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

Marco Bonetti

CRC TRR 257 Young Scientists Meeting

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]

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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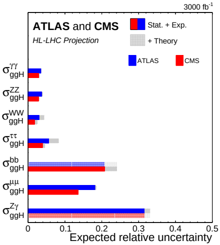
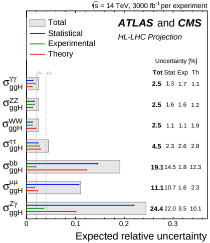
HL-LHC projections





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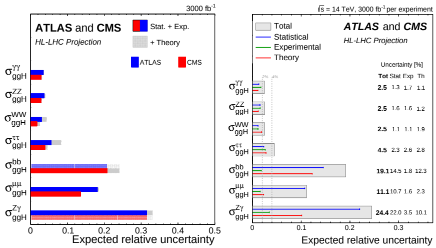
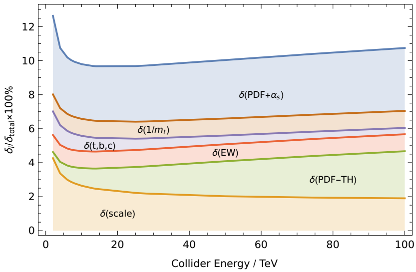


Theoretical uncertainties



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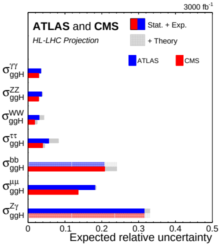

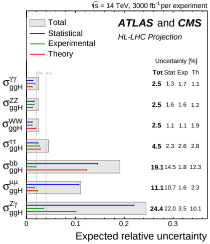

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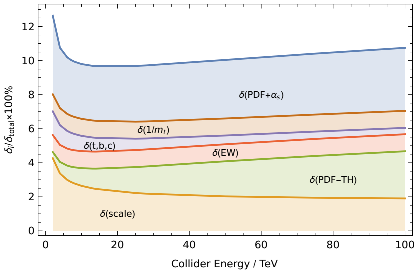


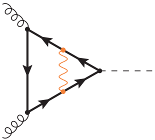
What is the source of $\delta(\text{EW})$?

QCD-EW contributions

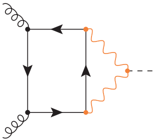
[ph0404071] [ph0407249] [ph0610033]

Exact LO Electroweak contributions

Yukawa coupling $\alpha_S \alpha Y_t$



Electroweak coupling $\alpha_S \alpha^2 v$



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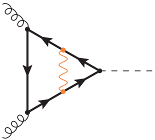

- Dominated by **top quark**
- $\sim 0.5\,\%$ of $\sigma^{\text{LO}}_{\text{QCD}}$

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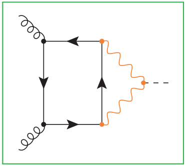

- Dominated by light quarks
- $+5.3\,\%$ of $\sigma^{\text{LO}}_{\text{QCD}}$

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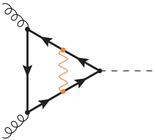

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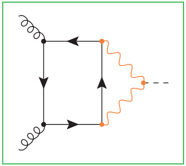

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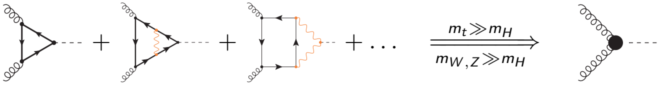
NLO QCD corrections in HEFT



$$\xrightarrow[m_{W,Z} \gg m_H]{m_t \gg m_H} \quad \sim \quad \mathcal{C}\, G_a^{\mu\nu} G^a_{\mu\nu} H$$

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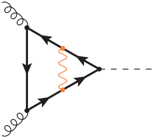

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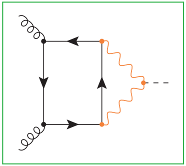

