Precision Higgs Physics

CRC Annual Meeting 2021

Robert Harlander, 28 May 2021

Institute for Theoretical Particle Physics and Cosmology
RWTH AACHEN UNIVERSITY

A MODEL OF LEPTONS*

Steven Weinberg†
Laboratory for Nuclear Science and Physics Department,
Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received 17 October 1967)

Nobel 1979

Therefore, we shall construct our Lagrangian out of L and R, plus gauge fields $\vec{A}_\mu$ and B_μ coupled to $\vec{T}$ and Y, plus a spin-zero doublet

$$\varphi = \begin{pmatrix} \varphi^0 \\ \varphi^- \end{pmatrix} \qquad (3)$$

whose vacuum expectation value will break $\vec{T}$ and Y and give the electron its mass. The on-

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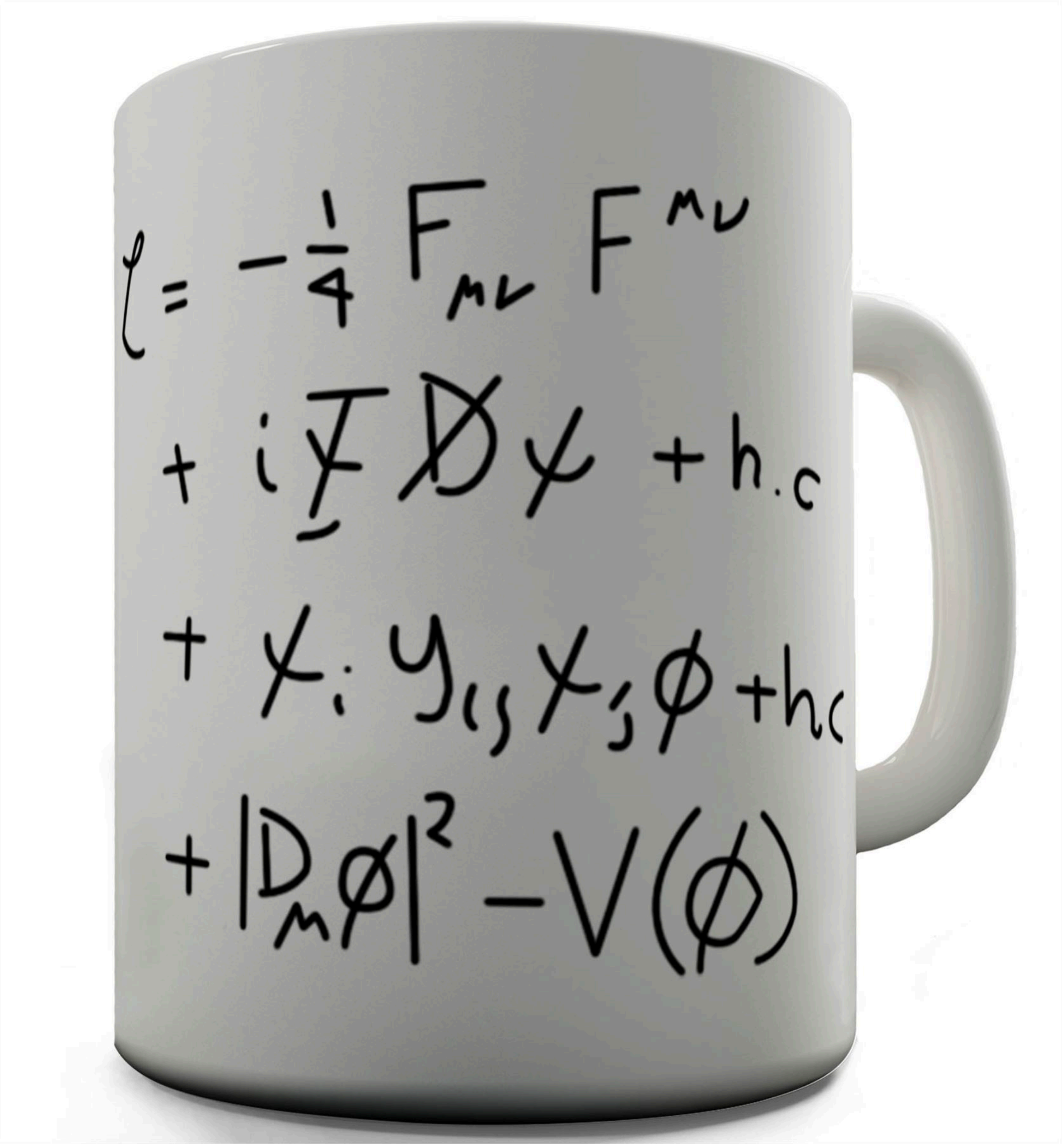
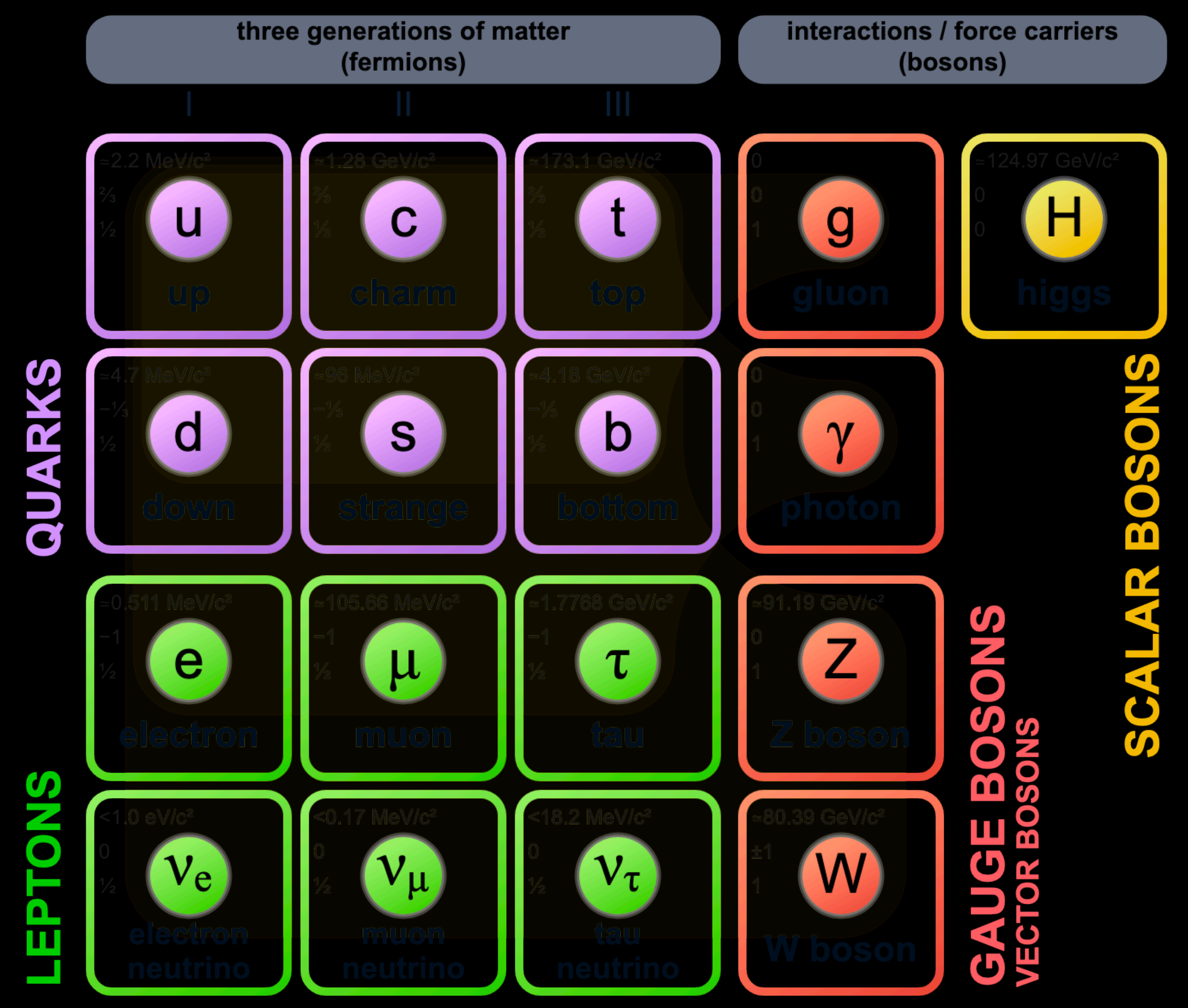
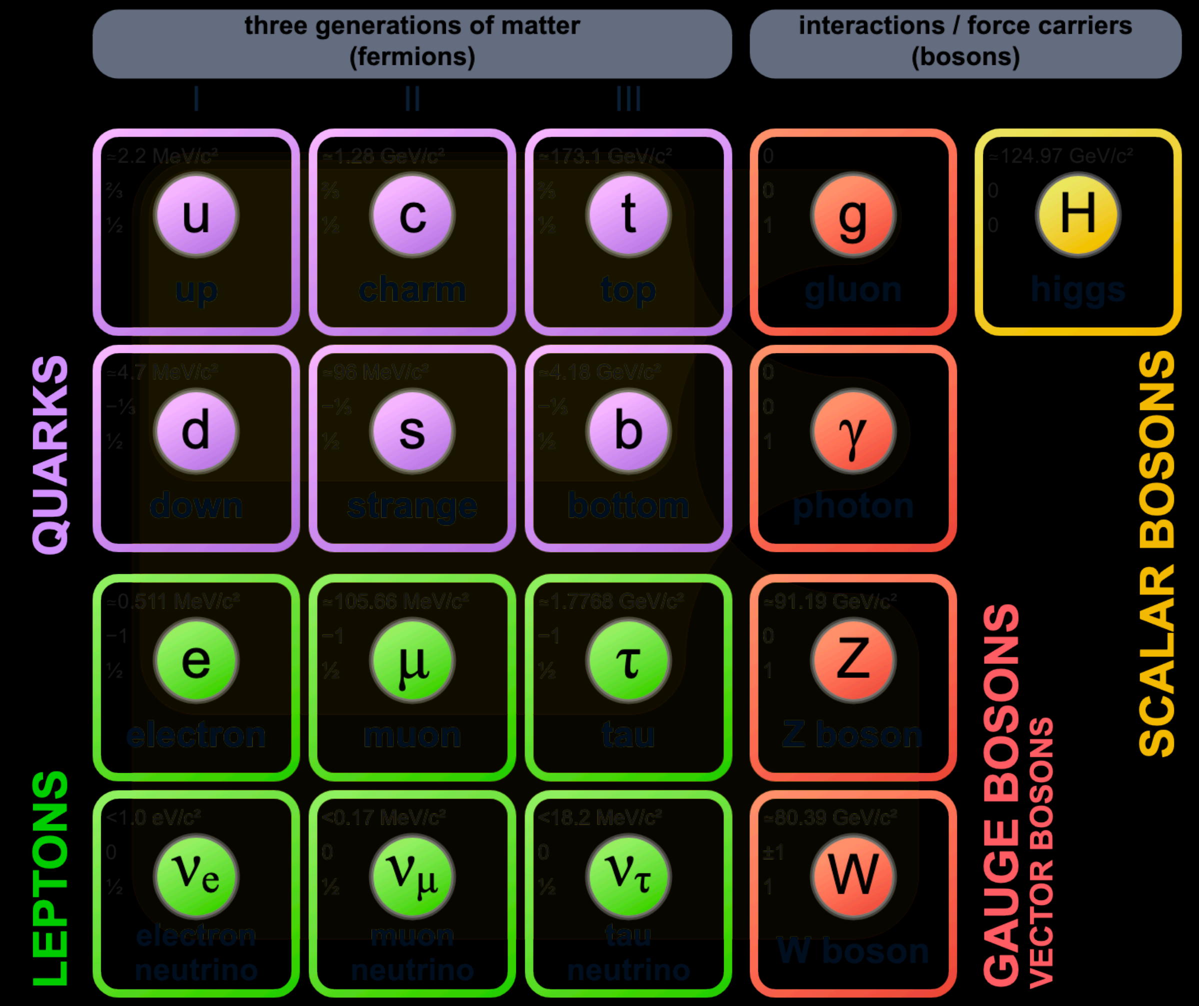
whose vacuum expectation value will break $\vec{T}$ and Y and give the electron its mass. The on-

interaction is multiplied by a factor $-\frac{1}{2}$ rather than $\frac{3}{2}$. Of course our model has too many arbitrary features for these predictions to be taken very seriously, but it is worth keeping in mind that the standard calculation[8] of the


$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$
$+ i \bar{\psi} \not{D} \psi + h.c$
$+ \psi_i y_{ij} \psi_j \phi + h.c$
$+ |D_\mu \phi|^2 - V(\phi)$



three generations of matter (fermions)
interactions / force carriers (bosons)
u
c
t
g
H
d
s
b
γ
e
μ
τ
Z
νe
νμ
ντ
W
QUARKS
LEPTONS
GAUGE BOSONS
VECTOR BOSONS
SCALAR BOSONS



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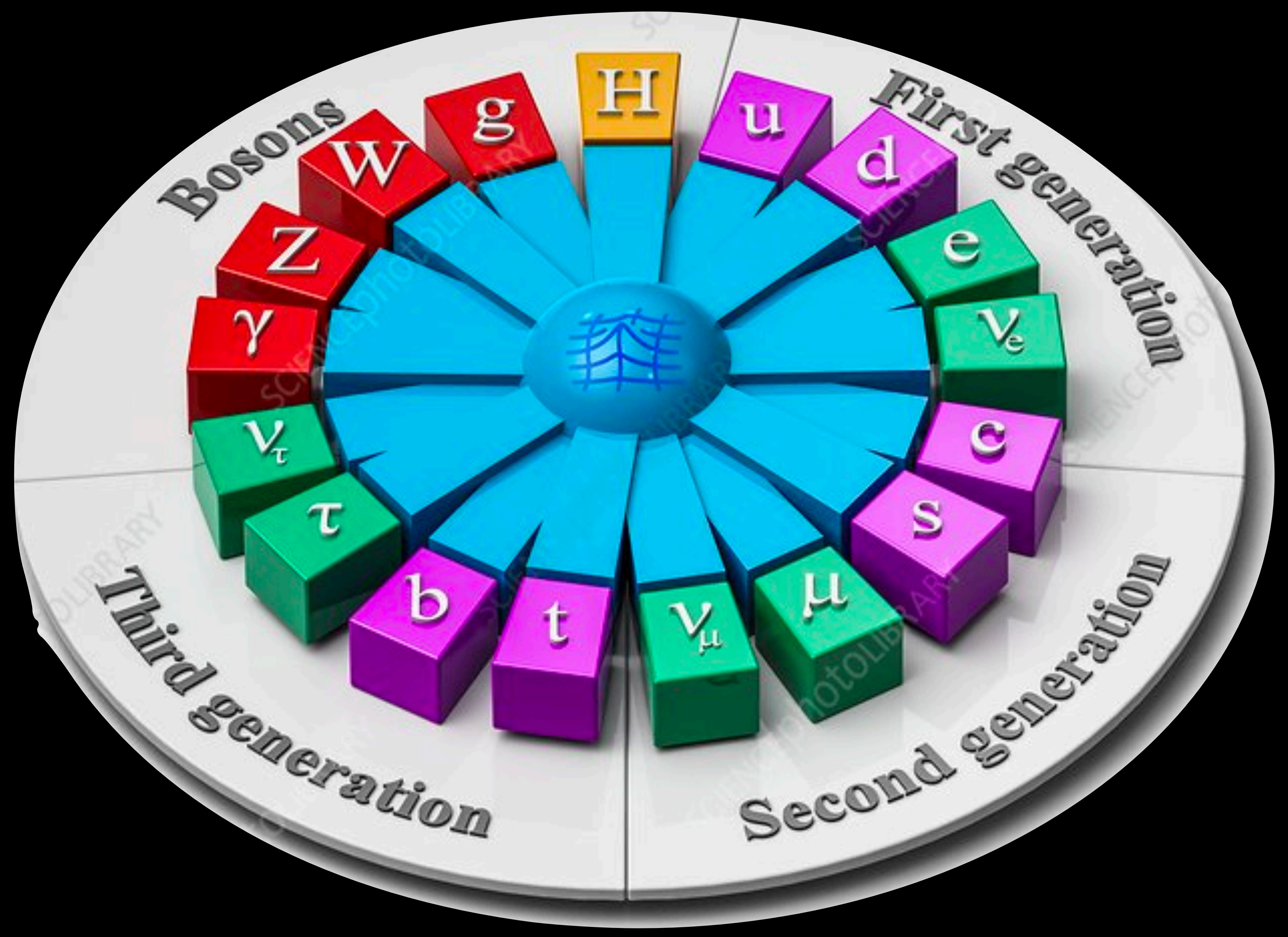

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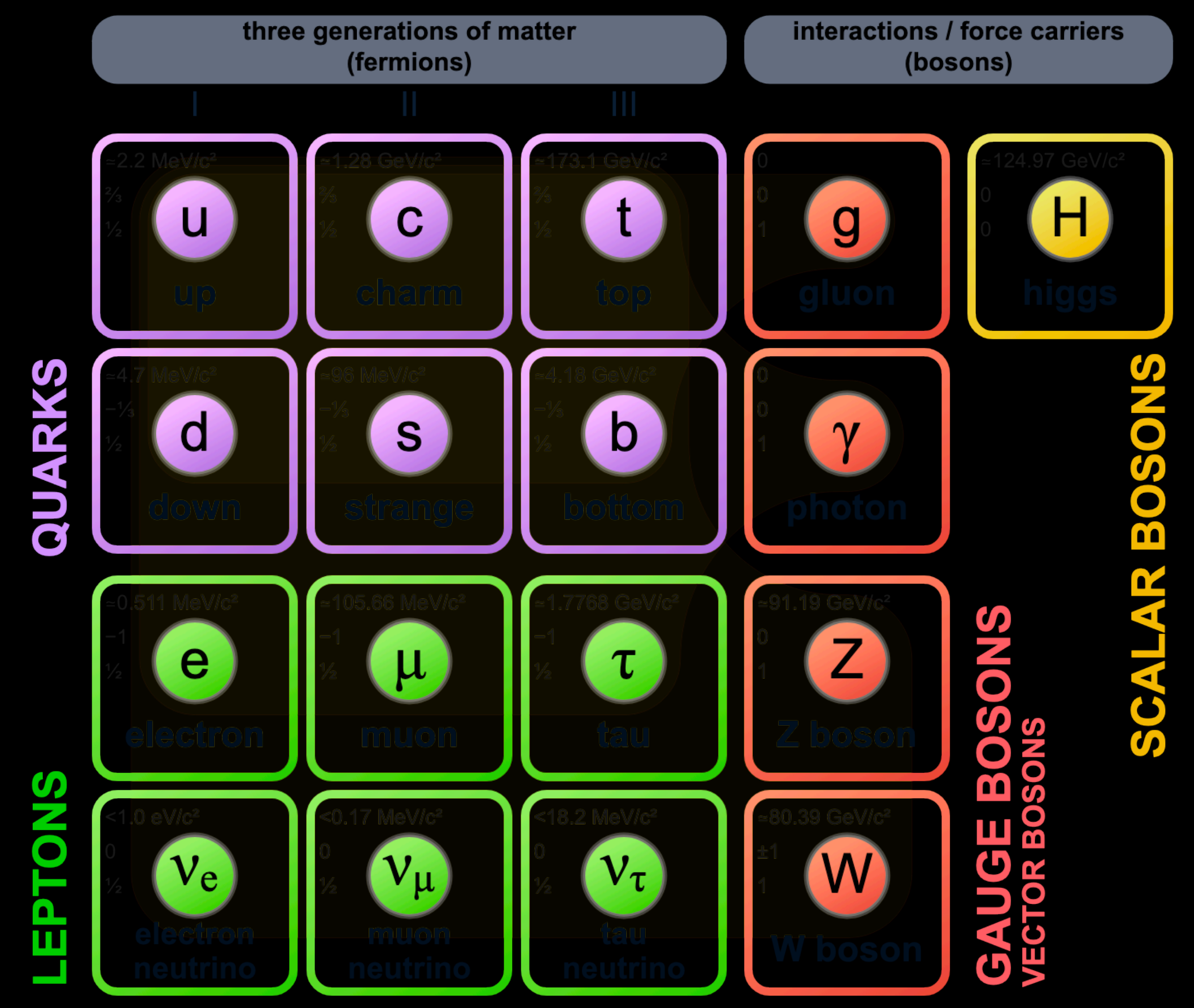

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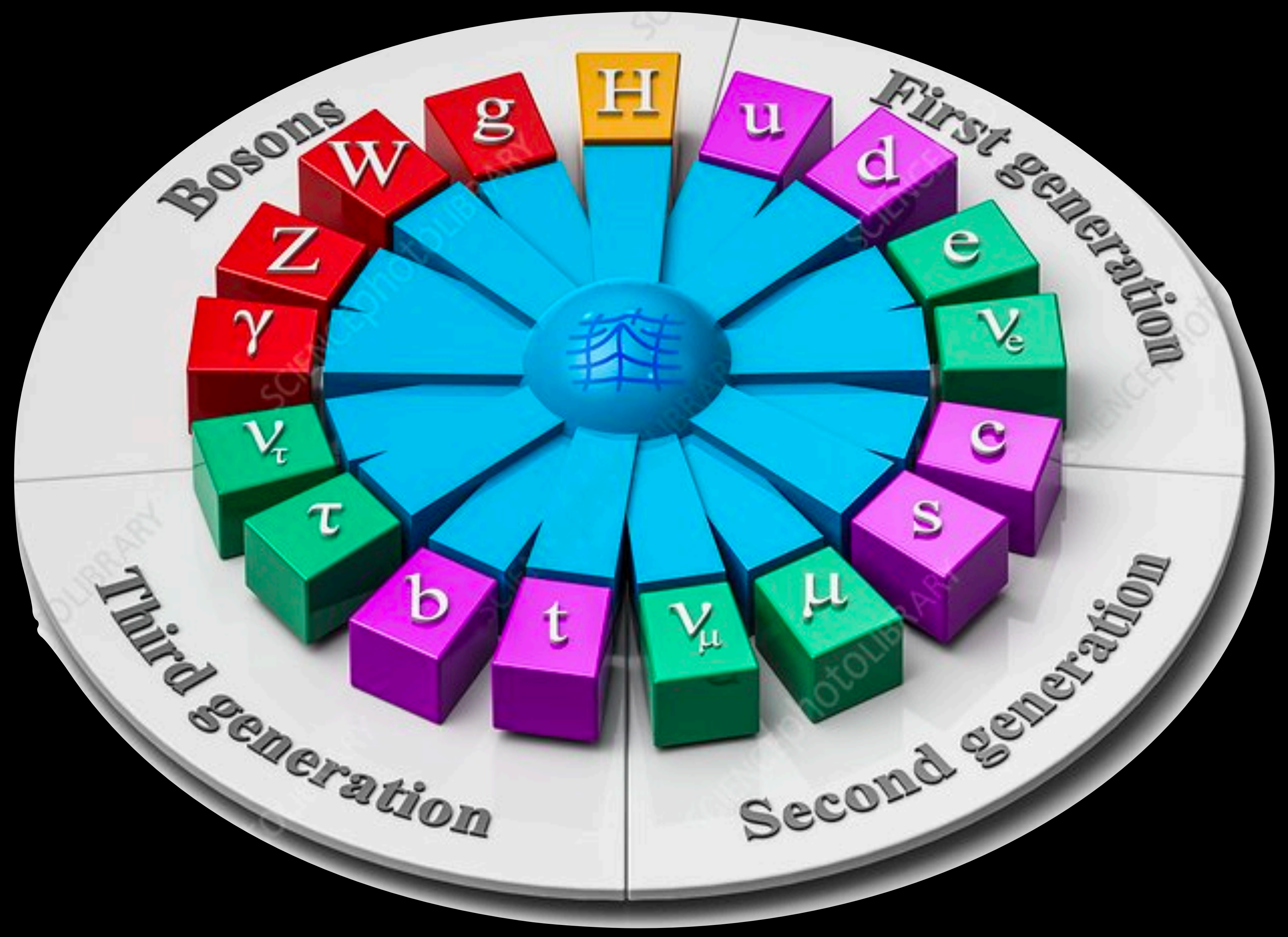

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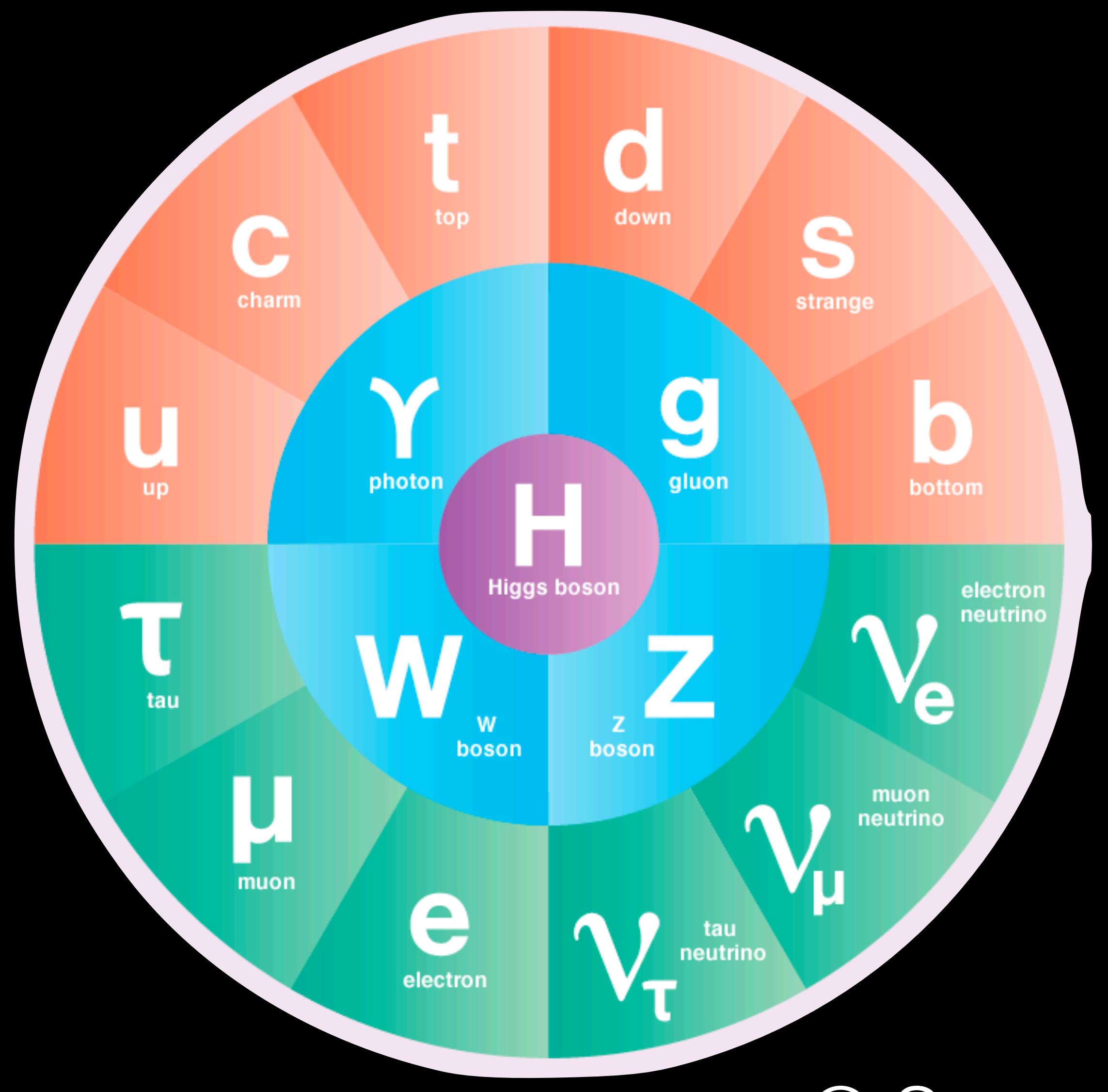

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Particle Zoo ♥ CERN & LHC
The PARTICLE ZOO
Subatomic Particle Plush Toys FROM THE STANDARD MODEL OF PHYSICS & beyond!
QUARKS
UP QUARK A teeny little point inside the proton and neutron, it is friends forever with the down quark.
CHARM QUARK A second generation quark, he is charmed, indeed.
TOP QUARK This heavyweight champion doesn't live long enough to make friends with anyone.
DOWN QUARK A tiny little point inside the proton and neutron, it is friends forever with the up quark.
STRANGE QUARK What's so strange about this second generation quark?
BOTTOM QUARK This third generation quark is puttin' on the pounds.
FORCE CARRIERS
PHOTON The massless wavicle we know and love.
GLUON The "glue" of the strong nuclear force.
W BOSON
Z BOSON
As the carrier particles of the weak nuclear force, they're downright obese.
LEPTONS
ELECTRON-NEUTRINO This minuscule bandit is so light, he is practically massless.
MUON-NEUTRINO Like the other 2 neutrinos, he's got an identity crisis from oscillation.
TAU-NEUTRINO He's a tau now, but what type of neutrino will he be next?
ELECTRON A familiar friend, this negatively charged, busy li'l guy likes to bond.
MUON A "heavy electron" who lives fast and dies young.
TAU A "heavy muon" who could stand to lose a little weight.
THEORETICALS
HIGGS BOSON He's the one everyone wants to meet, but for now he's playing hard to get. You'd be smiling too if everyone was looking to interview you.
GRAVITON Still unobserved, yet theoretically everywhere, he's got big legs for jumping branes.
TACHYON Can this devious and clever particle really travel faster than light?
DARK MATTER The mysterious missing mass. Difficult to see because he's so dark.
NUCLEONS
PROTON We would not be here without her positivity.
NEUTRON He insists on remaining neutral.
Visit the ANTIPARTICLE ANNEX You can now buy antimatter on the web!
NEW! GIFT CARDS
STAMPSHEET Twenty-three particles on one 8.5x11" sheet of perforated "stamps"

10^{-35}m

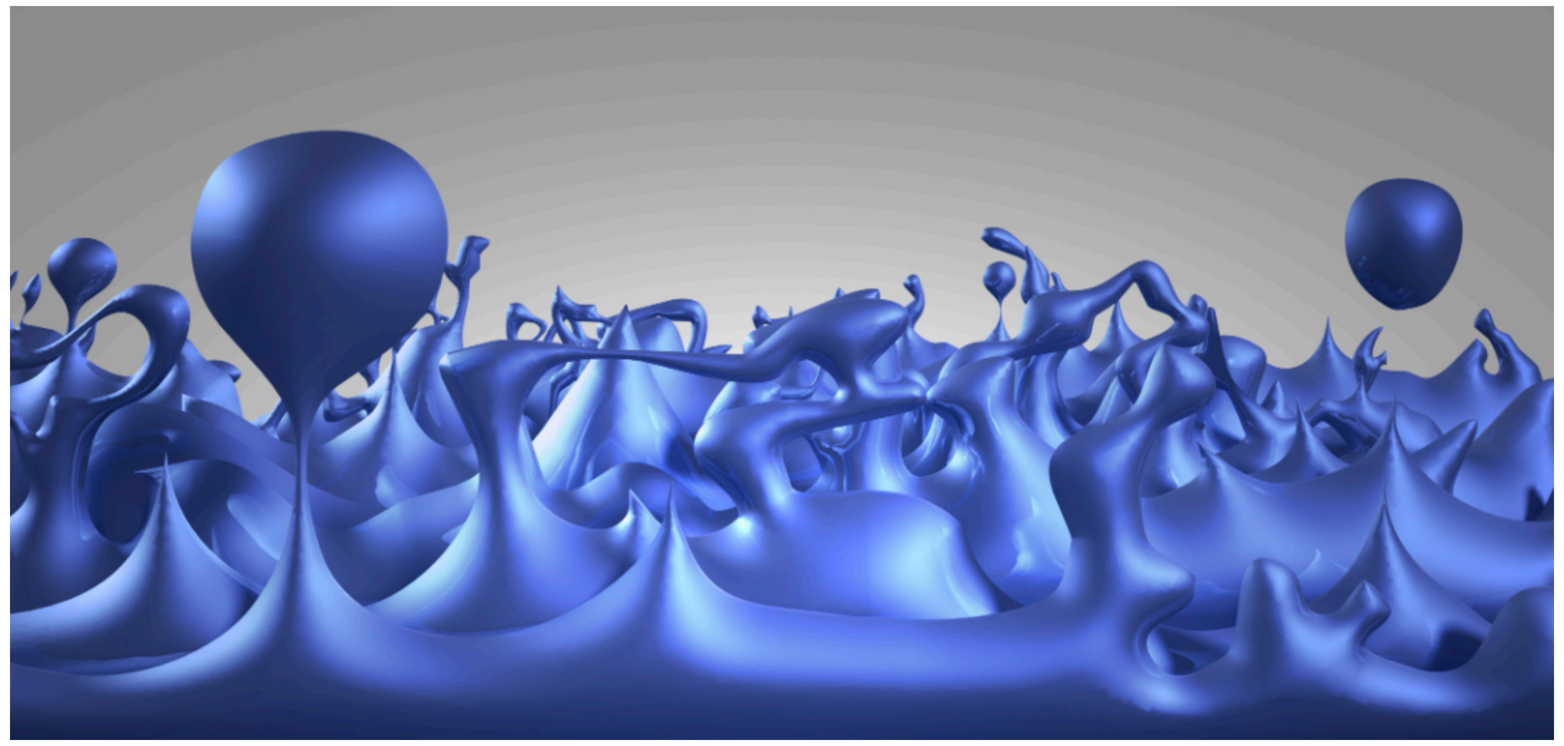


Image Credit: NASA/CXC/ M.Weiss

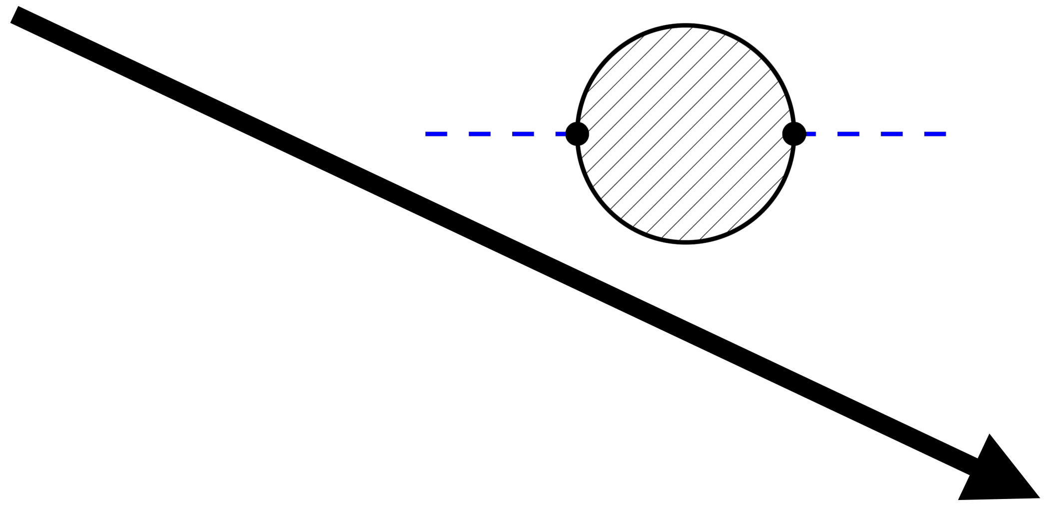
NATURALNESS, CHIRAL SYMMETRY, AND SPONTANEOUS

CHIRAL SYMMETRY BREAKING

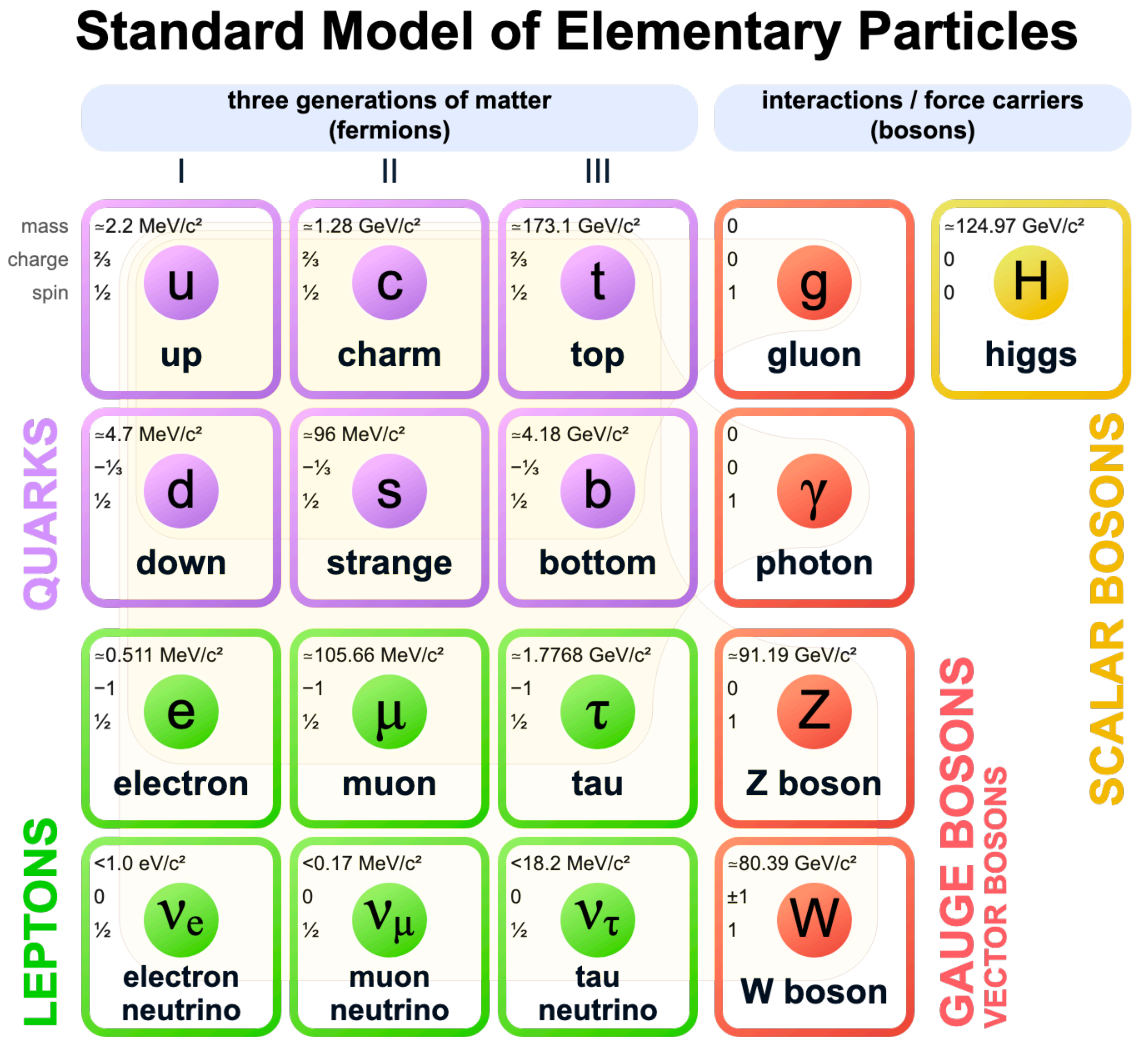
G. 't Hooft 1980

magnitude smaller than another then the smallest must satisfy our "dogma" separately. As we will see, naturalness will put the severest restriction on the occurrence of scalar particles in renormalizable theories. In fact we conjecture that this is the reason why light, weakly interacting scalar particles are not seen.

