THE Q_T-SUBTRACTION FORMALISM AT N^3LO

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OUTLINE

- Introduction and motivation
- Main idea behind the qT-subtraction method
- qT-subtraction ingredients at N^3LO
- Higgs Phenomenology at N^3LO
- Outlook

INTRODUCTION

- No striking manifestation of New Physics (NP) beyond the Standard Model (SM) at the LHC
- "Precision Physics" represents *the key instrument* to find NP
- In this framework QCD perturbative corrections play a crucial role
- Until a few years ago, the standard for such calculations was next-to-leading order (NLO) accuracy
- In the past recent years a number of growing next-to-next-to-leading order (NNLO) results were computed

INTRODUCTION

- No striking manifestation of New Physics (NP) beyond the Standard Model (SM) at the LHC
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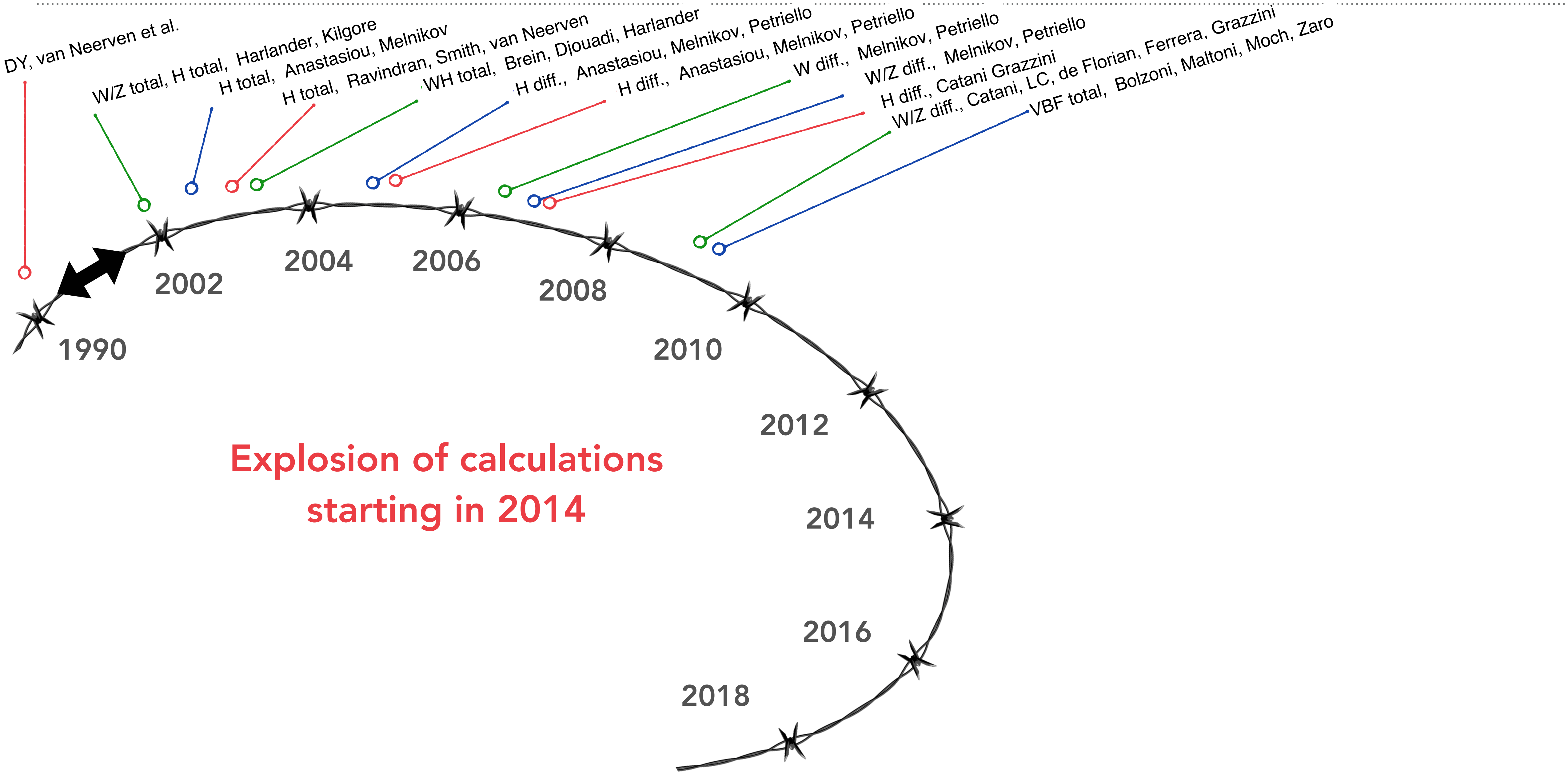
- Until a few years ago, the standard for such calculations was next-to-leading order (NLO) accuracy
- In the past recent years a number of growing next-to-next-to-leading order (NNLO) results were computed

↓

"The NNLO revolution"

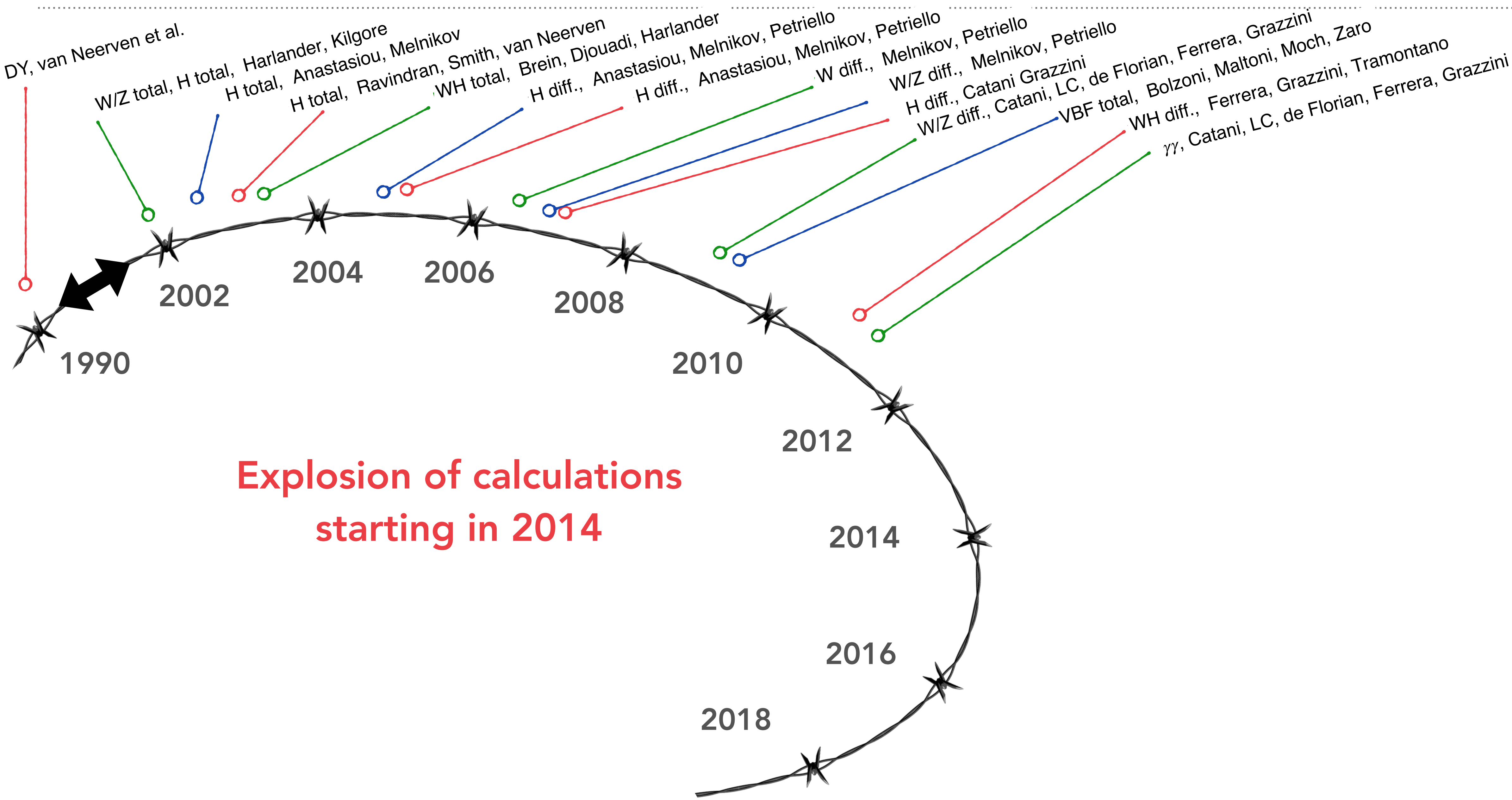
THE NNLO STANDARD

NNLO HADRON-COLLIDER CALCULATIONS VS. TIME



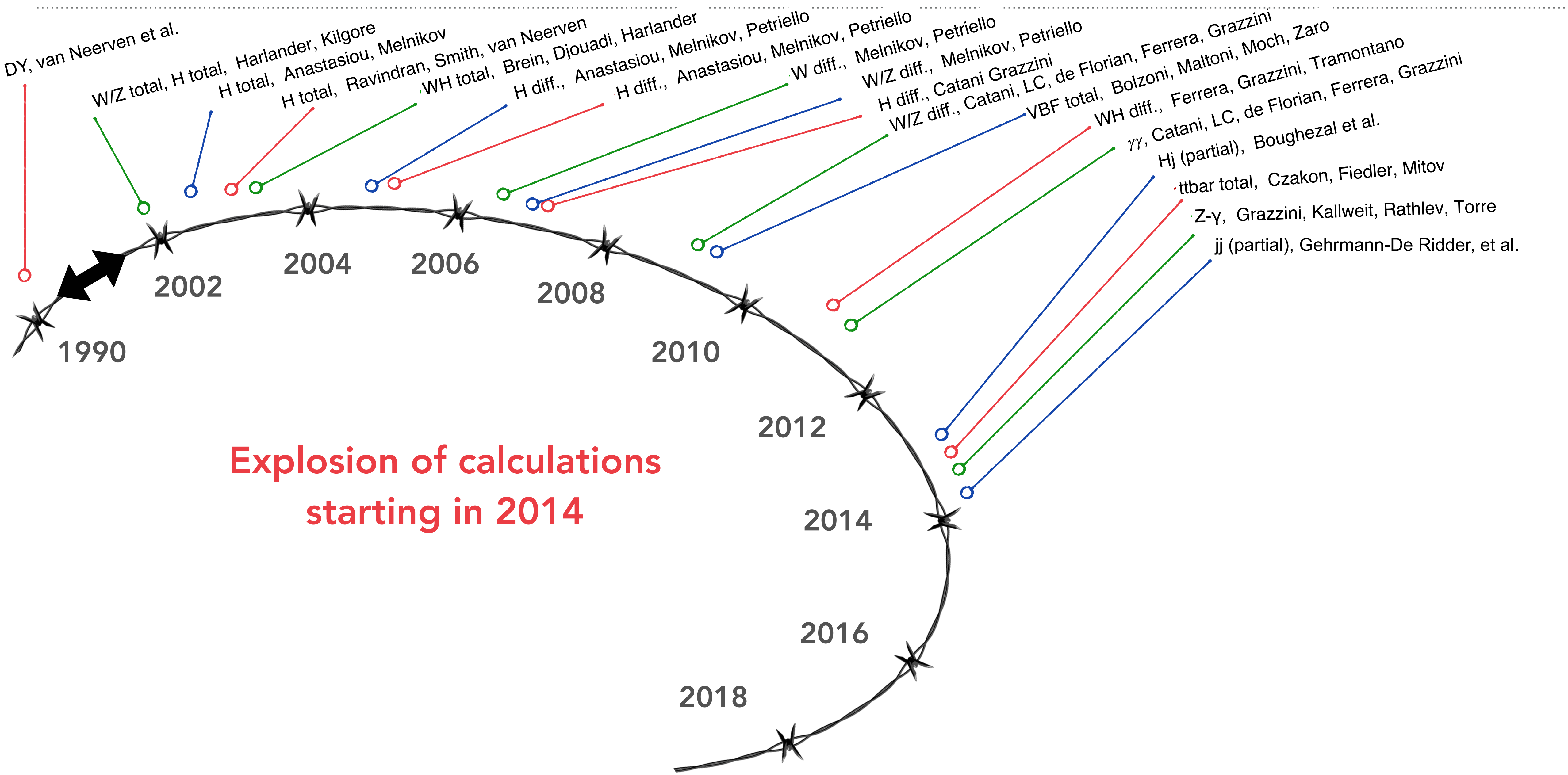
THE NNLO STANDARD

NNLO HADRON-COLLIDER CALCULATIONS VS. TIME



THE NNLO STANDARD

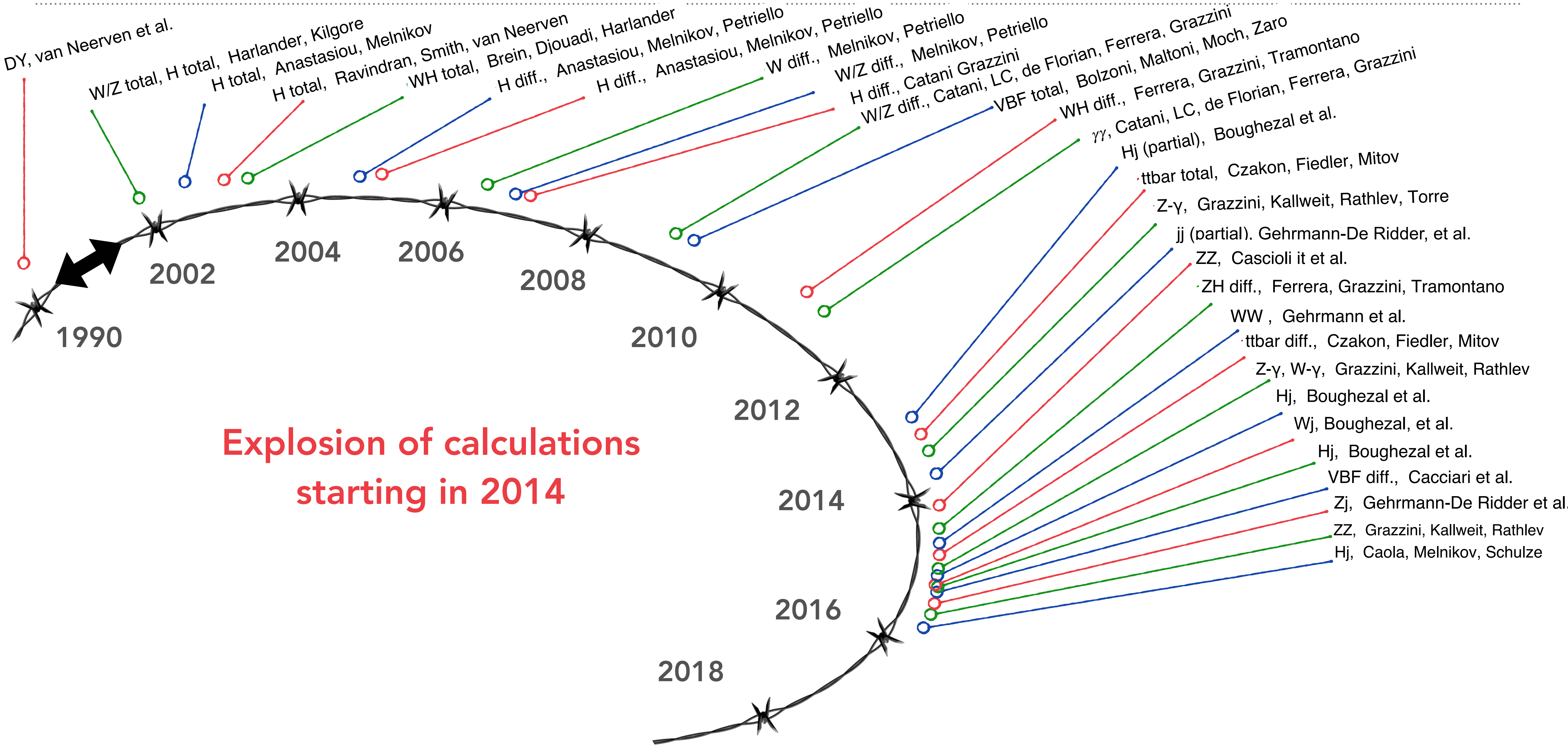
NNLO HADRON-COLLIDER CALCULATIONS VS. TIME



