A1a

Quark-mass effects in Higgs-boson production in gluon fusion

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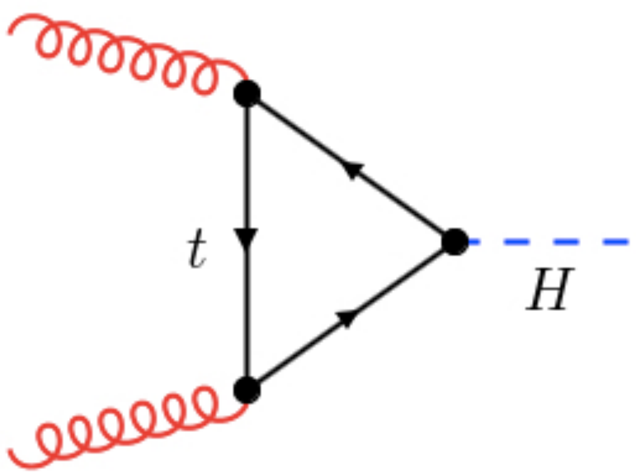
Goals

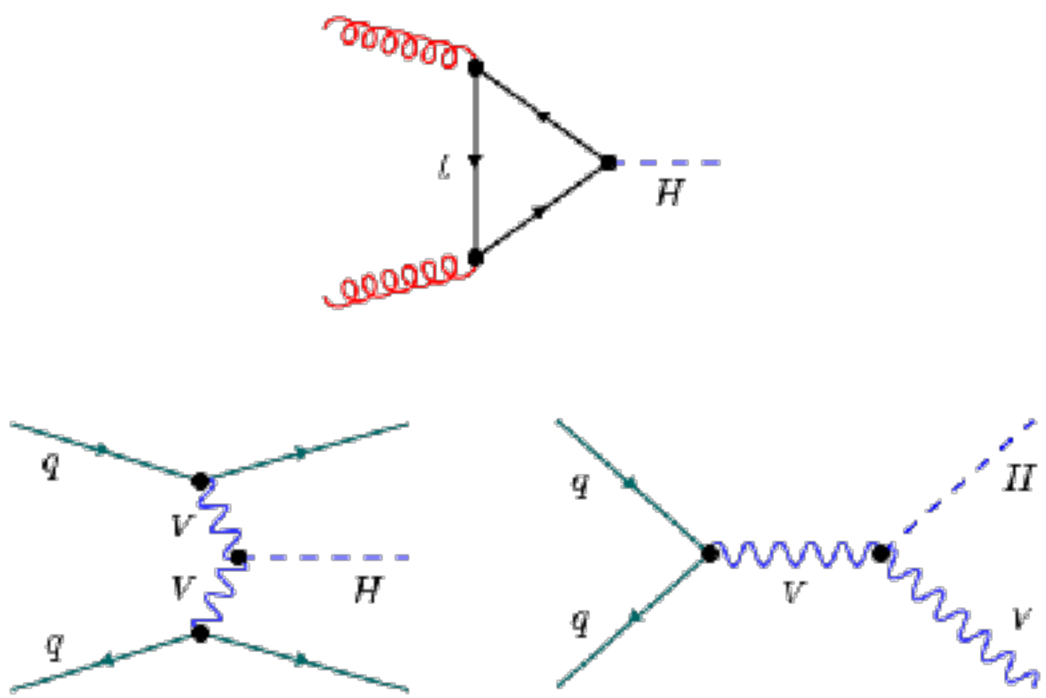
Full quark mass dependence at NNLO.



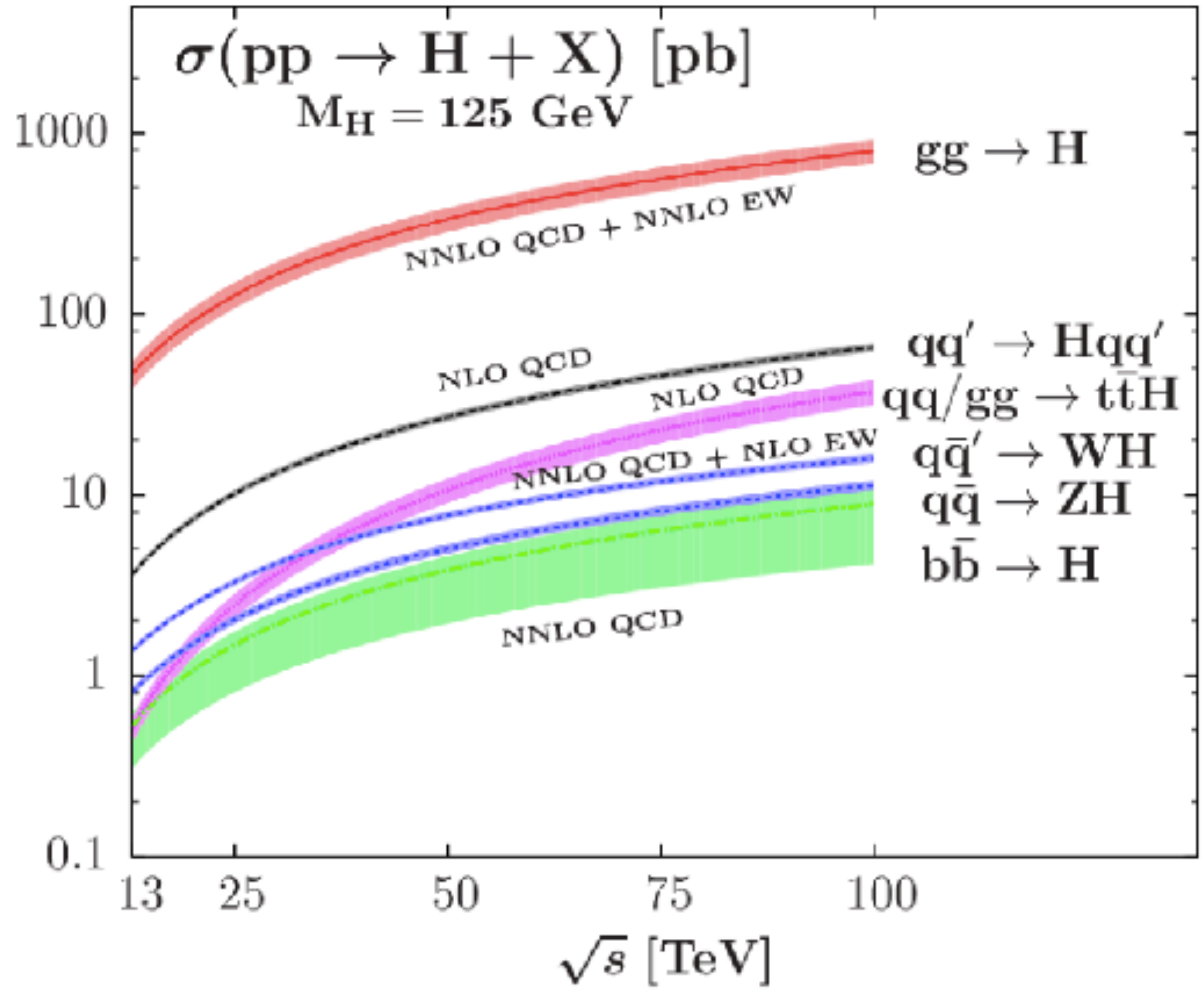
Total cross section.
Differential distributions.

Also "extreme" phase space regions: resummation.

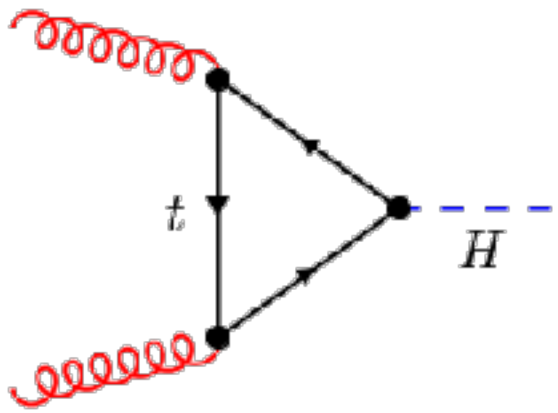
Why?



t
H
q
V
V
H
q
q
H
q
V
V



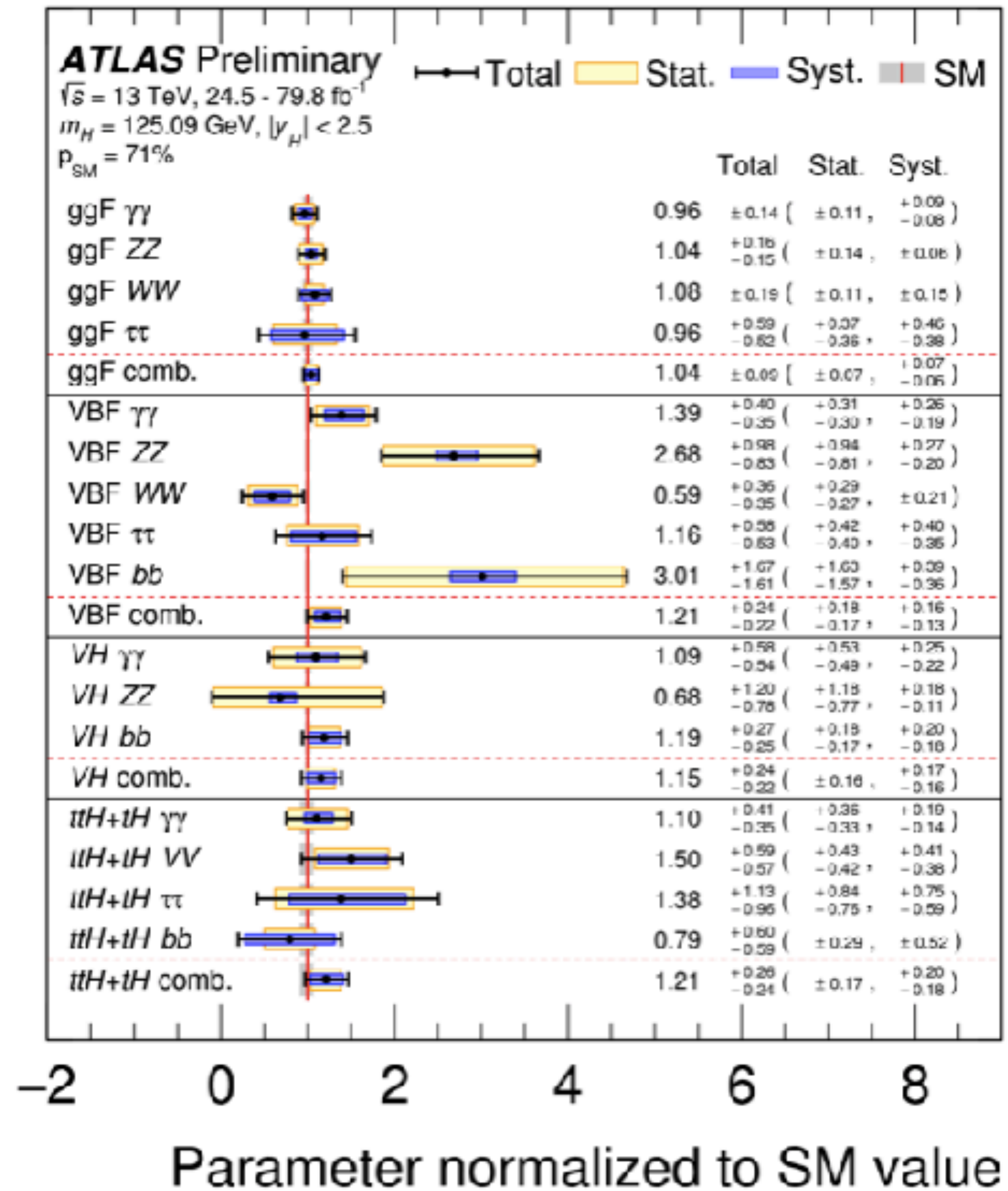
$\sigma(\mathrm{pp} \to \mathrm{H} + \mathrm{X})$ [pb]
$\mathrm{M_H} = 125$ GeV
$\mathrm{gg} \to \mathrm{H}$
NNLO QCD + NNLO EW
$\mathrm{qq}' \to \mathrm{Hqq}'$
NLO QCD
NLO QCD
$\mathrm{qq/gg} \to \mathrm{t\bar{t}H}$
NNLO QCD + NLO EW
$\mathrm{q\bar{q}}' \to \mathrm{WH}$
$\mathrm{q\bar{q}} \to \mathrm{ZH}$
$\mathrm{b\bar{b}} \to \mathrm{H}$
NNLO QCD
1000
100
10
1
0.1
13
25
50
75
100
$\sqrt{s}$ [TeV]



