Top and b mass effects in Higgs production at LHC

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in collaboration with
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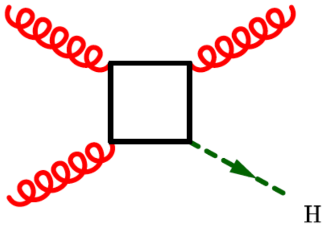
LNF 7 February 2024

Higgs p_T distribution at LHC



- 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

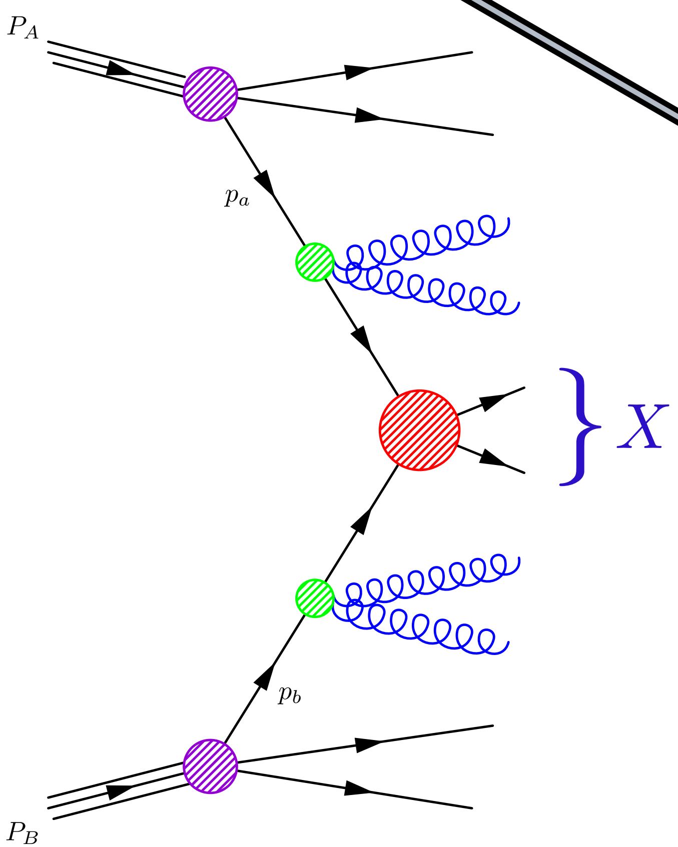
- QCD NLO corrections to the top- and *b*-quark mass effects on the Higgs p_T distribution, in the on-shell and MSbar mass renormalisation schemes

Parton model

extracted from data
evolved through DGLAP

computed in QCD

factorising short- and long-range interactions



$$\sigma_X = \sum_{a,b} \int_0^1 dx_1 dx_2\, f_{a/A}(x_1,\mu_F^2)\, f_{b/B}(x_2,\mu_F^2)$$
$$\times\ \hat{\sigma}_{ab\to X}\left(x_1, x_2, \{p_i^\mu\}; \alpha_S(\mu_R^2), \alpha(\mu_F^2), \frac{Q^2}{\mu_R^2}, \frac{Q^2}{\mu_F^2}\right)$$

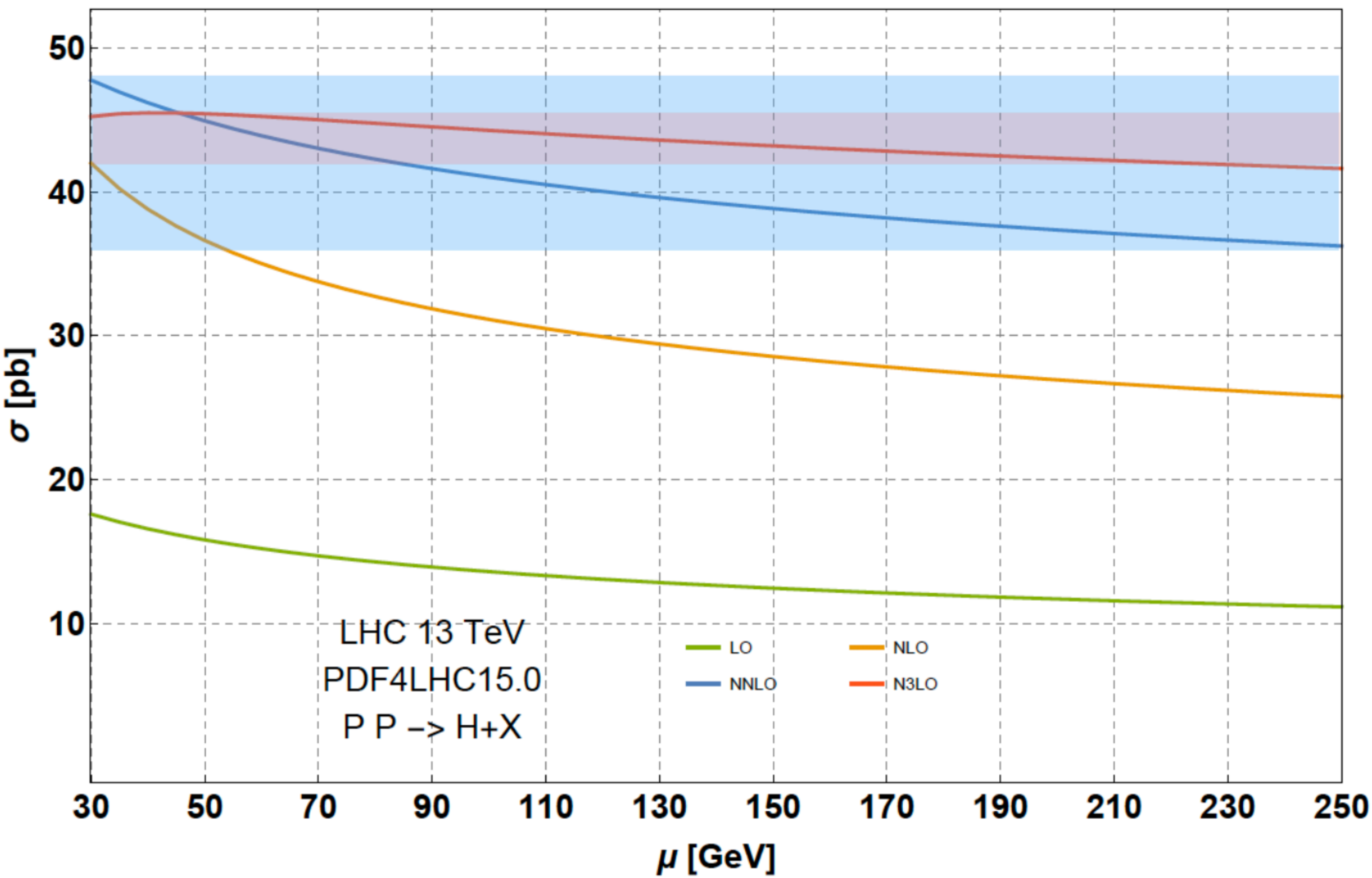
$$X = W, Z, H, Q\bar{Q}, \text{high-}E_T\text{jets}, \ldots$$

$\hat{\sigma}$ is known as a fixed-order expansion in α_S

$$\hat{\sigma} = C\alpha_S^n(1 + c_1\alpha_S + c_2\alpha_S^2 + \ldots)$$

$c_1 =$ NLO $\qquad c_2 =$ NNLO

the computed cross section depends on unphysical scales: μ_R and μ_F



< 5%

from F. Maltoni's talk at GGI tea breaks 2021

- the crucial ingredient of a parton cross section is the amplitude

$$\hat{\sigma} \sim \int dP_{PS} \, |\mathcal{M}|^2$$

- amplitudes are on-shell and gauge-invariant objects

- amplitudes exhibit unexpected symmetries

Parke-Taylor formula for MHV *n*-gluon amplitudes

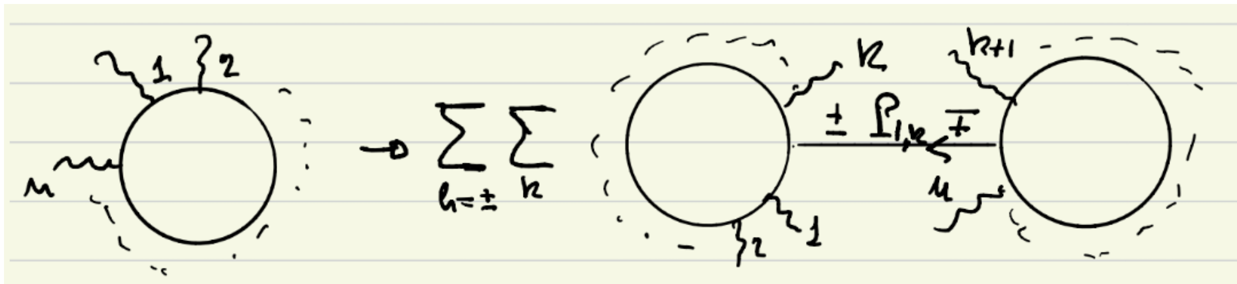
$$A_4^{tree}(1^+, 2^+, \ldots, i^-, \ldots, j^-, \ldots, n^+) = \frac{\langle ij \rangle^4}{\langle 12 \rangle \langle 23 \rangle \ldots \langle (n-1)n \rangle \langle n1 \rangle}$$

