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Institute for Theoretical Particle Physics

SMEFT in the Higgs Sector
Higher Loop Contributions

Marco Vitti (Karlsruhe Institute of Technology, TTP and IAP)

QCD@LHC, Freiburg, 7 Oct 2024

Work in collaboration with E. Balzani, G. Degrassi, S. Di Noi, R. Gröber, G. Heinrich, J. Lang

SMEFT Framework

Effects due to heavy New Physics can be parametrized by supplementing the SM Lagrangian with higher-dimensional operators that:

- Respect the symmetries of the SM: SU(3) × SU(2) × U(1) and Lorentz
- Are built from SM fields
- Are suppressed by powers of a NP scale Λ

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_{D=5}^{\infty} \frac{1}{\Lambda^{D-4}} \mathcal{C}_i^{(D)} \mathcal{O}_i^{(D)}$$

- The Lagrangian is built without knowing the underlying UV theory (Bottom-up approach)
- The Wilson Coefficients can probe classes of UV models all at once
- This talk: SMEFT at D=6 → Operators defined in the Warsaw basis [Grzadkowski et al. - 1008.4884]

Light-Quark Yukawa Couplings at the LHC

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- Projected bounds on coupling modifiers $\kappa_q = y_q / y_q^{SM}$ at HL-LHC [de Blas et al. - 1905.03764]

$$\kappa_u < 560; \quad \kappa_d < 260; \quad \kappa_s < 13; \quad \kappa_c < 1.2$$

- Alternative: sensitivity from specific processes

  - Higgs decays (mainly charm) [Bodwin et al. - 1306.5770; Kagan et al – 1406.1722; König, Neubert – 1505.03870; Alte et al. - 1609.06310]

    See talk by A. Raspiareza

  - Higgs+jet → diff. distributions [Bishara et al. - 1606.09253; Soreq et al. - 1606.09621; Bonner, Logan - 1608.04376]

  - Other approaches [Aguilar-Saavedra et al. - 2008.12538, Falkowski et al. - 2011.09551; Vignaroli – 2205.09449; Yu - 1609.06592]

  - HH production [Alasfar, Corral Lopez, Gröber – 1909.05279; Alasfar et al. - 2207.04157]

- Off-shell Higgs production with H→ZZ→4l decay [Balzani, Gröber, MV - 2304.09772]

  See also [Zhou - 1505.06369]

  Evidence at LHC [CMS – 2202.06923; ATLAS - 2304.01532]

Light-Quark Yukawas in SMEFT

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- We are interested in modifications of the Yukawa sector via D=6 operators

SM

$$\mathcal{L}_y = -y^u_{ij}\bar{Q}^i_L\tilde{\phi}u^j_R - y^d_{ij}\bar{Q}^i_L\phi d^j_R + \text{ h.c.}$$

$$\Delta\mathcal{L}_y = \frac{\phi^\dagger\phi}{\Lambda^2}\left((C_{u\phi})_{ij}\bar{Q}^i_L\tilde{\phi}u^j_R + (C_{d\phi})_{ij}\bar{Q}^i_L\phi d^j_R + \text{ h.c. }\right)$$

D=6

- After EWSB and rotation to mass basis, Lagrangian for Higgs coupling to quarks is

$$\mathcal{L} \supset g_{hq_i\bar{q}_j}\bar{q}_j q_i h + g_{hhq_i\bar{q}_j}\bar{q}_j q_i h^2 + g_{hhhq_i\bar{q}_j}\bar{q}_j q_i h^3$$

$$g_{hq_i\bar{q}_j} = \frac{m_q}{v}\delta_{ij} - \frac{1}{\sqrt{2}}\frac{v^2}{\Lambda^2}(\tilde{C}_{q\phi})_{ij}\,, \quad g_{hhq_i\bar{q}_j} = -\frac{3}{2\sqrt{2}}\frac{v}{\Lambda^2}(\tilde{C}_{q\phi})_{ij}\,, \quad g_{hhhq_i\bar{q}_j} = -\frac{1}{2\sqrt{2}}\frac{1}{\Lambda^2}(\tilde{C}_{q\phi})_{ij}$$

- If we assume flavor-diagonal couplings → $g_{hq\bar{q}} = \kappa_q \frac{m_q}{v}$

Enhancing Light Yukawas in *pp* → *ZZ*

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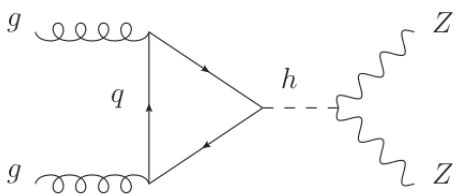
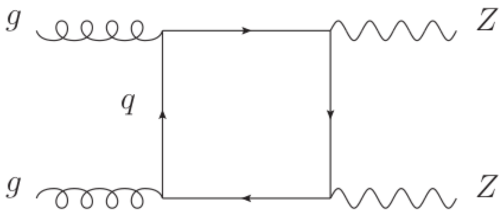
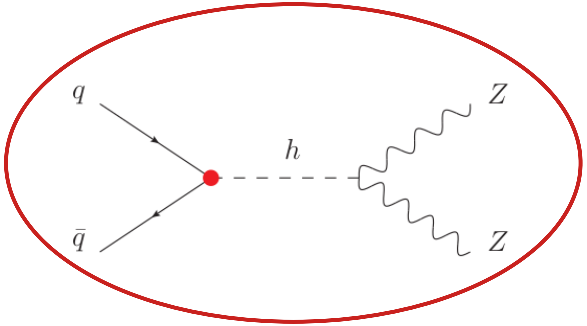
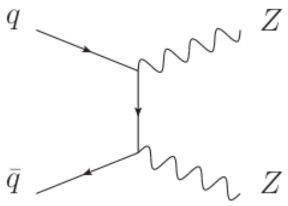
- Negligible effects in ggF
  → treated as SM
- Largest modifications in qq-channel
- NP in coupling with PDFs
  → focus only on first generation







Signal



$$g_{hq\bar{q}} = \kappa_q \frac{m_q}{v}$$

Off-Shell Higgs Production

$\tilde{C}_{d\phi}/(1\ \mathrm{TeV}^2) = 0.45$ $\tilde{C}_{u\phi}/(1\ \mathrm{TeV}^2) = 0.21$

