

A1a

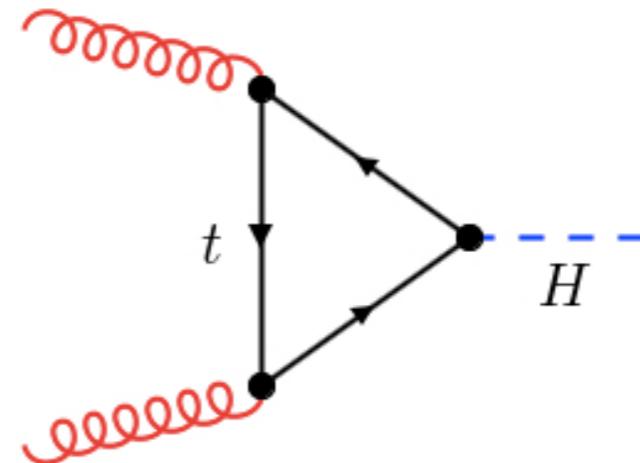
Quark-mass effects in Higgs-boson production in gluon fusion

PIs: Michał Czakon, Robert Harlander

Goals

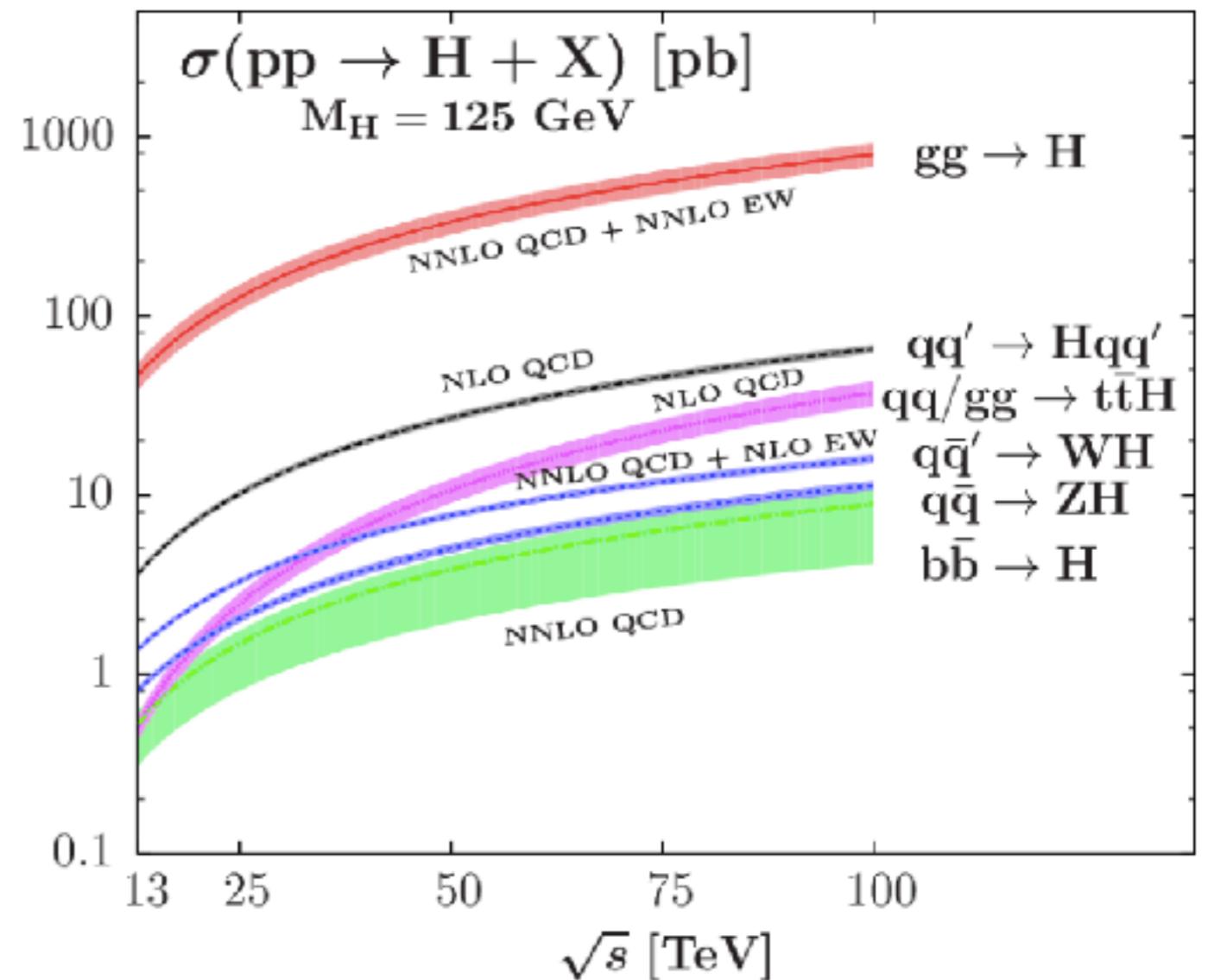
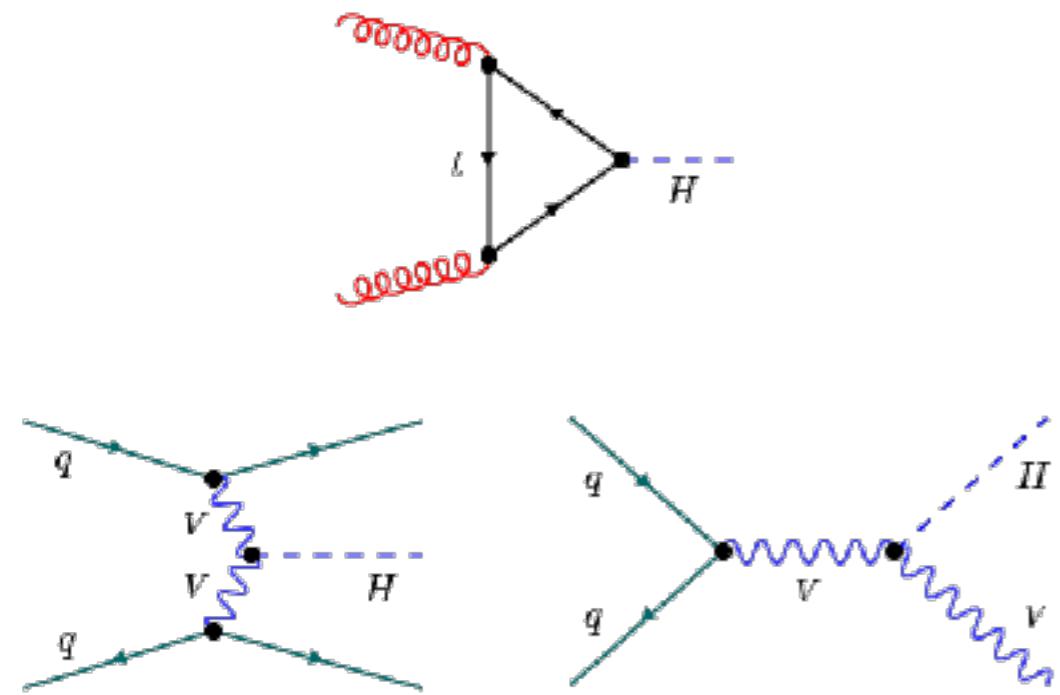
Full quark mass dependence
at NNLO.

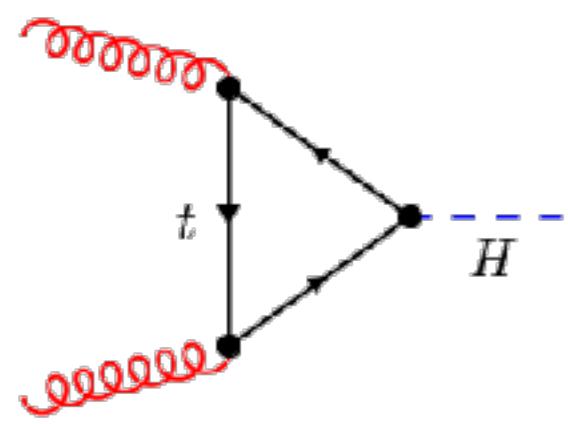
Total cross section.
Differential distributions.



Also “extreme” phase space regions: resummation.

Why?

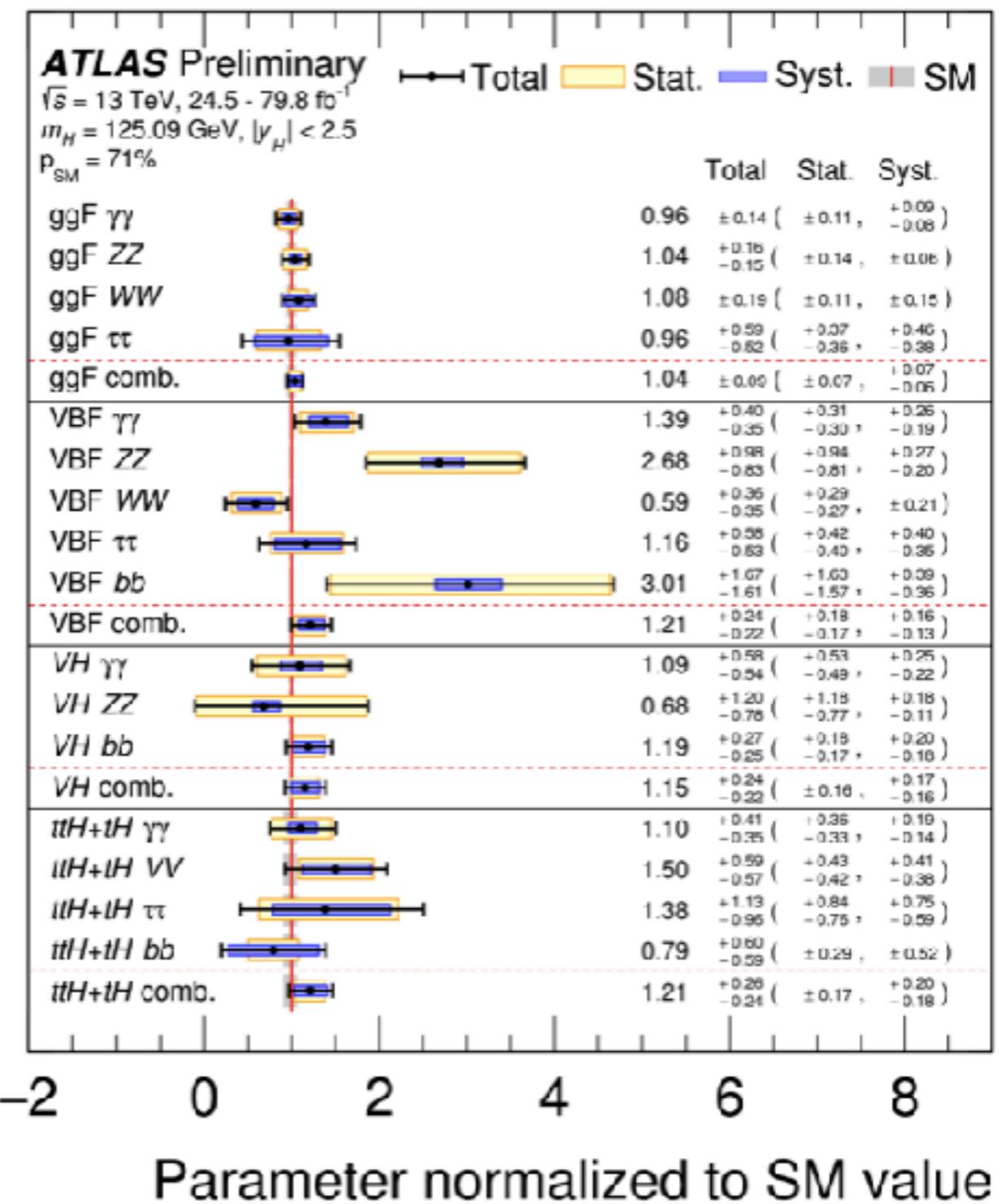




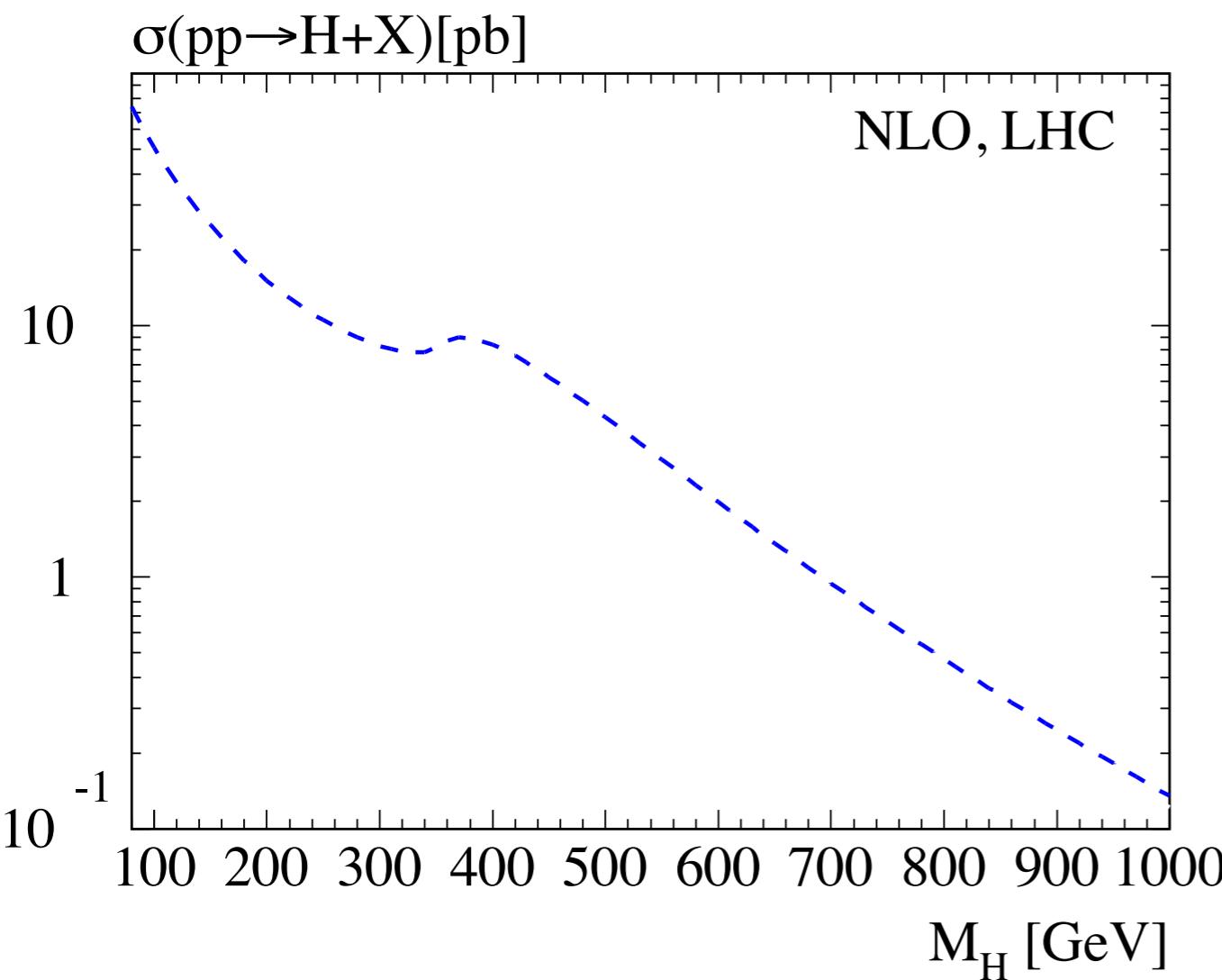
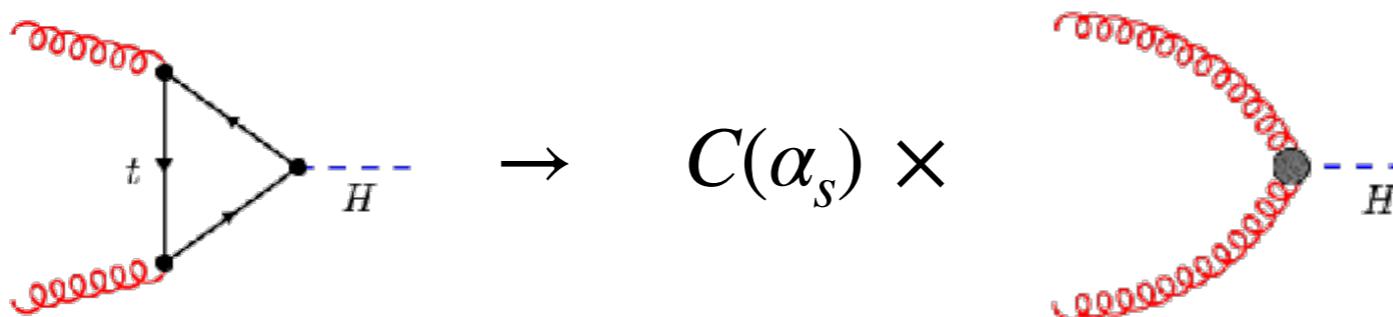
Enters many Higgs measurements