RGE



10^{-18}m



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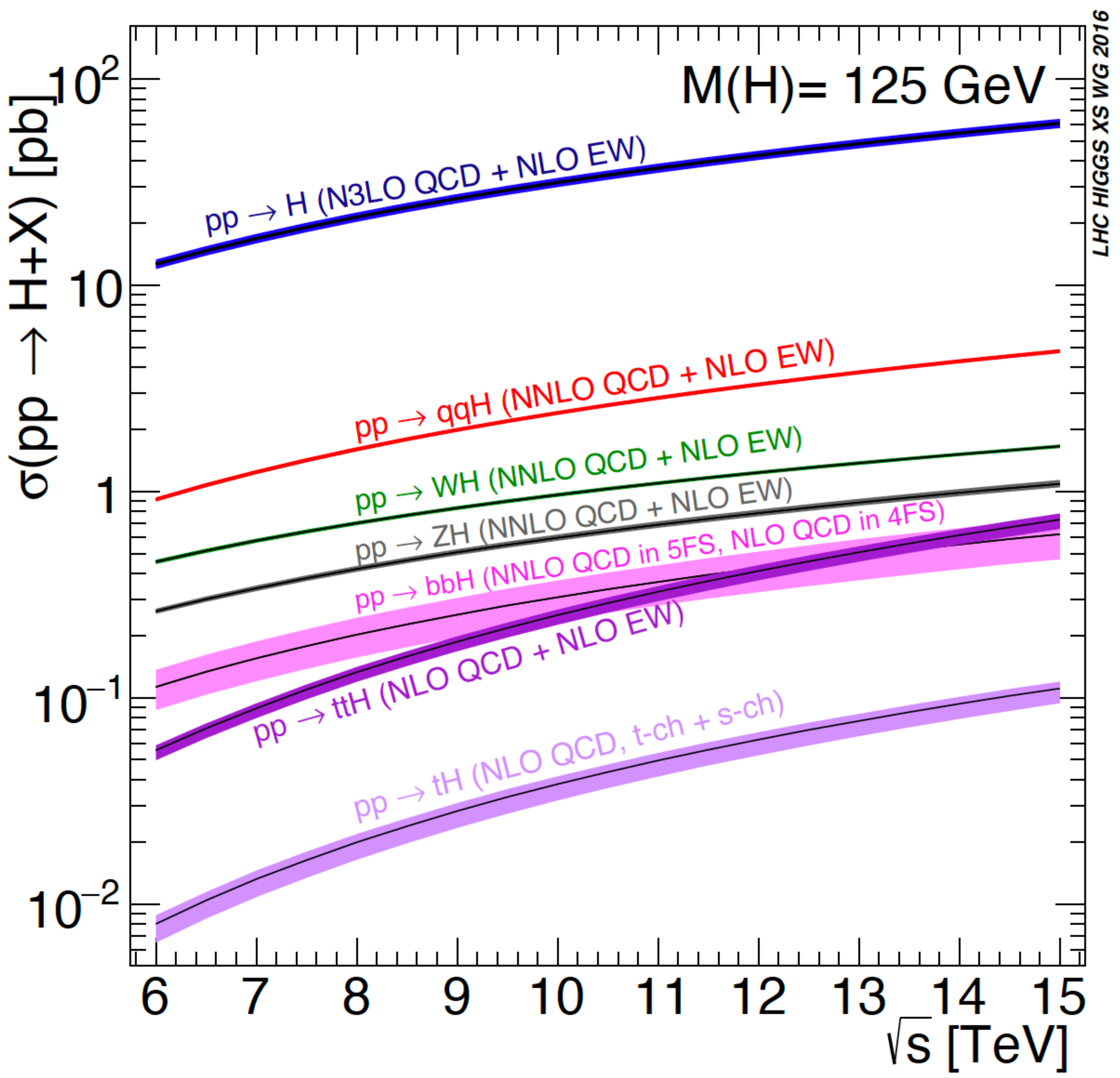
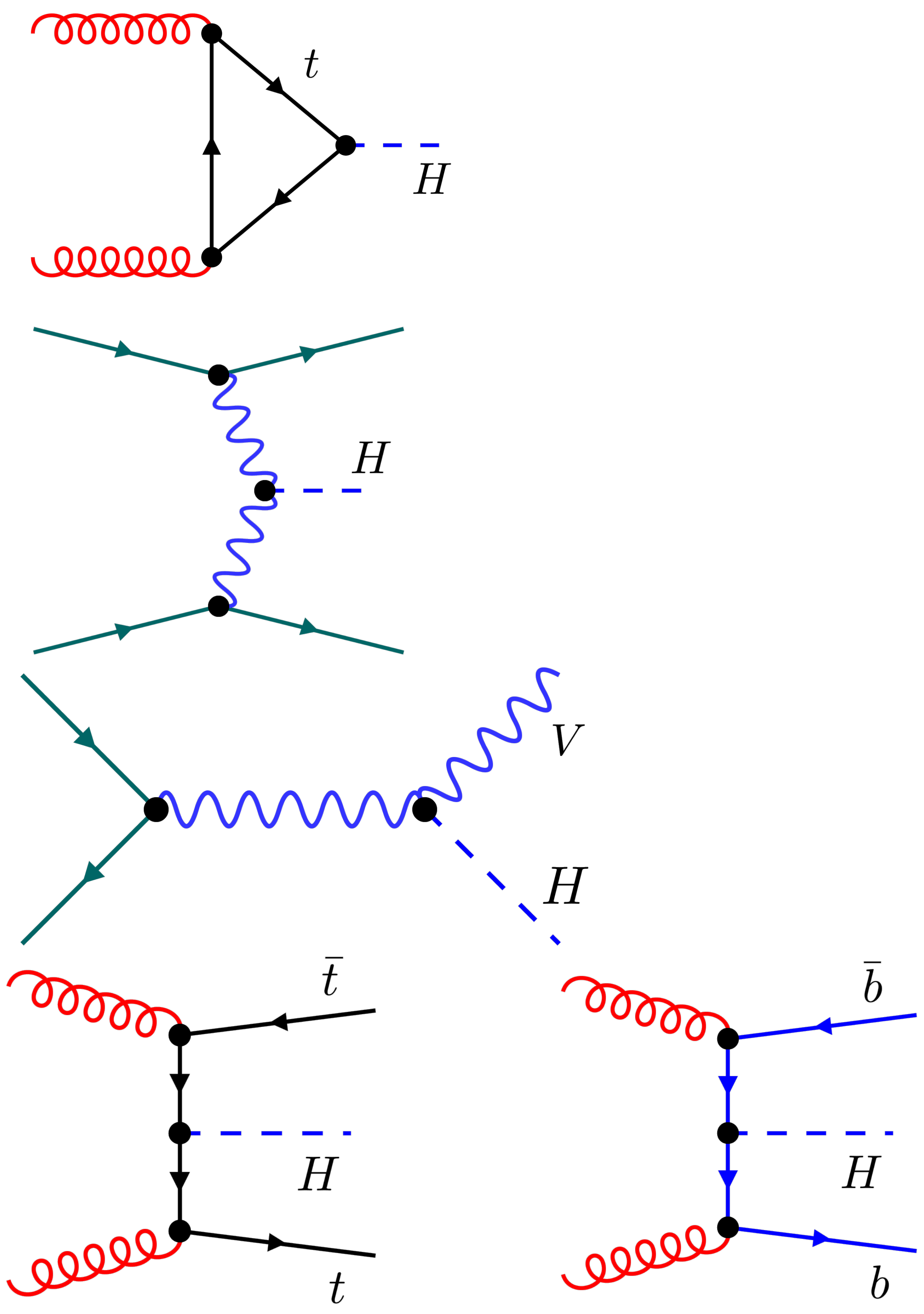
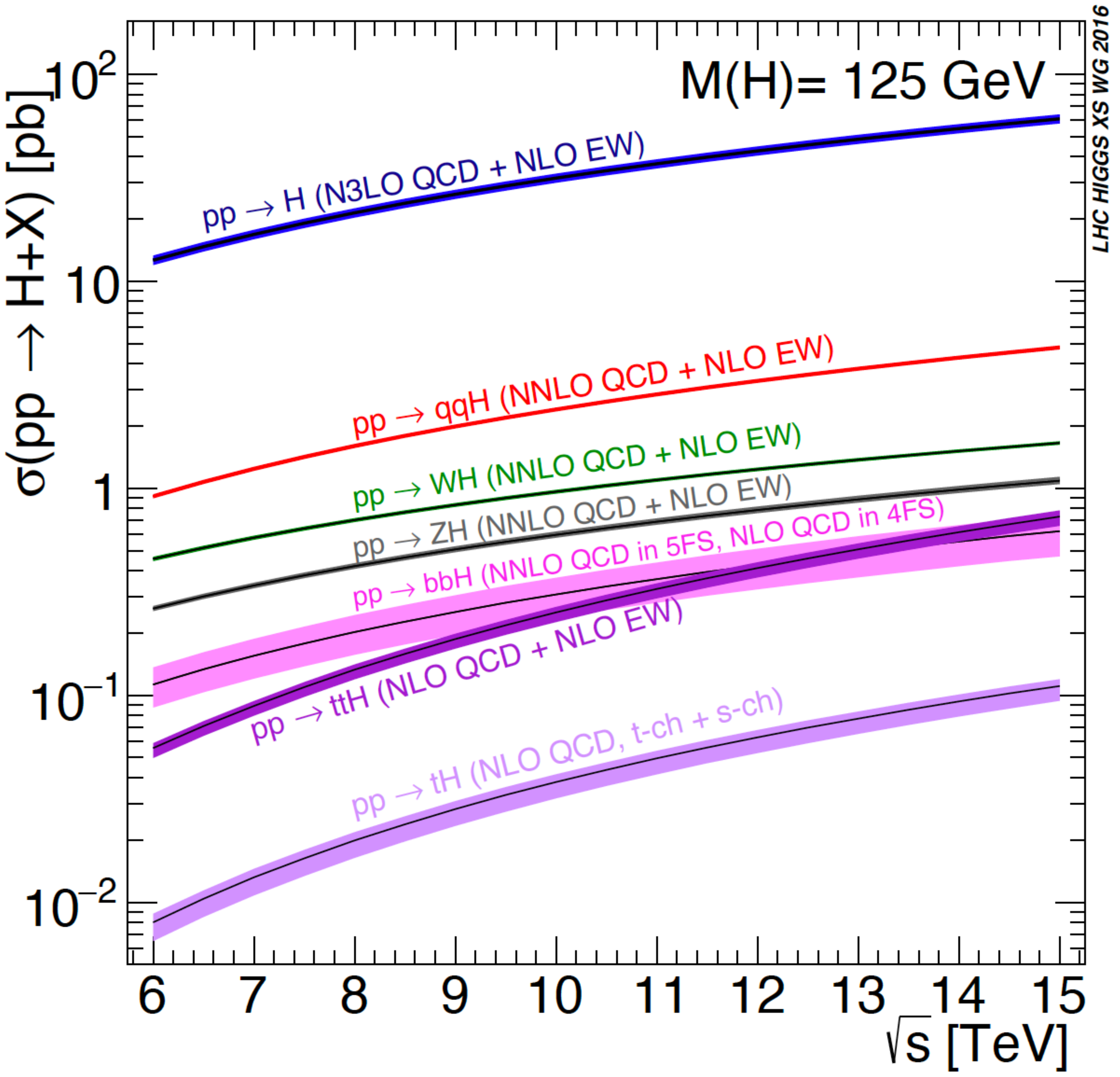

M(H)= 125 GeV
LHC HIGGS XS WG 2016
pp → H (N3LO QCD + NLO EW)
pp → qqH (NNLO QCD + NLO EW)
pp → WH (NNLO QCD + NLO EW)
pp → ZH (NNLO QCD + NLO EW)
pp → bbH (NNLO QCD in 5FS, NLO QCD in 4FS)
pp → ttH (NLO QCD + NLO EW)
pp → tH (NLO QCD, t-ch + s-ch)
σ(pp → H+X) [pb]
√s [TeV]


t
H
H
V
H
$\bar{t}$
H
t
$\bar{b}$
H
b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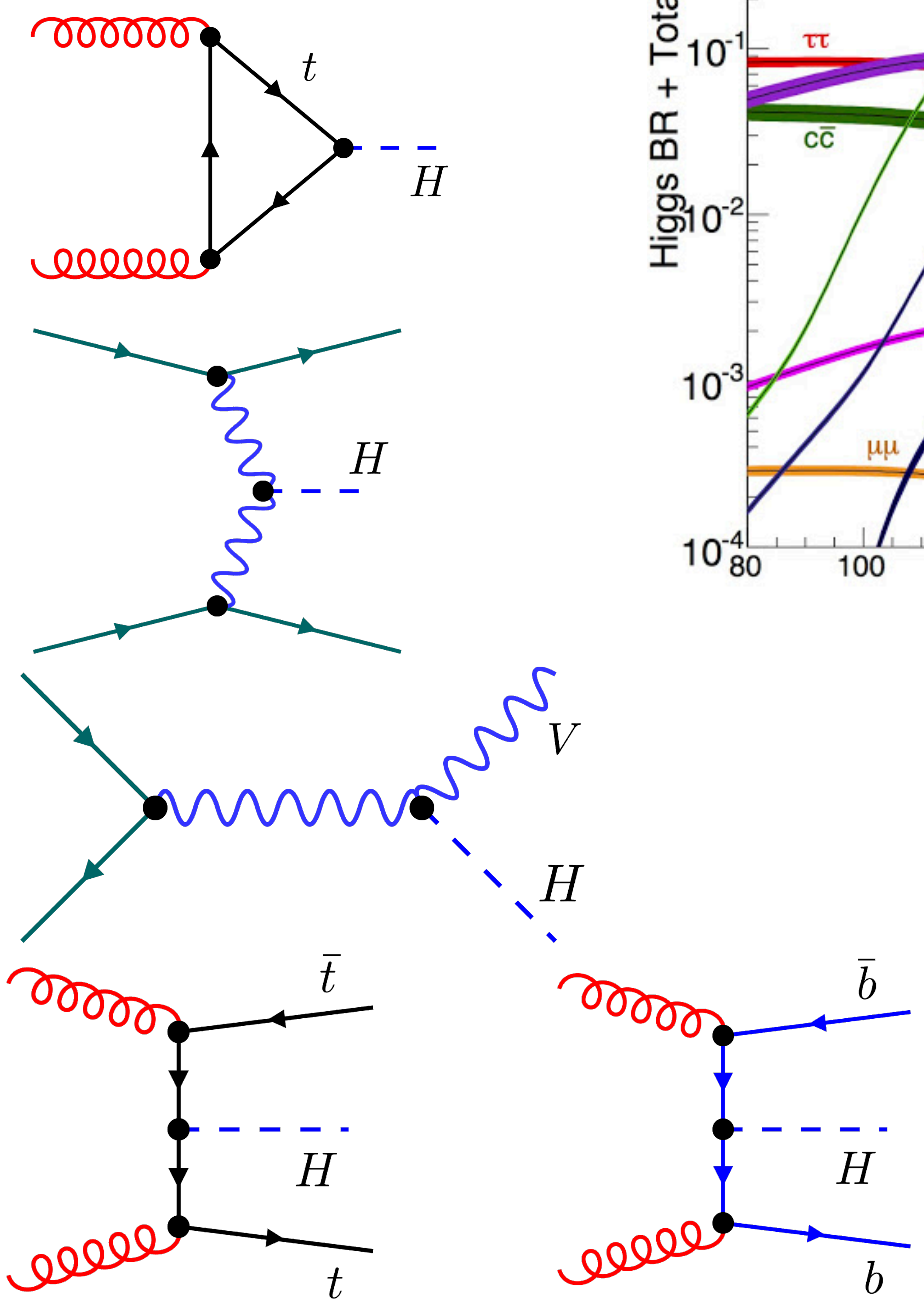
√s [TeV]


t
H
H
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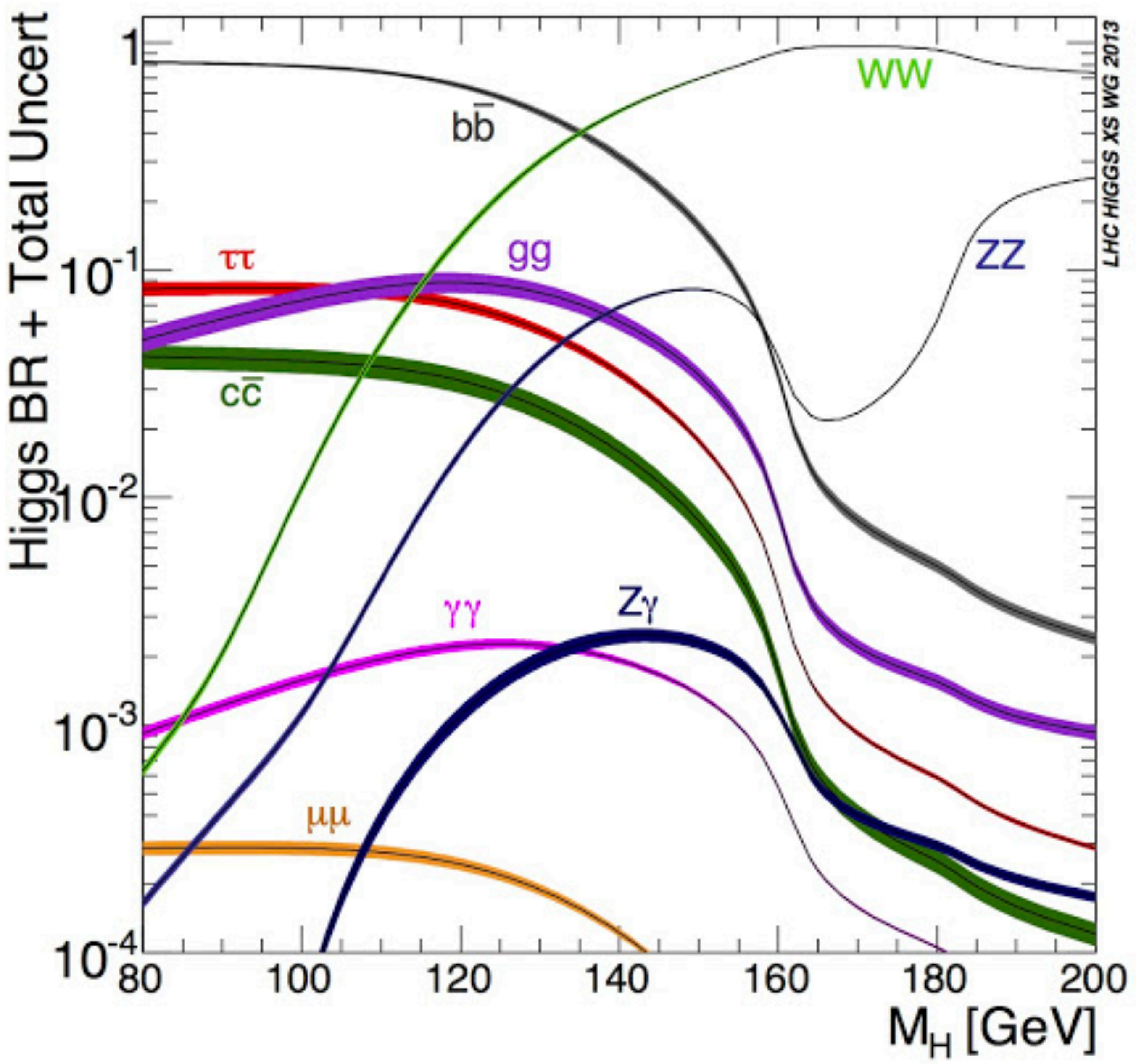
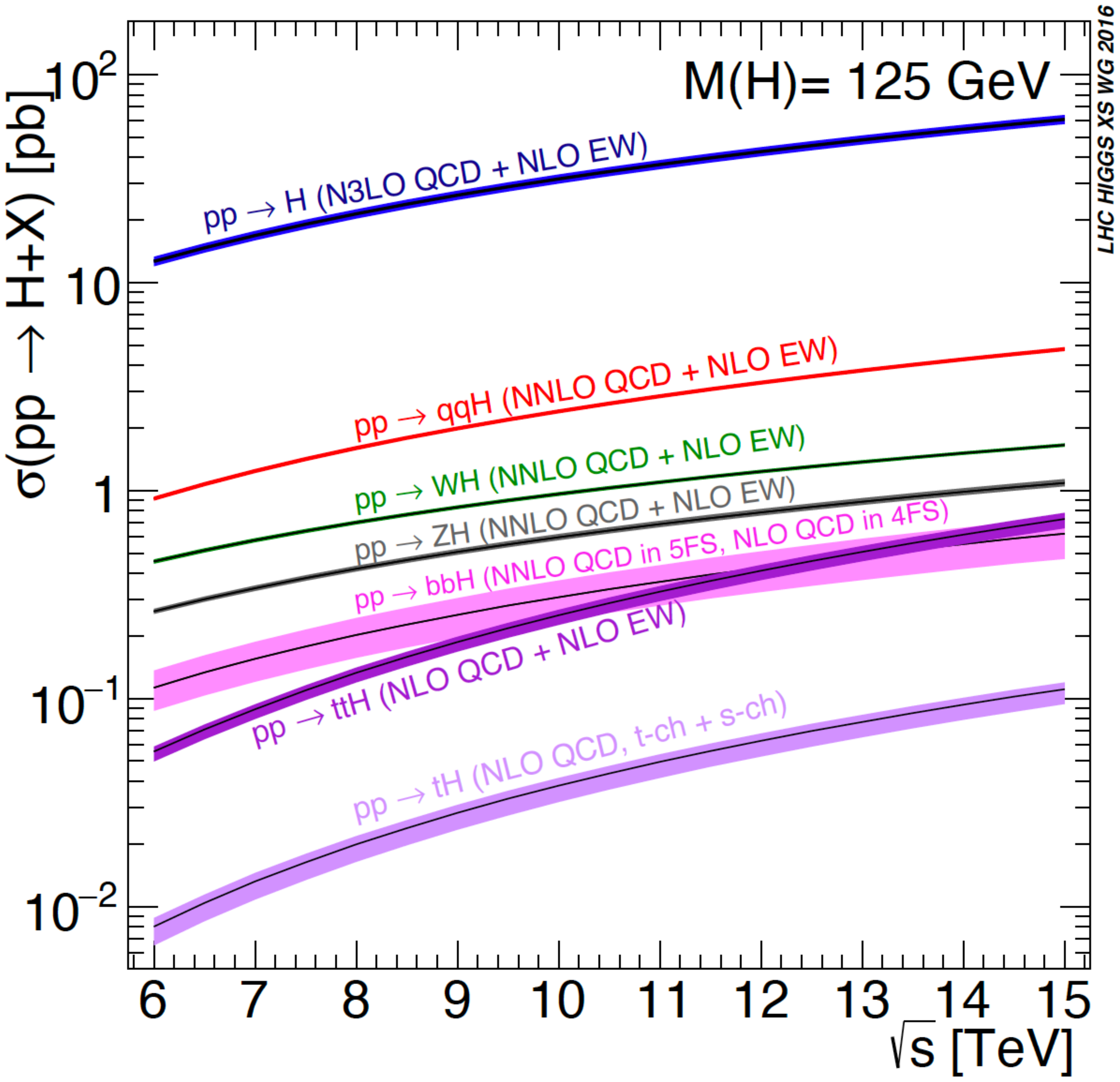
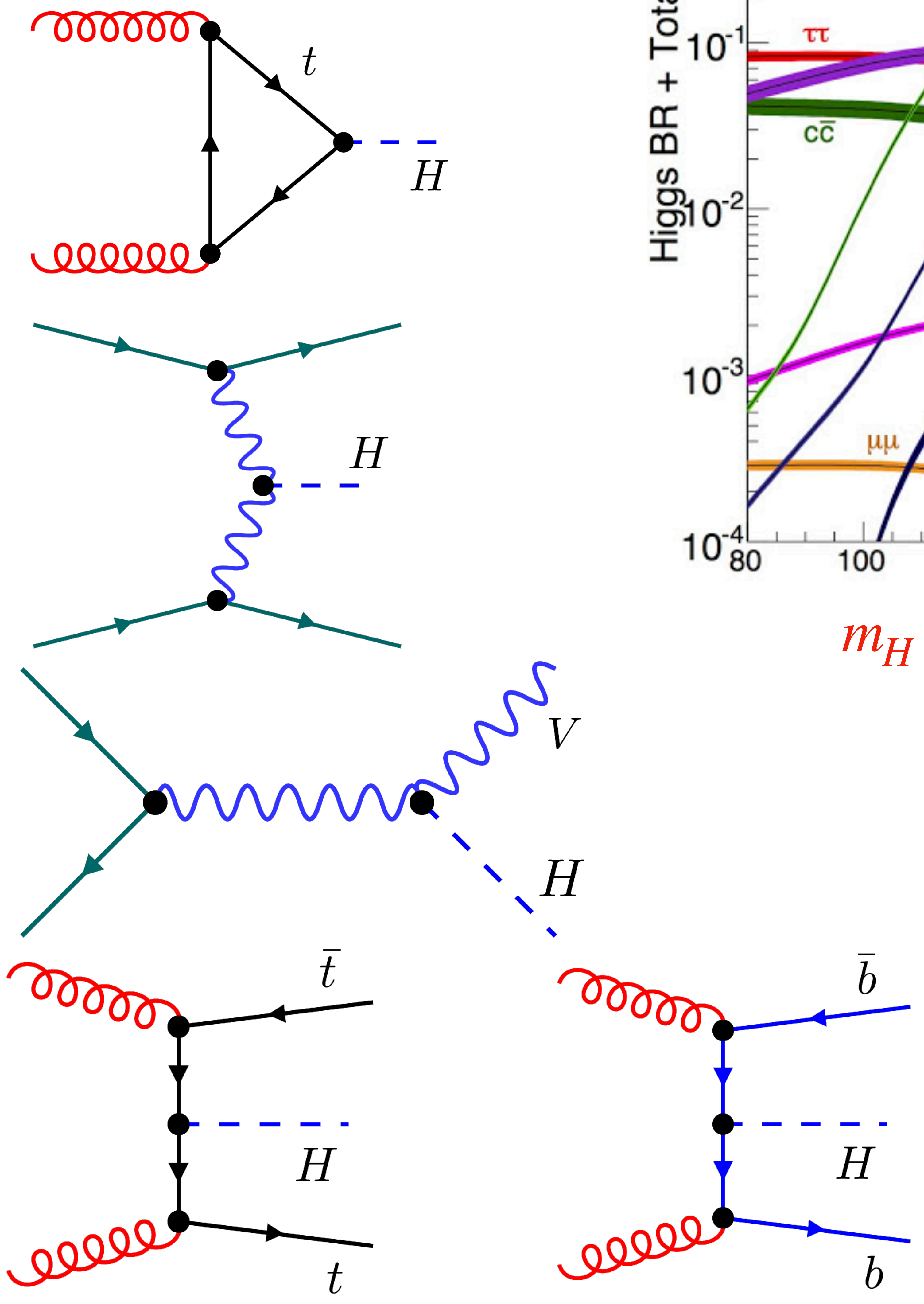
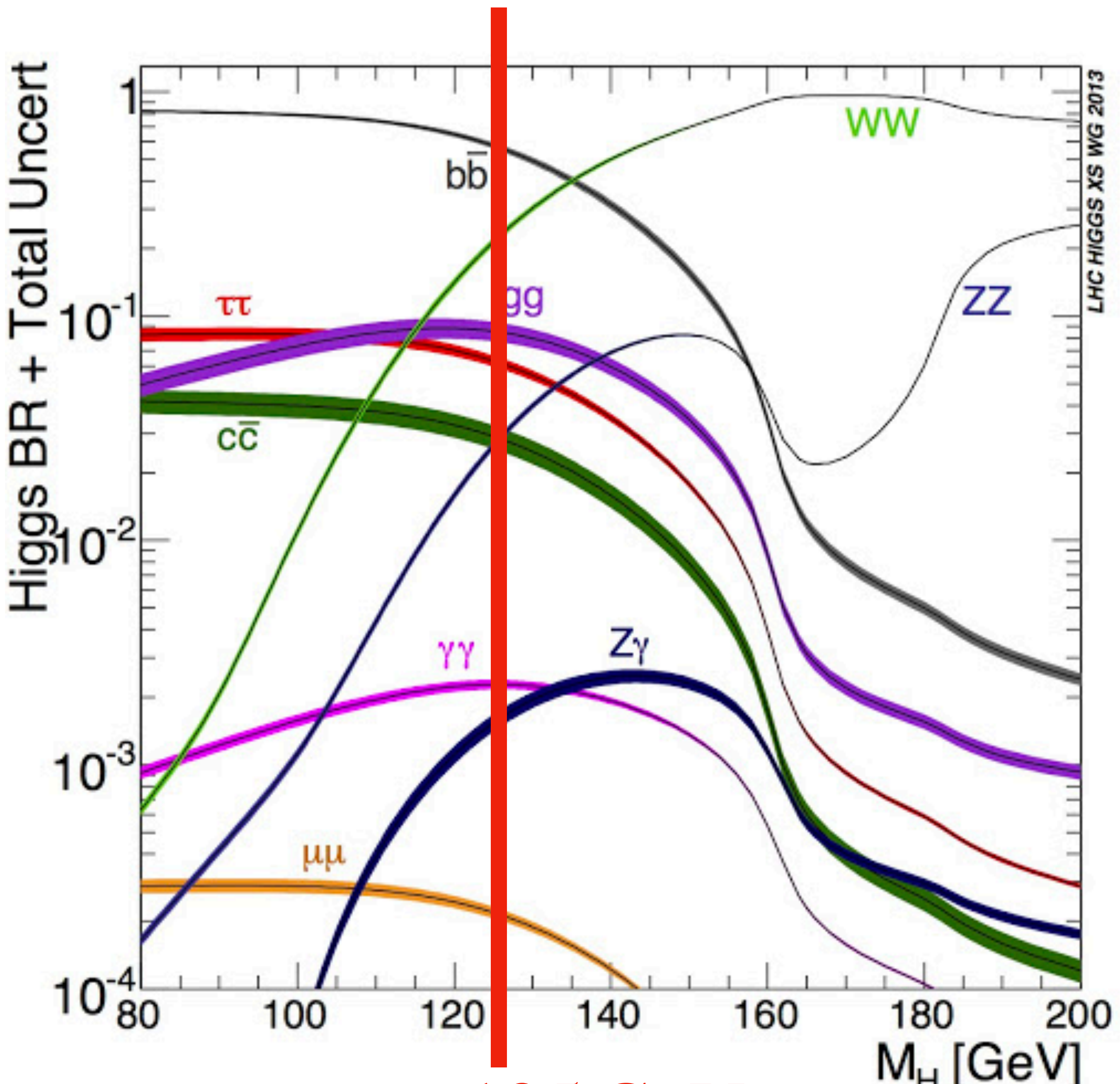
H
t̄
H
t
b̄
H
b


Higgs BR + Total Uncert
LHC HIGGS XS WG 2013
bb̄
WW
ττ
gg
ZZ
cc̄
γγ
Zγ
μμ
M_H [GeV]







$m_H = 125\,\mathrm{GeV}$

Collider Physics at the Precision Frontier

P3H-20-044

Gudrun Heinrich

Karlsruhe Institute of Technology, Institute for Theoretical Physics, Wolfgang-Gaede-Str. 1, 76131 Karlsruhe, Germany

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
$^{+0.21\%}_{-2.37\%}$	$\pm0.37\%$	$\pm1.16\%$	$\pm1\%$	$\pm0.83\%$	$\pm1\%$

LHCH(XS)WG YR4 ’16

Inclusive gluon fusion cross section:

$$
\begin{aligned}
48.58\,\text{pb} = \quad & 16.00\,\text{pb} & (+32.9\%) & \quad (\text{LO, rEFT}) \\
& +20.84\,\text{pb} & (+42.9\%) & \quad (\text{NLO, rEFT}) \\
& -\;\;2.05\,\text{pb} & (-4.2\%) & \quad ((t,b,c),\text{ exact NLO}) \\
& +\;\;9.56\,\text{pb} & (+19.7\%) & \quad (\text{NNLO, rEFT}) \\
& +\;\;0.34\,\text{pb} & (+0.7\%) & \quad (\text{NNLO}, 1/m_t) \\
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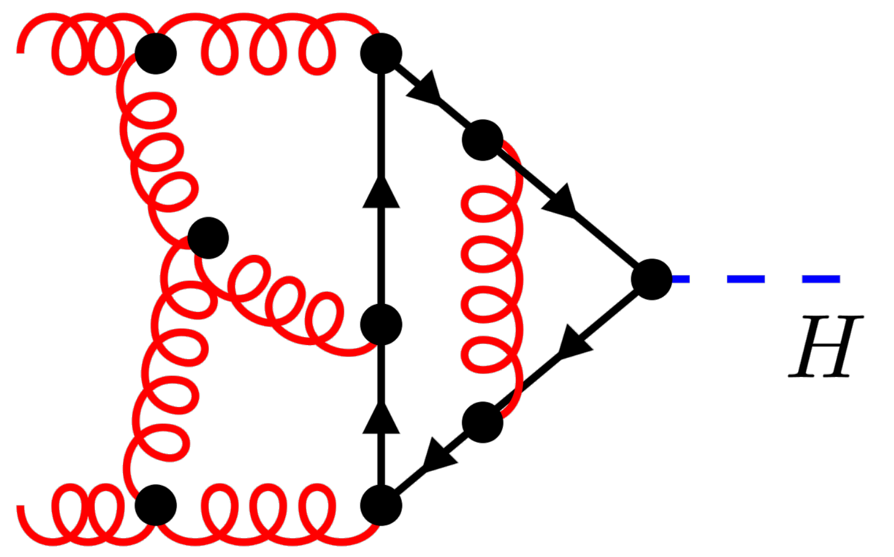
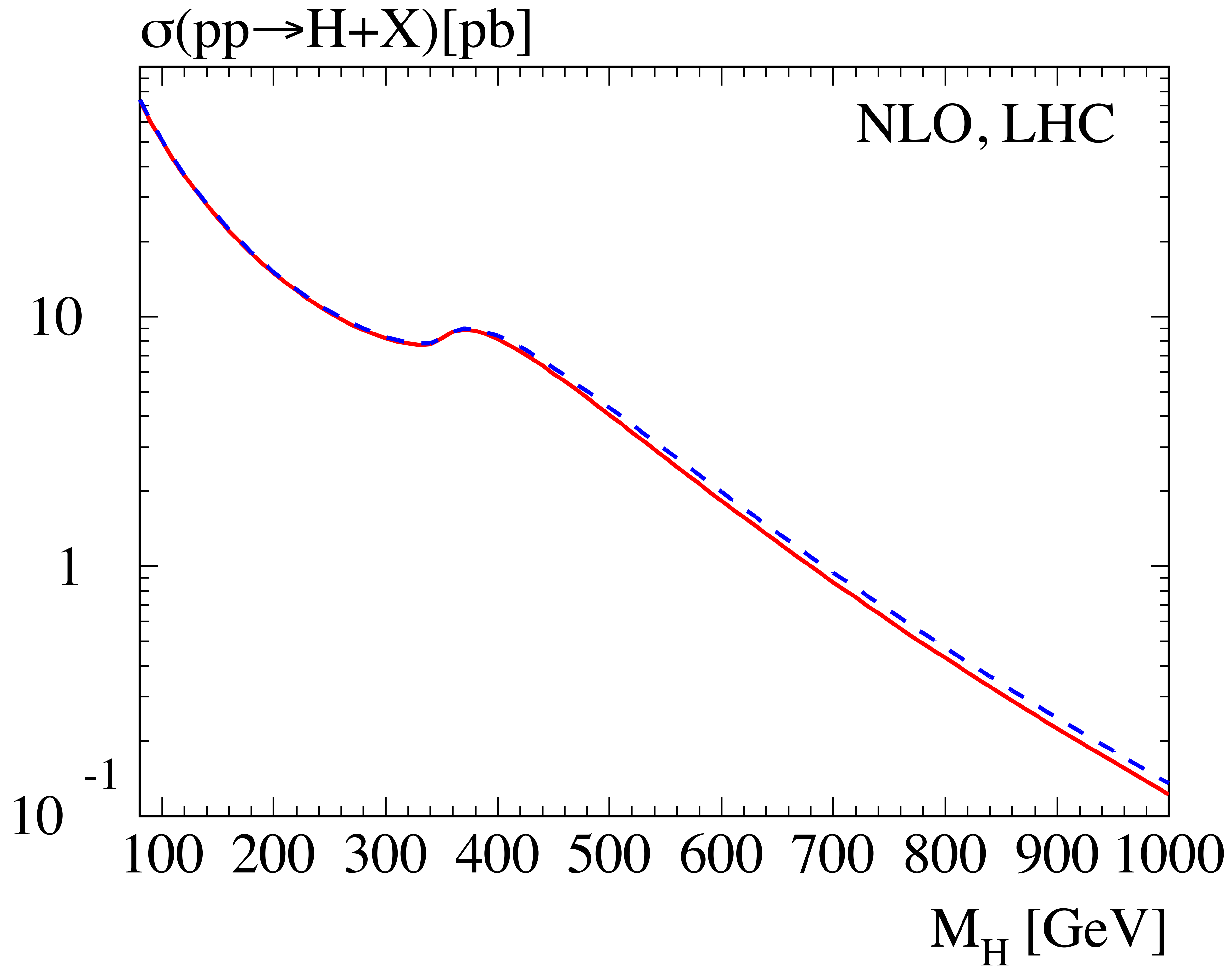
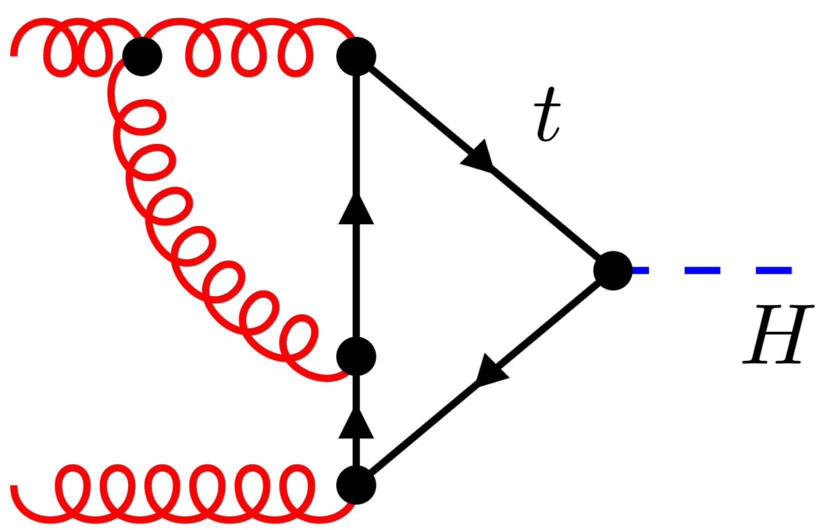
& +\;\;1.49\,\text{pb} & (+3.1\%) & \quad (\text{N}^3\text{LO, rEFT})
\end{aligned}
$$





Graudenz, Djouadi, Spira, Zerwas ‘93



$$\sigma^{\rm HO}_{\rm HEFT} = \sigma^{\rm LO}\left(\frac{\sigma^{\rm HO}}{\sigma^{\rm LO}}\right)_{m_t\to\infty}$$

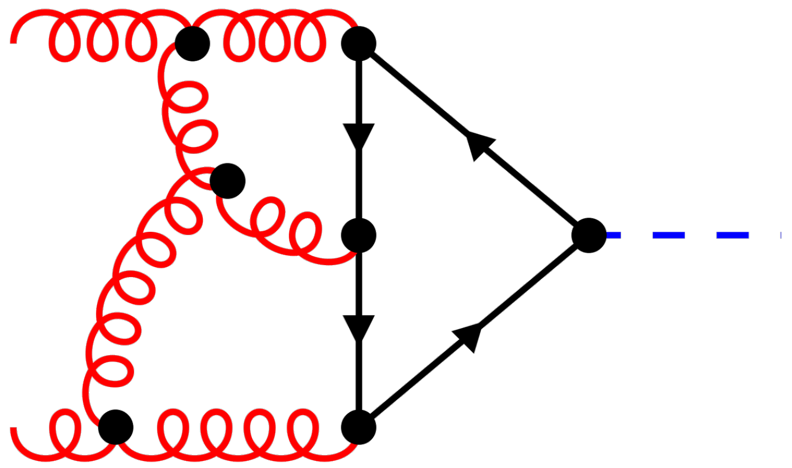
$$\sigma^{\rm NLO}_{\rm exact} = (1-0.008)\cdot\sigma^{\rm NLO}_{\rm HEFT}$$

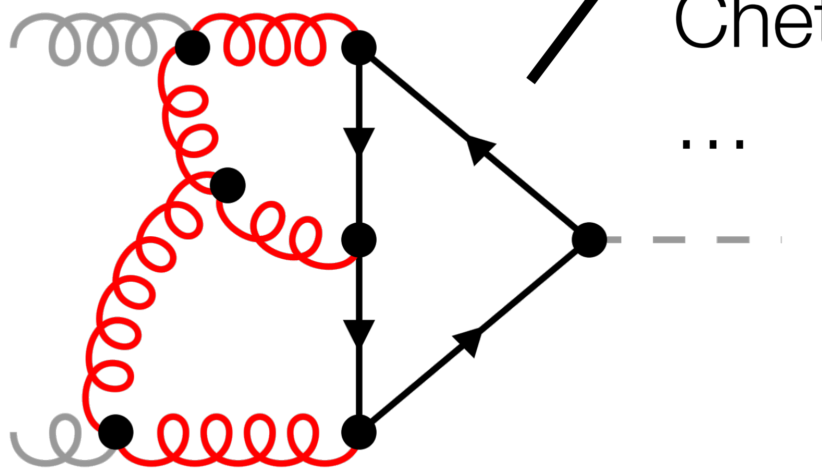
for $m_H = 125\,\text{GeV}$

$$\mathscr{L}_{\rm SM}$$

$$\Big\downarrow\; m_t \to \infty$$

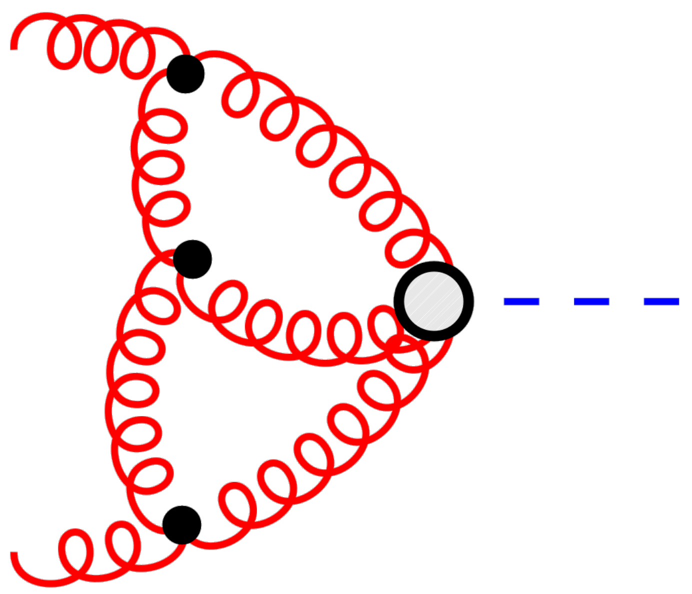
$$\mathscr{L}_{\rm eff} = C_1(\alpha_s)\,\frac{H}{v}\,{\rm Tr}\,G_{\mu\nu}G^{\mu\nu} + \mathscr{L}^{n_f=5}_{\rm QCD}$$

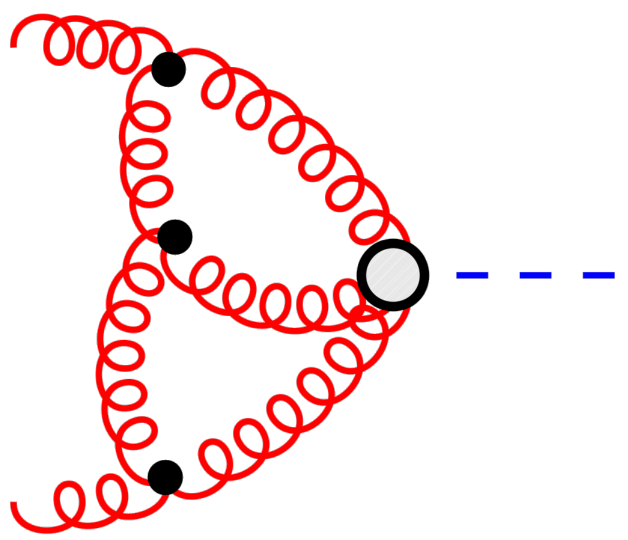




Chetyrkin, Kniehl, Steinhauser '98

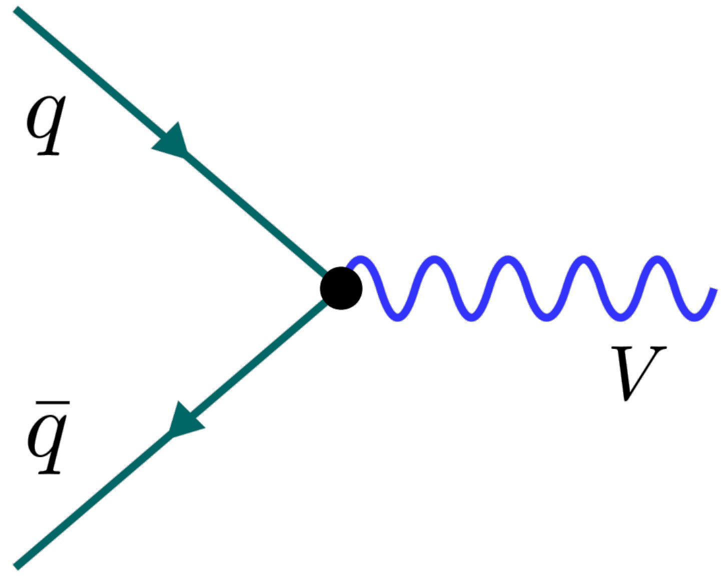
…

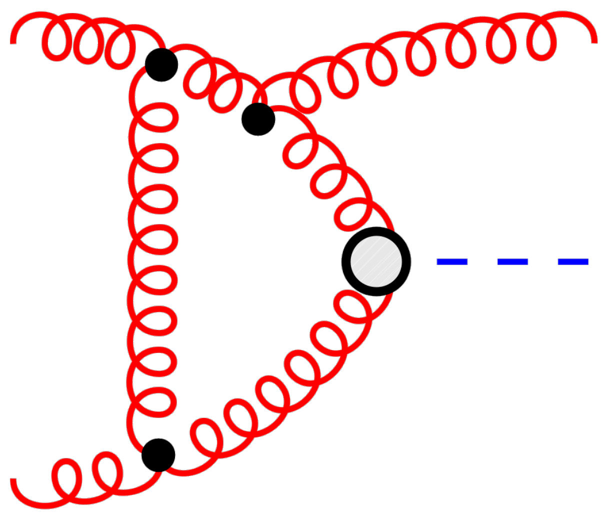




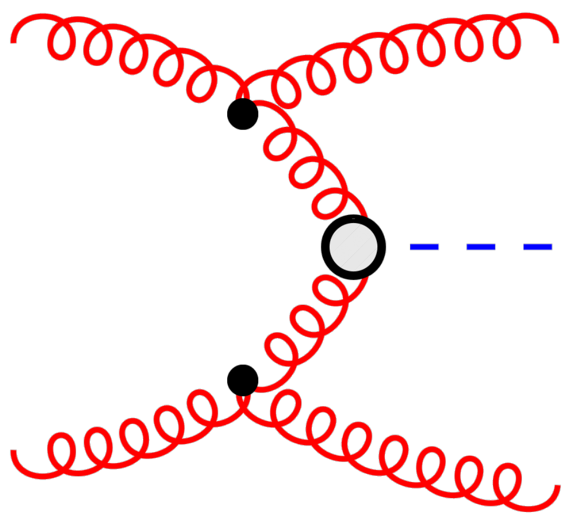
- need to cancel IR divergences
- around ’01: only NLO methods
- but: NNLO Drell-Yan 1990

v. Neerven et al.