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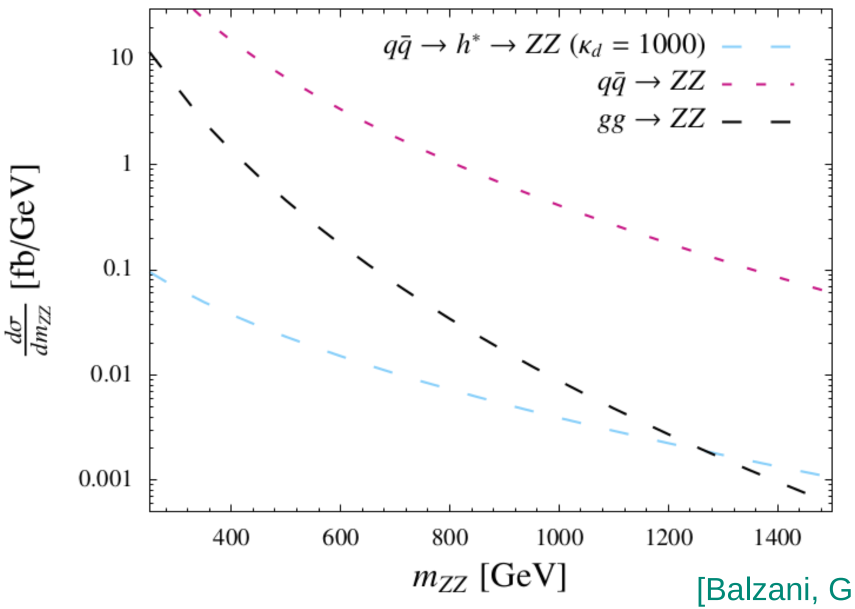
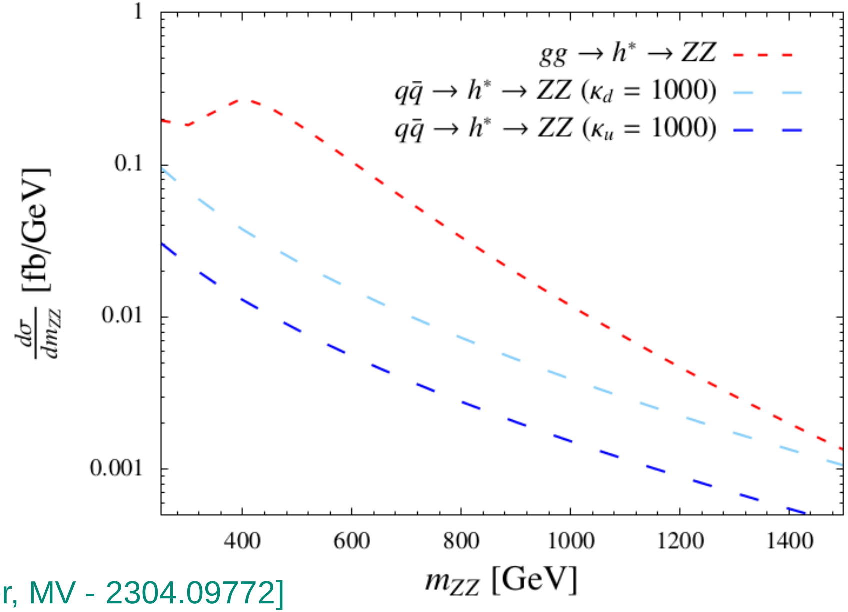
Comparing all partonic channels



Comparing Higgs-mediated channels



[Balzani, Gröber, MV - 2304.09772]

Signal gains importance because of destructive interference in $gg \to ZZ$

Signal gains importance because of different fall of PDFs

Kinematic Discriminants

[Campbell et al. - 1311.3589; CMS – 2202.06923; Haisch, Koole – 2111.12589, ...]

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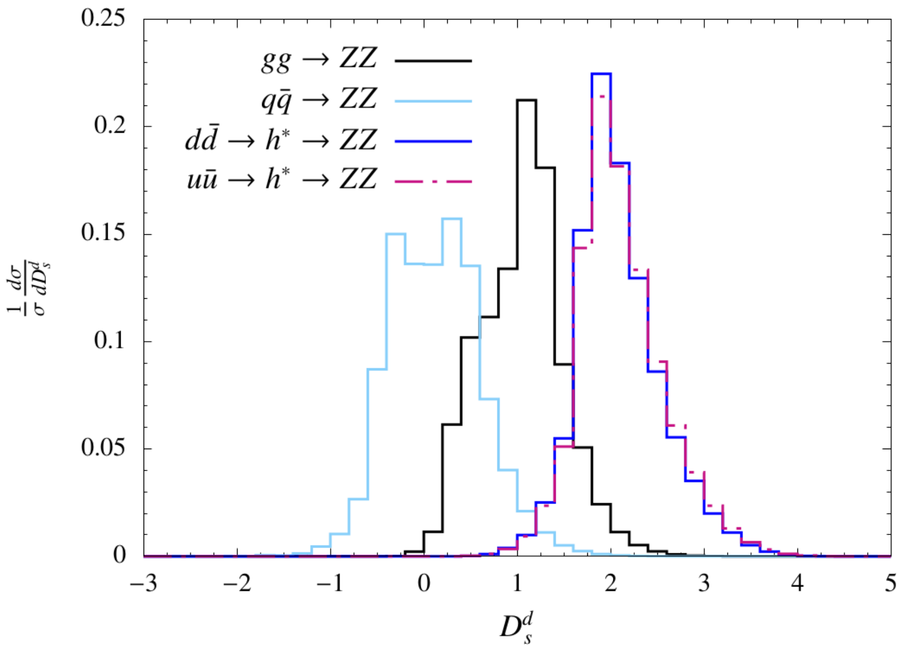
$$P_{ij}(v) = \frac{1}{\sigma_{ij\to 4\ell}} \int dx_1 dx_2 \delta(x_1 x_2 E^2_{CMS} - m^2_{4\ell}) f_i(x_1) f_j(x_2) \hat{\sigma}_{ij}(x_1, x_2, v)$$

$$D^d_s = \log_{10}\left(\frac{P^{sig}_{d\bar{d}}}{P^{back}_{q\bar{q}} + P^{back}_{gg}}\right)$$

- For $D^d_s > 2$ selects basically only events from signal process
- Not possible to distinguish between $d\bar{d} \to h^*$ and $u\bar{u} \to h^*$