Precise theory understanding is essential

$\text{LO} \longrightarrow \text{NLO} \longrightarrow \text{NNLO}$
 1978 1991 2002
 $\longrightarrow \text{N}^3\text{LO}$
 2015

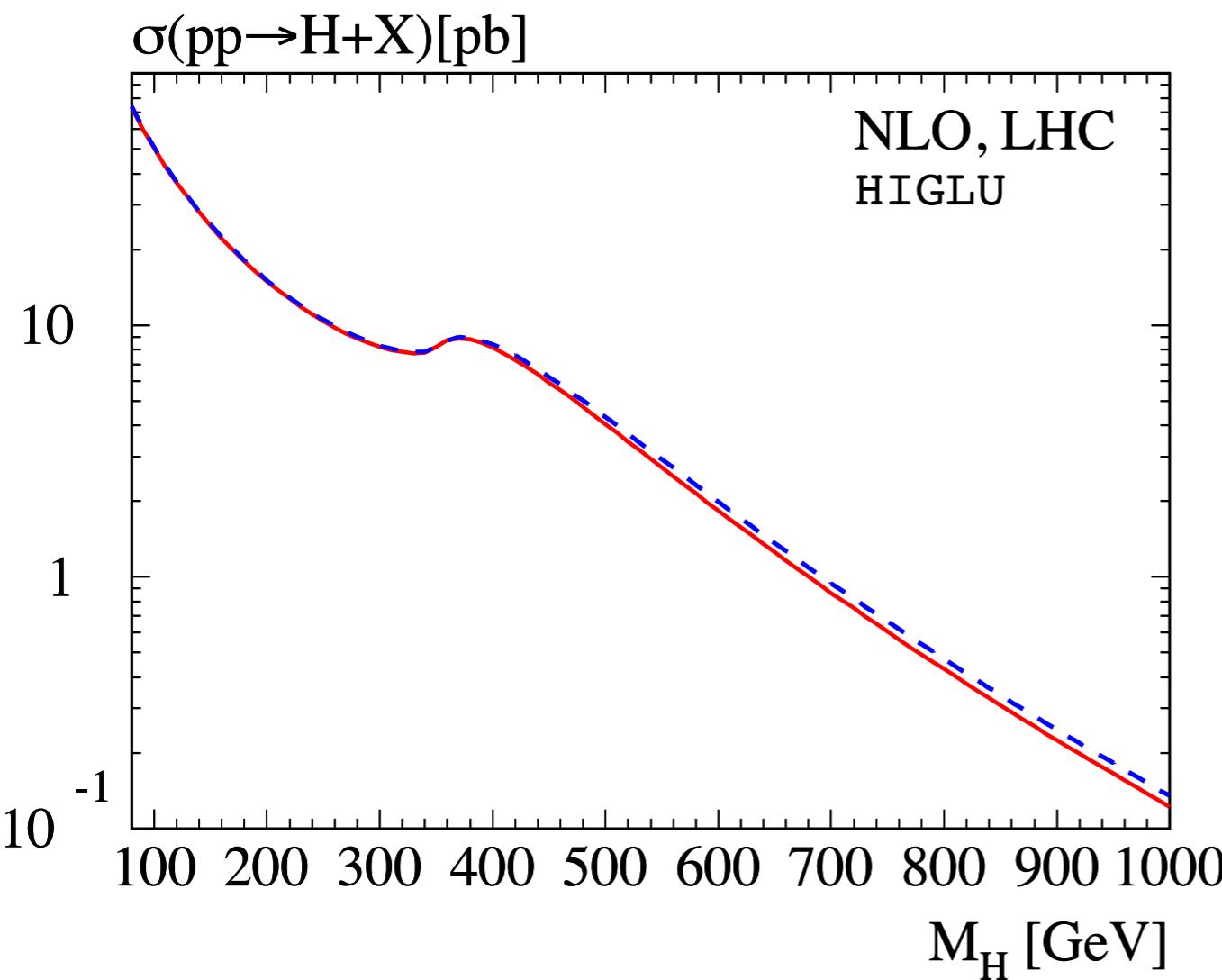
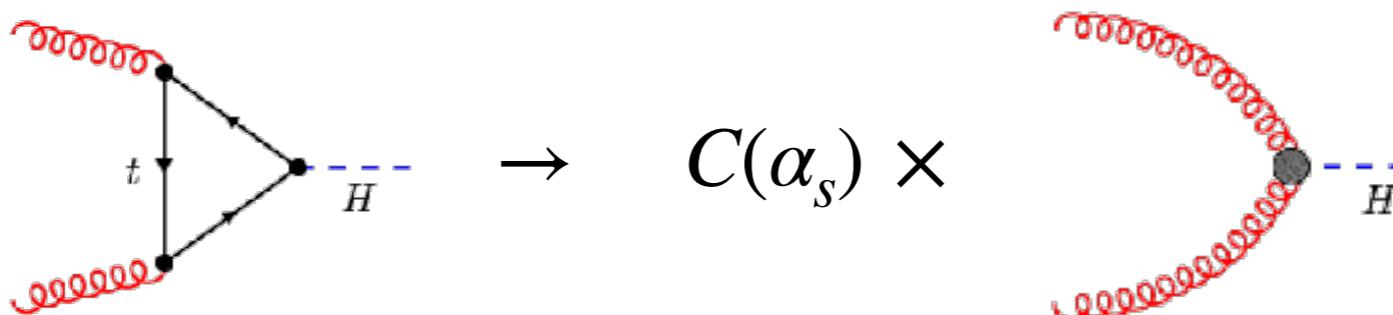


Higgs Effective Field Theory (HEFT)



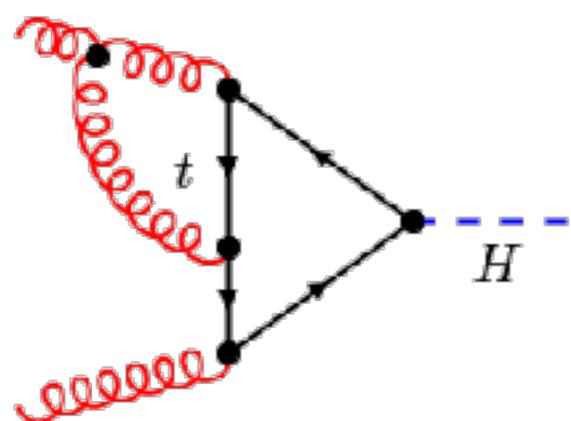
$$\sigma_{\infty}^{\text{HO}} \equiv \sigma^{\text{LO}}(m_t) \left(\frac{\sigma^{\text{HO}}}{\sigma^{\text{LO}}} \right)_{m_t \rightarrow \infty}$$

Higgs Effective Field Theory (HEFT)



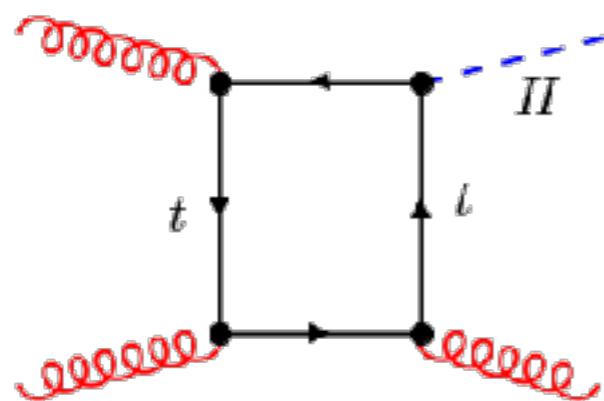
$$\sigma_{\infty}^{\text{HO}} \equiv \sigma^{\text{LO}}(m_t) \left(\frac{\sigma^{\text{HO}}}{\sigma^{\text{LO}}} \right)_{m_t \rightarrow \infty}$$

HEFT for the total xsec

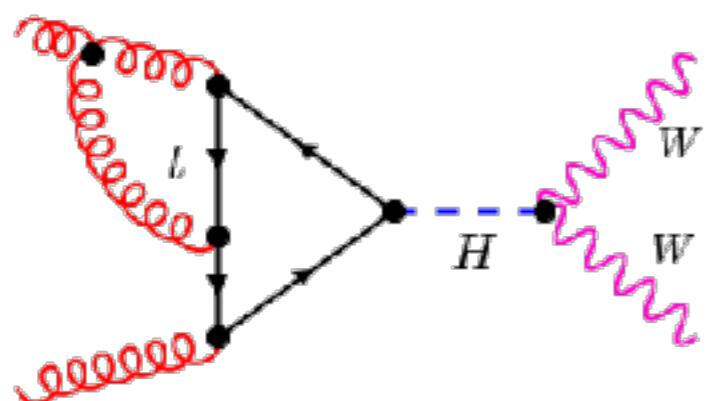


$$\delta(\hat{s} - M_H^2)$$

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

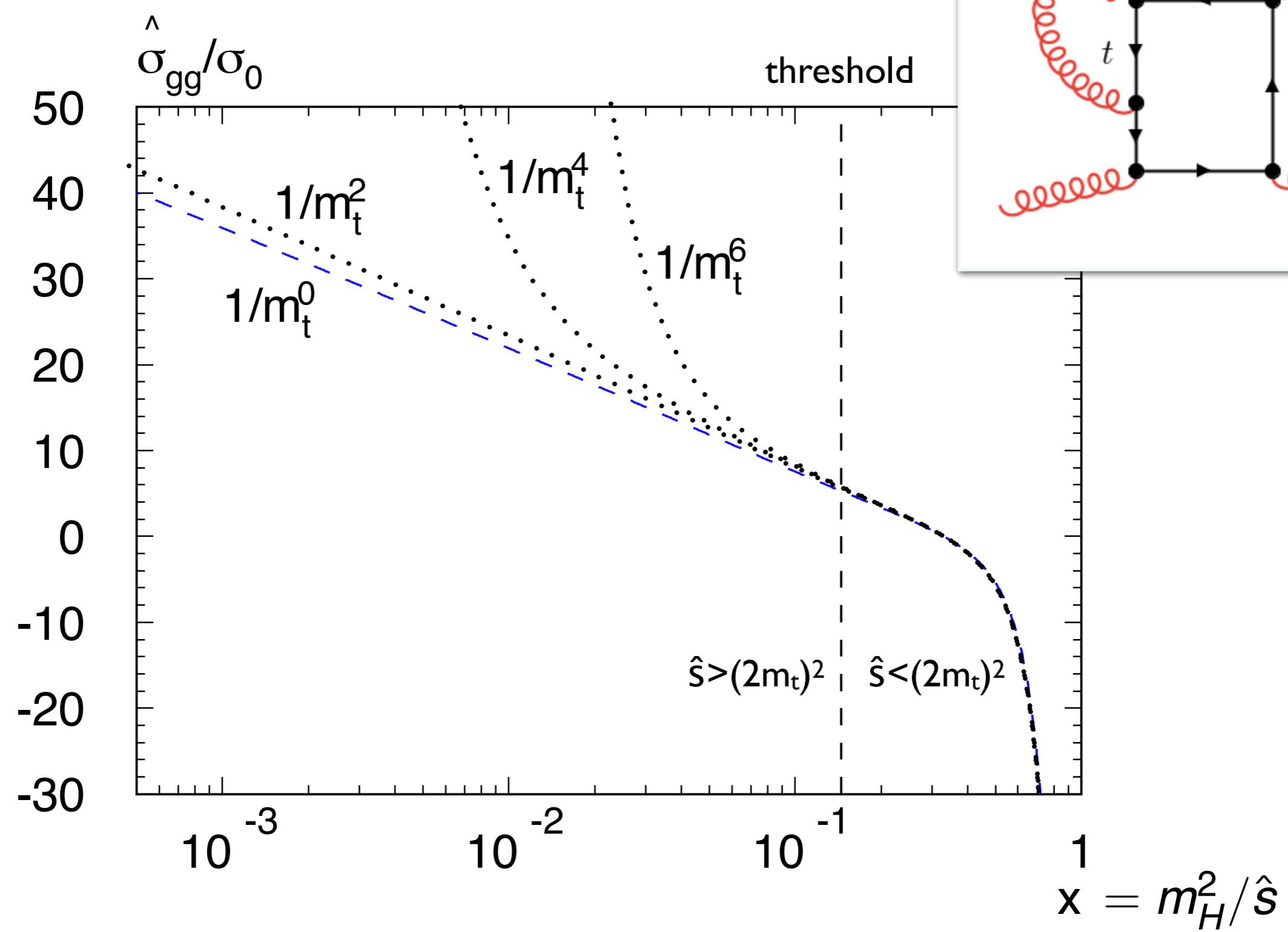


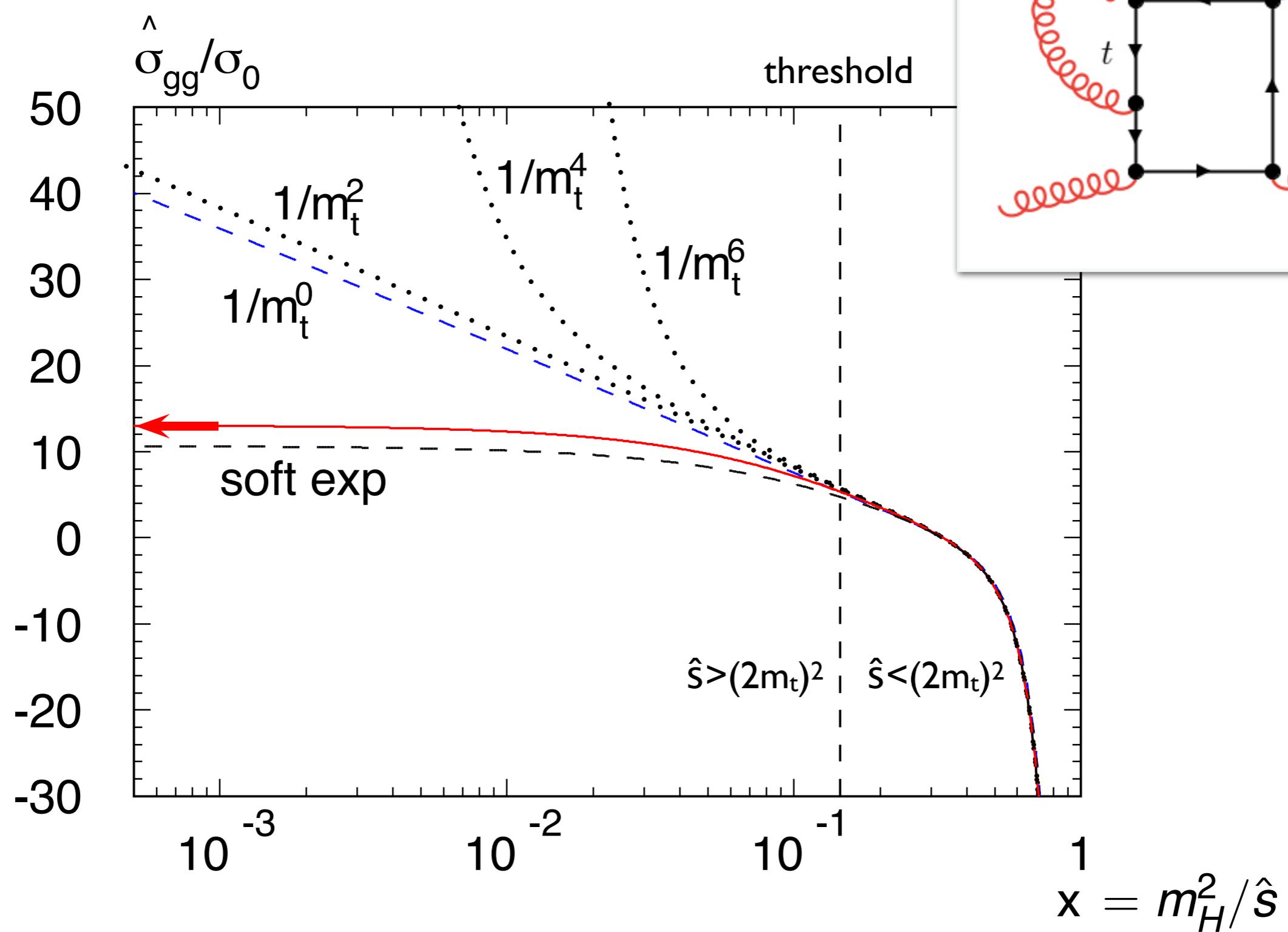
$$M_H^2 < \hat{s} < s = 14 \text{ TeV}$$

