Precision physics in SMEFT with ~~mult~~iboson
d

1st COMETA Meeting

Izmir, Turkey

28 February 2024

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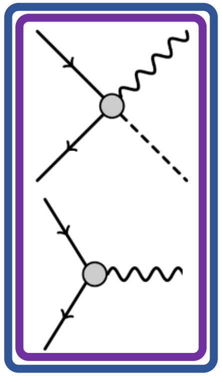
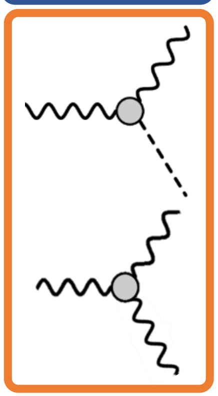
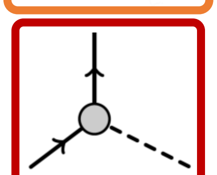
Wilson Coefficients and how to bound them

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \frac{c_i^{(8)}}{\Lambda^4}\mathcal{O}_i^{(8)} + \mathcal{O}(\frac{1}{\Lambda^5})$$

Same particles and gauge symmetries as the SM







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

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

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

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

Dipoles

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

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

Yukawa

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

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

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

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

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

Fermion current

$$\mathcal{O}_{\text{W}} = \epsilon^{IJK} W^{I\,\nu}_{\mu} W^{J\,\rho}_{\nu} W^{K\,\mu}_{\rho}$$

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

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

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

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

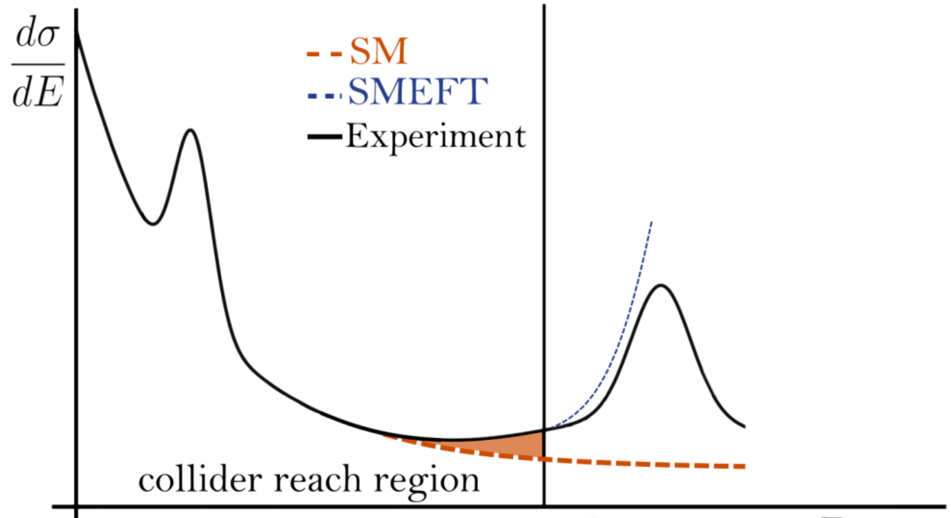
$$\mathcal{O}_{\varphi\widetilde{\text{B}}} = H^\dagger H\, B^{\mu\nu} \widetilde{B}_{\mu\nu}$$

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

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

Bosonic

Why Diboson?: Its effect on the tails



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

	SM	BSM
$q_{L,R}\bar{q}_{L,R} \to V_L V_L(h)$	~ 1	$\sim E^2/M^2$
$q_{L,R}\bar{q}_{L,R} \to V_\pm V_L(h)$	$\sim m_W/E$	$\sim m_W E/M^2$
$q_{L,R}\bar{q}_{L,R} \to V_\pm V_\pm$	$\sim m_W^2/E^2$	$\sim E^2/M^2$
$q_{L,R}\bar{q}_{L,R} \to V_\pm V_\mp$	~ 1	~ 1

Franceschini et al [1712.01310]

Vh: A diboson case study

Based on: Bishara, Englert, Grojean, Panico, ANR [2208.11134]

Many dim-6 operators affect *Vh*…

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

MFV suppressed

Sub-leading energy growth

No interference with SM for massless quarks

…but just a few are well probed.

A trick of the tails

V = W, Z $$q\bar{q}' \to Vh$$

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

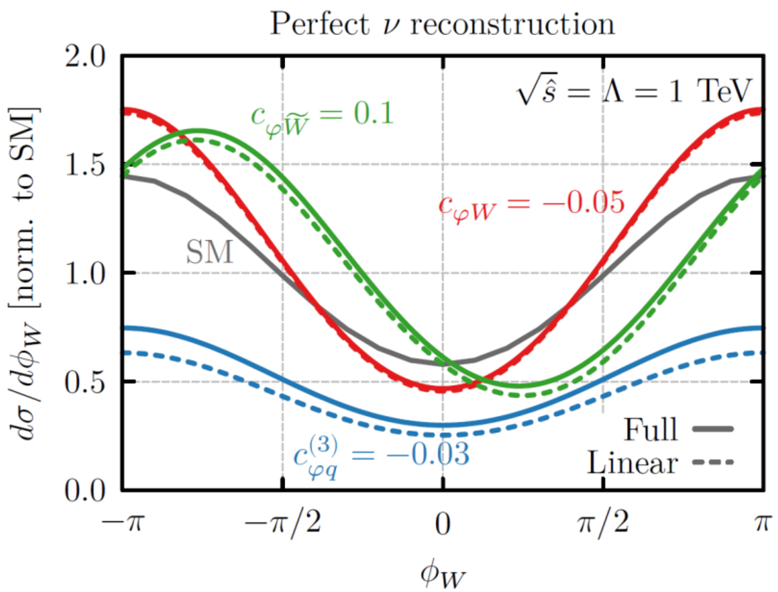
$$\mathcal{O}_{\varphi f} = \mathcal{O}_{\varphi q}^{(3)},\, \mathcal{O}_{\varphi q}^{(1)},\, \mathcal{O}_{\varphi u},\, \mathcal{O}_{\varphi d}$$

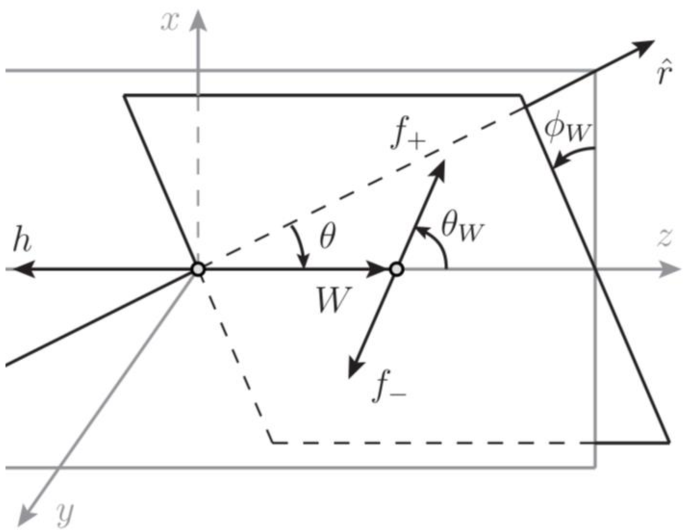
Differential in p_T ⟶ Same-polarization Interference