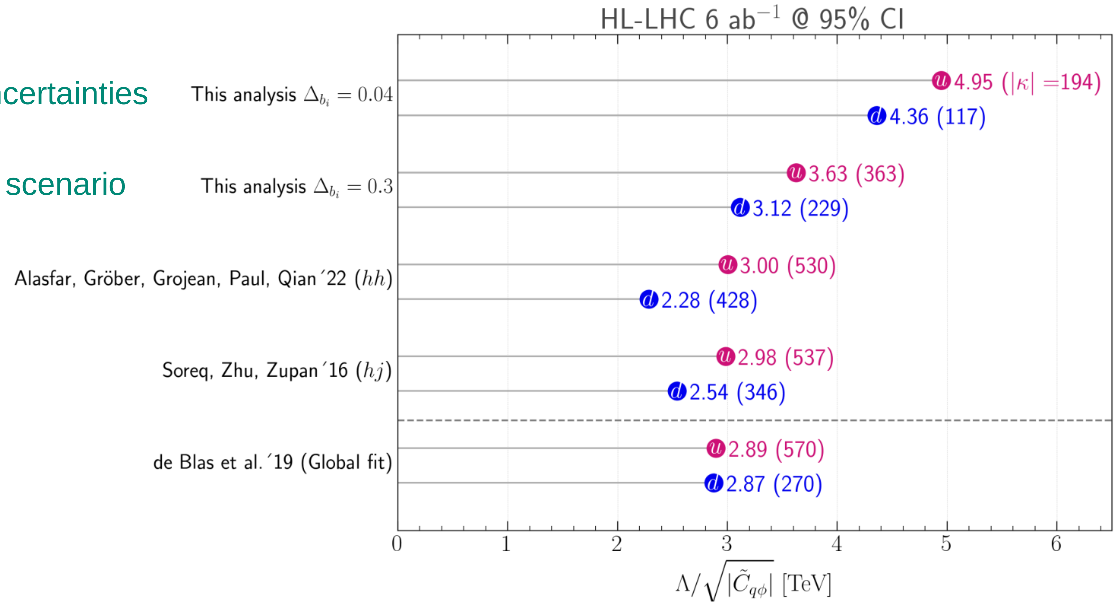
[Balzani, Gröber, MV - 2304.09772]

Comparison with Previous Studies

- Shape analysis on D_s^d distributions – off-shell region defined by $m_{ZZ} > 250\,\mathrm{GeV}$
- Consider only the ZZ→4l final state

HL-LHC S2 uncertainties

Conservative scenario



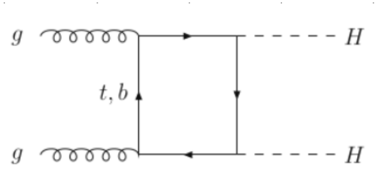
[Balzani, Gröber, MV - 2304.09772]

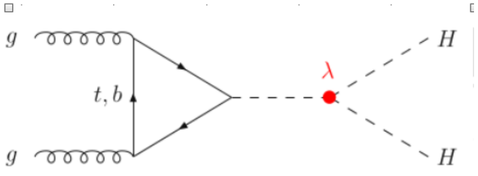
Higgs Probes of Trilinear Coupling

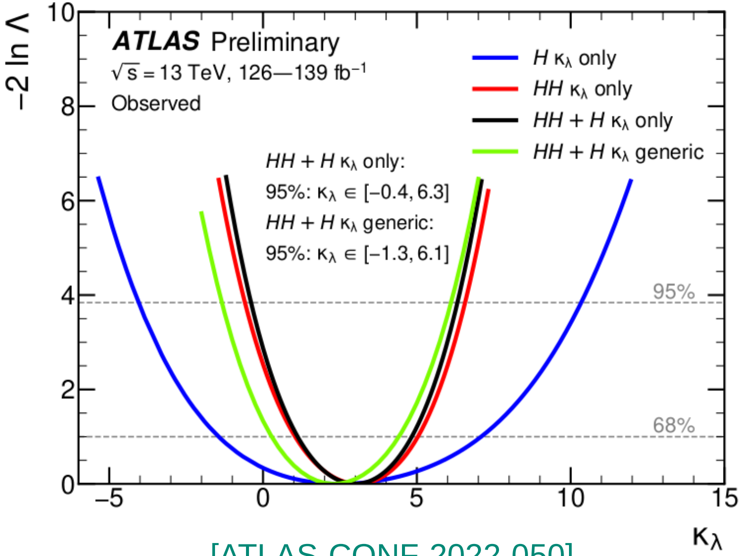
$$V(h) = \frac{m_H^2}{2} h^2 + \lambda_3 v h^3 + \frac{\lambda_4}{4} h^4$$

- HH production has the best sensitivity

See talk by N. P. Readioff





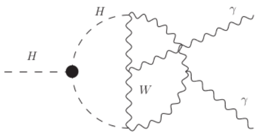


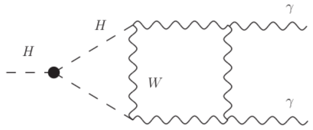
[ATLAS-CONF-2022-050]

- Single-Higgs measurements are helpful, too

[McCullough - 1312.3322;
Gorbahn, Haisch – 1607.03773;
Degrassi, Giardino, Maltoni, Pagani – 1607.04251;
Bizon, Gorbahn, Haisch, Zanderighi – 1610.05771;
Maltoni, Pagani, Shivaji, Zhao – 1709.08649;
Di Vita, Grojean, Panico, Riembau, Vantalon – 1704.01953;
Degrassi, Vitti - 1912.06429]

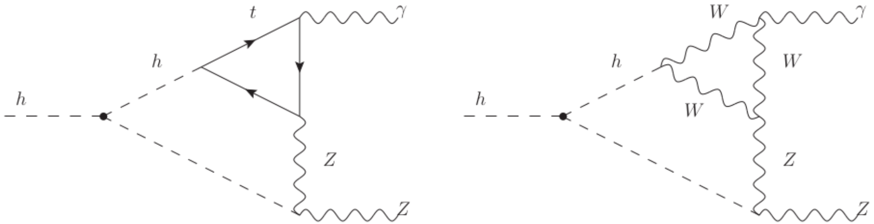
- In this case, λ_3 enters via loop contributions





Trilinear coupling in $H \to Z\gamma$

[Degrassi, Vitti - 1912.06429]



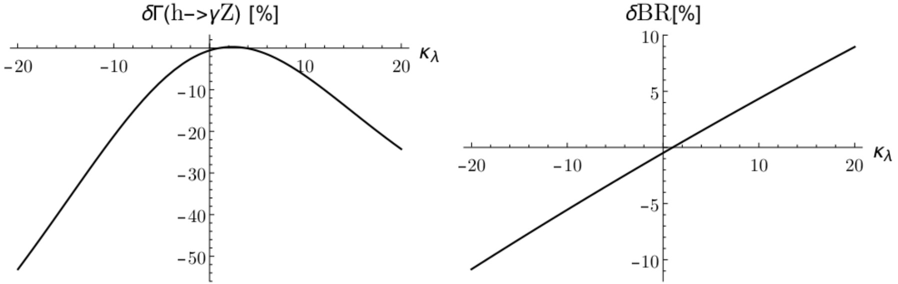
- Recent evidence in [ATLAS, CMS - 2309.03501]
- The trilinear coupling enters at two loops
- Amplitude obtained from a Taylor expansion in the external momenta

$$\frac{q_1^2}{4m^2}, \frac{q_2^2}{4m^2}, \frac{q_1 \cdot q_2}{4m^2} \ll 1 \qquad m = m_H, m_t, m_W, m_Z$$