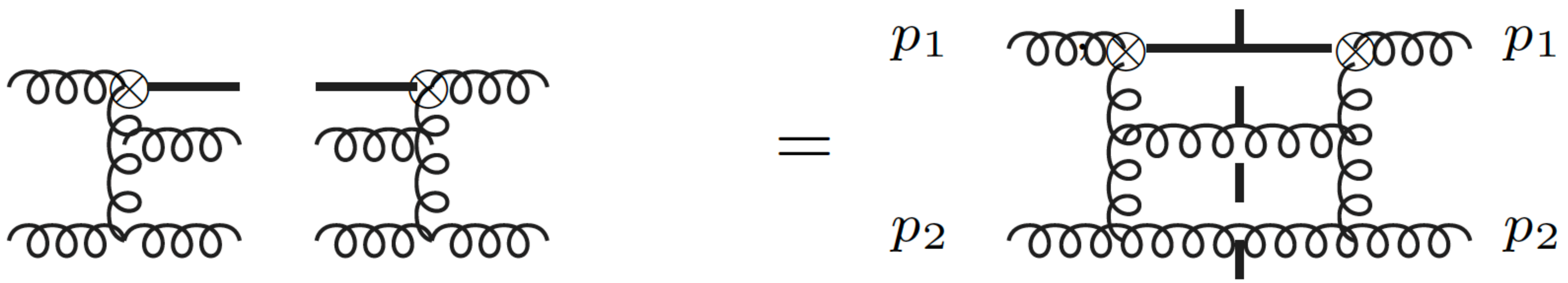
perform phase space integrals analytically
in D dimensions



IR poles cancel analytically (no “subtraction scheme”)

still: phase space integration complicated (back then…)

Reverse unitarity:



$$2i\pi\delta\left(p^2 - m^2\right) \to \frac{1}{p^2 - m^2 + i0} - \frac{1}{p^2 - m^2 - i0}$$

Anastasiou, Melnikov ‘02
Anastasiou, Dixon, Melnikov ‘03

Treat phase space integrals like loop integrals:

integration-by-parts → master integrals → differential equations

soft expansion: $z = \hat{s}/M_H^2 \to 1$

$$\hat{\sigma}_{ij} = \sum_{n\geq 0} \left(\frac{\alpha_s}{\pi}\right)^n \hat{\sigma}_{ij}^{(n)} \,,$$

$$\hat{\sigma}_{ij}^{(n)} = a^{(n)}\,\delta(1-x) + \sum_{k=0}^{2n-1} b_k^{(n)} \left[\frac{\ln^k(1-x)}{1-x}\right]_+$$

$$+ \sum_{l=0}^{\infty} \sum_{k=0}^{2n-1} c_{lk}^{(n)} (1-x)^l \ln^k(1-x) \,,$$

soft expansion: $z = \hat{s}/M_H^2 \to 1$

soft-virtual approximation

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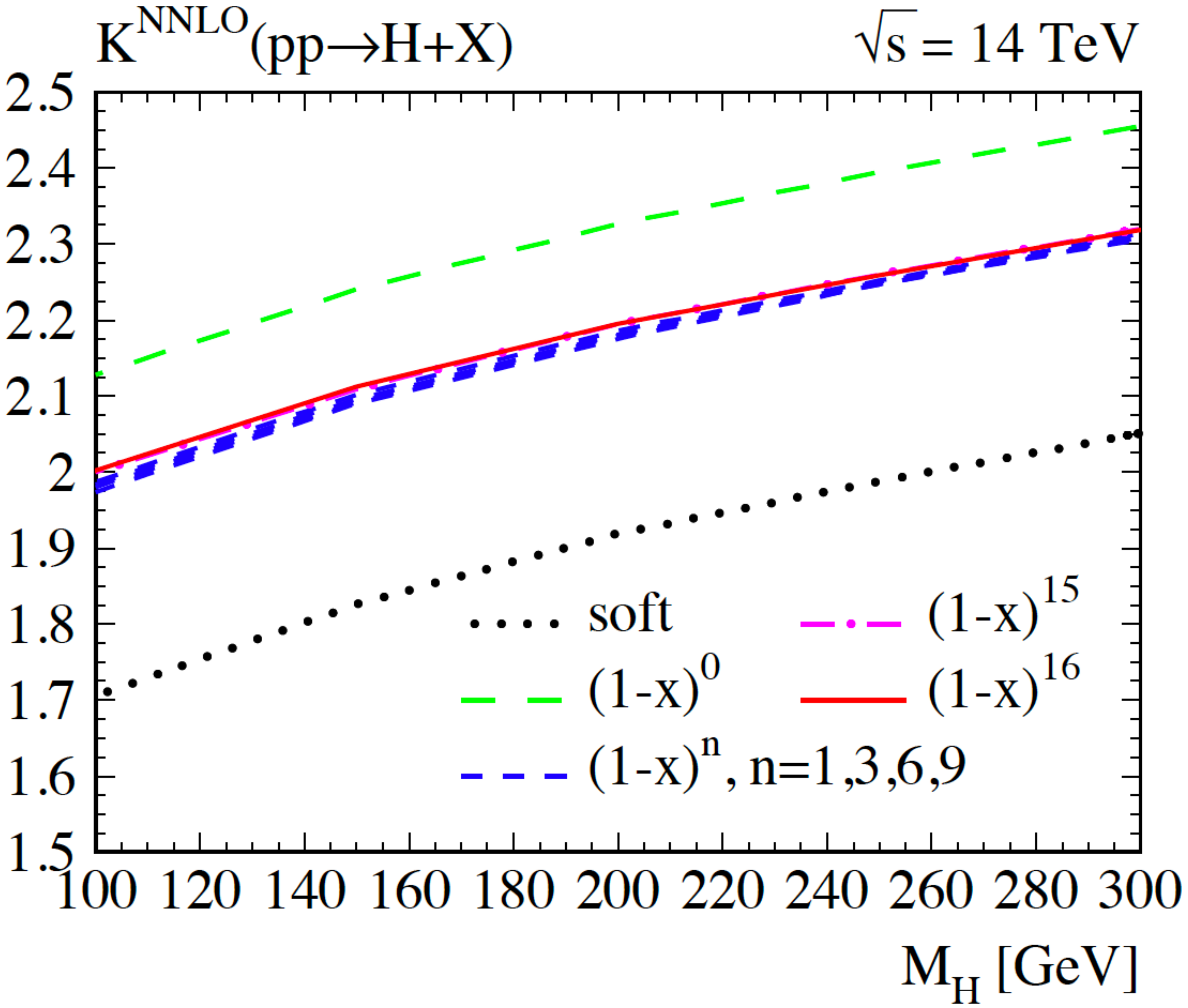
soft-virtual approximation

$l = 0,\ k > 0$: next-to-soft approximation

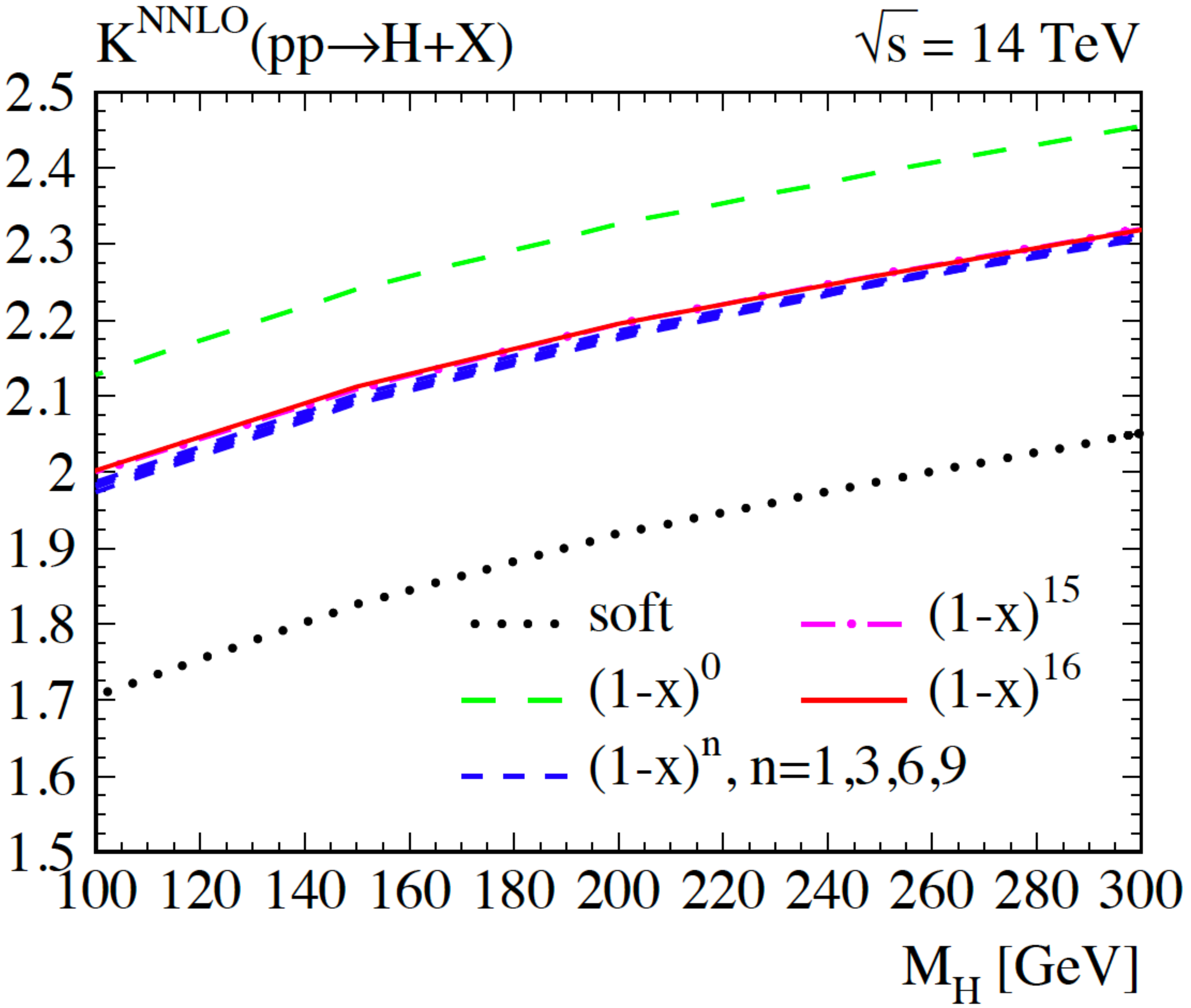
Krämer, Laenen, Spira '96

NNLO



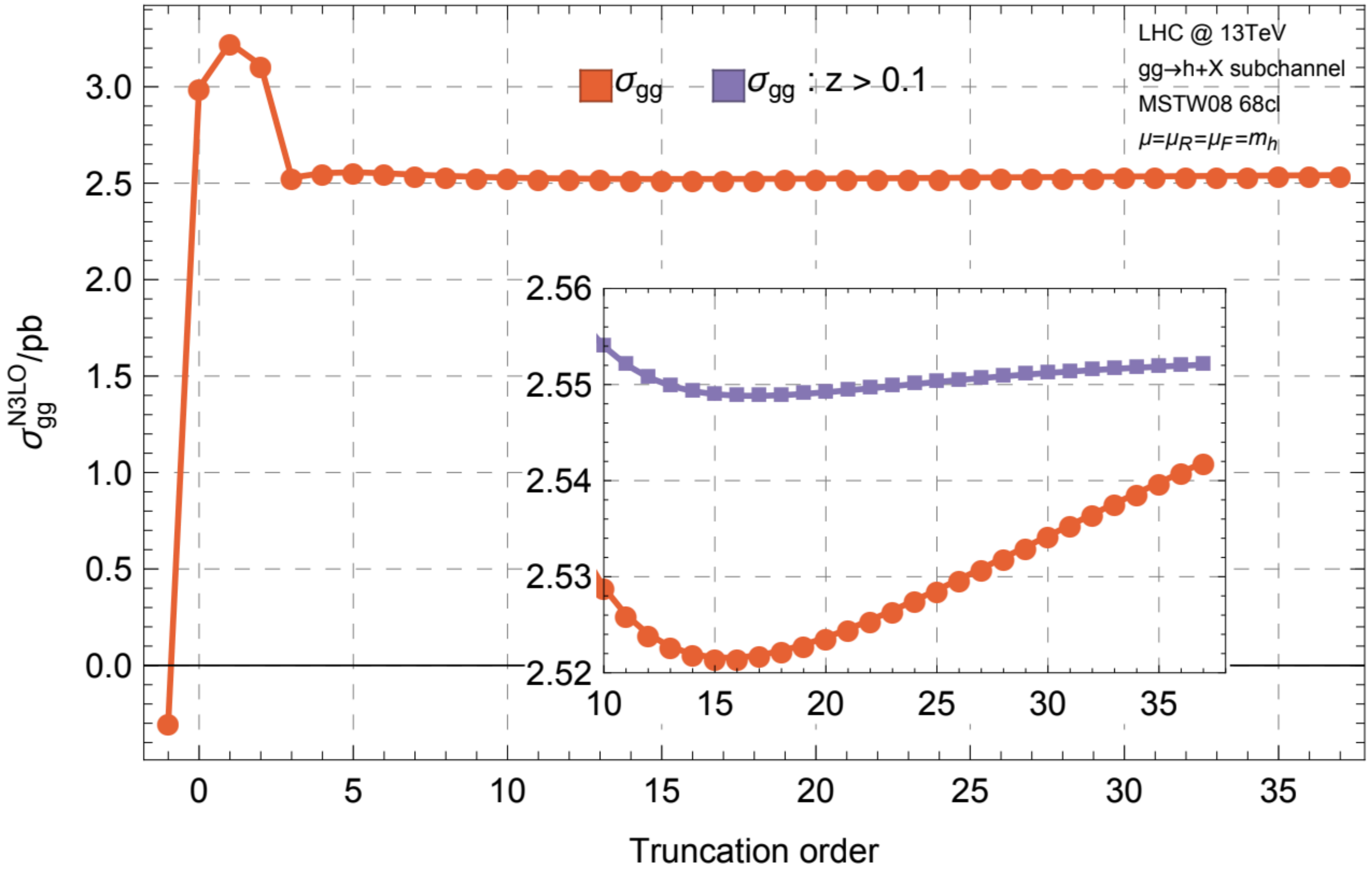
RH, Kilgore '02

NNLO



RH, Kilgore '02

N³LO



Anastasiou, Duhr, Dulat, Herzog, Mistlberger '15

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LHCHWG YR4 '16

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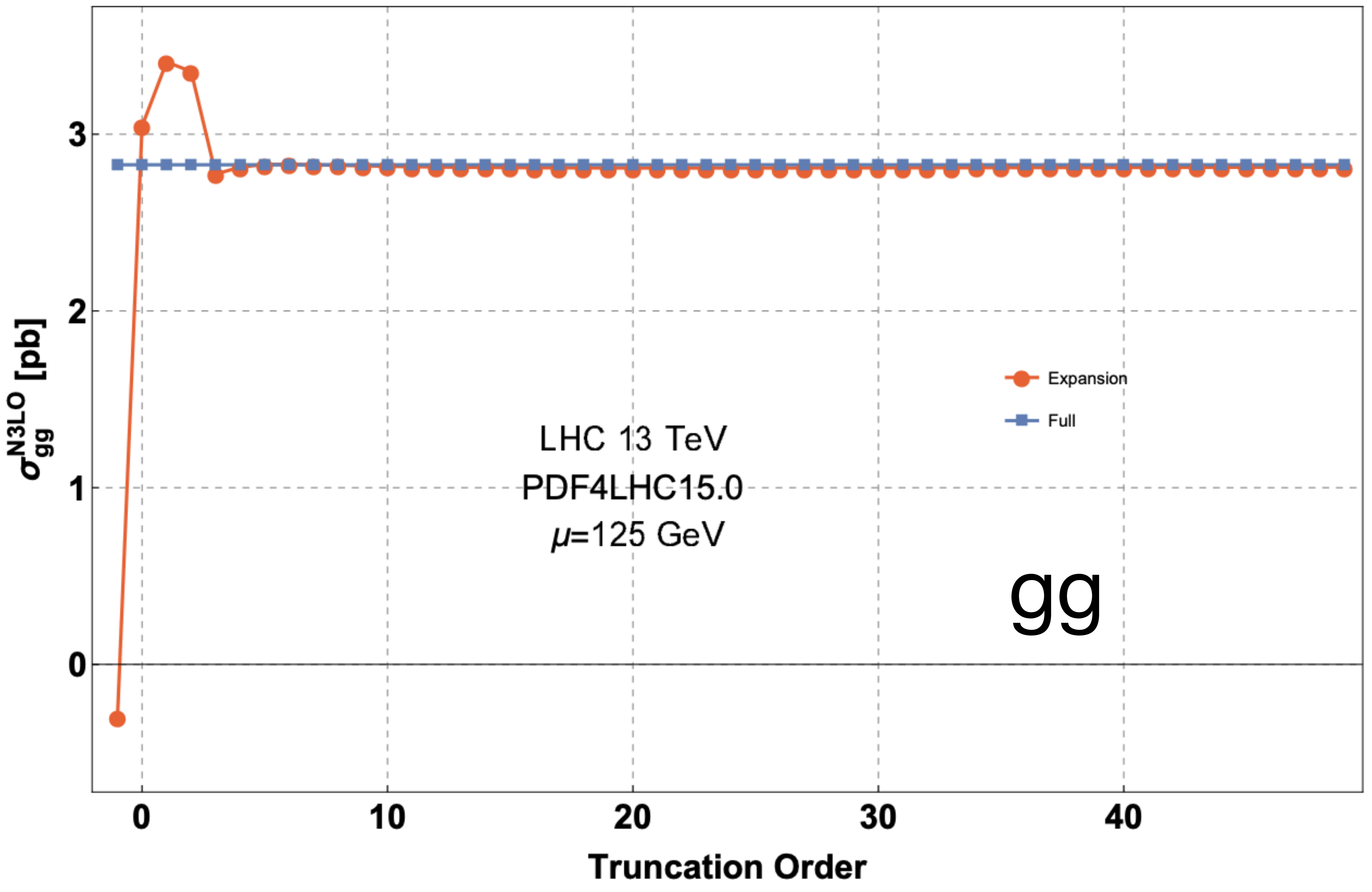
LHCHWG YR4 ‘16



Mistlberger ‘18

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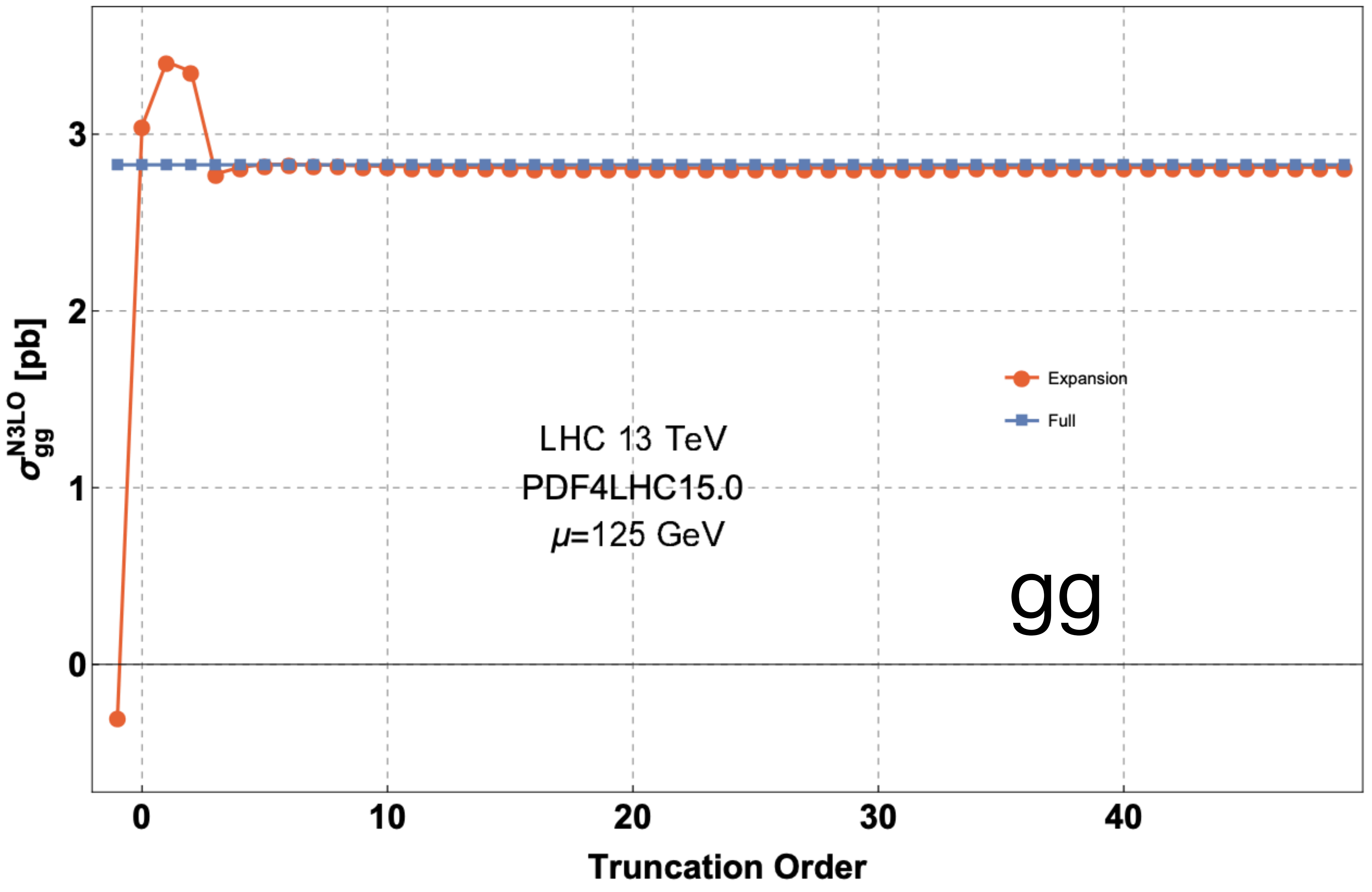
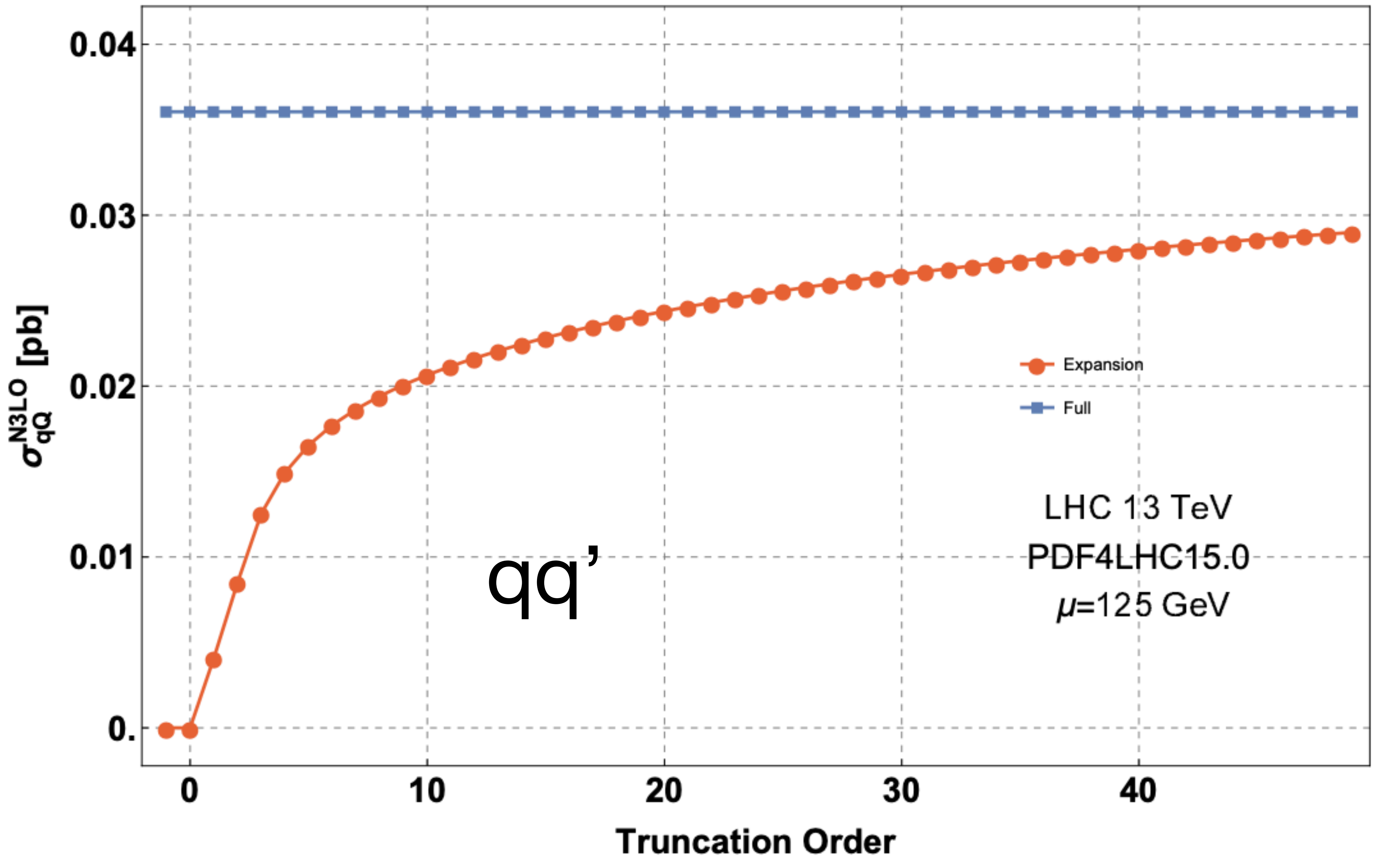
LHCHWG YR4 ‘16





Mistlberger ‘18

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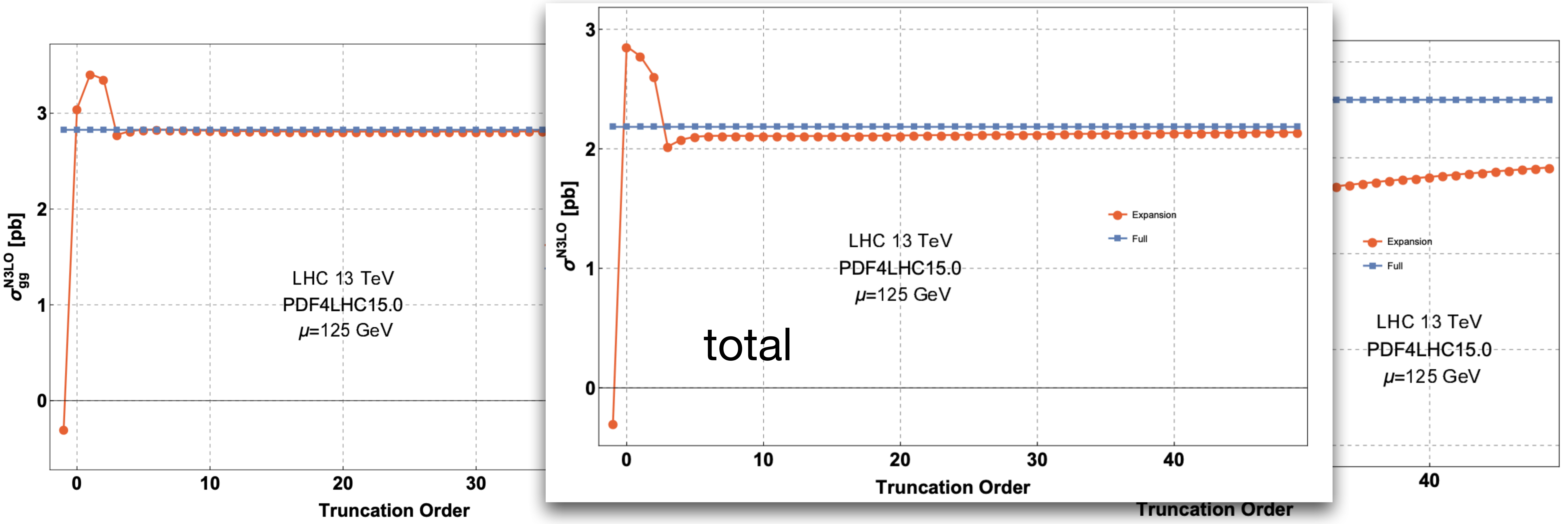
LHCHWG YR4 ‘16



Mistlberger ‘18

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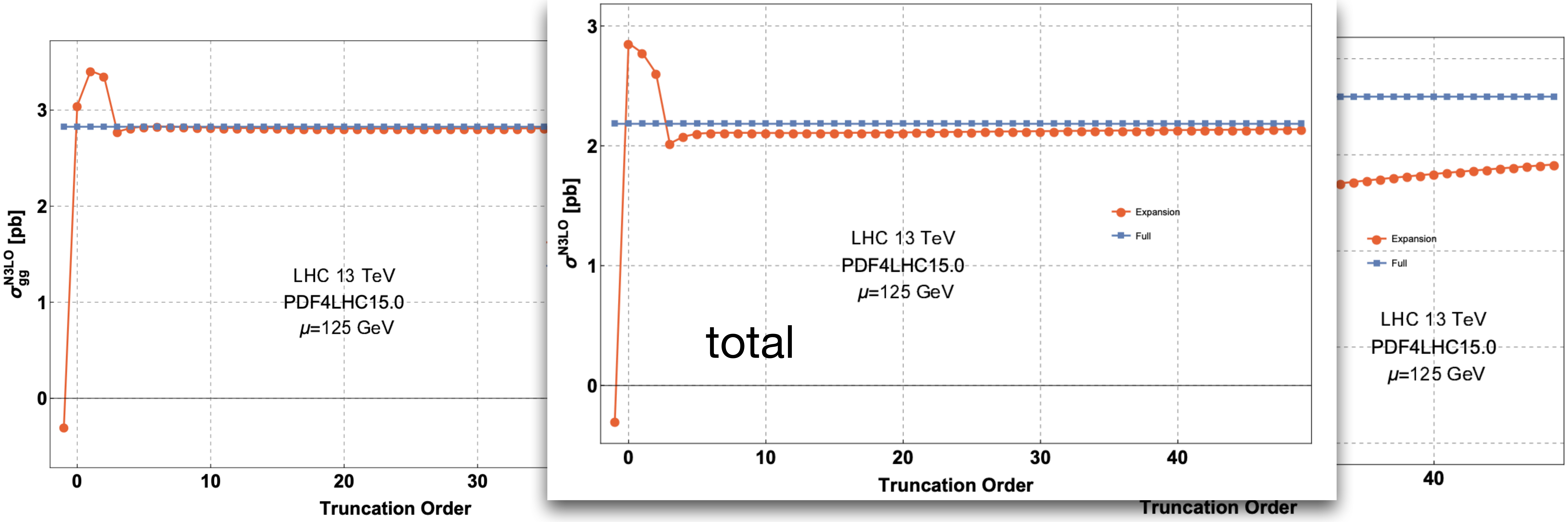
$+0.21\%$ -2.37%	$\pm 0.37\%$	$\pm 1.16\%$	$\pm 1\%$	$\pm 0.83\%$	$\pm 1\%$

LHCHWG YR4 ‘16



Mistlberger ‘18

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

LHCHWG YR4 '16

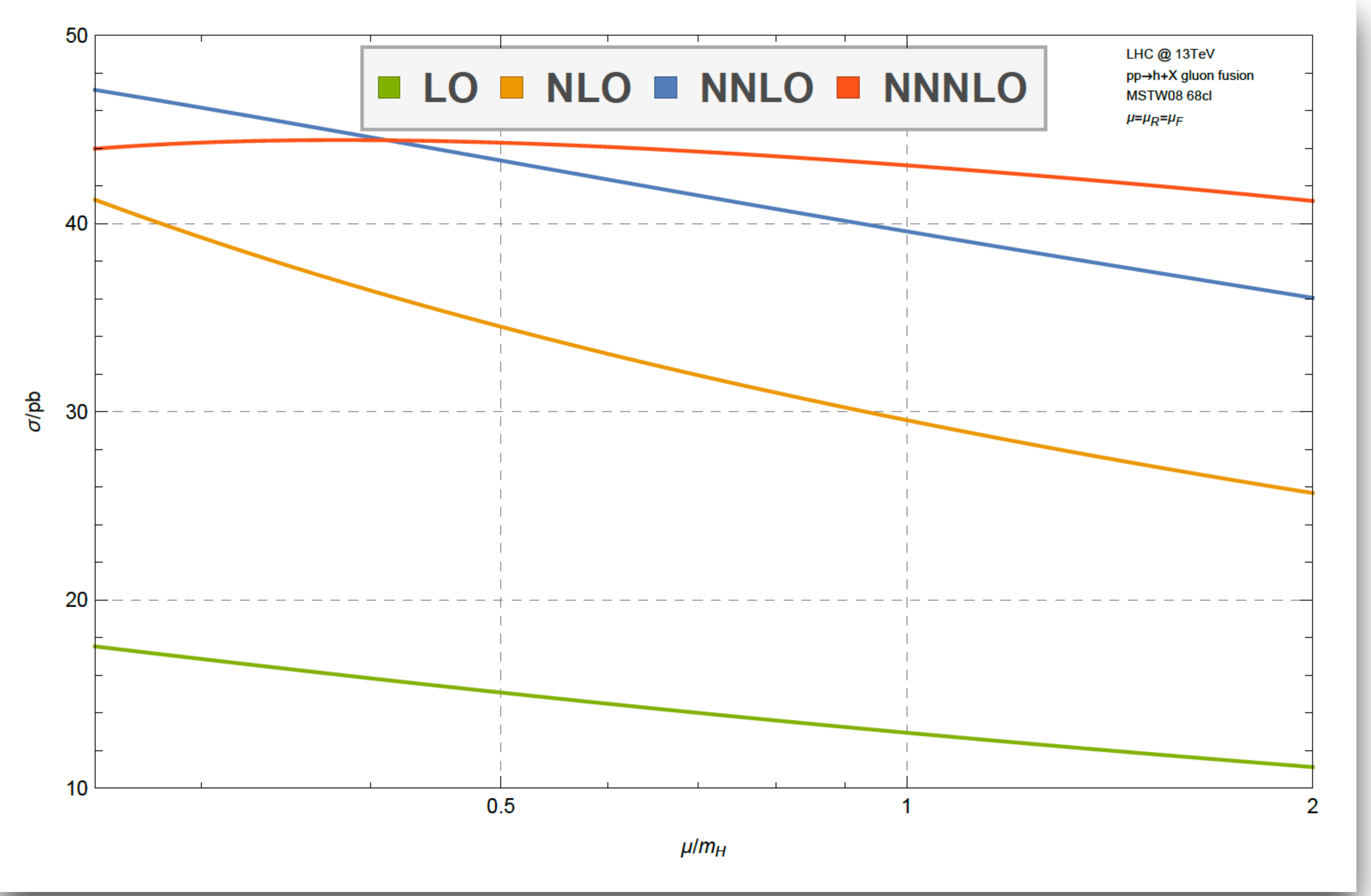
$48.58\,\text{pb} =$	$16.00\,\text{pb}$	$(+32.9\%)$	(LO, rEFT)
	$+\,20.84\,\text{pb}$	$(+42.9\%)$	(NLO, rEFT)
	$-\,2.05\,\text{pb}$	(-4.2%)	$((t,b,c)$, exact NLO)
	$+\,9.56\,\text{pb}$	$(+19.7\%)$	(NNLO, rEFT)
	$+\,0.34\,\text{pb}$	$(+0.7\%)$	(NNLO, $1/m_t$)
	$+\,2.40\,\text{pb}$	$(+4.9\%)$	(EW, QCD-EW)
	$+\,1.49\,\text{pb}$	$(+3.1\%)$	(N^3LO, rEFT)

$K \approx 3$

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

LHCHWG YR4 '16

$$48.58\,\text{pb} = 16.00\,\text{pb} + 20.84\,\text{pb} - 2.05\,\text{pb} + 9.56\,\text{pb} + 0.34\,\text{pb} + 2.40\,\text{pb} + 1.49\,\text{pb}$$



$K \approx 3$

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

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

P3H-20-054

G. Das [*a], S. Moch [†b] and A. Vogt [‡c]

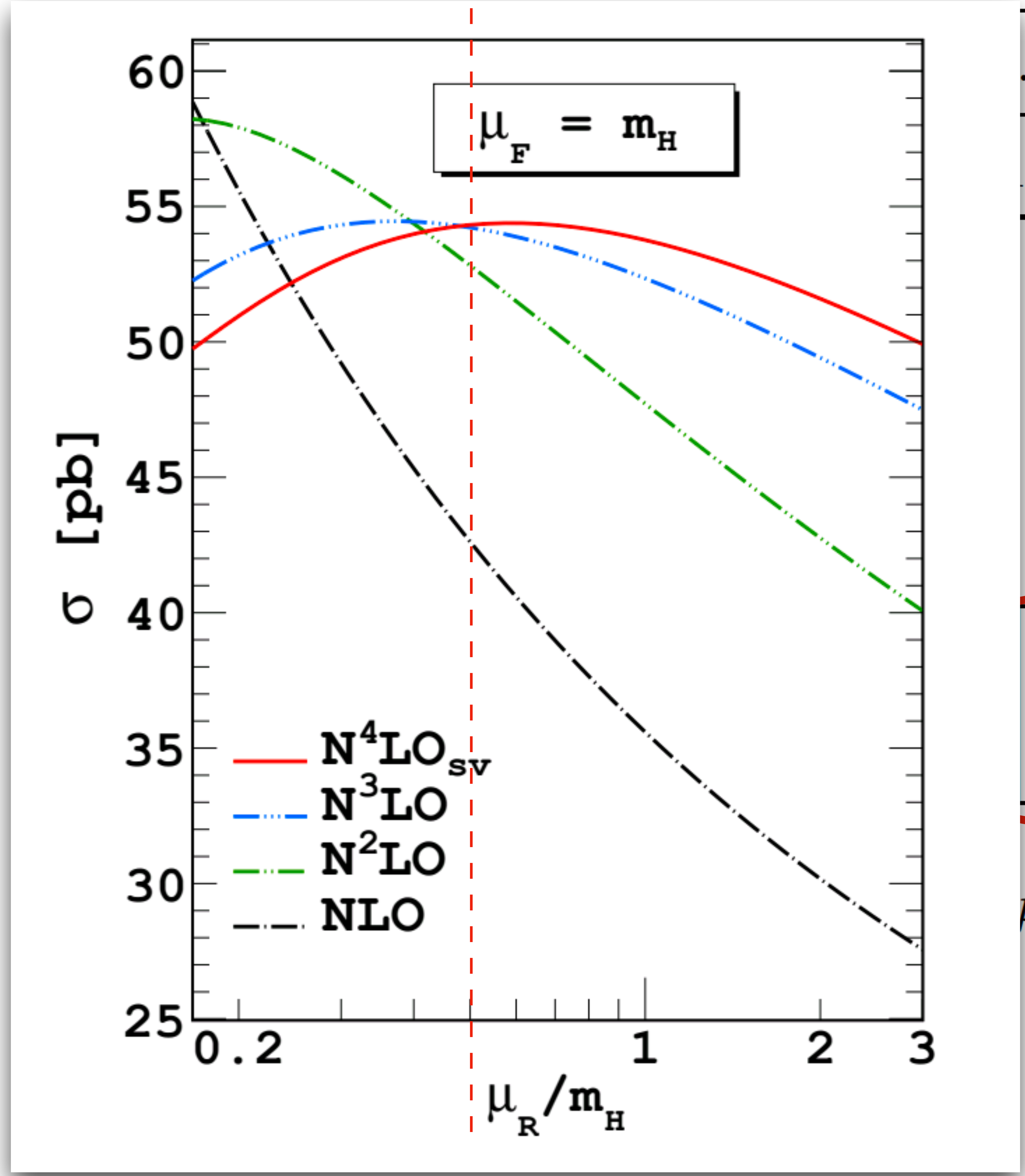
soft-virtual approximation

$$\hat{\sigma}_{ij} = \sum_{n\geq 0} \left(\frac{\alpha_s}{\pi}\right)^n \hat{\sigma}_{ij}^{(n)} \,,$$

$$\hat{\sigma}_{ij}^{(n)} = a^{(n)}\,\delta(1-x) + \sum_{k=0}^{2n-1} b_k^{(n)} \left[\frac{\ln^k(1-x)}{1-x}\right]_+ + \sum_{l=0}^{\infty}\sum_{k=0}^{2n-1} c_{lk}^{(n)}\,(1-x)^l \ln^k(1-x) \,,$$

