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

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Institute for Theoretical Particle Physics and Cosmology

RWTH AACHEN UNIVERSITY

TRR 257 - Particle Physics Phenomenology after the Higgs Discovery

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

1. Motivations & Overview
2. Process
3. Calculational details
4. Conlcusions

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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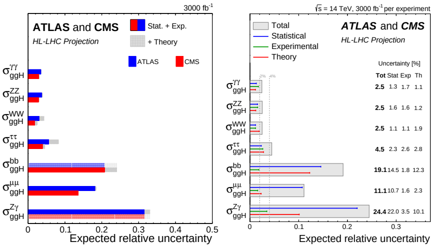
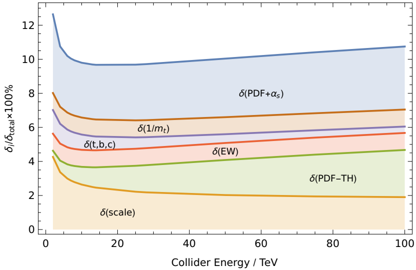
HL-LHC projections



Theoretical uncertainties



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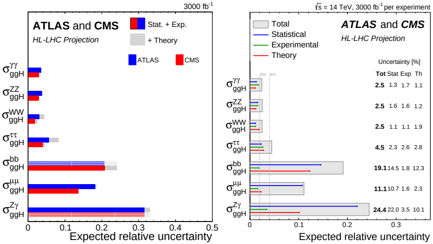

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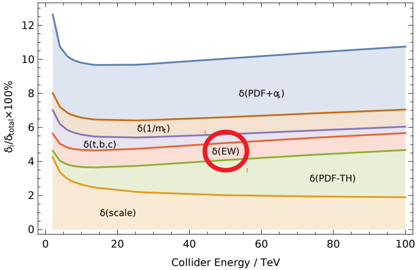


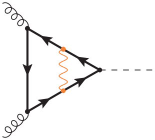
Only HEFT estimate at NLO, QCD corrections might enhance discrepancies

Exact NLO QCD-EW computation necessary

QCD-EW contributions

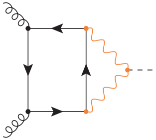
[ph0404071] [ph0407249] [ph0610033]

Yukawa coupling αY_t



- Dominated by **top quark**
- $\sim 0.5\,\%$ of $\sigma^{\mathrm{LO}}_{\mathrm{QCD}}$

Electroweak coupling $\alpha^2 v$



- Dominated by light quarks
- $+5.3\,\%$ of $\sigma^{\mathrm{LO}}_{\mathrm{QCD}}$

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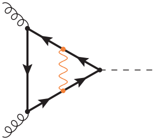

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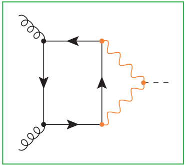

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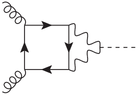
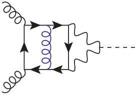
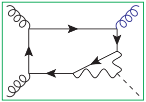
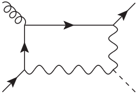
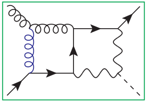
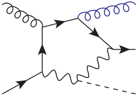
Partons	LO	NLO virtual	NLO real
g g			
g q g $\bar{q}$ q $\bar{q}$			

Tensor decomposition

- $q\bar{q}V$ contains chiral couplings

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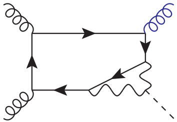

Closed fermion loop

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

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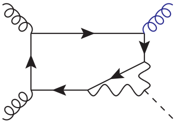

Loop of massless quarks: sum over complete generations removes explicit γ_5, rescaled couplings

$$F_{\text{QCD}} \quad \Rightarrow \quad 4F_W + \frac{2}{\cos^4\theta_W}\left(\frac{5}{4} - \frac{7}{3}\sin^2\theta_W + \frac{22}{9}\sin^4\theta_W\right)F_Z$$

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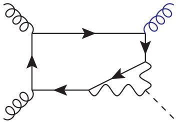

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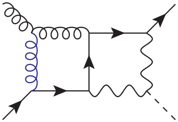
Open quark line