# external gluons	# Feynman diagrams
4	4
6	220
8	34,300
10	10,521,900

# of Feynman diagrams grows factorially with # of gluons

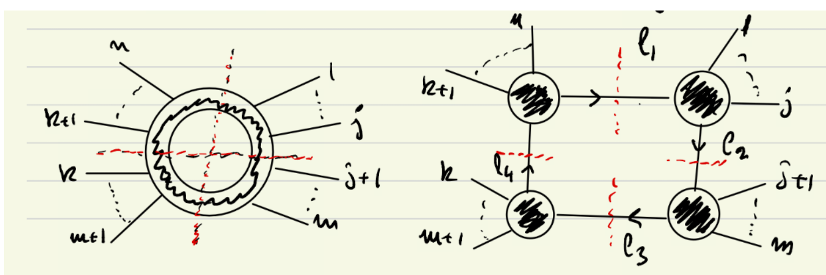
Tree amplitudes

- Britto Cachazo Feng Witten (BCFW) on-shell recursion relations



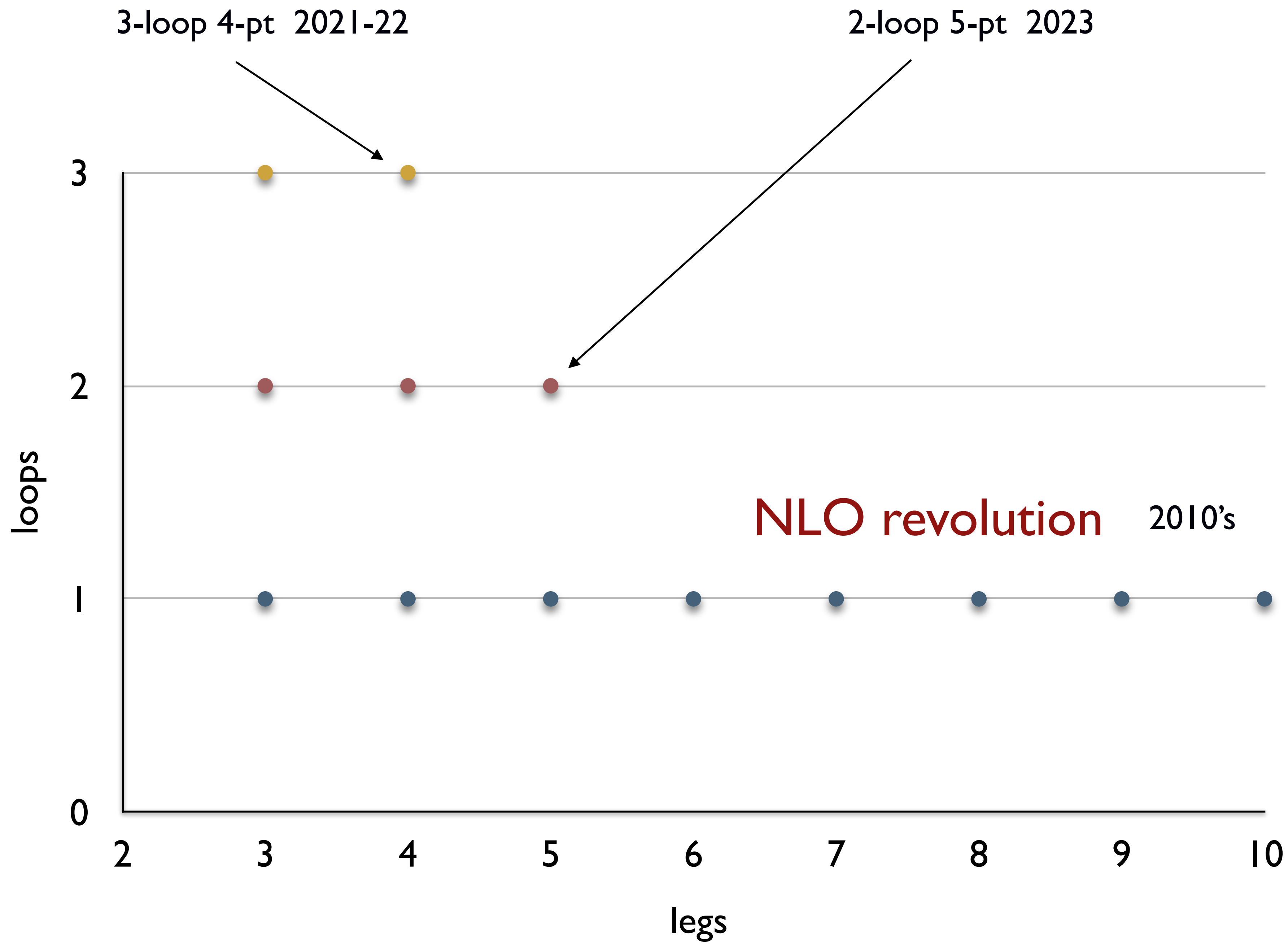
One-loop amplitudes

- generalised unitarity



Galileo Galilei Medal 2023

"for the development of powerful methods for high-order perturbative calculations in quantum field theory"


3-loop 4-pt 2021-22
2-loop 5-pt 2023
3
2
1
0
loops
NLO revolution
2010's
2
3
4
5
6
7
8
9
10
legs

Tree level: computed without Feynman diagrams

One loop: computed without Feynman diagrams

Two loops: oh no! Feynman diagrams again …

although many modern techniques (tensor decomposition, integration by parts identities, method of differential equations) have been devised to compute multiloop Feynman integrals

Do we need a completely different approach?

from G. Heinrich's talk at LNF in May 2019

… but through multiloop amplitude studies,
beautiful mathematical structures were uncovered…

Polylogarithms

- classical polylogarithms $\mathrm{Li}_m(z) = \int_0^z dt \frac{\mathrm{Li}_{m-1}(t)}{t} = \sum_{n=1}^{\infty} \frac{z^n}{n^m}$ $\quad \mathrm{Li}_1(z) = \sum_{n=1}^{\infty} \frac{z^n}{n} = -\ln(1-z)$

Euler 1768
Spence 1809

- multiple polylogarithms

$$G(a,\vec{w};z) = \int_0^z \frac{\mathrm{d}t}{t-a} G(\vec{w};t)\,, \qquad G(a;z) = \ln\left(1-\frac{z}{a}\right) \qquad a,\vec{w} \in \mathbb{C}$$

Goncharov 1998

classical polylogarithms are multiple polylogarithms with specific roots

$$G(\vec{0}_n;x) = \frac{1}{n!}\ln^n x \qquad G(\vec{a}_n;x) = \frac{1}{n!}\ln^n\left(1-\frac{x}{a}\right) \qquad G(\vec{0}_{n-1},a;x) = -\mathrm{Li}_n\left(\frac{x}{a}\right)$$

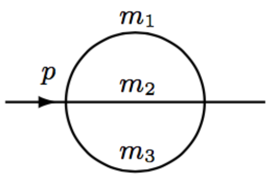
- multiple polylogarithms are endowed with a rich algebraic structure

Hopf Algebra → functional identities among polylogarithms

- multiple polylogarithms are iterated integrals on the Riemann sphere

Elliptic iterated integrals

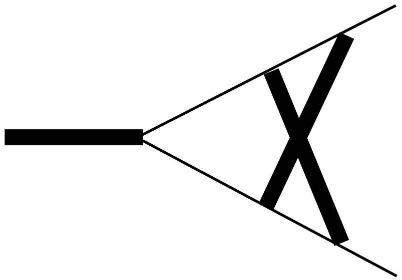
- 2-loop sunrise graph



Sabry 1962: …;Broadhurst 1989; …; Bloch Vanhove 2013; …
Brödel Duhr Dulat Penante Tancredi 2017-2019

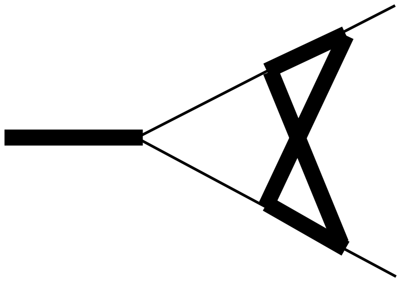
- 2-loop 3-pt functions

electroweak form factor



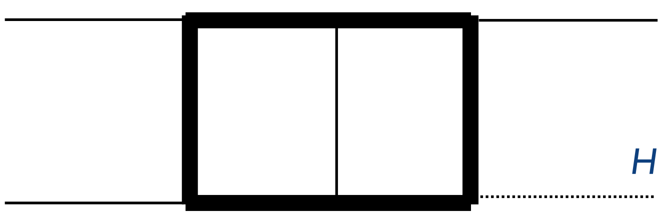
Aglietti Bonciani Grassi Remiddi 2007

t-*t*bar



von Manteuffel Tancredi 2017

- 2-loop 4-pt function for Higgs + 1 jet

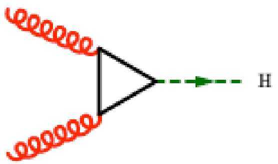


Bonciani VDD Frellesvig Henn Moriello Smirnov 2016

first instance of elliptic iterated integrals in a genuine 4-pt topology

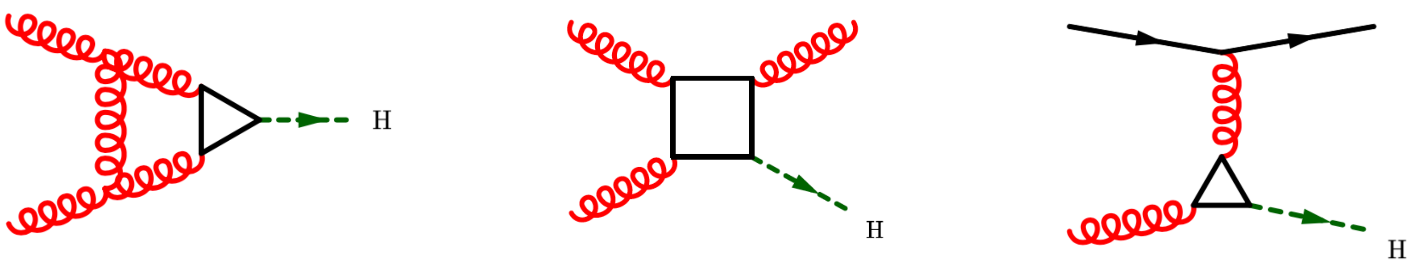
Higgs production at LHC

- 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 are known for top-, *b*- and charm-quark loops
  (in principle for any heavy quark mass)