δ(scale)	δ(trunc)	δ(PDF-TH)	δ(EW)	$\delta(t,b,c)$	$\delta(1/m_t)$
		.56 pb	±0.49 pb	±0.40 pb	±0.49 pb
		.16			

$\mu_R = m_H/2$



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

P3H-20-054

G. Das [*a], S. Moch [†b] and A. Vogt [‡c]

soft-virtual approximation

$$\left[\frac{\ln^k(1-x)}{1-x}\right]_+$$

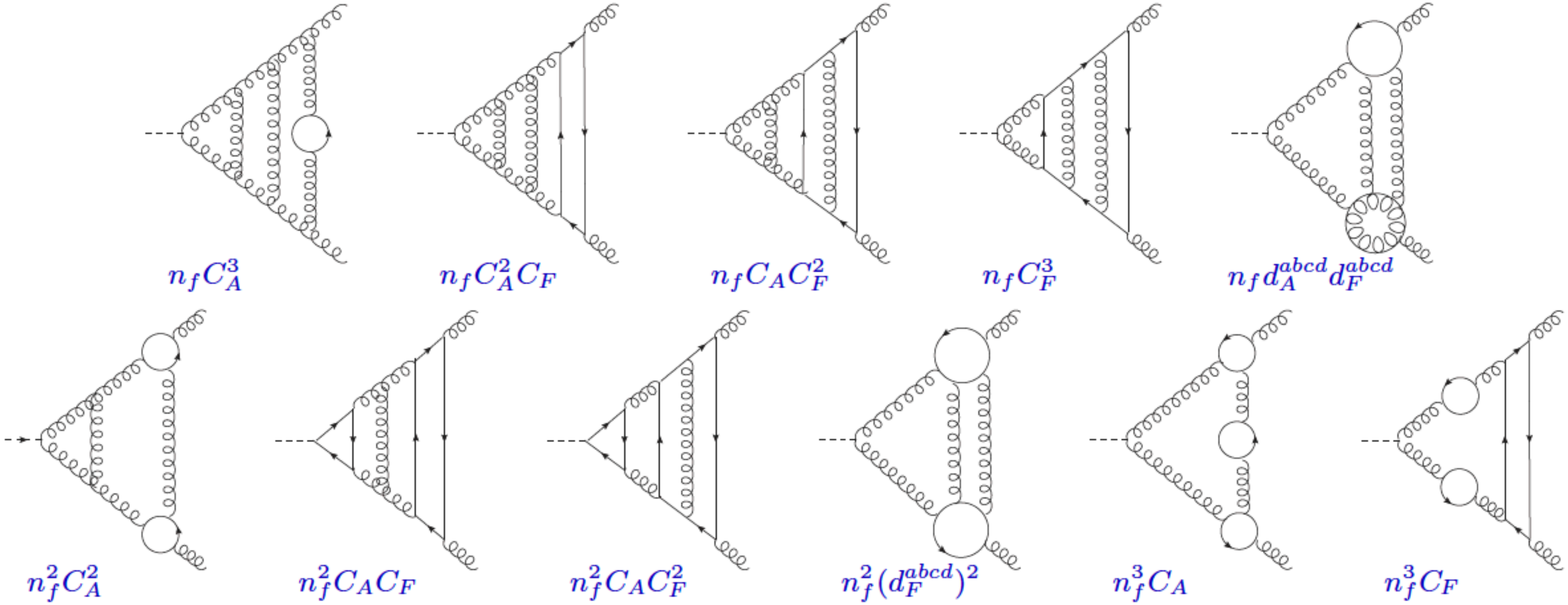
$$^k(1-x)\,,$$

TTK Institute for Theoretical Particle Physics and Cosmology
RWTH AACHEN UNIVERSITY

Fermionic corrections to quark and gluon form factors in four-loop QCD

Roman N. Lee,[1] Andreas von Manteuffel,[2] Robert M. Schabinger,[2]
Alexander V. Smirnov,[3] Vladimir A. Smirnov,[4] and Matthias Steinhauser[5]

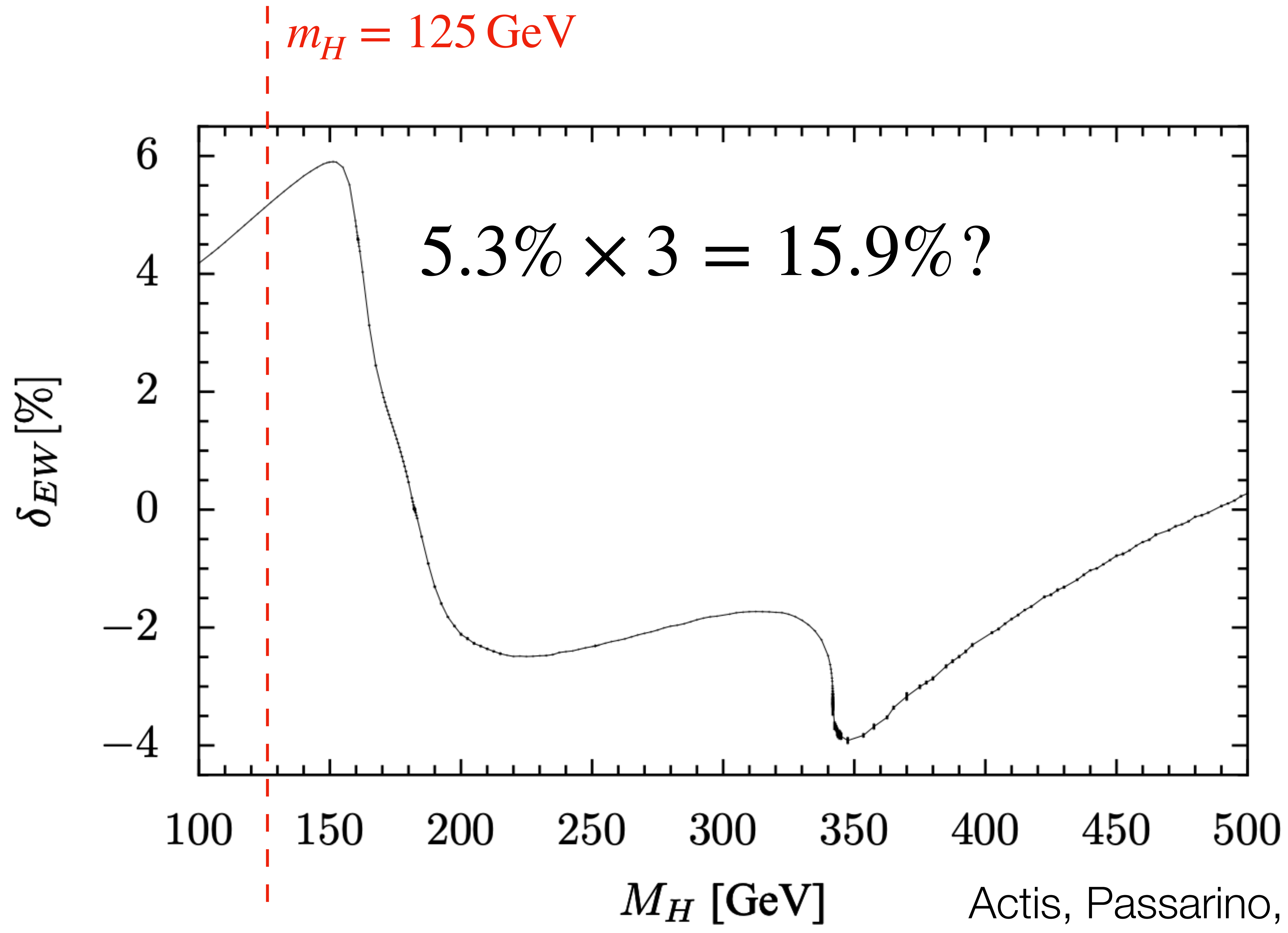
P3H-21-013



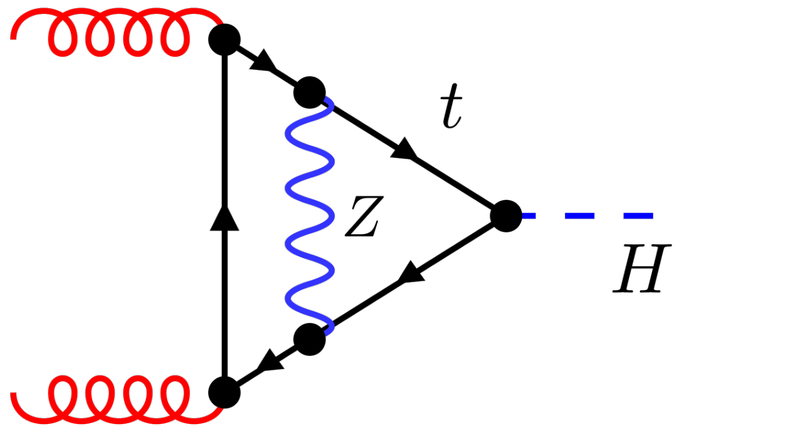
δ(scale)	δ(trunc)	δ(PDF-TH)	δ(EW)	$\delta(t,b,c)$	$\delta(1/m_t)$
$^{+0.10}_{-1.15}$ pb	± 0.18 pb	± 0.56 pb	± 0.49 pb	± 0.40 pb	± 0.49 pb
$^{+0.21\%}_{-2.37\%}$	$\pm 0.37\%$	$\pm 1.16\%$	$\pm 1\%$	$\pm 0.83\%$	$\pm 1\%$

LHCHWG YR4 '16

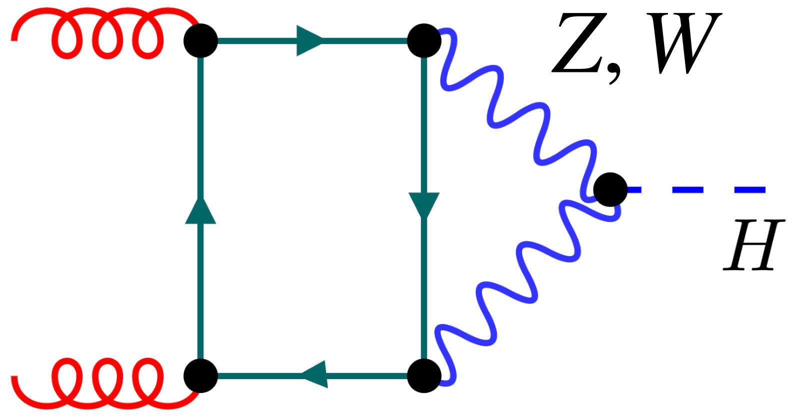
δ(scale)	δ(trunc)	δ(PDF-TH)	δ(EW)	$\delta(t,b,c)$	$\delta(1/m_t)$
+0.10 pb −1.15 pb	±0.18 pb	±0.56 pb	±0.49 pb	±0.40 pb	±0.49 pb
+0.21% −2.37%	±0.37%	±1.16%	±1%	±0.83%	±1%



Actis, Passarino, Sturm, Uccirati '08

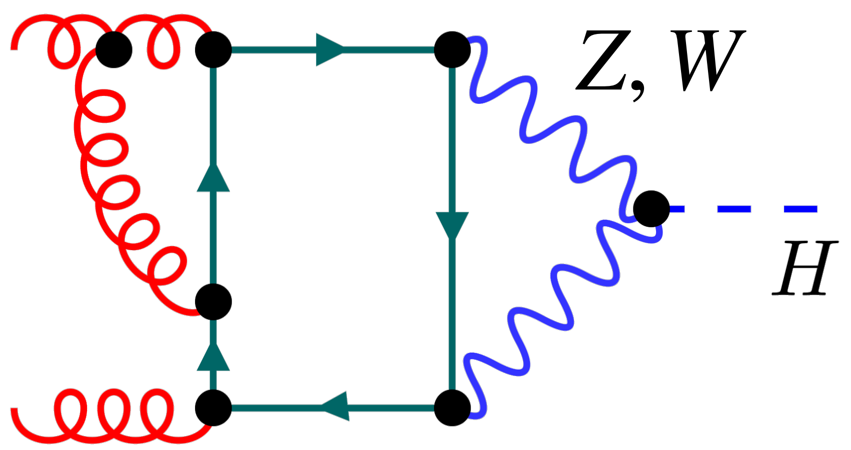


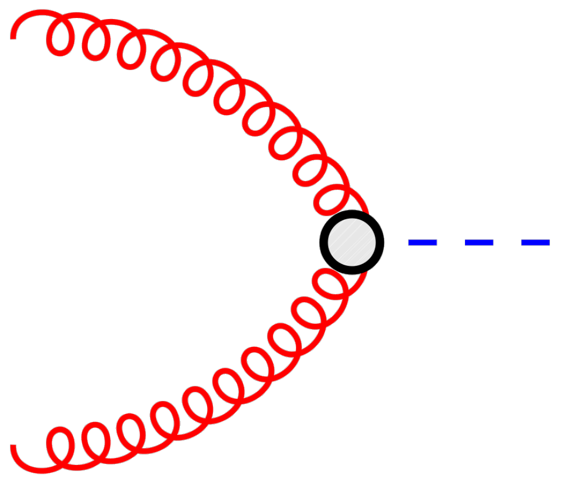
negligible at 125



dominant

Mixed QCD/EW effects



Factorization hypothesis: $\sigma \sim C^2 \cdot \Big|$  $+ \cdots \Big|^2$

$$C \sim (1 + \lambda_{\rm EW}) \left(1 + a_s C^{(1)}_{\rm QCD} + \ldots\right) = 1 + \lambda_{\rm EW} + a_s C^{(1)}_{\rm QCD} + \lambda_{\rm EW} a_s C^{(1)}_{\rm QCD} + \ldots$$

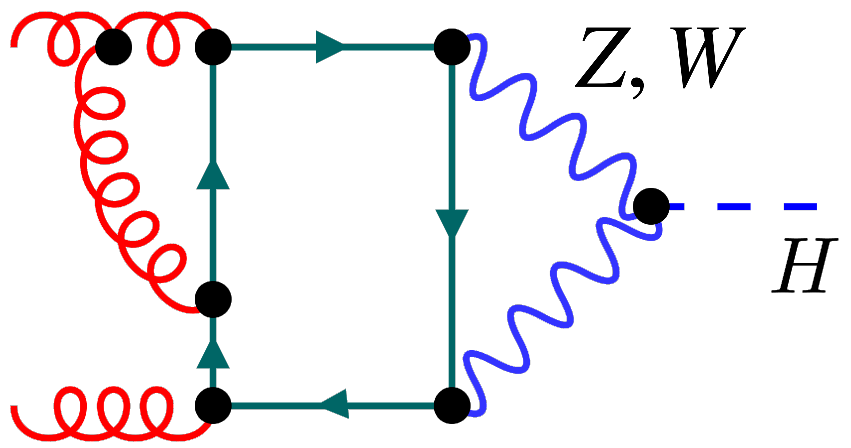
$$= 1 + \lambda_{\rm EW} + a_s C^{(1)}_{\rm QCD} + \lambda_{\rm EW} a_s C^{(1)}_{w} + \ldots$$

$\lambda_{\rm EW}$: 0.026 $\quad C^{(1)}_{\rm QCD}$: $\frac{11}{4} = 2.75$

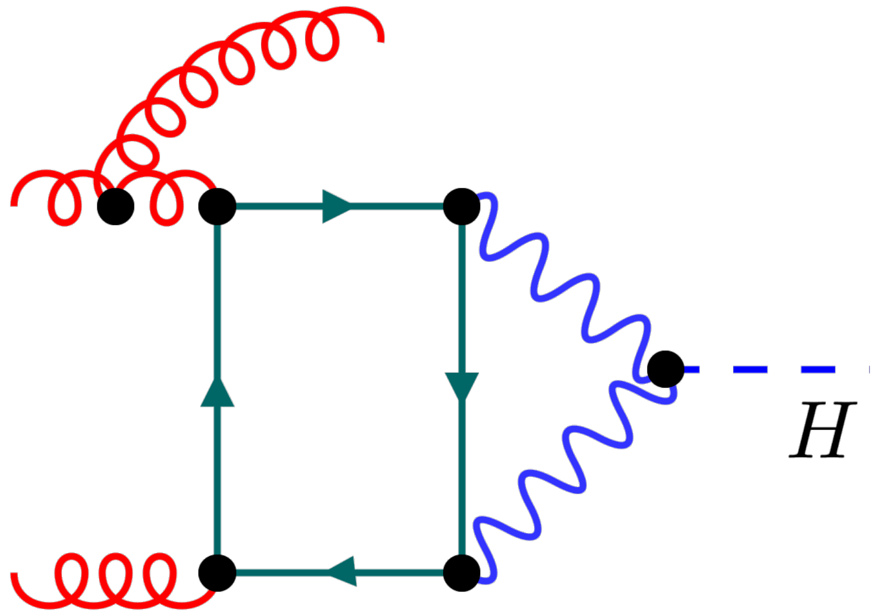
$M_W, M_Z \gg M_H$: $\quad C^{(1)}_w = \frac{7}{6} \approx 1.17$ [Anastasiou, Boughezal, Petriello '09]

varying $C^{(1)}_w$: 1% uncertainty estimate

Mixed QCD/EW effects



complete



soft gluon

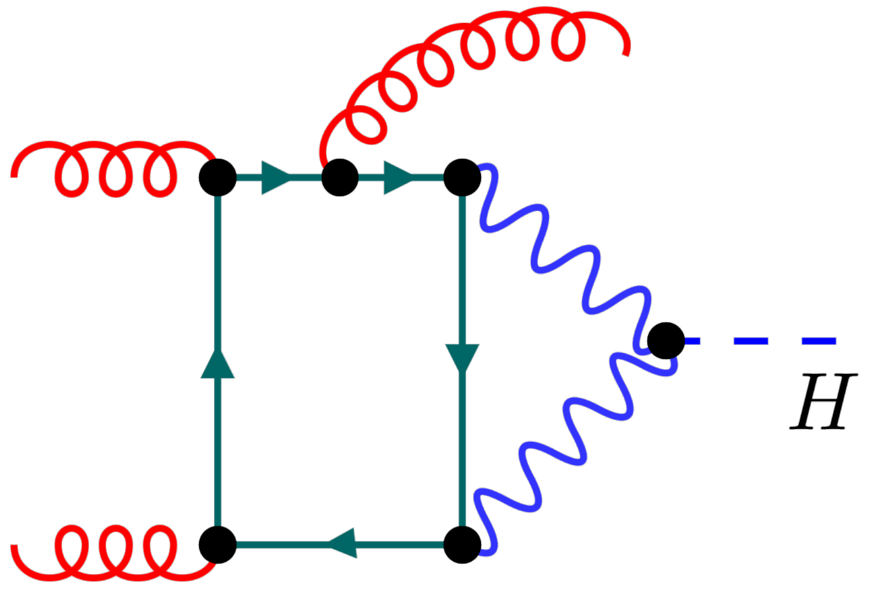
Bonetti, Melnikov, Tancredi '17

$$\lim_{E_4\to 0}\left|A_{\rm NLO}^{\rm real}\right|^2 = \frac{\alpha_s}{4\pi} N_C \frac{2p_1\cdot p_2}{p_1\cdot p_4 p_2\cdot p_4}\left|A_{\rm LO}\right|^2 + \mathcal{O}\left(p_4^{-1}\right),$$

$$\sigma_{\rm LO}^{\rm QCD} = 20.6\,{\rm pb}, \qquad \sigma_{\rm LO}^{\rm QCD\text{-}EW} = 21.7\,{\rm pb} \quad \Rightarrow \quad +5.3\% \text{ at LO}$$
$$\sigma_{\rm NLO}^{\rm QCD} = 32.7\,{\rm pb}, \qquad \sigma_{\rm NLO}^{\rm QCD\text{-}EW} = 34.4\,{\rm pb} \quad \Rightarrow \quad +5.2\% \text{ at NLO}$$

Anastasiou, Del Duca, Furlan, Mistlberger, Moriello, Schweitzer, Specchia '18 $m_W, m_Z \to 0$

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%	$\pm 0.37\%$ ✓	$\pm 1.16\%$	$\pm 1\%$	$\pm 0.83\%$	$\pm 1\%$



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

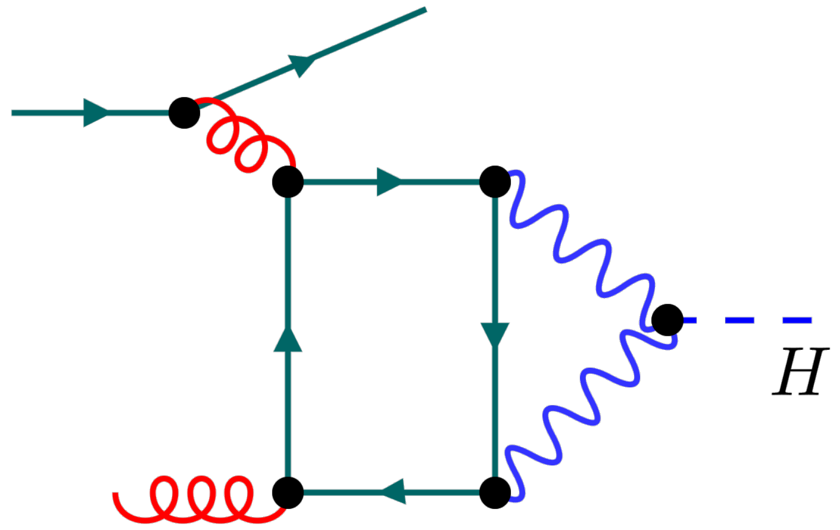
P3H-20-036

Marco Bonetti[a,b] Erik Panzer[c] Vladimir A. Smirnov[d,e] Lorenzo Tancredi[f]

[a] *Institute for Theoretical Particle Physics, KIT, Wolfgang-Gaede-Strasse 1, D-76128 Karlsruhe, Germany*

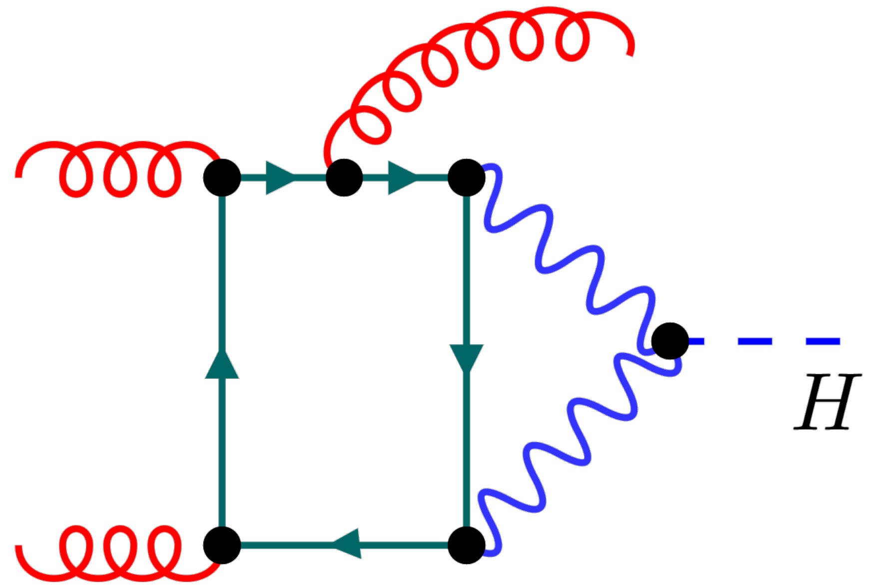
[b] *Institute for Theoretical Particle Physics and Cosmology, RWTH Aachen University, Sommerfeldstrasse 16, D-52056 Aachen, Germany*

also: Becchetti, Bonciani, Del Duca, Hirschi, Moriello ‘21
Hirschi, Lionetti, Schweitzer ‘19



missing

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%	±0.37% ✓	±1.16%	±1% ✓	±0.83%	±1%



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

P3H-20-036

Marco Bonetti[a,b] Erik Panzer[c] Vladimir A. Smirnov[d,e] Lorenzo Tancredi[f]

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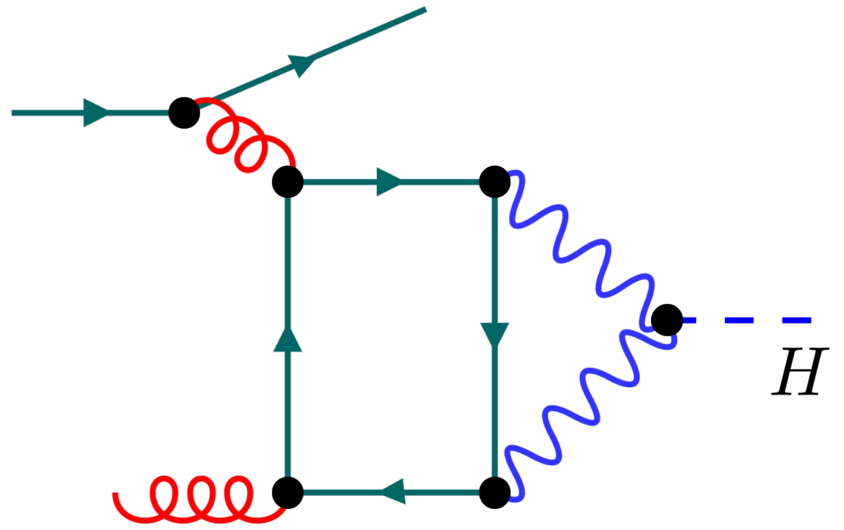
[b] *Institute for Theoretical Particle Physics and Cosmology, RWTH Aachen University, Sommerfeldstrasse 16, D-52056 Aachen, Germany*



missing

also: Becchetti, Bonciani, Del Duca, Hirschi, Moriello '21
Hirschi, Lionetti, Schweitzer '19

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

LHCHWG YR4 '16

NNLO cross section with

NNLO PDFs NLO PDFs

$$\frac{1}{2}\left|\frac{\sigma_{EFT}^{(2),NNLO}-\sigma_{EFT}^{(2),NLO}}{\sigma_{EFT}^{(2),NNLO}}\right| = \frac{1}{2}\,2.31\% = 1.16\%$$

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%	±0.37%	±1.16%	±1%	±0.83%	±1%

LHCHWG YR4 '16

$$\sigma^{\rm HO}_{\rm HEFT} = \sigma^{\rm LO}\left(\frac{\sigma^{\rm HO}}{\sigma^{\rm LO}}\right)_{m_t\to\infty}$$

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%)	($\rm N^3LO$, rEFT)

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%	$\pm 0.37\%$ ✓	$\pm 1.16\%$	$\pm 1\%$ ✓	$\pm 0.83\%$	$\pm 1\%$

NLO:

	α_s^2	α_s^3	Δm_t		
gg	$16.30\ +$	19.64	$+0.0345$	$+0.2\,\%$	$\to +0.1\,\%$
qg		1.49	-0.3696	$-24.8\,\%$	$\to -1.0\,\%$
qq		0.02	$+0.0322$	$+161\,\%$	$\to +0.1\,\%$
total	$16.30\ +$	21.15	-0.3029	$+1.4\,\%$	$\to -0.8\,\%$

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%	$\pm 0.37\%$ ✓	$\pm 1.16\%$	$\pm 1\%$ ✓	$\pm 0.83\%$	$\pm 1\%$

NNLO:

	α_s^2 + α_s^3 + α_s^4		
gg	$16.30 + 19.64 + 8.76$	$0.2\,\%$	$\to 0.04\,\%$
qg	$1.49 + 0.84$	$24.8\,\%$	$\to 0.4\,\%$
qq	$0.02 + 0.10$	$161\,\%$	$\to 0.3\,\%$
total	$16.30 + 21.15 + 9.79$	$3.5\,\%$	$\to 0.74\,\%$

$$\mathscr{L}_{\rm SM}$$

$$\Big\downarrow\, m_t \to \infty$$

$$\mathscr{L}_{\rm eff} = C_1(\alpha_s)\,\frac{H}{v}\,{\rm Tr}\,G_{\mu\nu}G^{\mu\nu} + \mathscr{L}_{\rm QCD}^{n_f=5}$$

$$\mathscr{L}_{\text{SM}}$$

$$\Big\downarrow\; m_t \to \infty$$

$$\mathscr{L}_{\text{eff}} = C_1(\alpha_s)\,\frac{H}{v}\text{Tr}\,G_{\mu\nu}G^{\mu\nu} + \mathscr{L}_{\text{QCD}}^{n_f=5}$$

higher orders in 1/mt:
need higher dimensional operators

$$\mathscr{L}_{\rm SM}$$

$$\Big\downarrow\; m_t \to \infty$$

$$\mathscr{L}_{\rm eff} = C_1(\alpha_s)\,\frac{H}{v}\,{\rm Tr}\,G_{\mu\nu}G^{\mu\nu} + \mathscr{L}_{\rm QCD}^{n_f=5}$$

higher orders in 1/mt:
need higher dimensional operators

$$C_2(\alpha_s)\langle\frac{H}{v}{\rm Tr}\,G_{\mu\nu}G^{\mu\rho}G^{\nu}_{\rho}\rangle$$

dim 6 (0 + 1)

$$\mathcal{O}''_{6;1} = \frac{1}{3}\mathrm{Tr}(F_{12}F_{13}F_{23})\,. \quad (B.1)$$

dim 8 (1 + 1)

$$\mathcal{O}''_{8;1} = \mathrm{Tr}(D_1F_{23}D_4F_{23}F_{14});\ \mathcal{O}''_{8;2} = \mathrm{Tr}(D_1F_{23}D_1F_{24}F_{34})\,. \quad (B.2)$$

dim 10 (3 + 2)

$$\mathcal{O}''_{10;1} = \mathrm{Tr}(D_{12}F_{34}D_{15}F_{34}F_{25}),\ \mathcal{O}''_{10;2} = \mathrm{Tr}(D_{12}F_{34}D_5F_{34}D_1F_{25}),\ \mathcal{O}''_{10;3} = \mathrm{Tr}(D_2F_{34}D_{15}F_{34}D_1F_{25});$$
$$\mathcal{O}''_{10;4} = \mathrm{Tr}(D_{12}F_{34}D_1F_{35}D_2F_{45}),\ \mathcal{O}''_{10;5} = \mathrm{Tr}(D_{12}F_{34}D_{12}F_{35}F_{45})\,. \quad (B.3)$$

dim 12 (6 + 4)

$$\mathcal{O}''_{12;1} = \mathrm{Tr}(D_{123}F_{45}D_{126}F_{45}F_{36}),\ \mathcal{O}''_{12;2} = \mathrm{Tr}(D_{123}F_{45}D_{16}F_{45}D_2F_{36}),\ \mathcal{O}''_{12;3} = \mathrm{Tr}(D_{13}F_{45}D_{126}F_{45}D_2F_{36}),$$
$$\mathcal{O}''_{12;4} = \mathrm{Tr}(D_{123}F_{45}D_6F_{45}D_{12}F_{36}),\ \mathcal{O}''_{12;5} = \mathrm{Tr}(D_{13}F_{45}D_{26}F_{45}D_{12}F_{36}),\ \mathcal{O}''_{12;6} = \mathrm{Tr}(D_3F_{45}D_{126}F_{45}D_{12}F_{36});$$
$$\mathcal{O}''_{12;7} = \mathrm{Tr}(D_{12}F_{45}D_{13}F_{46}D_{23}F_{56}),\ \mathcal{O}''_{12;8} = \mathrm{Tr}(D_{12}F_{45}D_{123}F_{46}D_3F_{56}),\ \mathcal{O}''_{12;9} = \mathrm{Tr}(D_{123}F_{45}D_{12}F_{46}D_3F_{56}),$$
$$\mathcal{O}''_{12;10} = \mathrm{Tr}(D_{123}F_{45}D_{123}F_{46}F_{56})\,. \quad (B.4)$$

dim 14 (10 + 5)

$$\mathcal{O}''_{14;1} = \mathrm{Tr}(D_{1234}F_{56}D_{1237}F_{56}F_{47}),\ \mathcal{O}''_{14;2} = \mathrm{Tr}(D_{1234}F_{56}D_{127}F_{56}D_3F_{47}),\ \mathcal{O}''_{14;3} = \mathrm{Tr}(D_{124}F_{56}D_{1237}F_{56}D_3F_{47}),$$
$$\mathcal{O}''_{14;4} = \mathrm{Tr}(D_{1234}F_{56}D_{17}F_{56}D_{23}F_{47}),\ \mathcal{O}''_{14;5} = \mathrm{Tr}(D_{124}F_{56}D_{137}F_{56}D_{23}F_{47}),\ \mathcal{O}''_{14;6} = \mathrm{Tr}(D_{14}F_{56}D_{1237}F_{56}D_{23}F_{47})$$
$$\mathcal{O}''_{14;7} = \mathrm{Tr}(D_{1234}F_{56}D_7F_{56}D_{123}F_{47}),\ \mathcal{O}''_{14;8} = \mathrm{Tr}(D_{124}F_{56}D_{37}F_{56}D_{123}F_{47}),\ \mathcal{O}''_{14;9} = \mathrm{Tr}(D_{14}F_{56}D_{237}F_{56}D_{123}F_{47}),$$
$$\mathcal{O}''_{14;10} = \mathrm{Tr}(D_4F_{56}D_{1237}F_{56}D_{123}F_{47});$$
$$\mathcal{O}''_{14;11} = \mathrm{Tr}(D_{123}F_{56}D_{124}F_{57}D_{34}F_{67}),\ \mathcal{O}''_{14;12} = \mathrm{Tr}(D_{1234}F_{56}D_{12}F_{57}D_{34}F_{67}),\ \mathcal{O}''_{14;13} = \mathrm{Tr}(D_{123}F_{56}D_{1234}F_{57}D_4F_{67}),$$
$$\mathcal{O}''_{14;14} = \mathrm{Tr}(D_{1234}F_{56}D_{123}F_{57}D_4F_{67}),\ \mathcal{O}''_{14;15} = \mathrm{Tr}(D_{1234}F_{56}D_{1234}F_{57}F_{67})\,. \quad (B.5)$$

dim 16 (15 + 7)

$$\mathcal{O}''_{16;1} = \mathrm{Tr}(D_{12345}F_{67}D_{12348}F_{67}F_{58}),\ \mathcal{O}''_{16;2} = \mathrm{Tr}(D_{12345}F_{67}D_{1238}F_{67}D_4F_{58}),\ \mathcal{O}''_{16;3} = \mathrm{Tr}(D_{1235}F_{67}D_{12348}F_{67}D_4F_{58}),$$
$$\mathcal{O}''_{16;4} = \mathrm{Tr}(D_{12345}F_{67}D_{128}F_{67}D_{34}F_{58}),\ \mathcal{O}''_{16;5} = \mathrm{Tr}(D_{1235}F_{67}D_{1248}F_{67}D_{34}F_{58}),\ \mathcal{O}''_{16;6} = \mathrm{Tr}(D_{125}F_{67}D_{12348}F_{67}D_{34}F_{58})$$
$$\mathcal{O}''_{16;7} = \mathrm{Tr}(D_{12345}F_{67}D_{18}F_{67}D_{234}F_{58}),\ \mathcal{O}''_{16;8} = \mathrm{Tr}(D_{1235}F_{67}D_{148}F_{67}D_{234}F_{58}),\ \mathcal{O}''_{16;9} = \mathrm{Tr}(D_{125}F_{67}D_{1348}F_{67}D_{234}F_{58}),$$
$$\mathcal{O}''_{16;10} = \mathrm{Tr}(D_{15}F_{67}D_{12348}F_{67}D_{234}F_{58}),\ \mathcal{O}''_{16;11} = \mathrm{Tr}(D_{12345}F_{67}D_8F_{67}D_{1234}F_{58}),\ \mathcal{O}''_{16;12} = \mathrm{Tr}(D_{1235}F_{67}D_{48}F_{67}D_{1234}F_{58}),$$
$$\mathcal{O}''_{16;13} = \mathrm{Tr}(D_{125}F_{67}D_{348}F_{67}D_{1234}F_{58}),\ \mathcal{O}''_{16;14} = \mathrm{Tr}(D_{15}F_{67}D_{2348}F_{67}D_{1234}F_{58}),\ \mathcal{O}''_{16;15} = \mathrm{Tr}(D_5F_{67}D_{12348}F_{67}D_{1234}F_{58});$$
$$\mathcal{O}''_{16;16} = \mathrm{Tr}(D_{1234}F_{67}D_{125}F_{68}D_{345}F_{78}),\ \mathcal{O}''_{16;17} = \mathrm{Tr}(D_{123}F_{67}D_{12345}F_{68}D_{45}F_{78}),\ \mathcal{O}''_{16;18} = \mathrm{Tr}(D_{1234}F_{67}D_{1235}F_{68}D_{45}F_{78}),$$
$$\mathcal{O}''_{16;19} = \mathrm{Tr}(D_{12345}F_{67}D_{123}F_{68}D_{45}F_{78}),\ \mathcal{O}''_{16;20} = \mathrm{Tr}(D_{1234}F_{67}D_{12345}F_{68}D_5F_{78}),\ \mathcal{O}''_{16;21} = \mathrm{Tr}(D_{12345}F_{67}D_{1234}F_{68}D_5F_{78}),$$
$$\mathcal{O}''_{16;22} = \mathrm{Tr}(D_{12345}F_{67}D_{12345}F_{68}F_{78})\,. \quad (B.6)$$

Jin, Ren, Yang ‘21

dim 6 $(0+1)$

$$\mathcal{O}''_{6;1} = \frac{1}{3}\mathrm{Tr}(F_{12}F_{13}F_{23})\,. \tag{B.1}$$

dim 8 $(1+1)$

$$\mathcal{O}''_{8;1} = \mathrm{Tr}(D_1F_{23}D_4F_{23}F_{14});\ \ \mathcal{O}''_{8;2} = \mathrm{Tr}(D_1F_{23}D_1F_{24}F_{34})\,. \tag{B.2}$$

dim 10 $(3+2)$

$$\begin{aligned}&\mathcal{O}''_{10;1} = \mathrm{Tr}(D_{12}F_{34}D_{15}F_{34}F_{25}),\ \ \mathcal{O}''_{10;2} = \mathrm{Tr}(D_{12}F_{34}D_5F_{34}D_1F_{25}),\ \ \mathcal{O}''_{10;3} = \mathrm{Tr}(D_2F_{34}D_{15}F_{34}D_1F_{25});\\ &\mathcal{O}''_{10;4} = \mathrm{Tr}(D_{12}F_{34}D_1F_{35}D_2F_{45}),\ \ \mathcal{O}''_{10;5} = \mathrm{Tr}(D_{12}F_{34}D_{12}F_{35}F_{45})\,.\end{aligned} \tag{B.3}$$

dim 12 $(6+4)$

$$\begin{aligned}&\mathcal{O}''_{12;1} = \mathrm{Tr}(D_{123}F_{45}D_{126}F_{45}F_{36}),\ \ \mathcal{O}''_{12;2} = \mathrm{Tr}(D_{123}F_{45}D_{16}F_{45}D_2F_{36}),\ \ \mathcal{O}''_{12;3} = \mathrm{Tr}(D_{13}F_{45}D_{126}F_{45}D_2F_{36}),\\ &\mathcal{O}''_{12;4} = \mathrm{Tr}(D_{123}F_{45}D_6F_{45}D_{12}F_{36}),\ \ \mathcal{O}''_{12;5} = \mathrm{Tr}(D_{13}F_{45}D_{26}F_{45}D_{12}F_{36}),\ \ \mathcal{O}''_{12;6} = \mathrm{Tr}(D_3F_{45}D_{126}F_{45}D_{12}F_{36});\\ &\mathcal{O}''_{12;7} = \mathrm{Tr}(D_{12}F_{45}D_{13}F_{46}D_{23}F_{56}),\ \ \mathcal{O}''_{12;8} = \mathrm{Tr}(D_{12}F_{45}D_{123}F_{46}D_3F_{56}),\ \ \mathcal{O}''_{12;9} = \mathrm{Tr}(D_{123}F_{45}D_{12}F_{46}D_3F_{56}),\\ &\mathcal{O}''_{12;10} = \mathrm{Tr}(D_{123}F_{45}D_{123}F_{46}F_{56})\,.\end{aligned} \tag{B.4}$$

dim 14 $(10+5)$

$$\begin{aligned}&\mathcal{O}''_{14;1} = \mathrm{Tr}(D_{1234}F_{56}D_{1237}F_{56}F_{47}),\ \ \mathcal{O}''_{14;2} = \mathrm{Tr}(D_{1234}F_{56}D_{127}F_{56}D_3F_{47}),\ \ \mathcal{O}''_{14;3} = \mathrm{Tr}(D_{124}F_{56}D_{1237}F_{56}D_3F_{47}),\\ &\mathcal{O}''_{14;4} = \mathrm{Tr}(D_{1234}F_{56}D_{17}F_{56}D_{23}F_{47}),\ \ \mathcal{O}''_{14;5} = \mathrm{Tr}(D_{124}F_{56}D_{137}F_{56}D_{23}F_{47}),\ \ \mathcal{O}''_{14;6} = \mathrm{Tr}(D_{14}F_{56}D_{1237}F_{56}D_{23}F_{47})\\ &\mathcal{O}''_{14;7} = \mathrm{Tr}(D_{1234}F_{56}D_7F_{56}D_{123}F_{47}),\ \ \mathcal{O}''_{14;8} = \mathrm{Tr}(D_{124}F_{56}D_{37}F_{56}D_{123}F_{47}),\ \ \mathcal{O}''_{14;9} = \mathrm{Tr}(D_{14}F_{56}D_{237}F_{56}D_{123}F_{47}),\\ &\mathcal{O}''_{14;10} = \mathrm{Tr}(D_4F_{56}D_{1237}F_{56}D_{123}F_{47});\\ &\mathcal{O}''_{14;11} = \mathrm{Tr}(D_{123}F_{56}D_{124}F_{57}D_{34}F_{67}),\ \ \mathcal{O}''_{14;12} = \mathrm{Tr}(D_{1234}F_{56}D_{12}F_{57}D_{34}F_{67}),\ \ \mathcal{O}''_{14;13} = \mathrm{Tr}(D_{123}F_{56}D_{1234}F_{57}D_4F_{67}),\\ &\mathcal{O}''_{14;14} = \mathrm{Tr}(D_{1234}F_{56}D_{123}F_{57}D_4F_{67}),\ \ \mathcal{O}''_{14;15} = \mathrm{Tr}(D_{1234}F_{56}D_{1234}F_{57}F_{67})\,.\end{aligned} \tag{B.5}$$

dim 16 $(15+7)$

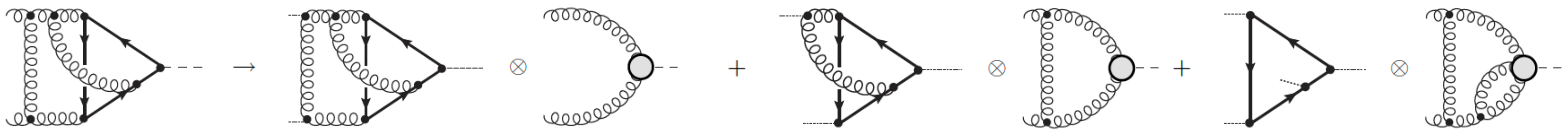
$$\begin{aligned}&\mathcal{O}''_{16;1} = \mathrm{Tr}(D_{12345}F_{67}D_{12348}F_{67}F_{58}),\ \ \mathcal{O}''_{16;2} = \mathrm{Tr}(D_{12345}F_{67}D_{1238}F_{67}D_4F_{58}),\ \ \mathcal{O}''_{16;3} = \mathrm{Tr}(D_{1235}F_{67}D_{12348}F_{67}D_4F_{58}),\\ &\mathcal{O}''_{16;4} = \mathrm{Tr}(D_{12345}F_{67}D_{128}F_{67}D_{34}F_{58}),\ \ \mathcal{O}''_{16;5} = \mathrm{Tr}(D_{1235}F_{67}D_{1248}F_{67}D_{34}F_{58}),\ \ \mathcal{O}''_{16;6} = \mathrm{Tr}(D_{125}F_{67}D_{12348}F_{67}D_{34}F_{58})\\ &\mathcal{O}''_{16;7} = \mathrm{Tr}(D_{12345}F_{67}D_{18}F_{67}D_{234}F_{58}),\ \ \mathcal{O}''_{16;8} = \mathrm{Tr}(D_{1235}F_{67}D_{148}F_{67}D_{234}F_{58}),\ \ \mathcal{O}''_{16;9} = \mathrm{Tr}(D_{125}F_{67}D_{1348}F_{67}D_{234}F_{58}),\\ &\mathcal{O}''_{16;10} = \mathrm{Tr}(D_{15}F_{67}D_{12348}F_{67}D_{234}F_{58}),\ \ \mathcal{O}''_{16;11} = \mathrm{Tr}(D_{12345}F_{67}D_8F_{67}D_{1234}F_{58}),\ \ \mathcal{O}''_{16;12} = \mathrm{Tr}(D_{1235}F_{67}D_{48}F_{67}D_{1234}F_{58}),\\ &\mathcal{O}''_{16;13} = \mathrm{Tr}(D_{125}F_{67}D_{348}F_{67}D_{1234}F_{58}),\ \ \mathcal{O}''_{16;14} = \mathrm{Tr}(D_{15}F_{67}D_{2348}F_{67}D_{1234}F_{58}),\ \ \mathcal{O}''_{16;15} = \mathrm{Tr}(D_5F_{67}D_{12348}F_{67}D_{1234}F_{58});\\ &\mathcal{O}''_{16;16} = \mathrm{Tr}(D_{1234}F_{67}D_{125}F_{68}D_{345}F_{78}),\ \ \mathcal{O}''_{16;17} = \mathrm{Tr}(D_{123}F_{67}D_{12345}F_{68}D_{45}F_{78}),\ \ \mathcal{O}''_{16;18} = \mathrm{Tr}(D_{1234}F_{67}D_{1235}F_{68}D_{45}F_{78}),\\ &\mathcal{O}''_{16;19} = \mathrm{Tr}(D_{12345}F_{67}D_{123}F_{68}D_{45}F_{78}),\ \ \mathcal{O}''_{16;20} = \mathrm{Tr}(D_{1234}F_{67}D_{12345}F_{68}D_5F_{78}),\ \ \mathcal{O}''_{16;21} = \mathrm{Tr}(D_{12345}F_{67}D_{1234}F_{68}D_5F_{78}),\\ &\mathcal{O}''_{16;22} = \mathrm{Tr}(D_{12345}F_{67}D_{12345}F_{68}F_{78})\,.\end{aligned} \tag{B.6}$$

