Recent Progress in top-quark physics

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DESY Theory Workshop
"Synergies towards the future SM"
DESY, Hamburg, September 23-26, 2025

Top quark is a recurrent topic in DESY Theory Workshops: see talks in previous editions:
K. Melnikov (2015), M. Czakon and F. Maltoni (2018), M. Worek (2022) ---> plenary
+ many parallel session contributions

Parallel session contributions in this edition: pheno-1 session on wednesday afternoon

Top quark: main features

* SM particle with the largest mass

- short decay width:
  - top quark decays before hadronizing:
    - window on perturbative physics
    - decay products preserve polarization
    - decay in Wb –--> charged leptons, b-jets and missing energy
      –--> light jets and b-jets
- closest to heavy BSM
- biggest coupling to the Higgs:
  - window on EWSB
  - smallness of the Higgs boson mass
  - stability of the EW vacuum

Precise determination of parameters: mass and width relevant for increasing insights on the aspects above

Outline

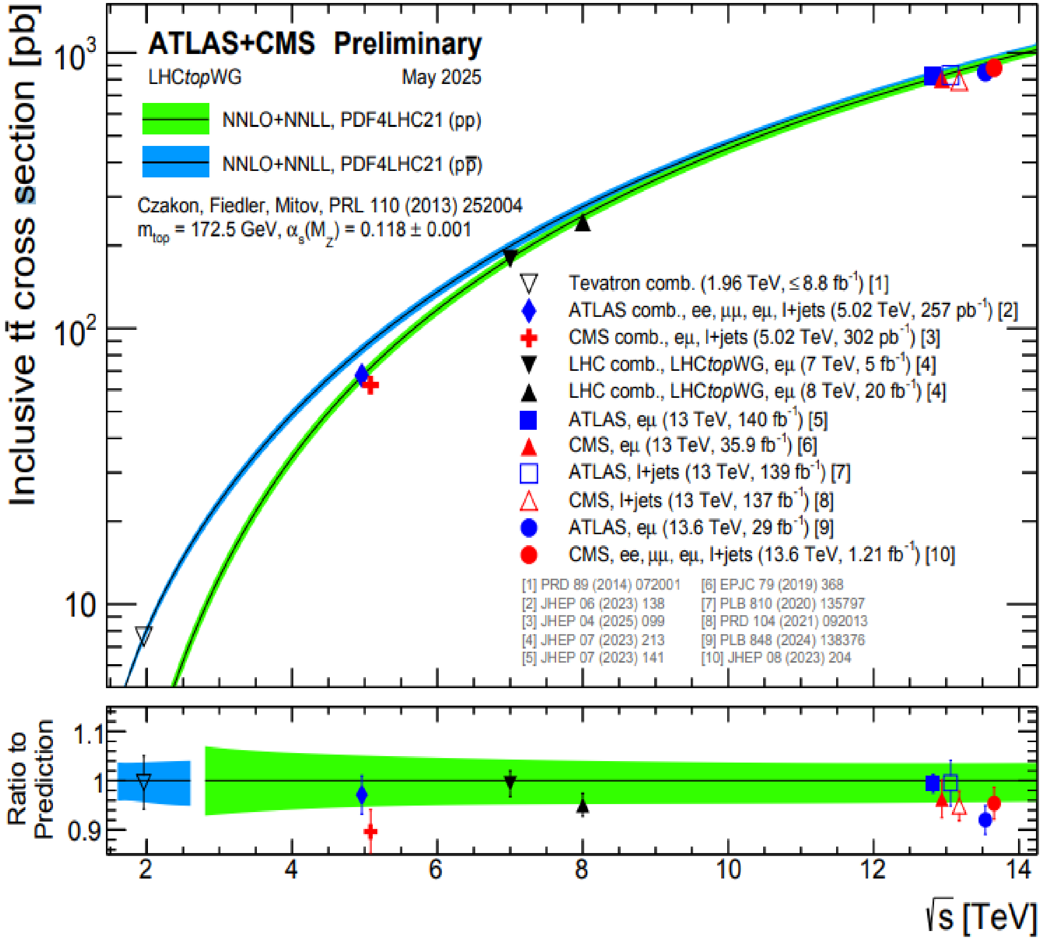
Disclaimer: one can only cover some aspects in 30 minutes
Personal choice, guided by intention to cover recent progress in theory and experiment, biased by personal experience and limited to LHC

