

Top and b mass effects in the p_T distribution of Higgs production

Vittorio Del Duca

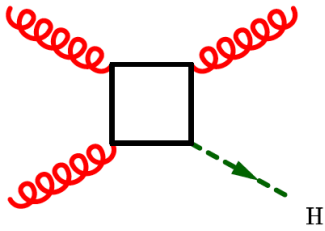
ETH Zürich & U. Zürich & INFN

in collaboration with

R. Bonciani, H. Frellesvig, M. Hidding, V. Hirschi,
F. Moriello, G. Salvatori, G. Somogyi, F. Tramontano

LHCHWG CERN 28 November 2022

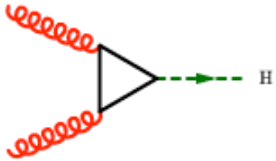
Higgs p_T distribution at LHC



- QCD NLO corrections to the top- and b -quark loop contributions to the Higgs p_T distribution, in the on-shell and $\overline{\text{MS}}$ mass renormalisation schemes
- high- p_T tail of the Higgs p_T distribution is sensitive to the structure of the loop-mediated Higgs-gluon coupling
New Physics particles circulating in the loop would modify it

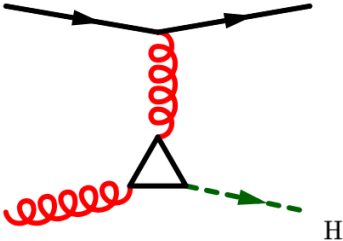
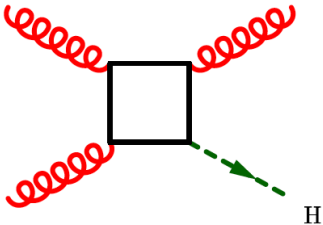
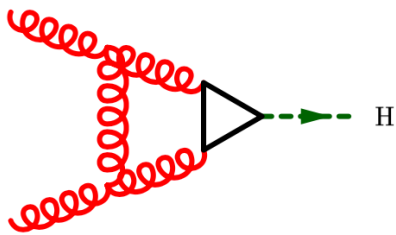
Higgs production at LHC

- In proton collisions, the Higgs boson is produced mostly via gluon fusion
- The gluons do not couple directly to the Higgs boson
- For matter, the coupling is mediated by a heavy quark loop
- The largest contribution comes from the top-quark loop
- The production mode is (roughly) proportional to the top Yukawa coupling y_t^2



- QCD NLO corrections (for any heavy quark mass)

Djouadi Graudenz Spira Zerwas 1991-1995



- QCD NLO corrections are about 100% larger than leading order

- QCD NNLO corrections are known for the top-quark loop only

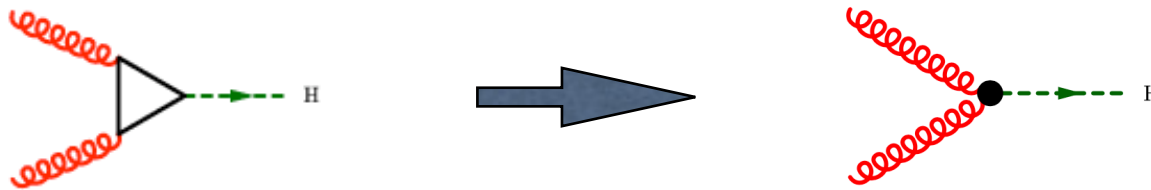
QCD NLO corrections

				$\frac{\sigma_{t+b}}{\sigma_t} - 1$	
σ_{EFT}^{LO}	15.05 pb	σ_{EFT}^{NLO}	34.66 pb	LO $\mathcal{O}(\alpha_s^2)$	- 6.6 %
$R_{LO} \sigma_{EFT}^{LO}$	16.00 pb	$R_{LO} \sigma_{EFT}^{NLO}$	36.84 pb	NLO $\mathcal{O}(\alpha_s^2) + \mathcal{O}(\alpha_s^3)$	- 4.5 %
$\sigma_{ex;t}^{LO}$	16.00 pb	$\sigma_{ex;t}^{NLO}$	36.60 pb	NLO $\mathcal{O}(\alpha_s^3)$	- 2.8 %
$\sigma_{ex;t+b}^{LO}$	14.94 pb	$\sigma_{ex;t+b}^{NLO}$	34.96 pb		
$\sigma_{ex;t+b+c}^{LO}$	14.83 pb	$\sigma_{ex;t+b+c}^{NLO}$	34.77 pb		

Anastasiou Duhr Dulat Furlan Gehrmann Herzog Lazopoulos Mistlberger 2016

Higgs Effective Field Theory

$$m_H \ll 2m_t$$



all amplitudes are reduced by one loop

$$R_{LO} = \frac{\sigma_{ex;t}^{LO}}{\sigma_{EFT}^{LO}} = 1.063$$

rescaled HEFT (rHEFT) does a good job (< 1%) in approximating the exact (only top) NLO σ but misses the t - b interference

Top-quark mass corrections are known at NNLO

Czakon Harlander Klappert Niggetiedt 2021

channel	$\sigma_{\text{HEFT}}^{\text{NNLO}}$ [pb]	$(\sigma_{\text{exact}}^{\text{NNLO}} - \sigma_{\text{HEFT}}^{\text{NNLO}})$ [pb]		$(\sigma_{\text{exact}}^{\text{NNLO}} / \sigma_{\text{HEFT}}^{\text{NNLO}} - 1)$ [%]
	$\mathcal{O}(\alpha_s^2) + \mathcal{O}(\alpha_s^3) + \mathcal{O}(\alpha_s^4)$	$\mathcal{O}(\alpha_s^3)$	$\mathcal{O}(\alpha_s^4)$	
$\sqrt{s} = 8 \text{ TeV}$				
<i>gg</i>	7.39 + 8.58 + 3.88	+0.0353	+0.0879 ± 0.0005	+0.62
<i>qg</i>	0.55 + 0.26	-0.1397	-0.0021 ± 0.0005	-18
<i>qq</i>	0.01 + 0.04	+0.0171	-0.0191 ± 0.0002	-4
total	7.39 + 9.15 + 4.18	-0.0873	+0.0667 ± 0.0007	-0.10
$\sqrt{s} = 13 \text{ TeV}$				
<i>gg</i>	16.30 + 19.64 + 8.76	+0.0345	+0.2431 ± 0.0020	+0.62
<i>qg</i>	1.49 + 0.84	-0.3696	-0.0115 ± 0.0010	-16
<i>qq</i>	0.02 + 0.10	+0.0322	-0.0501 ± 0.0006	-15
total	16.30 + 21.15 + 9.79	-0.3029	+0.1815 ± 0.0023	-0.26

HEFT not so good for *qg* and *qq* channels

for top-quark mass, used $m_t^2/m_H^2 = 23/12$ (on-shell scheme)

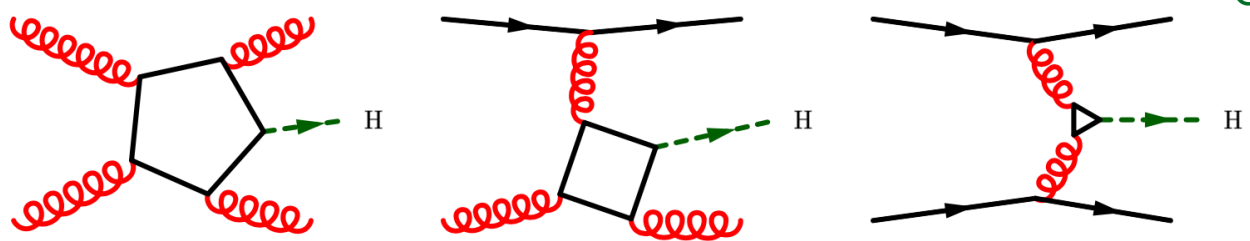
The main obstacle when calculating the total cross section with full top-mass dependence are the two-loop single-emission amplitudes.