Resurrecting the interference in diboson

Angular observables improve sensitivity

Azatov et al [1707.08060]; Panico et al [1708.07823]; Azatov et al [1901.04821];
Banerjee et al [1905.02728, 1912.07628]; Bishara, ANR et al [2004.06122]…



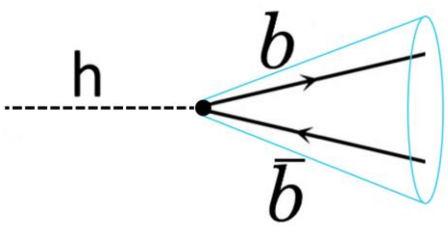


$$\sigma^{int}_{\mathcal{O}^{(3)}_{\varphi q}} \sim \frac{\hat{s}}{\Lambda^2} \qquad \sigma^{int}_{\mathcal{O}_{\varphi W}} \sim \frac{\sqrt{\hat{s}} M_W}{\Lambda^2} \cos(\phi_W) \qquad \sigma^{int}_{\mathcal{O}_{\varphi\widetilde{W}}} \sim \frac{\sqrt{\hat{s}} M_W}{\Lambda^2} \sin(\phi_W)$$

Bonus: CP-odd observables!

The power of combining regimes

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

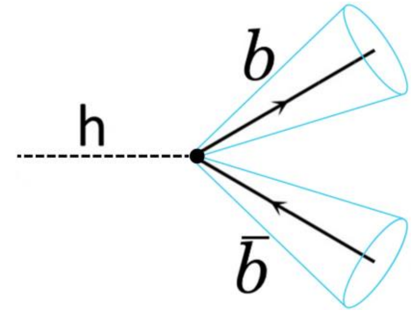
Scale-invariant tagging

Gouzevitch et al [1303.6636]
Bishara et al [1611.03860]

With use of Mass-drop tagging

Butterworth et al, 0802.2470

Resolved



ATLAS, 2007.02873

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

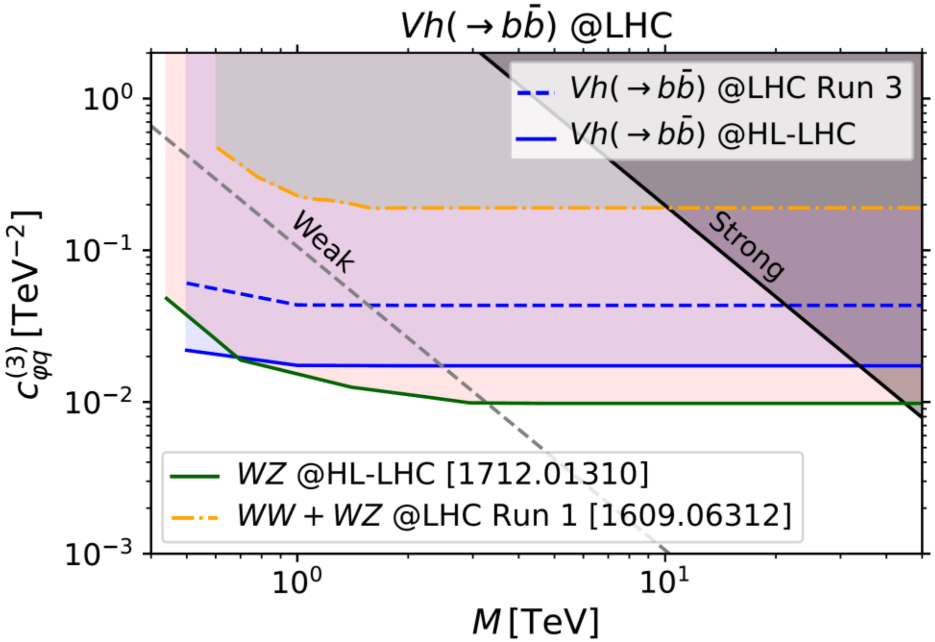
Measurements of WH and ZH production in the $H \to b\bar{b}$ decay channel in pp collisions at 13 TeV with the ATLAS detector

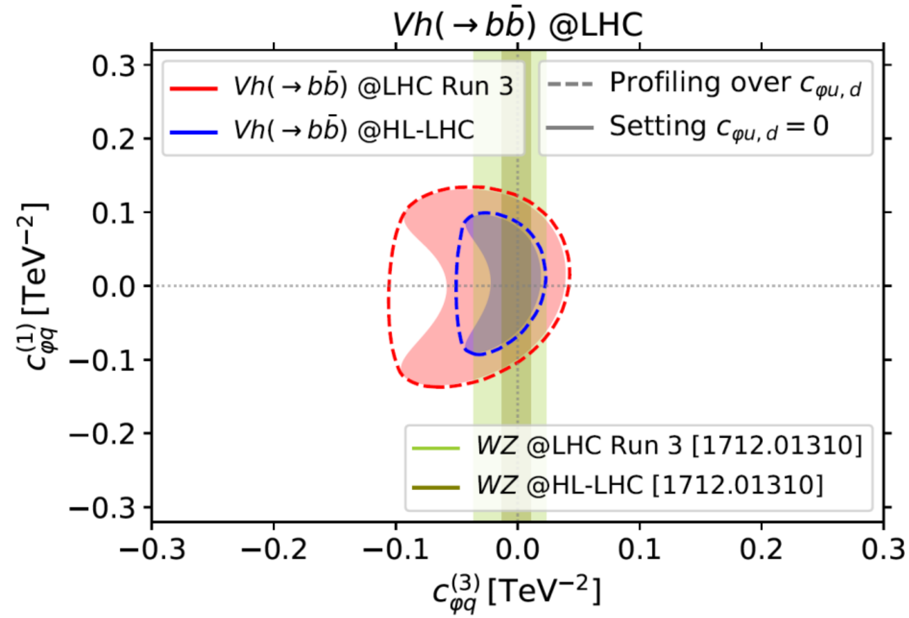
The ATLAS Collaboration

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

Adding Resolved category: 10-20% improvement at LHC

All of diboson at (HL-)LHC





LHC Run 3 → $\sim 2x$ → **HL-LHC**

LHC Run 3 is limited by statistics

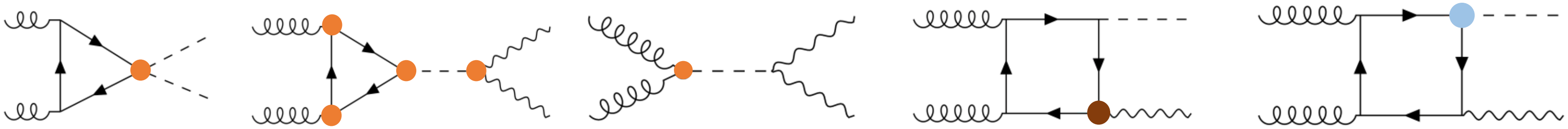
Combining diboson channels closes flat directions