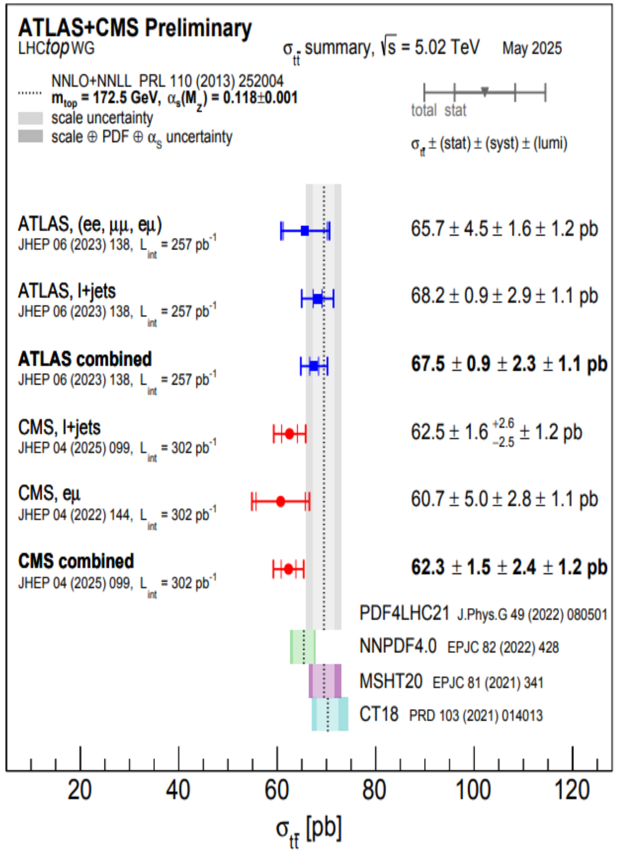
Topics:
* tt and ttj production
* applications: fit of top-quark mass, PDFs, $\alpha_s (m_Z)$
* single-top production and decay and applications
* off-shell tt production and decay
* toponium
* top-quark associated production with bosons (in particular: *H*, *W*)
* more rare processes (in particular tttt, ttbb)

For more insights, see also the simultaneous TOP 2025 Workshop
https://indico.cern.ch/event/1501204/timetable/

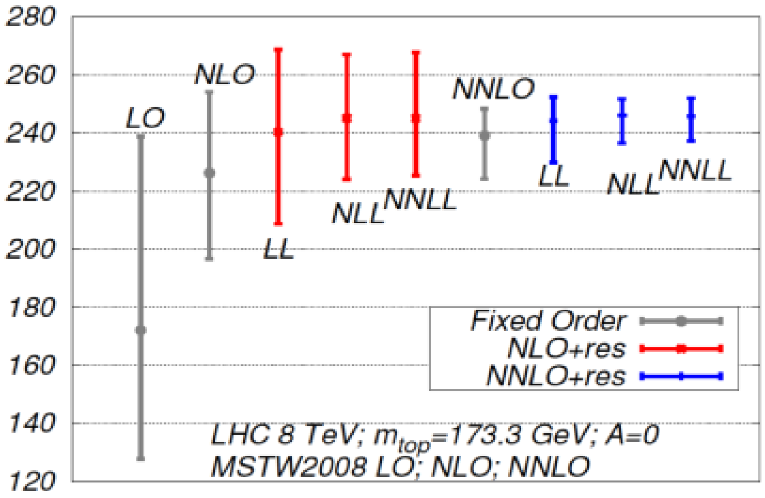
inclusive tt

Experiment: Top LHC WG, may 2025

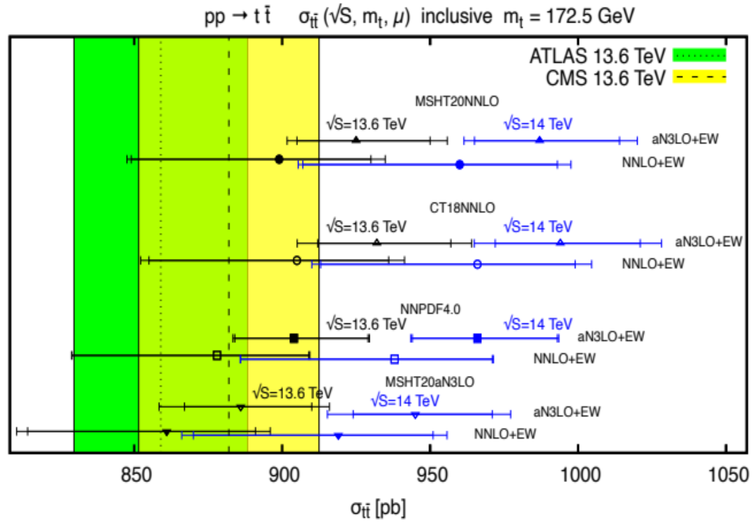




Theory:
FO further combined with threshold resummation, up to NNLO+NNLL



M. Czakon et al., S. Catani et al., etc



New measurement in pp at 5.02 TeV reference for PbPb

aN3LO+EW vs. N2LO+EW vs. data 2023
Kidonakis, [2306.06166]

