Precision Higgs Physics

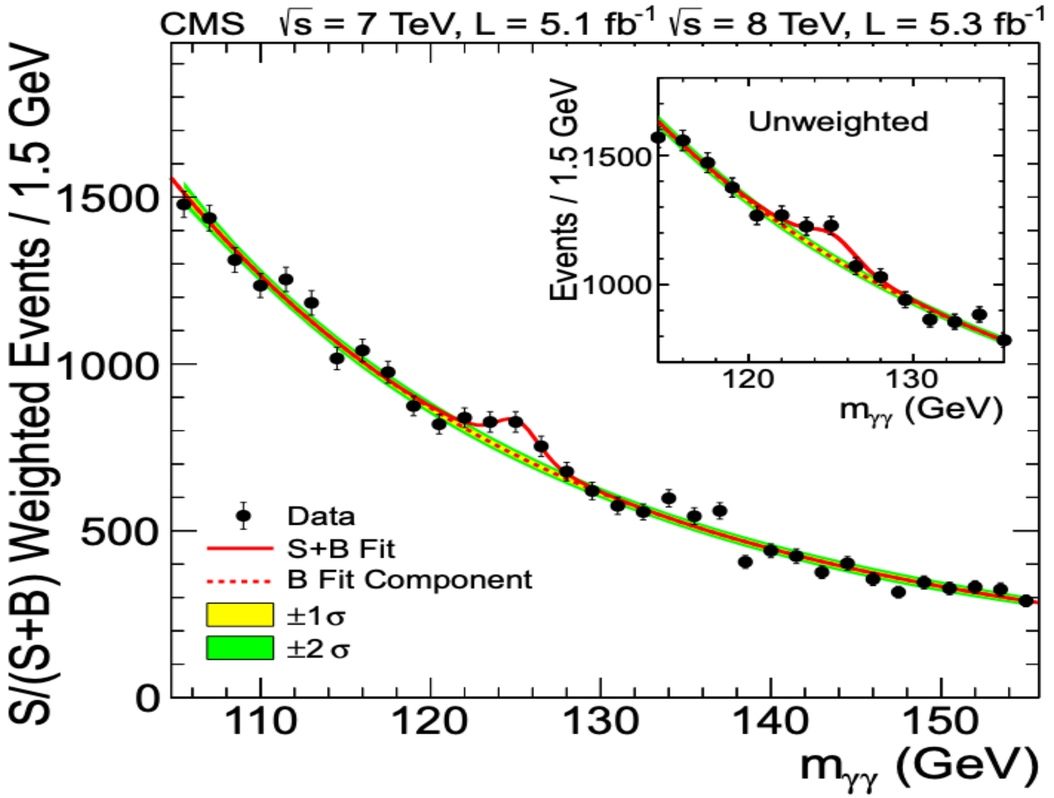
Robert Harlander
RWTH Aachen University

LHCP 2023, Belgrade

supported by

Deutsche Forschungsgemeinschaft DFG

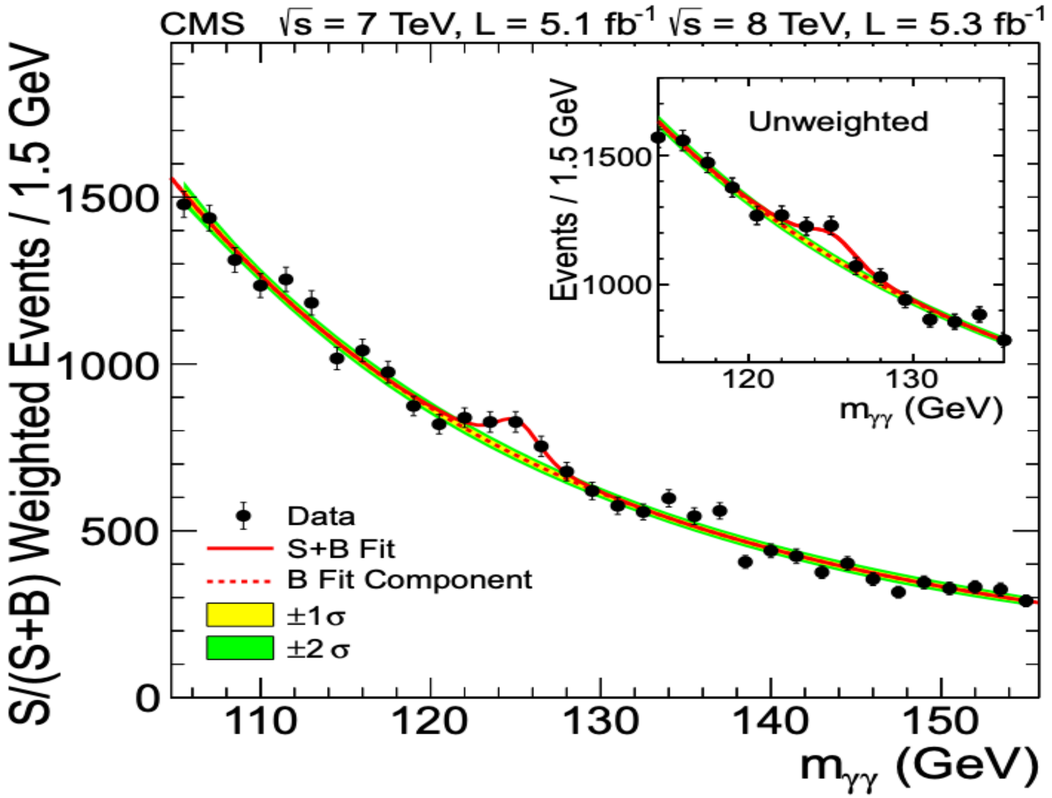
Bundesministerium für Bildung und Forschung



Observation of a New Boson at a Mass of 125 GeV with the CMS Experiment at the LHC #1

CMS Collaboration • Serguei Chatrchyan (Yerevan Phys. Inst.) et al. (Jul, 2012)

Published in: *Phys.Lett.B* 716 (2012) 30-61 • e-Print: 1207.7235 [hep-ex]



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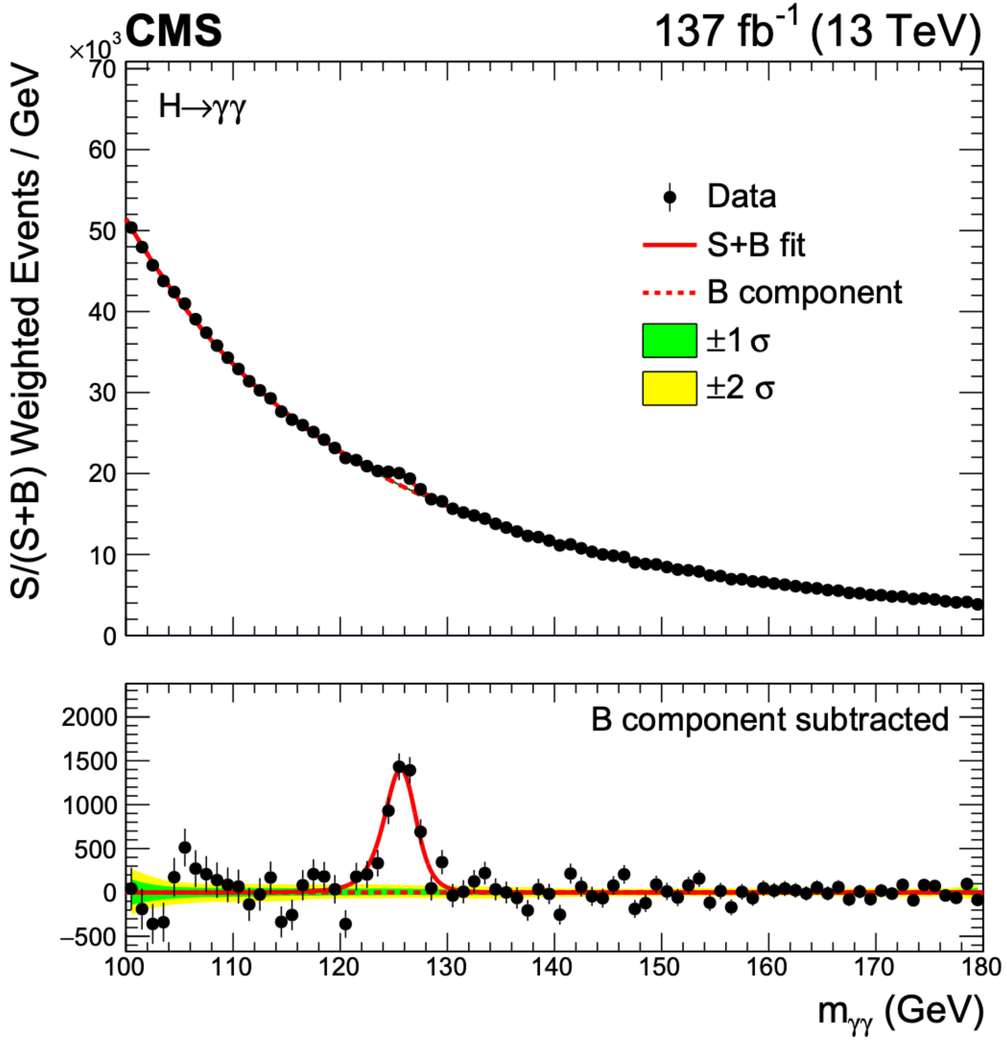


Measurement of the Higgs boson inclusive and differential fiducial production cross sections in the diphoton decay channel with pp collisions at $\sqrt{s}$ = 13 TeV

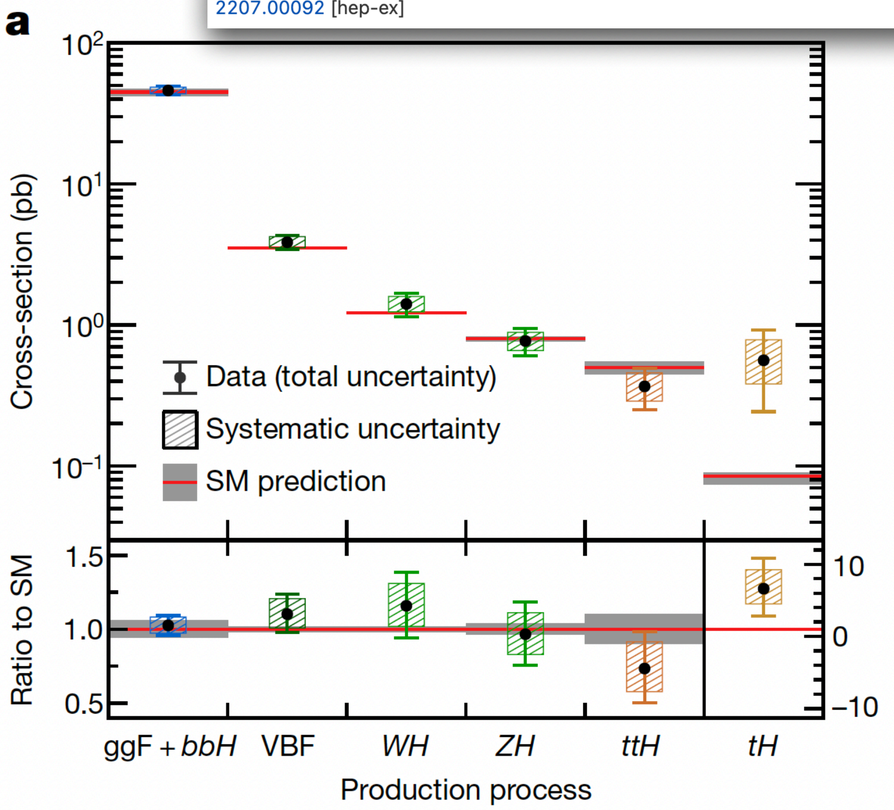
CMS Collaboration (Aug 25, 2022)

e-Print: 2208.12279 [hep-ex]

A detailed map of Higgs boson interactions by the ATLAS experiment ten years after the discovery #1

ATLAS Collaboration (Jun 30, 2022)

Published in: *Nature* 607 (2022) 7917, 52-59, *Nature* 612 (2022) 7941, E24 (erratum) • e-Print: 2207.00092 [hep-ex]



A portrait of the Higgs boson by the CMS experiment ten years after the discovery #1

CMS Collaboration • Armen Tumasyan (Tbilisi, Inst. Phys.) et al. (Jun 30, 2022)

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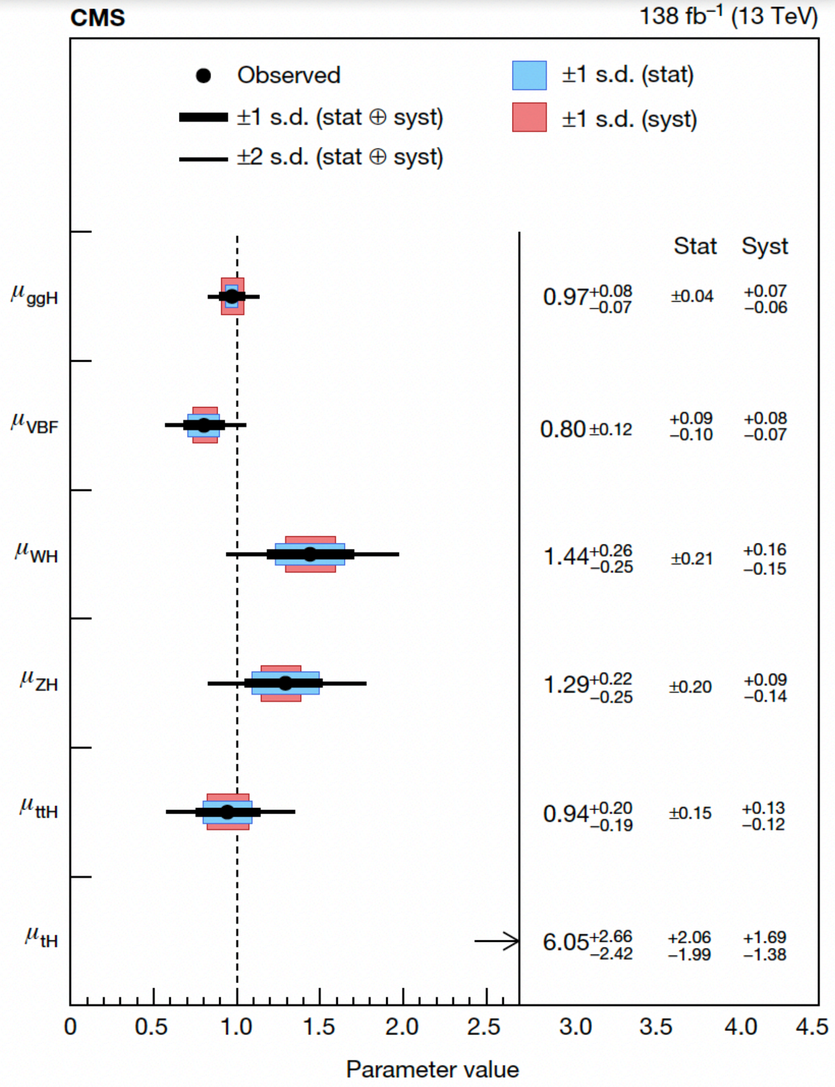

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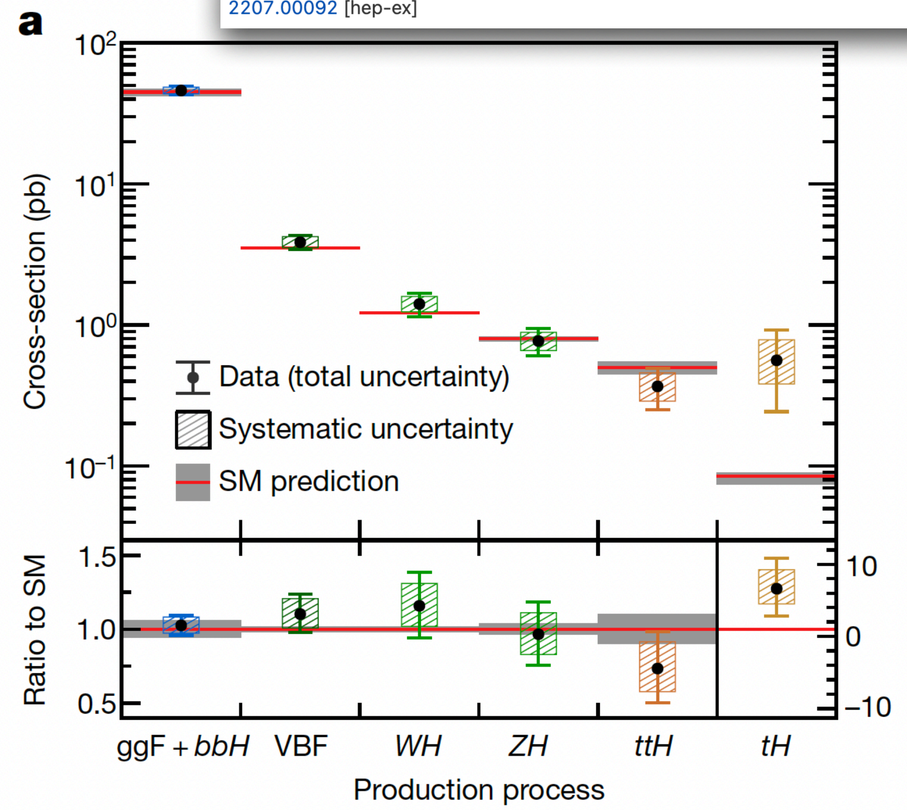

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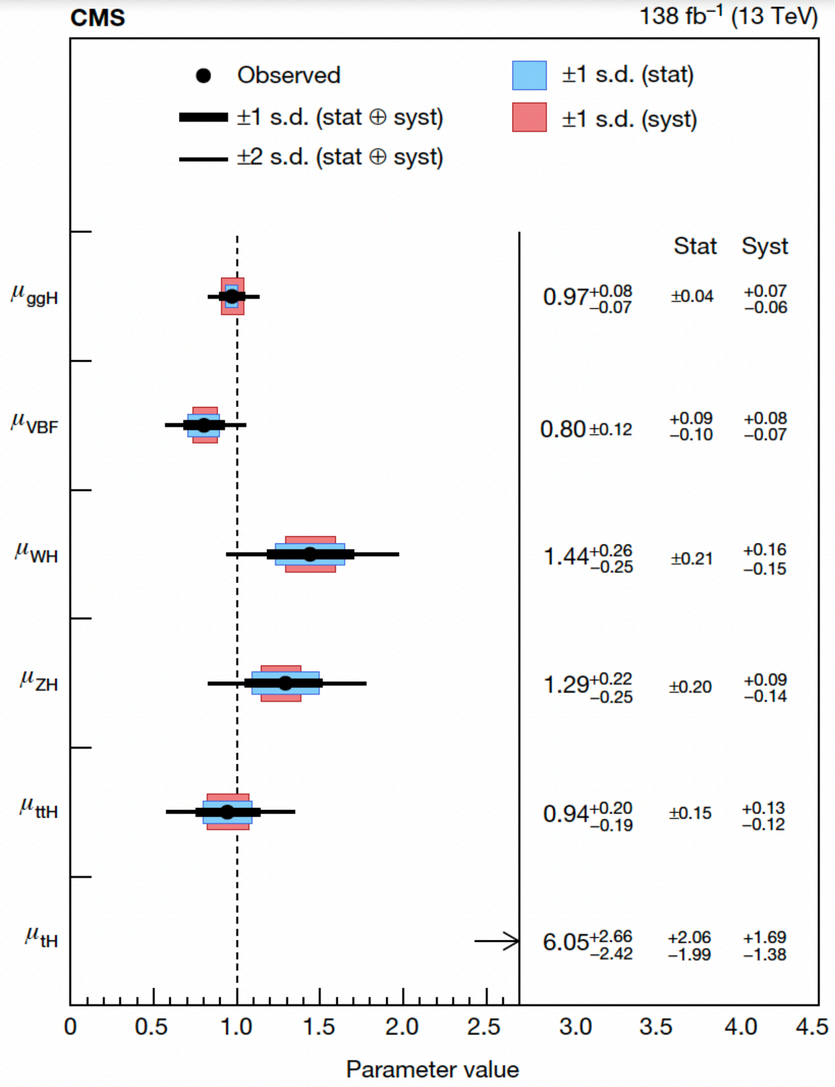

Theory: 2016!