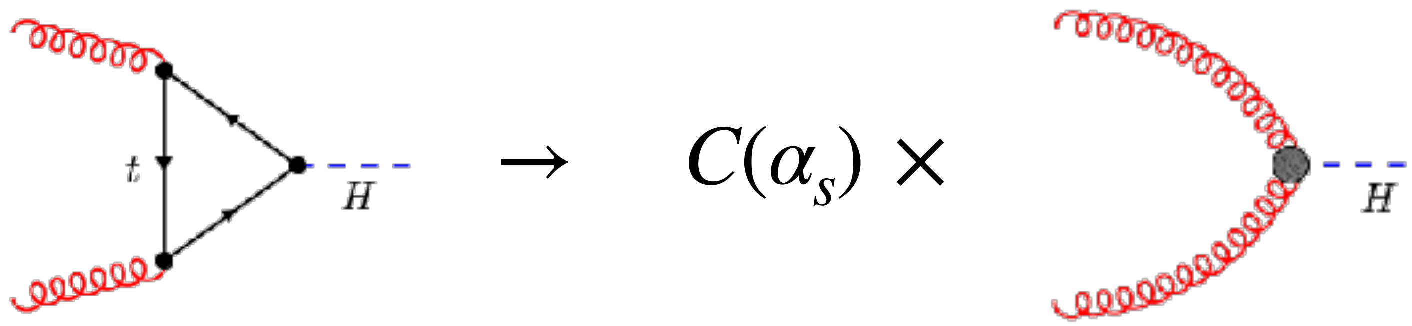
Enters many Higgs measurements

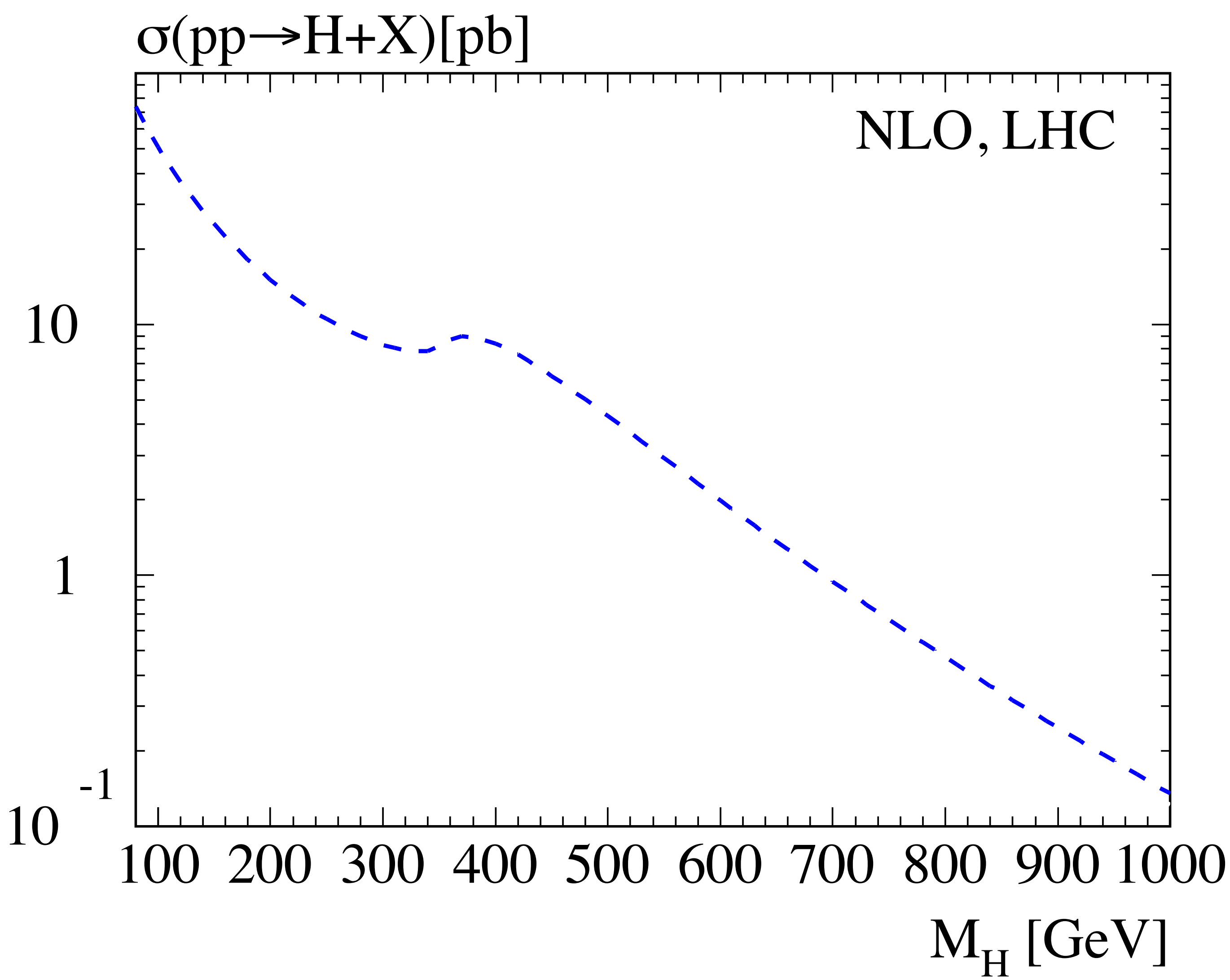
Precise theory understanding is essential

LO 1978 ⟶ NLO 1991 ⟶ NNLO 2002 ⟶ N^{3}LO 2015



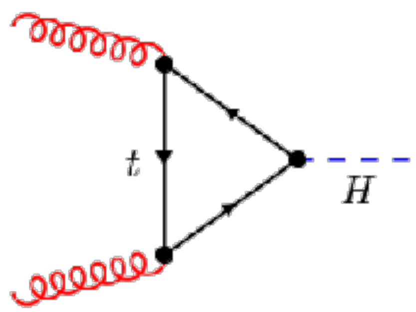
Higgs Effective Field Theory (HEFT)



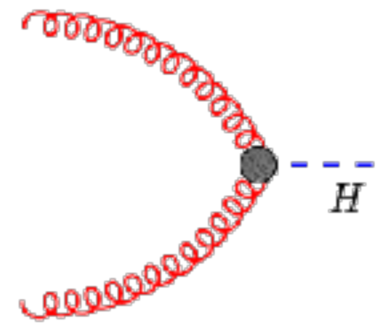


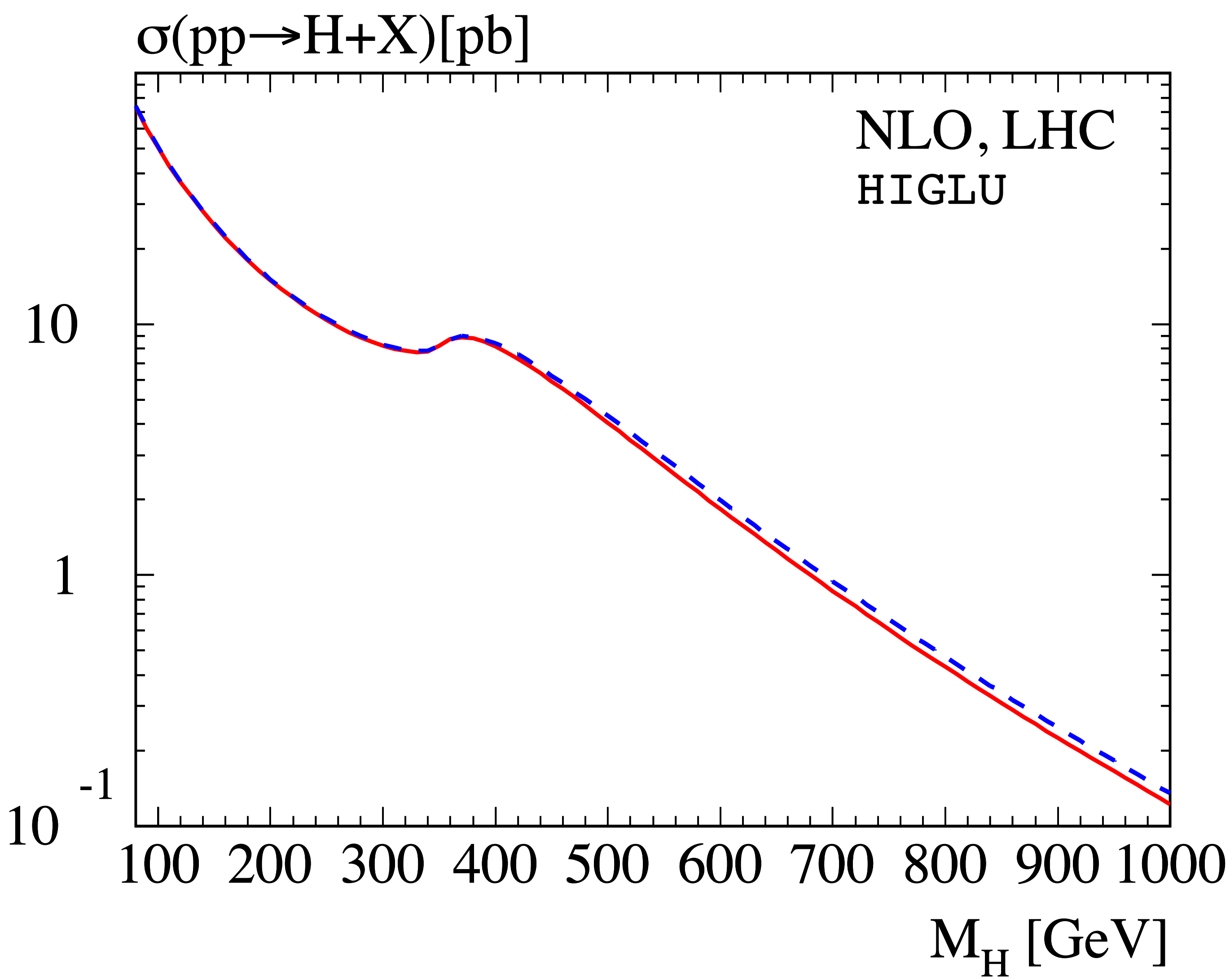
$$\sigma_\infty^{\mathrm{HO}} \equiv \sigma^{\mathrm{LO}}(m_t)\left(\frac{\sigma^{\mathrm{HO}}}{\sigma^{\mathrm{LO}}}\right)_{m_t\to\infty}$$

Higgs Effective Field Theory (HEFT)



$\rightarrow \quad C(\alpha_s) \times$

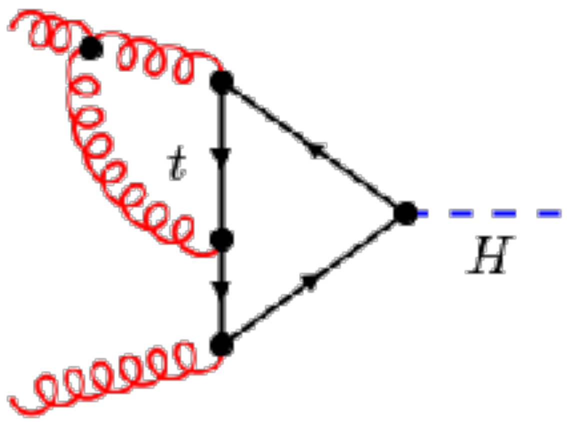




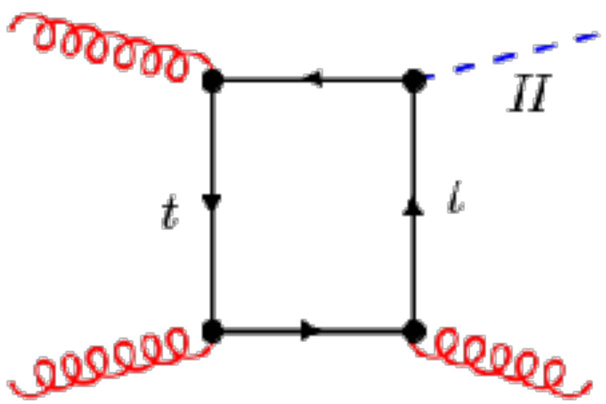
$$\sigma_\infty^{\text{HO}} \equiv \sigma^{\text{LO}}(m_t)\left(\frac{\sigma^{\text{HO}}}{\sigma^{\text{LO}}}\right)_{m_t\to\infty}$$