Djouadi Graudenz Spira Zerwas 1991-1995



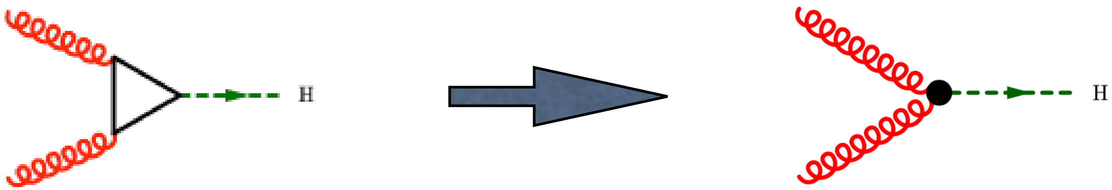
  - QCD NLO corrections are about 100% larger than leading order

- QCD NNLO corrections are known for top- and *b*-quark loops

Czakon Harlander Klappert Niggetiedt 2021 (top)
Czakon Eschment Niggetiedt Poncelet Schellenberger 2023 (top + *b*)

Higgs Effective Field Theory

- $m_H << 2m_t$



all amplitudes are reduced by one loop

$$R_{LO} = \frac{\sigma^{LO}_{ex:t}}{\sigma^{LO}_{EFT}} = 1.063$$

rescaled HEFT (rHEFT) tuned to reproduce the exact (only top) LO σ

- in HEFT QCD corrections have been computed at N^3LO

Anastasiou Duhr Dulat Herzog Mistlberger 2015
Mistlberger 2018

(in terms of MPLs and elliptic integrals)

- the N^3LO computation raised the central value by 3% and featured a 3% scale variation

Higgs production

Handbook 4 of LHC Higgs Cross Sections 2016

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

$$\sigma = 48.58\,\mathrm{pb}^{+2.22\,\mathrm{pb}\,(+4.56\%)}_{-3.27\,\mathrm{pb}\,(-6.72\%)}\ (\text{theory}) \pm 1.56\,\mathrm{pb}\,(3.20\%)\ (\text{PDF}+\alpha_s)$$

- The breakdown of the cross section

$$\begin{aligned} 48.58\,\mathrm{pb} = \;& 16.00\,\mathrm{pb} && (+32.9\%) && (\text{LO, rEFT}) \\ & + 20.84\,\mathrm{pb} && (+42.9\%) && (\text{NLO, rEFT}) \\ & - \;\; 2.05\,\mathrm{pb} && (-4.2\%) && ((t,b,c),\ \text{exact NLO}) \\ & + \;\; 9.56\,\mathrm{pb} && (+19.7\%) && (\text{NNLO, rEFT}) \\ & + \;\; 0.34\,\mathrm{pb} && (+0.2\%) && (\text{NNLO}, 1/m_t) \\ & + \;\; 2.40\,\mathrm{pb} && (+4.9\%) && (\text{EW, QCD-EW}) \\ & + \;\; 1.49\,\mathrm{pb} && (+3.1\%) && (\text{N}^3\text{LO, rEFT}) \end{aligned}$$

Anastasiou Duhr Dulat Furlan Gehrmann Herzog Lazopoulos Mistlberger 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

δ(scale)	δ(trunc)	δ(PDF-TH)	δ(EW)	$\delta(t,b,c)$	$\delta(1/m_t)$
$^{+0.10}_{-1.15}$ pb	±0.18 pb	±0.56 pb	±0.49 pb	±0.40 pb	±0.49 pb
$^{+0.21\%}_{-2.37\%}$	$\pm0.37\%$	$\pm1.16\%$	$\pm1\%$	$\pm0.83\%$	$\pm1\%$

δ(trunc) = 0.11 pb Mistlberger 2018

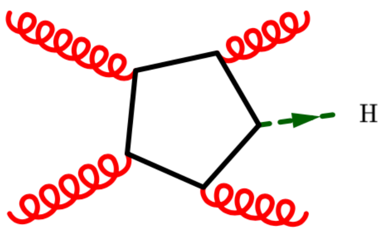
$\delta(1/m_t)$ = - 0.26% Czakon Harlander Klappert Niggetiedt 2021

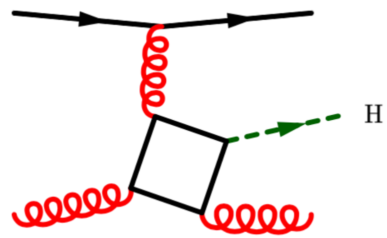
δ(t, b) = - 4.6% Czakon Eschment Niggetiedt Poncelet Schellenberger 2023

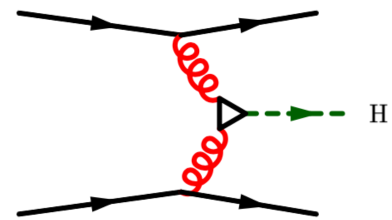
QCD NNLO corrections

- Higgs + 4-parton amplitudes at one loop

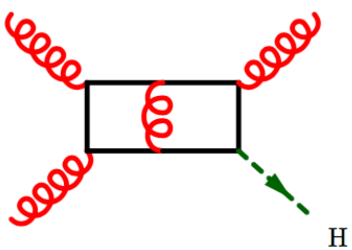
VDD Kilgore Oleari Schmidt Zeppenfeld 2001
Budge Campbell De Laurentis K. Ellis Seth 2020
OpenLoops

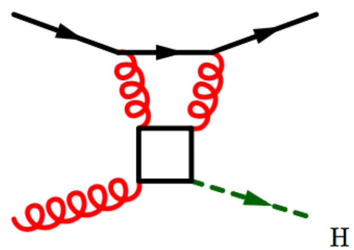






- Higgs + 3-parton amplitudes at two loops

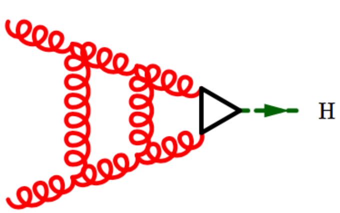




top loop: Jones Kerner Luisoni 2018
Czakon Harlander Klappert Niggetiedt 2021

Bonciani VDD Frellesvig Moriello Hidding
Hirschi Salvatori Somogyi Tramontano 2022

- $gg \rightarrow$ Higgs amplitudes at three loops



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

Czakon Niggetiedt 2020
Harlander Prausa Usovitsch 2019

two scales: top loop + *b*-quark loop

Niggetiedt Usovitsch 2023

QCD NNLO corrections

- Top and *b*-quark mass corrections at NNLO

Czakon Harlander Klappert Niggetiedt 2021 (top)
Czakon Eschment Niggetiedt Poncelet Schellenberger 2023 (top + *b*)

Order	σ_{HEFT} [pb]	$(\sigma_t - \sigma_{\mathrm{HEFT}})$ [pb]	$\sigma_{t\text{-}b\text{-interference}}$ [pb]	$\sigma_{t\text{-}b\text{-interference}}/\sigma_{\mathrm{HEFT}}$ [%]
$\sqrt{s} = 8$ TeV				
$\mathcal{O}(\alpha_s^2)$	$+7.39$	–	-0.895	
LO	$7.39^{+1.98}_{-1.40}$	–	$-0.895^{+0.17}_{-0.24}$	-12
$\mathcal{O}(\alpha_s^3)$	$+9.14$	-0.0873	$-0.269(2)$	
NLO	$16.53^{+3.63}_{-2.73}$	$-0.0873^{+0.030}_{-0.052}$	$-1.16^{+0.10}_{-0.08}$	$-7.0^{+1.0}_{-0.8}$
$\mathcal{O}(\alpha_s^4)$	$+4.19$	$+0.0523(2)$	$+0.167(3)$	
NNLO	$20.72^{+1.84}_{-2.06}$	$-0.350(2)^{+0.048}_{-0.013}$	$-0.998(4)^{+0.12}_{-0.05}$	$-4.8^{+0.9}_{-0.8}$
$\sqrt{s} = 13$ TeV				
$\mathcal{O}(\alpha_s^2)$	$+16.30$	–	-1.975	
LO	$16.30^{+4.36}_{-3.10}$	–	$-1.98^{+0.37}_{-0.53}$	-12
$\mathcal{O}(\alpha_s^3)$	$+21.14$	$-0.3029(2)$	$-0.447(4)$	
NLO	$37.44^{+8.42}_{-6.29}$	$-0.3029(2)^{+0.10}_{-0.17}$	$-2.42^{+0.19}_{-0.12}$	$-6.5^{+0.9}_{-0.8}$
$\mathcal{O}(\alpha_s^4)$	$+9.72$	$+0.147(1)$	$+0.434(8)$	
NNLO	$47.16^{+4.21}_{-4.77}$	$-0.158(1)^{+0.13}_{-0.03}$	$-1.99(1)^{+0.30}_{-0.15}$	$-4.2^{+0.9}_{-0.8}$

