

Mixed QCD-EW corrections to quark-induced Higgs production at hadron colliders

Federico Ripani

In Collaboration with:

R. Bonciani, F. Coro, F. Tramontano

hp2 2026

Karlsruhe, 8th October 2026



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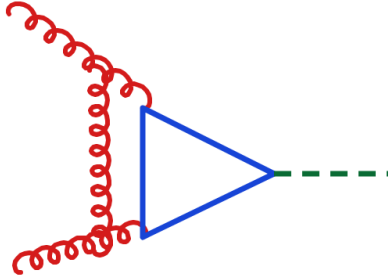
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ggF prediction 10 years ago

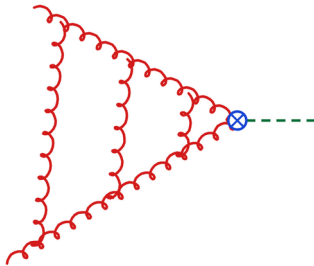
The gluon fusion channel accounts for about 87% of Higgs production

- Exact NLO-QCD: Quark mass effects (t-b-c) represent a correction of -4.2% to the total cross section



[Graudenz, Spira, Zerwas '93]
[Spira, Djouadi, Graudenz, Zerwas '95]

- N3LO in HEFT (infinite top-mass limit) raised the central value of the total cross section by 3% and featured a 3-4% scale variation

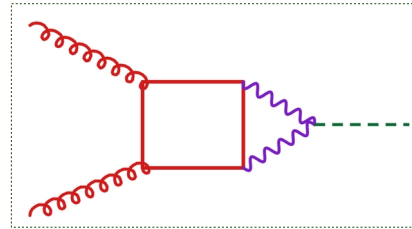


[Anastasiou, Duhr, Dulat, Herzog, Mistlberger '15]
[Mistlberger '18]

ggF prediction 10 years ago

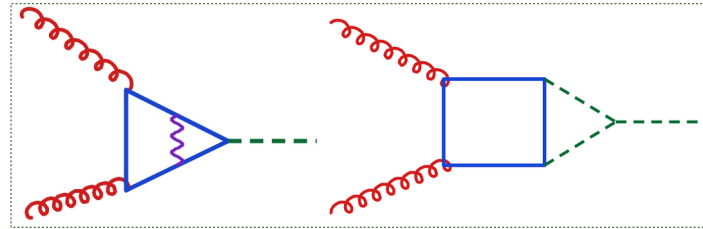
The gluon fusion channel accounts for about 87% of Higgs production

- $\alpha^2 \alpha_s^2 \sim \alpha \alpha_s^4$ (EW $\sim$ NNLO QCD)



Light-quark
contribution
~95% of the EW
corrections

[Aglietti, Bonciani, Degrassi, Vicini '04]

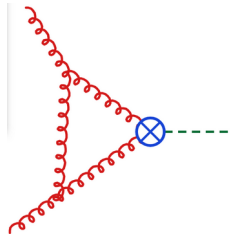


heavy-quark
contribution
~5% of the EW
corrections

[Degrassi, Maltoni '04]

[Actis, Passarino, Sturm, Uccirati '08]

- Mixed QCD-EW corrections $\mathcal{O}(\alpha^2 \alpha_s^3)$ estimated through EFT with W and Z integrated out.
Total EW corrections are 5% of the total cross section, with uncertainty of 1%



$$C \equiv C_{QCD} + \lambda_{EW} (1 + C_{1w} a_s + C_{2w} a_s^2 + \dots) \quad C_{1w} = \frac{7}{6}$$

[Anastasiou, Boughezal, Petriello '09]

ggF prediction 10 years ago

The gluon fusion channel accounts for about 87% of Higgs production

- Including quark mass effects, EW corrections and N3LO HEFT the cross section at 13 TeV is

$$\sigma = 48.58 \text{ pb}^{+2.22 \text{ pb} (+4.56\%)}_{-3.27 \text{ pb} (-6.72\%)} (\text{theory}) \pm 1.56 \text{ pb} (3.20\%) (\text{PDF} + \alpha_s).$$

