Precision studies at FCC-hh

With diboson (Vh) production

FCC Phenomenology Workshop

6 July 2023

CERN, Switzerland

Alejo N. Rossia

Department of Physics and Astronomy

University of Manchester

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 2208.11134 (JHEP 06 (2023) 077)

MANCHESTER 1824

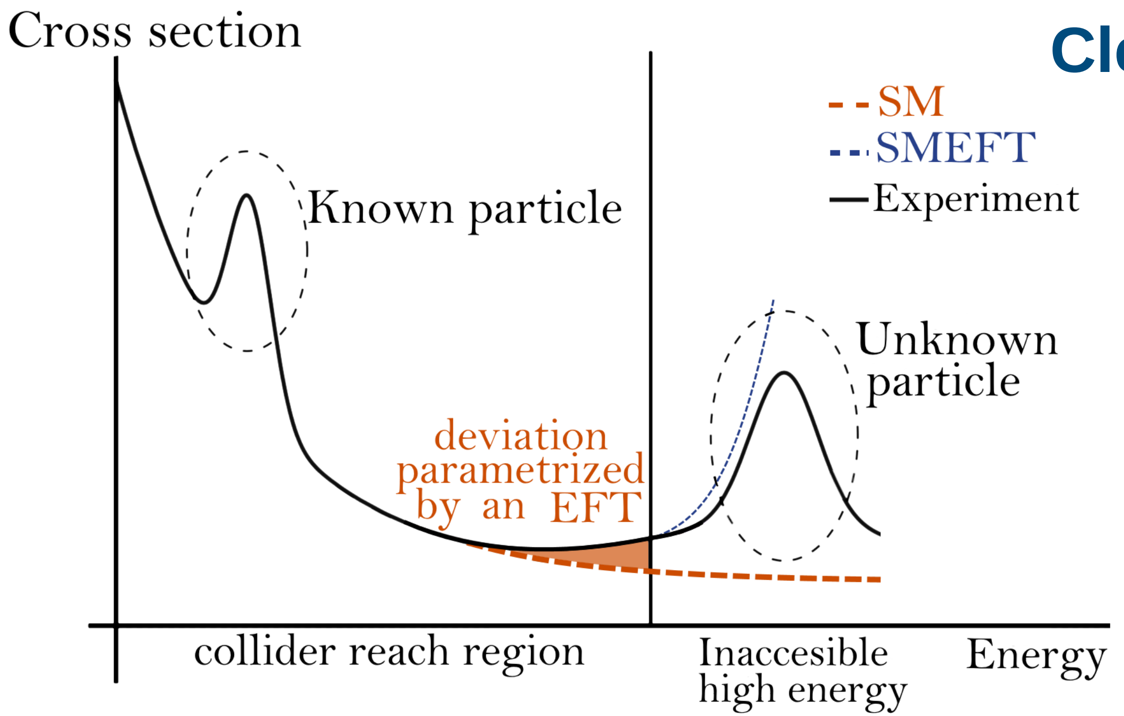
The University of Manchester

A trick of the tail

Precision with hadron colliders? Yes!

A trick of the tail

Precision with hadron colliders? Yes!



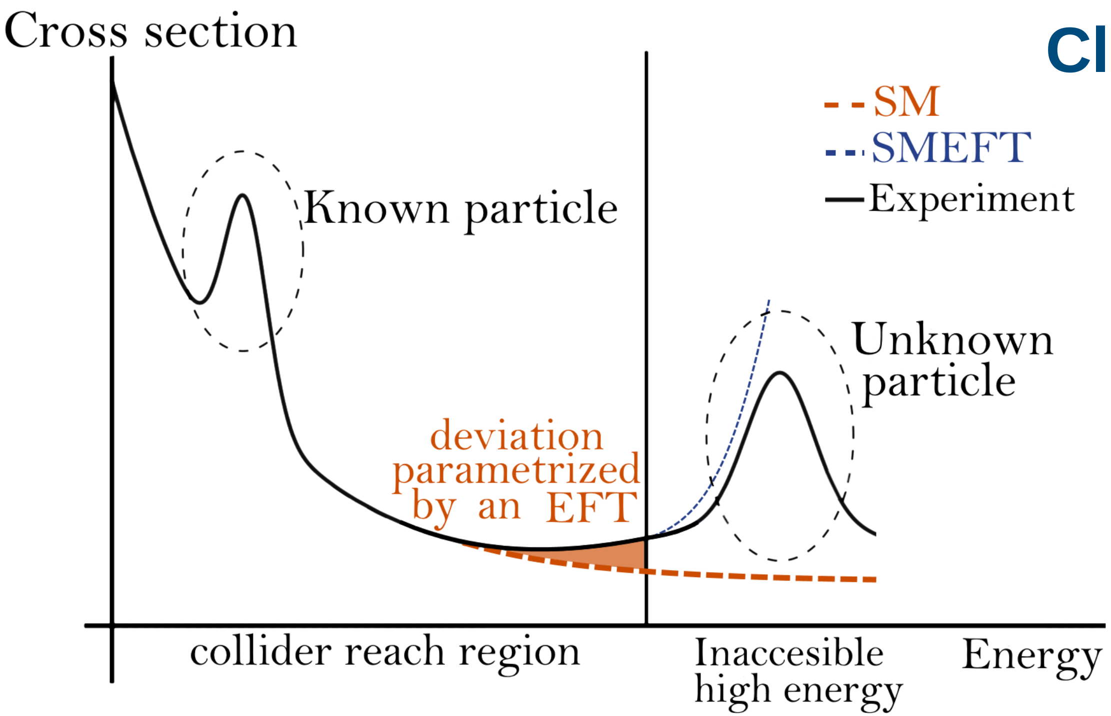
Original fig. by C. Severi, M. Thomas, E. Vryonidou

Clean channels + NP effects that grow with E

Tail hunting!

A trick of the tail

Precision with hadron colliders? Yes!



Original fig. by C. Severi, M. Thomas, E. Vryonidou

Clean channels + NP effects that grow with E

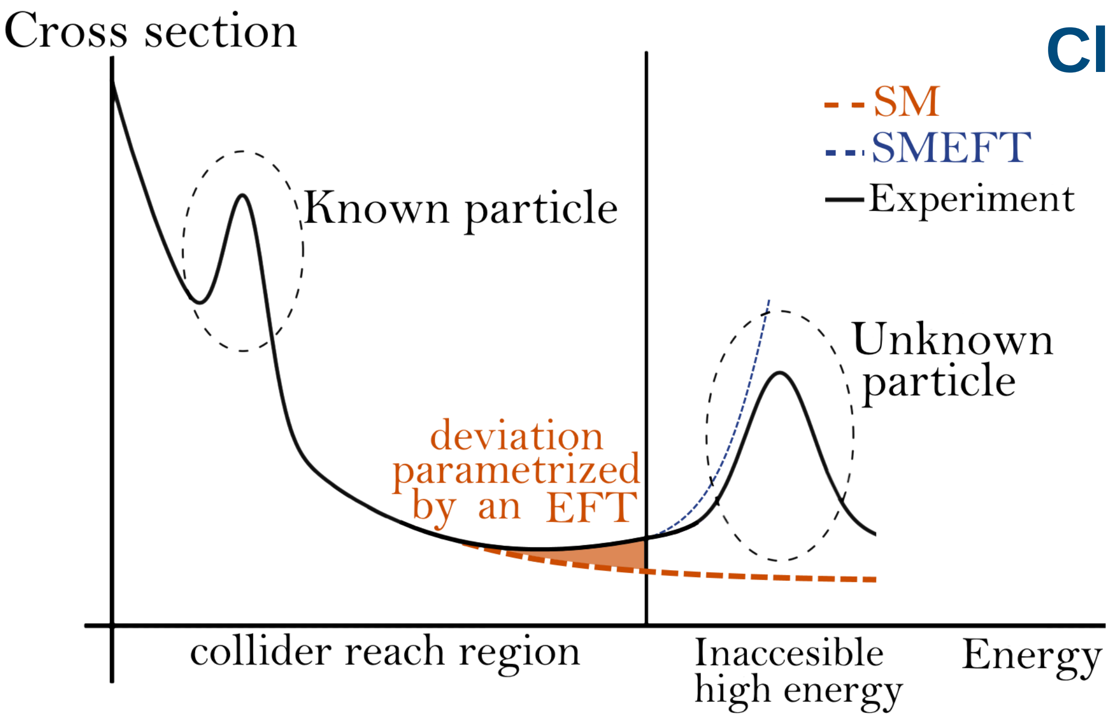
Tail hunting!

Heavy New Physics

Effective Field Theories

A trick of the tail

Precision with hadron colliders? Yes!



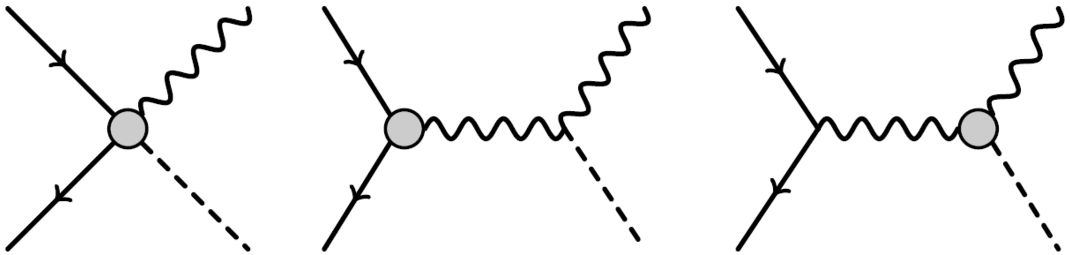
Original fig. by C. Severi, M. Thomas, E. Vryonidou

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.

Standard Model EFT (SMEFT)

Standard Model EFT (SMEFT)

- **Field content and gauge symmetries of the SM and linearly realized EWSB.**

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

Standard Model EFT (SMEFT)

- **Field content and gauge symmetries of the SM and linearly realized EWSB.**

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

Standard Model EFT (SMEFT)

- **Field content and gauge symmetries of the SM and linearly realized EWSB.**

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

- **Assume MFV and flavor universality.**

For other flavour scen., see A.R., M. Thomas, E. Vryonidou arXiv:2306.09963

Standard Model EFT (SMEFT)

- **Field content and gauge symmetries of the SM and linearly realized EWSB.**

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

- **Assume MFV and flavor universality.**

For other flavour scen., see A.R., M. Thomas, E. Vryonidou arXiv:2306.09963

$$\sigma = |\mathcal{M}_{SM}|^2 + \underbrace{2\mathrm{Re}\left(\mathcal{M}_{SM}\mathcal{M}^*_{BSM}\right)}_{\propto\, \mathcal{C}_i^{(6)}/\Lambda^2} + \underbrace{|\mathcal{M}_{BSM}|^2}_{\propto \left(\mathcal{C}_i^{(6)}/\Lambda^2\right)^2}$$

Interference

New collider, new opportunities

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

New collider, new opportunities

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
$\tau\tau$	$6 \cdot 10^{-2}$	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
$\mu\mu$	$4 \cdot 10^{-4}$	10^0	10^1	10^2

New collider, new opportunities

For $p_T^h > 550$ GeV:

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

	Higgs decay	Higgs BR	n_{HL-LHC}	n_{HE-LHC}	n_{FCC-hh}
Today	$\bar{b}b$	$6 \cdot 10^{-1}$	10^3		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
	$\mu\mu$	$4 \cdot 10^{-4}$	10^0	10^1	10^2

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

New collider, new opportunities

For $p_T^h > 550$ GeV:

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

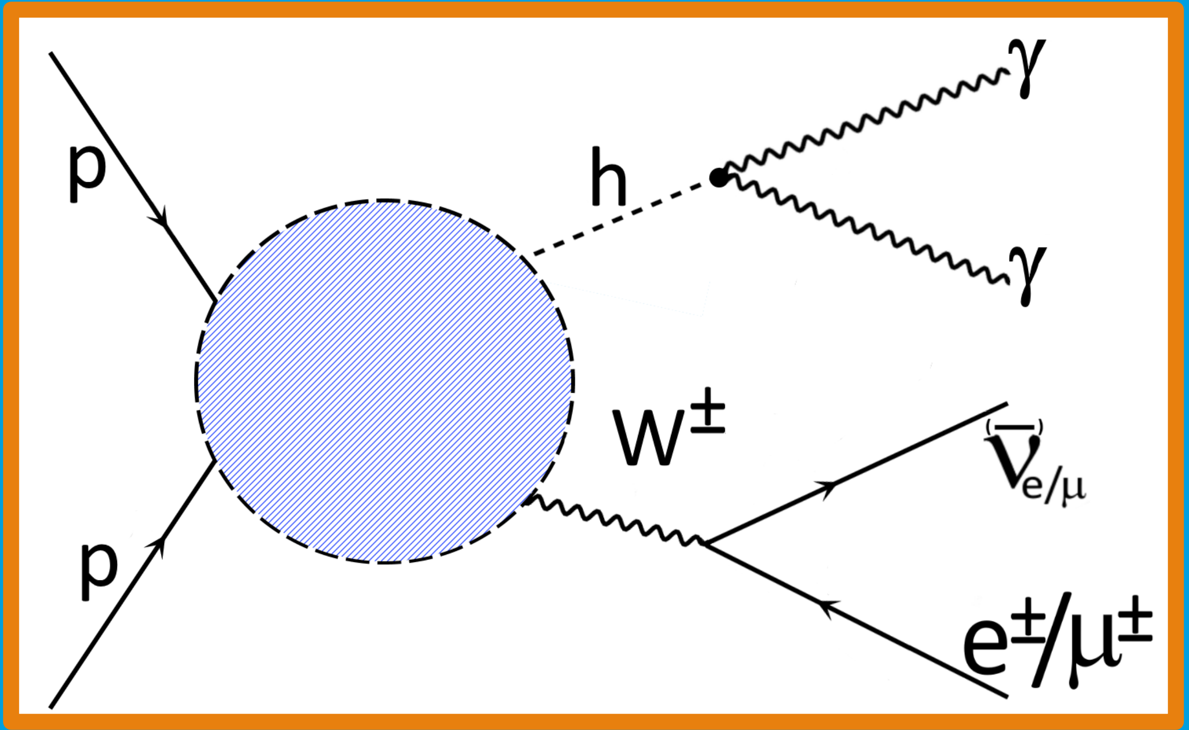
	Higgs decay	Higgs BR	n_{HL-LHC}	n_{HE-LHC}	n_{FCC-hh}
Today	$\bar{b}b$	$6 \cdot 10^{-1}$	10^3		10^5
	$\tau\tau$	$6 \cdot 10^{-2}$	10^2	10^3	10^4
Future	$\gamma\gamma$	$2 \cdot 10^{-3}$			10^3
	$4l$	$2 \cdot 10^{-3}$	10^0	10^2	10^3
	$\mu\mu$	$4 \cdot 10^{-4}$	10^0	10^1	10^2

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

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

Leptonic diphoton Wh.

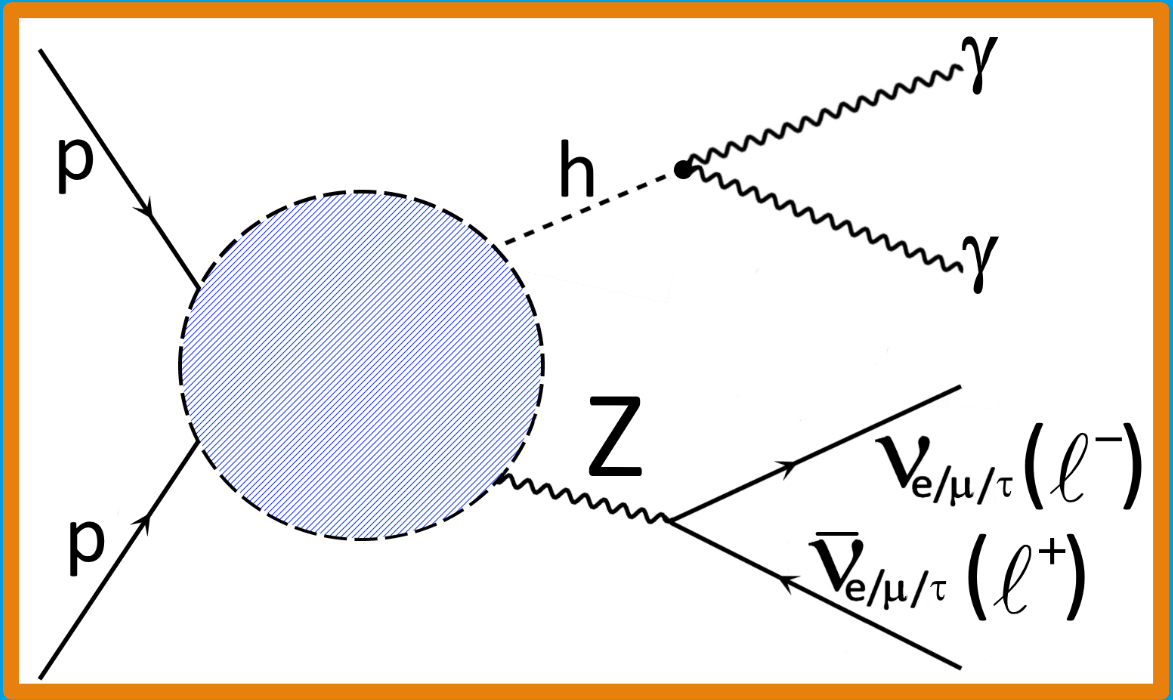
arXiv 2004.06122 (JHEP 07 (2020) 075)



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

Diphoton Zh.