	σ_t	σ_{t+b}	$\frac{\sigma_{t+b}}{\sigma_t} - 1$	$\frac{\sigma_{t+b}}{\sigma_{\mathrm{HEFT}}} - 1$
$O(\alpha_s^3)$	20.84 pb	20.39 pb	- 2.14 %	- 3.55 %
$O(\alpha_s^2 + \alpha_s^3)$	37.14 pb	34.71 pb	- 6.5 %	- 7.3 %
$O(\alpha_s^4)$	9.87 pb	10.30 pb	+ 4.3 %	+ 6.0 %
$O(\alpha_s^2 + \alpha_s^3 + \alpha_s^4)$	47.00 pb	45.01 pb	- 4.2 %	- 4.6 %

- top-*b* interference has a larger effect than top-quark corrections

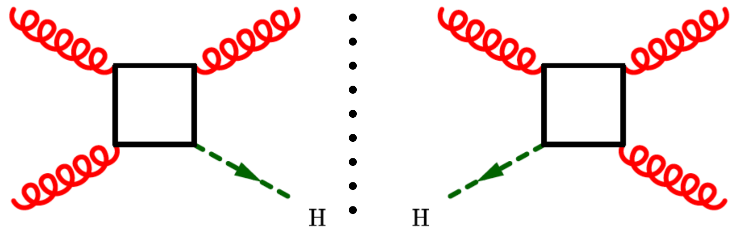
- top-*b* interference as large at $O(\alpha_s^4)$ as it is at $O(\alpha_s^3)$, but with opposite sign (and larger than expected from NLO scale uncertainties)

- 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

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 ($H \to \gamma\gamma$)

- 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 MSbar schemes
    for top- and *b*-quarks (for any heavy quark mass), with MSbar scheme

    Bonciani VDD Frellesvig Moriello Hidding Hirschi Salvatori Somogyi Tramontano 2022

- HEFT $m_H << 2m_t$ and $p_T << m_t$ — 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 Gehrmann Glover Jaquier 2016

Higgs p_T distribution at LHC

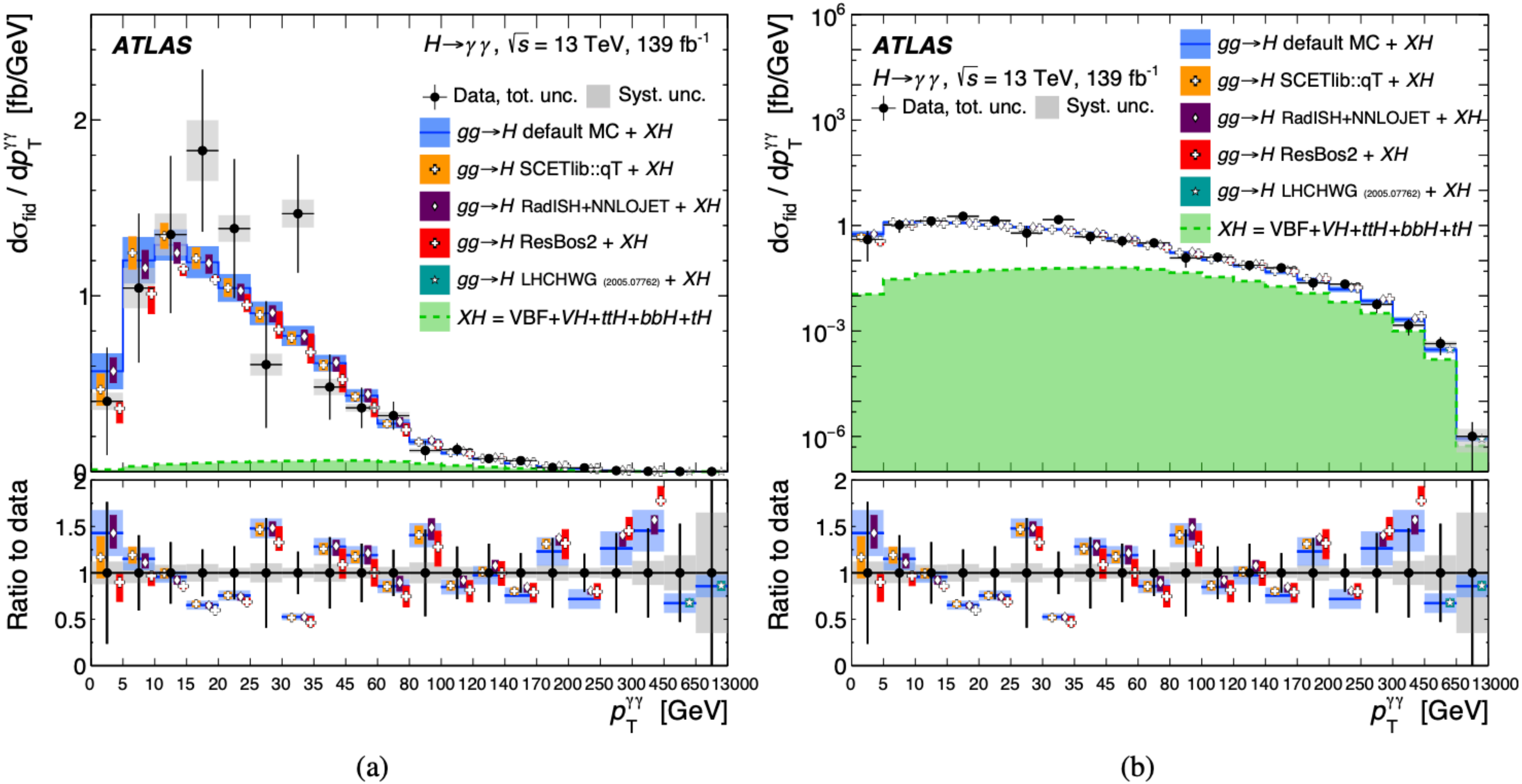
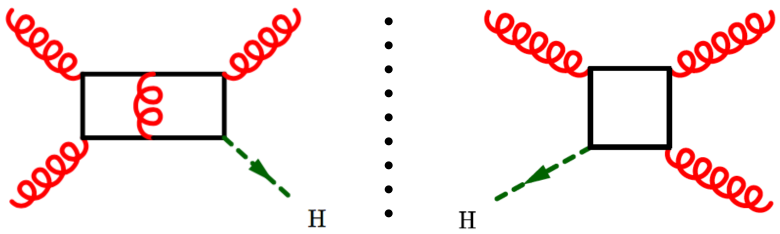


Figure 8: Particle-level fiducial differential cross-sections times branching ratio for the diphoton variable $p_T^{\gamma\gamma}$ in (a) linear and (b) logarithmic scale. The measured cross-sections are compared with several predictions changing the

ATLAS arXiv:2202.00487

Higgs p_T distribution at NLO

- virtual corrections



top-quark loop

Jones Kerner Luisoni 2018
Czakon Harlander Klappert Niggetiedt 2021

top- and *b*-quark (any heavy quark) loop

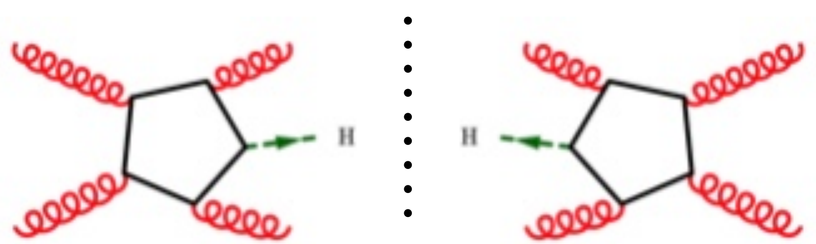
Bonciani VDD Frellesvig Henn Moriello V. Smirnov 2016
all above + Hidding Maestri Salvatori 2019

Bonciani VDD Frellesvig Moriello Hidding Hirschi Salvatori Somogyi Tramontano 2022

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

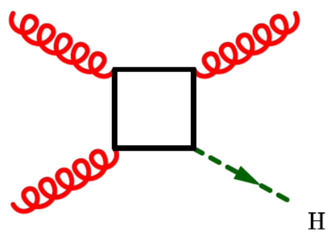
in the loop

- real corrections



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

- one-loop amplitudes for Higgs + 3-partons



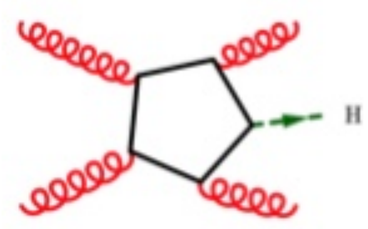
leading order: up to $O(\varepsilon^2)$

analytic: up to $O(\varepsilon^0)$ — K. Ellis Hinchliffe Soldate van der Bij 1988

numeric: up to $O(\varepsilon^2)$

(numeric) derivative for mass renormalisation

- one-loop amplitudes for Higgs + 4-partons



NLO real corrections: up to $O(\varepsilon^0)$

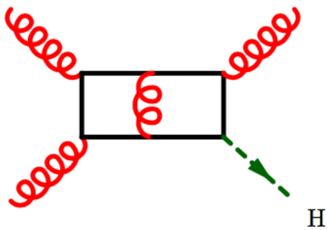
analytic: unitarity-cut methods (taken from MCFM-9.1)

