Swiss National Science Foundation

Universität Zürich[UZH]

Precise predictions for $t\bar{t}H$ production at the LHC

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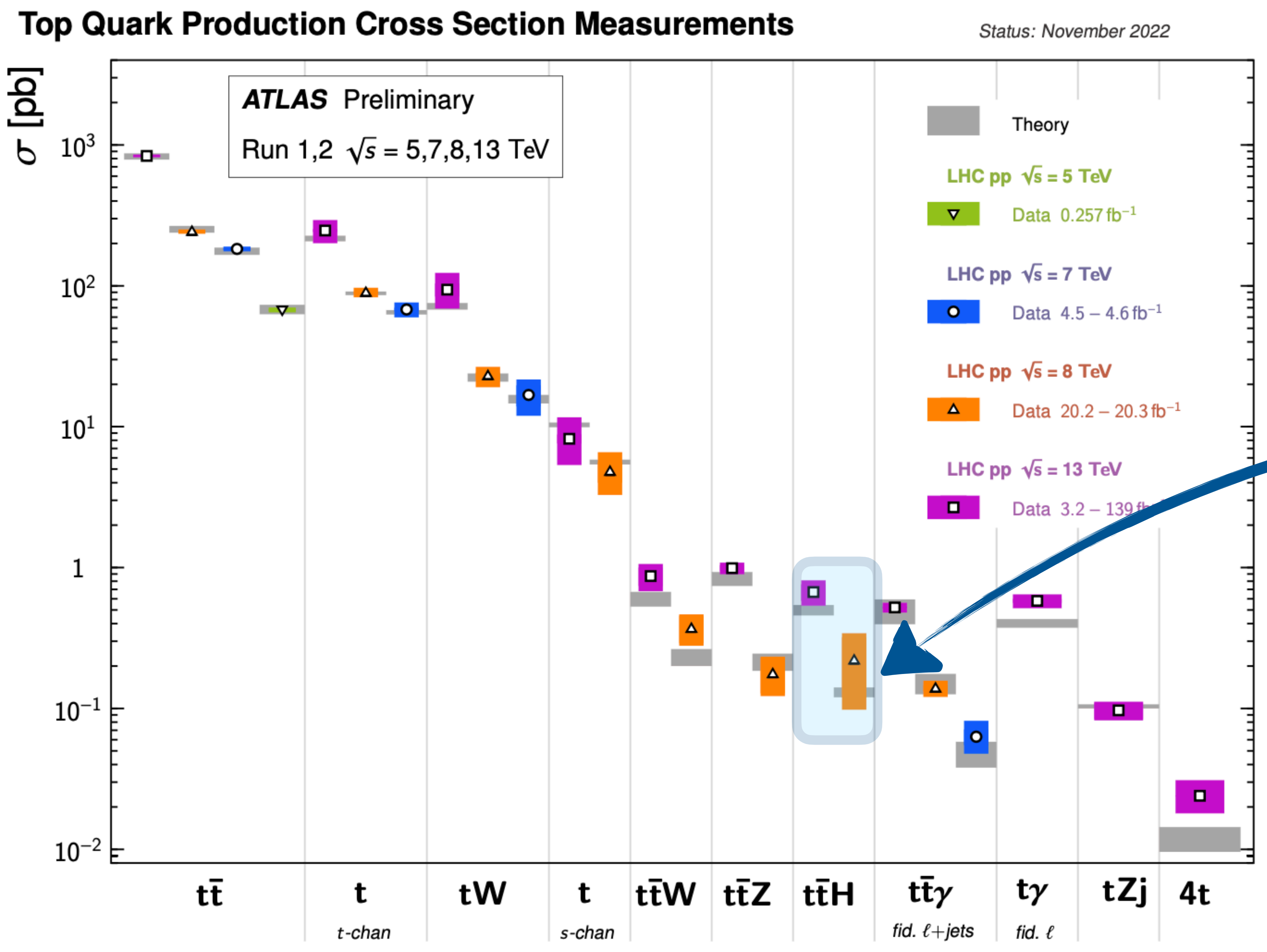
based on **Phys.Rev.Lett. 130** (2023) in collaboration with
S.Catani, S.Devoto, M.Grazzini, S.Kallweit and J.Mazzitelli
+ **work in progress**

Why is $t\bar{t}H$ production interesting ?

motivations:

- the study of the Higgs boson is **one of the priorities** in the LHC experimental program, after its discovery in 2012
- the Higgs boson couplings to SM particles are proportional to their masses: **special role played by the top quark**!
- only about 1 % of the Higgs bosons are produced in association with a top-quark pair (first observation in 2018) but…
- the production mode $pp \to t\bar{t}H$ allows for a direct measurement of the **top-quark Yukawa coupling**



the cross section is at least two orders of magnitude smaller than in the case of $t\bar{t}$ production but …
the process is crucial for characterising the interaction of top quarks with the Higgs sector

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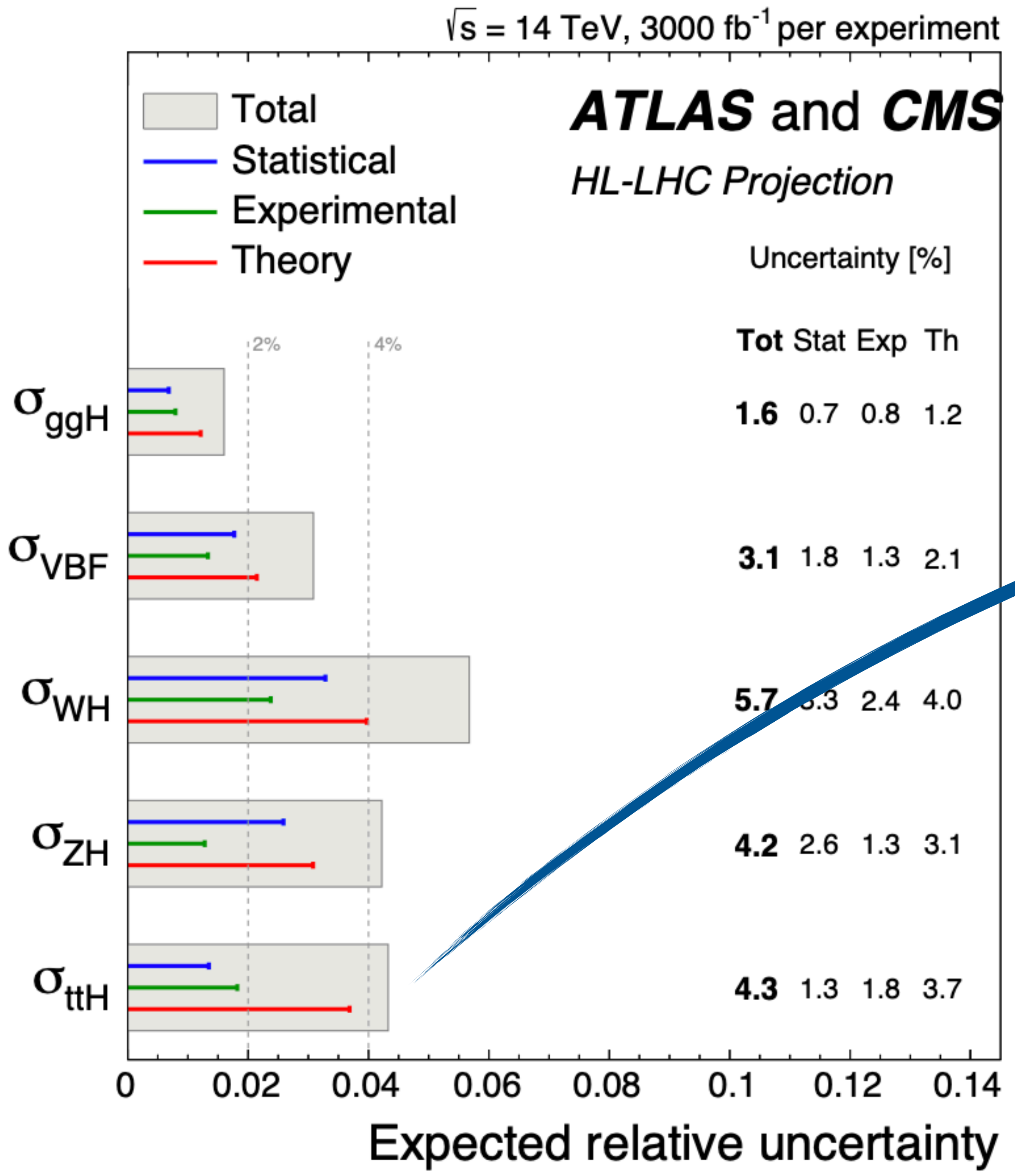

[Report from WG2 (2019)]

the current experimental accuracy is $\mathcal{O}(20\%)$ but, according to the HL-LHC projections, it is expected to go down to $\mathcal{O}(2\%)$

the extraction of the $t\bar{t}H(H \to b\bar{b})$ signal is limited by the theoretical uncertainties in the modelling of the backgrounds, mainly $t\bar{t}b\bar{b}$ and $t\bar{t}$ + light-flavour jets

moreover, NLO QCD + EW theory predictions equipped with NNLL soft-gluon resummation are affected by $\mathcal{O}(10\%)$ uncertainty

Theoretical predictions for $t\bar{t}H$

state of the art:

- ☑ **NLO QCD** corrections (*on-shell top quarks*) [Beenakker, Dittmaier, Krämer, Plumper, Spira, Zerwas (2001,2003) [Reina, Dawson, Wackeroth, Jackson, Orr (2001,2003)]
- ☑ **NLO EW** corrections (*on-shell top quarks*) [Frixione, Hirschi, Pagani, Shao, Zaro (2015)]
- ☑ **NLO QCD** corrections (*leptonically decaying top quarks*) [Denner, Feger (2015)] [Stremmer, Malgorzata (2022)]
- ☑ **NLO QCD + EW** corrections (*off-shell top quarks*) [Denner, Lang, Pellen, Uccirati (2017)]
- ☑ **NLO QCD + EW** corrections (*on-shell top quarks*), including **NNLL** soft-gluon resummation [Broggio et al.] [Kulesza et al.]
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- ☑ **complete NNLO QCD** predictions with approximated two-loop amplitudes [Catani, Devoto, Grazzini, Kallweit, Mazzitelli, **CS** (2022)]

  first NNLO calculation!

FOCUS OF THIS TALK!

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main bottleneck

see Anton's talk

Two-loop amplitudes for ttH production: the quark-initiated Nf-part
Bakul Agarwal, Gudrun Heinrich, Stephen P. Jones, Matthias Kerner, Sven Yannick Klein, Jannis Lang, Vitaly Magerya, Anton Olsson

One loop QCD corrections to $gg \to t\bar{t}H$ at $\mathcal{O}(\epsilon^2)$
Federico Buccioni, Philipp Alexander Kreer, Xiao Liu, Lorenzo Tancredi

Two-loop QCD amplitudes for $t\bar{t}H$ production from boosted limit
Guoxing Wang, Tianya Xia, Li Lin Yang, Xiaoping Ye

see Guoxing's talk

HOT TOPIC !!

Two-Loop Master Integrals for Leading-Color $pp \to t\bar{t}H$ Amplitudes with a Light-Quark Loop
F. Febres Cordero, G. Figueiredo, M. Kraus, B. Page, L. Reina

Theoretical predictions for $t\bar{t}H$

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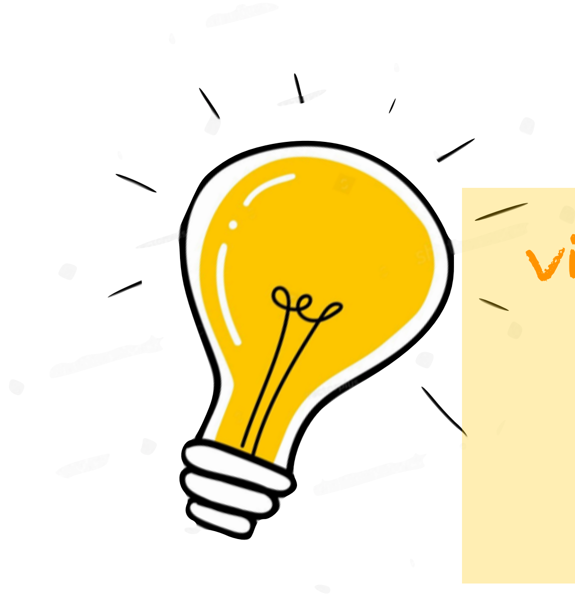


viable strategy: development of physically motivated, reasonable and reliable approximations of the double-virtual contribution

see also Vasily's talk ($Zb\bar{b}$) and Paolo's talk ($WW\gamma$)

Our subtraction framework: q_T-slicing

[Catani, Grazzini (2007)]