After the expansion $q_1^2 = 0, q_2^2 = m_Z^2, q_1 \cdot q_2 = (m_H^2 - m_Z^2)/2$

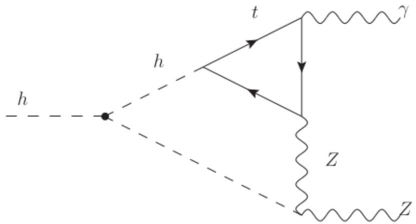
- Sensitivity comparable to other single-Higgs processes

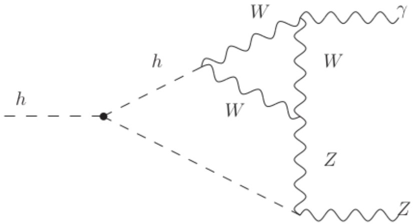
[Degrassi, Giardino, Maltoni, Pagani – 1607.04251]



Trilinear coupling in $H \to Z\gamma$

[Degrassi, Vitti - 1912.06429]





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After the expansion $q_1^2 = 0, q_2^2 = m_Z^2, q_1 \cdot q_2 = (m_H^2 - m_Z^2)/2$

- Connection to SMEFT: calculation using

$$V^{NP} = \sum_{n=1}^{N} c_{2n} (\Phi^\dagger \Phi)^n \,, \qquad \Phi = \begin{pmatrix} \phi^+ \\ \frac{1}{\sqrt{2}}(v + h + i\phi_2) \end{pmatrix}$$

- When truncating at $n \leq 3$ recover SMEFT with only $\mathcal{O}_\phi = \left(\Phi^\dagger \Phi\right)^3$ switched on

4-top operators in the SMEFT

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- Loosely constrained, difficult to access directly

Constraints possible from

- Top-quark data

[Zhang – 1708.05928
D'Hondt, Mariotti, Mimasu, Moortgat, Zhang – 1807.02130
Hartland, Maltoni, Nocera, Rojo, Slade, Vryonidou, Zhang – 1901.05965
Brivio, Bruggisser, Maltoni, Moutafis, Plehn, Vryonidou, Westhoff, Zhang – 1910.03606
Ellis, Madigan, Mimasu, Sanz You – 2012.02779
SMEFiT Collaboration – 2105.00006
Degrande, Rosenfeld, Vasquez - 2402.06528
Celada, Giani, ter Hoeve, Mantani, Rojo, Rossia, Thomas, Vryonidou - 2404.12809]

- EWPOs

[Dawson, Giardino – 2201.09887;
de Blas, Chala, Santiago - 1507.00757]

$$\begin{aligned}\mathcal{L}_{4t} = &\frac{\mathcal{C}^{(1)}_{QQ}}{\Lambda^2}\left(\bar{Q}_L\gamma_\mu Q_L\right)\left(\bar{Q}_L\gamma^\mu Q_L\right)\\ &+\frac{\mathcal{C}^{(3)}_{QQ}}{\Lambda^2}\left(\bar{Q}_L\tau^I\gamma_\mu Q_L\right)\left(\bar{Q}_L\tau^I\gamma^\mu Q_L\right)\\ &+\frac{\mathcal{C}^{(1)}_{Qt}}{\Lambda^2}\left(\bar{Q}_L\gamma_\mu Q_L\right)\left(\bar{t}_R\gamma^\mu t_R\right)\\ &+\frac{\mathcal{C}^{(8)}_{Qt}}{\Lambda^2}\left(\bar{Q}_L T^A\gamma_\mu Q_L\right)\left(\bar{t}_R T^A\gamma^\mu t_R\right)\\ &+\frac{\mathcal{C}_{tt}}{\Lambda^2}\left(\bar{t}_R\gamma_\mu t_R\right)\left(\bar{t}_R\gamma^\mu t_R\right).\end{aligned}$$

Single-Higgs Processes and 4-top Operators

- Competitive bounds from single-Higgs production and decay [Alasfar, de Blas, Gröber - 2202.02333]

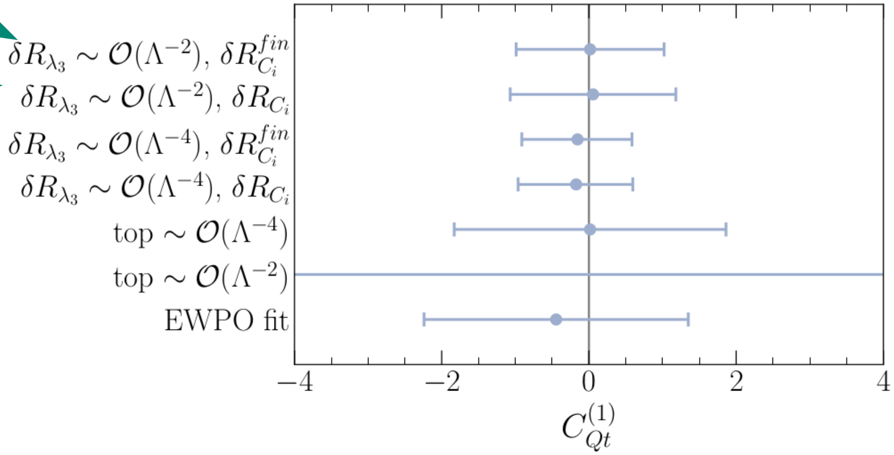
$$\{gg \to H; t\bar{t}H; H \to \gamma\gamma; H \to gg; H \to b\bar{b}\}$$

- $\mathcal{O}_\phi$ included in the fit → bounds on Higgs trilinear coupling become less stringent

[Alasfar, de Blas, Gröber - 2202.02333]

