LOOP-INDUCED PROBES OF NEW PHYSICS

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Durham 12/01/2018

[Gorbahn, Haisch – 1607.03773]
[WB, Gorbahn, Haisch, Zanderighi – 1610.05771]
[Bishara, Haisch, Monni, Re – 1606.09253]

HIGGS WITHIN STANDARD MODEL

- within Standard Model (SM), the mass and the self-interactions of the Higgs field are parametrised by:

$$\boxed{\mathcal{L}_{\rm SM} = \ldots -\frac{1}{2} m_h h^2 - \lambda v h^3 - \frac{1}{4}\kappa h^4}$$

$$\boxed{\lambda = \kappa = \frac{m_h^2}{2v^2}}$$

- since 2012 we know not only vev but also mass of the Higgs
- Higgs self-couplings have not been tested yet – important goal for the forthcoming LHC runs (and possible future colliders)
- one way to constrain λ and κ is by measuring multi-Higgs production channels
  >> limited sensitivity at the LHC (even HL-LHC)
  >> at 14 TeV:

$$\sigma_{hh} \sim \mathcal{O}(35 \text{ fb})$$
$$\sigma_{hhh} \sim \mathcal{O}(0.1 \text{ fb})$$

- self-coupling coefficients $\Rightarrow$ important for pinning down mechanism of EWSB

NEW PHYSICS PARAMETRISATION

- Standard Model Effective Field Theory (SMEFT) – convenient way of parametrising BSM phenomena using SM degrees of freedom

Wilson coefficients

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_k \frac{\bar{c}_k}{v^2} O_k$$

O_k is a dimension six operator

- in our case we consider the following extensions:

$$O_6 = -\lambda \left(H^\dagger H\right)^3, \qquad O_H = \frac{1}{2}\partial_\mu \left(H^\dagger H\right)\partial^\mu \left(H^\dagger H\right)$$

- which implies:

$$-\lambda v h^3 \longrightarrow -\lambda v \left(1 + \bar{c}_6 - \frac{3}{2}\bar{c}_H\right) h^3$$

- correspondence to anomalous coupling framework (kappa-framework): $\kappa = 1 + \bar{c}_6$

[Degrassi, Giardino, Maltoni, Pagani; 1607.04251]

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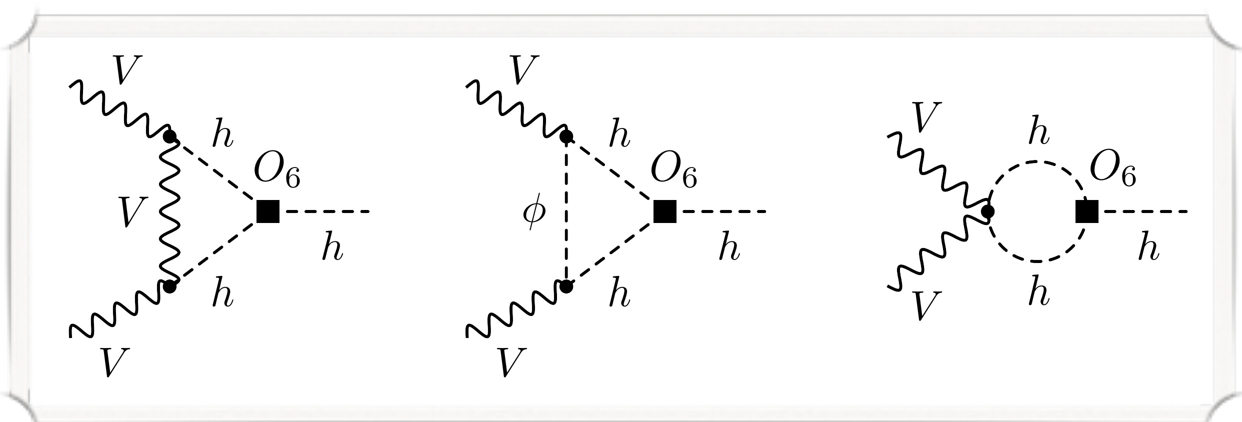
can be probed by means other than VBF/VH

- correspondence to anomalous coupling framework (kappa-framework): $\kappa = 1 + \bar{c}_6$

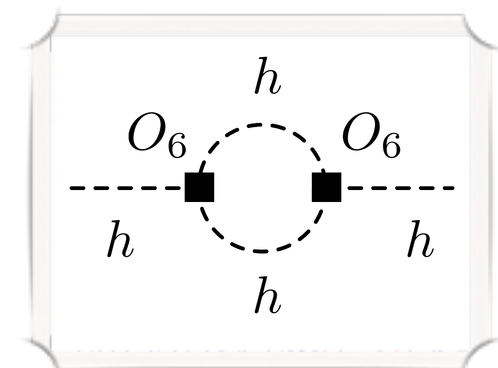
[Degrassi, Giardino, Maltoni, Pagani; 1607.04251]

CORRECTIONS TO THE VVH-VERTEX

- vertex: $\boxed{V^\mu(q_1) + V^\nu(q_1) \longrightarrow h(q_1+q_2)}$
- two sources of corrections:
  – logs associated with RGE that connects new physics scale (Λ) with EW scale ($\mu_{\rm w}$)
  – finite contributions from the VVH Green's function corrections
- finite contributions consist of:
  >>> extra diagrams contributing to the VVH vertex:



  >>> wave-function renormalisation corrections



- this leads to expression in terms of form-factors:

$$\Gamma^{\mu\nu}_{\rm V}(q_1,q_2) = 2\left(\sqrt{2}G_F\right)^{1/2} m^2_{\rm V}\left[\eta^{\mu\nu}\left(1+\mathcal{F}_1(q_1^2,q_2^2)\right) + q_1^\mu q_2^\nu \mathcal{F}_2(q_1^2,q_2^2)\right]$$

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at 1-loop O_6 does not mix with other operators

- finite contributions consist of:
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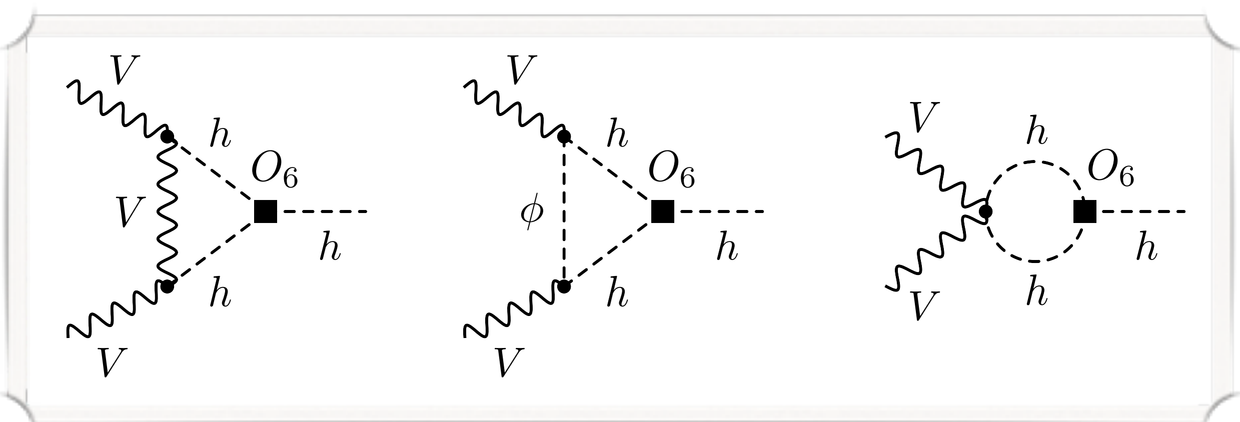

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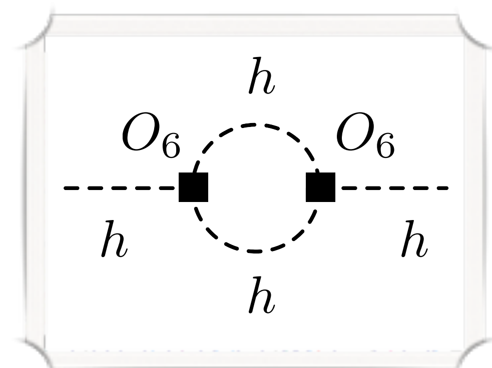

