

MiNNLOps for $t\bar{t}H$: first NNLO+PS predictions at the LHC

CHIARA SAVOINI

based on ***JHEP* 06 (2026) 070** in collaboration with
*C. Biello**, *C. Signorile-Signorile* and *M. Wiesemann*

QCD@LHC 2026 — Oxford, October 1st 2026

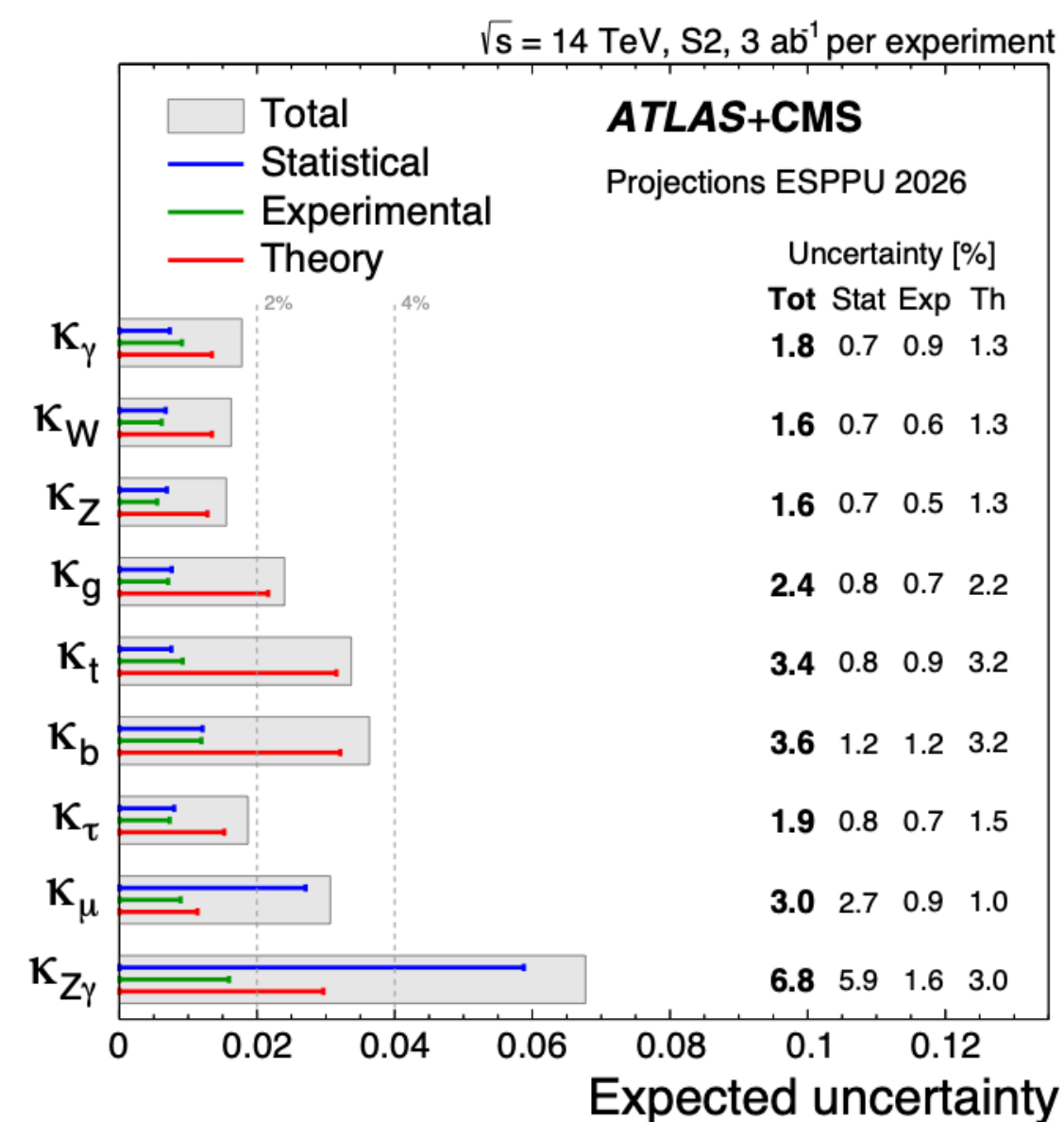
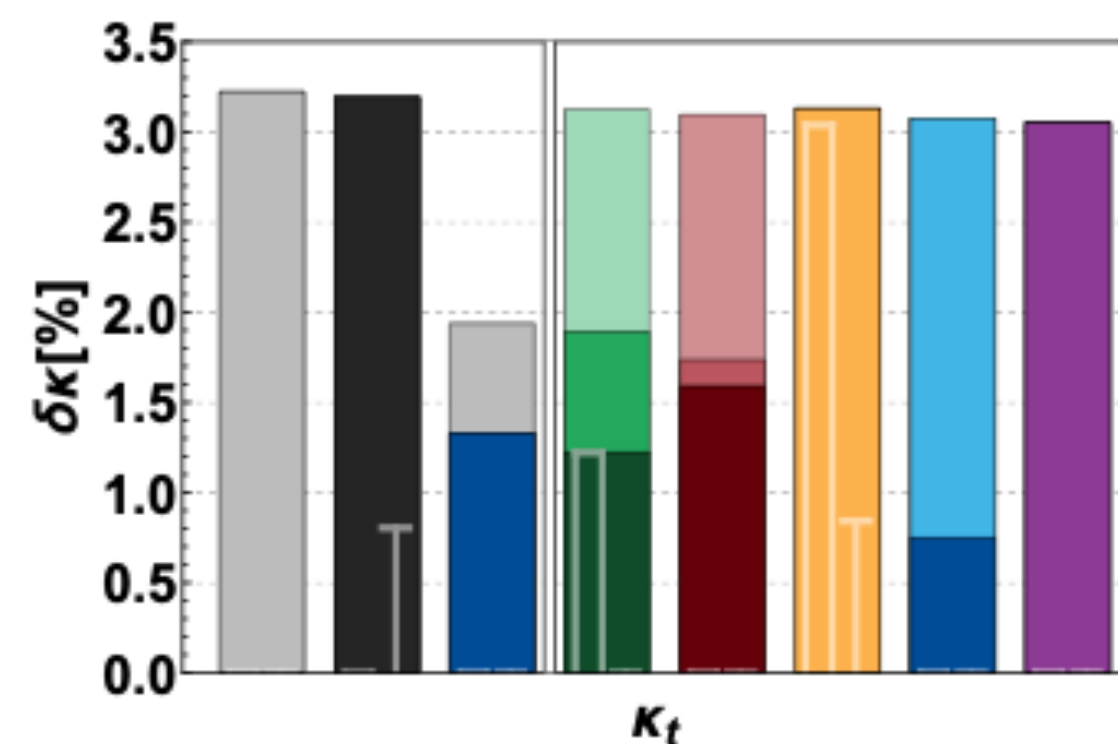
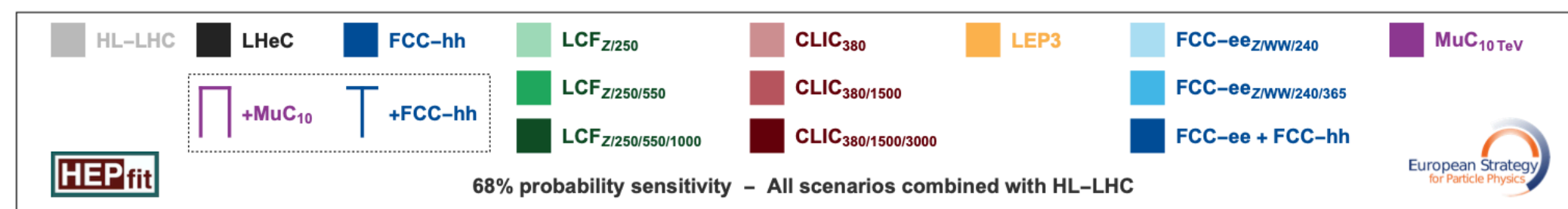
* a special thanks to Christian for the nice drawings!

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

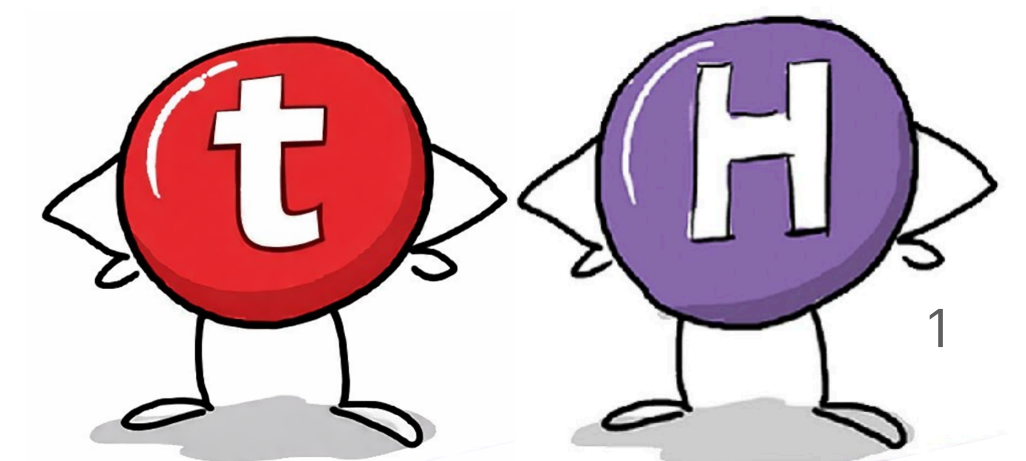
- ▶ the study of the Higgs boson is **one of the priorities** in the LHC experimental program, after its discovery in 2012
- ▶ only about 1 % of the Higgs bosons are produced in association with a top-quark pair (first observation in 2018) but...
- ▶ the production mode $pp \rightarrow t\bar{t}H$ allows for a **direct** measurement of the **top-quark Yukawa coupling**
- ▶ $t\bar{t}H$ is also part of an extremely rich research programme at the core of the **scientific strategy for future colliders**

indirect model-dependent probes are for example the Higgs gluon-fusion production (via a top-quark loop) and $pp \rightarrow t\bar{t}t\bar{t}$ (at tree-level via diagrams featuring an off-shell Higgs propagator)

[Physics Briefing Book (arXiv: 2511.03883)]



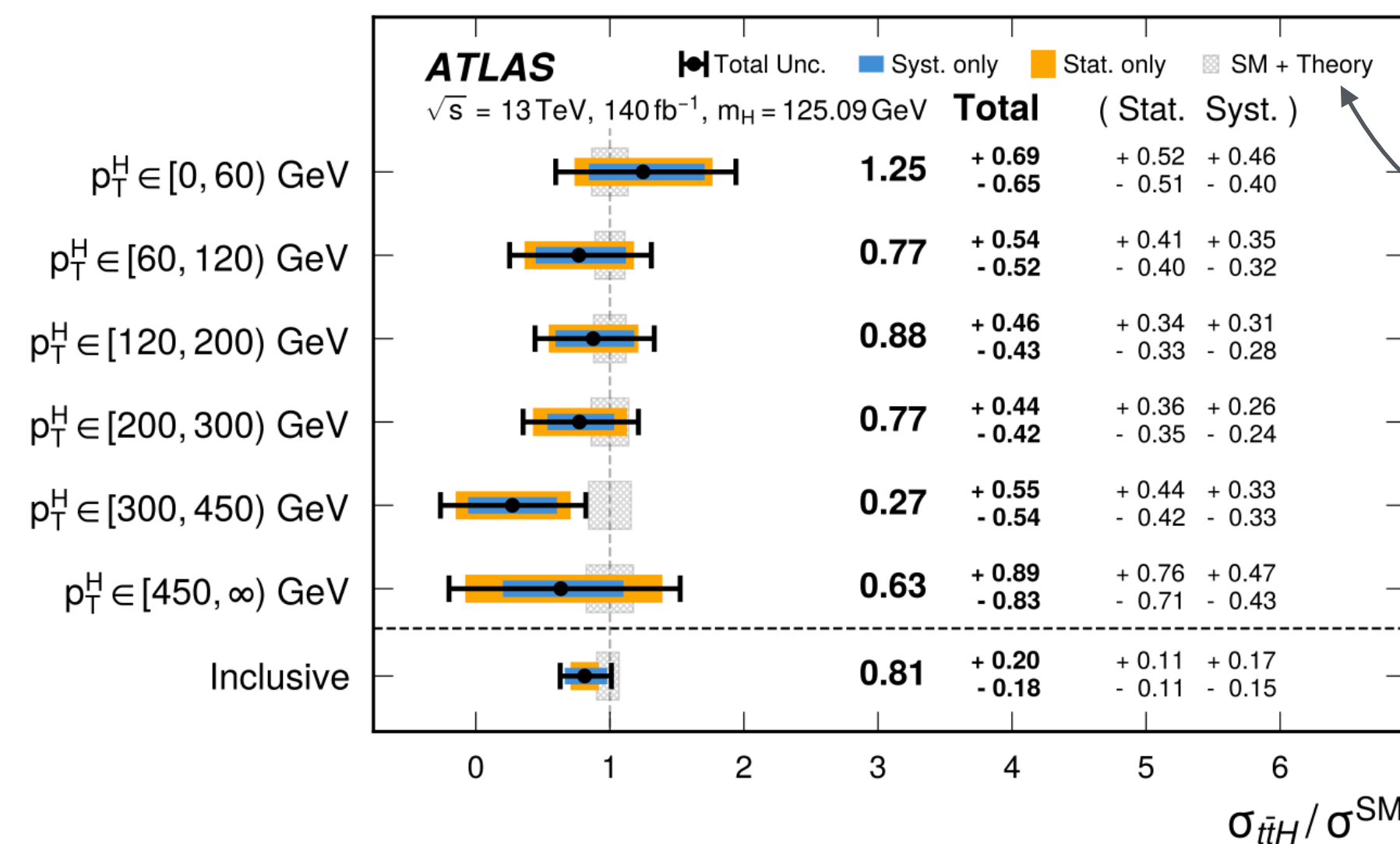
[Highlights of the HL-LHC physics projections by ATLAS and CMS (arXiv: 2504.00672)]



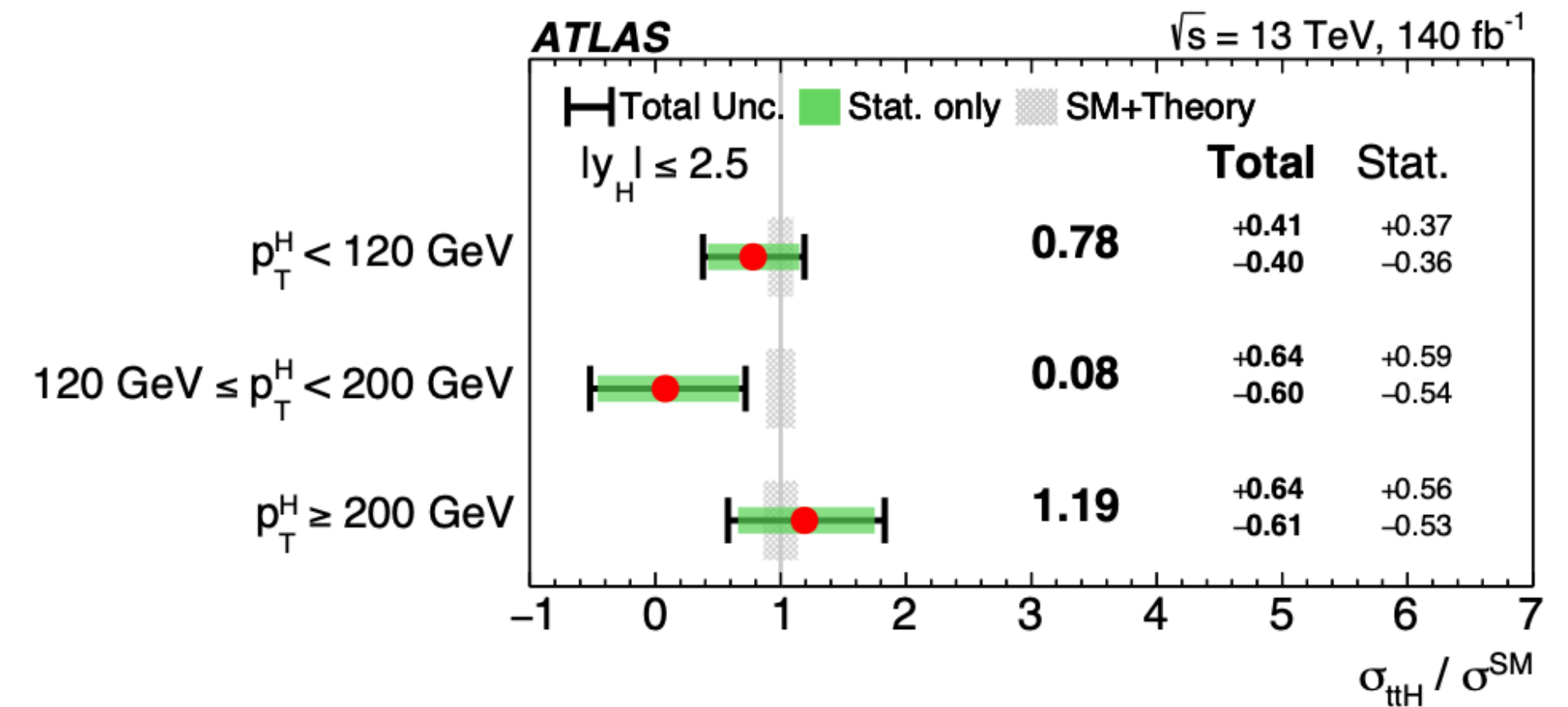
Why is $t\bar{t}H$ production interesting ?

- the experimental measurements are well established at the inclusive level, and the **first differential results** became available

[ATLAS 2407.10904] $H \rightarrow b\bar{b}$ signature (full Run-II)



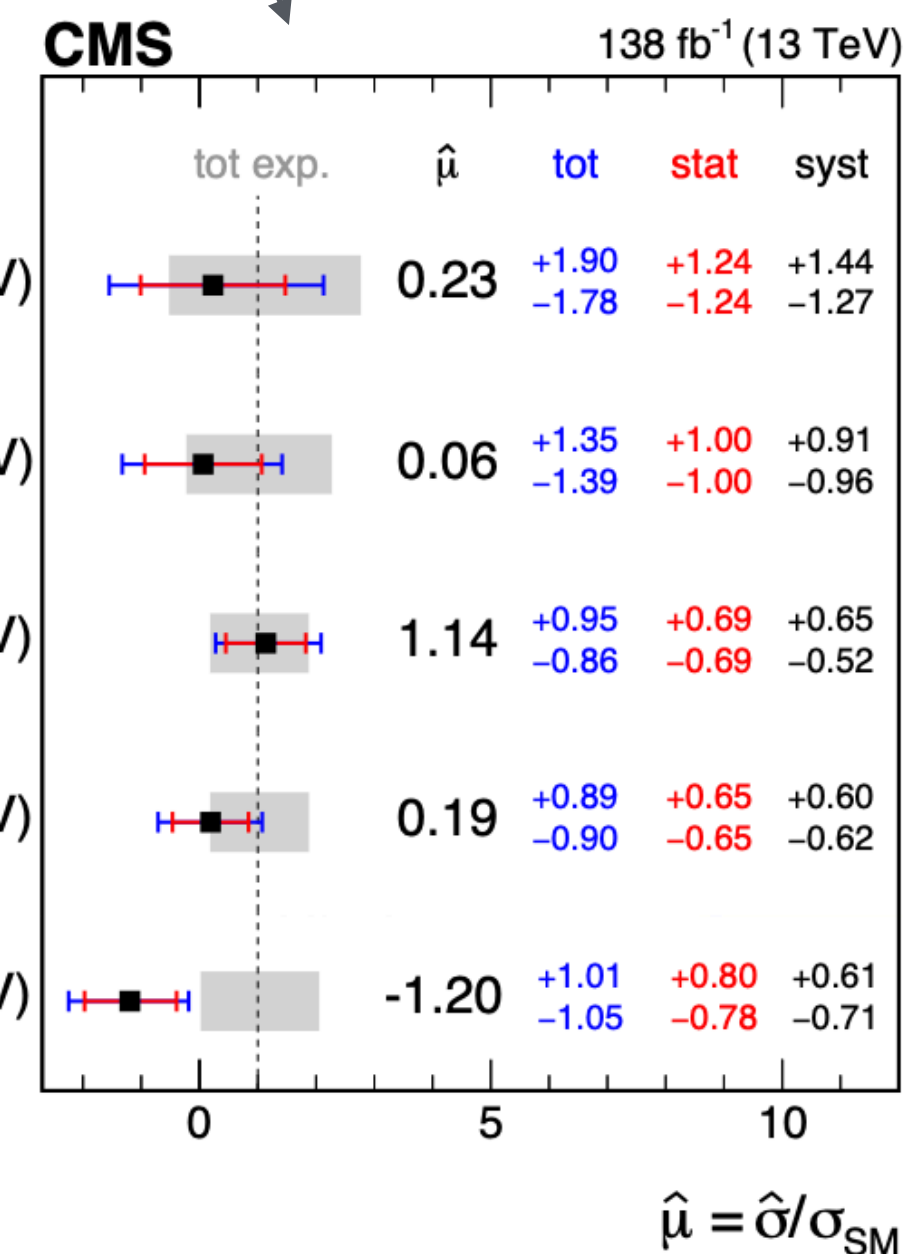
based on the Higgs WG report 2016



[ATLAS 2510.23755]
multi-lepton signature
(full Run-II)