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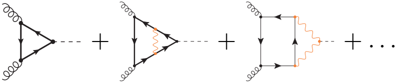
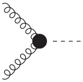


$$\xrightarrow[m_{W,Z} \gg m_H]{m_t \gg m_H}$$



$$\sim \quad \mathcal{C}\, G^{\mu\nu}_a G^a_{\mu\nu} H$$

- Wrong mass relations
- QCD corrections might be large

QCD-EW contributions

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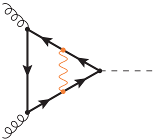

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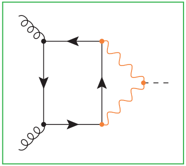

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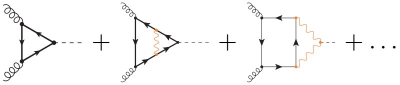

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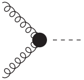

$$\sim \quad \mathcal{C}\, G_a^{\mu\nu} G^a_{\mu\nu} H$$

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Exact NLO computation required

QCD-EW contributions at the LHC

$$\sigma_{PP\to H+j}(\mu) = \int_0^1 \int_0^1 \mathrm{d}x_1 \mathrm{d}x_2 f_{a/P}(x_1,\mu) f_{b/P}(x_2,\mu) \overline{\sigma}_{ab\to H+j}$$

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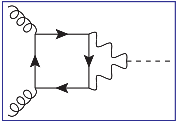
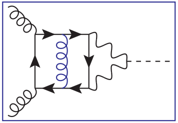
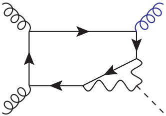
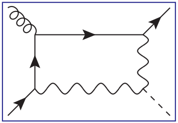
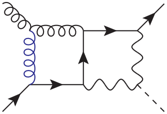
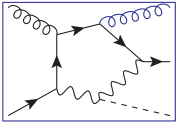
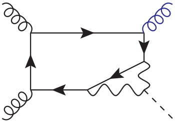
We consider $\alpha^2 v$ contributions

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

Tensor decomposition: $gg \to Hg$



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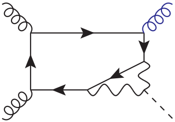

Contributions from γ_5

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

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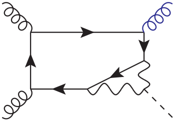

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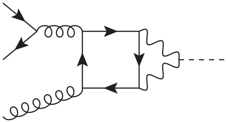
Loop of massless quarks: sum over complete generations removes explicit γ_5, rescaled couplings

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

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

Tensor decomposition $qg \to Hq$



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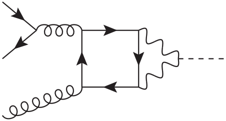

Contributions from γ_5

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

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

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

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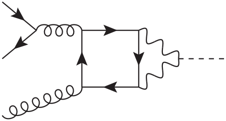
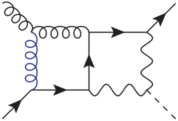




Contributions from γ_5

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

$$T^{c_3}_{j_1 j_2}\,\overline{v}_{s_1}(\mathrm{p}_1)\left[\tau_1^\mu(\mathcal{F}_1^{\text{closed}}+\mathbb{P}_C\mathcal{F}_{C,1}^{\text{open}})+\tau_2^\mu(\mathcal{F}_2^{\text{closed}}+\mathbb{P}_C\mathcal{F}_{C,2}^{\text{open}})\right]u_{s_2}(\mathrm{p}_2)\epsilon_\mu^{\lambda_3}(\mathrm{p}_3)$$

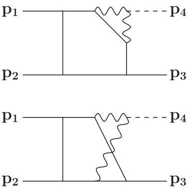
$$\mathcal{F}_j^{\text{closed}} = 4\,A_j^{\text{closed}}(m_W^2) \quad + \quad \frac{2}{\cos^4\theta_W}\left(\frac{5}{4}-\frac{7}{3}\sin^2\theta_W+\frac{22}{9}\sin^4\theta_W\right)A_j^{\text{closed}}(m_Z^2)$$