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$$\Gamma_{\mathrm{V}}^{\mu\nu}(q_1,q_2) = 2\left(\sqrt{2}G_F\right)^{1/2} m_{\mathrm{V}}^2\left[\eta^{\mu\nu}\left(1+\mathcal{F}_1(q_1^2,q_2^2)\right) + q_1^\mu q_2^\nu \mathcal{F}_2(q_1^2,q_2^2)\right]$$

CORRECTIONS TO THE VVH-VERTEX

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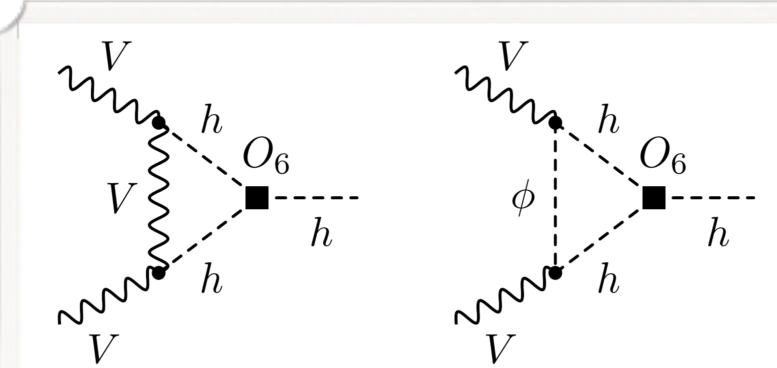
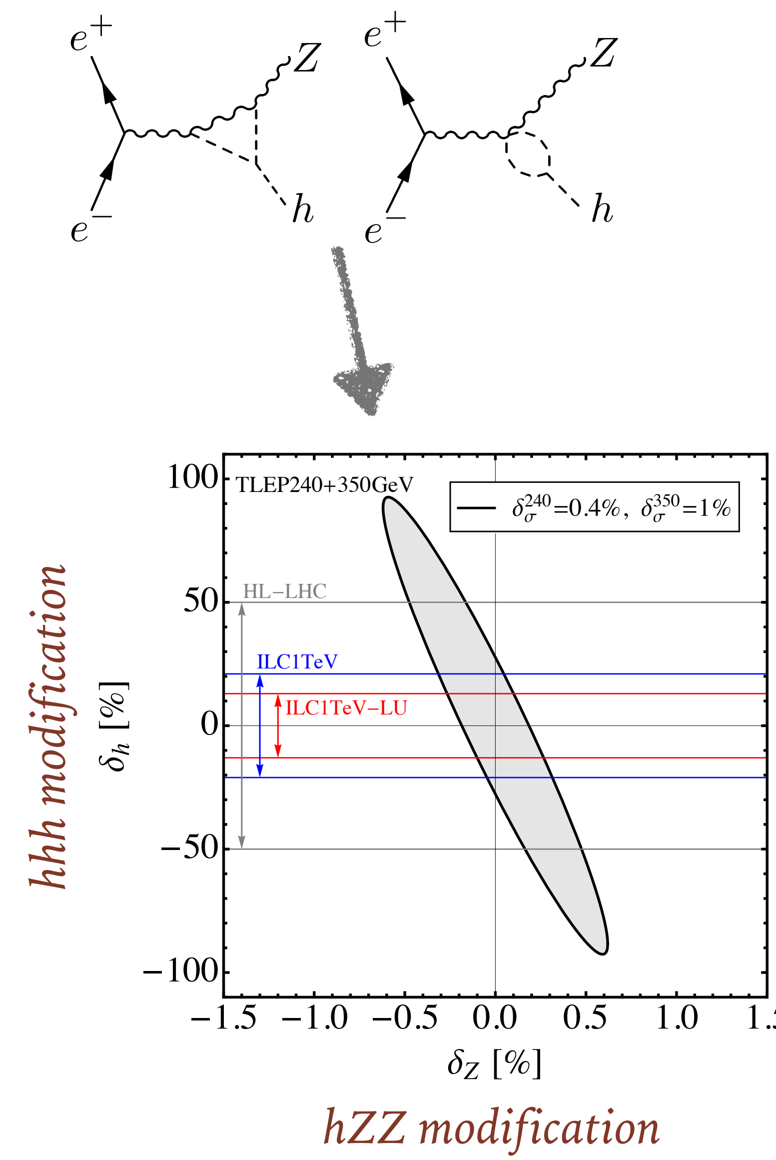


  >>> wave-function renormalisation corrections
- this leads to expression in terms of form-factors:

$$\Gamma_{\rm V}^{\mu\nu}(q_1, q_2) = 2\left(\sqrt{2}G_F\right)^{1/2} m_{\rm V}^2 \Big[\eta^{\mu\nu}\,(1 +$$

[McCollough; 1312.3322]

>> applied to ee future collider



CORRECTIONS TO THE VVH-VERTEX

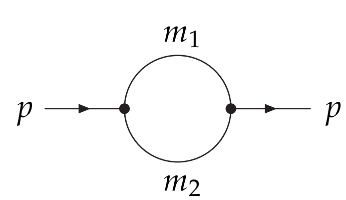
$$\Gamma^{\mu\nu}_{\mathrm{V}}(q_1,q_2) = 2\left(\sqrt{2}G_F\right)^{1/2} m^2_{\mathrm{V}}\left[\eta^{\mu\nu}\left(1+\mathcal{F}_1(q_1^2,q_2^2)\right) + q_1^\mu q_2^\nu \mathcal{F}_2(q_1^2,q_2^2)\right]$$

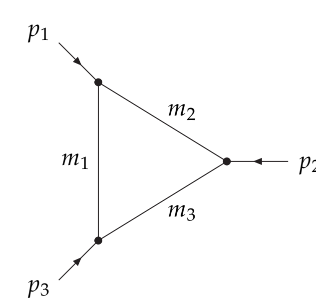
- 1-loop expressions for the form factors:

$$\mathcal{F}_1(q_1^2,q_2^2) = \frac{\lambda\bar{c}_6}{(4\pi)^2}\Big(-3B_0 - 12\big(m_{\mathrm{V}}^2 C_0 - C_{00}\big) - \frac{9}{2}m_h^2(\bar{c}_6+2)B_0'\Big)$$
$$\mathcal{F}_2(q_1^2,q_2^2) = \frac{\lambda\bar{c}_6}{(4\pi)^2}\,12\Big(C_1 + C_{11} + C_{12}\Big)$$

with the two- and three-point integrals:

$$B_0 = B_0\big(m_h^2, m_h^2, m_h^2\big)\,, \qquad C_0 = C_0\big(m_h^2, q_1^2, q_2^2, m_h^2, m_h^2, m_V^2\big)$$





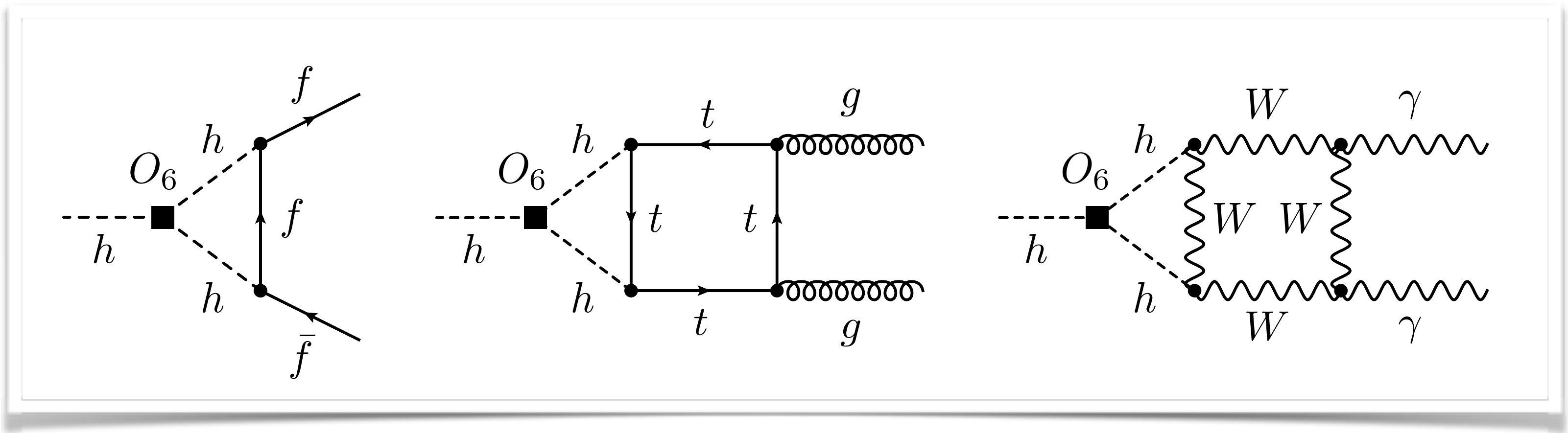
and tensor integrals expressed as:

$$C^\mu = \sum_{i=1,2} p_i^\mu C_i\,, \qquad C^{\mu\nu} = \eta^{\mu\nu}C_{00} + \sum_{i,j=1,2} p_i^\mu p_j^\nu C_{ij}$$