Czakon Harlander Klappert Niggetiedt 2021

QCD NNLO corrections

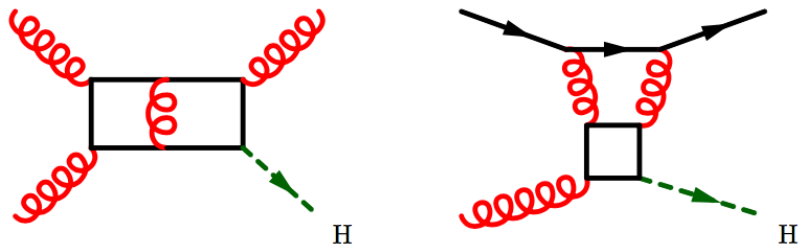
Higgs + 4-parton amplitudes at one loop

VDD Kilgore Oleari Schmidt Zeppenfeld 2001
Budge Campbell De Laurentis K. Ellis Seth 2020



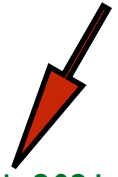
OpenLoops

Higgs + 3-parton amplitudes at two loops

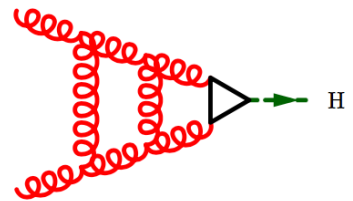


top loop: Jones Kerner Luisoni 2018
Czakon Harlander Klappert Niggetiedt 2021

Bonciani VDD Frellesvig Moriello Hidding
Hirschi Salvatori Somogyi Tramontano 2022



gg → Higgs amplitudes at three loops

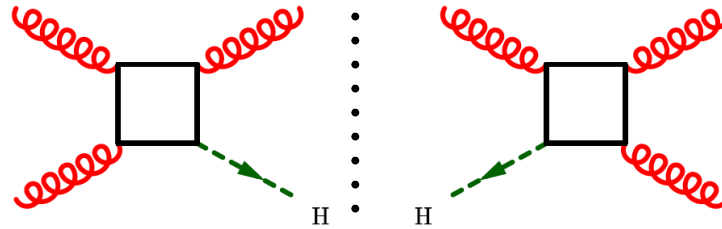


one scale: one & two top loops
one top loop + light-quark loop
two scales: one top loop + b-quark loop

Czakon Niggetiedt 2020
Harlander Prausa Usovitsch 2019

Higgs p_T distribution at LHC

leading order



K. Ellis Hinchliffe Soldate van der Bij 1988

high- p_T tail of the Higgs p_T distribution is sensitive to the structure of the loop-mediated Higgs-gluon coupling
New Physics particles circulating in the loop would modify it

in high- p_T regime, clean signature of decay products ($H \rightarrow \gamma\gamma$)

QCD NLO corrections

for the top-quark, with on-shell scheme

Jones Kerner Luisoni 2018
Chen Huss Jones Kerner Lang Lindert Zhang 2021

for the top-quark, with on-shell and $\overline{\text{MS}}$ schemes

for top- and b -quarks (for any heavy quark mass), with $\overline{\text{MS}}$ scheme

Bonciani VDD Frellesvig Moriello Hidding Hirschi Salvatori Somogyi Tramontano 2022

HEFT $m_H \ll 2m_t$ and $p_T \ll m_t$

Baur Glover 1990

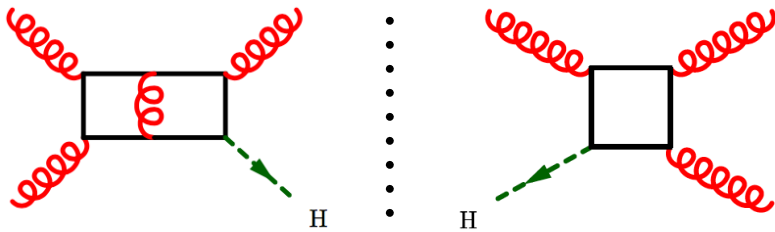
QCD corrections are known at NNLO in HEFT, and yield a 15% increase wrt NLO

Boughezal Caola Melnikov Petriello Schulze 2015
Boughezal Focke Giele Liu Petriello 2015
Chen Cruz-Martinez Gehrman Glover Jaquier 2016

Higgs p_T distribution at NLO



virtual corrections



top-quark loop

Jones Kerner Luisoni 2018

Czakon Harlander Klappert Niggetiedt 2021

any heavy quark in the loop

Bonciani VDD Frellesvig Henn Moriello V. Smirnov 2016

all above + Hidding Maestri Salvatori 2019

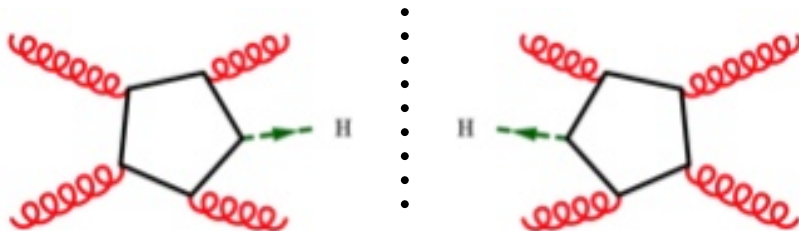
Bonciani VDD Frellesvig Moriello Hidding Hirschi Salvatori Somogyi Tramontano 2022



multi-scale problem with complicated analytic structure
elliptic iterated integrals appear



real corrections

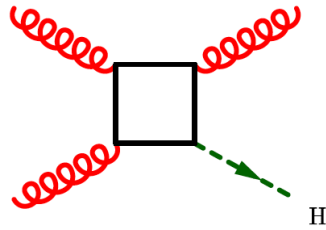


VDD Kilgore Oleari Schmidt Zeppenfeld 2001

Budge Campbell De Laurentis K. Ellis Seth 2020



one-loop amplitudes for Higgs + 3-partons



leading order: up to $\mathcal{O}(\epsilon^2)$

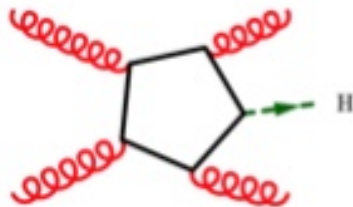
analytic: up to $\mathcal{O}(\epsilon^0)$

numeric: up to $\mathcal{O}(\epsilon^2)$

K. Ellis Hinchliffe Soldate van der Bij 1988

(numeric) derivative for mass renormalisation

one-loop amplitudes for Higgs + 4-partons



NLO real corrections: up to $\mathcal{O}(\epsilon^0)$

analytic: unitarity-cut methods (taken from MCFM-9.1)