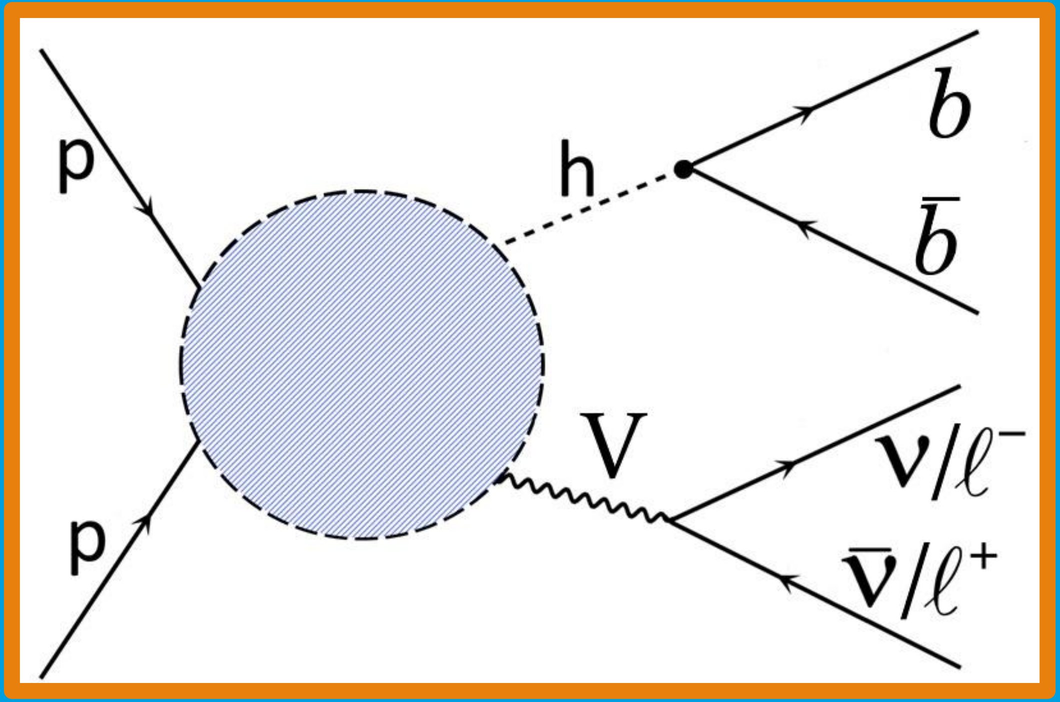
arXiv 2011.13941 (JHEP 04 (2021) 154)



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

Let them be quarks.

arXiv 2208.11134 (JHEP 06 (2023) 077)



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

Vh. What New Physics can we probe?

- **In Warsaw basis**

$$\mathcal{O}_{\varphi \mathrm{W}} \qquad \mathcal{O}_{\varphi \widetilde{\mathrm{W}}} \qquad \mathcal{O}_{\varphi q}^{(3)} \qquad \mathcal{O}_{\varphi q}^{(1)} \qquad \mathcal{O}_{\varphi d} \qquad \mathcal{O}_{\varphi u}$$

$$\mathcal{O}_{\varphi q}^{(3)} = (\bar{Q}_L \sigma^a \gamma^\mu Q_L) \left(i H^\dagger \sigma^a \overleftrightarrow{D}_\mu H \right), \quad \mathcal{O}_{\varphi q}^{(1)} = (\bar{Q}_L \gamma^\mu Q_L) \left(i H^\dagger \overleftrightarrow{D}_\mu H \right),$$

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

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

Vh. What New Physics can we probe?

- **In Warsaw basis**

Wh $\qquad$ Zh

$\mathcal{O}_{\varphi \mathrm{W}}$ $\quad$ $\mathcal{O}_{\varphi \widetilde{\mathrm{W}}}$ $\quad$ $\mathcal{O}_{\varphi q}^{(3)}$ $\quad$ $\mathcal{O}_{\varphi q}^{(1)}$ $\quad$ $\mathcal{O}_{\varphi d}$ $\quad$ $\mathcal{O}_{\varphi u}$

$$\mathcal{O}_{\varphi q}^{(3)} = (\bar{Q}_L \sigma^a \gamma^\mu Q_L)\left(iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H\right), \quad \mathcal{O}_{\varphi q}^{(1)} = (\bar{Q}_L \gamma^\mu Q_L)\left(iH^\dagger \overleftrightarrow{D}_\mu H\right),$$

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

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

Vh.

High-energy behaviour

Amplitude level

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

Vh. High-energy behaviour

Amplitude level

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

Cross section level

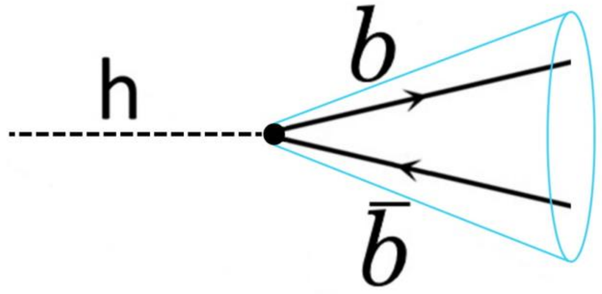
σ_{int}/σ_{SM}	$p_T^h,\ p_T^V$ bins	
$\mathcal{O}_{\varphi f}$	$\sim \frac{\hat{s}}{\Lambda^2}$	
$\mathcal{O}_{\varphi \mathrm{W}}$	$\sim \frac{m_W^2}{\Lambda^2}$	
$\mathcal{O}_{\varphi \widetilde{\mathrm{W}}}$	$= 0$	

Differential in p_T → Only same polarization and CP interfere

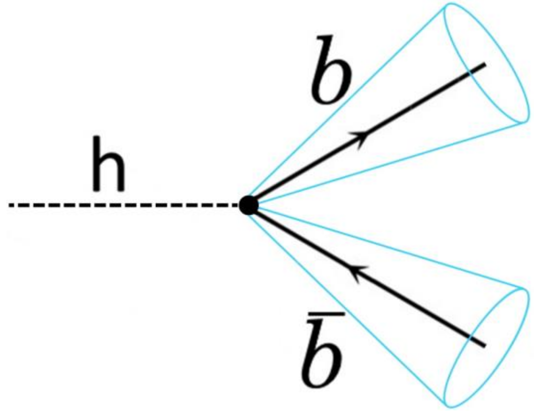
Vh.

Combining regimes in $h \to b\bar{b}$

Boosted

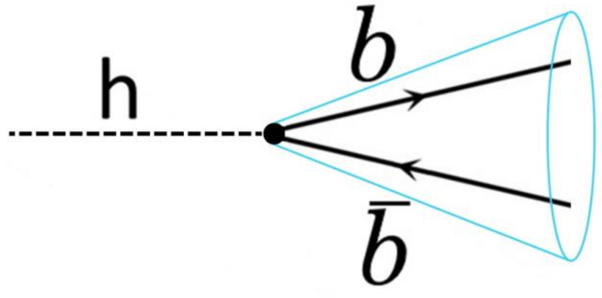


Resolved



Combining regimes in $h \to b\bar{b}$

Boosted



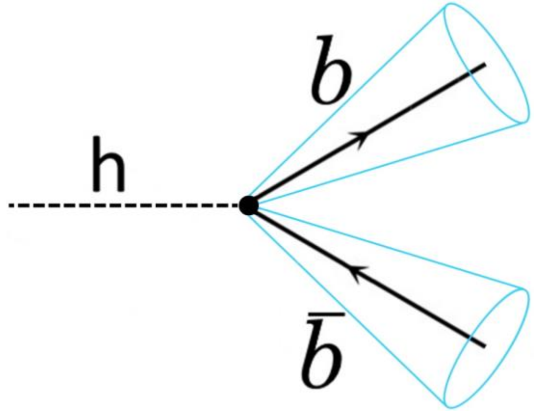
ATLAS, 2008.02508

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



ATLAS, 2007.02873

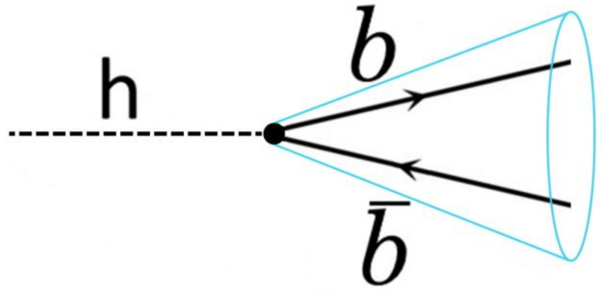
DOI: 10.1140/epjc/s10052-020-08677-2 9th March 2021

Measurements of WH and ZH production in the $H \to b\bar{b}$ decay channel in pp collisions at 13 TeV with the ATLAS detector

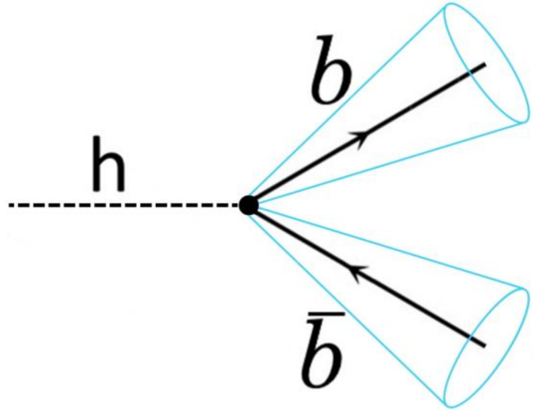
The ATLAS Collaboration

Vh. Combining regimes in $h \to b\bar{b}$

Boosted



Resolved



Scale-invariant tagging

Gouzevitch et al, 1303.6636
Bishara et al, 1611.03860

With use of Mass-drop tagging

Butterworth et al, 0802.2470

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

ATLAS, 2007.02873

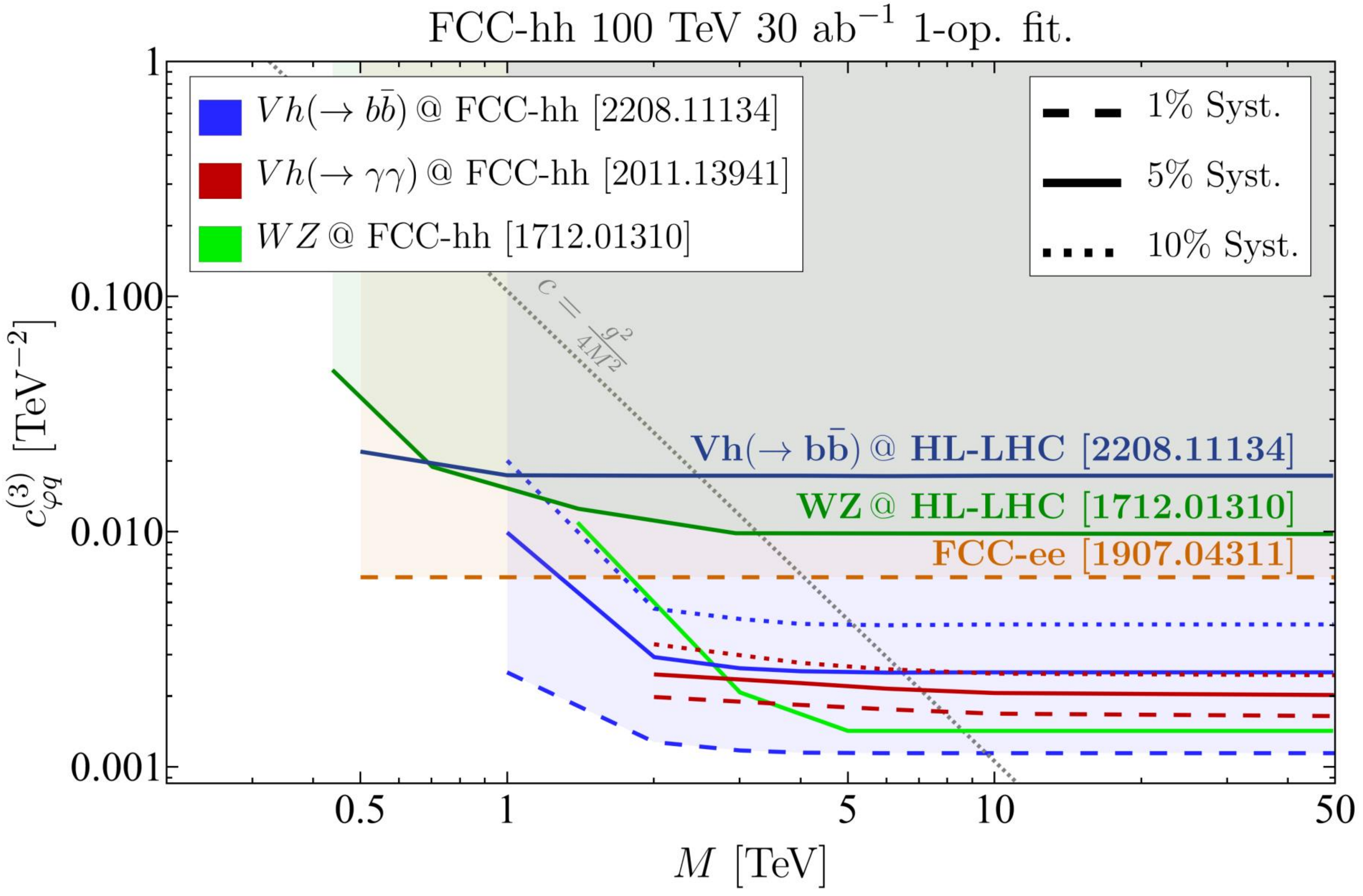
DOI: 10.1140/epjc/s10052-020-08677-2 9th March 2021

Measurements of WH and ZH production in the $H \to b\bar{b}$ decay channel in pp collisions at 13 TeV with the ATLAS detector

The ATLAS Collaboration

This strategy improves the bounds ~7% w.r.t. boosted-only at FCC-hh

95% C.L. on $c_{\varphi q}^{(3)}$



Double binning.

Angular binning: a qualitative advantage.

Wh. Probing bosonic operators

Cross section level

σ_{int}/σ_{SM}	$p_T^h,\ p_T^V$ bins	$p_T^h,\ p_T^V$ and angular bins
$\mathcal{O}_{\varphi f}$	$\sim \frac{\hat{s}}{\Lambda^2}$	$\sim \frac{\hat{s}}{\Lambda^2}$
$\mathcal{O}_{\varphi \mathrm{W}}$	$\sim \frac{m_W^2}{\Lambda^2}$	$\sim \frac{m_W^2}{\Lambda^2}$
$\mathcal{O}_{\varphi \widetilde{\mathrm{W}}}$	$= 0$	$\sim \frac{m_W \sqrt{\hat{s}}}{\Lambda^2}$