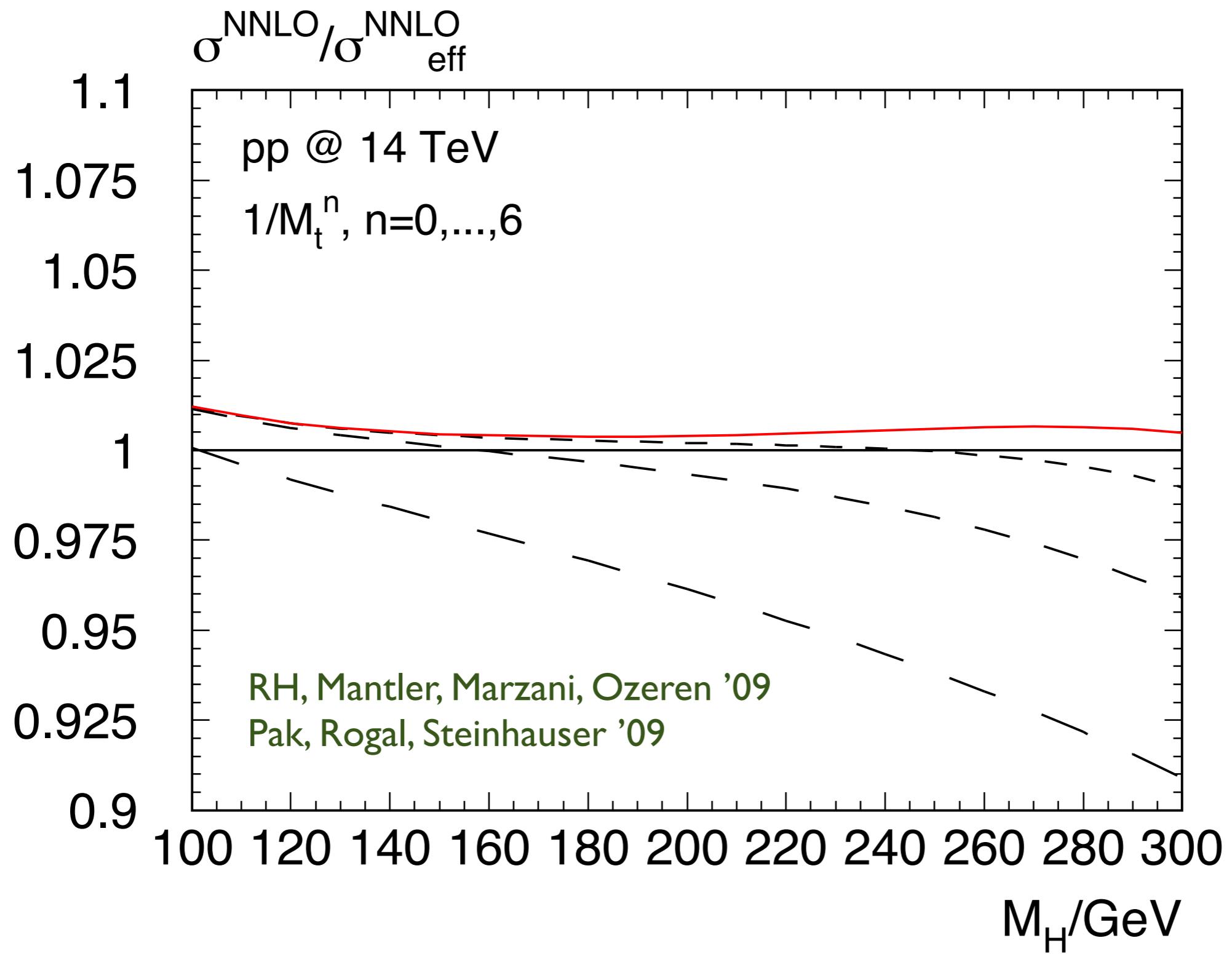


off-shell production

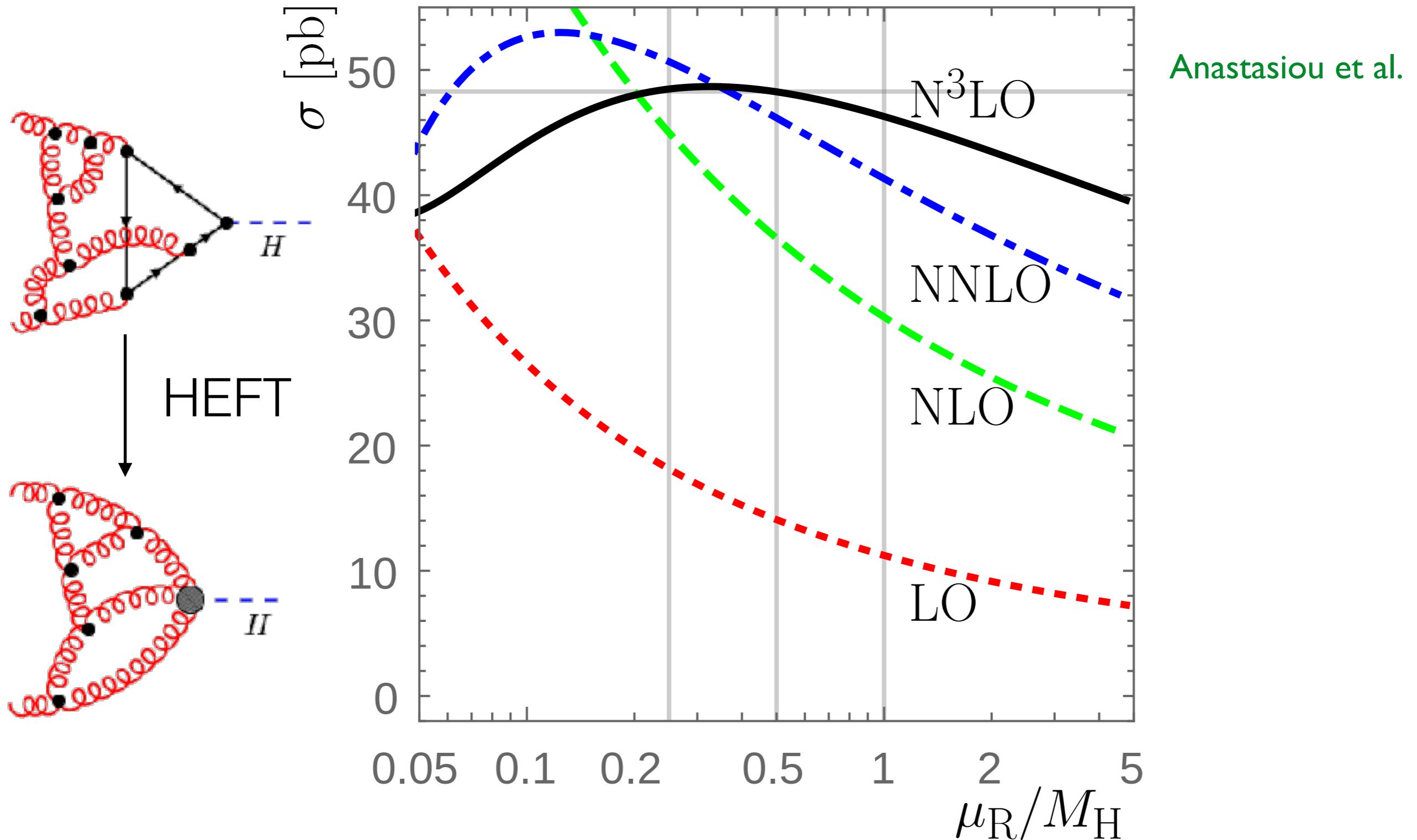




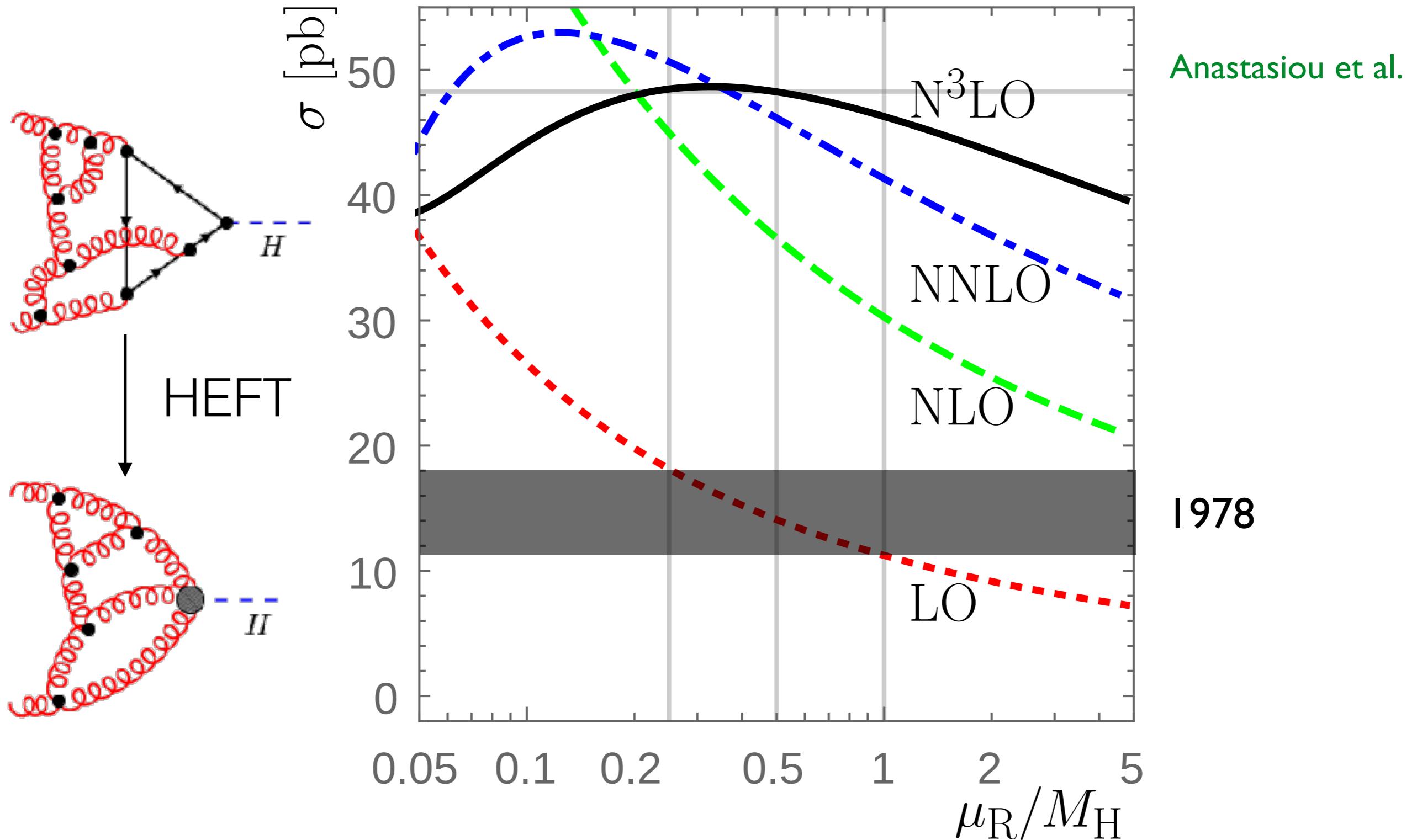




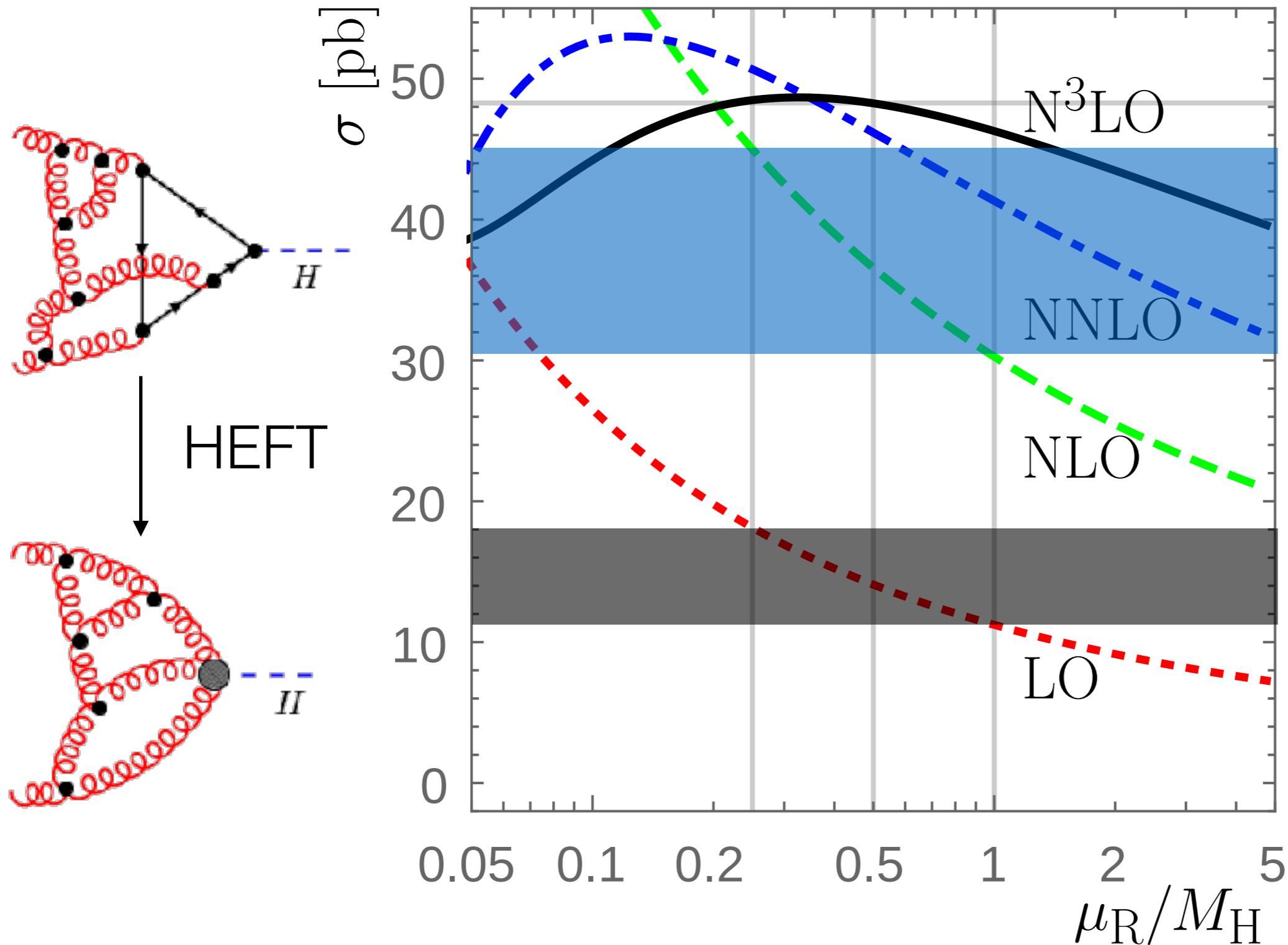
Total cross section in HEFT through N³LO:



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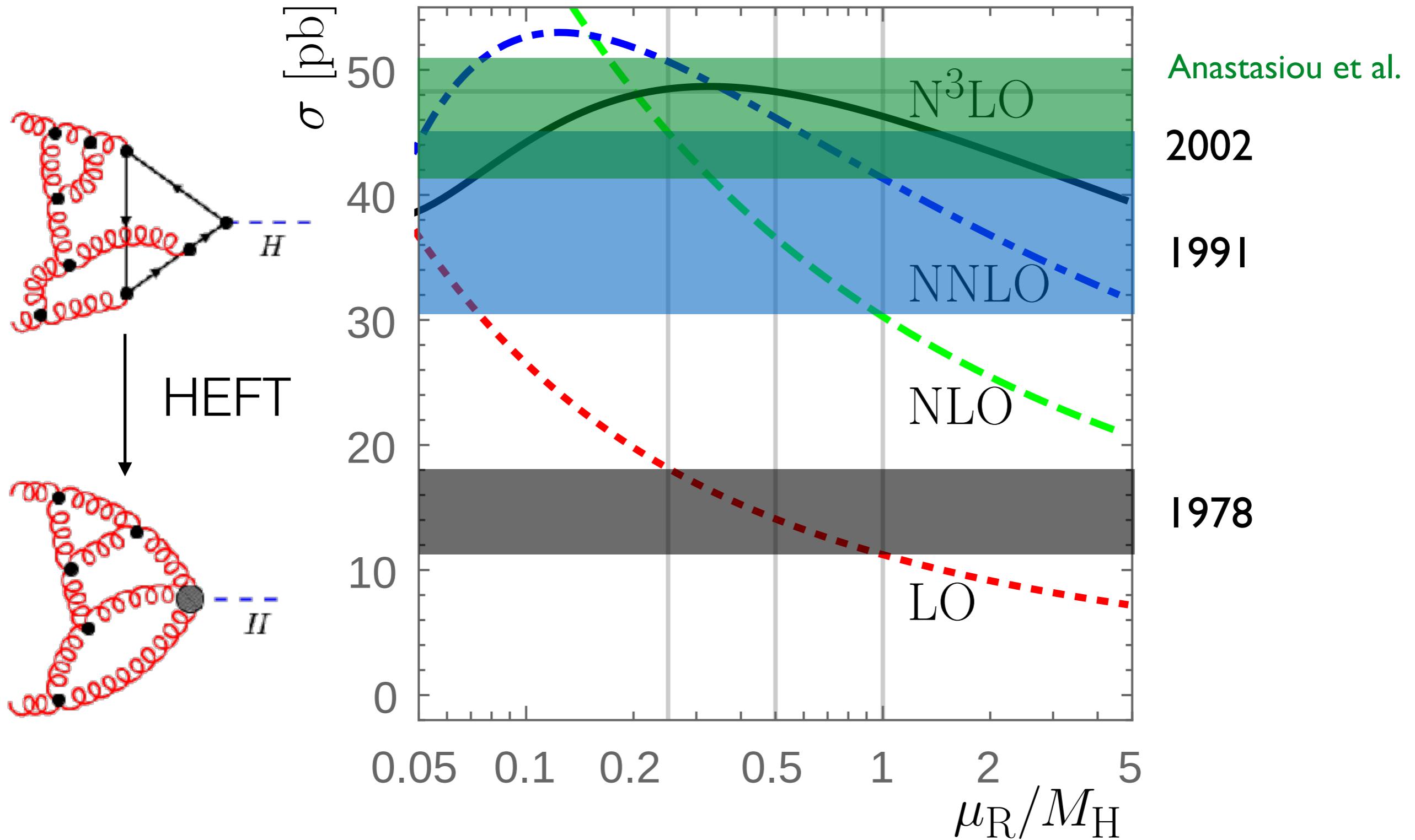


Anastasiou et al.