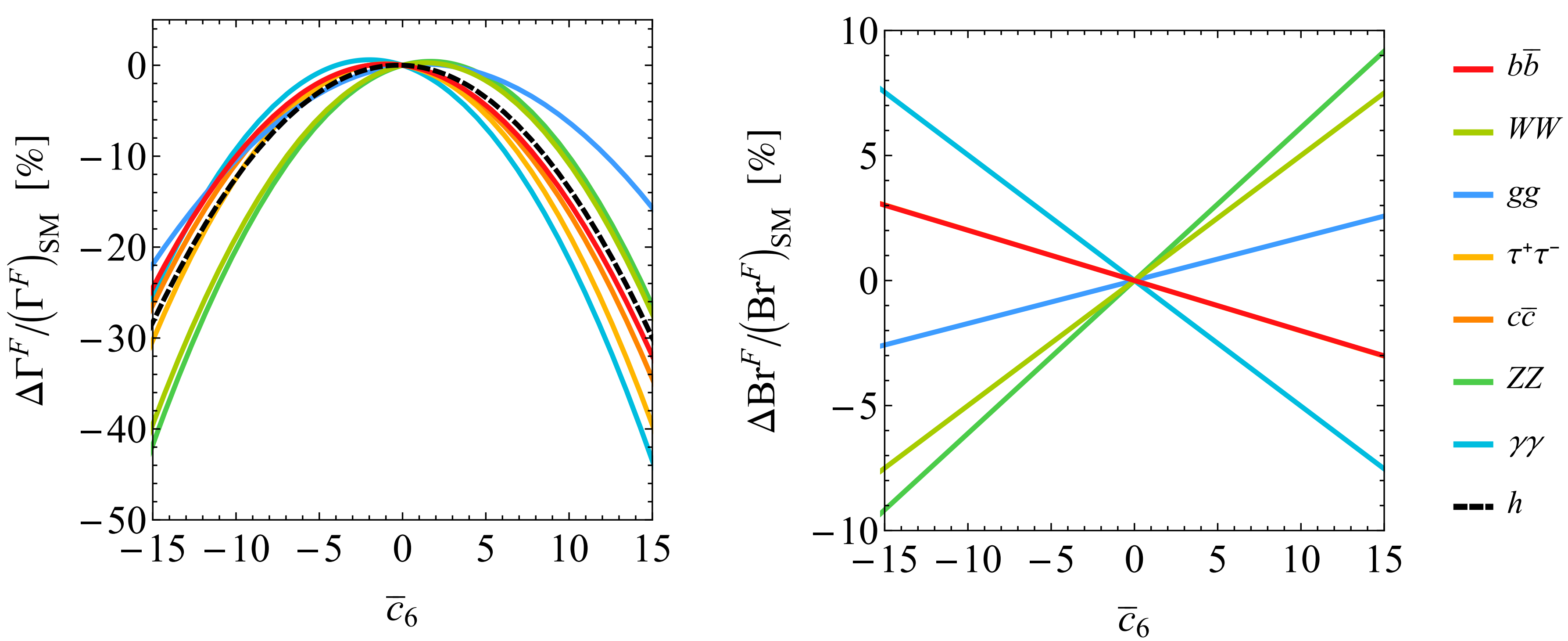
[Gorbahn, Haisch – 1607.03773]
[WB, Gorbahn, Haisch, Zanderighi – 1610.05771]

CORRECTIONS TO THE PARTIAL WIDTHS

- the same operator will modify the partial widths of the Higgs boson, via the diagrams:

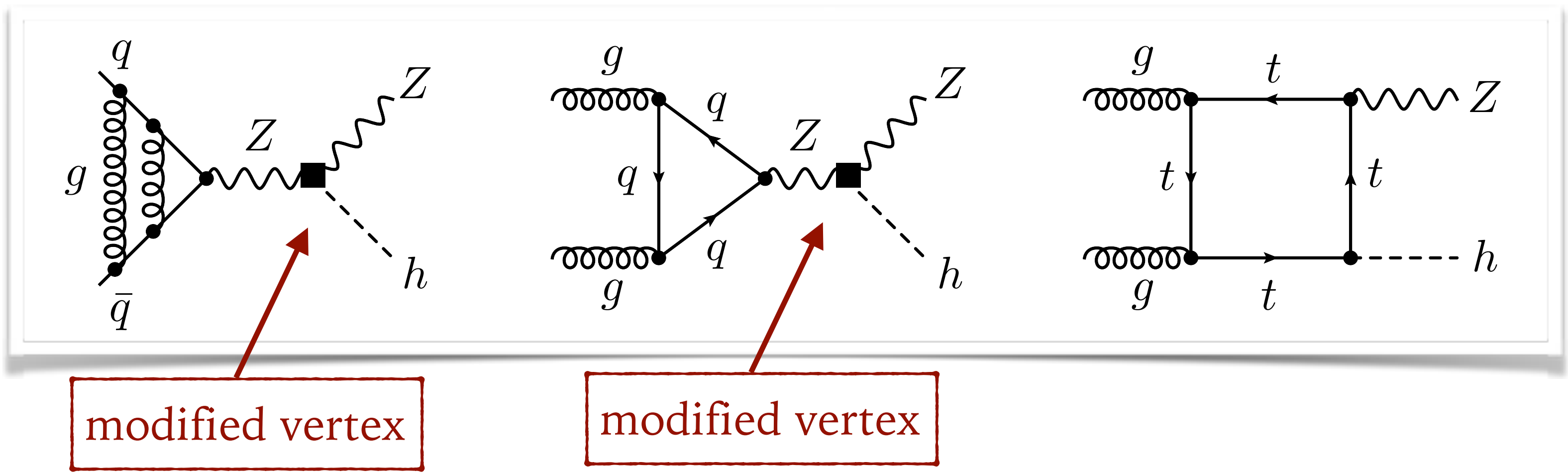


>> these affect all types of decays: to fermions, gluons, photons and weak gauge bosons



(1) DESCRIPTION OF THE VH CALCULATION

- QCD corrections “almost” factorize:



  >> the last diagram (only ZH production, not for WH):

  – purely NNLO contribution

  – modified vertex would require two-loop integrals which are not known

  [neglected in our calculation]

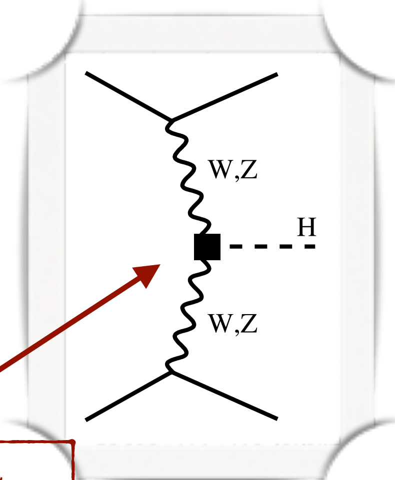
- in our prediction we have identified and altered the `MCFM-8.0` code which provides fully differential description of the VH production at NNLO QCD

[Campbell,Ellis,Williams – 1601.00658]

(2) DESCRIPTION OF THE VBF CALCULATION

- the differential VBF cross-section can be parametrised using the modified VVH vertex and hadronic tensors:

$$d\sigma_{\mathrm{VBF}} = \frac{G_F^2 m_V^4}{s} \Delta_V^2(Q_1^2)\Delta_V^2(Q_2^2) \times W_{\mu\nu}^V(x_1, Q_1^2)\,\Gamma_V^{\mu\rho}(Q_1, Q_2)\left(\Gamma_V^{\nu\sigma}(Q_1, Q_2)\right)^* W_{\rho\sigma}^V(x_2, Q_2^2)\, d\Omega$$



hadronic tensors (in terms of DIS structure functions: F_1, F_2, F_3)

modified vertex

- after tensor reduction we get:

DIS structure functions

$$W_{\mu\nu}^V(x_1, Q_1^2)\,\Gamma_V^{\mu\rho}(Q_1, Q_2)\left(\Gamma_V^{\nu\sigma}(Q_1, Q_2)\right)^* W_{\rho\sigma}^V(x_2, Q_2^2) = 4\sqrt{2}G_F m_V^4 \sum_{m,n}^{3} w_{mn} F_m^V(x_1, Q_1^2)\, F_n^V(x_2, Q_2^2)$$

coefficients – functions of Lorentz invariants and loop-integrals (encode new physics)

- numerical implementation using fully-differential VBF code from (NNLO QCD):

[Cacciari,Dreyer,Karlberg,Salam,Zanderighi – 1506.02660]

NUMERICAL RESULTS

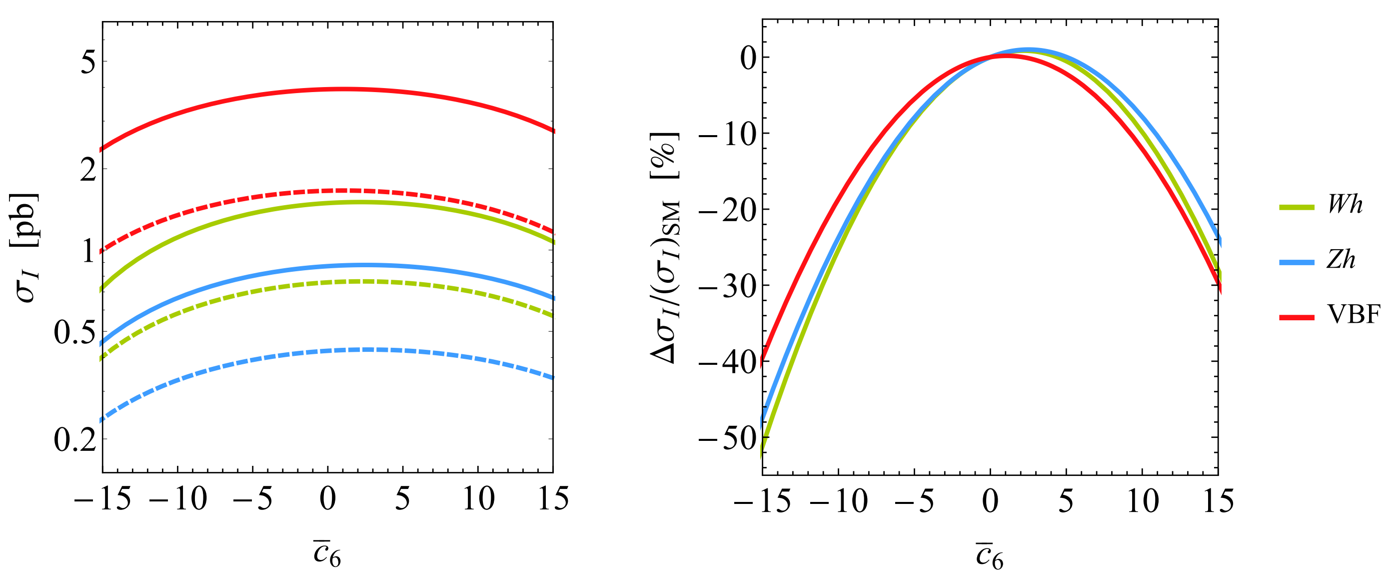
- total cross-section dependence on anomalous coupling c₆:

$$\sigma_{Wh}^{8\,\mathrm{TeV}} = (\sigma_{Wh}^{8\,\mathrm{TeV}})_{\mathrm{SM}}\left(1 + 7.4\cdot 10^{-3}\,\bar{c}_6 - 1.5\cdot 10^{-3}\,\bar{c}_6^2\right), \qquad \sigma_{Wh}^{13\,\mathrm{TeV}} = (\sigma_{Wh}^{13\,\mathrm{TeV}})_{\mathrm{SM}}\left(1 + 8.2\cdot 10^{-3}\,\bar{c}_6 - 1.5\cdot 10^{-3}\,\bar{c}_6^2\right),$$

$$\sigma_{Zh}^{8\,\mathrm{TeV}} = (\sigma_{Zh}^{8\,\mathrm{TeV}})_{\mathrm{SM}}\left(1 + 7.5\cdot 10^{-3}\,\bar{c}_6 - 1.5\cdot 10^{-3}\,\bar{c}_6^2\right), \qquad \sigma_{Zh}^{13\,\mathrm{TeV}} = (\sigma_{Zh}^{13\,\mathrm{TeV}})_{\mathrm{SM}}\left(1 + 8.0\cdot 10^{-3}\,\bar{c}_6 - 1.5\cdot 10^{-3}\,\bar{c}_6^2\right),$$

$$\sigma_{\mathrm{VBF}}^{8\,\mathrm{TeV}} = (\sigma_{\mathrm{VBF}}^{8\,\mathrm{TeV}})_{\mathrm{SM}}\left(1 + 3.3\cdot 10^{-3}\,\bar{c}_6 - 1.5\cdot 10^{-3}\,\bar{c}_6^2\right) \qquad \sigma_{\mathrm{VBF}}^{13\,\mathrm{TeV}} = (\sigma_{\mathrm{VBF}}^{13\,\mathrm{TeV}})_{\mathrm{SM}}\left(1 + 3.3\cdot 10^{-3}\,\bar{c}_6 - 1.5\cdot 10^{-3}\,\bar{c}_6^2\right)$$