Diboson:
Beyond the Basics

Loop-induced processes matter

ANR, M. Thomas, E. Vryonidou [2306.18215]

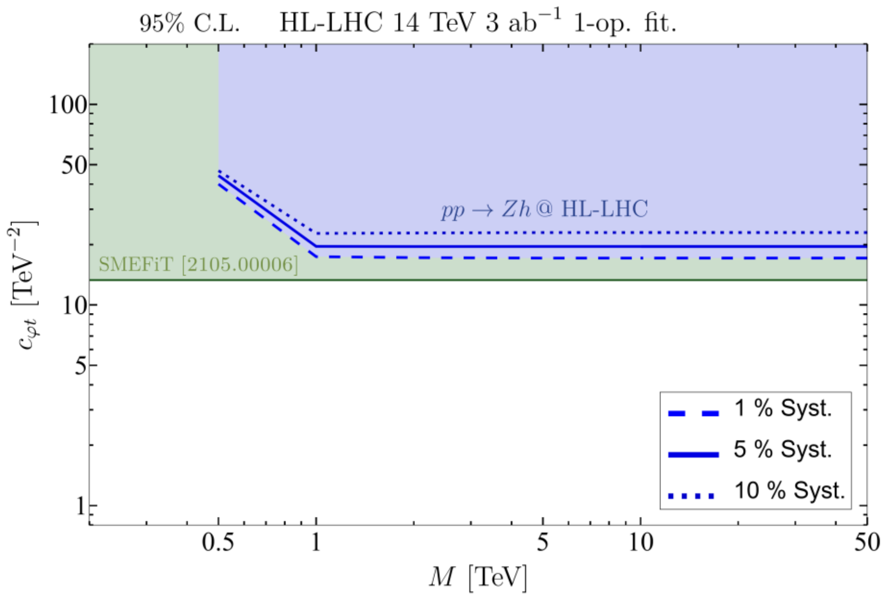
Dim-6 SMEFT effects in $gg \to HH, ZH, ZZ, WW$



$\mathcal{M}_{++00} \sim$

$\mathcal{O}_{\varphi t}$	$\mathcal{O}_{\varphi Q}^{(-)}$	$\mathcal{O}_{t\varphi}$
$\frac{m_t^2\, v\, e\, g_s^2}{32\pi^2\, m_Z\, c_W\, s_W}\left[\log\left(\frac{s}{m_t^2}\right) - i\pi\right]^2$	$\frac{m_t^2\, v\, e\, g_s^2}{32\pi^2\, m_Z\, c_W\, s_W}\left[\log\left(\frac{s}{m_t^2}\right) - i\pi\right]^2$	$\frac{m_t\, v^2\, e\, g_s^2}{32\sqrt{2}\pi^2\, m_Z\, c_W\, s_W}\left[\log\left(\frac{s}{m_t^2}\right) - i\pi\right]^2$

$gg \to ZH$



Interesting interplay with quark channel at NNLO

R. Gauld, U. Haisch, L. Schnell [2311.06107]

Dimension-8 effects in WW, WZ, WH and ZH

C. Degrande, H. Li [2303.10493]

T. Corbett, A. Martin [2306.00053]

$$q\bar{q} \to WZ$$

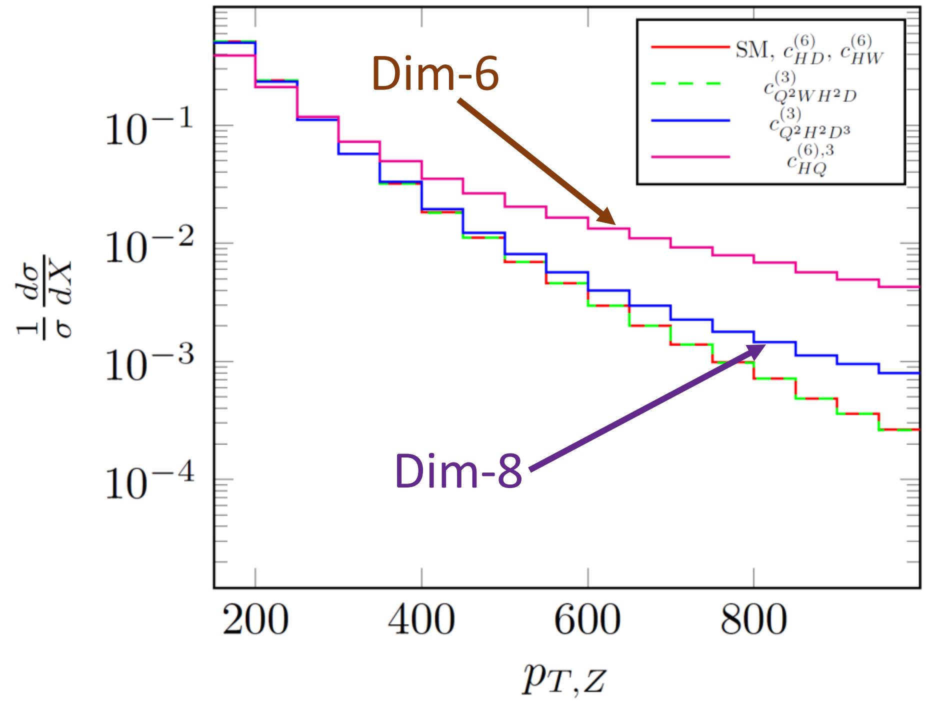
Operator	$2\,\mathrm{Re}(\mathcal{A}^{\mathrm{SM}}\mathcal{A}^{\mathrm{NP}*})$	$2\int d\Omega\,\mathrm{Re}(\mathcal{A}^{\mathrm{SM}}\mathcal{A}^{\mathrm{NP}*})$
$\mathcal{O}_4$	$u\bar{d}:\ e_4 S^2 + f_4 S + g_4$	$\overline{e}_4 S^2 + \overline{f}_4 S + \overline{g}_4$
$\mathcal{O}_5$	$u\bar{d}:\ \frac{\Gamma_W}{M_W}(f_5 S + g_5)$	$\frac{\Gamma_W}{M_W}(\overline{f}_5 S + \overline{g}_5)$
$\mathcal{O}_6$	$u\bar{d}:\ e_6 S^2 + f_6 S + g_6$	$\overline{e}_6 S^2 + \overline{f}_6 S + \overline{g}_6$
$\mathcal{O}_7$	$u\bar{d}:\ \frac{\Gamma_W}{M_W}(f_7 S + g_7)$	$\frac{\Gamma_W}{M_W}(\overline{f}_7 S + \overline{g}_7)$
$\mathcal{O}_{11}$	$u\bar{d}:\ g_{11}\frac{\Gamma_W}{M_W}$	0
$\mathcal{O}_{12}$	$u\bar{d}:\ e_{12} S^2 + f_{12} S + g_{12}$	$\overline{e}_{12} S^2 + \overline{f}_{12} S + \overline{g}_{12}$
$\mathcal{O}_{13}$	$u\bar{d}:\ e_{13} S^2 + f_{13} S + g_{13}$	$\overline{e}_{13} S^2 + \overline{f}_{13} S + \overline{g}_{13}$
$\mathcal{O}_{18}$	$u\bar{d}:\ 0$	0

$$\mathcal{O}_4 = iW^{I\mu}{}_{\lambda}B^{\nu\lambda}\left(\bar{q}^{i}_{\mathrm{L}p}\gamma_\nu\left(\tau^I\right)_i{}^j\overleftrightarrow{D}_\mu q_{\mathrm{L}rj}\right)$$

$$\mathcal{O}_{12} = i\epsilon^{IJK}\tilde{W}^{I\mu}{}_{\nu}W^{J\nu}{}_{\lambda}\left(\bar{q}^{i}_{\mathrm{L}p}\gamma^\lambda\left(\tau^K\right)_i{}^j\overleftrightarrow{D}_\mu q_{\mathrm{L}rj}\right)$$