Handbook of LHC Higgs Cross Sections: 4. Deciphering the Nature of the Higgs Sector #1

LHC Higgs Cross Section Working Group • D. de Florian (ICAS, UNSAM, Buenos Aires) et al. (Oct 25, 2016)

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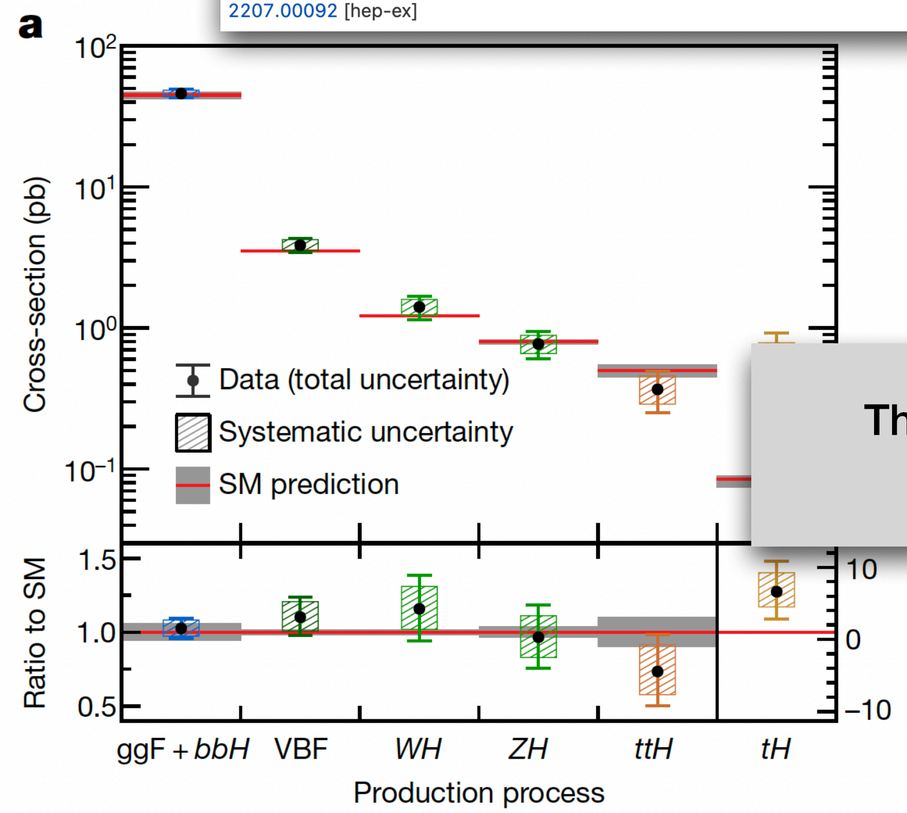

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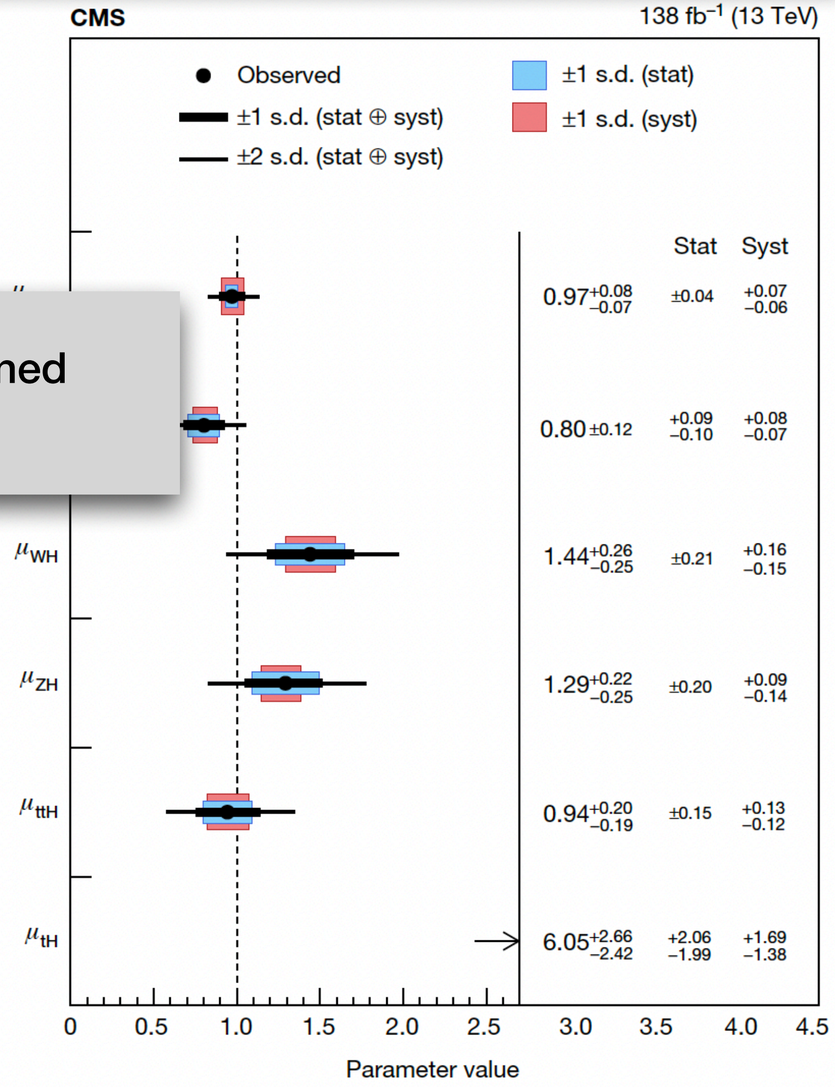

This talk: only work that happened *after* YR4!

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Higher-order predictions for Higgs processes

Robert Harlander
RWTH Aachen University

Higgs 2022, Pisa

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Theorist complains about missing citations - again!

By X. BARRY MENNS

Renowned theorist Robert Harlander has raised concerns regarding missing citations in recent academic publications. In a recent interview, Harlander expressed his frustration, emphasizing the importance of proper attribution and intellectual integrity in the scientific community. Harlander, known for his groundbreaking contributions in the field, called for stricter adherence to citation standards to ensure accurate credit to original works. He urged researchers and authors to be diligent in acknowledging and referencing relevant sources, highlighting the significance of academic rigor and transparent scholarship. Harlander's critique has sparked a debate among scholars, prompting discussions on the responsible use of citations and the preservation of academic integrity.

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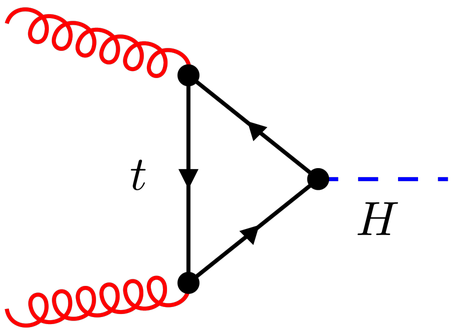
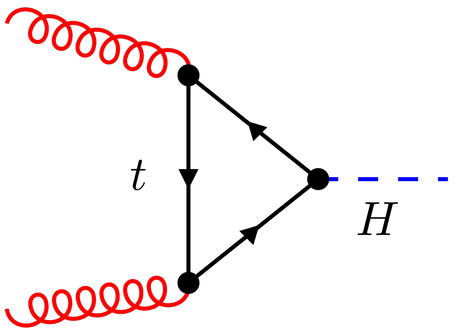


in YR4

Inclusive gluon fusion cross section:



in YR4

$$
\begin{aligned}
48.58\,\text{pb} = \quad & 16.00\,\text{pb} && (+32.9\%) && (\text{LO, rEFT}) \\
& +20.84\,\text{pb} && (+42.9\%) && (\text{NLO, rEFT}) \\
& -\ 2.05\,\text{pb} && (-4.2\%) && ((t,b,c)\text{, exact NLO}) \\
& +\ 9.56\,\text{pb} && (+19.7\%) && (\text{NNLO, rEFT}) \\
& +\ 0.34\,\text{pb} && (+0.7\%) && (\text{NNLO, } 1/m_t) \\
& +\ 2.40\,\text{pb} && (+4.9\%) && (\text{EW, QCD-EW}) \\
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\end{aligned}
$$

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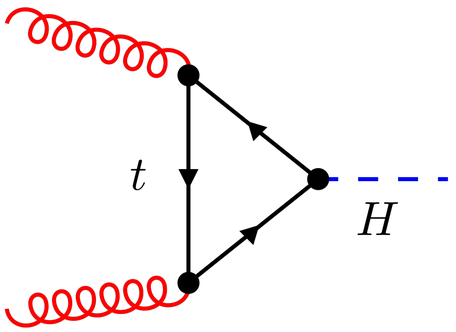
Inclusive gluon fusion cross section:



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Uncertainty estimate:

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

LHCH(XS)WG YR4 '16

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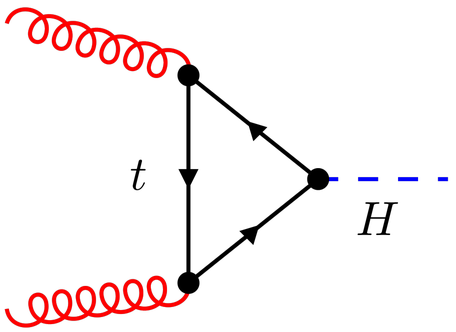

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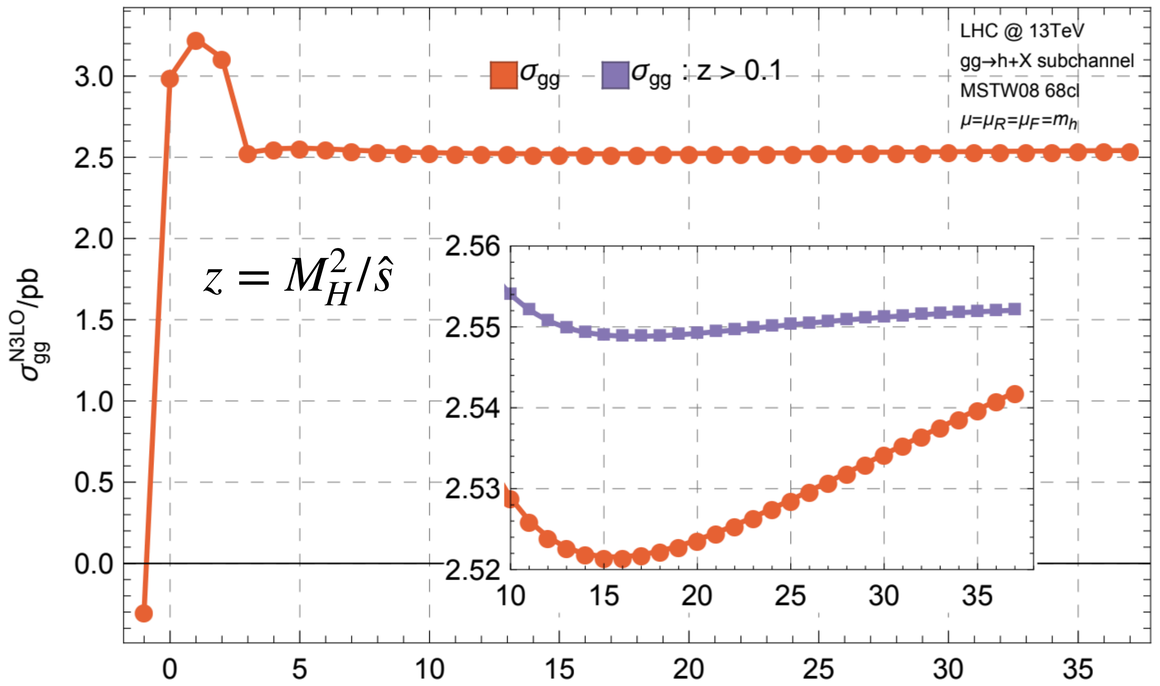
LHCH(XS)WG YR4 '16

$$\hat{\sigma}(z) = \hat{\sigma}(z \to 1) + \mathcal{O}(1-z)^{39}$$



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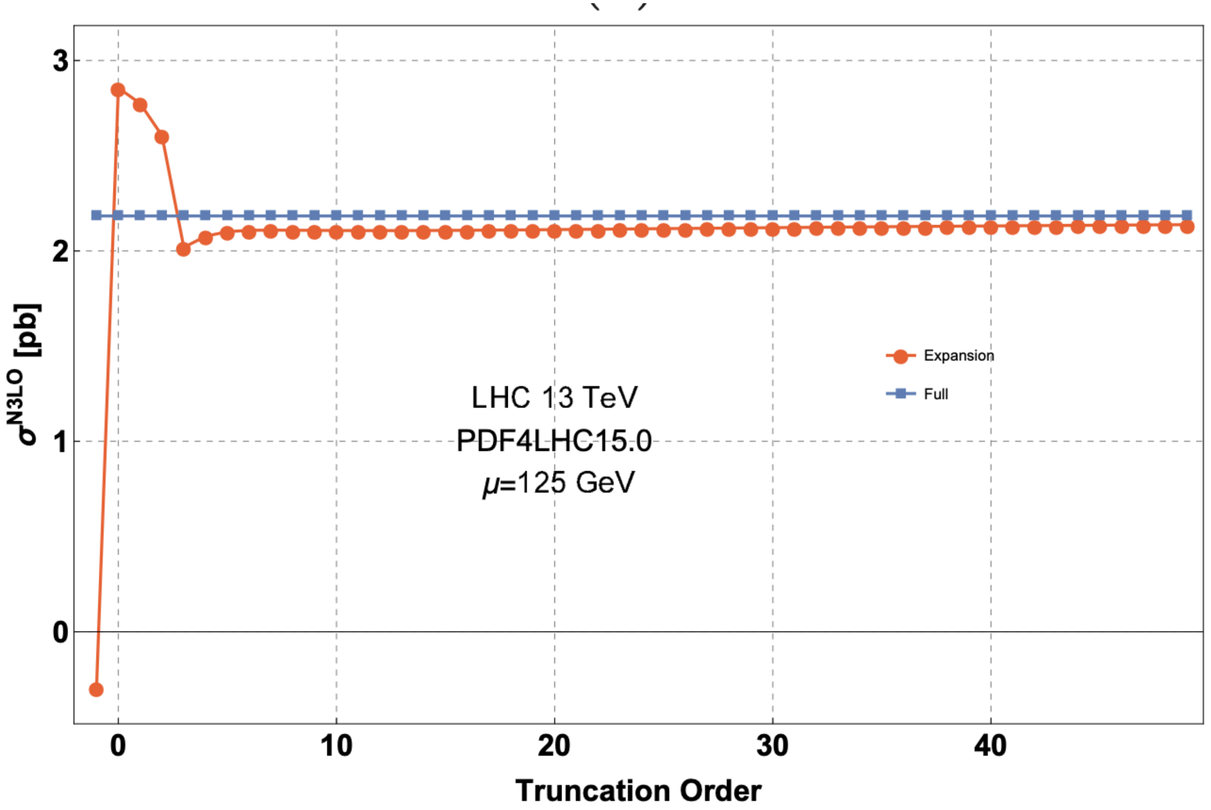

exact z dependence:

Higgs boson production at hadron colliders at N^{3}LO in QCD #4

Bernhard Mistlberger (CERN) (Feb 2, 2018)

Published in: *JHEP* 05 (2018) 028 • e-Print: 1802.00833 [hep-ph]

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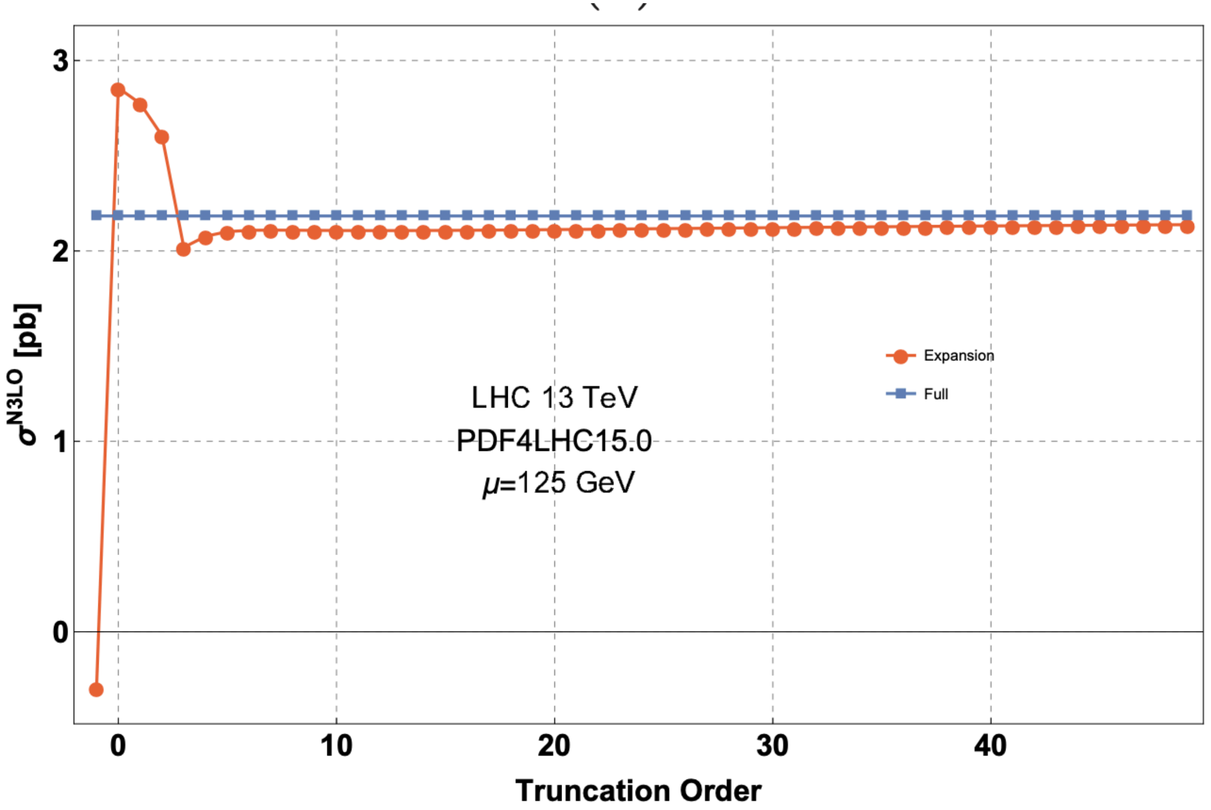