HEFT for the total xsec

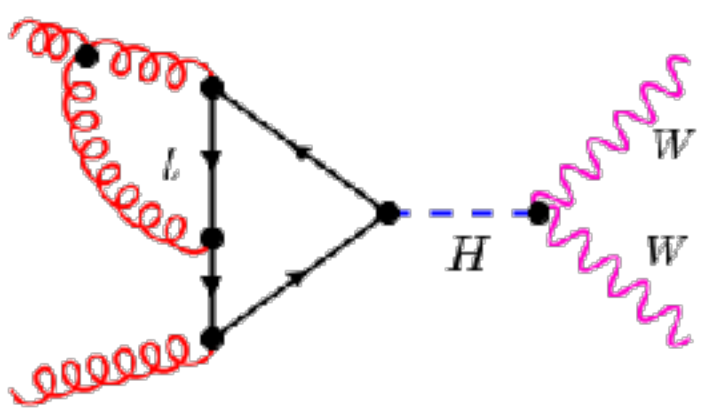
$$2m_t > M_H, \hat{s}$$



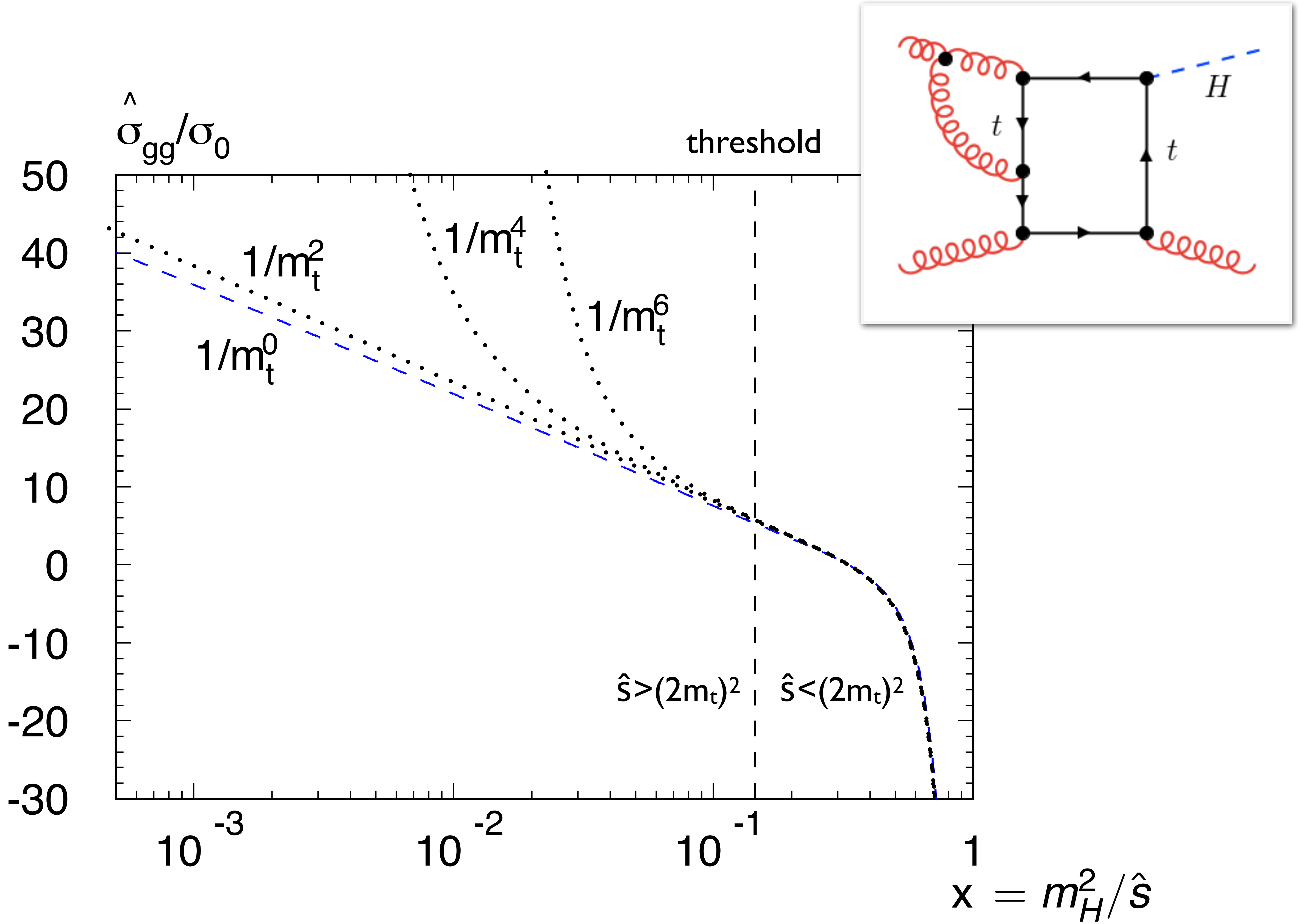
$\delta(\hat{s} - M_H^2)$ ✔



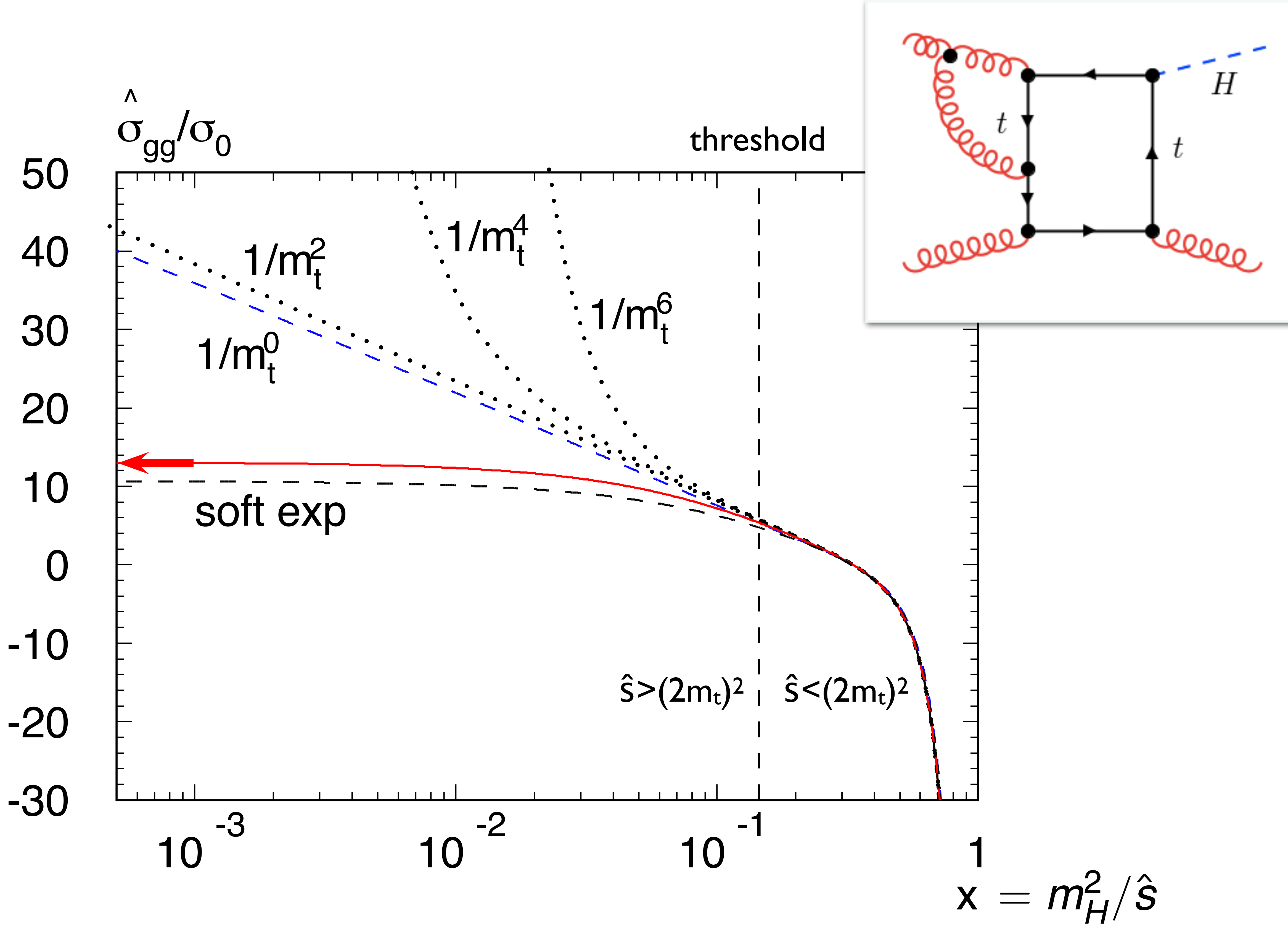
$M_H^2 < \hat{s} < s = 14\,\text{TeV}$ ✘

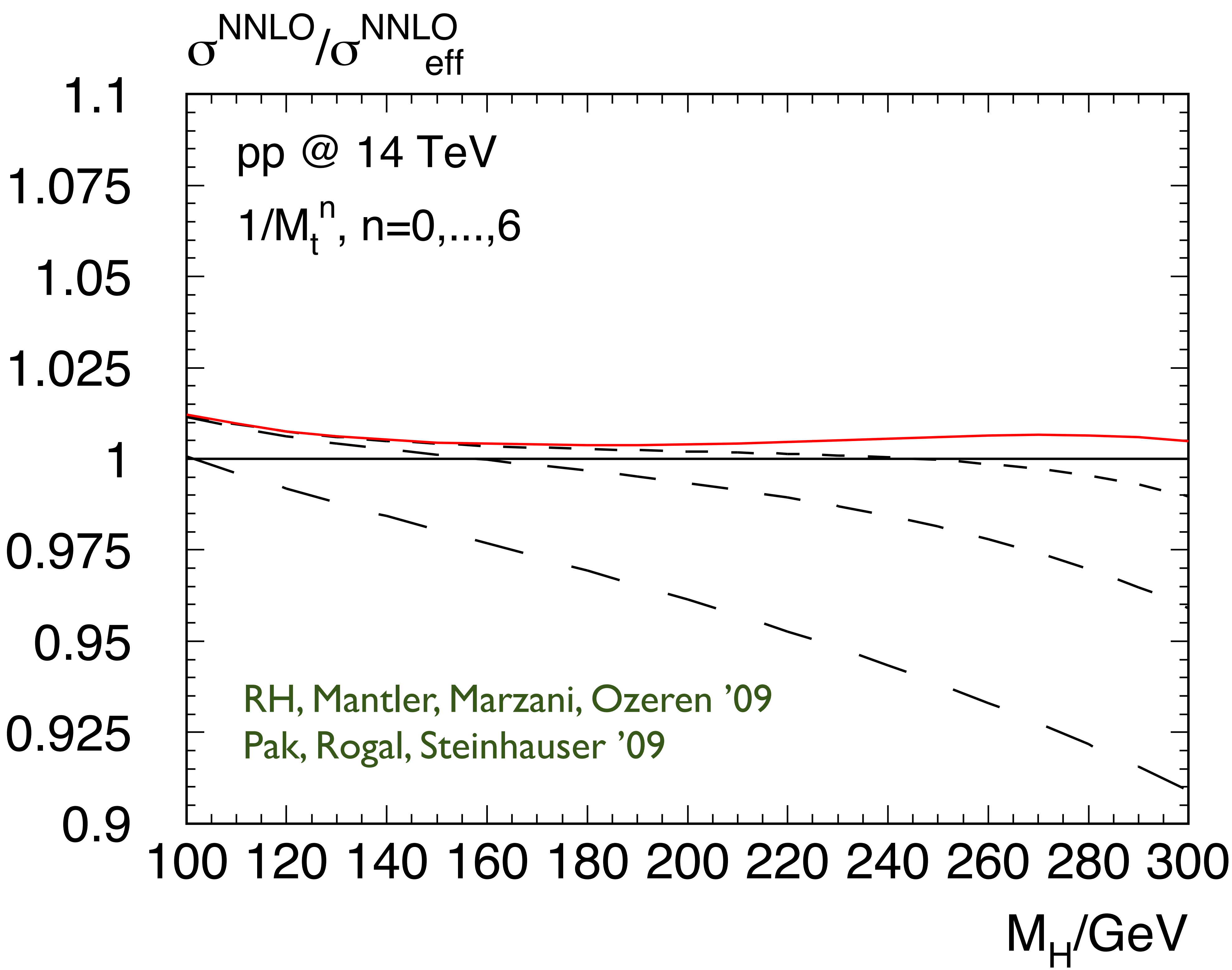


off-shell production ✘

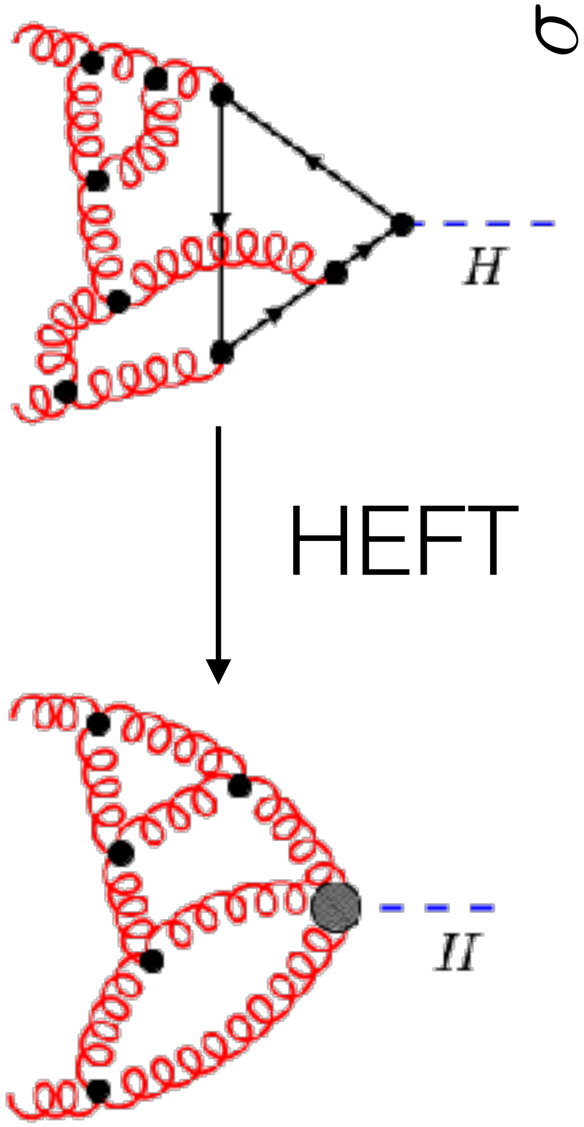


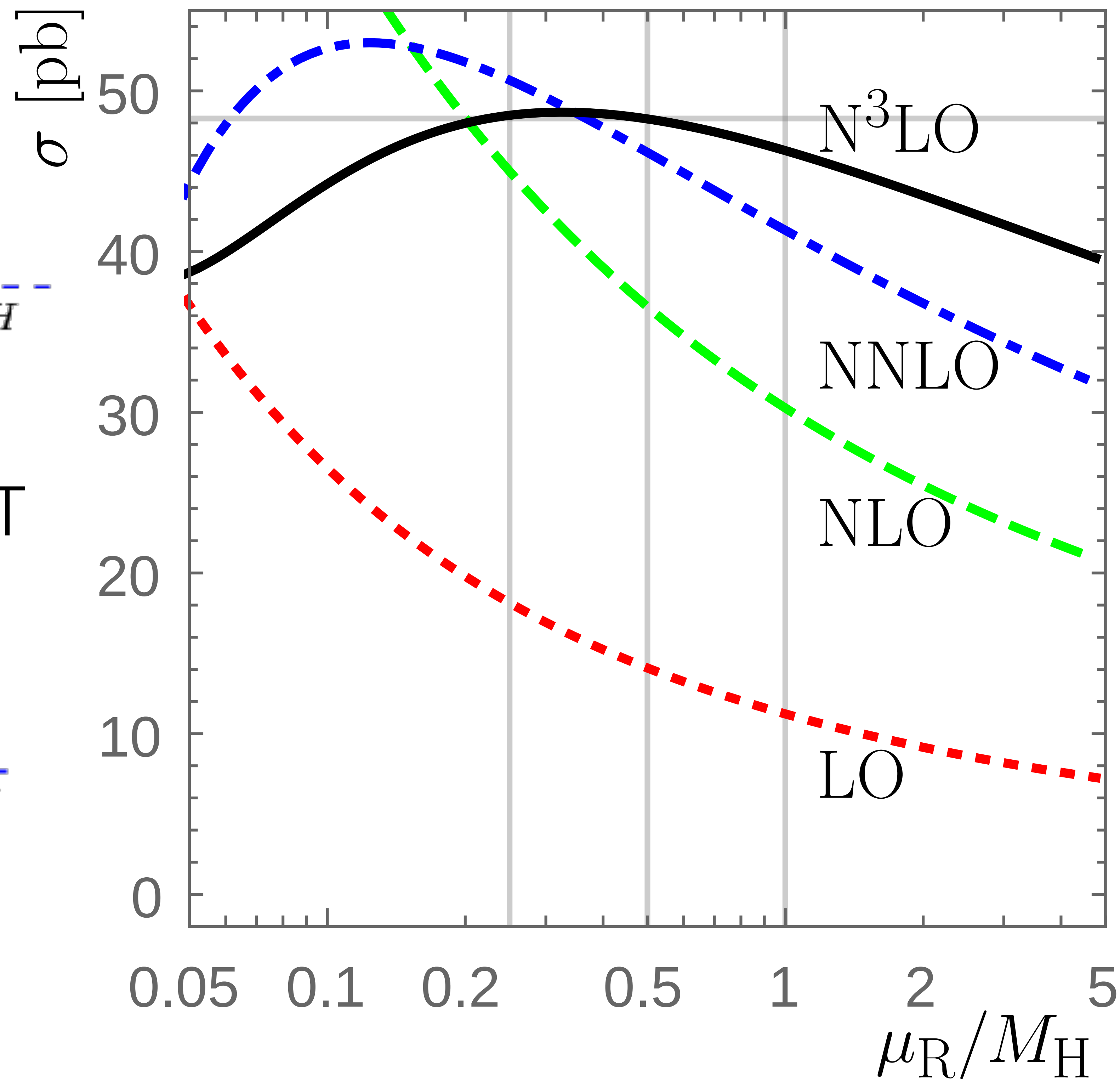
$\hat{\sigma}_{gg}/\sigma_0$
threshold
50
40
30
20
10
0
-10
-20
-30
$1/m_t^2$
$1/m_t^4$
$1/m_t^6$
$1/m_t^0$
$\hat{s}>(2m_t)^2$
$\hat{s}<(2m_t)^2$
10^{-3}
10^{-2}
10^{-1}
1
$x = m_H^2/\hat{s}$
t
t
H


$\hat{\sigma}_{gg}/\sigma_0$
threshold
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
$\hat{s}>(2m_t)^2$
$\hat{s}<(2m_t)^2$
10^{-3}
10^{-2}
10^{-1}
1
$x = m_H^2/\hat{s}$
t
t
H


σ^NNLO/σ^NNLO_eff
1.1
1.075
1.05
1.025
1
0.975
0.95
0.925
0.9
pp @ 14 TeV
1/M_t^n, n=0,...,6
RH, Mantler, Marzani, Ozeren '09
Pak, Rogal, Steinhauser '09
100 120 140 160 180 200 220 240 260 280 300
M_H/GeV

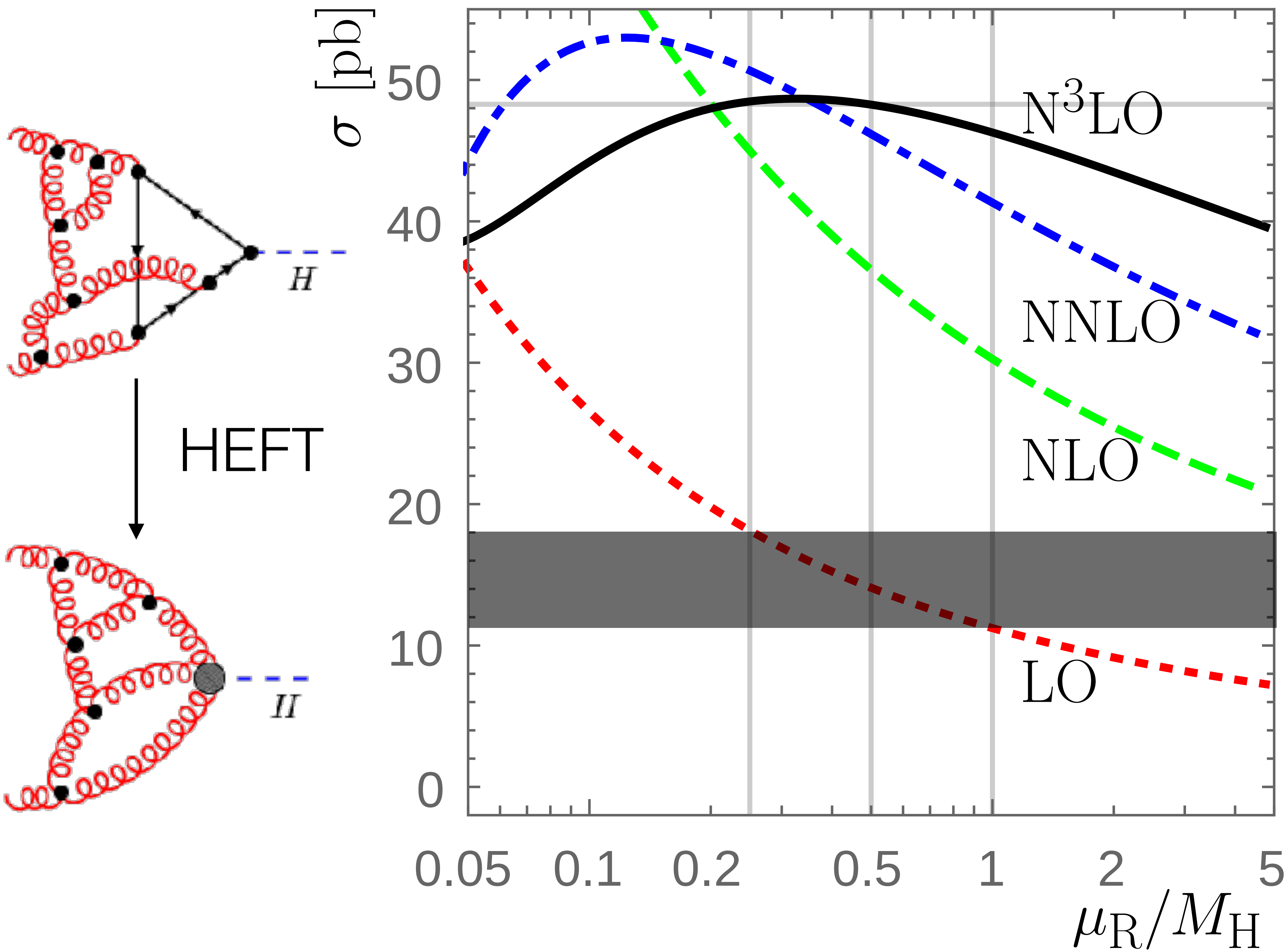
Total cross section in HEFT through N³LO:





Anastasiou et al.