Several operators generate maximal energy growth

$$pp \to Z^{\pm}(\ell^+\ell^-)H$$



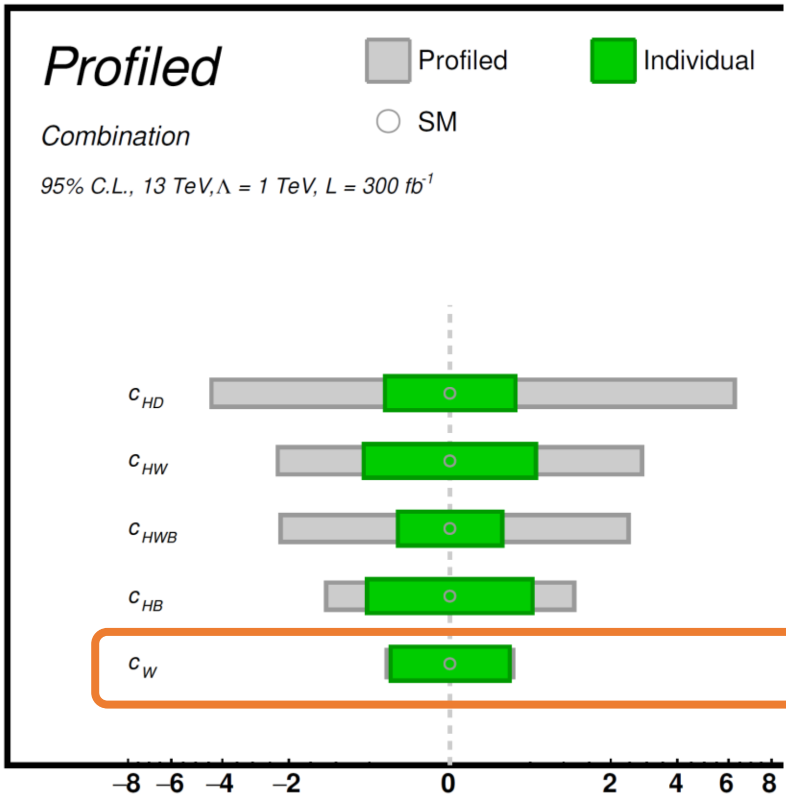
$$c_i^{(6),(8)} = 1/(3\,\mathrm{TeV})^{2,4}$$

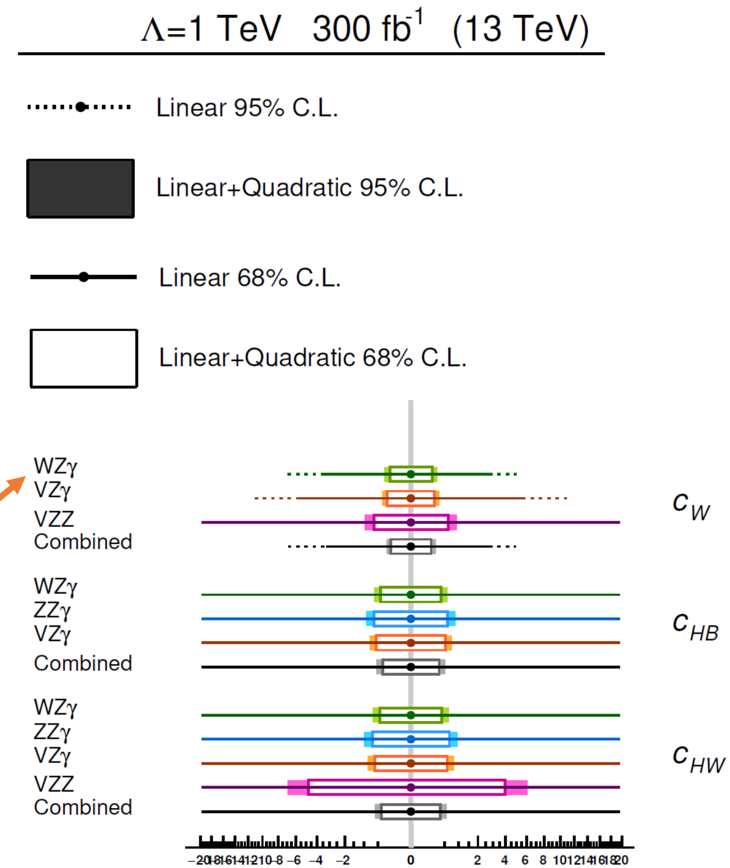
Mild effect due to SM-suppressed interference

Extra bosons for extra fun: Triboson

R. Bellan, S. Bhattacharya, G. Boldrini, F. Cetorelli, P. Govoni [2303.18215]

$\mathrm{WZZ},\ \mathrm{ZZZ},\ \mathrm{WZ}\gamma,\ \mathrm{ZZ}\gamma$





$c_W\ \varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$

Stay tuned, more to come!

See E. Celada's talk tomorrow

E. Celada et al [24XX.ZZZYY]

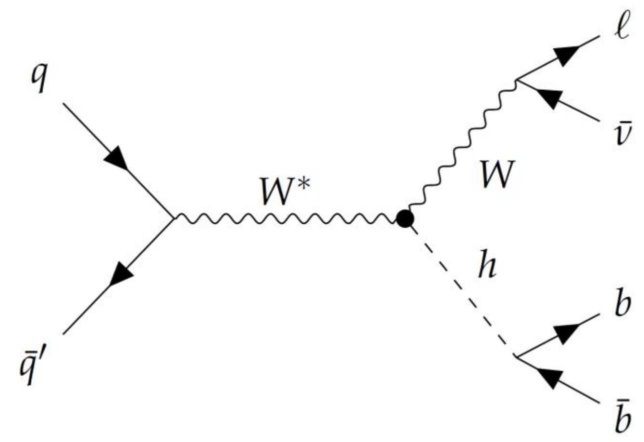
WH goes CP-odd at LHC

R. Barrué, P. Conde-Muíño, V. Dao, R. Santos [2308.02882]

$$\tilde{\mathcal{O}}_{HW} = \frac{c_{\tilde{H}W}}{\Lambda^2} H^\dagger H \tilde{W}^I_{\mu\nu} W^{I\mu\nu} = \frac{c_{\tilde{H}W}}{\Lambda^2} H^\dagger H \epsilon_{\mu\nu\rho\sigma} W^{I\rho\sigma} W^{I\mu\nu}$$