Uncertainty source	$\Delta\sigma_{t\bar{t}H}$ (fb)	$\Delta\sigma_{t\bar{t}H}/\sigma_{t\bar{t}H}$ (%)
Process modelling		
<i>t$\bar{t}$H</i> modelling		
<i>t$\bar{t}$H</i> radiation	+35	-21
<i>t$\bar{t}$H</i> parton shower	+32	-19
<i>t$\bar{t}$H</i> matching	<0.1	-0.3
<i>t$\bar{t}$H</i> theory	+25	-17
<i>t$\bar{t}$ + $\geq 1b$ modelling</i>		
<i>t$\bar{t}$ + $\geq 1b$ radiation</i>	± 31	± 8
<i>t$\bar{t}$ + $\geq 1b$ parton shower</i>	± 29	± 7
<i>t$\bar{t}$ + $\geq 1b$ matching</i>	± 19	± 5

dominant uncertainties

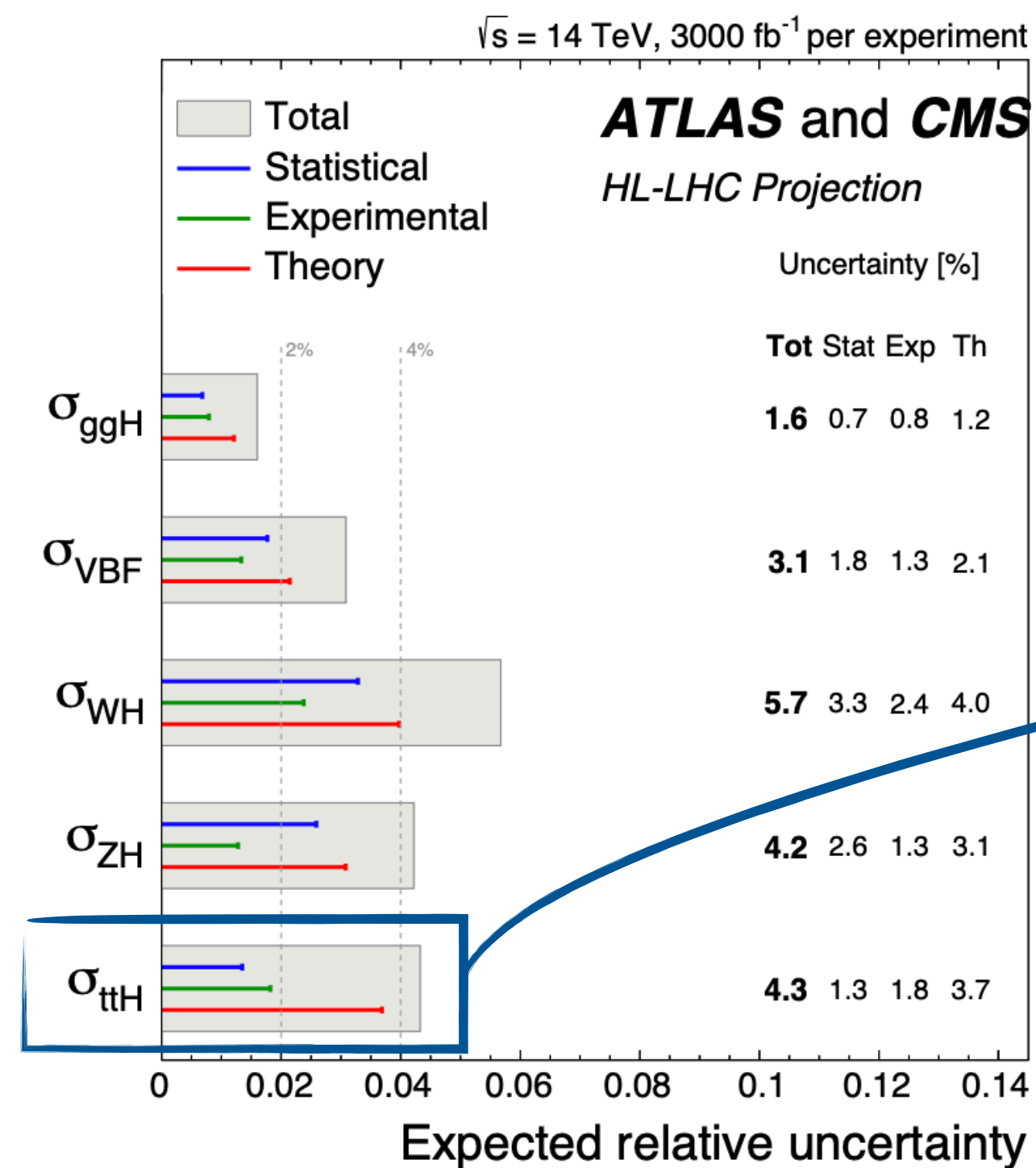


[CMS 2407.10896]
 $H \rightarrow b\bar{b}$ signature

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

- ▶ according to the HL-LHC projections, many Higgs measurements will enter the **few-percent regime**
- ▶ **theory uncertainties** will become **dominant** in the error budget

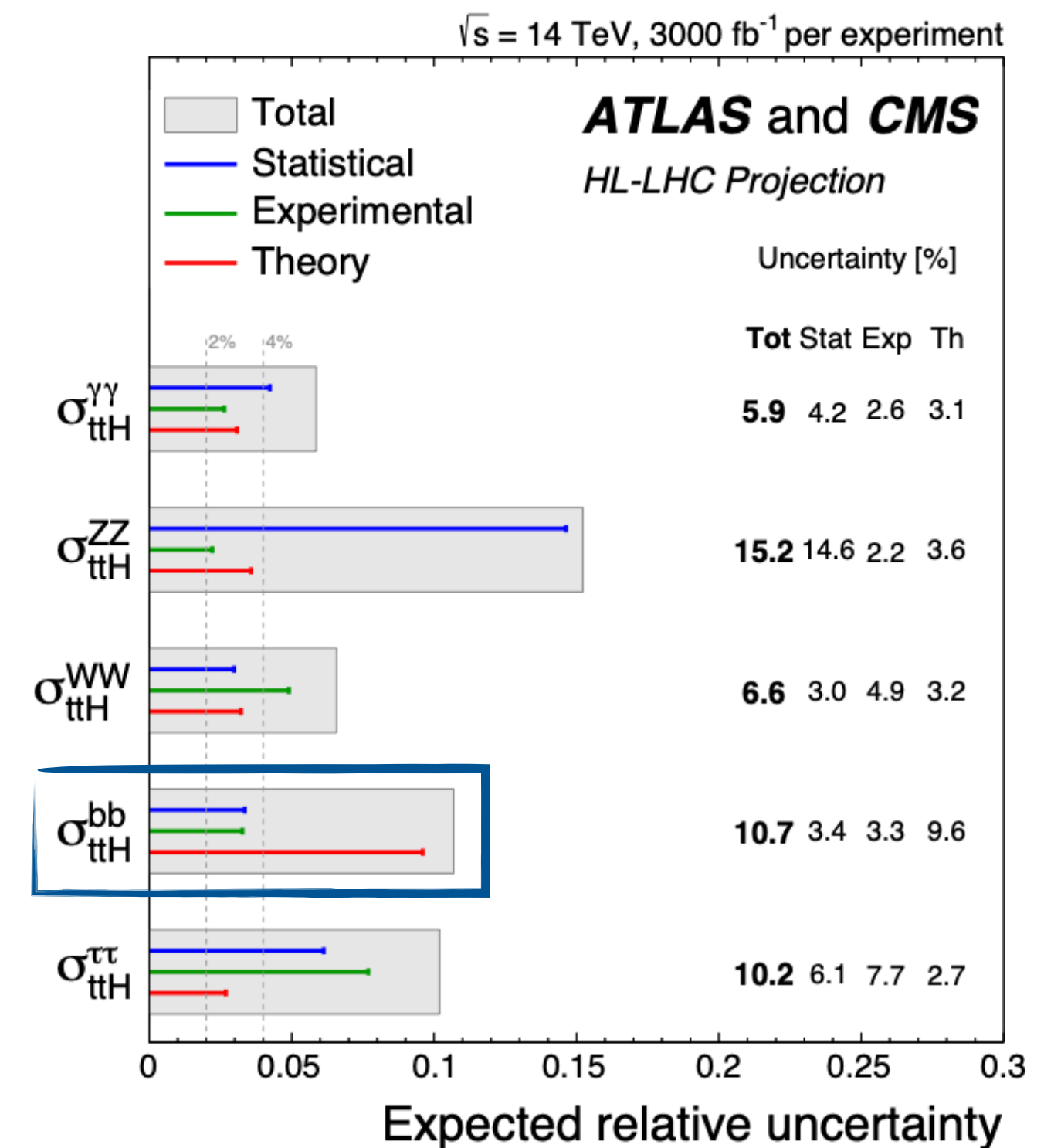
Higgs production modes



[Report from WG2 (arXiv 1902.00134)]

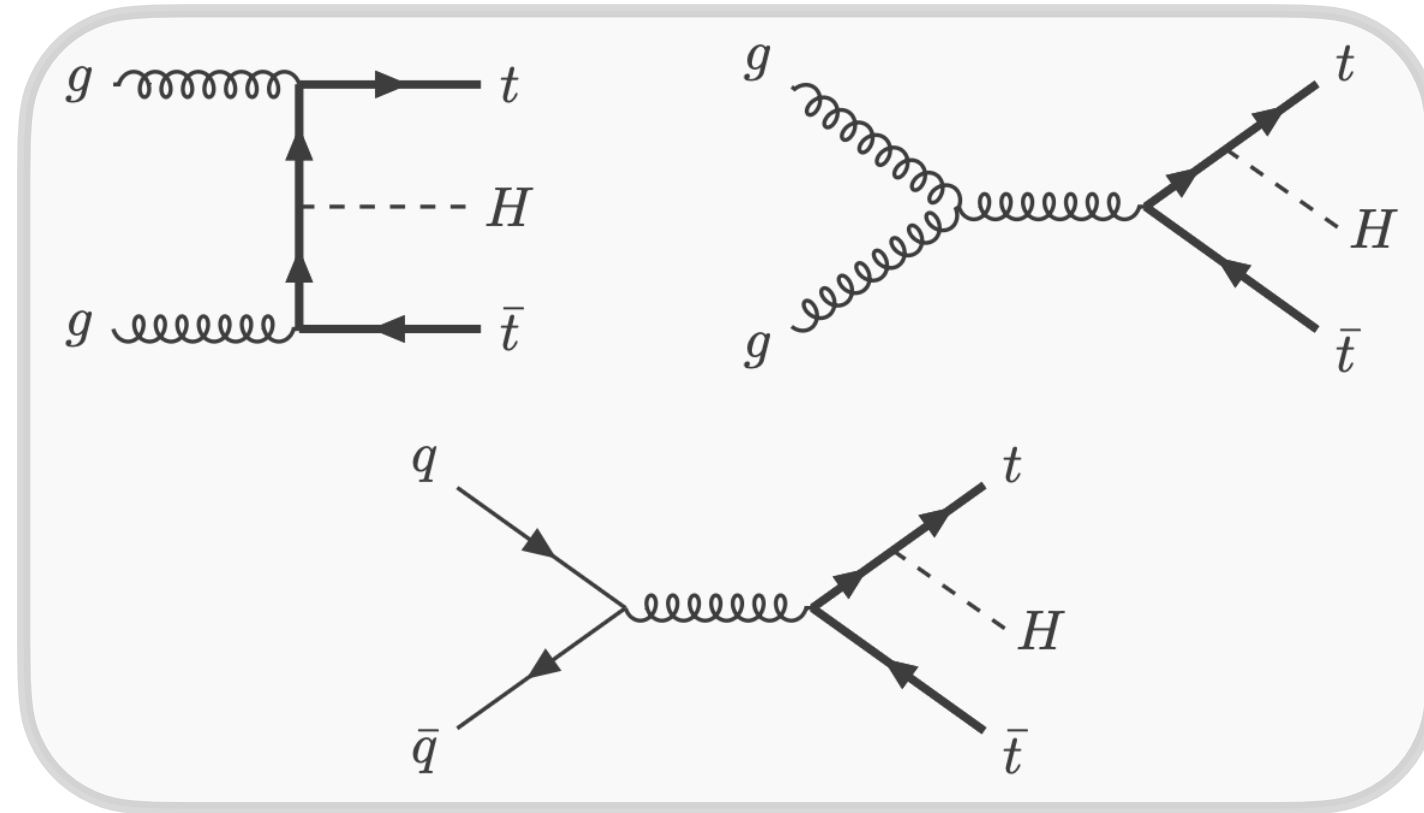
the current experimental accuracy is $\mathcal{O}(20\%)$ but, according to the HL-LHC projections, it is expected to go down to $\mathcal{O}(2\%)$

$t\bar{t}H$ cross-section in the different decay modes



crucial to provide more precise TH predictions: higher-order corrections, realistic modelling of the decay etc.

State-of-the-art of theoretical predictions

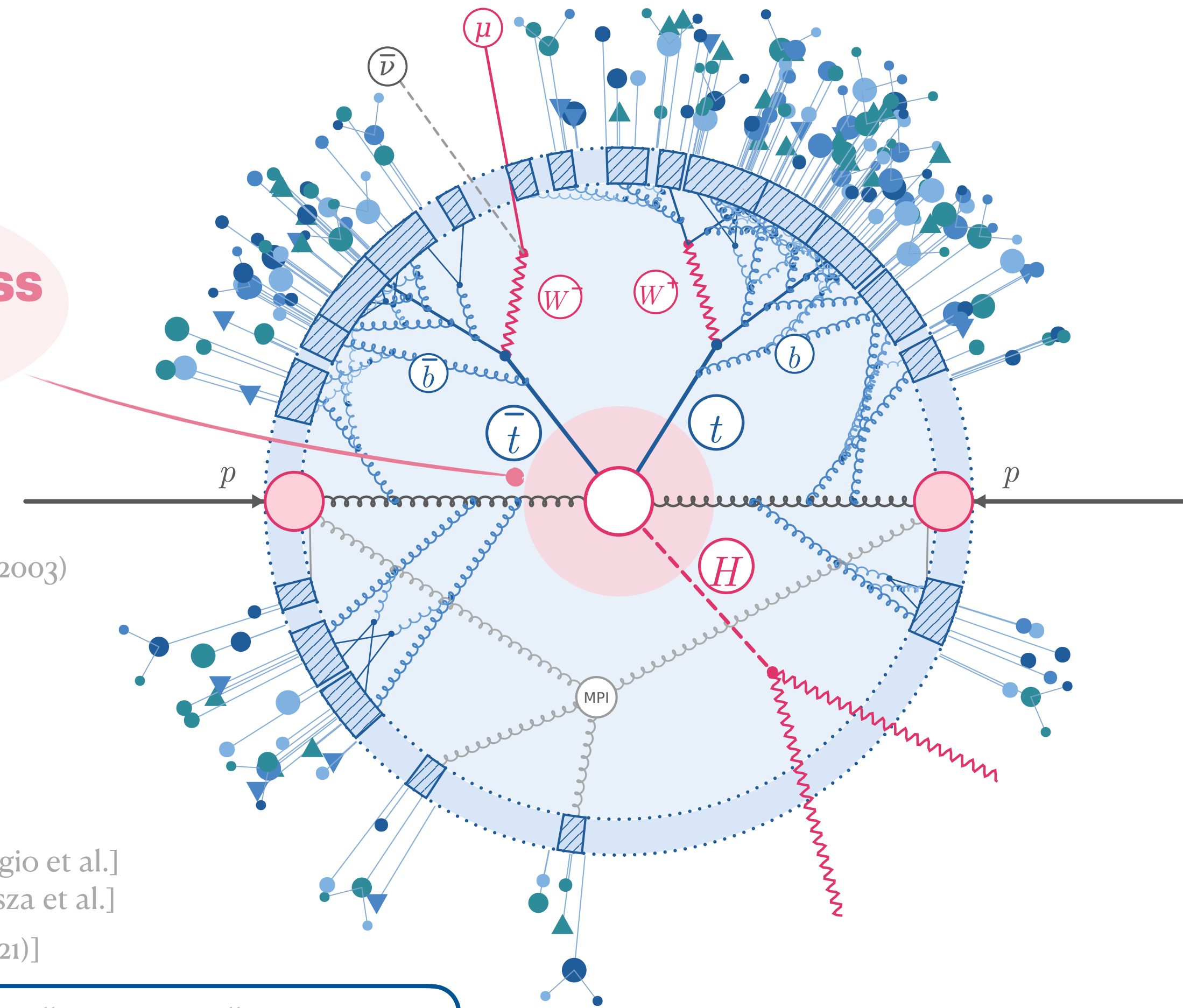


Hard process

✓ High precision

at fixed order:

- ✓ **NLO QCD** corrections (*on-shell top quarks*) [Beenakker, Dittmaier, Krämer, Plumper, Spira, Zerwas (2001,2003)]
- ✓ **NLO EW** corrections (*on-shell top quarks*) [Reina, Dawson, Wackerroth, Jackson, Orr (2001,2003)]
- ✓ **NLO QCD** corrections (*leptonically decaying top quarks*) [Denner, Feger (2015)]
- ✓ **NLO QCD + EW** corrections (*off-shell top quarks*) [Stremmer, Malgorzata (2022)]
- ✓ **NLO QCD + EW** corrections (*on-shell top quarks*), including **NNLL** soft-gluon resummation [Denner, Lang, Pellen, Uccirati (2017)]
- ✓ **NNLO QCD** contributions for the **off-diagonal** partonic channels [Broggio et al.] [Kulesza et al.]
- ✓ **NNLO QCD** contributions for the **off-diagonal** partonic channels [Catani, Fabre, Grazzini, Kallweit (2021)]
- ✓ **complete NNLO QCD** predictions with approximated two-loop amplitudes [Catani, Devoto, Grazzini, Kallweit, Mazzitelli, CS (2022)]
- ✓ + complete set of **EW** corrections [Devoto, Grazzini, Kallweit, Mazzitelli, CS (2024)]
- ✓ + matched with **NNLL resummation** [LHC HWG Report 5 (arXiv: 2503.15043)]



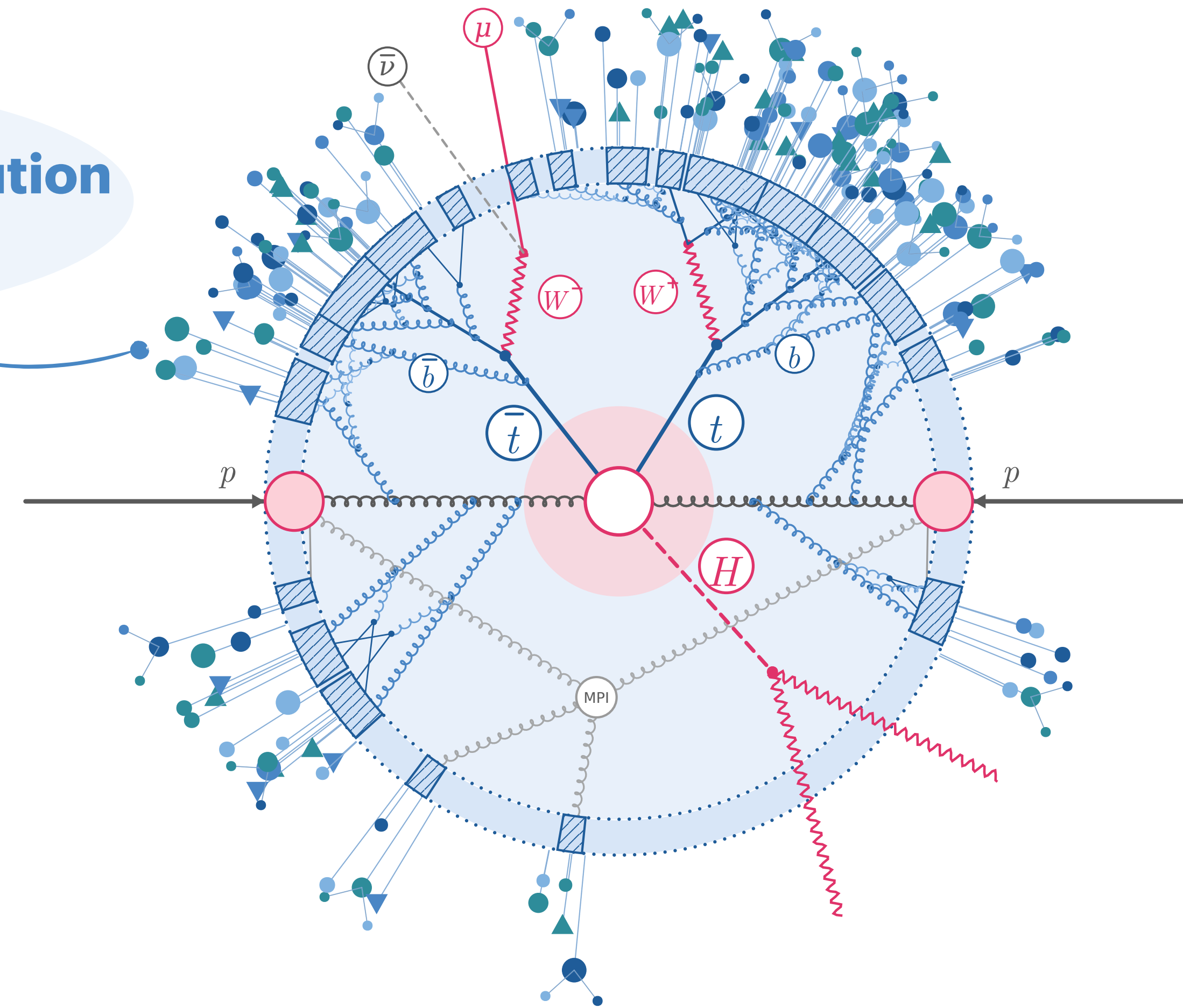
State-of-the-art of theoretical predictions