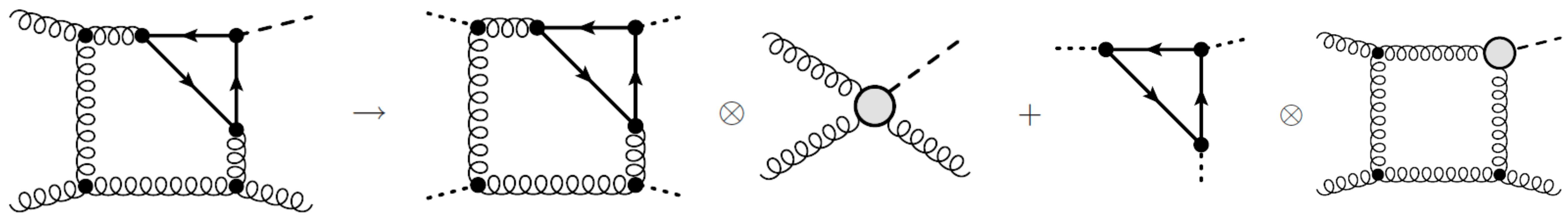
Instead: asymptotic expansions

Jin, Ren, Yang '21

Asymptotic expansions

Calculating Wilson coefficient and matrix element “at once”:

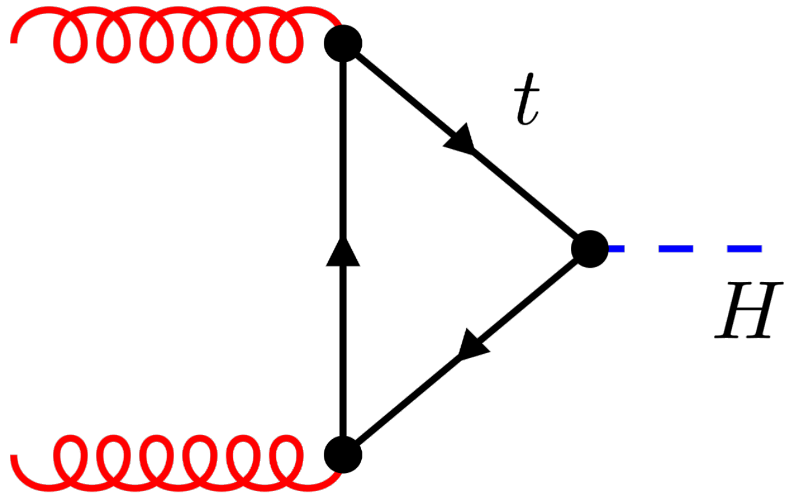




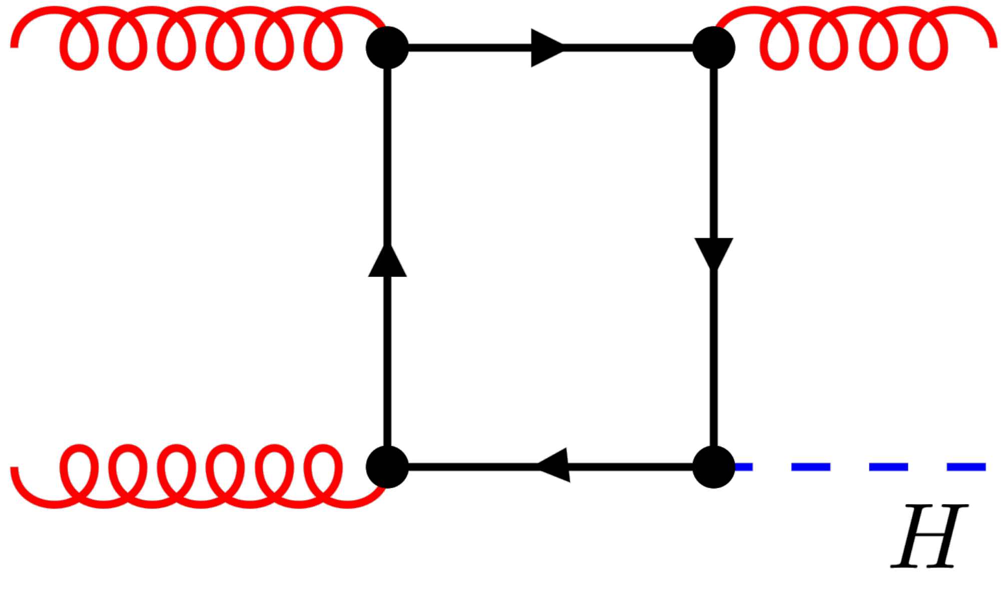
RH, Ozeren ‘09

Pak, Regal, Steinhauser ‘09

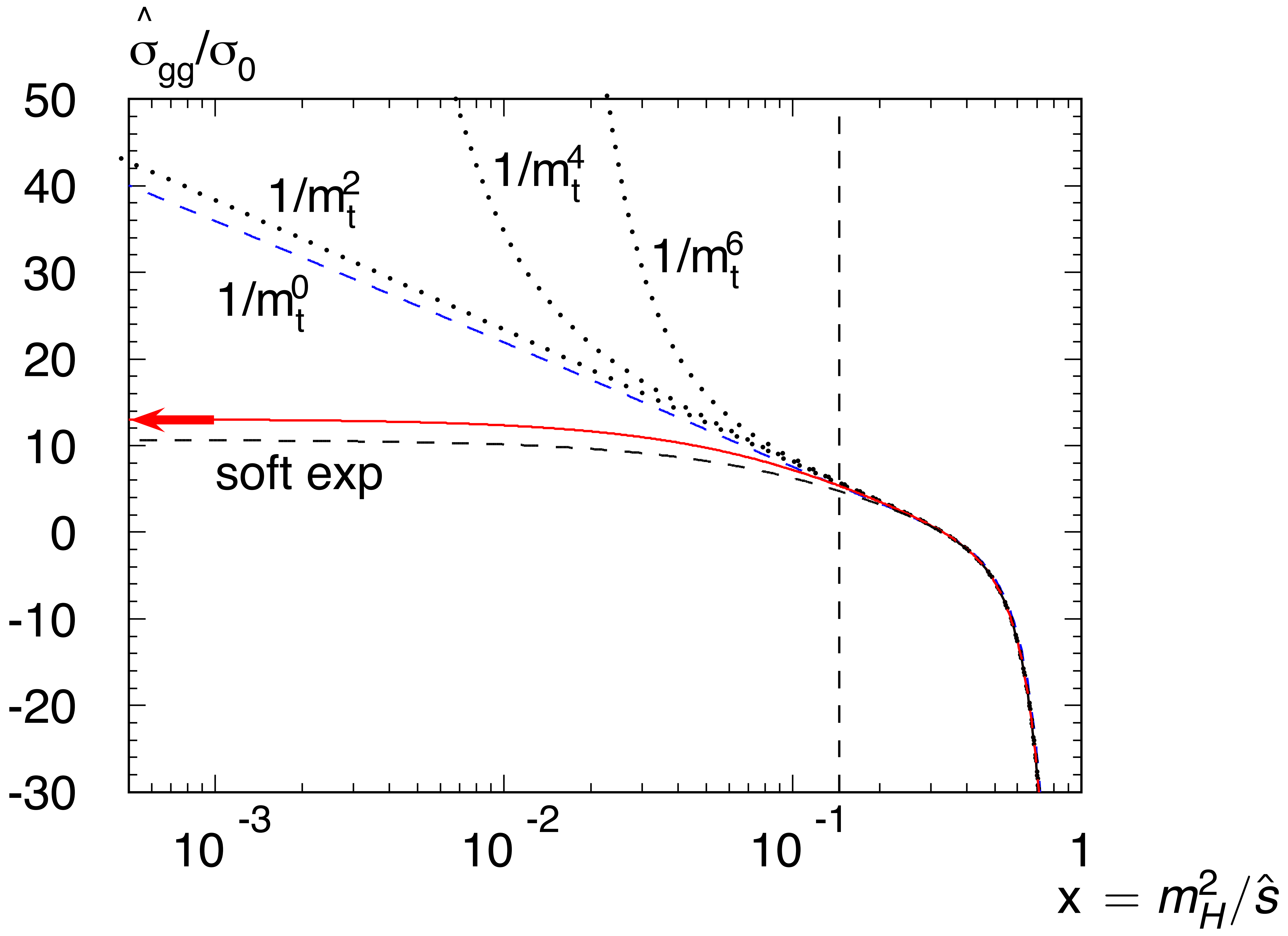
problem:



$$\hat{s} = m_H^2 < 4m_t^2$$

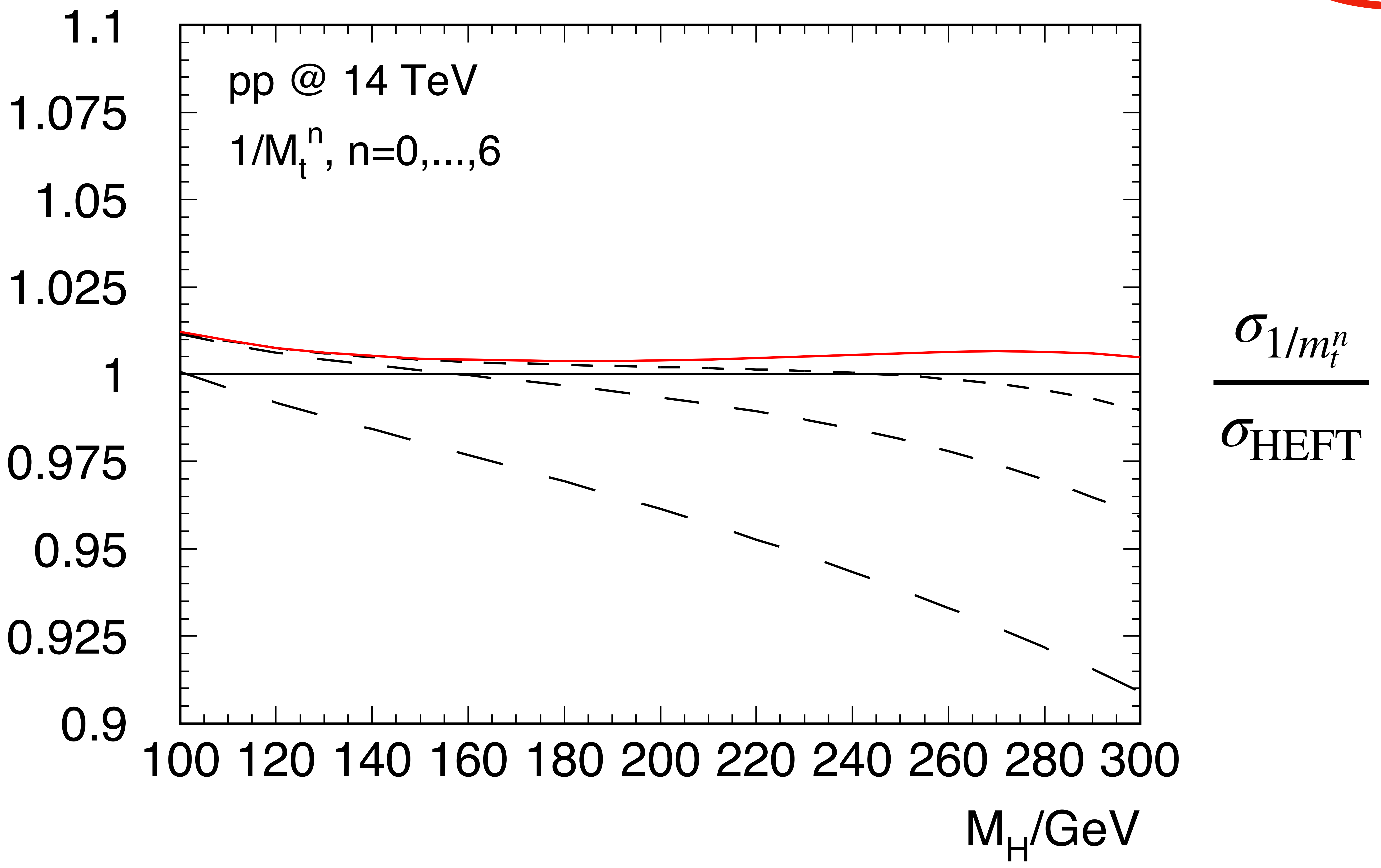


$$m_H^2 < \hat{s} < s < 13\,\text{TeV}$$



$\hat{\sigma}_{gg}/\sigma_0$
50
40
30
20
10
0
-10
-20
-30
$1/m_t^2$
$1/m_t^4$
$1/m_t^6$
$1/m_t^0$
soft exp
10^{-3}
10^{-2}
10^{-1}
1
$x = m_H^2/\hat{s}$

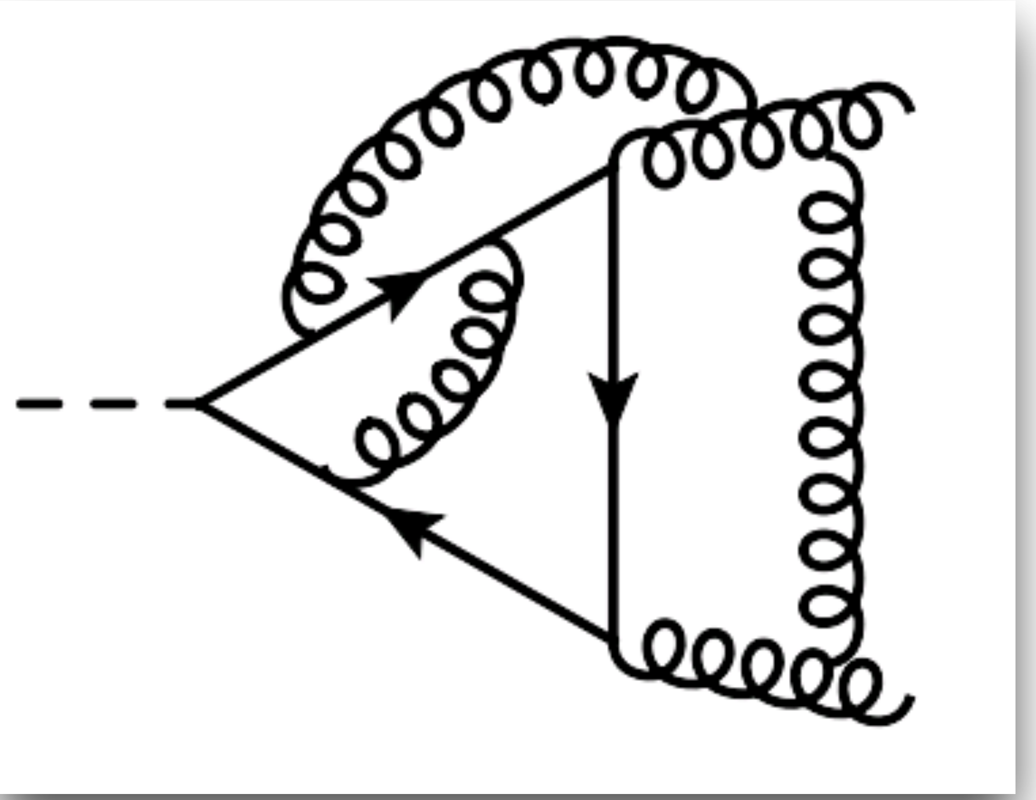
δ(scale)	δ(trunc)	δ(PDF-TH)	δ(EW)	$\delta(t,b,c)$	$\delta(1/m_t)$
$+0.10$ pb -1.15 pb	± 0.18 pb	± 0.56 pb	± 0.49 pb	± 0.40 pb	± 0.49 pb
$+0.21\%$ -2.37%	$\pm 0.37\%$	$\pm 1.16\%$	$\pm 1\%$	$\pm 0.83\%$	$\pm 1\%$



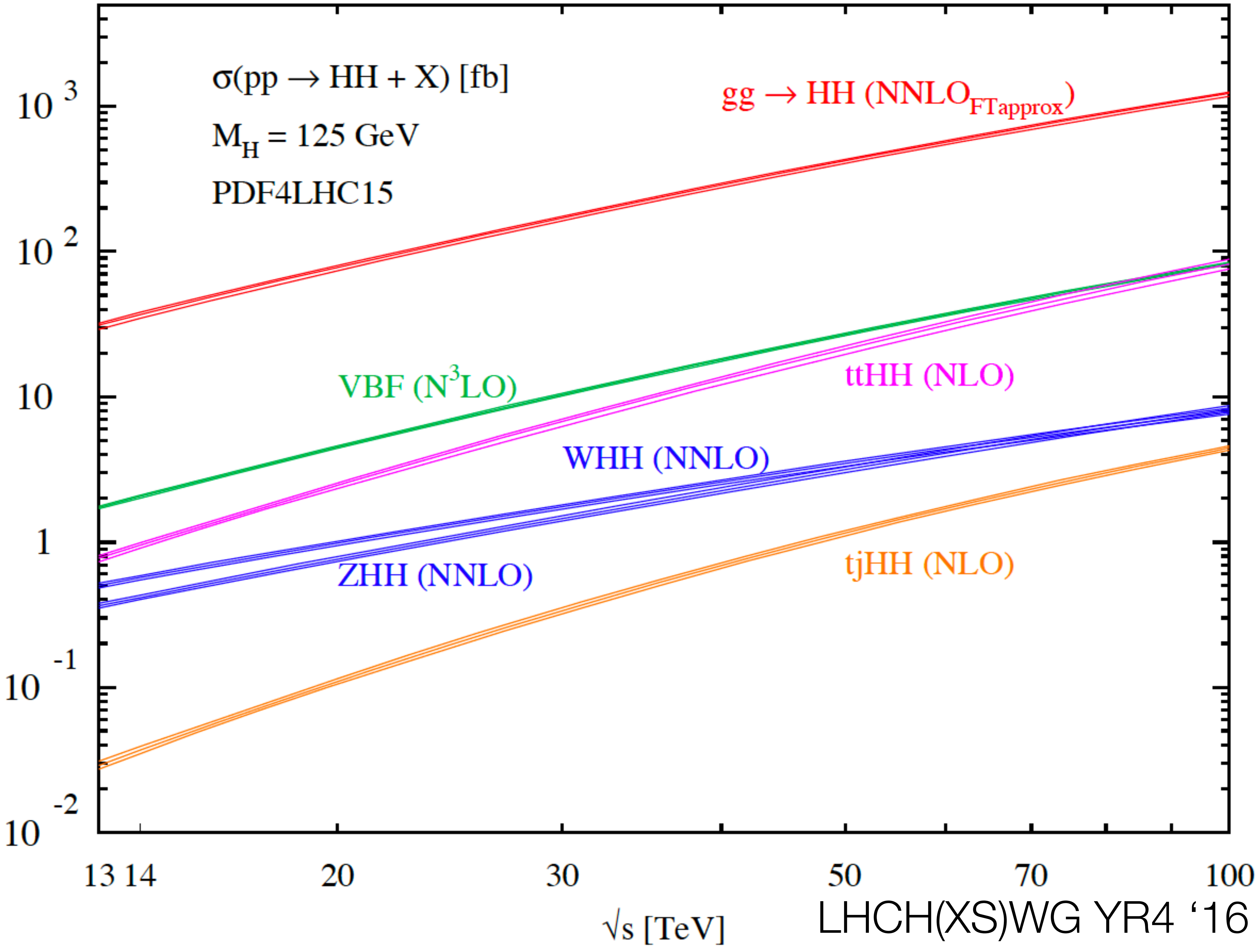
Top Quark Mass Effects in Next-To-Next-To-Next-To-Leading Order Higgs Boson Production: Virtual Corrections

P3H-19-045

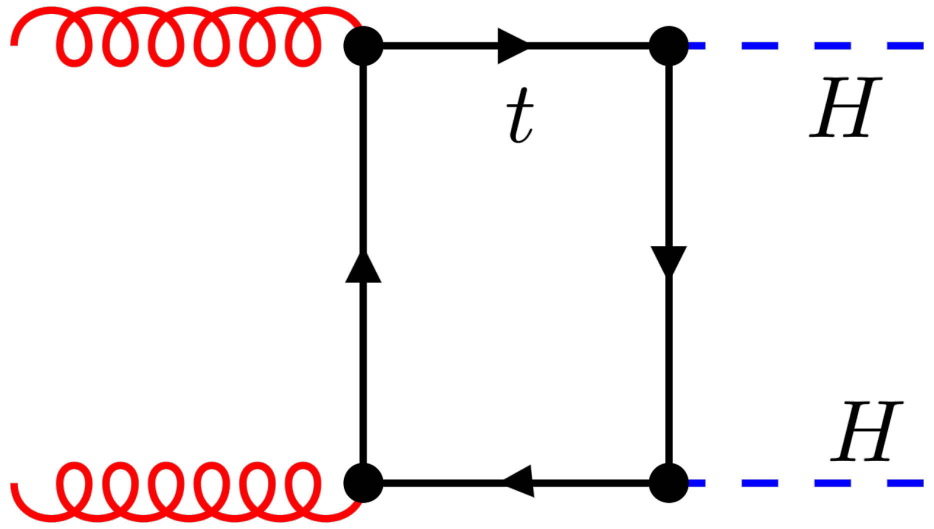
Joshua Davies,[1,*] Florian Herren,[1,†] and Matthias Steinhauser[1,‡]



Double-Higgs production

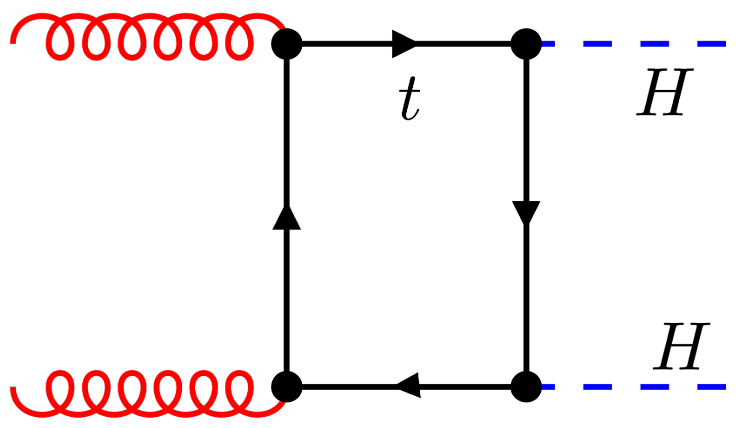


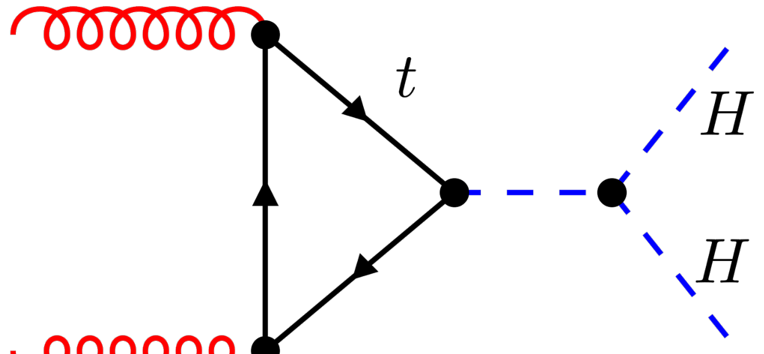
LHCH(XS)WG YR4 ‘16

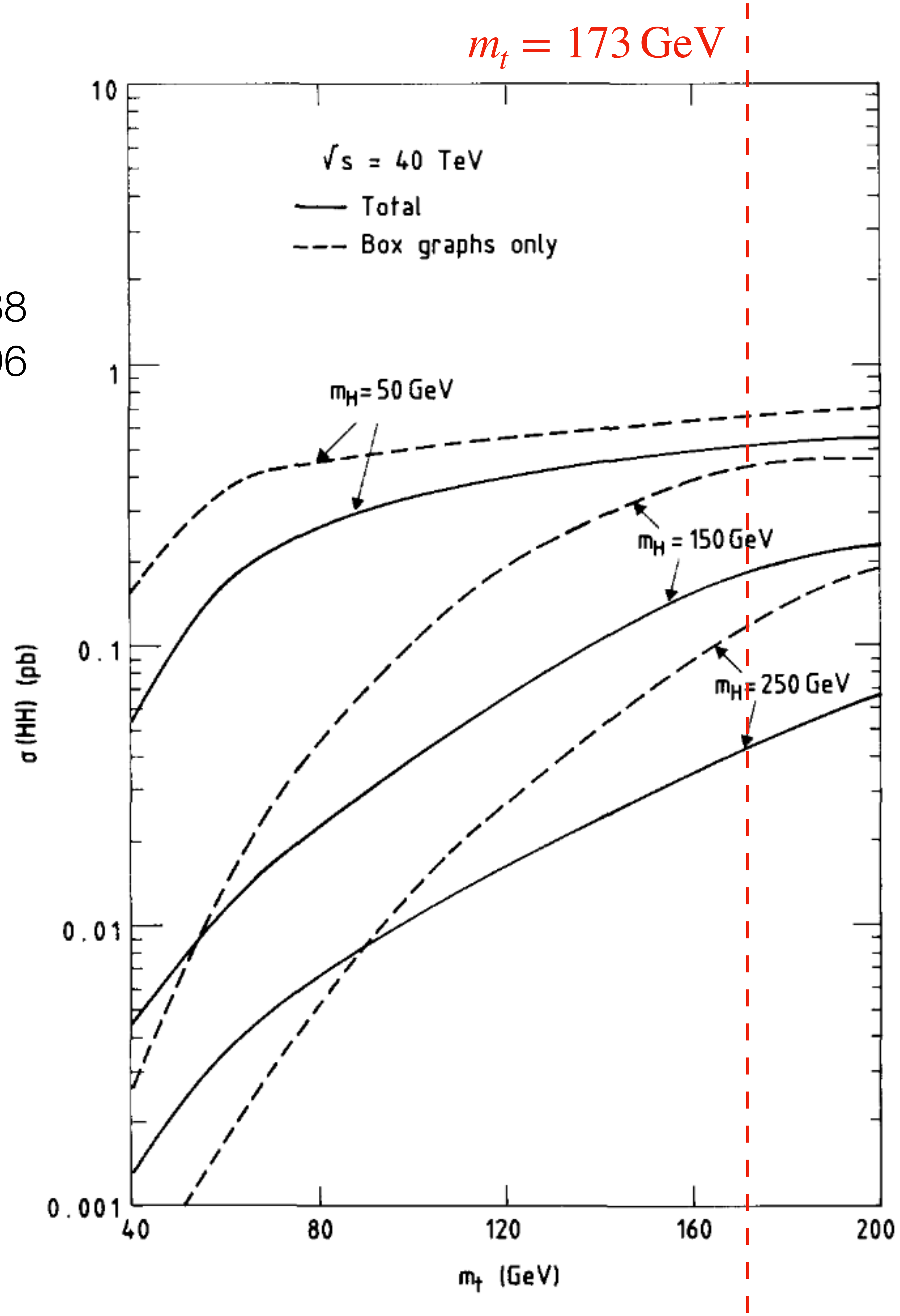


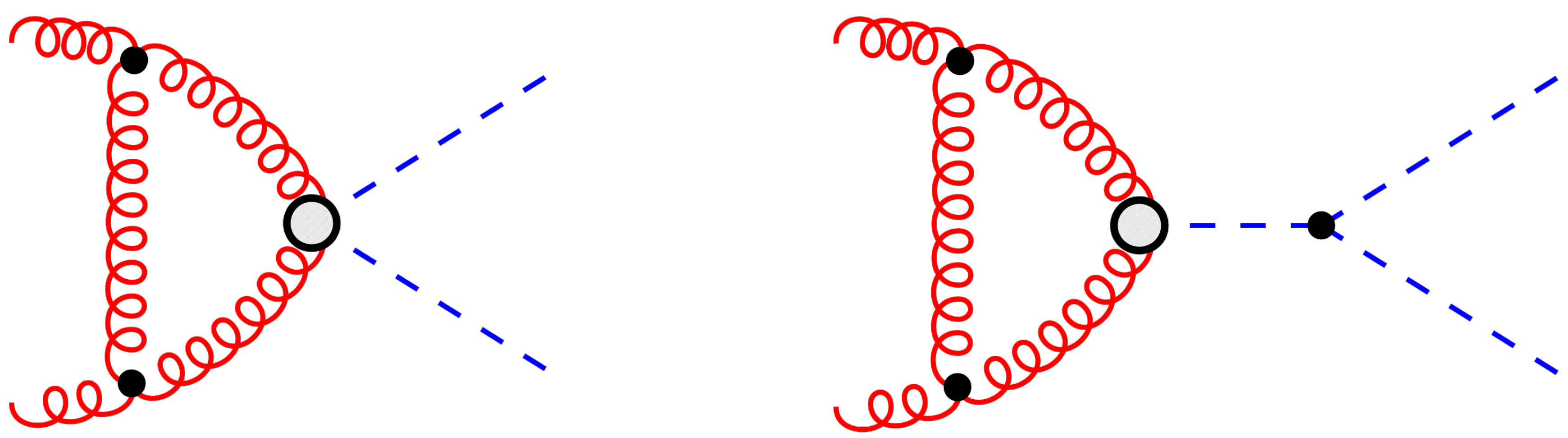
Double-Higgs production

v.d.Bij, Glover '88
Plehn, Spira, Zerwas '96

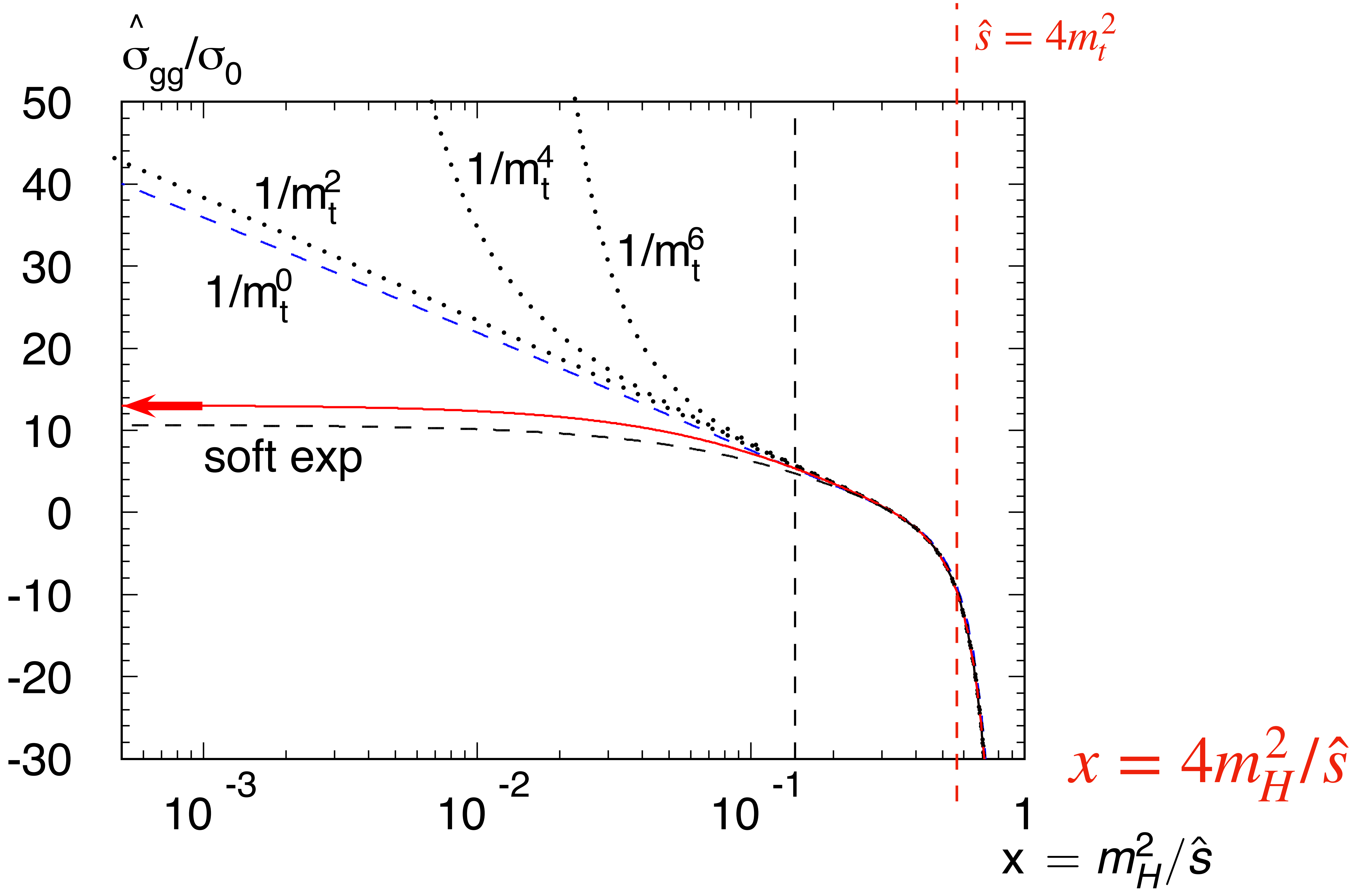






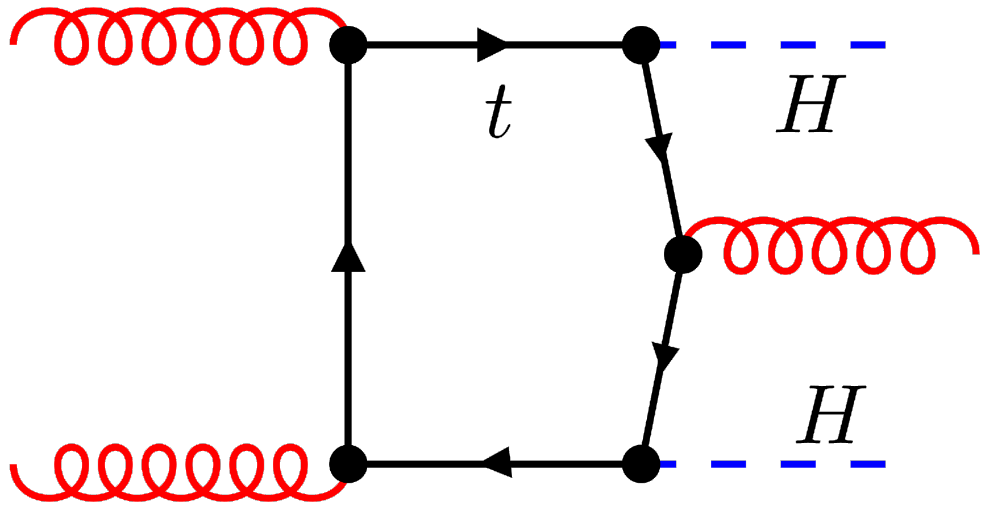


Dawson, Dittmaier, Spira '98



FT_{approx} real radiation exact

Maltoni, Vryonidou, Zaro '14



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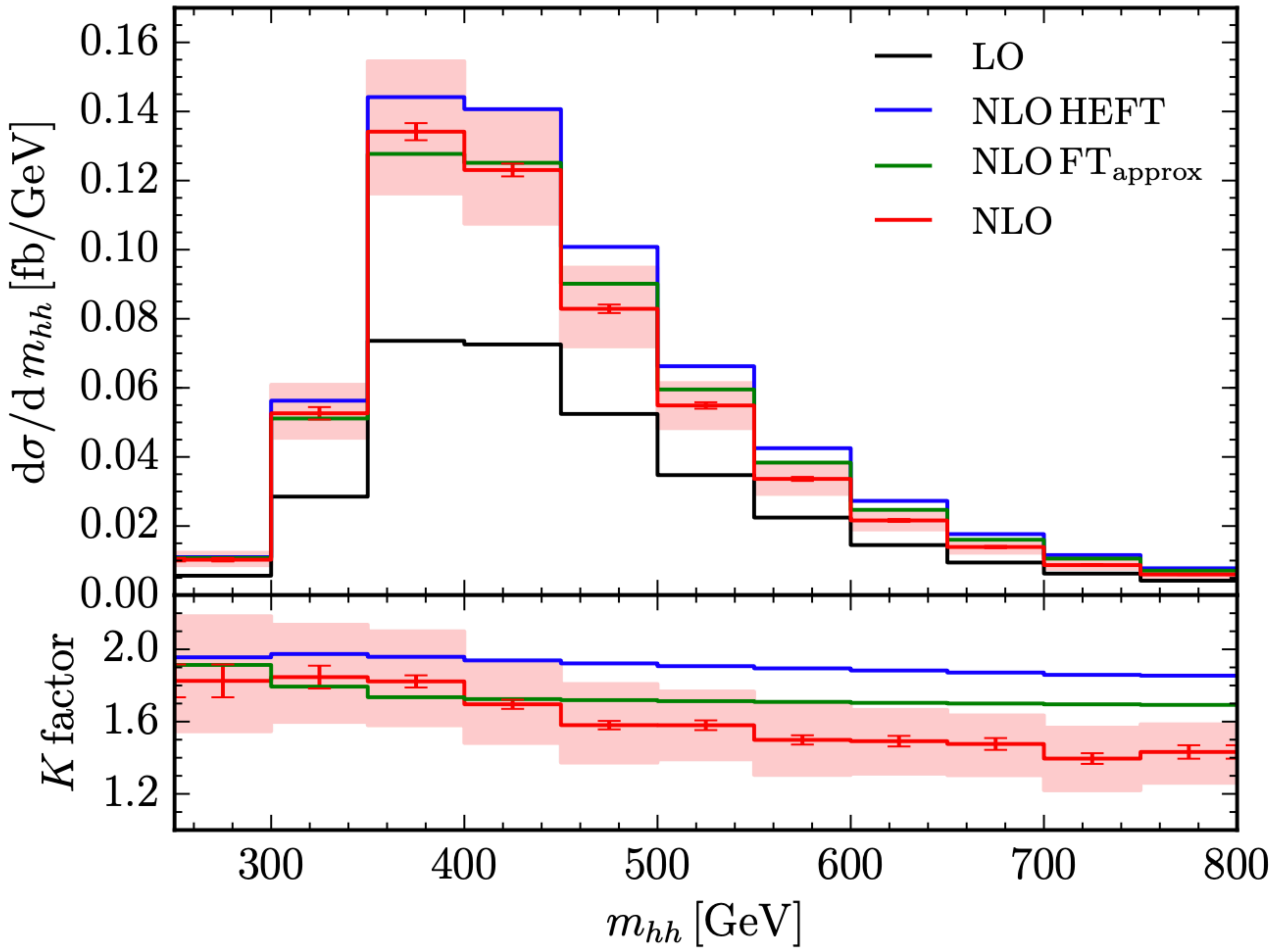
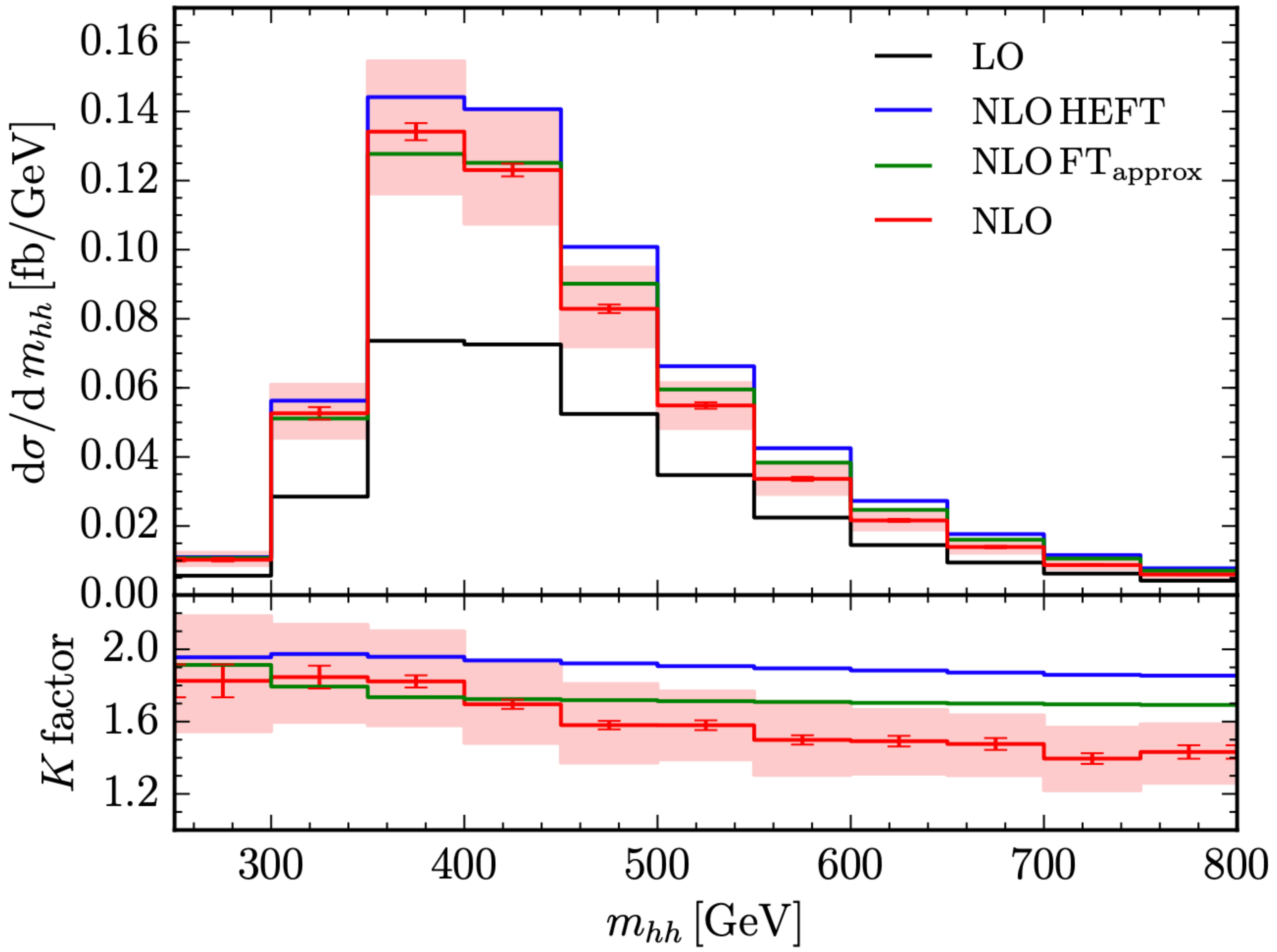
HEFT and sub-leading terms in $1/m_t$ through NLO