Observable	Linearized limits	Full limits
$Q_\ell \cos\delta^+ \in [-1.0, -2/3, -1/3, 0., 1/3, 2/3]$	$[-0.227, 0.227]$	$[-0.264, 0.216]$
$m_T^{\ell\nu b\bar{b}} \in [0, 400, 800]$ GeV $\otimes$ $Q_\ell \cos\delta^+ \in [-1.0, -2/3, -1/3, 0., 1/3, 2/3]$	$[-0.093, 0.093]$	$[-0.096, 0.096]$
$p_T^W \in [0, 75, 150, 250, 400, 600]$ GeV $\otimes$ $Q_\ell \cos\delta^+ \in [-1.0, -2/3, -1/3, 0., 1/3, 2/3]$	$[-0.088, 0.088]$	$[-0.096, 0.072]$
SALLY, w/ ν 4-vector	$[-0.056, 0.056]$	$[-0.072, 0.144]$
SALLY, w/ detector-level observables	$[-0.067, 0.067]$	$[-0.144, 0.096]$

MadMiner



Not a surprise! →

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

Bishara, ANR, et al [2004.06122]

NLO effects? Coming soon…

ANR, E. Vryonidou [24XX.ZZZYY]

Other diboson channels are also great CPV probes

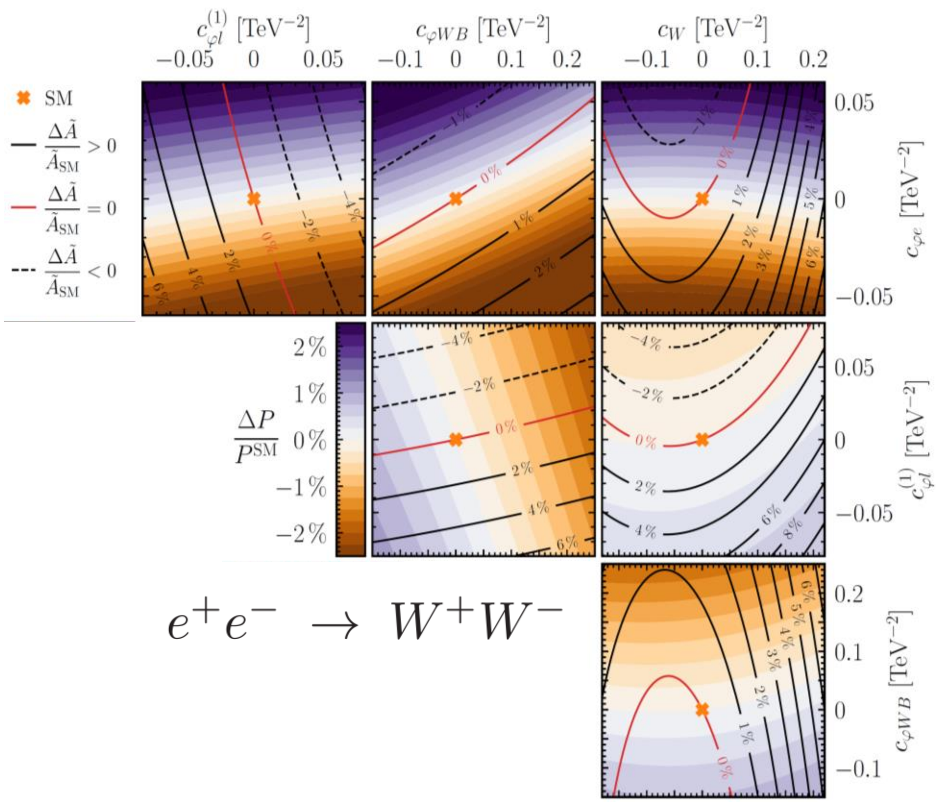
N. Clarke Hall, et al [2209.05143]