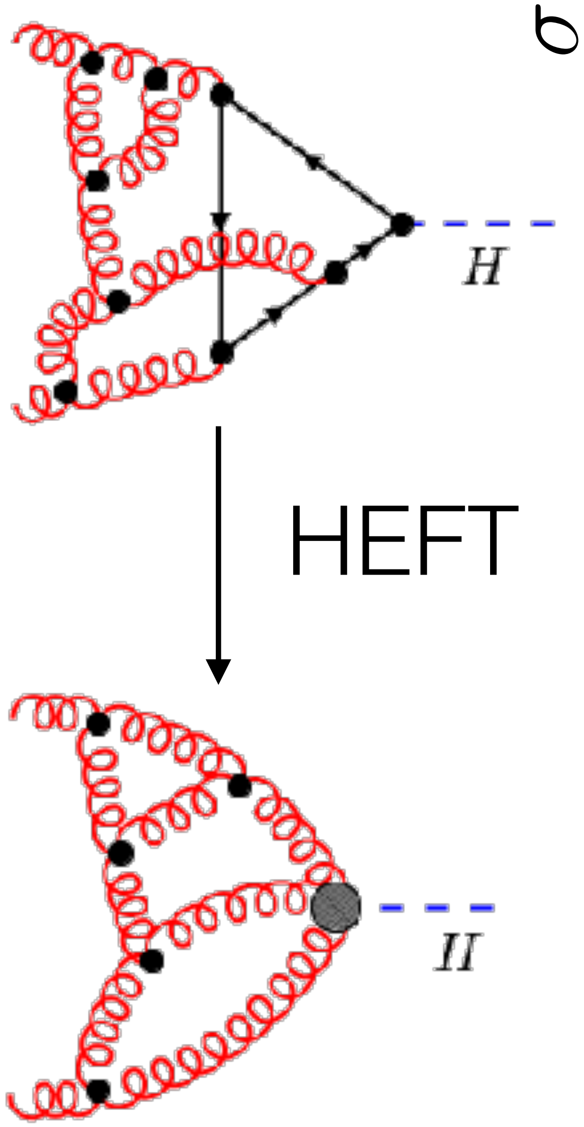
Total cross section in HEFT through N3LO:

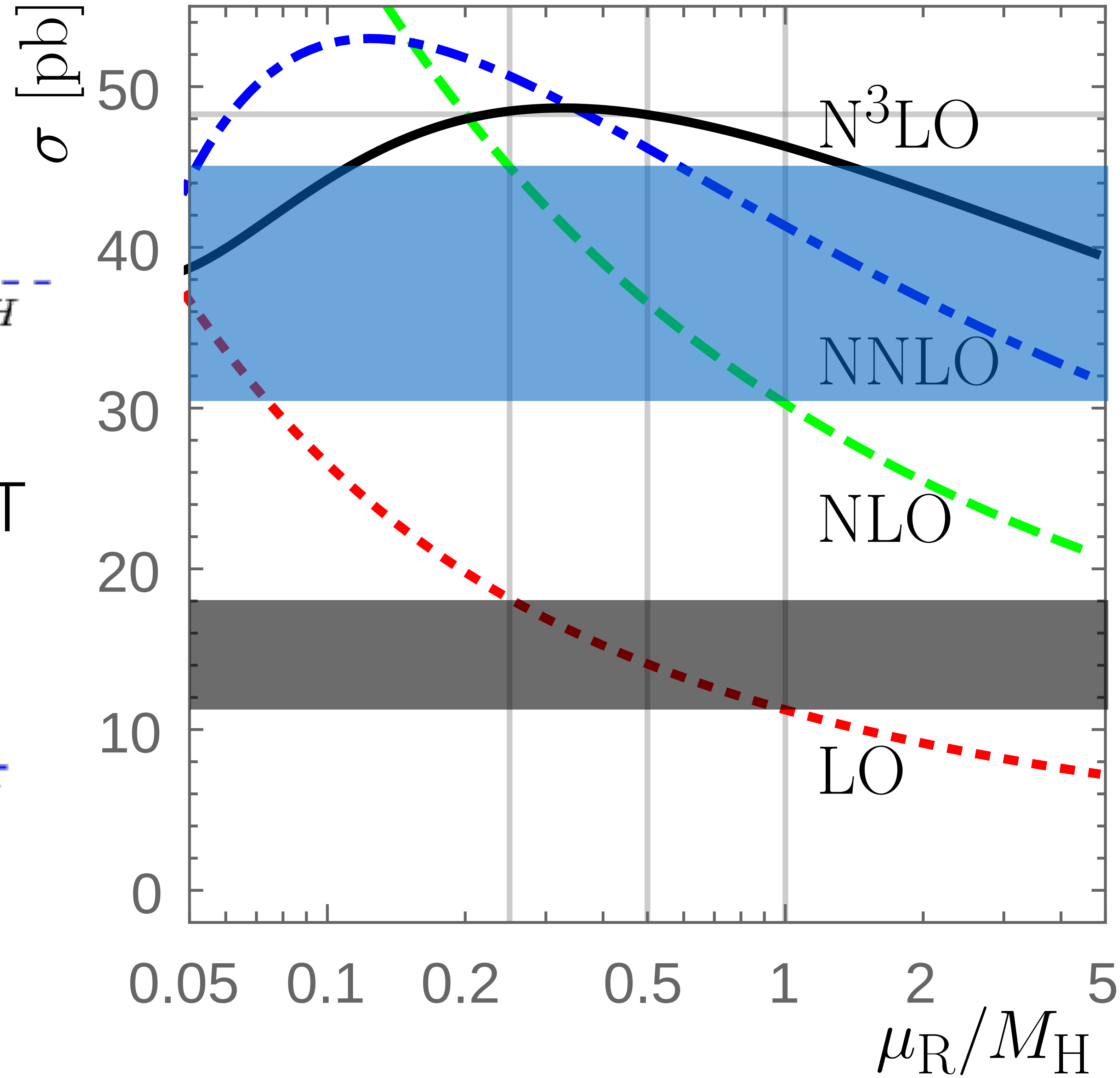


Anastasiou et al.

1978

Total cross section in HEFT through N³LO:



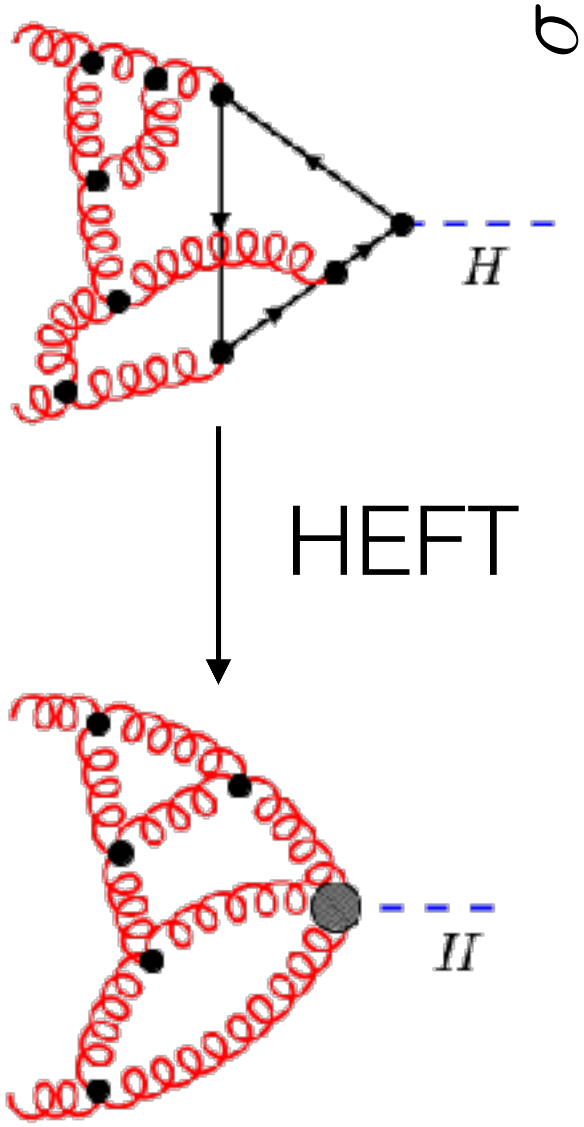


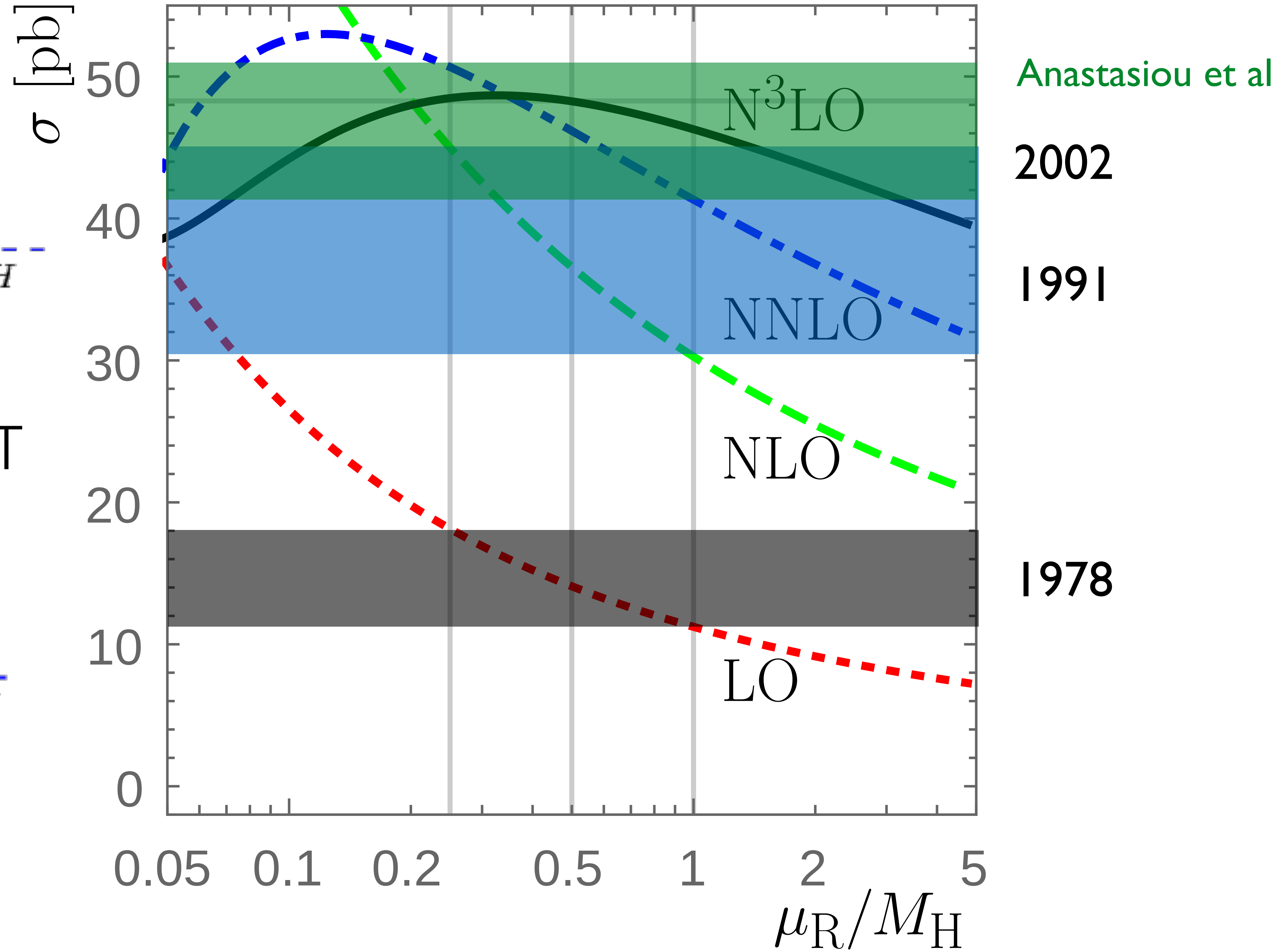
Anastasiou et al.