Budge Campbell De Laurentis K. Ellis Seth 2020

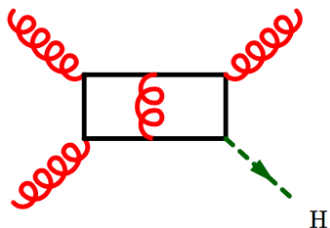
numeric: GoSam & MG5_aMC

run time

analytic: few ms/pt

numeric: $\mathcal{O}(100)$ times slower than analytic

two-loop amplitudes for Higgs + 3-partons



NLO virtual corrections

amplitude \rightarrow form factors \rightarrow scalar integrals \rightarrow Master Integrals
IBP

run time: 5 — 60 min/pt

FIRE-KIRA

4 scales, $s, t, m_H, m_t \rightarrow$ 3 external parameters

7 seven-propagator integral families

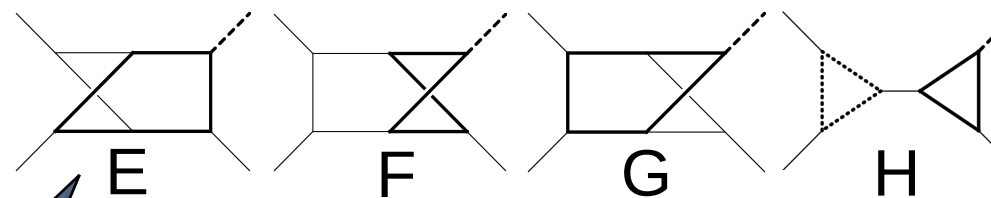
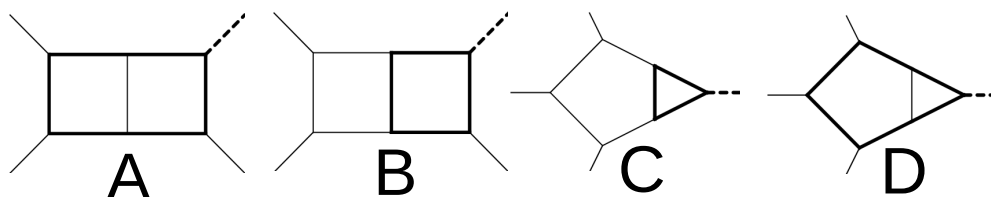
Bonciani VDD Frellesvig Henn Moriello Smirnov 2016 (A, B, C, D)

Bonciani VDD Frellesvig Henn Hidding Maestri Moriello Salvatori Smirnov 2019 (F)

Frellesvig Hidding Maestri Moriello Salvatori 2019 (G)

Bonciani VDD Frellesvig Moriello Hidding Hirschi Salvatori Somogyi Tramontano 2022 (H)

elliptic



MIs

A: 72

B: 5

C: 45

D: 17

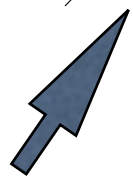
F: 73

G: 84

H: 12

= 0

colour conservation

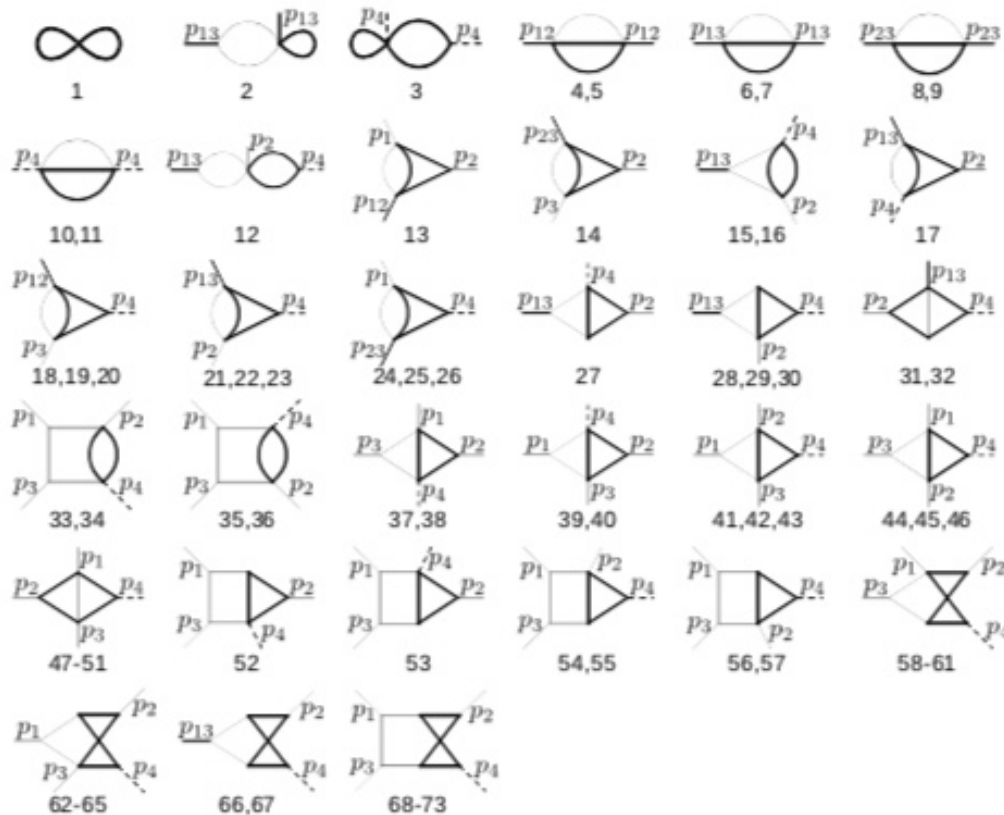


elliptic



two masses

Family F: 73 MIs (65 in the polylogarithmic sector, 8 in the elliptic sector)
 alphabet: 69 independent letters, with 12 independent square roots



↑
 ↗
 elliptic

Differential Equations



Differential Equation method to solve the MIs

$$\partial_i f(x_n; \varepsilon) = A_i(x_n; \varepsilon) f(x_n; \varepsilon)$$

f : N-vector of MIs, A_i : NxN matrix, $i=1, \dots, n$ external parameters

but in some cases ε -independent form

$$\partial_i f(x_n; \varepsilon) = \varepsilon A_i(x_n) f(x_n; \varepsilon)$$

Henn 2013

solution in terms of iterated integrals



mass values are floating \rightarrow

DEs solved with 3 (top) or 4 (top and b) external parameters

DEs: Series Expansion Method

- Take two points (a_1, \dots, a_n) and (b_1, \dots, b_n) in the n -dim parameter space, and parametrise the contour $\gamma(t)$ that connects the two points

$$\gamma(t) : t \rightarrow \{x_1(t), \dots, x_n(t)\} \quad \vec{x}(0) = \vec{a}, \quad \vec{x}(1) = \vec{b}$$

and write the differential equation with respect to t .

Then find a solution about a point τ by series expanding the coefficient matrix A and then iteratively integrating it.

The procedure works for both polylogarithmic and elliptic sectors

Moriello 2019

- numerical solution of DEs through **DiffExp**:
Mathematica implementation of Moriello's series expansion method

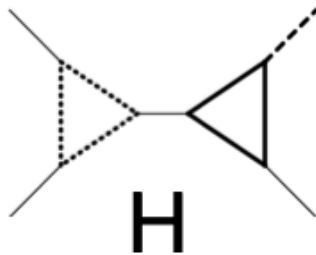
Hidding 2021

- checked with AMFlow Liu Ma Wang 2018

two-loop amplitudes for Higgs + 3-partons: Renormalisation

Bonciani VDD Frellesvig Moriello Hidding Hirschi Salvatori Somogyi Tramontano 2022

- coupling constant: 5-flavour running in $\overline{\text{MS}}$
- renormalisation:
 - top Yukawa coupling and top mass in OS scheme (massless b)
 - top Yukawa coupling and top mass in $\overline{\text{MS}}$ scheme (massless b)
 - top and b Yukawa couplings and masses in $\overline{\text{MS}}$ scheme



massive b in Higgs- b loop
massless b in b loop

alternative:

massive b everywhere,

but requires 4-flavour running and including $gg \rightarrow Hbb$

two-loop amplitudes for Higgs + 3-partons: validation checks

IR poles

$$\mathcal{M}_{ij,IR}^{(2)} \propto I_{ij}^{(1)}(\{p\}, \epsilon) \mathcal{M}_{ij}^{(1)}$$