- cross section for the production of a triggered $Q\bar{Q}F$ final state at N^{k}LO

crucial to keep the mass of the heavy quark m_Q

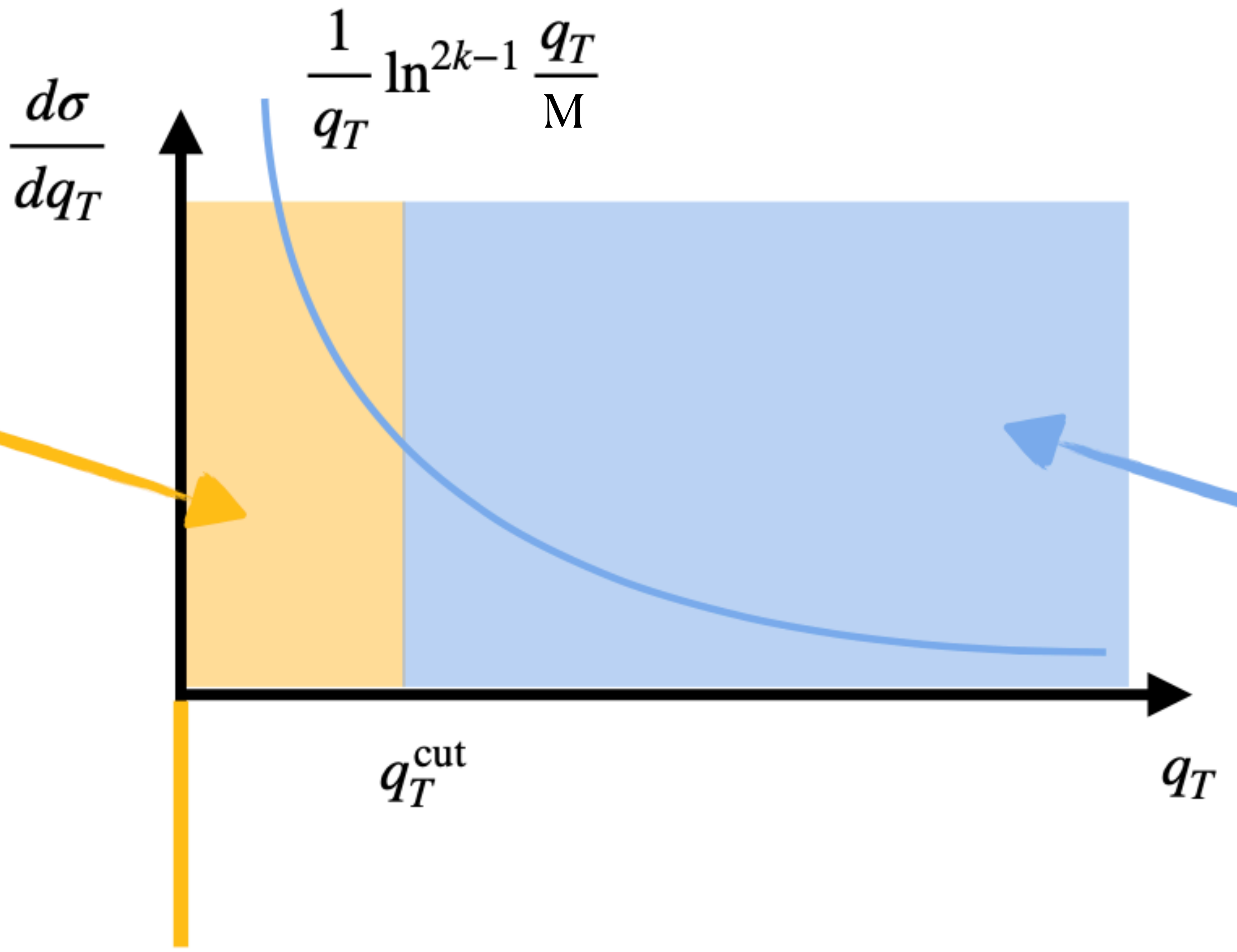
to complete an NNLO computation: crucial to construct an NNLO subtraction/slicing scheme and have all scattering amplitudes available

$$\sigma = \int_{<q_T^{\rm cut}} dq_T \frac{d\sigma}{dq_T} + \int_{>q_T^{\rm cut}} dq_T \frac{d\sigma}{dq_T}$$

all emissions are unresolved

we can exploit the QCD factorisation of the matrix elements in the singular soft and/or collinear limits

ingredients from q_T - resummation



1 emission is always resolved

the complexity of the calculation is reduced by 1 order

logarithmic IR sensitivity to the cut

q_T is the transverse momentum of the $Q\bar{Q}F$ system

$$d\sigma_{N^kLO} = \mathscr{H}_{N^kLO} \otimes d\sigma_{LO} + [d\sigma^R_{N^{k-1}LO} - d\sigma^{CT}_{N^kLO}]_{q_T > q_T^{\rm cut}} + \mathcal{O}((q_T^{\rm cut})^p)$$

Our subtraction framework: q_T-slicing [Catani, Grazzini (2007)]

- <u>master formula</u> at NNLO

$$d\sigma_{NNLO} = \mathcal{H}_{NNLO} \otimes d\sigma_{LO} + [d\sigma^{R}_{NLO} - d\sigma^{CT}_{NNLO}]_{q_T > q_T^{\text{cut}}} + \mathcal{O}((q_T^{\text{cut}})^p)$$

- ☑ all required **tree-level** and **one-loop** matrix elements are known and can be evaluated with **automated tools** like OpenLoops2 [Buccioni, Lang, Lindert, Maierhöfer, Pozzorini, Zhang, Zoller (2019)]

- ☑ the remaining NLO-type singularities can be removed by applying a **local subtraction** method [Catani, Seymour (1998)] [Catani, Dittmaier, Seymour, Trocsanyi (2002)]

- ☑ **automatised numerical implementation** in the MATRIX framework, which relies on the efficient multi-channel Monte Carlo integrator MUNICH [Grazzini, Kallweit, Wiesemann (2017)]

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$$d\sigma_{NNLO} = \mathcal{H}_{NNLO} \otimes d\sigma_{LO} + [d\sigma^{R}_{NLO} - d\sigma^{CT}_{NNLO}]_{q_T > q_T^{\rm cut}} + \mathcal{O}((q_T^{\rm cut})^p)$$

☑ the hard-collinear coefficient receives contributions also from the **two-loop virtual amplitudes**

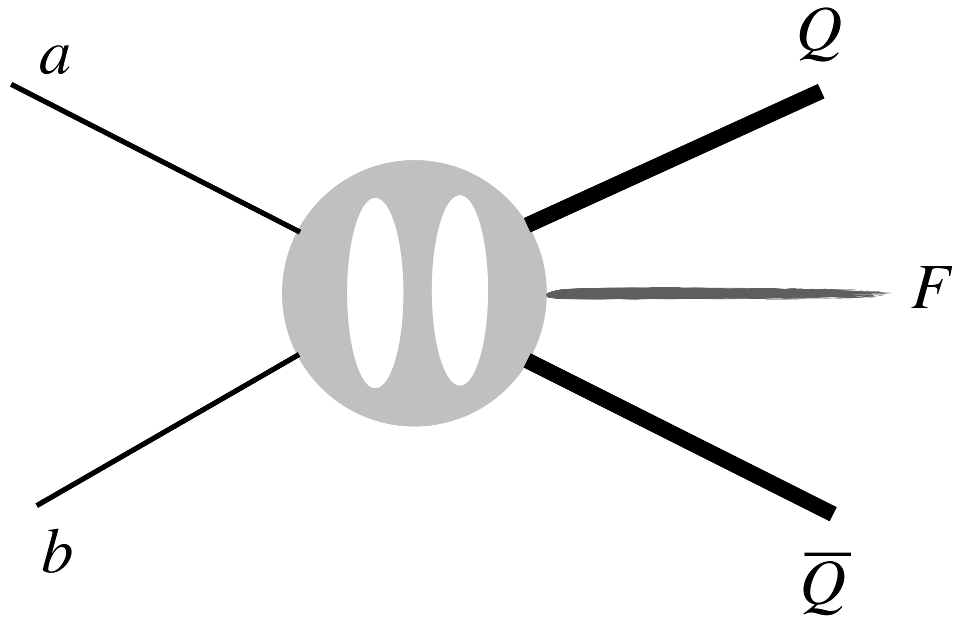
$$\mathcal{H}_{NNLO} = H^{(2)}\delta(1-z_1)\delta(1-z_2) + \delta\mathcal{H}^{(2)}(z_1, z_2)$$

where $$H^{(2)} = \left.\frac{2\Re(\mathcal{M}^{(2)}_{fin}(\mu_{IR},\mu_R)\mathcal{M}^{(0)*})}{|\mathcal{M}^{(0)}|^2}\right|_{\mu_R=\mu_{IR}=Q}$$

UV renormalised and IR subtracted amplitude at scale μ_{IR}

[Ferroglia, Neubert, Pecjac, Yang (2009)]

Q is the invariant mass of the $Q\bar{Q}F$ system



conceptual and technical challenges:

1. appearance of new mathematical functions
2. current analytic and numerical methods may not be enough
3. possible to find an amplitude representation that allows us for a numerically stable evaluation?

main bottleneck: $2 \to 3$ and higher multiplicity two-loop amplitudes involving heavy loops and (many) external massive legs are currently out of reach. They require major breakthroughs

Our subtraction framework: q_T-slicing

[Catani, Grazzini (2007)]

- master formula at NNLO

$$d\sigma_{NNLO} = \mathcal{H}_{NNLO} \otimes d\sigma_{LO} + [d\sigma^{R}_{NLO} - d\sigma^{CT}_{NNLO}]_{q_T > q_T^{\rm cut}} + \mathcal{O}((q_T^{\rm cut})^p)$$

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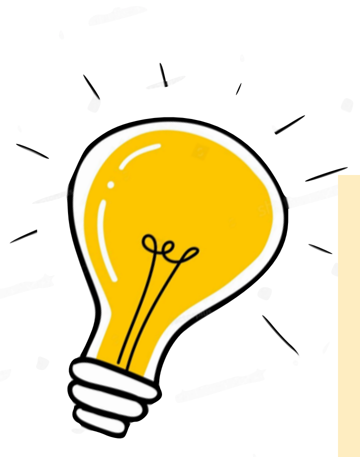
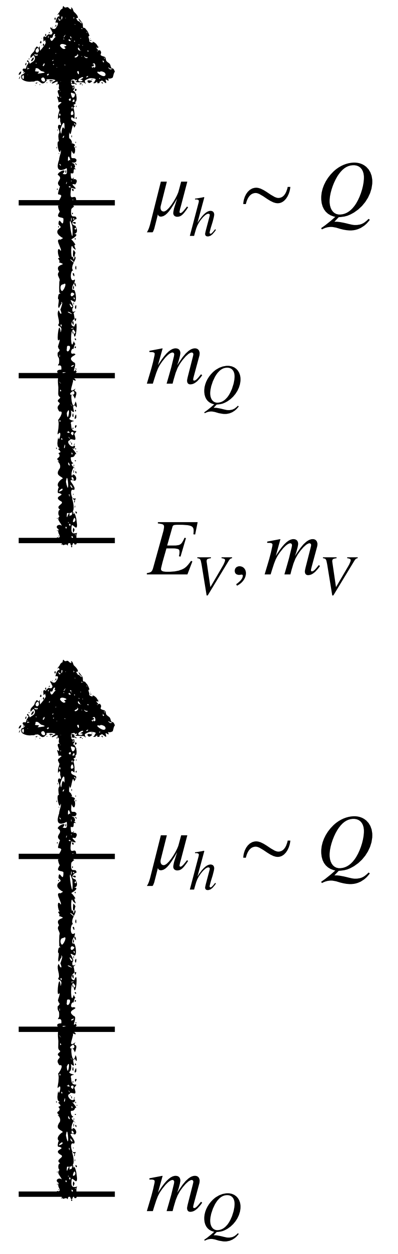


strategy: exploit the factorisation properties of QCD matrix elements in two different and rather complementary kinematic regimes

1. soft limit for the external boson V ($E_V \to 0, m_V \to 0$)

2. high-energy limit (ultra-relativistic quarks) ($m_Q \ll \mu_h$)



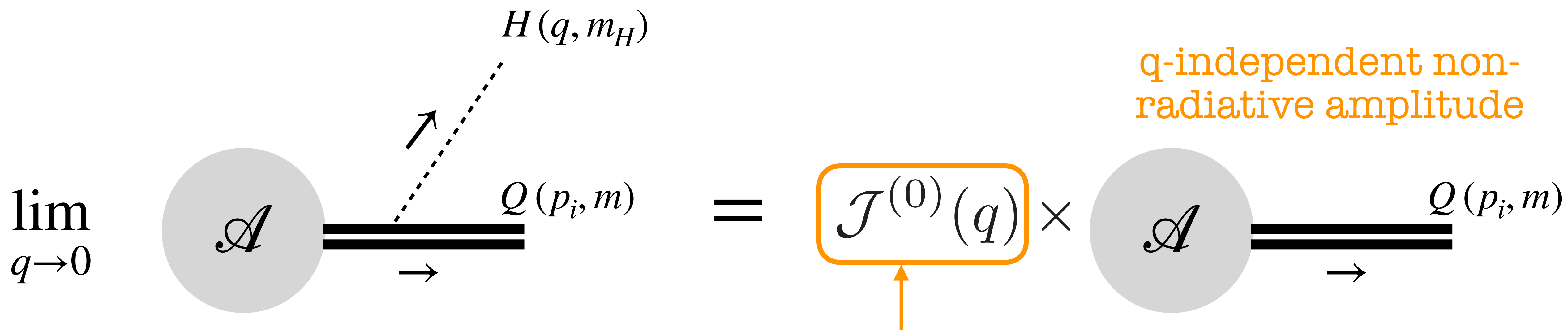
Soft Higgs-boson approximation

- We want to study the soft Higgs-boson limit for the amplitude associated with

$$a(k_1) + b(k_2) \to Q(p_1, m)\overline{Q}(p_2, m)....Q(p_{N-1}, m)\overline{Q}(p_N, m) + H(q, m_H)$$

one or more heavy-quark pairs with the same mass

- at tree-level, it is straightforward to show that the **LP factorisation** reads



$$\mathcal{J}^{(0)}(q) = \frac{m}{v}\sum_i \frac{m}{p_i \cdot q}$$

scalar eikonal current

- at bare level, the naïve factorisation formula holds true at all orders in α_s, due to the **abelian nature** of the Higgs boson

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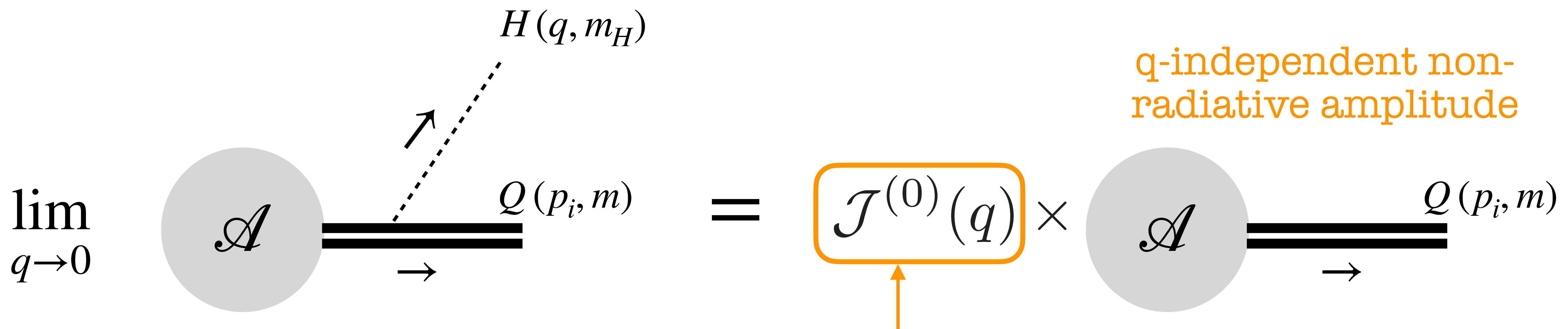

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scalar eikonal current

- at bare level, the naïve factorisation formula holds true at all orders in α_s, due to the **abelian nature** of the Higgs boson
- … but the renormalisation of the heavy-quark mass and wave function changes the **overall normalisation** by

up to two-loop order

soft limit of the scalar form factor for the heavy quark [Bernreuther et al. (2005)] [Blümlein et al. (2017)]

$$F(\alpha_s^{(n_l)}(\mu_R); m/\mu_R) = 1 + \frac{\alpha_s^{(n_l)}(\mu_R)}{2\pi}(-3C_F) + \left(\frac{\alpha_s^{(n_l)}(\mu_R)}{2\pi}\right)^2 \left(\frac{33}{4}C_F^2 - \frac{185}{12}C_F C_A + \frac{13}{6}C_F(n_l + n_h) - 6C_F \beta_0^{(n_l)} \ln \frac{\mu_R^2}{m^2}\right) + \mathcal{O}(\alpha_s^3)$$

Soft Higgs-boson approximation

how did we derive F ?