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

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

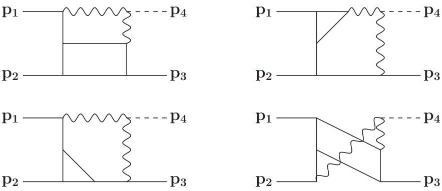
Reduction to MIs

ggHg



61 MIs

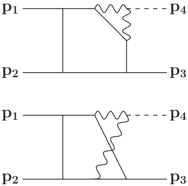
Additional for $qgH\overline{q}$



30 MIs

Reduction to MIs

ggHg



61 MIs

4 square roots

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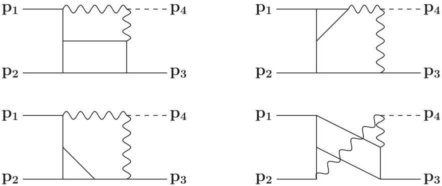

30 MIs

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Reduction to MIs

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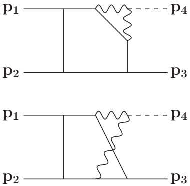

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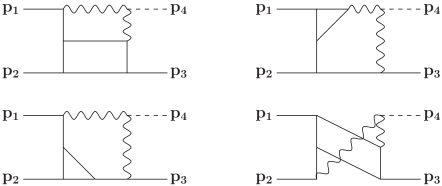

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Differential equations for MIs

- Evolution in t, u, and m_V^2, large-mass limit as boundary condition

Reduction to MIs

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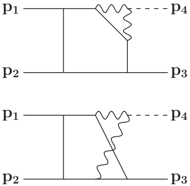

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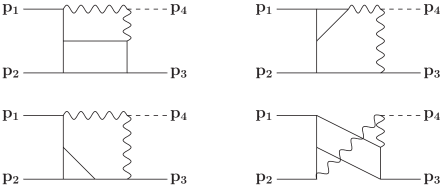

30 MIs

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Differential equations for MIs

- Evolution in t, u, and m_V^2, large-mass limit as boundary condition
- DEs for *ggHg* in $\epsilon\, \mathrm{d}\log$ form
- Single MIs contain at most 3 square roots and are rationalizable
- No global rationalization found

Reduction to MIs

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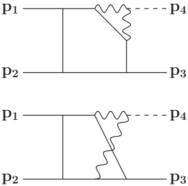

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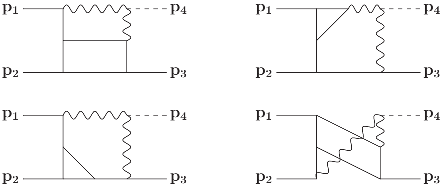

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DEs uneffective for *ggHg* & $qgH\bar{q}$

Direct integration & linear reducibility

[Panzer,2014]

Direct integration over Feynman parameters

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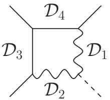
[Panzer,2014]

Direct integration over Feynman parameters



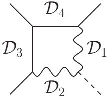
$$\propto \int_0^1 \mathrm{d}x_2 \int_0^1 \mathrm{d}x_1 \int_0^1 \mathrm{d}x_3 \int_0^1 \mathrm{d}x_4 \, \frac{\delta(1-X)}{\left[\sum x_j \mathcal{D}_j\right]^A}$$

$$\propto \int_0^1 \mathrm{d}x_2 \, G(x_2 + \sqrt{\alpha x_2 + \beta} \ldots ; x_2) + \ldots$$

Direct integration & linear reducibility

[Panzer,2014]

Direct integration over Feynman parameters



$$\propto \int_0^1 \mathrm{d}x_2 \int_0^1 \mathrm{d}x_1 \int_0^1 \mathrm{d}x_3 \int_0^1 \mathrm{d}x_4 \, \frac{\delta(1-X)}{\left[\sum x_j \mathcal{D}_j\right]^A}$$

$$\propto \int_0^1 \mathrm{d}x_2 \, G(x_2 + \sqrt{\alpha x_2 + \beta} \ldots ; x_2) + \ldots$$