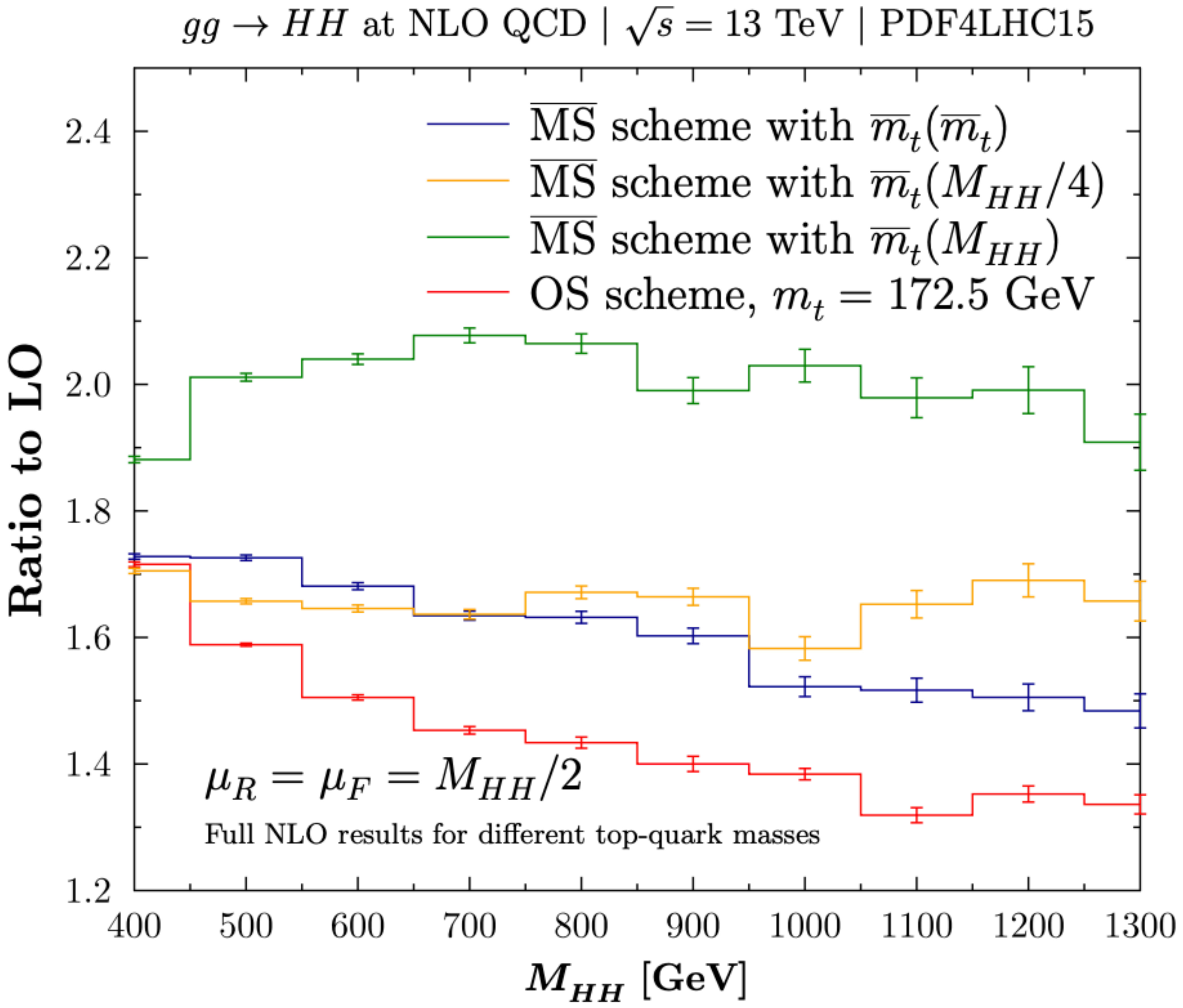
HEFT through N^3LO



Borowka, Greiner, Heinrich, Jones, Kerner, Schlenk, Schubert, Zirke '16

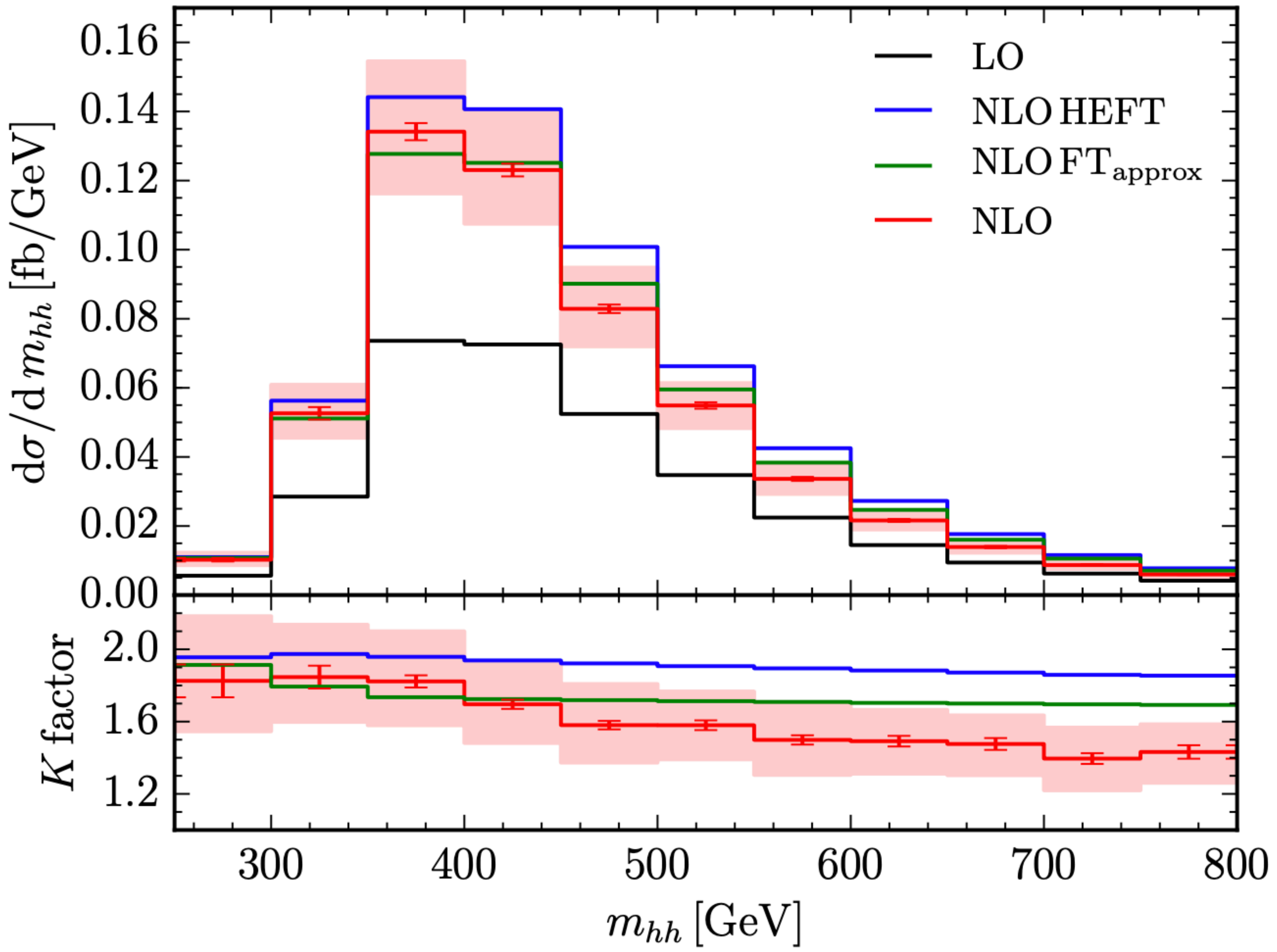
Baglio, Campanario, Glaus, Mühlleitner, Spira, Streicher '19

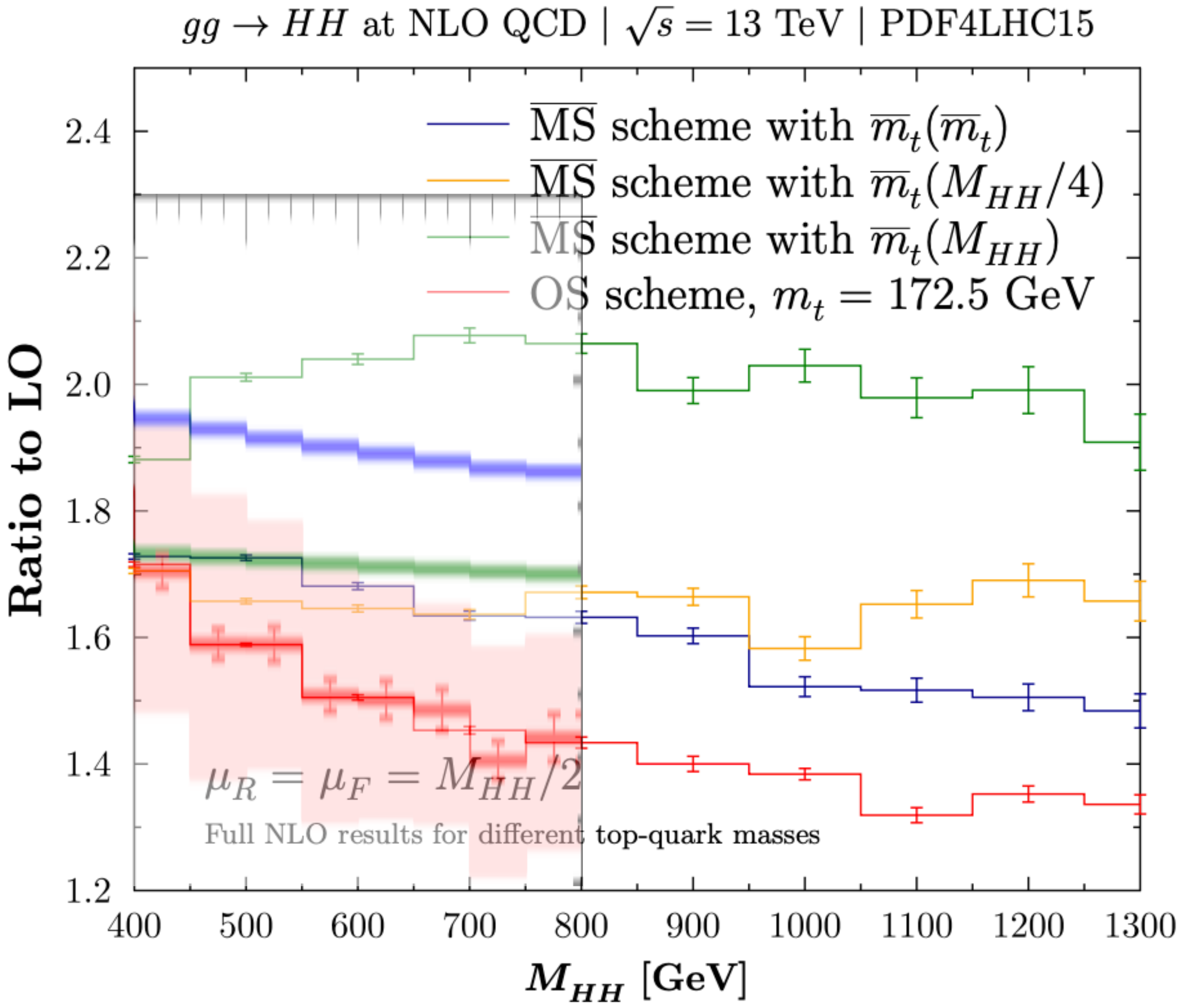




Baglio, Campanario, Glaus, Mühlleitner, Ronca, Spira '20

Borowka, Greiner, Heinrich, Jones, Kerner, Schlenk, Schubert, Zirke '16
Baglio, Campanario, Glaus, Mühlleitner, Spira, Streicher '19

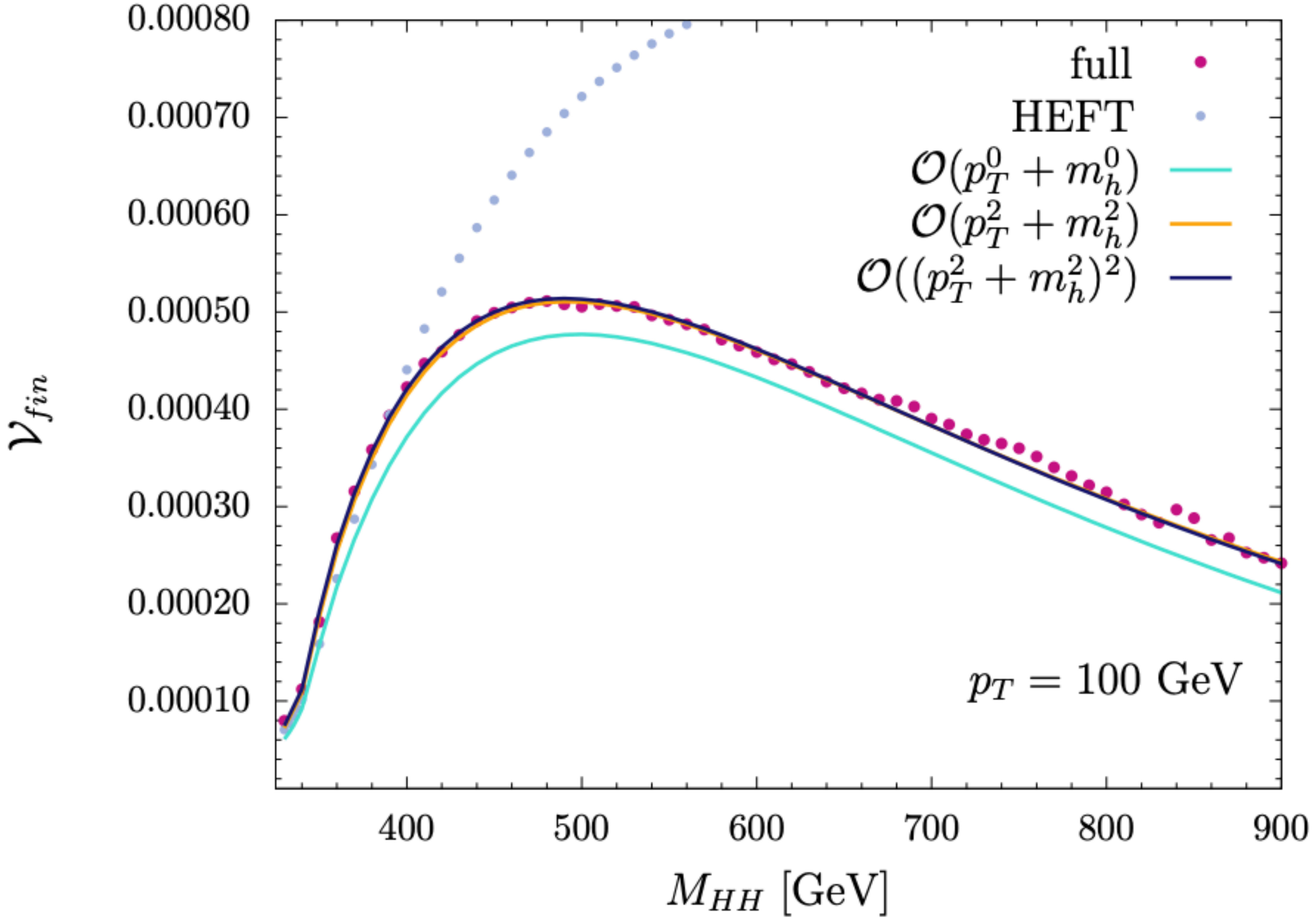




Baglio, Campanario, Glaus, Mühlleitner, Ronca, Spira ‘20

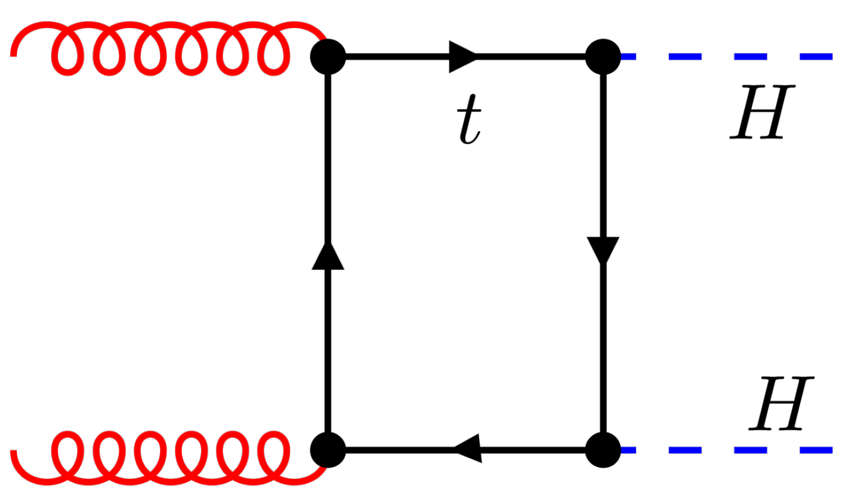
Borowka, Greiner, Heinrich, Jones, Kerner, Schlenk, Schubert, Zirke ‘16
Baglio, Campanario, Glaus, Mühlleitner, Spira, Streicher ‘19

Improved/alternative approximations:

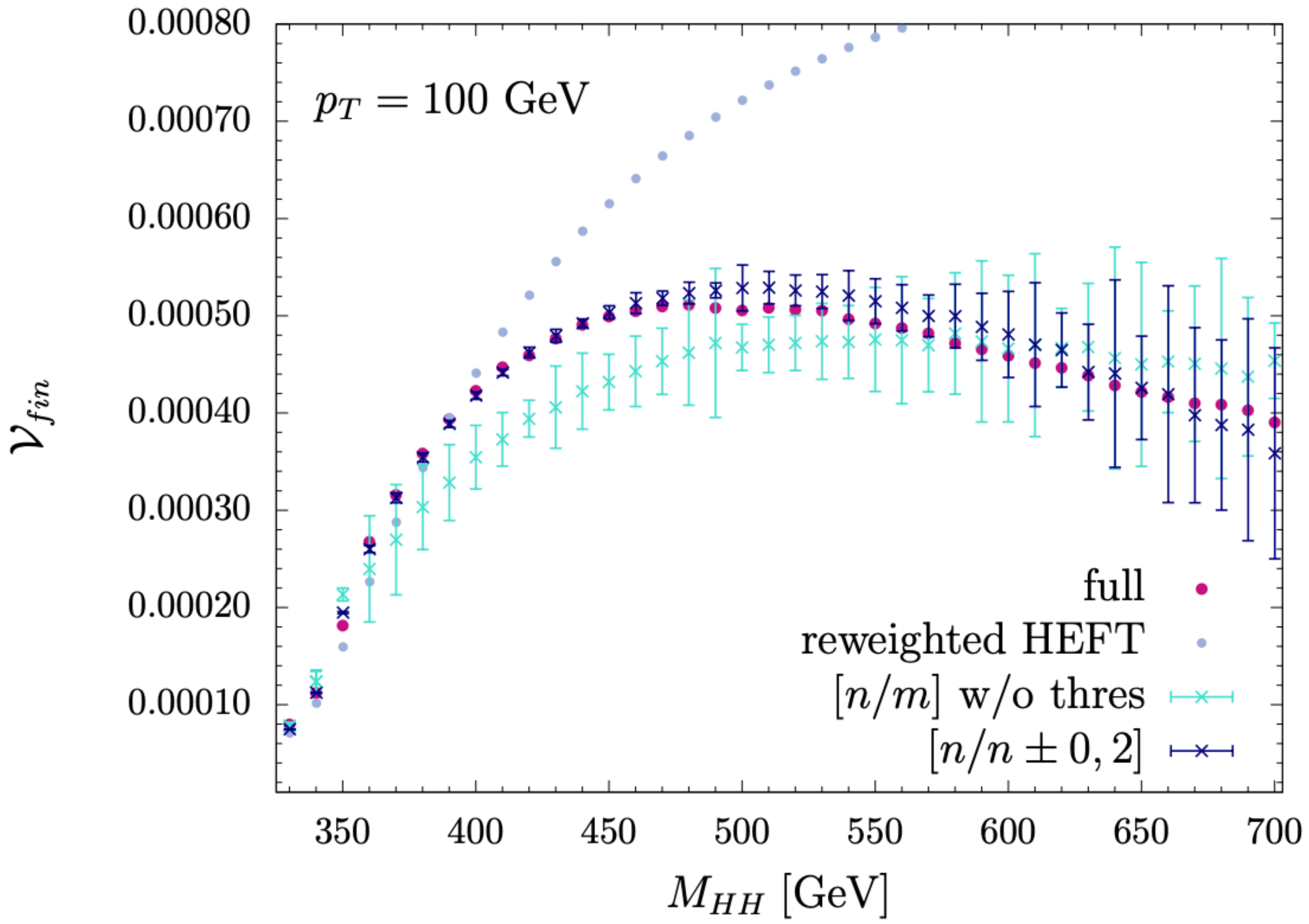


small p_T expansion

Bonciani, Degrassi, Giardino, Gröber '18



Improved/alternative approximations:



Padé approximation

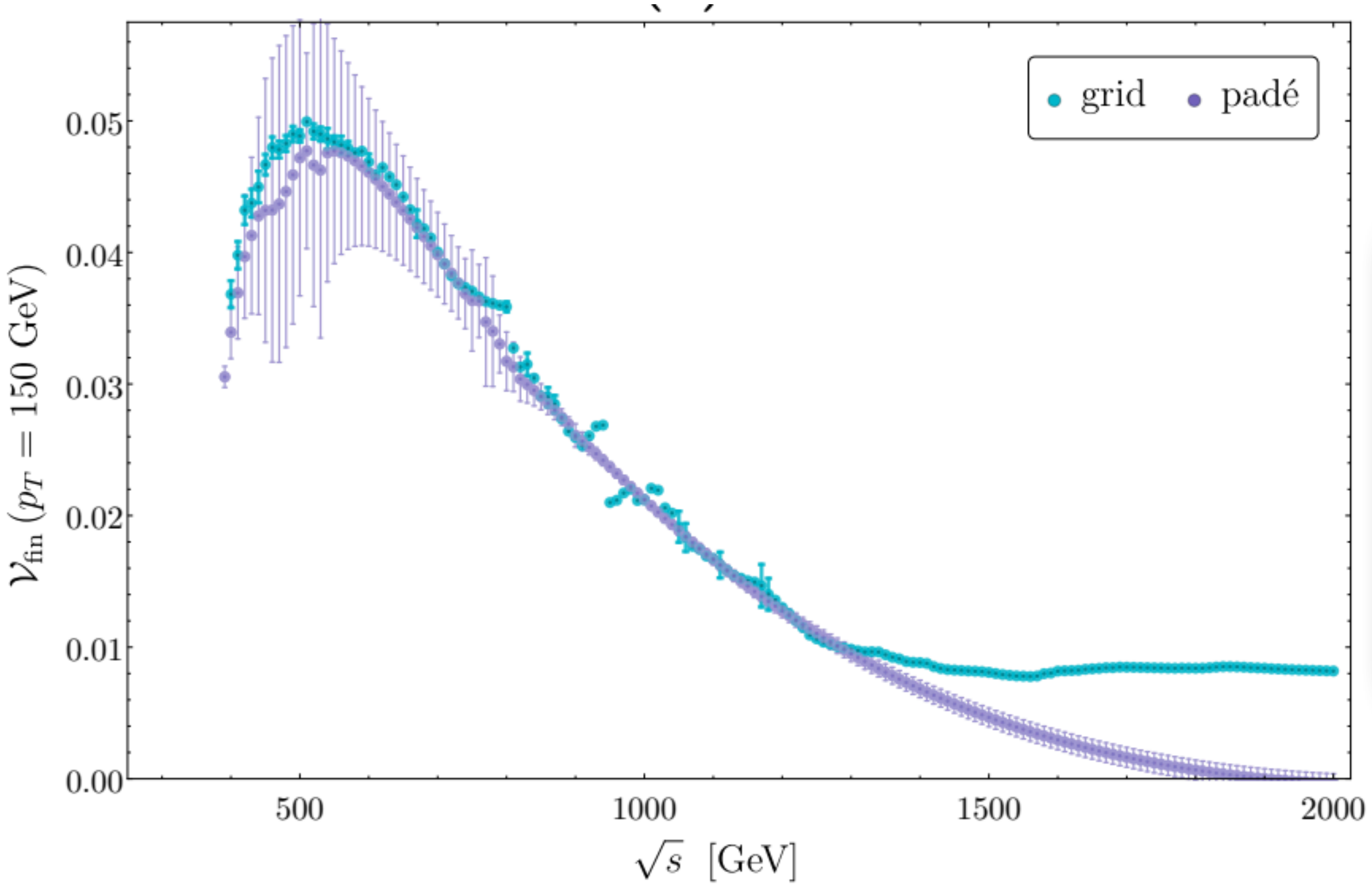
Gröber, Maier, Rauh '18

1/mt with threshold expansion:

$$F^{2l}_{\triangle,C_F} \overset{z\to 1}{\asymp} \pi^2(1-z)\ln(1-z) - \frac{\pi(40-3\pi^2)}{12}(1-z)^{3/2} + \frac{2\pi^2}{3}(1-z)^2\ln(1-z) + \mathcal{O}\left((1-z)^{5/2}\right), \quad (10)$$

Combination with high-energy form factors ($\sqrt{\hat{s}} \gg m_t > m_H, m_W$):

Davies, Mishima, Steinhauser, Wellmann ‘18



Double Higgs boson production at NLO: combining the exact numerical result and high-energy expansion

P3H-19-015

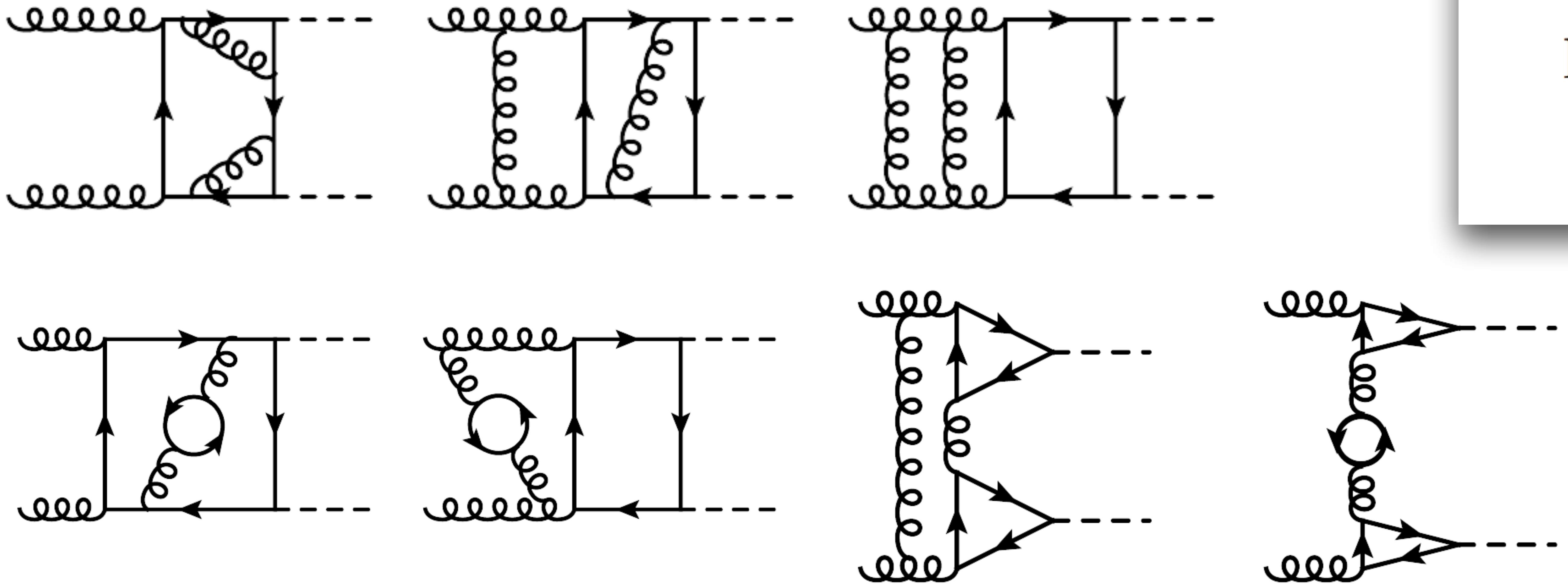
Joshua Davies[a], Gudrun Heinrich[b], Stephen P. Jones[c], Matthias Kerner[d], Go Mishima[a,e], Matthias Steinhauser[a], David Wellmann[a]

Combination with NNLO

Grazzini, Heinrich, Jones, Kallweit, Kerner, Lindert, Mazzitelli ‘18

N^{3}LO in heavy-top limit

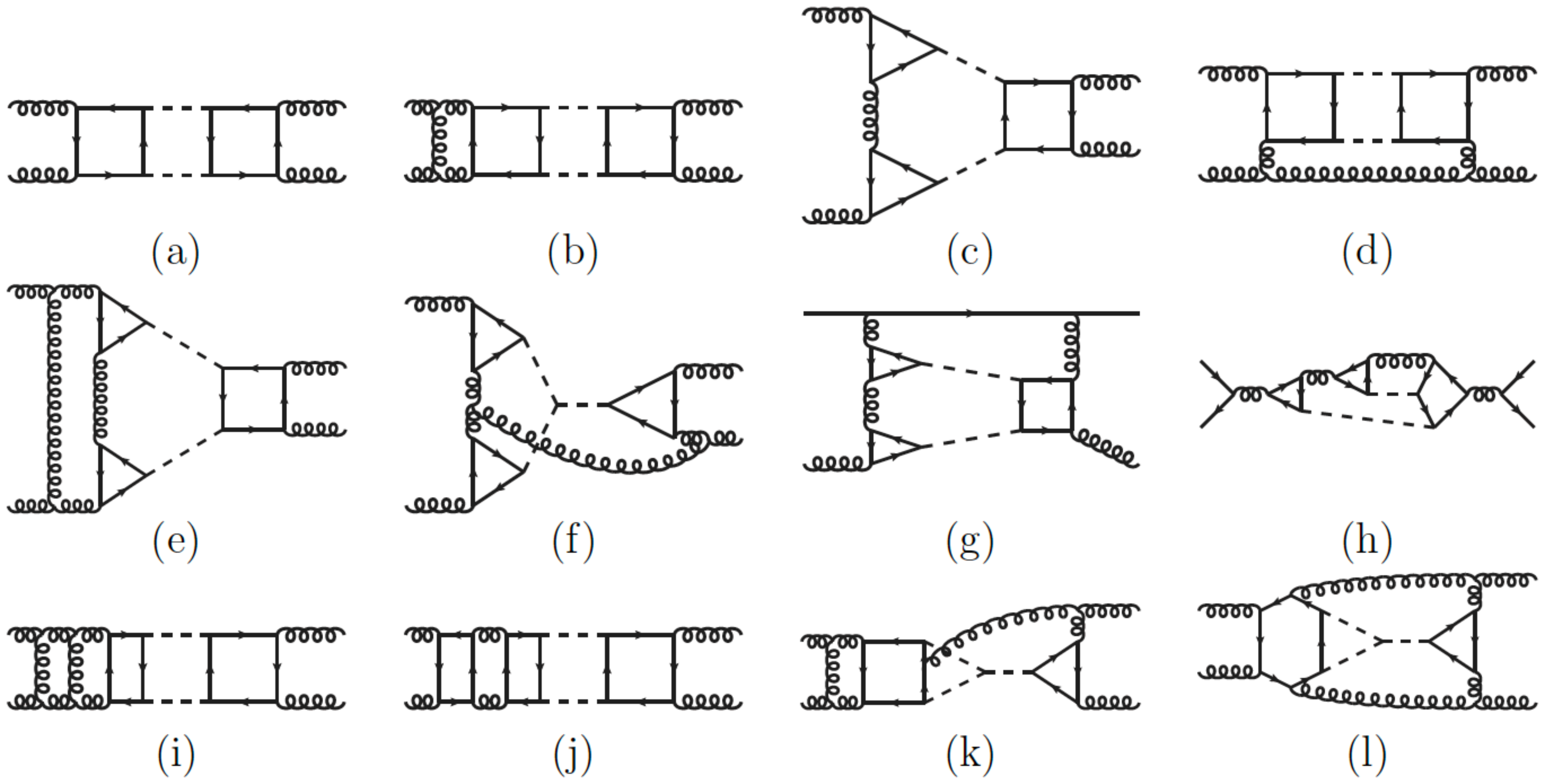
Chen, Li, Shao, Wang ‘20



Three-loop form factors for Higgs boson pair production in the large top mass limit

P3H-19-030

Joshua Davies and Matthias Steinhauser,



Real-virtual corrections to Higgs boson pair production at NNLO: three closed top quark loops

P3H-19-009

Joshua Davies[a], Florian Herren[a], Go Mishima[a,b], Matthias Steinhauser[a]

Application to BSM

$$\mathcal{L} \supset -m_t \left(c_t \frac{h}{v} + c_{tt} \frac{h^2}{v^2} \right) \bar{t}\, t - c_{hhh} \frac{m_h^2}{2v} h^3 + \frac{\alpha_s}{8\pi} \left(c_{ggh} \frac{h}{v} + c_{gghh} \frac{h^2}{v^2} \right) G^a_{\mu\nu} G^{a,\mu\nu}$$

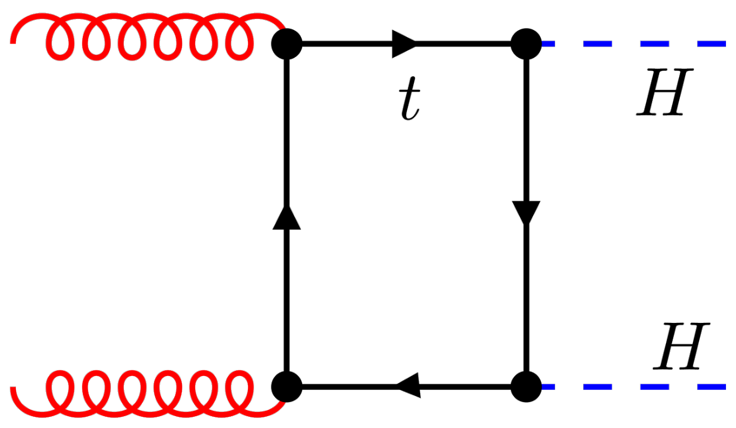
A non-linear EFT description of $gg \to HH$ at NLO interfaced to POWHEG

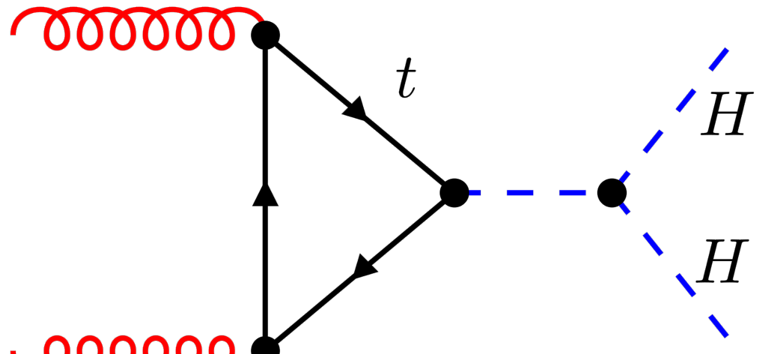
P3H-20-026

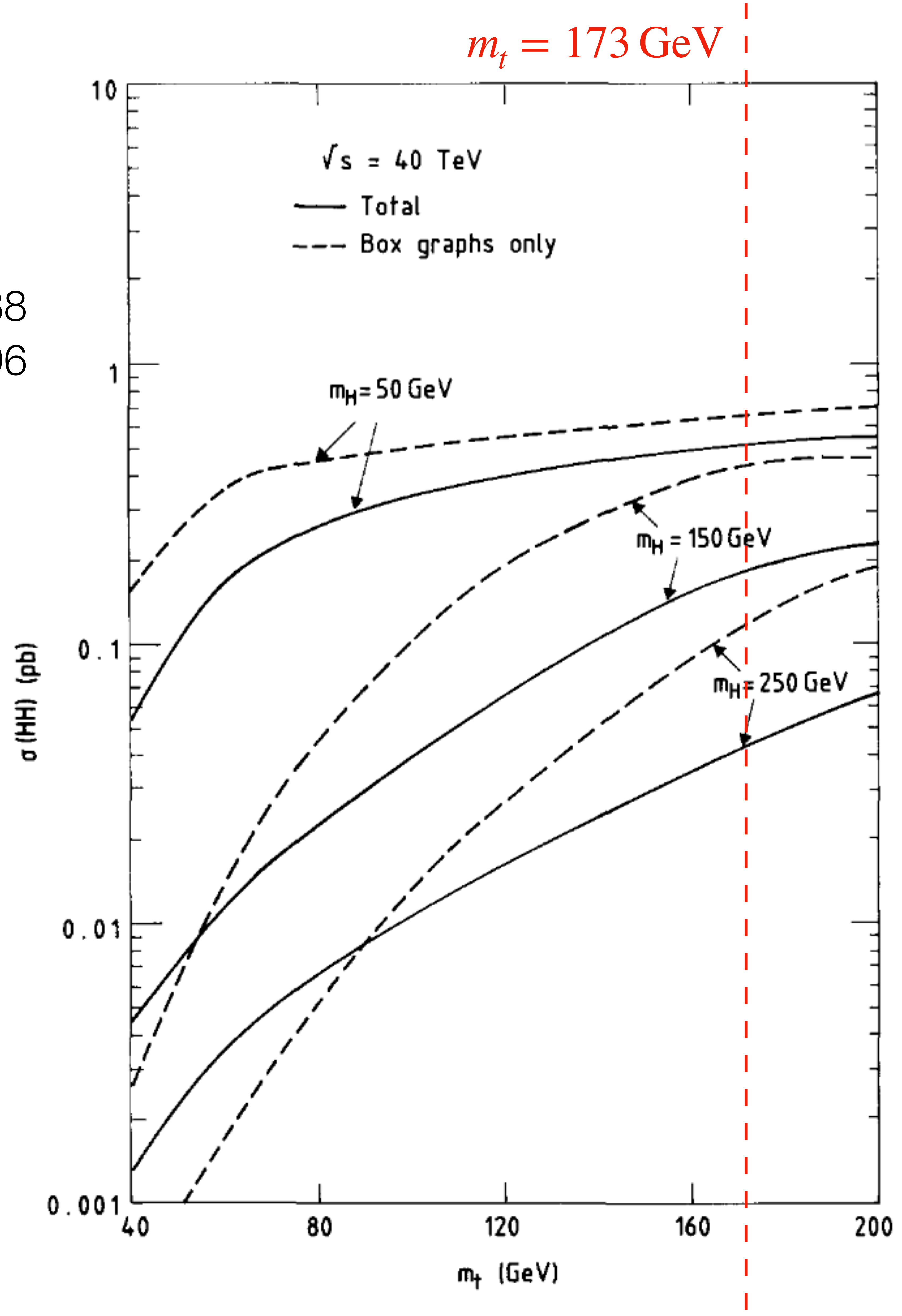
Gudrun Heinrich,[a] Stephen P. Jones,[b] Matthias Kerner,[c] Ludovic Scyboz[d]