- To extract the explicit form of F up to three-loop order, we rely on the well-known **Higgs low-energy theorems** (LETs)

  [Shifman, Vainshtein, Voloshin, Zakharov (1979)]
  [Kniehl, Spira (1995)]

- LETs provide a connection between amplitudes of two processes which differ by the insertion of an external Higgs-boson line carrying zero momentum
- in **our specific case**:

$$\lim_{q\to 0} \mathcal{M}^{bare}_{Q\to QH}(p,q) = \frac{m_0}{v}\frac{\partial}{\partial m_0}\mathcal{M}^{bare}_{Q\to Q}(p)\Big|_{p^2=m^2}$$

$$\mathcal{M}^{bare}_{Q\to Q}(p) = \overline{Q}_0\left\{m_0(-1+\Sigma_S(p^2,m_0)) + \not{p}\,\Sigma_V(p^2,m_0)\right\}Q_0$$

unrenormalised heavy-quark self-energy

[Broadhurst, Grafe, Gray, Schilcher (1990)]
[Broadhurst, Gray, Schilcher (1991)]

The LETs can be derived by observing that:

1. the Higgs-boson interaction with a massive fermion emerges from the mass term by substituting:

$$m_0 \to m_0\left(1+\frac{H}{v}\right) \equiv m_0(H)$$

2. if the Higgs boson carries zero momentum, the corresponding field is constant

$$\frac{1}{\not{p}-m_0(H)} \simeq \frac{1}{\not{p}-m_0}\frac{m_0}{v}\frac{1}{\not{p}-m_0}H = \frac{m_0}{v}H\left(\frac{\partial}{\partial m_0}\frac{1}{\not{p}-m_0}\right)$$

- <u>next steps</u>:
  - renormalisation of the quark mass and wave function $m_0\overline{Q}_0Q_0 = m\overline{Q}QZ_mZ_2$
  - $\overline{\text{MS}}$ renormalisation of the strong coupling $\frac{g_s^2}{4\pi} = \left(\frac{e^{\gamma_E}\mu_R{}^2}{4\pi}\right)^{\epsilon}\alpha_s^{(n_f)}(\mu_R)\left\{1-\frac{\alpha_s^{(n_f)}(\mu_R)}{2\pi}\frac{\beta_0^{(n_f)}}{\epsilon}+\left(\frac{\alpha_s^{(n_f)}(\mu_R)}{2\pi}\right)^2\left[\left(\frac{\beta_0^{(n_f)}}{\epsilon}\right)^2-\frac{\beta_1^{(n_f)}}{2\epsilon}\right]+\mathcal{O}(\alpha_s^3)\right\}$

    \+ decoupling of the n_h heavy quarks of mass m

    [Chetyrkin, Kniehl, Steinhauser (1997)]

Soft Higgs-boson approximation

- **LP master formula** in the soft Higgs limit ($q \to 0$, $m_H \ll m$):

$$\mathcal{M}(p_1, p_2 ... p_N, q) \simeq F(\alpha_s(\mu_R); m/\mu_R) \frac{m}{v} \left(\sum_{i=1}^{N} \frac{m}{p_i \cdot q} \right) \mathcal{M}(p_1, p_2 ... p_N)$$

all-order UV renormalised amplitudes

- observations:
  - $F(\alpha_s(\mu_R); m/\mu_R)$ is perturbatively calculable, finite and gauge-independent
  - it can be derived by applying the so-called Higgs Low Energy theorems (LETs)

[Shifman, Vainshtein, Voloshin, Zakharov (1979)]
[Kniehl, Spira (1995)]

we proved the relation with the soft limit of the scalar FF up to three-loop order
[Fael, Lange, Schönwald, Steinhauser (2022, 2023)]

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  - the IR singularity structure of the scattering amplitude is left changed
  - the non-radiative amplitude must be evaluated on a set of projected momenta (to preserve momentum conservation)
  - for the specific case of **$t\bar{t}H$ production**, the non-radiative amplitude is known up to two-loop order

    [Bärnreuther, Czakon, Fiedler (2013)]

the soft factorisation formulae could provide a powerful cross check of future exact amplitude calculations, in this specific kinematic limit

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why soft Higgs approximation 

a careful assessment of the quality of the approximation is required

Results: systematic uncertainties

setup: NNLO NNPDF31, $m_H = 125GeV$, $m_t = 173.3GeV$, $\mu_R = \mu_F = (2m_t + m_H)/2$

	$\sqrt{s} = 13$ TeV		$\sqrt{s} = 100$ TeV	
σ [fb]	gg	$q\bar{q}$	gg	$q\bar{q}$
σ_{LO}	261.58	129.47	23055	2323.7
$\Delta\sigma_{\mathrm{NLO,H}}$	88.62	7.826	8205	217.0
$\Delta\sigma_{\mathrm{NLO,H}}\|_{\mathrm{soft}}$	61.98	7.413	5612	206.0
$\Delta\sigma_{\mathrm{NNLO,H}}\|_{\mathrm{soft}}$	$-2.980(3)$	$2.622(0)$	$-239.4(4)$	$65.45(1)$

- at NLO, difference of **5%** (**30%**) in $q\bar{q}$ (gg) channel
- at NNLO, the hard-virtual contribution is about **1%** of the LO cross section in gg and **2-3%** in $q\bar{q}$ small!
- our prescription to provide a conservative uncertainty is:
  - ☑ apply the approximation at a **different subtraction scale** (vary μ_{IR} by a factor 2 around Q); add the two-loop shift based on the exact tree-level and one-loop $t\bar{t}H$ amplitudes
  - ☑ take into account the NLO discrepancy and multiply it by a **tolerance factor 3**
  - ☑ combine **linearly** the gg and $q\bar{q}$ channels

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FINAL UNCERTAINTY:

$\pm 0.6\,\%$ on σ_{NNLO} , $\pm 15\,\%$ on $\Delta\sigma_{NNLO}$

it is clear that the quality of the final result depends on the size of the contribution we are approximating

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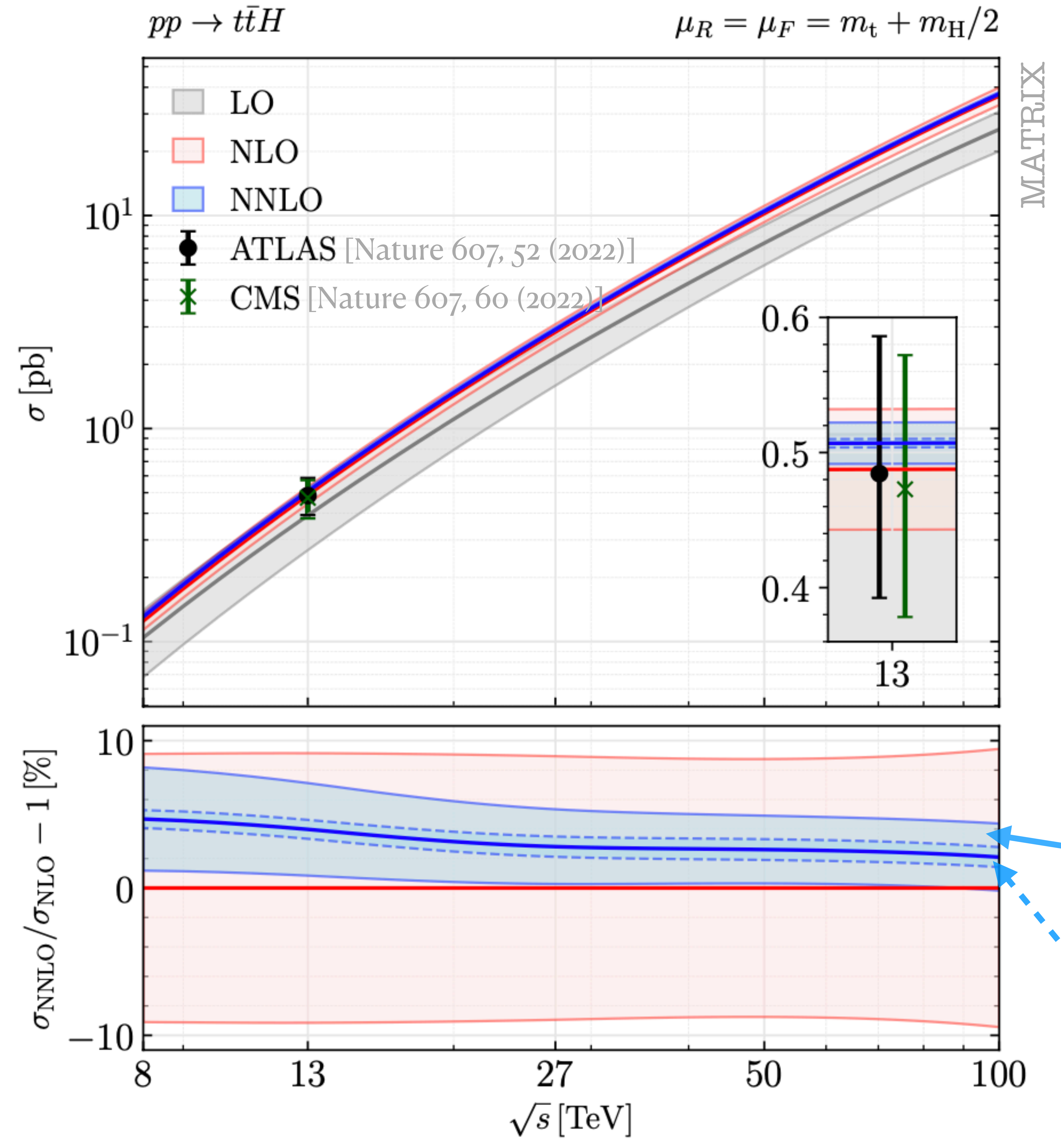
Results: total cross section

setup: NNLO NNPDF31, $m_H = 125GeV$, $m_t = 173.3GeV$, $\mu_R = \mu_F = (2m_t + m_H)/2$



symmetrised 7-point scale variation

systematic + soft-approximation

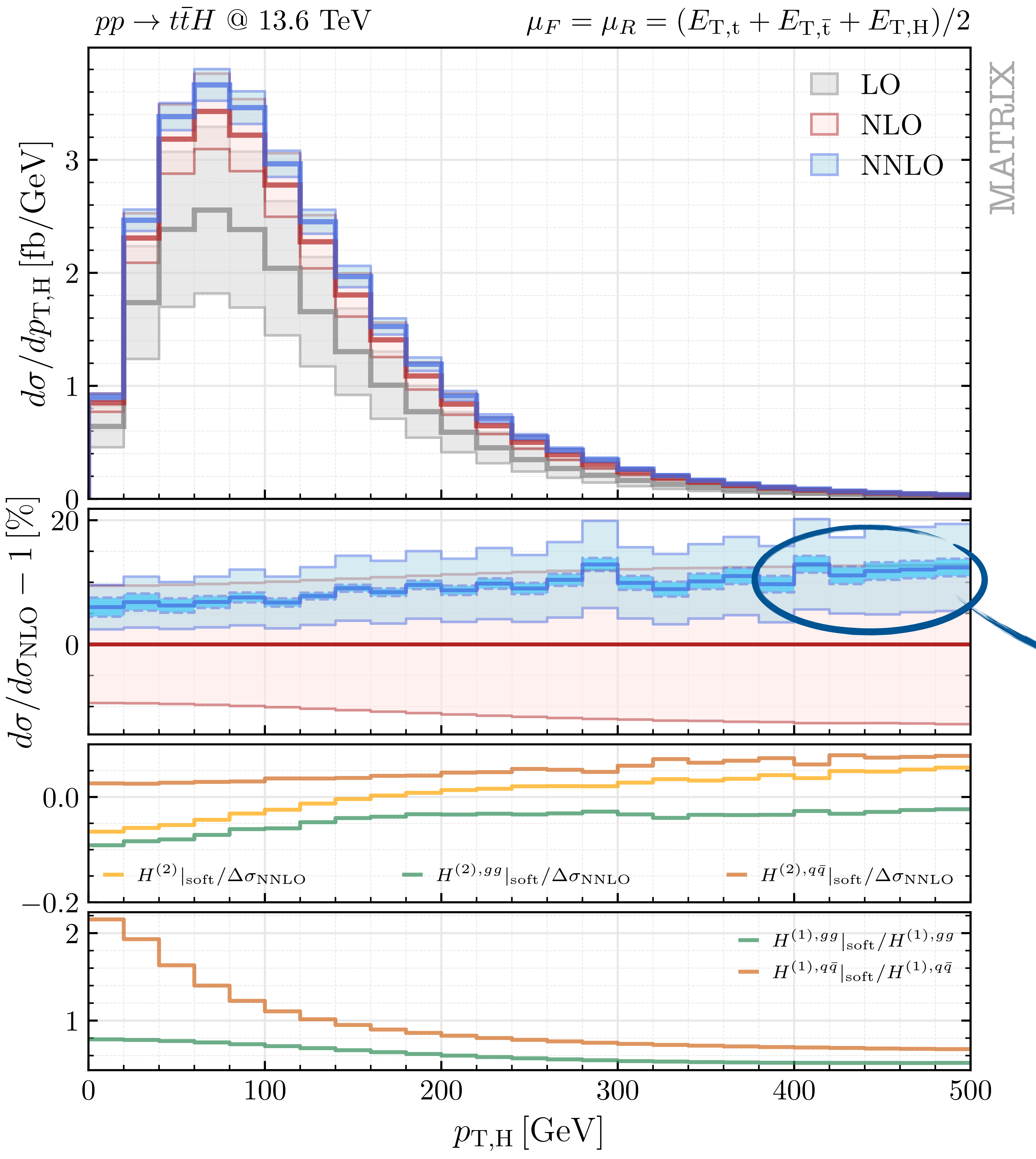
σ [pb]	$\sqrt{s} = 13$ TeV	$\sqrt{s} = 100$ TeV
σ_{LO}	$0.3910\,^{+31.3\%}_{-22.2\%}$	$25.38\,^{+21.1\%}_{-16.0\%}$
σ_{NLO}	$0.4875\,^{+5.6\%}_{-9.1\%}$	$36.43\,^{+9.4\%}_{-8.7\%}$
σ_{NNLO}	$0.5070\,(31)^{+0.9\%}_{-3.0\%}$	$37.20(25)\,^{+0.1\%}_{-2.2\%}$

- at NLO: **+25 (+44)%** at $\sqrt{s} = 13\,(100)\,TeV$
- at NNLO: **+4 (+2)%** at $\sqrt{s} = 13\,(100)\,TeV$
- nice perturbative convergence with **significant reduction** of the theory uncertainties $\mathcal{O}(3\%)$

First differential results: "soft-based"

Higgs transverse momentum

setup: NNLO NNPDF31, $m_H = 125GeV$, $m_t = 173.3GeV$, $\mu_R = \mu_F = (E_{T,t} + E_{T,\bar{t}} + E_{T,H})/2$



- significant reduction of the perturbative uncertainties
- soft-approximation uncertainty computed on a **bin-by-bin basis** (NLO discrepancy multiplied by a constant tolerance factor 3)

oversimplified procedure ...