Move γ_5 to touch a spinor, "polarized" rescaling

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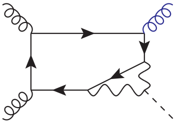

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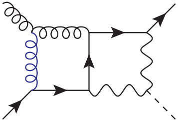
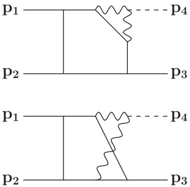


Move γ_5 to touch a spinor, "polarized" rescaling

$$F^R_{\mathrm{QCD}} \quad \Rightarrow \quad 1F_W \quad + \quad \frac{2}{\cos^4\theta_W}\left(T_q - Q_q\sin^2\theta_W\right)^2 F_Z$$

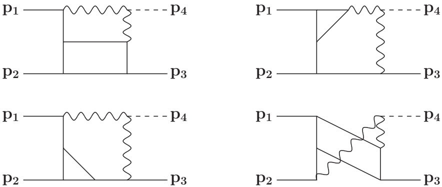
$$F^L_{\mathrm{QCD}} \quad \Rightarrow \quad \frac{2}{\cos^4\theta_W} Q_q^2 \sin^4\theta_W F_Z$$

Reduction to MIs



61 MIs

4 square roots



30 MIs

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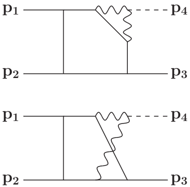
Reduction to MIs



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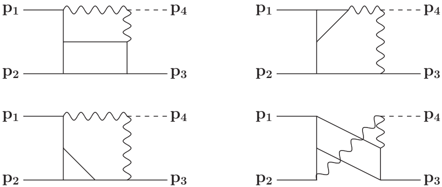

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Linear reducibility

- Integration over Feynman–Schwinger parameters
- There exists an integration order for the kernel $\mathfrak{log}\, R$

$$\int_0^{+\infty} \mathrm{d}\, z_1 \cdots \int_0^{+\infty} \mathrm{d}\, z_k \;\mathfrak{log}\, R_k(z_k) \Rightarrow \int_0^{+\infty} \mathrm{d}\, z_1 \;\mathfrak{log}\, R_1(z_1)$$

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

- Integration over $\mathrm{d}\log$s: result as GPLs
- No integration variables under square roots: no rationalization needed

A quasi-finite basis

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

- 2-loop MIs highly divergent: up to ϵ^{-4}
- Amplitudes well behaved: $ggHg$: ϵ^{0} $qgH\overline{q}$: ϵ^{-2}

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Quasi-finite basis

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

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

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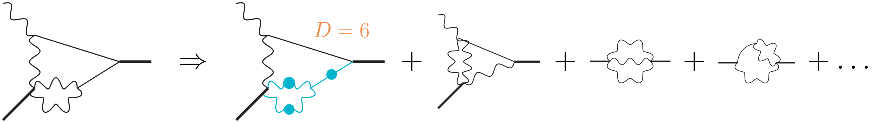

Simplifying the amplitude

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

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

Simplifying the amplitude

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

1. Partial fraction decomposition

$$A = \left[\frac{3}{2}\frac{1}{y(x+y)} - \frac{1}{2}\frac{1}{y(x-y)}\right] G_1 + \left[\frac{1}{y(x-y)} - \frac{1}{x-y} - \frac{1}{y}\right] G_2 + \left[\frac{1}{2}\frac{1}{y(x-y)} + \frac{3}{2}\frac{1}{y(x+y)} - \frac{1}{x-y} - \frac{1}{y}\right] G_3 + \ldots$$

Simplifying the amplitude

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

1. Partial fraction decomposition
2. Basis of algebraic prefactors

$$A = \left[\frac{3}{2}\frac{1}{y(x+y)} - \frac{1}{2}\frac{1}{y(x-y)}\right](G_1 + G_3) + \left[\frac{1}{y(x-y)} - \frac{1}{x-y} - \frac{1}{y}\right](G_2 + G_3) + \ldots$$