- worth noting: quadratic term is unique (for large c₆ deviations from SM are driven by quadratic term)




```
 8 TeV = dashed lines
13 TeV = solid lines
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VH: fully inclusive

VBF selection cuts:
- > two jets with: $p_{t,j} > 25\mathrm{GeV}$ & $|y_j| < 4.5$
- > two hardest jets in opposite hemispheres and: $\Delta y_{12} > 5.0$ & $M_{12} > 600\mathrm{GeV}$
- > jets with anti-kT, R=0.4

NUMERICAL RESULTS

- total cross-section dependence on anomalous coupling c_6:

$$\sigma_{Wh}^{8\,\mathrm{TeV}} = (\sigma_{Wh}^{8\,\mathrm{TeV}})_{\mathrm{SM}} \left(1 + 7.4 \cdot 10^{-3}\ \bar{c}_6 - 1.5 \cdot 10^{-3}\ \bar{c}_6^2\right) , \qquad \sigma_{Wh}^{13\,\mathrm{TeV}} = (\sigma_{Wh}^{13\,\mathrm{TeV}})_{\mathrm{SM}} \left(1 + 8.2 \cdot 10^{-3}\ \bar{c}_6 - 1.5 \cdot 10^{-3}\ \bar{c}_6^2\right) ,$$

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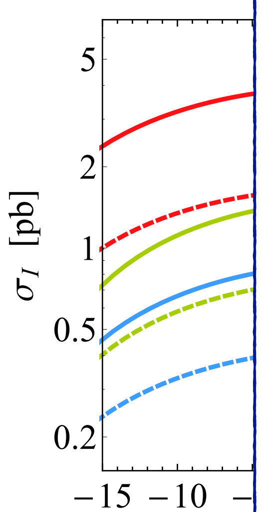
- worth noti … by
quadratic t…

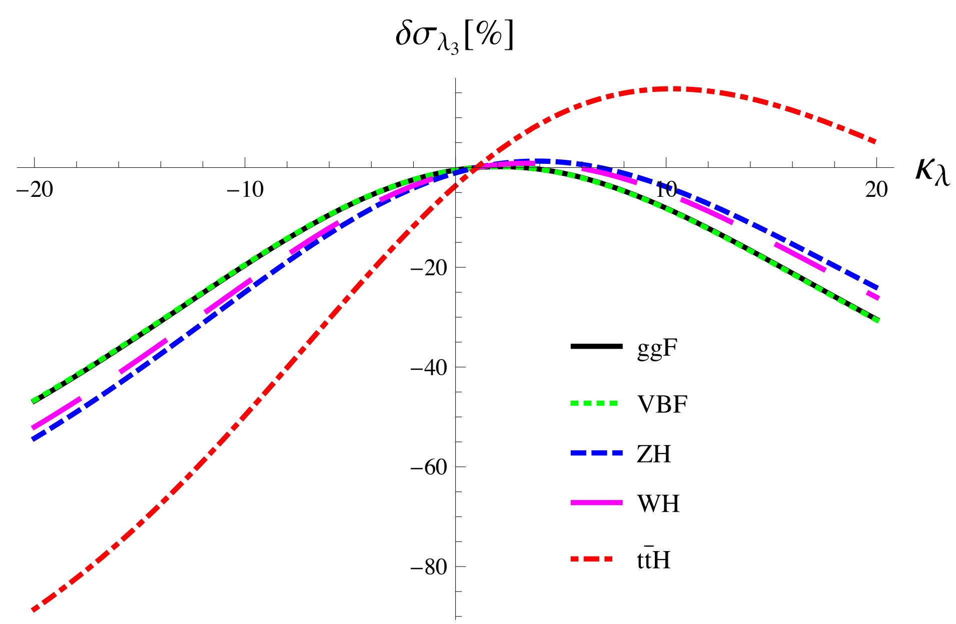


$|y_j| < 4.5$
…nispheres and:
…00GeV

Worth noting: [Degrassi,Giardino,Maltoni,Pagani – 1607.04251]

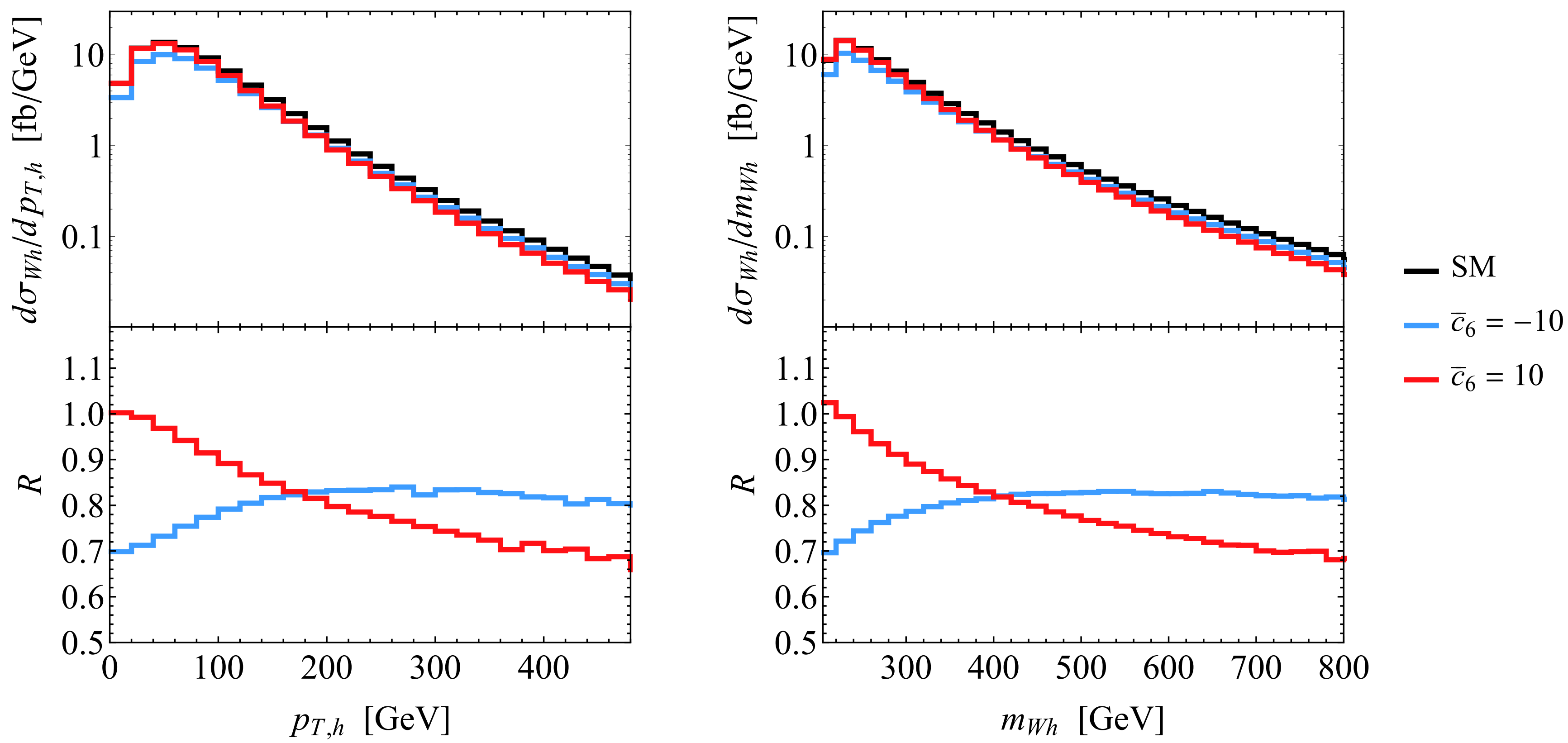
> for VBF, VH, ggH very similar dependence

> for ttH linear terms very different – distinguishable curve



NUMERICAL RESULTS - DISTRIBUTIONS (WH)

- distributions with a SM baseline and two variations c_6=+10 and c_6=−10:



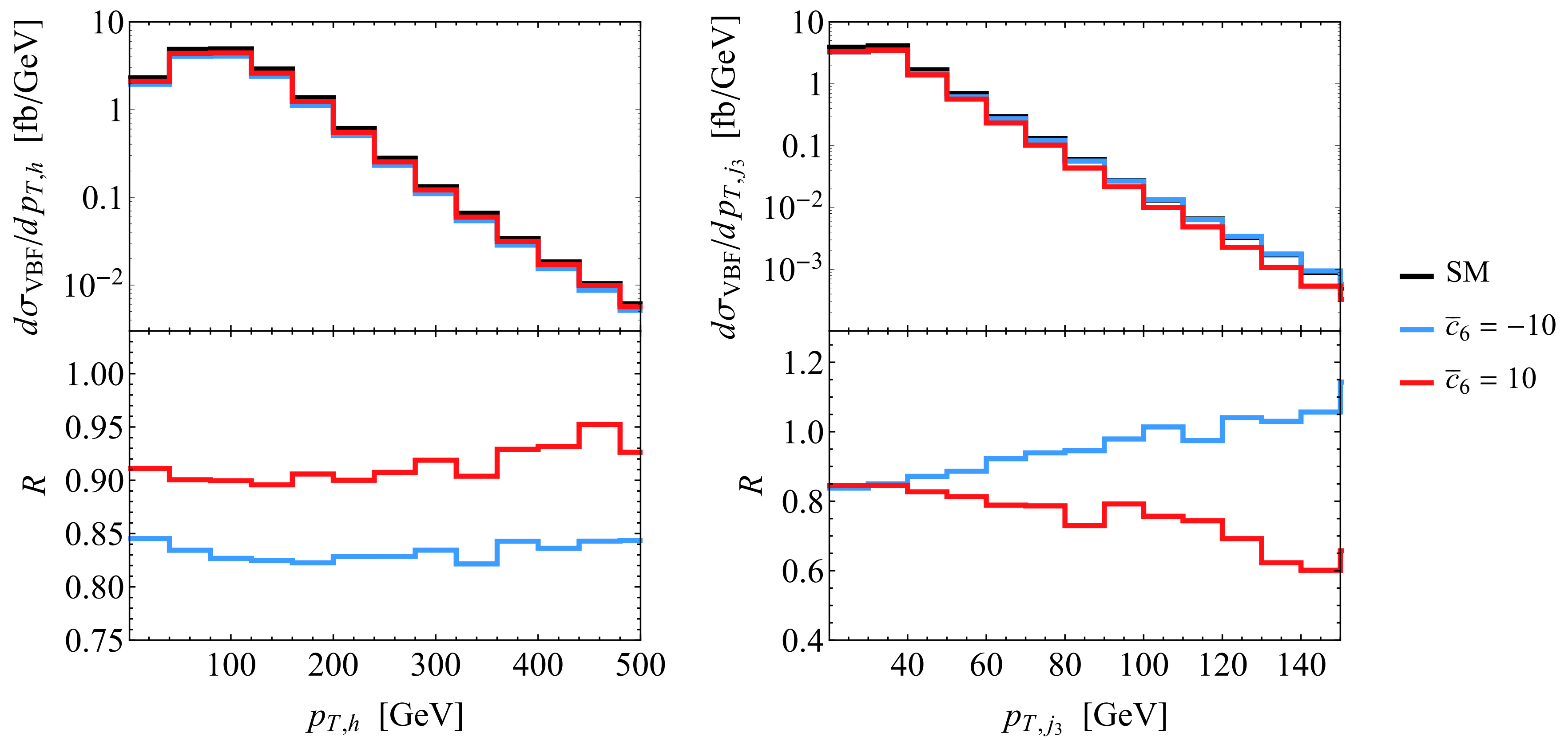
- behaviour of the distribution at large-pT(H) / large-M(WH):
  > contributions to these parts are dominated by parts of the phase-space with large-$\sqrt{s}$
  > the O_6-correction scales as:

$$\lim_{\sqrt{s}\to\infty} \delta_V = \frac{\lambda \bar{c}_6}{(4\pi)^2}\left(-9m_h^2\left(\bar{c}_6+2\right)B_0'\right) = -1.5\cdot 10^{-3}\;\bar{c}_6\left(\bar{c}_6+2\right)$$

- all of the non-trivial modifications at the intermediate pT(H) / intermediate M(WH) values

NUMERICAL RESULTS - DISTRIBUTIONS (VBF)

- distributions with a SM baseline and two variations $c_6=+10$ and $c_6=-10$:



- pT(H) distribution only mildly modified (even for large-pT values one of the gauge boson virtualises may be very small + for fixed-pT a range of Q_1 and Q_2 may be probed)
- when pT(j_3) is hard both Q_1 and Q_2 tend to be hard, increase in magnitude of Q_1,Q_2 results in linear modification of the form factors > seen from the ratio to the SM