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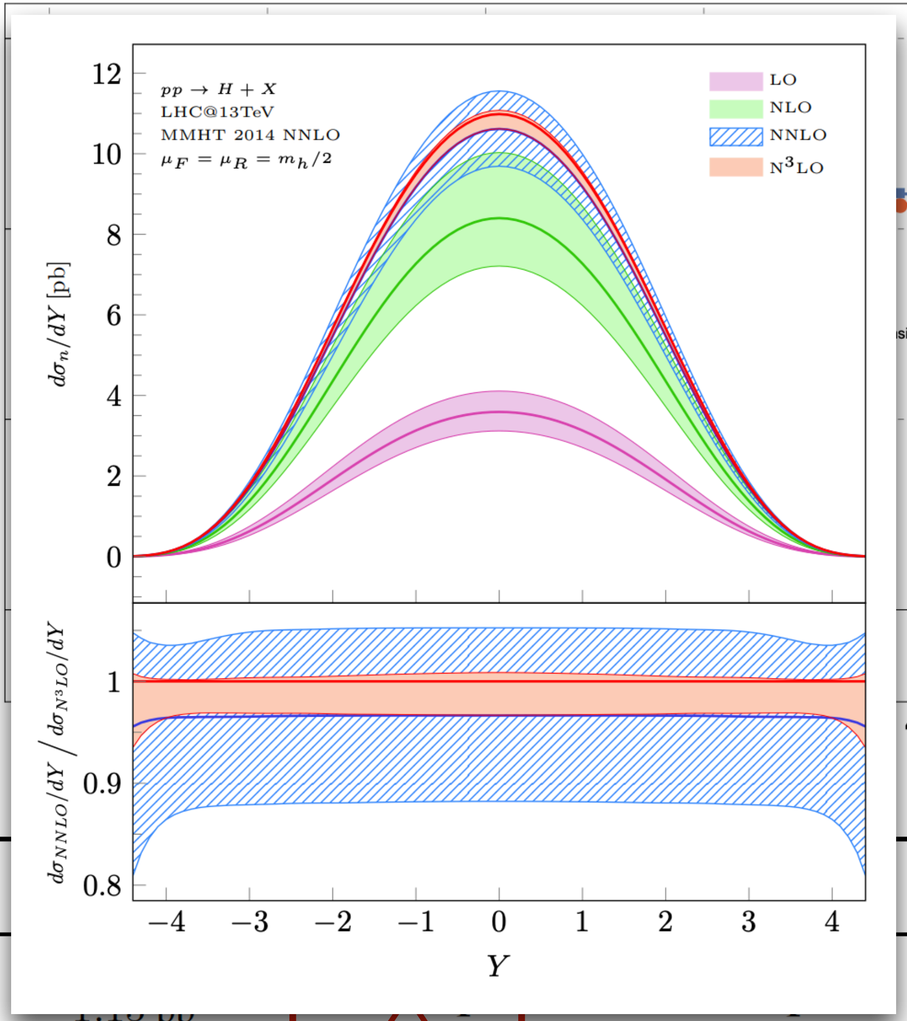

σ^{N3LO} [pb]

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Published in: *JHEP* 05 (2018) 028 • e-Print: 1802.00833 [hep-ph]

Precision predictions at N^{3}LO for the Higgs boson rapidity distribution at the LHC #136

Falko Dulat (SLAC), Bernhard Mistlberger (MIT, Cambridge, CTP), Andrea Pelloni (Zurich, ETH) (Oct 22, 2018)

Published in: *Phys.Rev.D* 99 (2019) 3, 034004 • e-Print: 1810.09462 [hep-ph]

Fully Differential Higgs Boson Production to Third Order in QCD #98

X. Chen (Zurich U. and KIT, Karlsruhe, TP and KIT, Karlsruhe, IAP), T. Gehrmann (Zurich U.), E.W.N. Glover (Durham U., IPPP), A. Huss (CERN), B. Mistlberger (SLAC) et al. (Feb 15, 2021)

Published in: *Phys.Rev.Lett.* 127 (2021) 7, 072002 • e-Print: 2102.07607 [hep-ph]

δ(EW)

± 0.49 p

$+0.21\%$ -2.37% $\pm 0.37\%$ $\pm 1.16\%$ $\pm 1\%$

LHCH(XS)WG YR4 '16

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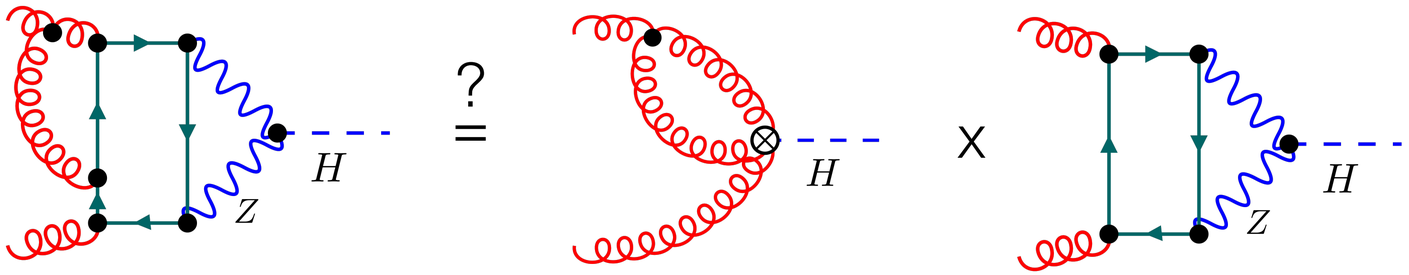

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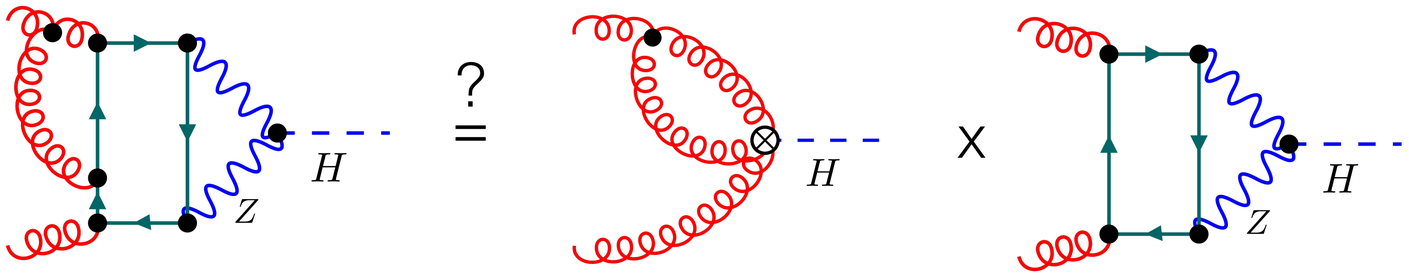

Higher order corrections to mixed QCD-EW contributions to Higgs boson production in gluon fusion #1

Marco Bonetti (KIT, Karlsruhe), Kirill Melnikov (KIT, Karlsruhe), Lorenzo Tancredi (CERN) (Jan 31, 2018)

Published in: *Phys.Rev.D* 97 (2018) 5, 056017, *Phys.Rev.D* 97 (2018) 9, 099906 (erratum) • e-Print: 1801.10403 [hep-ph]

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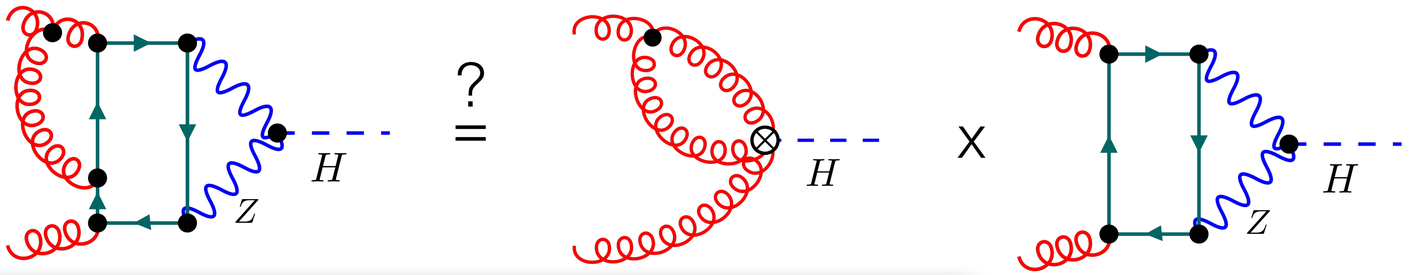

Two-loop mixed QCD-EW corrections to $q\bar{q}$ → Hg, qg → Hq, and $\bar{q}g$ → $H\bar{q}$ #15

Marco Bonetti (RWTH Aachen U.), Erik Panzer (Oxford U., Inst. Math.), Lorenzo Tancredi (Munich, Tech. U.) (Mar 31, 2022)

Published in: *JHEP* 06 (2022) 115 • e-Print: 2203.17202 [hep-ph]

Two-loop amplitude for mixed QCD-EW corrections to gg → Hg #31

Matteo Becchetti (Turin U. and INFN, Turin), Francesco Moriello (Zurich, ETH), Armin Schweitzer (Zurich, ETH) (Dec 14, 2021)

Published in: *JHEP* 04 (2022) 139 • e-Print: 2112.07578 [hep-ph]

Two-loop mixed QCD-EW corrections to $gg \to Hg$ #66

Marco Bonetti (Karlsruhe U., ITP and RWTH Aachen U.), Erik Panzer (U. Oxford (main)), Vladimir A. Smirnov (SINP, Moscow), Lorenzo Tancredi (Oxford U., Theor. Phys.) (Jul 19, 2020)

Published in: *JHEP* 11 (2020) 045 • e-Print: 2007.09813 [hep-ph]

Next-to-leading order corrections to light-quark mixed QCD-EW contributions to Higgs boson production #1

Matteo Becchetti (Turin U. and INFN, Turin), Roberto Bonciani (Rome U. and INFN, Rome), Vittorio Del Duca (Zurich, ETH and Frascati), Valentin Hirschi (Zurich, ETH), Francesco Moriello (Zurich, ETH) et al. (Oct 19, 2020)

Published in: *Phys.Rev.D* 103 (2021) 5, 054037 • e-Print: 2010.09451 [hep-ph]

Higher order corrections to mixed QCD-EW contributions to Higgs boson production in gluon fusion #1

Marco Bonetti (KIT, Karlsruhe), Kirill Melnikov (KIT, Karlsruhe), Lorenzo Tancredi (CERN) (Jan 31, 2018)

Published in: *Phys.Rev.D* 97 (2018) 5, 056017, *Phys.Rev.D* 97 (2018) 9, 099906 (erratum) • e-Print: 1801.10403 [hep-ph]

$\delta(\mathrm{EW})$	$\delta(t,b,c)$	$\delta(1/m_t)$
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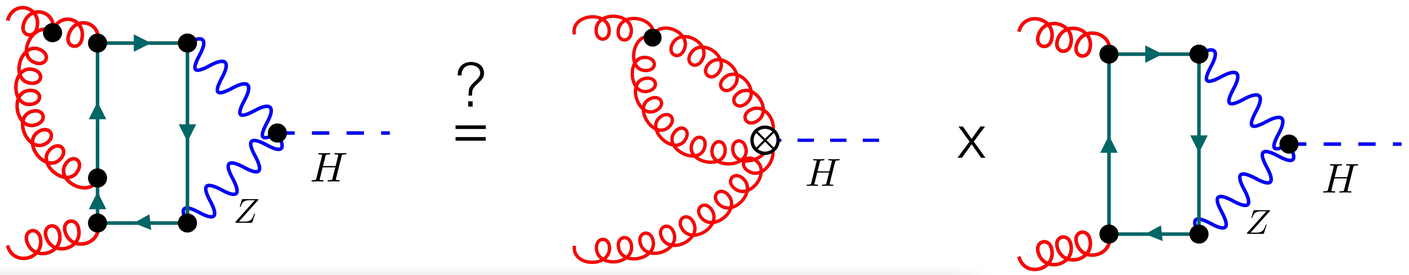
LHCH(XS)WG YR4 '16



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Published in: *JHEP* 06 (2022) 115 • e-Print: 2203.17202 [hep-ph]

Two-loop amplitude for mixed QCD-EW corrections to gg → Hg #31

Matteo Becchetti (Turin U. and INFN, Turin), Francesco Moriello (Zurich, ETH), Armin Schweitzer (Zurich, ETH) (Dec 14, 2021)

Published in: *JHEP* 04 (2022) 139 • e-Print: 2112.07578 [hep-ph]

Two-loop mixed QCD-EW corrections to $gg \to Hg$ #66

Marco Bonetti (Karlsruhe U., ITP and RWTH Aachen U.), Erik Panzer (U. Oxford (main)), Vladimir A. Smirnov (SINP, Moscow), Lorenzo Tancredi (Oxford U., Theor. Phys.) (Jul 19, 2020)

Published in: *JHEP* 11 (2020) 045 • e-Print: 2007.09813 [hep-ph]

Next-to-leading order corrections to light-quark mixed QCD-EW contributions to Higgs boson production #1

Matteo Becchetti (Turin U. and INFN, Turin), Roberto Bonciani (Rome U. and INFN, Rome), Vittorio Del Duca (Zurich, ETH and Frascati), Valentin Hirschi (Zurich, ETH), Francesco Moriello (Zurich, ETH) et al. (Oct 19, 2020)

Published in: *Phys.Rev.D* 103 (2021) 5, 054037 • e-Print: 2010.09451 [hep-ph]

Higher order corrections to mixed QCD-EW contributions to Higgs boson production in gluon fusion #1

Marco Bonetti (KIT, Karlsruhe), Kirill Melnikov (KIT, Karlsruhe), Lorenzo Tancredi (CERN) (Jan 31, 2018)

Published in: *Phys.Rev.D* 97 (2018) 5, 056017, *Phys.Rev.D* 97 (2018) 9, 099906 (erratum) • e-Print: 1801.10403 [hep-ph]

$\delta(\mathrm{EW})$	$\delta(t,b,c)$	$\delta(1/m_t)$
± 0.49 pb	± 0.40 pb	± 0.49 pb
$\pm 1\%$	$\pm 0.83\%$	$\pm 1\%$

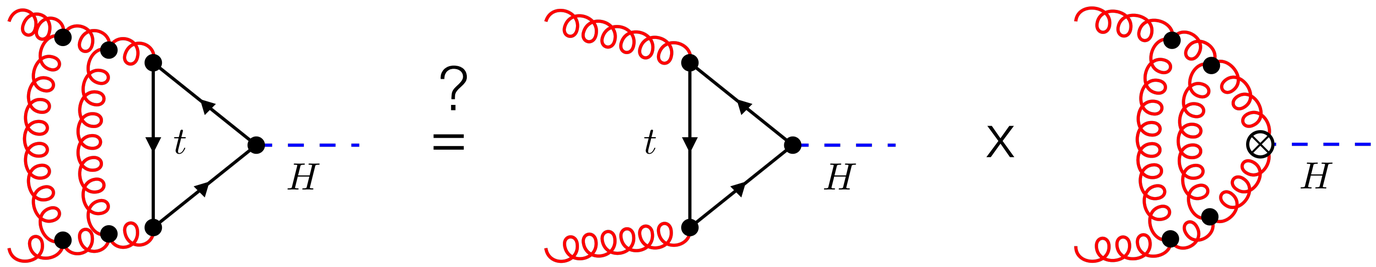
LHCH(XS)WG YR4 '16

δ(scale)	δ(trunc)	δ(PDF-TH)	δ(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%	$\pm 0.37\%$	$\pm 1.16\%$	$\pm 1\%$	$\pm 0.83\%$	$\pm 1\%$

LHCH(XS)WG YR4 '16

δ(scale)	δ(trunc)	δ(PDF-TH)	δ(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%	$\pm 0.37\%$	$\pm 1.16\%$	$\pm 1\%$	$\pm 0.83\%$	$\pm 1\%$

LHCH(XS)WG YR4 '16



Inclusive gluon fusion 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	(+0.7%)	(NNLO, $1/m_t$)
	+ 2.40 pb	(+4.9%)	(EW, QCD-EW)
	+ 1.49 pb	(+3.1%)	(N^{3}LO, rEFT)

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

LHCH(XS)WG YR4 '16

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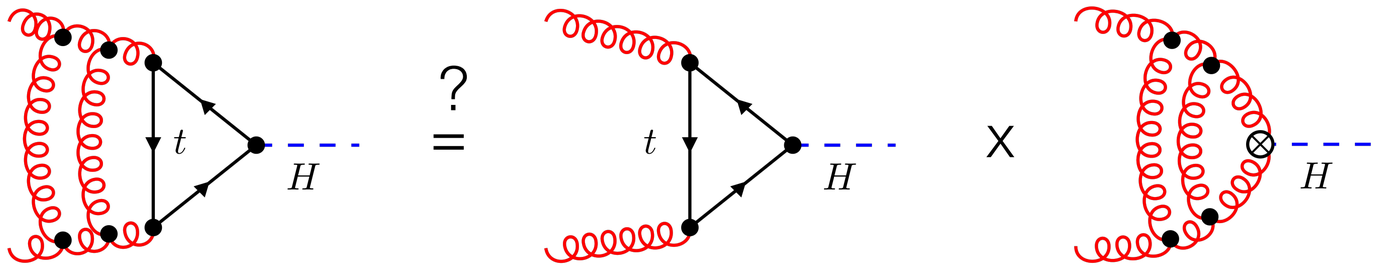

Channel	$(\sigma^{\text{NNLO}}_{\text{exact}}/\sigma^{\text{NNLO}}_{\text{HEFT}} - 1)$ [%]
$\sqrt{s} = 8$ TeV	
gg	+0.62
qg	−18
qq	−4
Total	−0.10
$\sqrt{s} = 13$ TeV	
gg	+0.62
qg	−16
qq	−15
Total	−0.26

Inclusive gluon fusion cross section:

48.58 pb =	16.00 pb	(+32.9%)	(LO, rEFT)
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	+ 1.49 pb	(+3.1%)	(N^{3}LO, rEFT)

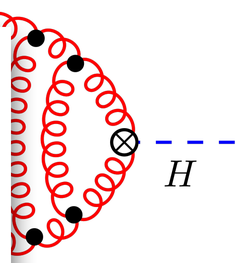
Exact Top-Quark Mass Dependence in Hadronic Higgs Production #1

M. Czakon (Aachen, Tech. Hochsch.), R.V. Harlander (Aachen, Tech. Hochsch.), J. Klappert (Aachen, Tech. Hochsch.), M. Niggetiedt (Aachen, Tech. Hochsch.) (May 10, 2021)

Published in: *Phys.Rev.Lett.* 127 (2021) 16, 162002 • e-Print: 2105.04436 [hep-ph]

δ(scale)	δ(trunc)	δ(PDF-TH)	δ(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%	$\pm 0.37\%$	$\pm 1.16\%$	$\pm 1\%$	$\pm 0.83\%$	$\pm 1\%$

LHCH(XS)WG YR4 '16



Top quark mass dependence of the Higgs boson-gluon form factor at three loops #112

Joshua Davies (KIT, Karlsruhe, TTP), Ramona Gröber (Humboldt U., Berlin), Andreas Maier (DESY, Zeuthen), Thomas Rauh (U. Bern, AEC), Matthias Steinhauser (KIT, Karlsruhe, TTP) (Jun 3, 2019)

Published in: *Phys.Rev.D* 100 (2019) 3, 034017, *Phys.Rev.D* 102 (2020) 5, 059901 (erratum) • e-Print: 1906.00982 [hep-ph]

The light-fermion contribution to the exact Higgs-gluon form factor in QCD #106

Robert V. Harlander (Aachen, Tech. Hochsch.), Mario Prausa (Freiburg U.), Johann Usovitsch (Trinity Coll., Dublin) (Jul 16, 2019)

