NLO mixed QCD-electroweak corrections to Higgs boson gluon fusion

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Annual meeting of the SFB TRR 257

Institut für Theoretische Teilchenphysik und Kosmologie

RWTH AACHEN UNIVERSITY

In collaboration with
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Topics

Particle physics after the Higgs boson

2012 direct detection of the Higgs boson

- SM complete: all particles observed, all free parameters fixed

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- Direct observation: main paradigm
  On-shell production and subsequent decay
- Indirect search: complementary approach
  Investigation of known processes at higher precision to unveil deviations
  - Accurate experimental results
  - Small theoretical uncertainties

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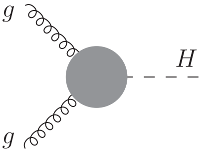
Higgs boson: good candidate

- Yukawa coupling
- Only spin-0 elementary particle in the SM
- Still under investigation

Higgs boson precision physics [1602.00695] [1610.07922] [1802.00833]

Higgs gluon fusion

- LHC main H production channel: 90 % $\sigma^{\text{tot}}_{gg\to H}$ at 13 TeV



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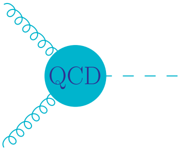
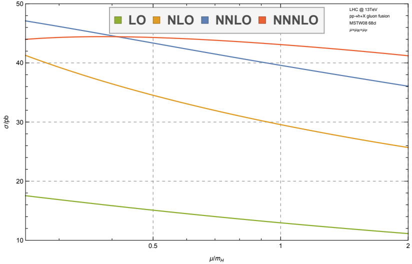


$\Rightarrow$



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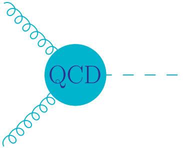

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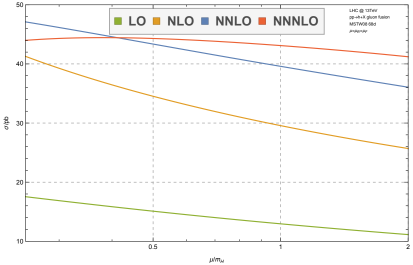

Sub-dominant contributions & uncertainties now important

Uncertainty: $\sim 1\,\%$ each

Quark mass dependence | Electroweak contributions | PDF refinement

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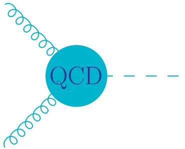

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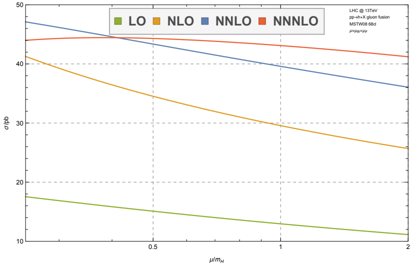

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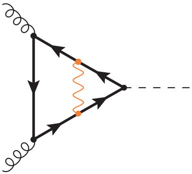
QCD-Electroweak contributions [ph0404071] [ph0407249] [ph0610033]

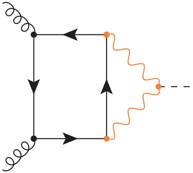
Leading Order

Yukawa coupling $\alpha_S \alpha \mathbf{Y_t}$



- top dominant

Electroweak coupling $\alpha_S \alpha^2 v$



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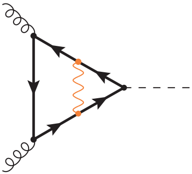

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- $\sim 0.5\,\%$ of $\sigma^{\text{LO}}_{\text{QCD}}$

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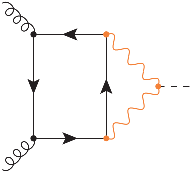

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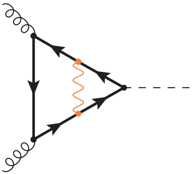

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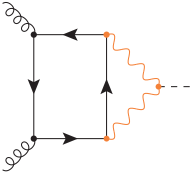

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Next-to-Leading Order

Next order ⇒ NLO small

$+1\,\%$ of $\sigma^{\text{NLO}}_{\text{QCD}}$

Gluon fusion ⇒ NLO large

$+5\,\%$ of $\sigma^{\text{NLO}}_{\text{QCD}}$

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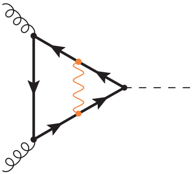

