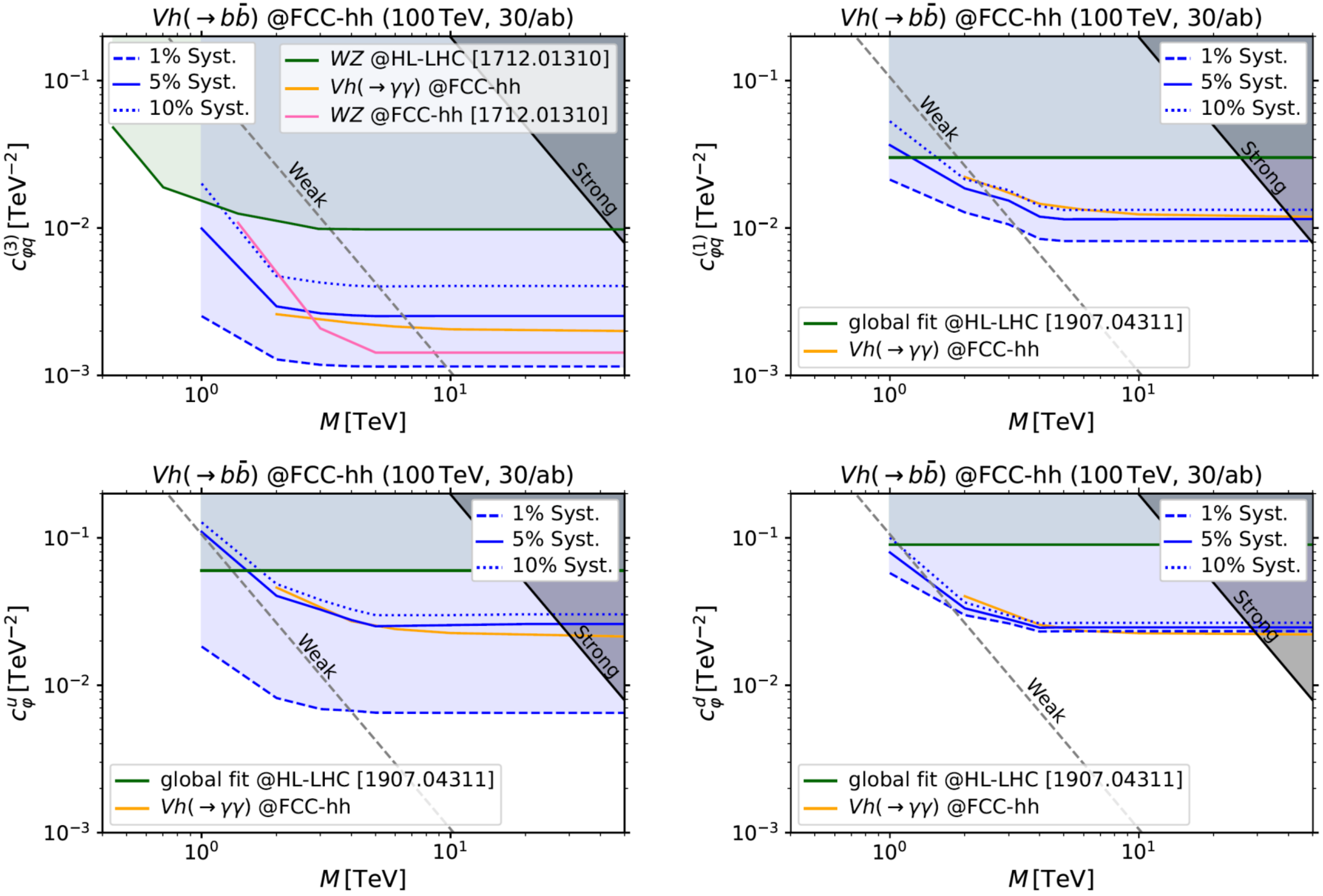
$h \to b\bar{b}$



Vh(→bb̄) @LHC
Vh(→bb̄) @LHC Run 3
Vh(→bb̄) @HL-LHC
WZ @HL-LHC [1712.01310]
WW + WZ @LHC Run 1 [1609.06312]
Weak
Strong
$c_{\varphi q}^{(3)}$ [TeV^{-2}]
M [TeV]
Vh(→bb̄) @LHC
Vh(→bb̄) @LHC Run 3
Vh(→bb̄) @HL-LHC
global fit @HL-LHC [1907.04311]
global fit @LHC Run 2 [1803.03252]
$c_{\varphi q}^{(1)}$ [TeV^{-2}]
M [TeV]
Vh(→bb̄) @LHC
Vh(→bb̄) @LHC Run 3
Vh(→bb̄) @HL-LHC
global fit @HL-LHC [1907.04311]
global fit @LHC Run 2 [1803.03252]
c_{φ}^{u} [TeV^{-2}]
M [TeV]
Vh(→bb̄) @LHC
Vh(→bb̄) @LHC Run 3
Vh(→bb̄) @HL-LHC
global fit @HL-LHC [1907.04311]
global fit @LHC Run 2 [1803.03252]
c_{φ}^{d} [TeV^{-2}]
M [TeV]

Vh.