differential tt

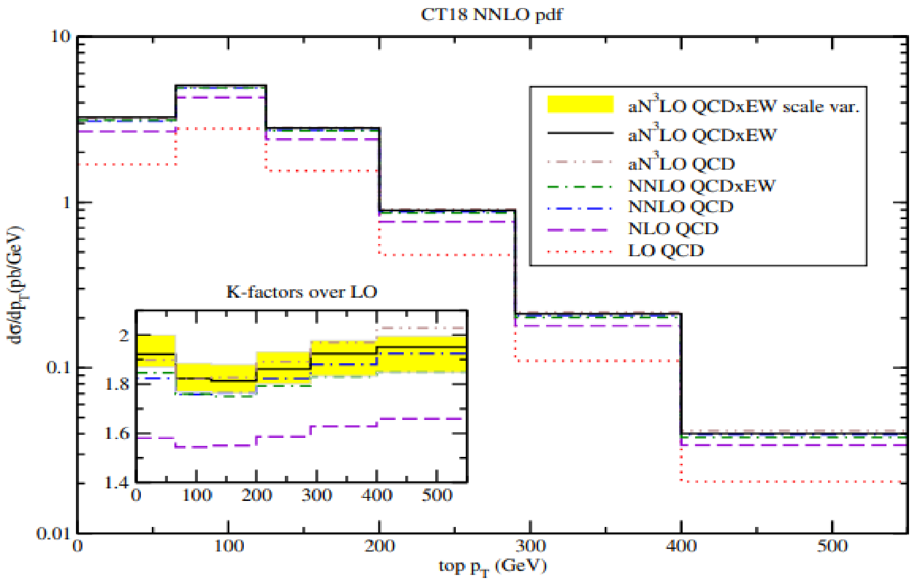
M. Czakon et al., S. Catani et al., N, Kidonakis

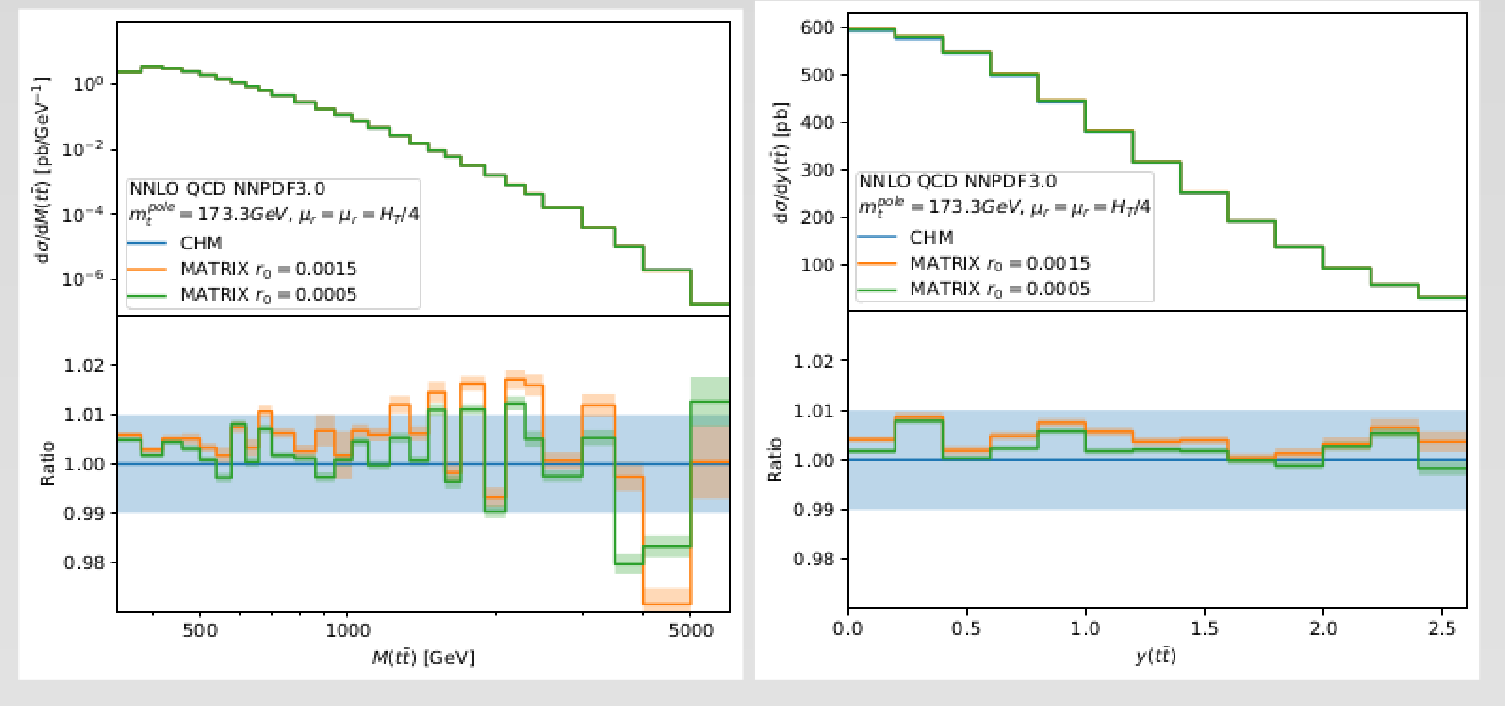
- NNLO QCD available since many years with the STRIPPER and q_T-subtraction schemes
- publicly available through High-TEA and MATRIX