- the systematic uncertainties seem to be under control, but are they trustable?

in the tail of the $p_{T,H}$ distribution, far from the region of validity of the soft-approximation, the systematic errors are "artificially" too small

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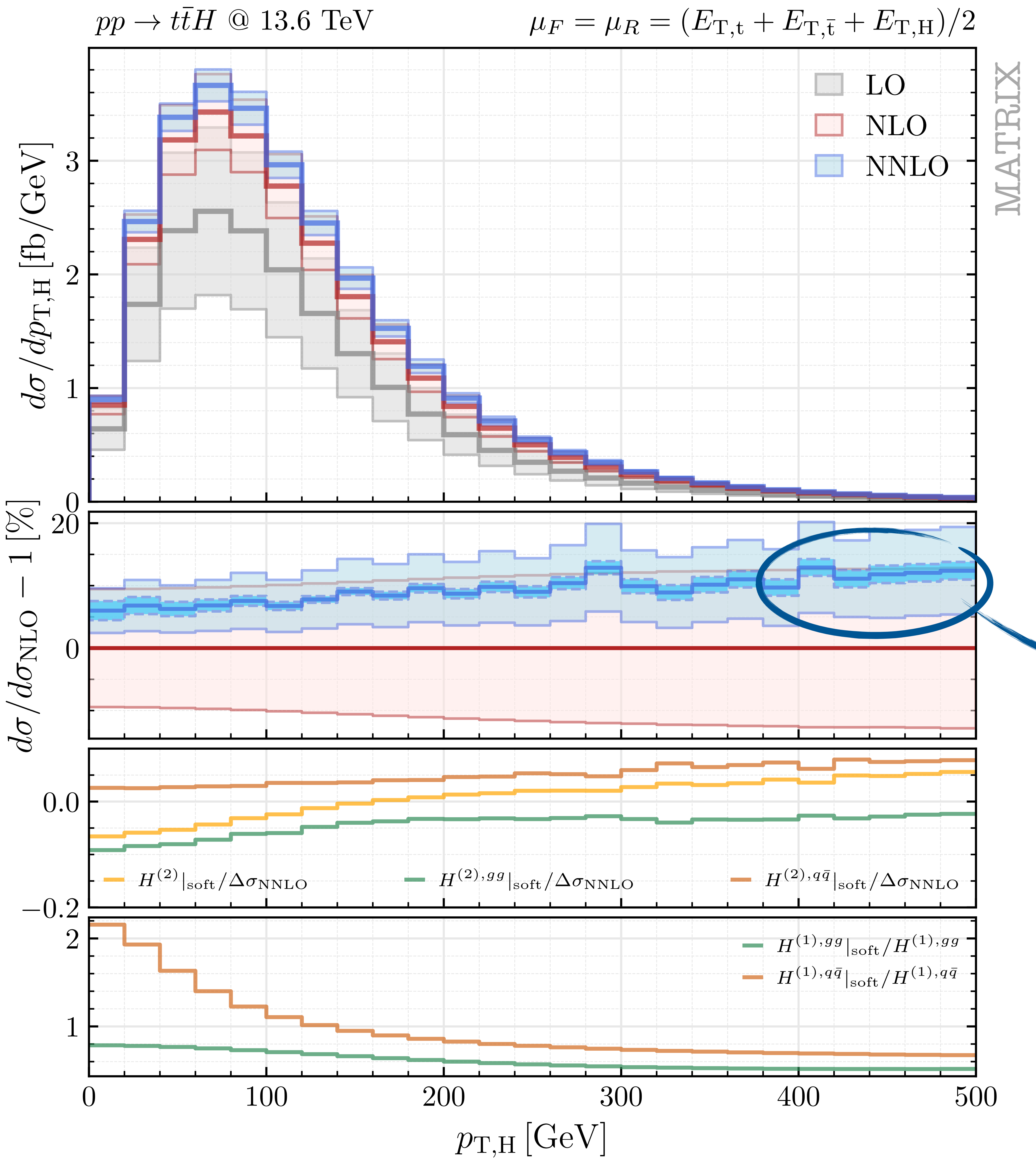

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in the tail of the $p_{T,H}$ distribution, far from the region of validity of the soft-approximation, the systematic errors are "artificially" too small

can we refine our approximation?

our idea consists in exploiting also the MASSIFICATION procedure and relying on the LC two-loop massless amplitudes for $pp \to Hb\bar{b}$

[Badger at al. (2021)]

Mass factorisation or massification

original formulation

[Penin (2006)]
[Moch, Mitov (2007)]

- **idea**: reconstruct the massive amplitudes, in the ultra-relativistic quark limit $m \ll Q$, up to power corrections $\mathcal{O}(m^2/Q^2)$
- If contributions from **heavy-quark loops** are **neglected**, the master formula is

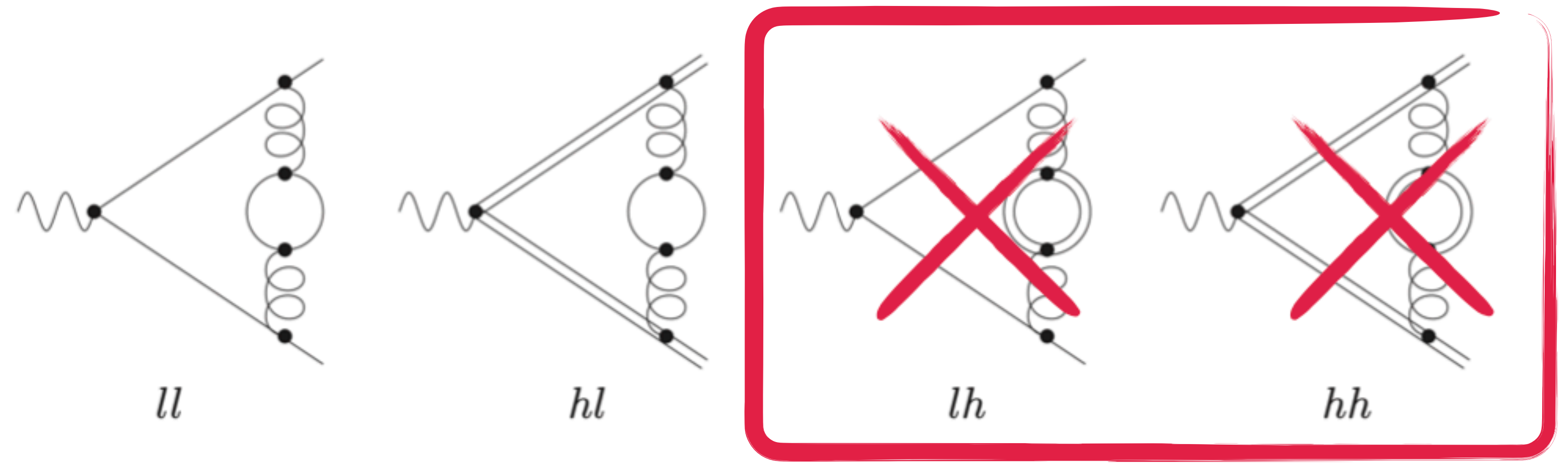
we are "dressing" n_Q external quarks with a mass m

$$|\mathcal{M}_{\mathcal{P}}^{(m)}\rangle = \left(Z_{[Q]}^{(m|0)}\left(\frac{m^2}{\mu^2}, \alpha_s(\mu^2), \epsilon\right)\right)^{n_Q/2} |\mathcal{M}_{\mathcal{P}}\rangle$$

all-order UV renormalised amplitudes in $\overline{\text{MS}}$ scheme with n_l running quarks

universal, perturbatively computable, ratio between massive and massless FFs

$$Z_{[Q]}^{(m|0)}\left(\frac{m^2}{\mu^2}, \alpha_s(\mu^2), \epsilon\right) = \mathcal{F}^{[Q\bar{Q}\to F]}\left(\frac{Q^2}{\mu^2}, \frac{m^2}{\mu^2}, \alpha_s(\mu^2), \epsilon\right)\left(\mathcal{F}_0^{[q\bar{q}\to F]}\left(\frac{Q^2}{\mu^2}, \alpha_s(\mu^2), \epsilon\right)\right)^{-1}$$



the mass "screens" collinear singularities

1. all ϵ poles, n_h-independent logarithms of the mass and finite terms of the massive amplitude are predicted
2. it can be viewed as a change in regularisation scheme

Mass factorisation or massification

[Wang et al. (2023)]

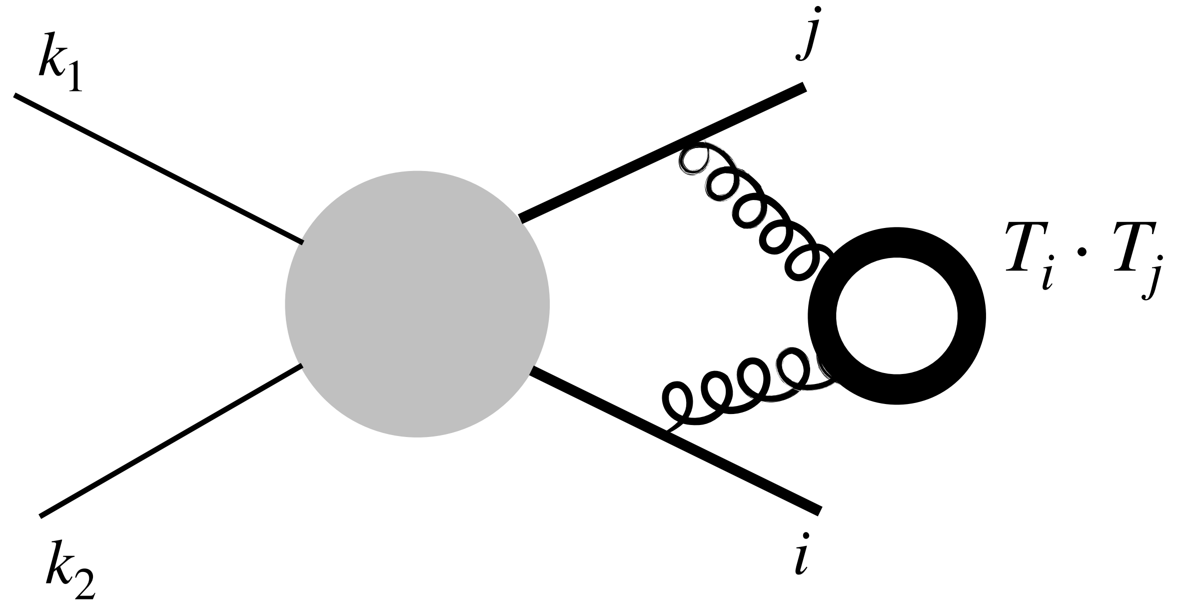
- If contributions from **heavy-quark loops** are **included**, a non-trivial soft function emerges starting from α_s^2
- the master formula gets modified as

[Becher, Melnikov (2007)]
[Engel et al. (2019)]

$$|\mathcal{M}_{\mathcal{P}}^{(m)}\rangle = \prod_i \left(Z_{[i]}^{(m|0)}\left(\frac{m^2}{\mu^2}, \alpha_s^{(n_f)}(\mu^2), \epsilon\right)\right)^{1/2} \mathcal{S}\left(\frac{m^2}{\mu^2}, \frac{m^2}{s_{ij}}, \alpha_s^{(n_f)}(\mu^2), \epsilon\right) |\mathcal{M}_{\mathcal{P}}\rangle$$

all-order UV renormalised amplitudes in $\overline{\text{MS}}$ scheme with $n_f = n_l + n_h$ running quarks

process-dependent **SOFT** function, operator in colour space, it starts contributing at two-loop order



$$\mathcal{S}\left(\frac{m^2}{\mu^2}, \frac{m^2}{s_{ij}}, \alpha_s^{(n_f)}(\mu^2), \epsilon\right) = 1 + \left(\frac{\alpha_s^{(n_f)}}{4\pi}\right)^2 n_h \sum_{i>j} (-\mathbf{T}_i \cdot \mathbf{T}_j)\, \mathcal{S}^{(2)}\left(\frac{m^2}{\mu^2}, \frac{m^2}{s_{ij}}, \epsilon\right) + \mathcal{O}(\alpha_s^3)$$

$$\text{with} \quad \mathcal{S}^{(2)}\left(\frac{m^2}{\mu^2}, \frac{m^2}{s_{ij}}, \epsilon\right) = T_R \left(\frac{\mu^2}{m^2}\right)^{2\epsilon} \left(-\frac{4}{3\epsilon^2} + \frac{20}{9\epsilon} - \frac{112}{27} - \frac{4\zeta_2}{3}\right) \log\left(\frac{-s_{ij}}{m^2}\right)$$

see Guoxing's talk

Mass factorisation or massification

generalised formulation

[Wang et al. (2023)]

- If contributions from **heavy-quark loops** are **included**, a non-trivial soft function emerges starting from α_s^2
- the master formula gets modified as