HIGGS SELF-COUPLING – ESTIMATION

- $pp \to 2H \to 2b2\bar{b}$:
  ATLAS, LHC Run I: $-15.5 < c_6 < +18.1$ @95% CL
  ATLAS, HL-LHC(3 ab^{-1}): $-2.3 < c_6 < +7.7$ @95% CL

- define signal strengths in standard way:

$$\mu_I^F = \frac{\sigma_I}{(\sigma_I)_{\rm SM}} \frac{{\rm Br}^F}{({\rm Br}^F)_{\rm SM}}$$

- performing χ^2 fit we obtain at 95% CL:

$-13.6 < c_6 < +16.9$ [LHC Run I]	[ATLAS-CONF-2015-044]
$-7.0 < c_6 < +10.9$ [HL-LHC, with theory uncert.]	[ATL-PHYS-PUB-2014-016]
$-6.2 < c_6 < +9.6$ [HL-LHC, no theory uncert.]	

- **CONCLUSION**:
  – The indirect probes provide competitive way of measuring the Higgs self-coupling.
  – A comparison of predictions with/without theory uncertainty shows that the theoretical uncertainty is not the limiting factor.

WHY DOES IT MATTER?

- if the predictive power is similar to the one of double-Higgs production why bother?
- situation changes when more additional operators considered

[Di Vita, Grojean, Panico, Riembau, Vantalon – 1704.01953]

"We show that a global fit exploiting only single-Higgs inclusive data suffers from degeneracies that prevent one from extracting robust bounds on each individual coupling."

EXAMPLE:

> add the following operators (that modify VVH vertex at tree-level):

$$O_6 = -\lambda \left(H^\dagger H\right)^3$$

$$O_{HW} = \frac{8i}{g}\left(D_\mu H^\dagger \tau^i D_\nu H\right) W^{i,\mu\nu}$$

$$O_W = \frac{4i}{g}\left(H^\dagger \tau^i \overleftrightarrow{D}_\mu H\right) D_\nu W^{i,\mu\nu}$$

$$O_B = \frac{2ig'}{g^2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right) D_\nu B^{\mu\nu}$$

> consider two scenarios:

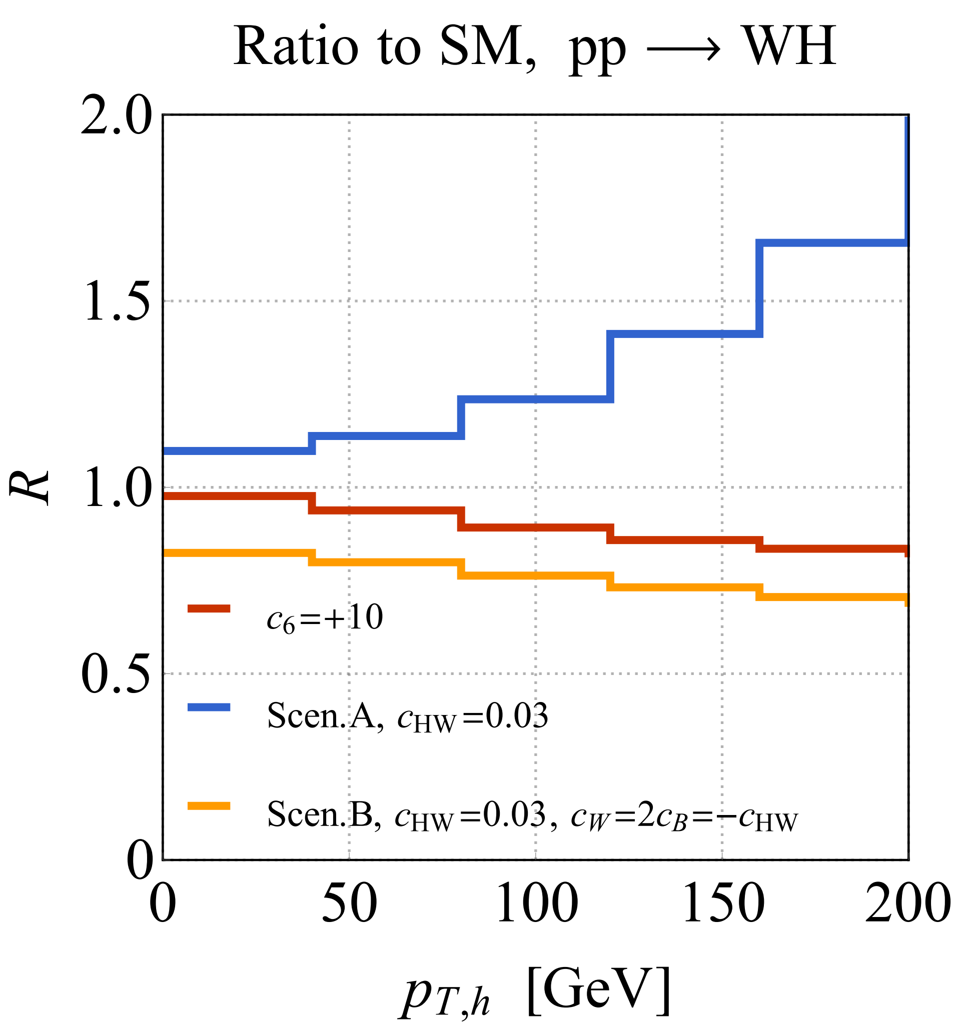
Scenario A: cHW-free, cW = cB = 0, c6=0

Scenario B: cHW-free, cW = 2cB = –cHW, c6=0

[Degrande, Fuks, Mawatari, Mimasu, Sanz – 1609.04833]

In scenario A: R ~ pT(H) ^ 2

In scenario B: R ~ const



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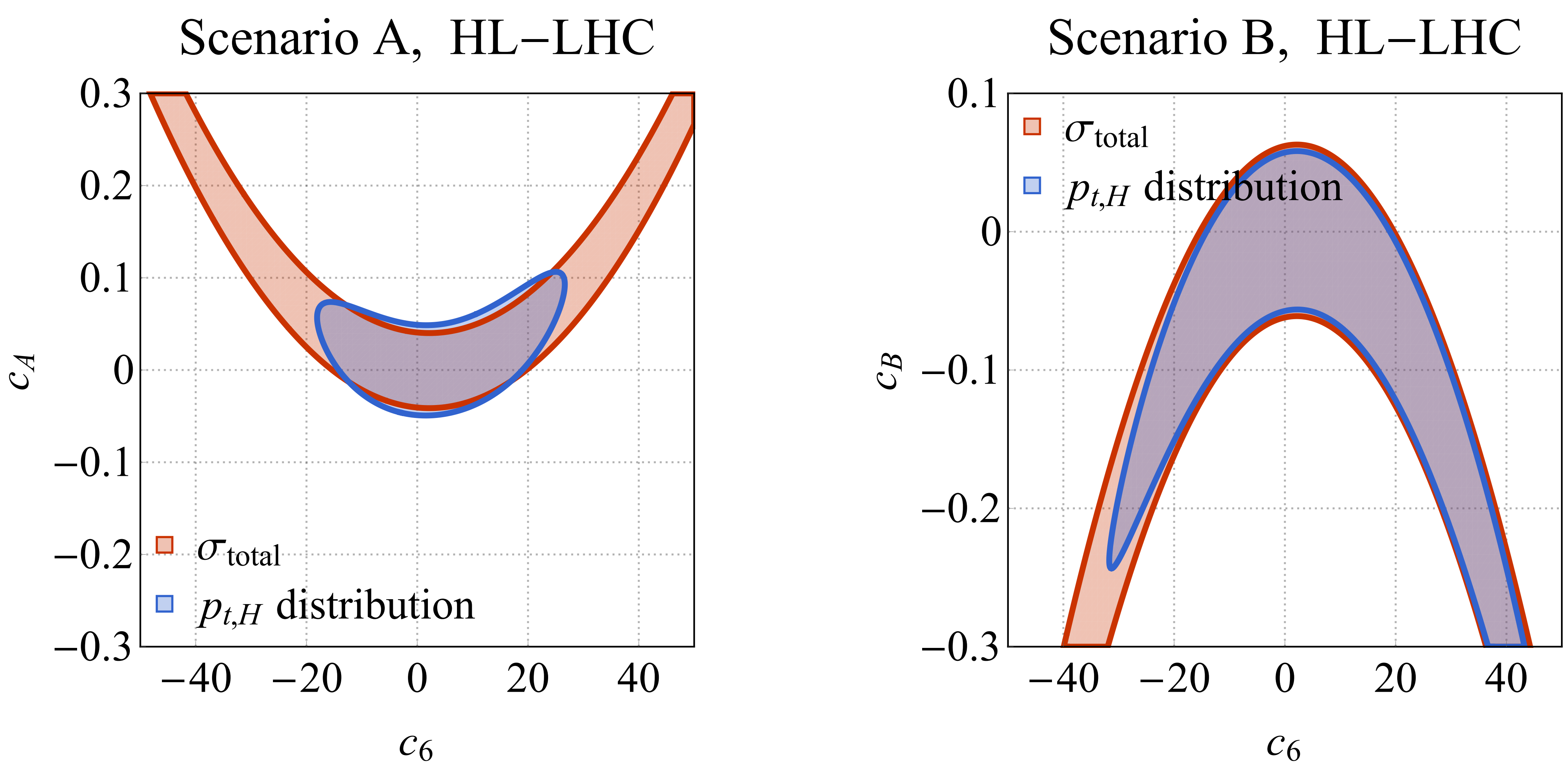
> "We show that a global fit exploiting only single-Higgs inclusive data suffers from degeneracies that prevent one from extracting robust bounds on each individual coupling."

EXAMPLE:

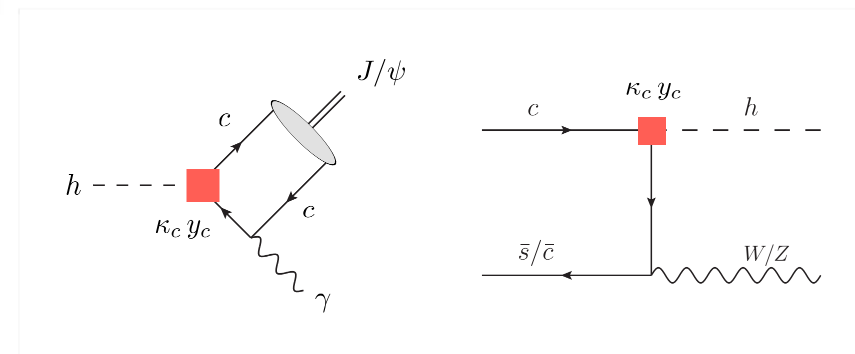
> assuming each bin of the pT(H) distribution in WH-channel measured with accuracy ~20%



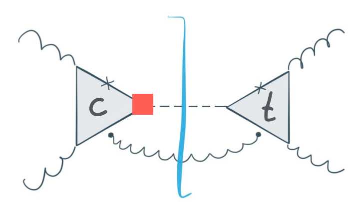
[Bishara, Haisch, Monni, Re – 1606.09253]

ANOTHER STORY: LIGHT-YUKAWAS

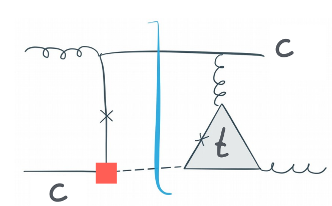