Slide inspired in Gavin Salam's talk

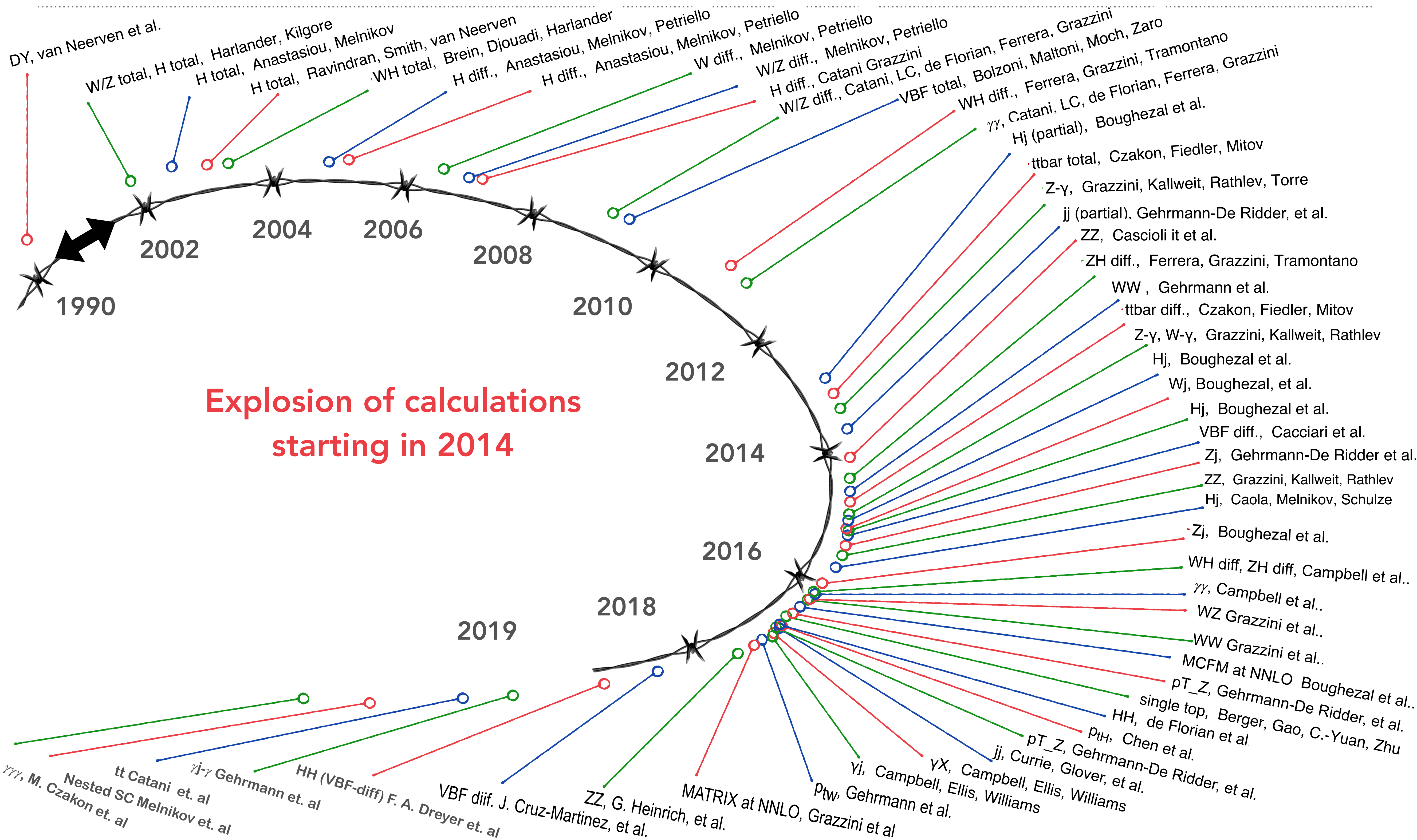
THE NNLO STANDARD

NNLO HADRON-COLLIDER CALCULATIONS VS. TIME



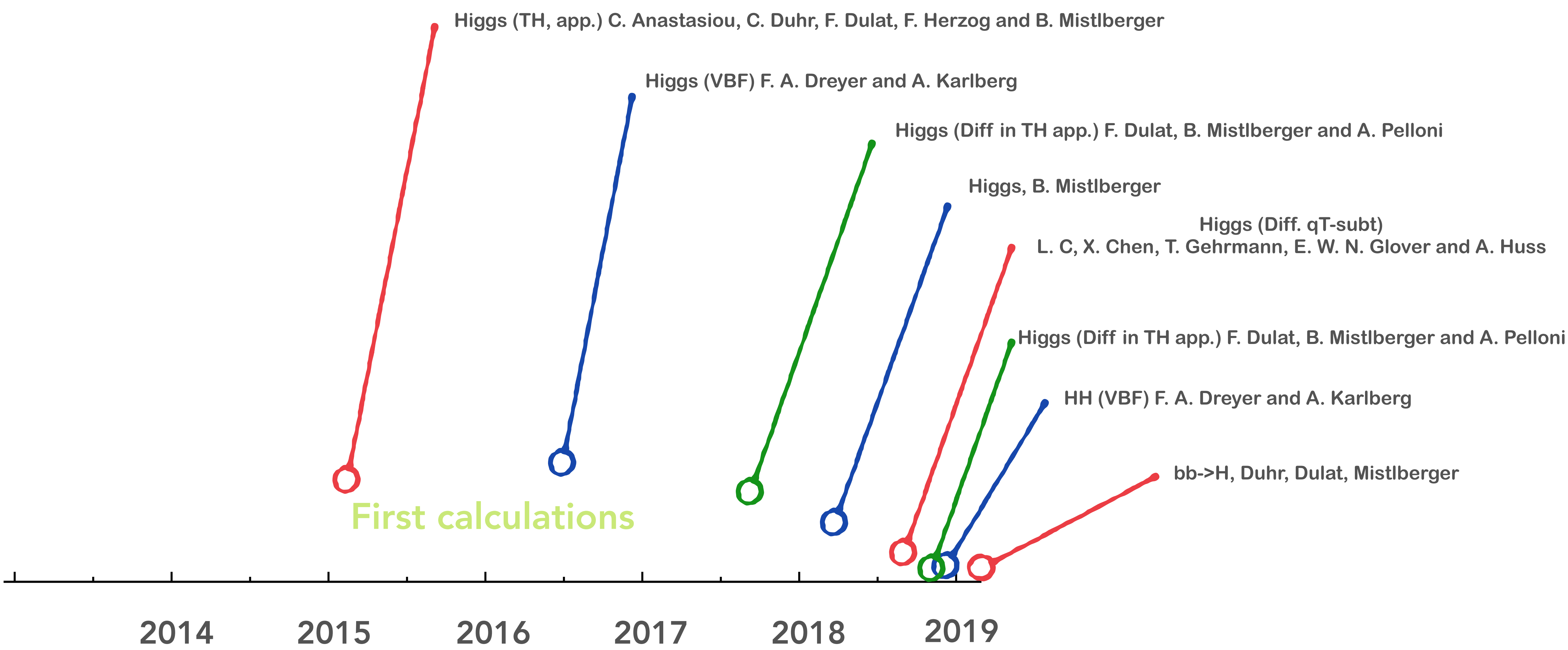
THE NNLO STANDARD

NNLO HADRON-COLLIDER CALCULATIONS VS. TIME



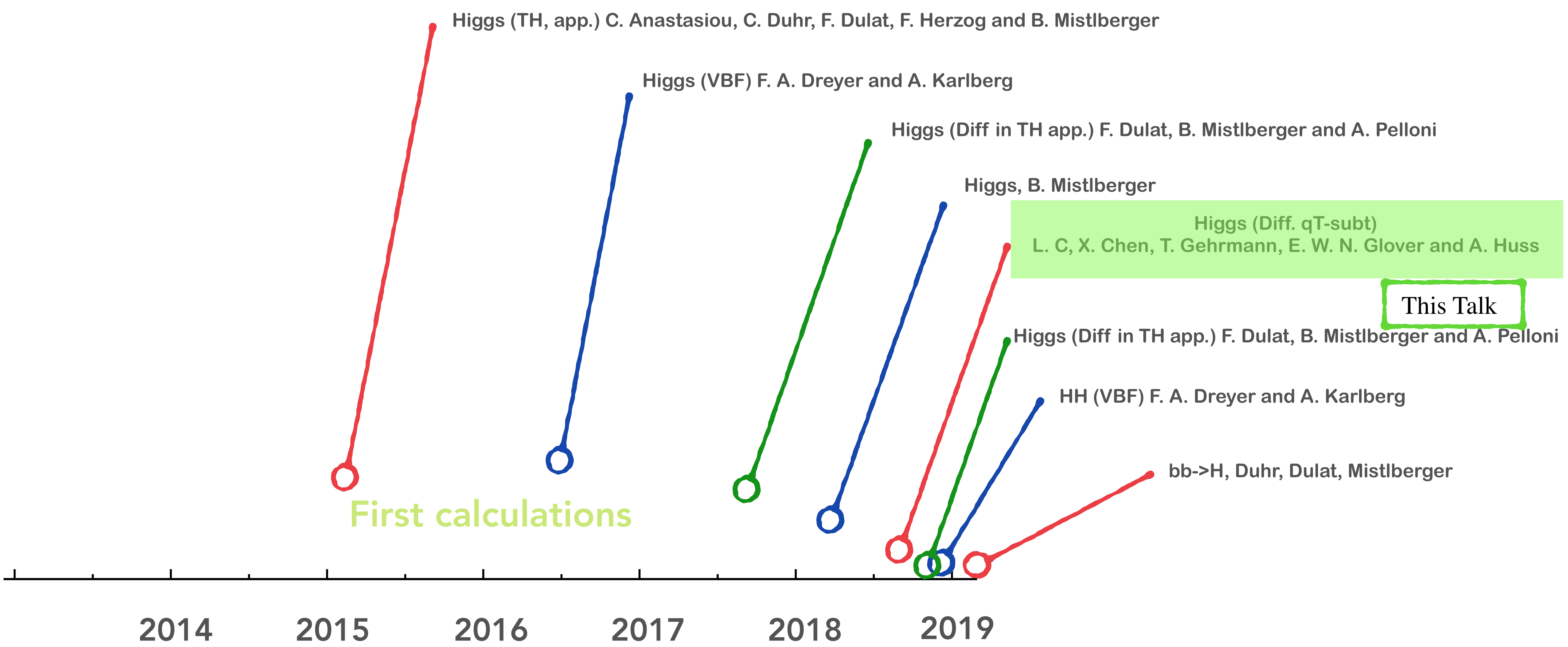
THE N^{3}LO ERA

N^{3}LO HADRON-COLLIDER CALCULATIONS VS. TIME



THE N^3LO ERA

N^3LO HADRON-COLLIDER CALCULATIONS VS. TIME



THE QT-SUBTRACTION/RESUMMATION FORMALISM

NNLO+NNLL QCD

The method

Explicit form qT-subt. Ingredients

Helicity-Flip Contributions

Universal relation between hard-virtual factors and two-loop scattering amplitudes

Colourless final states →
- S. Catani and M. Grazzini (2007)
- G. Bozzi, S. Catani, D. de Florian and M. Grazzini (2005)
- S. Catani and M. Grazzini (2011)
- S. Catani, L. C, D. de Florian, G. Ferrera and M. Grazzini (2013)

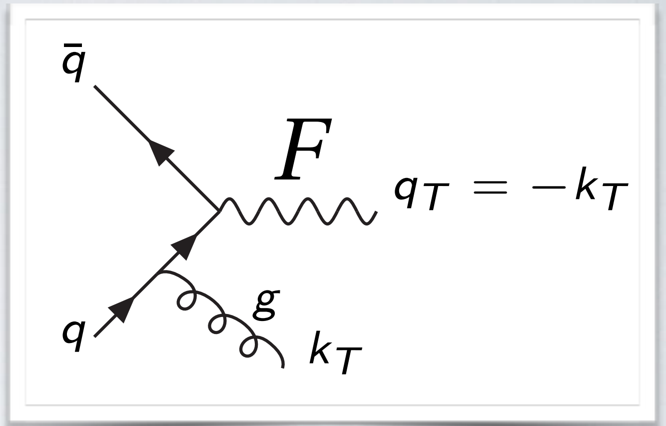
Heavy quark production → S. Catani, S. Devoto, M. Grazzini, S. Kallweit and J. Mazzitelli and H. Sargsyan (2019)

Extension at NLO+NLL QED+QCD → L. C, G. Ferrera and G. F. R. Sborlini (2018) ← Giancarlo's Talk

THE N^{3}LO QT-SUBTRACTION METHOD

- We consider the inclusive hard-scattering reaction

$$h_1 + h_2 \longrightarrow F(Q) + X$$



  - h_i = hadron (i=1,2)
  - Colourless final state F with transverse momentum qT and invariant mass Q

- We are interested in the QCD corrections to this process F

- The basic idea behind the method Catani, Grazzini (2007)

$$\mathrm{d}\sigma^{F}_{\mathrm{N^nLO}}(q_T \neq 0) \equiv \mathrm{d}\sigma^{F+\mathrm{jets}}_{\mathrm{N^{n-1}LO}} \quad \text{with} \quad n = 1, 2, 3$$

- $\mathrm{d}\sigma^{F+\mathrm{jets}}_{\mathrm{N^{n-1}LO}}$ can be computed with the well known subtractions methods at NLO and NNLO
- The remaining true N^{n}LO divergencies are associated to the small-qT limit

THE N^{3}LO QT-SUBTRACTION METHOD

- The generic form of the qT-subtraction method

Catani, Grazzini (2007)

$$\mathrm{d}\sigma^{F}_{\mathrm{N^nLO}} = \mathcal{H}^{F}_{\mathrm{N^nLO}} \otimes \mathrm{d}\sigma^{F}_{\mathrm{LO}} + \left[\mathrm{d}\sigma^{F+\mathrm{jets}}_{\mathrm{N^{n-1}LO}} - \mathrm{d}\sigma^{F\,\mathrm{CT}}_{\mathrm{N^nLO}}\right] \quad \text{with} \quad n = 1, 2, 3$$

$$\mathrm{d}\sigma^{F\,\mathrm{CT}}_{\mathrm{N^nLO}} = \Sigma^{F}_{\mathrm{N^nLO}}(q_T^2/M^2)\ \mathrm{d}^2\mathbf{q}_T \otimes \mathrm{d}\sigma^{F}_{\mathrm{LO}}$$

- How to calculate the qT-subtraction ingredients?

$$\left(\Sigma^{F}_{c\bar{c}\leftarrow ab}\left(\frac{q_T^2}{M^2};\frac{M^2}{\hat{s}};\alpha_{\mathrm{s}}\right) + \mathcal{H}^{F}_{c\bar{c}\leftarrow ab}\left(\frac{M^2}{\hat{s}};\alpha_{\mathrm{s}}\right)\right) \otimes \mathrm{d}\left[\sigma^{F;(0)}_{c\bar{c}}\right]_{ab} = \frac{M^2}{s}\int_0^\infty \mathrm{d}b\,\frac{b}{2}J_0(bq_T)$$
$$\times\, S_c(M,b)\int_{x_1}^1 \frac{\mathrm{d}z_1}{z_1}\int_{x_2}^1 \frac{\mathrm{d}z_2}{z_2}\mathrm{d}\hat{\sigma}^{F;(0)}_{c\bar{c}}\ f_{a/h_1}\left(x_1/z_1, b_0^2/b^2\right)\ f_{b/h_2}\left(x_2/z_2, b_0^2/b^2\right)\ \left[H^F C_1 C_2\right]_{c\bar{c};ab}$$

- Expanding the resummation formula at fixed order

J. C. Collins, D. E. Soper and G. Sterman (1985)
S. Catani, D. de Florian and M. Grazzini (2001)
S. Catani and M. Grazzini (2011)

THE N³LO QT-SUBTRACTION METHOD

- Expanding at fixed-order the following expression

$$\left(\Sigma^F_{c\bar{c}\leftarrow ab}\left(\frac{q_T^2}{M^2};\frac{M^2}{\hat{s}};\alpha_s\right)+\mathcal{H}^F_{c\bar{c}\leftarrow ab}\left(\frac{M^2}{\hat{s}};\alpha_s\right)\right)\otimes \mathrm{d}\left[\sigma^{F;(0)}_{c\bar{c}}\right]_{ab}=\frac{M^2}{s}\int_0^\infty \mathrm{d}b\frac{b}{2}J_0(bq_T)$$
$$\times\, S_c(M,b)\int_{x_1}^1\frac{\mathrm{d}z_1}{z_1}\int_{x_2}^1\frac{\mathrm{d}z_2}{z_2}\mathrm{d}\hat{\sigma}^{F;(0)}_{c\bar{c}}\, f_{a/h_1}\left(x_1/z_1,b_0^2/b^2\right)f_{b/h_2}\left(x_2/z_2,b_0^2/b^2\right)\ \left[H^F C_1 C_2\right]_{c\bar{c};ab}$$

$$\Sigma^F(q_T/Q)\xrightarrow[q_T\to 0]{}\sum_{n=1}^{\infty}\left(\frac{\alpha_S}{\pi}\right)^n\sum_{k=1}^{2n}\Sigma^{F(n;k)}\frac{Q^2}{q_T^2}\ln^{k-1}\frac{Q^2}{q_T^2}$$

Contribution of all large logarithmic terms
In the small-qT limit

$$\mathcal{H}^F_{c\bar{c}\leftarrow ab}\rightarrow\sum_{n=1}^{\infty}\left(\frac{\alpha_s}{\pi}\right)^n\mathcal{H}^{F(n)}_{c\bar{c}\leftarrow ab}\,\delta(q_T^2)$$

Free of large logarithmic terms
in the small-qT limit

$$\mathrm{d}\sigma^F_{\mathrm{N^nLO}}=\mathcal{H}^F_{\mathrm{N^nLO}}\otimes\mathrm{d}\sigma^F_{\mathrm{LO}}+\left[\mathrm{d}\sigma^{F+\mathrm{jets}}_{\mathrm{N^{n-1}LO}}-\mathrm{d}\sigma^{F\,\mathrm{CT}}_{\mathrm{N^nLO}}\right]\quad \text{with}\quad n=1,2,3$$

$$\mathrm{d}\sigma^{F\,\mathrm{CT}}_{\mathrm{N^nLO}}=\Sigma^F_{\mathrm{N^nLO}}(q_T^2/M^2)\ \mathrm{d}^2\mathbf{q}_T\otimes\mathrm{d}\sigma^F_{\mathrm{LO}}$$

THE N^{3}LO QT-SUBTRACTION METHOD

- Expanding at fixed-order the following expression

$$\left(\Sigma^F_{c\bar{c}\leftarrow ab}\left(\frac{q_T^2}{M^2};\frac{M^2}{\hat{s}};\alpha_s\right)+\mathcal{H}^F_{c\bar{c}\leftarrow ab}\left(\frac{M^2}{\hat{s}};\alpha_s\right)\right)\otimes \mathrm{d}\left[\sigma^{F;(0)}_{c\bar{c}}\right]_{ab}=\frac{M^2}{s}\int_0^\infty \mathrm{d}b\frac{b}{2}J_0(bq_T)$$
$$\times\, S_c(M,b)\int_{x_1}^1\frac{\mathrm{d}z_1}{z_1}\int_{x_2}^1\frac{\mathrm{d}z_2}{z_2}\mathrm{d}\hat{\sigma}^{F;(0)}_{c\bar{c}}\; f_{a/h_1}\left(x_1/z_1,b_0^2/b^2\right) f_{b/h_2}\left(x_2/z_2,b_0^2/b^2\right)\;\left[H^F C_1 C_2\right]_{c\bar{c};ab}$$

$$x_1=\frac{M}{\sqrt{s}}\,e^{+y}\;,\qquad x_2=\frac{M}{\sqrt{s}}\,e^{-y}$$

$$S_c(M,b)=\exp\left\{-\int_{b_0^2/b^2}^{M^2}\frac{\mathrm{d}q^2}{q^2}\left[A_c(\alpha_s(q^2))\,\ln\frac{M^2}{q^2}+B_c(\alpha_s(q^2))\right]\right\}$$

Sudakov form factor

Catani, Grazzini (2011)

$$\left[H^{F=H}C_1C_2\right]_{gg;ab}=H_g^{F=H}(\alpha_s(M^2))\;\left[\,C_{g\,a}(z_1;\alpha_s(b_0^2/b^2))\;C_{g\,b}(z_2;\alpha_s(b_0^2/b^2))\right.$$
$$\left.+\,G_{g\,a}(z_1;\alpha_s(b_0^2/b^2))\;G_{g\,b}(z_2;\alpha_s(b_0^2/b^2))\,\right]$$

Last line not present in qq initiated sub-processes

$$z\;=\;M^2/\hat{s}$$

$$C_{g\,a}(z;\alpha_s)=\delta_{g\,a}\;\delta(1-z)+\sum_{n=1}^{\infty}\left(\frac{\alpha_s}{\pi}\right)^n C^{(n)}_{g\,a}(z)$$

Collinear coefficient functions

$$G_{g\,a}(z;\alpha_s)=\sum_{n=1}^{\infty}\left(\frac{\alpha_s}{\pi}\right)^n G^{(n)}_{g\,a}(z)$$

Helicity-flip functions in gg initiated processes

$$H_g^{F=H}(\alpha_s)=1+\sum_{n=1}^{\infty}\left(\frac{\alpha_s}{\pi}\right)^n H_g^{F=H\,;(n)}$$

Hard virtual factors (loop-virtual contributions)

THE N^{3}LO QT-SUBTRACTION METHOD

Third-order ingredients

- All the ingredients which describe the cancellation of the large logarithmic terms (in the small-qT limit) are known from the previous orders (NNLO and NLO) (using convolutions written in function of Goncharov PolyLogarithms GPLS)

$$\Sigma^F(q_T/Q) \xrightarrow[q_T \to 0]{} \sum_{n=1}^{\infty} \left(\frac{\alpha_S}{\pi}\right)^n \sum_{k=1}^{2n} \Sigma^{F(n;k)} \frac{Q^2}{q_T^2} \ln^{k-1} \frac{Q^2}{q_T^2}$$

- The third-order contribution at qT = 0 presents two missing pieces
  - The universal relation between the three-loop virtual scattering amplitudes and the hard-virtual factor
  - The collinear coefficient functions at the third-order

THE N^{3}LO QT-SUBTRACTION METHOD

Third-order ingredients at qT = 0

De Florian, Grazzini (2001)

- The hard-virtual, collinear and helicity-flip contributions

$$\mathcal{H}^{H;(1)}_{gg\leftarrow ab}(z) = \delta_{ga}\,\delta_{gb}\,\delta(1-z)\,H_g^{H;(1)} + \delta_{ga}\,C^{(1)}_{gb}(z) + \delta_{gb}\,C^{(1)}_{ga}(z)\ ,$$

$$\mathcal{H}^{H;(2)}_{gg\leftarrow ab}(z) = \delta_{ga}\,\delta_{gb}\,\delta(1-z)\,H_g^{H;(2)} + \delta_{ga}\,C^{(2)}_{gb}(z) + \delta_{gb}\,C^{(2)}_{ga}(z) + H_g^{H;(1)}\left(\delta_{ga}\,C^{(1)}_{gb}(z) + \delta_{gb}\,C^{(1)}_{ga}(z)\right) + \left(C^{(1)}_{ga}\otimes C^{(1)}_{gb}\right)(z) + \left(G^{(1)}_{ga}\otimes G^{(1)}_{gb}\right)(z)$$

S. Catani, L. C, D. de Florian, G. Ferrera and M. Grazzini (2013)

$$\begin{aligned}\mathcal{H}^{H;(3)}_{gg\leftarrow ab}(z) = {} & \delta_{ga}\,\delta_{gb}\,\delta(1-z)\,H_g^{H;(3)} + \delta_{ga}\,C^{(3)}_{gb}(z) + \delta_{gb}\,C^{(3)}_{ga}(z) \\ & + \left(G^{(1)}_{ga}\otimes G^{(2)}_{gb}\right)(z) + \left(G^{(2)}_{ga}\otimes G^{(1)}_{gb}\right)(z) \\ & + H_g^{H;(1)}\left(\delta_{ga}\,C^{(2)}_{gb}(z) + \delta_{gb}\,C^{(2)}_{ga}(z)\right) + H_g^{H;(2)}\left(\delta_{ga}\,C^{(1)}_{gb}(z) + \delta_{gb}\,C^{(1)}_{ga}(z)\right) \\ & + \left(C^{(1)}_{ga}\otimes C^{(2)}_{gb}\right)(z) + \left(C^{(2)}_{ga}\otimes C^{(1)}_{gb}\right)(z) \\ & + H_g^{H;(1)}\left(C^{(1)}_{ga}\otimes C^{(1)}_{gb}\right)(z) + H_g^{H;(1)}\left(G^{(1)}_{ga}\otimes G^{(1)}_{gb}\right)(z)\ .\end{aligned}$$

Where we fix μR=μF=M

Scale dependent terms already known from NNLO

THE N^{3}LO QT-SUBTRACTION METHOD

Third-order ingredients at qT = 0

- The hard-virtual, collinear and helicity-flip contributions

D. Gutierrez-Reyes, S. Leal-Gomez, I. Scimemi, and A. Vladimirov (2019)
M. Luo, T. Yang, H. Xing Zhu, and Y. Jiao Zhu (2019)

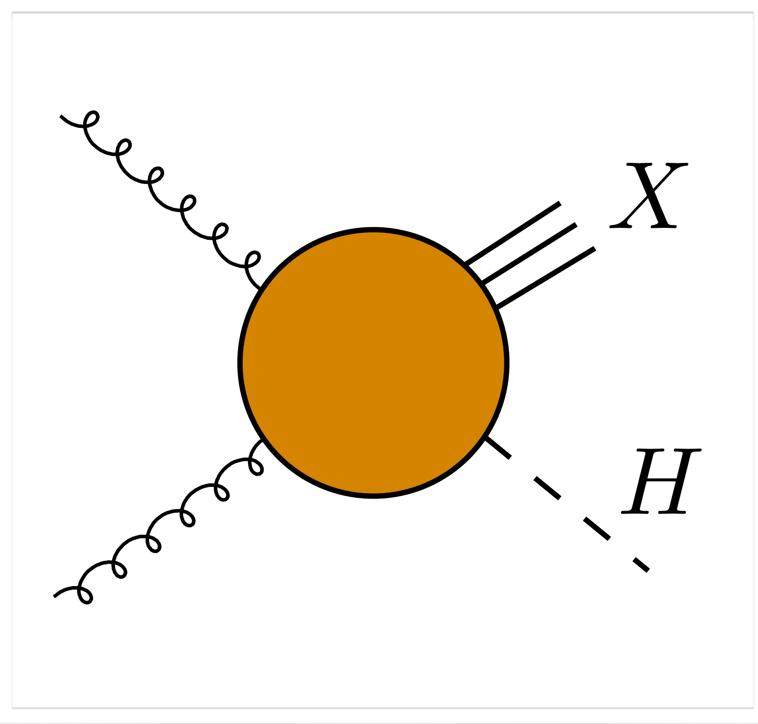
These ingredients are partially known or completely missing

$$
\begin{aligned}
\mathcal{H}^{H;(3)}_{gg\leftarrow ab}(z) = {} & \delta_{ga}\,\delta_{gb}\,\delta(1-z)\,H^{H;(3)}_g + \delta_{ga}\,C^{(3)}_{gb}(z) + \delta_{gb}\,C^{(3)}_{ga}(z) \\
& + \left(G^{(1)}_{ga} \otimes G^{(2)}_{gb}\right)(z) + \left(G^{(2)}_{ga} \otimes G^{(1)}_{gb}\right)(z) \\
& + H^{H;(1)}_g \left(\delta_{ga}\,C^{(2)}_{gb}(z) + \delta_{gb}\,C^{(2)}_{ga}(z)\right) + H^{H;(2)}_g \left(\delta_{ga}\,C^{(1)}_{gb}(z) + \delta_{gb}\,C^{(1)}_{ga}(z)\right) \\
& + \left(C^{(1)}_{ga} \otimes C^{(2)}_{gb}\right)(z) + \left(C^{(2)}_{ga} \otimes C^{(1)}_{gb}\right)(z) \\
& + H^{H;(1)}_g \left(C^{(1)}_{ga} \otimes C^{(1)}_{gb}\right)(z) + H^{H;(1)}_g \left(G^{(1)}_{ga} \otimes G^{(1)}_{gb}\right)(z)\,.
\end{aligned}
$$

Where we fix μR=μF=M

THE N^{3}LO QT-SUBTRACTION METHOD

Up to the previous slide the discussion about the N^{3}LO qT-subtraction formalism, was completely general. The following slides are for final processes F initiated by gluon fusion. In particular for Higgs boson production via gluon fusion in the large top-mass limit.



THE N^3LO CONTRIBUTIONS AT QT=0

THE N^{3}LO QT-SUBTRACTION METHOD

L. C, X. Chen, T. Gehrmann, E. W. N. Glover, and A. Huss (2018)

Third-order ingredients at qT = 0

- These ingredients are partially known or completely missing

$$H_g^{H;(3)} \quad ; \quad C_{ga}^{(3)} \quad ; \quad G_{ga}^{(2)}$$

D. Gutierrez-Reyes, S. Leal-Gomez, I. Scimemi, and A. Vladimirov (2019)
M. Luo, T. Yang, H. Xing Zhu, Y. Jiao Zhu (2019)

Nonetheless, within the qT-subtraction formalism, $\mathcal{H}_{gg\leftarrow ab}^{H;(3)}$ can be reliably approximated for any hard-scattering process whose corresponding total cross section is known at N^{3}LO.