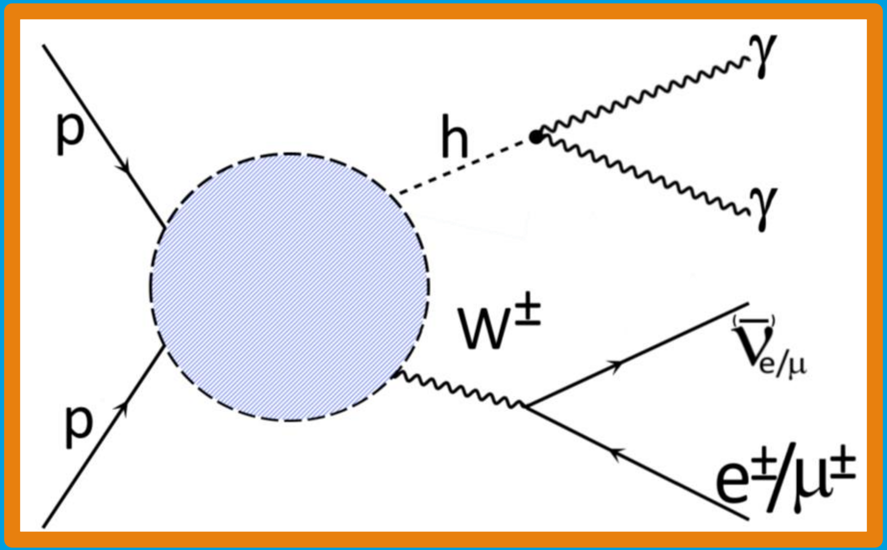
$h \to b\bar{b}$



Vh(→bb̄) @FCC-hh (100 TeV, 30/ab)
1% Syst.
5% Syst.
10% Syst.
WZ @HL-LHC [1712.01310]
Vh(→γγ) @FCC-hh
WZ @FCC-hh [1712.01310]
global fit @HL-LHC [1907.04311]
Weak
Strong
M [TeV]
c_φq^(3) [TeV^−2]
c_φq^(1) [TeV^−2]
c_φ^u [TeV^−2]
c_φ^d [TeV^−2]

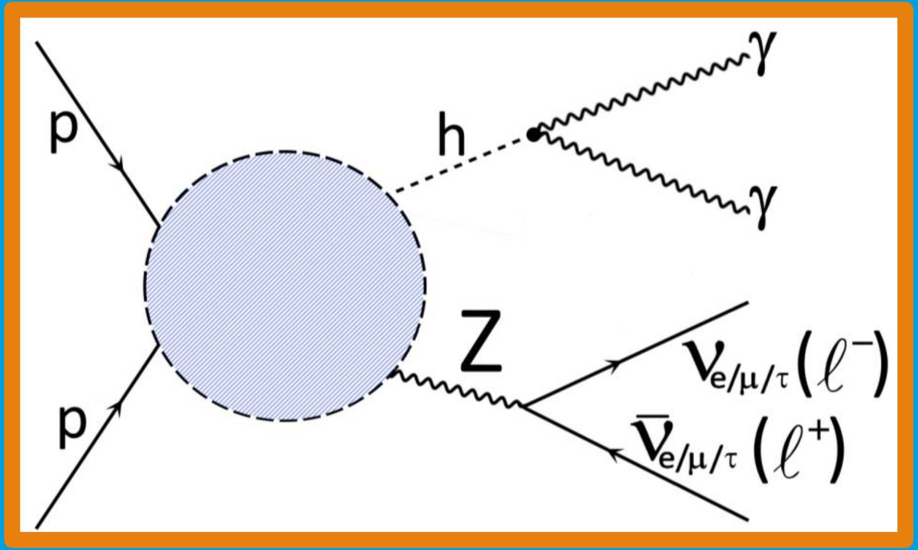
Diphotonic Vh:
A summary from the future.

arXiv 2004.06122 (JHEP 07 (2020) 075)