Linear reducibility

There exists an integration order for the kernel f_0

$$\int_0^{+\infty} \mathrm{d}z_1 \cdots \int_0^{+\infty} \mathrm{d}z_k \, f_0$$

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

Direct integration & linear reducibility

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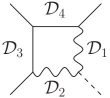
Direct integration over Feynman parameters



$$\propto \int_0^1 \mathrm{d}x_3 \int_0^1 \mathrm{d}x_2 \int_0^1 \mathrm{d}x_1 \int_0^1 \mathrm{d}x_4 \, \frac{\delta(1-X)}{\left[\sum x_j \mathcal{D}_j\right]^A}$$

$$\propto \int_0^1 \mathrm{d}x_3 \, G(\alpha + \sqrt{\beta} \ldots ; x_3) + \ldots$$

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

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

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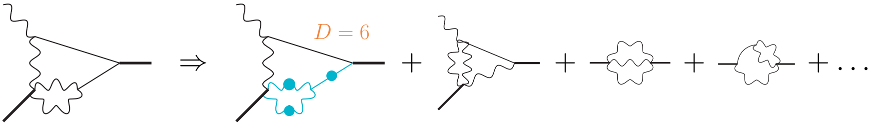

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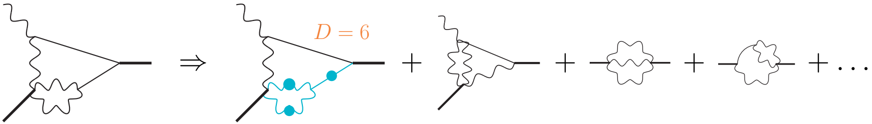

- MIs are shifted into finite integrals and divergent sub-graphs
- Good choices do not worsen the poles in the coefficients

Simplifying the amplitude

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

$\sim 1\,\text{GiB}$

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

Simplifying the amplitude

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

$\sim 1\,\text{GiB}$

$\downarrow$

5526 (6789)

1. Basis of algebraic prefactors
   - Partial fraction decomposition (without extra poles)
   - Basis of algebraic monomials
   - Basis of algebraic prefactors

$$
\begin{aligned}
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
\end{aligned}
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$\downarrow$

5526 (6789)

$\downarrow$

690 (3823)

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

Simplifying the amplitude

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   - Partial fraction decomposition (without extra poles)
   - Basis of algebraic monomials
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2. Linearly independent transcendental expressions
   - Numerical checks for zeroes & implementation
   - PSLQ reduction

$\sim 1\,\text{GiB}$

$\downarrow$

5526 (6789)

$\downarrow$

690 (3823)

$\downarrow$

325 (983)

$\sim 1\,\text{MiB}$

$$
\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}
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   - Partial fraction decomposition (without extra poles)
   - Basis of algebraic monomials
   - Basis of algebraic prefactors
2. Linearly independent transcendental expressions
   - Numerical checks for zeroes & implementation
   - PSLQ reduction
3. Manipulation of GPLs
   - GPLs into log, Li_2, Li_3. . .

$\sim$ 1 GiB

↓

5526 (6789)

↓

690 (3823)

↓

325 (983)

$\sim$ 1 MiB

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

$qgH\bar{q}$: finite remainder

$$\mathcal{F}^{\text{closed}} = \left(\frac{\alpha_S^0}{2\pi}\right) \mathcal{F}_1^{\text{closed}} \qquad \mathcal{F}^{\text{open}} = \mathcal{F}_0^{\text{open}} + \left(\frac{\alpha_S^0}{2\pi}\right) [\mathcal{B}\, N_C + \mathcal{C}\, N_C^{-1}]$$

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1. UV div. α_S renormalization only

$$\alpha_S^0 = \alpha_S \left(\frac{\mu_R^2}{\mu_0^2}\right)^{\epsilon} S_\epsilon^{-1} \left[1 + \alpha_S \frac{\beta_0}{\epsilon} + O\left(\alpha_S^2\right)\right]$$