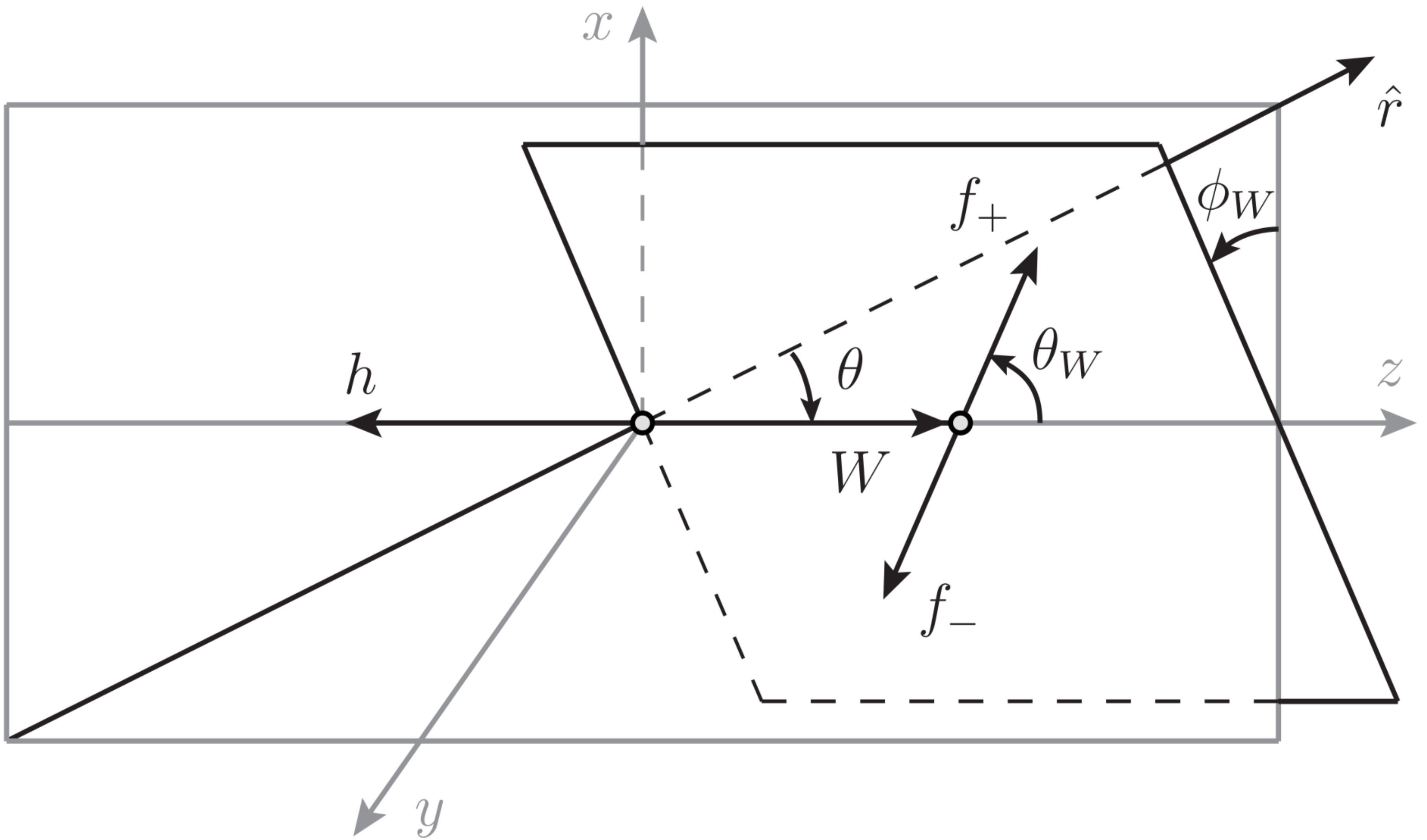
Differential in p_T and decay angles

↓

Different polarizations and CP interfere

Interference patterns

Measuring angles resurrects interference



Wh. Angular binning for CP-odd operators

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

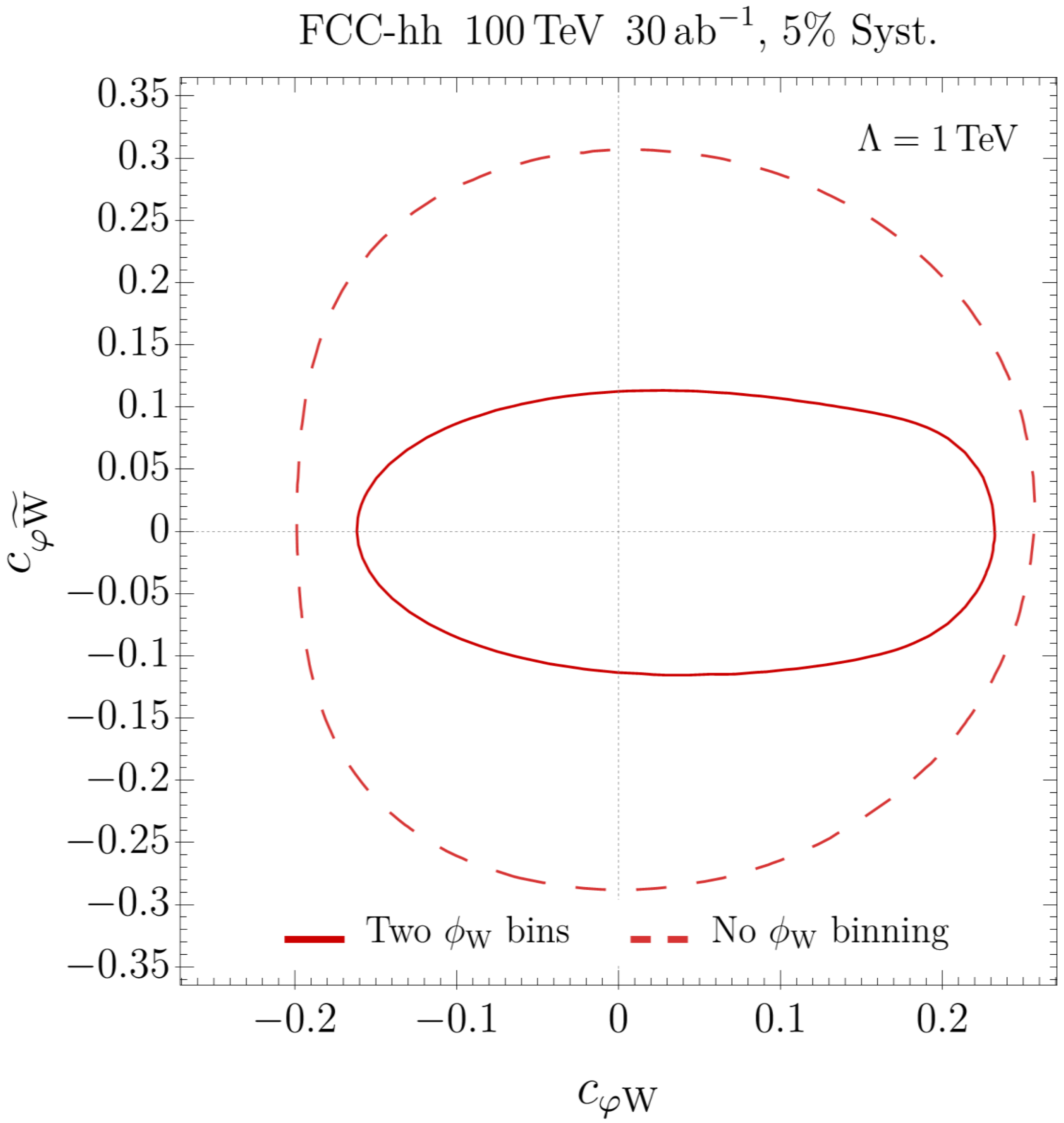
Wh. Angular binning for CP-odd operators

Differential in p_T^h and ϕ_W

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

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

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



Zh. Rapidity binning to lift cancellations

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

Cancellation of up and down contributions

Zh. Rapidity binning to lift cancellations

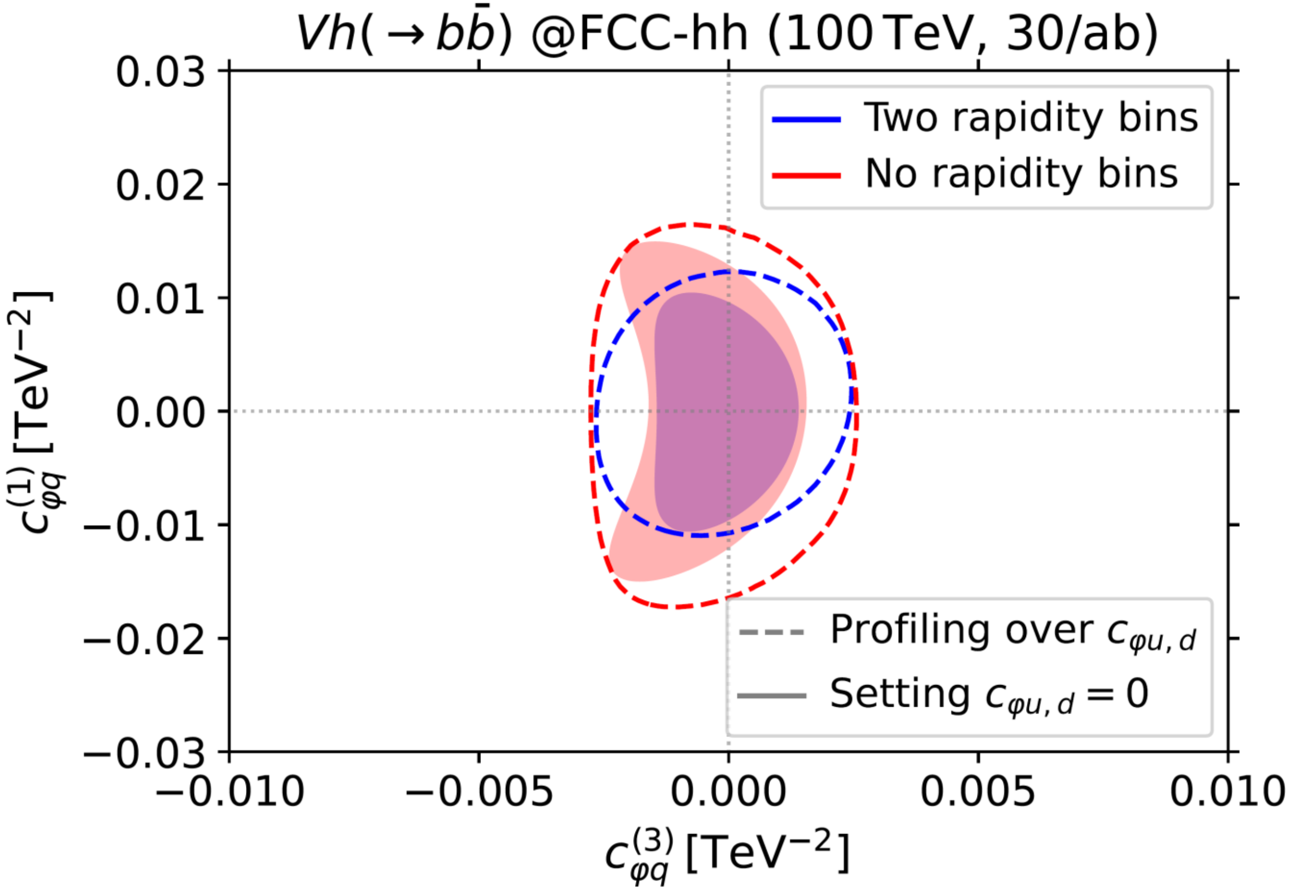
$$\sigma^{int}_{\mathcal{O}^{(1)}_{\varphi q}} \propto s_W^2 Q - T_3$$

Cancellation of up and down contributions

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

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

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



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

Exploiting complementarity.

A showcase for the full diboson and FCC programs.

Vh. Impact on aTGC bounds

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

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

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

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

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

Vh. Impact on aTGC bounds

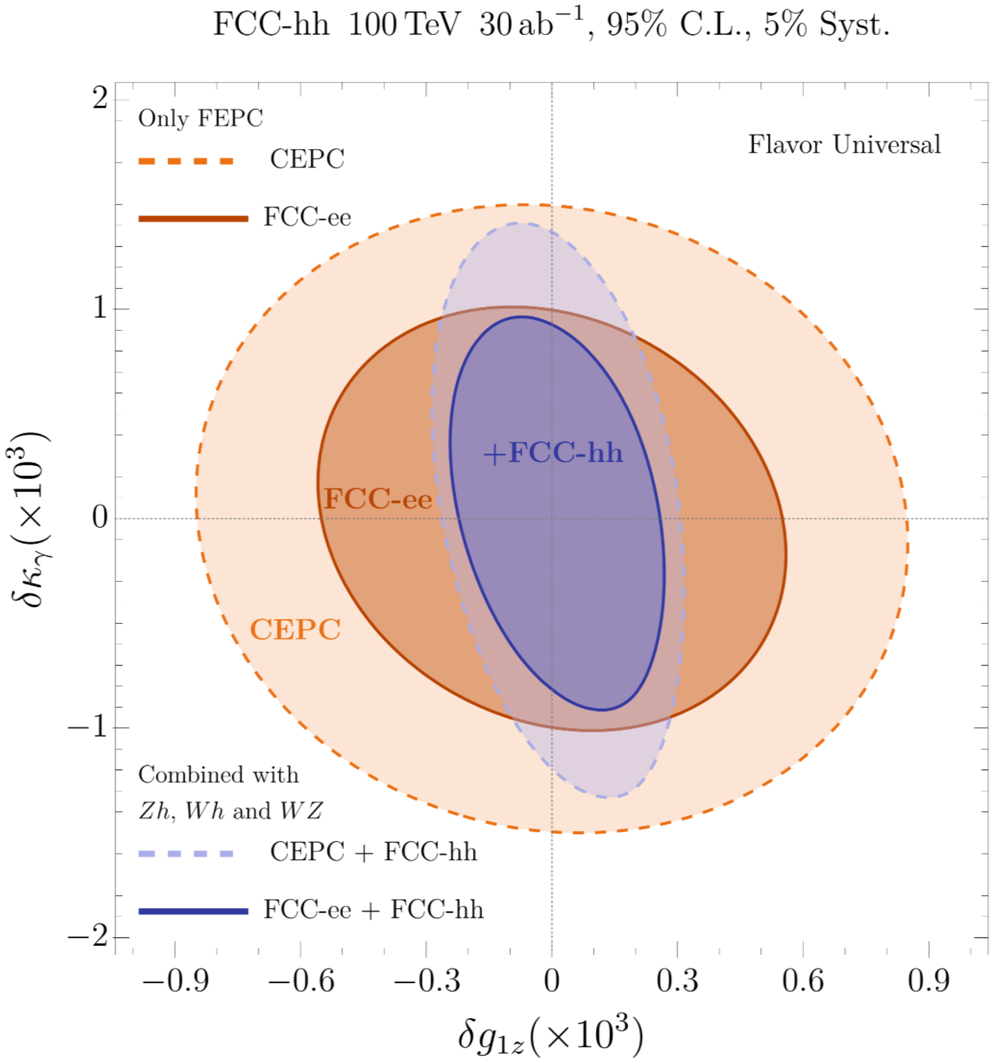
$$c_{\varphi q}^{(3)} = +\frac{\Lambda^2}{4m_W^2} g^2 \left(\delta g_L^{Zu} - \delta g_L^{Zd} - c_{\rm W}^2\, \delta g_{1z}\right)$$

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

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

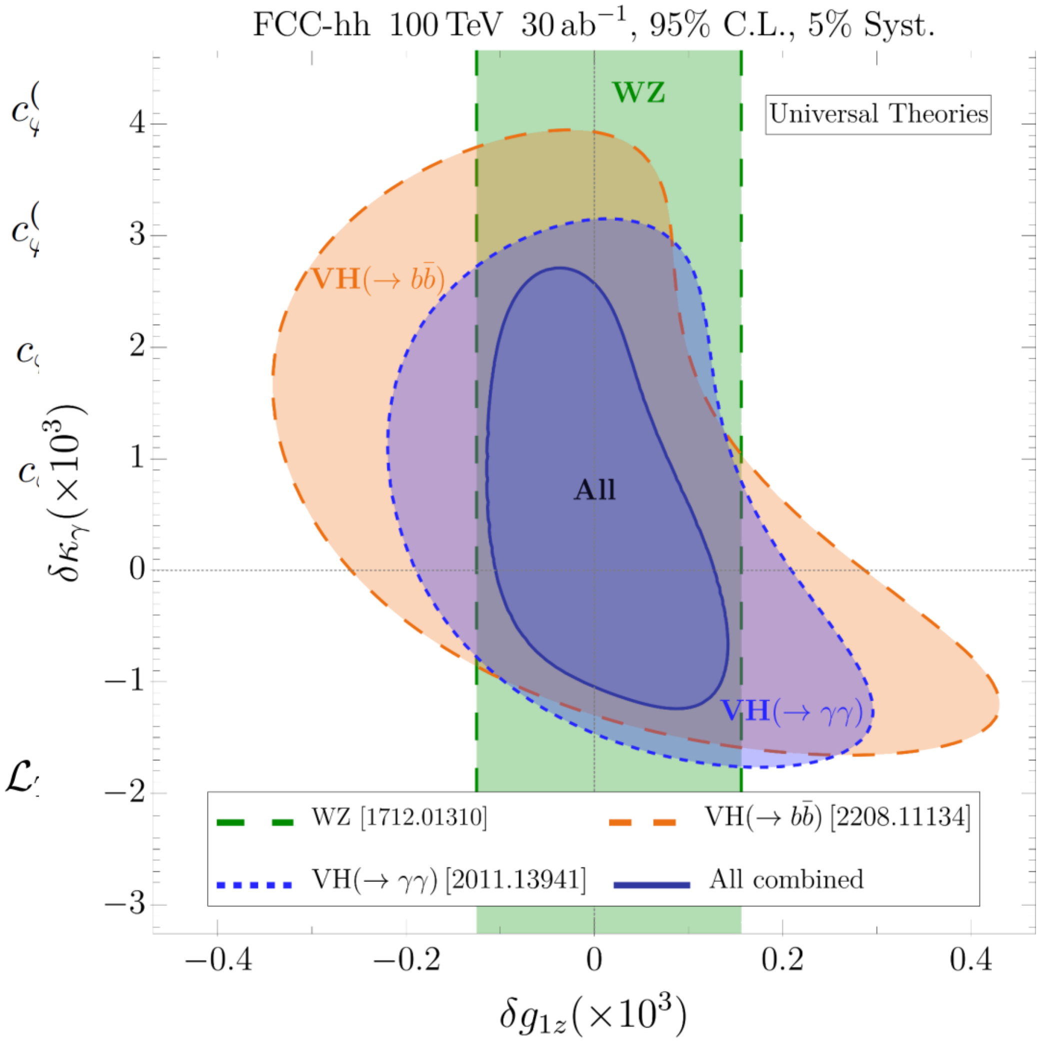
$$c_{\varphi d} = -\frac{\Lambda^2}{2m_W^2} g^2 \left(\delta g_R^{Zd} - \frac{1}{3}\left(t_{\rm W}^2 \delta\kappa_\gamma - s_{\rm W}^2 \delta g_{1z}\right)\right)$$