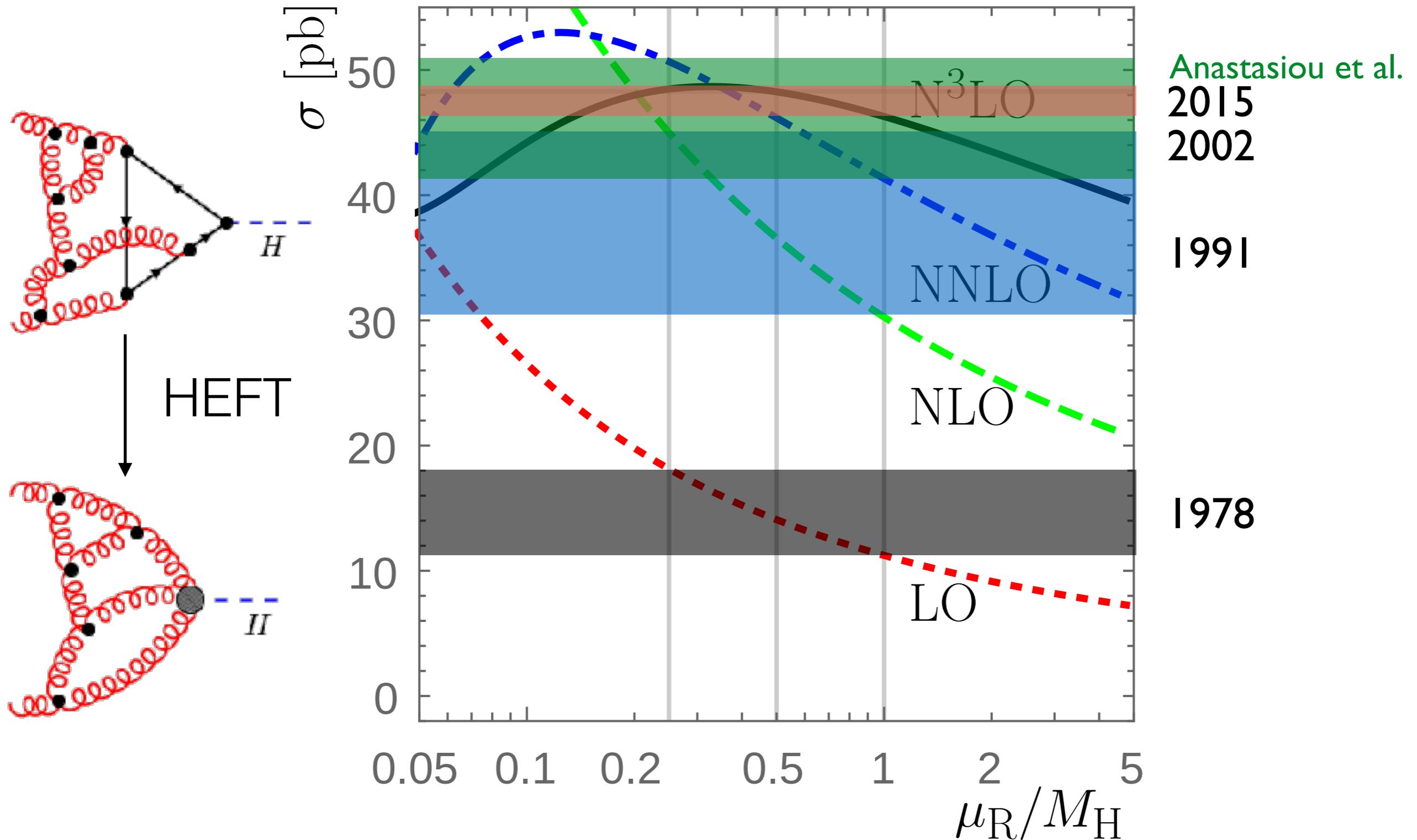
1991

1978

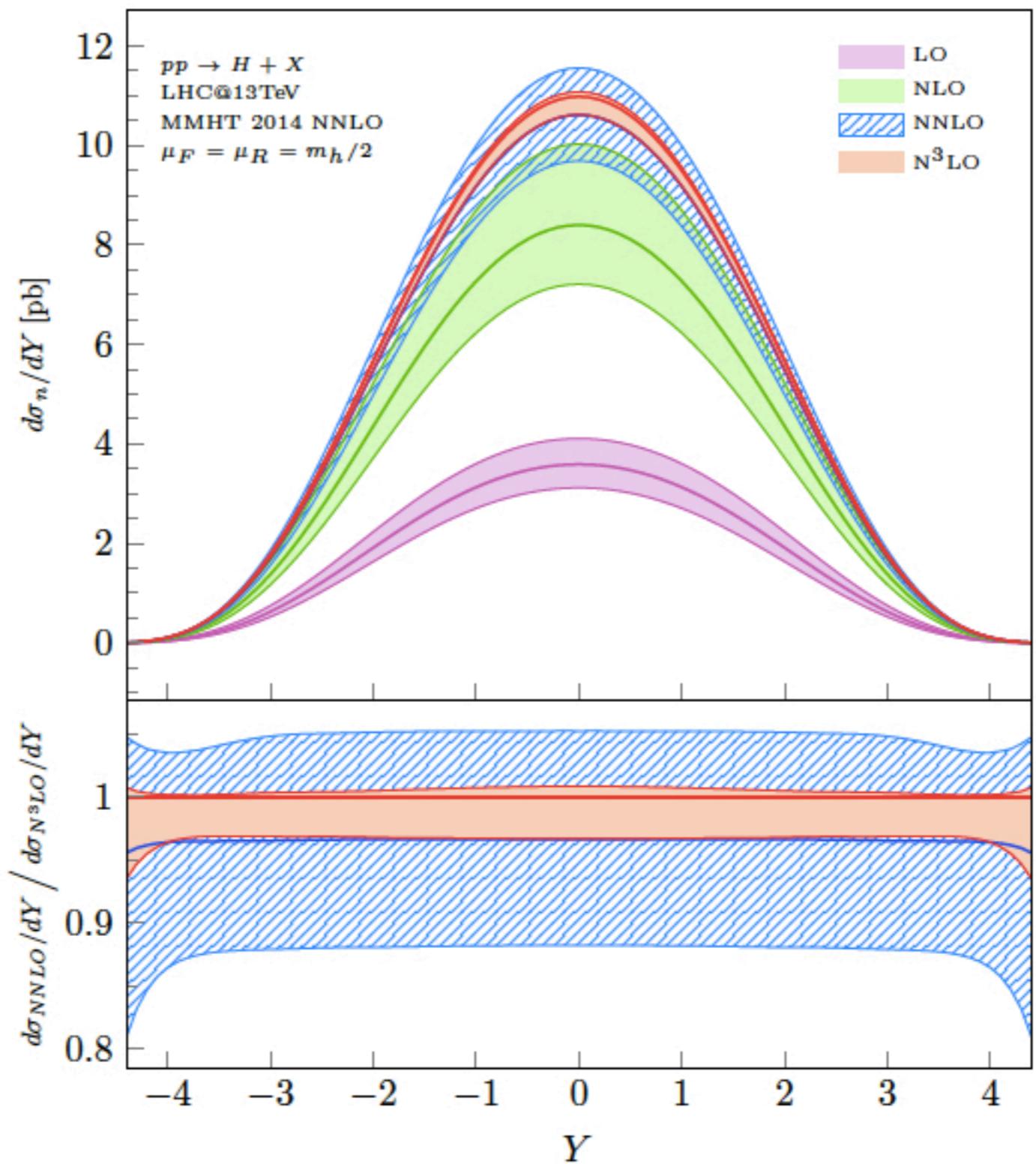
Total cross section in HEFT through N³LO:



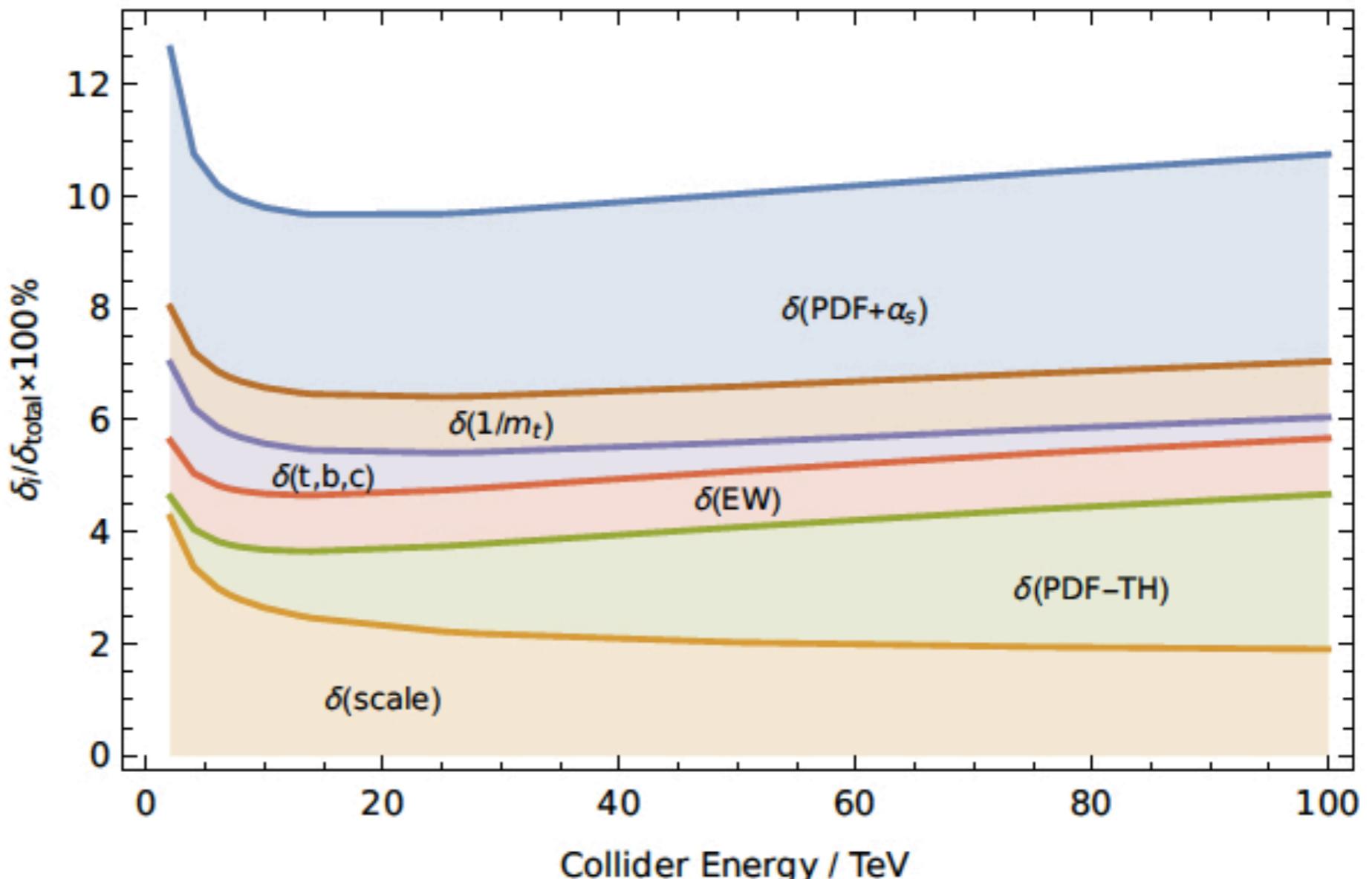
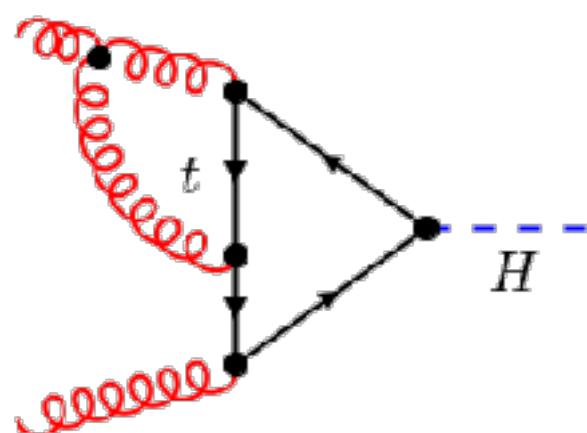
Total cross section in HEFT through N³LO:



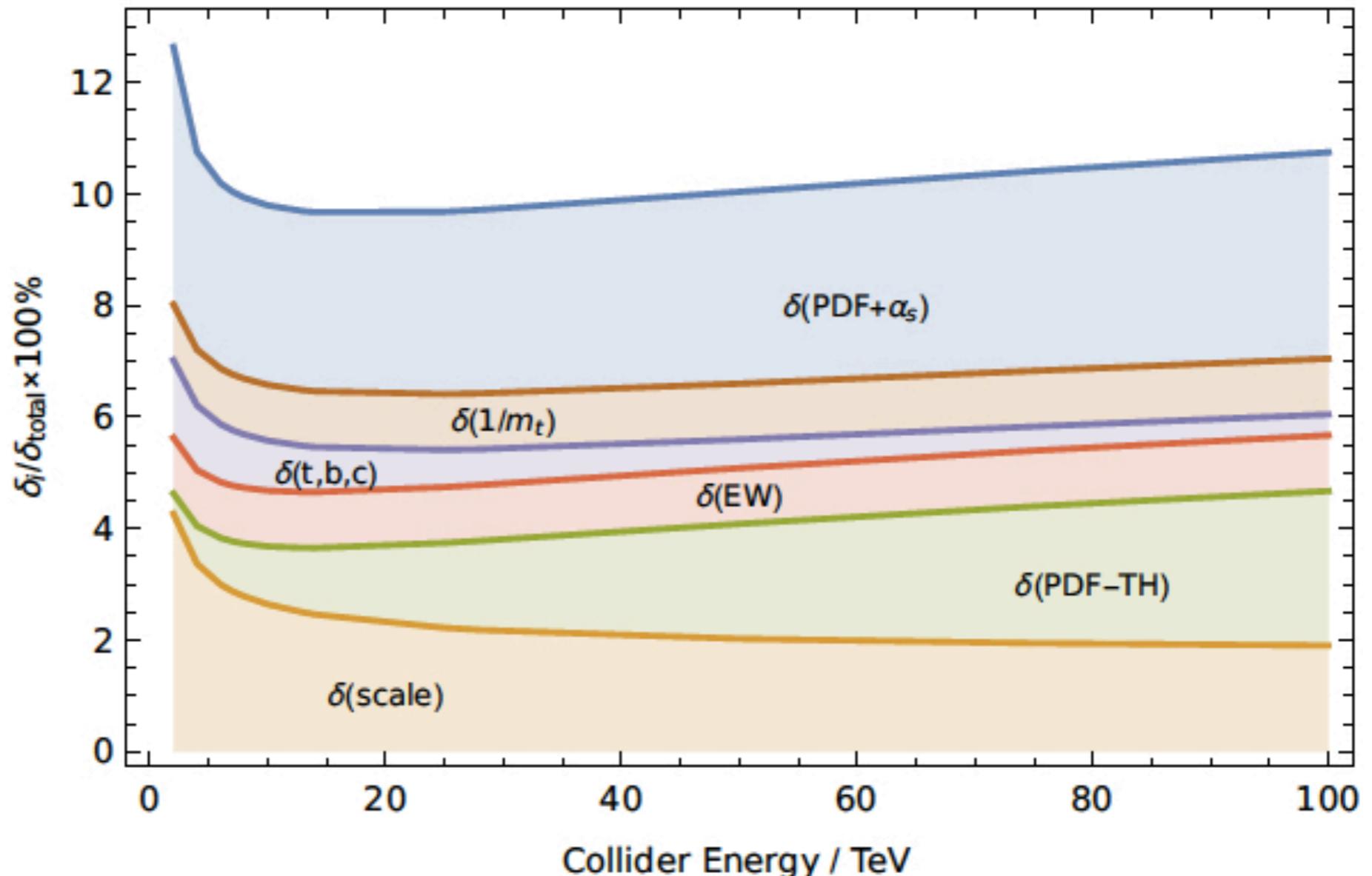
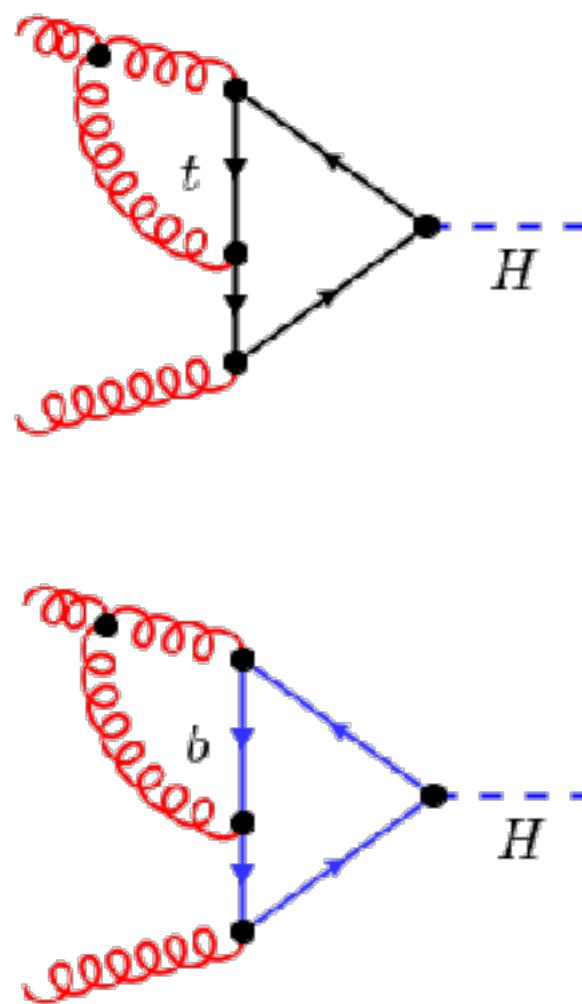
Cieri et al. '18
Dulat, Mistlberger, Pelloni '18