G. Bozzi, S. Catani, D. de Florian and M. Grazzini (2005)

- In our case we use the N^{3}LO Higgs boson cross section recently calculated and implemented in the numerical code ihixs 2.0

B. Mistlberger (2018)

F. Dulat, A. Lazopoulos and B. Mistlberger (2018)

THE N^{3}LO QT-SUBTRACTION METHOD

L. C, X. Chen, T. Gehrmann, E. W. N. Glover, and A. Huss (2018)

Third-order ingredients at qT = 0

- Numerical procedure to extract

$$H_g^{H;(3)} \quad ; \quad C_{ga}^{(3)} \quad ; \quad G_{ga}^{(2)}$$

D. Gutierrez-Reyes, S. Leal-Gomez, I. Scimemi, and A. Vladimirov (2019)
M. Luo, T. Yang, H. Xing Zhu, Y. Jiao Zhu (2019)

- Starting point is the sketchy form of the qT-subtraction method

$$\mathrm{d}\sigma^F_{\mathrm{N^nLO}} = \mathcal{H}^F_{\mathrm{N^nLO}} \otimes \mathrm{d}\sigma^F_{\mathrm{LO}} + \left[\mathrm{d}\sigma^{F+\mathrm{jets}}_{\mathrm{N^{n-1}LO}} - \mathrm{d}\sigma^{F\,\mathrm{CT}}_{\mathrm{N^nLO}}\right] \quad \text{with} \quad n = 1, 2, 3$$

$$\hat{\sigma}^{\mathrm{tot}}_{F\,ab}(M, \hat{s}; \alpha_s(\mu_R^2), \mu_R^2, \mu_F^2) = \int_0^\infty \mathrm{d}q_T^2 \, \frac{\mathrm{d}\hat{\sigma}_{F\,ab}}{\mathrm{d}q_T^2}(q_T, M, \hat{s}; \alpha_s(\mu_R^2), \mu_R^2, \mu_F^2)$$

$$\sigma^{F\,(\mathrm{tot.})}_{\mathrm{N^nLO}} = \mathcal{H}^F_{\mathrm{N^nLO}} \otimes \sigma^F_{\mathrm{LO}} + \int_0^\infty \mathrm{d}q_T^2 \, \frac{\mathrm{d}\sigma^{F\,(\mathrm{fin.})}_{\mathrm{N^nLO}}}{\mathrm{d}q_T^2}$$

$$\frac{\mathrm{d}\hat{\sigma}^{(\mathrm{fin.})}_{F\,ab}}{\mathrm{d}q_T^2} \equiv \left[\frac{\mathrm{d}\hat{\sigma}^{F+\mathrm{jets}}_{ab}}{\mathrm{d}q_T^2} - \frac{\mathrm{d}\hat{\sigma}^{F\,\mathrm{CT}}_{ab}}{\mathrm{d}q_T^2}\right]$$

THE N^{3}LO QT-SUBTRACTION METHOD

L. C, X. Chen, T. Gehrmann, E. W. N. Glover, and A. Huss (2018)

Third-order ingredients at qT = 0

- Subtracting two consecutive orders, we arrive to an expression that can be used to extract numerically the missing terms

$$\left(\frac{\alpha_s}{\pi}\right)^3 \frac{M^2}{\hat{s}} \sum_c \sigma^{(0)}_{c\bar{c},F}(\alpha_s, M)\, \mathcal{H}^{F;(3)}_{c\bar{c}\leftarrow ab}\left(\frac{M^2}{\hat{s}}; \frac{M^2}{\mu_R^2}, \frac{M^2}{\mu_F^2}\right)$$
$$= \left\{\left[\hat{\sigma}^{\text{tot}}_{F\,ab}\right]_{\text{N}^3\text{LO}} - \left[\hat{\sigma}^{\text{tot}}_{F\,ab}\right]_{\text{NNLO}}\right\} - \int_0^\infty \mathrm{d}q_T^2 \left\{\left[\frac{\mathrm{d}\hat{\sigma}^{(\text{fin.})}_{F\,ab}}{\mathrm{d}q_T^2}\right]_{\text{N}^3\text{LO}} - \left[\frac{\mathrm{d}\hat{\sigma}^{(\text{fin.})}_{F\,ab}}{\mathrm{d}q_T^2}\right]_{\text{NNLO}}\right\}$$

$$\begin{aligned}
\mathcal{H}^{H;(3)}_{gg\leftarrow ab}(z) = {} & \delta_{ga}\,\delta_{gb}\,\delta(1-z)\,H^{H;(3)}_g + \delta_{ga}\,C^{(3)}_{gb}(z) + \delta_{gb}\,C^{(3)}_{ga}(z) \\
& + \left(G^{(1)}_{ga} \otimes G^{(2)}_{gb}\right)(z) + \left(G^{(2)}_{ga} \otimes G^{(1)}_{gb}\right)(z) \\
& + H^{H;(1)}_g \left(\delta_{ga}\,C^{(2)}_{gb}(z) + \delta_{gb}\,C^{(2)}_{ga}(z)\right) + H^{H;(2)}_g \left(\delta_{ga}\,C^{(1)}_{gb}(z) + \delta_{gb}\,C^{(1)}_{ga}(z)\right) \\
& + \left(C^{(1)}_{ga} \otimes C^{(2)}_{gb}\right)(z) + \left(C^{(2)}_{ga} \otimes C^{(1)}_{gb}\right)(z) \\
& + H^{H;(1)}_g \left(C^{(1)}_{ga} \otimes C^{(1)}_{gb}\right)(z) + H^{H;(1)}_g \left(G^{(1)}_{ga} \otimes G^{(1)}_{gb}\right)(z)\,.
\end{aligned}$$

THE N^{3}LO QT-SUBTRACTION METHOD

L. C, X. Chen, T. Gehrmann, E. W. N. Glover, and A. Huss (2018)

Third-order ingredients at qT = 0

- Subtracting two consecutive orders, we arrive to an expression that can be used to extract numerically the missing terms

$$\left(\frac{\alpha_s}{\pi}\right)^3 \frac{M^2}{\hat{s}} \sum_c \sigma^{(0)}_{c\bar{c},F}(\alpha_s, M)\, \mathcal{H}^{F;(3)}_{c\bar{c}\leftarrow ab}\left(\frac{M^2}{\hat{s}}; \frac{M^2}{\mu_R^2}, \frac{M^2}{\mu_F^2}\right)$$
$$= \left\{\left[\hat{\sigma}^{\text{tot}}_{F\,ab}\right]_{\text{N}^3\text{LO}} - \left[\hat{\sigma}^{\text{tot}}_{F\,ab}\right]_{\text{NNLO}}\right\} - \int_0^\infty dq_T^2 \left\{\left[\frac{d\hat{\sigma}^{(\text{fin.})}_{F\,ab}}{dq_T^2}\right]_{\text{N}^3\text{LO}} - \left[\frac{d\hat{\sigma}^{(\text{fin.})}_{F\,ab}}{dq_T^2}\right]_{\text{NNLO}}\right\}$$

We extract numerically these information that we put in a constant (independent of z)

$$C_{N3}\; \delta_{g\,a}\,\delta_{g\,b}\,\delta(1-z) \;\leftarrow\; \delta_{g\,a}\,\delta_{g\,b}\,\delta(1-z)\left[H_g^{H;(3)}\right]_{(\delta^{q_T}_{(2)})} + \delta_{g\,a}\,C^{(3)}_{g\,b}(z) + \delta_{g\,b}\,C^{(3)}_{g\,a}(z)$$
$$+\left(G^{(1)}_{g\,a}\otimes G^{(2)}_{g\,b}\right)(z) + \left(G^{(2)}_{g\,a}\otimes G^{(1)}_{g\,b}\right)(z)\;,$$

Exact numerical extraction

Approximation of a z function by a constant (a delta term)

THE N^{3}LO QT-SUBTRACTION METHOD

L. C, X. Chen, T. Gehrmann, E. W. N. Glover, and A. Huss (2018)

Third-order ingredients at qT = 0

- Subtracting two consecutive orders, we arrive to an expression that can be used to extract numerically the missing terms

$$\left(\frac{\alpha_s}{\pi}\right)^3 \frac{M^2}{\hat{s}} \sum_c \sigma^{(0)}_{c\bar{c},F}(\alpha_s, M)\, \mathcal{H}^{F;(3)}_{c\bar{c}\leftarrow ab}\left(\frac{M^2}{\hat{s}}; \frac{M^2}{\mu_R^2}, \frac{M^2}{\mu_F^2}\right)$$
$$= \left\{\left[\hat{\sigma}^{\rm tot}_{F\,ab}\right]_{\rm N^3LO} - \left[\hat{\sigma}^{\rm tot}_{F\,ab}\right]_{\rm NNLO}\right\} - \int_0^\infty dq_T^2 \left\{\left[\frac{d\hat{\sigma}^{(\rm fin.)}_{F\,ab}}{dq_T^2}\right]_{\rm N^3LO} - \left[\frac{d\hat{\sigma}^{(\rm fin.)}_{F\,ab}}{dq_T^2}\right]_{\rm NNLO}\right\}$$

We extract numerically these information that we put in a constant (independent of z)

$$C_{N3}\;\; \delta_{g\,a}\,\delta_{g\,b}\,\delta(1-z) \;\leftarrow\; \delta_{g\,a}\,\delta_{g\,b}\,\delta(1-z)\,\left[H_g^{H;(3)}\right]_{(\delta^{q_T}_{(2)})} + \delta_{g\,a}\,C^{(3)}_{g\,b}(z) + \delta_{g\,b}\,C^{(3)}_{g\,a}(z)$$
$$+ \left(G^{(1)}_{g\,a} \otimes G^{(2)}_{g\,b}\right)(z) + \left(G^{(2)}_{g\,a} \otimes G^{(1)}_{g\,b}\right)(z)\;\;,$$

Let me postpone the discussion of the universal terms inside the hard-virtual factors, since it is orthogonal to the following slides

$$H_g^{H;(3)} \equiv \widetilde{H}_g^{H;(3)} + \left[H_g^{H;(3)}\right]_{(\delta^{q_T}_{(2)})}$$

Third order constant of "soft origin", belonging to the finite part of the third order structure of the IR singularities

THE N^{3}LO QT-SUBTRACTION METHOD

L. C, X. Chen, T. Gehrmann, E. W. N. Glover, and A. Huss (2018)

Third-order ingredients at qT = 0

- Subtracting two consecutive orders, we arrive to an expression that can be used to extract numerically the missing terms

$$\left(\frac{\alpha_s}{\pi}\right)^3 \frac{M^2}{\hat{s}} \sum_c \sigma^{(0)}_{c\bar{c},\,F}(\alpha_s, M)\, \mathcal{H}^{F;(3)}_{c\bar{c}\leftarrow ab}\left(\frac{M^2}{\hat{s}}; \frac{M^2}{\mu_R^2}, \frac{M^2}{\mu_F^2}\right)$$
$$= \left\{\left[\hat{\sigma}^{\rm tot}_{F\,ab}\right]_{\rm N^3LO} - \left[\hat{\sigma}^{\rm tot}_{F\,ab}\right]_{\rm NNLO}\right\} - \int_0^\infty {\rm d}q_T^2 \left\{\left[\frac{{\rm d}\hat{\sigma}^{(\rm fin.)}_{F\,ab}}{{\rm d}q_T^2}\right]_{\rm N^3LO} - \left[\frac{{\rm d}\hat{\sigma}^{(\rm fin.)}_{F\,ab}}{{\rm d}q_T^2}\right]_{\rm NNLO}\right\}$$

Total exact Xsec. from B. Mistlberger (2018)

Ihixs 2.0: F. Dulat, A. Lazopoulos and B. Mistlberger (2018)

THE N^{3}LO QT-SUBTRACTION METHOD

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$$= \left\{\left[\hat{\sigma}^{\text{tot}}_{F\,ab}\right]_{\text{N}^3\text{LO}} - \left[\hat{\sigma}^{\text{tot}}_{F\,ab}\right]_{\text{NNLO}}\right\} - \int_{\text{qTcut}^2}^{\infty} dq_T^2 \left\{\left[\frac{d\hat{\sigma}^{(\text{fin.})}_{F\,ab}}{dq_T^2}\right]_{\text{N}^3\text{LO}} - \left[\frac{d\hat{\sigma}^{(\text{fin.})}_{F\,ab}}{dq_T^2}\right]_{\text{NNLO}}\right\}$$

The lower limit in the integral has to be replaced by a technical cut, the qTcut

$$\frac{d\hat{\sigma}^{(\text{fin.})}_{F\,ab}}{dq_T^2} \equiv \left[\frac{d\hat{\sigma}^{F+\text{jets}}_{ab}}{dq_T^2} - \frac{d\hat{\sigma}^{F\ \text{CT}}_{ab}}{dq_T^2}\right]$$

NNLOJET
X. Chen, J. Cruz-Martinez, T. Gehrmann, E. W. N. Glover and M. Jaquier (2016)

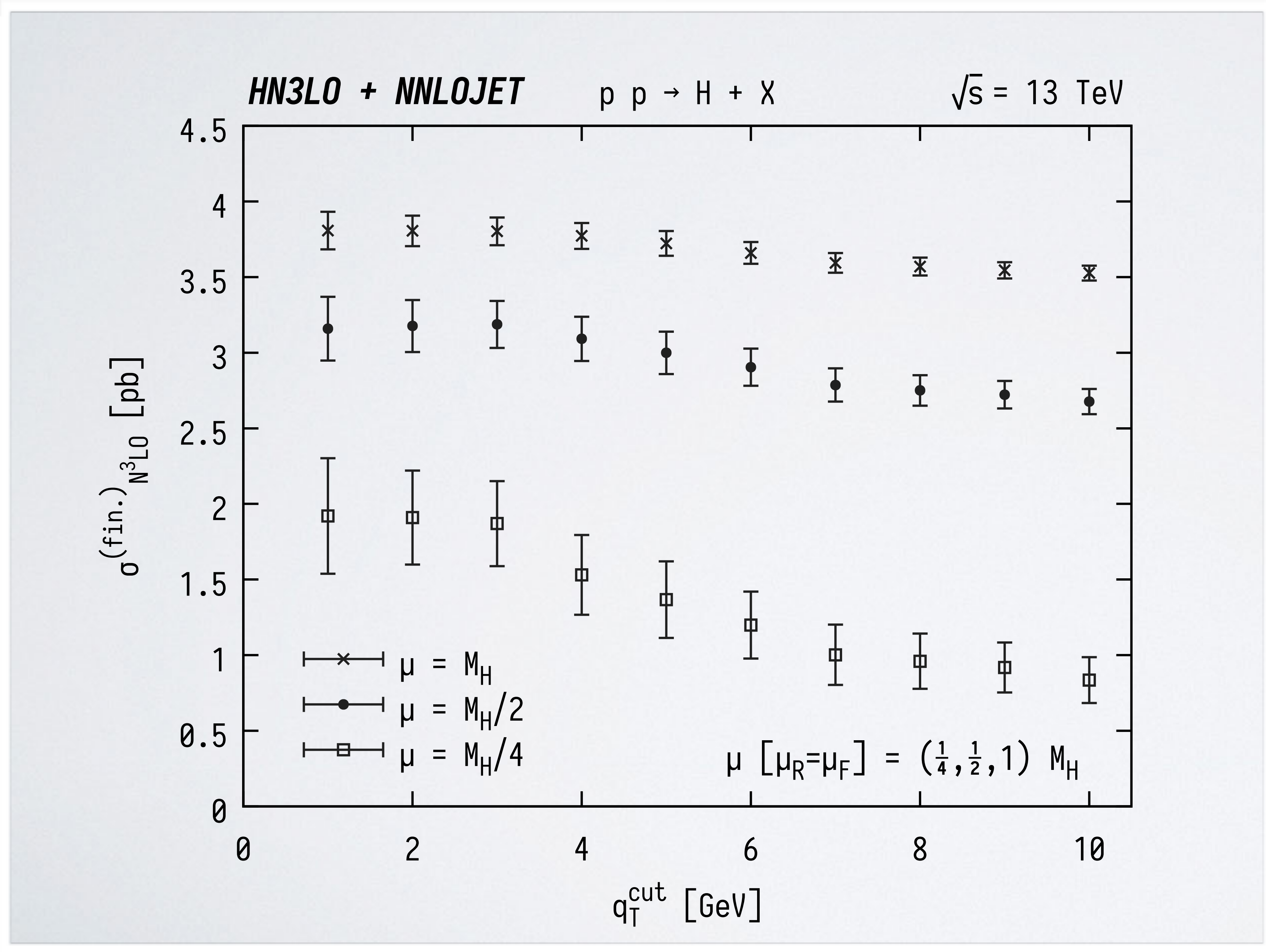
HN3LO
LC (2018)

THE N^{3}LO QT-SUBTRACTION METHOD

L. C, X. Chen, T. Gehrmann, E. W. N. Glover, and A. Huss (2018)

Third-order ingredients at qT = 0

- For the extraction, we consider Higgs boson production at N^{3}LO in gluon fusion in the large top mass limit, at $\sqrt{s} = 13$ TeV



$$\int_{q_T^{cut\,2}}^{\infty} dq_T^2 \left[\frac{\sigma_{N^3LO}^{F(fin.)}}{q_T^2} - \frac{\sigma_{N^2LO}^{F(fin.)}}{q_T^2} \right]$$

THE N^{3}LO QT-SUBTRACTION METHOD

L. C, X. Chen, T. Gehrmann, E. W. N. Glover, and A. Huss (2018)

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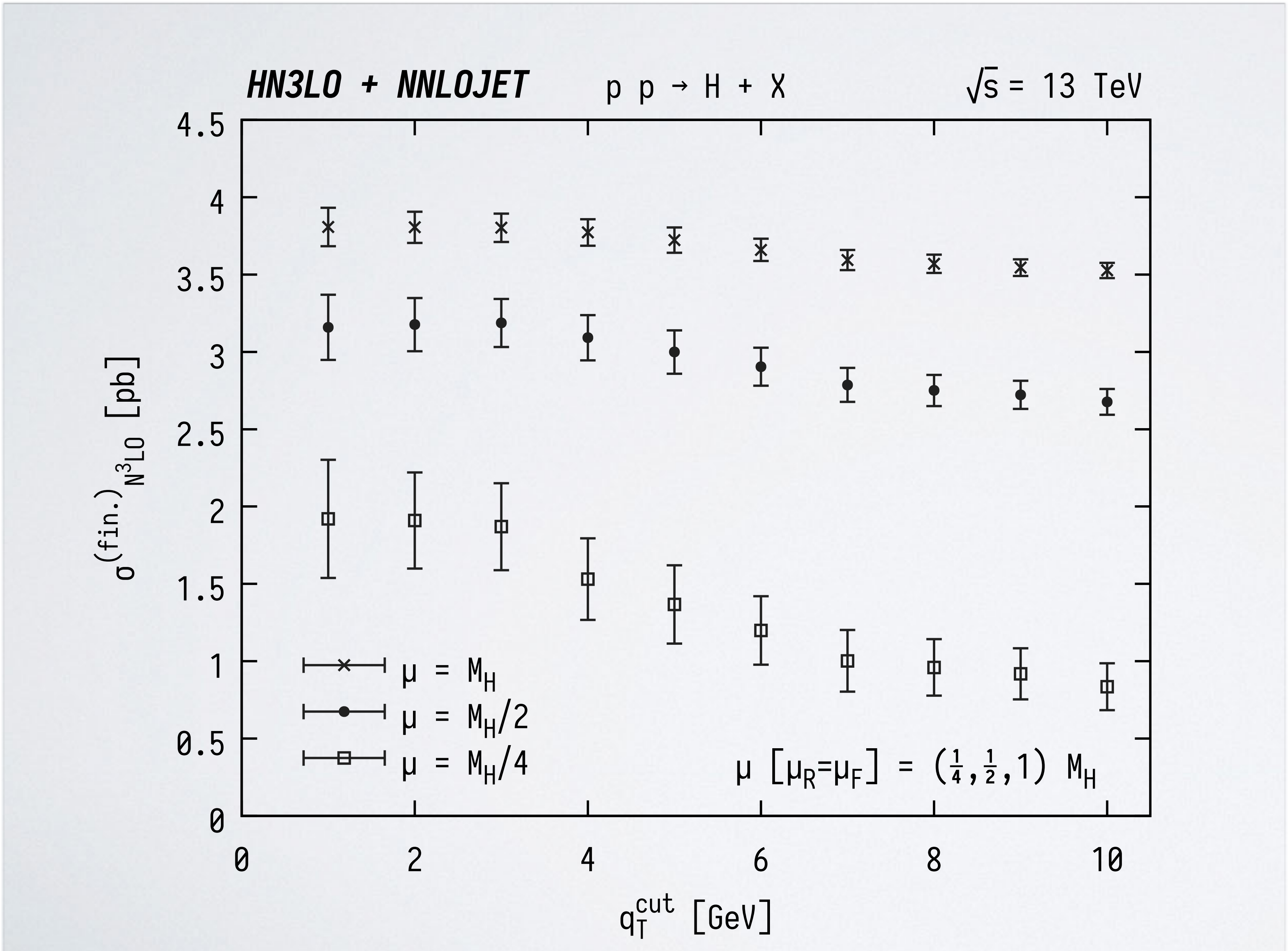


For the extraction procedure , the NNLO Xsection is taken from the analytical result, therefore, there is no systematic uncertainty from the NNLO

$$\int_{q_T^{cut2}}^{\infty} dq_T^2 \left[\frac{\sigma^{F(fin.)}_{N^3LO}}{q_T^2} - \frac{\sigma^{F(fin.)}_{N^2LO}}{q_T^2} \right]$$

$$C_{N3} = -943 \pm 222$$

The size of the uncertainty bands are almost entirely due to the F+Jet calculation