- The breakdown of the cross section

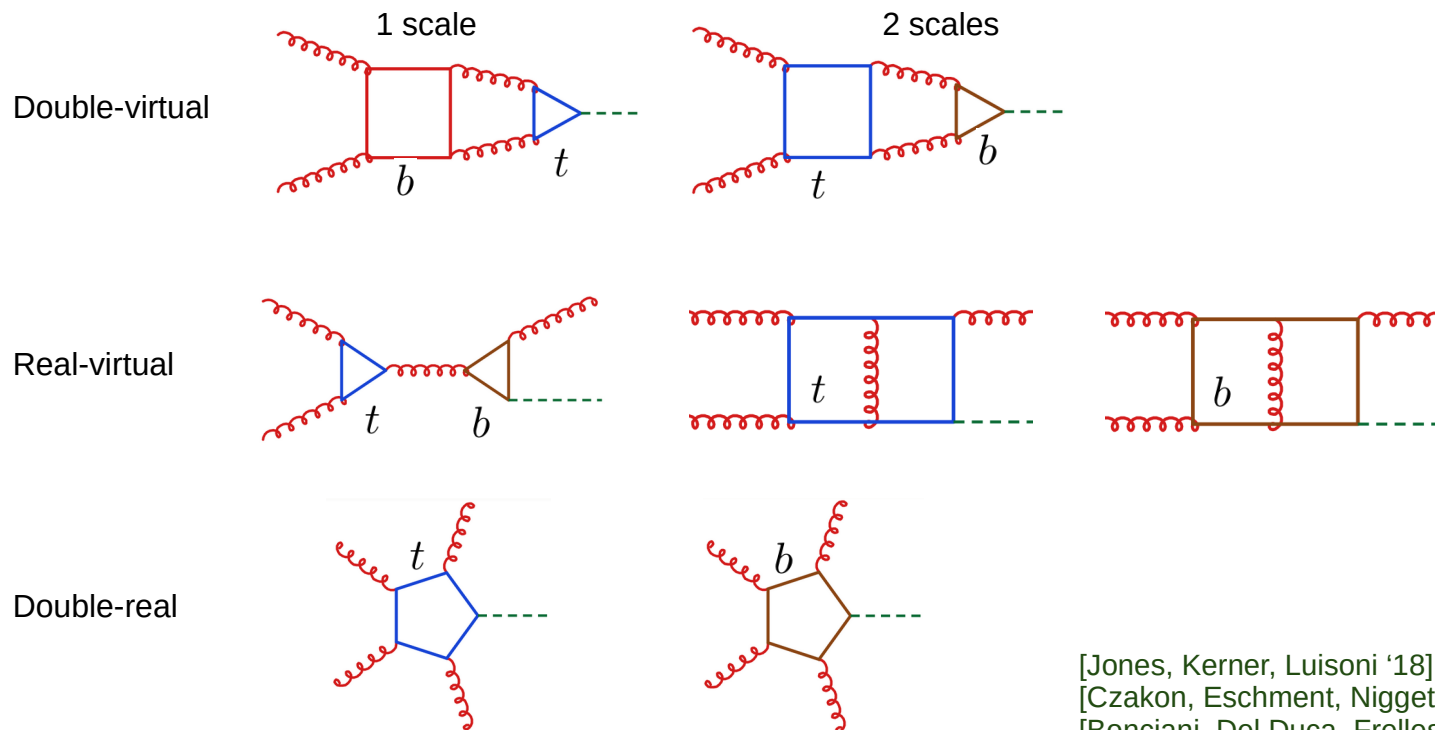
$$\begin{aligned} 48.58 \text{ pb} = & 16.00 \text{ pb} \quad (+32.9\%) \quad (\text{LO, rEFT}) \\ & + 20.84 \text{ pb} \quad (+42.9\%) \quad (\text{NLO, rEFT}) \\ & - 2.05 \text{ pb} \quad (-4.2\%) \quad ((t, b, c), \text{ exact NLO}) \\ & + 9.56 \text{ pb} \quad (+19.7\%) \quad (\text{NNLO, rEFT}) \\ & + 0.34 \text{ pb} \quad (+0.2\%) \quad (\text{NNLO, } 1/m_t) \\ & + 2.40 \text{ pb} \quad (+4.9\%) \quad (\text{EW, QCD-EW}) \\ & + 1.49 \text{ pb} \quad (+3.1\%) \quad (\text{N}^3\text{LO, rEFT}) \end{aligned}$$