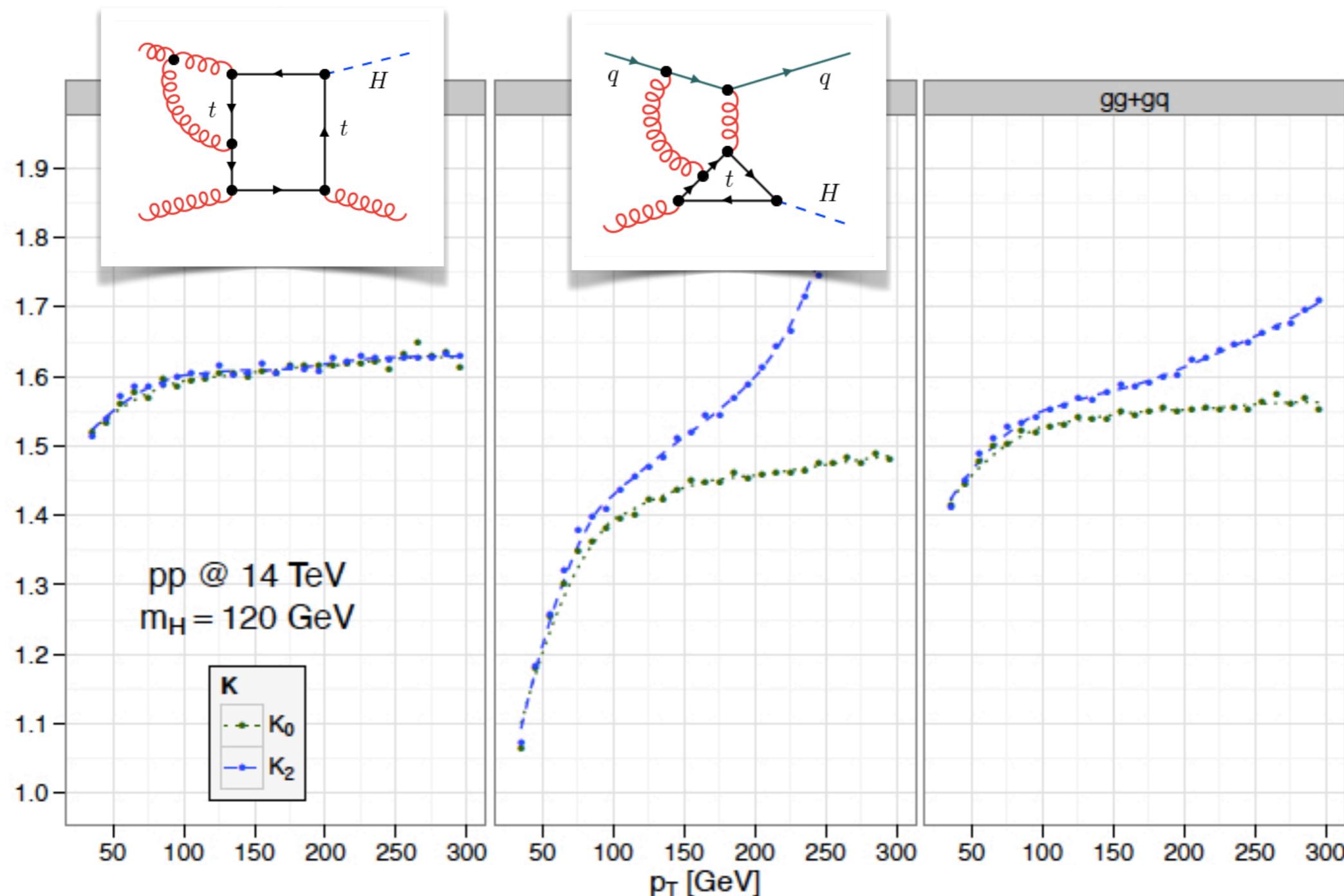
Uncertainties



Uncertainties

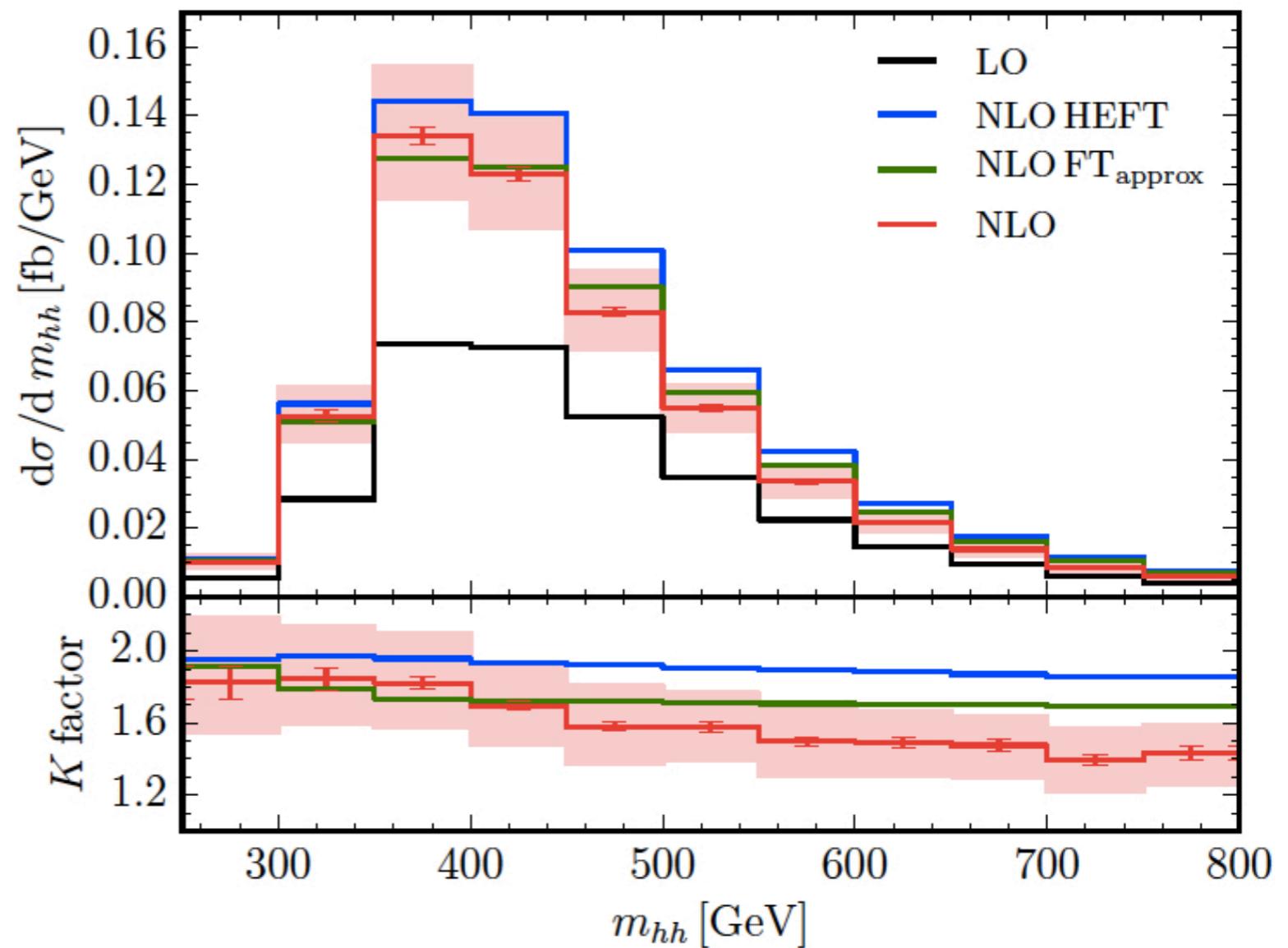
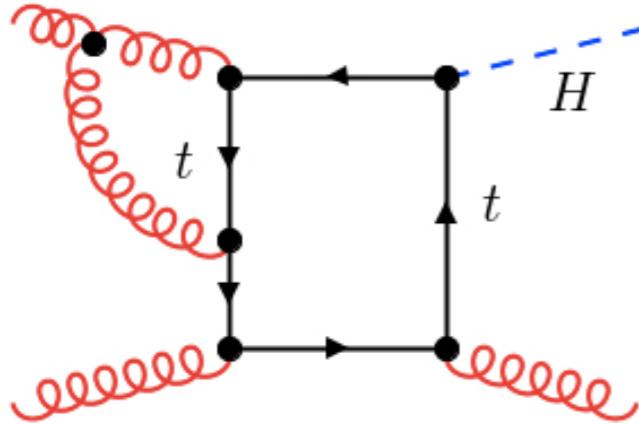


p_T distribution: $1/m_t$ expansion



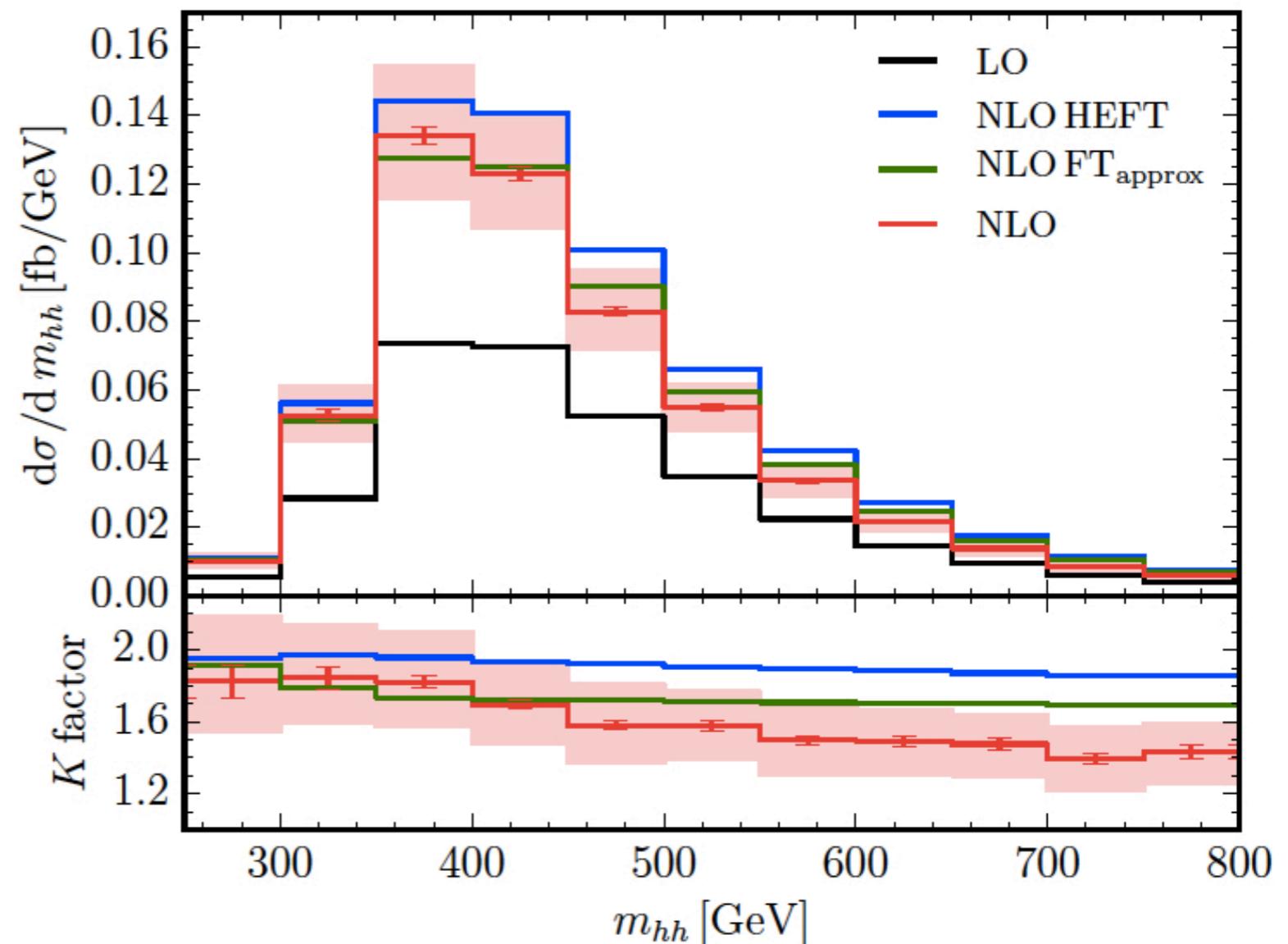
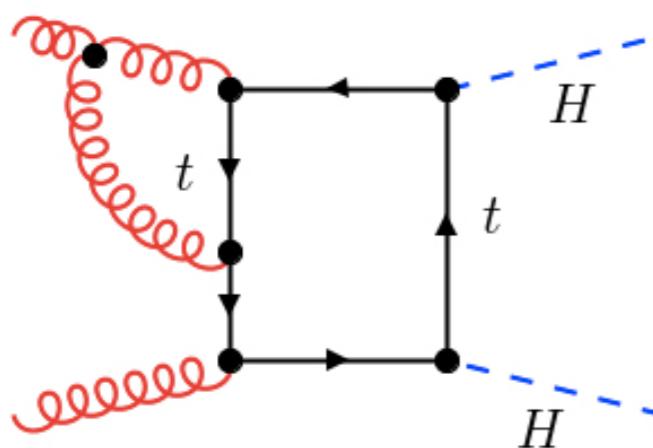
Harlander, Neumann '12