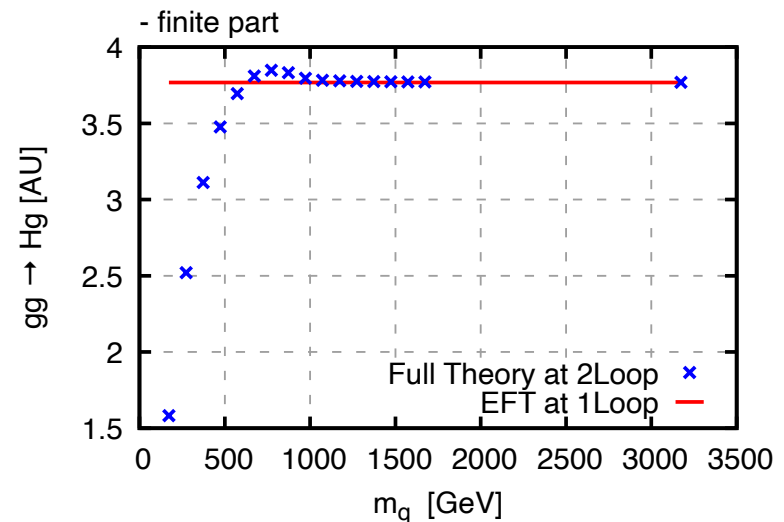
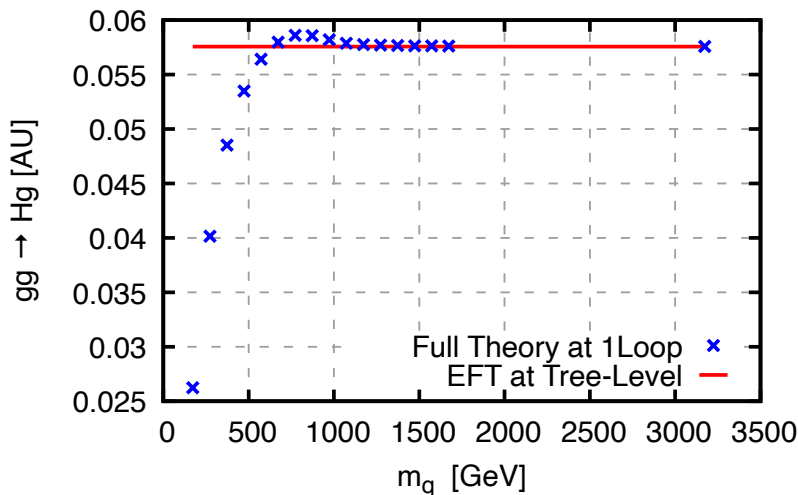
with insertion operators

$$I_{gg}^{(1)}(\{p\}, \epsilon) = -\frac{\alpha_S}{\pi} \frac{(4\pi)^\epsilon}{\Gamma(1-\epsilon)} \left(\frac{N_c}{\epsilon^2} + \frac{\beta_0}{\epsilon} \right) \left[\left(\frac{\mu^2}{-s} \right)^\epsilon + \left(\frac{\mu^2}{-t} \right)^\epsilon + \left(\frac{\mu^2}{-u} \right)^\epsilon \right]$$

$$I_{q\bar{q}}^{(1)}(\{p\}, \epsilon) = -\frac{\alpha_S}{2\pi} \frac{(4\pi)^\epsilon}{\Gamma(1-\epsilon)} \left\{ -\left(\frac{N_c}{\epsilon^2} + \frac{3N_c}{4\epsilon} + \frac{\beta_0}{2\epsilon} \right) \left[\left(\frac{\mu^2}{-t} \right)^\epsilon + \left(\frac{\mu^2}{-u} \right)^\epsilon \right] + \frac{1}{N_c} \left(\frac{1}{\epsilon^2} + \frac{3}{2\epsilon} \right) \left(\frac{\mu^2}{-s} \right)^\epsilon \right\}$$

agreement with HEFT limit

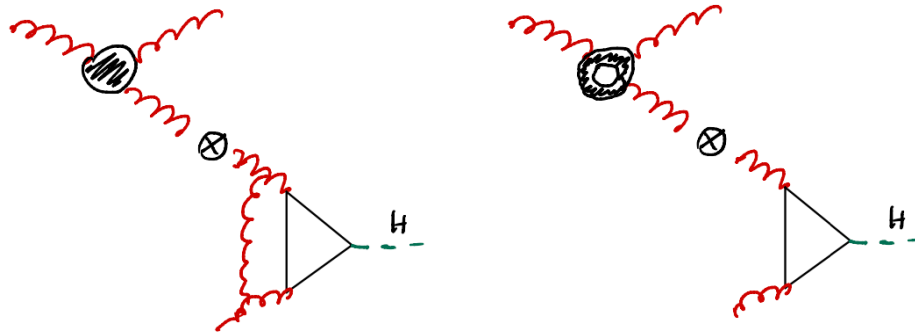
$$\mathcal{M} = \mathcal{M}_{HEFT} + \mathcal{O}\left(\frac{1}{M_t}\right)$$



two-loop amplitudes for Higgs + 3-partons: validation checks

soft and collinear limits

(these are checks on real-virtual parts of NNLO cross section, however they are feasible on our two-loop amplitudes)



Aglietti Bonciani Degrassi Vicini 2006

Bern Dixon Dunbar Kosower 1994
Bern Kilgore SchmidtVDD 1998-99
Kosower Uwer 1999

one-loop 2-parton splitting functions

one-loop 1-soft-gluon factor

Bern Kilgore SchmidtVDD 1998-99
Catani Grazzini 2000

checked also “two-loop photon correction”

Higgs p_T distribution at NLO: checks with previous results



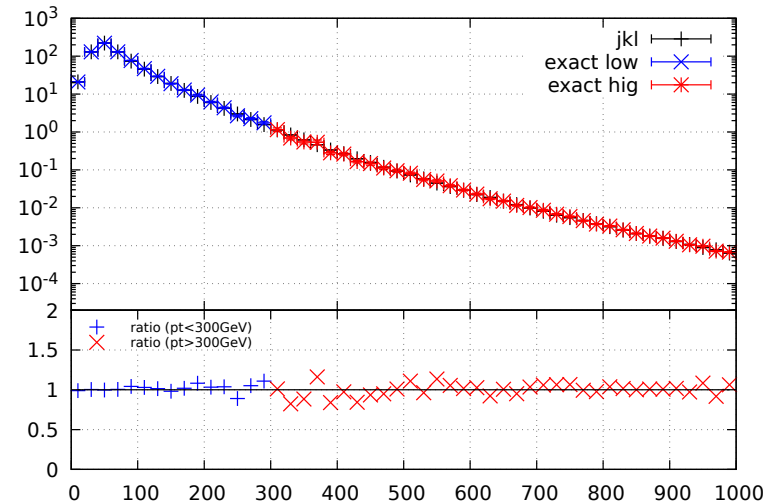
inclusive p_T distribution ($p_{T,j} > 30$ GeV)
with OS mass renormalisation

our result

$$\sigma_{NLO} = 14.37 \pm 0.05 \text{ pb}$$

Chen Huss Jones Kerner Lang Lindert Zhang 2021
(Jones Kerner Luisoni 2018-2021)