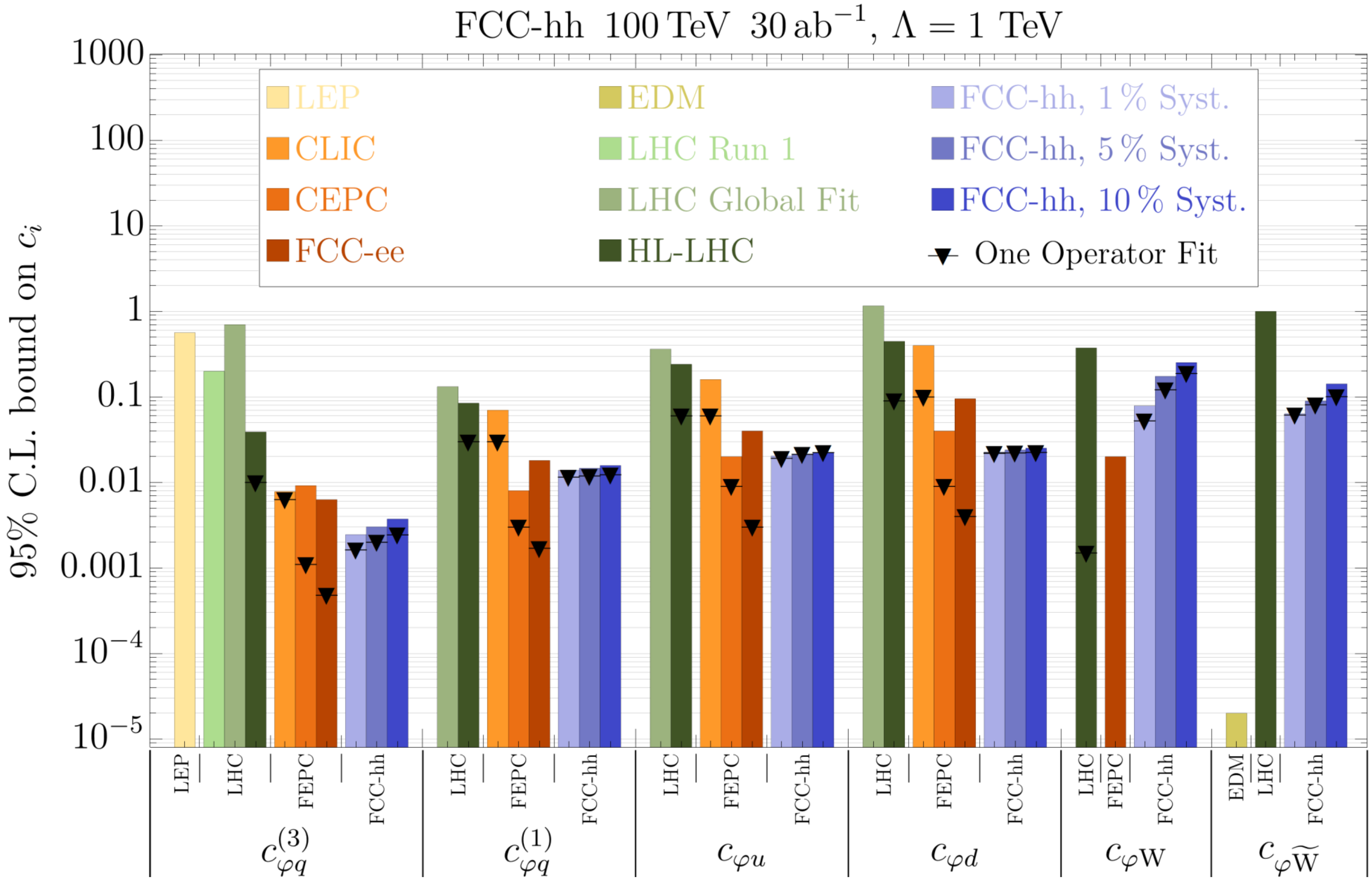
$$pp \to W^{\pm}h \to l^{\pm}\nu\,\gamma\gamma$$

arXiv 2011.13941 (JHEP 04 (2021) 154)

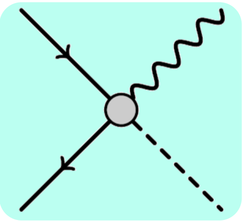
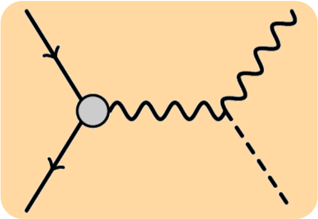
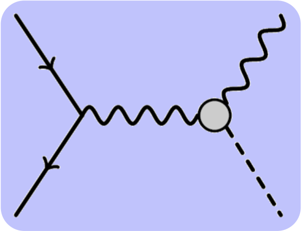
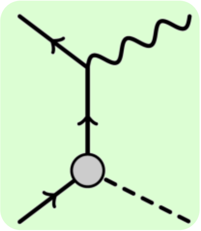


$$pp \to Zh \to l^{+}l^{-}\ (\nu\bar{\nu})\,\gamma\gamma$$

Vh. Diphotonic channel in perspective



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**