Parton shower & hadronisation

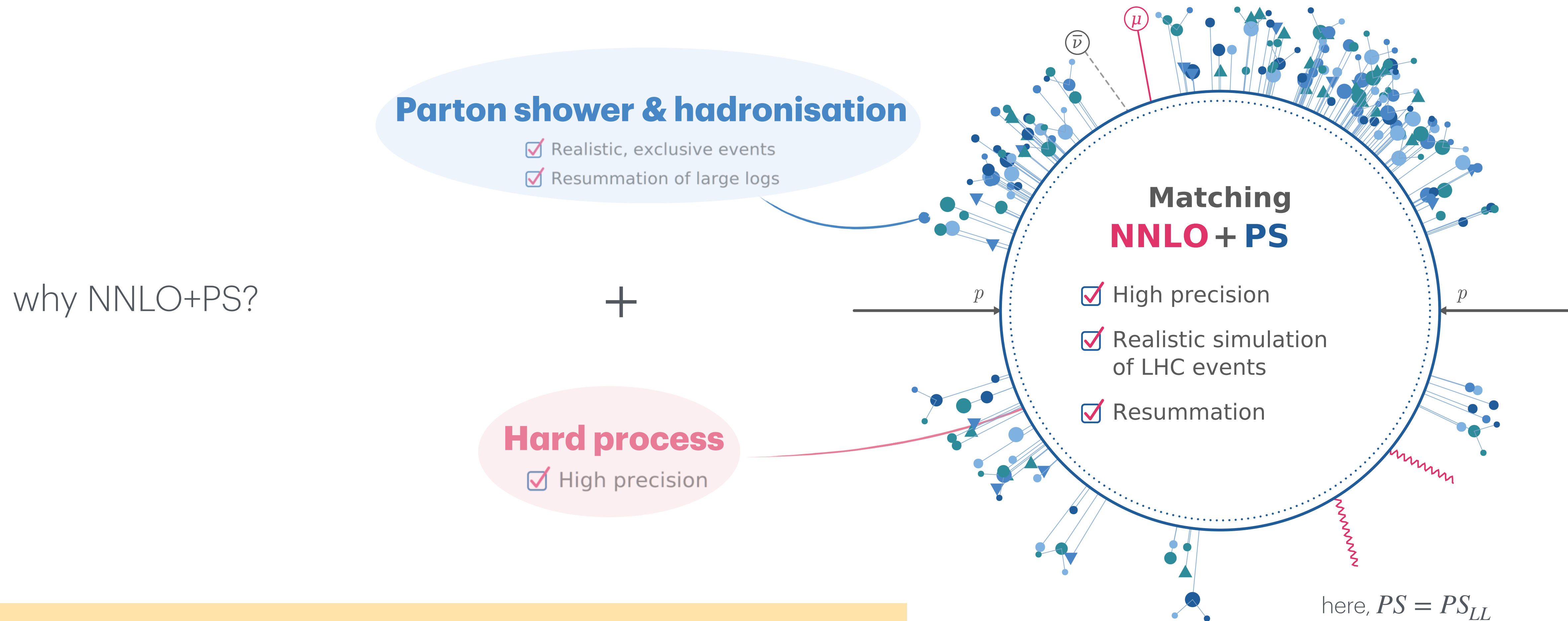
- ✓ Realistic, exclusive events
- ✓ Resummation of large logs

matching with parton showers:

- ✓ **NLO QCD** + PS_{LL} (*on-shell top quarks*) [Frederix, Frixione, Hirschi, Maltoni, Pittau, Torrielli (2011)]
[Hartanto, Jäger, Reina, Wackerath (2015)]



State-of-the-art of theoretical predictions



NNLO+PS is the current state of the art for precision LHC phenomenology

two main approaches: GENEVA [1311.0286] and **MiNNLOps** [1908.06987]

MiNNLOPS method in a nutshell

method: [Monni, Nason, Re, Wieseemann, Zanderighi (2019)]

- it builds on POWHEG [Frixione, Nason, Oleari (2007)]
 - ✓ for a given process X , NLO accuracy for the process XJ
 - ✓ natural matching with the first additional shower radiation
- intermediate MiNLO' step [Hamilton, Nason, Oleari, Zanderighi (2012, 2013)]
 - ✓ NLO accuracy for the targeted process X via a factorised Sudakov form factor and prescription for scale setting
- spreading of additional contributions to reach NNLO accuracy for X

accuracy:

- ✓ **NNLO** for observables inclusive over QCD emissions
- ✓ **NLO** for observables sensitive to one resolved jet
- ✓ leading logarithmic structure of traditional parton showers is preserved
- ✓ efficient and flexible framework

master formula:

$$d\sigma_X^{\text{MiNNLOPS}} = d\Phi_{XJ} \bar{B}^{\text{MiNNLOPS}} \times \left\{ \Delta_{\text{pwg}}(\Lambda_{\text{pwg}}) + d\Phi_{\text{rad}} \Delta_{\text{pwg}}(p_{T,\text{rad}}) \frac{R_{XJ}}{B_{XJ}} \right\}$$

POWHEG Sudakov

$$\bar{B}^{\text{MiNNLOPS}} \sim e^{-\tilde{S}(p_T)} \left\{ \frac{\alpha_s(p_T)}{2\pi} d\sigma_{XJ}^{(1)} \left(1 + \frac{\alpha_s(p_T)}{2\pi} \tilde{S}^{(1)}(p_T) \right) + \left(\frac{\alpha_s(p_T)}{2\pi} \right)^2 d\sigma_{XJ}^{(2)} + \underbrace{D^{(\geq 3)}(p_T)}_{\text{singular and constant terms in } p_T} \times F^{\text{corr}} \right\}$$

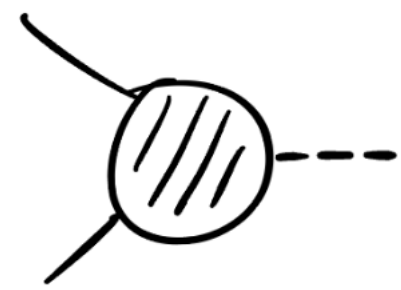
modified POWHEG function

transverse-momentum Sudakov

spreading function

MiNNLOPS method in a nutshell

method: [Monni, Nason, Re, Wieseemann, Zanderighi (2019)]



$gg \rightarrow H, W/Z$ [1908.06987, 2006.04133, 2402.00596, 2407.01354]

$q\bar{q} \rightarrow H$ [2402.04025, 2510.18815, to appear]

$Z\gamma$ [2010.10478, 2108.11315]

WW [2103.12077]

ZZ [2108.05337]

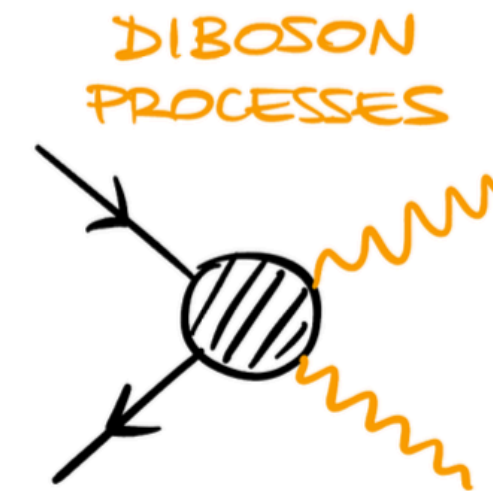
$WH/ZH(H \rightarrow b\bar{b})$ [2112.04168]

$\gamma\gamma$ [2204.12602]

WZ [2208.12660]

SMEFT studies [2204.00663, 2311.06107]

HH [2606.05300] see F. Garosi's talk



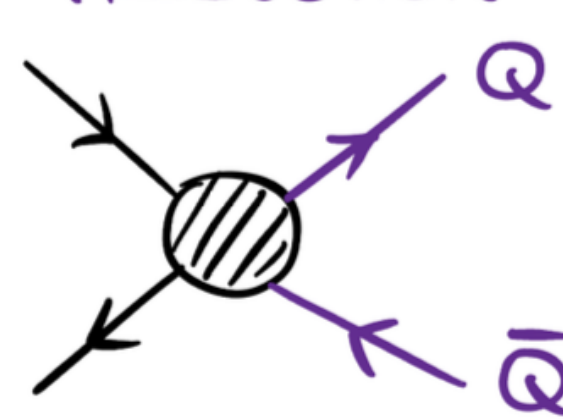
accuracy:

- ✓ **NNLO** for observables inclusive over QCD emissions
- ✓ **NLO** for observables sensitive to one resolved jet
- ✓ leading logarithmic structure of traditional parton showers is preserved
- ✓ efficient and flexible framework

applications in hadronic collisions:

several processes with different features and increasing complexity

HEAVY-QUARK PRODUCTION



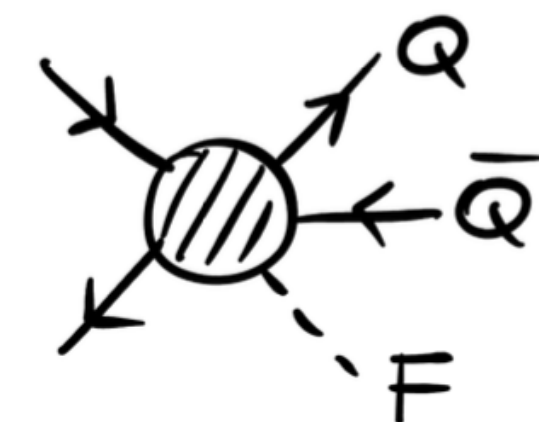
$t\bar{t}$ [2012.14267, 2112.12135]

$b\bar{b}$ [2302.01645]

$b\bar{b}Z$ [2404.08598]

$b\bar{b}H$ [2412.09510]

this talk! $t\bar{t}H$ [2603.06143]



possible thanks to the two-loop soft-function in arbitrary kinematics [2509.17509]

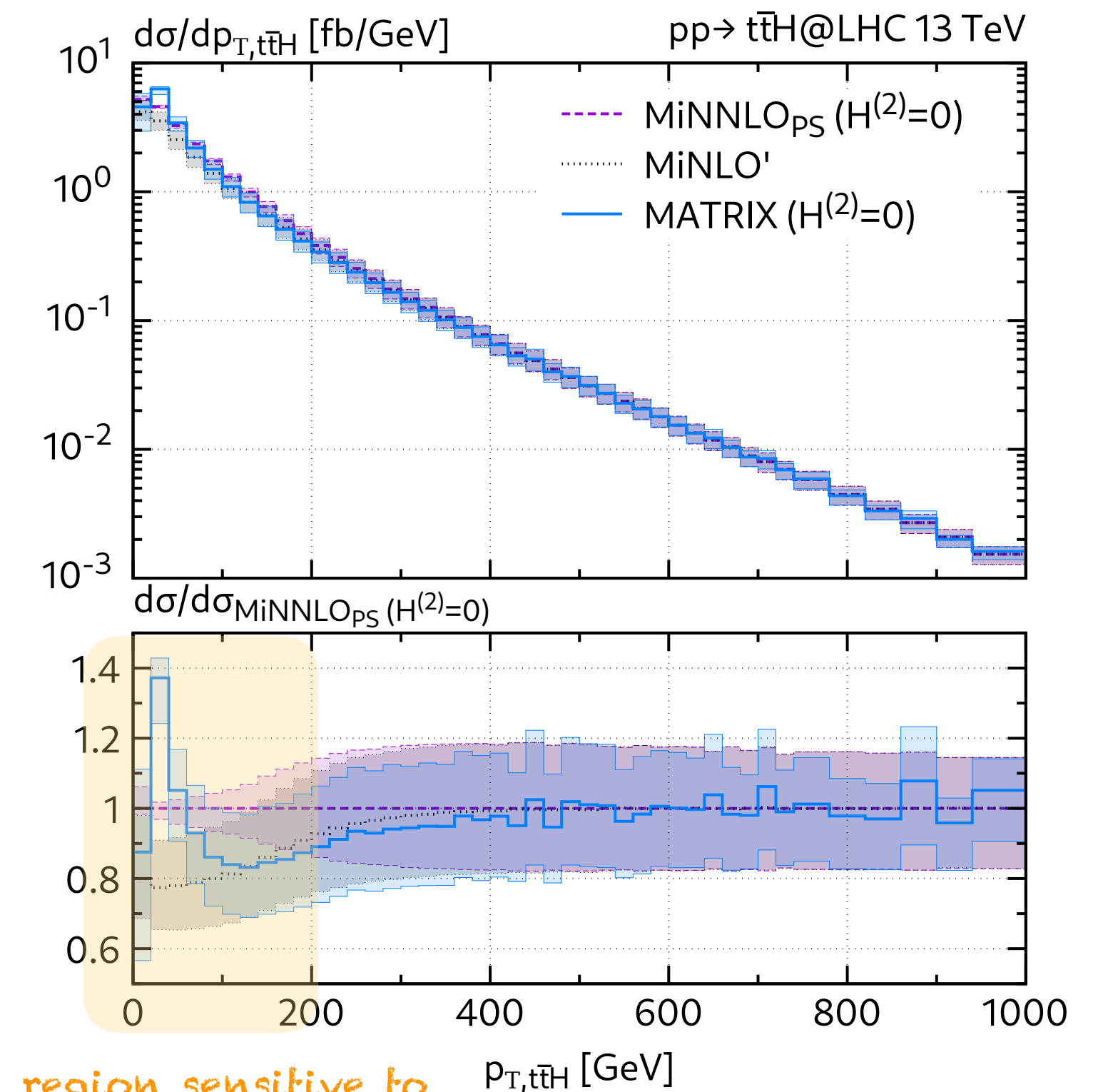
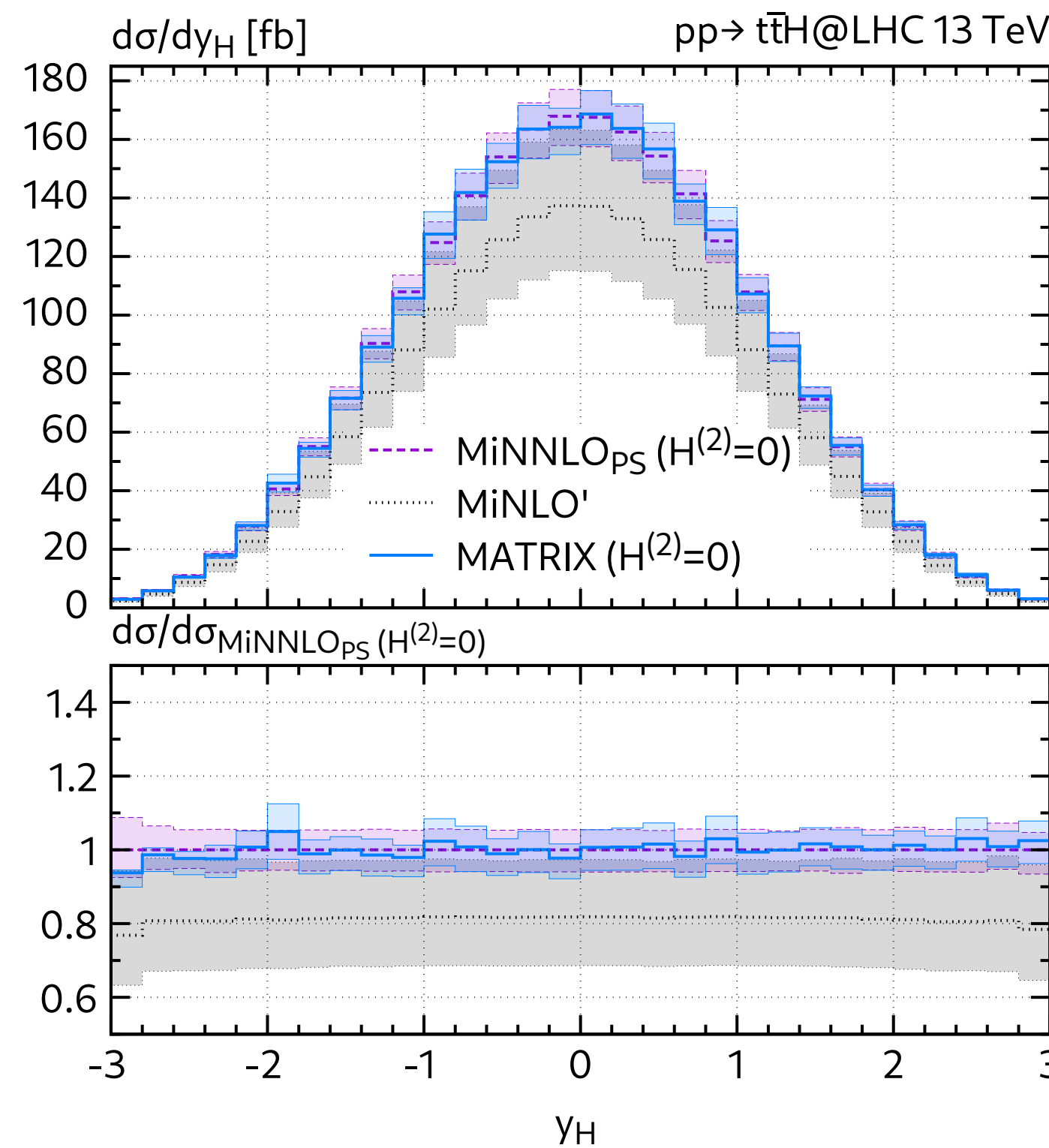
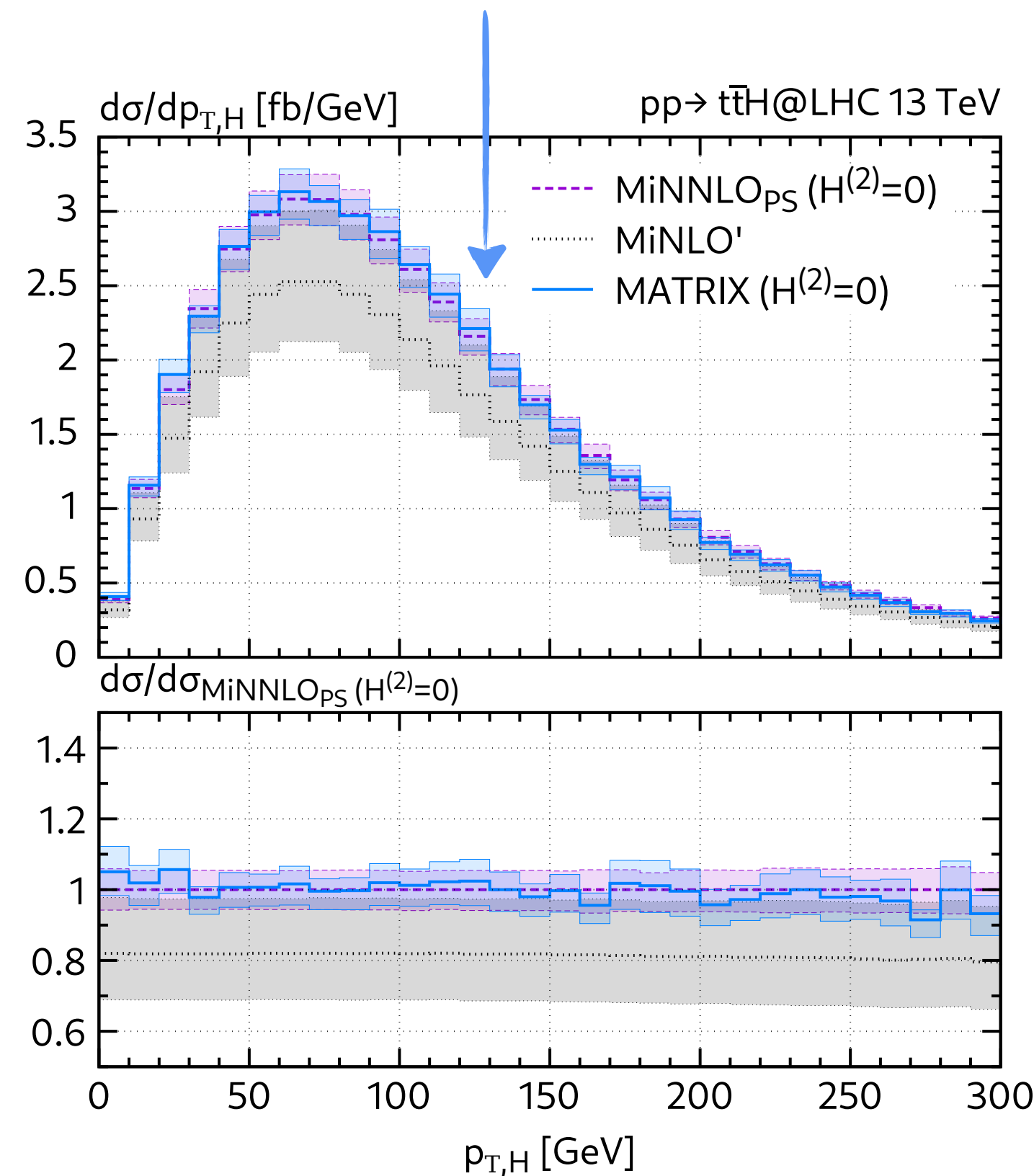
Validation against fixed-order predictions

setup: NNPDF31_nnlo_as_0118, $m_H = 125\text{GeV}$, $m_t = 173.2\text{GeV}$, $\mu_R = \mu_F = m_{t\bar{t}H}$

same setup as ref. 2411.15340 except for the scale choice

extensive comparisons against MATRIX
(without including the two-loop contribution)

	MINLO'	MINNLO _{PS} ($\mathbb{H}^{(2)} = 0$)	MATRIX ($\mathbb{H}^{(2)} = 0$)
$\sigma_{\text{inclusive}}^{t\bar{t}H}(\sqrt{s} = 13\text{ TeV})$	$0.3864(2)^{+19.2\%}_{-16.2\%}\text{ pb}$	$0.4734(2)^{+5.4\%}_{-5.9\%}\text{ pb}$	$0.4742(9)^{+4.7\%}_{-6.0\%}\text{ pb}$



region sensitive to
resummation effects

KEY VALIDATION STEP: first time a QGF process is compared against a fixed-order prediction to assess the NNLO accuracy of the matched calculation

The two-loop bottleneck and its approximation

Two-Loop Master Integrals for Leading-Color $pp \rightarrow t\bar{t}H$ Amplitudes with a Light-Quark Loop

F. Febres Cordero, G. Figueiredo, M. Kraus, B. Page, L. Reina

Two-loop amplitudes for $t\bar{t}H$ production: the quark-initiated N_f -part

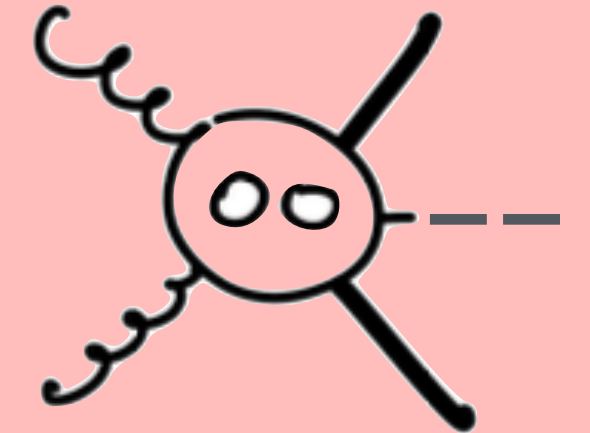
Bakul Agarwal, Gudrun Heinrich, Stephen P. Jones, Matthias Kerner, Sven Yannick Klein, Jannis Lang, Vitaly Magerya, Anton Olsson