$$\sigma_{NLO} = 14.15 \pm 0.07 \text{ pb}$$



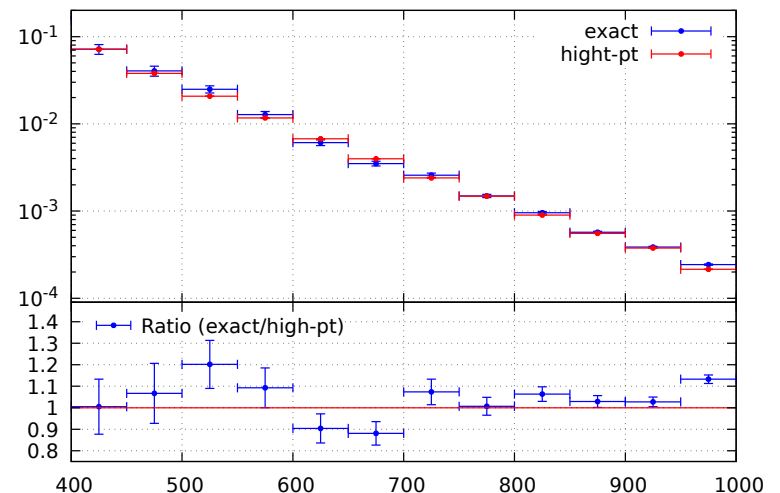
high p_T tail of distribution

checked with approximate high- p_T distribution

Lindert Melnikov Kudashkin Wever 2018

based on approximate high- p_T two-loop amplitudes

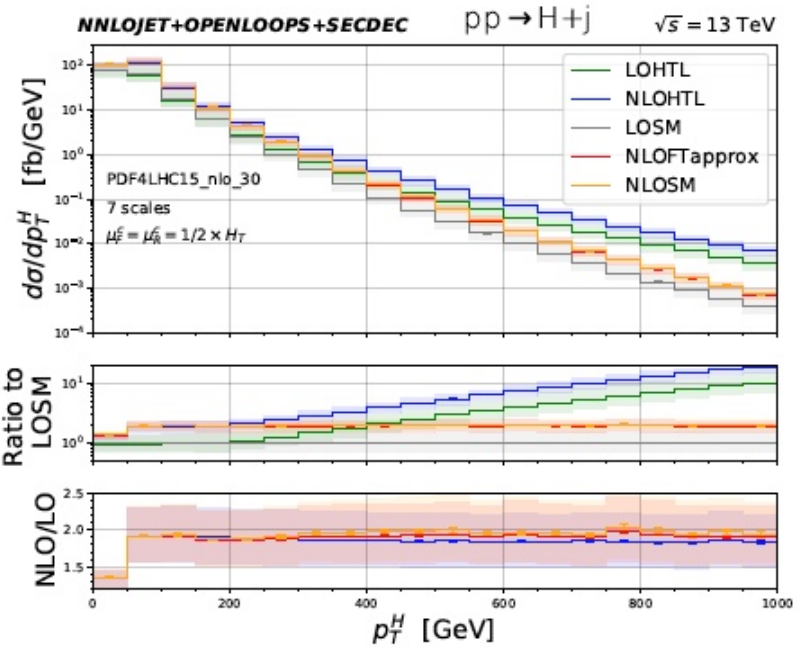
Melnikov Kudashkin Wever 2018



Higgs p_T distribution at LHC



QCD NLO corrections for the top-quark (on-shell mass renormalisation)



Jones Kerner Luisoni 2018
 Chen Huss Jones Kerner Lang Lindert Zhang 2021



$$\frac{d\sigma}{dp_T^2} \propto \frac{1}{p_T^2} \quad \text{in HEFT NLO corrections}$$

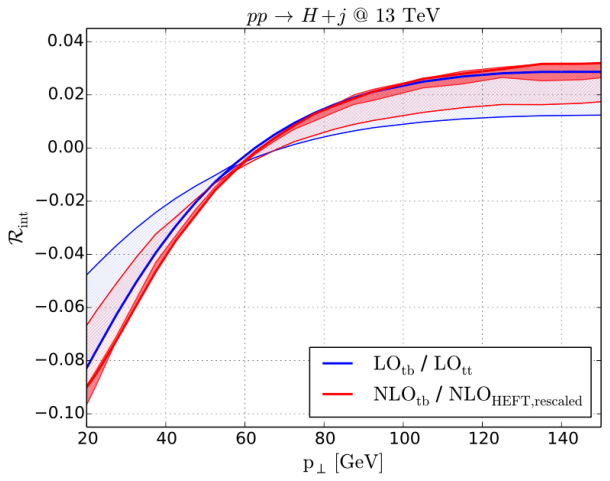
$$\frac{d\sigma}{dp_T^2} \propto \frac{1}{(p_T^2)^2} \quad \text{in top NLO corrections}$$

NLO/LO in HEFT and top loop agree to O(10%)



QCD NLO corrections to top-b interference, using top-quark loop in HEFT and b -quark loop in small m_b limit

Lindert Melnikov Tancredi Wever 2017



Higgs p_T distribution at NLO

- p_T distribution computed with CoLorFuLNLO dual subtraction Somogyi 2009
Prisco Tramontano 2020
 - evaluated on:
 - 3×10^4 pt for OS top (1.4×10^4 pt on basic grid, 1.6×10^4 pt on biased grid)
 - 9×10^4 pt for MSbar top
 - 1.8×10^5 pt for MSbar top and b
 - set-up
 - $\sqrt{s} = 13 \text{ TeV}$
 - $m_H = 125.25 \text{ GeV}$
 - $m_t^{\text{OS}} = 172.5 \text{ GeV}$
 - $m_t^{\overline{\text{MS}}}(m_t^{\overline{\text{MS}}}) = 163.4 \text{ GeV}$
 - $m_b^{\overline{\text{MS}}}(m_b^{\overline{\text{MS}}}) = 4.18 \text{ GeV}$
 - $G_F = 1.16639 \cdot 10^{-5} \text{ GeV}^{-2}$
 - NNPDF40_nlo_as_01180
- $p_{T,j_1} > 20 \text{ GeV}$
anti-kt algorithm with $R = 0.4$
7-pt scale variation about:
$$\mu_R^0 = \mu_F^0 = \frac{H_T}{2} = \frac{1}{2} \left(\sqrt{m_H^2 + p_T^2} + \sum_i |p_{T,i}| \right)$$

inclusive Higgs p_T distribution



QCD NLO corrections Bonciani VDD Frellesvig Moriello Hidding Hirschi Salvatori Somogyi Tramontano 2022