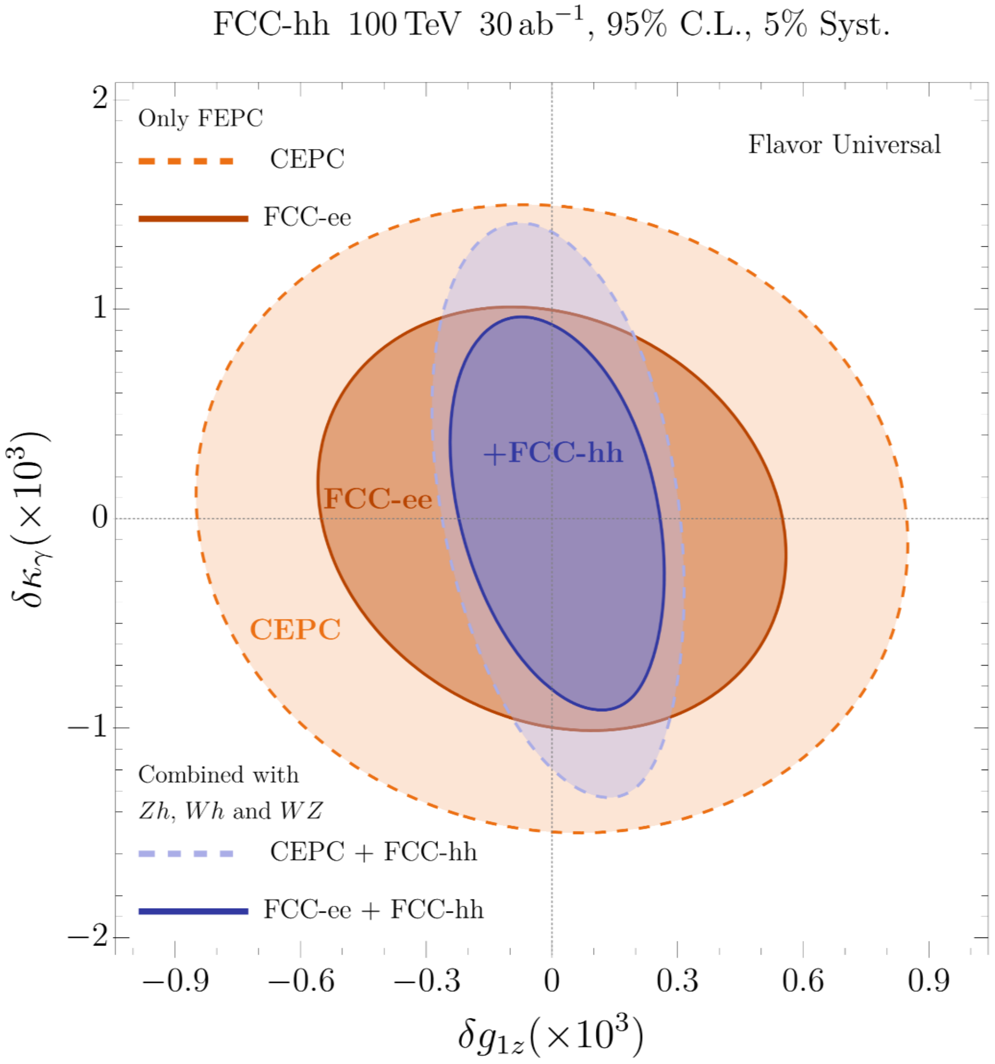
$$\mathcal{L}_{TGC} \supset ie\left(1 + \delta\kappa_\gamma\right) A^{\mu\nu} W_\mu^+ W_\nu^- + ig\, c_W \left(1 + \delta g_{1z}\right)\left(W_{\mu\nu}^+ W^{-,\mu} - W_{\mu\nu}^- W^{+,\mu}\right) Z^\nu$$



Complementarity with future lepton colliders

Vh. Impact on aTGC bounds





Complementarity among diboson processes

Conclusions

- $(W, Z)\, h$ probes several operators.
- A simple p_T binning yields competitive sensitivity to $\mathcal{O}_{\varphi q}^{(3)}$.
- $h \to \gamma\gamma$ will become available at FCC-hh, opening new possibilities.
- $h \to \gamma\gamma$ and $h \to b\bar{b}$ achieve similar results in different ways.
- In Wh , a binning in ϕ_W gives an observable linear in $\mathcal{O}_{\varphi\widetilde{W}}$.
- In Zh, a binning in rapidity improves the sensitivity to $\mathcal{O}_{\varphi q}^{(1)}$.
- Wh and Zh with are not exploration channels, but important to probe different directions.

Thank you for your attention

Contact

MANCHESTER 1824
The University of Manchester

www.manchester.ac.uk

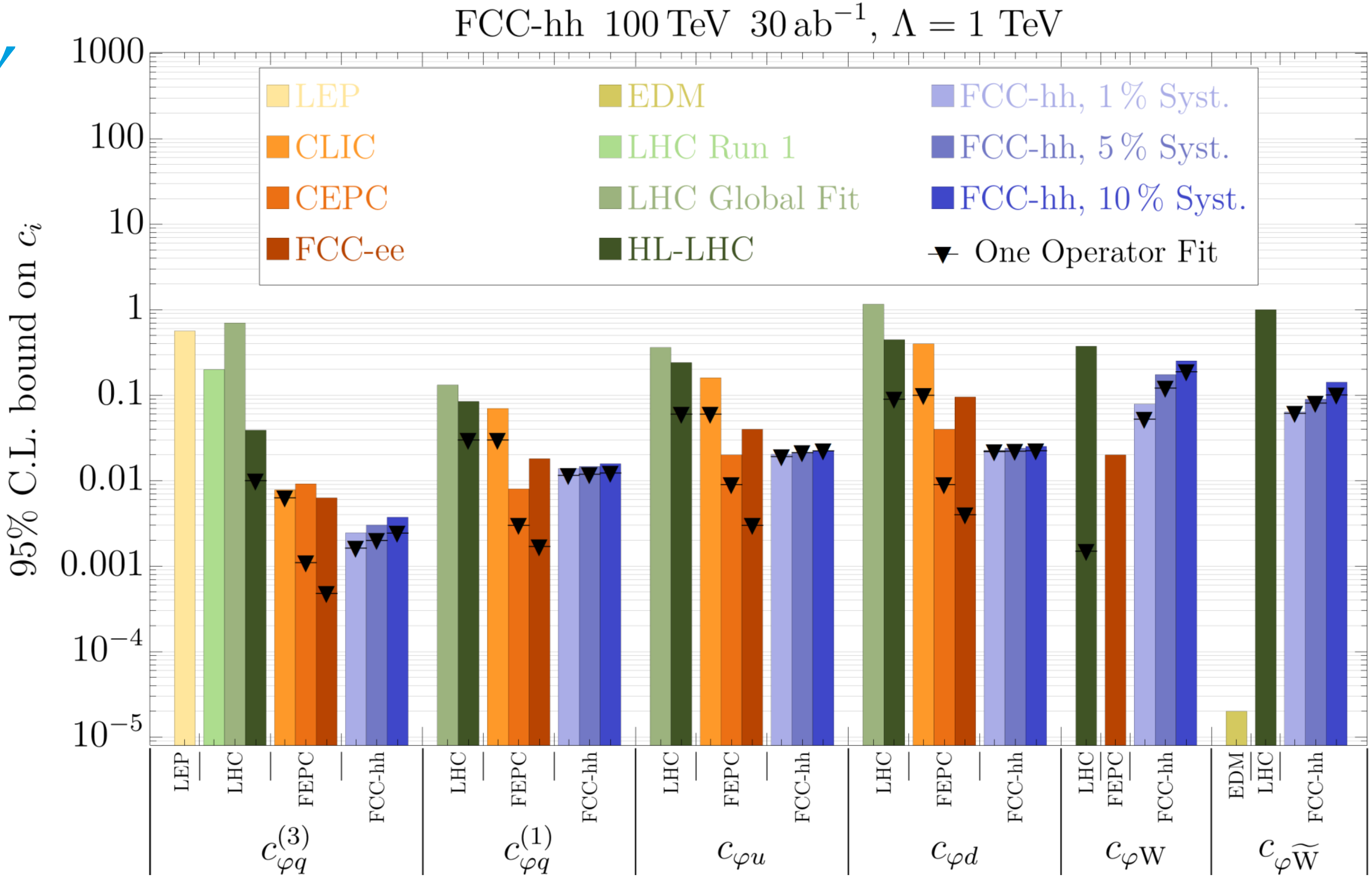
Alejo N. Rossia
HEP Theory Group – Dept. Of Physics and Astronomy
E-mail: alejo dot rossia at manchester dot ac dot uk
http://www.hep.man.ac.uk/

Appendix.

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

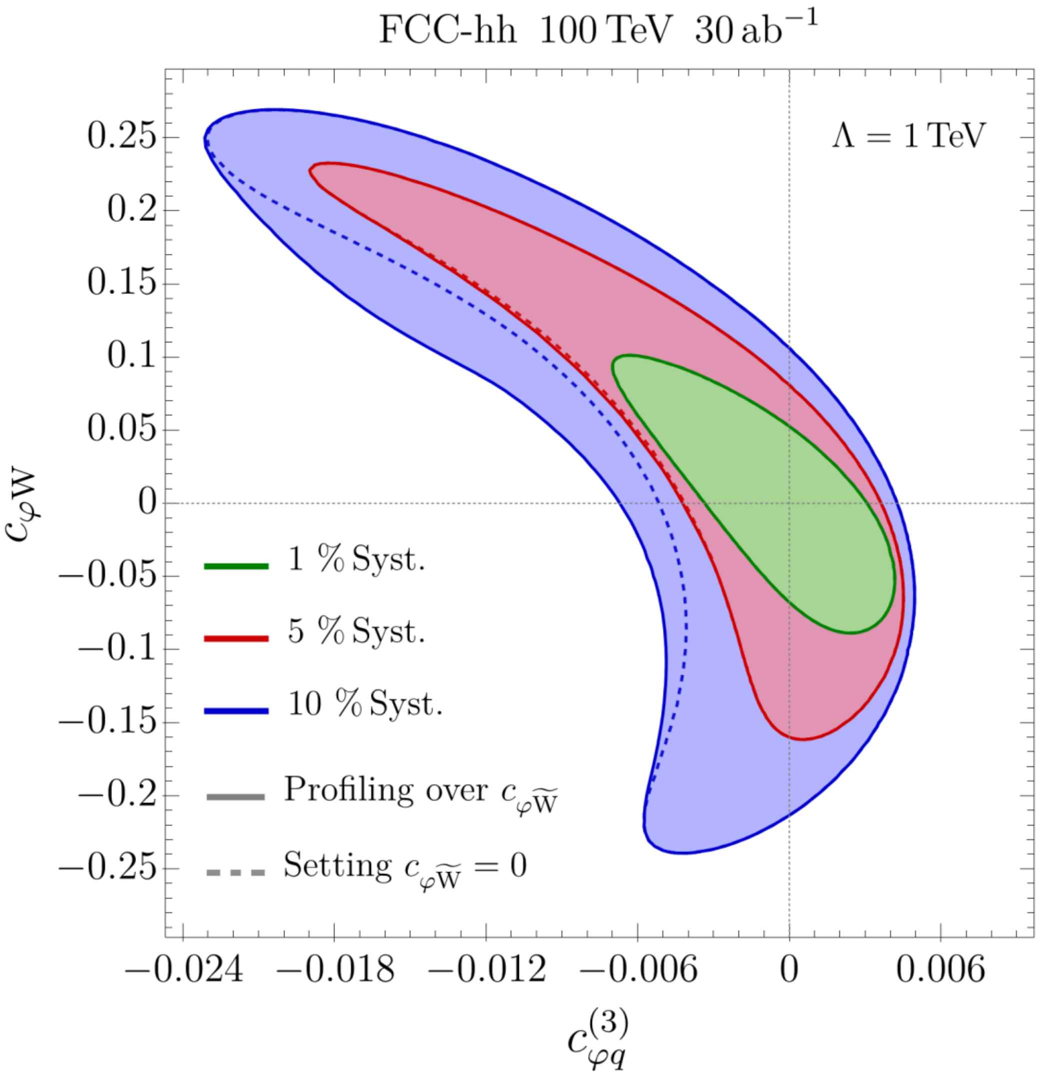
Vh. Comparing our bounds with other colliders

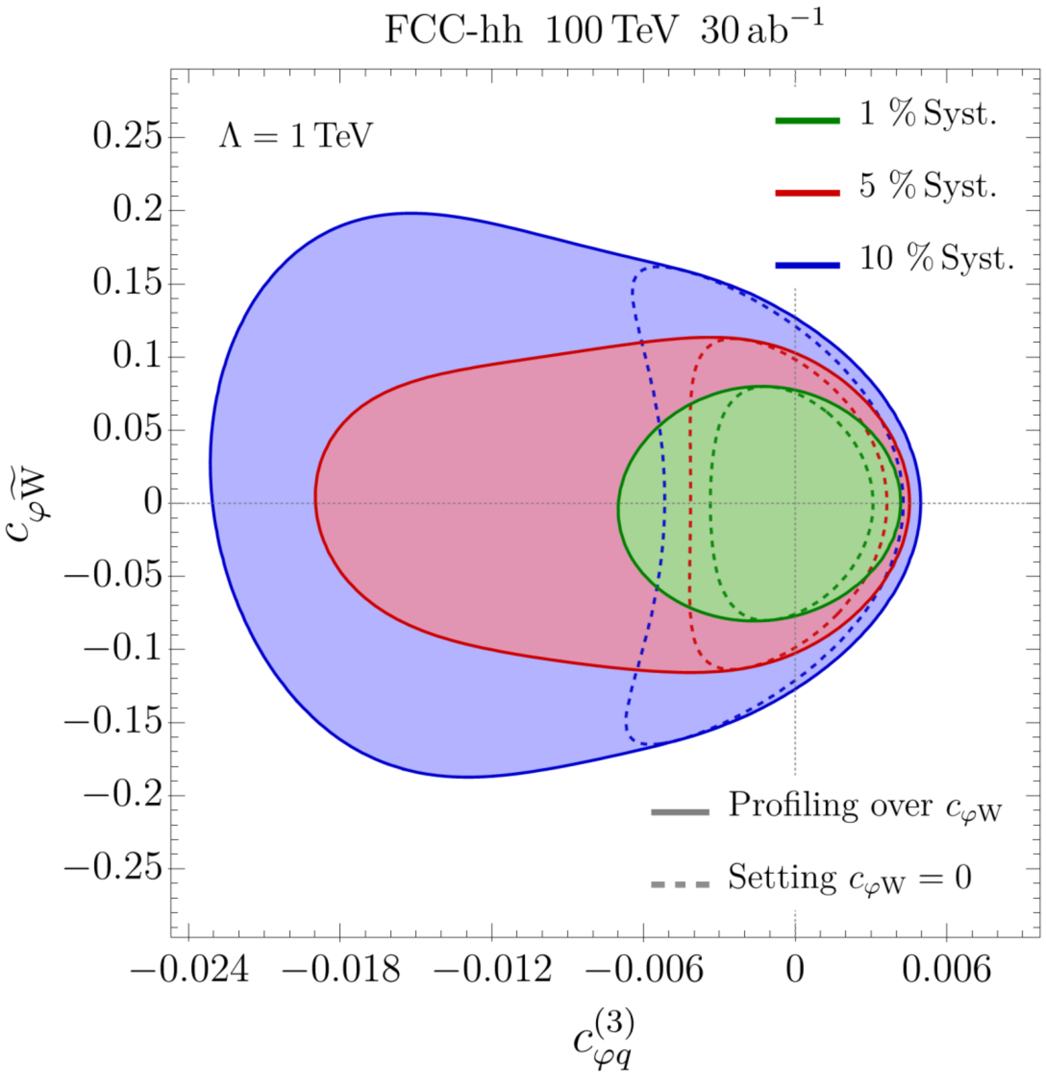
$h \to \gamma\gamma$



Wh. More results

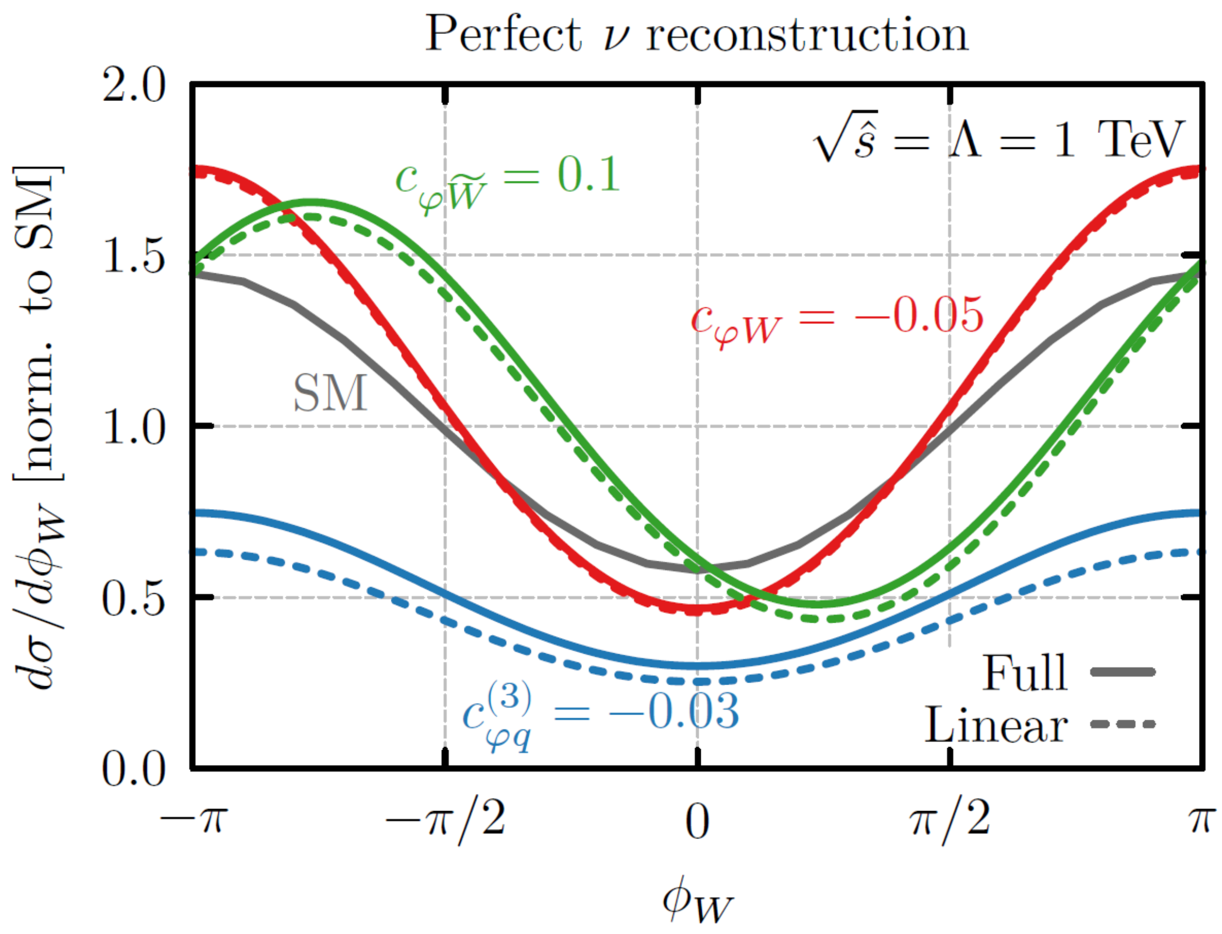
- 95% CL bounds





Wh.