No RGE logs included

RGE logs included



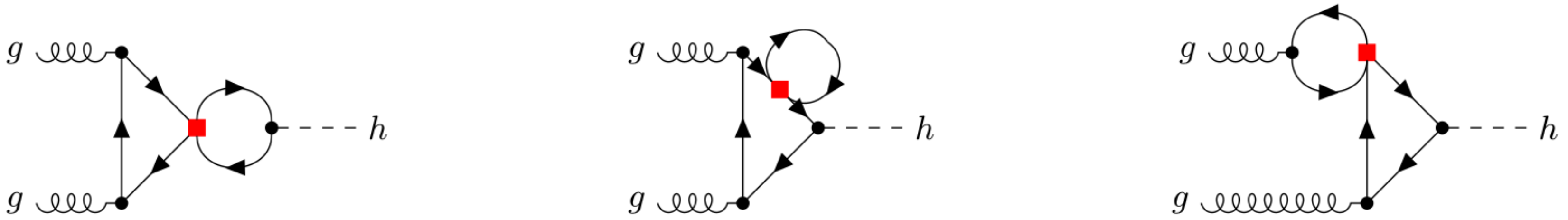
$\langle C_{Qt}^{(1)} \rangle$	95% CI
0.0	[-1.0, 1.0]
0.1	[-1.1, 1.2]
-0.2	[-0.9, 0.6]
-0.2	[-1.0, 0.6]
0.0	[-1.8, 1.9]
-18.0	[-195.0, 159.0]
-0.4	[-2.2, 1.4]

$$\frac{C_{Qt}^{(1)}}{\Lambda^2} \left(\bar{Q}_L \gamma_\mu Q_L\right) \left(\bar{t}_R \gamma^\mu t_R\right)$$

Stability wrt $(1/\Lambda)^n$ expansion

- **HH production** discussed in [Heinrich, Lang – 2311.15004; 2409.19578]
- In both cases the 4-top operators can enter at two loops

4-top Operators in $gg \to H$



- 4-top operators involve chiral projectors $\Rightarrow$ treatment of γ^5 required in Dim Reg

$$\gamma^5 = i\gamma^0\gamma^1\gamma^2\gamma^3 \;\Rightarrow\;$$ Intrisically 4-dimensional object

In $D \neq 4$, the following properties cannot be satisfied at the same time

- Anticommutativity $\Rightarrow \{\gamma^5, \gamma^\mu\} = 0$
- Cyclicity of Trace
- $\mathrm{Tr}[\gamma^\mu\gamma^\nu\gamma^\rho\gamma^\sigma\gamma^5] = 4i\,\varepsilon^{\mu\nu\rho\sigma}$

Vast(!) literature of approaches to address this. We considered two cases [Di Noi, Gröber, Heinrich, Lang, MV - 2310.18221]

Continuation Schemes for γ^5

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Naive Dim Reg (NDR)

[Chanowitz, Furman, Hinchliffe (‘79)]

- Extend $\{\gamma^5, \gamma^\mu\} = 0$ to $D \neq 4$

  Computationally convenient

  Cyclicity of trace lost

Breitenlohner, Maison, ‘t Hooft, Veltman (BMHV)

[’t Hooft, Veltman (‘72);
Breitenlohner, Maison (‘79)]

- Split the Dirac algebra

$$\gamma_\mu^{(D)} = \gamma_\mu^{(4)} + \gamma_\mu^{(D-4)},$$
$$\{\gamma_\mu^{(4)}, \gamma_5\} = 0, \quad [\gamma_\mu^{(D-4)}, \gamma_5] = 0$$

  Algebraically consistent

  Breaking of chiral WIs

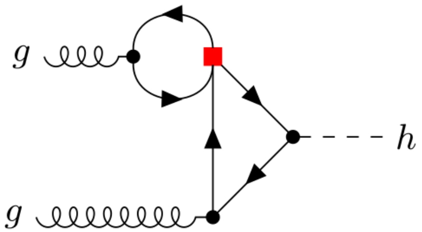
  [Larin - 9302240
  Bélusca-Maïto, Ilakovac, Kühler, Mador-Božinović, Stöckinger, Weißwange - 2303.09120
  Cornella, Feruglio, Vecchi - 2205.10381]

- Physical observables will be independent of the γ^5 scheme, but intermediate expressions will differ by $\mathcal{O}(\varepsilon)$ contributions

Scheme-Dependent Contributions

[Di Noi, Gröber, Heinrich, Lang, MV - 2310.18221]

- Scheme-dependent pole in the gluon-top vertex modification

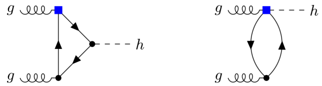


$$= \frac{K_{tG}}{2}\left(\mathcal{C}^{(1)}_{Qt} - \frac{1}{6}\mathcal{C}^{(8)}_{Qt}\right)\frac{1}{\Lambda^2}\frac{1}{\varepsilon}\frac{g_s m_t \sqrt{2}}{2\pi^2}\delta^{A_1A_2}(m_h^2/2\ g^{\mu_1\mu_2} - p_1^{\mu_2}p_2^{\mu_1})$$

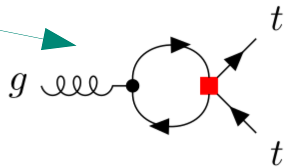
DIV

$$K_{tG} = \begin{cases} \frac{\sqrt{2}m_t g_s}{16\pi^2 v} & \text{(NDR)} \\ 0 & \text{(BMHV)} \end{cases}$$

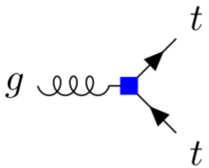
$$\mathcal{O}_{tG} = \bar{Q}_L \sigma^{\mu\nu} T^A t_R \tilde{\phi} G^A_{\mu\nu}$$



- This is due to a **finite mixing** with the chromomagnetic operator at one-loop



$$= \frac{\mathcal{C}^{(1)}_{Qt} - \frac{1}{6}\mathcal{C}^{(8)}_{Qt}}{\mathcal{C}_{tG}} K_{tG} \times$$



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[Di Noi, Gröber, Heinrich, Lang, MV - 2310.18221]

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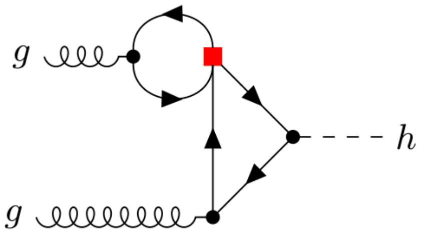
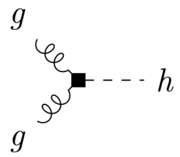


$$= \frac{K_{tG}}{2}\left(\mathcal{C}_{Qt}^{(1)} - \frac{1}{6}\mathcal{C}_{Qt}^{(8)}\right)\frac{1}{\Lambda^2}\frac{1}{\varepsilon}\frac{g_s m_t\sqrt{2}}{2\pi^2}\delta^{A_1A_2}\left(m_h^2/2\; g^{\mu_1\mu_2} - p_1^{\mu_2}p_2^{\mu_1}\right)$$

DIV

$$K_{tG} = \begin{cases} \frac{\sqrt{2}m_t g_s}{16\pi^2 v} & \text{(NDR)} \\ 0 & \text{(BMHV)} \end{cases}$$