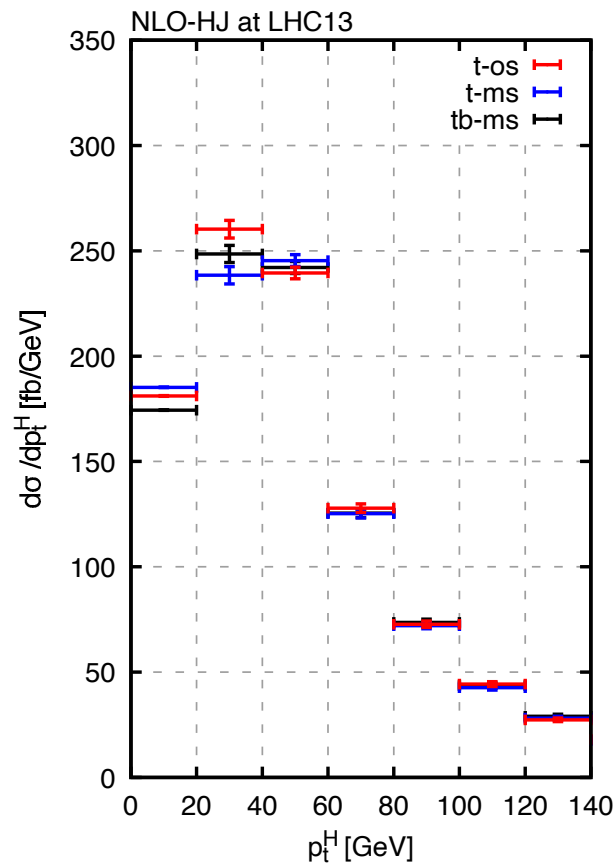
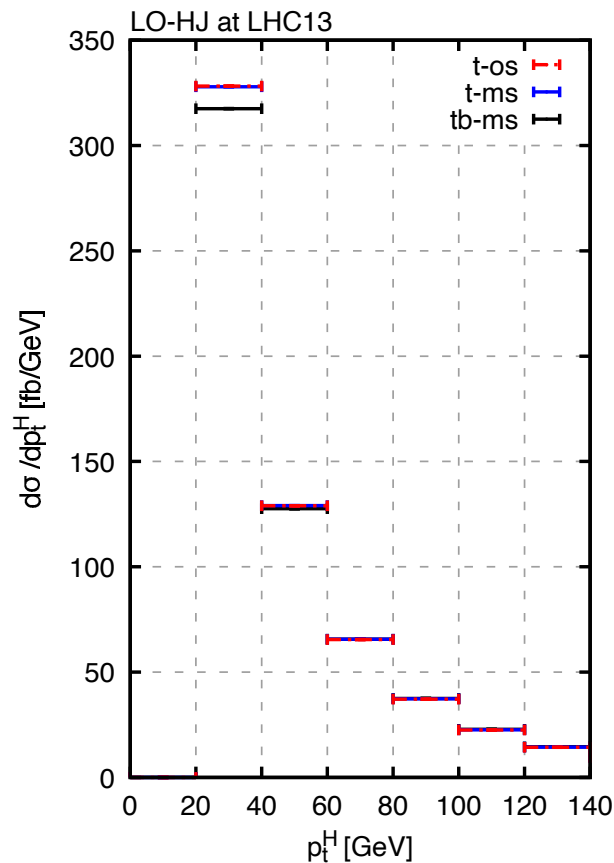
for the top-quark, with on-shell and $\overline{\text{MS}}$ schemes
for top- and b -quarks with $\overline{\text{MS}}$ scheme

renormalisation of internal masses	σ_{LO} [pb]	σ_{NLO} [pb]
top+bottom- $(\overline{\text{MS}})$	$12.318^{+4.711}_{-3.117}$	$19.89(8)^{+2.84}_{-3.19}$
top- $(\overline{\text{MS}})$	$12.538^{+4.822}_{-3.183}$	$19.90(8)^{+2.66}_{-2.85}$
top- (OS)	$12.551^{+4.933}_{-3.244}$	$20.22(8)^{+3.06}_{-3.09}$

- from LO to NLO large k factor and reduction of scale uncertainty
- top- b interference is a negative correction at $\mathcal{O}(\alpha_s^3)$ but positive at $\mathcal{O}(\alpha_s^4)$
- effect of top mass renormalisation utterly negligible at LO but 15 times bigger at NLO

$$\frac{\sigma_{t(\text{OS})}}{\sigma_{t(\overline{\text{MS}})}} - 1 = \begin{cases} 0.1\% \text{ at LO} \\ 1.6\% \text{ at NLO} \end{cases}$$

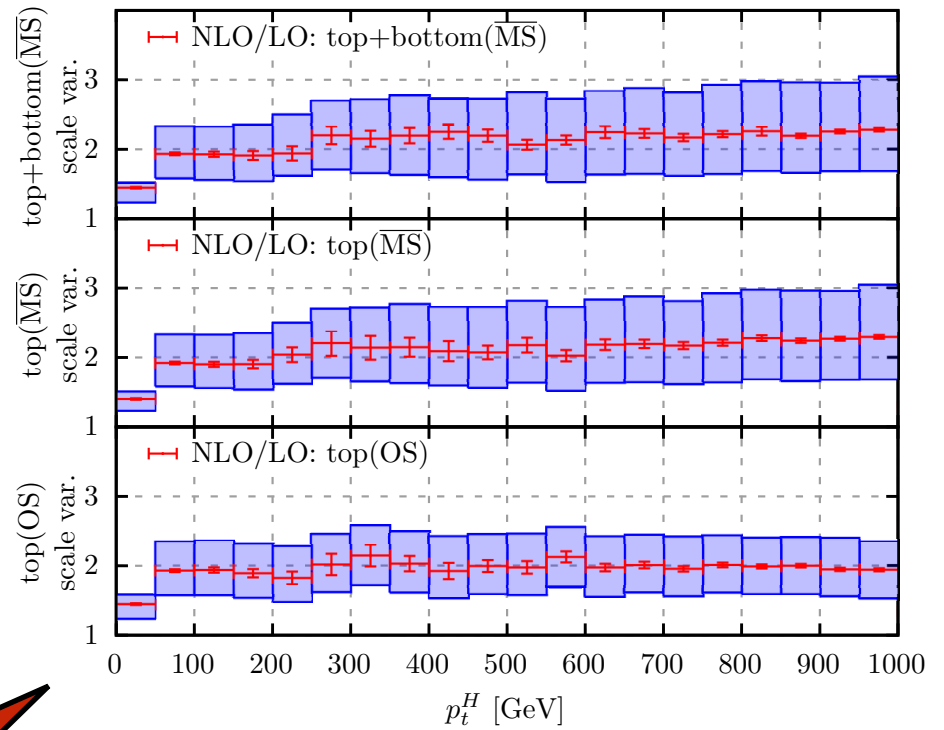
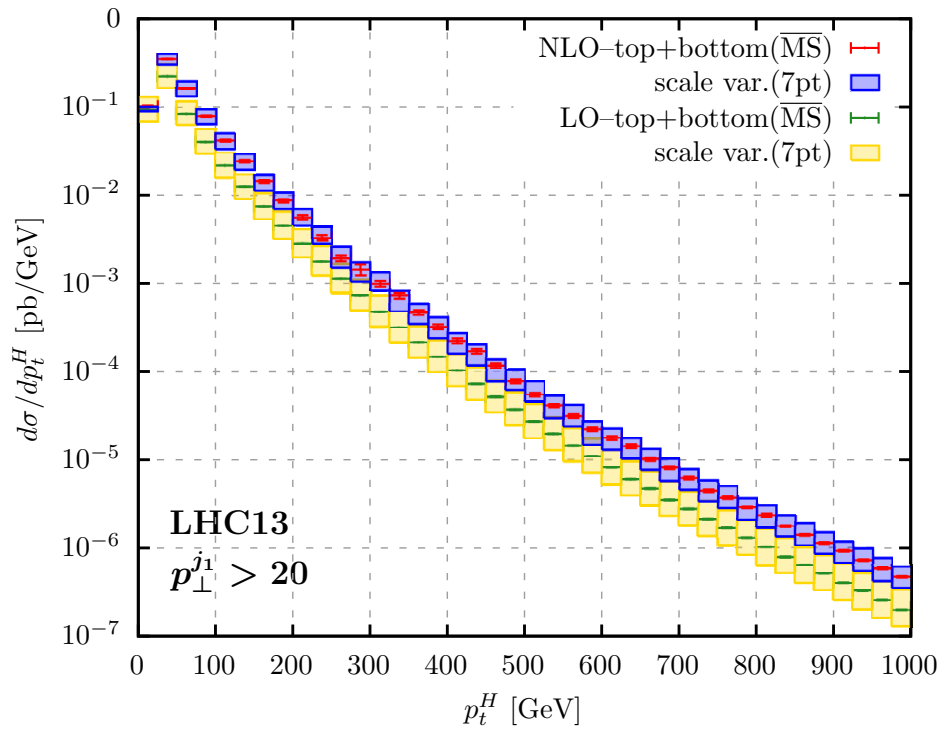
Higgs p_T distribution at low-intermediate p_T