Multiboson in the future

Diboson at FCC-ee

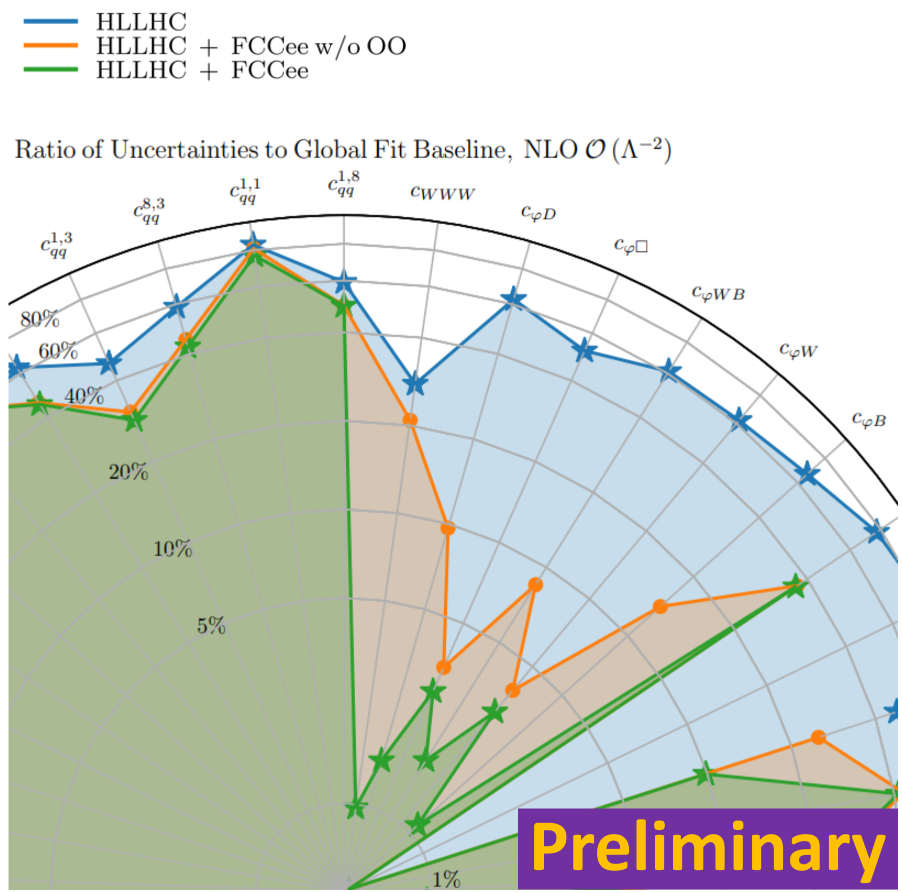
Entanglement in W^+W^-, W^+Z, ZZ

R. Aoude, et al [2307.09675]



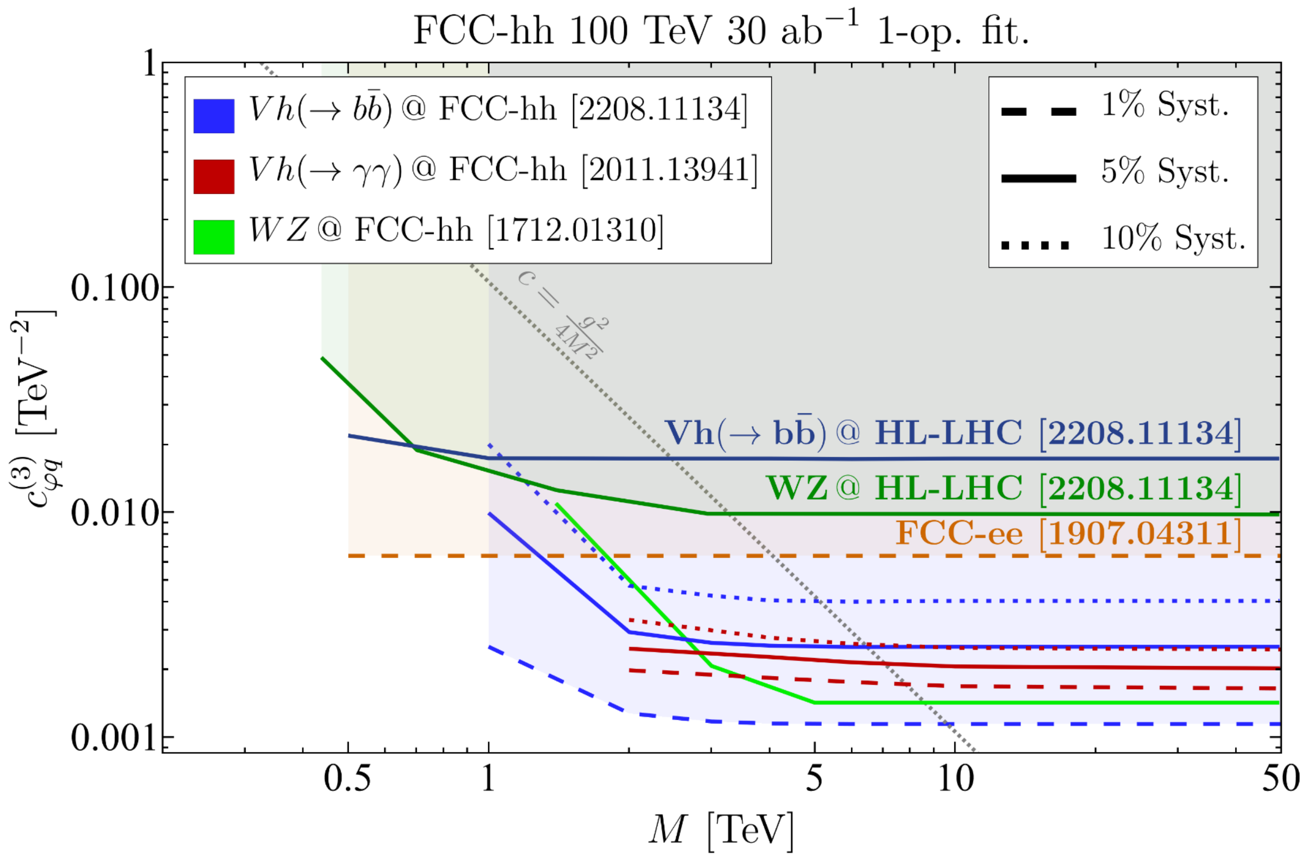
J. De Blas, et al [1907.04311, 2206.08326]

SMEFiT (w/ E. Celada, J. ter Hoeve, ANR) [24XX.YYYZZ]



All the W^+W^- power

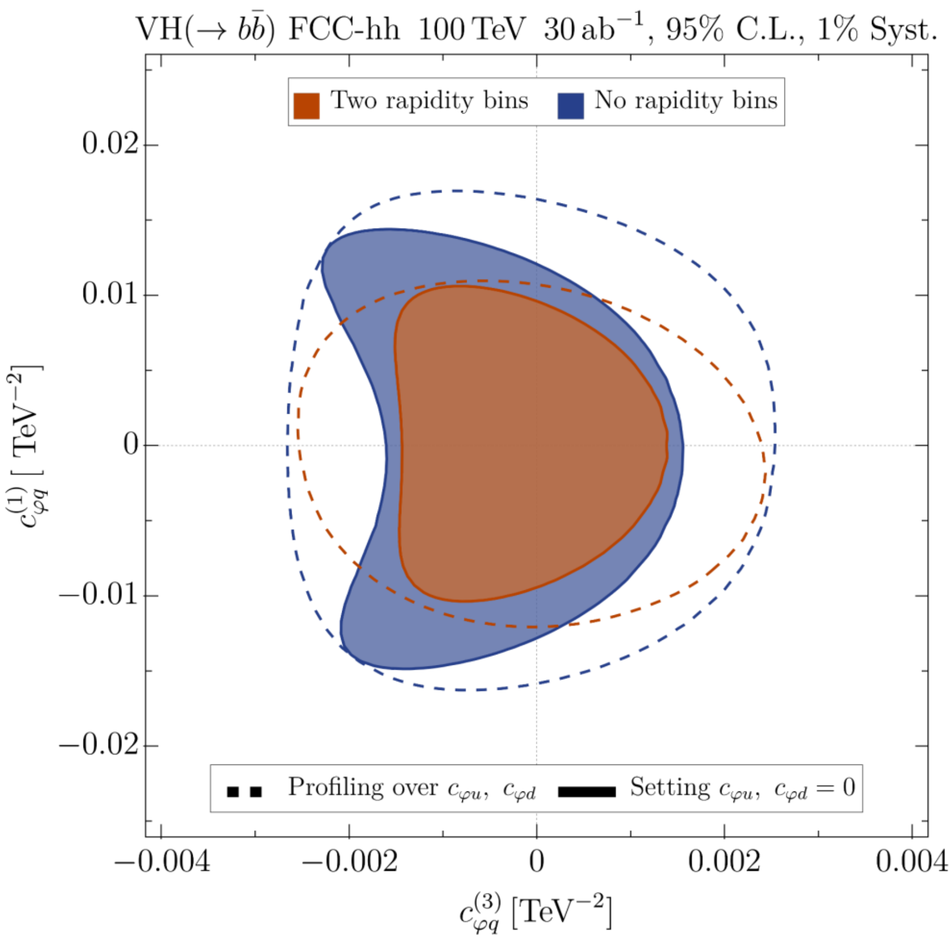
Diboson at FCC-hh
Improves the old, adds new channels