Simplifying the amplitude

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

1. Partial fraction decomposition
2. Basis of algebraic prefactors
3. Linearly independent transcendental expressions

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

Simplifying the amplitude

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

1. Partial fraction decomposition
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4. GPLs as Li functions

$$
\begin{aligned}
A = &\left[\frac{1}{2}\frac{1}{y(x-y)} + \frac{3}{2}\frac{1}{y(x+y)} - \frac{1}{x-y} - \frac{1}{y}\right](C_1 \log a_1 + C_2 \log a_2) + \\
&\left[\frac{1}{2}\frac{1}{y(x-y)} + \frac{3}{2}\frac{1}{y(x+y)} - \frac{1}{x-y} - \frac{1}{y}\right](C_4 \mathrm{Li}_2(b_1, b_2) + C_5 \log b_3 \log b_4) + \\
&\left[\frac{1}{2}\frac{1}{y(x-y)} + \frac{3}{2}\frac{1}{y(x+y)} - \frac{1}{x-y} - \frac{1}{y}\right](C_6 \log^3 c_1 + C_7 \zeta(3)) + \ldots
\end{aligned}
$$

Simplifying the amplitude

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

1. Partial fraction decomposition
2. Basis of algebraic prefactors
3. Linearly independent transcendental expressions
4. GPLs as Li functions
5. Helicity amplitudes

$$\mathcal{A}^{ggHg}_{+++} = \frac{m_h^2}{\sqrt{2}\langle 12\rangle\langle 23\rangle\langle 31\rangle}\frac{su}{m_h^2}\left(\mathcal{F}_1 + \frac{t}{u}\mathcal{F}_2 + \frac{t}{s}\mathcal{F}_2 + \frac{t}{2}\mathcal{F}_4\right)$$

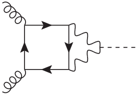
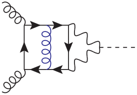
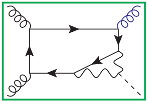
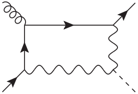
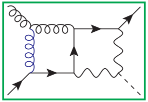
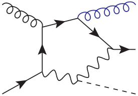
$$\mathcal{A}^{ggHg}_{++-} = \frac{[12]^3}{\sqrt{2}m_h^2[13][23]}\frac{um_h^2}{s}\left(\mathcal{F}_1 + \frac{t}{2}\mathcal{F}_4\right)$$

$$\mathcal{A}^{q\bar{q}Hg}_{RL+} = \frac{s}{\sqrt{2}}\frac{[23]^2}{[12]}\left(\mathcal{F}_C + \mathcal{F}_W + \mathcal{F}_Z\right)$$

$$\mathcal{A}^{q\bar{q}Hg}_{LR+} = \frac{s}{\sqrt{2}}\frac{[13]^2}{[12]}\left(\mathcal{F}_C + \mathcal{F}_Z\right)$$

Conclusions & Outlook

Complete analytic results

Partons	LO	NLO virtual	NLO real
$g \quad g$			
$g \quad q$ $g \quad \overline{q}$ $q \quad \overline{q}$			

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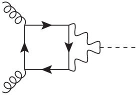
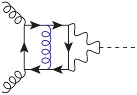
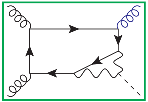
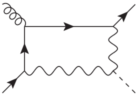
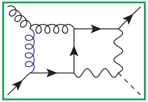
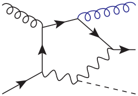
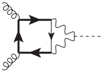
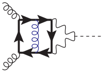
$g \quad g$			
$g \quad q$ $g \quad \bar{q}$ $q \quad \bar{q}$			

The road ahead

- Full $\sigma^{(\alpha_S^3 \alpha^2)}_{PP \to H+X}$ evaluation

$\sigma^{(\alpha_S^2 \alpha^2 + \alpha_S^3 \alpha^2)}_{gg \to H+X}$: [Becchetti. . . ,2020]

- Top quark inclusion

New challenges

- Expression optimization
- Non-vanishing γ_5 contributions & masses

Thank you for your attention

Institute for Theoretical Particle Physics and Cosmology

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TRR 257 - Particle Physics Phenomenology after the Higgs Discovery