Two-loop QCD amplitudes for $t\bar{t}H$ production from boosted limit

Guoxing Wang, Tianya Xia, Li Lin Yang, Xiaoping Ye

One loop QCD corrections to $gg \rightarrow t\bar{t}H$ at $\mathcal{O}(\epsilon^2)$

Federico Buccioni, Philipp Alexander Kreer, Xiao Liu, Lorenzo Tancredi



double-virtual

THE BOTTLENECK

- algebraic complexity: proliferation of scales
- analytic complexity: new mathematical structures (elliptic and beyond)
- difficulty in finding amplitude representations that lead to a numerically stable evaluation for pheno applications

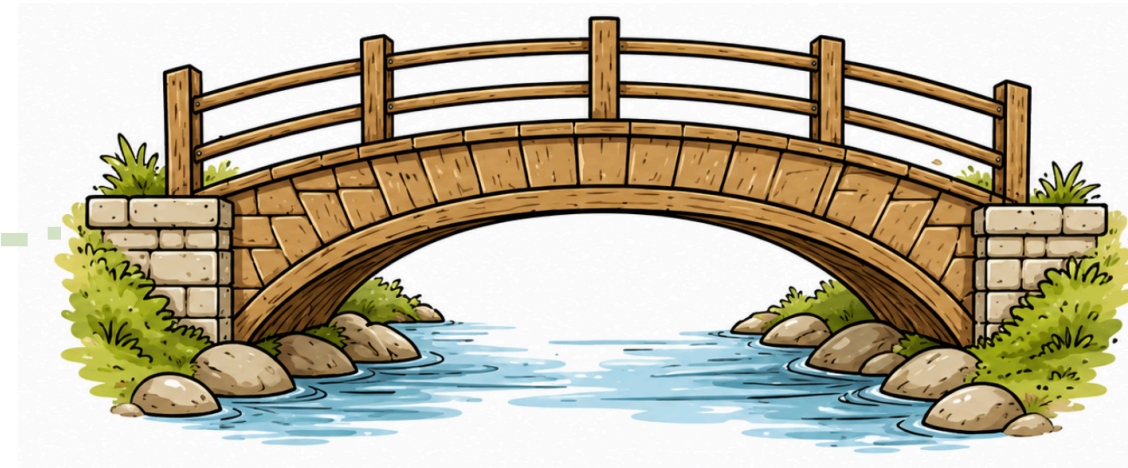


The two-loop bottleneck and its approximation

A VIABLE SOLUTION

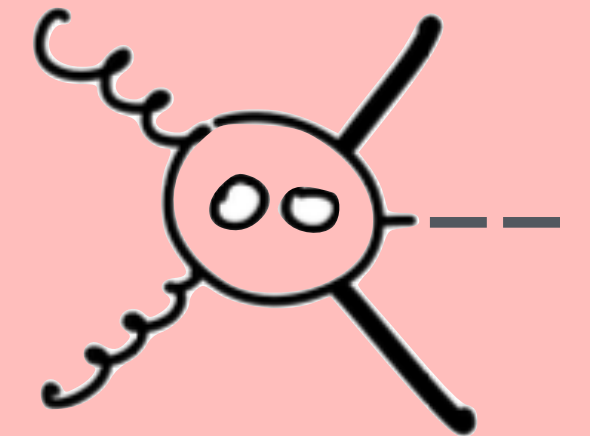


- develop controlled, physically motivated and reliable approximations
- assign a conservative and transparent systematic uncertainty, via a thorough validation
- ensure consistency with known constraints



PHENOMENOLOGICAL PREDICTIONS for XS
and related observables, ready to use!

THE BOTTLENECK



double-virtual

- algebraic complexity: proliferation of scales
- analytic complexity: new mathematical structures (elliptic and beyond)
- difficulty in finding amplitude representations that lead to a numerically stable evaluation for pheno applications



Approximation methods bridge the gap between formal complexity and desired phenomenological precision. However, exact results are crucial for “final” checks and should be incorporated as soon as they become available

The two-loop bottleneck and its approximation

Soft Higgs-boson approximation (SA)

based on LETs [Kniehl, Spira (1995)]

$$\lim_{q \rightarrow 0} \mathcal{A}^{\text{bare}} \xrightarrow{i} q \sim \underbrace{\mathcal{J}^{(0)}(q)}_{\frac{m}{v} \left(\sum_i \frac{m}{q \cdot p_i} \right)} \mathcal{A}^{\text{bare}}$$

$$\text{Diagram: } \text{Loop with } t, \bar{t}, H \sim \underbrace{\mathcal{F}(\alpha_s(\mu^2), \mu/m)}_{\text{soft limit of the heavy-quark scalar form factor}} \mathcal{J}^{(0)}(p_H) \text{Diagram: } \text{Loop with } t, \bar{t}$$

from grids

[Bernreuther et al. (2005)]
[Blümlein et al. (2017)]
[Fael et al. (2022, 2023)]

$t\bar{t}$: [Bärnreuther, Czakon, Fiedler (2013)]
[Chen, Czakon, Poncelet (2017)]

The approximations depend on **kinematical mappings**:
we have used the MATRIX choices [2411.15340] based on
detailed studies for $t\bar{t}H$ at next-to-leading order

High-energy limit for the top quarks (MA)

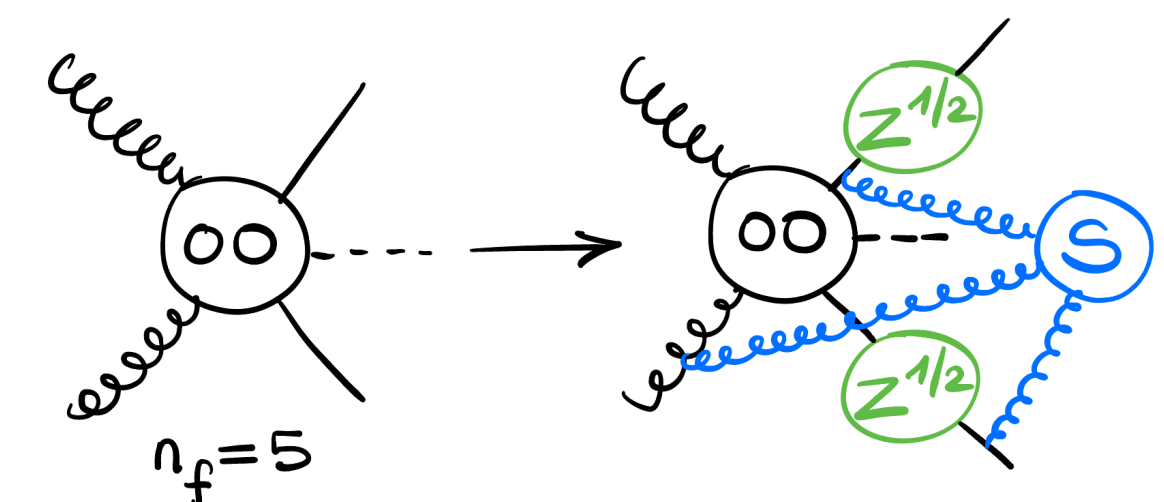
$$\text{Diagram: } \text{Loop with } t, \bar{t} = \left[\mathcal{F}^{(2)} \left(\log \left(\frac{m_t}{\mu} \right) \right) + \mathcal{S}^{(2)} \left(\frac{m_t}{\mu}, \{p\} \right) \right] \text{Diagram: } \text{Loop with } t, \bar{t}, m_t=0$$

$$+ \mathcal{F}^{(1)} \left(\log \left(\frac{m_t}{\mu} \right) \right) \text{Diagram: } \text{Loop with } t, \bar{t}, m_t=0 + \underbrace{\text{Diagram: } \text{Loop with } t, \bar{t}, m_t=0}_{2 \rightarrow 3 \text{ two-loop with massless tops}} + \mathcal{O} \left(\frac{m_t}{\mu} \right)$$

$b\bar{b}H$: [Badger et al. (2021), (2024)]

via the massification procedure:

[Moch, Mitov (2007)] [Wang et al. (2023)]



The two-loop bottleneck and its approximation

Pointwise combination (CA)

► **NEW** wrt *a posteriori* combinations adopted in fixed-order calculations

✓ kinematic-dependent weight function, defined for each phase-space point

► **advantages** of this procedure for an event generator:

✓ computational efficiency [it avoids the generation of two independent sets of events, one for each approximation]

✓ better control over the validity regions of the approximate double virtual [this info is “lost” at the level of unweighed events]

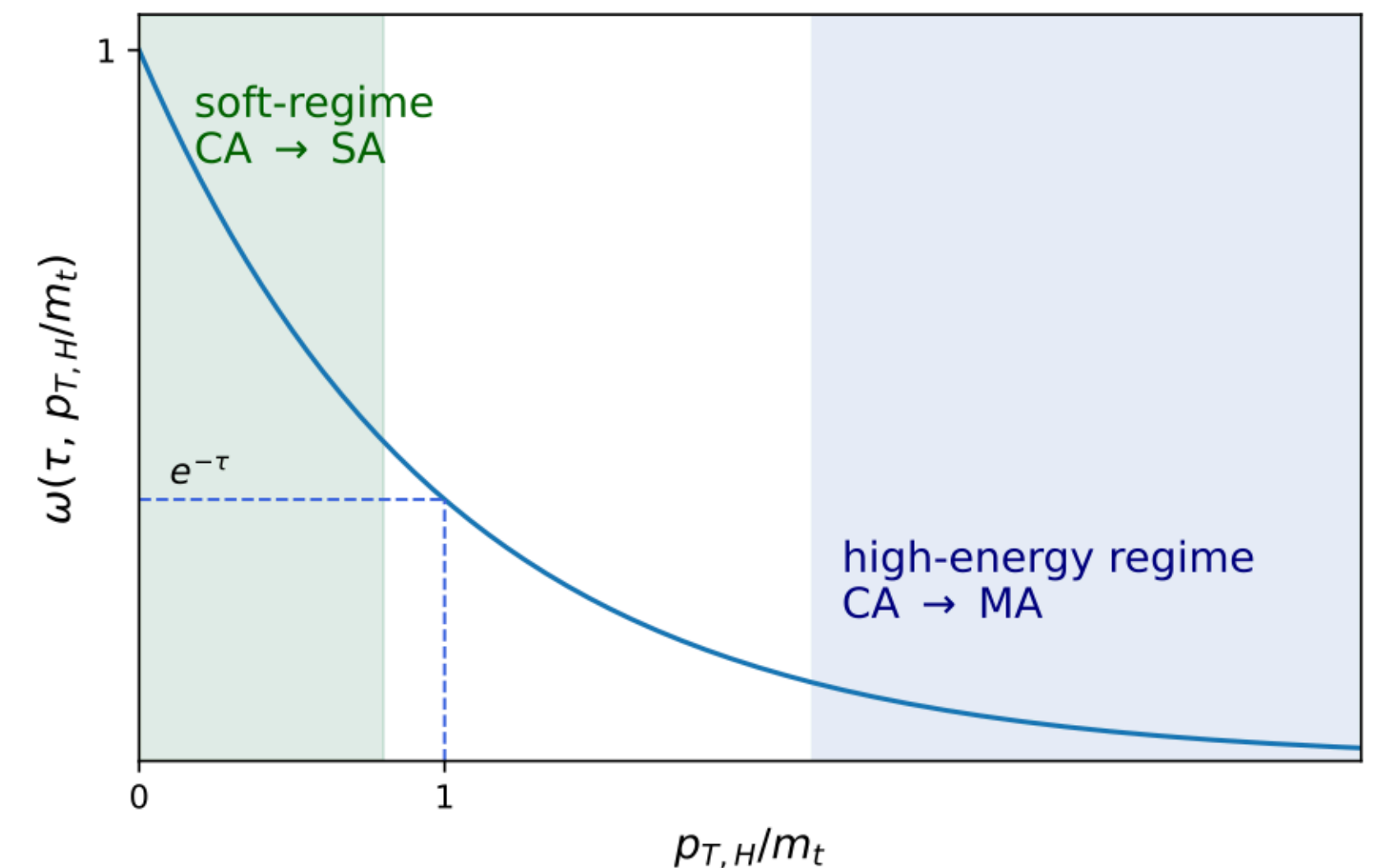
✓ reliable and practical uncertainty estimate covering all kinematic regions

conservative error estimate

- ✦ variation of the scale $\mu_{\text{IR}} = \eta m_{t\bar{t}H}$, with $\eta \in \{1/2, 1, 2\}$, at which CA is applied
- ✦ variation of the parameter τ (entering the def of ω) by a factor of 2 around the default value $\tau = 1$
- ✦ propagation of the one-loop discrepancy $\delta = |\mathbb{H}_{\text{CA}}^{(1)}(m_{t\bar{t}H})/\mathbb{H}^{(1)}(m_{t\bar{t}H}) - 1|$ as relative uncertainty at two loops

⇒ final uncertainty band given by the **envelope of these 11 predictions**

“calibration” observable: Higgs transverse momentum



$$\mathbb{H}_{\text{CA}}^{(n)}(\mu_{\text{IR}}) = \omega \mathbb{H}_{\text{SA}}^{(n)}(\tilde{\mathbb{P}}[\mu_{\text{IR}}]) + (1 - \omega) \mathbb{H}_{\text{MA}}^{(n)}(\bar{\mathbb{P}}[\mu_{\text{IR}}])$$

smooth weight function

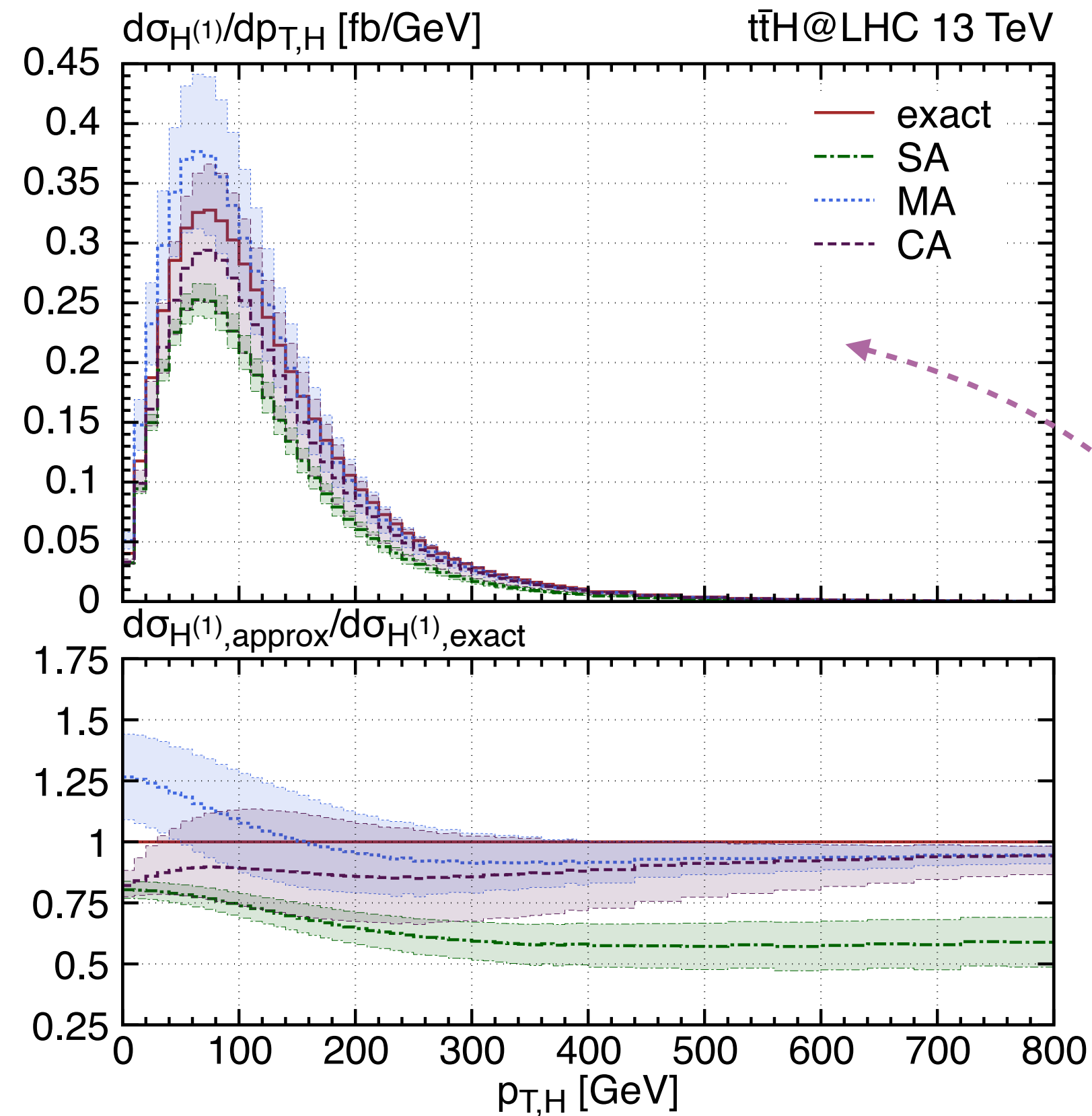
$$\omega(\tau, p_{T,H}/m_t) = \exp(-\tau p_{T,H}/m_t)$$

first time MA entirely in FC

Validation at NLO+PS

setup: NNPDF31_nnlo_as_0118, $m_H = 125\text{GeV}$, $m_t = 173.2\text{GeV}$, $\mu_R = \mu_F = m_{t\bar{t}H}$

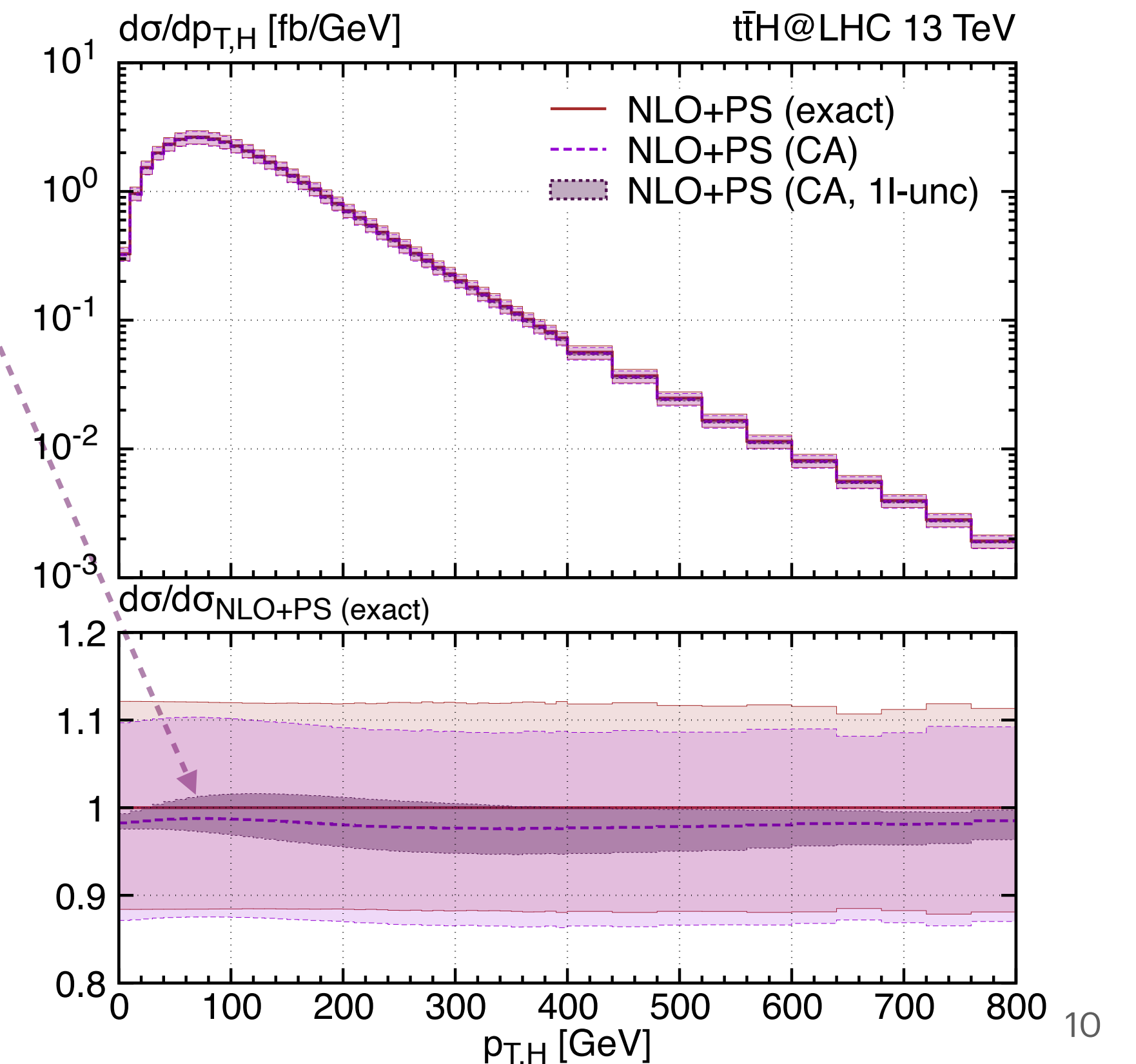
Higgs transverse momentum



$$d\sigma_{H^{(1)}} = \frac{\alpha_s(M)}{2\pi} \mathbb{H}^{(1)}(M) d\sigma_{\text{LO}}$$

- ▶ overall good agreement of CA at the one-loop level
- ▶ $\sim 2\%$ differences at NLO+PS accuracy
- ▶ conservative systematic uncertainty