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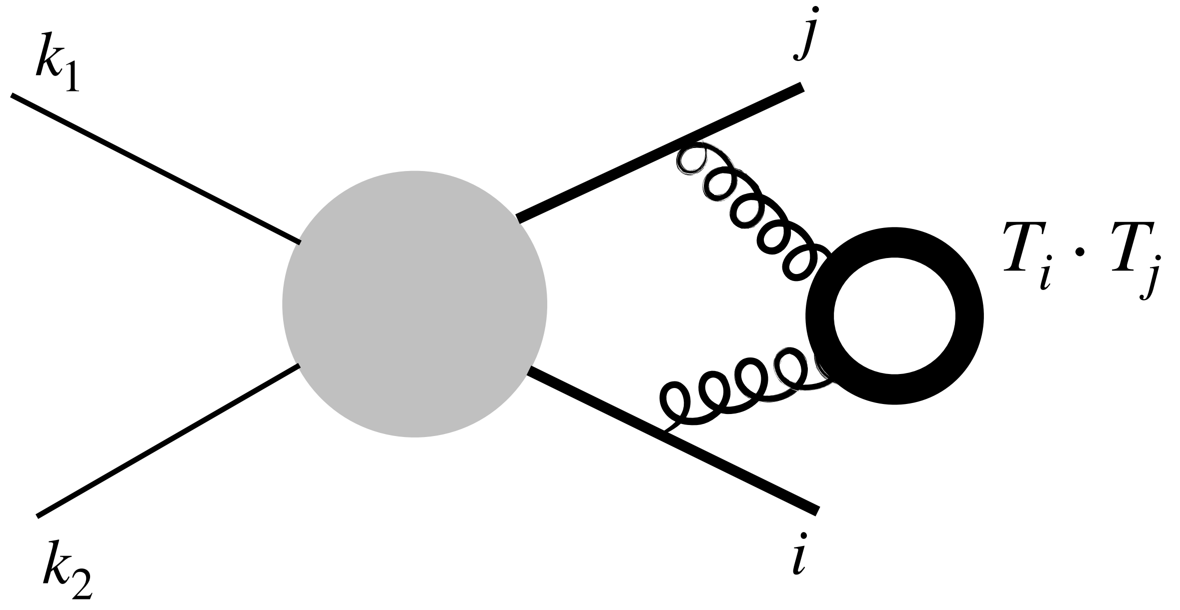


$$\mathcal{S} \left(\frac{m^2}{\mu^2}, \frac{m^2}{s_{ij}}, \alpha_s^{(n_f)}(\mu^2), \epsilon \right) = 1 + \left(\frac{\alpha_s^{(n_f)}}{4\pi} \right)^2 n_h \sum_{i>j} (-\mathbf{T}_i \cdot \mathbf{T}_j)\, \mathcal{S}^{(2)} \left(\frac{m^2}{\mu^2}, \frac{m^2}{s_{ij}}, \epsilon \right) + \mathcal{O}(\alpha_s^3)$$

with $$\mathcal{S}^{(2)} \left(\frac{m^2}{\mu^2}, \frac{m^2}{s_{ij}}, \epsilon \right) = T_R \left(\frac{\mu^2}{m^2} \right)^{2\epsilon} \left(-\frac{4}{3\epsilon^2} + \frac{20}{9\epsilon} - \frac{112}{27} - \frac{4\zeta_2}{3} \right) \log \left(\frac{-s_{ij}}{m^2} \right)$$

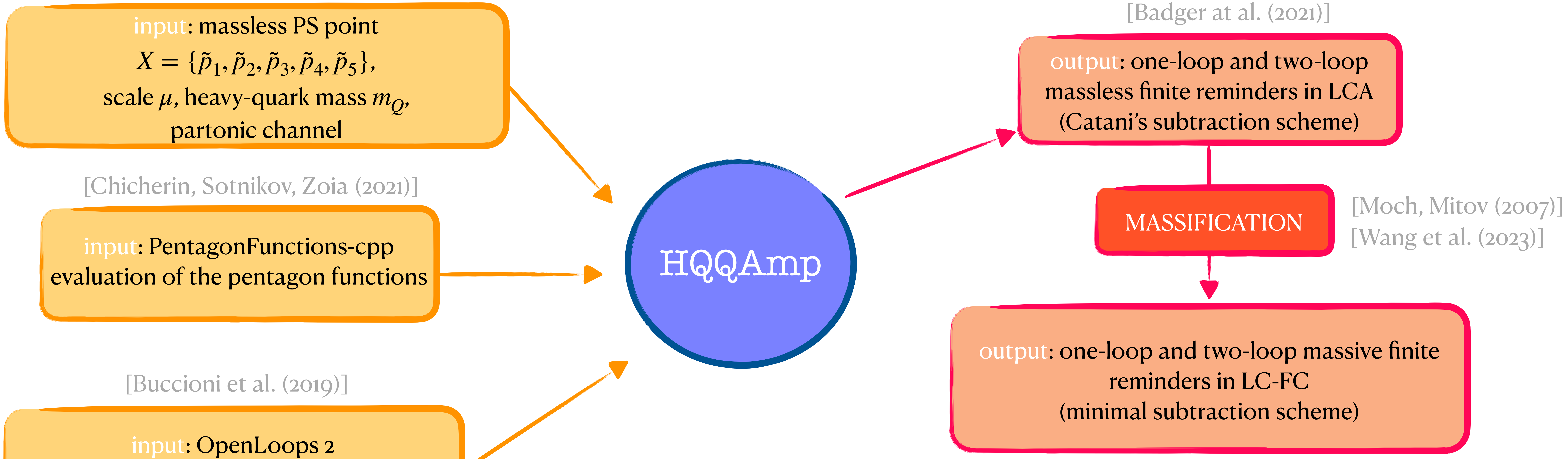
for the specific case of $Q\bar{Q}H$ production we can reconstruct the massive amplitudes, up to power corrections in the heavy-quark mass, by exploiting the corresponding (known) massless amplitudes

[Badger et al. (2021)]

HQQAmp: a massive C++ implementation

- We implemented the one-loop and two-loop massless amplitudes of [Badger at al. (2021)] in a **C++ library** for the efficient numerical evaluation of the **massified amplitudes**
- possibility of choosing the **precision** (double, quadruple or octuple) for the MIs and relative coefficients

$$q/g(p_1) + \bar{q}/g(p_2) \to H(p_3) + t(p_4) + \bar{t}(p_5)$$



cross-checked against an independent implementation by C.Biello

evaluation time per phase space point:
$\mathcal{O}(2-3s)$ for both partonic channels
[quadruple (double) precision for the coefficients (MIs)]

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$$q/g(p_1) + \bar{q}/g(p_2) \to H(p_3) + t(p_4) + \bar{t}(p_5)$$

input: massless PS point $X = \{\tilde{p}_1, \tilde{p}_2, \tilde{p}_3, \tilde{p}_4, \tilde{p}_5\}$, scale μ, heavy-quark mass m_Q, partonic channel

- mapping 0: preserve the 4-momentum of the heavy-quark pair $s_{QQ} = (p_4 + p_5)^2 = (\tilde{p}_4 + \tilde{p}_5)^2$

$$\tilde{p}_4^\mu = \beta_+ p_4^\mu - \beta_- p_5^\mu \,, \qquad \tilde{p}_5^\mu = \beta_+ p_5^\mu - \beta_- p_4^\mu \qquad \text{with} \quad \beta_\pm = \frac{1 \pm \beta}{2\beta} \,, \; \beta = \sqrt{1 - \frac{4m^2}{s_{QQ}}}$$

prevents potential collinear divergences due to $g \to b\bar{b}$

- mapping 1: preserve the 3-momenta of the heavy quarks and the 4-momentum of the Higgs boson

$$\tilde{p}_1^\mu = \tilde{E}_1(1,0,0,1) \,, \quad \tilde{p}_2^\mu = \tilde{E}_2(1,0,0,-1) \,,$$
$$\tilde{p}_3^\mu = p_3^\mu \,,$$
$$\tilde{p}_4^\mu = \left(\sqrt{p_{4,T}^2 + p_{4,z}^2}, \vec{p}_{4,T}, p_{4,z}\right) \,,$$
$$\tilde{p}_5^\mu = \left(\sqrt{p_{5,T}^2 + p_{5,z}^2}, \vec{p}_{5,T}, p_{5,z}\right)$$

- mapping 2: preserve the energy and longitudinal component of the 4-momenta of the heavy quarks

$$\tilde{p}_4^\mu = \left(E_4, \hat{p}_{4,T}\sqrt{p_{4,T}^2 + m^2}, p_{4,z}\right) \,,$$
$$\tilde{p}_5^\mu = \left(E_5, \hat{p}_{5,T}\sqrt{p_{5,T}^2 + m^2}, p_{5,z}\right)$$

prevents potential IS collinear divergences in gg channel (t-channel diagrams)

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$$|\mathcal{M}_m^{(\mathrm{fin,SCET})}\rangle = \mathbf{Z}^{-1}_{m\ll\mu_h}(\alpha_s^{(n_l)},\mu^2,m^2;\epsilon) Z_{[Q]}^{(m|0)}\left(\alpha_s^{(n_l)},\frac{\mu^2}{m^2};\epsilon\right)\mathbf{Z}_{(m=0)}(\alpha_s^{(n_l)},\mu^2;\epsilon)\,|\mathcal{M}_{(m=0)}^{(\mathrm{fin,SCET})}\rangle + \mathcal{O}\left(\frac{m^2}{\mu_h^2}\right)$$

$$|\mathcal{M}_m^{(\mathrm{fin,SCET})}\rangle = \mathcal{F}\left(\alpha_s^{(n_l)},\frac{\mu^2}{m^2}\right)|\mathcal{M}_{(m=0)}^{(\mathrm{fin,SCET})}\rangle$$

[Moch, Mitov (2007)]

with $$\mathcal{F}\left(\alpha_s^{(n_l)},\frac{\mu^2}{m^2}\right) = 1 + \frac{\alpha_s^{(n_l)}}{4\pi}\mathcal{F}^{(1)}\left(\frac{\mu^2}{m^2}\right) + \left(\frac{\alpha_s^{(n_l)}}{4\pi}\right)^2\mathcal{F}^{(2)}\left(\frac{\mu^2}{m^2}\right) + \mathcal{O}(\alpha_s^3)$$

it is not anymore an operator in colour space and it contains all mass logarithms!

$$\mathcal{F}^{(1)} = Z_{[Q]}^{(1),\epsilon^0}$$

$$\mathcal{F}^{(2)} = Z_{[Q]}^{(2),\epsilon^0} - Z_{[Q]}^{(1),1/\epsilon}Z_{[Q]}^{(1),\epsilon} - Z_{[Q]}^{(1),1/\epsilon^2}Z_{[Q]}^{(1),\epsilon^2}$$

process-independent!

[Badger at al. (2021)]

output: one-loop and two-loop massless finite reminders in LCA (Catani's subtraction scheme)

MASSIFICATION

output: one-loop and two-loop massive finite reminders in LC-FC (minimal subtraction scheme)

Yukawa renormalised ON-SHELL

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$$|\mathcal{M}_m^{(\text{fin,SCET})}\rangle = \mathbf{Z}^{-1}_{m\ll\mu_h}(\alpha_s^{(n_l)},\mu^2,m^2;\epsilon) Z_{[Q]}^{(m|0)}\left(\alpha_s^{(n_l)},\frac{\mu^2}{m^2};\epsilon\right)\mathbf{Z}_{(m=0)}(\alpha_s^{(n_l)},\mu^2;\epsilon)\,|\mathcal{M}_{(m=0)}^{(\text{fin,SCET})}\rangle + \mathcal{O}\left(\frac{m^2}{\mu_h^2}\right)$$

[Badger at al. (2021)]

output: one-loop and two-loop massless finite reminders in LCA (Catani's subtraction scheme)

$$|\mathcal{M}_m^{(\text{fin,SCET})}\rangle = \mathcal{F}\left(\alpha_s^{(n_l)},\frac{\mu^2}{m^2}\right)|\mathcal{M}_{(m=0)}^{(\text{fin,SCET})}\rangle$$

[Moch, Mitov (2007)]

MASSIFICATION

$$|\mathcal{M}_m^{(1),(\text{fin,SCET})}\rangle = |\mathcal{M}_{(m=0)}^{(1),(\text{fin,SCET})}\rangle + \mathcal{F}^{(1)}\,|\mathcal{M}_{(m=0)}^{(0)}\rangle$$

$$|\mathcal{M}_m^{(2),(\text{fin,SCET})}\rangle = |\mathcal{M}_{(m=0)}^{(2),(\text{fin,SCET})}\rangle + \mathcal{F}^{(1)}\,|\mathcal{M}_{(m=0)}^{(1),(\text{fin,SCET})}\rangle + \mathcal{F}^{(2)}\,|\mathcal{M}_{(m=0)}^{(0)}\rangle$$

massless two-loop contribution in LCA. All remaining terms can be "promoted" to FC

no need to implement the higher ϵ orders of the massless one-loop amplitude

output: one-loop and two-loop massive finite reminders in LC-FC (minimal subtraction scheme)

Yukawa renormalised ON-SHELL

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- possibility of choosing the **precision** (double, quadruple or octuple) for the MIs and relative coefficients

$$|\mathcal{M}_m^{(\mathrm{fin,SCET})}\rangle = \mathbf{Z}^{-1}_{m\ll\mu_h}(\alpha_s^{(n_f)},\mu^2,m^2;\epsilon) Z_{[Q]}^{(m|0)}\left(\alpha_s^{(n_f)},\frac{\mu^2}{m^2};\epsilon\right) Z_{[c]}^{(m|0)}\left(\alpha_s^{(n_f)},\frac{\mu^2}{m^2};\epsilon\right)$$
$$\times\, \boldsymbol{\mathcal{S}}(\alpha_s^{(n_f)},\mu^2,m^2,s_{ij};\epsilon)\mathbf{Z}_{(m=0)}(\alpha_s^{(n_f)},\mu^2;\epsilon)\ |\mathcal{M}_{(m=0)}^{(\mathrm{fin,SCET})}\rangle + \mathcal{O}\left(\frac{m^2}{\mu_h^2}\right)$$

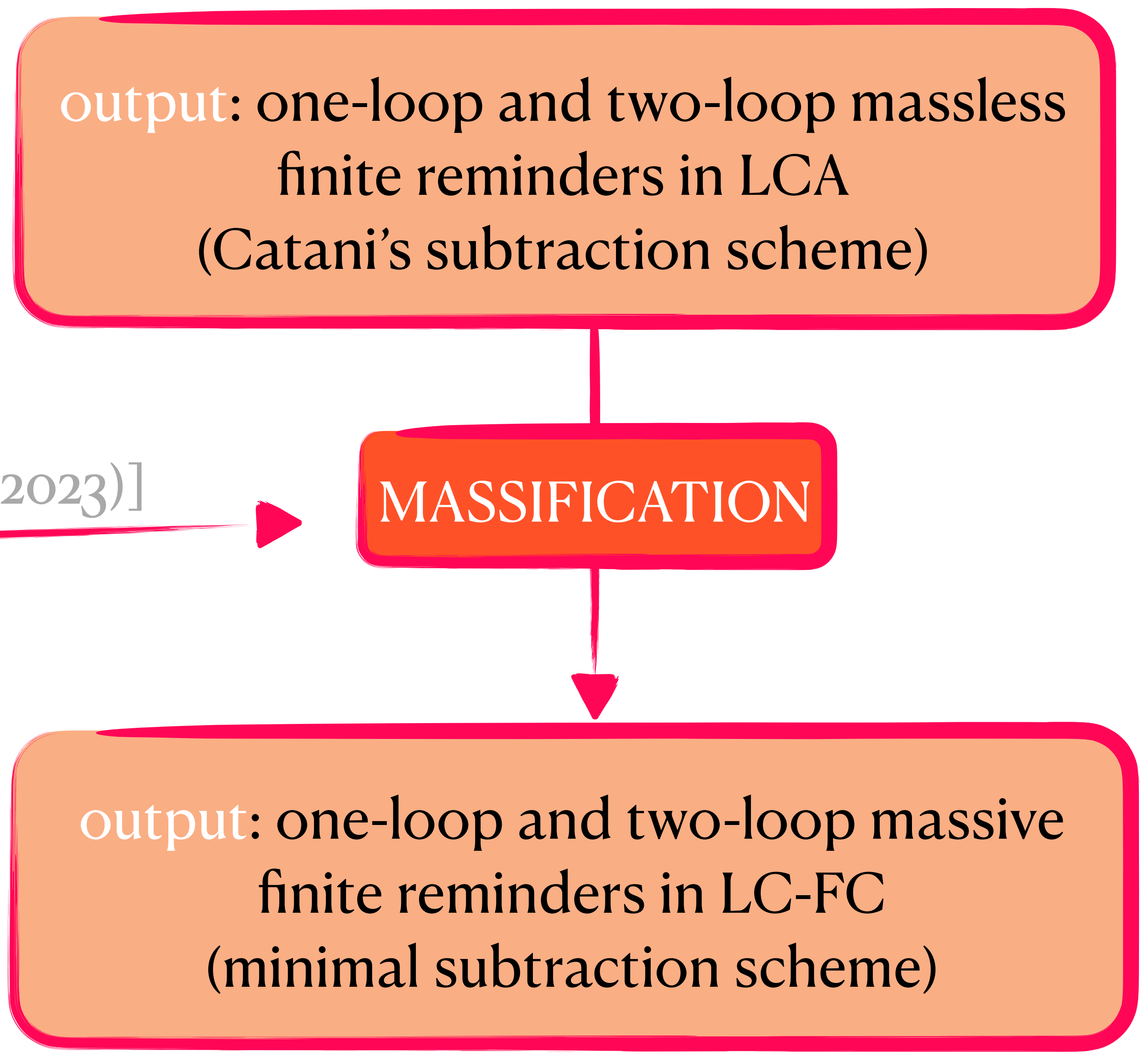
$$|\mathcal{M}_m^{(\mathrm{fin,SCET})}\rangle = \boldsymbol{\mathcal{F}}_{[c]}\left(\alpha_s^{(n_f)},\frac{\mu^2}{m^2},\frac{\mu^2}{s_{ij}}\right)|\mathcal{M}_{(m=0)}^{(\mathrm{fin,SCET})}\rangle$$