Interference patterns



Differential in p_T^h and ϕ_W

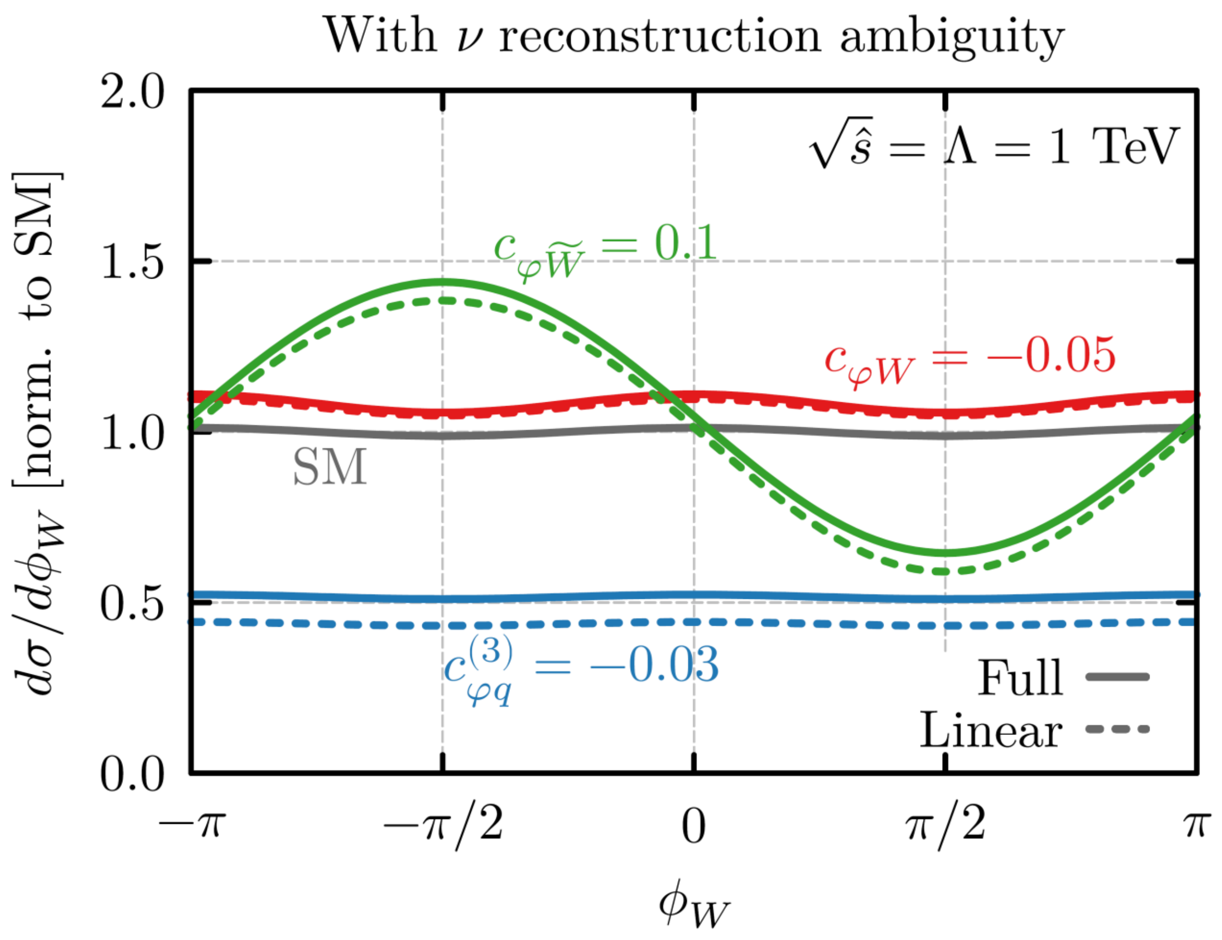
$$\sigma^{int}_{\mathcal{O}^{(3)}_{\varphi q}} \sim \frac{\hat{s}}{\Lambda^2}$$

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

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

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

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

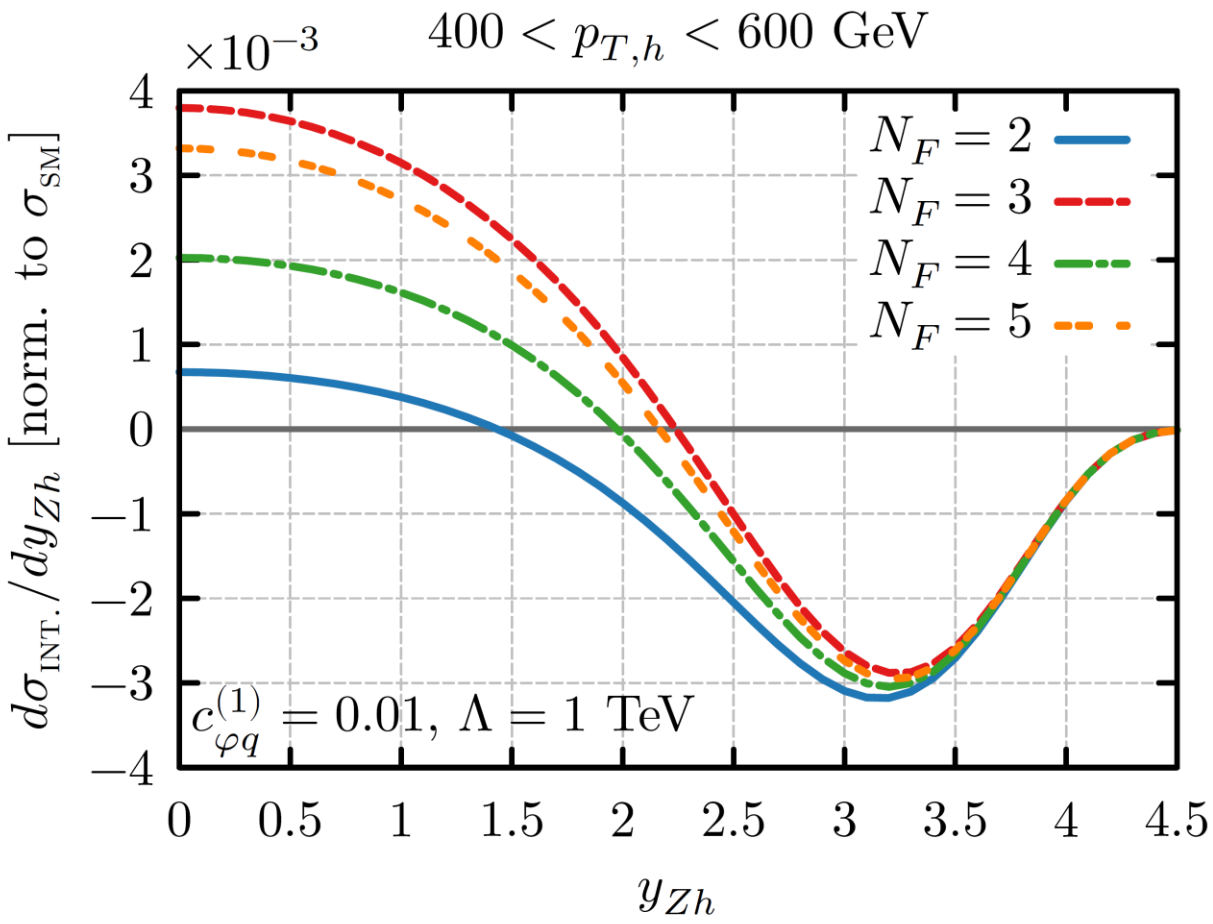
$(\phi_W \to \pi - \phi_W)$

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

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

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

Zh. Lifting up cancellations



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

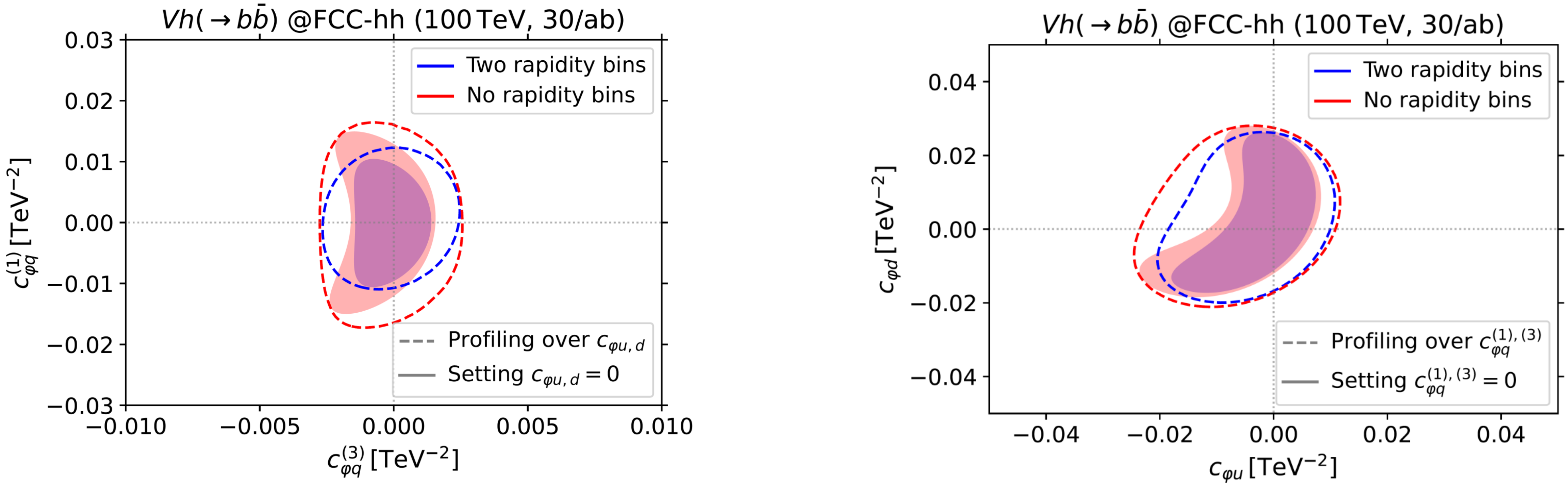
Cancellation of up and down contributions

Differential in p_T and rapidity

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

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

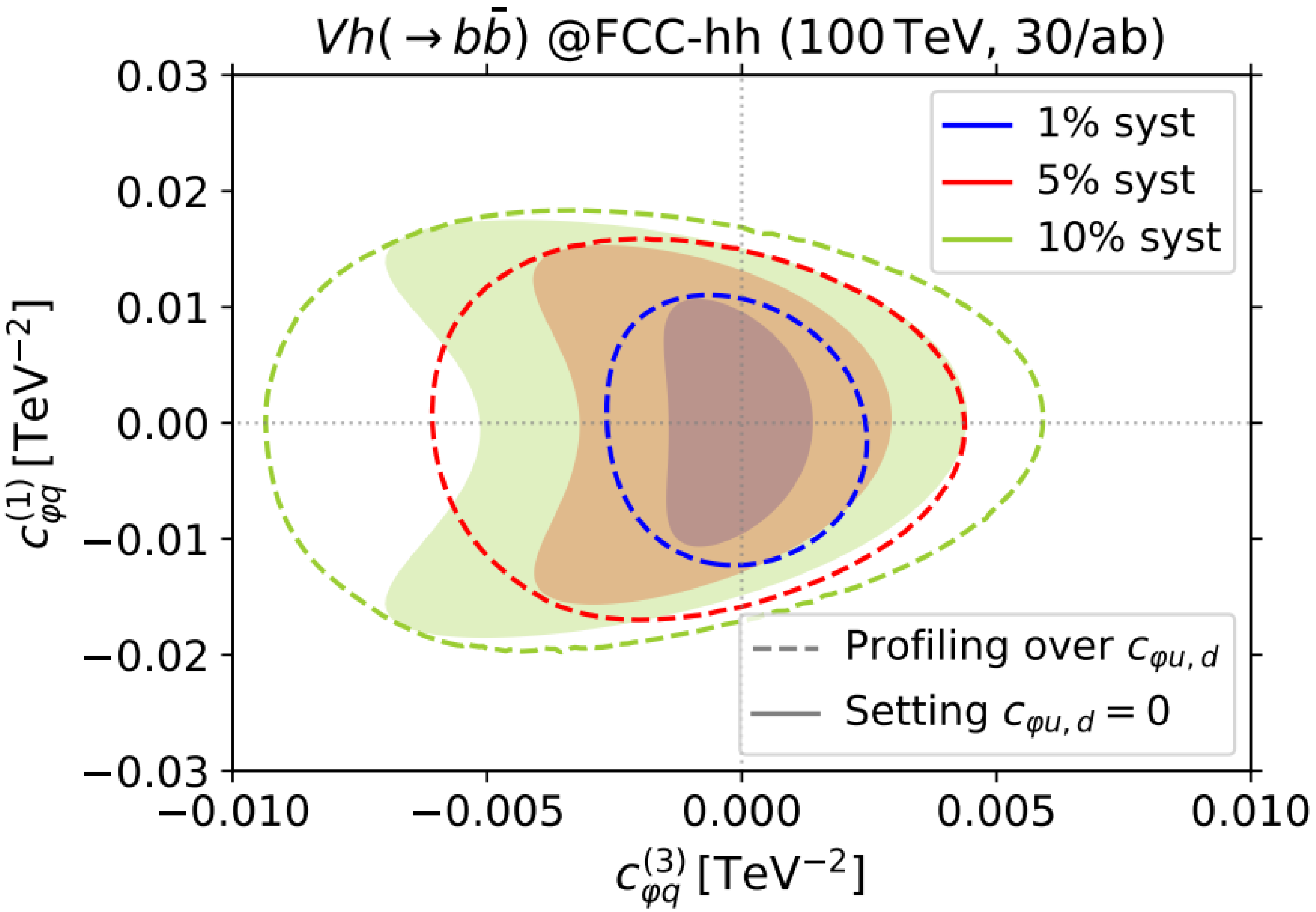
Vh. Rapidity binning effects



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

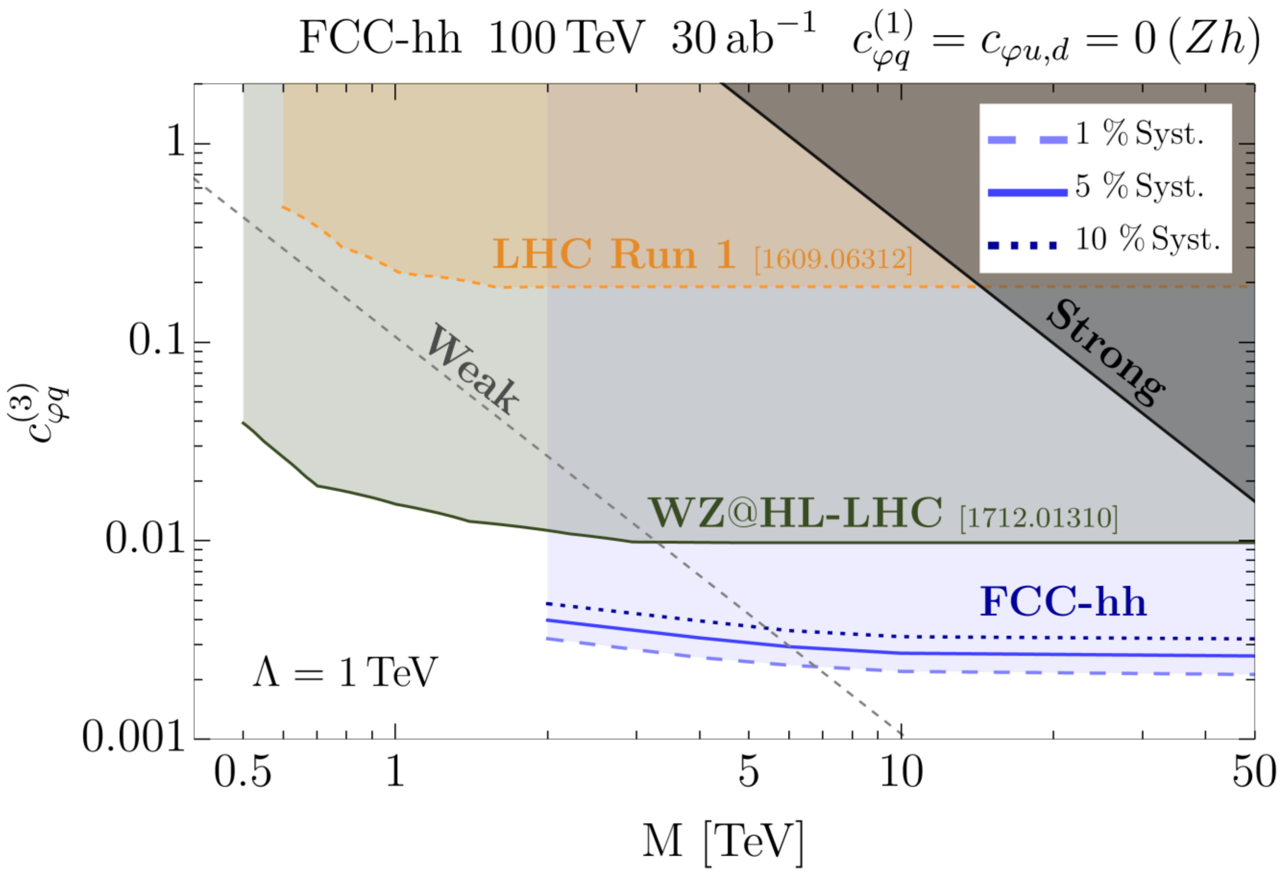
Reduces the correlation between $\mathcal{O}_{\varphi u}$ and $\mathcal{O}_{\varphi d}$.