HH production

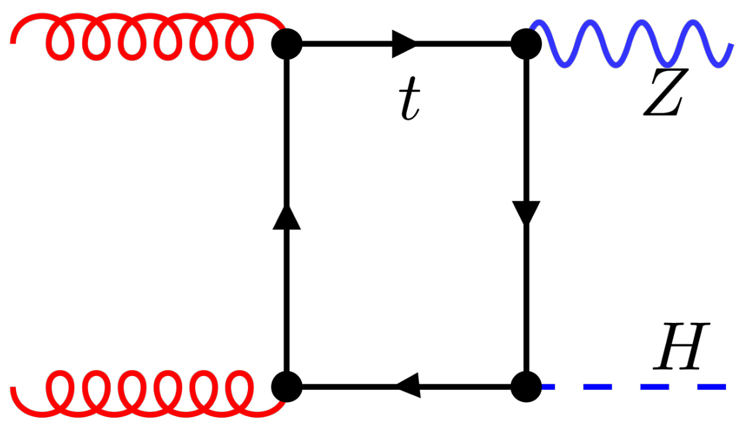
v.d.Bij, Glover ‘88
Plehn, Spira, Zerwas ‘96

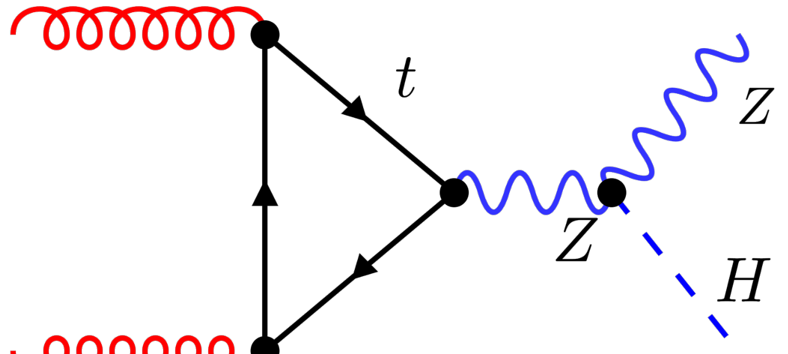






ZH production





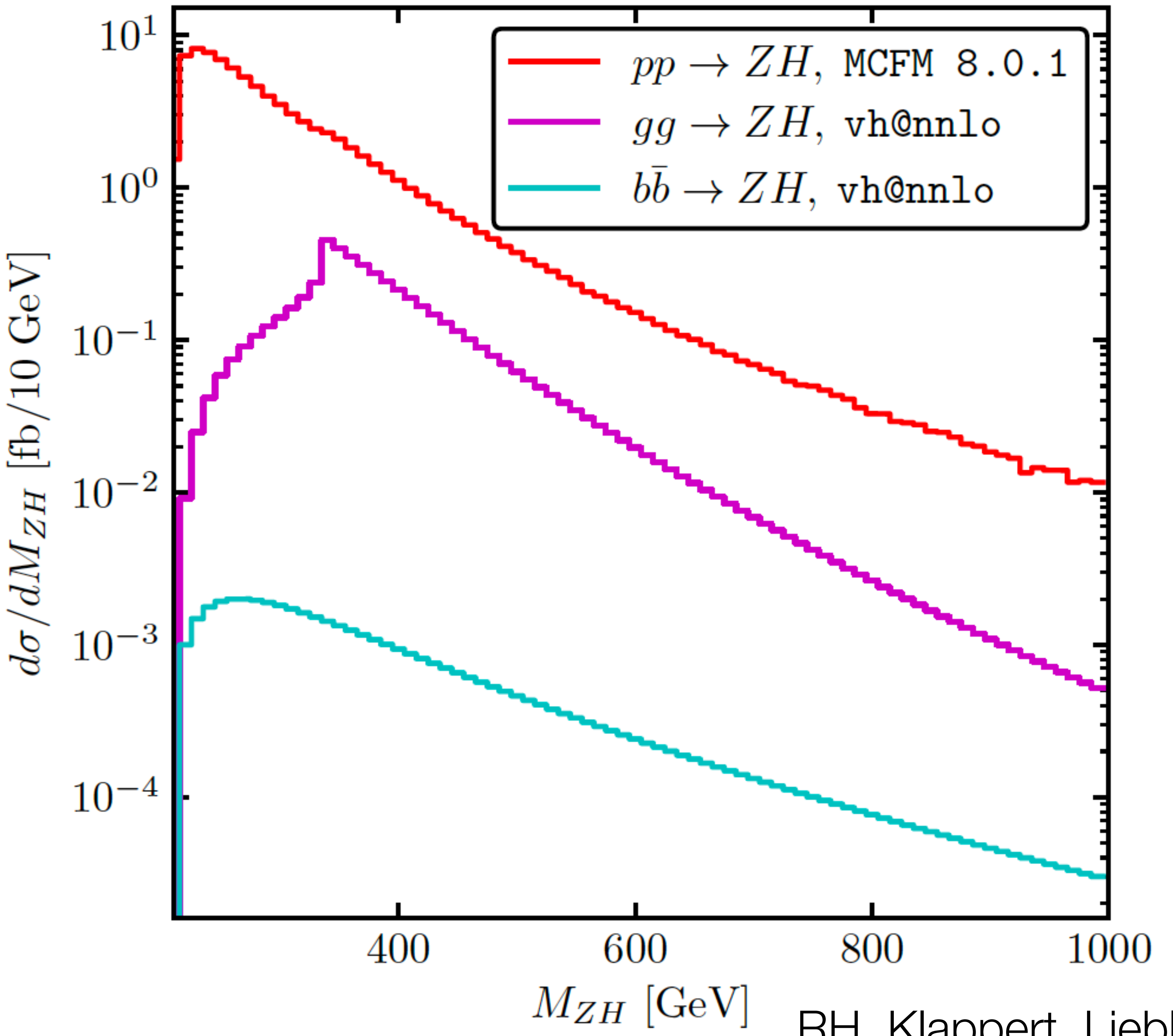
LO

Kniehl '90

NLO 1/mt

Altenkamp, Dittmaier, RH, Rzehak, Zirke '13

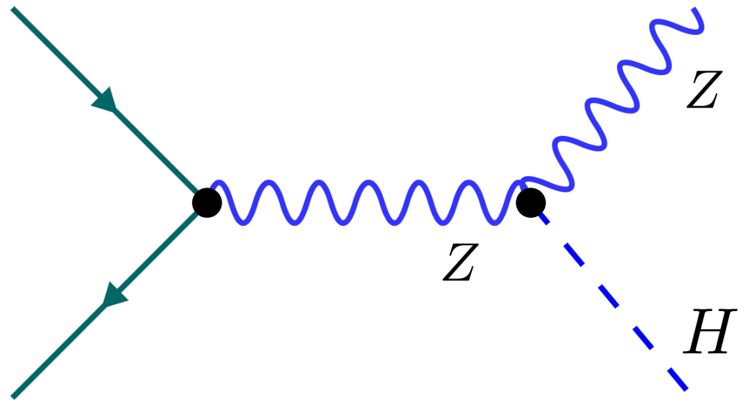
Hasselhuhn, Luthe, Steinhauser '17

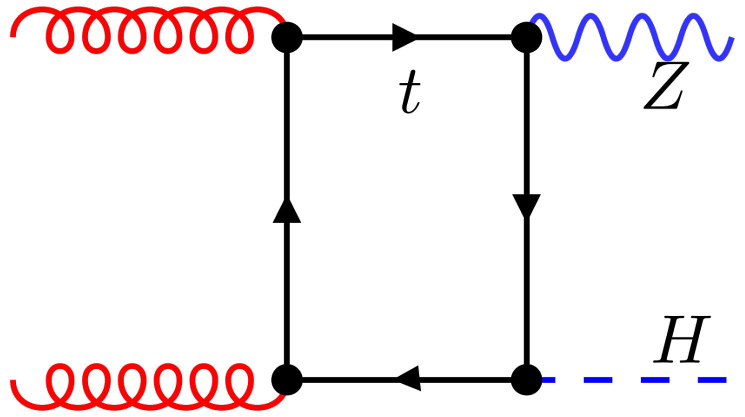


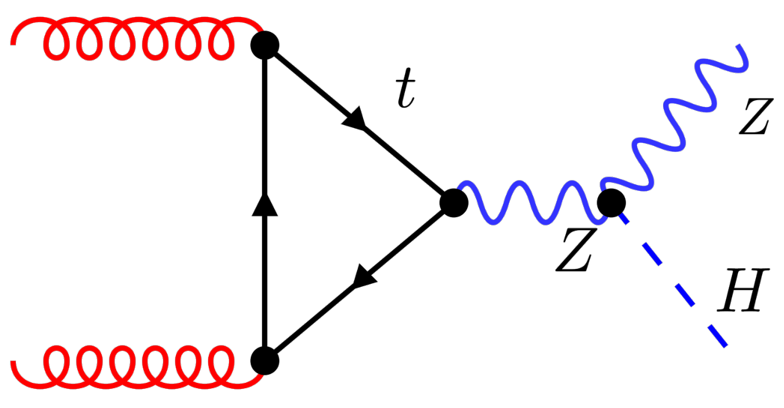
RH, Klappert, Liebler, Simon '18

RH, Klappert, Pandini, Papaefstathiou, '18

ZH production







LO

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Altenkamp, Dittmaier, RH, Rzehak, Zirke '13

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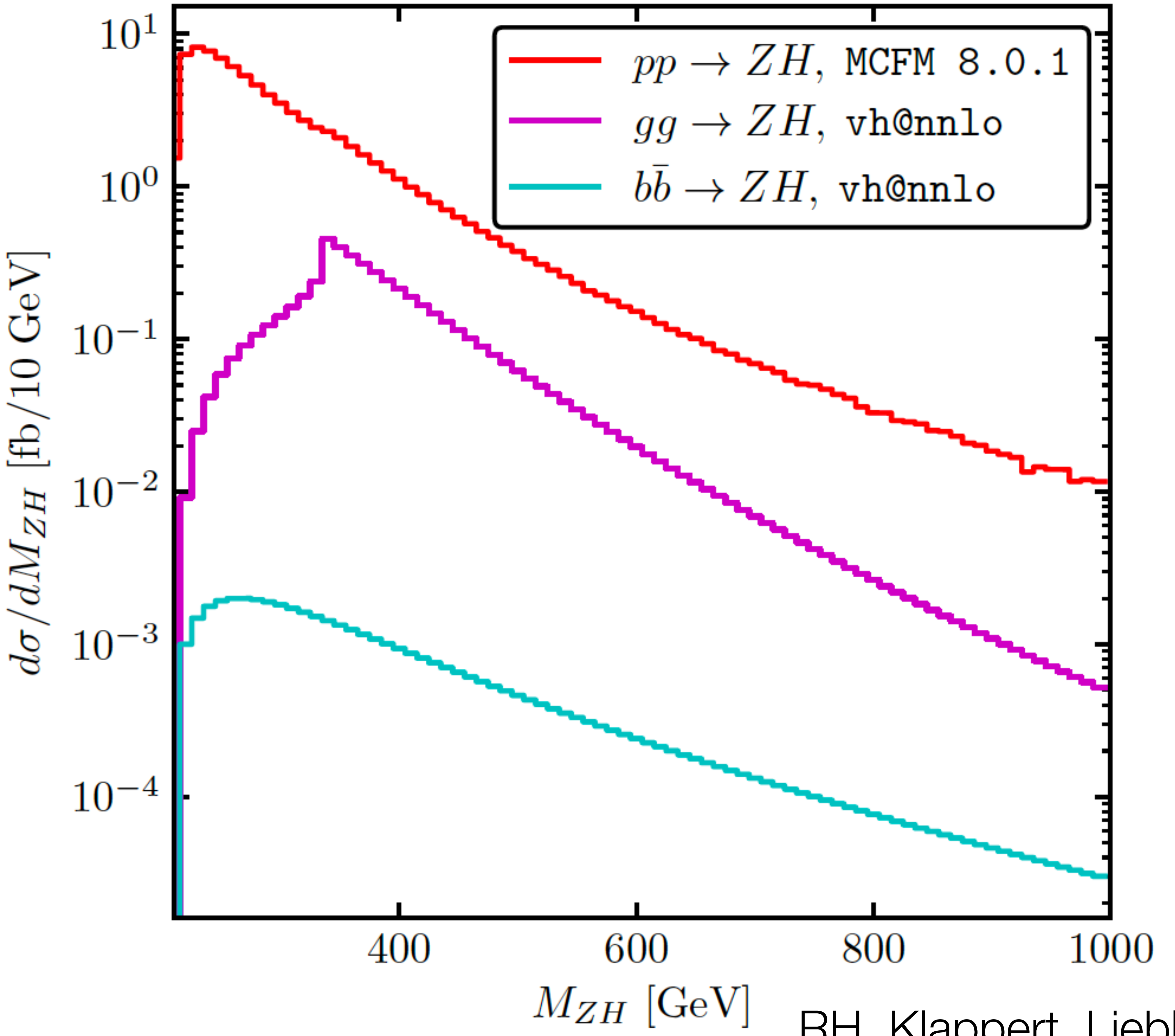
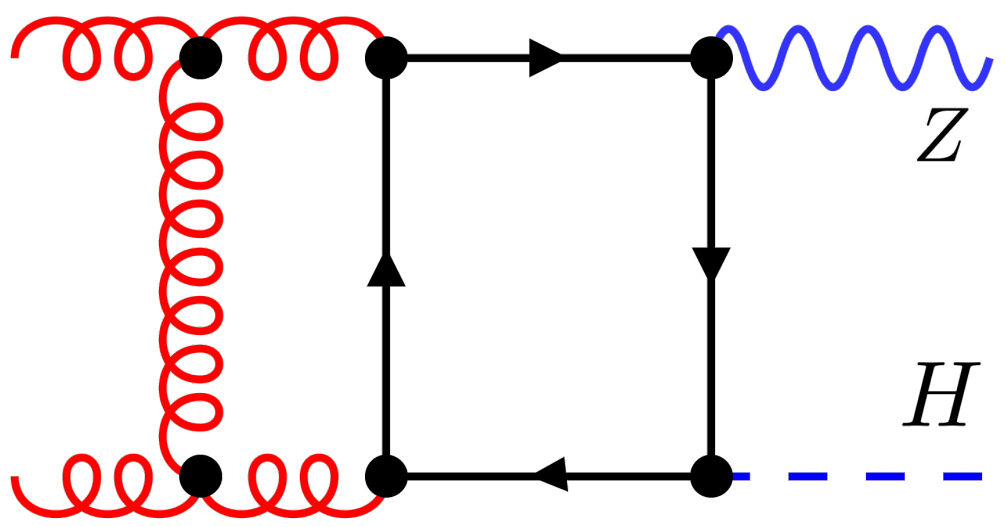


RH, Klappert, Liebler, Simon '18

RH, Klappert, Pandini, Papaefstathiou, '18 exact virtual:

ZH production in gluon fusion: two-loop amplitudes with full top quark mass dependence P3H-20-076

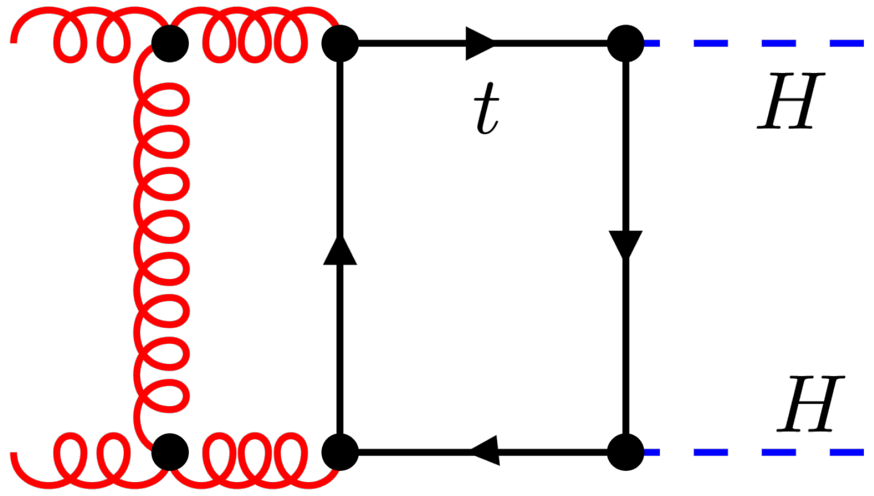
Long Chen,[a,f] Gudrun Heinrich,[b] Stephen P. Jones,[c,d] Matthias Kerner,[e] Jonas Klappert,[f] Johannes Schlenk[g]



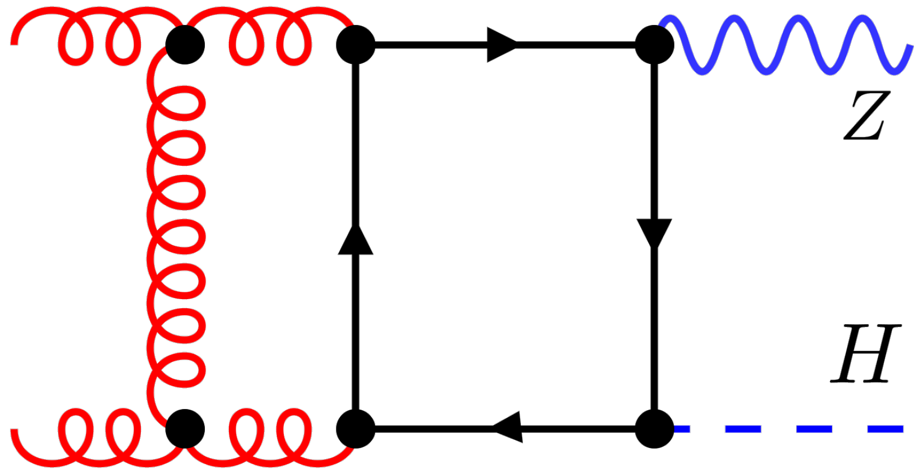
using Kira+FireFly:

Integral Reduction with Kira 2.0 and Finite Field Methods P3H-20-041

Jonas Klappert*,[a], Fabian Lange†,[a], Philipp Maierhöfer‡,[b], and Johann Usovitsch§,[c]



Borowka, Greiner, Heinrich, Jones, Kerner, Schlenk, Schubert, Zirke ‘16
Baglio, Campanario, Glaus, Mühlleitner, Spira, Streicher ‘19



ZH production in gluon fusion: two-loop amplitudes with full top quark mass dependence P3H-20-076

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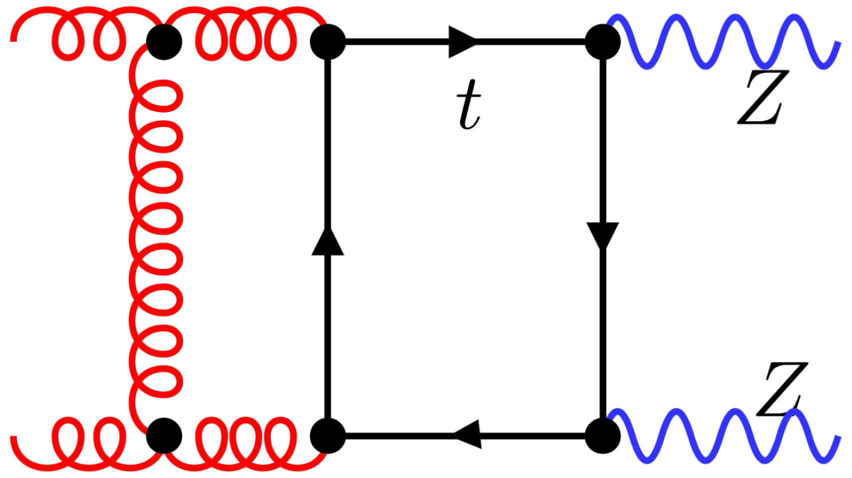
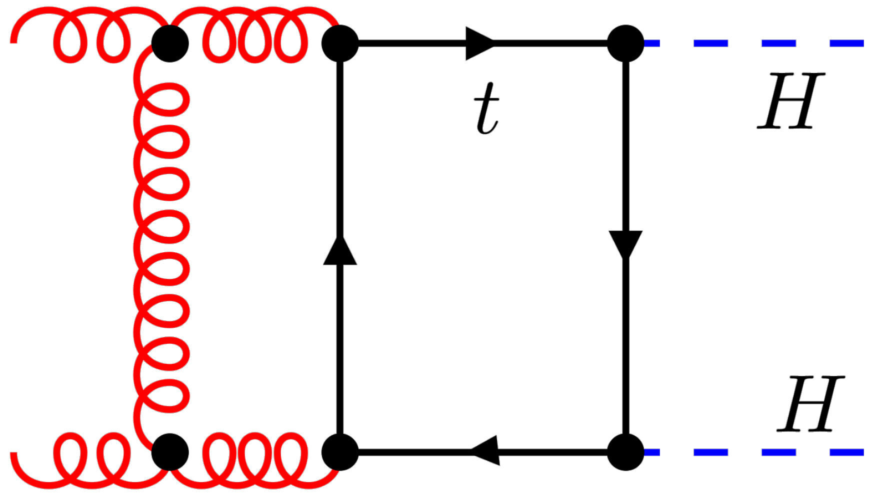


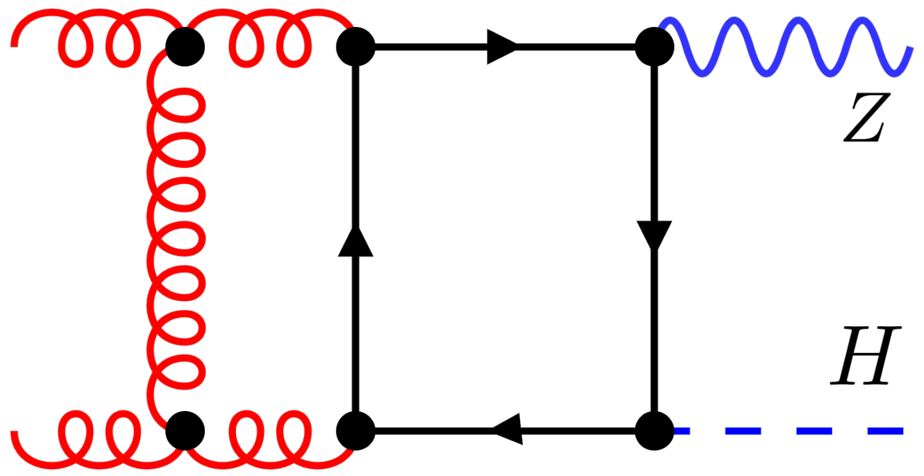
Top quark contribution to two-loop helicity amplitudes for Z boson pair production in gluon fusion

P3H-21-008

Christian Brønnum-Hansen and Chen-Yu Wang

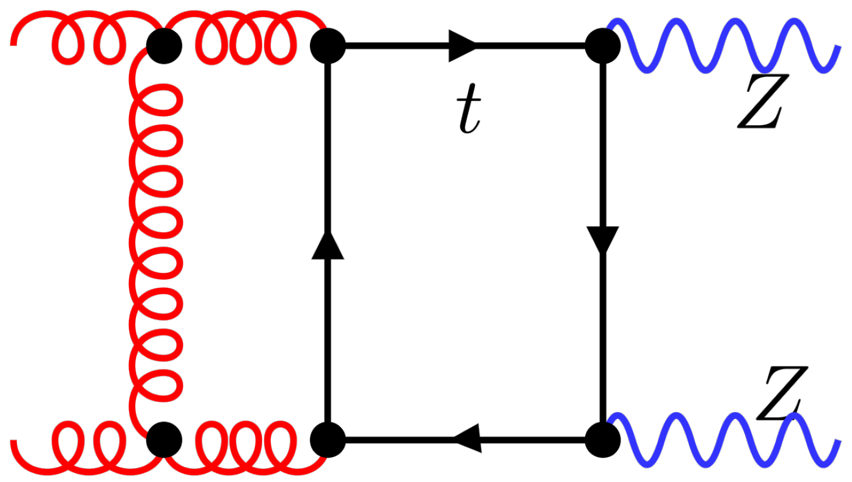


Borowka, Greiner, Heinrich, Jones, Kerner, Schlenk, Schubert, Zirke ‘16
Baglio, Campanario, Glaus, Mühlleitner, Spira, Streicher ‘19



ZH production in gluon fusion: two-loop amplitudes with full top quark mass dependence P3H-20-076

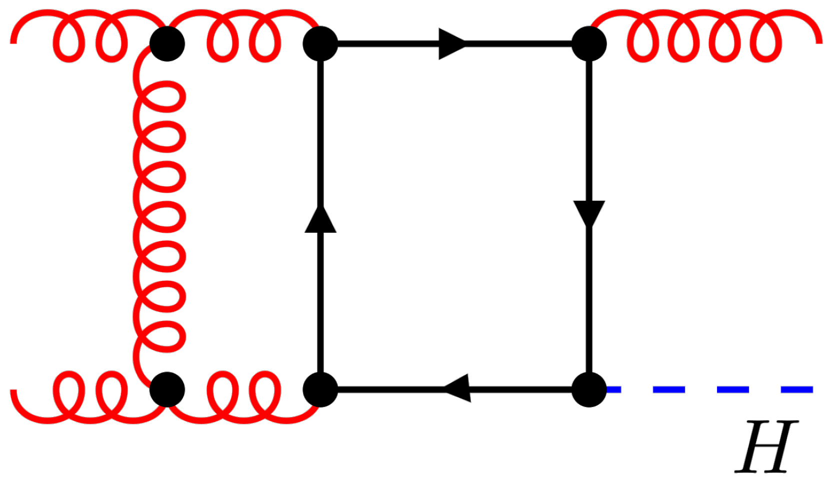
Long Chen,[a,f] Gudrun Heinrich,[b] Stephen P. Jones,[c,d] Matthias Kerner,[e] Jonas Klappert,[f] Johannes Schlenk[g]

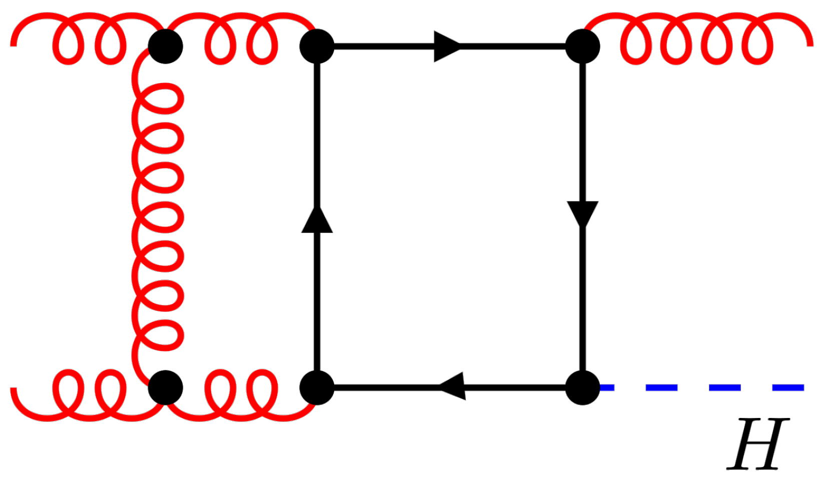


Top quark contribution to two-loop helicity amplitudes for Z boson pair production in gluon fusion

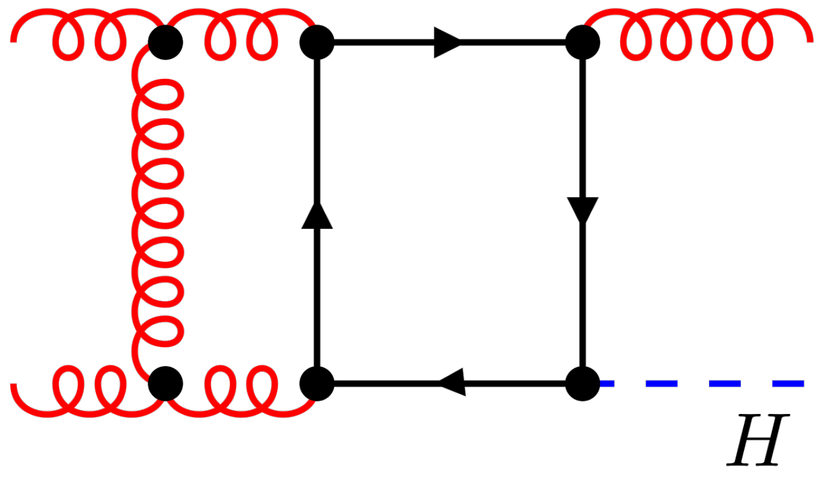
P3H-21-008

Christian Brønnum-Hansen and Chen-Yu Wang





Lindert, Kudashkin, Melnikov, Wever ‘18 (large p_T)
Jones, Kerner, Luisoni ‘18



Lindert, Kudashkin, Melnikov, Wever '18 (large p_T)
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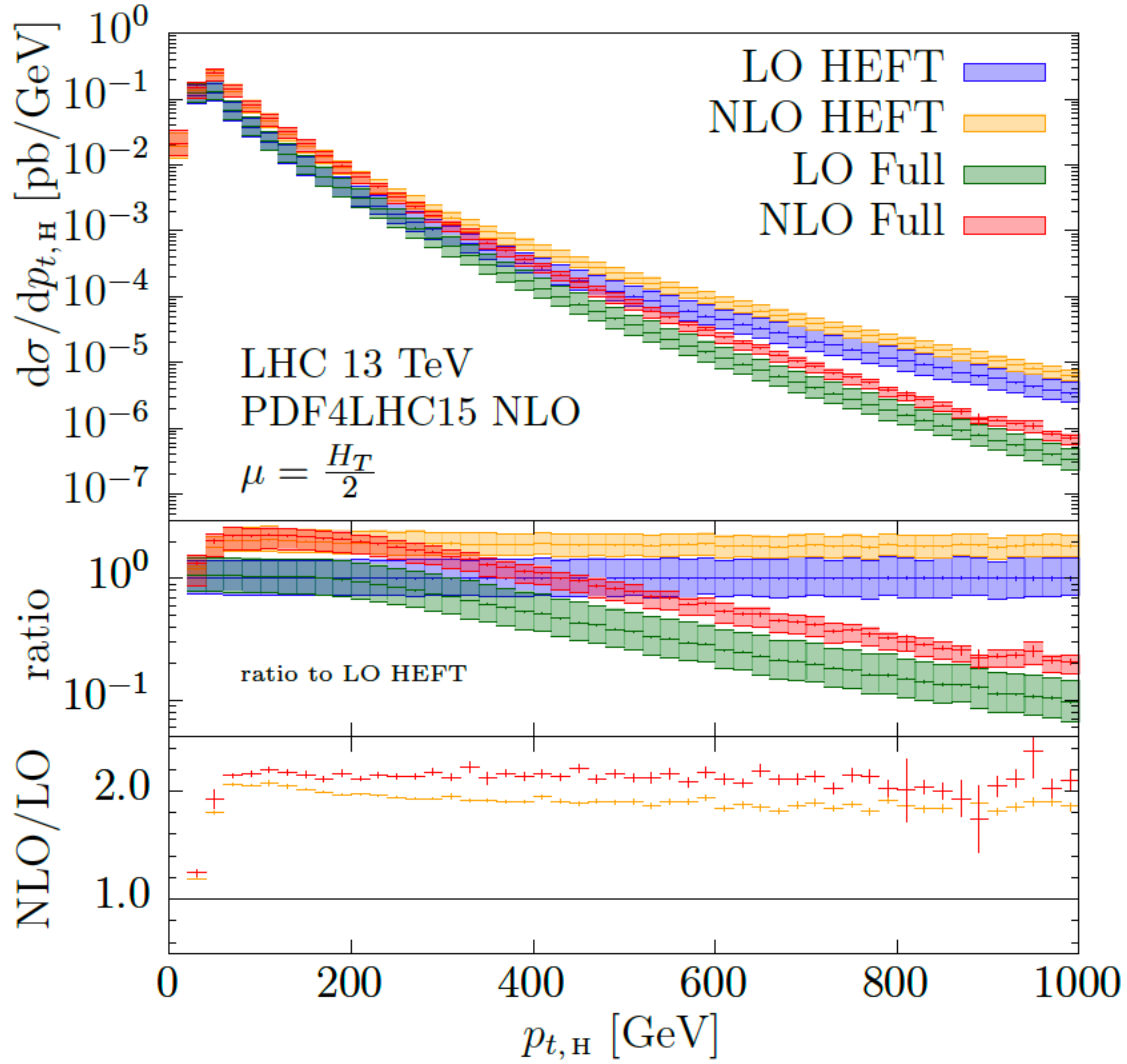

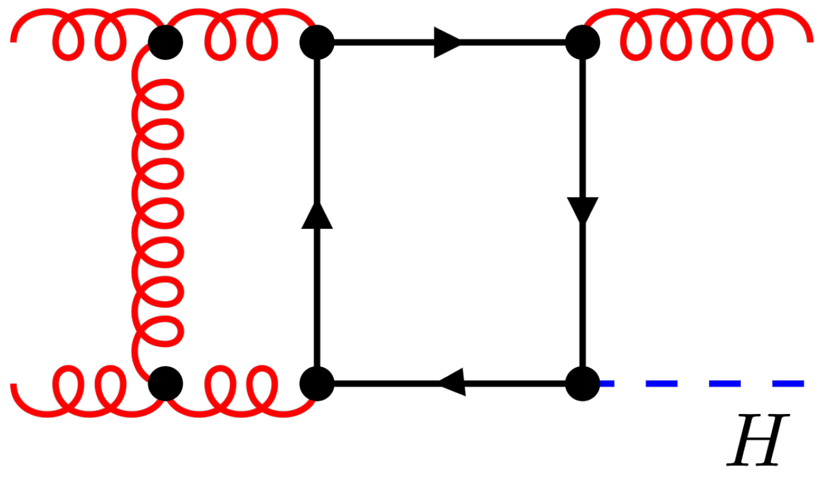

Lindert, Kudashkin, Melnikov, Wever '18 (large p_T)
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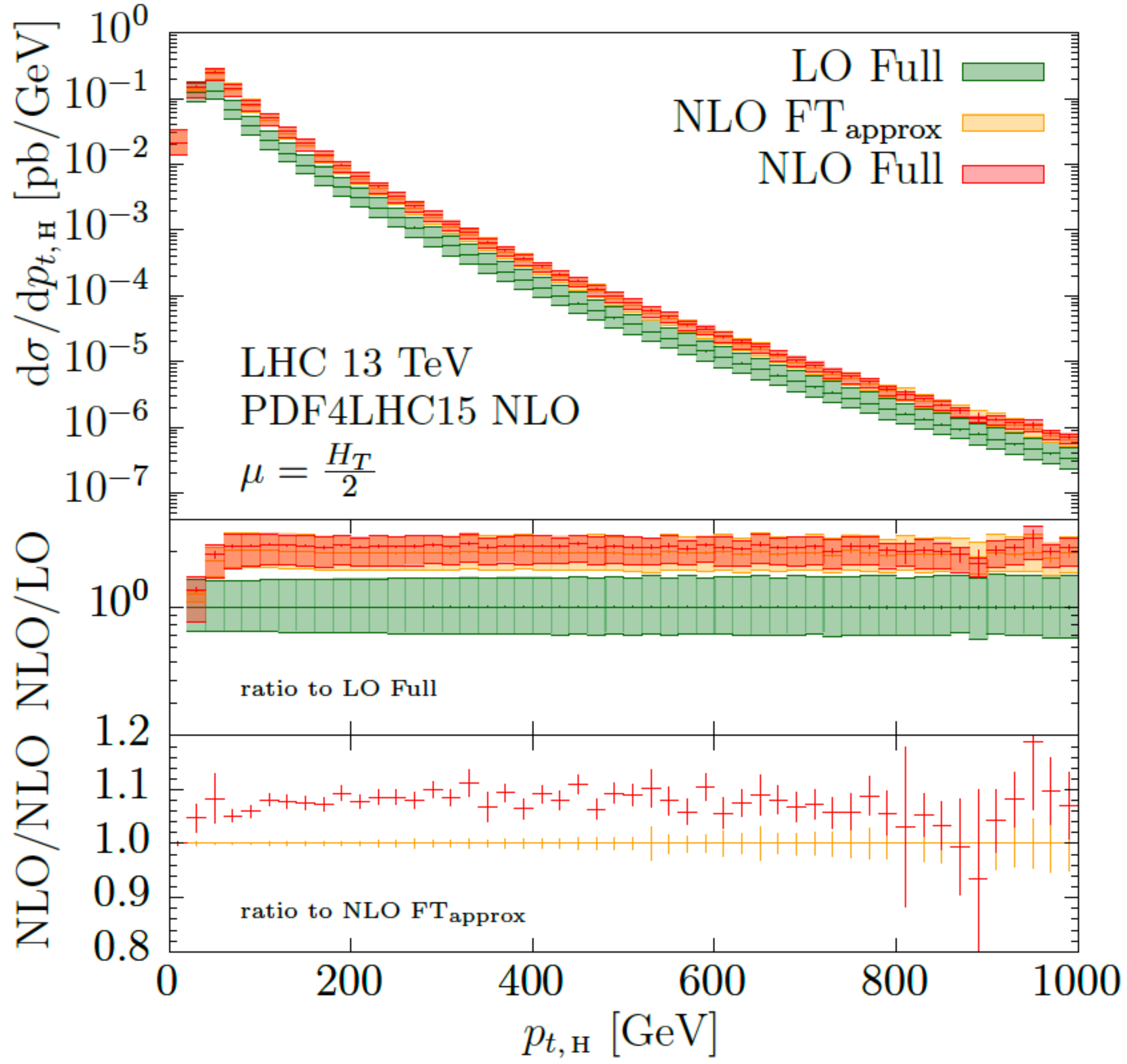

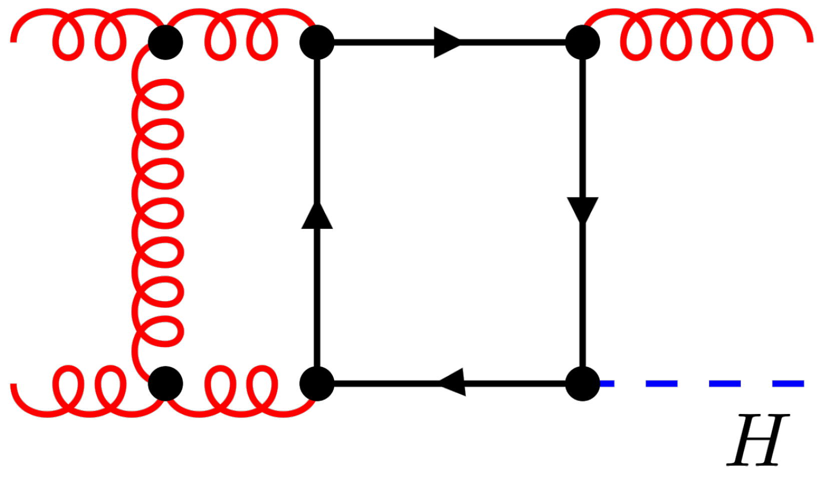

Lindert, Kudashkin, Melnikov, Wever '18 (large p_T)
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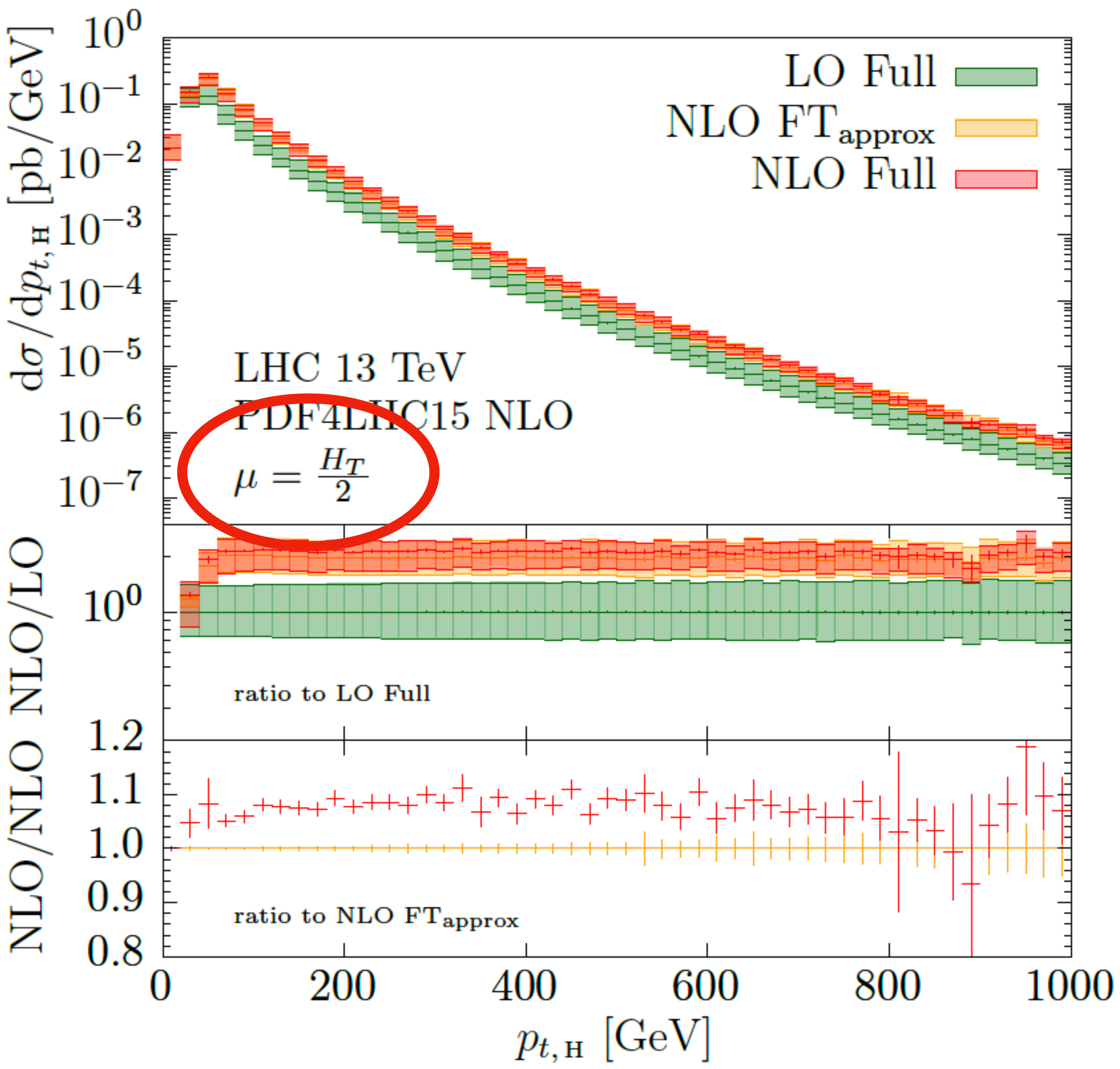