with
$$\boldsymbol{\mathcal{F}}^{(1)}_{[c]} = \mathcal{F}^{(1)} + \mathcal{F}^{(1)}_{[c]}$$
$$\boldsymbol{\mathcal{F}}^{(2)}_{[c]} = \mathcal{F}^{(2)} + \boldsymbol{\mathcal{S}}^{(2),\epsilon^0} + \mathcal{F}^{(2)}_{[c]}$$
$$+\, n_h\left(\frac{\pi^2}{18}+\frac{1}{3}l_{\mu m}^2\right)\mathbf{Z}^{(1),1/\epsilon}_{m\ll\mu_h} + n_h\left(-\frac{2}{9}\zeta_3+\frac{\pi^2}{18}l_{\mu m}+\frac{1}{9}l_{\mu m}^3\right)\mathbf{Z}^{(1),1/\epsilon^2}_{m\ll\mu_h}$$

it is now an operator in colour space, depending on the partonic channel $c \in \{g,q\}$

[Badger at al. (2021)]

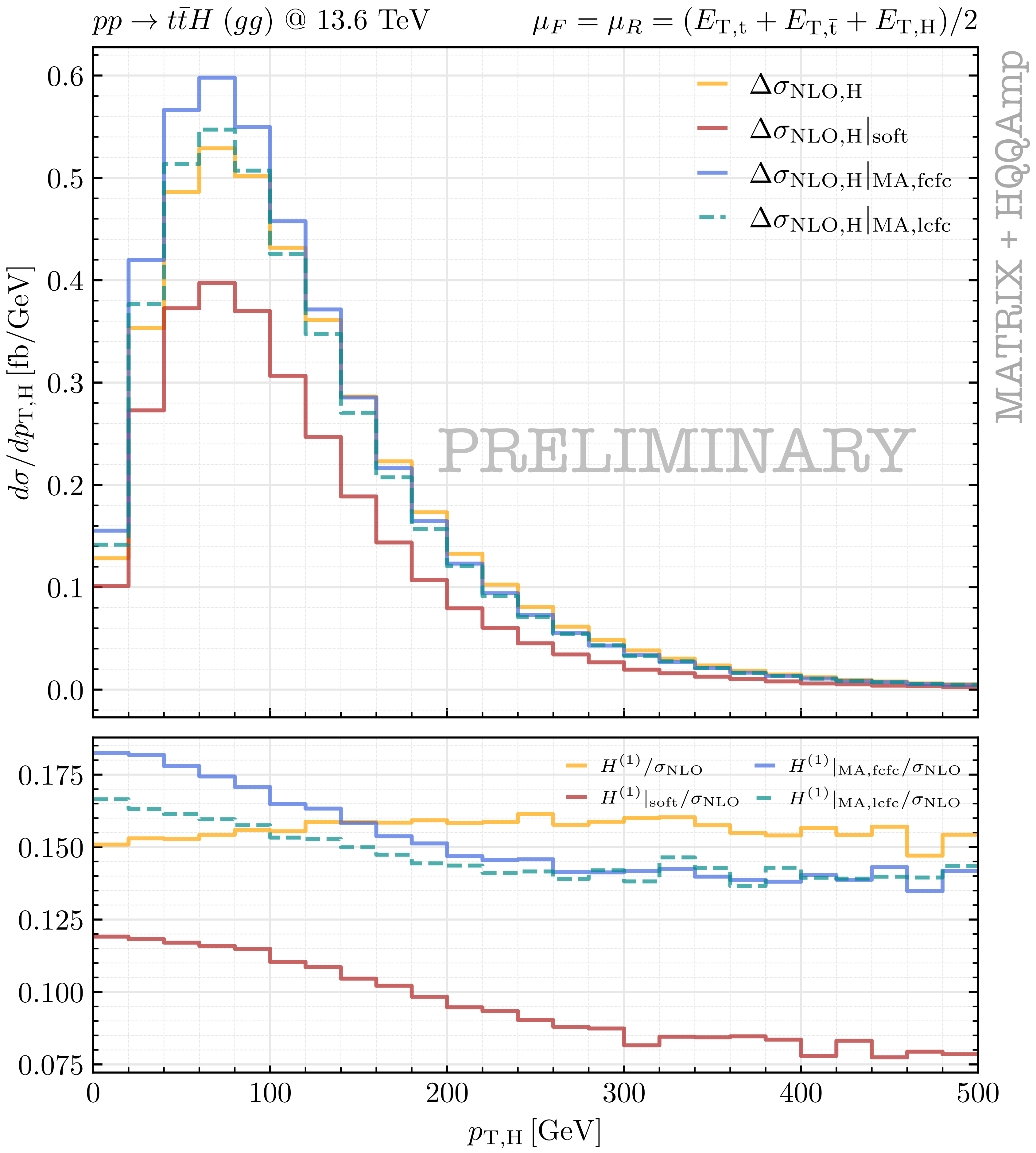
[Wang et al. (2023)]



Yukawa renormalised ON-SHELL

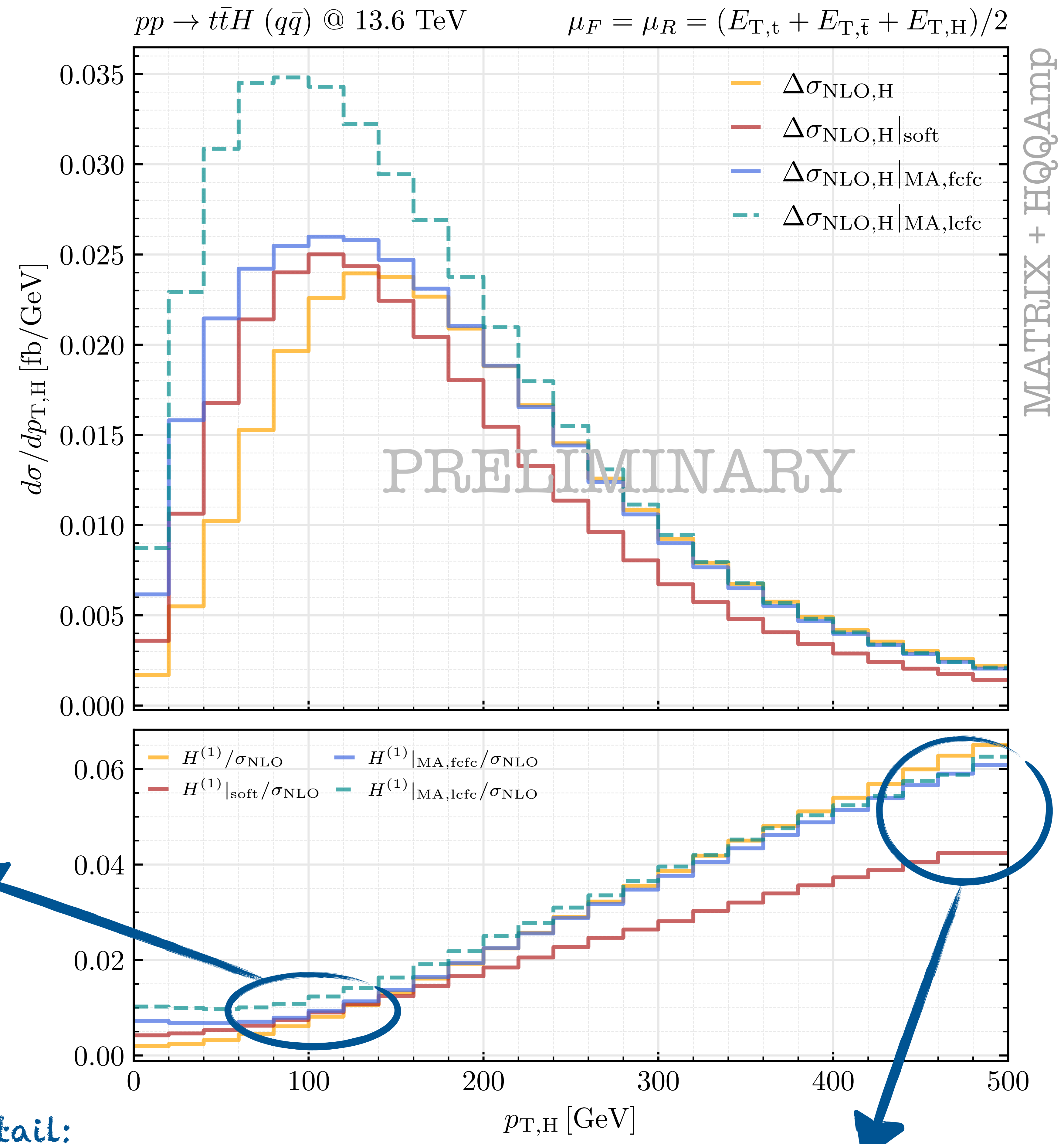
Quality of both approximations at NLO

setup: NNLO NNPDF31, $m_H = 125GeV$, $m_t = 173.3GeV$, $\mu_R = \mu_F = (E_{T,t} + E_{T,\bar{t}} + E_{T,H})/2$



around the peak:

1. FC-FC massification and soft approximation are nearly equivalent
2. LC-FC massification overestimates the exact result by almost a factor of 2



in the high-p_T tail:

1. missing subleading colour contributions are less relevant
2. soft approximation underestimates the exact result: $\mathcal{O}(2\%)$ difference of the NLO cross section