- Leads to a scheme-dependent anomalous dimension for $\mathcal{O}_{\phi G} = \phi^\dagger\phi G_{\mu\nu}G^{\mu\nu}$



$$16\pi^2\mu\frac{d\mathcal{C}_{\phi G}}{d\mu} = -4\sqrt{2}g_{h\bar{t}t}g_s\left(\mathcal{C}_{tG} + K_{tG}\left(\mathcal{C}_{Qt}^{(1)} - \frac{1}{6}\mathcal{C}_{Qt}^{(8)}\right)\right)$$

Two-loop

[Jenkins, Manohar, Trott – 1308.2627; 1310.4838; 1312.2014]

Scheme-Dependent Parameters

[Ciuchini, Franco, Reina, Silvestrini – 9311357;
Ciuchini, Franco, Martinelli, Reina, Silvestrini – 9307364
Buras, Misiak, Munz, Pokorski – 9311345
Herrlich, Nierste - 9412375]

- Observed in $b \to s\,\gamma\,(g)$ in the context of Weak EFT
- Obtain scheme-independent predictions via a finite renormalization of the parameters

$$\mathcal{C}_{tG}^{\rm NDR} = \mathcal{C}_{tG}^{\rm BMHV} - \left(\mathcal{C}_{Qt}^{(1)} - \frac{1}{6}\mathcal{C}_{Qt}^{(8)}\right)\frac{\sqrt{2}g_{h\bar{t}t}g_s}{16\pi^2},$$

$$g_{h\bar{t}t}^{\rm NDR} = g_{h\bar{t}t}^{\rm BMHV} - g_{h\bar{t}t}\left(\mathcal{C}_{Qt}^{(1)} + \frac{4}{3}\mathcal{C}_{Qt}^{(8)}\right)\frac{(m_h^2 - 6m_t^2)}{16\pi^2\Lambda^2},$$

$$m_t^{\rm NDR} = m_t^{\rm BMHV} + \left(\mathcal{C}_{Qt}^{(1)} + \frac{4}{3}\mathcal{C}_{Qt}^{(8)}\right)\frac{m_t^3}{8\pi^2\Lambda^2}.$$

- Confirmed by matching onto UV toy models in the two schemes
- Possibility to map predictions between schemes while remaining in the bottom-up approach

Loop- and Tree-Generated Operators

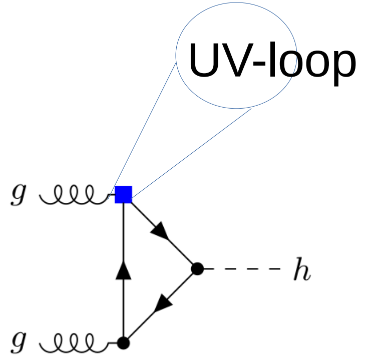
What does “higher loop” mean in SMEFT?

- In the SM, the definition is clear (just look at the Feynman diagram)
- In the SMEFT NP degrees of freedom are integrated out
- If the underlying UV theory is weakly coupled and renormalizable, there are classes of SMEFT operators that can be only generated from loop diagrams in the UV
  [Arzt, Einhorn, Wudka – 9405214]
- The WC of these loop-generated operators will include a suppression due to a loop factor
  [Buchalla, Heinrich, Müller-Salditt, Pandler - 2204.11808]

5–7: Fermion Bilinears (ψ^2)

non-hermitian ($\bar{L}R$)			
5: $\psi^2 H^3$ + h.c. [PTG]	6: $\psi^2 XH$ + h.c. [LG]		
Q_{eH} $(H^\dagger H)(\bar{\ell}_p e_r H)$	Q_{eW} $(\bar{\ell}_p \sigma^{\mu\nu} e_r)\tau^I H W^I_{\mu\nu}$	Q_{uG} $(\bar{q}_p \sigma^{\mu\nu} T^A u_r)\widetilde{H} G^A_{\mu\nu}$	Q_{dG} $(\bar{q}_p \sigma^{\mu\nu} T^A d_r) H G^A_{\mu\nu}$
Q_{uH} $(H^\dagger H)(\bar{q}_p u_r \widetilde{H})$	Q_{eB} $(\bar{\ell}_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$	Q_{uW} $(\bar{q}_p \sigma^{\mu\nu} u_r)\tau^I \widetilde{H} W^I_{\mu\nu}$	Q_{dW} $(\bar{q}_p \sigma^{\mu\nu} d_r)\tau^I H W^I_{\mu\nu}$
Q_{dH} $(H^\dagger H)(\bar{q}_p d_r H)$		Q_{uB} $(\bar{q}_p \sigma^{\mu\nu} u_r)\widetilde{H} B_{\mu\nu}$	Q_{dB} $(\bar{q}_p \sigma^{\mu\nu} d_r) H B_{\mu\nu}$

[Isidori, Wilsch, Wyler - 2303.16922]



Scheme-Dependent Parameters

- **IF** $\mathcal{O}_{tG}$ is loop-generated, the shift is of the same order of magnitude of the 4-top contribution

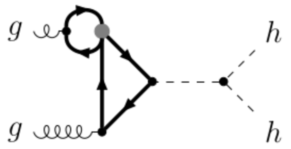
$$\frac{C_{tG}^{\text{NDR}}}{16\pi^2} = \frac{C_{tG}^{\text{BMHV}}}{16\pi^2} - \left(C_{Qt}^{(1)} - \frac{1}{6}C_{Qt}^{(8)}\right)\frac{\sqrt{2}g_{h\bar{t}t}g_s}{16\pi^2},$$

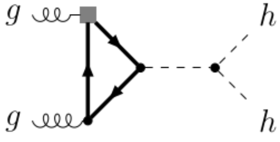
$$g_{h\bar{t}t}^{\text{NDR}} = g_{h\bar{t}t}^{\text{BMHV}} - g_{h\bar{t}t}\left(C_{Qt}^{(1)} + \frac{4}{3}C_{Qt}^{(8)}\right)\frac{(m_h^2 - 6m_t^2)}{16\pi^2\Lambda^2},$$