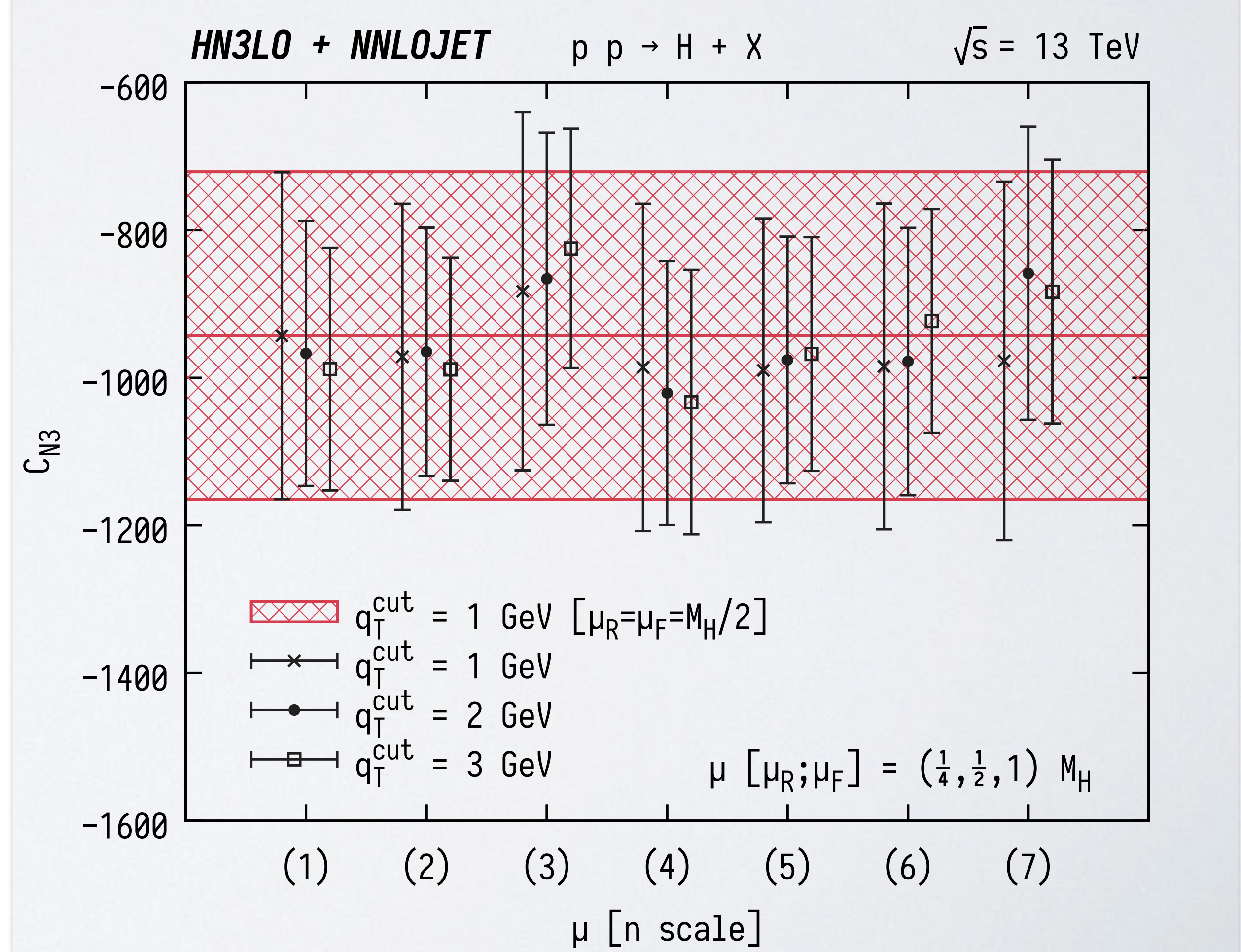
THE N^3LO QT-SUBTRACTION METHOD

L. C, X. Chen, T. Gehrmann, E. W. N. Glover, and A. Huss (2018)

Third-order ingredients at qT = 0

- Repeating the same procedure for 7-point scale variation

n	$[\tilde{\mu_R}, \tilde{\mu_F}]\ \times M_H$	C_{N3} ($q_T^{cut} = 1$ GeV)	C_{N3} ($q_T^{cut} = 2$ GeV)	C_{N3} ($q_T^{cut} = 3$ GeV)
(1)	[1/2, 1/2]	**−943 ± 222**	−967 ± 179	−988 ± 164
(2)	[1, 1]	−971 ± 207	−965 ± 168	−989 ± 151
(3)	[1/4, 1/4]	−883 ± 243	−866 ± 198	−850 ± 162
(4)	[1/2, 1]	−986 ± 222	−1021 ± 179	−1033 ± 179
(5)	[1, 1/2]	−990 ± 206	−976 ± 167	−968 ± 158
(6)	[1/2, 1/4]	−985 ± 221	−978 ± 181	−923 ± 152
(7)	[1/4, 1/2]	−977 ± 243	−859 ± 199	−883 ± 179



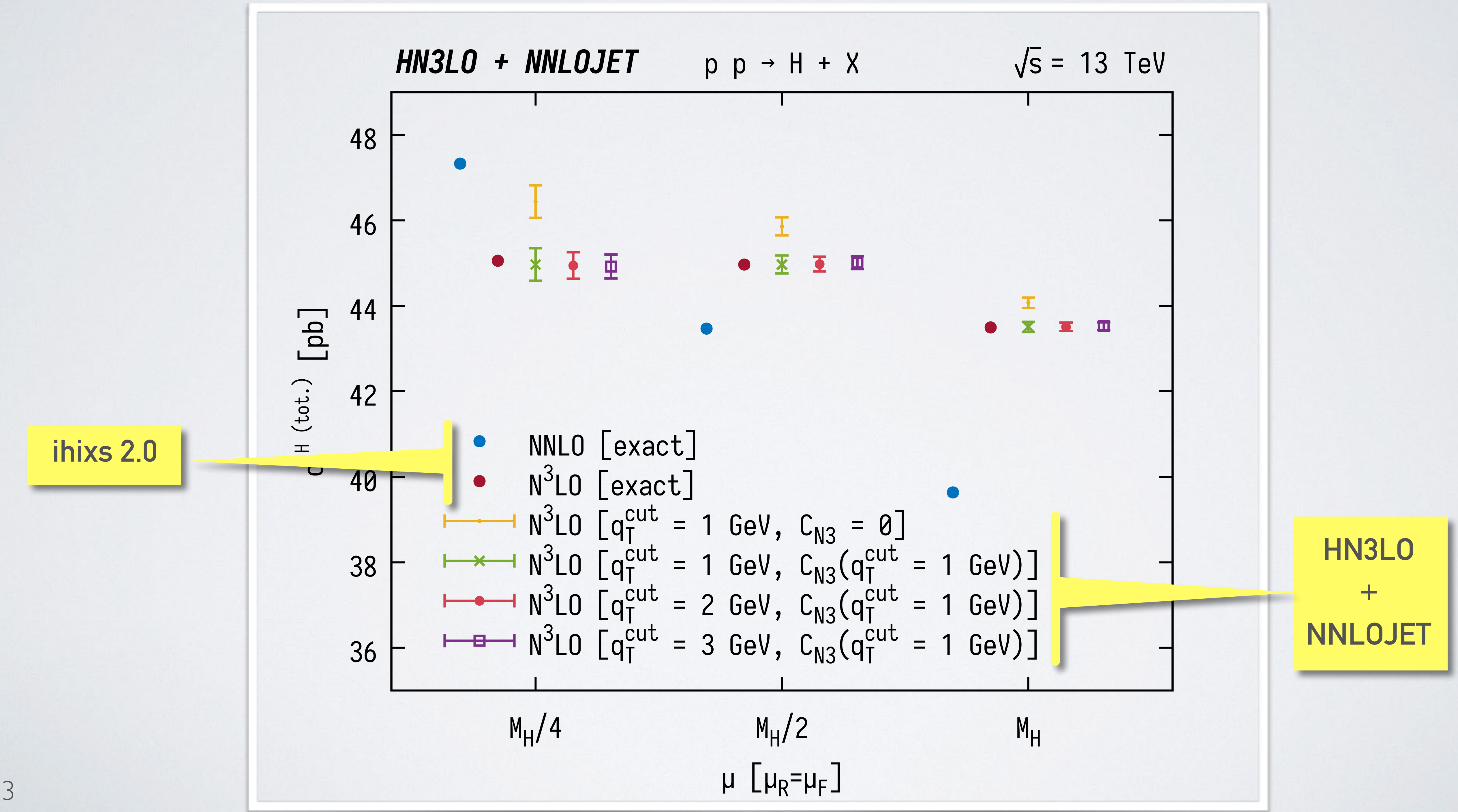
FIRST RESULTS AT N3LO

N3LO TOTAL XSECTION

THE N³LO TOTAL XSECTION

L. C, X. Chen, T. Gehrmann, E. W. N. Glover, and A. Huss (2018)

- With the extracted CN3 coefficient (only one value corresponding to the central scale) we can use the qT-subtraction method to predict total Xsections at N^3LO



THE N^{3}LO TOTAL XSECTION

L. C, X. Chen, T. Gehrmann, E. W. N. Glover, and A. Huss (2018)

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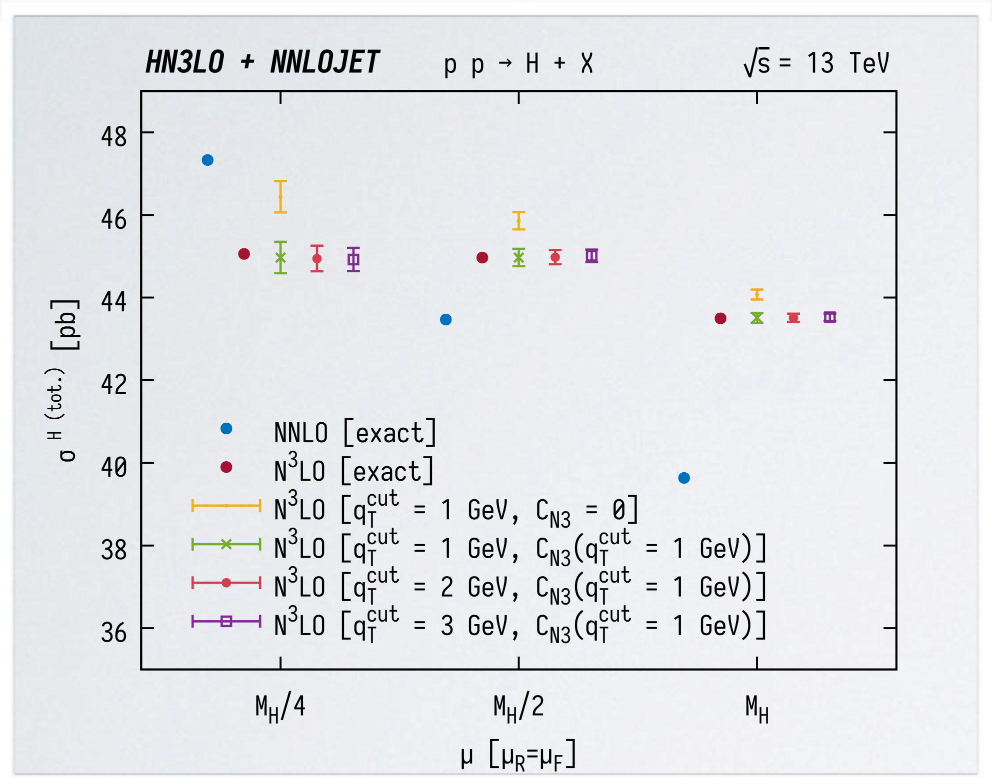


HN3LO + NNLOJET

ihixs 2.0

Using the extracted value of CN3, we performed a closure test for the inclusive total cross section for three different scale choices and find excellent agreement with the exact results (from ihixs 2.0) at the 0.2% level

$\sigma^{H\,(\text{tot.})}$ (pb)	Exact	q_T subtraction ($q_T^{\text{cut}} = 1$ GeV)	q_T subtraction ($q_T^{\text{cut}} = 2$ GeV)	q_T subtraction ($q_T^{\text{cut}} = 3$ GeV)	q_T subtraction ($C_{N3} = 0$)
N^{3}LO$[\mu = M_H/2]$	44.97	44.97 ± 0.21	44.98 ± 0.17	45.01 ± 0.15	45.86 ± 0.21
N^{3}LO$[\mu = M_H]$	43.50	43.51 ± 0.12	43.51 ± 0.10	43.53 ± 0.09	44.08 ± 0.12
N^{3}LO$[\mu = M_H/4]$	45.06	44.97 ± 0.38	44.95 ± 0.31	44.92 ± 0.28	46.44 ± 0.38
NNLO $[\mu = M_H/2]$	43.47	43.46 ± 0.02	43.46 ± 0.02	43.46 ± 0.02	43.46 ± 0.02
NNLO $[\mu = M_H]$	39.64	39.62 ± 0.02	39.62 ± 0.02	39.62 ± 0.02	39.62 ± 0.02
NNLO $[\mu = M_H/4]$	47.33	47.33 ± 0.02	47.33 ± 0.02	47.33 ± 0.02	47.33 ± 0.02

N3LO DIFFERENTIAL DISTRIBUTIONS

N^3LO DIFFERENTIAL DISTRIBUTIONS

L. C, X. Chen, T. Gehrmann, E. W. N. Glover, and A. Huss (2018)

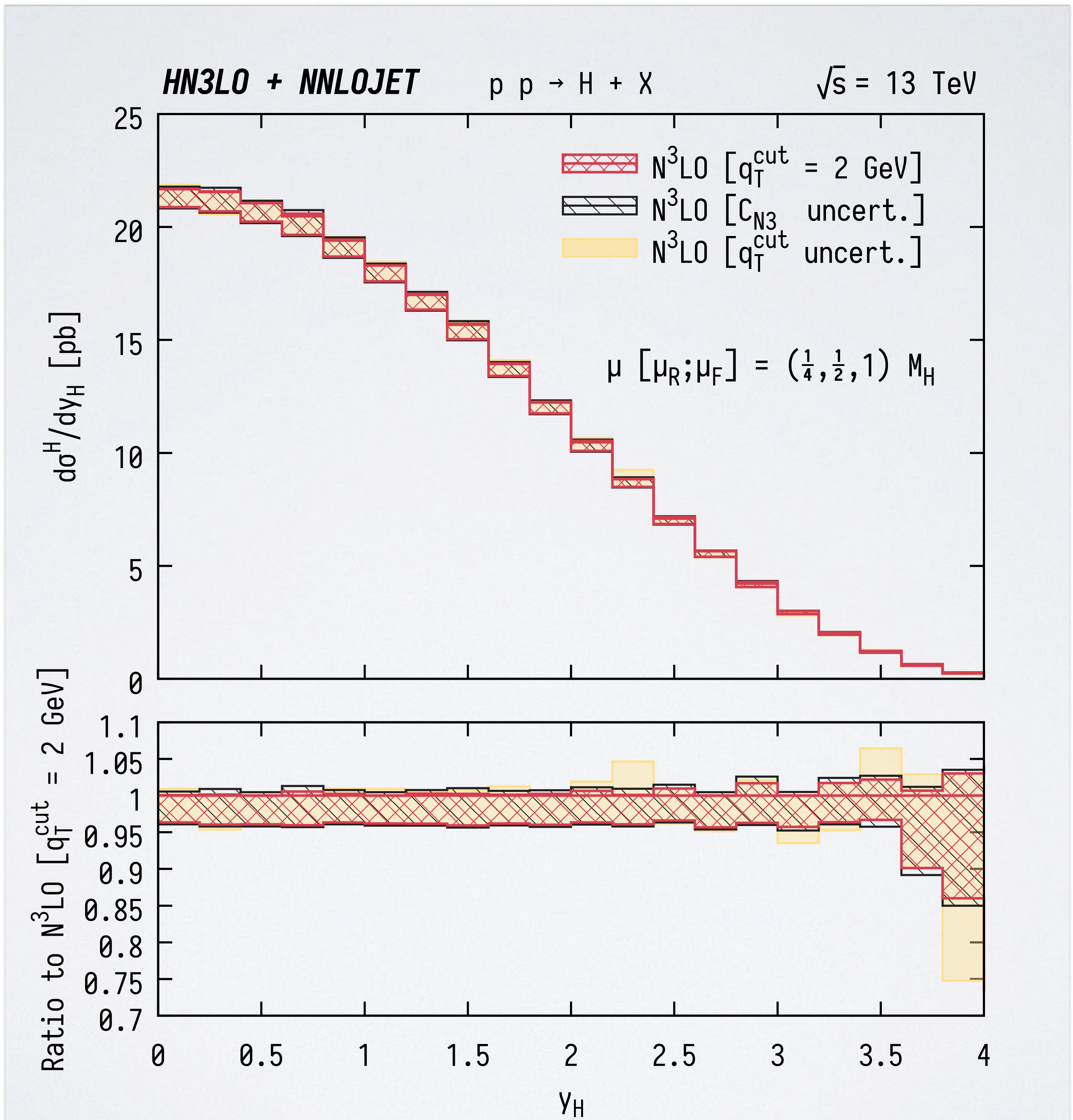
Uncertainties at N^3LO

N3LO prediction at qTcut=2GeV + qTcut uncertainties + systematic uncertainties

qTcut uncertainties Calculated taking three different predictions for qTcut = (2 ± 1) GeV

The black band is obtained as the envelope of the seven-point scale variation at qTcut = 2 GeV considering for each scale the two extremal CN3 coefficients corresponding to its maximum and minimum statistical deviations

CN3 = {−1165,−721}



In order to produce smooth histograms the code has to run for a couple of months in 2000 cores approx.

N^3LO DIFFERENTIAL DISTRIBUTIONS

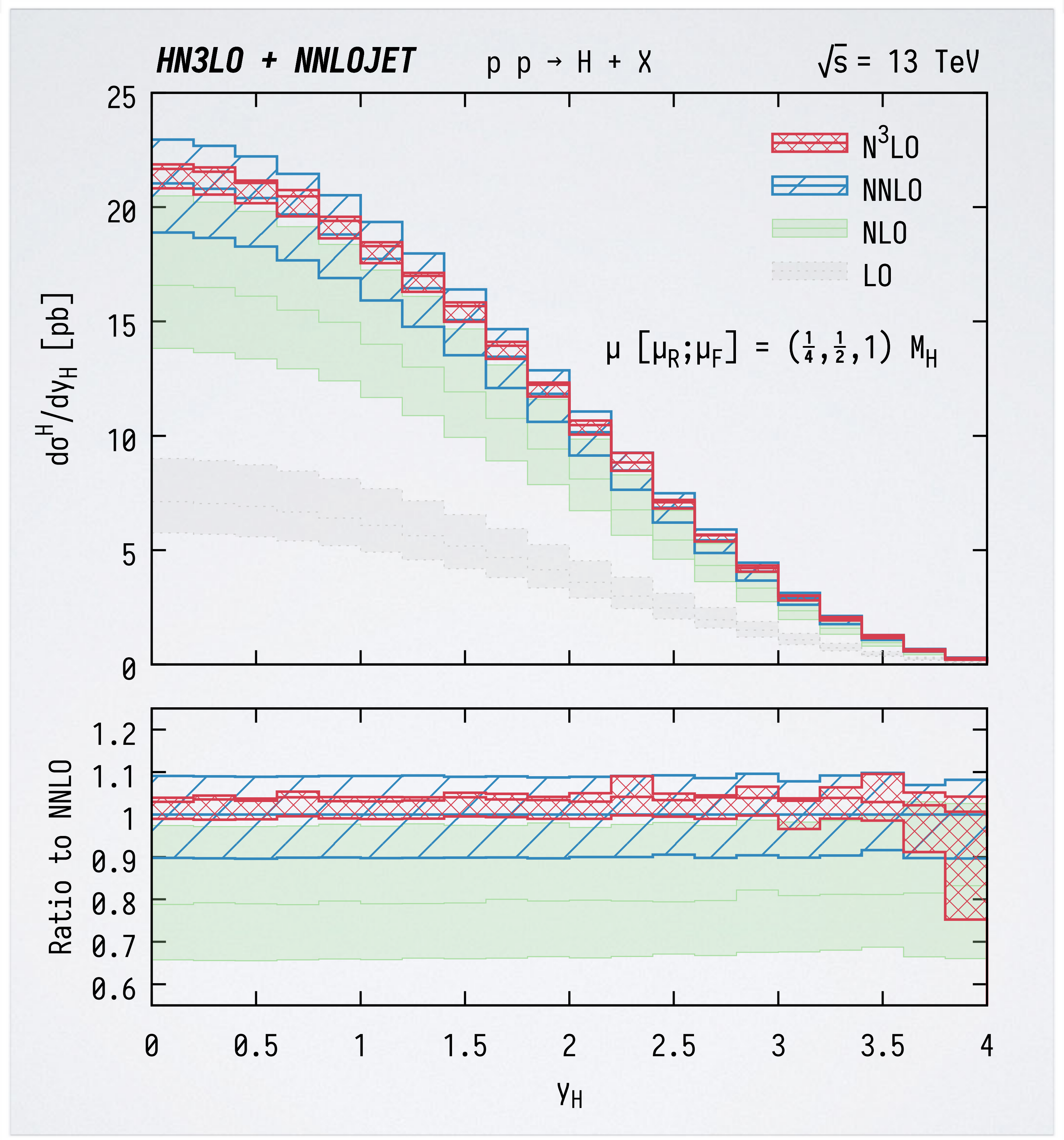
L. C, X. Chen, T. Gehrmann, E. W. N. Glover, and A. Huss (2018)

Rapidity distribution

We calculate the yH distribution at N3LO employing a seven-point scale variation and carefully assess systematic errors arising form different qTcut and CN3 values.

The combined theoretical uncertainty at N3LO is at most of ±5% level with respect to the central scale choice

N3LO prediction at qTcut=2GeV + qTcut uncertainties + systematic uncertainties

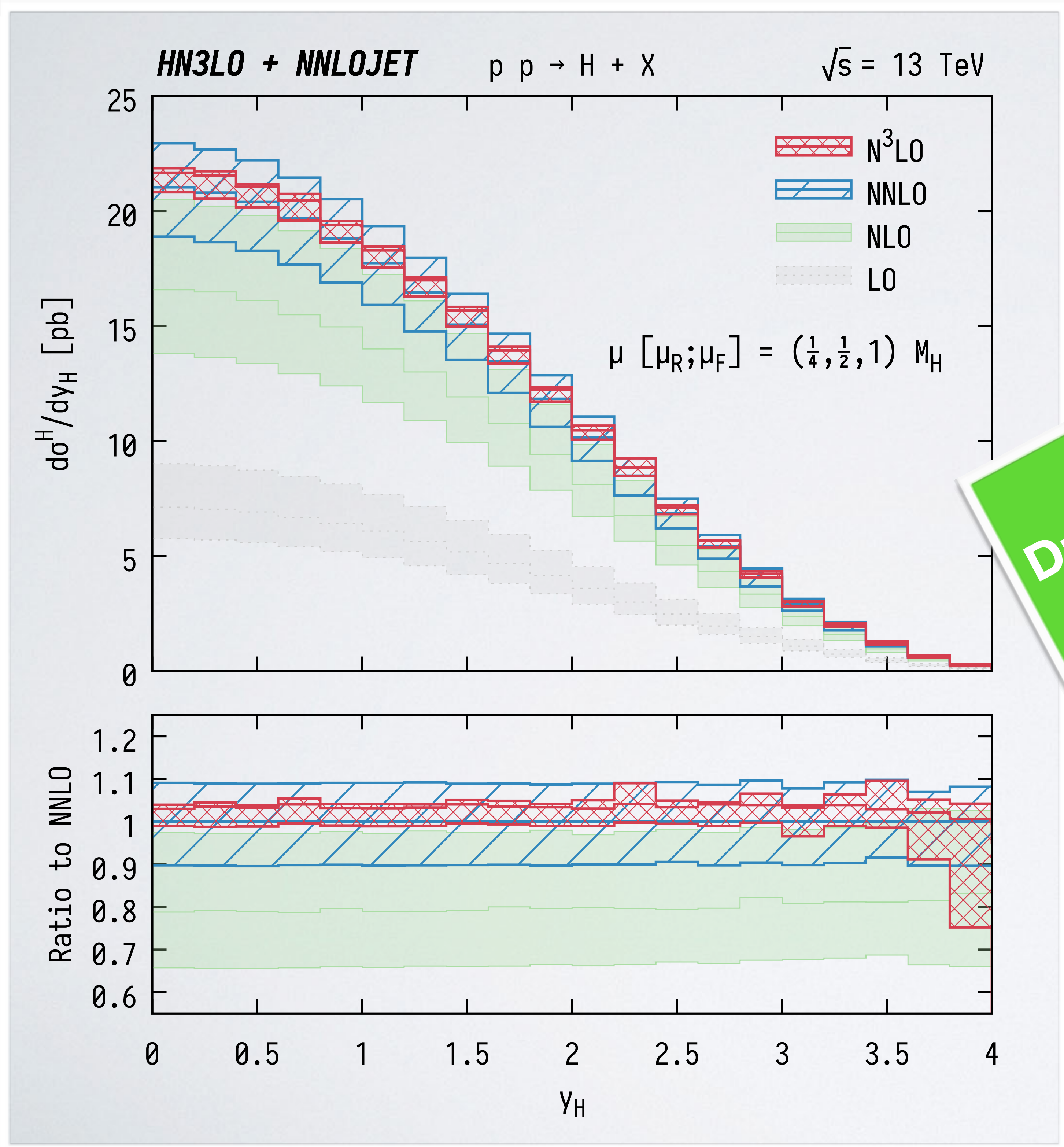


Compared to the NNLO yH distributions, we observe a large reduction of theory uncertainties by more than 50% at N3LO. The scale variation band at N3LO stays within the NNLO band with a flat K-factor of about 1.034 in the central rapidity region (|yH| ≤ 3.6).