Towards 1% precision

- Quark-mass effects at NNLO
- N4LO in HEFT → see Adi's talk
- Mixed QCD-EW corrections

Top-mass and top-bottom interference effects @ NNLO

- **5-flavor scheme:** bottom massive only when couples to the Higgs



[Jones, Kerner, Luisoni '18]

[Czakon, Eschment, Niggetiedt, Poncelet, Schellenberger '24]

[Bonciani, Del Duca, Frellesvig, Hidding, Hirschi, Moriello, Salvatori, Somogyi, Tramontano '24]

Top-mass and top-bottom interference effects @ NNLO

- **5-flavor scheme:** bottom massive only when couples to the Higgs

Order	σ_{HEFT} [pb]	$(\sigma_t - \sigma_{\text{HEFT}})$ [pb]	$\sigma_{t \times b}$ [pb]	$\sigma_{t \times b} (Y_{b,\overline{\text{MS}}})$ [pb]	$\sigma_{t \times b} / \sigma_{\text{HEFT}}$ [%]
$\sqrt{s} = 13 \text{ TeV}$					
$\mathcal{O}(\alpha_s^2)$	+16.30	–	–1.975	–1.223	
LO	$16.30^{+4.36}_{-3.10}$	–	$-1.98^{+0.38}_{-0.53}$	$-1.22^{+0.29}_{-0.44}$	–12
$\mathcal{O}(\alpha_s^3)$	+21.14	–0.303	–0.446(1)	–0.623(1)	
NLO	$37.44^{+8.42}_{-6.29}$	$-0.303^{+0.10}_{-0.17}$	$-2.42^{+0.19}_{-0.12}$	$-1.85^{+0.26}_{-0.26}$	$-6.5^{+0.9}_{-0.8}$
$\mathcal{O}(\alpha_s^4)$	+9.72	+0.147(1)	+0.434(8)	+0.019(5)	
NNLO	$47.16^{+4.21}_{-4.77}$	$-0.156(1)^{+0.13}_{-0.03}$	$-1.99(1)^{+0.30}_{-0.15}$	$-1.83(1)^{+0.08}_{-0.03}$	$-4.2^{+0.9}_{-0.8}$

- top-bottom interference larger than top-mass effect

[Czakon, Eschment, Niggetiedt, Poncelet, Schellenberger '24]

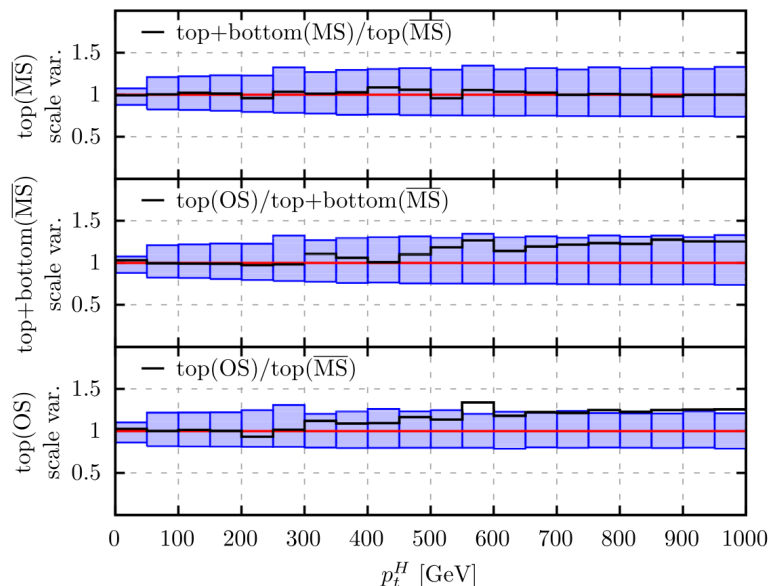
- top-bottom interference features renormalization scheme dependence:

- On-shell masses and Yukawa coupling $\longrightarrow \mathcal{O}(\alpha_s^4)$ as large as $\mathcal{O}(\alpha_s^3)$ with opposite sign, $\mathcal{O}(\alpha_s^4)$ larger than NLO scale variation, scale variation bigger at NNLO than NLO
- On-shell masses and $\overline{\text{MS}}$ Yukawa coupling $\longrightarrow$ Better convergence from NLO to NNLO

Top, bottom and top-bottom in the p_T distribution @ NNLO

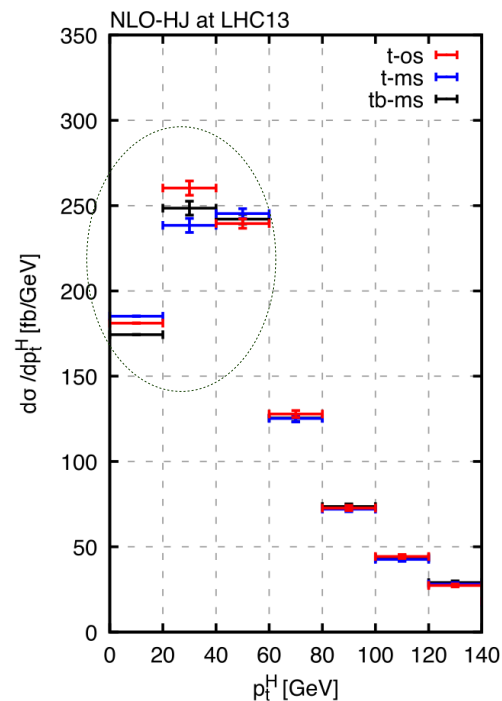
[Bonciani, Del Duca, Frellesvig, Hidding, Hirschi, Moriello, Salvatori, Somogyi, Tramontano '24]

- **5-flavor scheme:** bottom massive only when couples to the Higgs



- bottom and top-bottom effects negligible at high p_T ($>60\text{GeV}$)

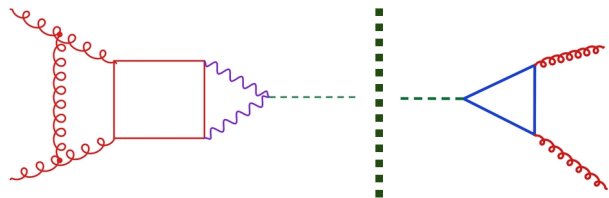
- $\overline{\text{MS}}$ distribution falls off faster than OS distribution



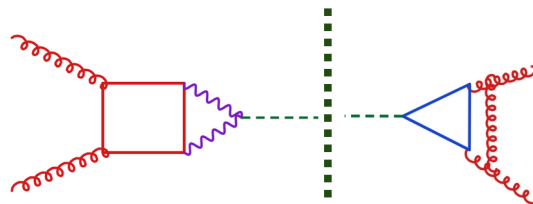
- top-bottom effect changes the shape at low p_T ($<60\text{GeV}$)

Mixed QCD-EW corrections (gluon channel)

● Double-virtual:



[Bonetti,Melnikov,Tancredi '18]



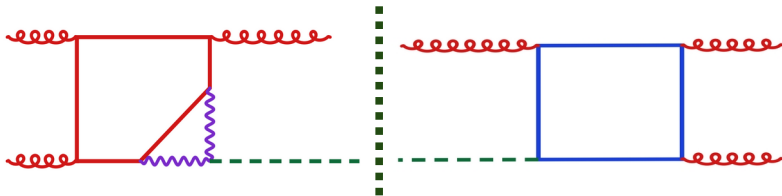
$$\mathcal{O}(\alpha^2 \alpha_s^3)$$

electroweak light-quark contribution



all MPLs

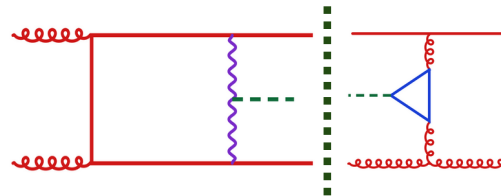
● Real-virtual:



[Bonetti,Panzer,Smirnov,Tancredi '20]

[Becchetti,Bonciani,Del Duca,Hirschi,Moriello,Schweitzer '21]

● Double-real:

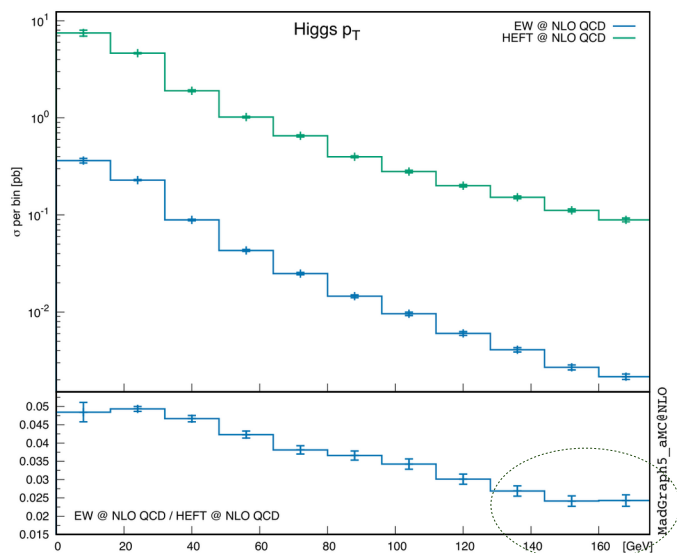


[Hirschi,Lionetti,Schweitzer '19]

Negligible

Mixed QCD-EW corrections (gluon channel)

● pT distribution NLO(EW)/NLO(HEFT)



modest violation of
electroweak factorisation

● Total cross-section

$$\sigma(\alpha_s^2 \alpha^2 + \alpha_s^3 \alpha^2)_{gg \rightarrow H+X} = 1.467(2) {}^{+18.7\%}_{-14.6\%} (\mu_R \text{ var.}) \pm 2\% (\text{PDF}) \text{ pb}$$

- 5.1% of the gg NLO HEFT
- Result within the uncertainty of the estimation based on electroweak factorisation and infinite W and Z mass limit
- Classical features of gg channel: LO and NLO of the same order, uncertainty band does not decrease at NLO

Mixed QCD-EW corrections (qg and qq channel)

- Estimation of NLO QCD-EW corrections to qg channel with HEFT K-factor $\mathcal{O}(\alpha^2 \alpha_s^3)$

is one of the main sources of uncertainty on EW corrections

$$\sigma_{qg \rightarrow H+X}^{\alpha_s^3 \alpha^2} \approx \sigma_{qg \rightarrow H+X}^{\alpha_s^2 \alpha^2} \frac{\sigma_{qg \rightarrow H+X}^{\alpha_s^3 \alpha}}{\sigma_{qg \rightarrow H+X}^{\alpha_s^2 \alpha}} = \begin{cases} -0.10 \pm 0.05 \text{ pb} ; \mu_{R/F} = M_H \\ 0.12 \pm 0.05 \text{ pb} ; \mu_{R/F} = \frac{M_H}{2} \end{cases}$$

[Becchetti, Bonciani, Del Duca, Hirschi, Moriello, Schweitzer '20]

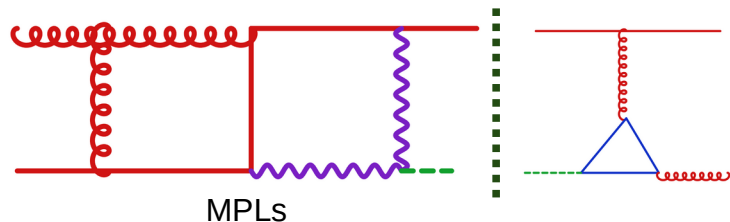
- Exact phenomenological study of **NLO QCD-EW corrections to qg (and qq) still missing**...we are close to have something (I hope)
- It is an NLO QCD correction with a one-loop born  FKS subtraction scheme
[Frixione, Kunszt, Signer '96]
[Catani, Seymour '97]

Mixed QCD-EW corrections (qg and qq channel)