1991

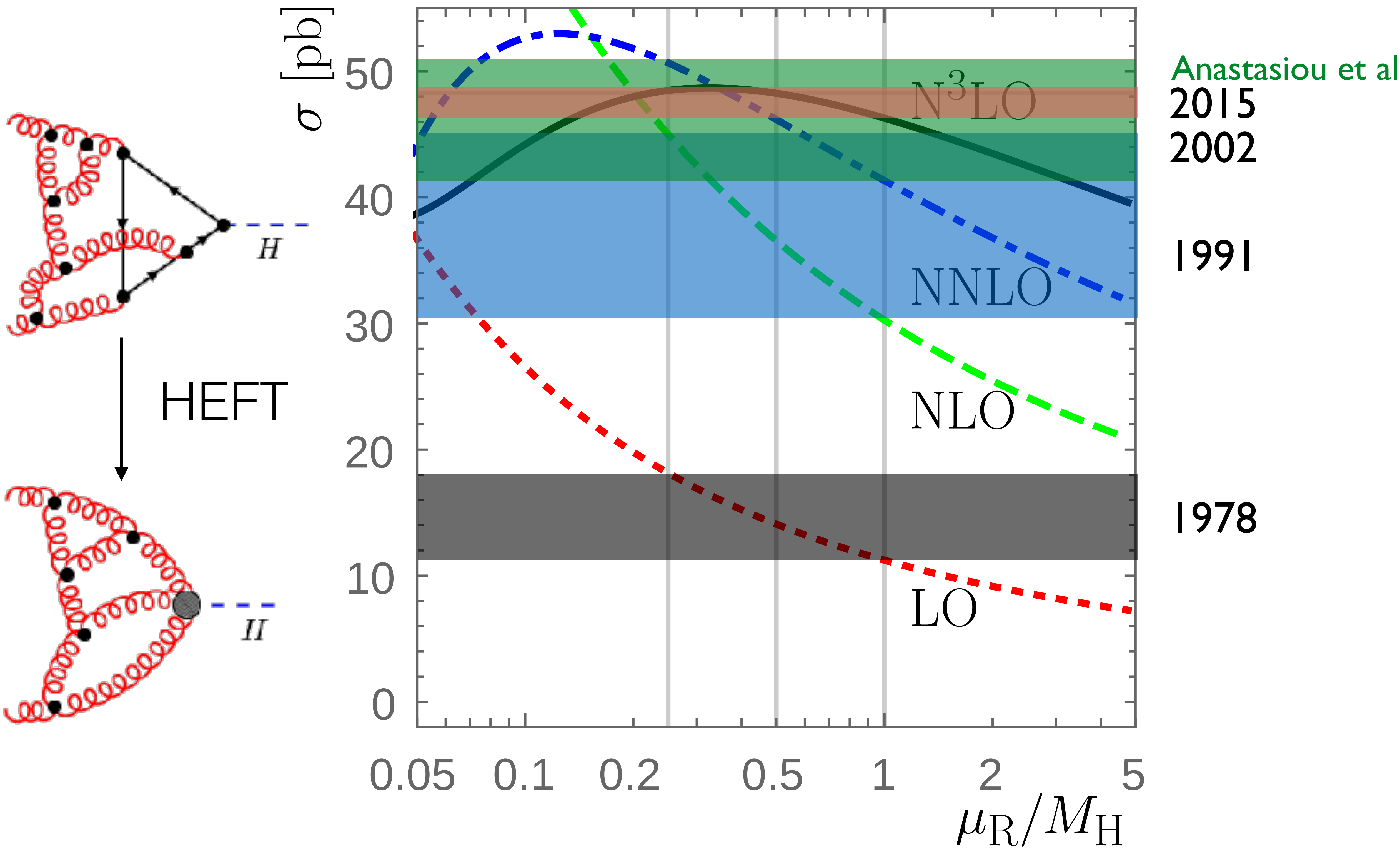
1978

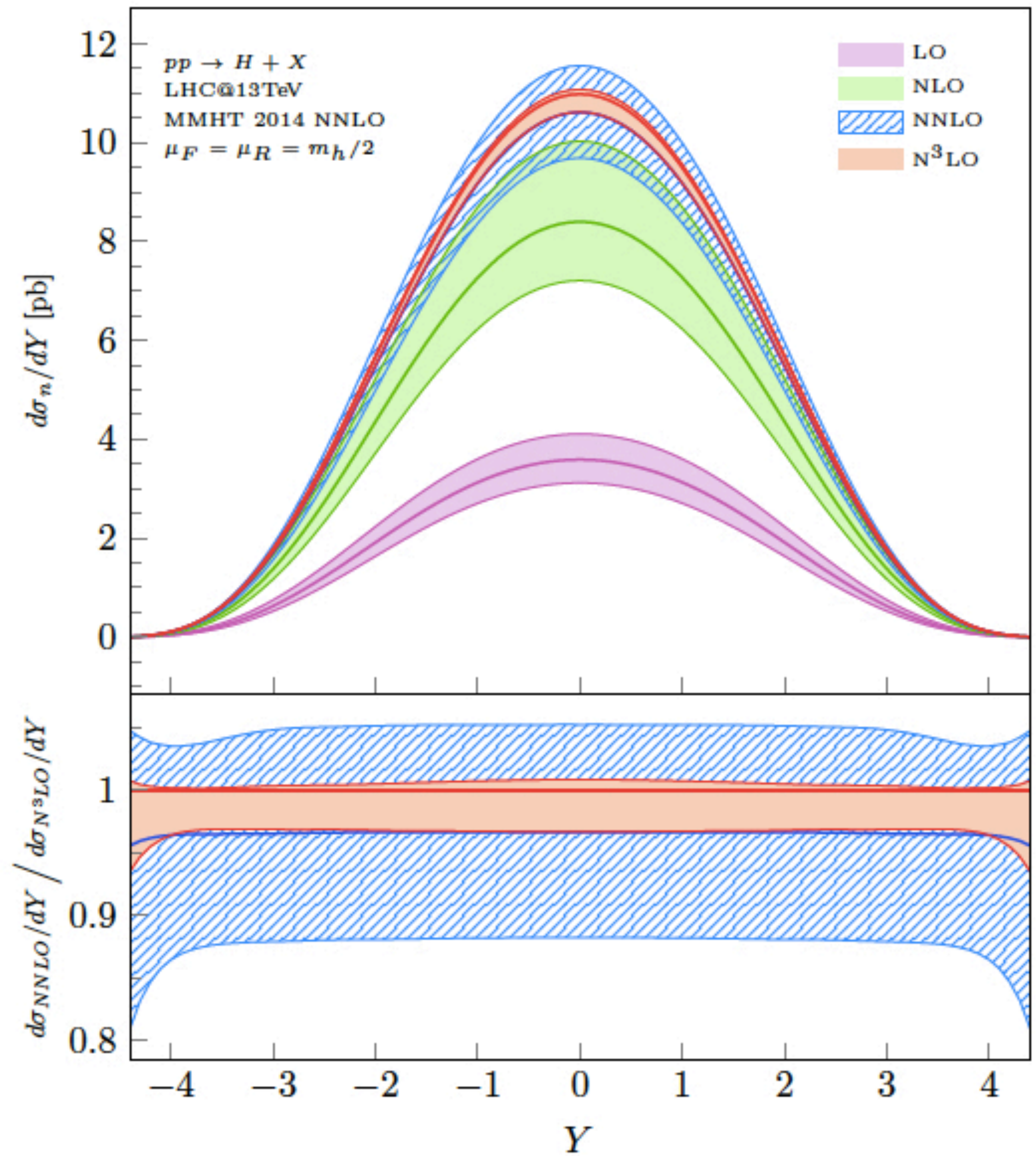
Total cross section in HEFT through N3LO:





Total cross section in HEFT through N^{3}LO:

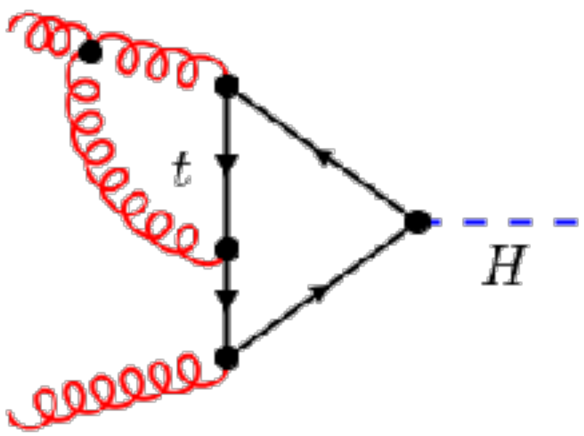


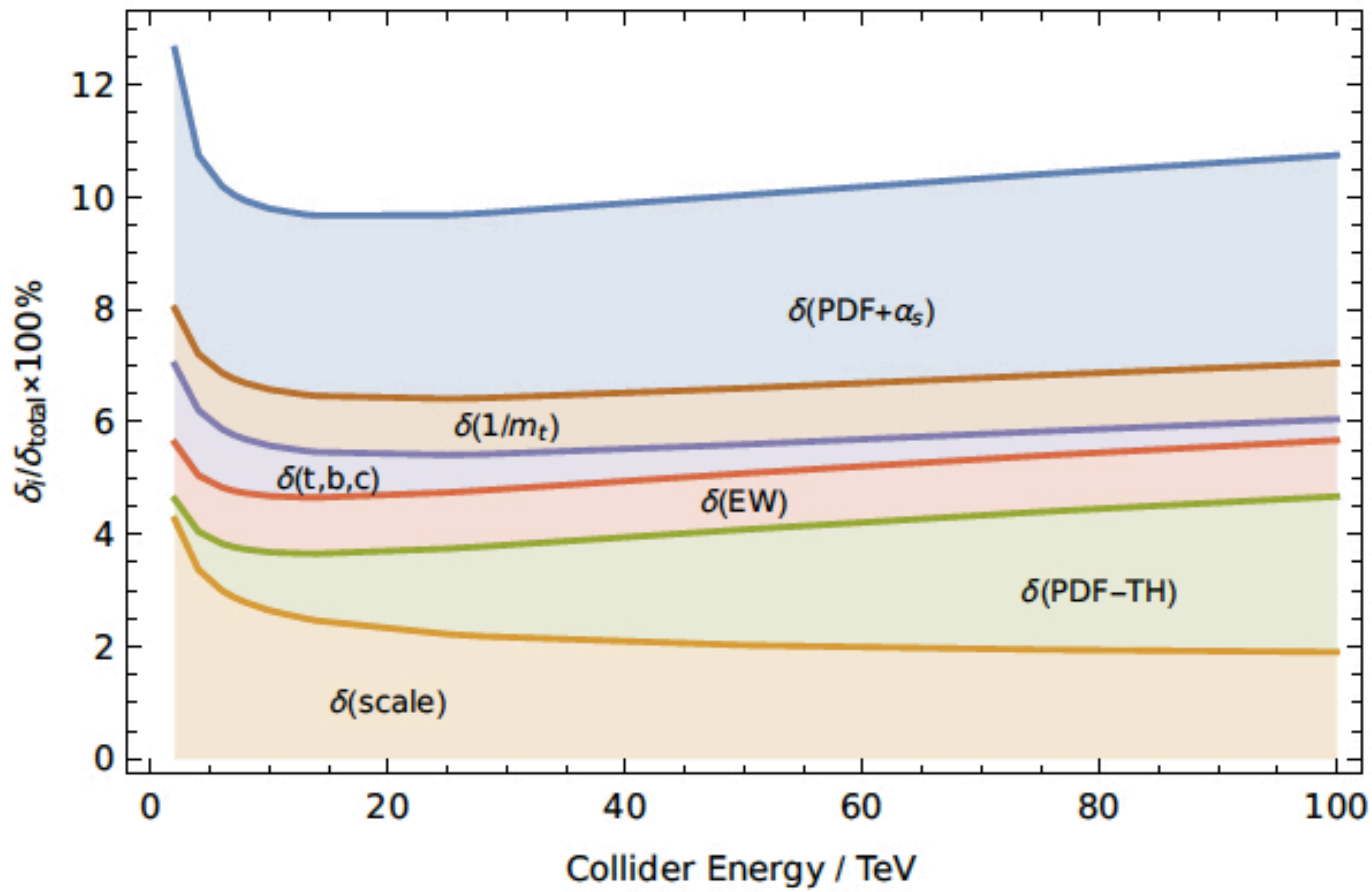


Cieri et al. '18

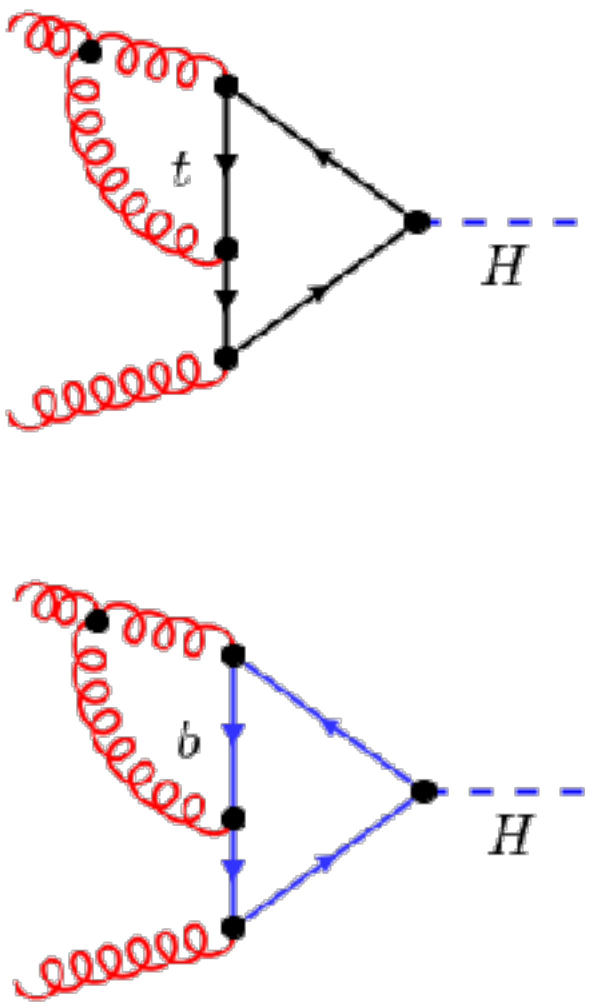
Dulat, Mistlberger, Pelloni '18

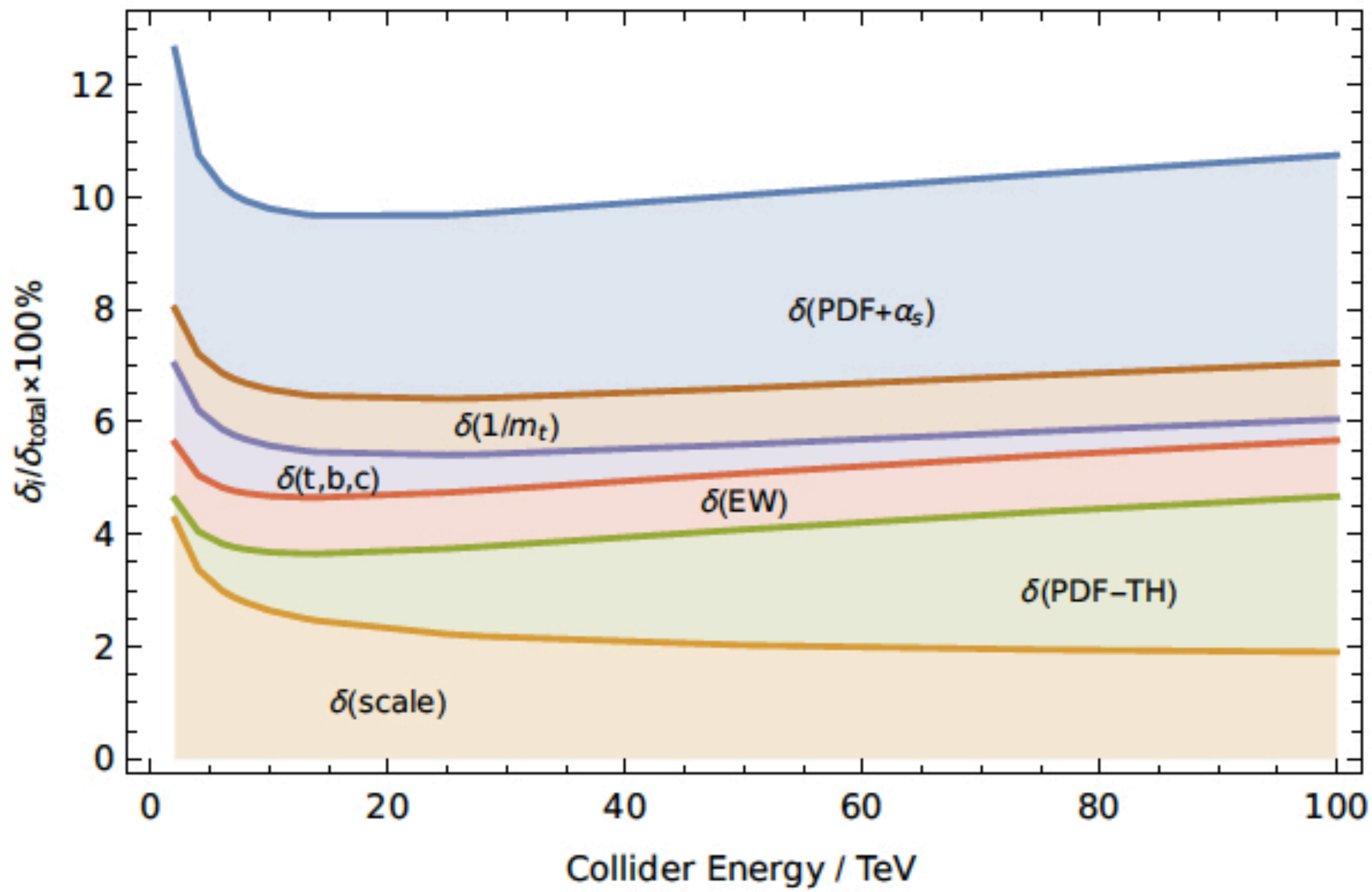
Uncertainties



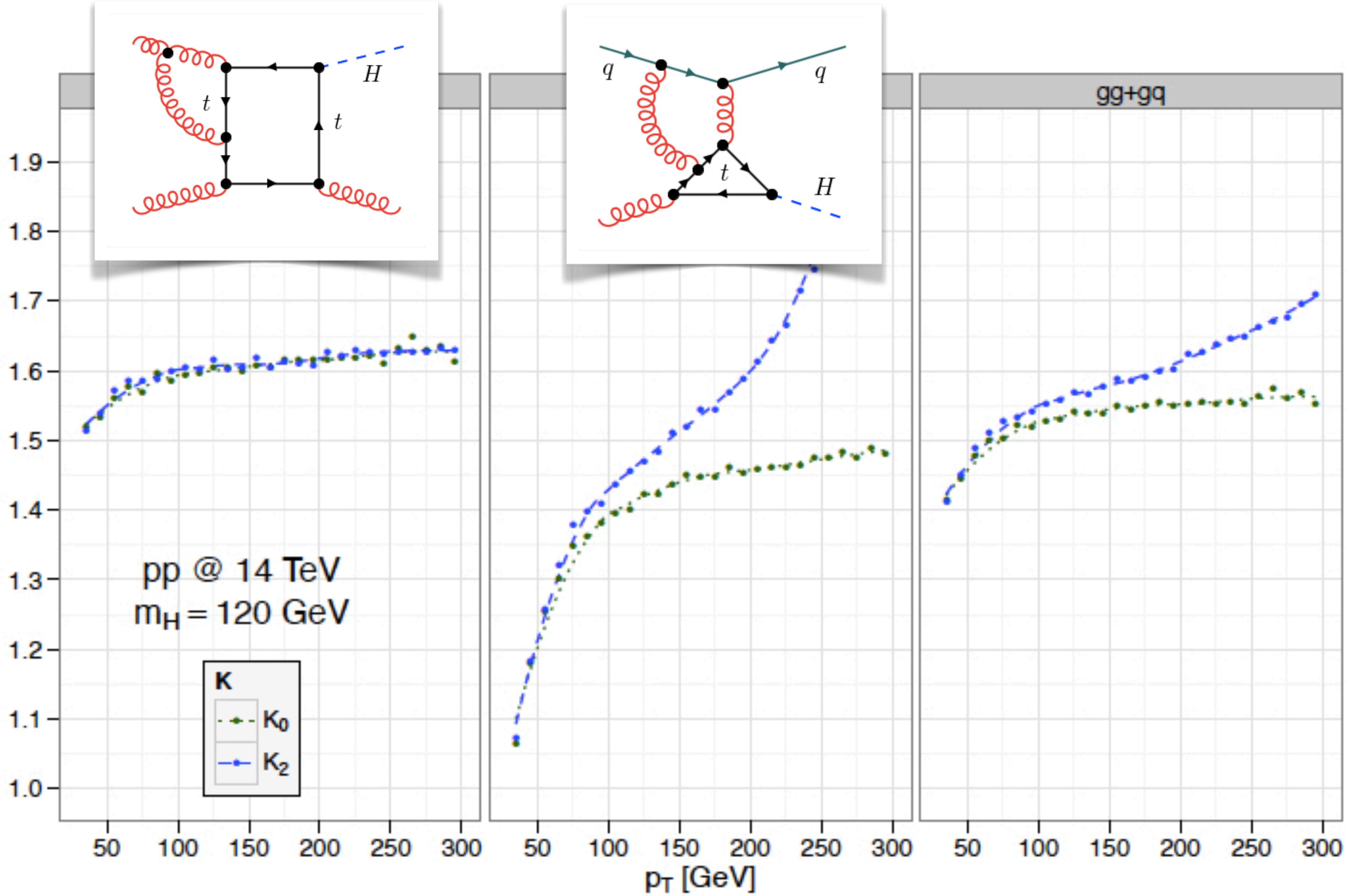


Uncertainties



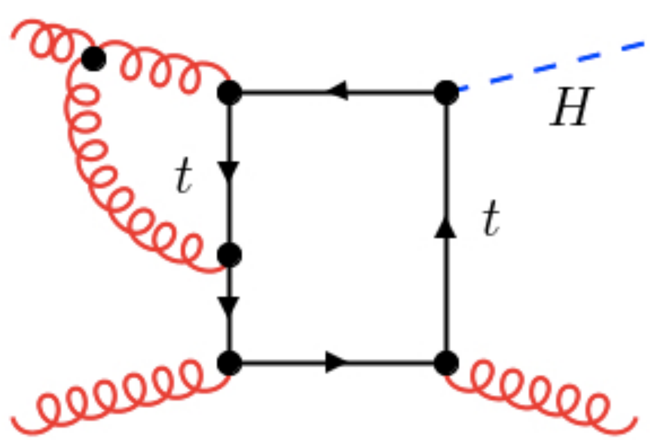


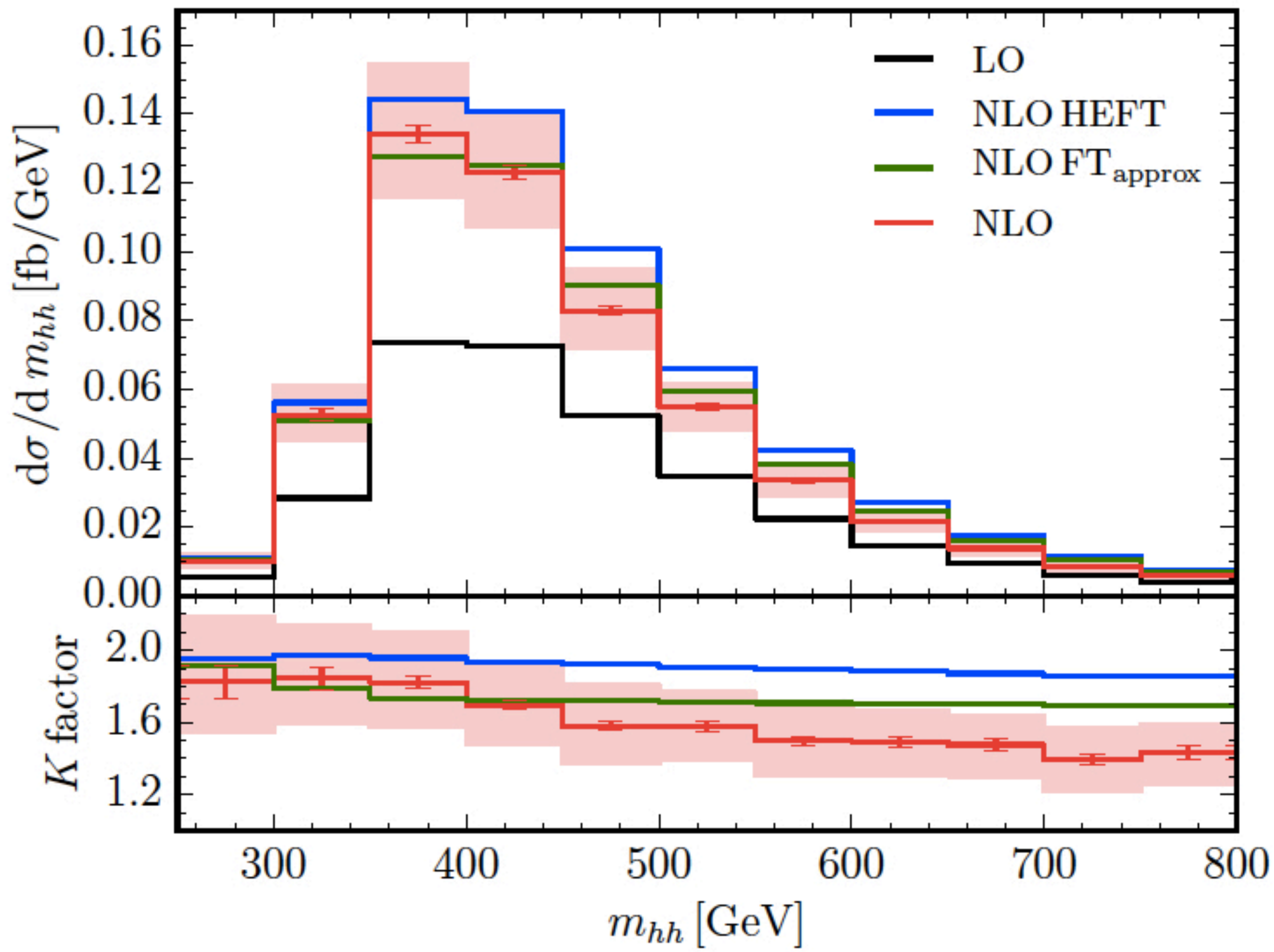
p_T distribution: $1/m_t$ expansion



Harlander, Neumann '12

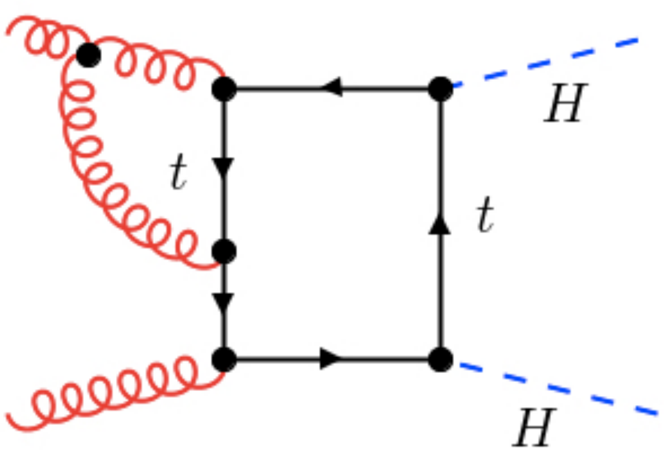
Comparison: HH

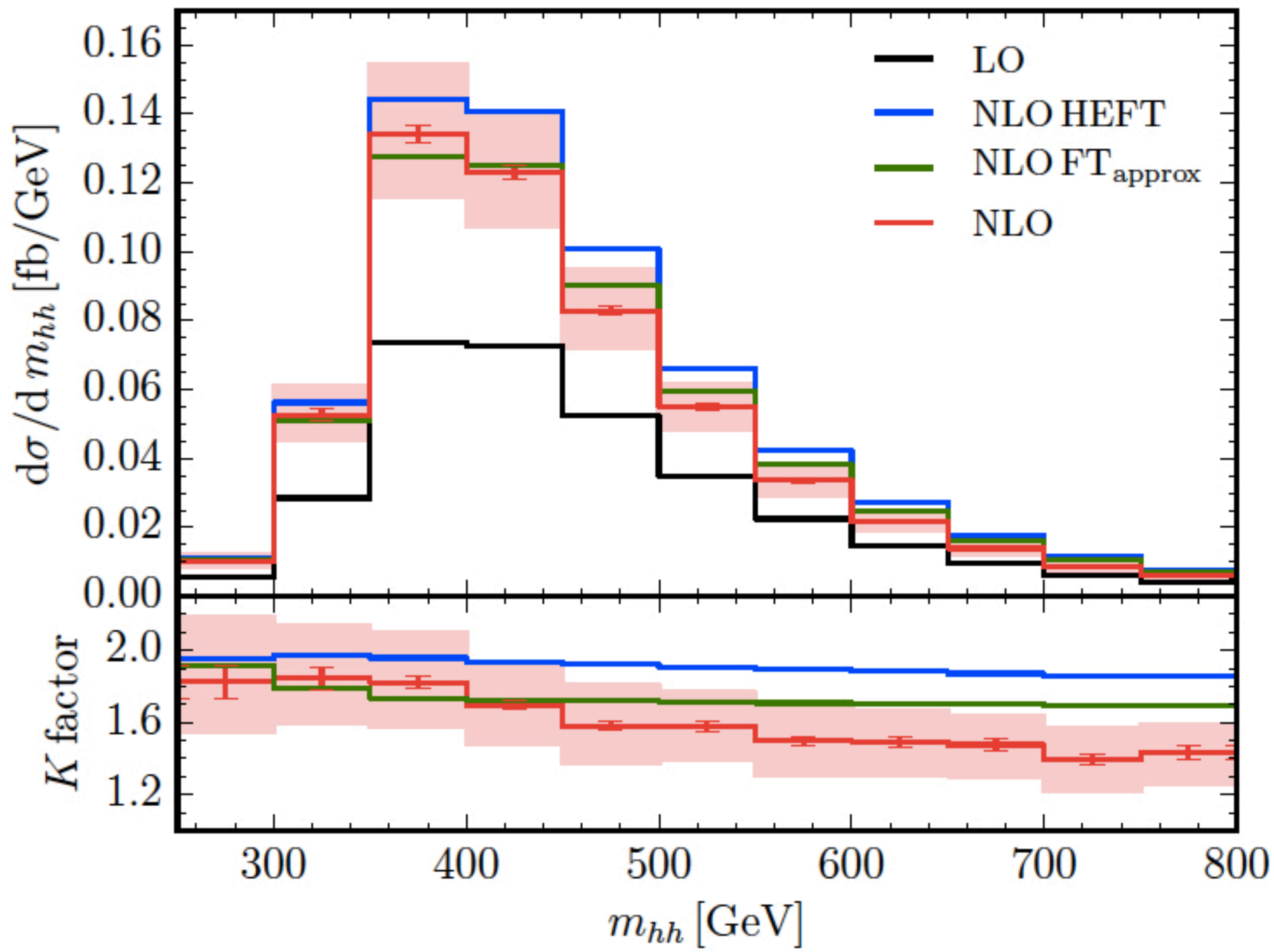




Borowka et al. ‘16
Baglio et al. ‘18

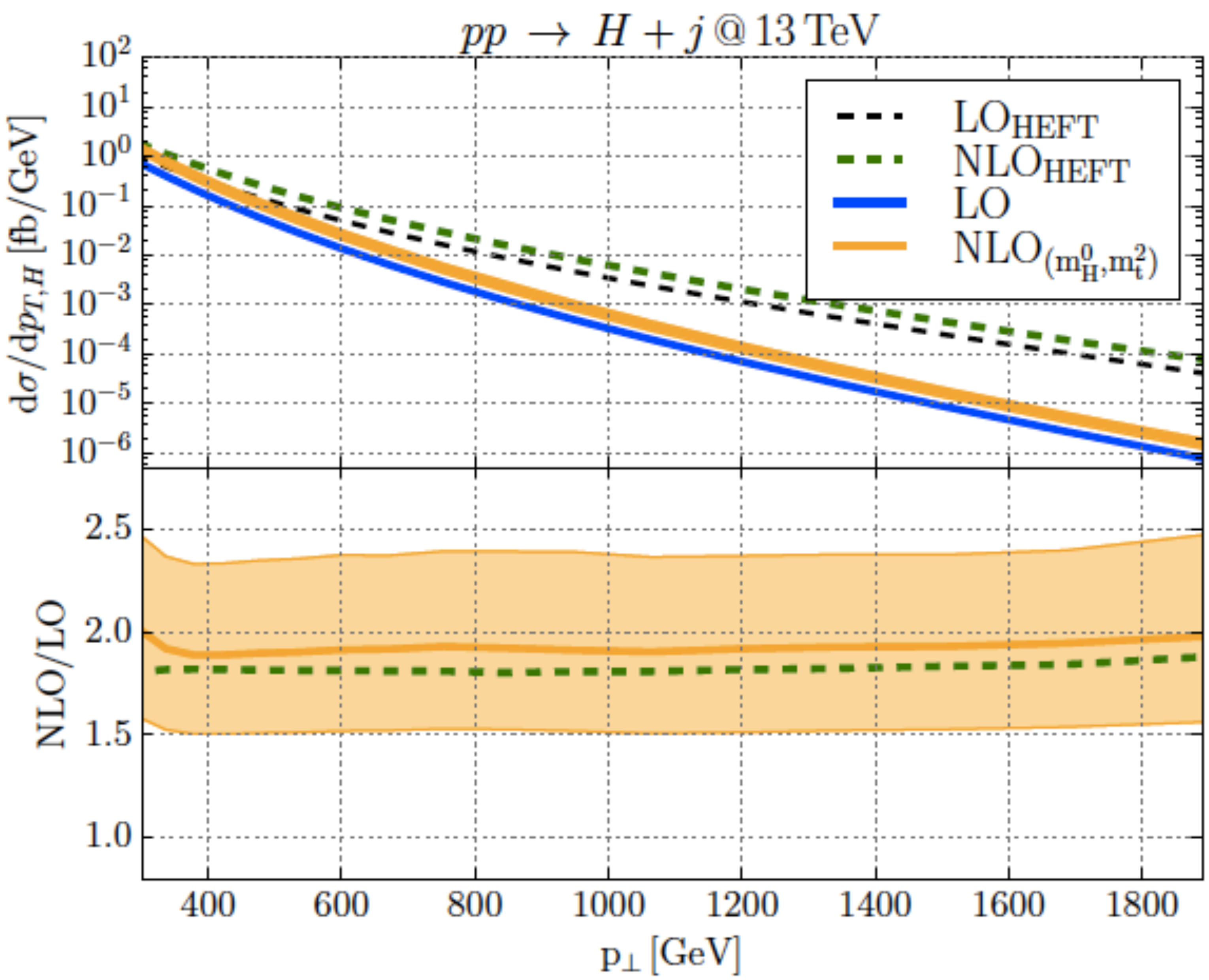
Comparison: HH

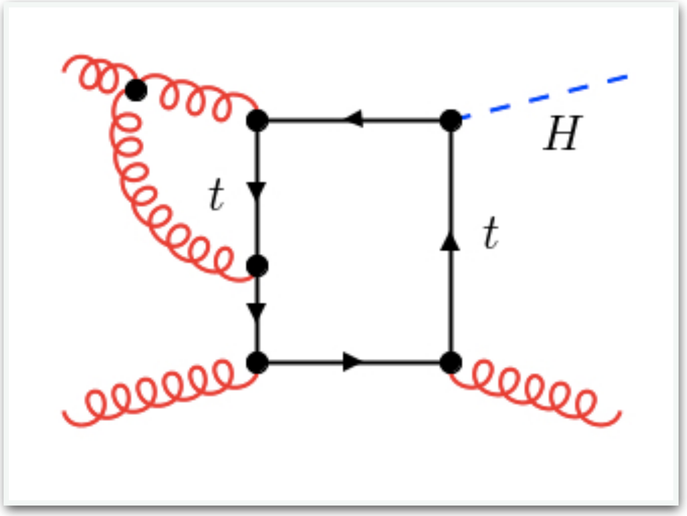




Borowka et al. '16
Baglio et al. '18

p_T distribution





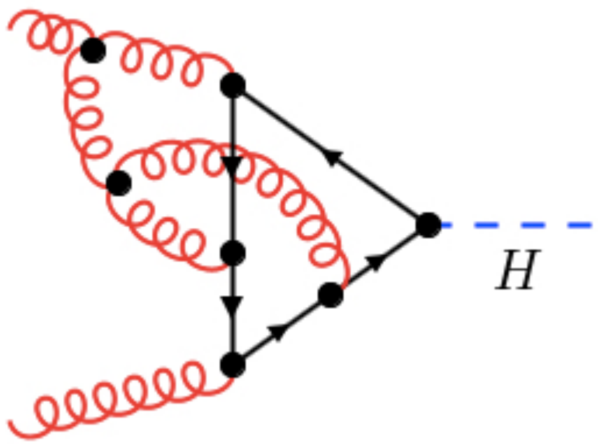
large-p_T:

Lindert, Kudashkin, Melnikov, Wever '18

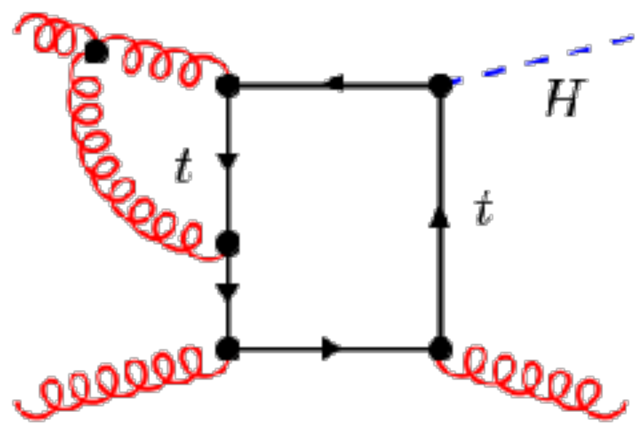
full:

S.P. Jones, Kerner, Luisoni '18

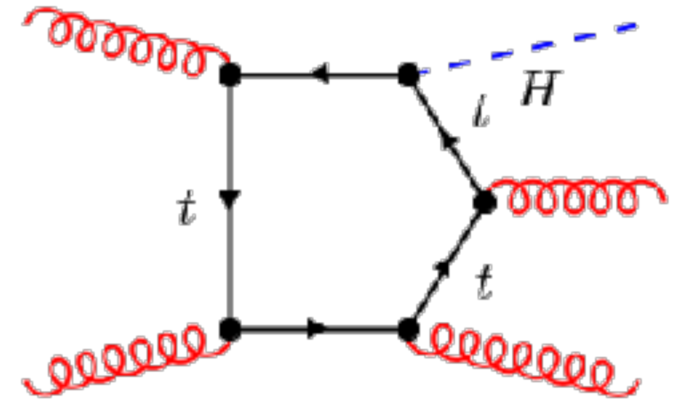
What is missing?



???



S.P. Jones, Kerner, Luisoni ‘18



Del Duca et al. ‘01

The usual problems:

Reduction:

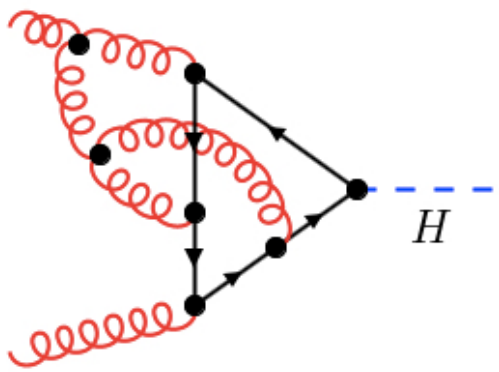
- solve large system of equations
- re-insert solution into amplitude

`FireFly`: solve on finite fields

Klappert, Lange (+ Klein) ‘19

FireFly Klappert, Lange (+ Klein) ‘19

P3H-20-010
P3H-20-041
P3H-19-007



→ millions of Feynman integrals

related by Integration-by-Parts identities

→ huge system of linear equations

solution: $$I = \sum_{n=1}^{\mathcal{O}(100)} c_n(d,z)\,\hat{I}_n$$

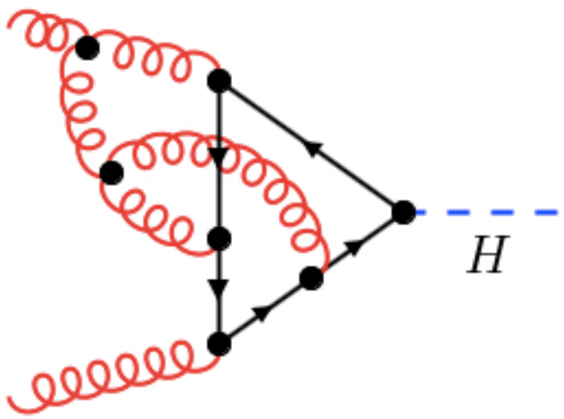
masters

rational functions

Reconstruct $c_n(d,z)$ by “probing” it with integer *d* and *z.*

Work on Finite Fields: $\mathbb{Z}_p$

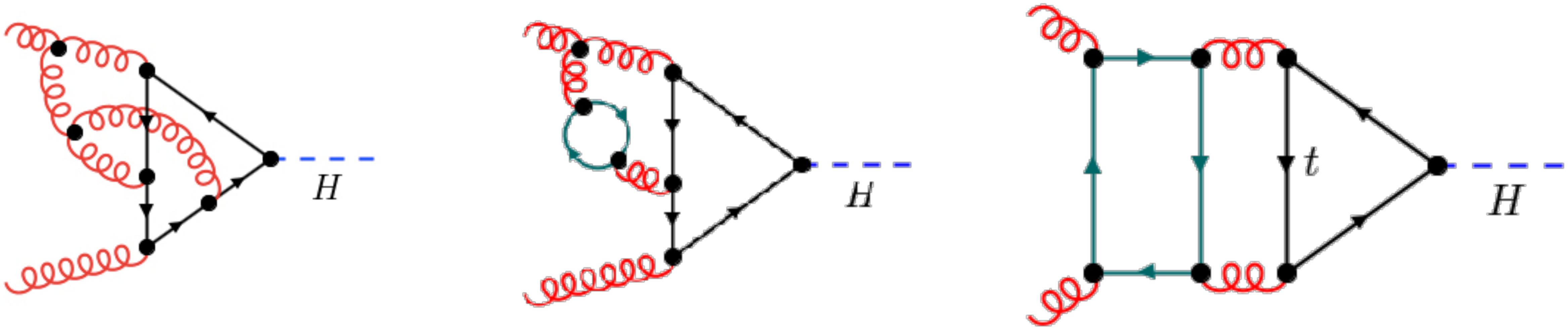
The three-loop form factor