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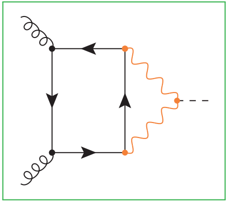

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Next-to-Leading Order

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Gluon fusion $\Rightarrow$ NLO large

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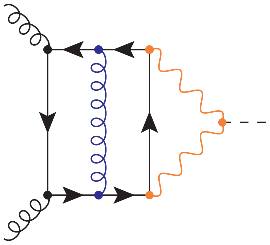
Exact NLO computation required

Construction of the amplitude

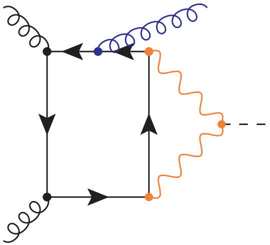
1. Feynman diagrams [Nog93]

Virtual NLO $\alpha_S^2\,\alpha^2\,v$



47 diagrams

Real NLO $\alpha_S^{3/2}\,\alpha^2\,v$



21 diagrams

Construction of the amplitude

1. Feynman diagrams [Nog93]
2. Tensor structures [1707.06453]

No axial terms: γ_5-dependence drops summing over isospin doublets

$gg \to H$

$$\mathcal{M}^{c_1 c_2}_{\lambda_1 \lambda_2} = \delta^{c_1 c_2} \epsilon_{\lambda_1}(\mathbf{p}_1) \cdot \epsilon_{\lambda_2}(\mathbf{p}_2) \left[\mathcal{F}_2 + \mathcal{F}_3\right]$$

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$gg \to Hg$

$$\mathcal{M}^{c_1 c_2 c_3}_{\lambda_1 \lambda_2 \lambda_3} = f^{c_1 c_2 c_3} \epsilon_{\lambda_1,\mu}(\mathbf{p}_1) \epsilon_{\lambda_2,\nu}(\mathbf{p}_2) \epsilon^{*}_{\lambda_3,\rho}(\mathbf{p}_3)$$
$$[g^{\mu\nu} p_2^{\rho} \, \mathcal{F}_{002} + g^{\mu\rho} p_1^{\nu} \, \mathcal{F}_{010} +$$
$$+ g^{\nu\rho} p_3^{\mu} \, \mathcal{F}_{300} + p_3^{\mu} p_1^{\nu} p_2^{\rho} \, \mathcal{F}_{312}]$$

Construction of the amplitude

1. Feynman diagrams [Nog93]
2. Tensor structures [1707.06453]
3. Form factors

Diagrams contain either only $W^{\pm}$ or only Z

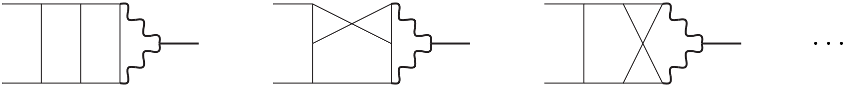
$$\mathcal{F} \propto 4\, A(\mathbf{x}, m_W) + \frac{2}{\cos^4\theta_W}\left[\frac{5}{4} - \frac{7}{3}\sin^2\theta_W + \frac{22}{9}\sin^4\theta_W\right] A(\mathbf{x}, m_Z)$$

- $W^{\pm}$ couples to $\{u, d, c, s\}$
- Z couples to $\{u, d, s, c, b\}$

Construction of the amplitude

1. Feynman diagrams [Nog93]
2. Tensor structures [1707.06453]
3. Form factors
4. Master Integrals [1201.4330] [1705.05610]

Virtual NLO: 95 3-loop MIs



Real NLO: 61 2-loop MIs

Evaluation of 3-point Master Integrals

1. Differential equations [Kot91] [ph9306240] [th9711188] [th9912329]

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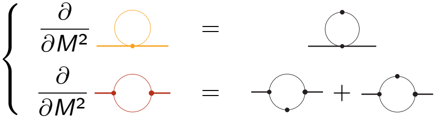
   - Differentiate the MIs w.r.t. masses or kinematics



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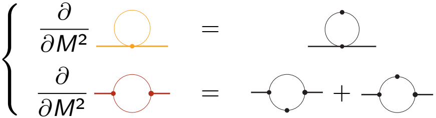
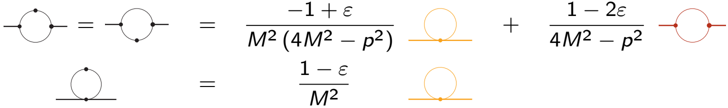


   - Apply IBPs to the r.h.s.