N^3LO DIFFERENTIAL DISTRIBUTIONS

L. C, X. Chen, T. Gehrmann, E. W. N. Glover, and A. Huss (2018)

Rapidity distribution



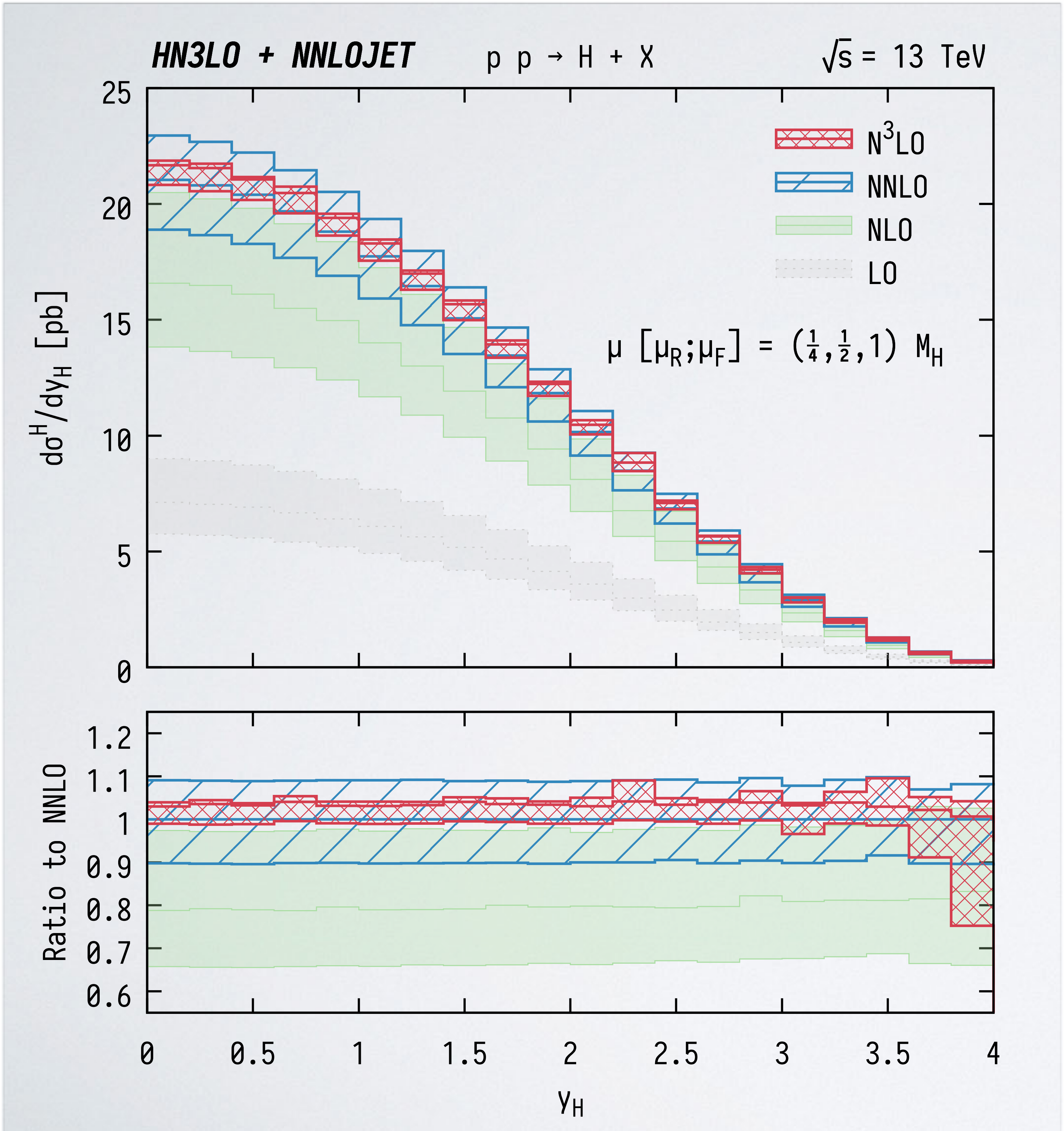
In agreement with
Dulat, Mistlberger and Pelloni (2018)
[Higgs production in TH expansion approximation]

Which is far from a trivial test!!

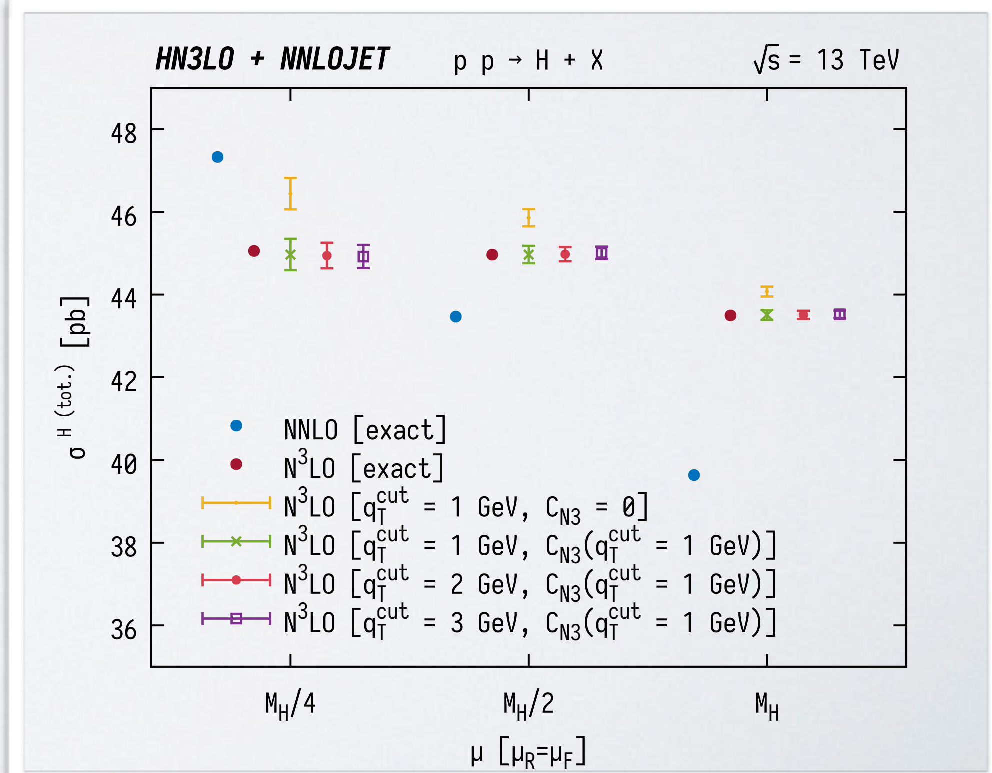
N^3LO DIFFERENTIAL DISTRIBUTIONS

L. C, X. Chen, T. Gehrmann, E. W. N. Glover, and A. Huss (2018)

Rapidity distribution



The central prediction at N^3LO, almost coincides with the upper edge of the band, as was already observed for the total cross section



N^3LO DIFFERENTIAL DISTRIBUTIONS

L. C, X. Chen, T. Gehrmann, E. W. N. Glover, and A. Huss (2018)

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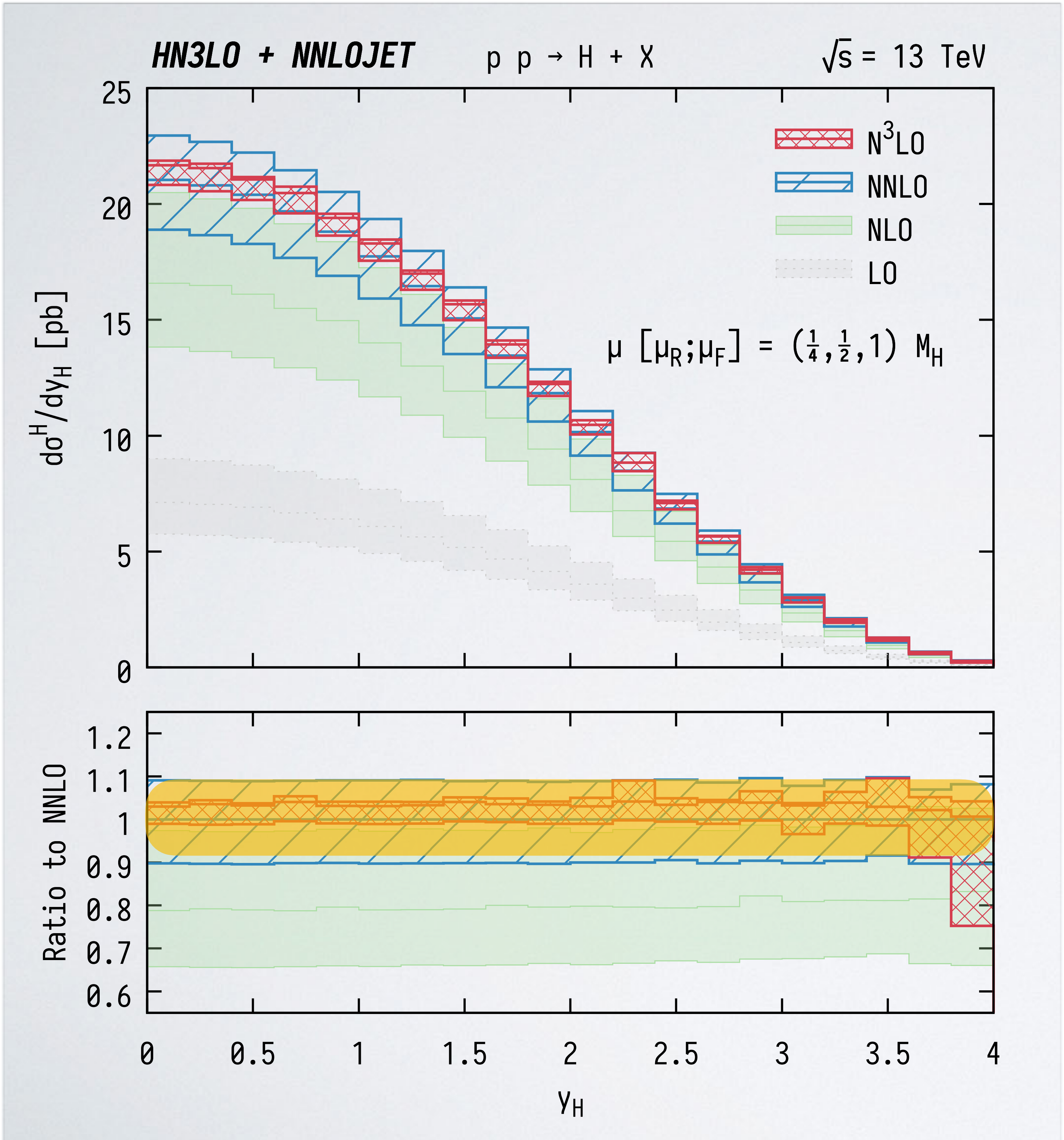

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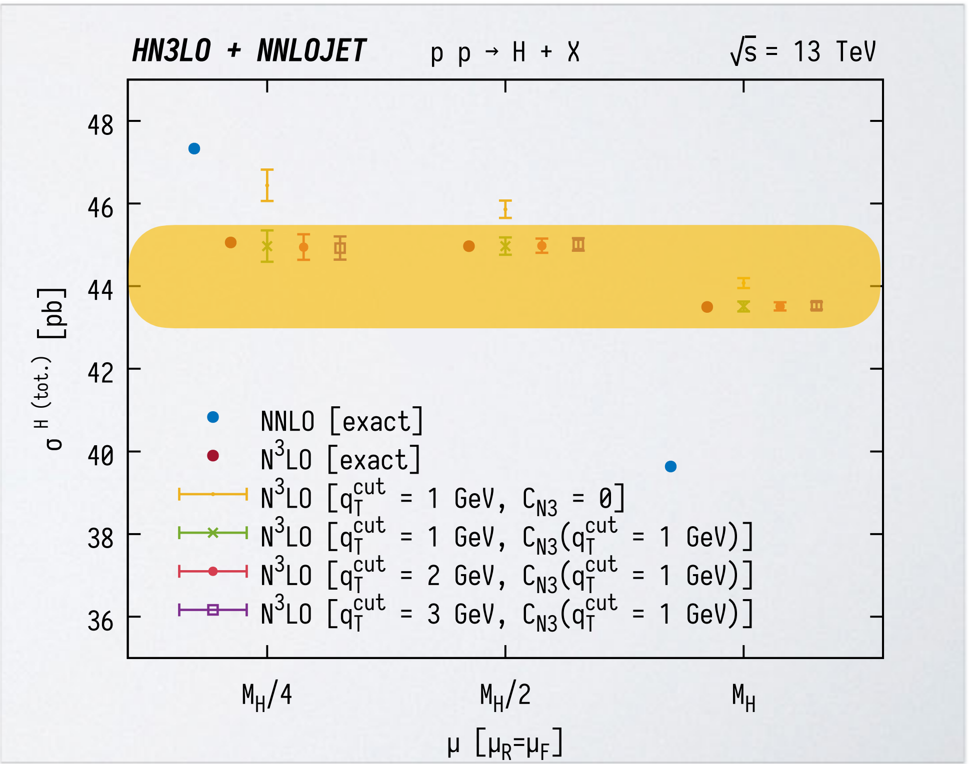


CONCLUSIONS AND OUTLOOK

- We presented results at N^3LO for completely differential distributions for observables measured at the LHC
  (in particular for Higgs boson production in gluon fusion)
- The qT-subtraction method at N^3LO, presented here, can be applied to other processes initiated by gluon fusion (if the three-loop scattering amplitudes are known),
  i.e the CN3 in gluon fusion is universal

We can describe IR safe differential observables,
not only the rapidity, and apply any set of cuts on the final state

CONCLUSIONS AND OUTLOOK

- We presented results at N^{3}LO for completely differential distributions for observables measured at the LHC
  (in particular for Higgs boson production in gluon fusion)
- The qT-subtraction method at N^{3}LO, presented here, can be applied to other processes initiated by gluon fusion (if the three-loop scattering amplitudes are known),
  i.e the CN3 in gluon fusion is universal
- More work is necessary in order to calculate the CN3 coefficient for processes initiated by qqb annihilation, since the total cross section at N^{3}LO for Drell-Yan is not known
- In the future, two elements are necessary in order to complete analytically the qT-subtraction method at N^{3}LO
  - The universal relation between the three-loop virtual scattering amplitudes and the hard virtual factor
  - The third order collinear functions

CONCLUSIONS AND OUTLOOK

- The approximation related to the CN3 coefficient in our approach **can be easily replaced by the full analytical results for the coefficients once available**
- Our results can be applied to perform qT-resummation at the corresponding level of logarithmic accuracy. **i.e without reweighing by the total cross section**

THANK YOU!

BACKUP SLIDES

N^3LO DIFFERENTIAL DISTRIBUTIONS

L. C, X. Chen, T. Gehrmann, E. W. N. Glover, and A. Huss (2018)

- The precedent results (CN3 coefficient) allow us to compute more exclusive observables (distributions) at N^3LO

- Before starting with the N^3LO computation, a couple of questions are in order (regarding CN3): **uncertainty introduced by the proposed numerical strategy?**

- In order to answer this question we can repeat the numerical strategy, but at one order less (NNLO) where all the coefficients are known analytically

$$
C_N \quad \delta_{g\,a}\,\delta_{g\,b}\,\delta(1-z) \;\leftarrow\; \delta_{g\,a}\,\delta_{g\,b}\,\delta(1-z)\left[H_g^{H;(2)}\right]_{(\delta_{(1)}^{q_T})} + \delta_{g\,a}\,C_{g\,b}^{(2)}(z) + \delta_{g\,b}\,C_{g\,a}^{(2)}(z) + \left(G_{g\,a}^{(1)} \otimes G_{g\,b}^{(1)}\right)(z)
$$

NNLO TEST

NNLO DIFFERENTIAL DISTRIBUTIONS

L. C, X. Chen, T. Gehrmann, E. W. N. Glover, and A. Huss (2018)

- In order to answer this question we can repeat the numerical strategy, at one order less (NNLO) where all the coefficient are known analytically

$$\mathcal{H}^{H;(2)}_{gg\leftarrow ab}(z) = \delta_{g\,a}\,\delta_{g\,b}\,\delta(1-z)\,H^{H;(2)}_g + \delta_{g\,a}\,C^{(2)}_{g\,b}(z) + \delta_{g\,b}\,C^{(2)}_{g\,a}(z) + H^{H;(1)}_g\left(\delta_{g\,a}\,C^{(1)}_{g\,b}(z) + \delta_{g\,b}\,C^{(1)}_{g\,a}(z)\right) + \left(C^{(1)}_{g\,a}\otimes C^{(1)}_{g\,b}\right)(z) + \left(G^{(1)}_{g\,a}\otimes G^{(1)}_{g\,b}\right)(z)\ .$$

Only scale independent part

$$C_N\ \ \delta_{g\,a}\,\delta_{g\,b}\,\delta(1-z)\ \leftarrow\ \delta_{g\,a}\,\delta_{g\,b}\,\delta(1-z)\left[H^{H;(2)}_g\right]_{(\delta^{qT}_{(1)})} + \delta_{g\,a}\,C^{(2)}_{g\,b}(z) + \delta_{g\,b}\,C^{(2)}_{g\,a}(z) + \left(G^{(1)}_{g\,a}\otimes G^{(1)}_{g\,b}\right)(z)$$

Second order constant of “soft origin”, belonging to the finite part of the second-order structure of the IR singularities

$$H^{H;(2)}_g \equiv \widetilde{H}^{H;(2)}_g + \left[H^{H;(2)}_g\right]_{(\delta^{qT}_{(1)})}$$

$$C_{N2} = 28 \pm 1$$

NNLO DIFFERENTIAL DISTRIBUTIONS

NNLO exercise

L. C, X. Chen, T. Gehrmann, E. W. N. Glover, and A. Huss (2018)

- In order to assess the intrinsic uncertainty of the method we can repeat the numerical strategy, at one order less (NNLO) where all the coefficients are known analytically

The uncertainties at the differential distributions are at the 0.2% level!

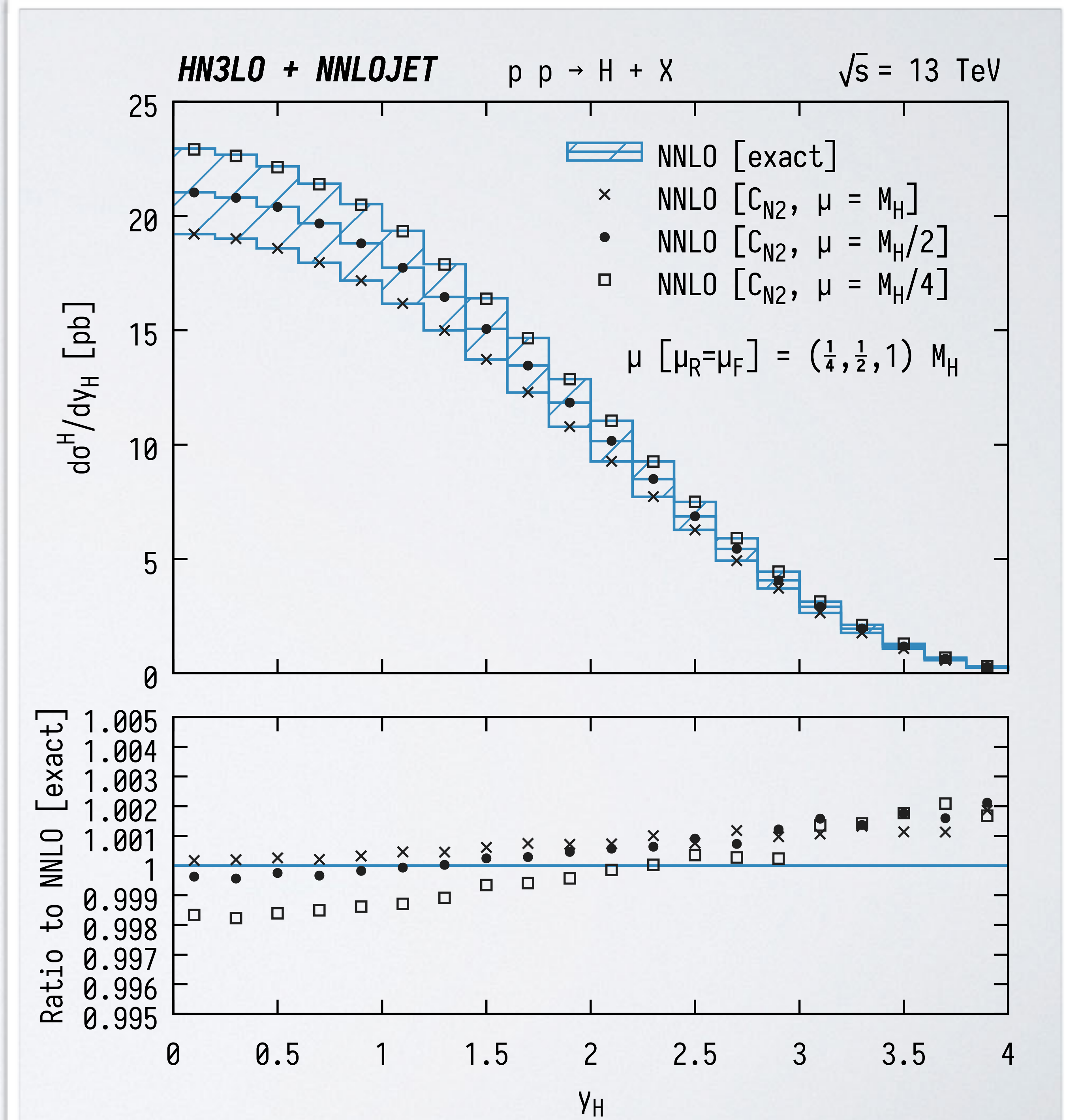
This is the expected level of precision in our approximation