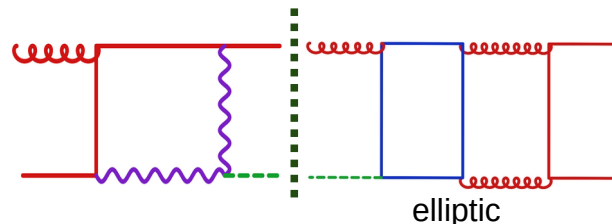
● Virtual:

electroweak light-quark contribution

$$\mathcal{O}(\alpha^2 \alpha_s^3)$$



[Bonetti, Panzer, Tancredi '22] ← analytical formula
We did an independent semi-analytical computation

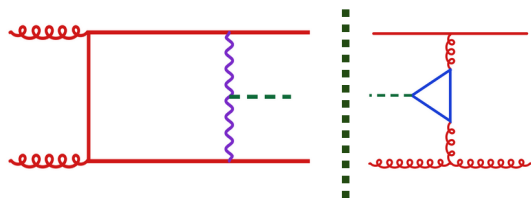


semi-analytical, numerical grid → [Bonciani, Del Duca, Frellesvig, Hidding, Hirschi, Moriello, Salvatori, Somogyi, Tramontano '24]

Numerical integration → [Jones, Kerner, Luisoni '18]

For an analytical computation of the master integrals see **Bakul's talk**

● Real:

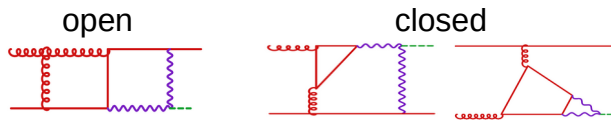


One-loop 2->3 matrix elements done with **Recola**

[Actis, Denner, Hofer, Lang, Scharf, Uccirati '17]

Two-loop amplitudes $gq(\bar{q}) \rightarrow q(\bar{q})H$, $q\bar{q} \rightarrow gH$

- $\mathcal{A}_\mu = \mathcal{A}_\mu^{\text{open}} + \mathcal{A}_\mu^{\text{closed}}$
- Anticommuting gamma5: $\{\gamma_\mu, \gamma_\nu\} = 2g_{\mu\nu}$, $\{\gamma_\mu, \gamma_5\} = 0$, $\gamma_5^2 = \mathbb{I}$



- Effective vector couplings depending on the helicity of the incoming quark:

$$\gamma^\mu (g_V^v + \gamma_5 g_V^a) \longrightarrow (g_V^v - g_V^a) \gamma^\mu \quad \text{Left-handed quark}$$

$$\gamma^\mu (g_V^v + \gamma_5 g_V^a) \longrightarrow (g_V^v + g_V^a) \gamma^\mu \quad \text{Right-handed quark}$$

- Usual form factor decomposition

$$\tau_{1,\mu} = \not{p}_1 p_{2\mu} - p_2 \cdot p_1 \gamma_\mu \quad \tau_{2,\mu} = \not{p}_1 p_{3\mu} - p_1 \cdot p_3 \gamma_\mu$$

- Open amplitude

$$\mathcal{A}_{R,\mu}^{\text{open}} = (g_Z^v + g_Z^a)^2 [\tau_{1,\mu} F_{1,m_Z}^{\text{open}} + \tau_{2,\mu} F_{2,m_Z}^{\text{open}}] \mathbb{P}_R$$

Right-handed quark does not interact with W

$$\mathcal{A}_{L,\mu}^{\text{open}} = [\tau_{1,\mu} F_{1,m_W}^{\text{open}} + \tau_{2,\mu} F_{2,m_W}^{\text{open}}] \mathbb{P}_L + (g_Z^v - g_Z^a)^2 [\tau_{1,\mu} F_{1,m_Z}^{\text{open}} + \tau_{2,\mu} F_{2,m_Z}^{\text{open}}] \mathbb{P}_L$$