- ▶ SA severely **underestimates** the exact one-loop result (in the whole range) with unreliable uncertainty bands
- ▶ MA **overestimates** in the low- $p_{T,H}$ region, but **asymptotically tends** to the exact result (as expected) and the corresponding uncertainty shrinks
- ▶ by construction, CA is driven by SA (MA) in the low (high) $p_{T,H}$ region



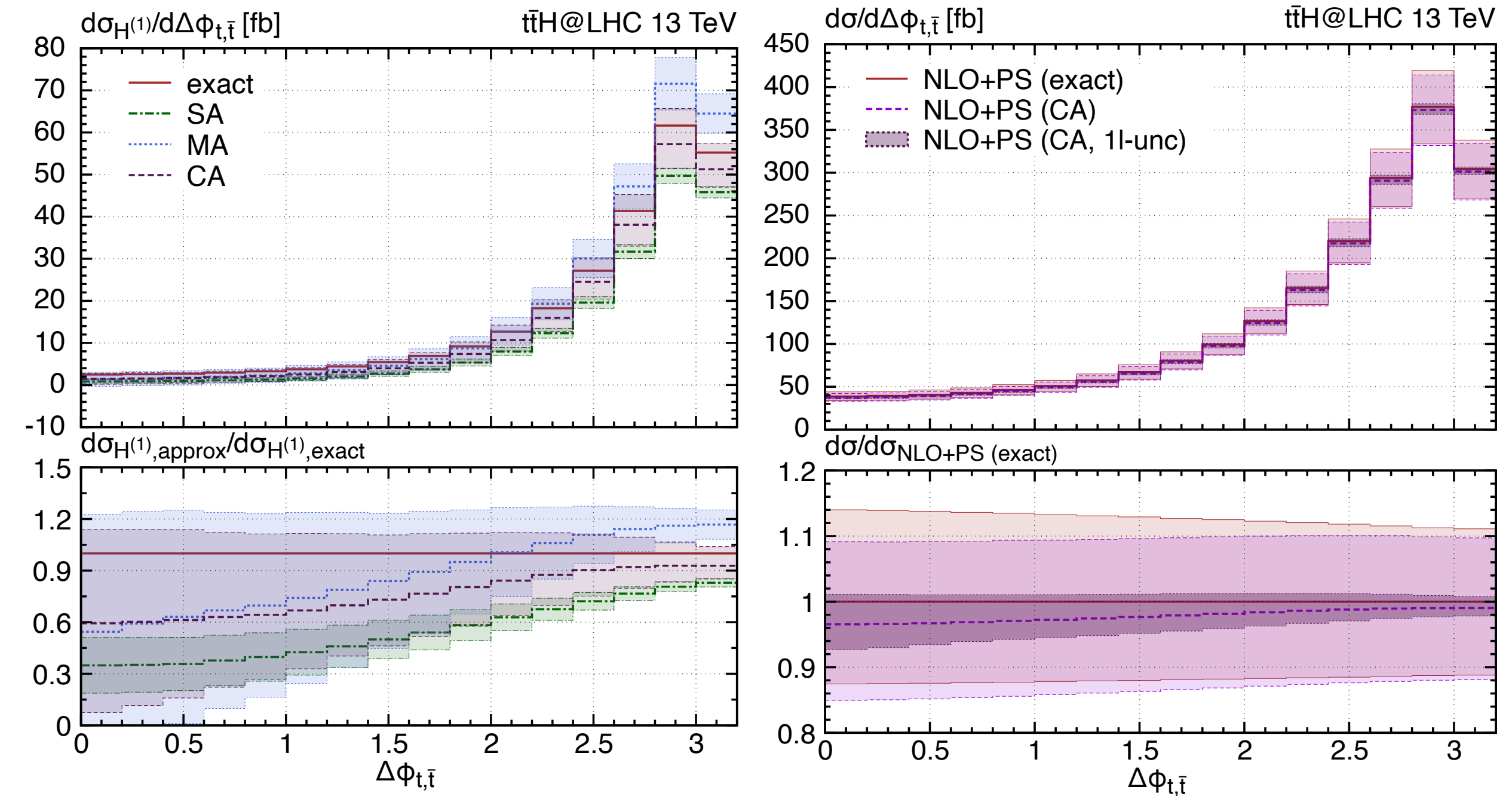
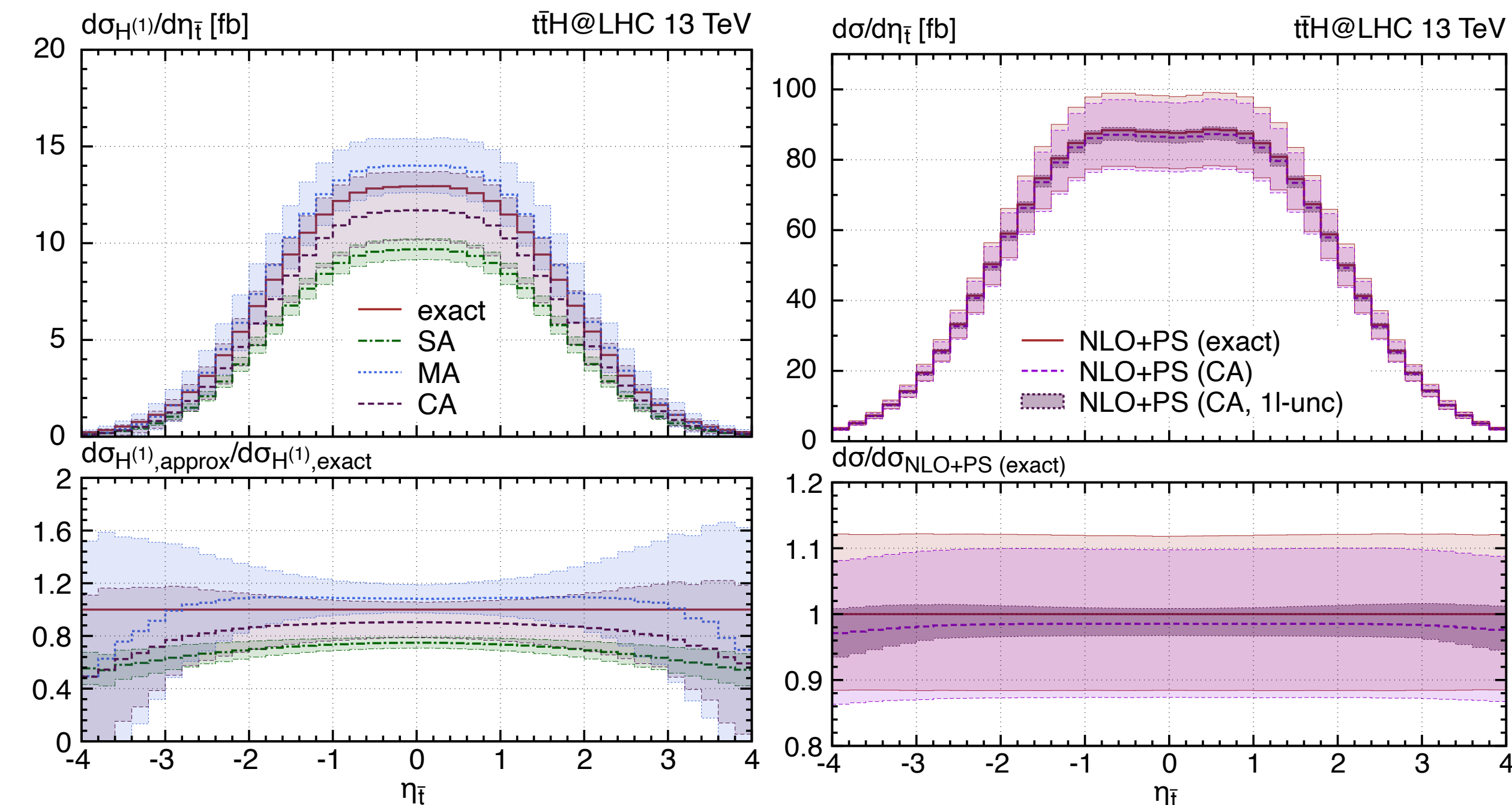
Validation at NLO+PS

setup: NNPDF31_nnlo_as_0118, $m_H = 125\text{GeV}$, $m_t = 173.2\text{GeV}$, $\mu_R = \mu_F = m_{t\bar{t}H}$

azimuthal-angle separation

top-quark rapidity

- ▶ example of an observable for which both SA and MA are **not reliable in the bulk**
- ▶ **shape distortions** of CA in the very forward region, where the cross section is small and the one-loop contribution is suppressed



- ▶ very pronounced shape distortions for $\Delta\phi_{t,\bar{t}} < \pi/2$
- ▶ the uncertainty band assigned to CA covers the exact result
- ▶ the **effect** on NLO+PS is however **smaller** than 4%

“worst” observables: angular distributions

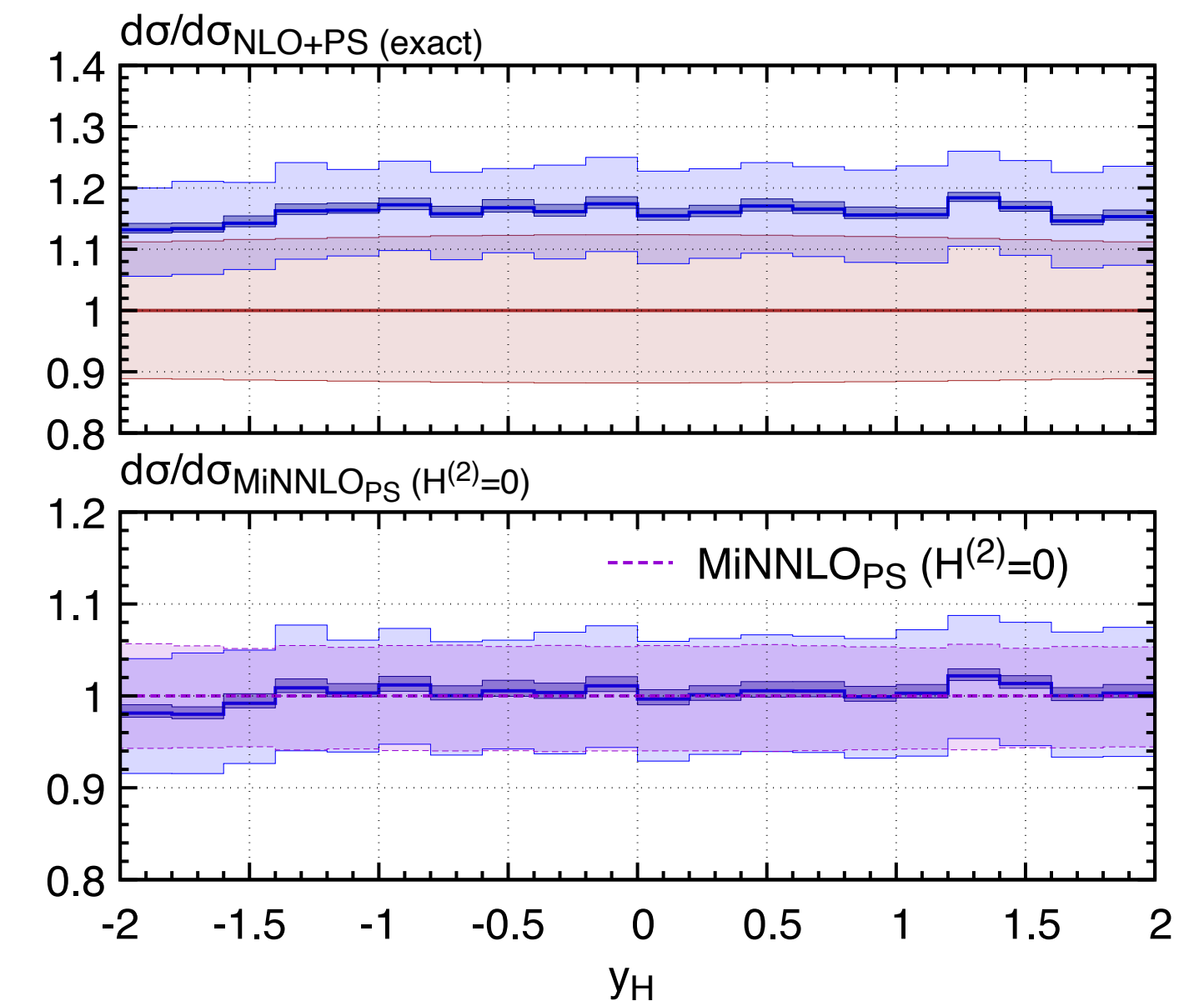
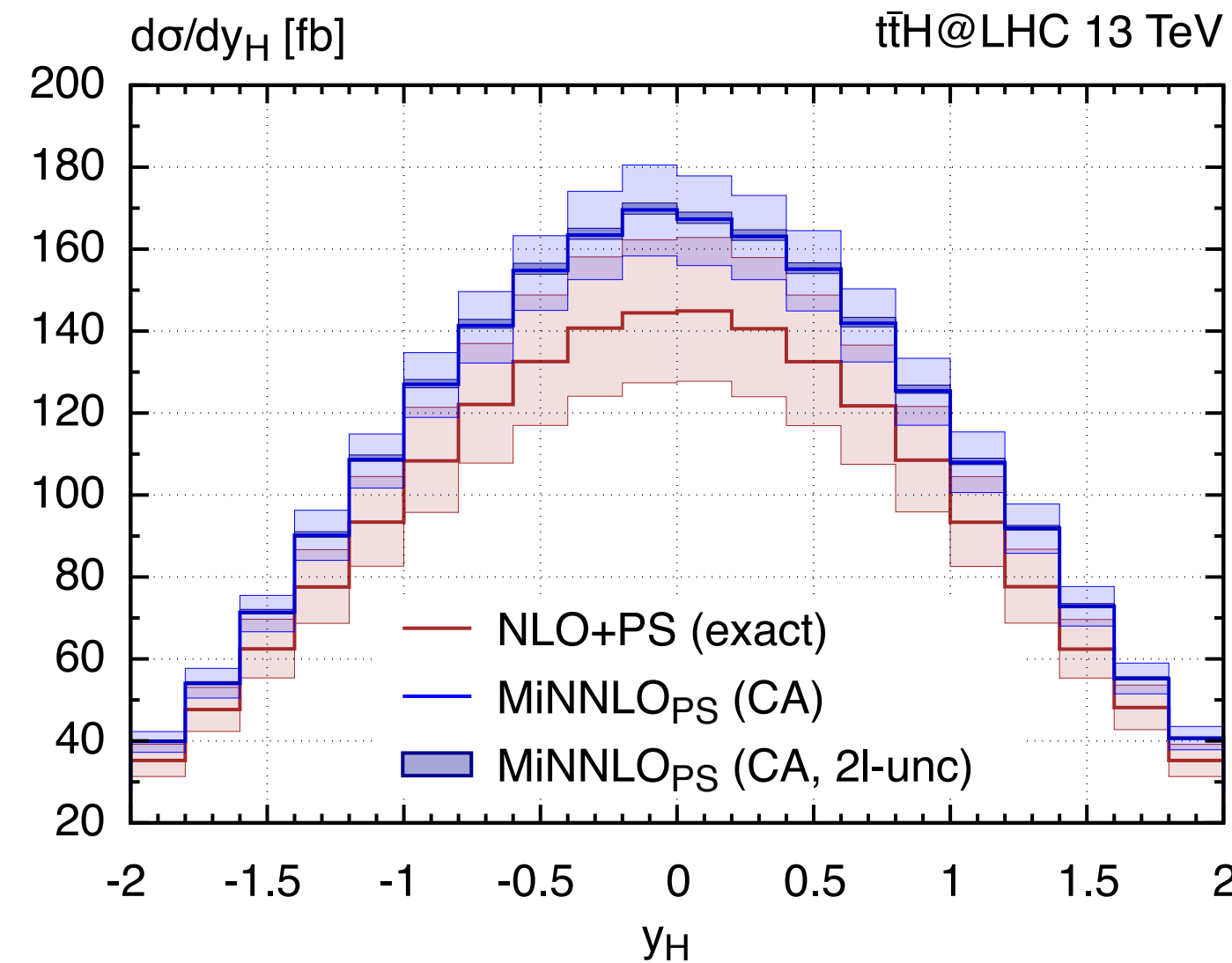
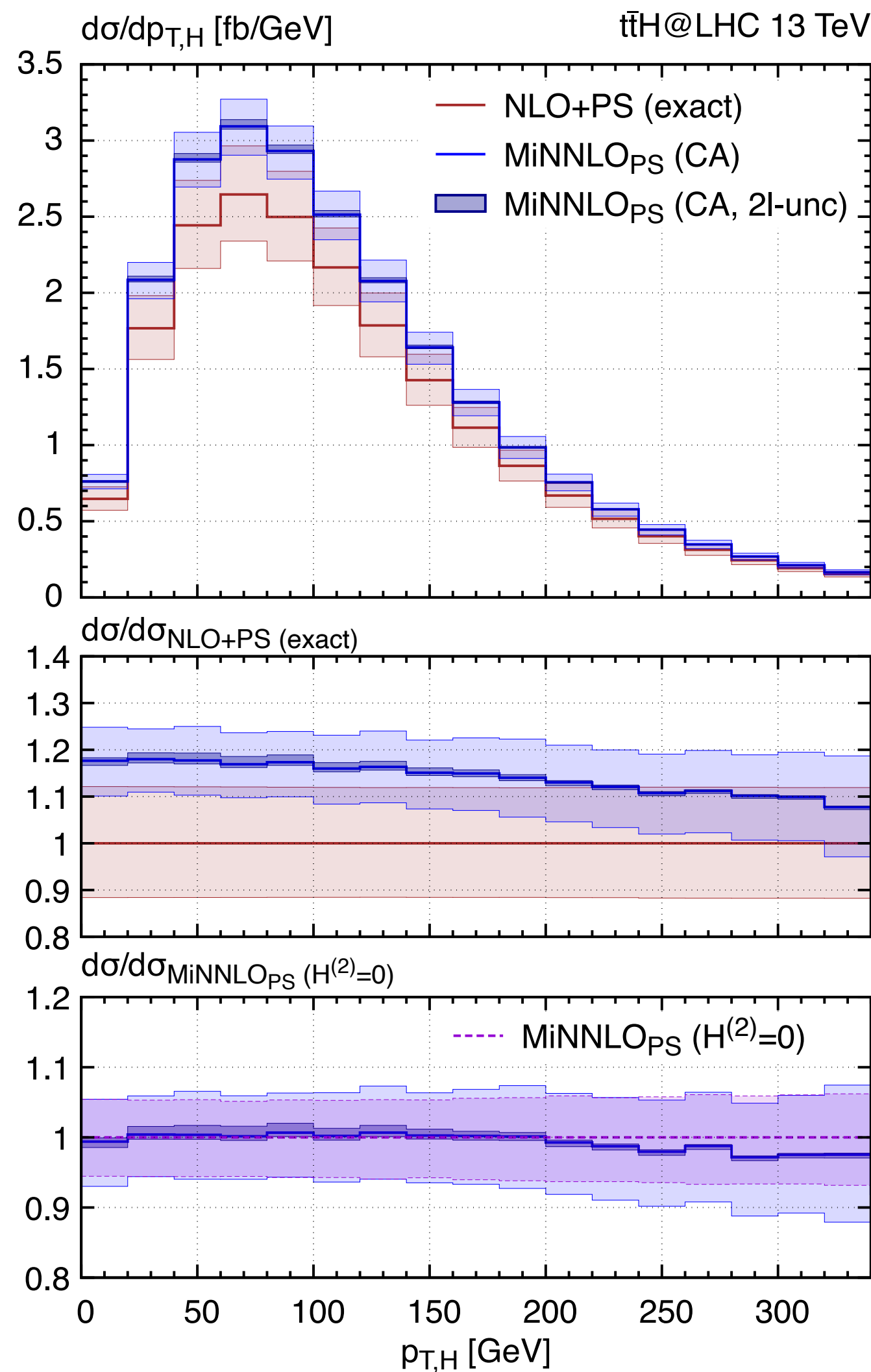
NNLO+PS inclusive setup

setup: NNPDF31_nnlo_as_0118, $m_H = 125\text{GeV}$, $m_t = 173.2\text{GeV}$, $\mu_R = \mu_F = m_{t\bar{t}H}$

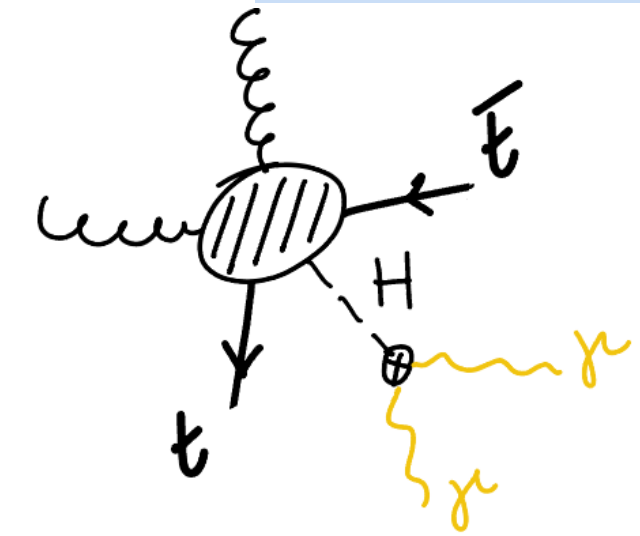
	NLO+PS (exact)	MIINNLO _{PS} ($\mathbb{H}^{(2)} = 0$)	MIINNLO _{PS} (CA)
$\sigma_{\text{inclusive}}^{t\bar{t}H}(\sqrt{s} = 13\text{ TeV})$	$0.4096(1)^{+12.0\%}_{-11.6\%}\text{ pb}$	$0.4734(2)^{+5.4\%}_{-5.9\%}\text{ pb}$	$0.4778(5)^{+6.1\%[+1.04\%]}_{-6.3\%[-0.57\%]}\text{ pb}$

- +15% corrections wrt NLO+PS
- reduction of the scale uncertainties
- below 1% impact of the two-loop hard-virtual contribution