With the exception of the scale MH/4, the rest of the scales show their best behaviour in the low rapidity region and they start to separate from the exact result at large rapidities, which is what we expect.

$$\mathcal{H}^{F;(2)}_{c\bar{c}\leftarrow ab}\left(H^{F;(2)}_{c};C^{(2)}_{ab};G^{(1)}_{ga}\right) \leftarrow \mathcal{H}^{F;(2)}_{c\bar{c}\leftarrow ab}\,(\mathrm{C_{N2}})$$

Approximated numerical extraction

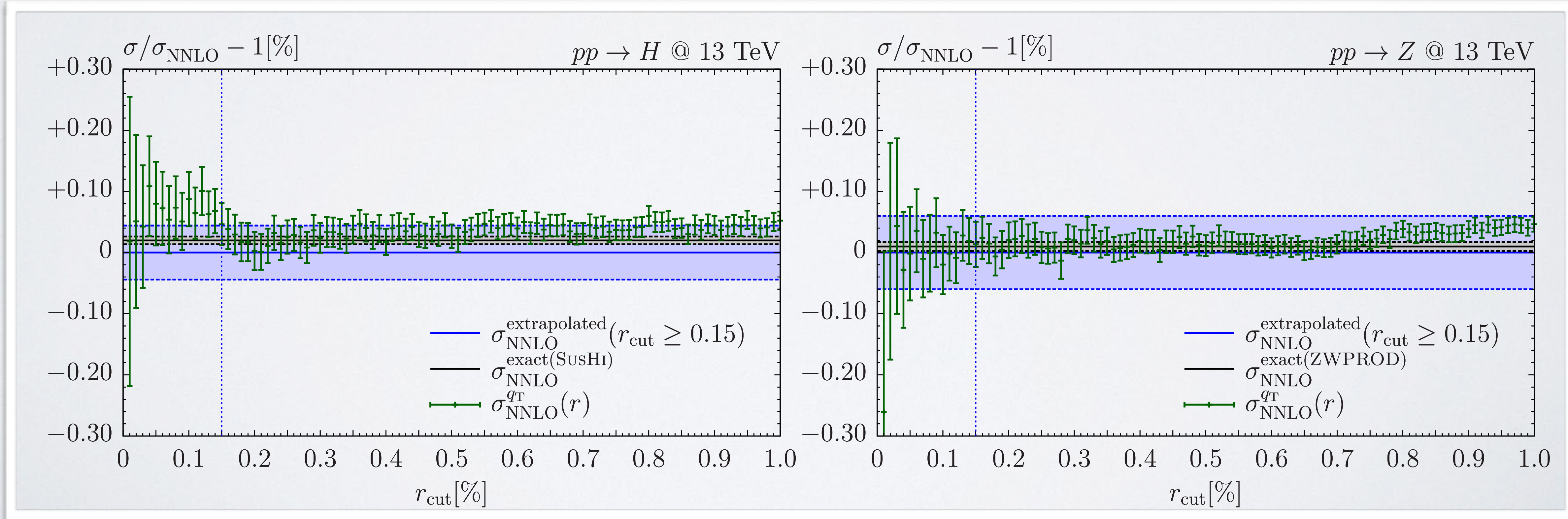
Exact numerical extraction



N3LO DIFFERENTIAL DISTRIBUTIONS

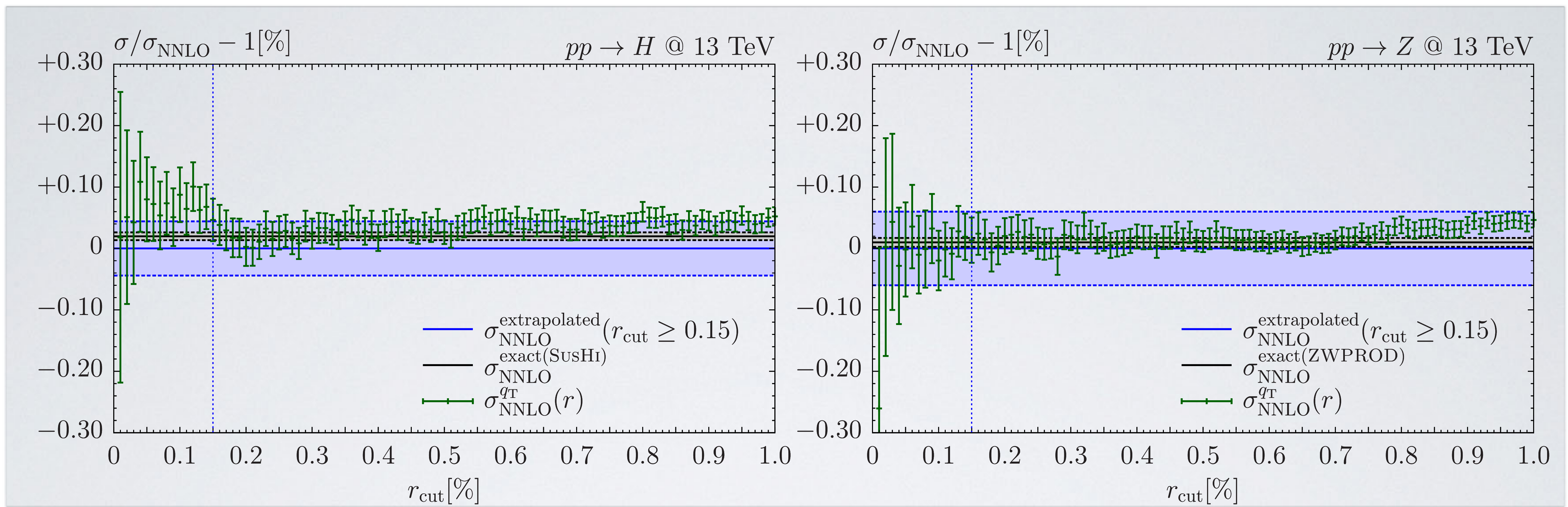
MOTIVATION

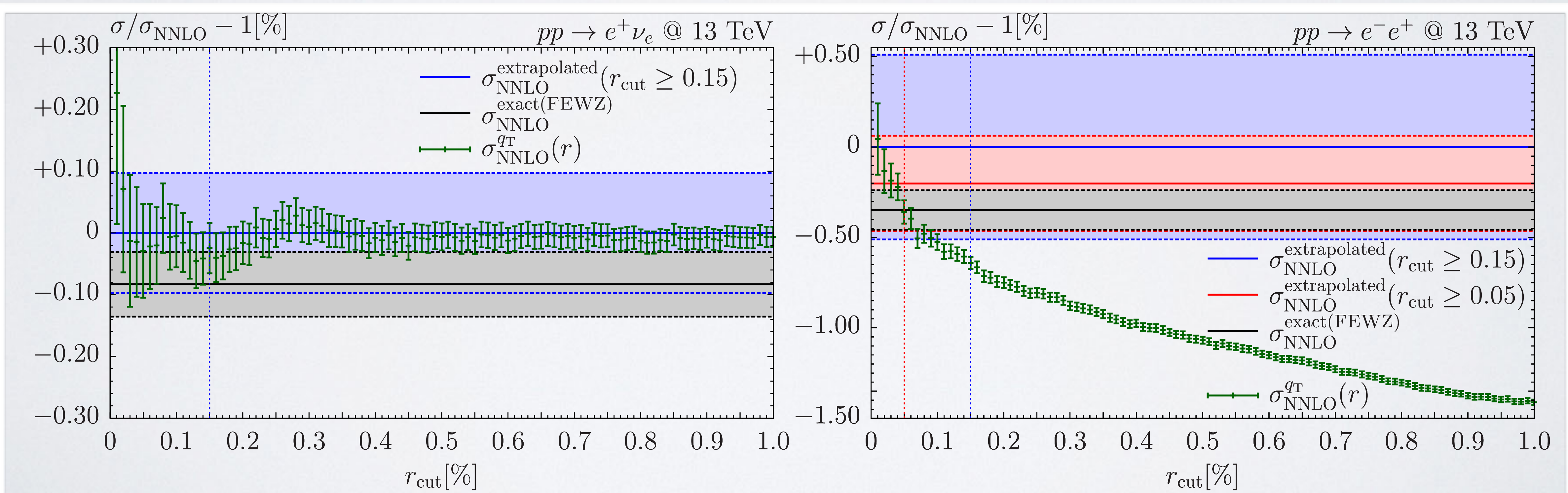
- Local subtractions are independent of any regularising parameter
- "Slicing" methods require the use of a cutoff to separate the different IR regions
- Such separation of the phase space introduces instabilities in the numerical evaluation of cross sections and differential distributions, and some care has to be taken in order to obtain stable and reliable results



M. Grazzini, S. Kallweit and M. Wiesemann (2017)

MOTIVATION





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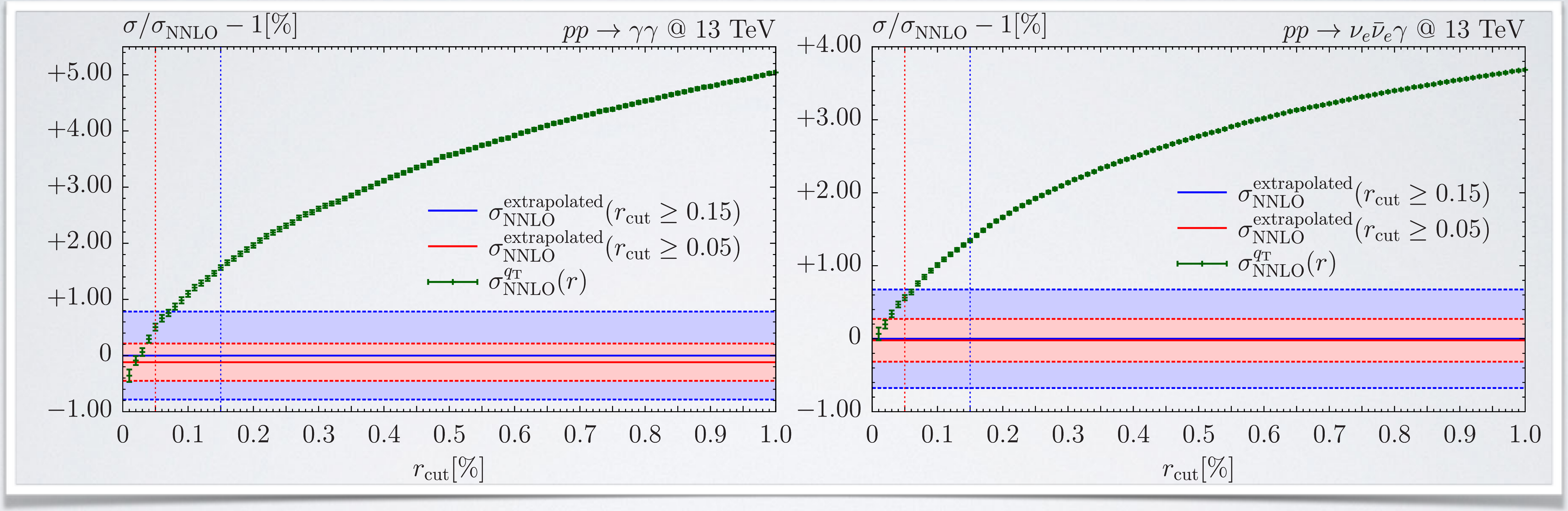

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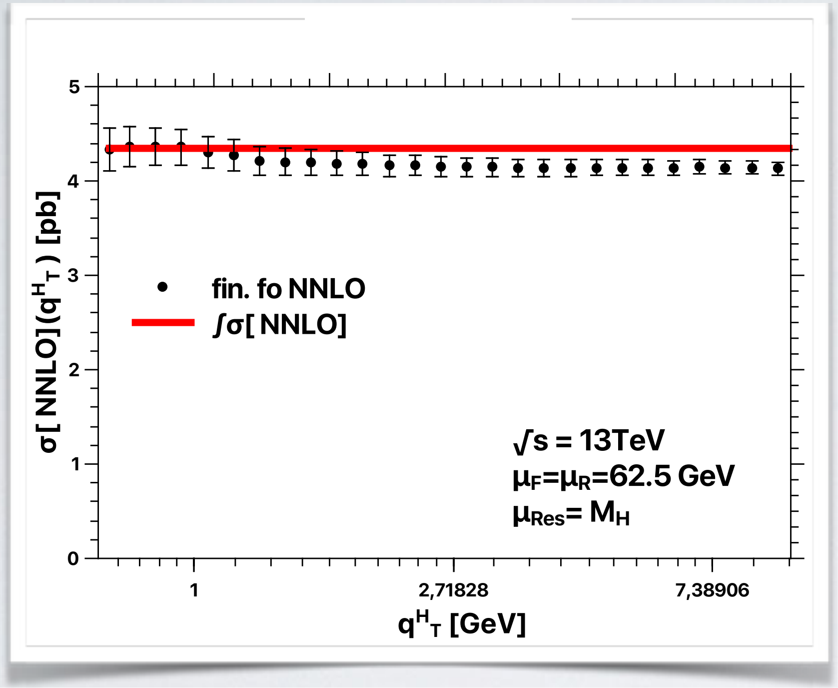
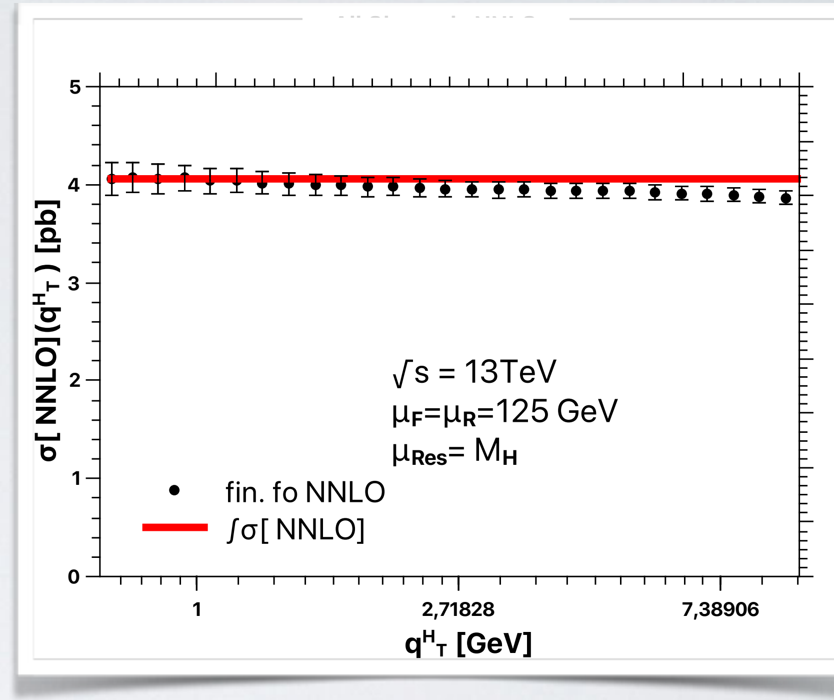
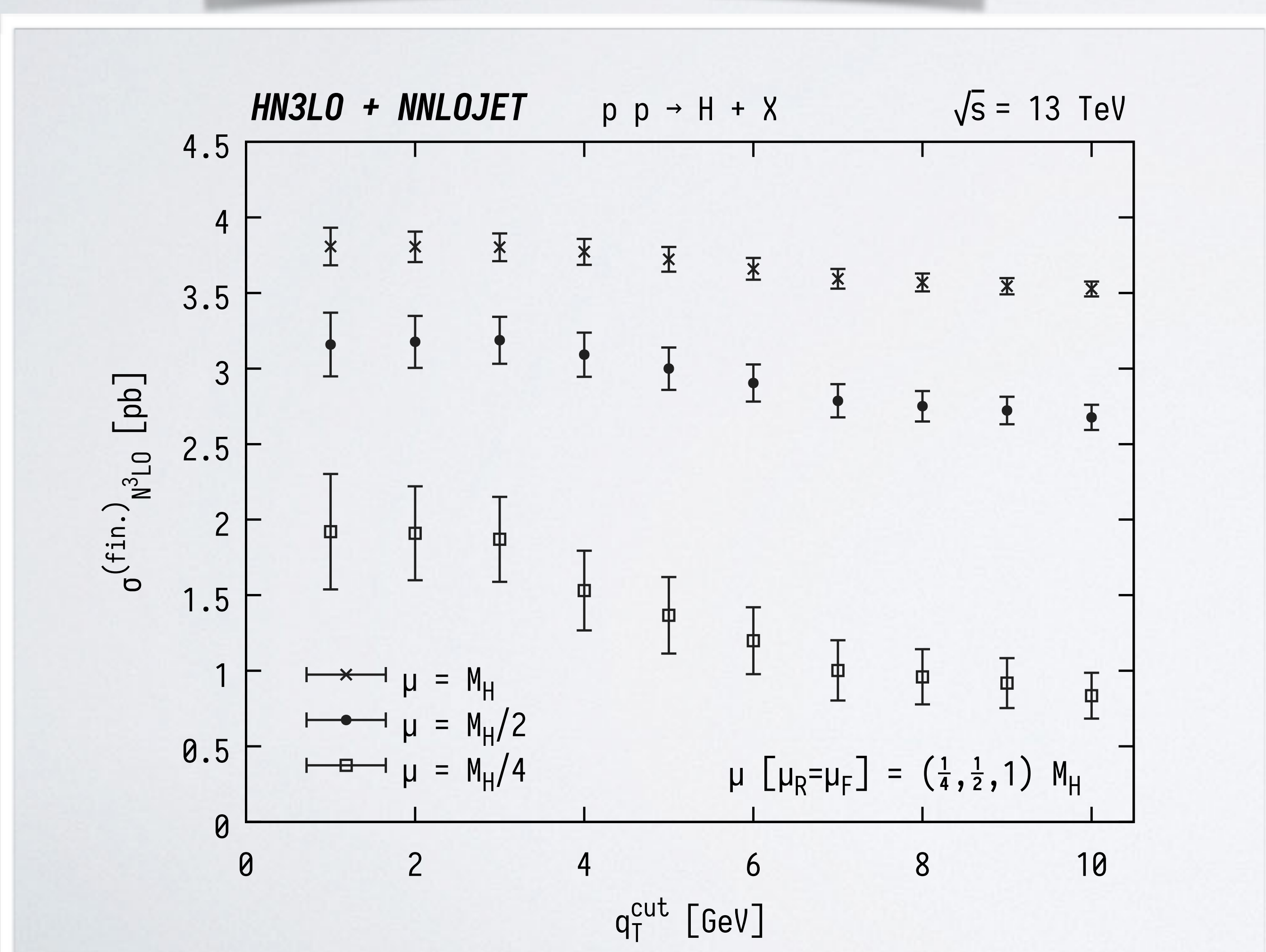
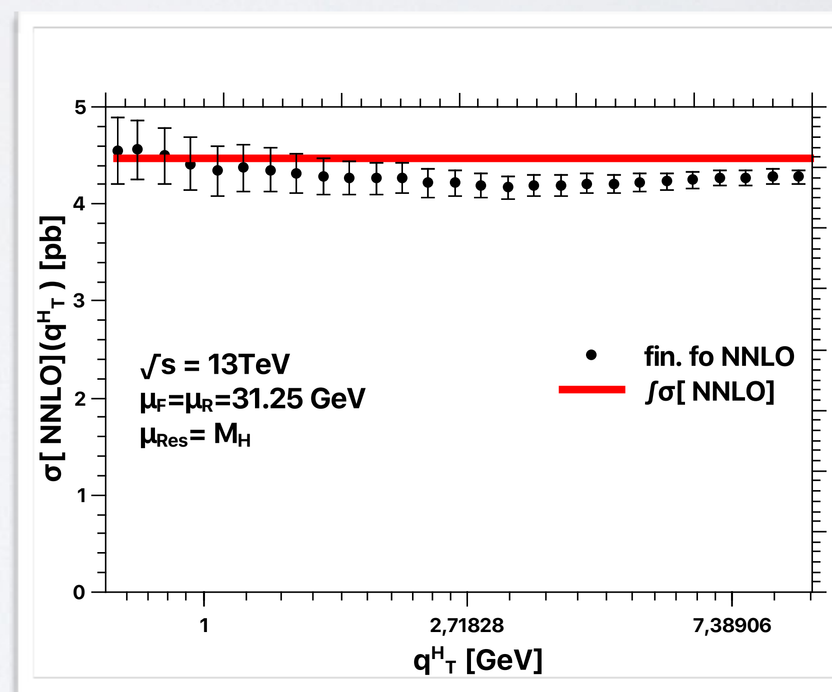








L. C, X. Chen, T. Gehrmann, E. W. N. Glover, and A. Huss (2018)

THE N^{3}LO QT-SUBTRACTION METHOD

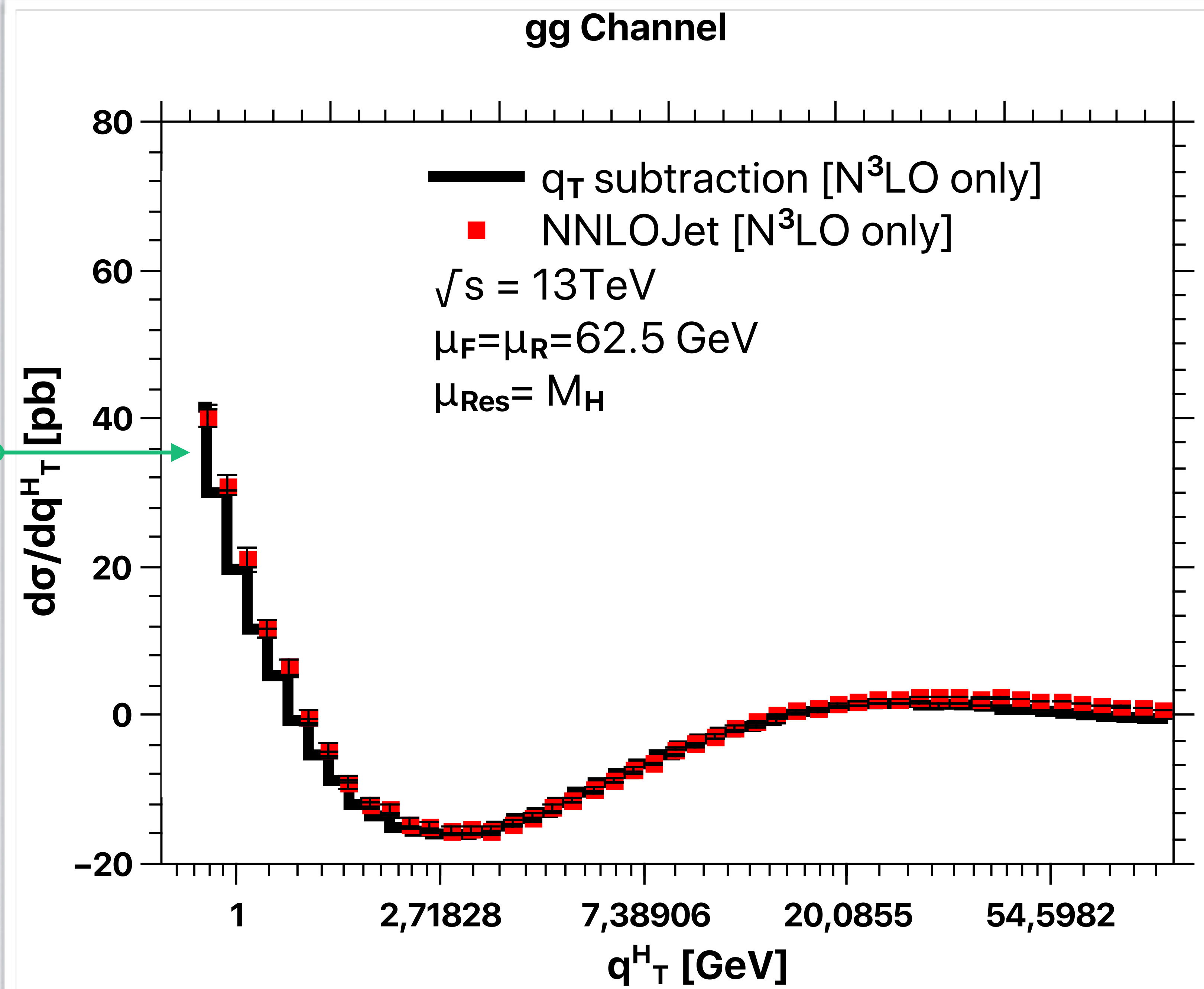
L. C, X. Chen, T. Gehrmann, E. W. N. Glover, and A. Huss (2018)