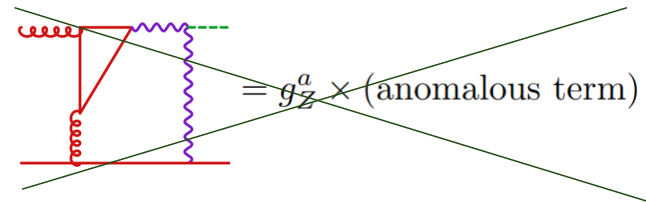
- Closed amplitude

$$\mathcal{A}_\mu^{\text{closed}} = N_{\text{iso}} (\tau_{1,\mu} F_{1,m_W}^{\text{closed}} + \tau_{2,\mu} F_{2,m_W}^{\text{closed}}) + [N_d ((g_{Z,d}^v)^2 + (g_{Z,d}^a)^2) + N_u ((g_{Z,u}^v)^2 + (g_{Z,u}^a)^2)] (\tau_{1,\mu} F_{1,m_Z}^{\text{closed}} + \tau_{2,\mu} F_{2,m_Z}^{\text{closed}})$$

Nothing new with respect to [Bonetti, Panzer, Tancredi '22]

$g_W^v = \frac{1}{2}$	$g_W^a = -\frac{1}{2}$
$g_Z^v = \frac{\sqrt{2}}{\cos^2 \theta_W} \left(\frac{T_q}{2} - \sin^2 \theta_W Q_q \right)$	$g_Z^a = -\frac{\sqrt{2}}{\cos^2 \theta_W} \frac{T_q}{2}$

- One weak-boson insertion



- Two weak-boson insertions

$$= \sum_{V,q} [(g_V^v)^2 + (g_V^a)^2] \times (\text{non-anomalous term}) + g_V^v g_V^a \times (\text{anomalous term})$$

$$N_{\text{iso}} = 2$$

$$N_d = 3$$

$$N_u = 2$$

Two-loop amplitudes $gq(\bar{q}) \rightarrow q(\bar{q})H$, $q\bar{q} \rightarrow gH$

- Open contribution starts at one-loop, closed contribution is a two-loop effect

$$F_{j,m_V}^{\text{open}} = \sqrt{\alpha_s} \left[F_{j,m_V}^{\text{open},(1)} + \left(\frac{\alpha_s}{2\pi} \right) F_{j,m_V}^{\text{open},(2)} + \mathcal{O}(\alpha_s^2) \right],$$

$$F_{j,m_V}^{\text{closed}} = \sqrt{\alpha_s} \left[\left(\frac{\alpha_s}{2\pi} \right) F_{j,m_V}^{\text{closed},(2)} + \mathcal{O}(\alpha_s^2) \right],$$

- Open amplitude is divergent, alpha strong renormalised in $\overline{\text{MS}}$ scheme

$$\mathcal{F}_{j,m_V}^{\text{open},(2)} = F_{j,m_V}^{\text{open},(2)} - \frac{1}{2} \frac{\beta_0}{\epsilon} \left(\frac{\mu^2}{m_V^2} \right)^{-\epsilon} F_{j,m_V}^{\text{open},(1)} - \mathbf{I}^{(1)} \left(\frac{\mu^2}{m_V^2} \right)^{-\epsilon} F_{j,m_V}^{\text{open},(1)}$$

Finite
remainder

UV counter term

IR counter term [Catani '98]

- $\mathcal{F}_{j,m_V}^{\text{open},(2)}$ can be expanded in N_c (number of colors) and N_f (number of active light-fermion)

$$\mathcal{F}_{j,m_V}^{\text{open},(2)} = \frac{1}{m_V^4} \left[N_f \mathcal{B}_{j,m_V} \left(\frac{s_{ij}}{m_V^2}, \frac{\mu^2}{m_V^2} \right) + N_c \mathcal{C}_{j,m_V} \left(\frac{s_{ij}}{m_V^2}, \frac{\mu^2}{m_V^2} \right) + \frac{1}{N_c} \mathcal{D}_{j,m_V} \left(\frac{s_{ij}}{m_V^2}, \frac{\mu^2}{m_V^2} \right) \right]$$

planar leading color
form factor

non-planar sub-leading
color form factor



Two-loop amplitudes $gq(\bar{q}) \rightarrow q(\bar{q})H$, $q\bar{q} \rightarrow gH$

- Pipeline of the computation of the form factors $F(\text{open},1)$, $F(\text{closed},2)$, B , C , D .