20-40 GeV bin
 260^{+16}_{-83} fb/GeV
 249^{+21}_{-65} fb/GeV
 238^{+27}_{-98} fb/GeV

- at **LO** no events below 20 GeV since $p_{T,j} > 20$ GeV
- at **LO** no appreciable difference between $t(\text{OS})$ and $t(\text{MSbar})$
- at **NLO** sizeable shape distortion in the lowest bins
- at **NLO** agreement (not shown) between exact and rHEFT in the low-middle p_T range
 HEFT $m_H \ll 2m_t$ and $m_b \ll p_T \ll m_t$
- scale uncertainty bands (not shown) are much larger than differences

Higgs p_T distribution at LHC

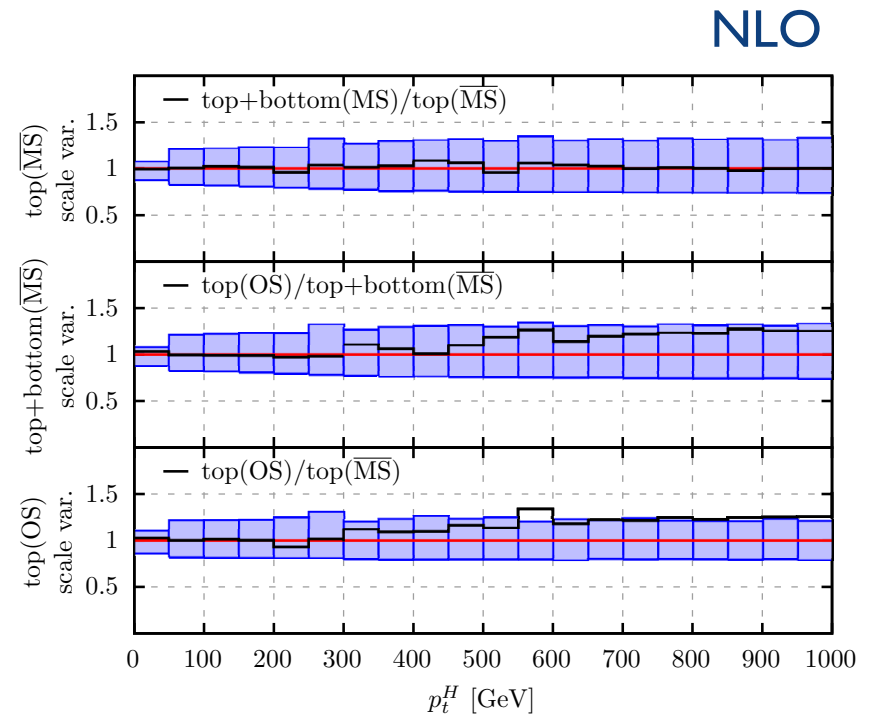
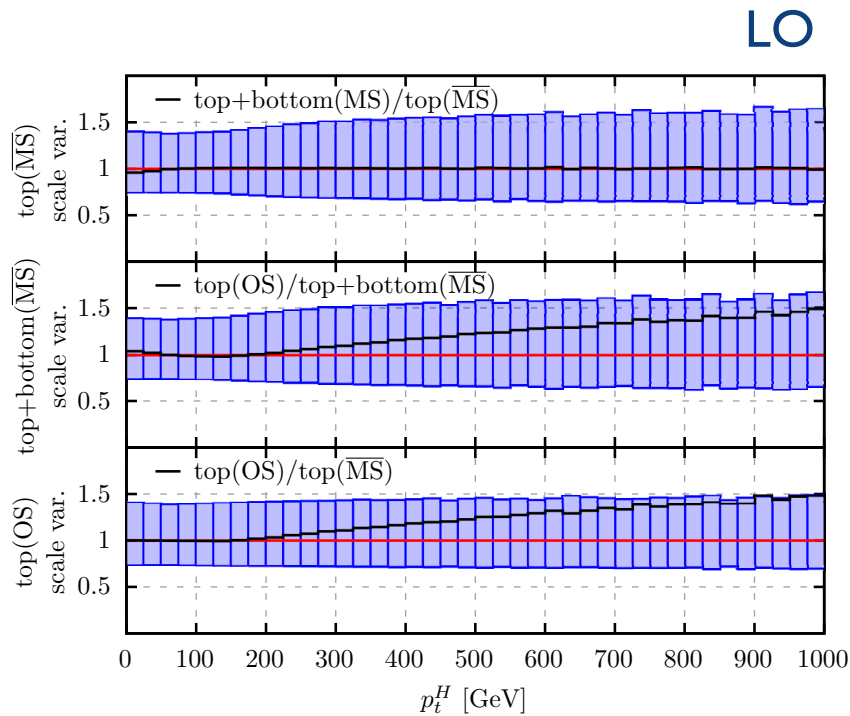


scale uncertainty bands = ratio of bands at NLO over central value at LO



k factor almost always larger than 2 for $\overline{\text{MS}}$, and about 2 for OS

Ratios of Higgs p_T distributions



- from **LO** to **NLO**, reduction of scale uncertainty and of mass renormalisation scheme dependence
- except in the lowest bins, no appreciable difference between $t+b(\overline{\text{MS}})$ and $t(\overline{\text{MS}})$
 The b quark, and thus top- b interference, is negligible, except at low end of p_T range
- p_T distribution for $t(\overline{\text{MS}})$ falls off faster than same for $t(\text{OS})$ as p_T increases because μ_R increases with p_T and so $m_t^{\overline{\text{MS}}}(\mu_R)$ decreases
- mass renormalisation scheme difference between $t(\overline{\text{MS}})$ and $t(\text{OS})$ is same size as scale uncertainty at high end of p_T range, both at **LO** and **NLO**

Conclusions

- we computed the Higgs p_T distribution at NLO in QCD including for the first time top and b quarks and the $\overline{\text{MS}}$ mass scheme
- computation has excellent numerical stability
- b quark, and thus top- b interference, is negligible, except at low end of p_T range, where it affects the shape of the distribution
- in the intermediate to high p_T range, use of top quark only is warranted, but sizeable dependence on mass renormalisation scheme
- p_T distribution can be improved:
mixed QCD-EW corrections (we already have $gg \rightarrow Hg$),
resummation,
top-charm interference, ...

Back-up slides

Higgs production

QCD corrections have been computed at N³LO in HEFT

Anastasiou Duhr Dulat Herzog Mistlberger 2015
Mistlberger 2018
(in terms of MPLs and elliptic integrals)

including quark-mass effects and QCD-EW interference the cross section 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

48.58 pb =	16.00 pb	(+32.9%)	(LO, rEFT)
	+ 20.84 pb	(+42.9%)	(NLO, rEFT)
	- 2.05 pb	(-4.2%)	((t, b, c), exact NLO)
	+ 9.56 pb	(+19.7%)	(NNLO, rEFT)
	+ 0.34 pb	(+0.2%)	(NNLO, 1/m _t)
	+ 2.40 pb	(+4.9%)	(EW, QCD-EW)
	+ 1.49 pb	(+3.1%)	(N ³ LO, rEFT)

Anastasiou Duhr Dulat Furlan Gehrmann Herzog Lazopoulos Mistlberger 2016
Handbook 4 of LHC Higgs Cross Sections 2016

Higgs production

Handbook 4 of LHC Higgs Cross Sections 2016

- 6 sources of uncertainties due to:
 - higher orders
 - truncation of the threshold expansion
 - PDFs
 - NLO corrections to QCD-EW interference
 - quark mass effects (2: top mass and top-b interference) at NNLO