First results divergent behaviour at the third-order

The presence of large logarithms in the small-qT limit requires qT-resummation for this observable

The sign in the exponent of the Sudakov predicts the sign of the divergent behaviour

NLO > 0
NNLO < 0
N3LO > 0



Higgs boson production in gluon fusion at Sqrt[s] = 13TeV at the LHC, in the large m_{top} limit

The N3LO CT is computed without approximation

The CT is shown here at qT > 0

$$S_c(M,b) = \exp\left\{-\int_{b_0^2/b^2}^{M^2} \frac{dq^2}{q^2}\left[A_c(\alpha_s(q^2))\,\ln\frac{M^2}{q^2} + B_c(\alpha_s(q^2))\right]\right\}$$

$$\Sigma^F(q_T/Q) \xrightarrow[q_T\to 0]{} \sum_{n=1}^{\infty}\left(\frac{\alpha_S}{\pi}\right)^n \sum_{k=1}^{2n} \Sigma^{F(n;k)}\,\frac{Q^2}{q_T^2}\ln^{k-1}\frac{Q^2}{q_T^2}$$

THE N^{3}LO QT-SUBTRACTION METHOD

L. C, X. Chen, T. Gehrmann, E. W. N. Glover, and A. Huss (2018)

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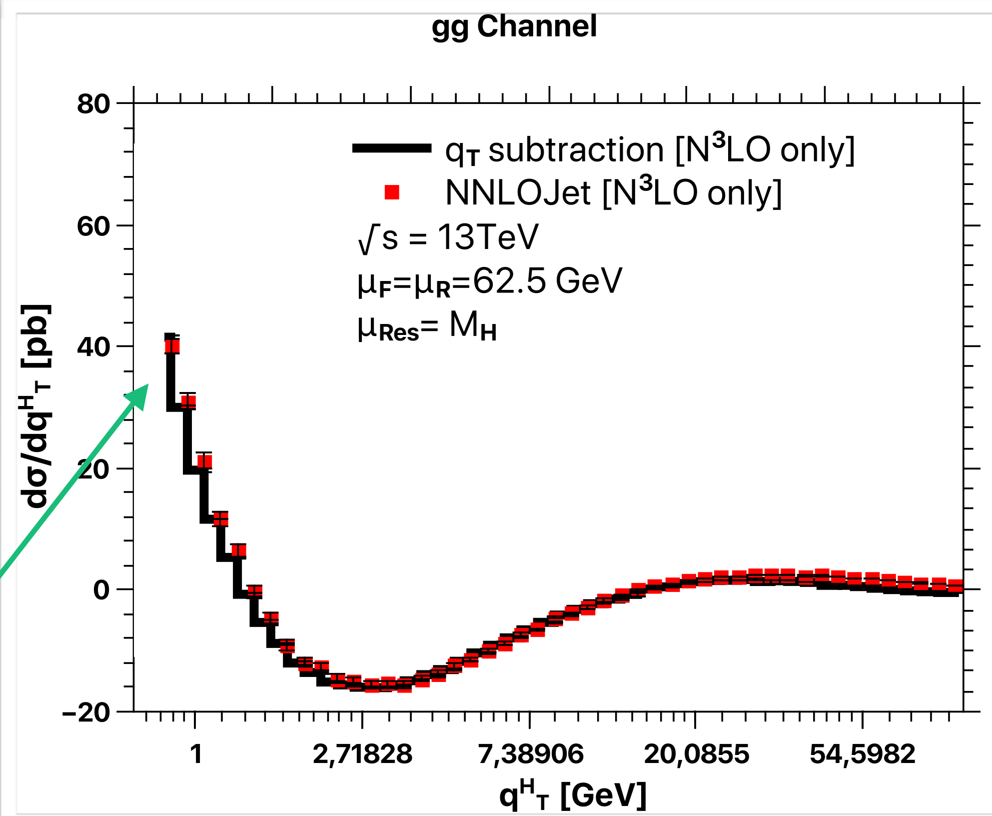

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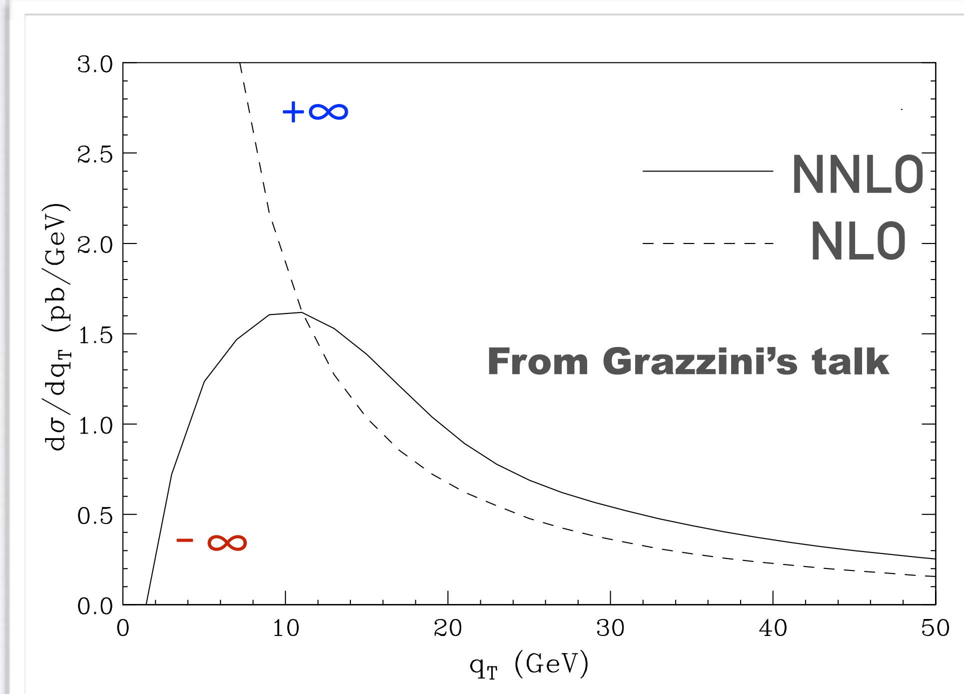


NLO	>	0
NNLO	<	0
N3LO	>	0

$$\text{NLO}: \quad \frac{d\sigma}{dq_T} \to +\infty \quad \text{as} \quad q_T \to 0$$

$$\text{NNLO}: \quad \frac{d\sigma}{dq_T} \to -\infty \quad \text{as} \quad q_T \to 0$$

$$\text{N}^3\text{LO}: \quad \frac{d\sigma}{dq_T} \to +\infty \quad \text{as} \quad q_T \to 0$$

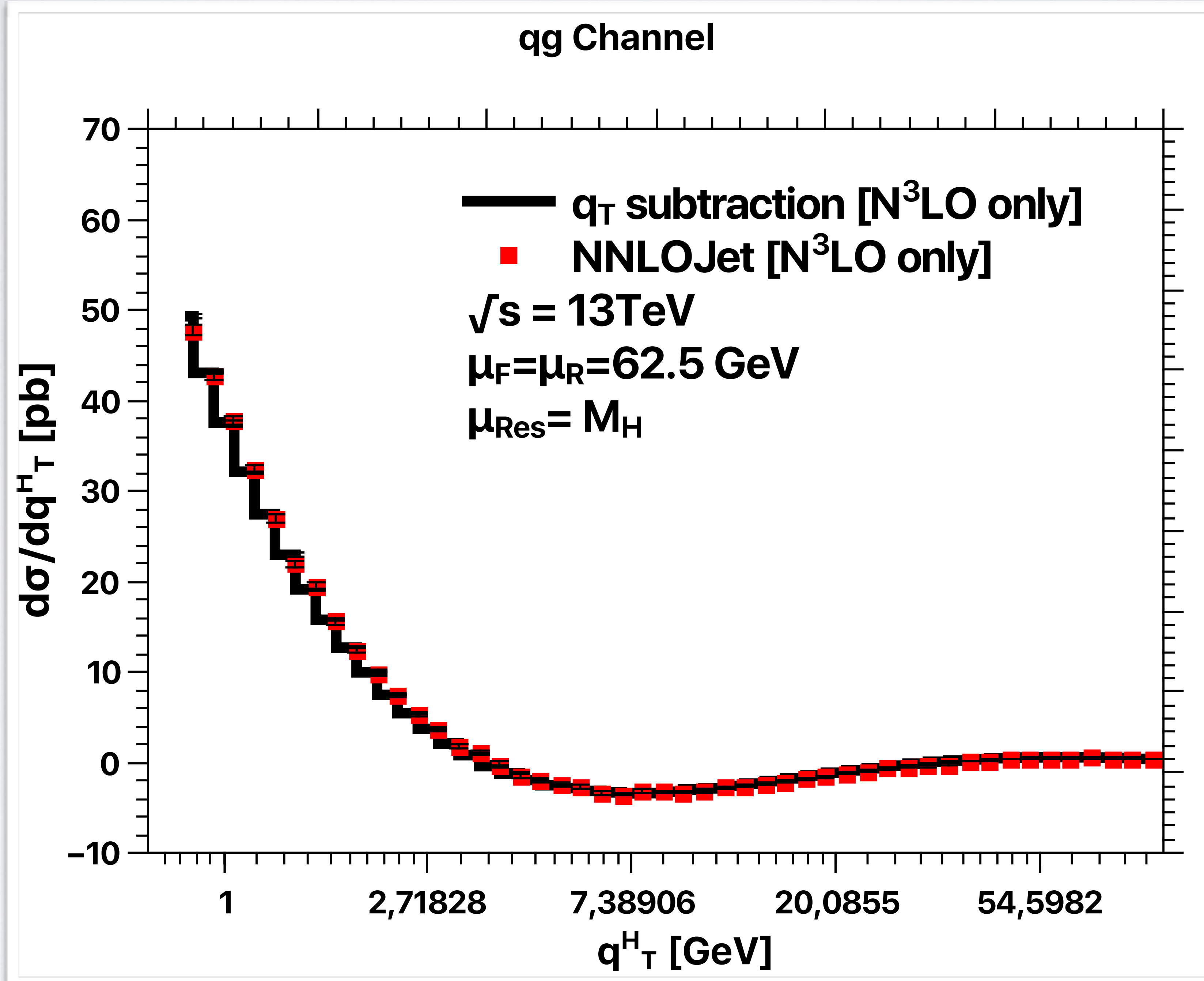
$$S_c(M,b) = \exp\left\{ -\int_{b_0^2/b^2}^{M^2} \frac{dq^2}{q^2} \left[A_c(\alpha_s(q^2)) \, \ln \frac{M^2}{q^2} + B_c(\alpha_s(q^2)) \right] \right\}$$

THE N^{3}LO QT-SUBTRACTION METHOD

L. C, X. Chen, T. Gehrmann, E. W. N. Glover, and A. Huss (2018)

First results divergent behaviour at the third-order

In the off-diagonal channels, the first power (most divergent) in the logarithmic expansion is not present.



Higgs boson production in gluon fusion at Sqrt[s] = 13TeV at the LHC, in the large m_{top} limit

The N3LO CT is computed without approximation

The CT is shown here at qT > 0 !

$$\Sigma^F(q_T/Q) \xrightarrow[q_T\to 0]{} \sum_{n=1}^{\infty}\left(\frac{\alpha_S}{\pi}\right)^n \sum_{k=1}^{2n} \Sigma^{F(n;k)} \frac{Q^2}{q_T^2} \ln^{k-1}\frac{Q^2}{q_T^2}$$

THE N^{3}LO QT-SUBTRACTION METHOD

L. C, X. Chen, T. Gehrmann, E. W. N. Glover, and A. Huss (2018)

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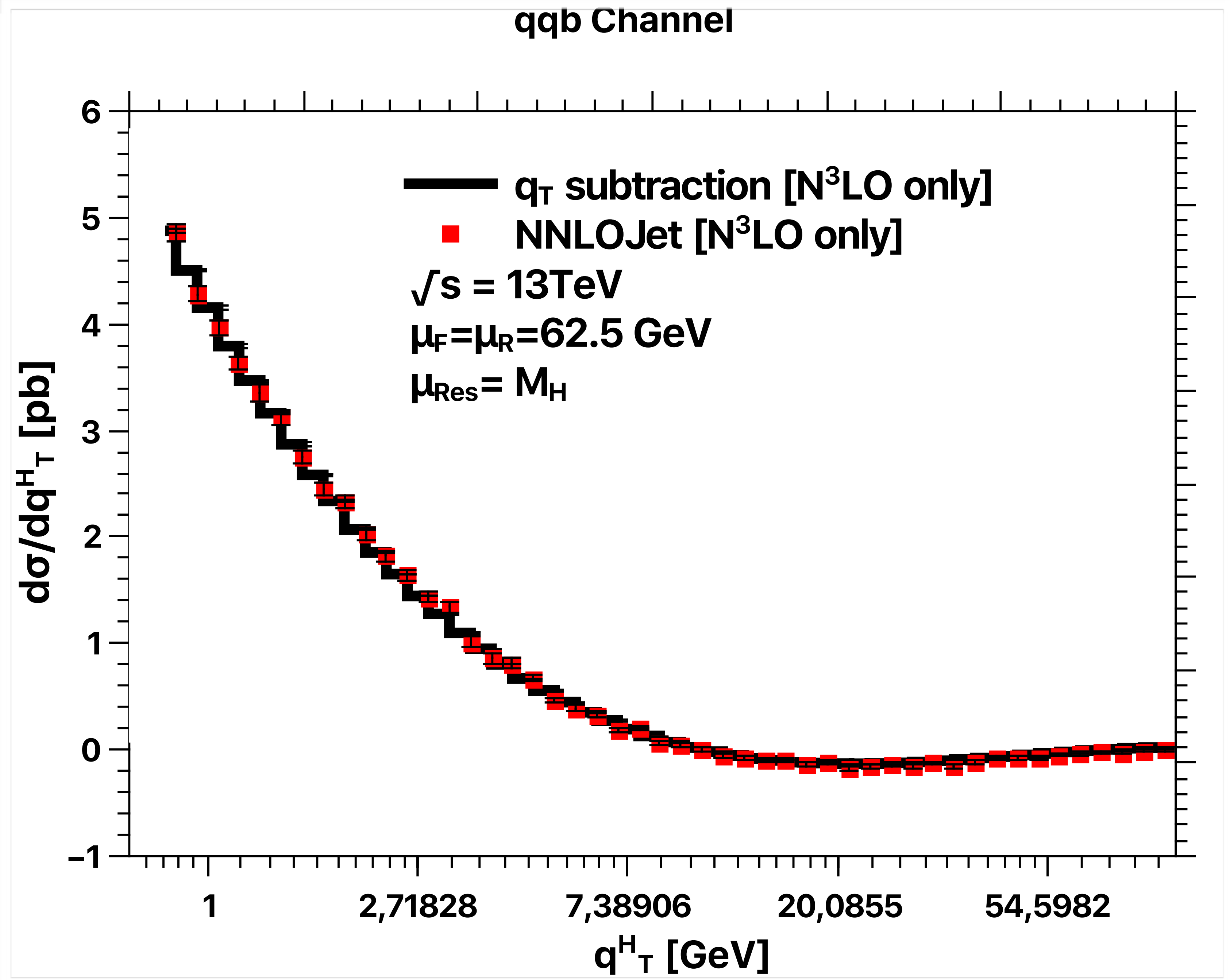

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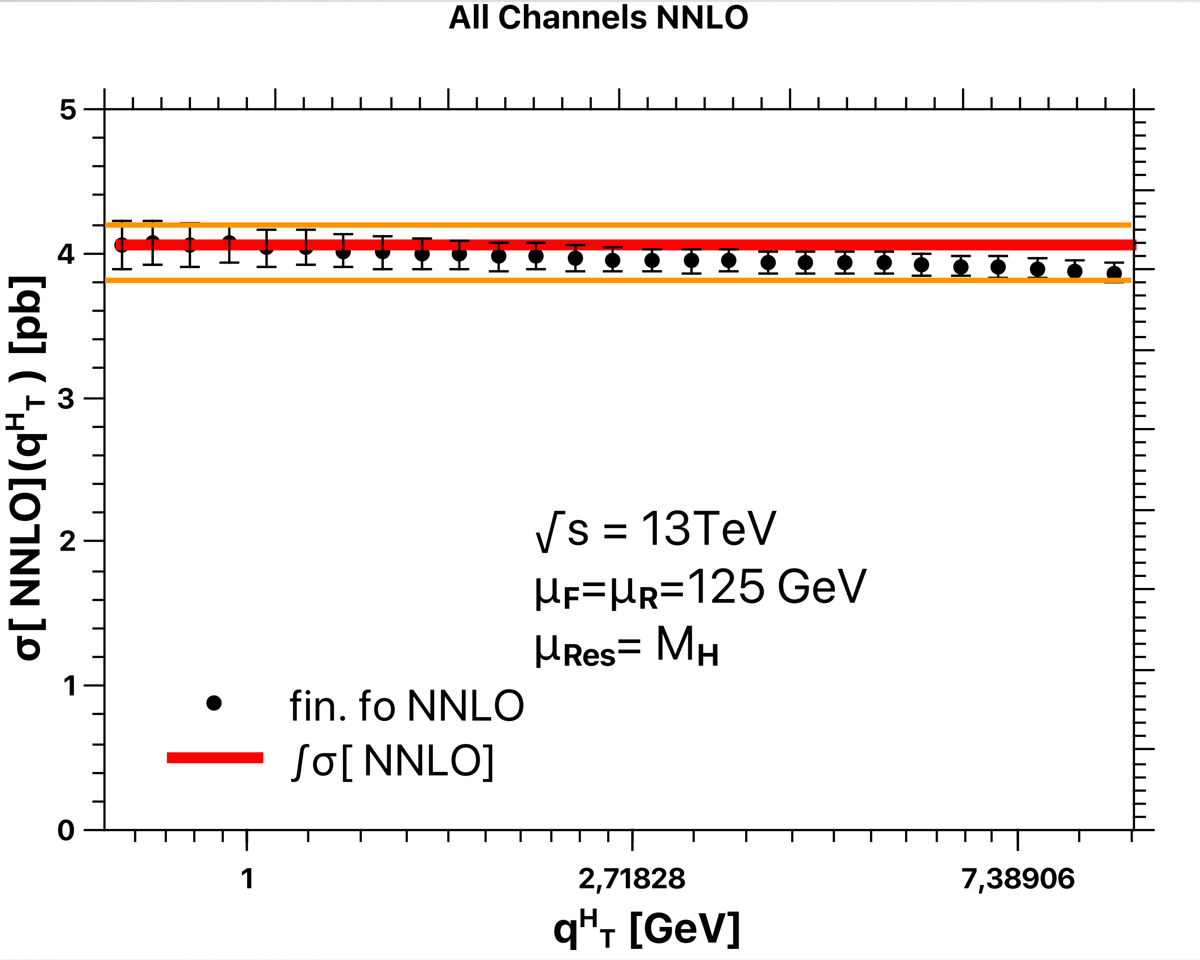
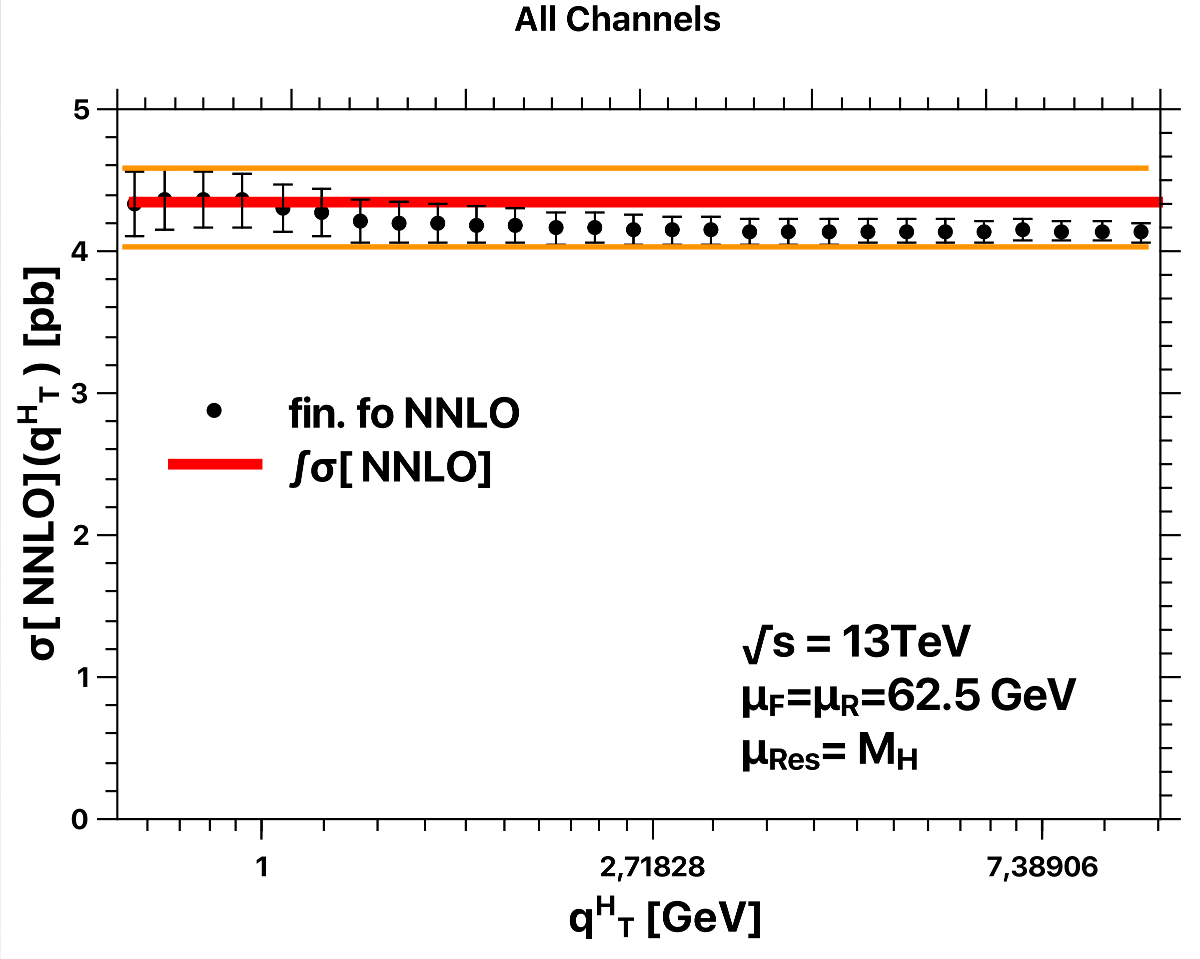
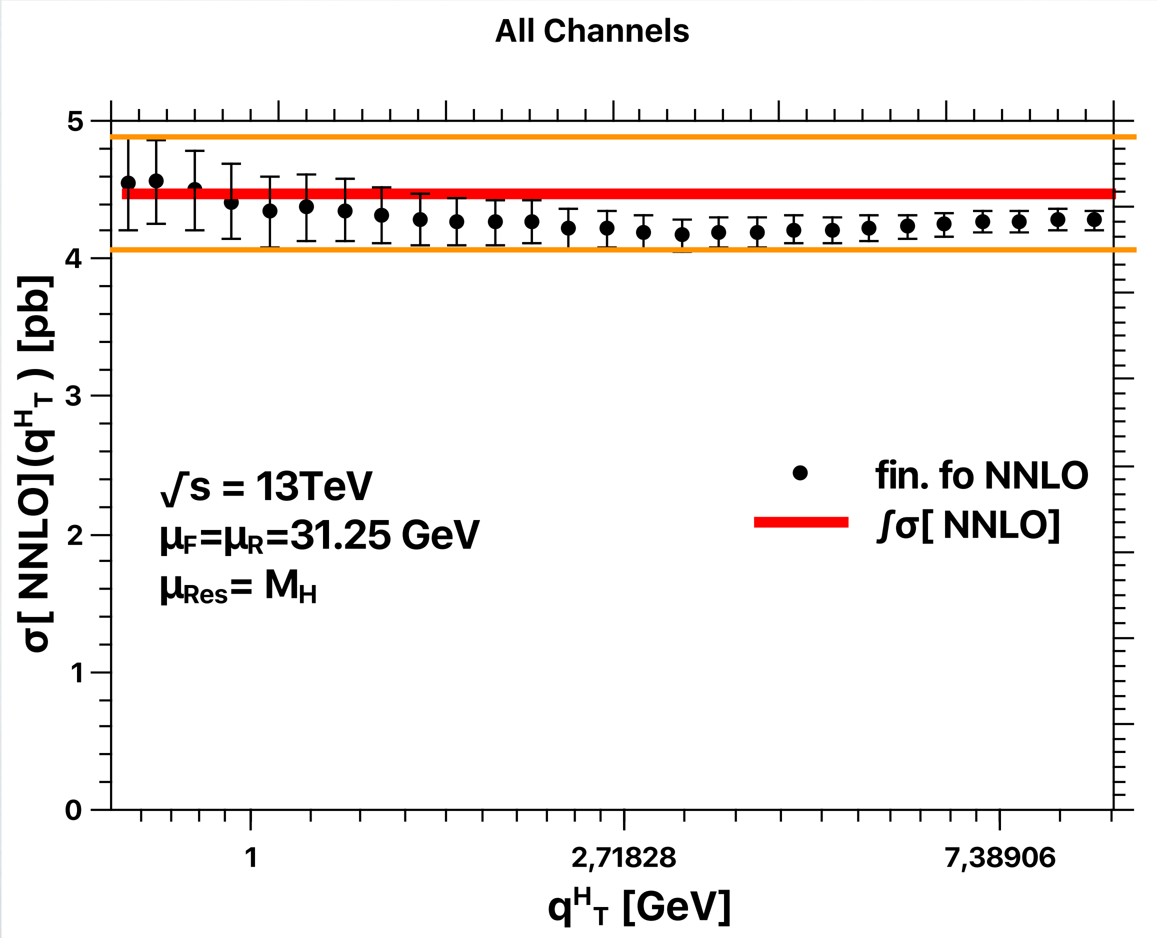