- extracting charm yukawa coupling is hard, but not hopeless at the HL-LHC
- several strategies proposed
- consider impact of modified charm yukawa on the transverse momentum distribution of the Higgs boson



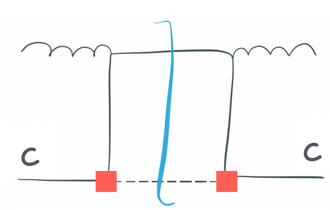
Charm contributions to pp→hj



$\sim \alpha_s^3\, \kappa_c \dfrac{m_c^2}{m_h^2} \ln^2\left(\dfrac{p_T^2}{m_c^2}\right)$

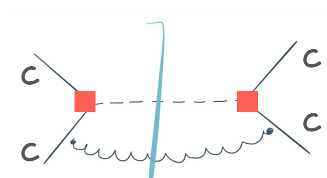


$\sim \alpha_s\, \alpha_s^2\, \kappa_c \dfrac{m_c^2}{m_h^2}$ $\quad (= 0$ in 4, 5 flavour scheme$)$



$\sim \alpha_s\, \alpha_s\, \kappa_c^2 \dfrac{m_c^2}{m_h^2}$

extra powers of α_s from charm PDF



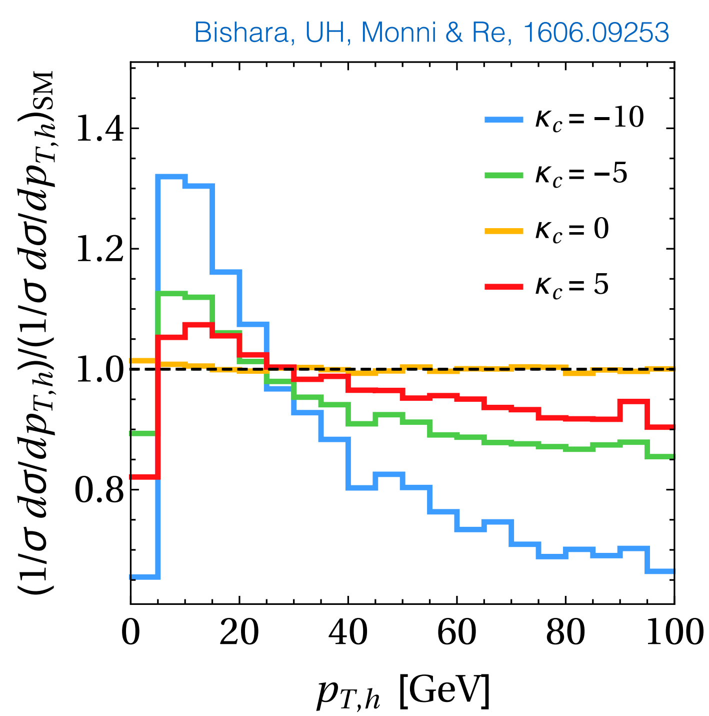
$\sim \alpha_s^2\, \alpha_s\, \kappa_c^2 \dfrac{m_c^2}{m_h^2}$

Slides thanks to Uli Haisch
[Talk @ Moriond-2017]

ANOTHER STORY: LIGHT-YUKAWAS

- pT(H) distribution evaluated at NLO QCD using MCFM-8.0
- log(pT(H)/mH) resummed at NNLL

Normalized $p_{T,h}$ spectra at 8 TeV



O(1) deviations in κ_c lead to few % effects in $p_{T,h}$ distribution

[Bishara, Haisch, Monni, Re – 1606.09253]

over κ_b, we find in the LHC Run II scenario the following 95% CL bound on the y_c modifications

$$\kappa_c \in [-1.4, 3.8] \quad \text{(LHC Run II)}\,, \tag{3}$$

while the corresponding HL-LHC bound reads

$$\kappa_c \in [-0.6, 3.0] \quad \text{(HL-LHC)}\,. \tag{4}$$

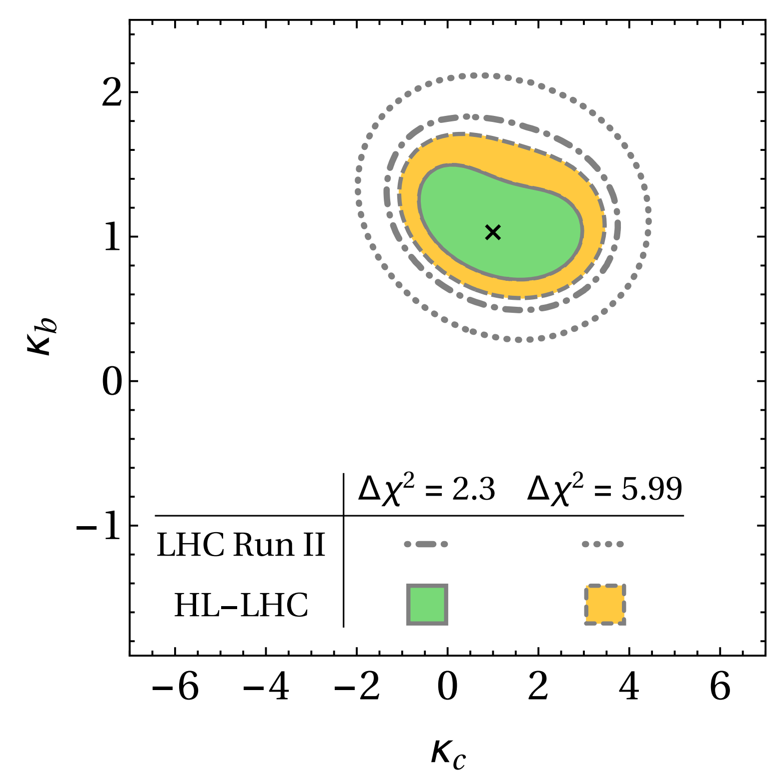
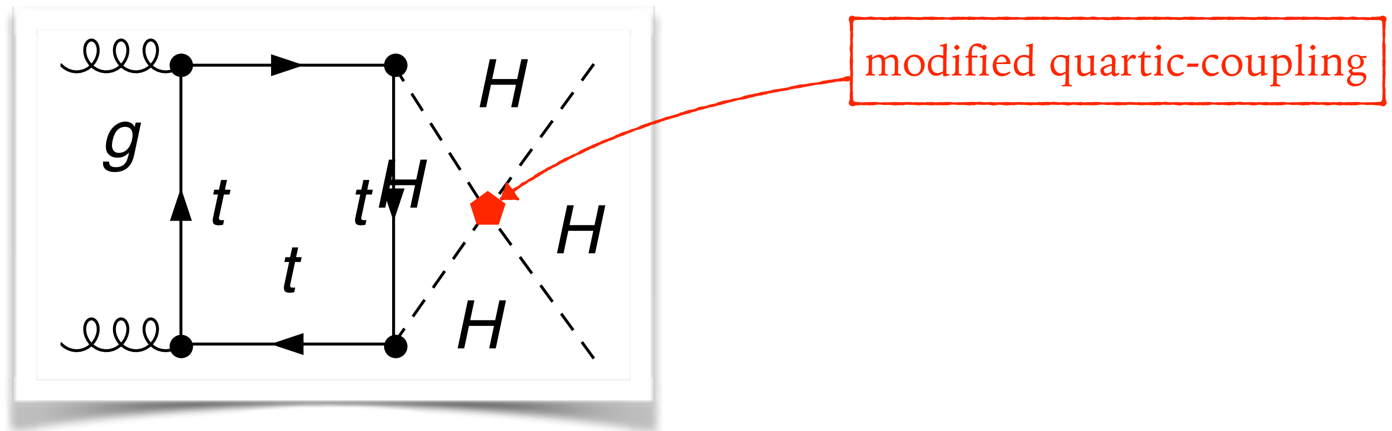


Figure 3: Projected future constraints in the κ_c–κ_b plane. The SM point is indicated by the black cross. The figure shows our projections for the LHC Run II (HL-LHC) with $0.3\,\text{ab}^{-1}$ ($3\,\text{ab}^{-1}$) of integrated luminosity at $\sqrt{s} = 13\,\text{TeV}$. The remaining assumptions entering our future predictions are detailed in the main text.

FUTURE WORK

- take a look at double-Higgs production channel: draw a two-loop diagram with modified quartic-coupling:



- decompose the amplitude into form-factors (F_1, F_2):

$$\mathcal{M}^{\mu\nu} = F_1(\hat{s}, \hat{t}, m_h^2, m_t^2, D)\, T_1^{\mu\nu} + F_2(\hat{s}, \hat{t}, m_h^2, m_t^2, D)\, T_2^{\mu\nu}$$

- evaluation of the two-loop integrals now possible using pySecDec tool

[Borowka, Heinrich, Jones, Kerner, Schlenk, Zicke – 1502.06595]

- evaluate the change in cross-section due to presence of modified quartic-coupling…

CONCLUSIONS