Published in: *JHEP* 10 (2019) 148, *JHEP* 08 (2020) 101 (erratum) • e-Print: 1907.06957 [hep-ph]

Top Quark Mass Effects in Higgs Boson Production at Four-Loop Order: Virtual Corrections #95

Joshua Davies (KIT, Karlsruhe, TTP), Florian Herren (KIT, Karlsruhe, TTP), Matthias Steinhauser (KIT, Karlsruhe, TTP) (Nov 22, 2019)

Published in: *Phys.Rev.Lett.* 124 (2020) 11, 112002 • e-Print: 1911.10214 [hep-ph]

Exact quark-mass dependence of the Higgs-gluon form factor at three loops in QCD #3

Micha L. Czakon (Aachen, Tech. Hochsch.), Marco Niggetiedt (Aachen, Tech. Hochsch.) (Jan 9, 2020)

Published in: *JHEP* 05 (2020) 149 • e-Print: 2001.03008 [hep-ph]

Channel	$(\sigma^{\rm NNLO}_{\rm exact}/\sigma^{\rm NNLO}_{\rm HEFT}-1)$ [%]
$\sqrt{s}=8$ TeV	
gg	+0.62
qg	−18
qq	−4
Total	−0.10
$\sqrt{s}=13$ TeV	
gg	+0.62
qg	−16
qq	−15
Total	−0.26

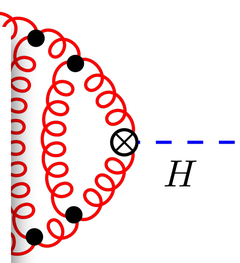
Exact Top-Quark Mass Dependence in Hadronic Higgs Production #1

M. Czakon (Aachen, Tech. Hochsch.), R.V. Harlander (Aachen, Tech. Hochsch.), J. Klappert (Aachen, Tech. Hochsch.), M. Niggetiedt (Aachen, Tech. Hochsch.) (May 10, 2021)

Published in: *Phys.Rev.Lett.* 127 (2021) 16, 162002 • e-Print: 2105.04436 [hep-ph]

	$\delta(t,b,c)$	$\delta(1/m_t)$
pb	±0.40 pb	±0.49 pb
	±0.83%	±1%

LHCH(XS)WG YR4 '16



Top quark mass dependence of the Higgs boson-gluon form factor at three loops #112

Joshua Davies (KIT, Karlsruhe, TTP), Ramona Gröber (Humboldt U., Berlin), Andreas Maier (DESY, Zeuthen), Thomas Rauh (U. Bern, AEC), Matthias Steinhauser (KIT, Karlsruhe, TTP) (Jun 3, 2019)

Published in: *Phys.Rev.D* 100 (2019) 3, 034017, *Phys.Rev.D* 102 (2020) 5, 059901 (erratum) • e-Print: 1906.00982 [hep-ph]

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Published in: *JHEP* 10 (2019) 148, *JHEP* 08 (2020) 101 (erratum) • e-Print: 1907.06957 [hep-ph]

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Published in: *Phys.Rev.Lett.* 124 (2020) 11, 112002 • e-Print: 1911.10214 [hep-ph]

Exact quark-mass dependence of the Higgs-gluon form factor at three loops in QCD #3

Micha L. Czakon (Aachen, Tech. Hochsch.), Marco Niggetiedt (Aachen, Tech. Hochsch.) (Jan 9, 2020)

Published in: *JHEP* 05 (2020) 149 • e-Print: 2001.03008 [hep-ph]

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gg	+0.62
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Total	−0.10
$\sqrt{s}=13$ TeV	
gg	+0.62
qg	−16
qq	−15
Total	−0.26

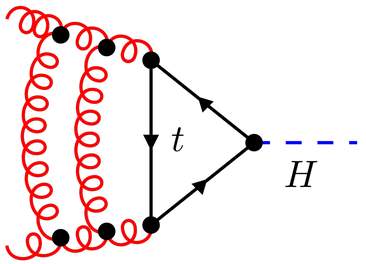
Exact Top-Quark Mass Dependence in Hadronic Higgs Production #1

M. Czakon (Aachen, Tech. Hochsch.), R.V. Harlander (Aachen, Tech. Hochsch.), J. Klappert (Aachen, Tech. Hochsch.), M. Niggetiedt (Aachen, Tech. Hochsch.) (May 10, 2021)

Published in: *Phys.Rev.Lett.* 127 (2021) 16, 162002 • e-Print: 2105.04436 [hep-ph]

	$\delta(t,b,c)$	$\delta(1/m_t)$
pb	±0.40 pb	±0.49 pb
	±0.83%	±1%

LHCH(XS)WG YR4 '16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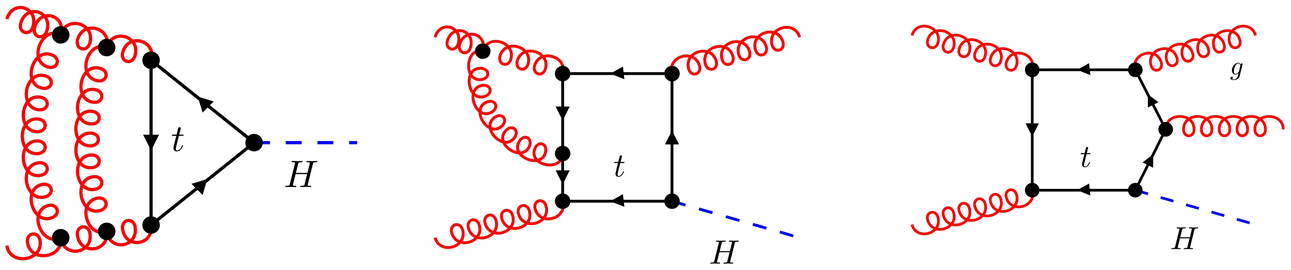
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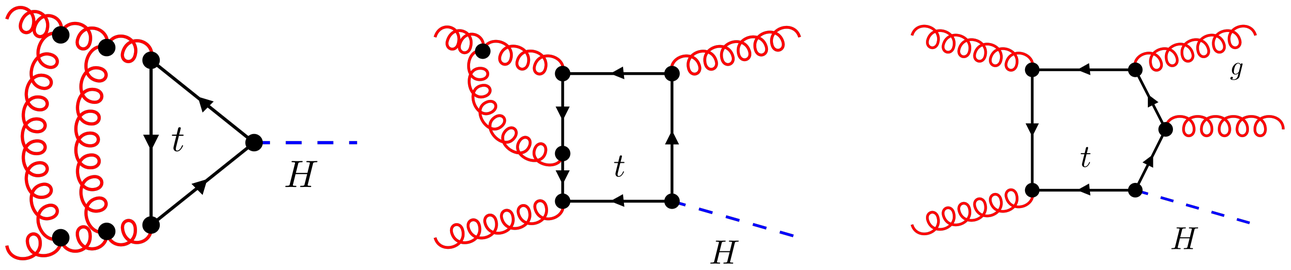
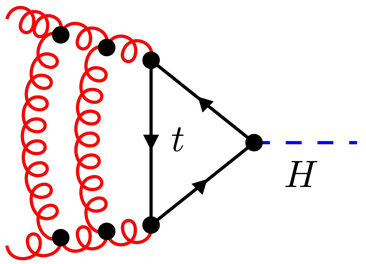
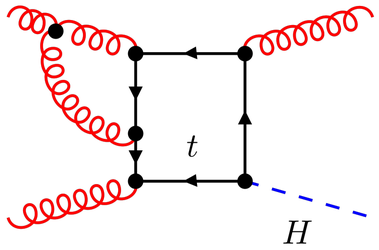
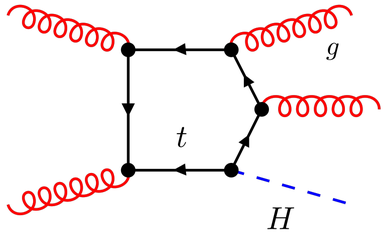


$$p_{T,H} \equiv 0$$







$p_{T,H} \equiv 0$

$p_{T,H} > 0$

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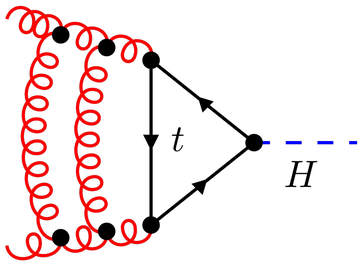
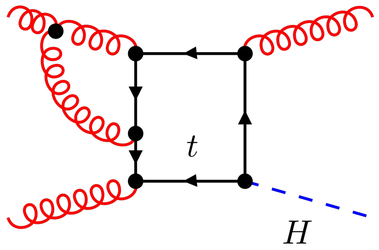
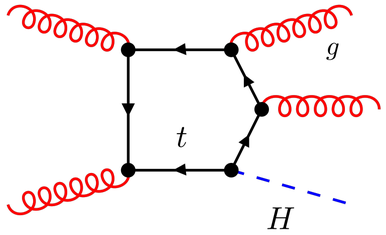


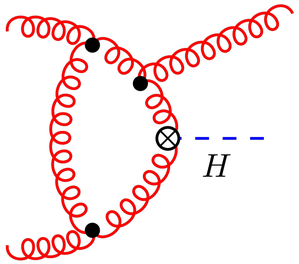


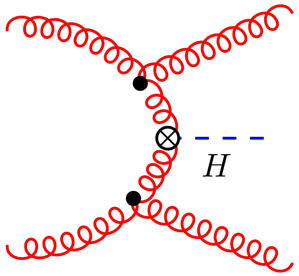


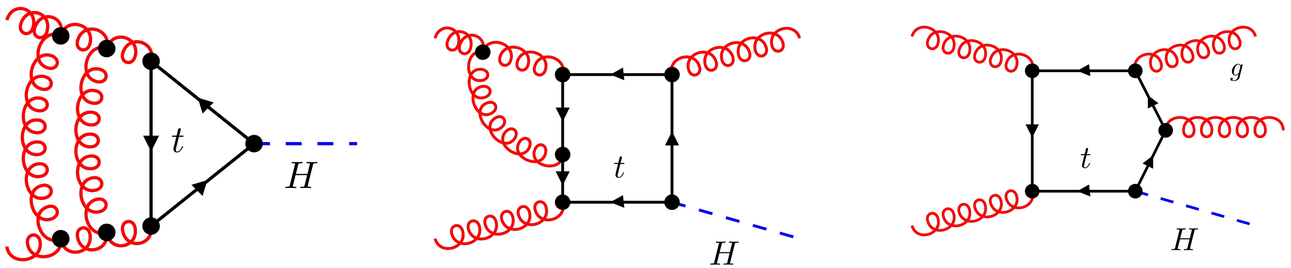
$p_{T,H} \equiv 0$

$p_{T,H} > 0$

VS.



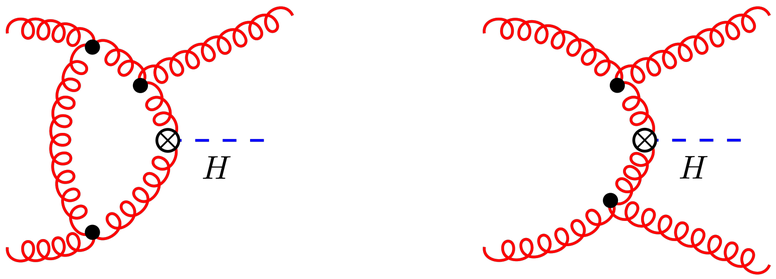


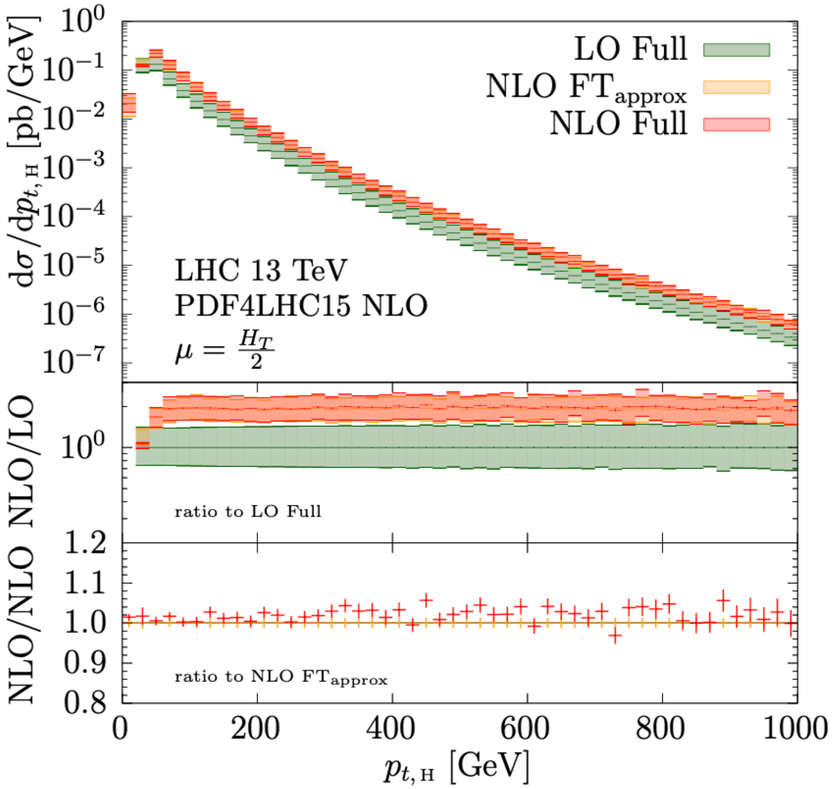


$p_{T,H} \equiv 0$

$p_{T,H} > 0$

vs.

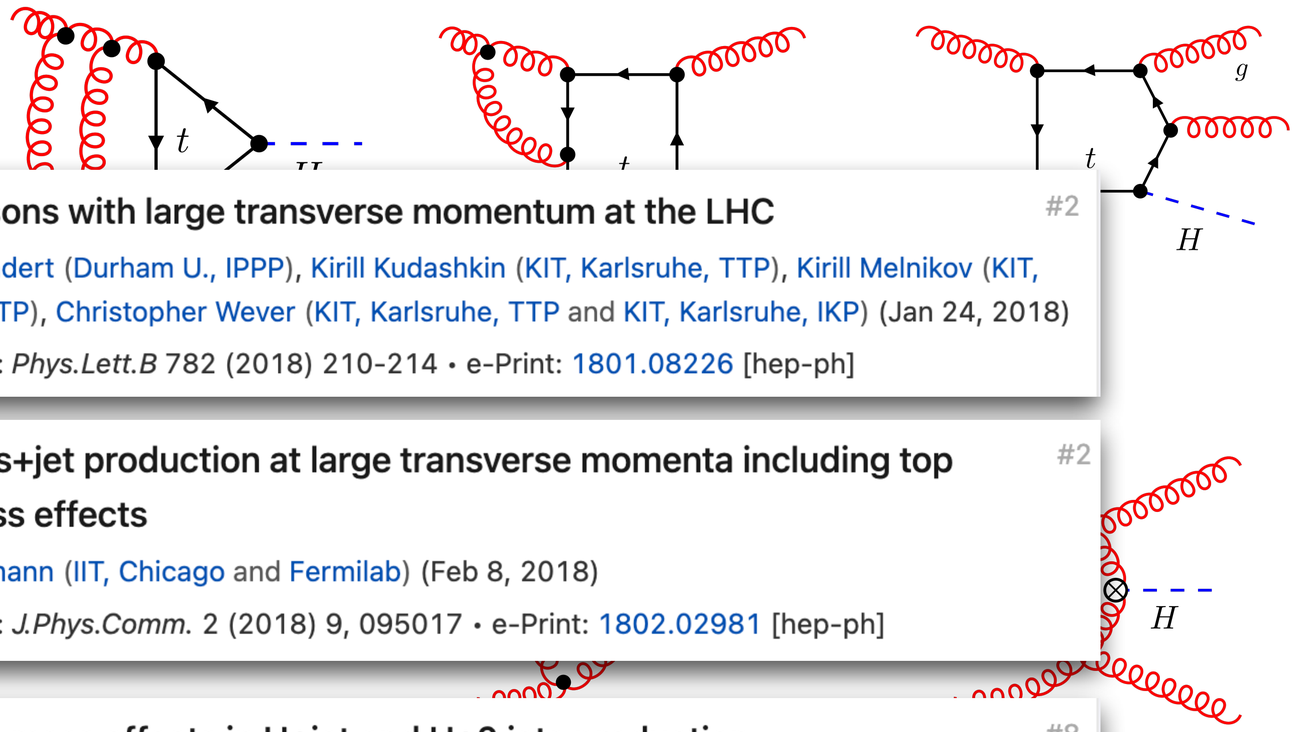




Next-to-Leading-Order QCD Corrections to Higgs Boson Plus Jet Production with Full Top-Quark Mass Dependence #1

S.P. Jones (Munich, Max Planck Inst.), M. Kerner (Munich, Max Planck Inst.), G. Luisoni (Munich, Max Planck Inst.) (Feb 1, 2018)

Published in: *Phys.Rev.Lett.* 120 (2018) 16, 162001, *Phys.Rev.Lett.* 128 (2022) 5, 059901 (erratum) • e-Print: 1802.00349 [hep-ph]



Higgs bosons with large transverse momentum at the LHC #2

Jonas M. Lindert (Durham U., IPPP), Kirill Kudashkin (KIT, Karlsruhe, TTP), Kirill Melnikov (KIT, Karlsruhe, TTP), Christopher Wever (KIT, Karlsruhe, TTP and KIT, Karlsruhe, IKP) (Jan 24, 2018)

Published in: *Phys.Lett.B* 782 (2018) 210-214 • e-Print: 1801.08226 [hep-ph]

NLO Higgs+jet production at large transverse momenta including top quark mass effects #2

Tobias Neumann (IIT, Chicago and Fermilab) (Feb 8, 2018)

Published in: *J.Phys.Comm.* 2 (2018) 9, 095017 • e-Print: 1802.02981 [hep-ph]

Top-quark mass effects in H+jet and H+2 jets production #8

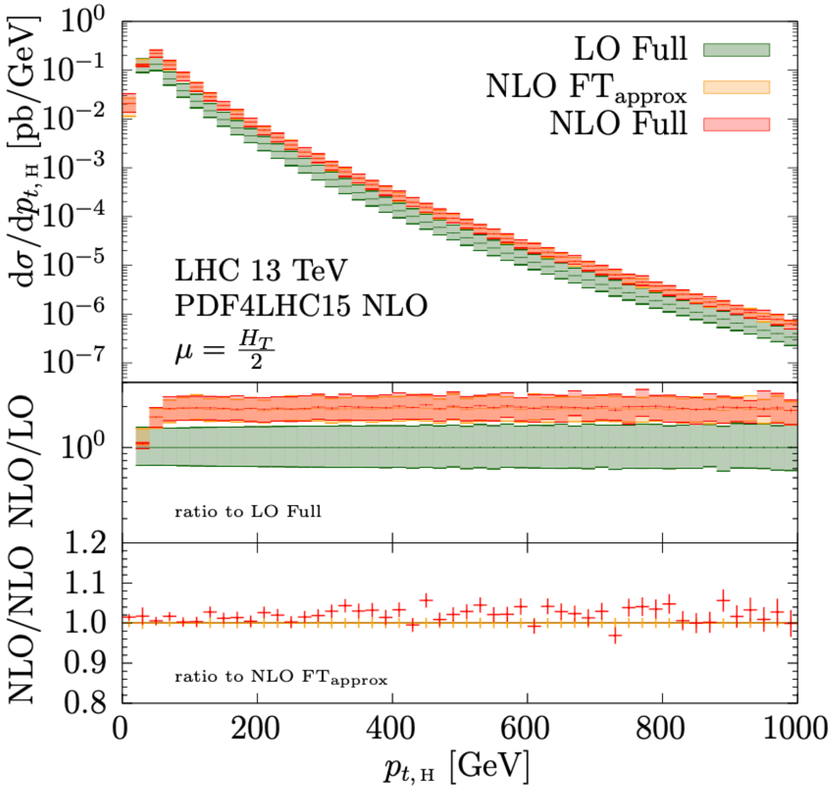
X. Chen (KIT, Karlsruhe and KIT, Karlsruhe, TP and Zurich U.), A. Huss (CERN), S.P. Jones (Durham U., IPPP), M. Kerner (KIT, Karlsruhe and KIT, Karlsruhe, TP and Zurich U.), J.-N. Lang (Zurich U.) et al. (Oct 13, 2021)