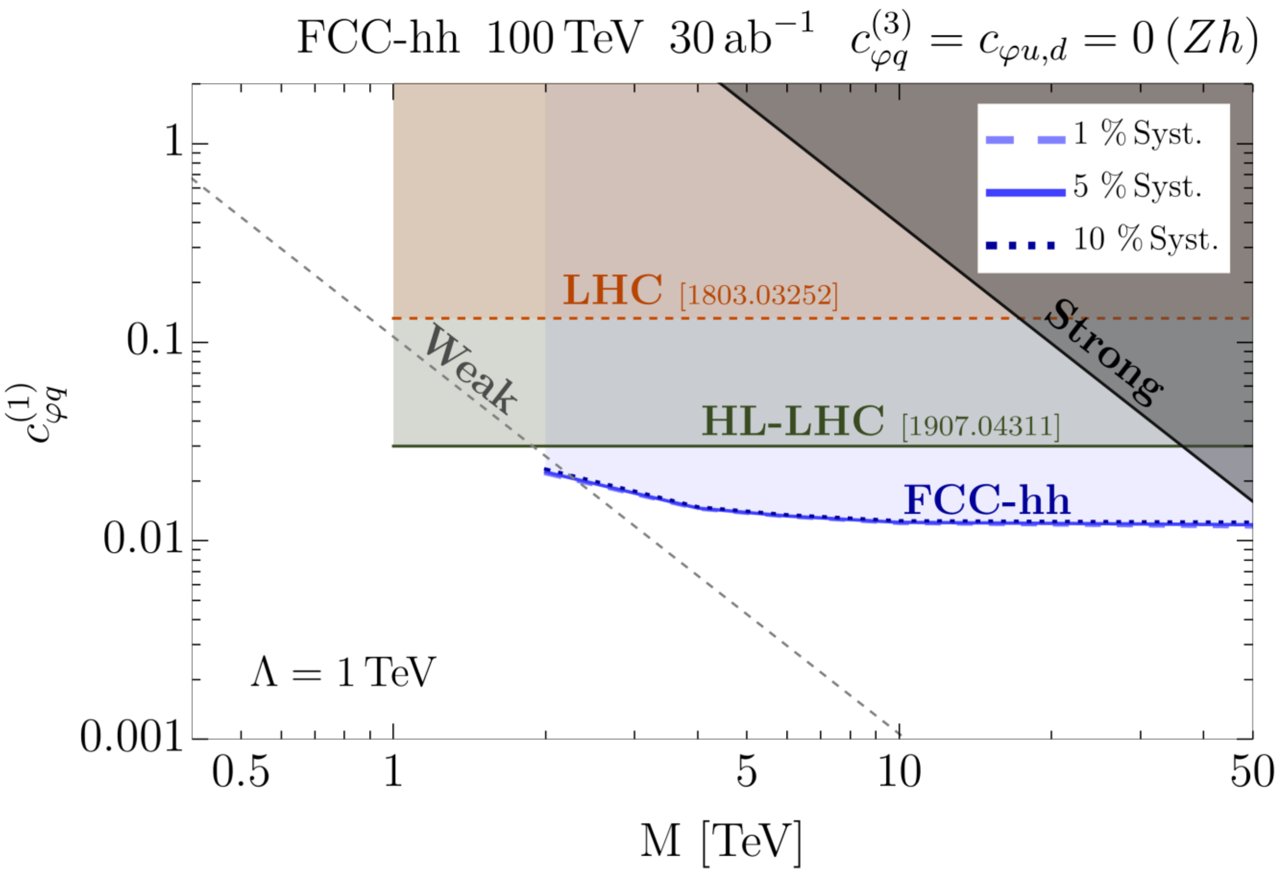
Vh. More results



Zh. More results

- 95% CL bounds

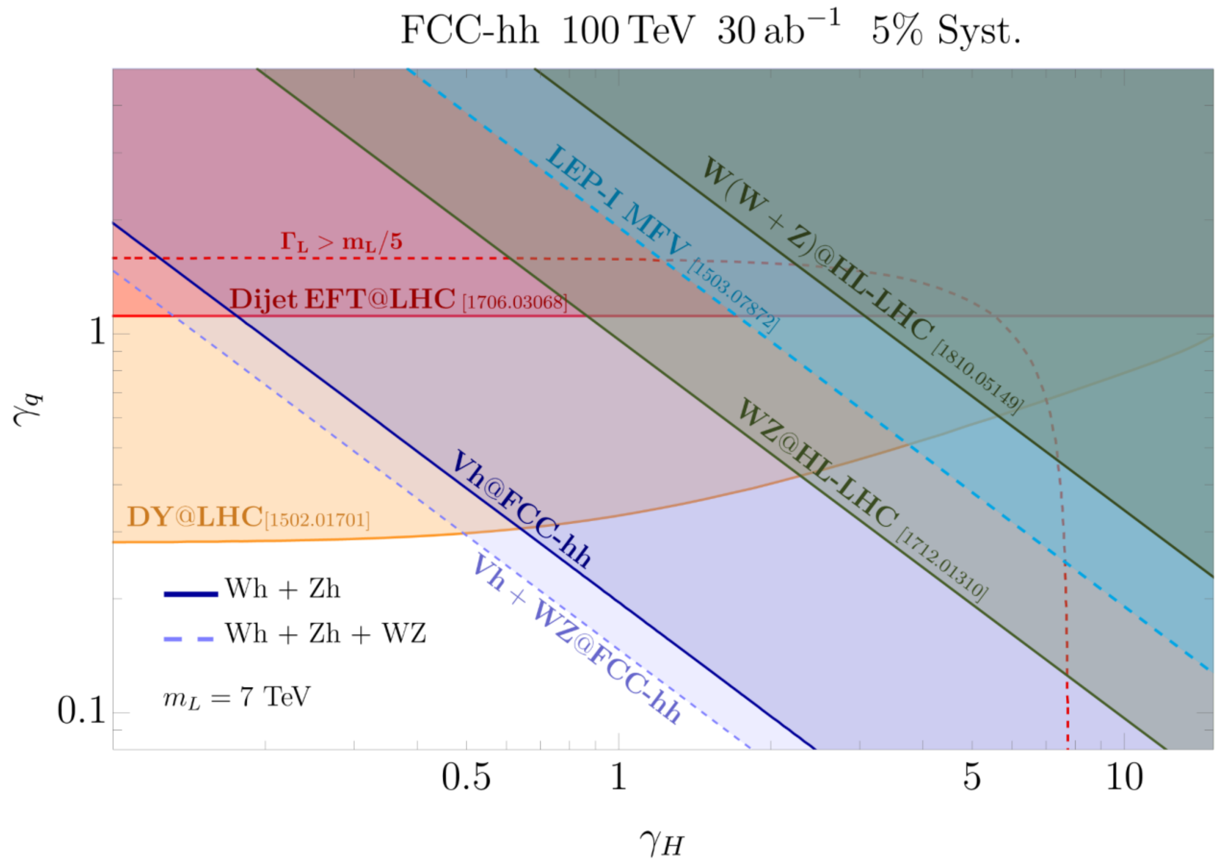


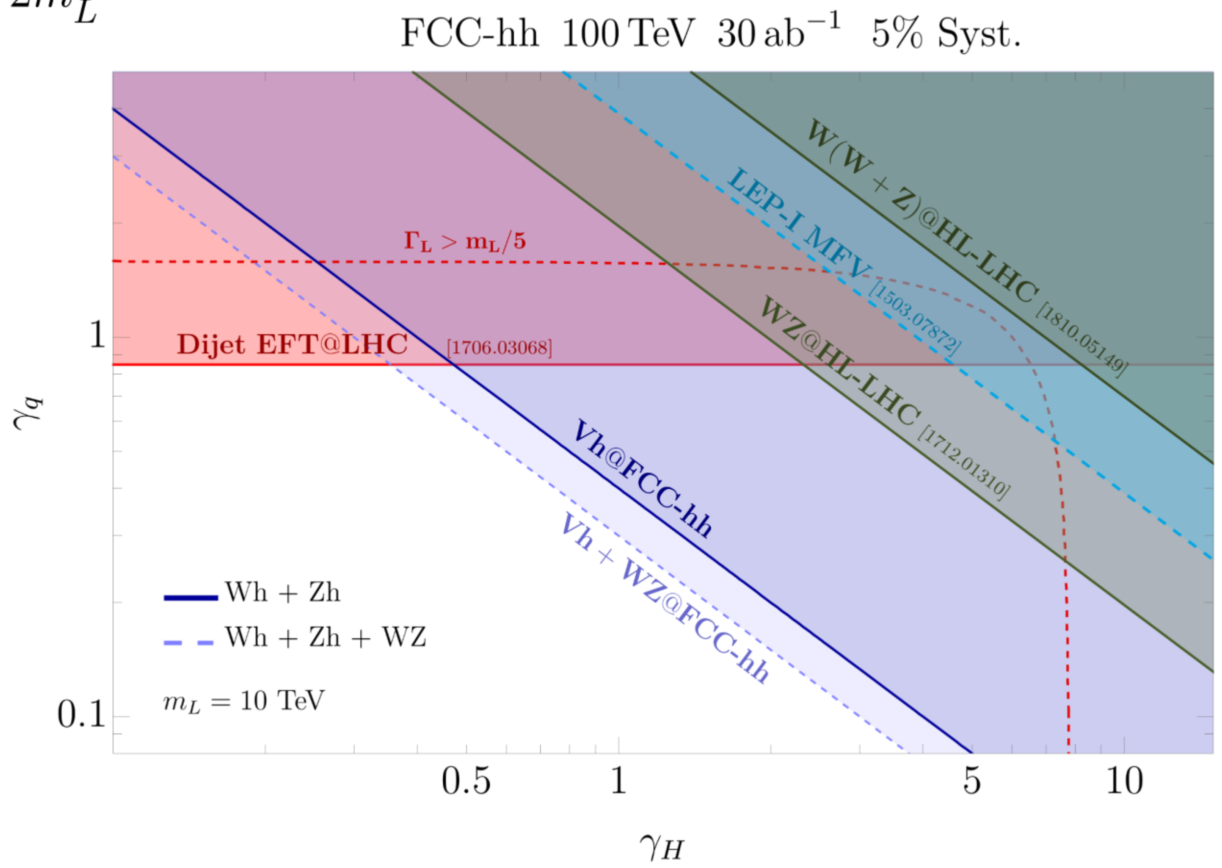


Vh. UV models: Spin-1 triplets

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

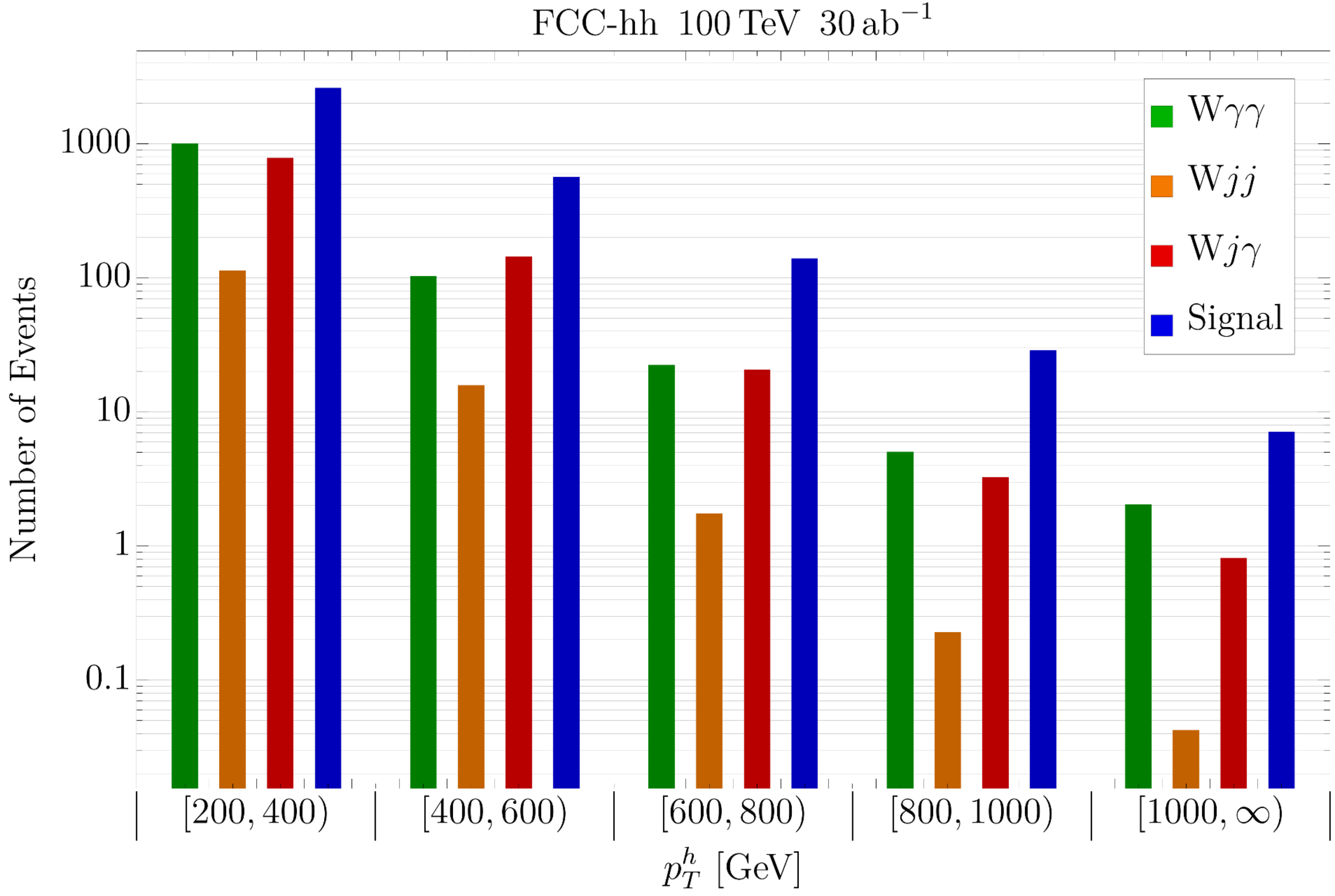
$$c^{(3)}_{\varphi q} = -\frac{\gamma_H \gamma_q}{2 m_L^2}$$