- loop-induced probes might provide a complimentary tool for putting bounds on the Higgs boson self-couplings
- examples considered so far provide bounds which are competitive with other strategies (trilinear Higgs coupling, charm yukawa coupling)
- many interesting paths to explore…

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THANK YOU!

BACKUP SLIDES

LHC Run I (VH+VBF) [ATLAS-CONF-2015-044]

To obtain the current constraints on $\bar{c}_6$ we use the LHC Run I combination of the ATLAS and CMS measurements of the Higgs boson production and decay rates [1]. In the case of the vector boson mediated production processes the relevant μ_I^F parameters read

$$\begin{aligned} \mu_V^{b\bar{b}} &= 0.65^{+0.30}_{-0.29}\,, \qquad \mu_V^{WW} = 1.38^{+0.41}_{-0.37}\,, \\ \mu_V^{\tau^+\tau^-} &= 1.12^{+0.37}_{-0.35}\,, \qquad \mu_V^{ZZ} = 0.48^{+1.37}_{-0.91}\,, \qquad \mu_V^{\gamma\gamma} = 1.05^{+0.44}_{-0.41}\,, \end{aligned} \tag{7.8}$$

HL-LHC [ATL-PHYS-PUB-2014-016]

> *with theory uncertainties:*

the ATLAS and CMS collaborations [75–80]. To estimate the sensitivity on $\bar{c}_6$ that can be reached at the HL-LHC with $3\,\mathrm{ab}^{-1}$ of data, we study two benchmark scenarios based on the results reported in the fourth and fifth column of table 1 of [77].[4] Our first scenario includes the current theory uncertainties and reads

$$\begin{aligned} \Delta\mu_{Wh}^{b\bar{b}} &= \pm 37\%\,, \qquad \Delta\mu_{Wh}^{\gamma\gamma} = \pm 19\%\,, \\ \Delta\mu_{Zh}^{b\bar{b}} &= \pm 14\%\,, \qquad \Delta\mu_{Zh}^{\gamma\gamma} = \pm 28\%\,, \qquad \Delta\mu_{Vh}^{ZZ} = \pm 13\%\,, \\ \Delta\mu_{\mathrm{VBF}}^{WW} &= \pm 15\%\,, \qquad \Delta\mu_{\mathrm{VBF}}^{\tau^+\tau^-} = \pm 19\%\,, \qquad \Delta\mu_{\mathrm{VBF}}^{ZZ} = \pm 21\%\,, \qquad \Delta\mu_{\mathrm{VBF}}^{\gamma\gamma} = \pm 22\%\,, \end{aligned} \tag{7.10}$$

> *without theory uncertainties:*

The corresponding relative uncertainties are

$$\begin{aligned} \Delta\mu_{Wh}^{b\bar{b}} &= \pm 36\%\,, \qquad \Delta\mu_{Wh}^{\gamma\gamma} = \pm 17\%\,, \\ \Delta\mu_{Zh}^{b\bar{b}} &= \pm 13\%\,, \qquad \Delta\mu_{Zh}^{\gamma\gamma} = \pm 27\%\,, \qquad \Delta\mu_{Vh}^{ZZ} = \pm 12\%\,, \\ \Delta\mu_{\mathrm{VBF}}^{WW} &= \pm 9\%\,, \qquad \Delta\mu_{\mathrm{VBF}}^{\tau^+\tau^-} = \pm 15\%\,, \qquad \Delta\mu_{\mathrm{VBF}}^{ZZ} = \pm 16\%\,, \qquad \Delta\mu_{\mathrm{VBF}}^{\gamma\gamma} = \pm 15\%\,. \end{aligned} \tag{7.11}$$