Budge Campbell De Laurentis K. Ellis Seth 2020

numeric: GoSam & MG5_aMC

run time
analytic: few ms/pt
numeric: O(100) times slower than analytic

two-loop amplitudes for Higgs + 3-partons



NLO virtual corrections

amplitude → form factors → scalar integrals → Master Integrals

IBP

FIRE-KIRA

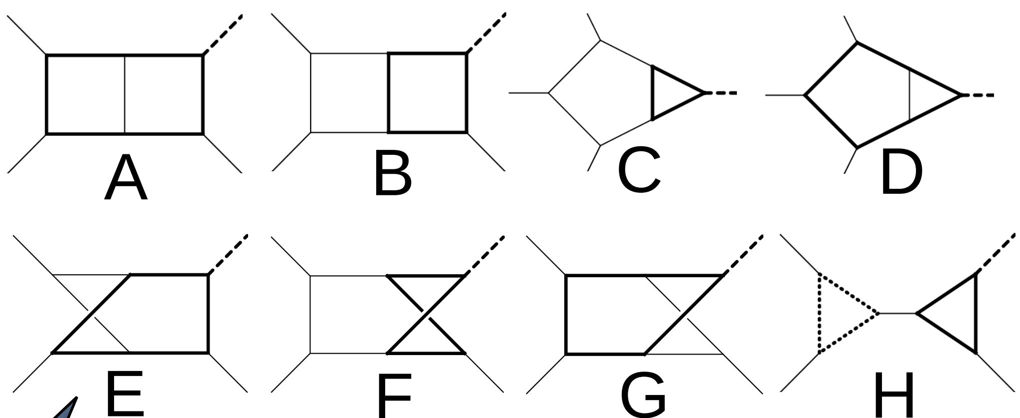
run time: 5 — 60 min/pt

4 scales, s, t, m_H, m_t → 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

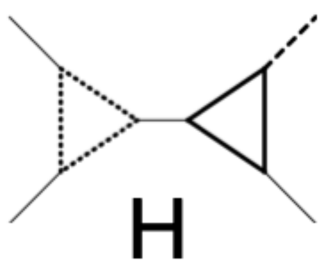
elliptic

two masses

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

Bonciani VDD Frellesvig Moriello Hidding Hirschi Salvatori Somogyi Tramontano 2022

- coupling constant: 5-flavour running in MSbar
- renormalisation:
  - top Yukawa coupling and top mass in OS scheme (massless *b*)
  - top Yukawa coupling and top mass in MSbar scheme (massless *b*)
  - top and *b* Yukawa couplings and masses in MSbar scheme



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

alternative:
massive *b* everywhere,
but requires 4-flavour running and including $gg \to Hbb$

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

- IR poles

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

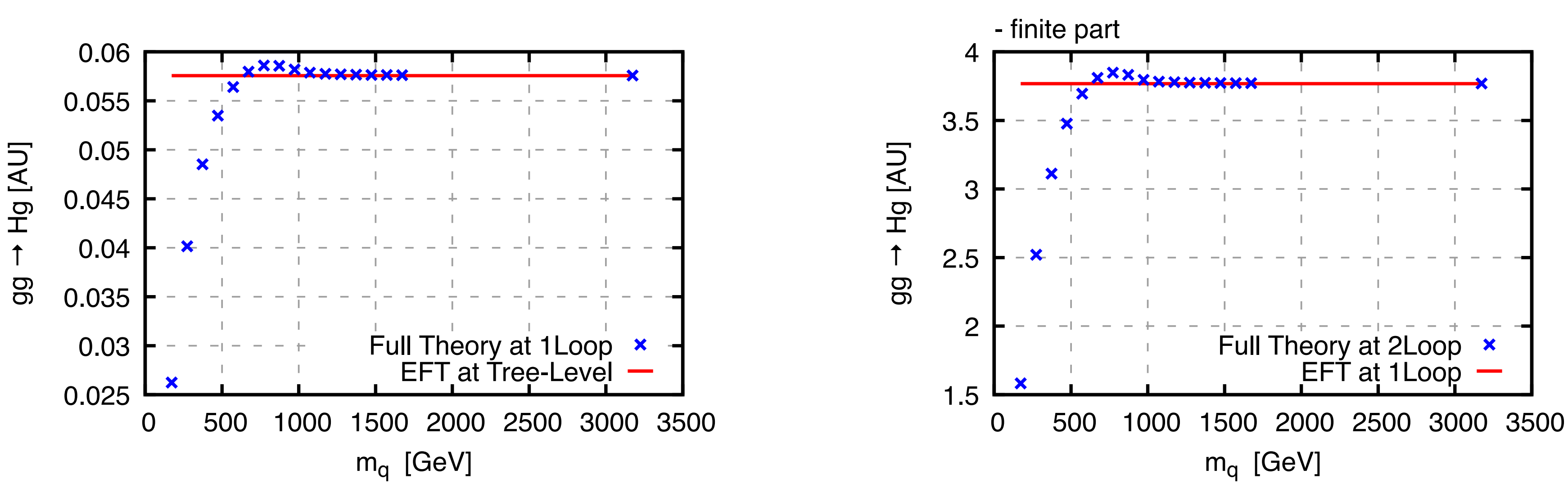
with insertion operators

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

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

- agreement with HEFT limit

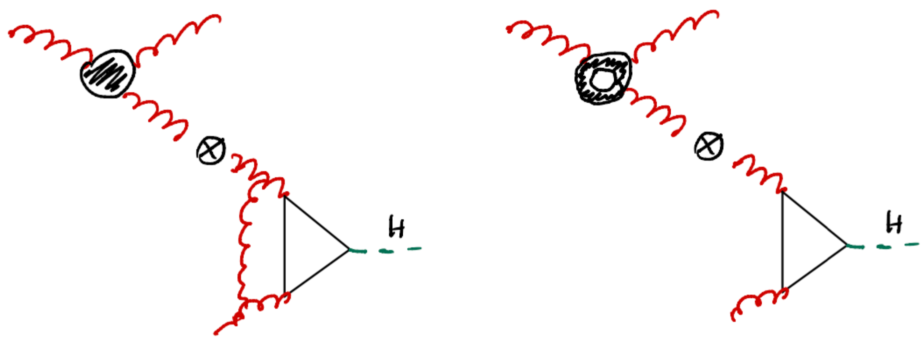
$$\mathcal{M} = \mathcal{M}_{HEFT} + \mathcal{O}\left(\frac{1}{M_t}\right)$$



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

one-loop 2-parton splitting functions — Bern Dixon Dunbar Kosower 1994; Bern Kilgore Schmidt VDD 1998-99; Kosower Uwer 1999

one-loop 1-soft-gluon factor — Bern Kilgore Schmidt VDD 1998-99; Catani Grazzini 2000

- checked also “two-loop photon correction”

Higgs p_T distribution at **NLO**: checks with previous results

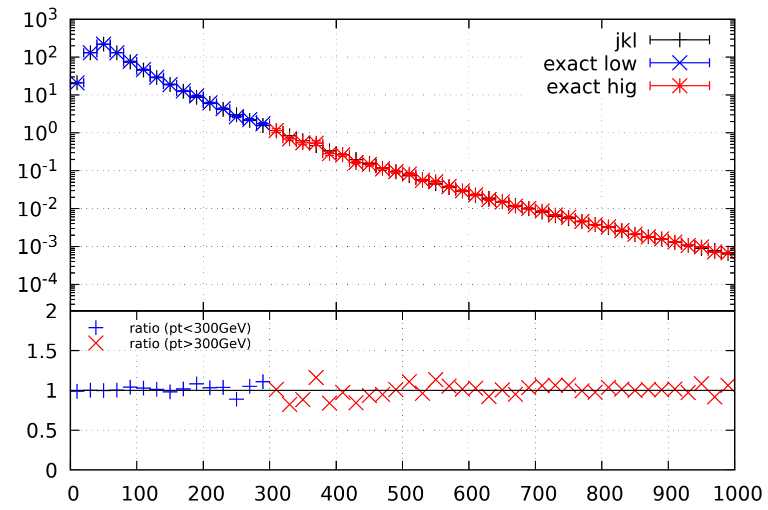
- inclusive p_T distribution ($p_{T,j}$ > 30 GeV) with OS mass renormalisation