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2. IR div. described by Catani's operator, removed by real corrections

$$\tilde{\mathcal{F}}_1^{\text{open}} = \mathrm{I}_{q\bar{q}g}^{(1)}\,\tilde{\mathcal{F}}_0^{\text{open}} + \mathcal{F}_{1,\text{fin}}$$

$$\mathrm{I}_{q\bar{q}g}^{(1)} = \frac{-e^{\epsilon\gamma}}{4\Gamma(1-\epsilon)}\left\{\mathcal{V}_q \frac{4C_F - 2C_A}{C_F}\left(-\frac{\mu_R^2}{s}\right)^{\epsilon} + \left(\mathcal{V}_g + \frac{C_A}{C_F}\mathcal{V}_q\right)\left[\left(-\frac{\mu_R^2}{t}\right)^{\epsilon} + \left(-\frac{\mu_R^2}{u}\right)^{\epsilon}\right]\right\}$$

$$\mathcal{V}_q = \frac{C_F}{\epsilon^2} + \frac{3C_F}{2\epsilon} \qquad \mathcal{V}_g = \frac{C_A}{\epsilon^2} + \frac{11C_A - 2N_f}{6\epsilon}$$

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$$\mathcal{F}_{\text{fin}}^{\text{closed}} = \left(\frac{\alpha_S}{2\pi}\right) \overline{\mathcal{F}}_1^{\text{closed}} \qquad \mathcal{F}_{\text{fin}}^{\text{open}} = \tilde{\mathcal{F}}_0^{\text{open}} + \left(\frac{\alpha_S}{2\pi}\right) \left[\overline{\mathcal{B}}\, N_C + \overline{\mathcal{C}}\, N_C^{-1} + \overline{\mathcal{D}}\, N_f\right]$$

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Helicity amplitudes

- Physical (and simpler) result

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ggHg

$$\mathcal{A}^{ggHg}_{+++} = \frac{m_H^2}{\sqrt{2}\langle 12\rangle\langle 23\rangle\langle 31\rangle}\,\frac{su}{m_H^2}\left(\mathcal{F}_1 + \frac{t}{u}\mathcal{F}_2 + \frac{t}{s}\mathcal{F}_3 + \frac{t}{2}\mathcal{F}_4\right)$$

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

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$$\mathcal{A}^{qgH\overline{q}}_{RL+} = \left\{\frac{1}{2}\left[4\mathcal{F}^{\text{closed}}_{1,m_W} + \frac{2}{\cos^4\theta_W}\left(\frac{5}{4} - \frac{7}{3}\sin^2\theta_W + \frac{22}{9}\sin^4\theta_W\right)\mathcal{F}^{\text{closed}}_{1,m_Z}\right] + \right.$$

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$ggHg$

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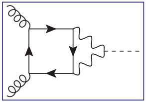
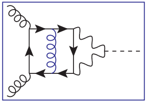
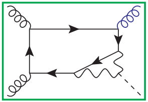
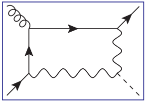
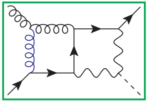
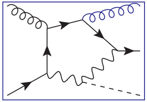
- $\mathcal{F}_{2,m_V}(t,u) = \mathcal{F}_{1,m_V}(u,t)$

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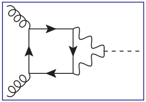
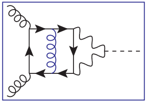
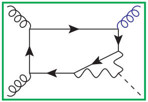
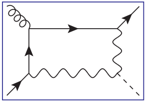
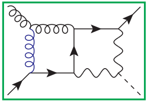
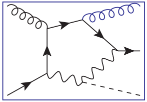
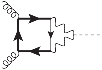
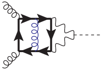
$g \quad g$			
$g \quad q$ $g \quad \bar{q}$ $q \quad \bar{q}$			

The next steps

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

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





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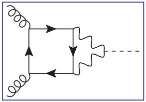
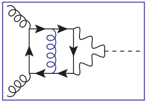
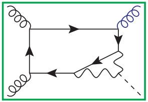
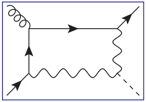
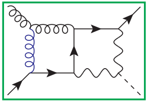
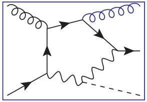
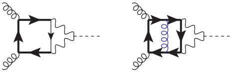
Partons	LO	NLO virtual	NLO real
g g			
g q g $\overline{q}$ q $\overline{q}$			

The next steps

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

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



New challenges

- Expression optimization
- Non-vanishing γ_5 contributions & masses

Thank you for your attention

TRR 257 - Particle Physics Phenomenology after the Higgs Discovery