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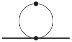
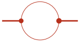
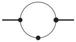
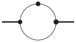
$\frac{\partial}{\partial M^2}$  $=$ 

$\frac{\partial}{\partial M^2}$  $=$  $+$ 

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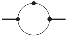
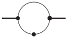
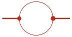
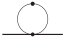
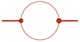
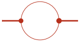
 $=$  $= \frac{-1+\varepsilon}{M^2\,(4M^2-p^2)}$  $+ \frac{1-2\varepsilon}{4M^2-p^2}$ 

 $= \frac{1-\varepsilon}{M^2}$ 

Homogeneous system of differential equations

$\frac{\partial}{\partial M^2}$  $= \frac{1-\varepsilon}{M^2}$ 

$\frac{\partial}{\partial M^2}$  $= \frac{-2+2\varepsilon}{M^2\,(4M^2-p^2)}$  $+ \frac{2-4\varepsilon}{4M^2-p^2}$ 

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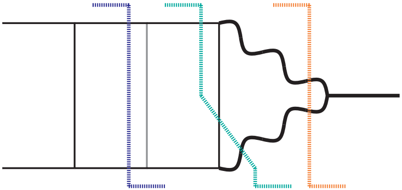
2. Canonical fuchsian form [1012.6032] [1304.1806] [1412.2296]

Highly non-trivial but very useful

$$\frac{\mathrm{d}}{\mathrm{d}y}\mathbf{F}(y,\varepsilon) = \varepsilon \sum_c \mathcal{B}_c \frac{1}{y-a_c}\mathbf{F}(y,\varepsilon)$$



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$y := \frac{\sqrt{1-4M^2/s}-1}{\sqrt{1-4M^2/s}+1}$	$+1$	$\mathrm{e}^{\pm i\pi/3}$	-1	$[0]$

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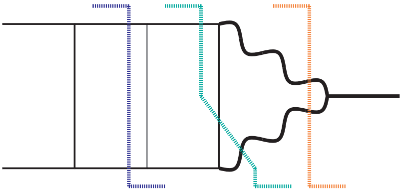

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$$
\begin{aligned}
\mathbf{F}(y,\varepsilon) = \; & \mathbf{F}_0^{(0)} \\
& + \varepsilon \left[\int_y \mathcal{B}(\xi_1)\, \mathrm{d}\xi_1 \; \mathbf{F}_0^{(0)} + \mathbf{F}_0^{(1)} \right] \\
& + \varepsilon^2 \left[\int_y \mathcal{B}(\xi_1) \int_{\xi_1} \mathcal{B}(\xi_2)\, \mathrm{d}\xi_2 \mathrm{d}\xi_1 \; \mathbf{F}_0^{(0)} + \int_y \mathcal{B}(\xi_2)\, \mathrm{d}\xi_2 \mathbf{F}_0^{(1)} + \mathbf{F}_0^{(2)} \right] \\
& + \mathcal{O}\left(\varepsilon^3\right)
\end{aligned}
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$$\mathbf{F}(y,\varepsilon) = \mathbf{F}_0^{(0)} + \varepsilon \left[\mathcal{G}(a_{c_1};y) \; \mathbf{F}_0^{(0)} + \mathbf{F}_0^{(1)} \right] + \varepsilon^2 \left[\mathcal{G}(a_{c_2},a_{c_1};y) \; \mathbf{F}_0^{(0)} + \mathcal{G}(a_{c_2};y) \; \mathbf{F}_0^{(1)} + \mathbf{F}_0^{(2)} \right] + \mathcal{O}\left(\varepsilon^3\right)$$

Goncharov Polylogarithms (GPLs)

$$G(a_{c_n}, a_{c_{n-1}}, \dots, a_{c_1}; y) = \int_0^y \frac{1}{\xi - a_{c_n}} G(a_{c_{n-1}}, \dots, a_{c_1}; \xi)\, \mathrm{d}\xi$$

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$$\lim_{\substack{M^2 \gg s \\ y \to 1}} \left[\ \mathbf{F}(y,\varepsilon) - \mathbf{L}(y,\varepsilon)\ \right] = 0$$