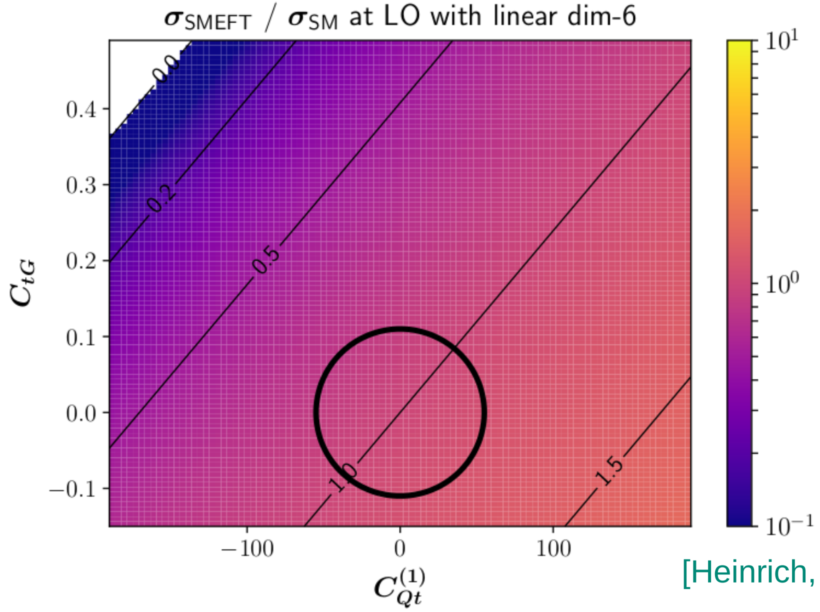
$$m_t^{\text{NDR}} = m_t^{\text{BMHV}} + \left(C_{Qt}^{(1)} + \frac{4}{3}C_{Qt}^{(8)}\right)\frac{m_t^3}{8\pi^2\Lambda^2}.$$

- Shifts for other parameters are higher-order in the loop counting

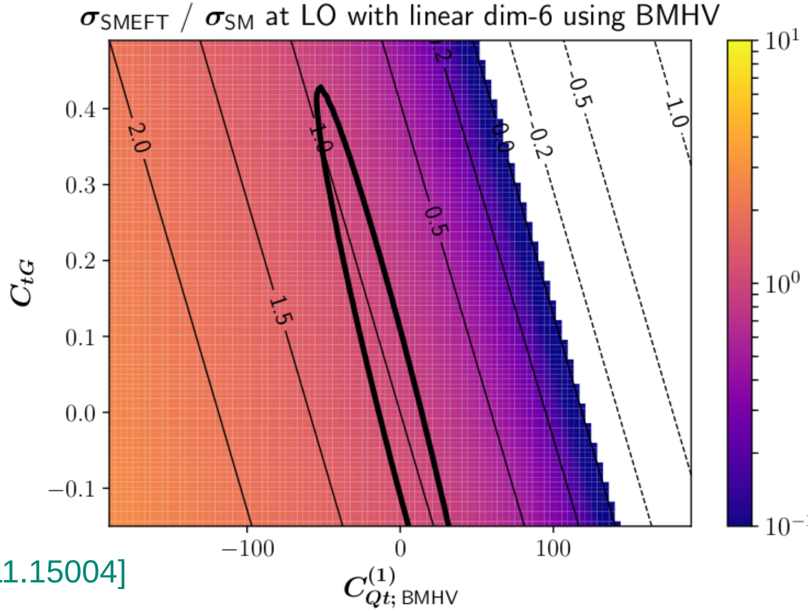
Effect of γ^5-scheme on $gg \to HH$







(NDR used for all contributions)



(4-top contribution computed in BMHV)

[Heinrich, Lang - 2311.15004]

$$\mathcal{C}_{tG}^{\text{NDR}} = \mathcal{C}_{tG}^{\text{BMHV}} - \left(\mathcal{C}_{Qt}^{(1)} - \frac{1}{6}\mathcal{C}_{Qt}^{(8)} \right) \frac{\sqrt{2} g_{h\bar{t}t} g_s}{16\pi^2}$$

Summary

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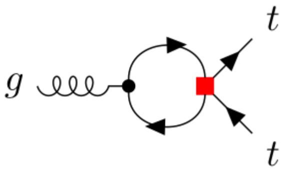
- Light-Yukawa probes discussed within the SMEFT framework
- Highlighted the potential of loop effects in Higgs processes to put competitive/complementary constraints on

  - Higgs self-coupling

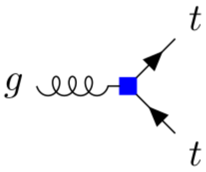
  - 4-top operators
- Higher-loop contributions require additional care in the the choice of calculational schemes employed
- Importance of being inclusive when choosing the set of operators, also because constraints on WCs may be scheme-dependent

Thank you for your attention!

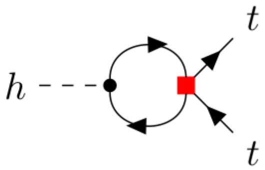
Finite mixing @ 1 Loop for 4-top operators



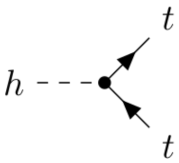
$$= \frac{\mathcal{C}_{Qt}^{(1)} - \frac{1}{6}\mathcal{C}_{Qt}^{(8)}}{\mathcal{C}_{tG}} K_{tG} \times$$



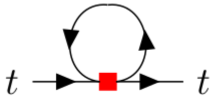
$$K_{tG} = \begin{cases} \frac{\sqrt{2} m_t g_s}{16\pi^2 v} & \text{(NDR)} \\ 0 & \text{(BMHV)} \end{cases}$$



$$\Big|_{\text{FIN}} = \frac{1}{\Lambda^2}\left(\mathcal{C}_{Qt}^{(1)} + \frac{4}{3}\mathcal{C}_{Qt}^{(8)}\right) \times \left(B_{h\bar{t}t} + K_{h\bar{t}t}\right) \times$$



$$K_{h\bar{t}t} = \begin{cases} \frac{(m_h^2 - 6m_t^2)}{16\pi^2} & \text{(NDR)} \\ 0 & \text{(BMHV)} \end{cases}$$