Published in: *JHEP* 03 (2022) 096 • e-Print: 2110.06953 [hep-ph]

Next-to-leading-order QCD Corrections to Higgs Production in association with a Jet #3

R. Bonciani (Rome U.), V. Del Duca (INFN, Rome and Zurich U. and Frascati), H. Frellesvig (Bohr Inst.), M. Hidding (Uppsala U.), V. Hirschi (CERN) et al. (Jun 21, 2022)

e-Print: 2206.10490 [hep-ph]



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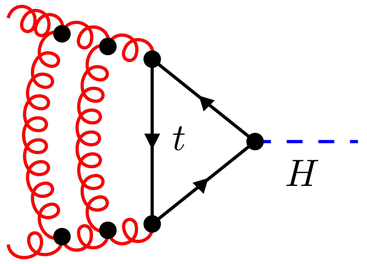
S.P. Jones (Munich, Max Planck Inst.), M. Kerner (Munich, Max Planck Inst.), G. Luisoni (Munich, Max Planck Inst.) (Feb 1, 2018)

Published in: *Phys.Rev.Lett.* 120 (2018) 16, 162001, *Phys.Rev.Lett.* 128 (2022) 5, 059901 (erratum) • e-Print: 1802.00349 [hep-ph]



δ(scale)	δ(trunc)	δ(PDF-TH)	δ(EW)	$\delta(t,b,c)$	$\delta(1/m_t)$
$^{+0.10\text{ pb}}_{-1.15\text{ pb}}$	± 0.18 pb	± 0.56 pb	± 0.49 pb	± 0.40 pb	± 0.49 pb
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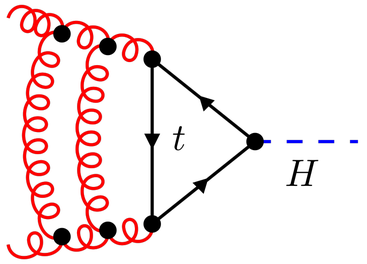
LHCH(XS)WG YR4 '16



δ(scale)	δ(trunc)	δ(PDF-TH)	δ(EW)	$\delta(t,b,c)$	$\delta(1/m_t)$
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LHCH(XS)WG YR4 '16

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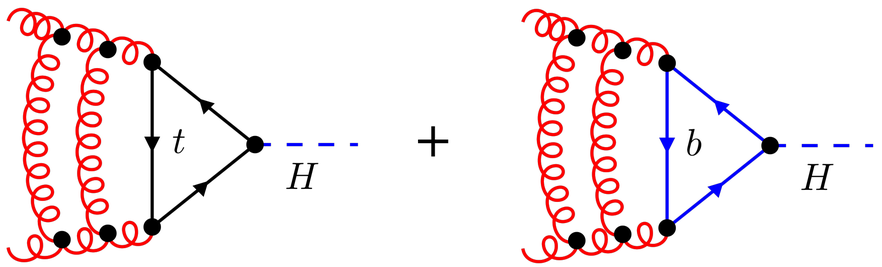

δ(scale)	δ(trunc)	δ(PDF-TH)	δ(EW)	$\delta(t,b,c)$	$\delta(1/m_t)$
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LHCH(XS)WG YR4 '16

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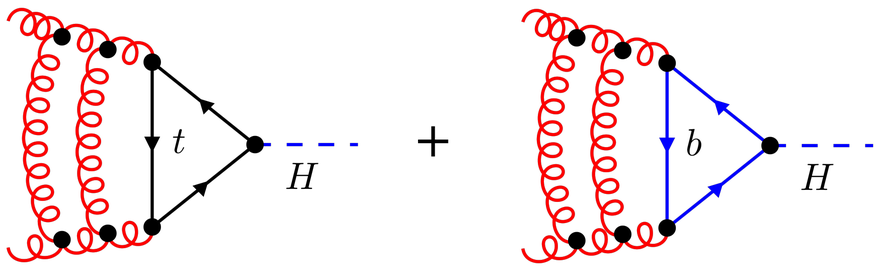
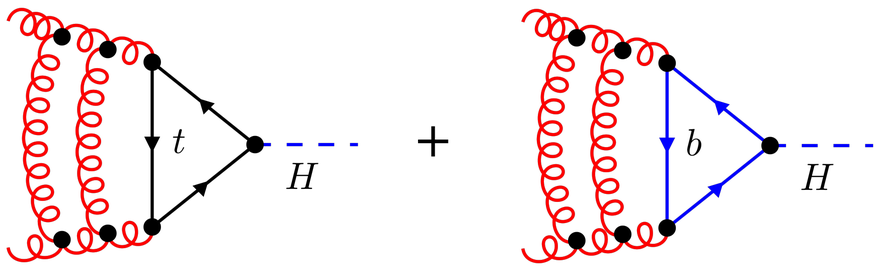


$$\frac{\alpha_s}{\pi} \ln^2 \frac{m_b^2}{M_H^2} \approx 1.3$$

δ(scale)	δ(trunc)	δ(PDF-TH)	δ(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%	$\pm 0.37\%$	$\pm 1.16\%$	$\pm 1\%$	$\pm 0.83\%$	$\pm 1\%$

LHCH(XS)WG YR4 '16



$$\frac{\alpha_s}{\pi} \ln^2 \frac{m_b^2}{M_H^2} \approx 1.3$$

On the light quark mass effects in Higgs boson production in gluon fusion #2

Kirill Melnikov (Karlsruhe U., TTP), Alexander Penin (Alberta U. and Karlsruhe U., TTP) (Feb 29, 2016)

Published in: *JHEP* 05 (2016) 172 • e-Print: 1602.09020 [hep-ph]

Bottom-quark effects in Higgs production at intermediate transverse momentum #18

Fabrizio Caola (Durham U., IPPP), Jonas M. Lindert (Durham U., IPPP), Kirill Melnikov (KIT, Karlsruhe, TTP), Pier Francesco Monni (CERN), Lorenzo Tancredi (CERN) et al. (Apr 20, 2018)

Published in: *JHEP* 09 (2018) 035 • e-Print: 1804.07632 [hep-ph]

Light Quark Mediated Higgs Boson Threshold Production in the Next-to-Leading Logarithmic Approximation #73

Charalampos Anastasiou (Alberta U.), Alexander Penin (Zurich, ETH) (Apr 7, 2020)

Published in: *JHEP* 07 (2020) 195, *JHEP* 01 (2021) 164 (erratum) • e-Print: 2004.03602 [hep-ph]

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

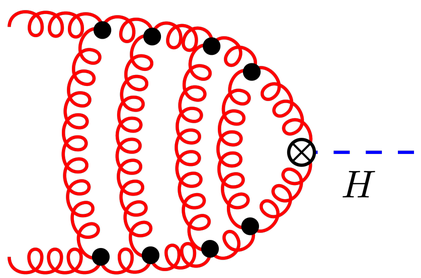
LHCH(XS)WG YR4 '16

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
$^{+0.21}_{-2.37}\%$	$\pm 0.37\%$	$\pm 1.16\%$	$\pm 1\%$	$\pm 0.83\%$	$\pm 1\%$

LHCH(XS)WG YR4 '16

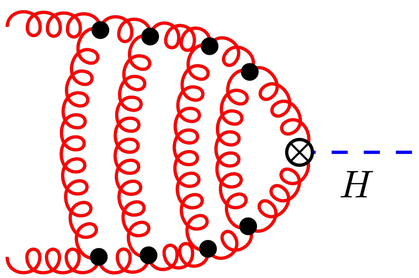
δ(scale)	δ(trunc)	δ(PDF-TH)	δ(EW)	$\delta(t,b,c)$	$\delta(1/m_t)$
$^{+0.10\text{ pb}}_{-1.15\text{ pb}}$	± 0.18 pb	± 0.56 pb	± 0.49 pb	± 0.40 pb	± 0.49 pb
$^{+0.21\%}_{-2.37\%}$	$\pm 0.37\%$	$\pm 1.16\%$	$\pm 1\%$	$\pm 0.83\%$	$\pm 1\%$

LHCH(XS)WG YR4 '16

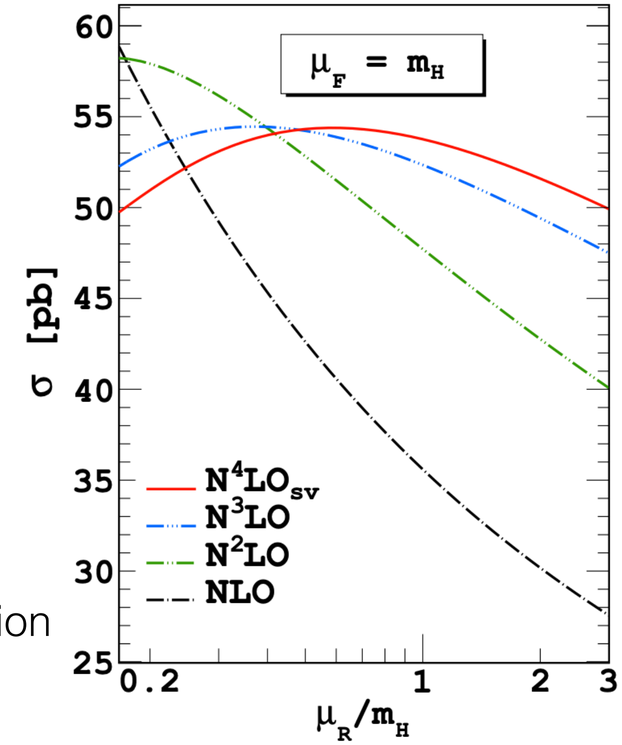


δ(scale)	δ(trunc)	δ(PDF-TH)	δ(EW)	$\delta(t,b,c)$	$\delta(1/m_t)$
$^{+0.10\text{ pb}}_{-1.15\text{ pb}}$	± 0.18 pb	± 0.56 pb	± 0.49 pb	± 0.40 pb	± 0.49 pb
$^{+0.21\%}_{-2.37\%}$	$\pm 0.37\%$	$\pm 1.16\%$	$\pm 1\%$	$\pm 0.83\%$	$\pm 1\%$

LHCH(XS)WG YR4 '16



soft-virtual approximation



Approximate four-loop QCD corrections to the Higgs-boson production cross section #1

G. Das (Siegen U.), S. Moch (Hamburg U., Inst. Theor. Phys. II), A. Vogt (Liverpool U., Dept. Math.) (Apr 1, 2020)

Published in: *Phys.Lett.B* 807 (2020) 135546 • e-Print: 2004.00563 [hep-ph]

δ(scale)	δ(trunc)	δ(PDF-TH)	δ(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%	$\pm 0.37\%$	$\pm 1.16\%$	$\pm 1\%$	$\pm 0.83\%$	$\pm 1\%$

LHCH(XS)WG YR4 '16

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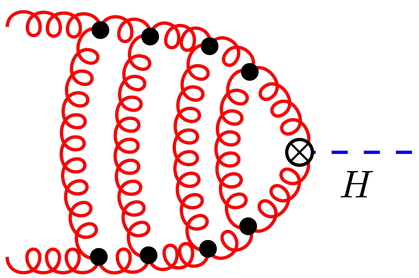
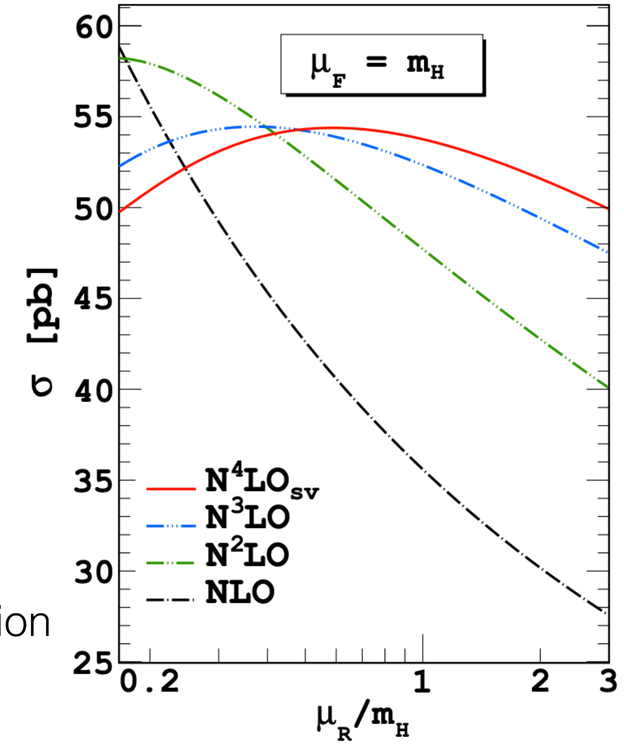


soft-virtual approximation



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G. Das (Siegen U.), S. Moch (Hamburg U., Inst. Theor. Phys. II), A. Vogt (Liverpool U., Dept. Math.) (Apr 1, 2020)

Published in: *Phys.Lett.B* 807 (2020) 135546 • e-Print: 2004.00563 [hep-ph]

Planar master integrals for four-loop form factors #22

Andreas von Manteuffel (Michigan State U.), Robert M. Schabinger (Michigan State U.) (Mar 14, 2019)

Published in: *JHEP* 05 (2019) 073 • e-Print: 1903.06171 [hep-ph]

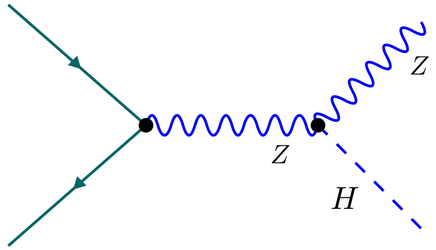
Quark and Gluon Form Factors in Four-Loop QCD #3

Roman N. Lee (Novosibirsk, IYF), Andreas von Manteuffel (Michigan State U.), Robert M. Schabinger (Michigan State U.), Alexander V. Smirnov (Lomonosov Moscow State U. and Unlisted, RU), Vladimir A. Smirnov (SINP, Moscow and Unlisted, RU) et al. (Feb 9, 2022)

Published in: *Phys.Rev.Lett.* 128 (2022) 21, 212002 • e-Print: 2202.04660 [hep-ph]

δ(scale)	δ(trunc)	δ(PDF-TH)	δ(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%	$\pm 0.37\%$	$\pm 1.16\%$	$\pm 1\%$	$\pm 0.83\%$	$\pm 1\%$

LHCH(XS)WG YR4 '16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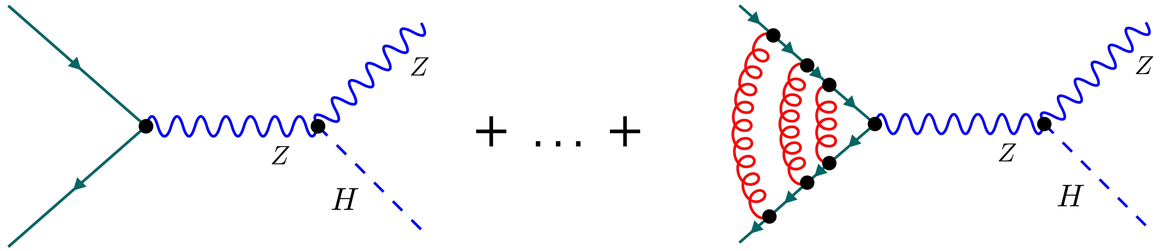
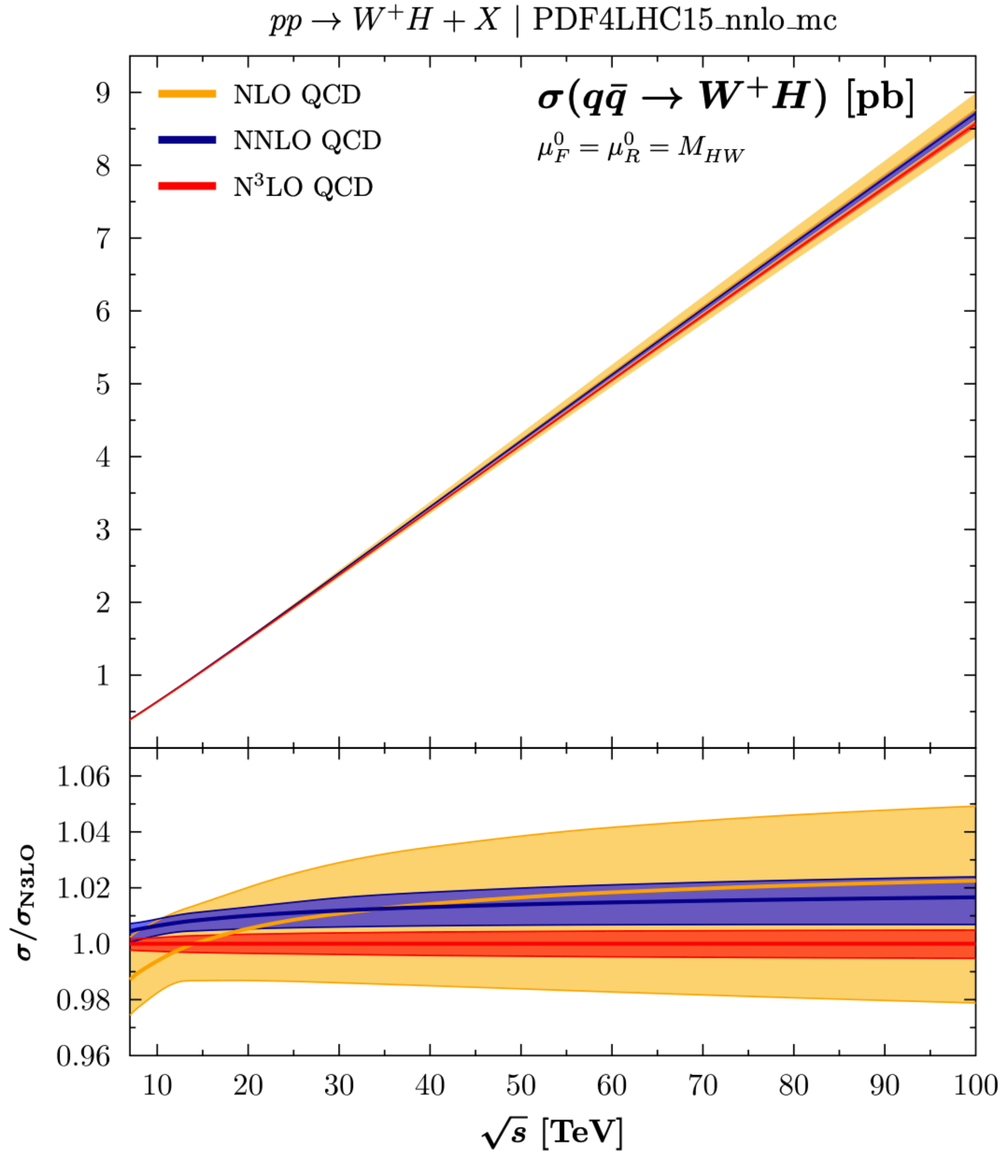
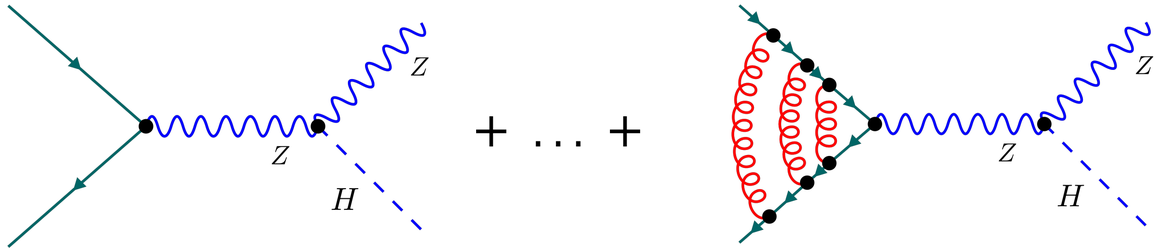