Comparison: HH



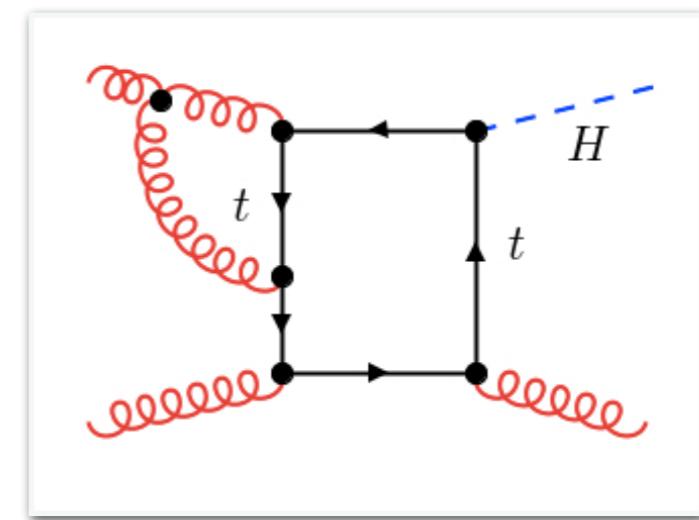
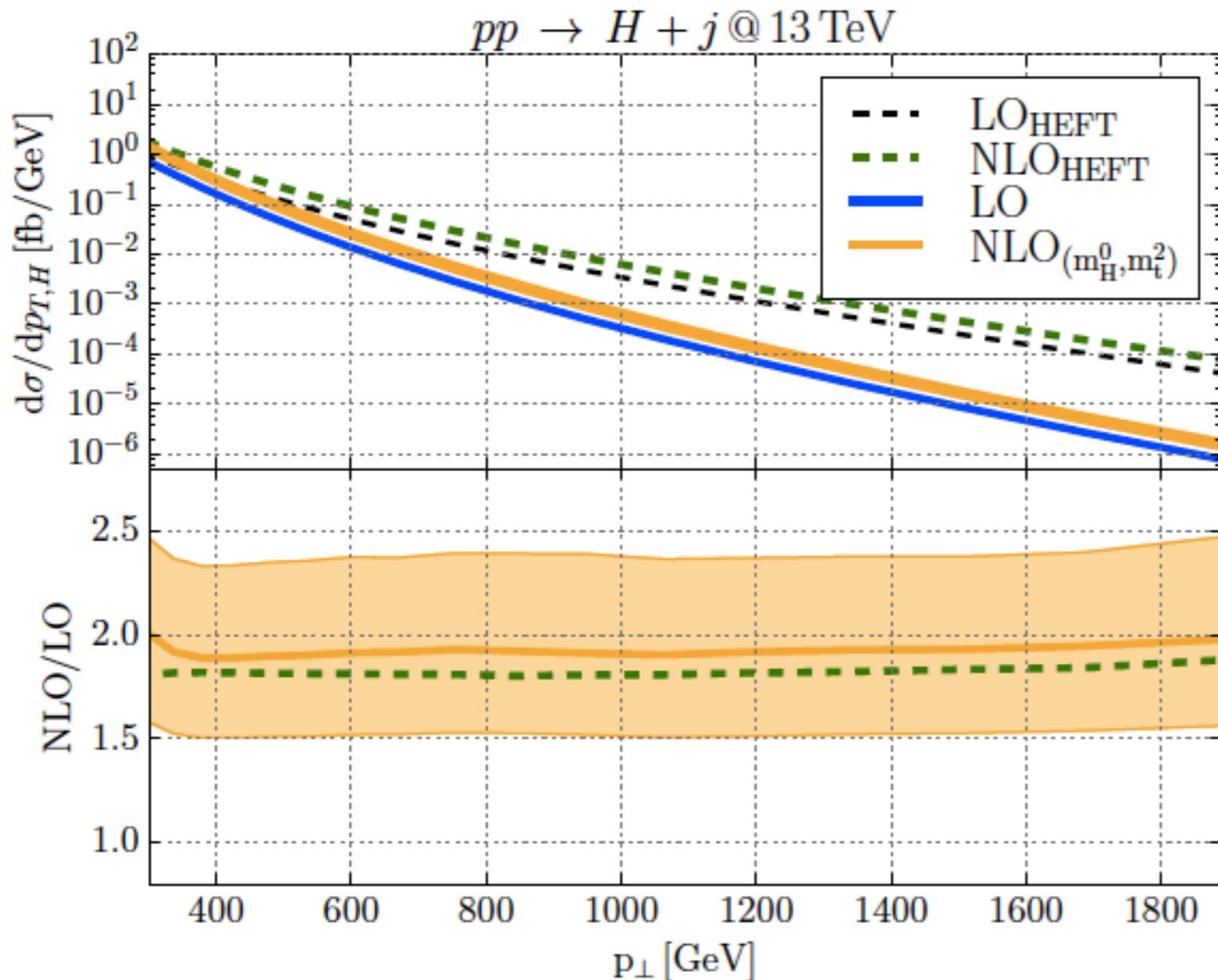
Borowka et al. '16
Baglio et al. '18

Comparison: HH



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

p_T distribution



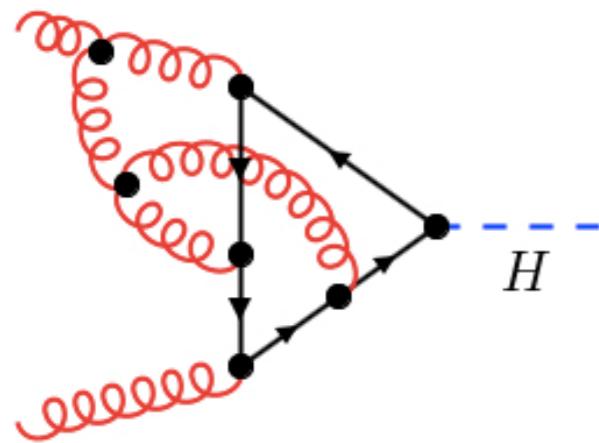
large- p_T :

Lindert, Kudashkin,
Melnikov, Wever '18

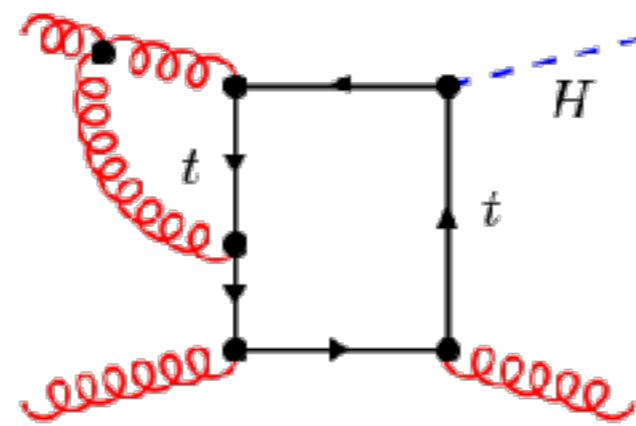
full:

S.P. Jones, Kerner, Luisoni '18

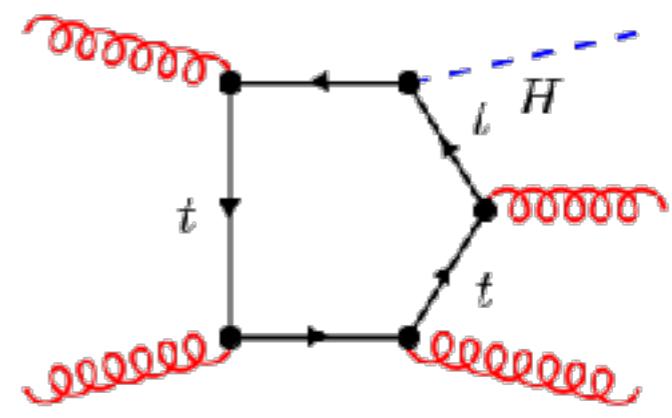
What is missing?



???



S.P. Jones, Kerner, Luisoni '18



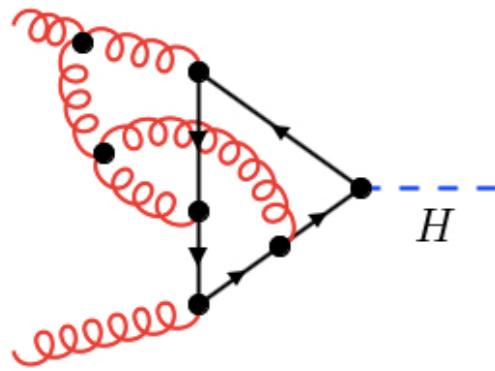
Del Duca et al. '01

The usual problems:

Reduction: • solve large system of equations
• re-insert solution into amplitude

FireFly: solve on finite fields

Klappert, Lange (+ Klein) '19



→ millions of Feynman integrals
related by Integration-by-Parts identities
→ huge system of linear equations

solution:

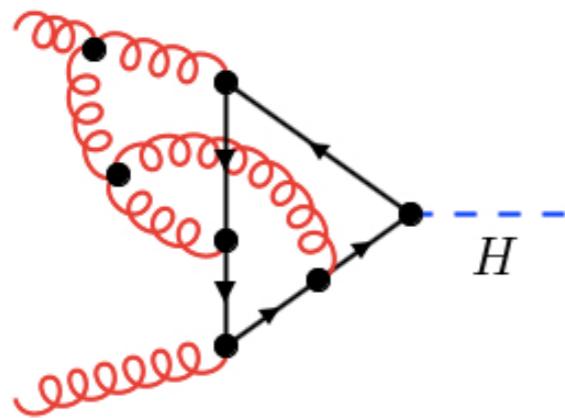
$$I = \sum_{n=1}^{\mathcal{O}(100)} c_n(d, z) \hat{I}_n$$

↗
masters
rational functions

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

Work on Finite Fields: \mathbb{Z}_p

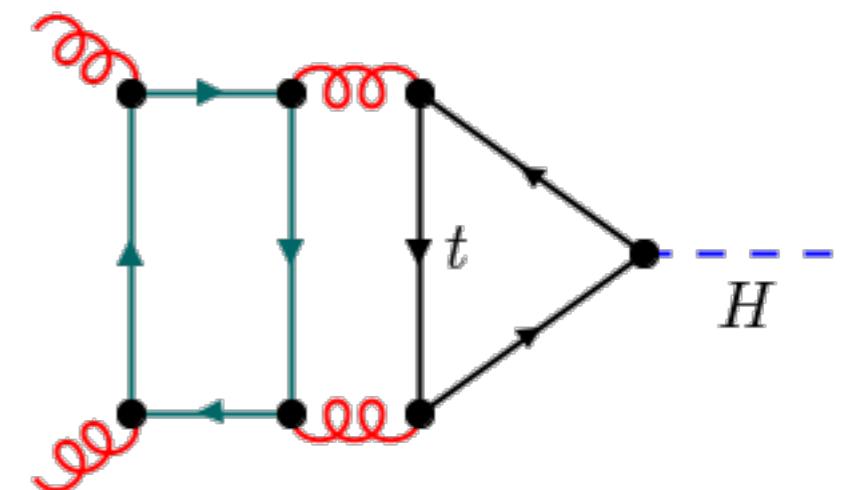
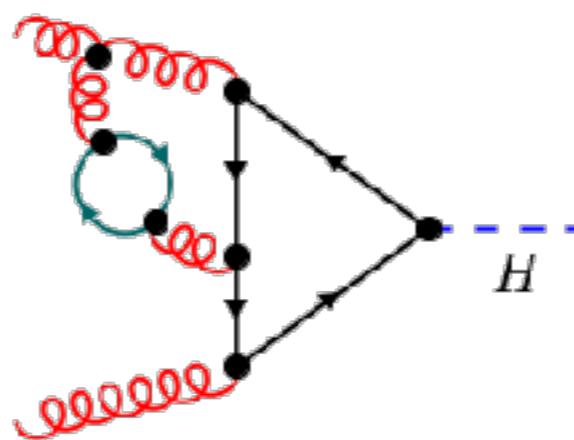
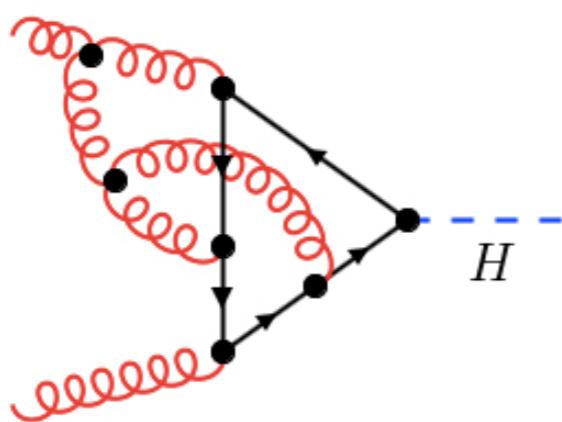
The three-loop form factor



Reduction:

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

Calculate masters



differential equations:

Prausa '17 epsilon

canonical basis:

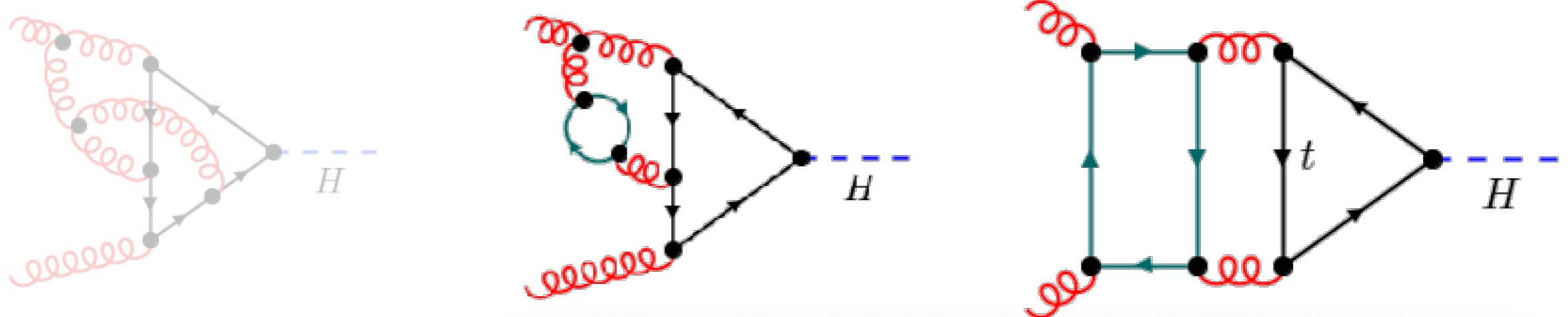
$$\partial_z \hat{I}_n(\epsilon, z) = M_{nm}(z) \hat{I}_m(\epsilon, z)$$



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

does not always work...

nl-terms

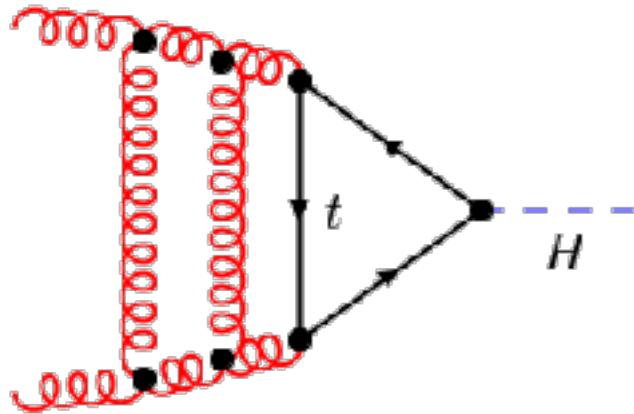


$$\begin{aligned} &+ \frac{16x(1-4x+x^2)}{3(1-x)^4} H_{1,0,0,0,1} + \frac{16x(1+x)(1+3x^2)}{3(1-x)^5} H_{0,0,-1,0,1} \\ &+ \frac{4x(1+x)(3+4x^2)}{3(1-x)^5} H_{0,0,1,0,0} + \frac{16x(3-3x+7x^2+x^3)}{3(1-x)^5} H_{1,0,0,-1,0} \\ &+ \frac{4x(7+x+12x^2+6x^3)}{(1-x)^5} H_{0,1,0,0,0} + \frac{4x(7-5x+19x^2+7x^3)}{3(1-x)^5} H_{1,0,1,0,0} \\ &+ \frac{4x(7-17x+31x^2+7x^3)}{3(1-x)^5} H_{0,1,0,0,1} + \frac{4x(11+5x+17x^2+11x^3)}{3(1-x)^5} H_{0,1,0,1,0} \\ &+ \frac{4x(13+x+25x^2+13x^3)}{3(1-x)^5} H_{0,1,1,0,0} + \frac{2x(1+x)}{3(1-x)^3} \left[29H_{-1,0} + 19H_{0,1} + 2H_{1,0} \right. \\ &\quad \left. + 6H_0 L_\mu \right] + \frac{x(1+x)(11-8x+11x^2)}{9(1-x)^5} \left[\pi^2 H_{-1} - 12H_{-1,-1,0} - 12H_{-1,0,1} \right] \\ &+ \frac{4x(1+4x-2x^2+x^3)}{9(1-x)^5} \left[\pi^2 H_{0,1,0} - 6H_{1,0,0,1,0} \right] + \frac{8x^2}{3(1-x)^4} \left[\pi^2 H_{1,1,0} - 9H_{1,1,0,0,0} \right. \\ &\quad \left. - 24H_{1,1,0,-1,0} - 24H_{1,1,0,0,1} - 6H_{1,1,0,1,0} - 12H_{1,1,1,0,0} - 3H_{0,0} L_\mu - 12H_{1,1} \zeta_3 \right] \\ &+ \frac{2x(1+x)^2}{9(1-x)^4} \left[2\pi^2 H_{0,1} + 2\pi^2 H_{0,0,-1} + 4\pi^2 H_{1,0,-1} + 48H_{0,-1,1,0} + 48H_{0,1,-1,0} \right. \\ &\quad \left. - 6H_{0,1,0,1} - 18H_{0,1,1,0} - 48H_{1,0,-1,-1,0} - 48H_{1,0,-1,0,1} + \pi^2 H_0 L_\mu + 24H_{0,-1,0} L_\mu \right] \end{aligned}$$