	σ_{NNLO} [pb] Best	σ_{NNLO} [pb] Worst
μ=MH/2	43.47(± 0.3%)	43.47(± 0.7%)
μ=MH	39.64(± 0.2%)	39.64(± 0.5%)
μ=MH/4	47.33(± 0.4%)	39.64(± 0.84%)

The variation is equivalent to rcut = (0.4 ; 8)%

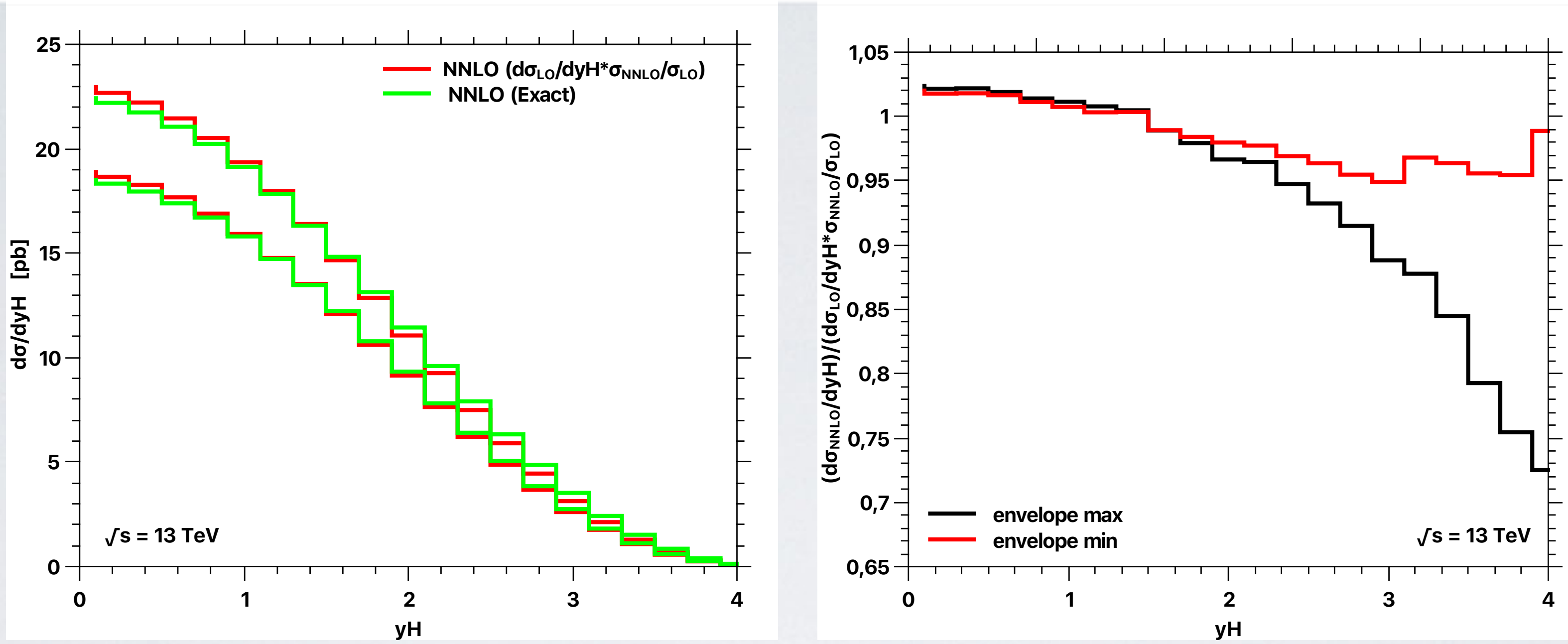


Figure A: The rapidity distribution of the Higgs boson at NNLO. We compare the exact result with the proposed approximation in the referee report detailed in Eq. (3). We use the 7-point scale variation as explained in the paper.

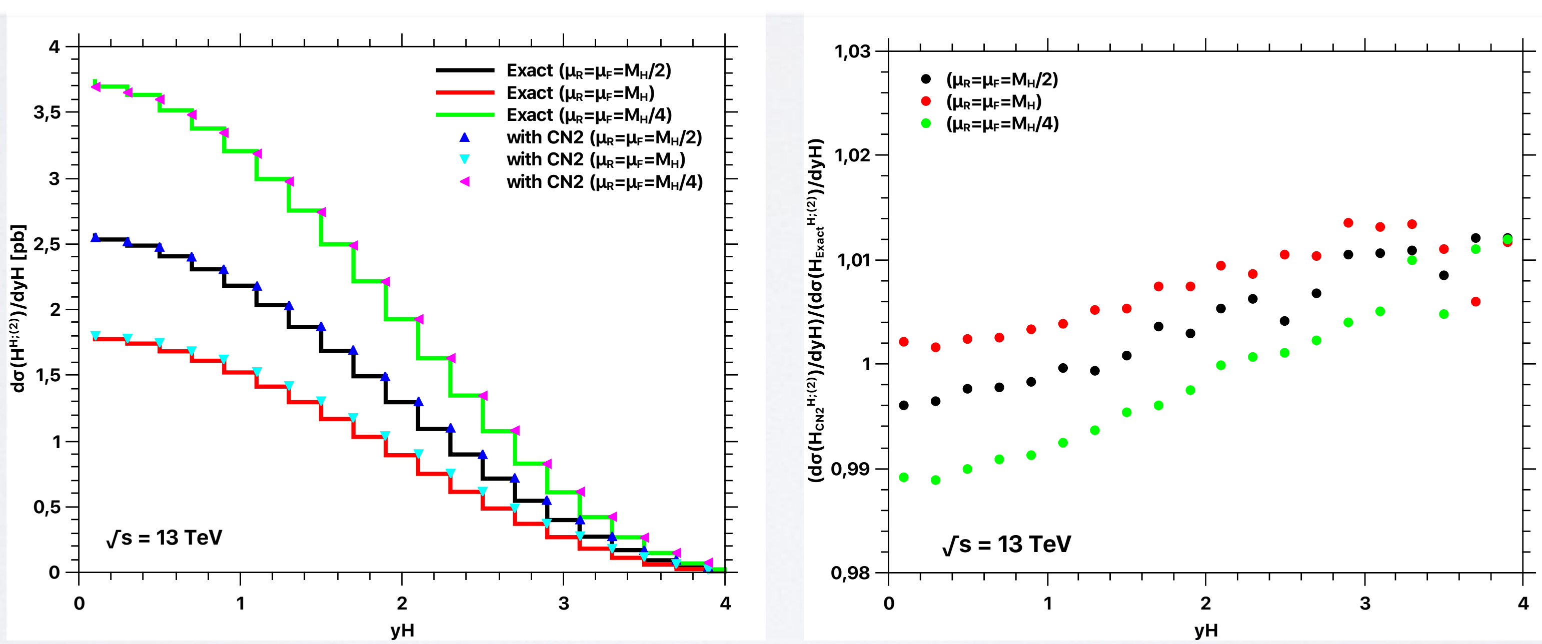
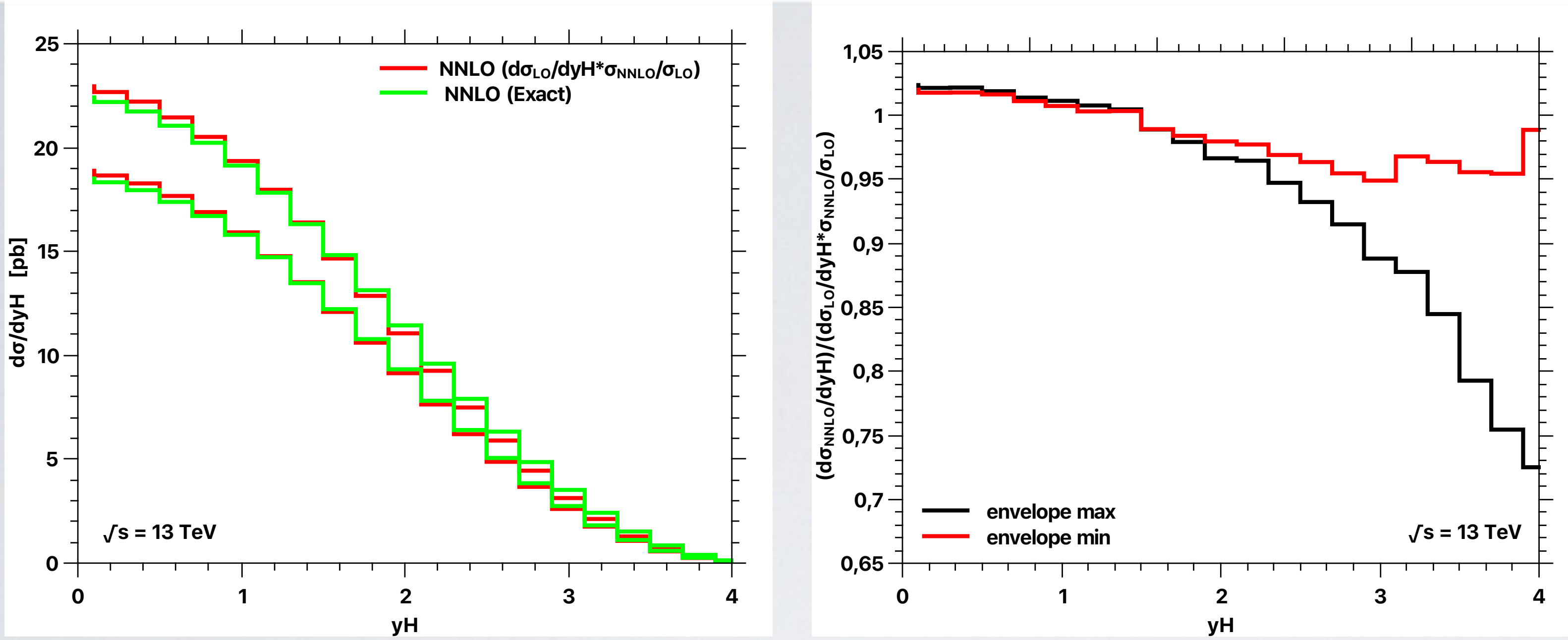


Figure D: The rapidity distribution of the coefficient functions $\mathcal{H}^{H;(2)}_{\mathrm{CN2}}$ and $\mathcal{H}^{H;(2)}_{\mathrm{exact}}$ and the corresponding ratio plot. For this particular example at NNLO, we employ the three-point scale variation: $\mu = \mu_{\mathrm{R}} = \mu_{\mathrm{F}} = \{M_H/4, M_H/2, M_H\}$.



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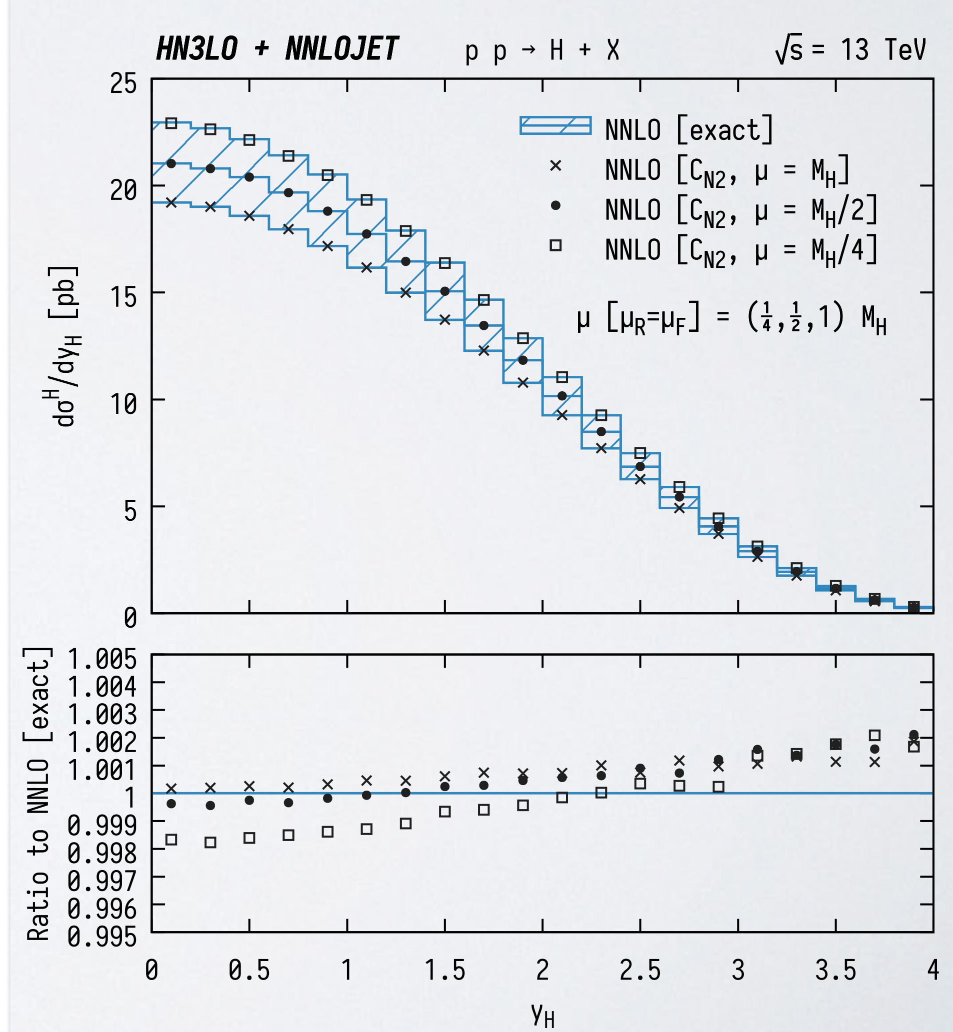
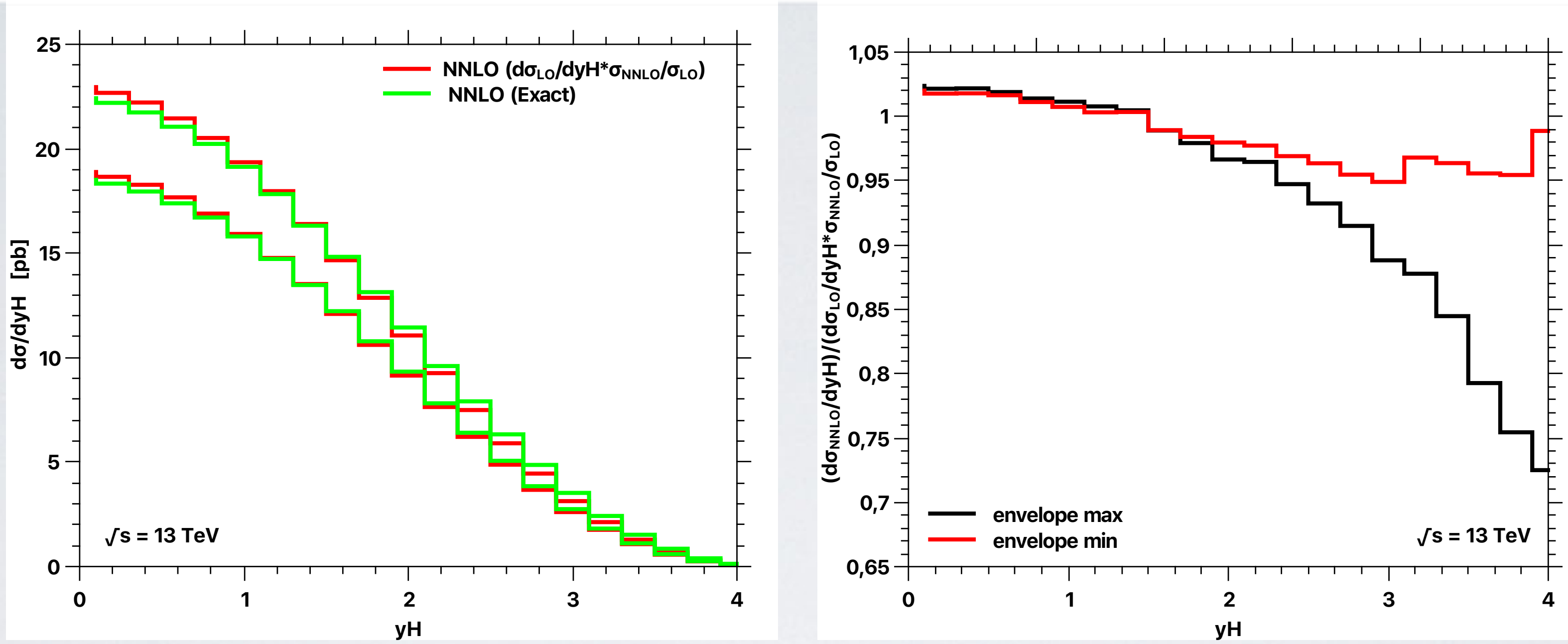
The uncertainties at the differential distributions are at the 0.2% level! Therefore concerning a global rescaling, we are comparing a 0.2% level of precision vs. a 30% of deviation from the exact result





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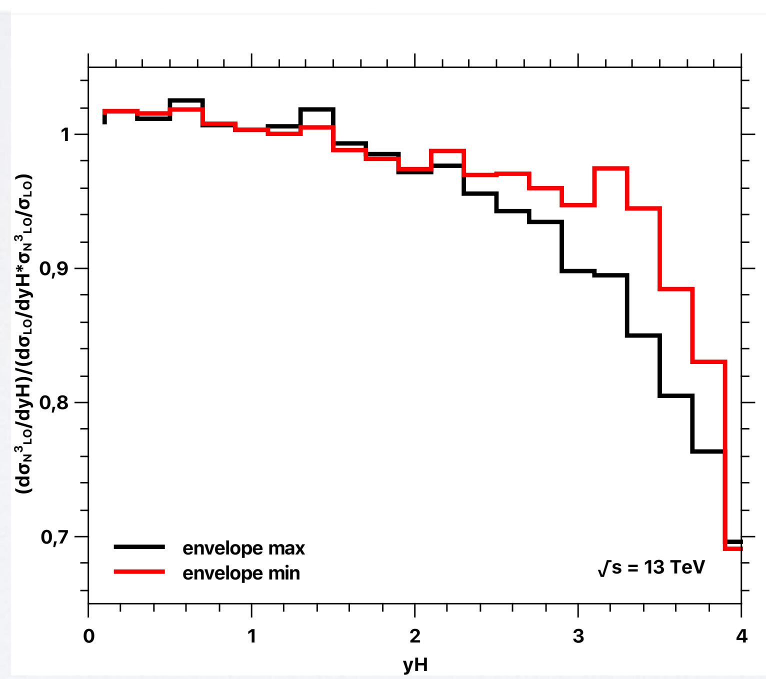

Figure B: Ratio between the N^{3}LO rapidity distribution as calculated in the paper (red band of Fig. 5 in the paper) and the suggested approximation in the referee report detailed in Eq. (3). We use the 7-point scale variation as described in the paper.