Inclusive production cross sections at N^{3}LO #1

Julien Baglio (CERN), Claude Duhr (U. Bonn, Phys. Inst., BCTP), Bernhard Mistlberger (SLAC), Robert Szafron (Brookhaven) (Sep 13, 2022)

Published in: *JHEP* 12 (2022) 066 • e-Print: 2209.06138 [hep-ph]





Inclusive production cross sections at N^{3}LO #1

Julien Baglio (CERN), Claude Duhr (U. Bonn, Phys. Inst., BCTP), Bernhard Mistlberger (SLAC), Robert Szafron (Brookhaven) (Sep 13, 2022)

Published in: *JHEP* 12 (2022) 066 • e-Print: 2209.06138 [hep-ph]

NNLO QCD corrections to associated WH production and $H \to b\bar{b}$ decay #59

Fabrizio Caola (Durham U., IPPP), Gionata Luisoni (Munich, Max Planck Inst.), Kirill Melnikov (KIT, Karlsruhe, TTP), Raoul Röntsch (KIT, Karlsruhe, TTP) (Dec 19, 2017)

Published in: *Phys.Rev.D* 97 (2018) 7, 074022 • e-Print: 1712.06954 [hep-ph]

Associated production of a Higgs boson decaying into bottom quarks at the LHC in full NNLO QCD #65

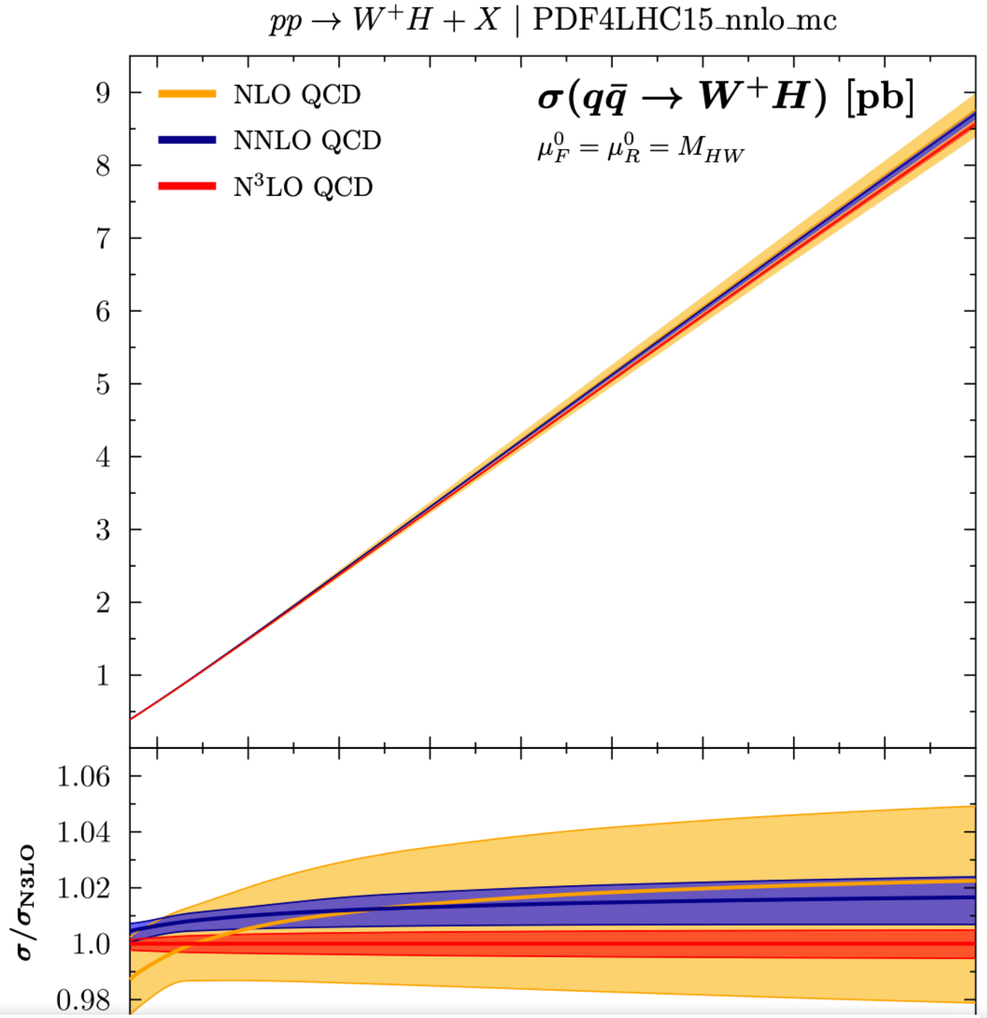
Giancarlo Ferrera (Milan U. and INFN, Milan), Gábor Somogyi (Debrecen U. and MTA-DE, Debrecen), Francesco Tramontano (Naples U. and INFN, Naples) (May 29, 2017)

Published in: *Phys.Lett.B* 780 (2018) 346-351 • e-Print: 1705.10304 [hep-ph]

Bottom quark mass effects in associated WH production with the $H \to b\bar{b}$ decay through NNLO QCD #28

Arnd Behring (KIT, Karlsruhe), Wojciech Bizoń (Karlsruhe U., ITP and KIT, Karlsruhe), Fabrizio Caola (Oxford U., Theor. Phys.), Kirill Melnikov (Karlsruhe U., ITP), Raoul Röntsch (CERN) (Mar 18, 2020)

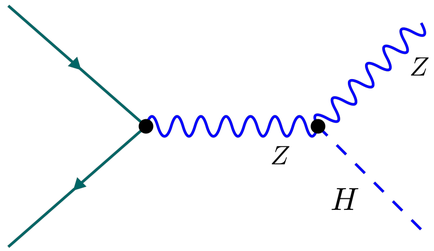
Published in: *Phys.Rev.D* 101 (2020) 11, 114012 • e-Print: 2003.08321 [hep-ph]



VH + jet production in hadron-hadron collisions up to order α_s^3 in perturbative QCD #11

R. Gauld (Nikhef, Amsterdam and Bonn U.), A. Gehrmann-De Ridder (Zurich, ETH and Zurich U.), E.W. N. Glover (Durham U., IPPP and Durham U.), A. Huss (CERN), I. Majer (Zurich, ETH) (Oct 25, 2021)

Published in: *JHEP* 03 (2022) 008 • e-Print: 2110.12992 [hep-ph]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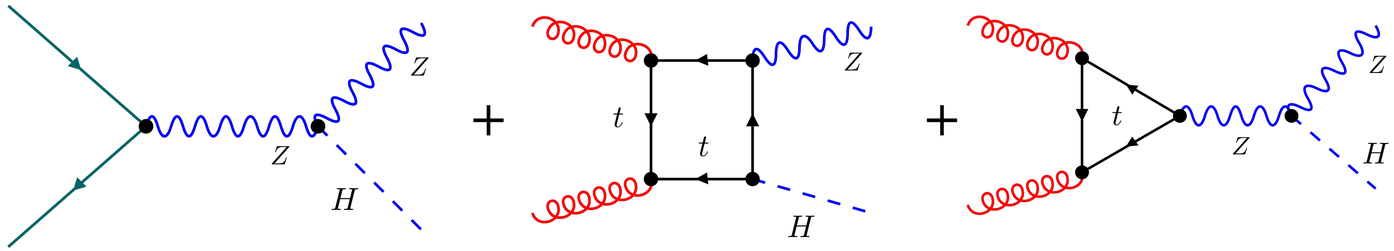
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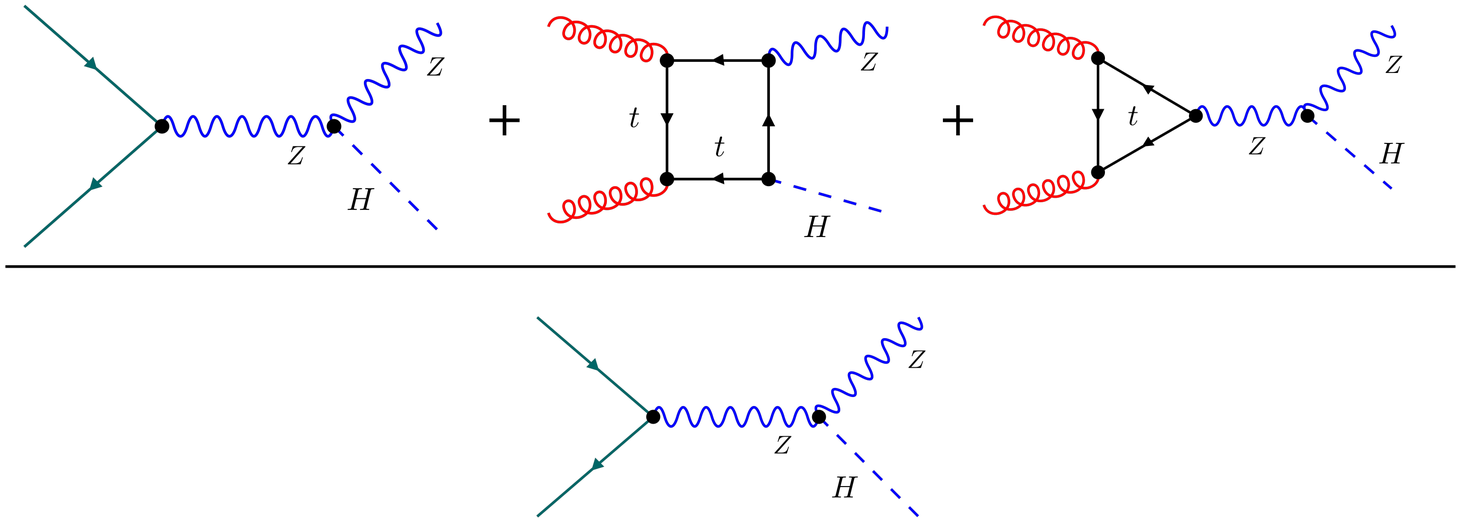
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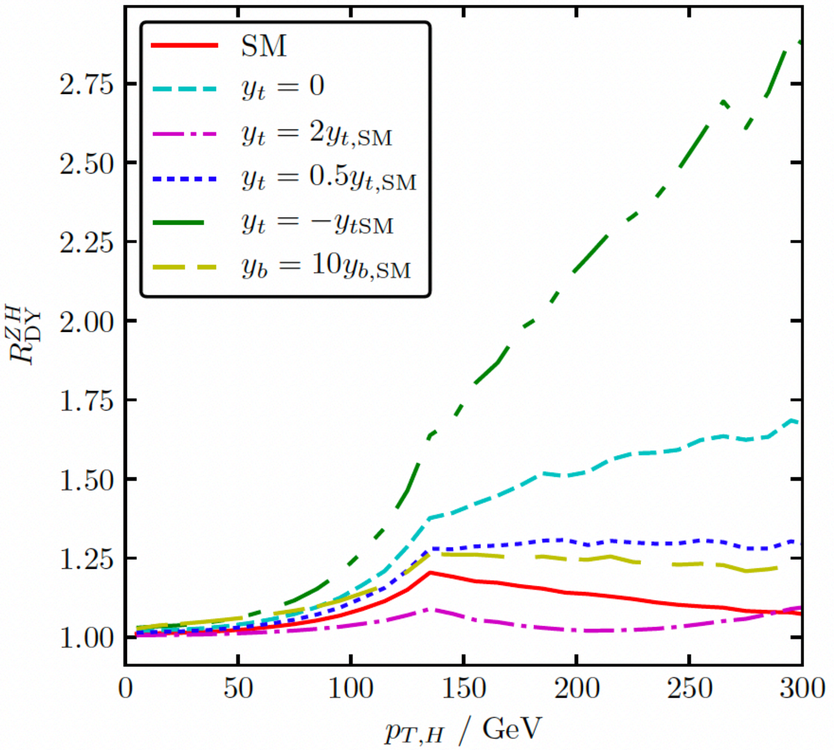
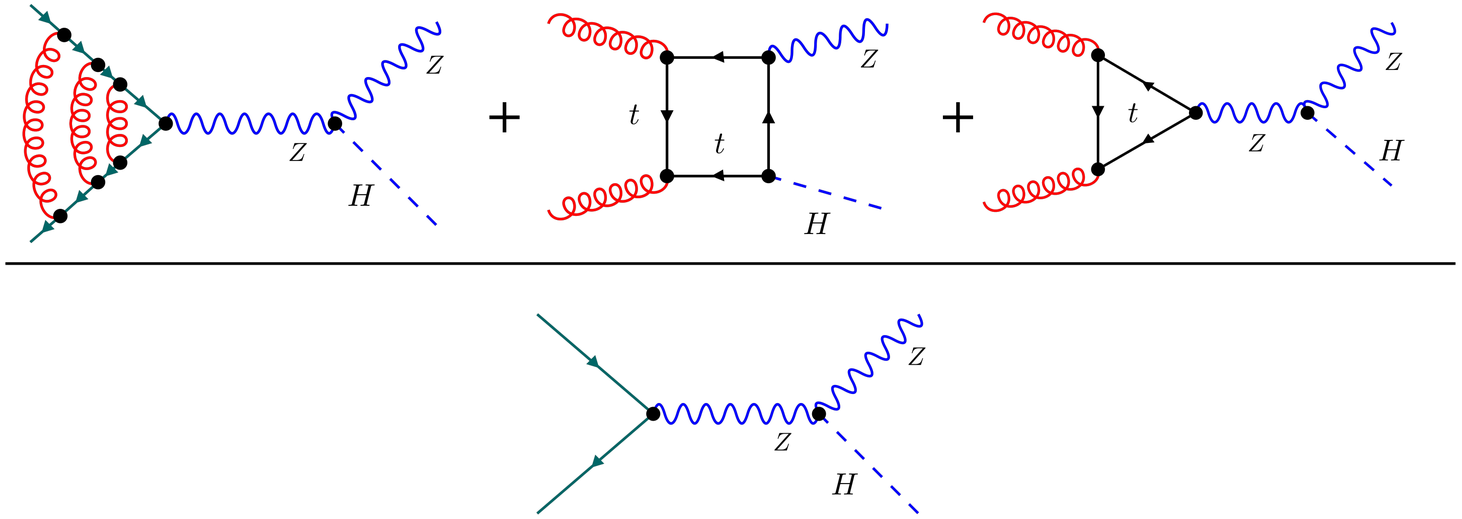

SM
$y_t = 0$
$y_t = 2y_{t,\mathrm{SM}}$
$y_t = 0.5y_{t,\mathrm{SM}}$
$y_t = -y_{t\mathrm{SM}}$
$y_b = 10y_{b,\mathrm{SM}}$
R^{ZH}_{DY}
2.75
2.50
2.25
2.00
1.75
1.50
1.25
1.00
0
50
100
150
200
250
300
$p_{T,H}$ / GeV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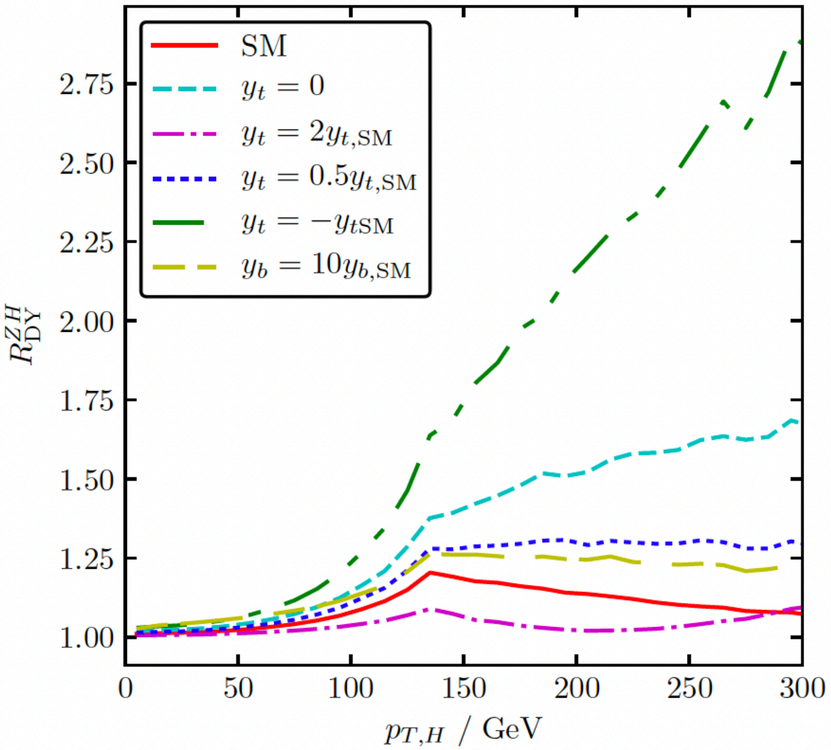
SM
$y_t = 0$
$y_t = 2y_{t,\mathrm{SM}}$
$y_t = 0.5y_{t,\mathrm{SM}}$
$y_t = -y_{t\mathrm{SM}}$
$y_b = 10y_{b,\mathrm{SM}}$
R^{ZH}_{DY}
2.75
2.50
2.25
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1.00
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200
250
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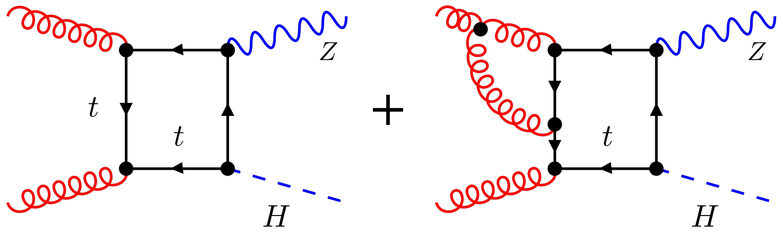
$p_{T,H}$ / GeV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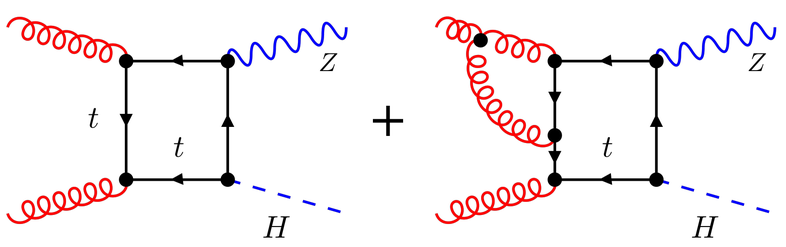
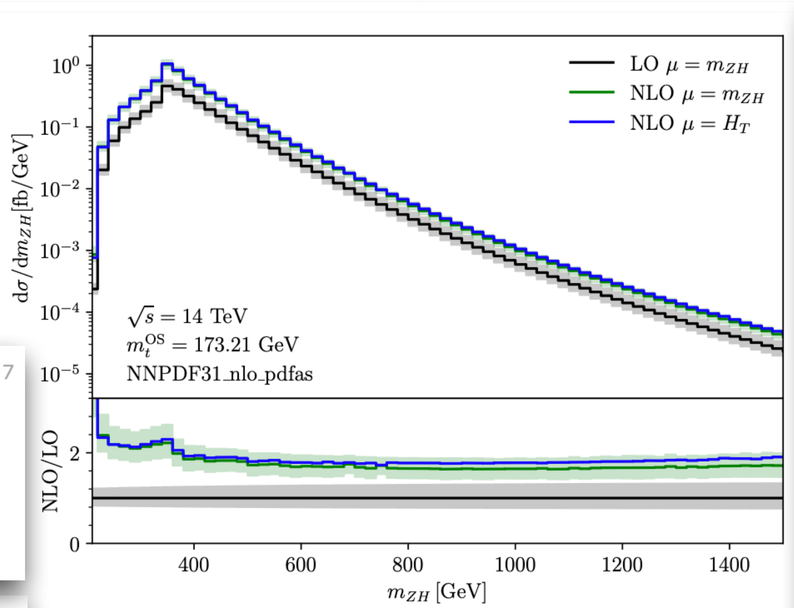
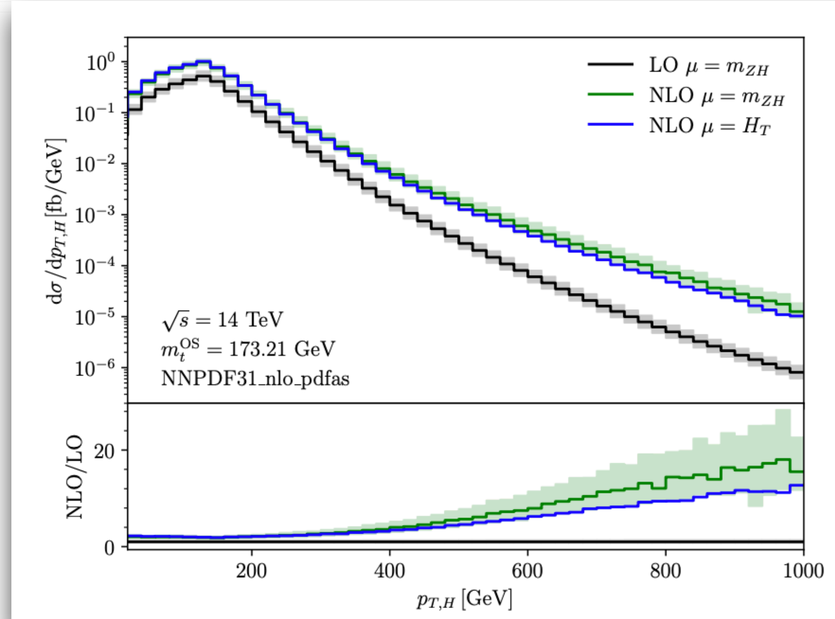