our result

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

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

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



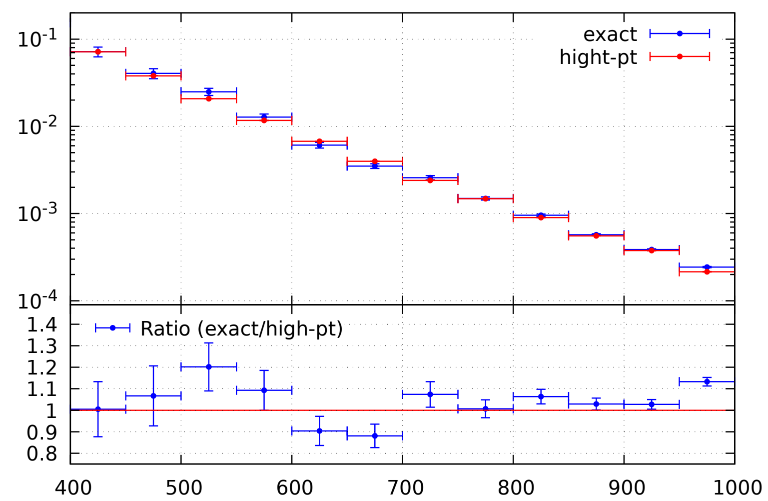
- high p_T tail of distribution

checked with approximate high-p_T distribution

Lindert Melnikov Kudashkin Wever 2018

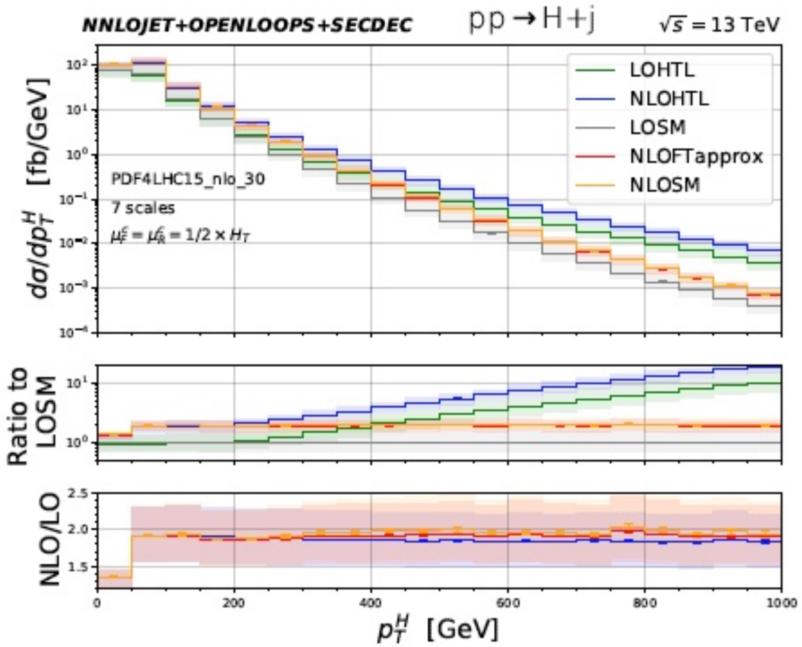
based on approximate high-p_T two-loop amplitudes

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

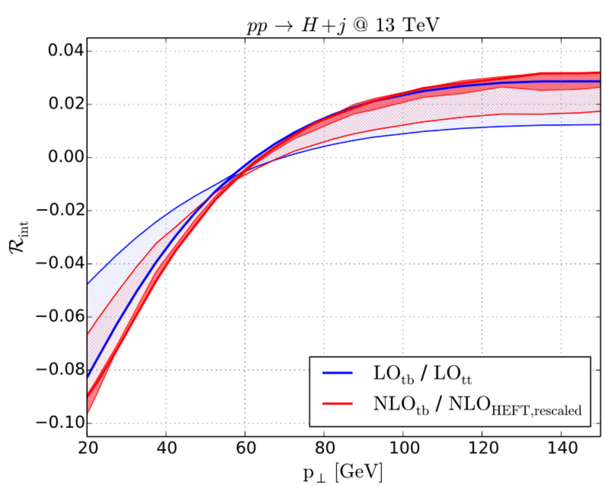
$\frac{d\sigma}{dp_T^2} \propto \frac{1}{p_T^2}$ in HEFT NLO corrections

$\frac{d\sigma}{dp_T^2} \propto \frac{1}{(p_T^2)^2}$ 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 — Somogyi 2009
  dual subtraction — Prisco Tramontano 2020

- evaluated on:
  3x10[4] pt for OS top (1.4x10[4] pt on basic grid, 1.6x10[4] pt on biased grid)
  9x10[4] pt for MSbar top
  1.8x10[5] pt for MSbar top and *b*

- set-up

$\sqrt{s} = 13\,\mathrm{TeV}$

$m_H = 125.25\,\mathrm{GeV}$

$m_t^{\mathrm{OS}} = 172.5\,\mathrm{GeV}$

$m_t^{\overline{\mathrm{MS}}}(m_t^{\overline{\mathrm{MS}}}) = 163.4\,\mathrm{GeV}$

$m_b^{\overline{\mathrm{MS}}}(m_b^{\overline{\mathrm{MS}}}) = 4.18\,\mathrm{GeV}$

$G_F = 1.16639 \cdot 10^{-5}\,\mathrm{GeV}^{-2}$

NNPDF40_nlo_as_01180

$p_{T,j_1} > 20\,\mathrm{GeV}$

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

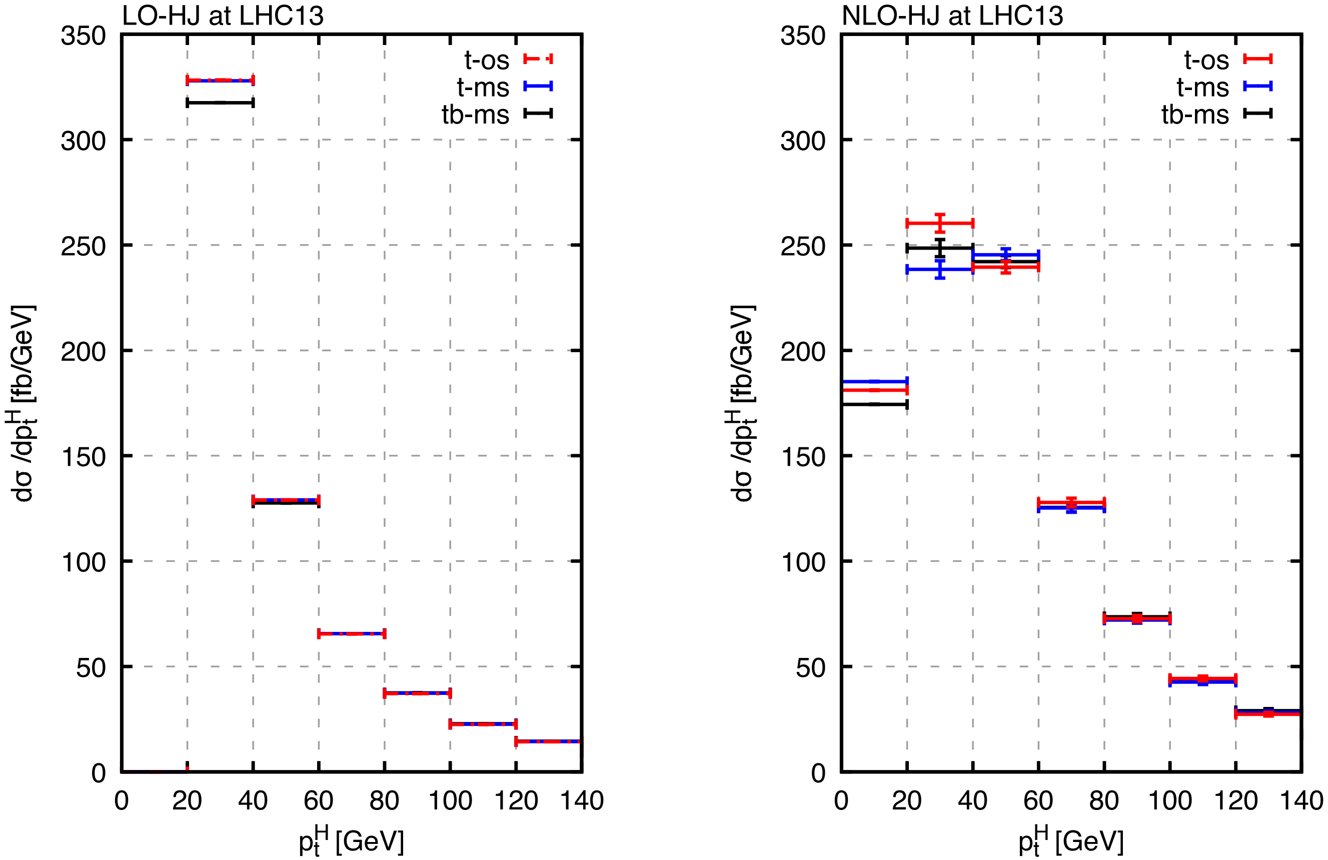
for the top-quark, with on-shell and MSbar schemes
for top- and *b*-quarks with MSbar scheme

renormalisation of internal masses	$\sigma_{\rm LO}$ [pb]	$\sigma_{\rm NLO}$ [pb]
top+bottom–($\overline{\rm MS}$)	$12.318^{+4.711}_{-3.117}$	$19.89(8)^{+2.84}_{-3.19}$
top–($\overline{\rm MS}$)	$12.538^{+4.822}_{-3.183}$	$19.90(8)^{+2.66}_{-2.85}$
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 $O(\alpha_s^3)$ but positive at $O(\alpha_s^4)$
- effect of top mass renormalisation utterly negligible at LO
but 15 times bigger at NLO