S. Devoto, M. Grazzini, S. Kallweit, J. Mazzitelli and **CS**, *in preparation*

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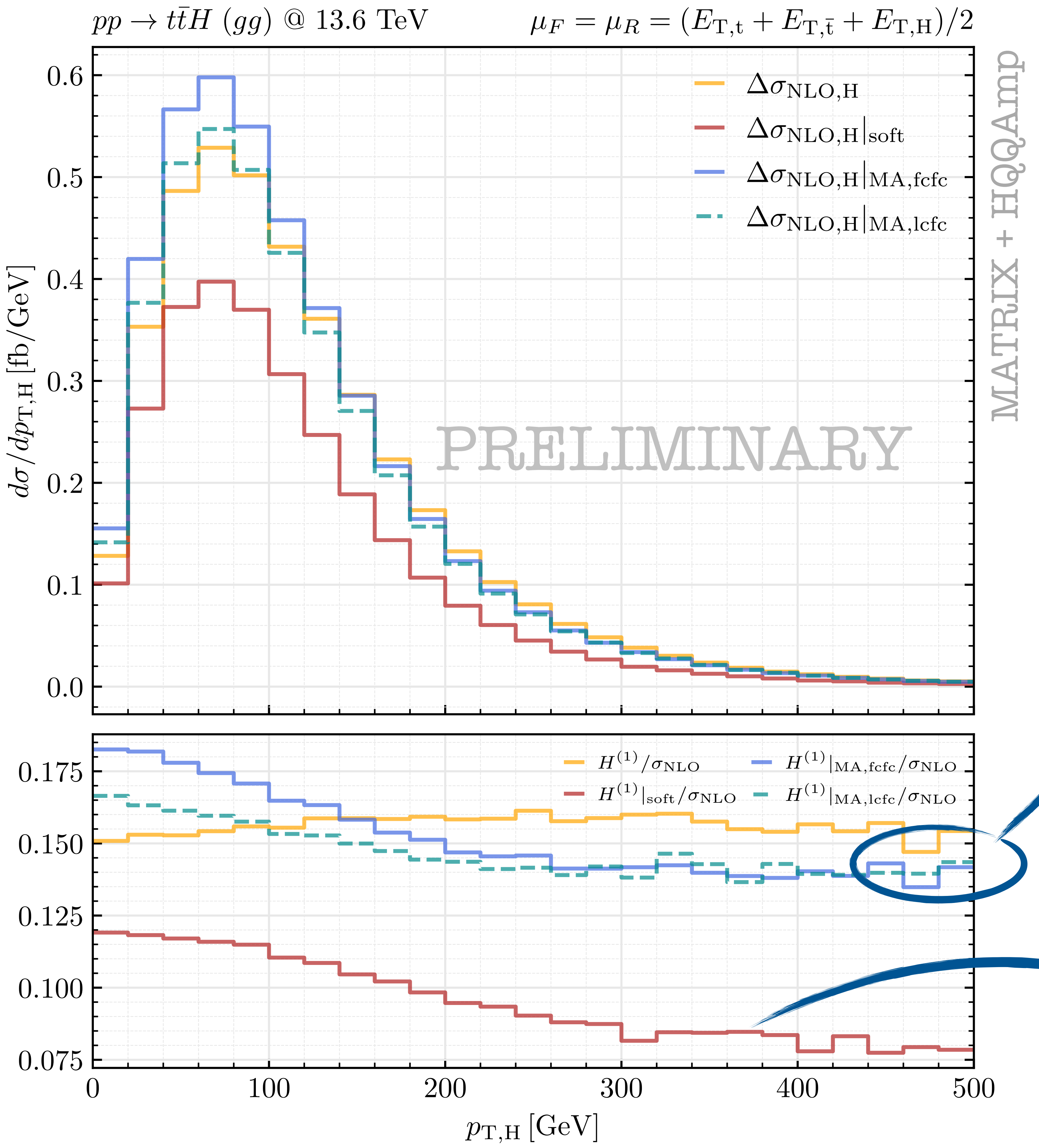
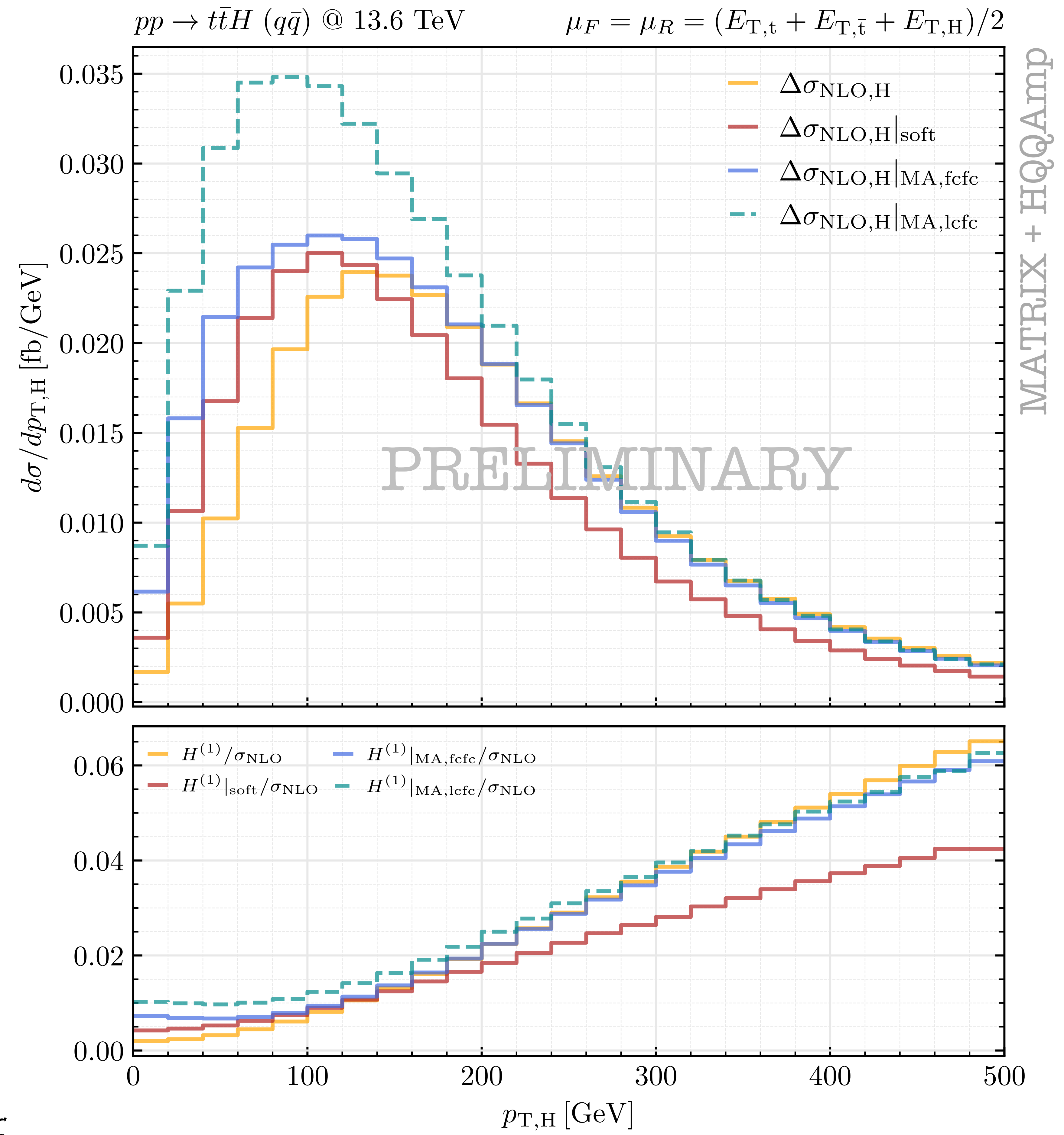


massified results are in good agreement with the exact one-loop, with effects of $\mathcal{O}(1\%)$ of the NLO cross section in the tail

soft-approximated result is systematically below the exact one-loop, with effects of $\mathcal{O}(8\%)$ of the NLO cross section in the tail



S. Devoto, M. Grazzini, S. Kallweit, J. Mazzitelli and **CS**, *in preparation*

First differential results: "best" $H^{(2)}$ prediction

setup: NNLO NNPDF31, $m_H = 125GeV$, $m_t = 173.3GeV$, $\mu_R = \mu_F = (E_{T,t} + E_{T,\bar{t}} + E_{T,H})/2$

H1-based error

$$\varepsilon_{\rm soft} = 2 \times \left| \frac{H^{(1)}|_{\rm soft}}{H^{(1)}} - 1 \right| \times \max\left(\left|H^{(2)}|_{\rm soft}\right|, \left|H^{(2)}|_{\rm MA}\right| \right)$$

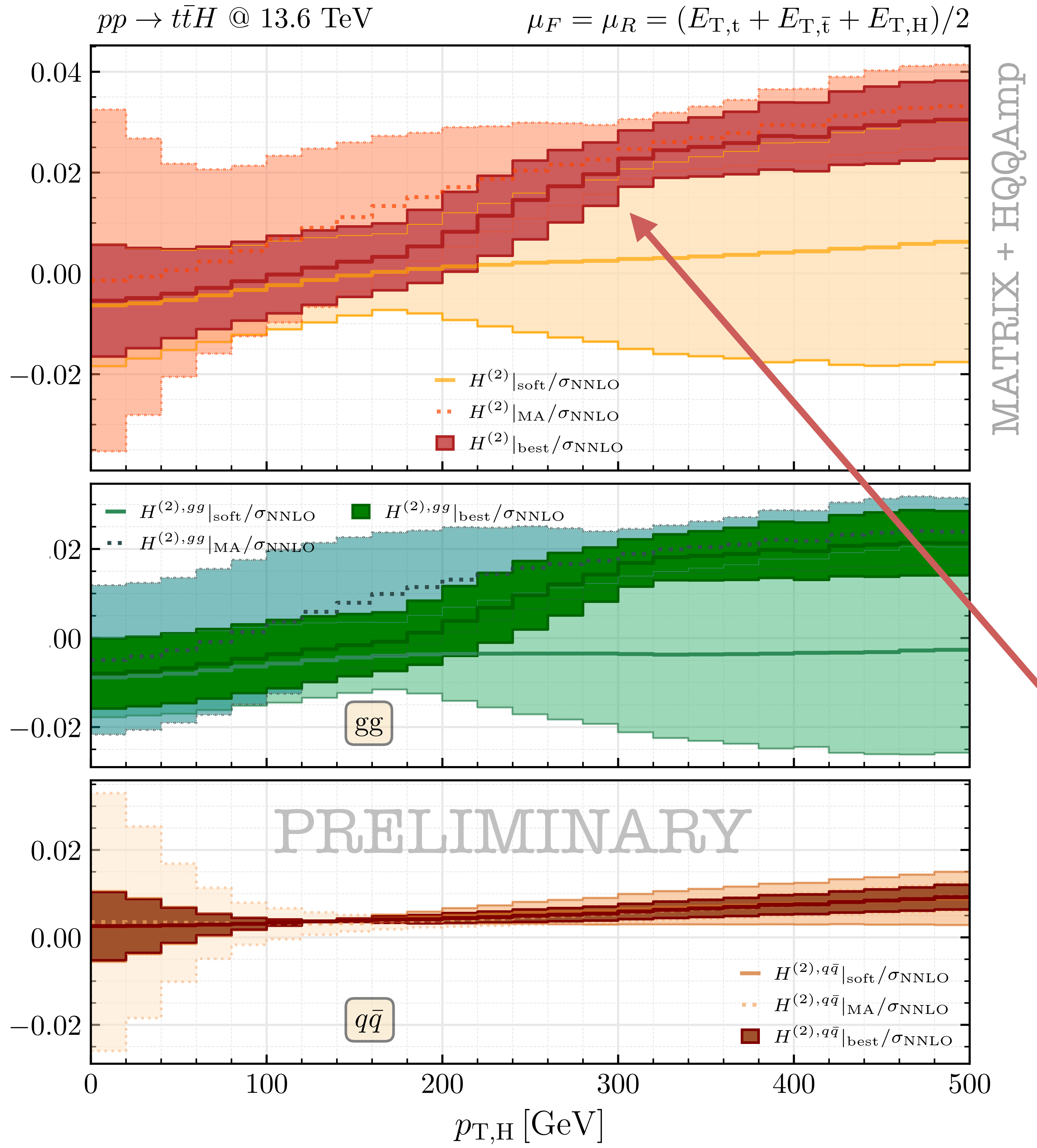
$$\varepsilon_{\rm MA} = 2 \times \max\left(\left| \frac{H^{(1)}|_{\rm MA,fcfc}}{H^{(1)}} - 1 \right|, \left| \frac{H^{(1)}|_{\rm MA,lcfc}}{H^{(1)}} - 1 \right| \right) \times \max\left(\left|H^{(2)}|_{\rm soft}\right|, \left|H^{(2)}|_{\rm MA}\right| \right)$$

μ_{IR}-variation error

$$\varsigma_{\rm soft} = \max\left(\left|H^{(2)}|_{\rm soft}(\tilde{Q}/2) + (Q/2 \to Q) - H^{(2)}|_{\rm soft}\right|, \left|H^{(2)}|_{\rm soft}(2\tilde{Q}) + (2Q \to Q) - H^{(2)}|_{\rm soft}\right| \right)$$

$$\varsigma_{\rm MA} = \max\left(\left|H^{(2)}|_{\rm MA}(\tilde{Q}/2) + (Q/2 \to Q) - H^{(2)}|_{\rm MA}\right|, \left|H^{(2)}|_{\rm MA}(2\tilde{Q}) + (2Q \to Q) - H^{(2)}|_{\rm MA}\right| \right)$$

the final systematic error ξ on each approximation and for each partonic channel is obtained by taking the maximum between ε and ζ



for each partonic channel:

$$H^{(2)}|_{\rm best} = \frac{\omega_{\rm soft} H^{(2)}|_{\rm soft} + \omega_{\rm MA} H^{(2)}|_{\rm MA}}{\omega_{\rm soft} + \omega_{\rm MA}}$$

$$\omega_{\rm soft} = \frac{1}{\xi^2_{\rm soft}}$$

$$\omega_{\rm MA} = \frac{1}{\xi^2_{\rm MA}}$$

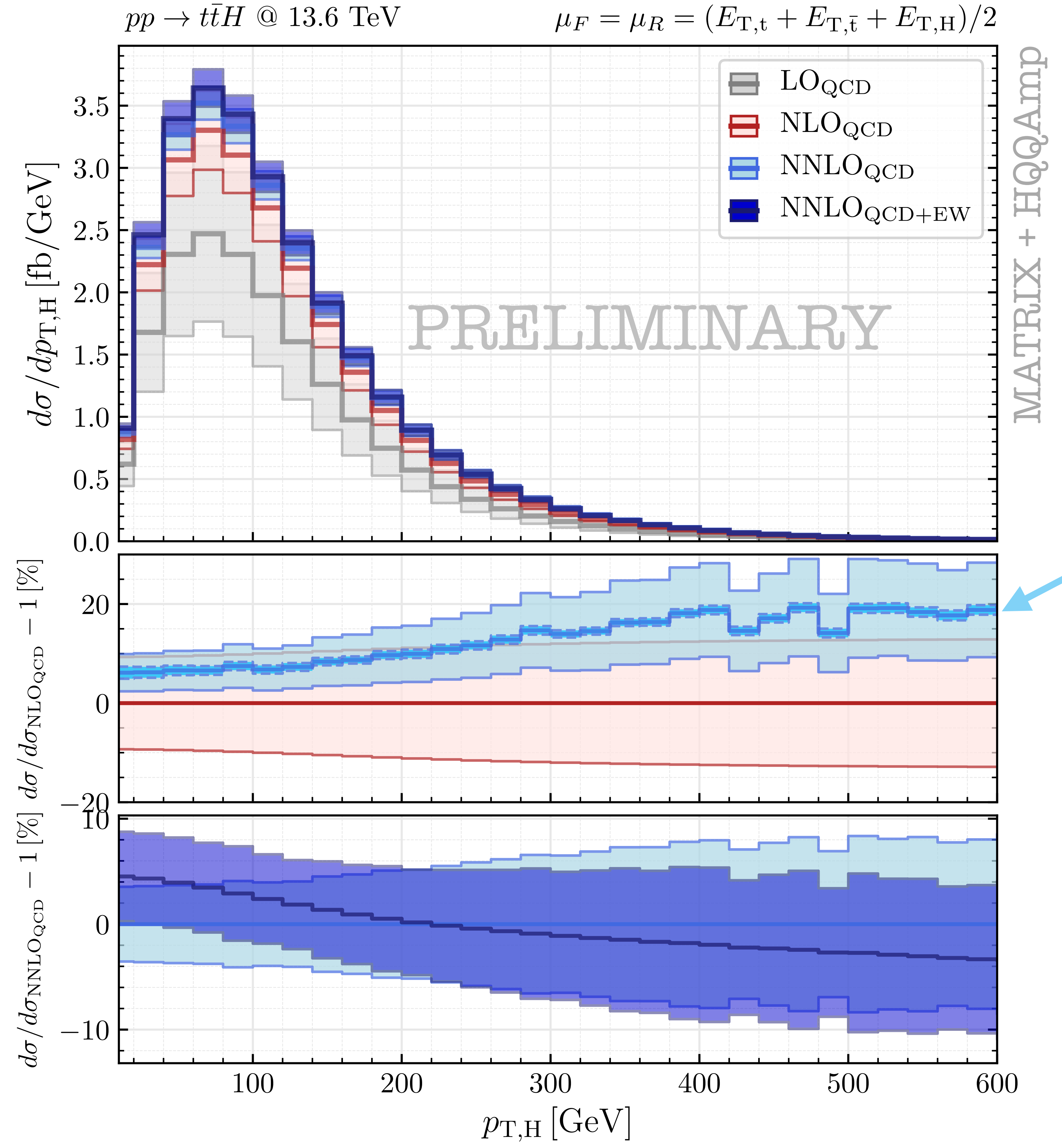
the errors on each channel are finally combined quadratically

1. the "best" prediction nicely interpolates between the two limits
2. the associated error does not vary strongly over the $p_{T,H}$ range
3. the individual soft and massified predictions have overlapping error bands