Reduction:

- millions of integrals → few hundred masters
- solve large system of equations
- re-insert solution into amplitude

Calculate masters



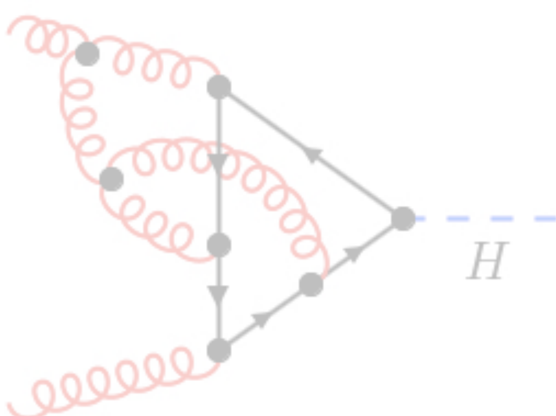
differential equations: $$\partial_z \hat{I}_n(\epsilon, z) = M_{nm}(z)\, \hat{I}_m(\epsilon, z)$$

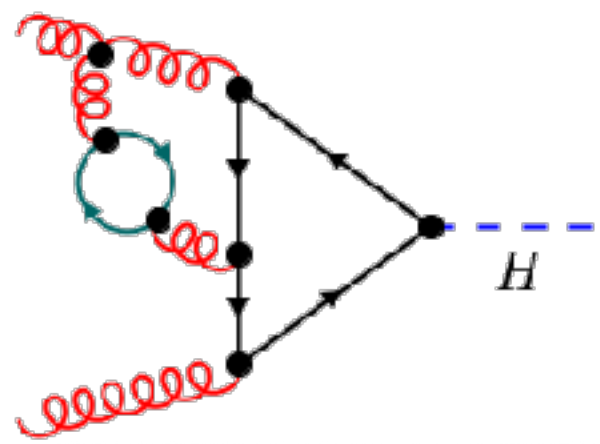
Prausa '17 epsilon $\downarrow$

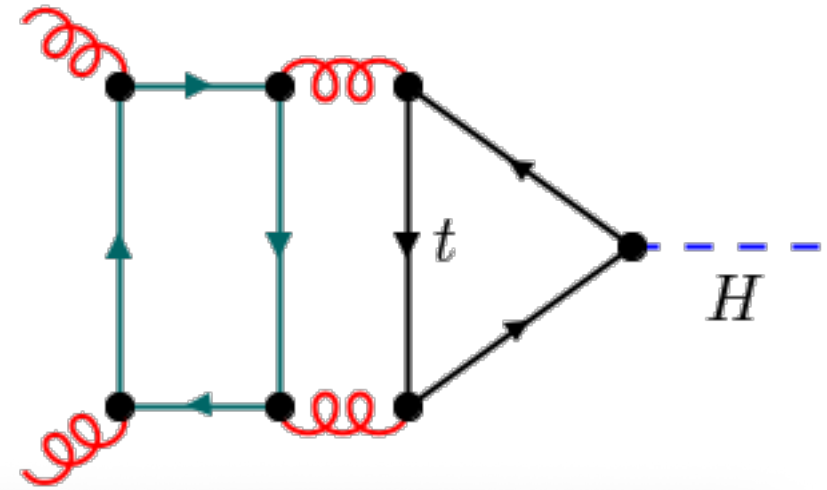
canonical basis: $$\partial_z \hat{J}_n(\epsilon, z) = \epsilon\, \tilde{M}_{nm}(z)\, \hat{J}_m(\epsilon, z)$$

does not always work…

nl-terms







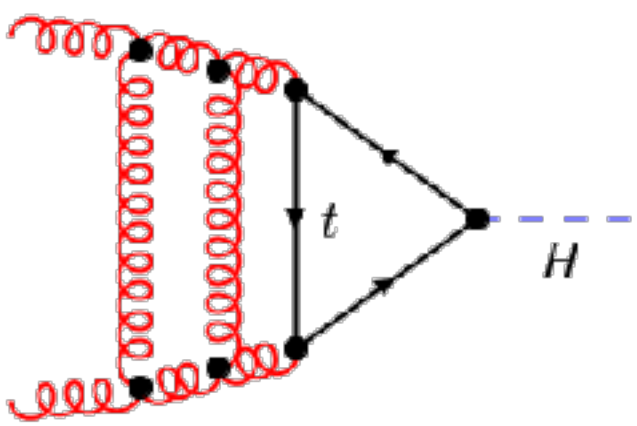
$$
\begin{aligned}
&+\frac{16x\,(1-4x+x^2)}{3(1-x)^4}H_{1,0,0,0,1}+\frac{16x(1+x)\,(1+3x^2)}{3(1-x)^5}H_{0,0,-1,0,1}\\
&+\frac{4x(1+x)\,(3+4x^2)}{3(1-x)^5}H_{0,0,1,0,0}+\frac{16x\,(3-3x+7x^2+x^3)}{3(1-x)^5}H_{1,0,0,-1,0}\\
&+\frac{4x\,(7+x+12x^2+6x^3)}{(1-x)^5}H_{0,1,0,0,0}+\frac{4x\,(7-5x+19x^2+7x^3)}{3(1-x)^5}H_{1,0,1,0,0}\\
&+\frac{4x\,(7-17x+31x^2+7x^3)}{3(1-x)^5}H_{0,1,0,0,1}+\frac{4x\,(11+5x+17x^2+11x^3)}{3(1-x)^5}H_{0,1,0,1,0}\\
&+\frac{4x\,(13+x+25x^2+13x^3)}{3(1-x)^5}H_{0,1,1,0,0}+\frac{2x(1+x)}{3(1-x)^3}\Big[29H_{-1,0}+19H_{0,1}+2H_{1,0}\\
&\quad+6H_0L_\mu\Big]+\frac{x(1+x)\,(11-8x+11x^2)}{9(1-x)^5}\Big[\pi^2H_{-1}-12H_{-1,-1,0}-12H_{-1,0,1}\Big]\\
&+\frac{4x\,(1+4x-2x^2+x^3)}{9(1-x)^5}\Big[\pi^2H_{0,1,0}-6H_{1,0,0,1,0}\Big]+\frac{8x^2}{3(1-x)^4}\Big[\pi^2H_{1,1,0}-9H_{1,1,0,0,0}\\
&\quad-24H_{1,1,0,-1,0}-24H_{1,1,0,0,1}-6H_{1,1,0,1,0}-12H_{1,1,1,0,0}-3H_{0,0}L_\mu-12H_{1,1}\zeta_3\Big]\\
&+\frac{2x(1+x)^2}{9(1-x)^4}\Big[2\pi^2H_{0,1}+2\pi^2H_{0,0,-1}+4\pi^2H_{1,0,-1}+48H_{0,-1,1,0}+48H_{0,1,-1,0}\\
&\quad-6H_{0,1,0,1}-18H_{0,1,1,0}-48H_{1,0,-1,-1,0}-48H_{1,0,-1,0,1}+\pi^2H_0L_\mu+24H_{0,-1,0}L_\mu
\end{aligned}
$$