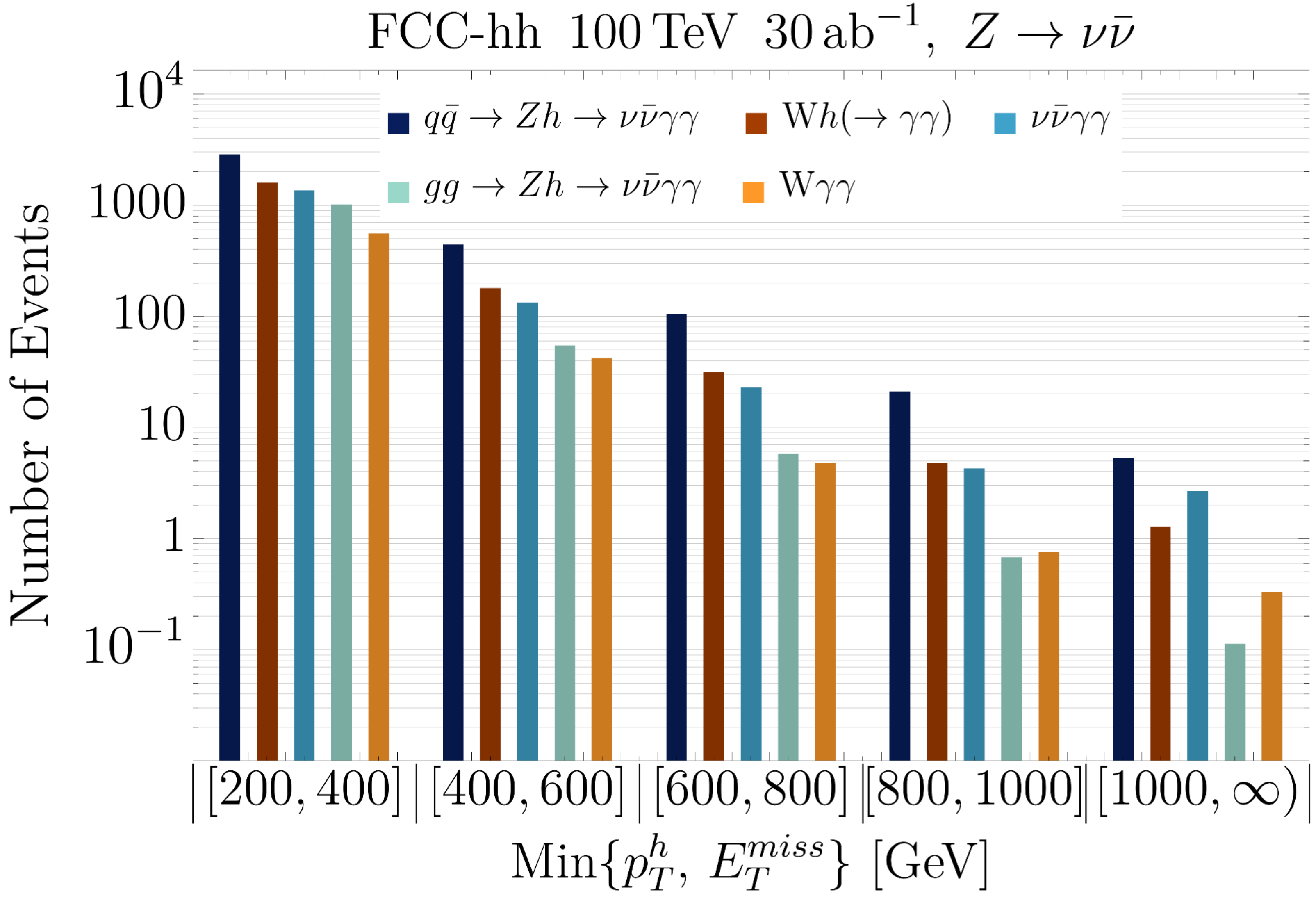
Wh. How big is the background?

- Events per bin for the relevant processes



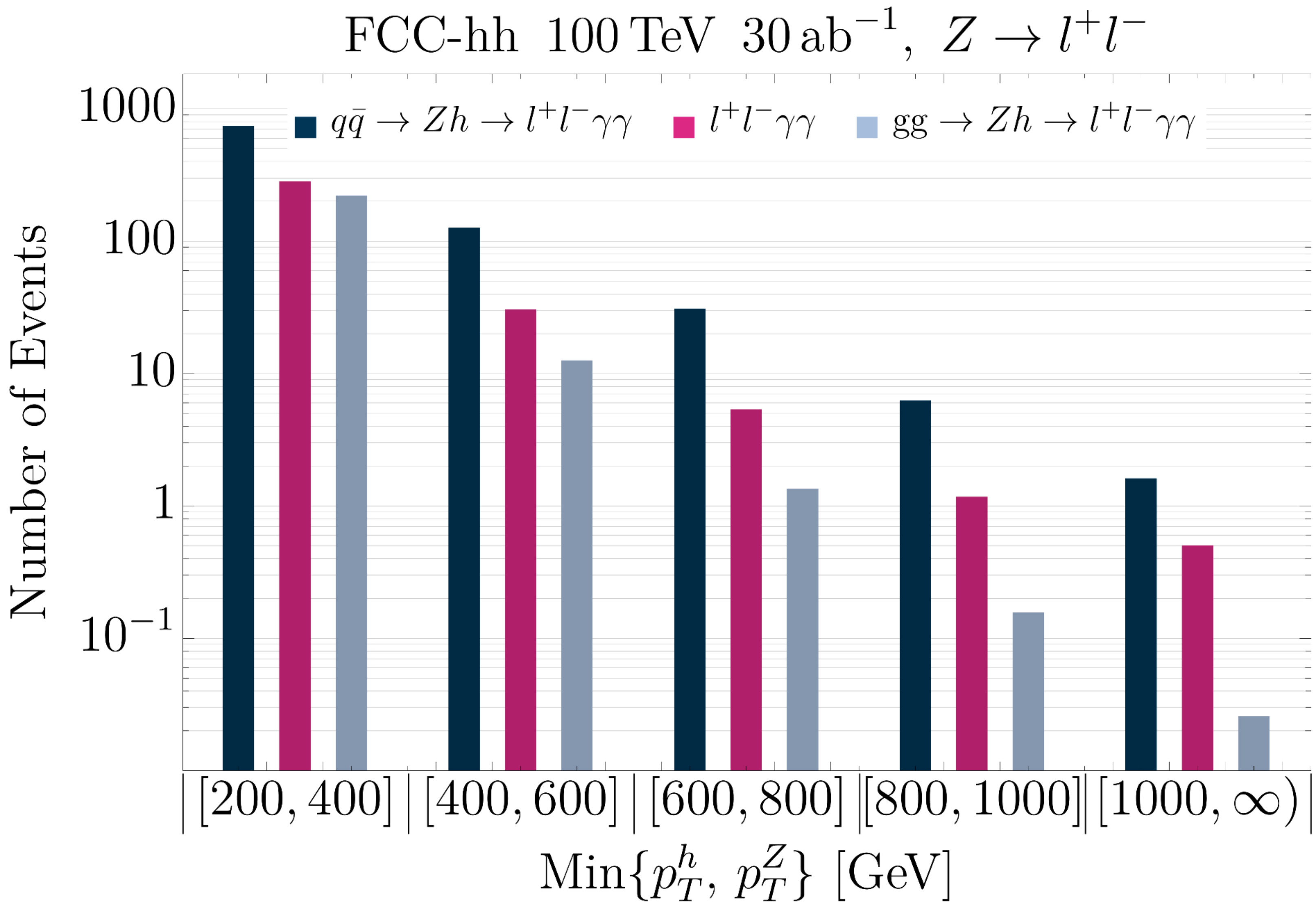
Zh. Signal and background

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



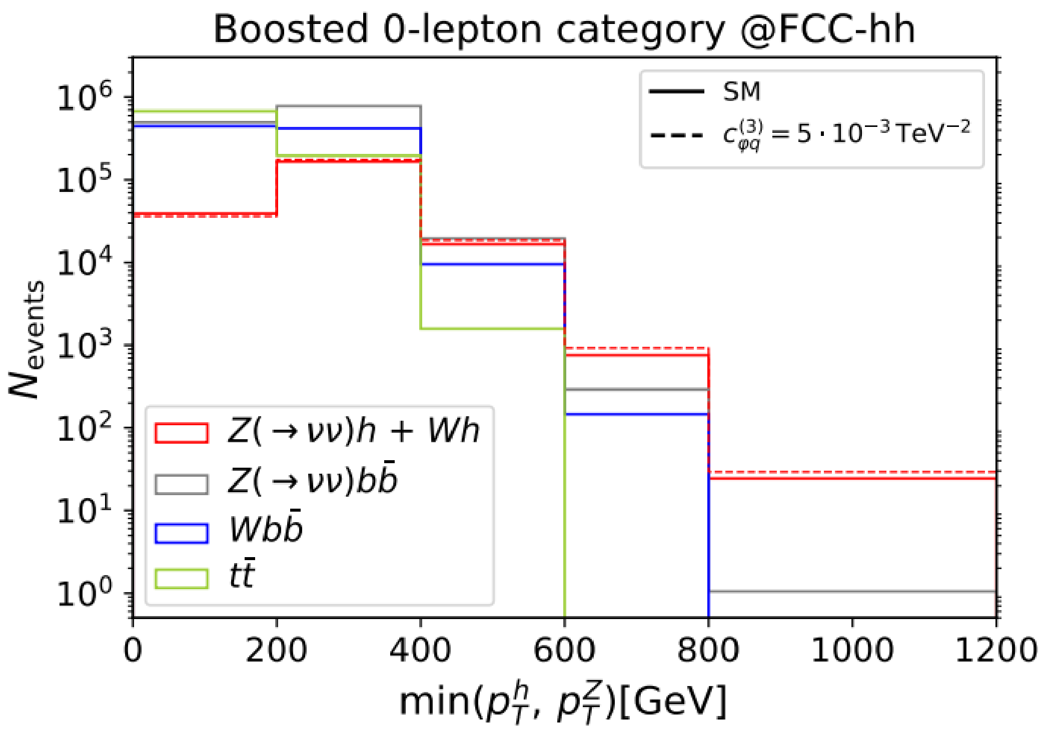
Zh. More results

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

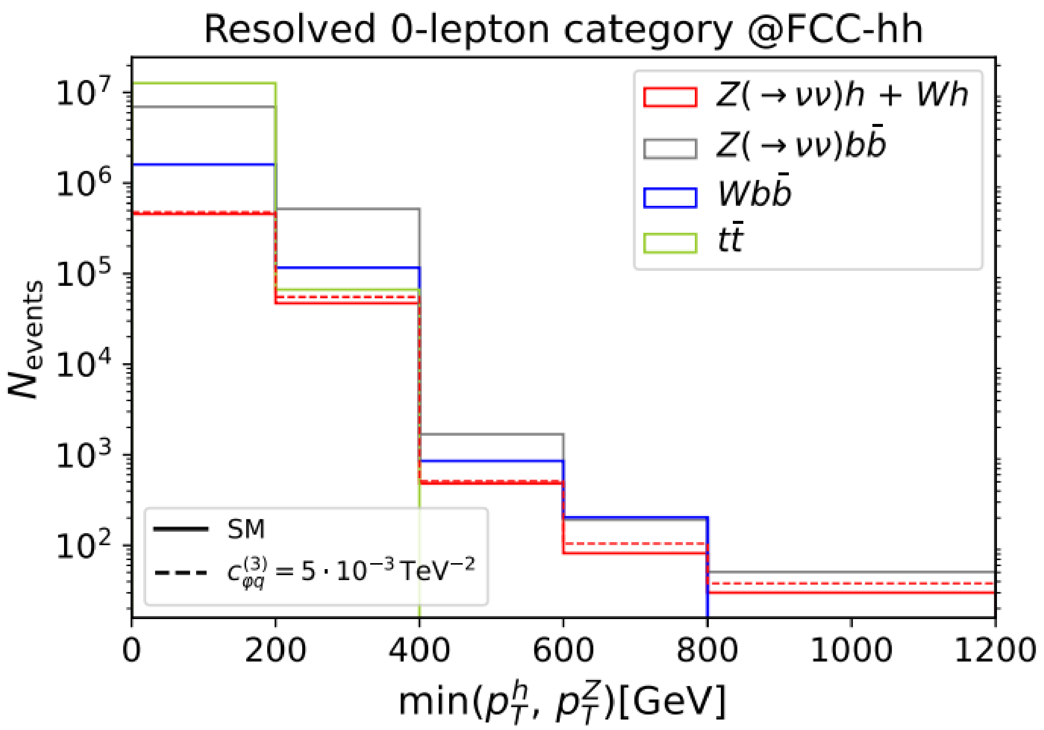


Vh.

$h \to b\bar{b}$



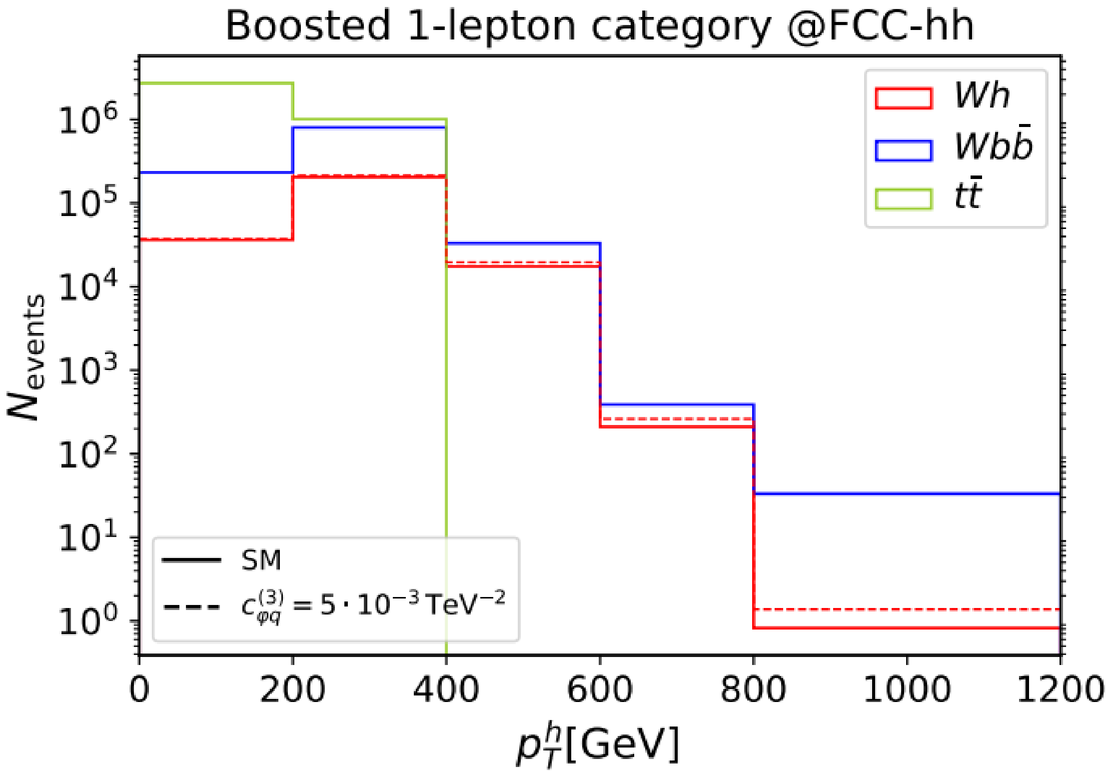
Boosted 0-lepton category @FCC-hh
SM
$c_{\varphi q}^{(3)} = 5 \cdot 10^{-3}\,\mathrm{TeV}^{-2}$
$Z(\to \nu\nu)h + Wh$
$Z(\to \nu\nu)b\bar{b}$
$Wb\bar{b}$
$t\bar{t}$
N_{events}
$\min(p_T^h, p_T^Z)$[GeV]



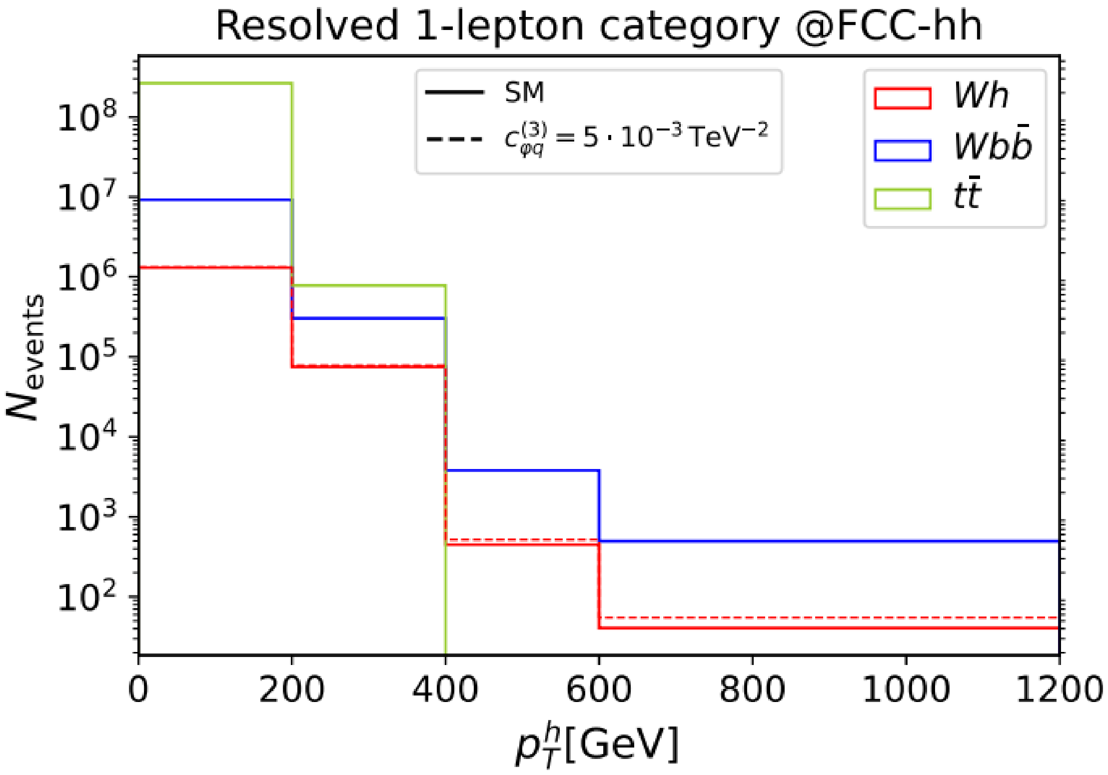
Resolved 0-lepton category @FCC-hh
$Z(\to \nu\nu)h + Wh$
$Z(\to \nu\nu)b\bar{b}$
$Wb\bar{b}$
$t\bar{t}$
SM
$c_{\varphi q}^{(3)} = 5 \cdot 10^{-3}\,\mathrm{TeV}^{-2}$
N_{events}
$\min(p_T^h, p_T^Z)$[GeV]

Vh.