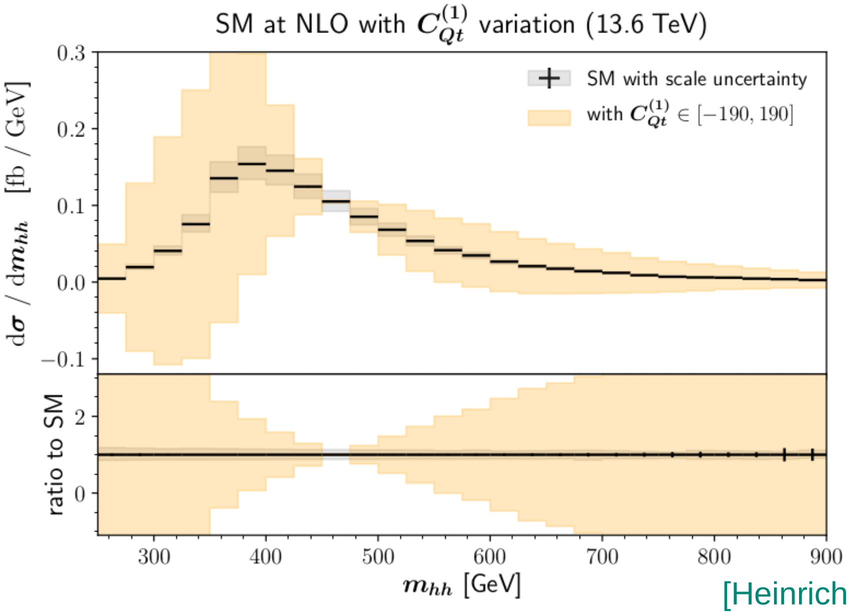


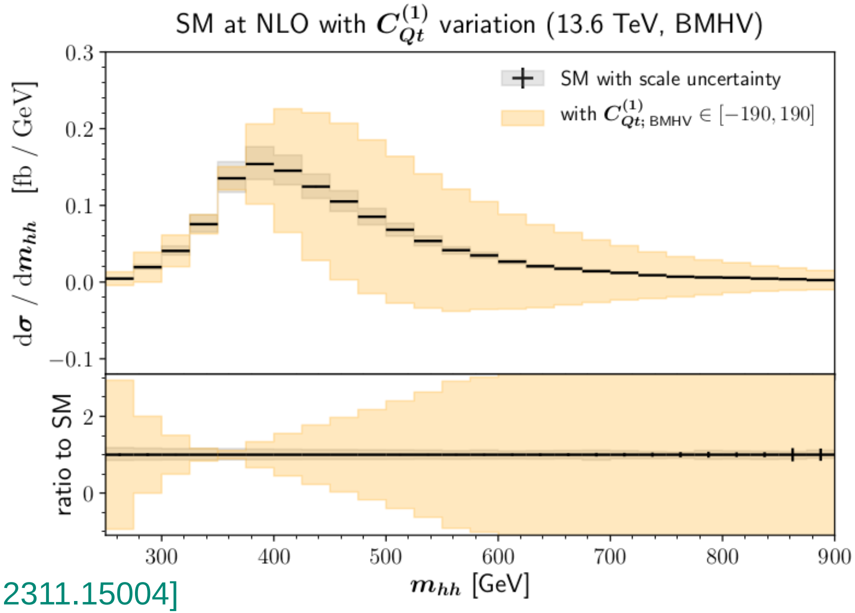
$$\Big|_{\text{FIN}} = \frac{1}{\Lambda^2}\left(\mathcal{C}_{Qt}^{(1)} + \frac{4}{3}\mathcal{C}_{Qt}^{(8)}\right) \times \left(B_{m_t} + K_{m_t}\right) \times$$

$$K_{m_t} = \begin{cases} -\frac{m_t^2}{8\pi^2} & \text{(NDR)} \\ 0 & \text{(BMHV)} \end{cases}$$

Effect of γ^5-scheme on $gg \to HH$

Karlsruhe Institute of Technology





[Heinrich, Lang - 2311.15004]

(NDR used for all contributions)

(4-top contribution computed in BMHV)

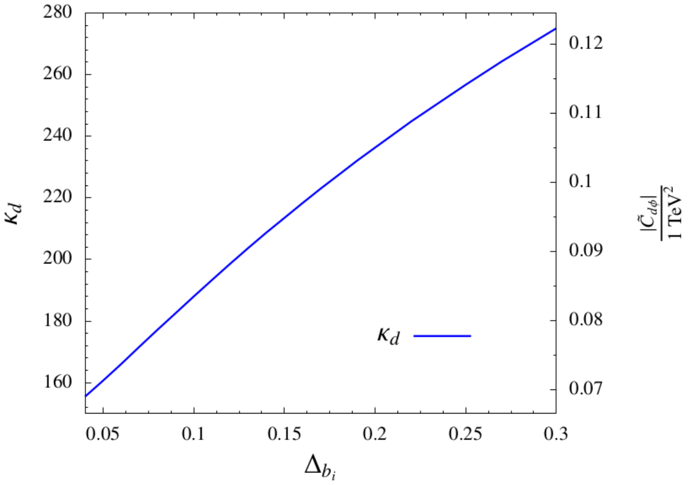
Light Yukawas - Phenomenological Analysis

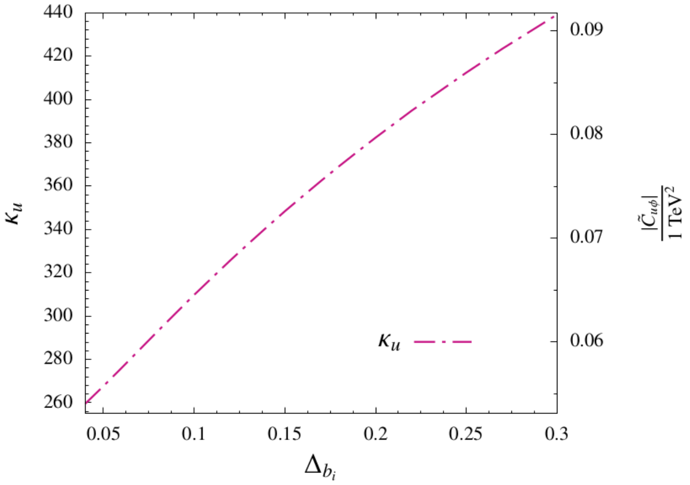
- Shape analysis on D_s^d distributions – off-shell region defined by $m_{ZZ} > 250\,\mathrm{GeV}$
- Consider only the ZZ→4l final state
- Efficiency factors obtained from MadGraph based on experimental cuts $(p_T > 10\,\mathrm{GeV},\ |\eta| < 2.5)$

For $\Delta_{b_i} = 0.04$
(HL-LHC S2 scenario)

$$|\tilde{C}_{d\phi}|/(1\ \mathrm{TeV})^2 < 0.069/\mathrm{TeV}^2$$
$$|\tilde{C}_{u\phi}|/(1\ \mathrm{TeV})^2 < 0.054/\mathrm{TeV}^2$$
$$\Updownarrow$$
$$(\kappa_d < 156)$$
$$(\kappa_u < 260)$$

$$Z_i = \sqrt{2\left[(s_i+b_i)\ln\frac{(s_i+b_i)(b_i+\sigma_{b_i}^2)}{b_i^2+(s_i+b_i)\sigma_{b_i}^2} - \frac{b_i^2}{\sigma_{b_i}^2}\ln\left(1+\frac{s_i\sigma_{b_i}^2}{b_i(b_i+\sigma_{b_i}^2)}\right)\right]} \qquad \sigma_{b_i} = \Delta_{b_i} b_i$$





Consistency of EFT Analysis

- Sensitivity is not affected (much) by the choice of invariant mass range