ZH production in gluon fusion: two-loop amplitudes with full top quark mass dependence #17

Long Chen (Munich, Max Planck Inst. and Aachen, Tech. Hochsch.), Gudrun Heinrich (KIT, Karlsruhe, TP), Stephen P. Jones (CERN and Durham U., IPPP), Matthias Kerner (Zurich U.), Jonas Klappert (RWTH Aachen U.) et al. (Nov 24, 2020)

Published in: *JHEP* 03 (2021) 125 • e-Print: 2011.12325 [hep-ph]

Gluon fusion production at NLO: merging the transverse momentum and the high-energy expansions #1

Luigi Bellafronte (Santiago de Compostela U., IGFAE), Giuseppe Degrassi (Rome III U. and INFN, Rome3), Pier Paolo Giardino (Santiago de Compostela U., IGFAE), Ramona Gröber (U. Padua, Dept. Phys. Astron. and INFN, Padua), Marco Vitti (Rome III U. and INFN, Rome3) (Feb 24, 2022)

Published in: *JHEP* 07 (2022) 069 • e-Print: 2202.12157 [hep-ph]

ZH production in gluon fusion at NLO in QCD #1

Long Chen (RWTH Aachen U. and Shandong U.), Joshua Davies (Sussex U.), Gudrun Heinrich (KIT, Karlsruhe), Stephen P. Jones (Durham U., IPPP), Matthias Kerner (KIT, Karlsruhe and KIT, Karlsruhe, IKP) et al. (Apr 11, 2022)

Published in: *JHEP* 08 (2022) 056 • e-Print: 2204.05225 [hep-ph]

On the NLO QCD corrections to gluon-initiated ZH production #2

Giuseppe Degrassi (CERN and Rome III U. and INFN, Rome3), Ramona Gröber (Padua U. and INFN, Padua), Marco Vitti (Rome III U. and INFN, Rome3), Xiaoran Zhao (Rome III U. and INFN, Rome3) (May 5, 2022)

Published in: *JHEP* 08 (2022) 009 • e-Print: 2205.02769 [hep-ph]

On top quark mass effects to $gg \to ZH$ at NLO #77

Alexander Hasselhuhn (KIT, Karlsruhe, TTP), Thomas Luthe (KIT, Karlsruhe, TTP), Matthias Steinhauser (Karlsruhe U., TTP) (Nov 17, 2016)

Published in: *JHEP* 01 (2017) 073 • e-Print: 1611.05881 [hep-ph]

Virtual corrections to $gg \to ZH$ in the high-energy and large-m_t limits #18

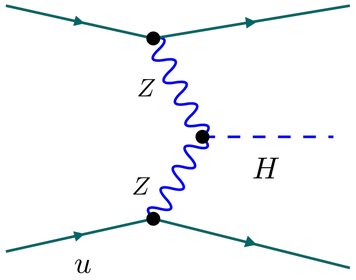
Joshua Davies (Sussex U.), Go Mishima (Tohoku U.), Matthias Steinhauser (Karlsruhe U., TTP) (Nov 24, 2020)

Published in: *JHEP* 03 (2021) 034 • e-Print: 2011.12314 [hep-ph]

Next-to-leading order corrections for gg→ZH with top quark mass dependence #10

Guoxing Wang (Zhejiang U., Inst. Mod. Phys.), Xiaofeng Xu (Bern U.), Yongqi Xu (Peking U. and Peking U., SKLNPT), Li Lin Yang (Zhejiang U., Inst. Mod. Phys.) (Jul 17, 2021)

Published in: *Phys.Lett.B* 829 (2022) 137087 • e-Print: 2107.08206 [hep-ph]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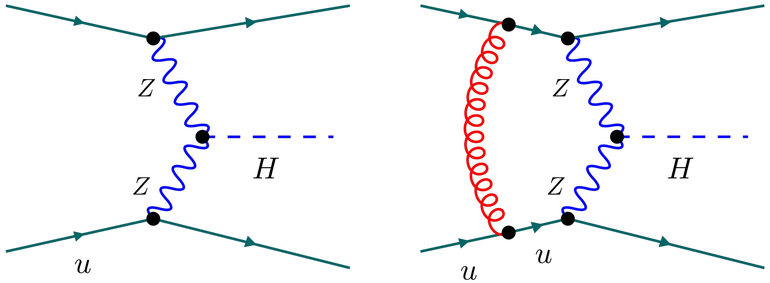
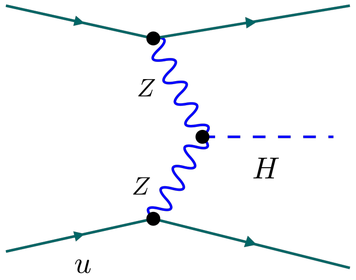
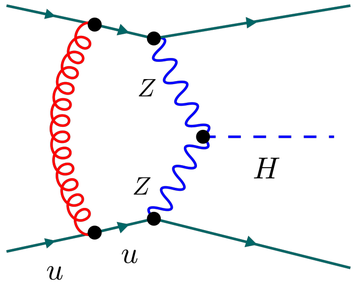
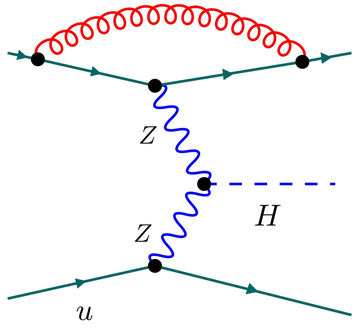


≈ 0 at NLO





≈ 0 at NLO



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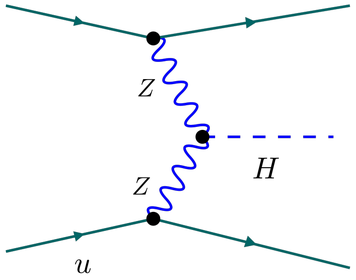

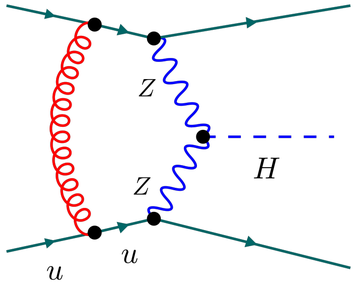

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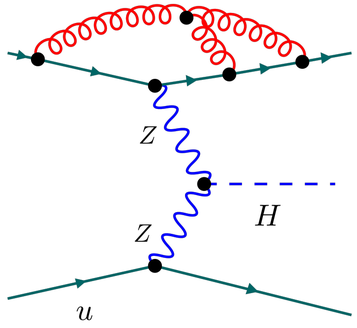

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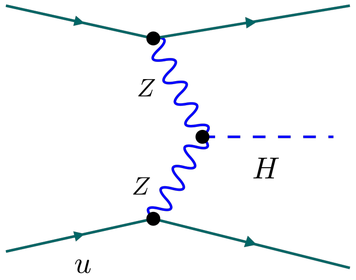

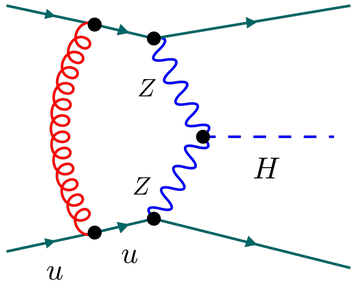

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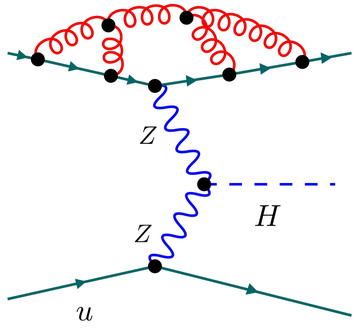

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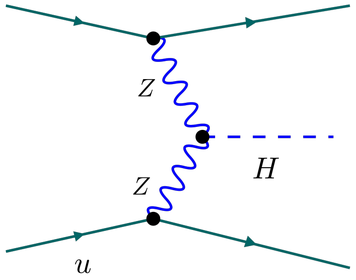
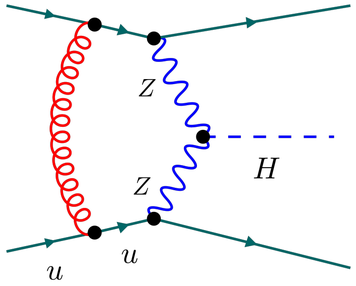
Vector-Boson Fusion Higgs Production at Three Loops in QCD #8

Frédéric A. Dreyer (UPMC, Paris (main) and Paris, LPTHE and CERN), Alexander Karlberg (Oxford U., Theor. Phys.) (Jun 2, 2016)

Published in: *Phys.Rev.Lett.* 117 (2016) 7, 072001 • e-Print: 1606.00840 [hep-ph]





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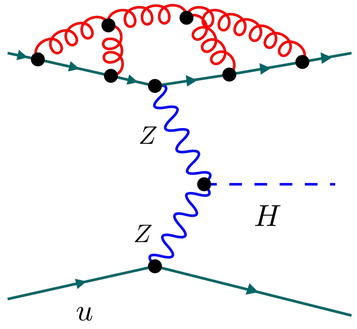

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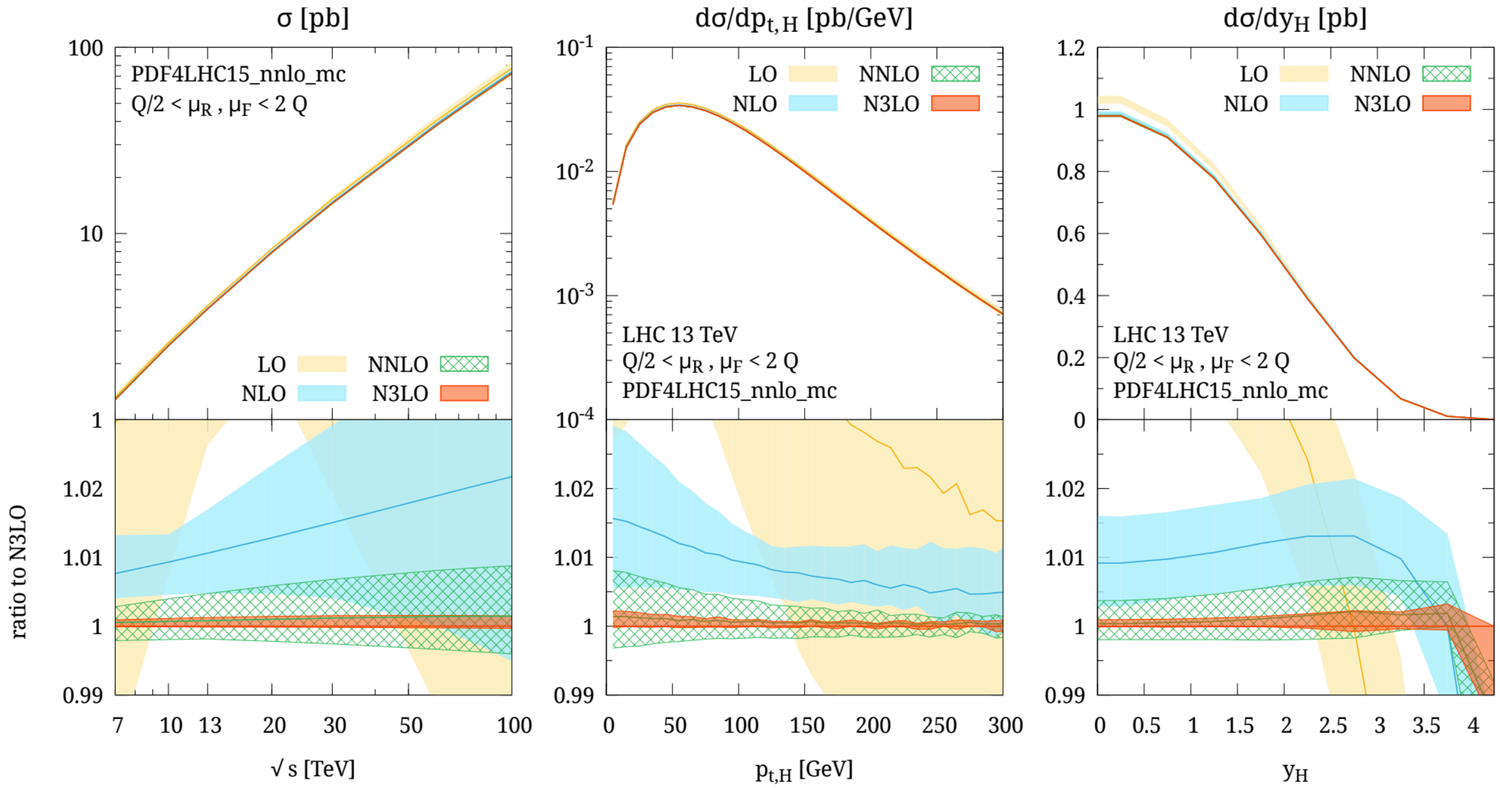

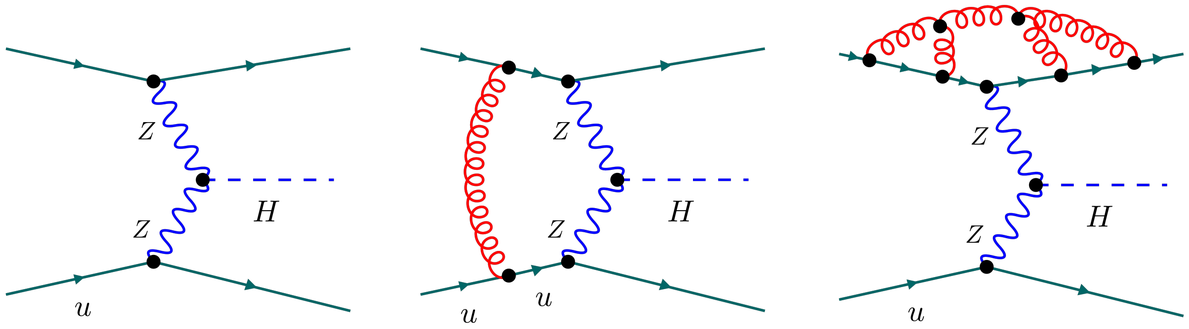
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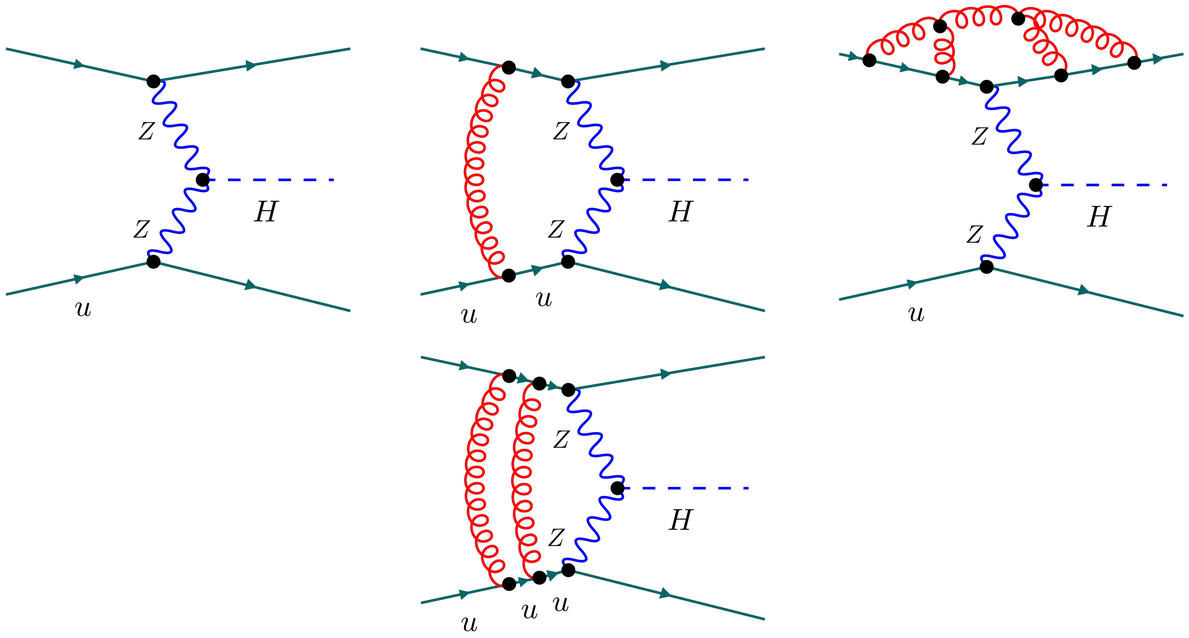
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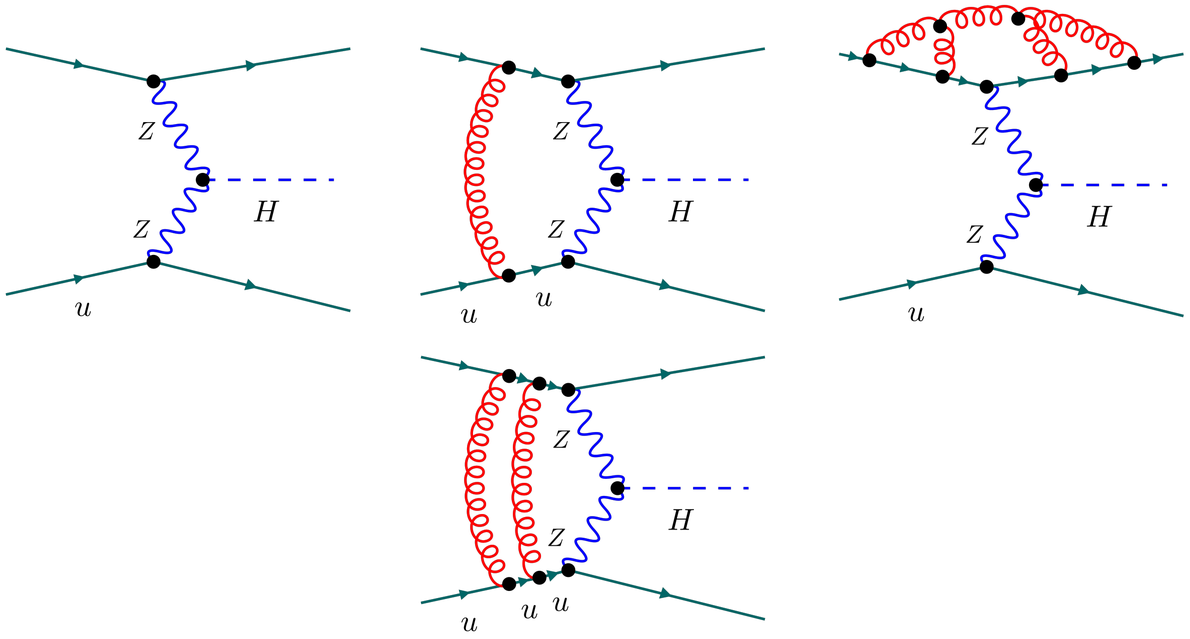