QGRAF	[Nogueira]
Mathematica+FORM	[Ruijl, Ueda, Vermaseren]
KIRA	[Klappert, Lange, Maierhofer, Usovitsch]
AMFlow	[Liu, Ma]
DiffExp	[Hidding]



Numerical cancellation of the poles



Finite remainder agree with [Bonetti, Panzer, Tancredi '22]

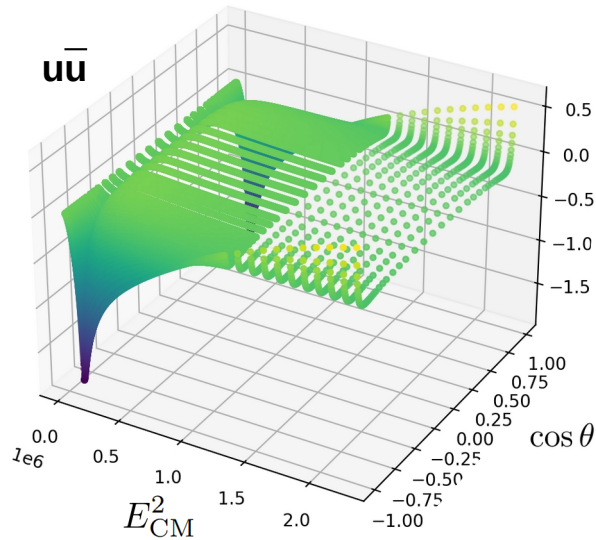
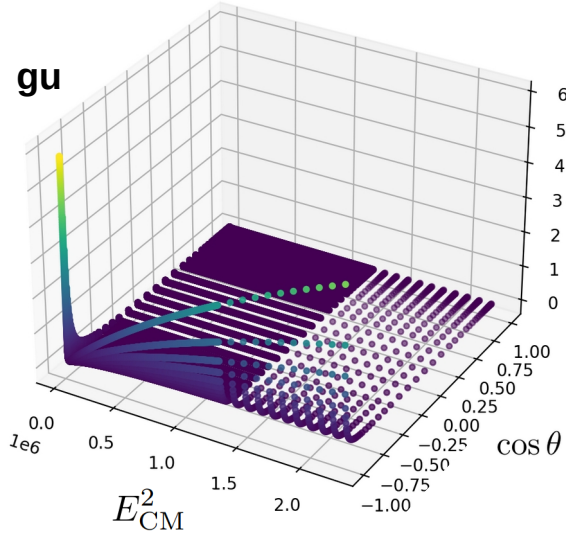
- Numerical grids for the form factors in 3 physical regions with 186K points each + RECOLA for one-loop QCD (also analytical)



Numerical grids for the interference

- **5-flavor scheme:** b-quark is active ($N_f=5$) but all electroweak contributions with also top-quark are neglected (b-quark present only with Z boson)

Numerical grids



$$m_W = 80.3692 \text{ GeV}$$

$$m_Z = 91.1880 \text{ GeV}$$

$$m_H = 125.200 \text{ GeV}$$

$$m_t = 172.400 \text{ GeV}$$

$$\cos \theta_W = \frac{m_W}{m_Z}$$

$$\sin \theta_W = \sqrt{1 - \cos^2 \theta_W}$$

- Divergences compromise the quality of the interpolation

Conclusions

- Mixed QCD-EW corrections to quark-initiated higgs production are the main source of uncertainty to a precise determination of the EW part of the cross-section
- Our expressions for the form factors are less elegant than [Bonetti, Panzer, Tancredi '22] but allowed us to build numerical grids for one of the double-virtual term
- How to make the most of the grids? Ideas are: On the fly evaluation using the grid (or a subset) as boundary points (as done for gg channel), subtraction of the divergent part,...
- Evaluation of Two-loop QCD amplitude of the second double-virtual term is already implemented ([Bonciani, Del Duca, Frellesvig, Hidding, Hirschi, Moriello, Salvatori, Somogyi, Tramontano '24]), we have only to interfere with the electroweak one-loop
- What about anomalous contribution? How small is it?