RH, Prausa, Usovitsch '19
P3H-19-021

Leading Color

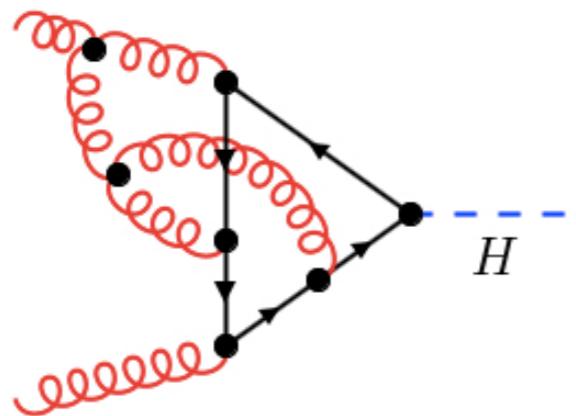
(12 pages of this)



$$\begin{aligned}
 & -\frac{500}{59} I_{\tau\tau\mu_4\omega_0\omega_0\omega_0} - \frac{25}{57} I_{\tau\tau\mu_4\omega_{-1}\omega_0\omega_0} - \frac{125}{44} I_{\tau\tau\mu_0\omega_1\omega_0\omega_0} - \frac{125}{39} I_{\tau\tau\kappa\omega_1\omega_0\omega_0} - \frac{125}{33} I_{\tau\tau\mu_0\omega_0\omega_1\omega_0} - \frac{125}{33} I_{\tau\tau\kappa\omega_0\omega_0\omega_1\omega_0} \\
 & - \frac{250}{39} I_{\tau\tau\mu_2\omega_0\omega_1\omega_0\omega_0} - \frac{50}{32} I_{\tau\tau\mu_4\omega_1\omega_1\omega_0} - \frac{125}{32} I_{\tau\tau\mu_1\omega_0\omega_1\omega_0\omega_0} - \frac{1000}{32} I_{\tau\tau\mu_8\omega_1\omega_0\omega_0} - \frac{250}{28} I_{\tau\tau\mu_4\omega_1\omega_0\omega_{-1}\omega_0} - \frac{400}{24} I_{\tau\tau\mu_4\omega_0\omega_0\omega_0\omega_0} \\
 & - \frac{500}{21} I_{\tau\tau\mu_4\omega_0\omega_1\omega_1\omega_0} - \frac{25}{19} I_{\tau\tau\kappa\omega_0\omega_1\omega_1\omega_0} - \frac{125}{12} I_{\tau\tau\mu_0\omega_1\omega_1\omega_0\omega_0} - \frac{125}{11} I_{\tau\tau\kappa\omega_1\omega_1\omega_0\omega_0} - \frac{11}{100} I_{\tau\tau\mu_4\omega_1\omega_0\omega_1\omega_0} - \frac{9}{1000} I_{\tau\tau\mu_8\omega_1\omega_1\omega_0} - \frac{250}{25} I_{\tau\tau\mu_4\omega_0\omega_0\omega_1\omega_0} \\
 & - \frac{8}{500} I_{\tau\tau\mu_6\omega_{-1}\omega_0\omega_0} - \frac{8}{1000} I_{\tau\tau\mu_5\omega_0\omega_0\omega_0} - \frac{125}{125} I_{\tau\tau\mu_8\omega_0\omega_{-1}\omega_1\omega_0} - \frac{3}{100} I_{\tau\tau\mu_4\omega_1\omega_0\omega_1\omega_0} - \frac{1000}{3} I_{\tau\tau\mu_8\omega_1\omega_1\omega_0} - \frac{250}{3} I_{\tau\tau\mu_3\omega_0\omega_0\omega_0\omega_0} \\
 & - \frac{125}{3} I_{\tau\tau\mu_0\omega_0\omega_1\omega_0\omega_0} - \frac{125}{5} I_{\tau\tau\mu_5\omega_{-1}\omega_0\omega_0} - \frac{5}{125} I_{\tau\tau\mu_3\omega_1\omega_0\omega_{-1}\omega_0} - \frac{3}{125} I_{\tau\tau\mu_3\omega_0\omega_0\omega_0\omega_0} - \frac{200}{3} I_{\tau\tau\mu_8\omega_0\omega_1\omega_0} - \frac{200}{1} I_{\tau\tau\mu_5\omega_0\omega_1\omega_0} \\
 & - \frac{250}{3} I_{\tau\tau\mu_3\omega_0\omega_1\omega_1\omega_0} - \frac{250}{3} I_{\tau\tau\mu_8\omega_1\omega_0\omega_{-1}\omega_0} - \frac{3}{400} I_{\tau\tau\mu_8\omega_0\omega_0\omega_0\omega_0} - \frac{3}{500} I_{\tau\tau\mu_5\omega_0\omega_1\omega_1\omega_0} - \frac{2}{125} I_{\tau\tau\mu_3\omega_1\omega_0\omega_0} - \frac{5}{1} I_{\tau\tau\mu_8\omega_1\omega_1\omega_0} \\
 & - \frac{1}{50} I_{\tau\tau\mu_3\omega_1\omega_0\omega_1\omega_0} - \frac{1}{100} I_{\tau\tau\mu_8\omega_1\omega_0\omega_1\omega_0} - \frac{1}{500} I_{\tau\tau\mu_8\omega_0\omega_1\omega_1\omega_0} - \frac{1}{1000} I_{\tau\tau\mu_8\omega_0\omega_{-1}\omega_0} + \frac{1}{25} I_{\tau\tau\mu_3\omega_0\omega_1\omega_0} + \frac{1}{25} I_{\tau\tau\mu_4\omega_0\omega_1\omega_0} \\
 & + \frac{1}{125} I_{\tau\tau\mu_3\omega_1\omega_1\omega_0\omega_0} + \frac{1}{125} I_{\tau\tau\mu_8\omega_0\omega_0\omega_1\omega_0} + \frac{1}{250} I_{\tau\tau\mu_8\omega_1\omega_1\omega_0\omega_0} + \frac{1}{500} I_{\tau\tau\mu_5\omega_0\omega_1\omega_1\omega_0} + \frac{1}{1000} I_{\tau\tau\mu_5\omega_0\omega_1\omega_1\omega_0} + \frac{2}{125} I_{\tau\tau\mu_3\omega_0\omega_0\omega_1\omega_0} \\
 & + \frac{6}{125} I_{\tau\tau\mu_5\omega_{-1}\omega_1\omega_0} + \frac{6}{125} I_{\tau\tau\mu_3\omega_0\omega_{-1}\omega_0} + \frac{6}{125} I_{\tau\tau\mu_8\omega_0\omega_{-1}\omega_0\omega_0} + \frac{9}{500} I_{\tau\tau\mu_3\omega_1\omega_0\omega_0\omega_0} + \frac{11}{1000} I_{\tau\tau\mu_5\omega_1\omega_0\omega_0\omega_0} + \frac{11}{125} I_{\tau\tau\mu_4\omega_0\omega_0\omega_1\omega_0} \\
 & + \frac{5}{11} I_{\tau\tau\mu_4\omega_1\omega_1\omega_0\omega_0} + \frac{11}{1000} I_{\tau\tau\mu_4\omega_0\omega_1\omega_0\omega_0} + \frac{12}{25} I_{\tau\tau\mu_0\omega_0\omega_0\omega_0\omega_0} + \frac{12}{25} I_{\tau\tau\kappa\omega_0\omega_0\omega_0\omega_0} + \frac{16}{125} I_{\tau\tau\mu_3\omega_0\omega_{-1}\omega_0\omega_0} + \frac{16}{25} I_{\tau\tau\mu_0\omega_1\omega_0\omega_1\omega_0} \\
 & + \frac{16}{250} I_{\tau\tau\kappa\omega_1\omega_0\omega_1\omega_0} + \frac{21}{1000} I_{\tau\tau\mu_6\omega_{-1}\omega_1\omega_0} + \frac{27}{25} I_{\tau\tau\mu_3\omega_0\omega_0\omega_{-1}\omega_0} + \frac{27}{500} I_{\tau\tau\mu_5\omega_0\omega_0\omega_{-1}\omega_0\omega_0} + \frac{48}{125} I_{\tau\tau\mu_0\omega_0\omega_1\omega_1\omega_0} + \frac{48}{125} I_{\tau\tau\kappa\omega_0\omega_1\omega_1\omega_0} \\
 & + \frac{59}{25} I_{\tau\tau\mu_2\omega_1\omega_0\omega_1\omega_0} + \frac{64}{125} I_{\tau\tau\kappa\omega_1\omega_0\omega_0} + \frac{66}{25} I_{\tau\tau\mu_4\omega_0\omega_{-1}\omega_0\omega_0} + \frac{66}{125} I_{\tau\tau\mu_4\omega_0\omega_1\omega_1\omega_0} + \frac{80}{500} I_{\tau\tau\mu_1\omega_1\omega_1\omega_0} + \frac{81}{500} I_{\tau\tau\mu_5\omega_0\omega_{-1}\omega_0} \\
 & + \frac{88}{25} I_{\tau\tau\mu_0\omega_1\omega_1\omega_0} + \frac{88}{25} I_{\tau\tau\mu_1\omega_1\omega_0\omega_1\omega_0} + \frac{96}{125} I_{\tau\tau\mu_0\omega_1\omega_0\omega_{-1}\omega_0} + \frac{96}{125} I_{\tau\tau\kappa\omega_1\omega_0\omega_{-1}\omega_0} + \frac{99}{1000} I_{\tau\tau\mu_4\omega_1\omega_0\omega_0\omega_0} + \frac{114}{5} I_{\tau\tau\mu_2\omega_1\omega_1\omega_0} \\
 & + \frac{144}{25} I_{\tau\tau\mu_4\omega_{-1}\omega_1\omega_0} + \frac{144}{125} I_{\tau\tau\mu_0\omega_0\omega_0\omega_0} + \frac{144}{125} I_{\tau\tau\kappa\omega_0\omega_0\omega_0} + \frac{174}{25} I_{\tau\tau\mu_1\omega_0\omega_1\omega_0} + \frac{177}{100} I_{\tau\tau\mu_2\omega_0\omega_0\omega_0\omega_0} + \frac{177}{125} I_{\tau\tau\mu_2\omega_0\omega_1\omega_1\omega_0} \\
 & + \frac{264}{368} I_{\tau\tau\mu_4\omega_1\omega_0\omega_1\omega_0} + \frac{288}{371} I_{\tau\tau\mu_1\omega_0\omega_1\omega_1\omega_0} + \frac{297}{525} I_{\tau\tau\mu_4\omega_0\omega_0\omega_{-1}\omega_0} + \frac{396}{581} I_{\tau\tau\mu_0\omega_0\omega_{-1}\omega_0\omega_0} + \frac{354}{768} I_{\tau\tau\mu_2\omega_1\omega_0\omega_{-1}\omega_0} \\
 & + \frac{25}{368} I_{\tau\tau\mu_0\omega_0\omega_1\omega_0} + \frac{250}{842} I_{\tau\tau\mu_4\omega_0\omega_{-1}\omega_0} + \frac{258}{2832} I_{\tau\tau\mu_1\omega_1\omega_0\omega_{-1}\omega_0} + \frac{258}{125} I_{\tau\tau\mu_2\omega_0\omega_{-1}\omega_0\omega_0} + \frac{768}{4224} I_{\tau\tau\mu_1\omega_0\omega_{-1}\omega_0\omega_0} + \frac{768}{9936} I_{\tau\tau\mu_2\omega_1\omega_0\omega_0} + \frac{35402}{125} I_{\tau\tau\mu_1\omega_1\omega_0\omega_0} \\
 & + \frac{39064}{125} I_{\tau\tau\mu_0\omega_1\omega_0\omega_0} + \frac{x(x^2 - 6x + 1)}{(x - 1)^5 (x^2 - 18x + 1)^2 (x^2 + 18x + 1)^3} (x^{12} - 40x^{11} + 1180x^{10} - 22828x^9 + 124175x^8 + 191060x^7 + 88744x^6 \\
 & + 191060x^5 + 124175x^4 - 22828x^3 + 1180x^2 - 40x + 1) \sqrt{1 - 18x + x^2} \frac{\psi^2}{\pi^3} \left(-\frac{15912}{125} I_{\tau\tau\mu_1\omega_0\omega_{-1}\omega_0} - \frac{7516}{125} I_{\tau\tau\mu_2\omega_0\omega_{-1}\omega_0} \right. \\
 & \left. - \frac{4752}{125} I_{\tau\tau\mu_1\omega_0\omega_0\omega_{-1}\omega_0} - \frac{4224}{125} I_{\tau\tau\mu_1\omega_0\omega_1\omega_0\omega_0} - \frac{3186}{125} I_{\tau\tau\mu_2\omega_0\omega_0\omega_{-1}\omega_0} - \frac{2882}{125} I_{\tau\tau\mu_2\omega_0\omega_1\omega_0\omega_0} - 1344 I_{\tau\tau\mu_0\omega_{-1}\omega_1\omega_0} \right. \\
 & \left. - \frac{1152}{5} I_{\tau\tau\mu_2\omega_{-1}\omega_1\omega_1\omega_0} - \frac{992}{125} I_{\tau\tau\mu_4\omega_1\omega_0\omega_0} - \frac{960}{125} I_{\tau\tau\mu_1\omega_{-1}\omega_1\omega_0} - \frac{864}{125} I_{\tau\tau\mu_0\omega_0\omega_0\omega_{-1}\omega_0} - \frac{864}{125} I_{\tau\tau\kappa\omega_0\omega_0\omega_{-1}\omega_0} - \frac{792}{125} I_{\tau\tau\mu_1\omega_1\omega_0\omega_0\omega_0} \right. \\
 & \left. - \frac{768}{125} I_{\tau\tau\mu_0\omega_0\omega_{-1}\omega_0\omega_0} - \frac{768}{125} I_{\tau\tau\kappa\omega_0\omega_{-1}\omega_0\omega_0} - \frac{709}{500} I_{\tau\tau\mu_5\omega_1\omega_0\omega_0\omega_0} - \frac{704}{125} I_{\tau\tau\mu_1\omega_0\omega_0\omega_1\omega_0} - \frac{531}{125} I_{\tau\tau\mu_2\omega_1\omega_0\omega_0\omega_0} - \frac{472}{125} I_{\tau\tau\mu_2\omega_0\omega_0\omega_1\omega_0} \right. \\
 & \left. - \frac{384}{125} I_{\tau\tau\kappa\omega_0\omega_1\omega_0\omega_0} - \frac{352}{125} I_{\tau\tau\mu_1\omega_1\omega_1\omega_0\omega_0} - \frac{264}{125} I_{\tau\tau\mu_4\omega_0\omega_{-1}\omega_1\omega_0} - \frac{236}{125} I_{\tau\tau\mu_2\omega_1\omega_1\omega_0\omega_0} - \frac{25}{25} I_{\tau\tau\mu_4\omega_{-1}\omega_0\omega_0} - \frac{144}{125} I_{\tau\tau\mu_0\omega_1\omega_0\omega_0\omega_0} \right. \\
 & \left. - \frac{144}{125} I_{\tau\tau\kappa\omega_1\omega_0\omega_0\omega_0} - \frac{128}{125} I_{\tau\tau\mu_0\omega_0\omega_0\omega_1\omega_0} - \frac{128}{125} I_{\tau\tau\kappa\omega_0\omega_0\omega_1\omega_0} - \frac{109}{250} I_{\tau\tau\mu_4\omega_0\omega_0\omega_0\omega_0} - \frac{88}{125} I_{\tau\tau\mu_1\omega_0\omega_1\omega_0\omega_0} - \frac{64}{25} I_{\tau\tau\kappa\omega_0\omega_1\omega_0\omega_0} \right. \\
 & \left. - \frac{64}{125} I_{\tau\tau\mu_0\omega_1\omega_1\omega_0\omega_0} - \frac{64}{125} I_{\tau\tau\kappa\omega_1\omega_1\omega_0\omega_0} - \frac{59}{125} I_{\tau\tau\mu_2\omega_0\omega_1\omega_0\omega_0} - \frac{57}{25} I_{\tau\tau\mu_4\omega_1\omega_1\omega_0\omega_0} - \frac{56}{25} I_{\tau\tau\mu_2\omega_0\omega_1\omega_0\omega_0} - \frac{48}{125} I_{\tau\tau\mu_3\omega_0\omega_{-1}\omega_1\omega_0} \right. \\
 & \left. - \frac{39}{500} I_{\tau\tau\mu_6\omega_1\omega_0\omega_0} - \frac{33}{125} I_{\tau\tau\mu_4\omega_1\omega_0\omega_{-1}\omega_0} - \frac{33}{200} I_{\tau\tau\mu_4\omega_0\omega_0\omega_0\omega_0} - \frac{33}{250} I_{\tau\tau\mu_4\omega_0\omega_1\omega_1\omega_0} - \frac{24}{125} I_{\tau\tau\mu_5\omega_0\omega_{-1}\omega_1\omega_0} - \frac{21}{250} I_{\tau\tau\mu_6\omega_{-1}\omega_0\omega_0} \right)
 \end{aligned}$$

