

Mixed QCD-electroweak corrections to Higgs plus jet production at the LHC

Marco Bonetti

SM@LHC 2022



In collaboration with
E. Panzer, V. A. Smirnov, L. Tancredi
[2007.09813] [2203.17202]

Higgs boson at the LHC

[1602.00695] [1610.07922] [1802.00833]

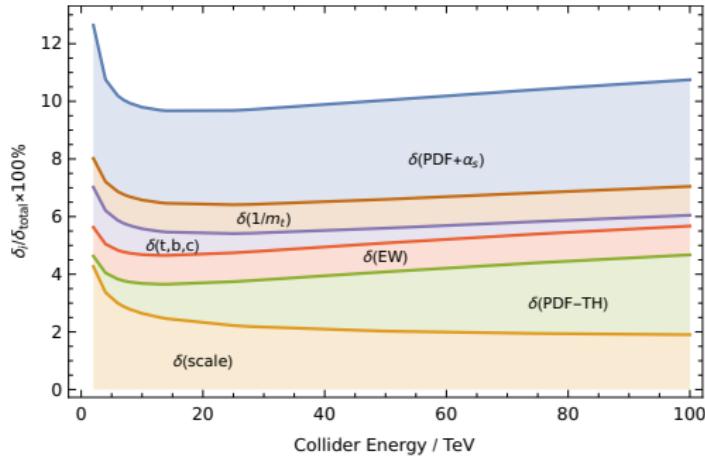
Higgs production modes					
ggH	VVH	WH	ZH	$t\bar{t}H$	Total
$44.1^{+11\%}_{-11\%}$	$3.78^{+2\%}_{-2\%}$	$1.37^{+2\%}_{-2\%}$	$0.88^{+5\%}_{-5\%}$	$0.51^{+9\%}_{-13\%}$	50.6

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Theoretical uncertainties

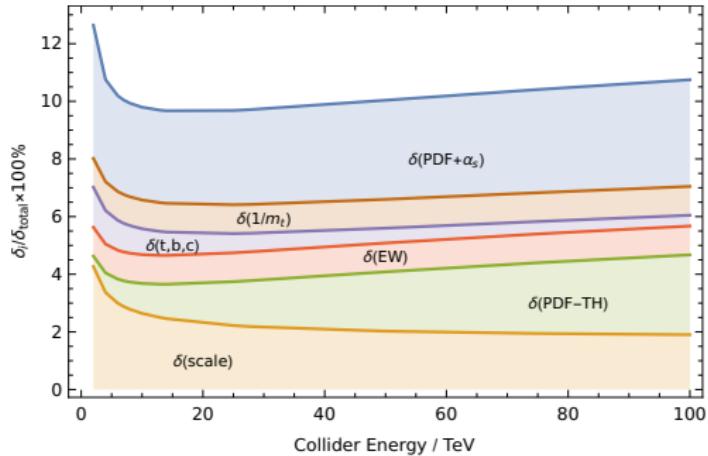


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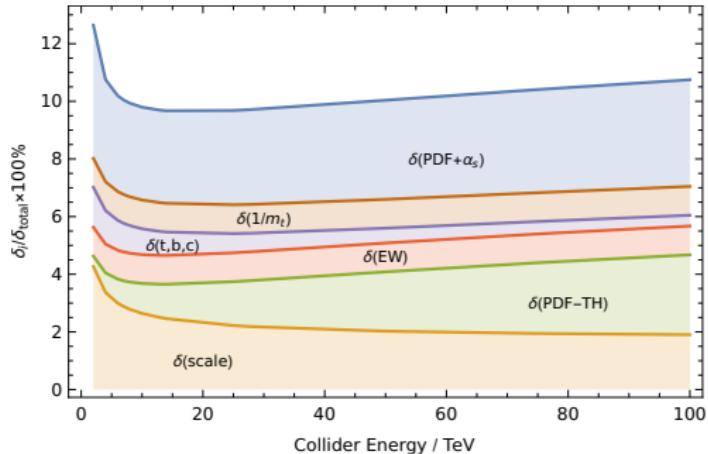
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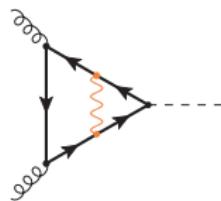
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Exact NLO QCD-EW computation necessary