S. Devoto, M. Grazzini, S. Kallweit, J. Mazzitelli and **CS**, *in preparation*

NNLO QCD + EW corrections

setup: NNLO NNPDF40_nnlo_as_0118_qed, $m_H = 125.09 GeV$, $m_t = 172.5 GeV$



systematic error associated with the "best" prediction for the double-virtual contribution

total XS at fixed scale $\mu_R = \mu_F = m_t + m_H/2$

σ [fb]	$\sqrt{s} = 13.6$ TeV
$\sigma_{\mathrm{LO_{QCD}}}$	$423.438^{+30.7\%}_{-21.8\%}$
$\sigma_{\mathrm{NLO_{QCD}}}$	$528.665^{+5.7\%}_{-9.0\%}$
$\sigma^{\mathrm{SA}}_{\mathrm{NNLO_{QCD}}}$	$548.8\,(3.4)^{+0.8\%}_{-3.0\%}$
$\sigma^{\mathrm{best}}_{\mathrm{NNLO_{QCD}}}$	$550.5\,(4.6)^{+0.9\%}_{-3.0\%}$
$\sigma^{\mathrm{best}}_{\mathrm{NNLO_{QCD+EW}}}$	$562.3\,(4.6)^{+1.1\%}_{-3.0\%}$

- NNLO QCD predictions based on the soft-approximated and "best" double virtual are **fully compatible**: difference of 0.3 %
- the **systematic uncertainty** based on the refined prescription is **slightly larger**: $\mathcal{O}(0.8\%)$ instead of $\mathcal{O}(0.6\%)$ of the NNLO cross section

S. Devoto, M. Grazzini, S. Kallweit, J. Mazzitelli and **CS**, *in preparation*

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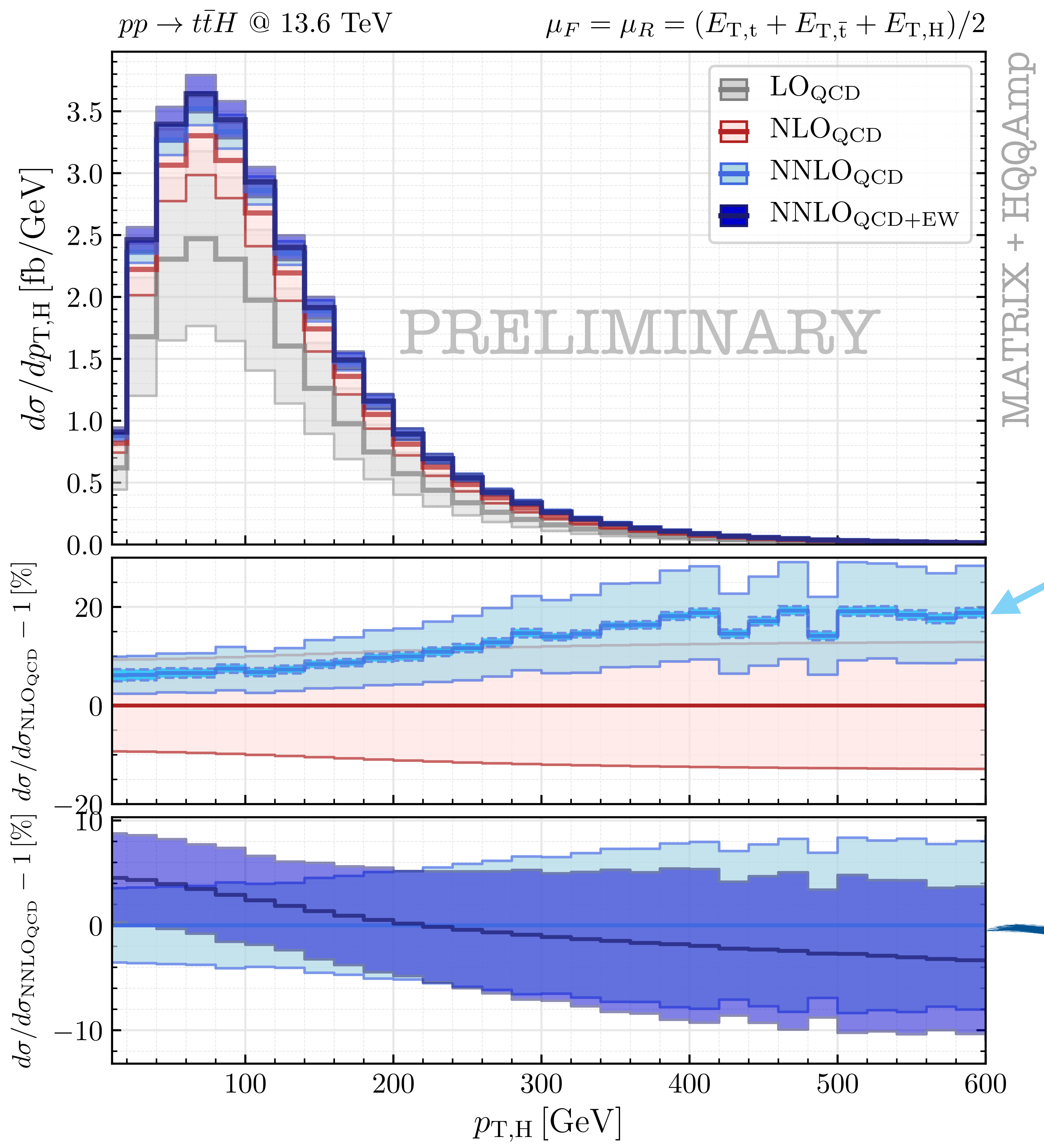

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$\sigma^{best}_{NNLO_{QCD+EW}}$	$562.3\,(4.6)^{+1.1\%}_{-3.0\%}$

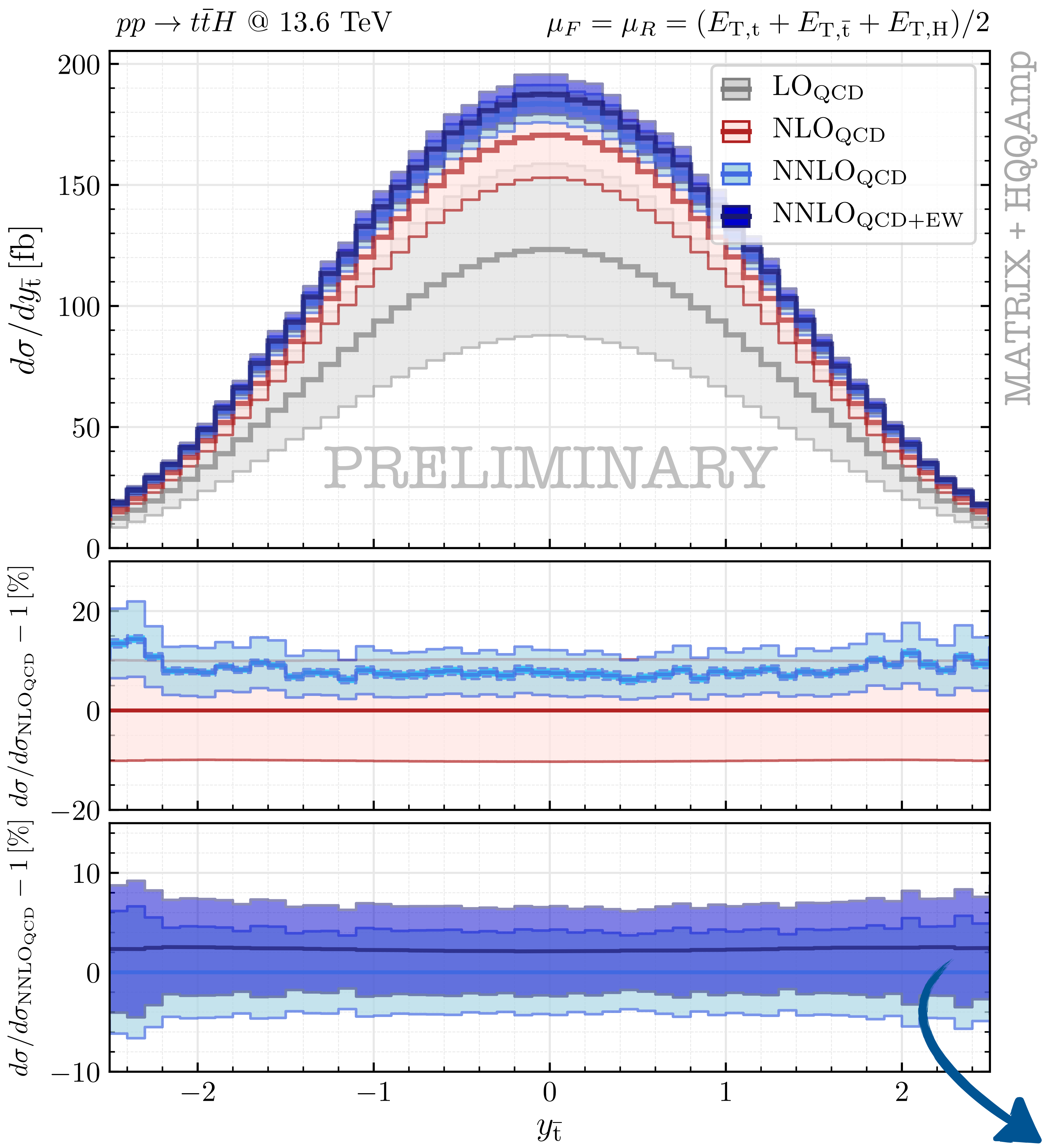
- inclusion of **all subdominant LO** ($\mathcal{O}(\alpha_s\alpha^2)$, $\mathcal{O}(\alpha^3)$) **and NLO** ($\mathcal{O}(\alpha_s^2\alpha^2)$, $\mathcal{O}(\alpha_s\alpha^3)$, $\mathcal{O}(\alpha^4)$) contributions: $+2\,\%$ at the cross section level

positive (negative) subdominant LO and NLO corrections in the small (large) $p_{T,H}$ region

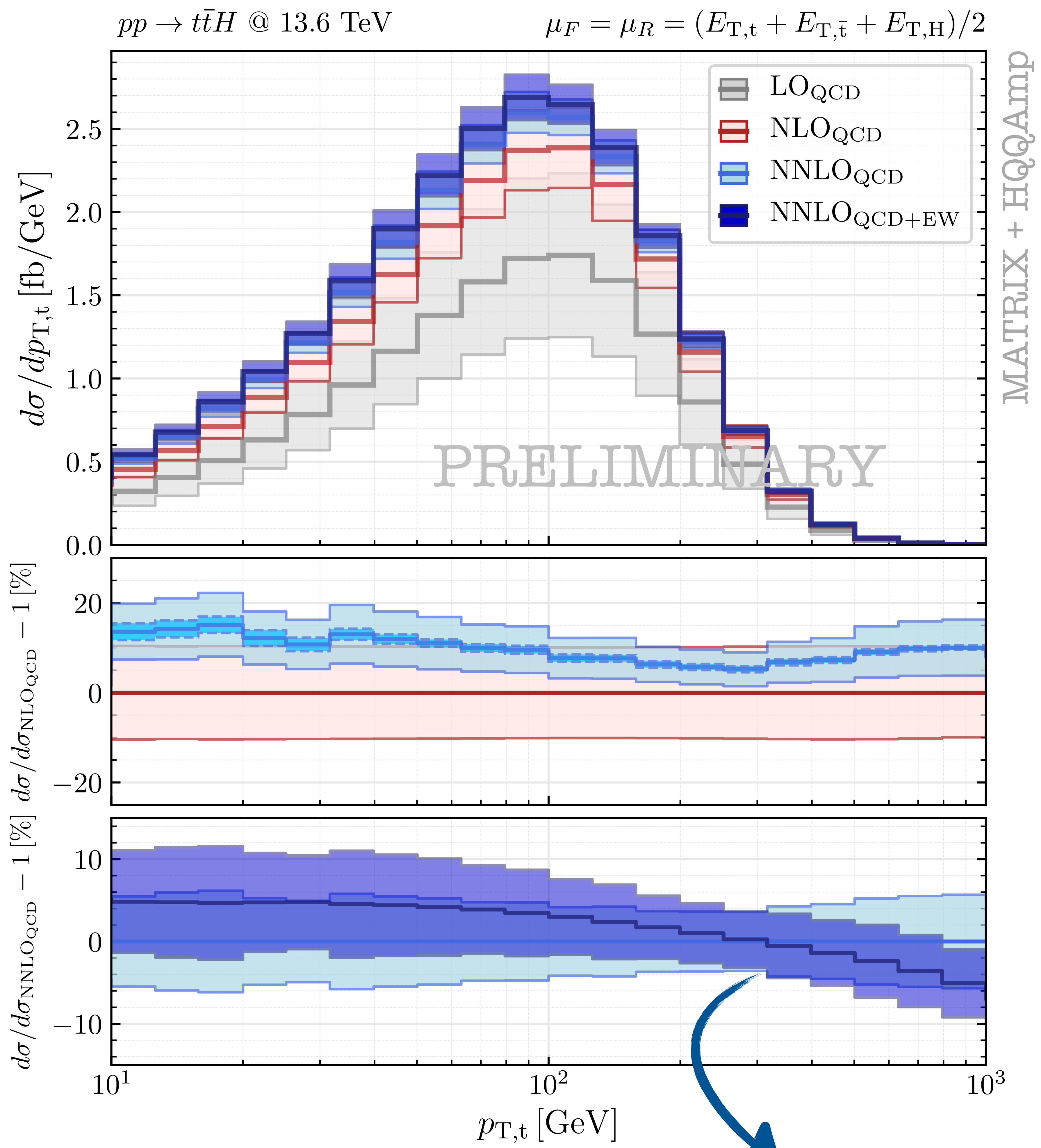
S. Devoto, M. Grazzini, S. Kallweit, J. Mazzitelli and **CS**, *in preparation*

NNLO QCD + EW corrections

setup: NNLO NNPDF40_nnlo_as_0118_qed, $m_H = 125.09 GeV$, $m_t = 172.5 GeV$



constant shift



sensitivity to Sudakov logarithms

S. Devoto, M. Grazzini, S. Kallweit, J. Mazzitelli and **CS**, *in preparation*

Conclusions

- As the LHC has entered its "precision" phase, more accurate theoretical predictions are of paramount importance
- the current frontier is represented by NNLO corrections for $2 \to 3$ processes with **several massive external legs**

main bottleneck: two-loop amplitudes

- the associated production of a Higgs boson with a top-quark pair ($t\bar{t}H$) belongs to this category and it is crucial for the measurement of the top-Yukawa coupling
- strategy: develop physically motivated, reasonable and reliable **approximations** for the double-virtual contribution

SOFT-BOSON APPROXIMATION MASSIFICATION

- the quantitative impact of the genuine two-loop contribution, in our computation, is relatively **small** (~1% on σ_{NNLO})
- thus we have achieved a **good control** of the systematic uncertainties and a **reduction** of the perturbative uncertainties
- we have "updated" our previous prediction for the total cross section by designing a more solid estimate of the double-virtual contribution based on both approximations
- we have shown **preliminary differential results** for the Higgs transverse momentum (and few other distributions)
- we have included the full tower of **EW corrections**

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THANK YOU!! stay tuned!!