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

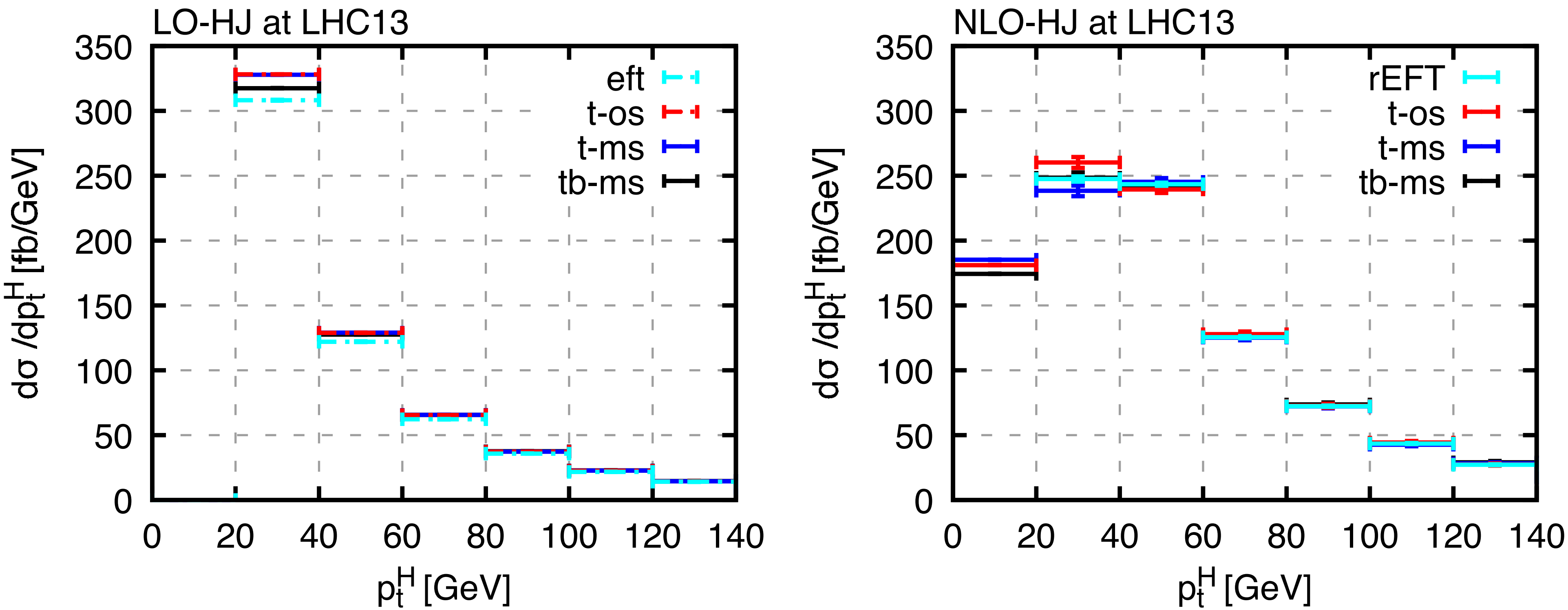
Higgs p_T distribution at low-intermediate p_T



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(OS) and t(MSbar)
- at NLO sizeable shape distortion in the lowest bins
- scale uncertainty bands (not shown) are much larger than differences

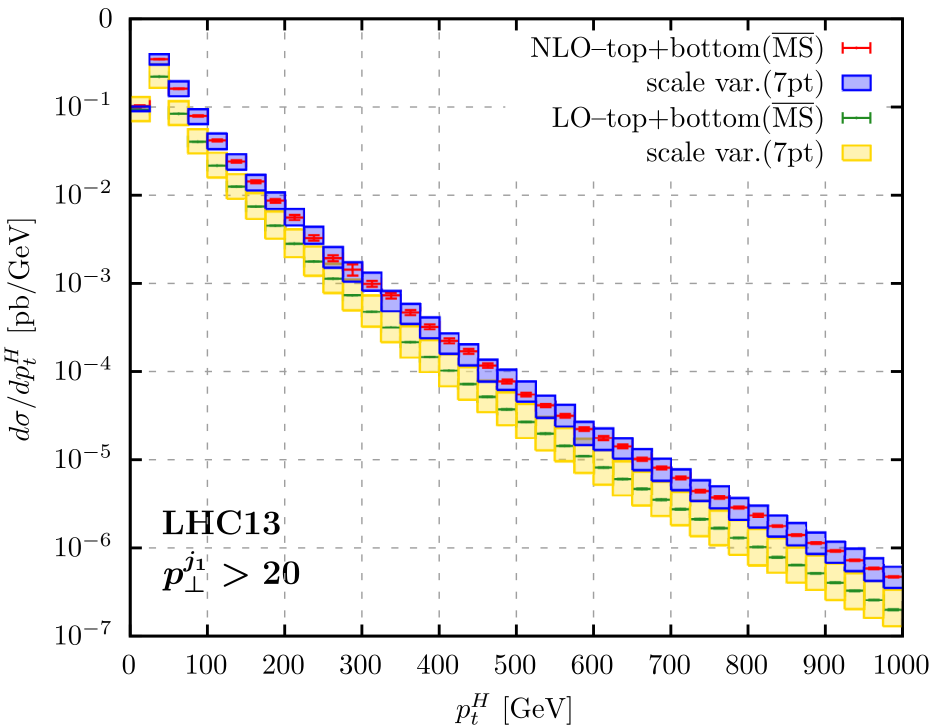
Higgs p_T distribution at low-intermediate p_T