► **two examples** of observables: the $p_{T,H}$ distribution shows shape distortions induced by the NNLO corrections; on the contrary, their impact is almost flat in rapidity and invariant mass distributions



NNLO+PS fiducial setup: Higgs decay into photons



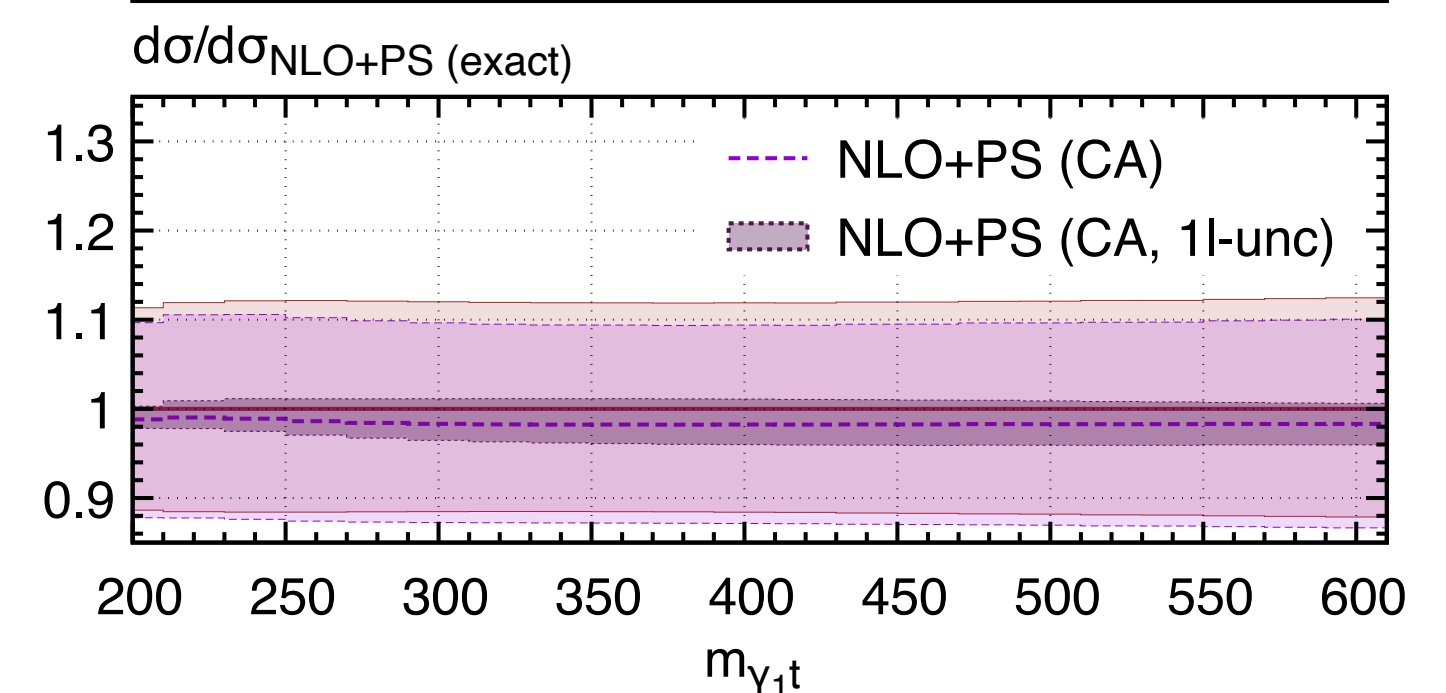
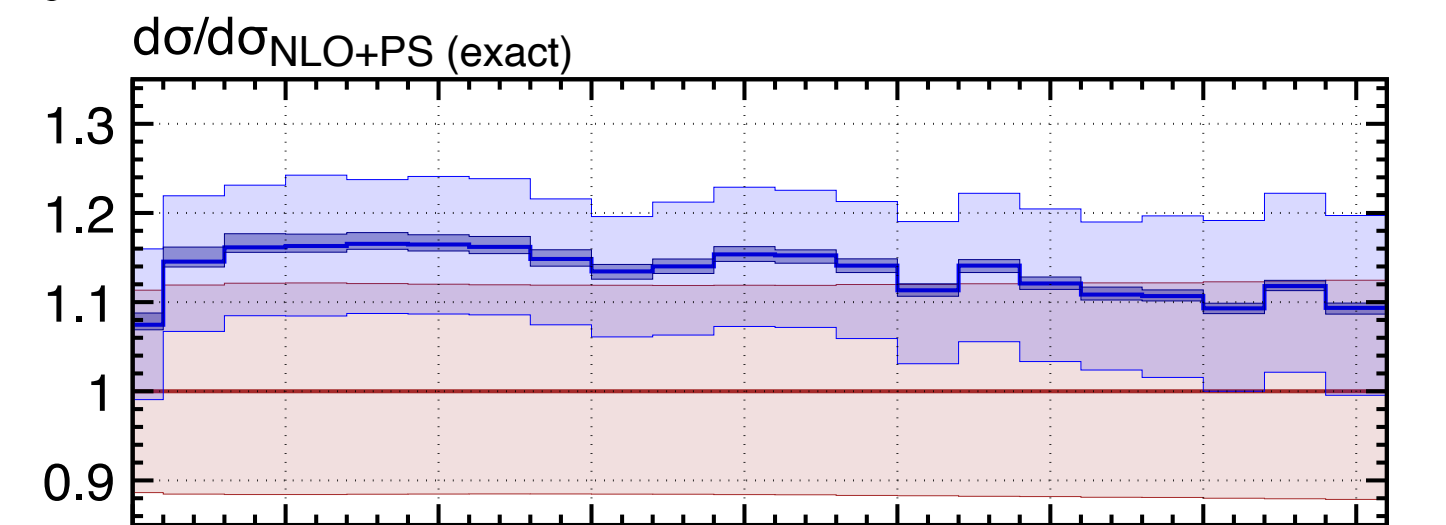
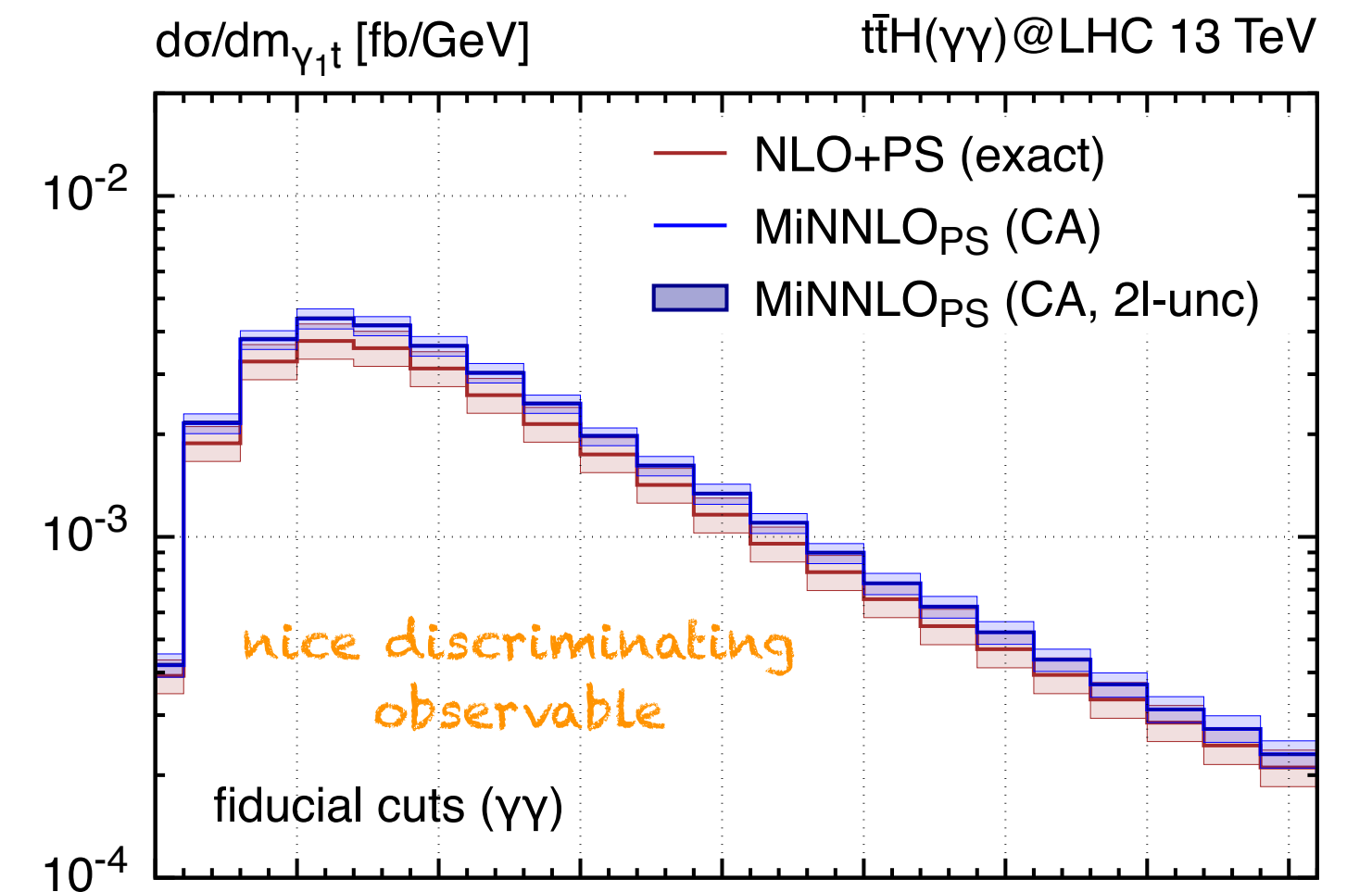
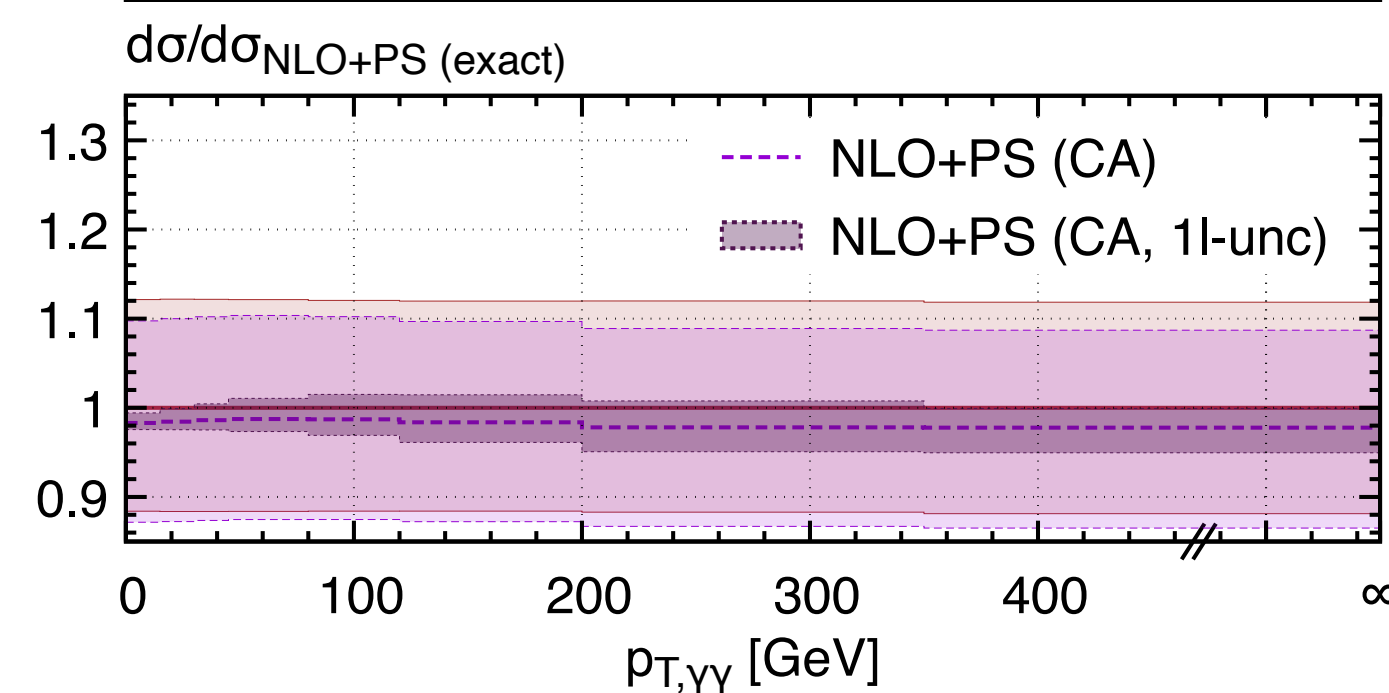
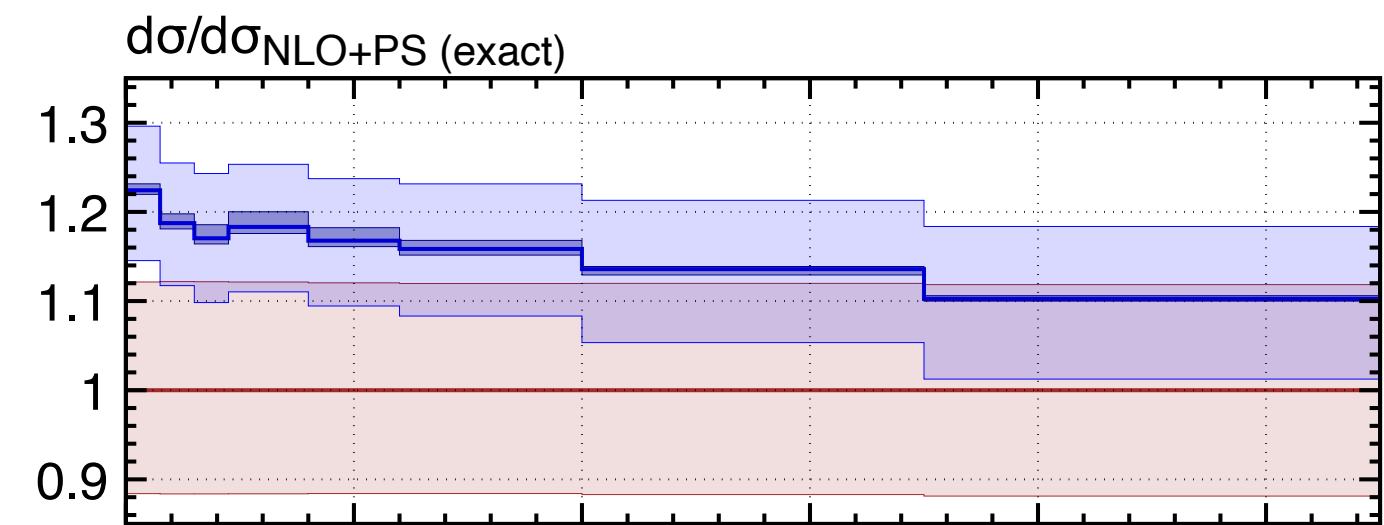
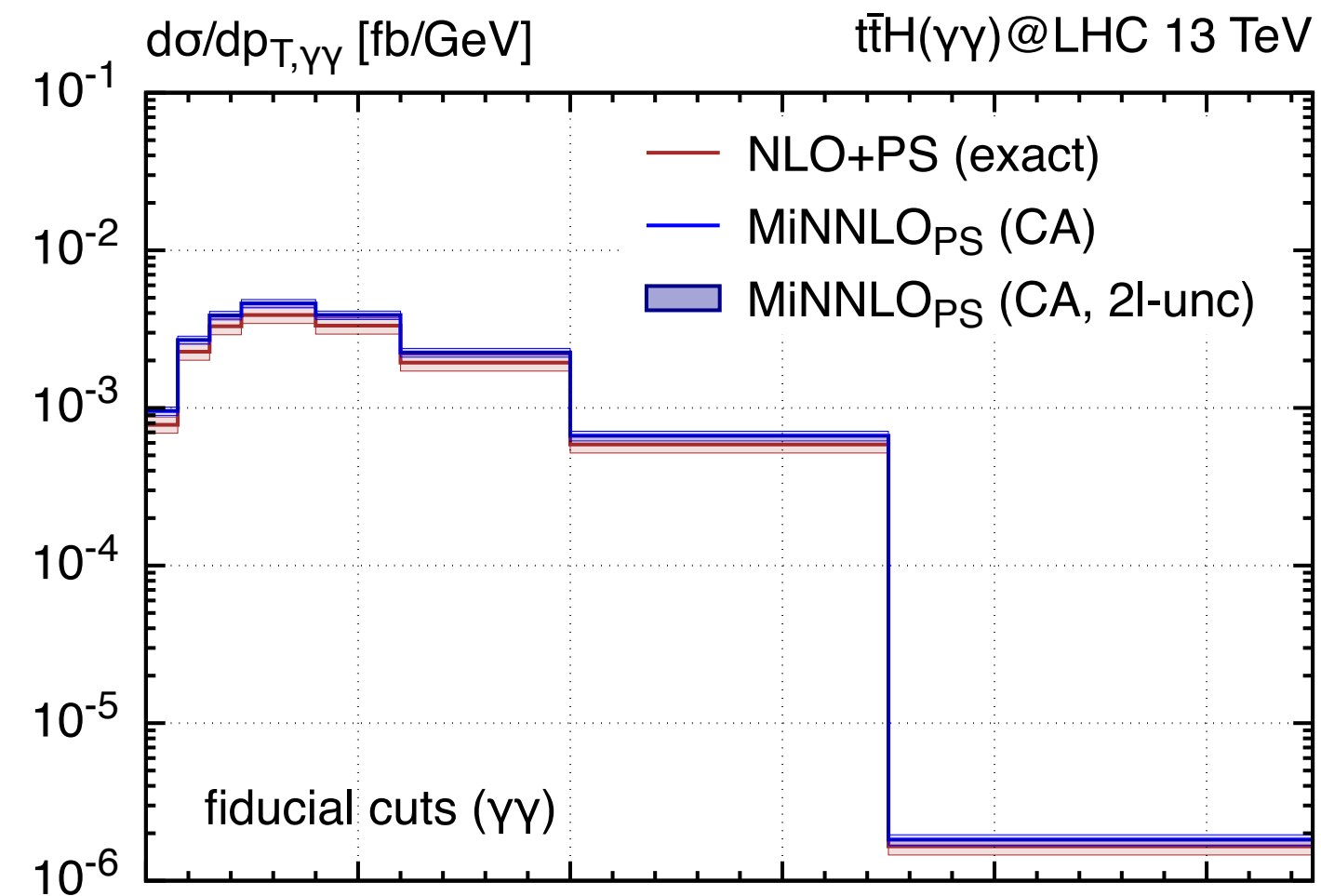
on-shell top quarks, $H \rightarrow \gamma\gamma$

$$p_{T,\gamma_1} > m_{\gamma_1,\gamma_2}/3, \quad p_{T,\gamma_2} > m_{\gamma_1,\gamma_2}/4$$

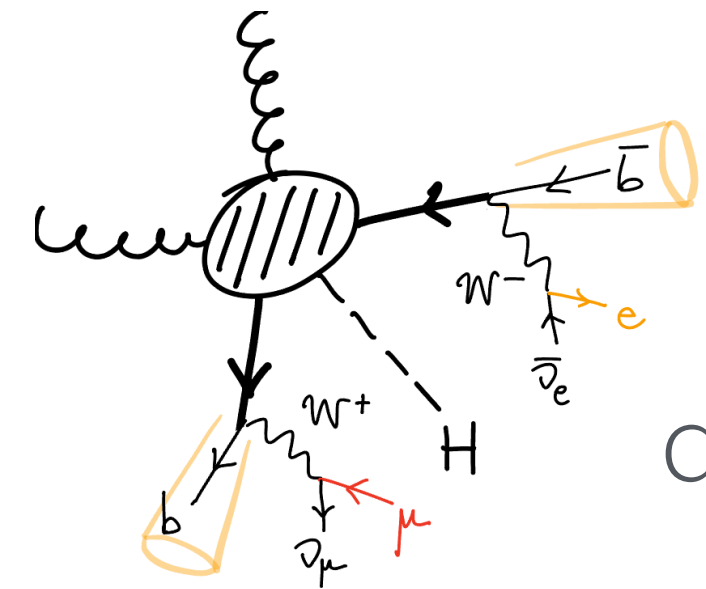
$$|\eta_{\gamma_{1,2}}| < 2.5$$

experimentally inspired fiducial selections

- **tree-level Higgs decay** included in NWA via PYTHIA8 (QCD accuracy of the shower preserved)
- the invariant mass $m_{\gamma_1,t}$ of the leading photon and the top quark is a representative example of observables used to discriminate between $t\bar{t}H$ and $t\bar{t}\gamma$