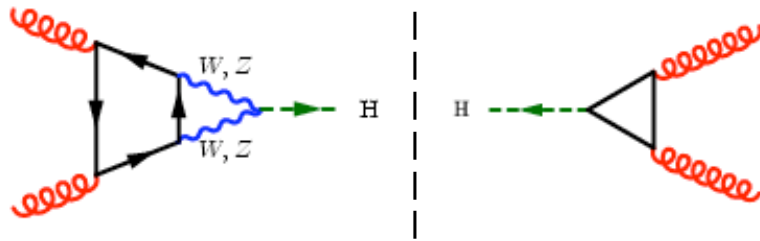
$\delta(\text{scale})$	$\delta(\text{trunc})$	$\delta(\text{PDF-TH})$	$\delta(\text{EW})$	$\delta(t, b, c)$	$\delta(1/m_t)$
+0.10 pb -1.15 pb	± 0.18 pb	± 0.56 pb	± 0.49 pb	± 0.40 pb	± 0.49 pb
+0.21% -2.37%	$\pm 0.37\%$	$\pm 1.16\%$	$\pm 1\%$	$\pm 0.83\%$	$\pm 1\%$

$$\delta(\text{trunc}) = 0.11 \text{ pb} \quad \text{Mistlberger 2018}$$

$$\delta(1/m_t) = -0.26\% \quad \text{Czakon Harlander Klappert Niggetiedt 2021}$$

QCD-EW interference

- The Higgs boson may (indirectly) couple to gluons also via the gauge coupling i.e. through a double (electroweak boson + quark) loop



Aglietti Bonciani Degrassi Vicini 2004
 (light fermion loop)
Degrassi Maltoni 2004
Actis Passarino Sturm Uccirati 2008
 (heavy fermion loop)

(in terms of MPLs)

(numerically
... elliptic integrals appear)

$O(\alpha_s^2 \alpha^2)$

- the top loop yields a 2% correction to the 5 light fermion loops

- gg-initiated QCD NLO corrections (light fermion loop)

computed in various approximations:

— $m_{W,Z} \rightarrow \infty$ limit

Anastasiou Boughezal Petriello 2009

— soft approximation

Bonetti Melnikov Tancredi 2018

— $m_{W,Z} \rightarrow 0$ limit

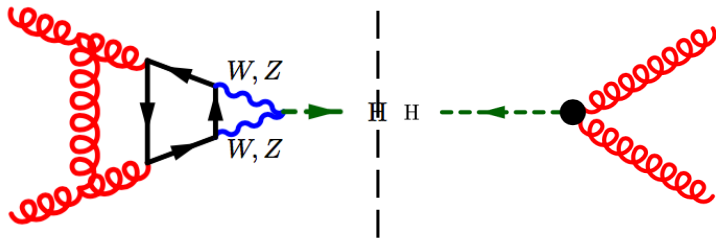
Anastasiou VDD Furlan Mistlberger Moriello Schweitzer Specchia 2018

and found to be about 5% wrt NLO (HEFT) cross section

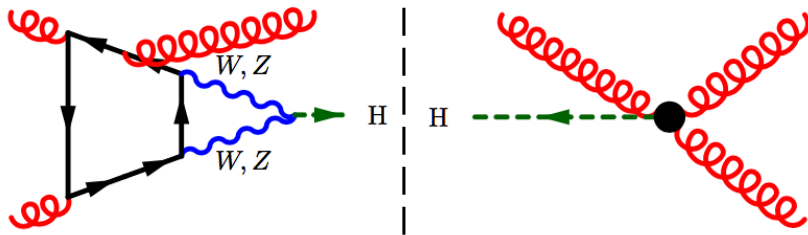
QCD-EW interference

🌐 gg-initiated QCD NLO corrections (light fermion loop): $O(\alpha_s^3 \alpha^2)$

Becchetti Bonciani VDD Hirschi Moriello Schweitzer 2020



Bonetti Melnikov Tancredi 2016



Becchetti Bonciani Casconi VDD Moriello 2018
 Bonetti Panzer V. Smirnov Tancredi 2020
 Becchetti Moriello Schweitzer 2021

IR local subtraction schemes

MadGraph MC@NLO

Frixione Kunszt Signer 1995
 Frederix Frixione Maltoni Stelzer 2009

COLORFUL

VDD Somogyi Trocsanyi 2006
 Somogyi 2009
 VDD Deutschmann Lionetti 2019

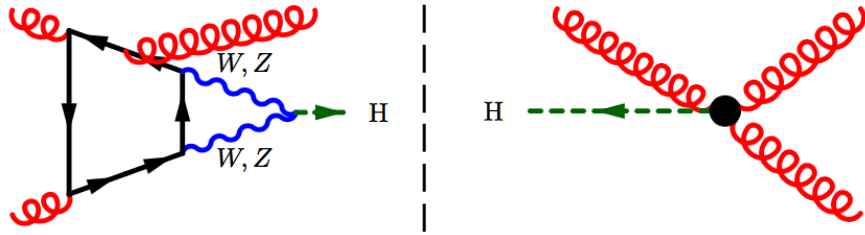
LO $\sigma_{gg \rightarrow H+X}^{(\alpha_s^2 \alpha^2)} = 0.68739_{-17.3\% -2.0\%}^{+23.4\% +2.0\%}$ pb

NLO $\sigma_{gg \rightarrow H+X}^{(\alpha_s^2 \alpha^2 + \alpha_s^3 \alpha^2)} = 1.467(2)_{-14.6\% -2.0\%}^{+18.7\% +2.0\%}$ pb i.e. NLO 110% wrt LO

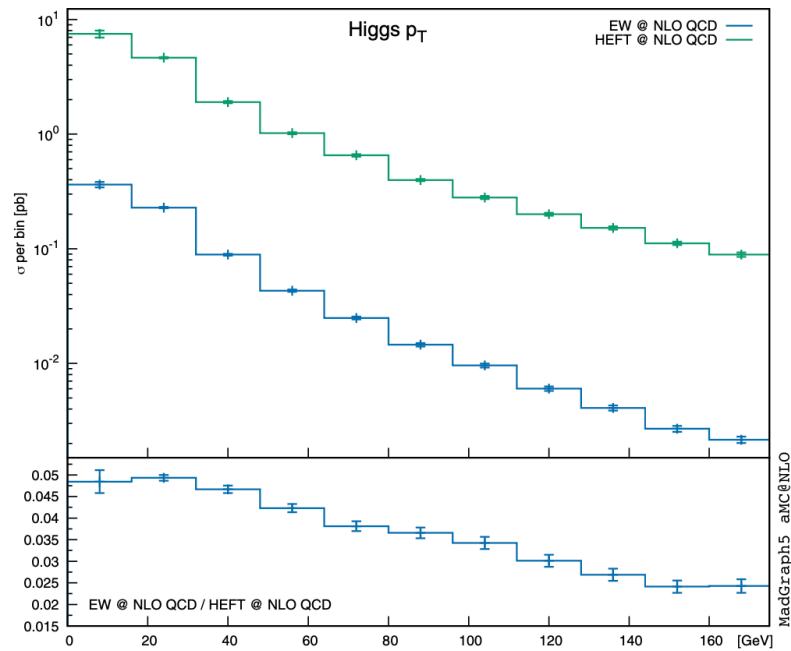
gg-initiated NLO corrections in HEFT $\sigma_{gg \rightarrow H+X}^{(\text{HEFT}, \alpha_s^2 \alpha + \alpha_s^3 \alpha)} = 30.484_{-15.3\% -1.9\%}^{+19.8\% +1.9\%}$ pb

thus our NLO result 4.8% wrt gg-initiated NLO HEFT

Higgs p_T distribution due to QCD-EW interference



Becchetti Bonciani VDD Hirschi Moriello Schweitzer 2020



gg-initiated QCD-EW p_T spectrum harder than HEFT