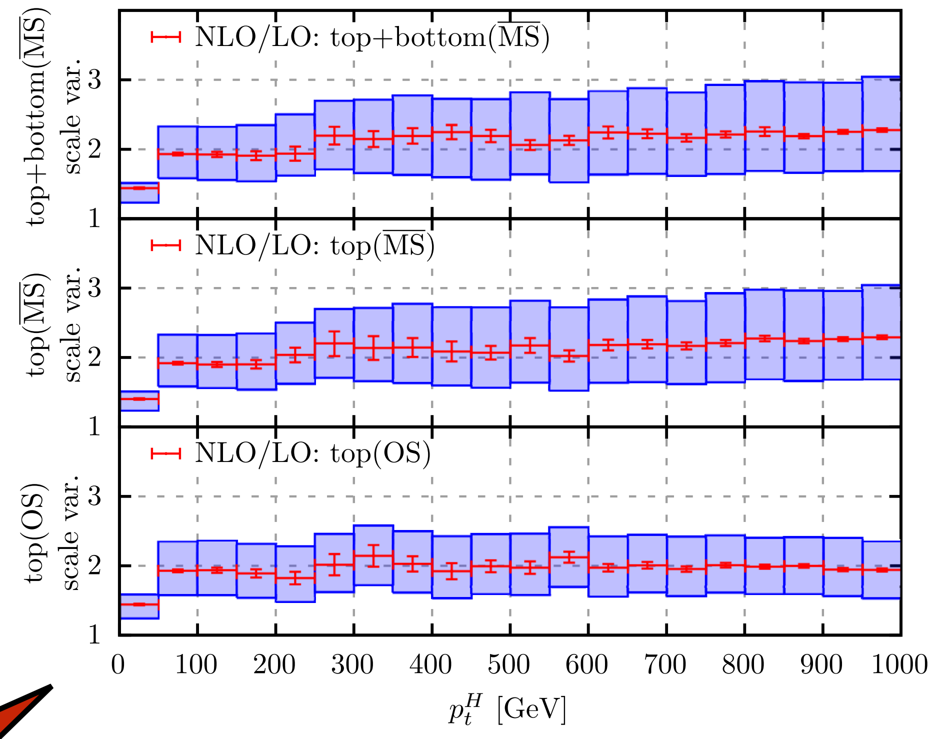


- at NLO agreement between exact and rHEFT in the low-middle p_T range

HEFT $m_H << 2m_t$ and $m_b << p_T << m_t$

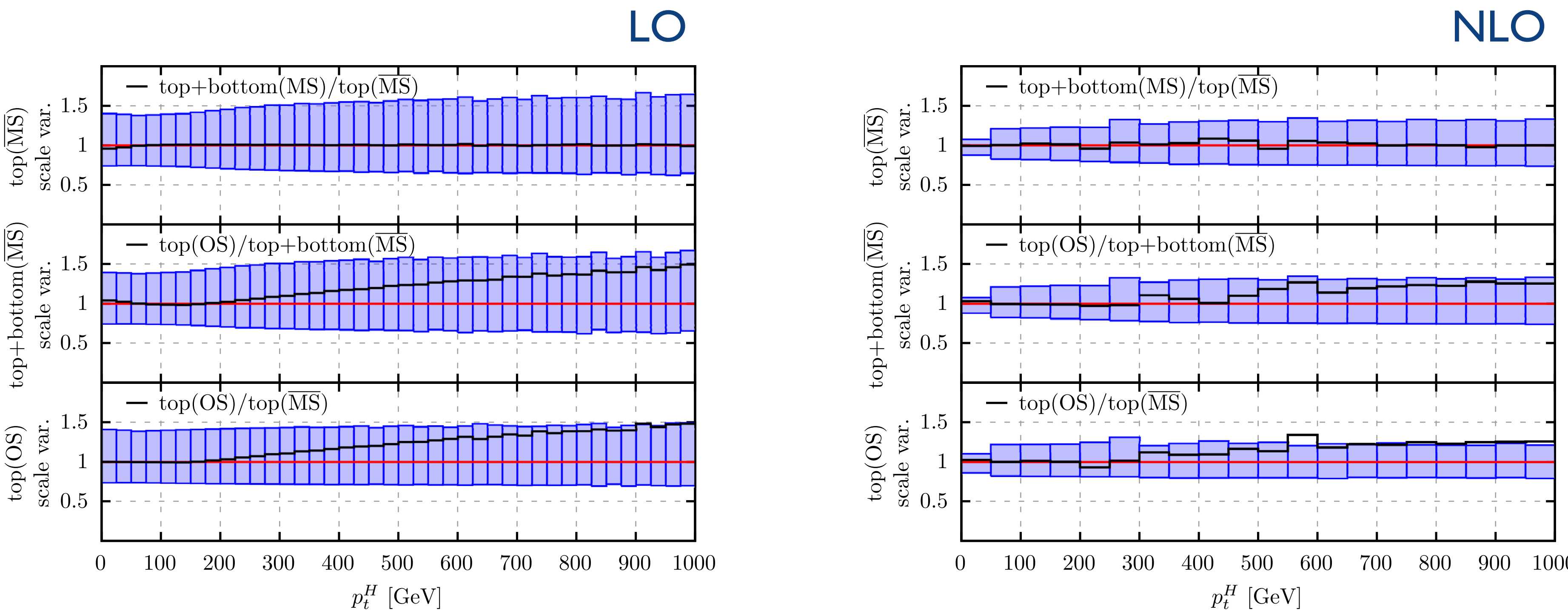
Higgs p_T distribution at LHC





- scale uncertainty bands = ratio of bands at NLO over central value at LO
- *k* factor almost always larger than 2 for MSbar, 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*(MSbar) and *t*(MSbar) The *b* quark, and thus top-*b* interference, is negligible, except at low end of p_T range
- p_T distribution for *t*(MSbar) falls off faster than same for *t*(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*(MSbar) and *t*(OS) is same size as scale uncertainty at high end of p_T range, both at LO and NLO

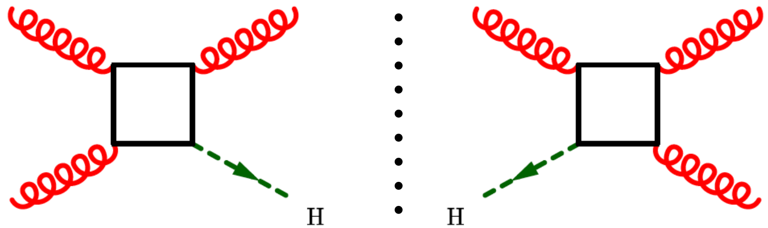
Conclusions

- we computed the Higgs p_T distribution at NLO in QCD
  including for the first time top and b quarks and the MSbar 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 $gg \to Hg$),
  resummation,
  top-charm interference, …

Back-up slides

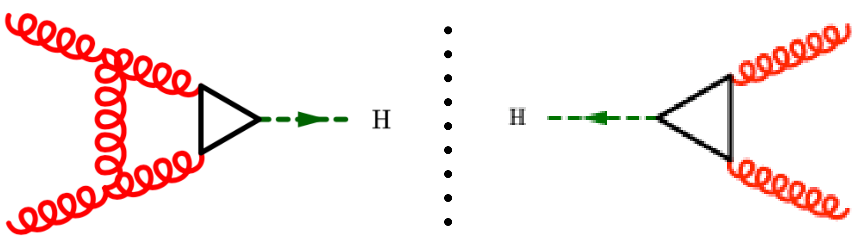
QCD NLO corrections

- real radiation



K. Ellis Hinchliffe Soldate van der Bij 1988

- virtual corrections



Djouadi Graudenz Spira Zerwas 1993
Anastasiou Beerli Bucherer Daleo Kunszt 2006
Aglietti Bonciani Degrassi Vicini 2006

} in terms of Harmonic Polylogarithms (HPL)

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,…,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 →
  DEs solved with 3 (top) or 4 (top and *b*) external parameters

DEs: Series Expansion Method

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

  $$\gamma(t) : t \to \{x_1(t), \ldots, x_n(t)\} \qquad \vec{x}(0) = \vec{a}\,, \qquad \vec{x}(1) = \vec{b}$$

  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

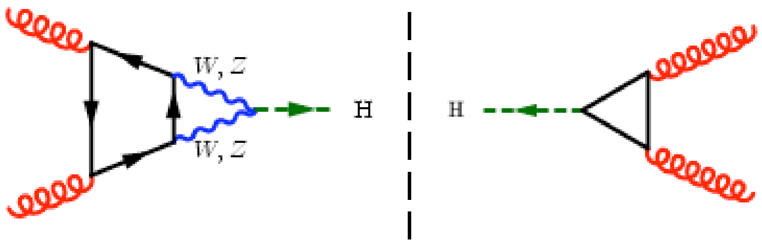
- numerical solution of DEs through DiffExp:
  Mathematica implementation of Moriello's series expansion method

  Hidding 2021

- checked with AMFlow   Liu Ma Wang 2018

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) (in terms of MPLs)
Degrassi Maltoni 2004
Actis Passarino Sturm Uccirati 2008
(heavy fermion loop) (numerically … elliptic integrals appear)

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

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

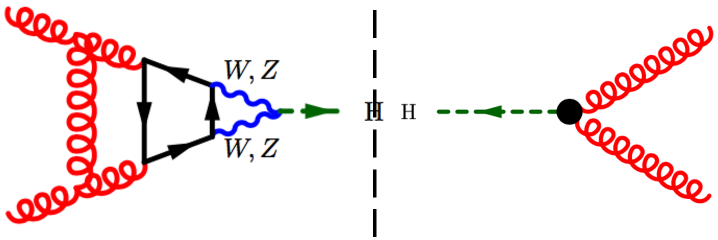
- gg-initiated QCD NLO corrections (light fermion loop) computed in various approximations:
  — $m_{w,z} \to \infty$ limit — Anastasiou Boughezal Petriello 2009
  — soft approximation — Bonetti Melnikov Tancredi 2018
  — $m_{w,z} \to 0$ limit — Anastasiou VDD Furlan Mistlberger Moriello Schweitzer Specchia 2018

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

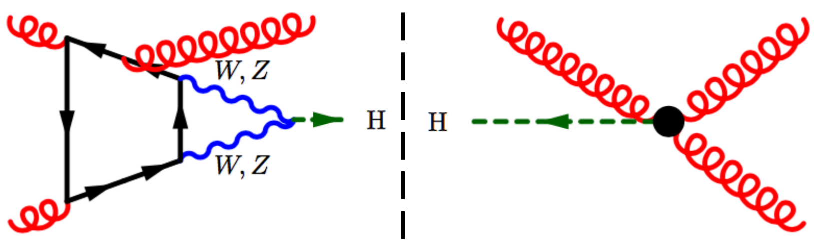
QCD-EW interference

- 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

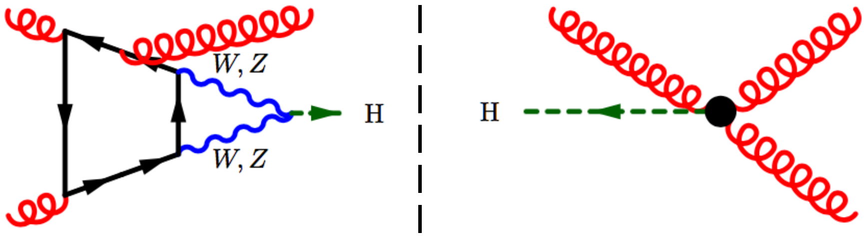
LO $\quad \sigma_{gg\to H+X}^{(\alpha_s^2\alpha^2)} = 0.68739^{+23.4\%+2.0\%}_{-17.3\%-2.0\%}$ pb

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

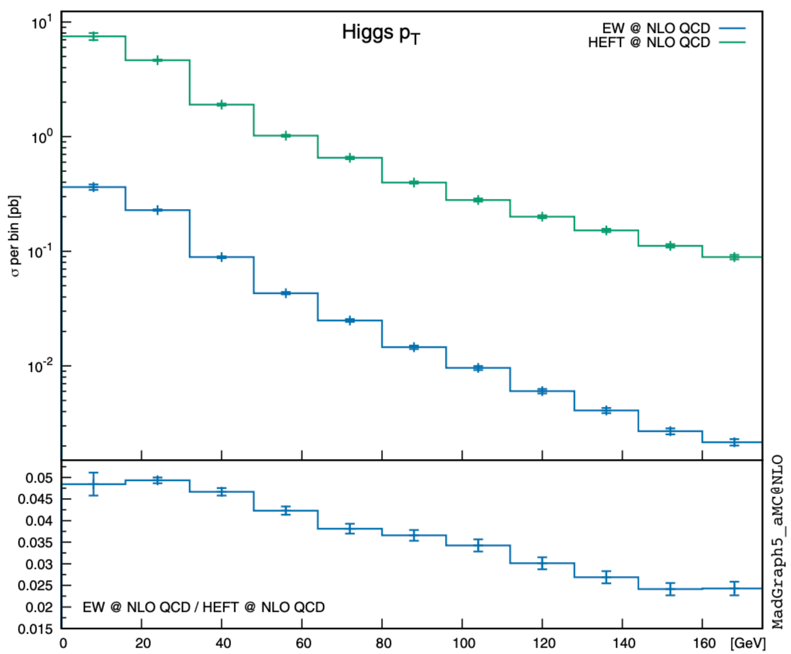
gg-initiated NLO corrections in HEFT $\quad \sigma_{gg\to H+X}^{(\mathrm{HEFT},\alpha_s^2\alpha+\alpha_s^3\alpha)} = 30.484^{+19.8\%+1.9\%}_{-15.3\%-1.9\%}$ pb

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