NNLO+PS fiducial setup: top-quark decays



dilepton signature

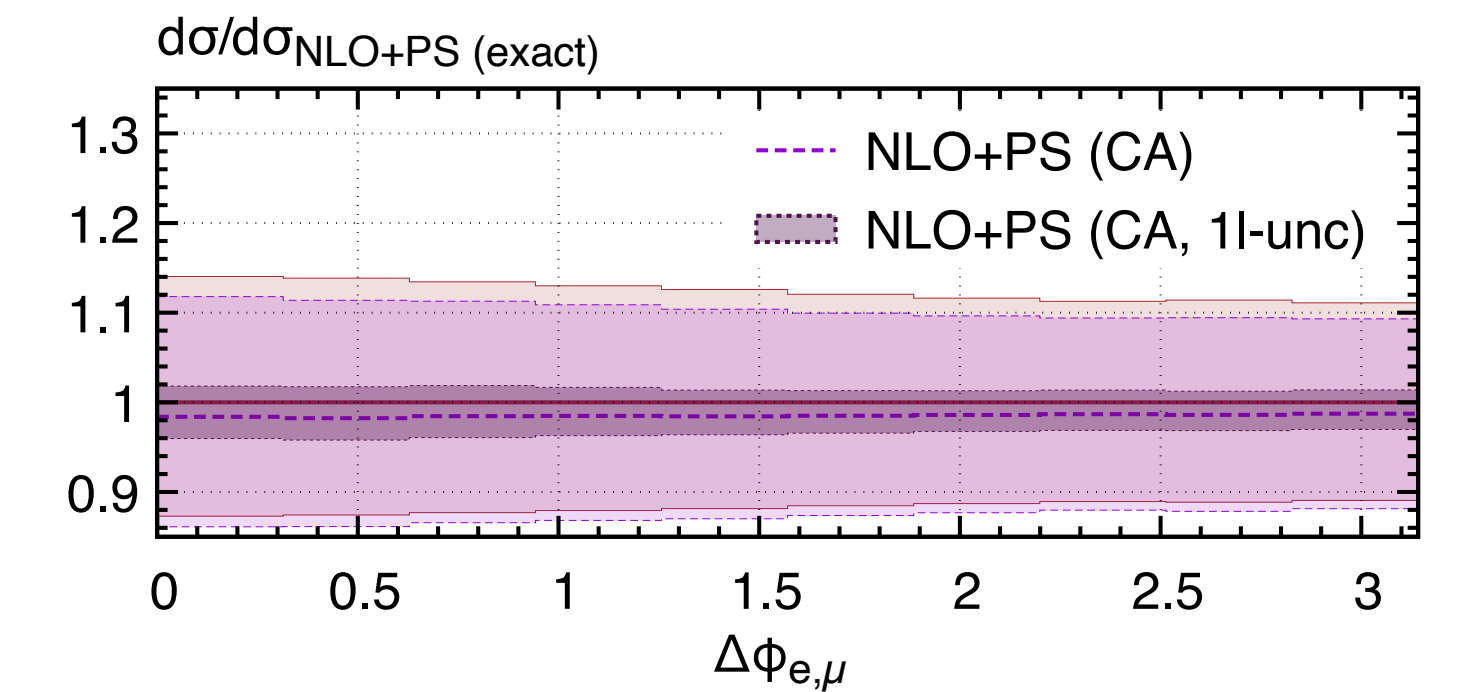
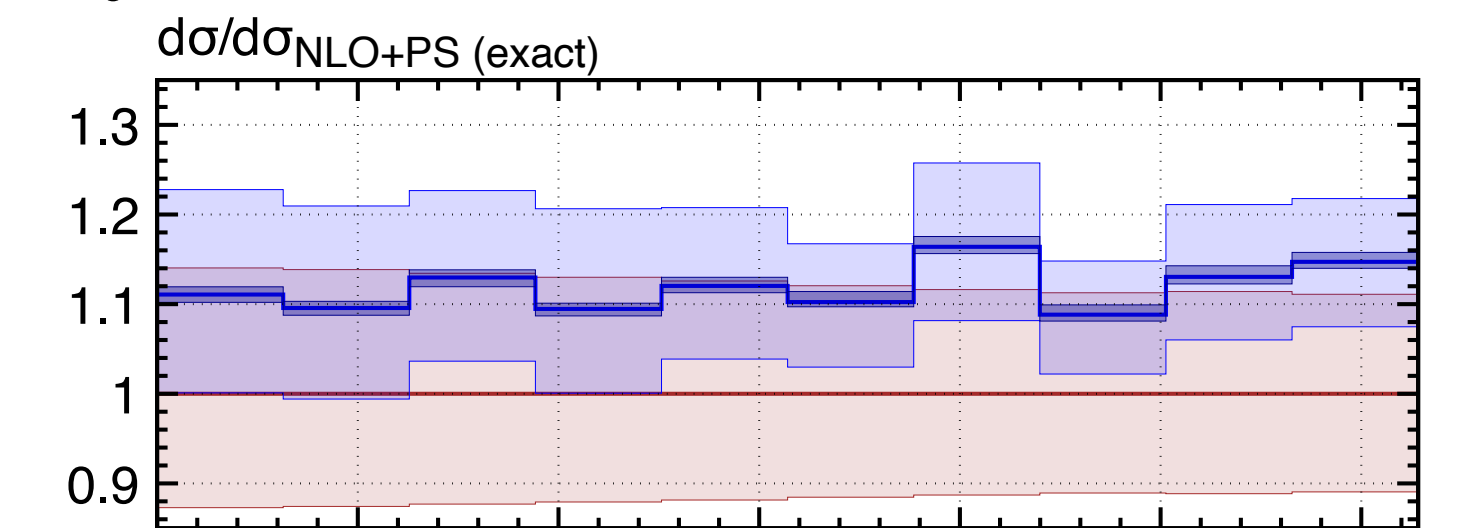
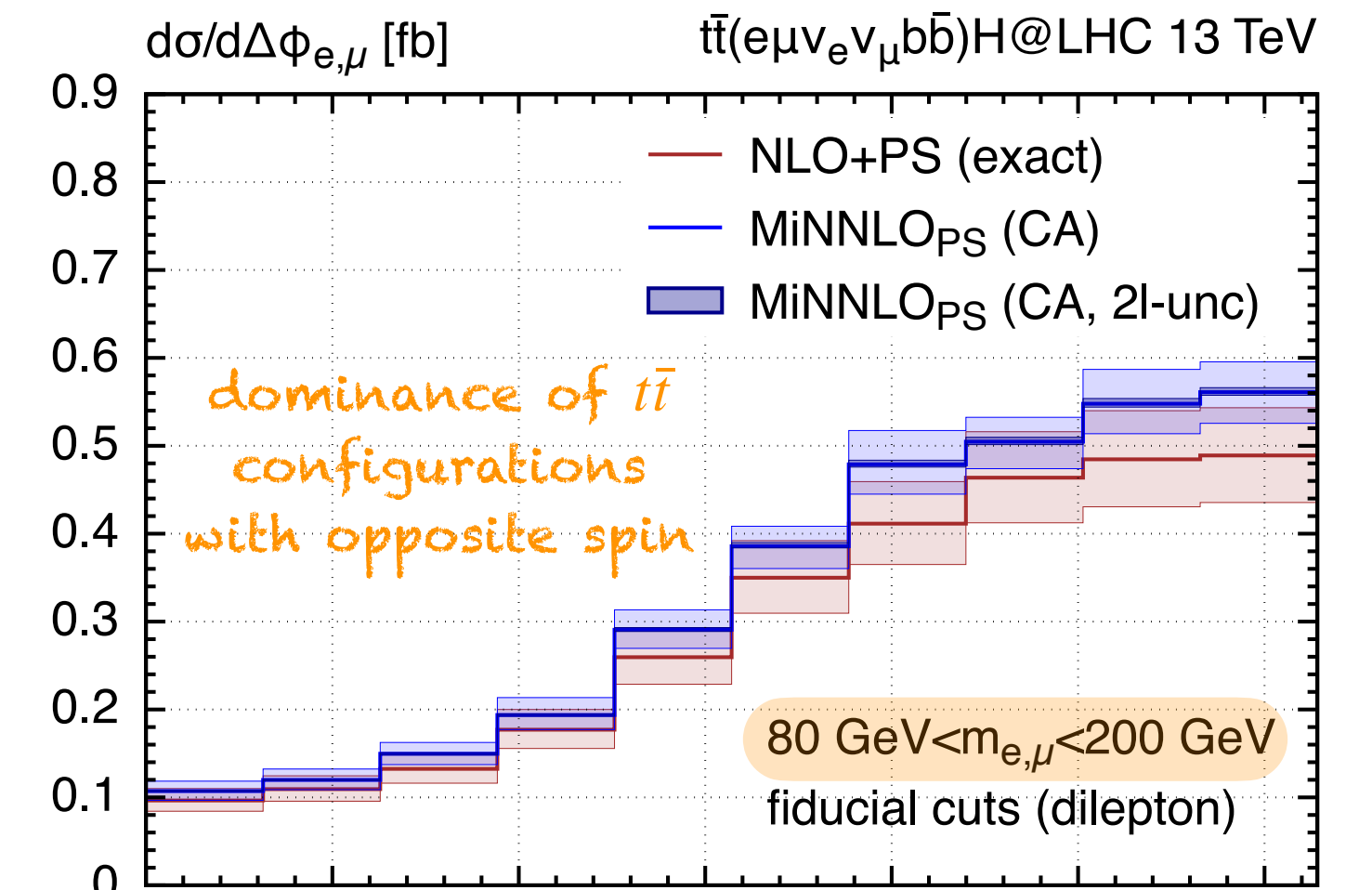
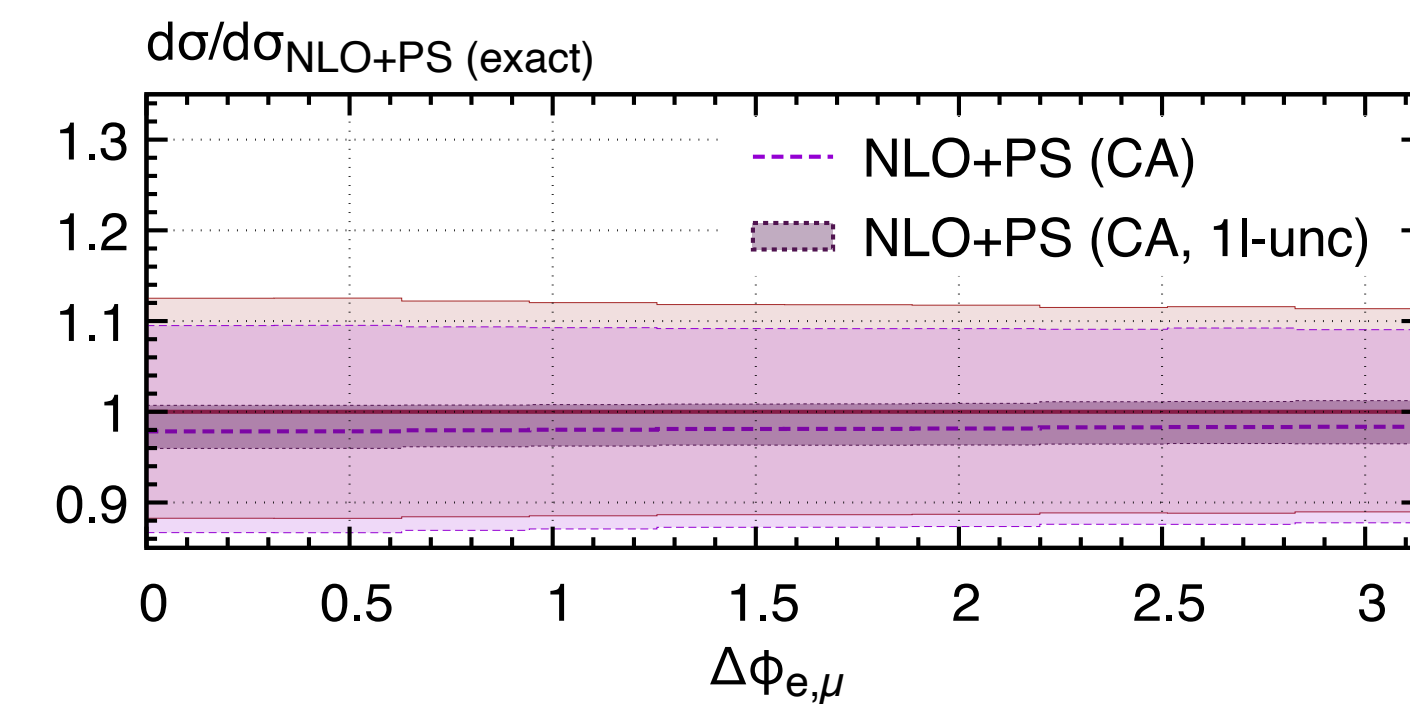
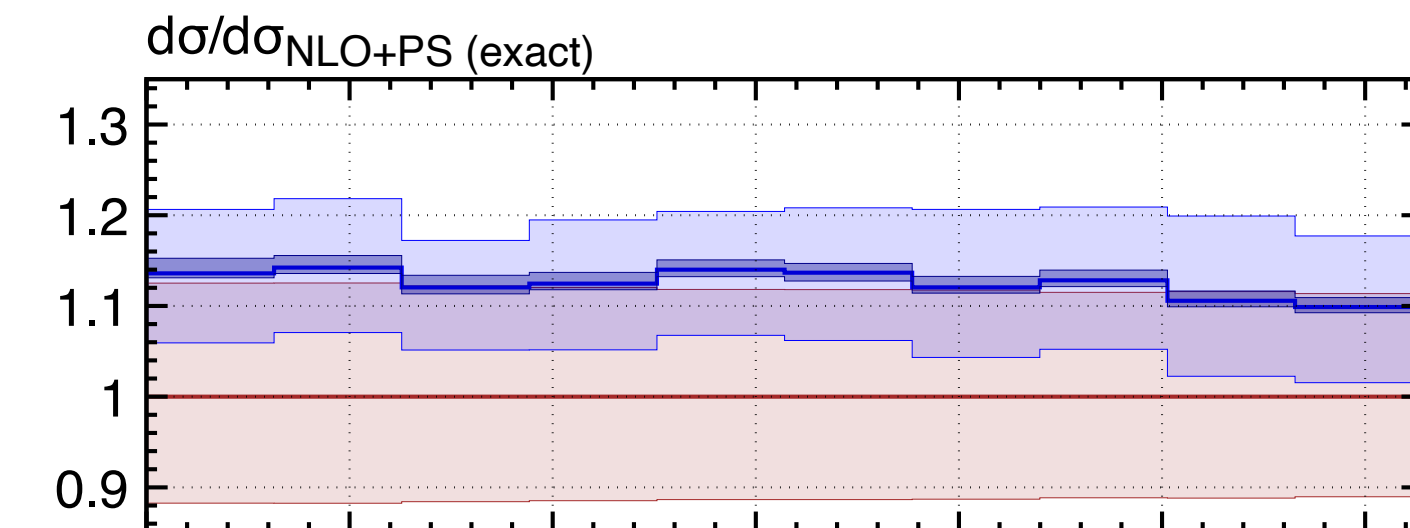
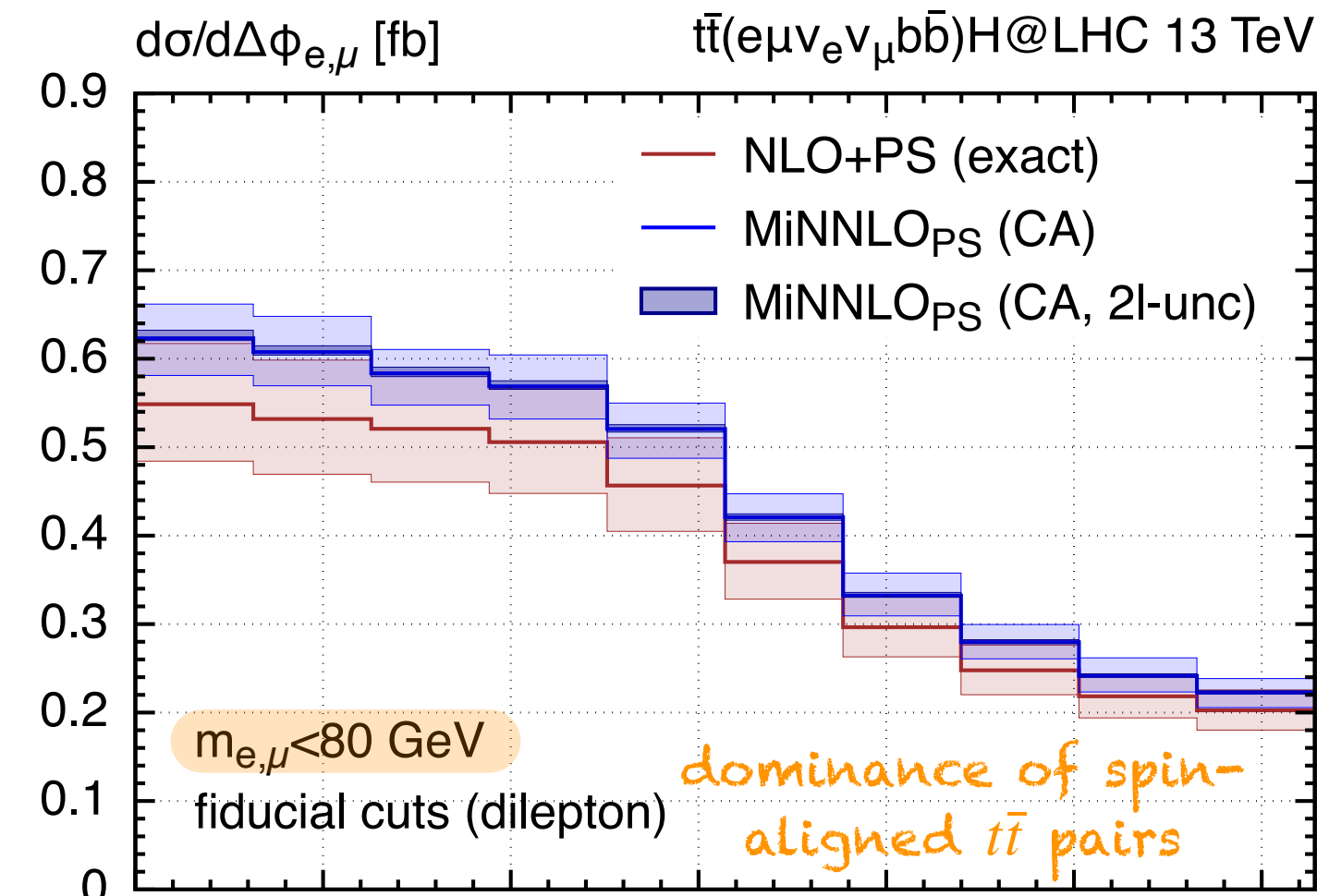
$$p_{T,j} > 25 \text{ GeV}, \quad |\eta_j| < 2.5$$

$$p_{T,\ell} > 10 \text{ GeV}, \quad |\eta_\ell| < 2.5 \quad \forall \ell \in \{e, \mu\}$$

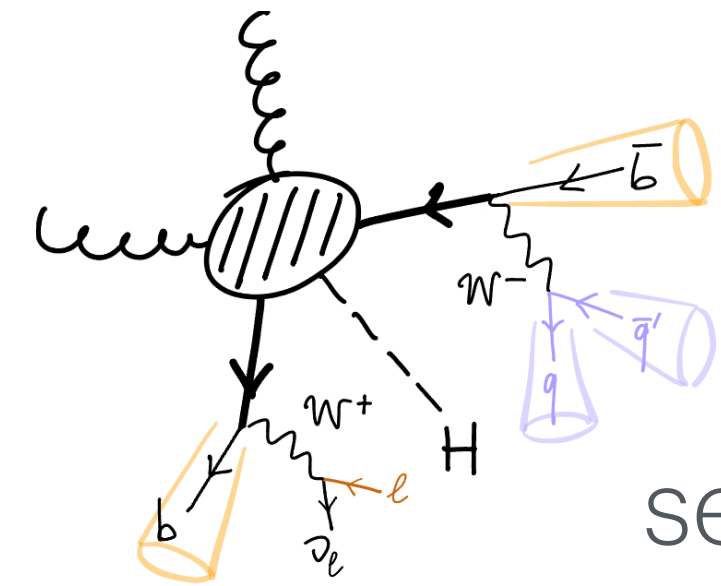
$$\max_{\ell \in \{e, \mu\}} p_{T,\ell} > 15 \text{ GeV}$$

lepton isolation
criterion: $\sum_{i \neq \ell, \Delta R(i, \ell) < 0.4} p_{T,i} < 0.35 p_{T,\ell}$

- **tree-level spin-correlated effects** from top decays are included in the generator
- the invariant mass of the charged lepton pair $m_{e,\mu}$ acts as a “**spin filter**” (smeared by the Higgs kinematics)
- the angular distribution $\Delta\phi_{e,\mu}$ retains a **strong sensitivity to the spin configuration** of the $t\bar{t}$ system