QCD-EW contributions

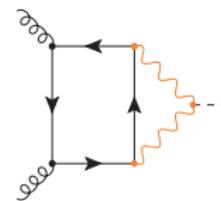
[ph0404071] [ph0407249] [ph0610033]

Yukawa coupling $\alpha_S \alpha Y_t$



- Dominated by **top quark**
- $\sim 0.5\%$ of $\sigma_{\text{QCD}}^{\text{LO}}$

Electroweak coupling $\alpha_S \alpha^2 v$

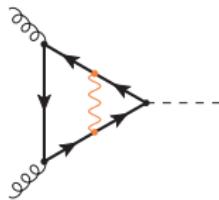


- Dominated by light quarks
- $+5.3\%$ of $\sigma_{\text{QCD}}^{\text{LO}}$

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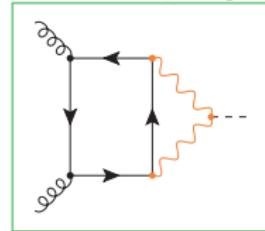
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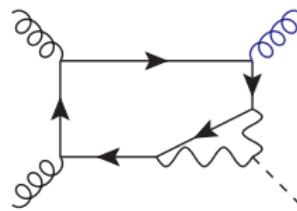
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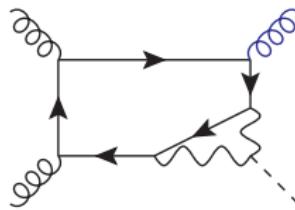
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	LO	NLO virtual	NLO real
$P \rightarrow g$			
$P \rightarrow q$			

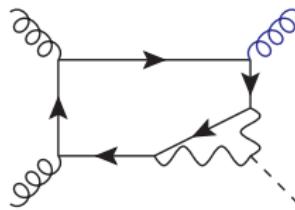
$gg \rightarrow Hg$ 

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Axial contributions from γ_5

Loop of massless quarks: sum over complete generations removes explicit γ_5 , axial contributions as rescaled couplings

$gg \rightarrow Hg$

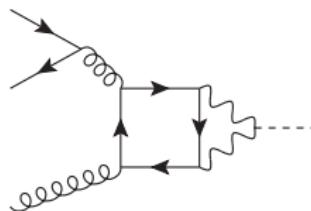


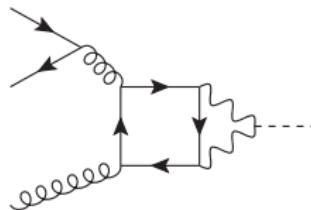
Axial contributions from γ_5

Loop of massless quarks: sum over complete generations removes explicit γ_5 , axial contributions as rescaled couplings

$$f^{c_1 c_2 c_3} \epsilon_{\lambda_1}^{\mu}(p_1) \epsilon_{\lambda_2}^{\nu}(p_2) \epsilon_{\lambda_3}^{\rho}(p_3) [\mathcal{F}_1 g_{\mu\nu} p_{2\rho} + \mathcal{F}_2 g_{\mu\rho} p_{2\nu} + \mathcal{F}_3 g_{\nu\rho} p_{2\mu} + \mathcal{F}_4 p_{3\mu} p_{1\nu} p_{2\rho}]$$

$$\mathcal{F}_j = 4 A_j(m_W^2) + \frac{2}{\cos^4 \theta_W} \left(\frac{5}{4} - \frac{7}{3} \sin^2 \theta_W + \frac{22}{9} \sin^4 \theta_W \right) A_j(m_Z^2)$$

$qg \rightarrow Hq$ 

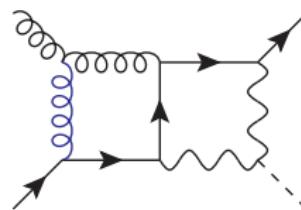
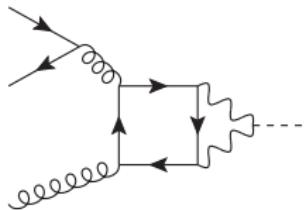
$qg \rightarrow Hq$


Axial contributions from γ_5

$\mathcal{F}_j^{\text{closed}}$ no γ_5

$$T_{j_1 j_2}^{c_3} \bar{v}_{s_1}(p_1) \left[\tau_1^\mu \mathcal{F}_1^{\text{closed}} + \tau_2^\mu \mathcal{F}_2^{\text{closed}} \right] u_{s_2}(p_2) \epsilon_\mu^{\lambda_3}(p_3)$$

$$\mathcal{F}_j^{\text{closed}} = 4 A_j^{\text{closed}}(m_W^2) + \frac{2}{\cos^4 \theta_W} \left(\frac{5}{4} - \frac{7}{3} \sin^2 \theta_W + \frac{22}{9} \sin^4 \theta_W \right) A_j^{\text{closed}}(m_Z^2)$$