Prausa, Usovitsch '20

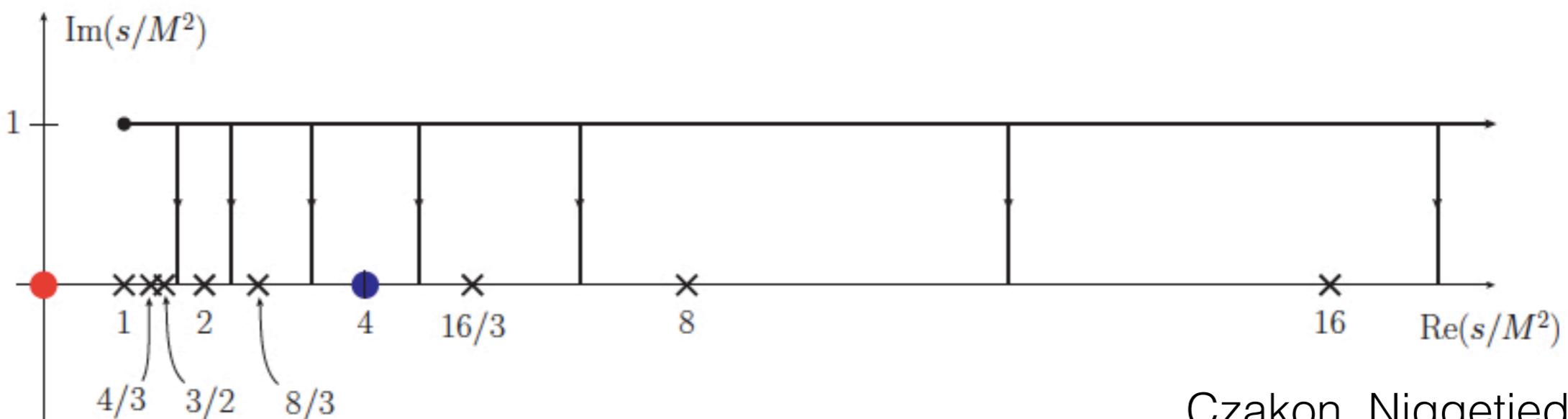
Full form factor



Calculate masters:

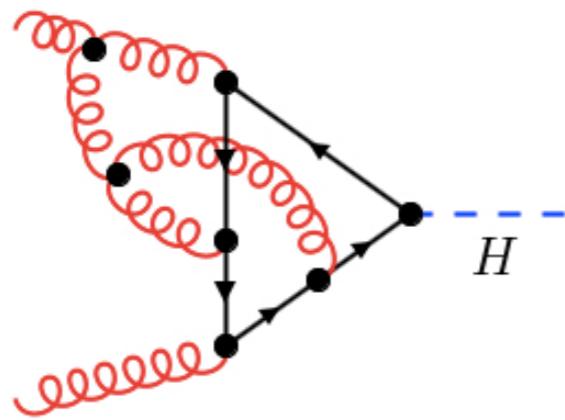
$$\partial_z \hat{I}_n(\epsilon, z) = M_{nm}(z) \hat{I}_m(d, z)$$

→ solve numerically



Czakon, Niggetiedt '20
P3H-20-001

Full form factor

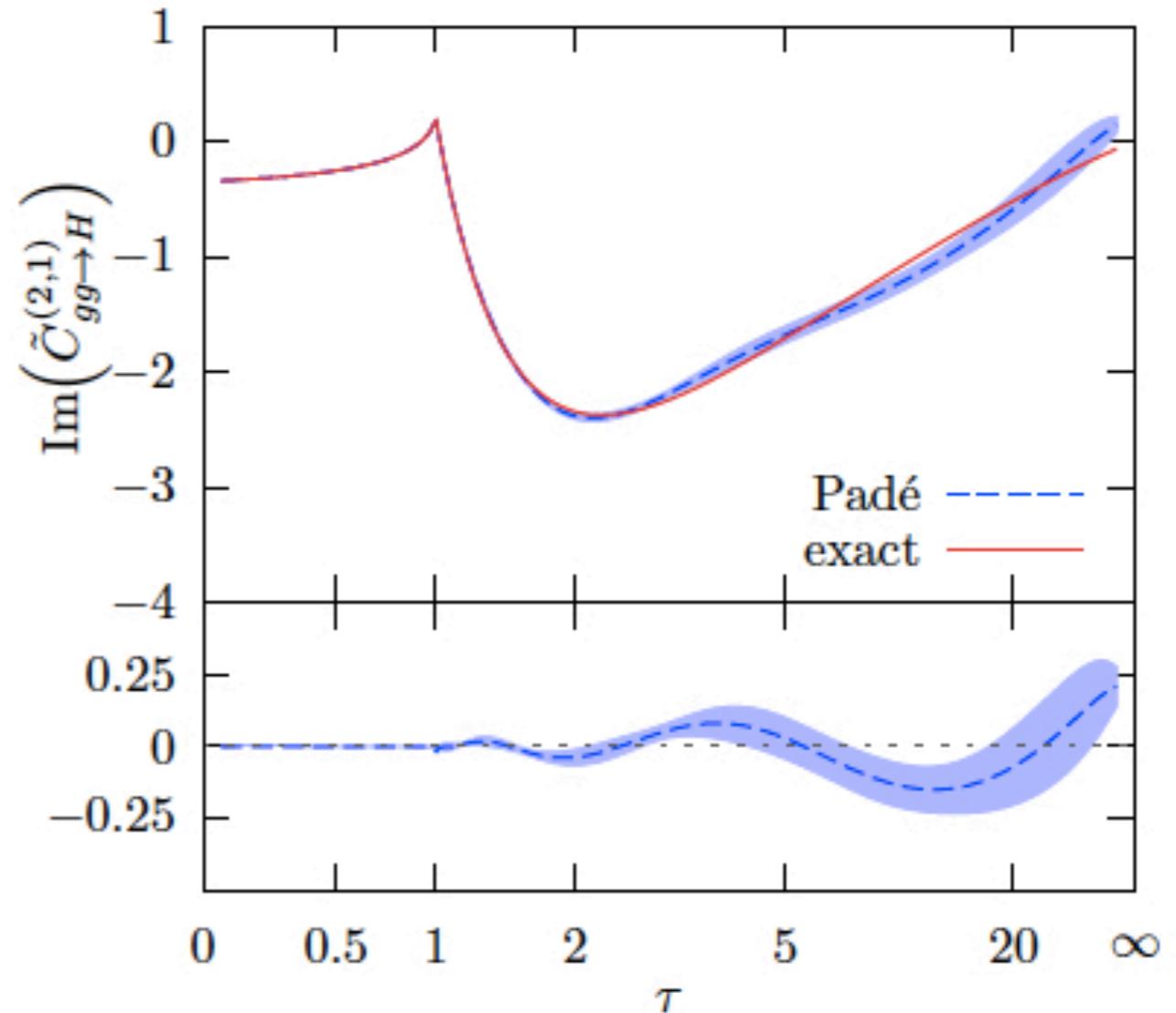
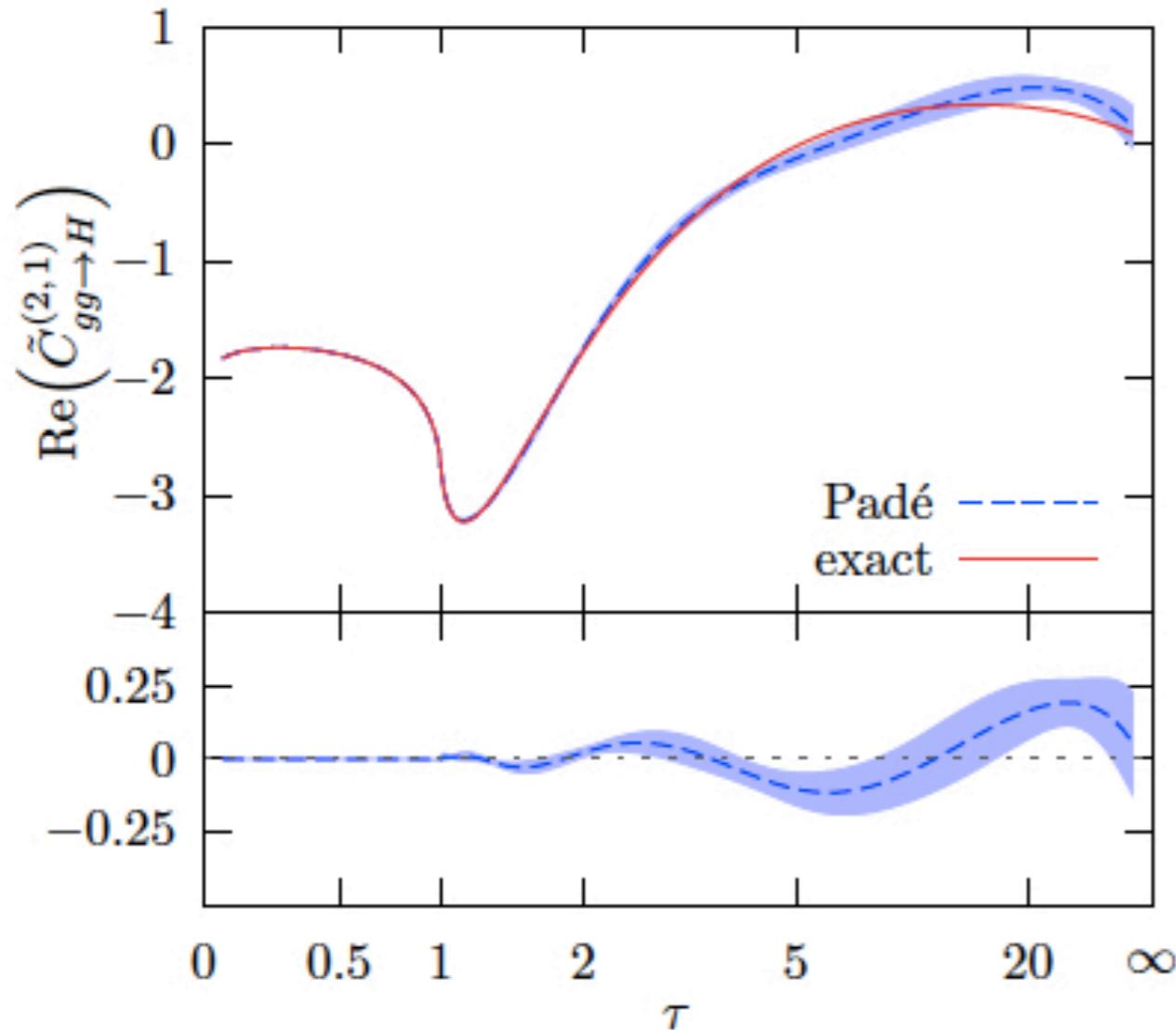


Padé approximations:

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

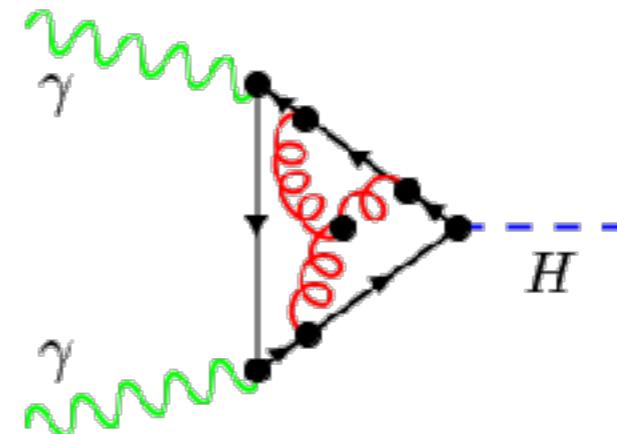
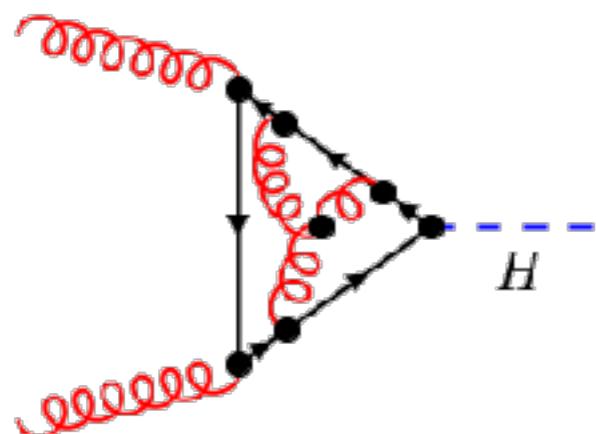
Davies et al. '19
P3H-19-012

Comparison

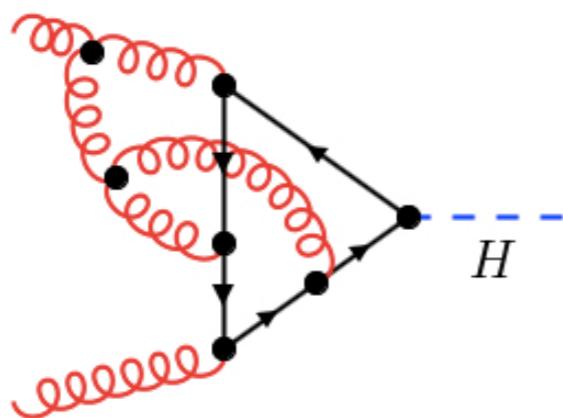


$$\tau = \frac{M_H^2}{4m_q^2}$$

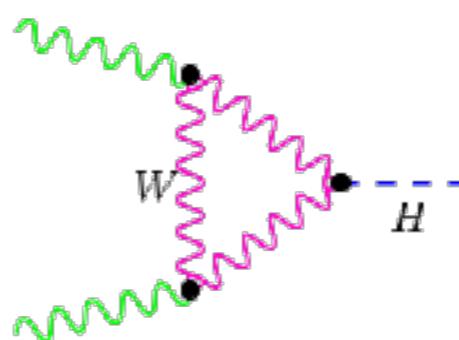
$$\underline{H} \rightarrow \gamma\gamma$$



Niggetiedt '20
P3H-20-050

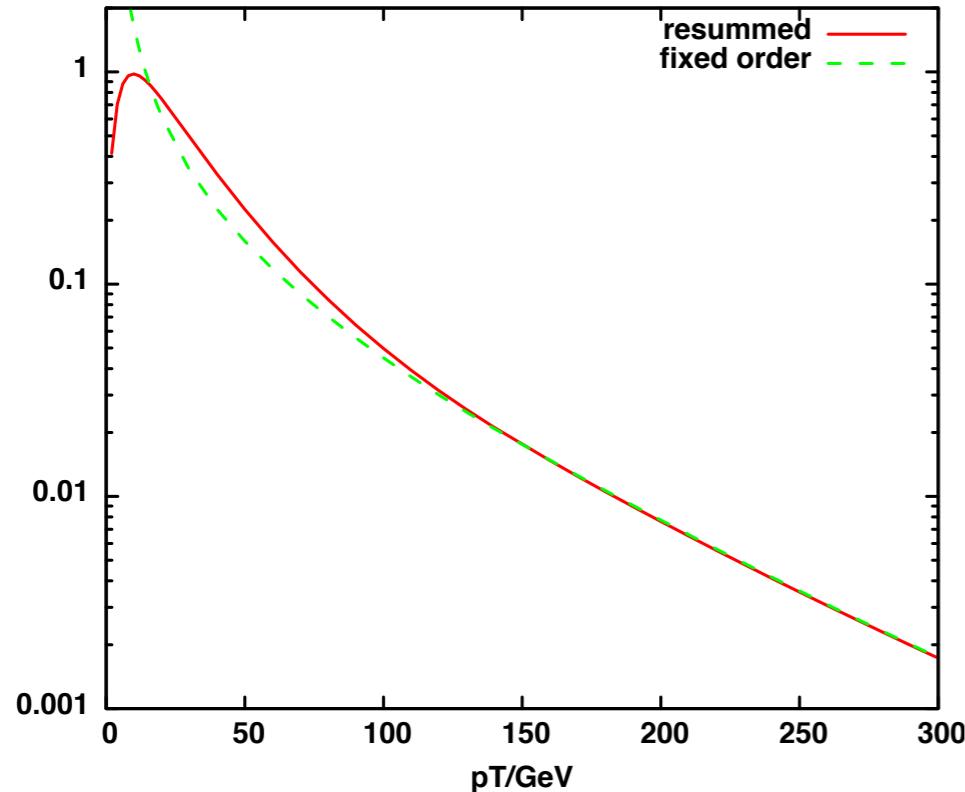


sub-leading to



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



$$m_b < p_T < M_H, m_t$$