RH, Prausa, Usovitsch ‘19

P3H-19-021

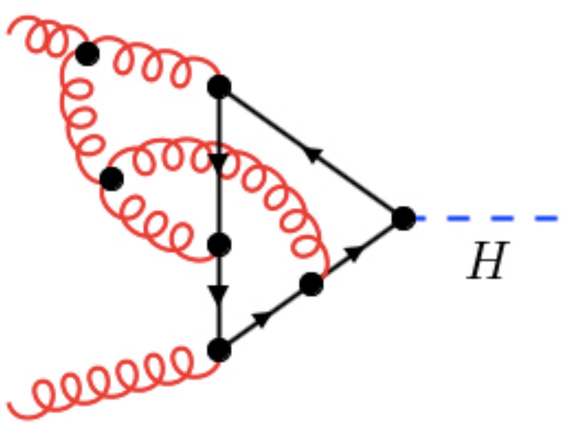
Leading Color

(12 pages of this)



Prausa, Usovitsch '20

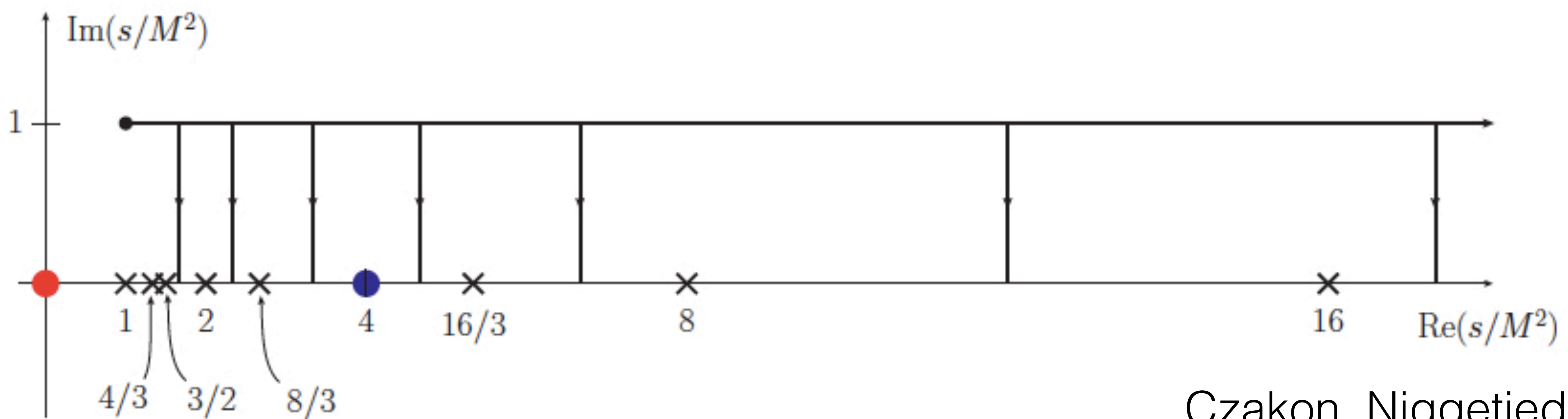
Full form factor



Calculate masters:

$$\partial_z \hat{I}_n(\epsilon, z) = M_{nm}(z)\, \hat{I}_m(d, z)$$

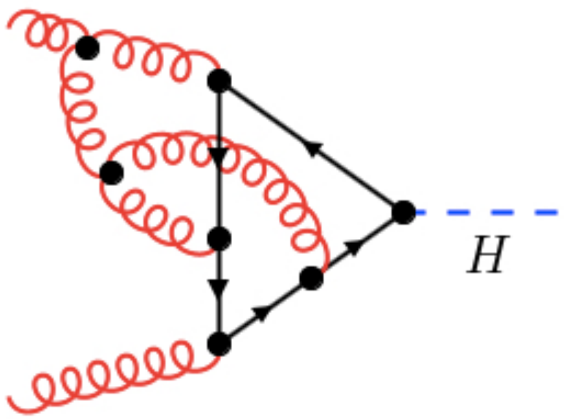
→ solve numerically



Czakon, Niggetiedt '20

P3H-20-001

Full form factor

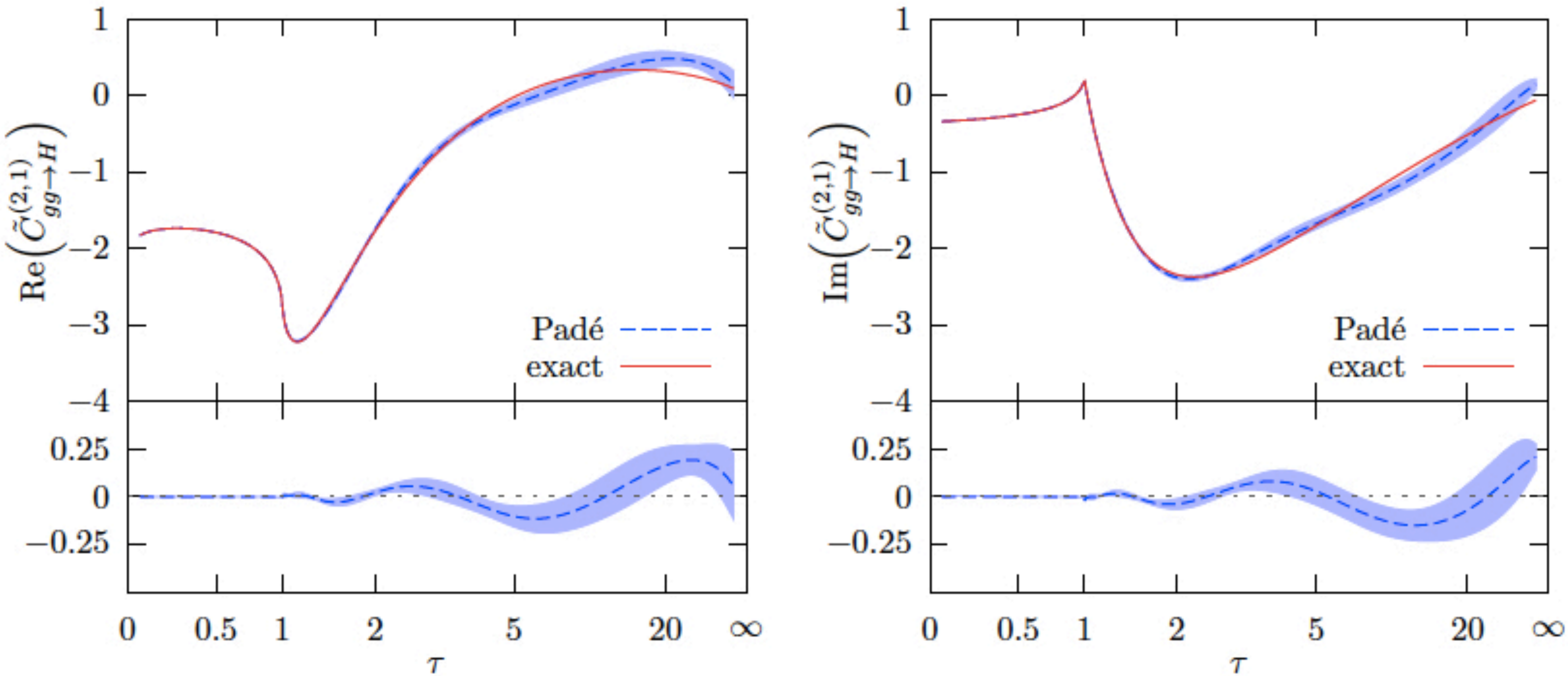


Padé approximations:

- Use expansions for
  - $m_t \to \infty$
  - top threshold, i.e. $\hat{s} \approx 4m_t^2$

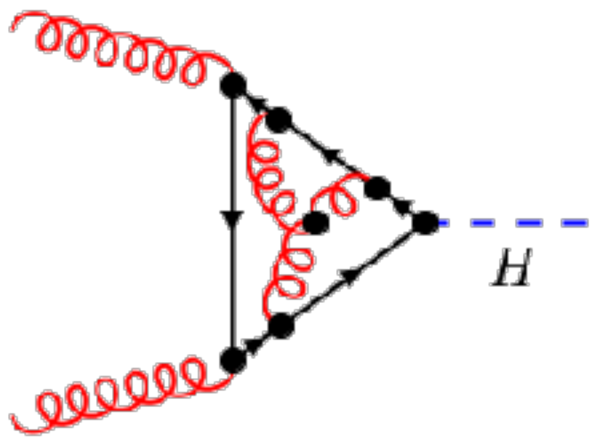
Davies et al. '19
P3H-19-012

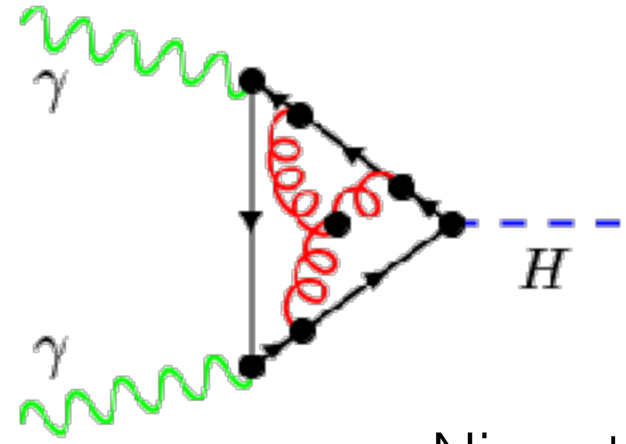
Comparison



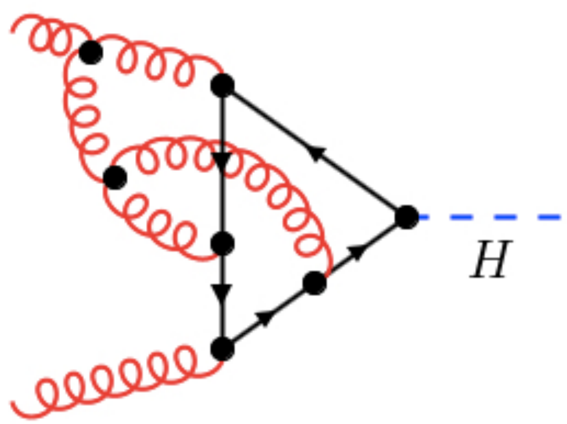
$$\tau = \frac{M_H^2}{4m_q^2}$$

$H \to \gamma\gamma$

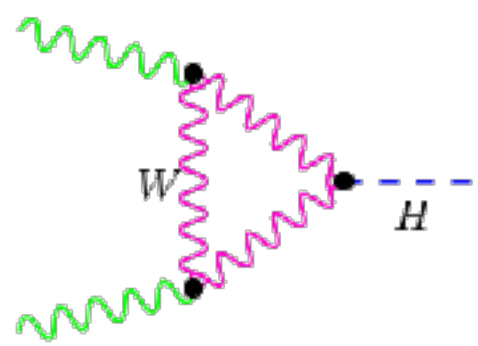




Niggetiedt '20
P3H-20-050

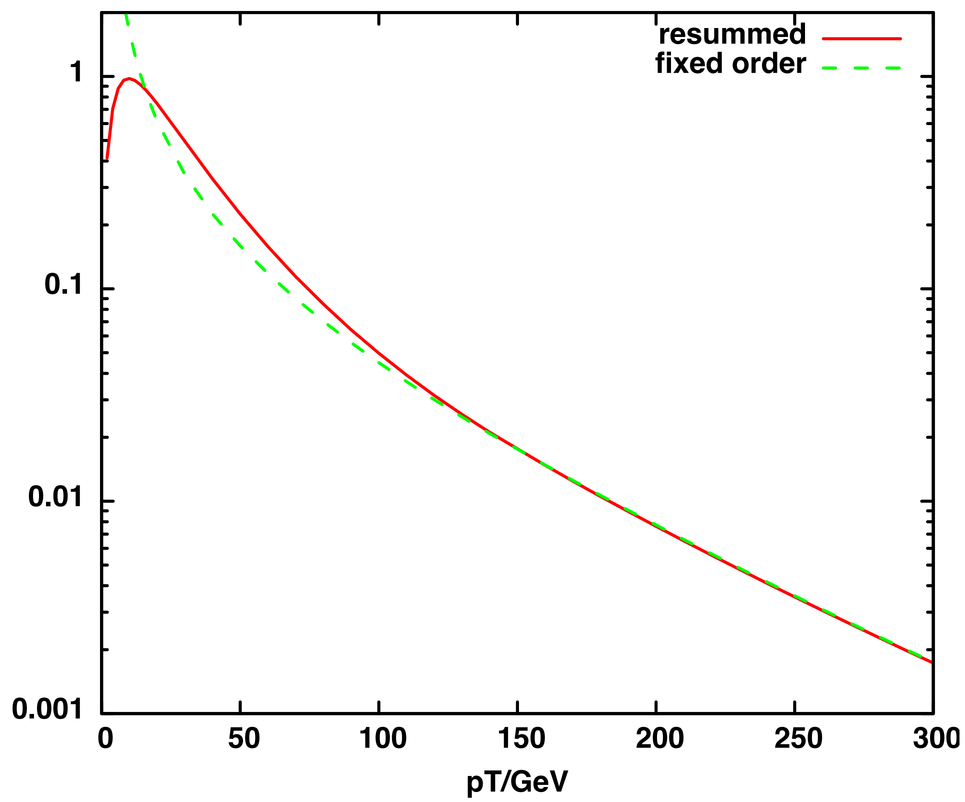


sub-leading to



Summary

- All parts to total xsec are available
- Putting things together: a matter of time
- Will decrease theoretical uncertainty by 1-2%
- Next stop: differential / fiducial xsecs
- Other progress: mixed EW/QCD Bonetti et al. '20 P3H-20-036
- Open issues: e.g. small/intermediate p_T



$$m_b < p_T < M_H, m_t$$