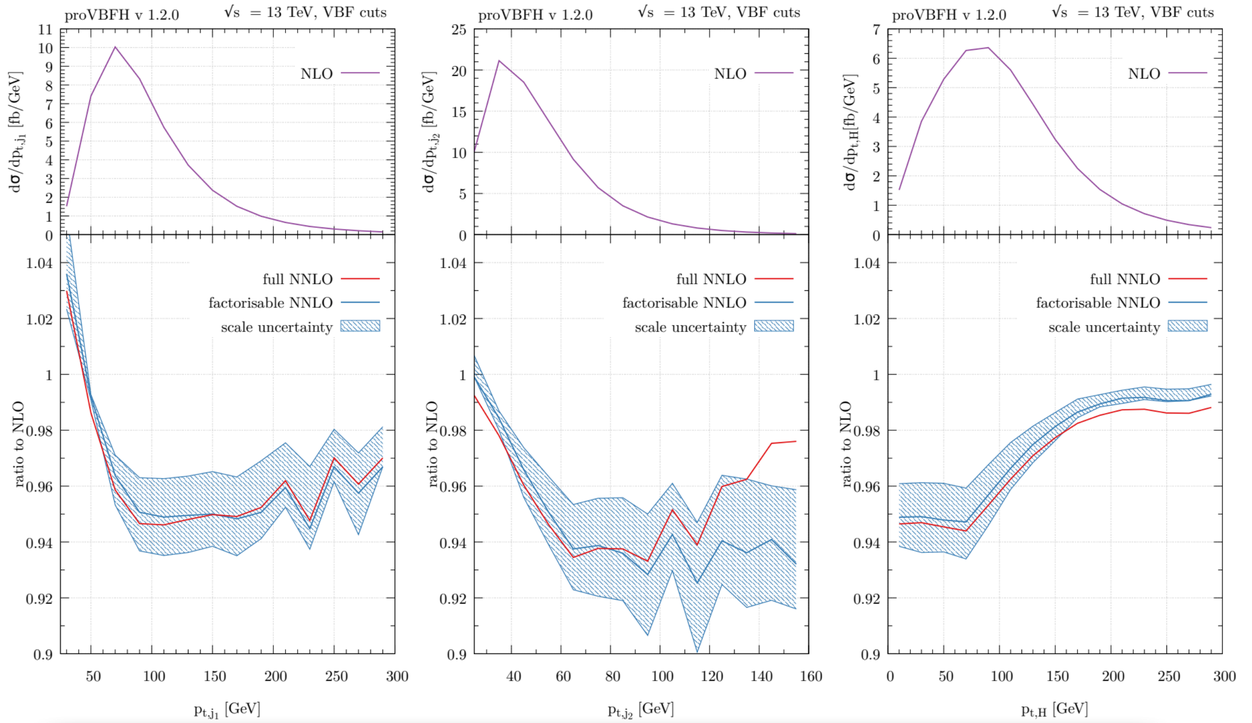

Nonfactorizable QCD Effects in Higgs Boson Production via Vector Boson Fusion #1

Tao Liu (Alberta U.), Kirill Melnikov (KIT, Karlsruhe, TTP), Alexander A. Penin (Alberta U. and KIT, Karlsruhe, TTP and Zurich, ETH) (Jun 26, 2019)

Published in: *Phys.Rev.Lett.* 123 (2019) 12, 122002 • e-Print: 1906.10899 [hep-ph]

On the impact of non-factorisable corrections in VBF single and double Higgs production #3

Frédéric A. Dreyer (Oxford U., Theor. Phys.), Alexander Karlberg (Oxford U., Theor. Phys.), Lorenzo Tancredi (Oxford U., Theor. Phys.) (May 22, 2020)

Published in: *JHEP* 10 (2020) 131 • e-Print: 2005.11334 [hep-ph]

Non-factorizable virtual corrections to Higgs boson production in weak boson fusion beyond the eikonal approximation #1

Ming-Ming Long (Karlsruhe U., TTP), Kirill Melnikov (Karlsruhe U., TTP), Jérémie Quarroz (Karlsruhe U., TTP) (May 22, 2023)

e-Print: 2305.12937 [hep-ph]

On the non-factorizable corrections to Higgs boson production in weak boson fusion #2

Konstantin Asteriadis (BNL, NSLS), Christian Brønnum-Hansen, Kirill Melnikov (KIT, Karlsruhe, TTP) (May 13, 2023)

e-Print: 2305.08016 [hep-ph]

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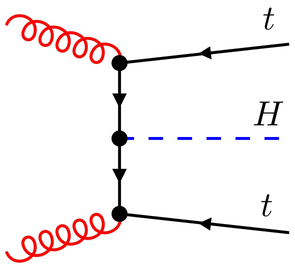
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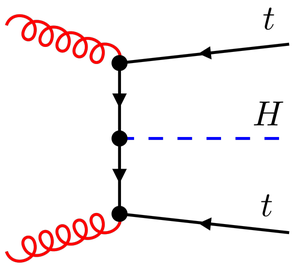

The simplest of them all: $t\bar{t}W^{\pm}$ at NLO accuracy in QCD #29

Giuseppe Bevilacqua (MTA-DE, Debrecen), Huan-Yu Bi (RWTH Aachen U.), Heribertus Bayu Hartanto (Durham U., IPPP), Manfred Kraus (Florida State U.), Malgorzata Worek (RWTH Aachen U.) (May 19, 2020)

Published in: *JHEP* 08 (2020) 043 • e-Print: 2005.09427 [hep-ph]

NLO QCD corrections to full off-shell production of $t\bar{t}Z$ including leptonic decays #4

Giuseppe Bevilacqua (MTA-DE, Debrecen and Debrecen U.), Heribertus Bayu Hartanto (Cambridge U.), Manfred Kraus (Florida State U.), Jasmina Nasufi (RWTH Aachen U.), Malgorzata Worek (RWTH Aachen U.) (Mar 29, 2022)

Published in: *JHEP* 08 (2022) 060 • e-Print: 2203.15688 [hep-ph]

Higgs production in association with off-shell top-antitop pairs at NLO EW and QCD at the LHC #18

Ansgar Denner (Wurzburg U.), Jean-Nicolas Lang (Wurzburg U.), Mathieu Pellen (Wurzburg U.), Sandro Uccirati (INFN, Turin and Turin U.) (Dec 21, 2016)

Published in: *JHEP* 02 (2017) 053 • e-Print: 1612.07138 [hep-ph]

tt¯bb¯ at the LHC: On the size of off-shell effects and prompt b-jet identification #1

Giuseppe Bevilacqua (MTA-DE, Debrecen and Debrecen U.), Huan-Yu Bi (RWTH Aachen U.), Heribertus Bayu Hartanto (Cambridge U.), Manfred Kraus (Florida State U.), Michele Lupattelli (RWTH Aachen U.) et al. (Feb 22, 2022)

Published in: *Phys.Rev.D* 107 (2023) 1, 014028 • e-Print: 2202.11186 [hep-ph]

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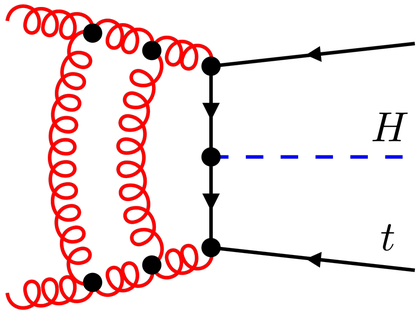

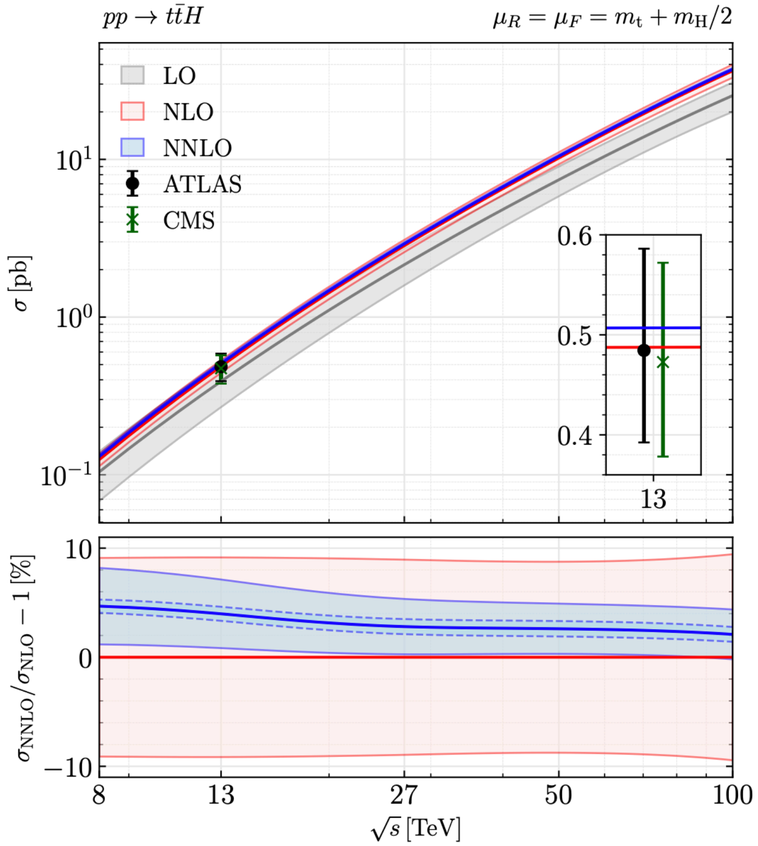

Higgs Boson Production in Association with a Top-Antitop Quark Pair in Next-to-Next-to-Leading Order QCD #1

Stefano Catani (INFN, Florence and Florence U.), Simone Devoto (INFN, Milan and Milan U.), Massimiliano Grazzini (Zurich U.), Stefan Kallweit (INFN, Milan Bicocca and Milan Bicocca U.), Javier Mazzitelli (Munich, Max Planck Inst. and PSI, Villigen) et al. (Oct 14, 2022)

Published in: *Phys.Rev.Lett.* 130 (2023) 11, 111902 • e-Print: 2210.07846 [hep-ph]

What I could not talk about …. Parton shower effects

Parton-shower effects in Higgs production via Vector-Boson Fusion #25

Barbara Jäger (Tubingen U.), Alexander Karlberg (Oxford U., Theor. Phys.), Simon Plätzer (Vienna U.), Johannes Scheller (Tubingen U.), Marco Zaro (INFN, Milan) (Mar 27, 2020)

Published in: *Eur.Phys.J.C* 80 (2020) 8, 756 • e-Print: 2003.12435 [hep-ph]

NLO QCD+EW predictions for HV and HV +jet production including parton-shower effects #63

Federico Granata (Milan Bicocca U. and INFN, Milan Bicocca), Jonas M. Lindert (Durham U. and Durham U., IPPP), Carlo Oleari (INFN, Milan Bicocca and Milan Bicocca U.), Stefano Pozzorini (Zurich U.) (Jun 12, 2017)

Published in: *JHEP* 09 (2017) 012 • e-Print: 1706.03522 [hep-ph]

Next-to-next-to-leading order event generation for VH production with H →$b\bar{b}$ decay #9

Silvia Zanoli (Munich, Max Planck Inst.), Mauro Chiesa (Pavia U.), Emanuele Re (INFN, Milan Bicocca and Annecy, LAPTH), Marius Wiesemann (Munich, Max Planck Inst.), Giulia Zanderighi (Munich, Max Planck Inst. and Munich, Tech. U.) (Dec 8, 2021)

Published in: *JHEP* 07 (2022) 008 • e-Print: 2112.04168 [hep-ph]

NNLOPS accurate associated HZ production with $H \to b\bar{b}$ decay at NLO #48

William Astill (Oxford U., Theor. Phys.), Wojciech Bizoń (Oxford U., Theor. Phys.), Emanuele Re (Annecy, LAPTH and CERN), Giulia Zanderighi (CERN and Oxford U., Theor. Phys.) (Apr 22, 2018)

Published in: *JHEP* 11 (2018) 157 • e-Print: 1804.08141 [hep-ph]

Higgsstrahlung at NNLL′+NNLO matched to parton showers in GENEVA #35

Simone Alioli (INFN, Milan Bicocca and Milan Bicocca U.), Alessandro Broggio (INFN, Milan Bicocca and Milan Bicocca U.), Stefan Kallweit (INFN, Milan Bicocca and Milan Bicocca U.), Matthew A. Lim (INFN, Milan Bicocca and Milan Bicocca U.), Luca Rottoli (INFN, Milan Bicocca and Milan Bicocca U.) (Sep 4, 2019)

Published in: *Phys.Rev.D* 100 (2019) 9, 096016 • e-Print: 1909.02026 [hep-ph]

What I could not talk about…

- HH
- off-shell Higgs production
- Higgs decays
- resummation
- EFT
- BSM
- …

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Conclusions

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Conclusions

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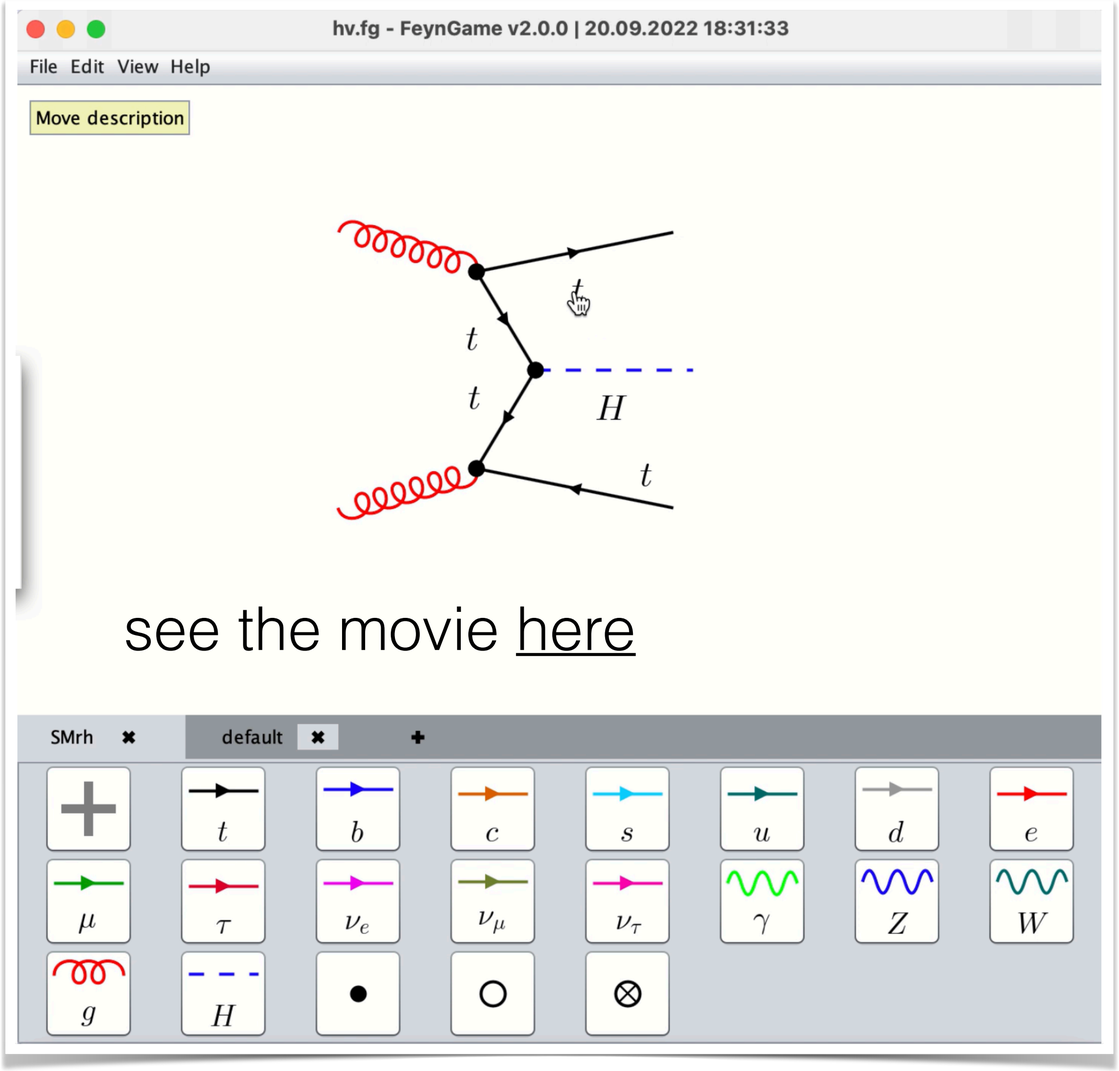
- enormous theoretical progress since YR4
- NNLO standard, N^{3}LO in full swing
- progress in all production modes
- take into account in analyses: LHCHWG is on it!

FeynGame #1

R.V. Harlander (Aachen, Tech. Hochsch.), S.Y. Klein (Aachen, Tech. Hochsch.), M. Lipp (Aachen, Tech. Hochsch.) (Feb 28, 2020)

Published in: *Comput.Phys.Commun.* 256 (2020) 107465 • e-Print: 2003.00896 [physics.ed-ph]

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