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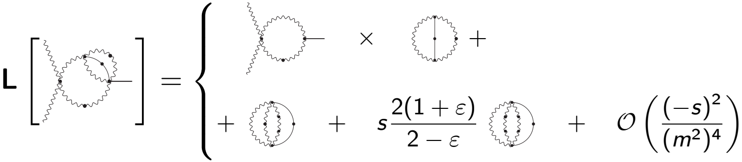
Large-mass expansion



$\mathbf{F}_0^{(n)}$	0	1	2	3	4	5	6
Values	1	—	π^2	$\zeta(3)$	π^4	$\pi^2\zeta(3)$ $\zeta(5)$	π^6 $\zeta^2(3)$

Real emissions

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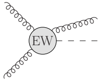
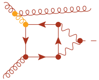
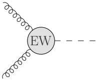
- Soft gluon approximation [ph0102227] [1209.0673]

- In $gg \to H$ PDFs suppress extra gluons with large momentum
- Eikonal approximation ($E_g \to 0$)

$\Big|$ 

$\Big|^2 \Rightarrow \Big|$ 
$\Big|^2 \Rightarrow 4\pi\alpha_S N_C \dfrac{2\, p_1 \cdot p_2}{p_1 \cdot p_4\; p_2 \cdot p_4} \Big|$ 

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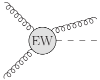
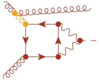
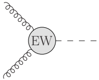
$\Big|$ 

$\Big|^2 \Rightarrow \Big|$  $\Big|^2 \Rightarrow 4\pi\alpha_S N_C \dfrac{2\,p_1 \cdot p_2}{p_1 \cdot p_4 \; p_2 \cdot p_4} \Big|$ 

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Real emissions

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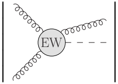

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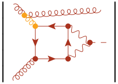

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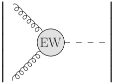

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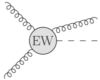
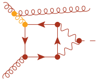
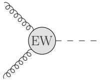
$\Big|$ 

$\Big|^2 \Rightarrow \Big|$  $\Big|^2 \Rightarrow 4\pi\alpha_S N_C \dfrac{2\, p_1 \cdot p_2}{p_1 \cdot p_4\; p_2 \cdot p_4} \Big|$ 

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- Cumbersome results: last two orders of the non-planar top sector missing

Direct integration

[1403.3385]

Feynman parameters

$$\mathcal{I}\left(a_1,\ldots,a_7\right) \propto \left[\prod_{k=1}^{7} \int_0^{+\infty} x_k^{a_k-1}\,\mathrm{d}x_k\right] \frac{\delta\left(1-\overline{x}\right)}{\mathcal{U}^{\sum a_i+3D/2}\mathcal{F}^{\sum a_i-D}}$$

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Master Integrals in quasi-finite basis computed using `HyperInt`.

$gg \to Hg$ amplitude

- Rich alphabet: 49 letters, 4 square roots

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- Final form of the amplitude

- $\Omega_{+++} \ni \log, \mathrm{Li}_2, \mathrm{Li}_3$: fast, stable expressions both in Euclidean and physical regions
- $\Omega_{++-} \ni \log, \mathrm{Li}_2, \mathrm{Li}_3, G_4$ (to be done: $G_4 \to \mathrm{Li}_4, \mathrm{Li}_{2,2}$)

Conclusions & Outlook

QCD-EW corrections to Higgs production: important for precision physics

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Analytic results for NLO QCD light-quark corrections to $gg \to H(g)$

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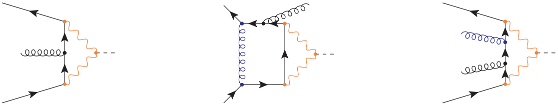
The road ahead

- $qg \to Hq$ QCD-EW with light quarks



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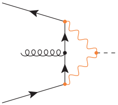
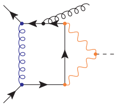
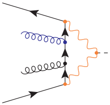
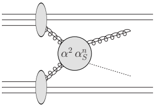




- Computation of $\sigma_{PP \to H+j}$ QCD-EW with light quarks



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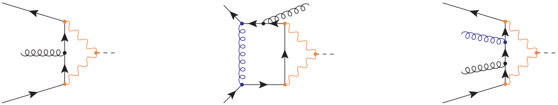

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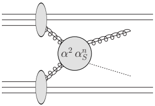

- Very long run: $\sigma_{PP \to H+j}$ QCD-EW top + light quarks

Thank you for your attention