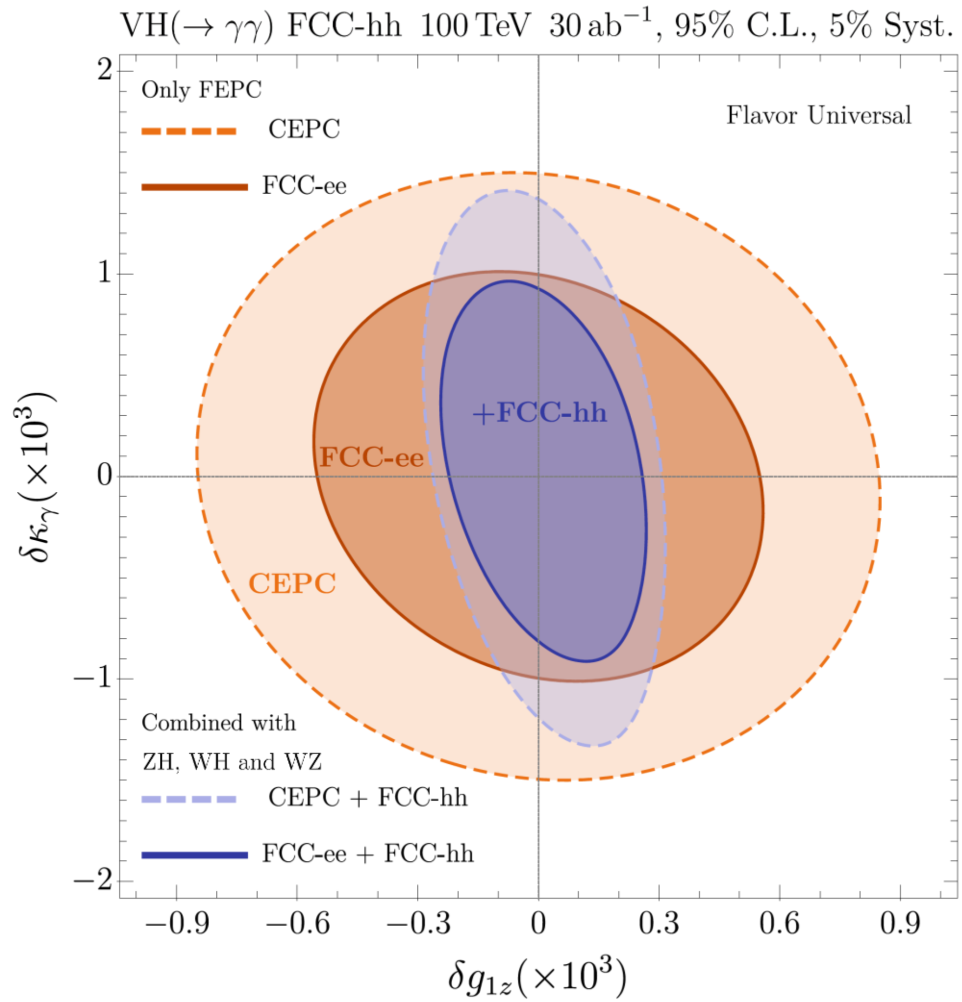


HL-LHC → FCC-hh (~5x)

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

The double-binning advantage at FCC-hh





Complementarity FCC-ee + FCC-hh

Concluding Multiremarks

- Diboson is a key process in the precision program at (HL-)LHC.
- Its several incarnations offer a very rich Physics landscape.
- NLO QCD effects are understood in CP-even cases. NLO EW and CP-odd are the next frontier and WIP.
- Dimension-8 and Triboson have just started being explored. Much to do!
- LHC has exceeded expectations, HH seems within reach.
- Multiboson will remain relevant for decades to come.

Thanks for your attention and happy workshop!

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

Appendix

Growing helicity amplitudes in $gg \to ZH$

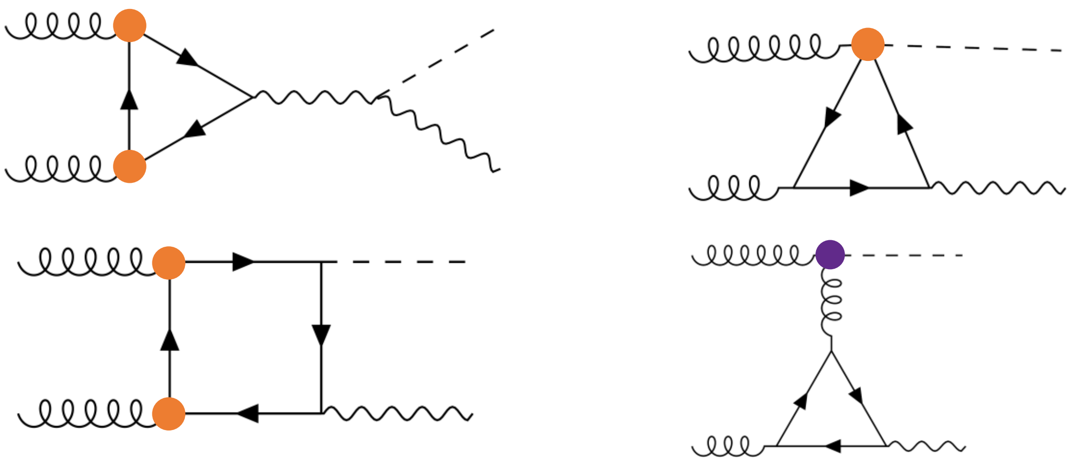
$\lambda_{g_1}, \lambda_{g_2}, \lambda_H, \lambda_Z$	$\mathcal{O}_{tG}$	$\mathcal{O}_{\varphi G}$
$+,+,0,+$	$\sqrt{s}\,\frac{m_t\, g_s^2\, g_{t,A}^Z}{\pi^2}\log\left(\frac{s}{m_t^2}\right)$	$-$
$+,+,0,-$	$\sqrt{s}\,\frac{m_t\, g_s^2\, g_{t,A}^Z}{\pi^2}\log\left(\frac{s}{m_t^2}\right)$	$-$
$+,+,0,0$	$\frac{m_t m_Z\, g_s^2\, g_{t,A}^Z}{\pi^2}\log^2\left(\frac{s}{m_t^2}\right)$	$\frac{m_t^2\, v\, g_s^2\, g_{t,A}^Z}{\pi^2\, m_Z}\log^2\left(\frac{s}{m_t^2}\right)$
$+,-,0,+$	$\sqrt{s}\,\frac{m_t\, g_s^2\, g_{t,A}^Z}{\pi^2}$	$-$
$+,-,0,0$	$s\,\frac{m_t\, g_s^2\, g_{t,A}^Z}{\pi^2 m_Z}$	$\frac{m_t^2\, v\, g_s^2\, g_{t,A}^Z}{\pi^2\, m_Z}\log^2\left(\frac{s}{m_t^2}\right)$