NNLO+PS fiducial setup: top-quark decays



semi-leptonic signature

$$p_{T,\ell} > 30 \text{ GeV}, \quad |\eta_\ell| < 2.4$$

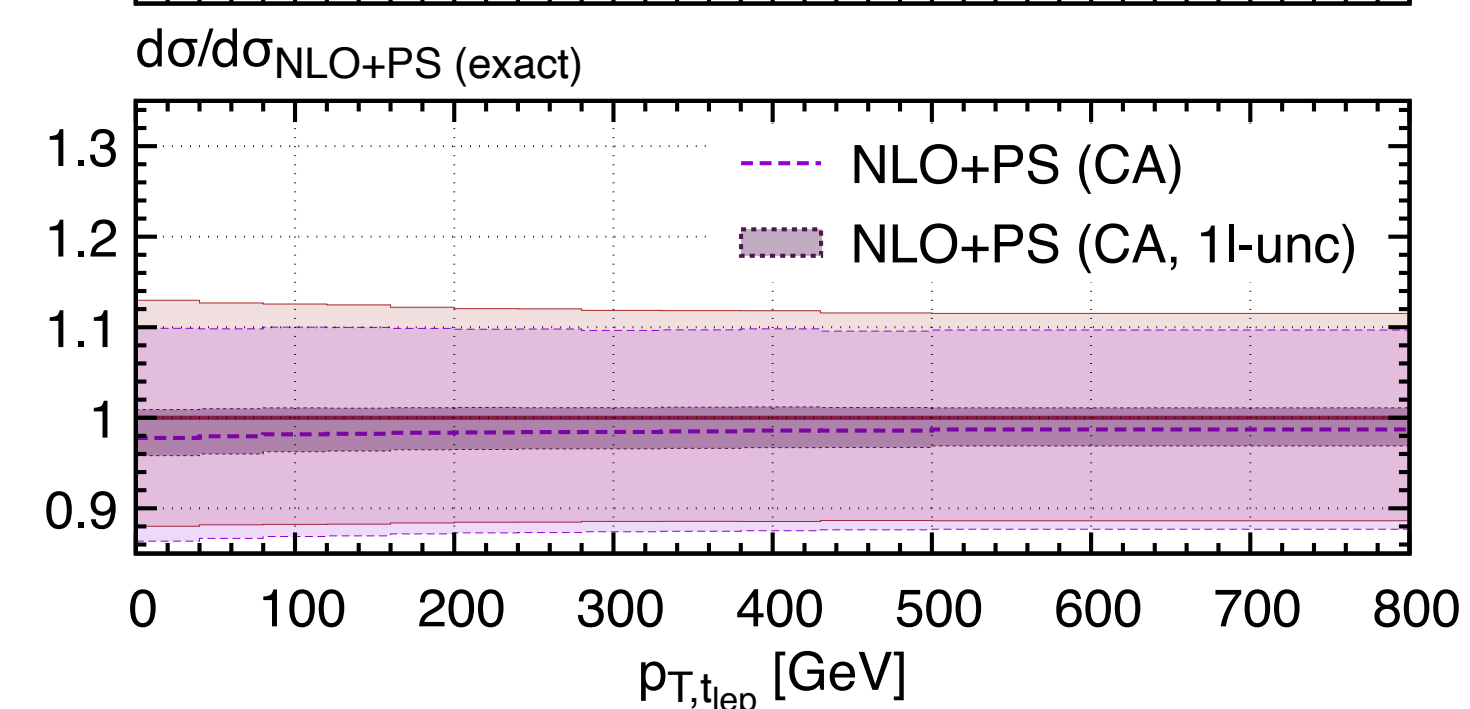
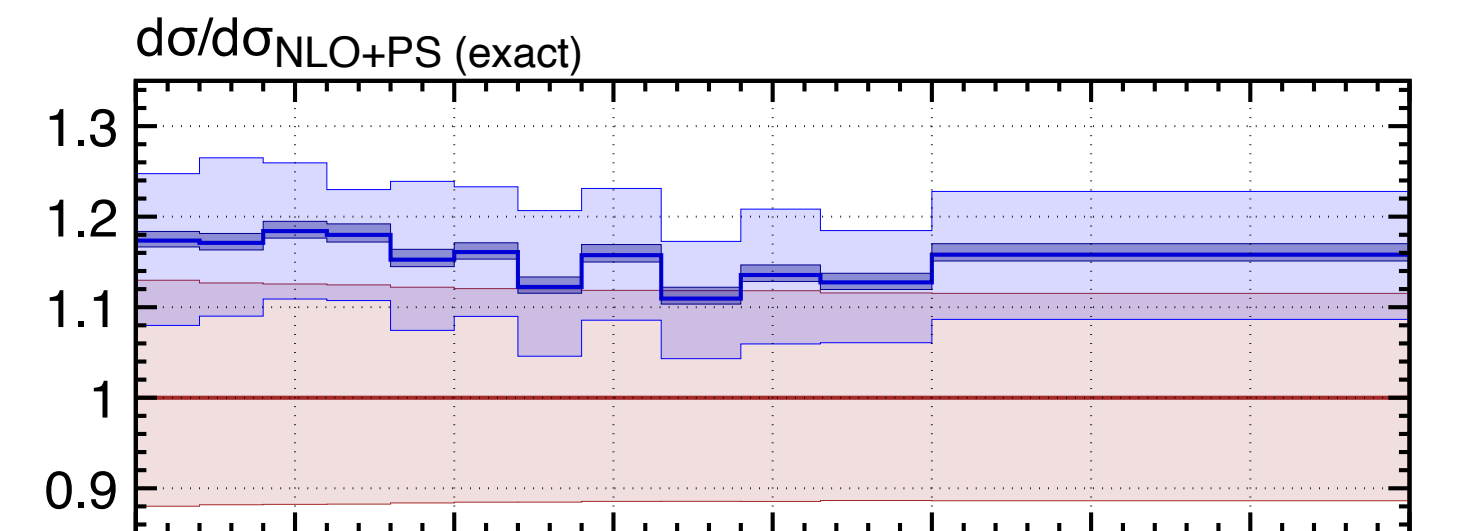
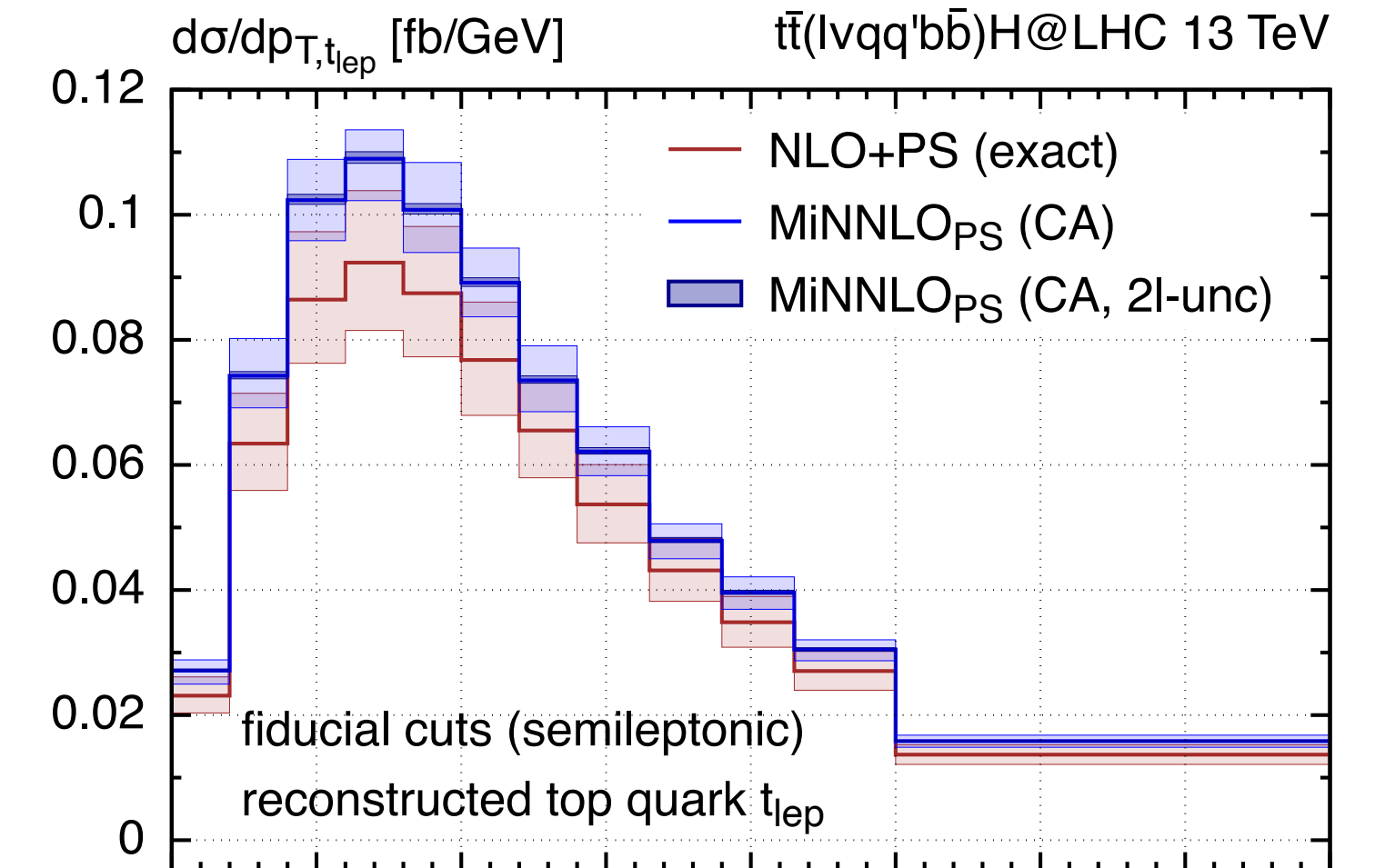
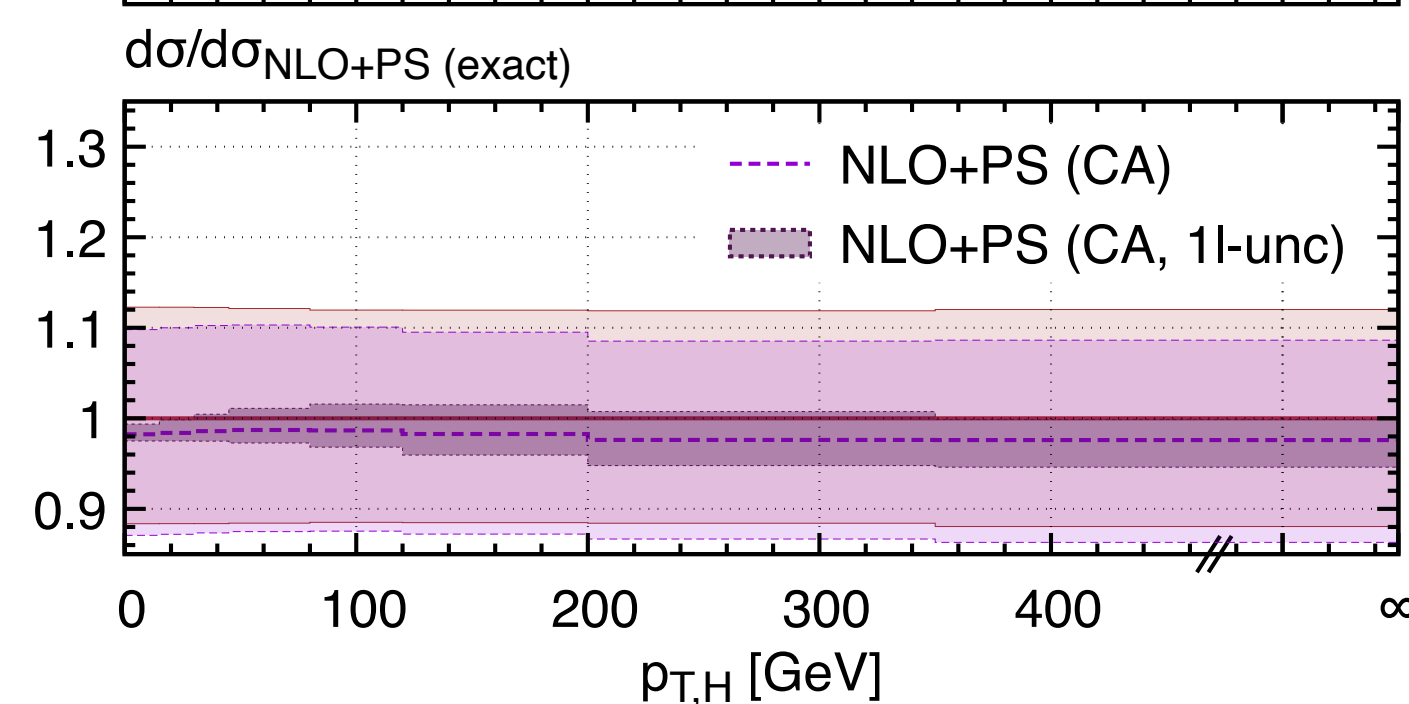
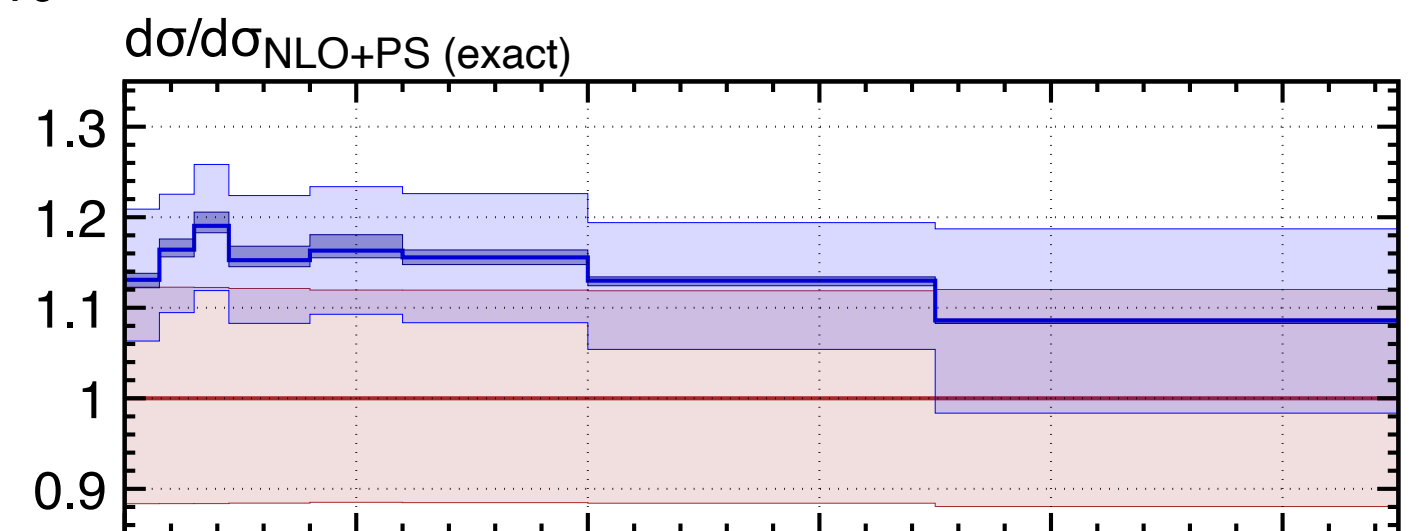
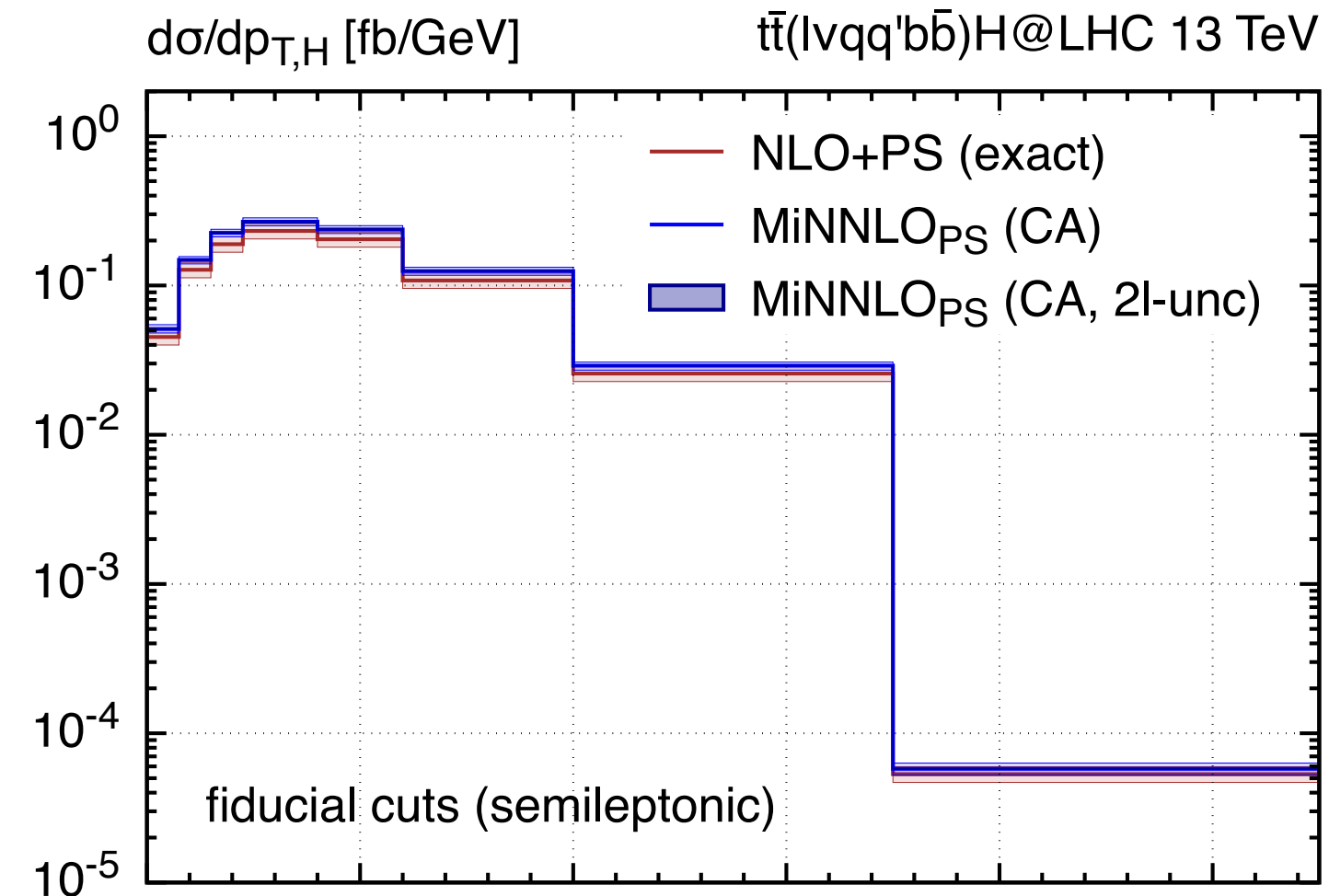
$$p_{T,j} > 25 \text{ GeV}, \quad |\eta_j| < 2.5$$

b-jet tagging if at least one bottom quark is
among the constituents of the jet

- ambiguities in the reconstruction of the intermediate top quarks: mimic exp. procedure via a **distance-to-the-resonance algorithm**

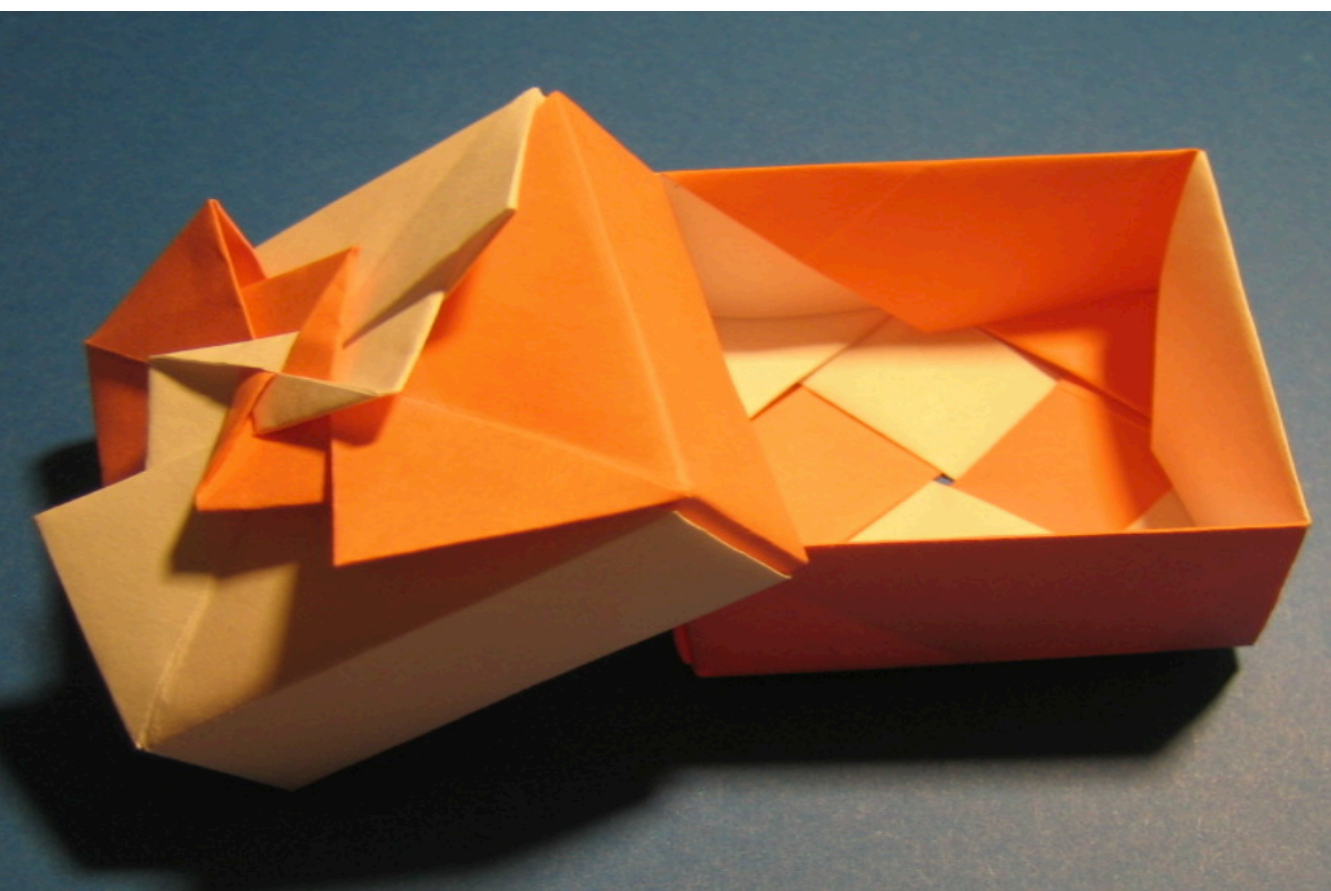
$$\delta_r = ((p_{\text{miss}} + p_\ell + p_{b_1})^2 - m_t^2)^2 + ((p_{j_1} + p_{j_2})^2 - m_W^2)^2 + ((p_{j_1} + p_{j_2} + p_{b_2})^2 - m_t^2)^2$$

- overall behaviour of top-quark independent observables similar to that seen in the dilepton case ($\times 6$ larger cross section due to the hadronic BR)



Conclusions

- ▶ We have presented a **new publicly available** MiNNLO_{PS} generator for $t\bar{t}H$ production
- ▶ **NNLO accuracy** is achieved everywhere (and confirmed by the comparison against fixed-order predictions) except for the double-virtual contribution
- ▶ The latter is estimated via a new **pointwise combination of two approximations** valid in the soft-boson and high-energy limits, respectively. A careful estimate of the corresponding systematic uncertainty is provided
- ▶ Our generator can reweight events (a posteriori) to efficiently include the exact two-loop contribution, once available
- ▶ The approach developed in this project can be extended to other processes of the same class (e.g. $t\bar{t}\gamma$, $t\bar{t}Z$, $t\bar{t}W$)



public release of the POWHEG-BOX-RES/ttHJ code, referred to as the ttH-MiNNLO event generator: <https://gitlab.com/POWHEG-BOX/RES>

user manual documenting all dependencies provided at [ttHJ/Docs/manual_ttH-MiNNLO.pdf](#)

framework ready to be used by other theorists and experimentalists!

Approximation methods – when reliably
designed and carefully validated – can
provide a powerful path toward
precision phenomenology

Thank you for your attention!