$qg \rightarrow Hq$


Axial contributions from γ_5

$\mathcal{F}_j^{\text{closed}}$ no γ_5
 $\mathcal{F}_j^{\text{open}}$ "polarized" coupling

$$T_{j_1 j_2}^{c_3} \bar{v}_{s_1}(p_1) \left[\tau_1^\mu (\mathcal{F}_1^{\text{closed}} + \mathbb{P}_L \mathcal{F}_1^{\text{open}}) + \tau_2^\mu (\mathcal{F}_2^{\text{closed}} + \mathbb{P}_L \mathcal{F}_2^{\text{open}}) \right] u_{s_2}(p_2) \epsilon_\mu^{\lambda_3}(p_3)$$

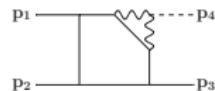
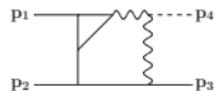
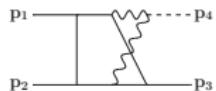
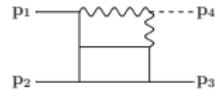
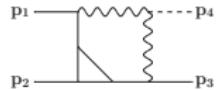
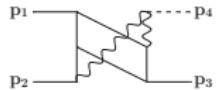
$$\mathcal{F}_{L,j}^{\text{open}} = \frac{2}{\cos^4 \theta_W} Q_q^2 \sin^4 \theta_W A_j^{\text{open}}(m_Z^2)$$

$$\mathcal{F}_{R,j}^{\text{open}} = 1 A_j^{\text{open}}(m_W^2) + \frac{2}{\cos^4 \theta_W} (T_q - Q_q \sin^2 \theta_W)^2 A_j^{\text{open}}(m_Z^2)$$

Solving MIs

[Panzer,2014]

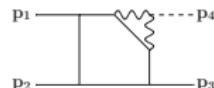
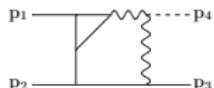
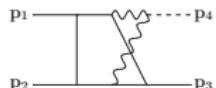
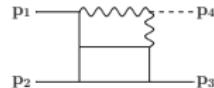
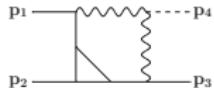
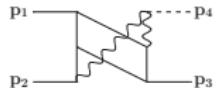
91 MIs



Solving MIs

[Panzer,2014]

91 MIs



Linear reducibility

- Integration over Feynman parameters
- There exists an integration order for the kernel f_0

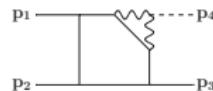
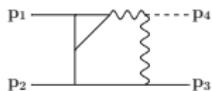
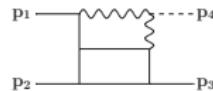
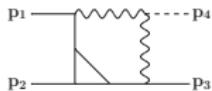
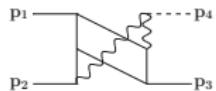
$$\int_0^{+\infty} dz_1 \cdots \int_0^{+\infty} dz_k f_0$$

such that each integral is a hyperlog of the next integration variable

Solving MIs

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$$\int_0^{+\infty} dz_1 \cdots \int_0^{+\infty} dz_k f_0$$

such that each integral is a hyperlog of the next integration variable

- Integration over d logs: GPLs
- No integration variables under square roots: no rationalization needed

Quasi-finite basis

[Tarasov,1996][Lee,2010][von Manteuffel. . . ,2015]

- 2-loop MIs highly divergent: up to ϵ^{-4}

- Amplitude not too divergent:

- $ggHg \quad \epsilon^0$

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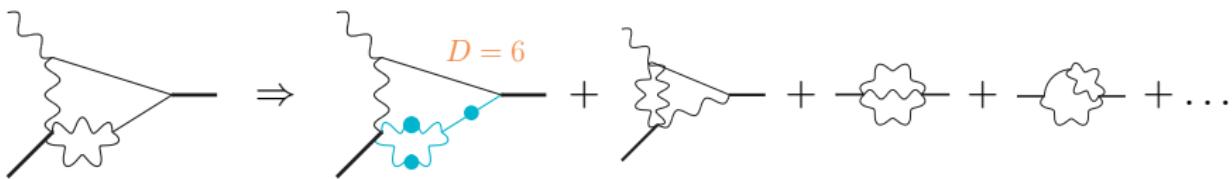
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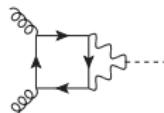
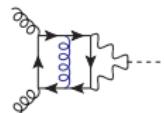
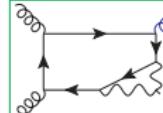
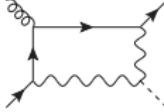
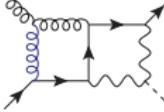
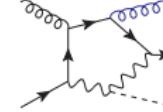
$$\mathcal{I}^{D+2}(a_1, \dots, a_7) = \frac{16}{s t u (D-4)(D-3)} \int \tilde{d}^D k_1 \tilde{d}^D k_1 \frac{G(k_1, k_2, p_1, p_2, p_3)}{\mathcal{D}_1^{a_1} \dots \mathcal{D}_7^{a_7}}$$

- **UV finiteness:** negative SDD by rising powers of (massive) propagators
- **IR finiteness:** Gram determinant cures soft & collinear divergences



Conclusions & Outlook

Complete analytic results

	LO	NLO virtual	NLO real
$P \rightarrow g$ $P \rightarrow g$			
$P \rightarrow g$ $P \rightarrow q$			

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The road ahead

- Full $\sigma_{PP \rightarrow H+X}^{(\alpha_S^3 \alpha^2)}$ evaluation
- Top quark inclusion

$\sigma_{gg \rightarrow H+X}^{(\alpha_S^2 \alpha^2 + \alpha_S^3 \alpha^2)}$: [Beccetti... ,2020]



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New challenges

- Expression optimization
- Non-vanishing γ_5 contributions

Thank you for your attention



BACKUP

Simplifying the amplitude

[Duhr. . . ,2019][Heller. . . ,2021]

Simplifying the amplitude

[Duhr. . . ,2019][Heller. . . ,2021]

$$A = \frac{2y - x}{y^3 - x^2y} G_1 + \frac{x - 1}{y(y - x)} G_2 + \frac{-x^2 - xy + 2x - y}{y(x - y)(x + y)} G_3$$

Simplifying the amplitude

[Duhr... ,2019][Heller... ,2021]

① Basis of algebraic prefactors

- Partial fraction decomposition
- Basis of algebraic prefactors

$$\begin{aligned} A &= \frac{2y - x}{y^3 - x^2y} G_1 + \frac{x - 1}{y(y - x)} G_2 + \frac{-x^2 - xy + 2x - y}{y(x - y)(x + y)} G_3 \\ &= \left[\frac{3}{2} \frac{1}{y(x + y)} - \frac{1}{2} \frac{1}{y(x - y)} \right] (G_1 + G_3) \end{aligned}$$

Simplifying the amplitude

[Duhr. . . , 2019][Heller. . . , 2021]

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- Basis of algebraic prefactors

② Linearly independent transcendental expressions

- PSLQ reduction

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 &= \left[\frac{1}{2} \frac{1}{y(x - y)} + \frac{3}{2} \frac{1}{y(x + y)} - \frac{1}{x - y} - \frac{1}{y} \right] (\textcolor{red}{G_1 + G_3})
 \end{aligned}$$

Simplifying the amplitude

[Duhr. . . , 2019][Heller. . . , 2021]

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③ Manipulation of GPLs

- Symbol reduction
- GPLs into logs, Li_2 , Li_3

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Simplifying the amplitude

[Duhr... ,2019][Heller... ,2021]

- ➊ Basis of algebraic prefactors
 - Partial fraction decomposition
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- ➋ Linearly independent transcendental expressions
 - PSLQ reduction
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Finite remainders

- Reduced expressions

$\mathcal{F}_{q\bar{q}Hg}^{1/N_c}$	From $\sim 1 \text{ GiB}$ to $\sim 1 \text{ MiB}$
$\mathcal{F}_{q\bar{q}Hg}^{1/N_c}$	From 5524 terms to 54
- Transcendental weight drop

A_{ggHg}^{+++}	Drop from weight 4 to weight 3
$\mathcal{F}_{q\bar{q}Hg}^{N_c}$, $\mathcal{F}_{q\bar{q}Hg}^{1/N_c}$	Drop from weight 5 to weight 4