$h \to b\bar{b}$



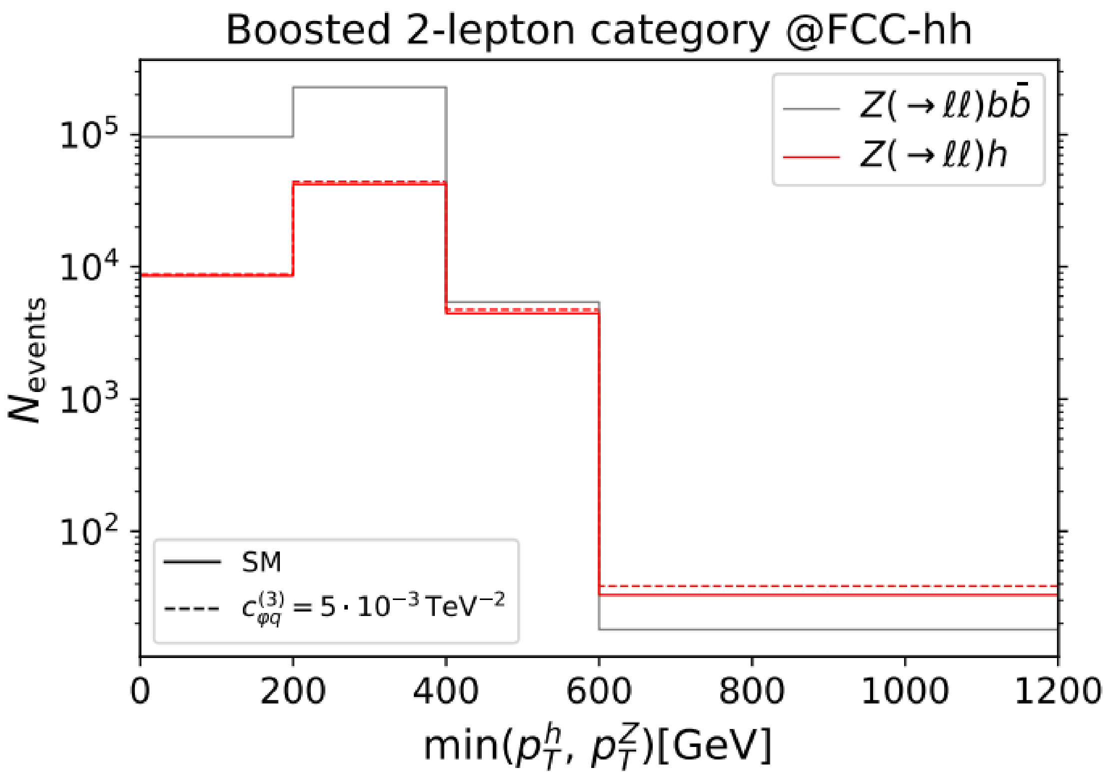
Boosted 1-lepton category @FCC-hh
N_{events}
p_T^h[GeV]
Wh
$Wb\bar{b}$
$t\bar{t}$
SM
$c_{\varphi q}^{(3)} = 5 \cdot 10^{-3}\,\text{TeV}^{-2}$



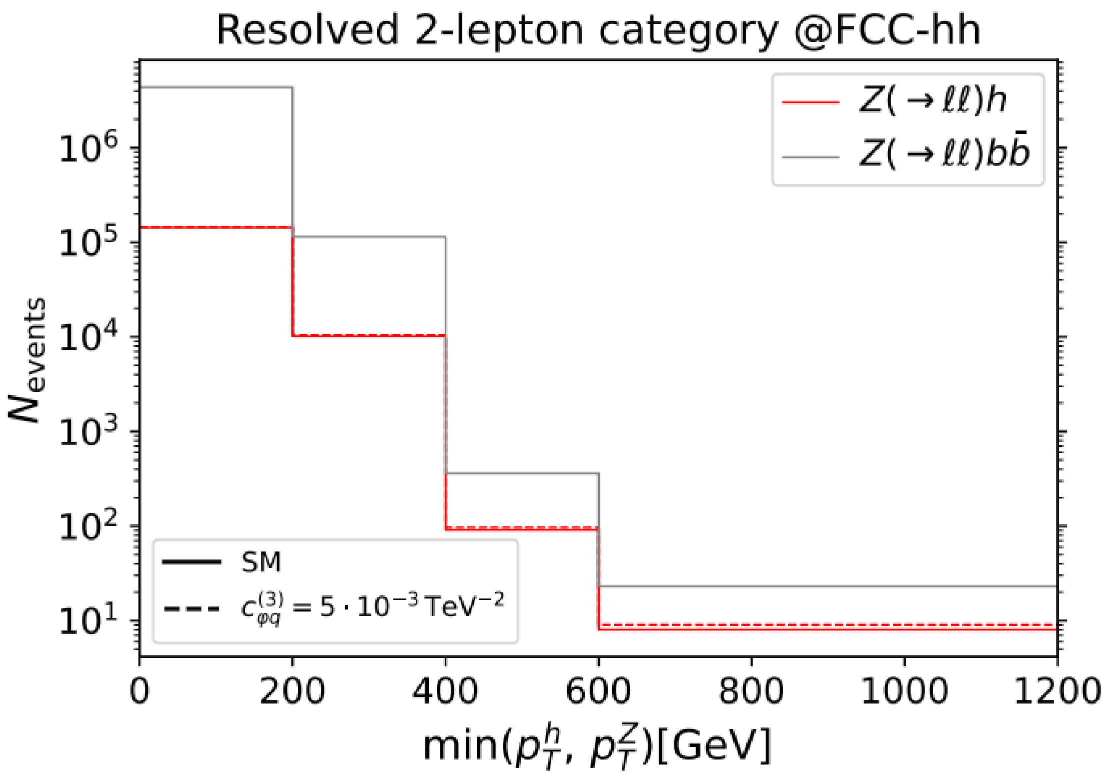
Resolved 1-lepton category @FCC-hh
N_{events}
p_T^h[GeV]
SM
$c_{\varphi q}^{(3)} = 5 \cdot 10^{-3}\,\text{TeV}^{-2}$
Wh
$Wb\bar{b}$
$t\bar{t}$

Vh.

$h \to b\bar{b}$



Boosted 2-lepton category @FCC-hh
$Z(\to \ell\ell)b\bar{b}$
$Z(\to \ell\ell)h$
SM
$c_{\varphi q}^{(3)} = 5 \cdot 10^{-3}\,\mathrm{TeV}^{-2}$
N_{events}
$\min(p_T^h,\, p_T^Z)[\mathrm{GeV}]$



Resolved 2-lepton category @FCC-hh
$Z(\to \ell\ell)h$
$Z(\to \ell\ell)b\bar{b}$
SM
$c_{\varphi q}^{(3)} = 5 \cdot 10^{-3}\,\mathrm{TeV}^{-2}$
N_{events}
$\min(p_T^h,\, p_T^Z)[\mathrm{GeV}]$

Vh.

$h \to b\bar{b}$

Coefficient	Profiled Fit		One-Operator Fit	
$c_{\varphi q}^{(3)}$ [TeV^{-2}]	$[-2.0,\ 2.1] \times 10^{-3}$	1% syst.	$[-1.1,\ 1.1] \times 10^{-3}$	1% syst.
	$[-4.9,\ 3.7] \times 10^{-3}$	5% syst.	$[-2.5,\ 2.4] \times 10^{-3}$	5% syst.
	$[-7.6,\ 5.1] \times 10^{-3}$	10% syst.	$[-4.0,\ 3.6] \times 10^{-3}$	10% syst.
$c_{\varphi q}^{(1)}$ [TeV^{-2}]	$[-10.6,\ 9.0] \times 10^{-3}$	1% syst.	$[-8.2,\ 8.1] \times 10^{-3}$	1% syst.
	$[-14.8,\ 13.6] \times 10^{-3}$	5% syst.	$[-11.3,\ 11.5] \times 10^{-3}$	5% syst.
	$[-17.2,\ 16.4] \times 10^{-3}$	10% syst.	$[-13.1,\ 13.3] \times 10^{-3}$	10% syst.
$c_{\varphi u}$ [TeV^{-2}]	$[-15.9,\ 9.0] \times 10^{-3}$	1% syst.	$[-6.2,\ 4.9] \times 10^{-3}$	1% syst.
	$[-27.0,\ 13.5] \times 10^{-3}$	5% syst.	$[-24.9,\ 8.2] \times 10^{-3}$	5% syst.
	$[-30.4,\ 16.4] \times 10^{-3}$	10% syst.	$[-30.2,\ 10.4] \times 10^{-3}$	10% syst.
$c_{\varphi d}$ [TeV^{-2}]	$[-17.9,\ 23.6] \times 10^{-3}$	1% syst.	$[-9.8,\ 23.0] \times 10^{-3}$	1% syst.
	$[-22.0,\ 26.5] \times 10^{-3}$	5% syst.	$[-14.0,\ 24.5] \times 10^{-3}$	5% syst.
	$[-25.1,\ 29.5] \times 10^{-3}$	10% syst.	$[-16.9,\ 26.4] \times 10^{-3}$	10% syst.

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.

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.

Zh.

Analysis details

- Selection cuts and binning:

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

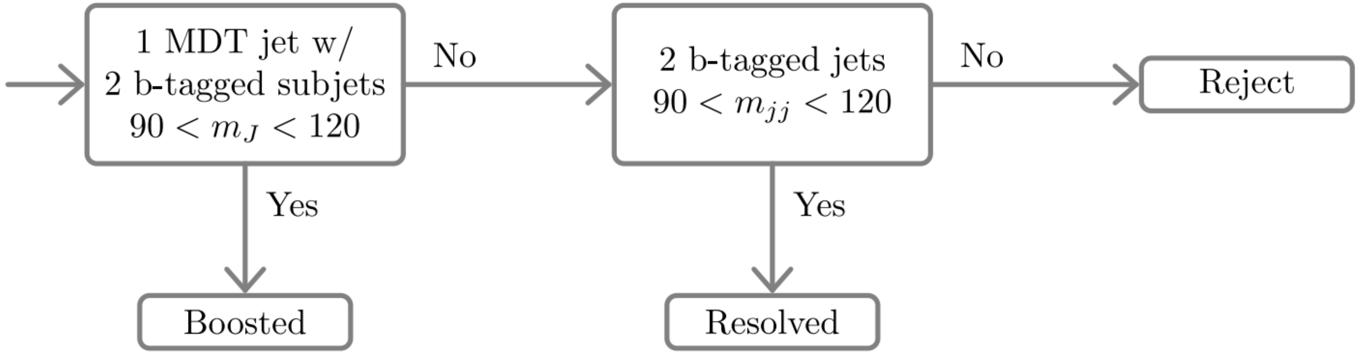
	Selection cuts
$p_{T,\min}^{\ell}$ [GeV]	30
$p_{T,\min}^{\gamma}$ [GeV]	50
$m_{\gamma\gamma}$ [GeV]	$[120, 130]$
$m_{l^+l^-}$ [GeV]	$[81, 101]$
$\Delta R_{\max}^{\gamma\gamma}$	$\{1.3, 0.9, 0.75, 0.6, 0.6\}$
$\Delta R_{\max}^{l^+l^-}$	$\{1.2, 0.8, 0.6, 0.5, 0.4\}$
$p_{T,\max}^{Zh}$ [GeV]	$\{200, 600,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

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

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

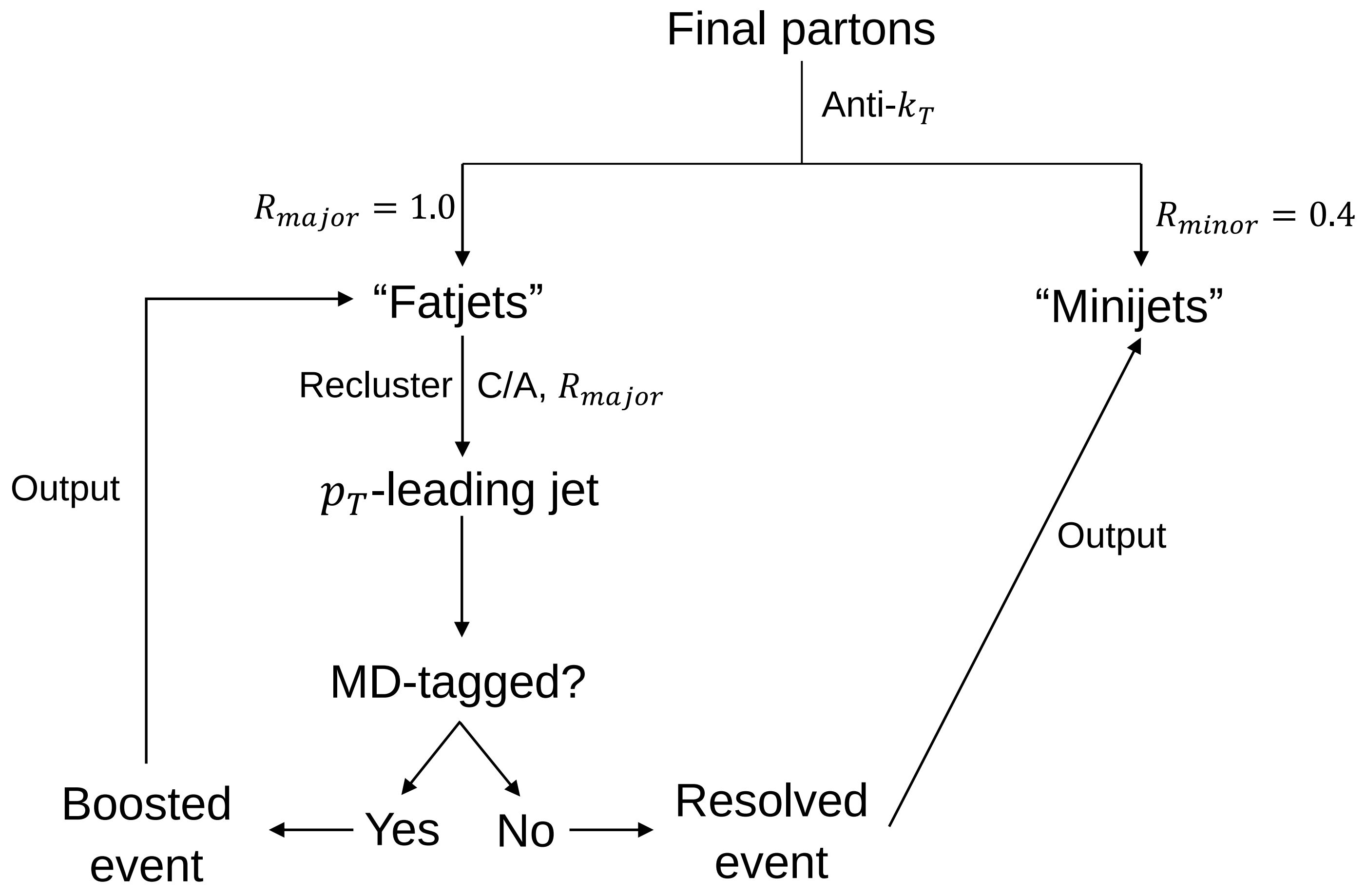
Vh.

Tagging algorithm



Vh.

Tagging algorithm



Vh.

(b-)Tagging algorithm

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

For Boosted events

Enough for Resolved events

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

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

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

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

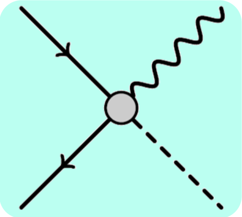
$$\mathrm{eff}_b^{\mathrm{FCC}} = \begin{cases} 0 & \text{if } p_T \leq 20\,\mathrm{GeV} \text{ or } |\eta| > 4.5 \\ 0.85 & \text{else} \end{cases}$$

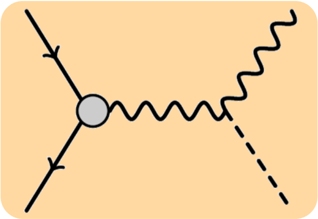
$$\mathrm{eff}_c^{\mathrm{FCC}} = \begin{cases} 0 & \text{if } p_T \leq 20\,\mathrm{GeV} \text{ or } |\eta| > 4.5 \\ 0.05 & \text{else} \end{cases}$$

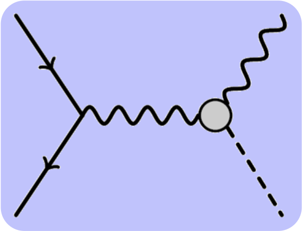
$$\mathrm{eff}_j^{\mathrm{FCC}} = \begin{cases} 0 & \text{if } p_T \leq 20\,\mathrm{GeV} \text{ or } |\eta| > 4.5 \\ 0.01 & \text{else} \end{cases}$$

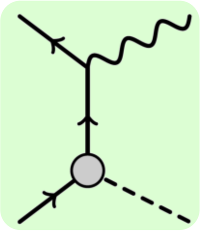
Vh.

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**