Tightly constrained

$$-0.019\,\text{TeV}^{-2} < c_{\varphi G} < 0.003\,\text{TeV}^{-2}$$

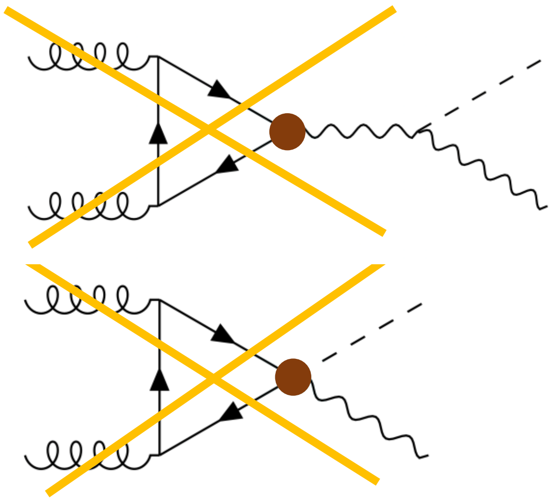
$$0.062\,\text{TeV}^{-2} < c_{tG} < 0.24\,\text{TeV}^{-2}$$

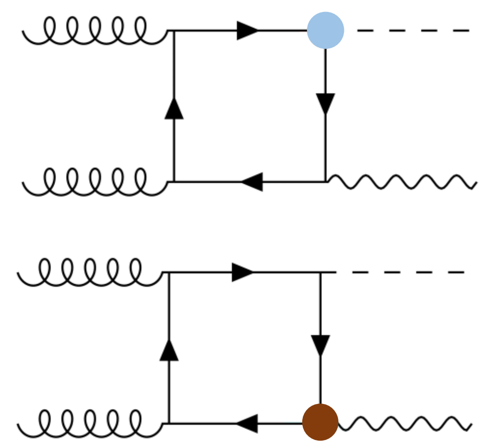
SMEFiT Collab. [arXiv:2105.00006]



Helicity amplitudes in $gg \to ZH$

$\lambda_{g_1}, \lambda_{g_2}, \lambda_H, \lambda_Z$	$\mathcal{O}_{\varphi t}$	$\mathcal{O}_{\varphi Q}^{(-)}$	$\mathcal{O}_{t\varphi}$
$+,+,0,0$	$\frac{m_t^2\, v\, e\, g_s^2}{32\pi^2\, m_Z\, c_W\, s_W}\left[\log\left(\frac{s}{m_t^2}\right) - i\pi\right]^2$	$\frac{m_t^2\, v\, e\, g_s^2}{32\pi^2\, m_Z\, c_W\, s_W}\left[\log\left(\frac{s}{m_t^2}\right) - i\pi\right]^2$	$\frac{m_t\, v^2\, e\, g_s^2}{32\sqrt{2}\pi^2\, m_Z\, c_W\, s_W}\left[\log\left(\frac{s}{m_t^2}\right) - i\pi\right]^2$





Sensitive only to $c_{\varphi Q}^{(-)} - c_{\varphi t} + \frac{c_{t\varphi}}{y_t}$ → exact degeneracy

The triangles cancel each other out

Bounds on Higgs and top operators from the tails of $pp \to ZH$

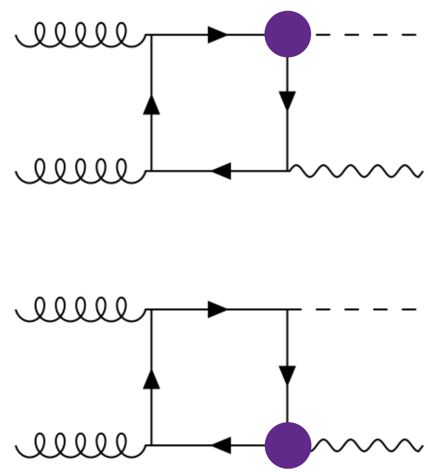
Third-generation operators

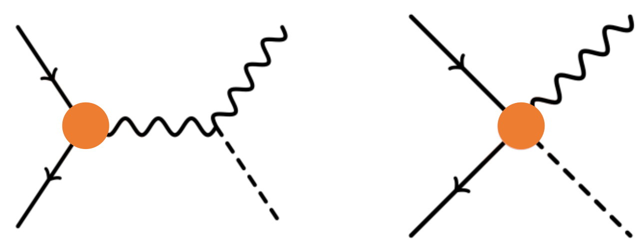
$\mathcal{O}_{\varphi Q}^{(1)}$	$c_{\varphi Q}^{(1)}$	$i(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar{Q}\gamma^\mu Q)$
$\mathcal{O}_{\varphi Q}^{(3)}$	$c_{\varphi Q}^{(3)}$	$i(\varphi^\dagger \overleftrightarrow{D}_\mu \tau_I \varphi)(\bar{Q}\gamma^\mu \tau^I Q)$
$\mathcal{O}_{\varphi Q}^{(-)}$	$c_{\varphi Q}^{(-)}$	$c_{\varphi Q}^{(1)} - c_{\varphi Q}^{(3)}$
$\mathcal{O}_{\varphi t}$	$c_{\varphi t}$	$i(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar{t}\gamma^\mu t)$
$\mathcal{O}_{t\varphi}$	$c_{t\varphi}$	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right)\bar{Q}\,t\,\tilde{\varphi} + \text{h.c.}$

Probed by $gg \to ZH$

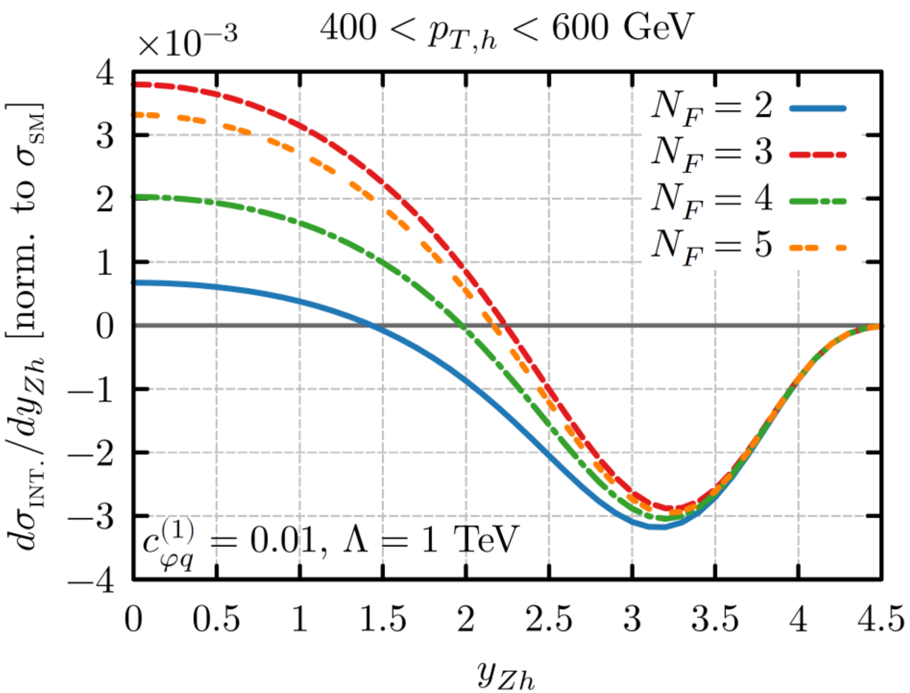
Probed by $qq \to ZH$

Quark and gluon channels interplay





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

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

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

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