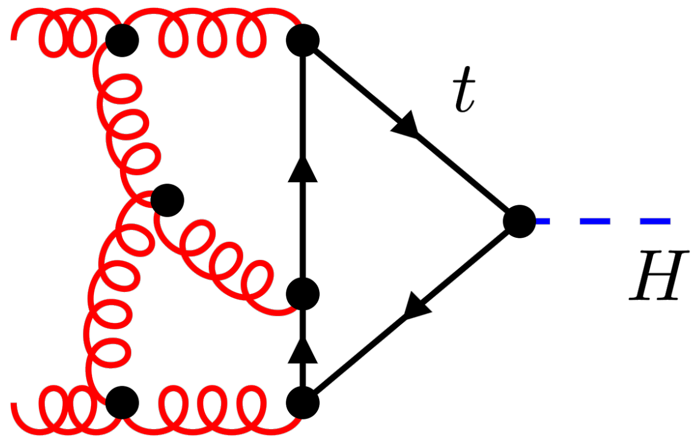

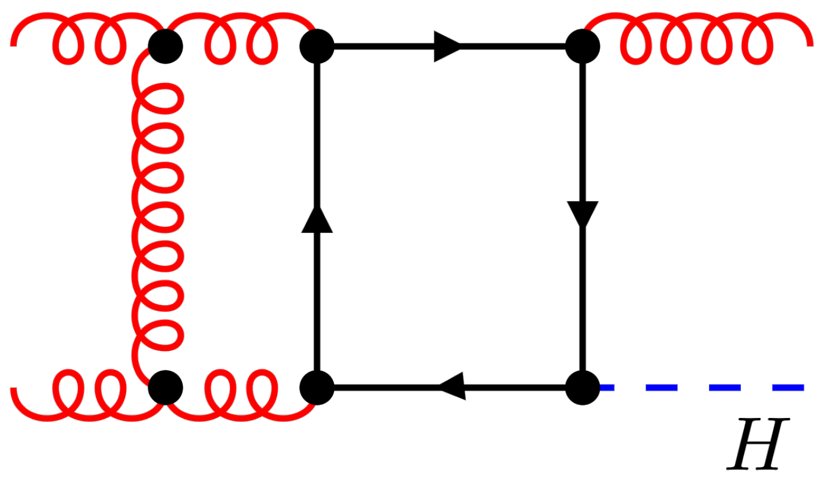

Lindert, Kudashkin, Melnikov, Wever ‘18 (large p_T)
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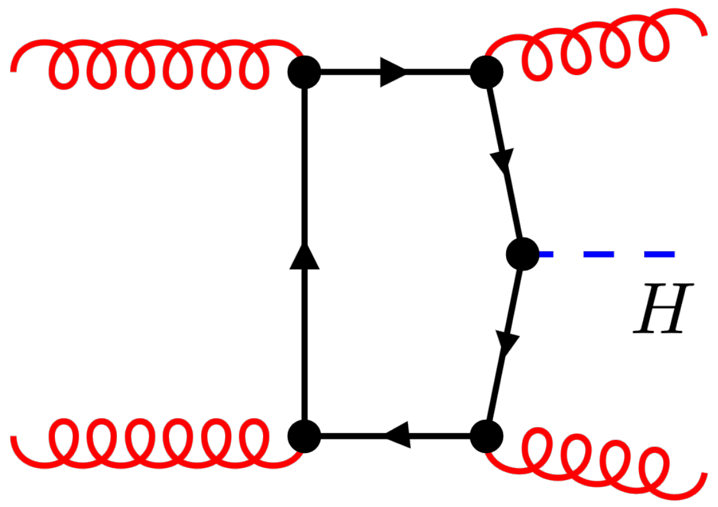
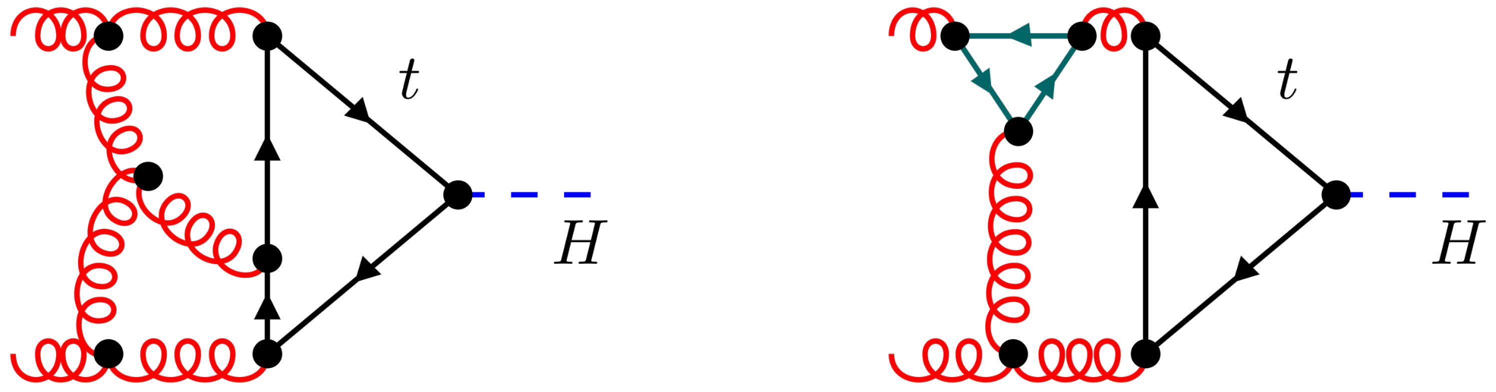
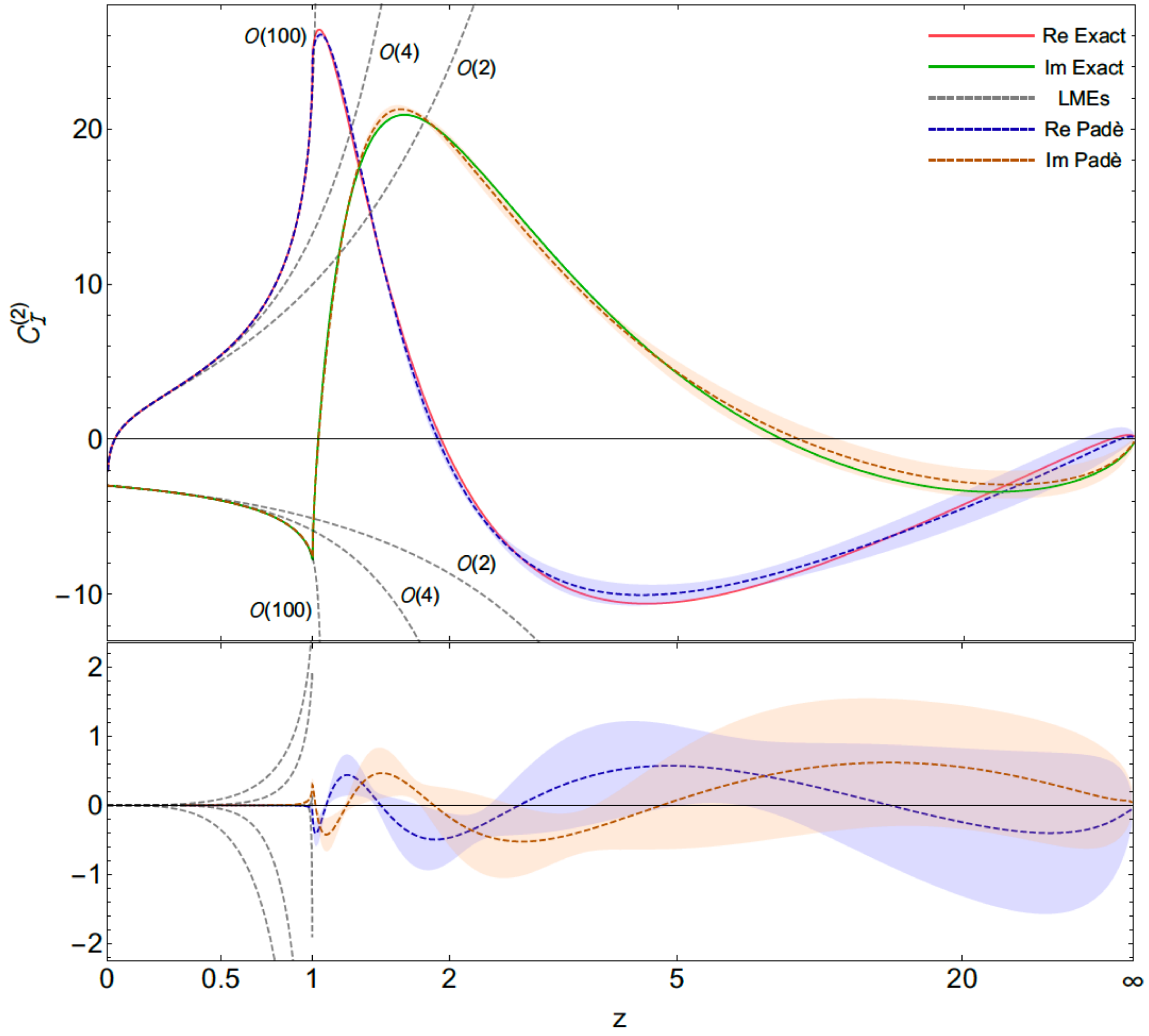


Del Duca, Kilgore, Schmidt, Oleari, Zeppenfeld ‘01

meanwhile: OpenLoops, MCFM, …





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

P3H-19-012

Joshua Davies[(a)], Ramona Gröber[(b)], Andreas Maier[(c)], Thomas Rauh[(d)], Matthias Steinhauser[(a)],

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

P3H-19-021

Robert V. Harlander[1], Mario Prausa[2], and Johann Usovitsch[3]

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

P3H-20-001

Michał Czakon and Marco Niggetiedt

δ(scale)	δ(trunc)	δ(PDF-TH)	δ(EW)	δ(t, b, c)	δ(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%	±0.37%	±1.16%	±1%	±0.83%	±1%

	α_s^2		α_s^3		α_s^4			
gg	16.30	+	19.64	+	8.76	0.2 %	2.8 %	→ + 0.5 %
qg			1.49	+	0.84	24.8 %	−1.4 %	→ − 0.02 %
qq			0.02	+	0.10	161 %	−50 %	→ − 0.1 %
total	16.30	+	21.15	+	9.79	3.5 %	+1.9 %	→ + 0.38 %

NLO+NNLO: −0.26 %

Exact top-quark mass dependence in hadronic Higgs production

M. Czakon, R.V. Harlander, J. Klappert, M. Niggetiedt
Institute for Theoretical Particle Physics and Cosmology, RWTH Aachen University, 52056 Aachen, Germany
(Dated: May 11, 2021)

P3H-21-031

δ(scale)	δ(trunc)	δ(PDF-TH)	δ(EW)	δ(t, b, c)	δ(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%	±0.37% ✔	±1.16%	±1% ✔	±0.83%	±1% ✔

	α_s^2	α_s^3	α_s^4			
gg	16.30 +	19.64 +	8.76	0.2 %	2.8 %	→ + 0.5 %
qg		1.49 +	0.84	24.8 %	−1.4 %	→ − 0.02 %
qq		0.02 +	0.10	161 %	−50 %	→ − 0.1 %
total	16.30 +	21.15 +	9.79	3.5 %	+1.9 %	→ + 0.38 %

Exact top-quark mass dependence in hadronic Higgs production

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(Dated: May 11, 2021)

P3H-21-031

NLO+NNLO: −0.26 %

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%	±0.37% ✓	±1.16%	±1% ✓	±0.83%	±1% ✓

	α_s^2 + α_s^3 + α_s^4			
gg	16.30 + 19.64 + 8.76	0.2 %	2.8 %	→ + 0.5 %
qg	1.49 + 0.84	24.8 %	−1.4 %	→ − 0.02 %
qq	0.02 + 0.10	161 %	−50 %	→ − 0.1 %
total	16.30 + 21.15 + 9.79	3.5 %	+1.9 %	→ + 0.38 %

NLO+NNLO: −0.26 %

Exact top-quark mass dependence in hadronic Higgs production

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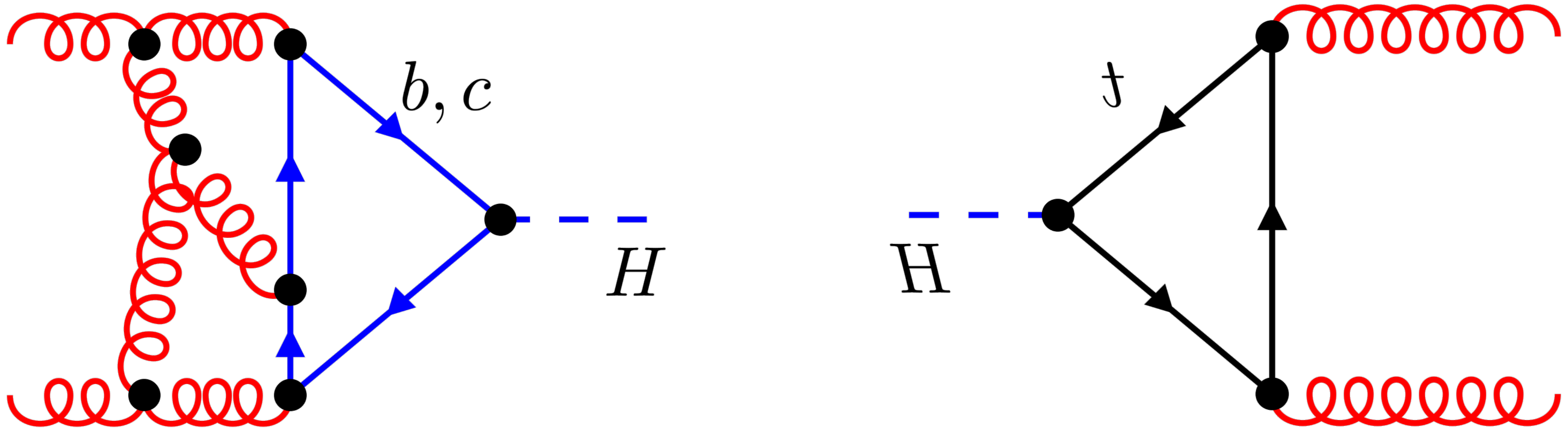
Institute for Theoretical Particle Physics and Cosmology, RWTH Aachen University, 52056 Aachen, Germany
(Dated: May 11, 2021)

YSF

P3H-21-031

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



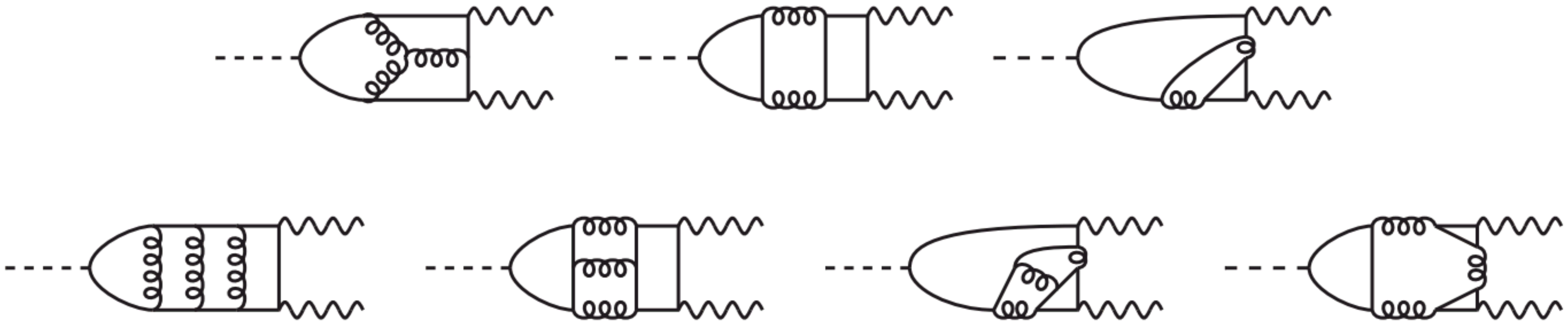
intricate structure of $\ln \dfrac{m_b}{m_H}$

Melnikov, Penin ‘16

Anastasiou, Penin ‘20

Liu, Mecaj, Neubert, Wang ‘20

What I could not talk about…



Exact quark-mass dependence of the Higgs-photon form factor at three loops in QCD

P3H-20-050

Marco Niggetiedt

3-loop exact

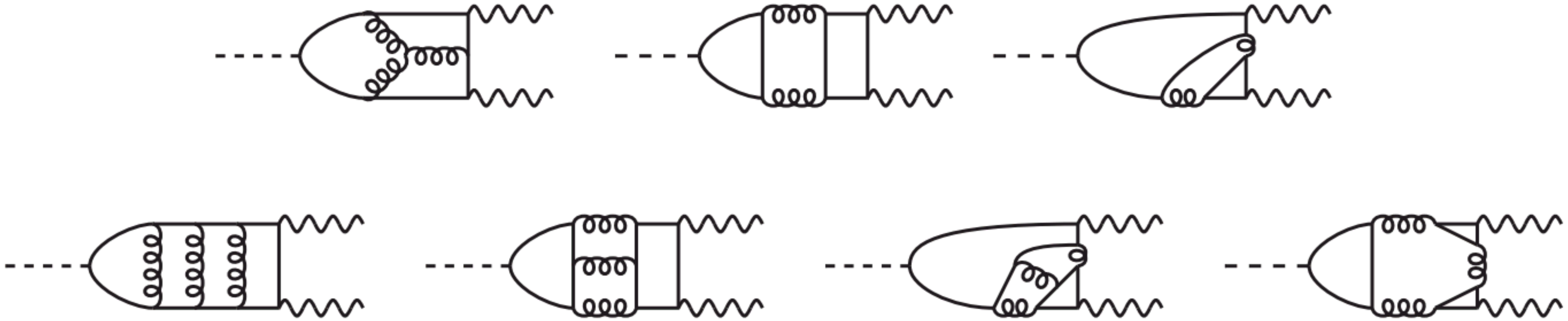
Higgs boson decay into photons at four loops

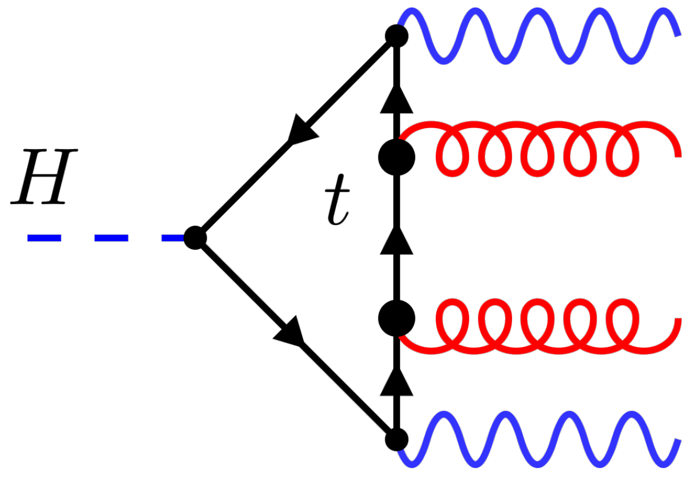
P3H-21-028

Joshua Davies[1] and Florian Herren[2*]

4-loop, expansion in 1/mt

What I could not talk about…





Exact quark-mass dependence of the Higgs-photon form factor at three loops in QCD

P3H-20-050

Marco Niggetiedt

3-loop exact

Higgs boson decay into photons at four loops

P3H-21-028

Joshua Davies[1] and Florian Herren[2*]

4-loop, expansion in 1/mt

NNLO QCD corrections to three-photon production at the LHC

P3H-19-041

Herschel A. Chawdhry,[a] Michał Czakon,[b] Alexander Mitov,[a] Rene Poncelet[a]

Two-loop leading-colour QCD helicity amplitudes for two-photon plus jet production at the LHC

P3H-21-014

Herschel A. Chawdhry,[a] Michał Czakon,[b] Alexander Mitov,[c] Rene Poncelet[c]

NNLO QCD corrections to diphoton production with an additional jet at the LHC

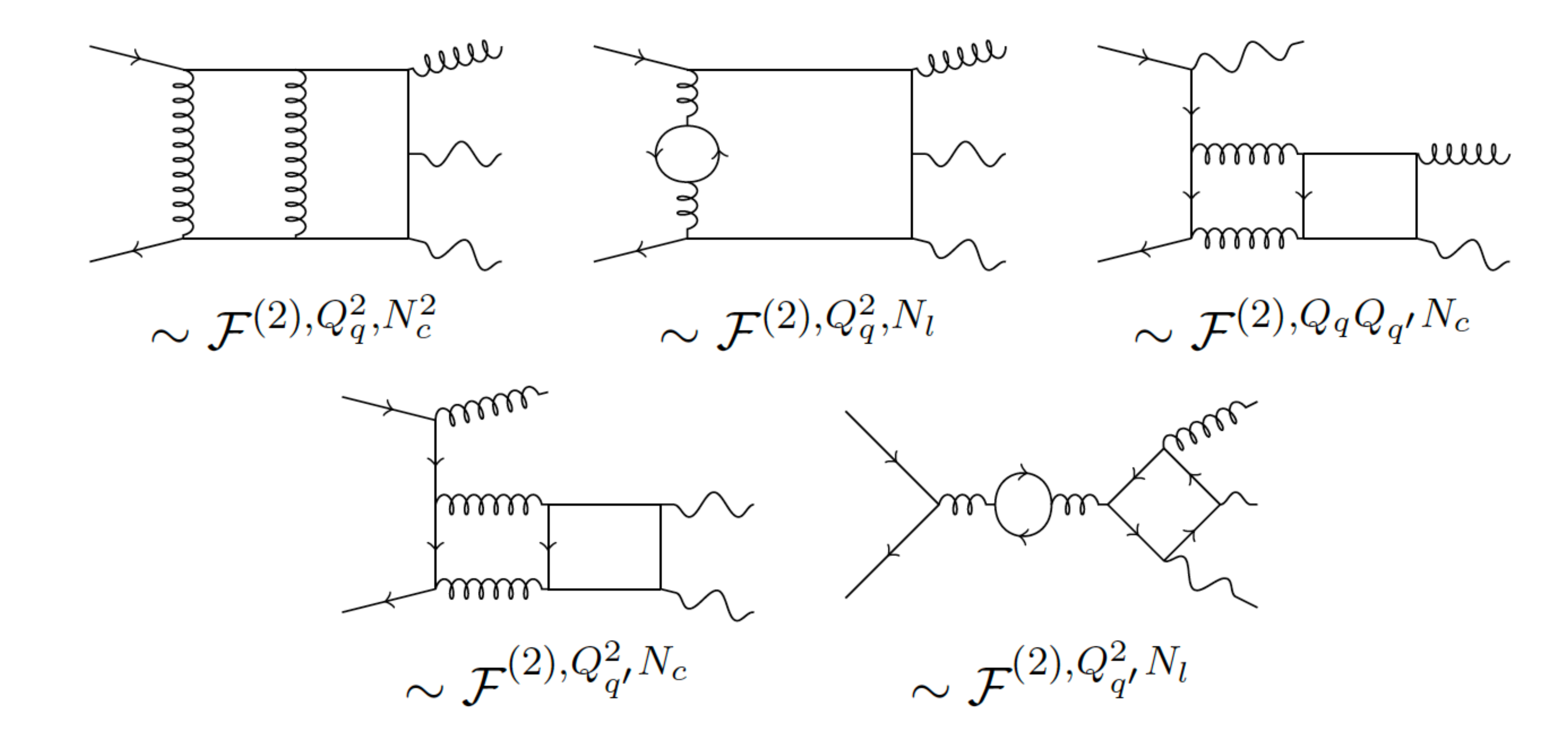
P3H-21-032

Herschel A. Chawdhry,[a] Michał Czakon,[b] Alexander Mitov,[c] Rene Poncelet[c]

Two-loop leading-color helicity amplitudes for three-photon production at the LHC

P3H-21-084

Herschel A. Chawdhry,[a] Michał Czakon,[b] Alexander Mitov,[c] Rene Poncelet[c]



also: Agarwal, Buccioni, von Manteuffel, Tancredi ‘21

What I could not talk about…

Energy-energy correlation in hadronic Higgs decays: analytic results and phenomenology at NLO

P3H-20-060

Jun Gao,[a,b] **Vladyslav Shtabovenko,**[c,e] **Tong-Zhi Yang,**[d,e]

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

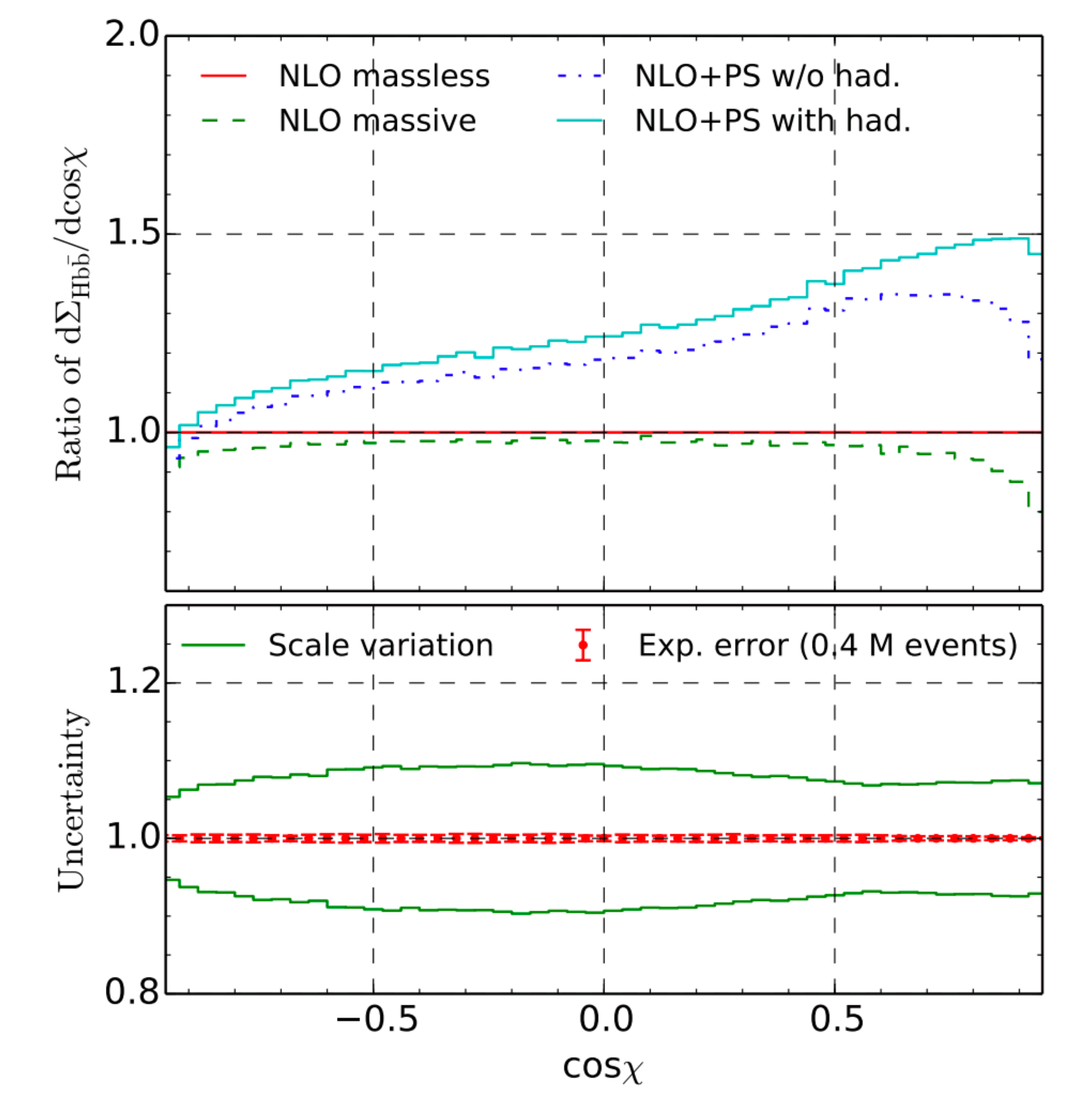
P3H-20-009

Arnd Behring,[1,*] Wojciech Bizoń,[1,2,†] Fabrizio Caola,[3,‡] Kirill Melnikov,[1,§] and Raoul Röntsch[4,¶]

Higgs decay into massive b-quarks at NNLO QCD in the nested soft-collinear subtraction scheme

P3H-19-047

Arnd Behring[a], Wojciech Bizoń[a,b].



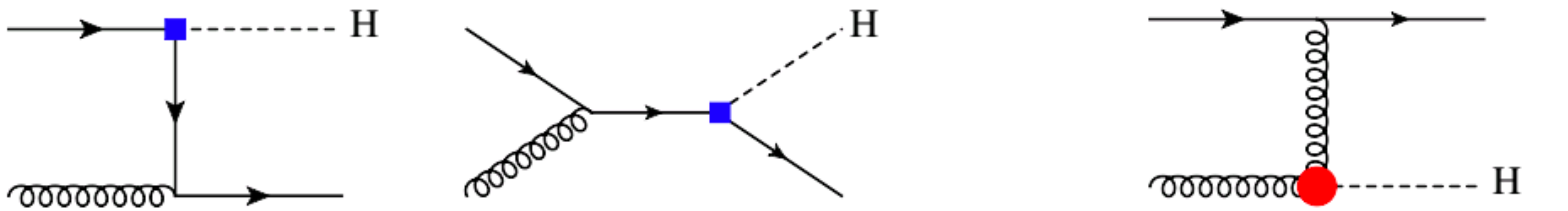
Order	b quarks	σ_{fid} [fb]	σ_{fid}(boosted) [fb]
LO	massive	$22.623^{+0.845}_{-1.047}$	$3.735^{+0.000}_{-0.016}$
	massless	$22.501^{+0.796}_{-1.007}$	$3.638^{+0.000}_{-0.009}$
NLO	massive	$25.364(1)^{+0.778}_{-0.756}$	$4.586(1)^{+0.158}_{-0.141}$
	massless	$24.421(1)^{+0.852}_{-0.879}$	$4.333(1)^{+0.165}_{-0.154}$
NNLO	massive	$24.225(4)^{+0.642}_{-0.742}$	$4.530(2)^{+0.071}_{-0.096}$
	massless	$22.781(3)^{+0.791}_{-0.898}$	$4.207(1)^{+0.097}_{-0.116}$

What I could not talk about…

On the interference of ggH and $c\bar{c}H$ Higgs production mechanisms and the determination of charm Yukawa coupling at the LHC

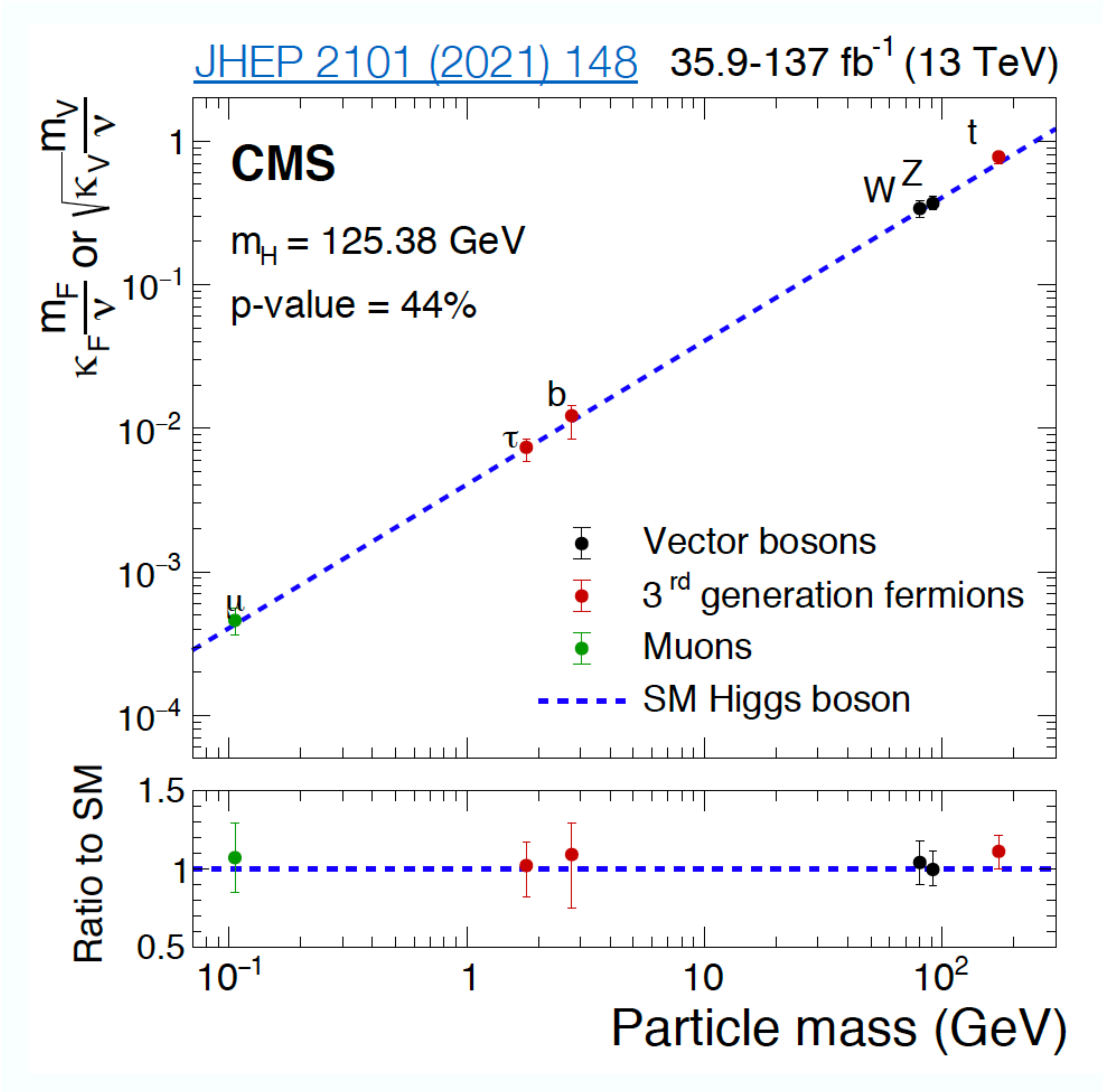
P3H-21-010

Wojciech Bizoń,[a,b] Kirill Melnikov,[a] Jérémie Quarroz[a]



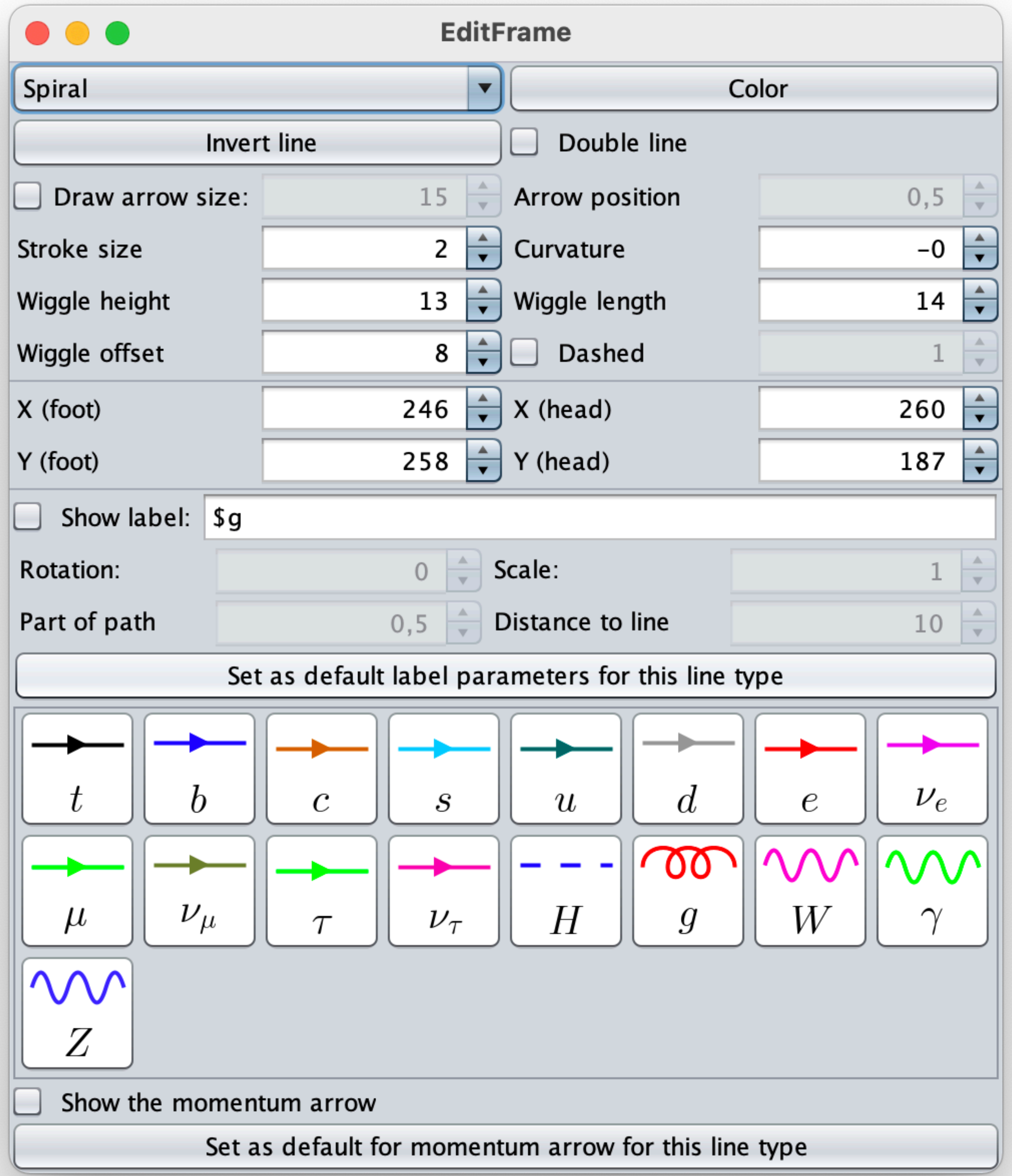
(a) Yukawa coupling

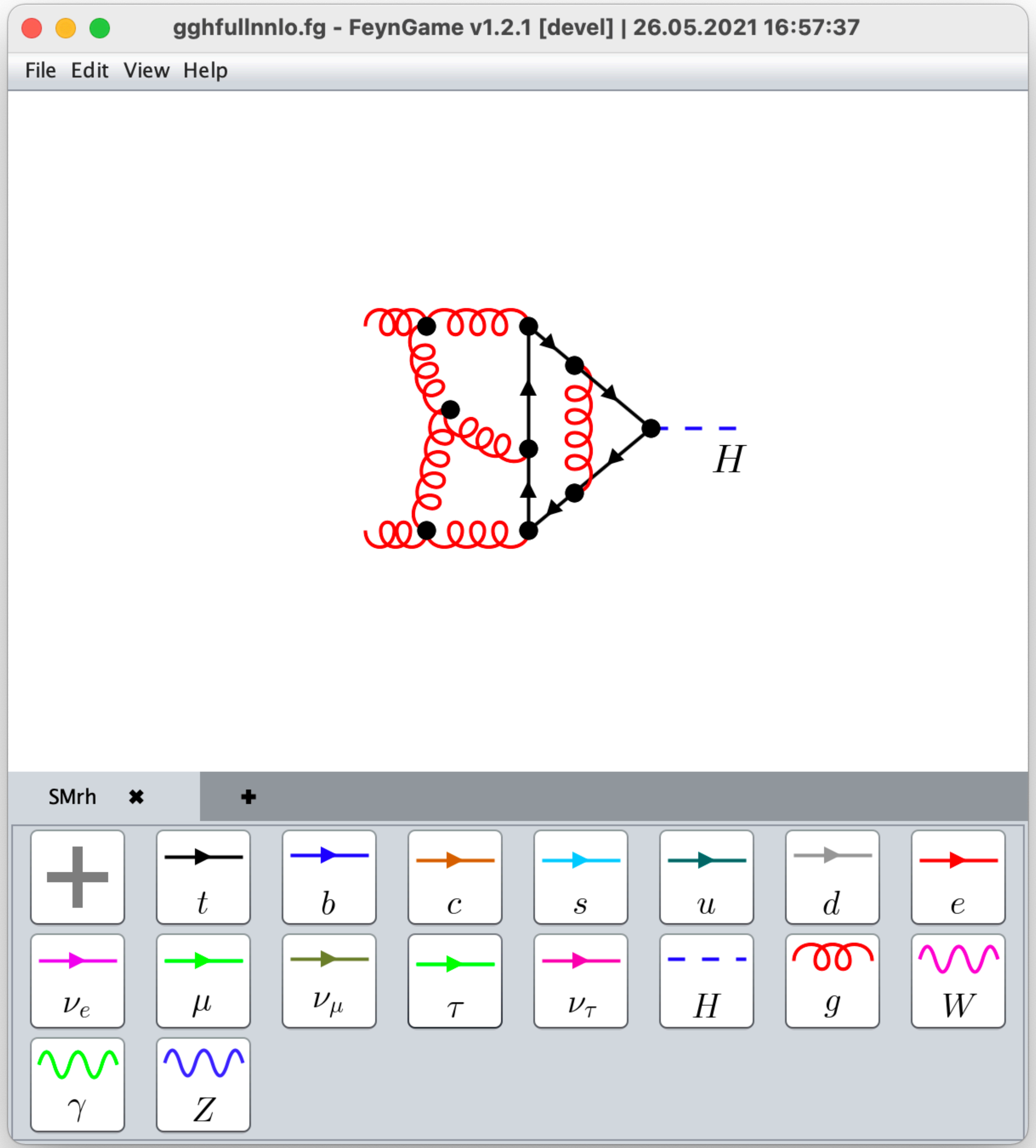
(b) Effective ggH vertex



interaction is multiplied by a factor $-\frac{3}{2}$ rather than $\frac{3}{2}$. Of course our model has too many arbitrary features for these predictions to be taken very seriously, but it is worth keeping in mind that the standard calculation[8] of the

Weinberg '67





FeynGame

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Thank you!