$$d\sigma^{t\bar{t}}_{(N)NLO} = \mathcal{H}^{t\bar{t}}_{(N)NLO} \otimes d\sigma^{t\bar{t}}_{LO} + \left[d\sigma^{t\bar{t}+jet}_{(N)LO} - d\sigma^{t\bar{t},CT}_{(N)NLO} \right]$$

- aNNLO and aN3LO via threshold resummation only for specific distributions

p p -> t $\bar{t}$ top p_T $\sqrt{S}$= 13 TeV $\mu=m_T$ m_t=172.5 GeV





power corrections for r_{cut} (cut on $r = q_T/m_{tt}$) finite; in practice good agreement with exact calculation, within uncertainties of the latter

differential tt at NNLO, in practice

M. Czakon et al., Carrazza et al. 2020, MVG et al. 2023, Devoto et al. 2025

In practice, computation time consuming if one aims to match current experimental accuracy
  a run with 0.02% accuracy on total cross-section, corresponding to < 0.5 % accuracy on differential distributions requires 350000 CPU hours.

Solution A): interpolation grids for (multi)-differential distributions
Interface of the NNLO codes to FastNLO/PineAPPL

https://ploughshare.web.cern.ch/ploughshare/

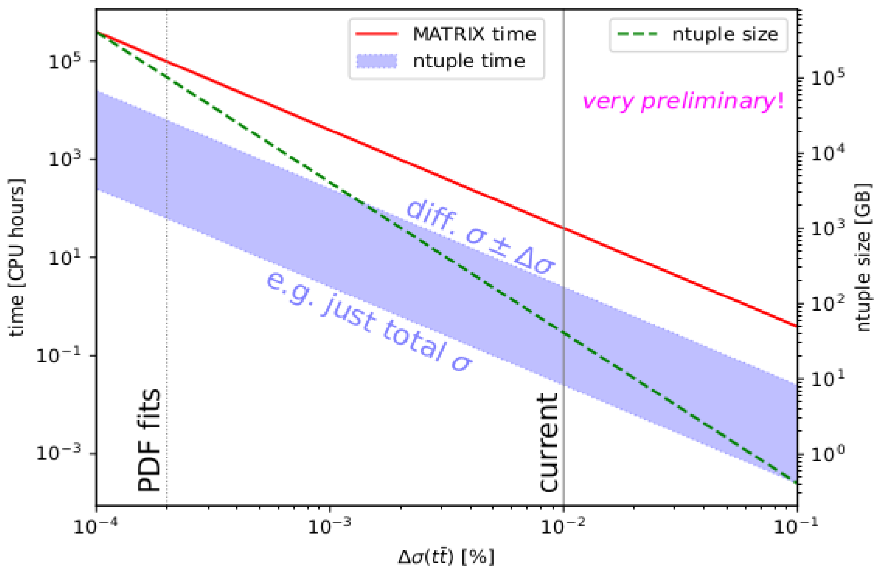
The Ploughshare C++ library can be called directly in your program (e.g. in the PineAPPL interface in xFitter), to download the grids.

CMS	pp nnlo	13 TeV	ttbar-mt1650	MATRIX	xFitter	2108.02803	xfitter-cms-ttbar-mt1650-arxiv-2108.02803
CMS	pp nnlo	13 TeV	ttbar-mt1675	MATRIX	xFitter	2108.02803	xfitter-cms-ttbar-mt1675-arxiv-2108.02803
CMS	pp nnlo	13 TeV	ttbar-mt1700	MATRIX	xFitter	2108.02803	xfitter-cms-ttbar-mt1700-arxiv-2108.02803
CMS	pp nnlo	13 TeV	ttbar-mt1725	MATRIX	xFitter	2108.02803	xfitter-cms-ttbar-mt1725-arxiv-2108.02803
CMS	pp nnlo	13 TeV	ttbar-mt1750	MATRIX	xFitter	2108.02803	xfitter-cms-ttbar-mt1750-arxiv-2108.02803
CMS	pp nnlo	13 TeV	ttbar-mt1775	MATRIX	xFitter	2108.02803	xfitter-cms-ttbar-mt1775-arxiv-2108.02803

Each grid is in PineAPPL format (.opt):
bins in $M(t\bar{t})$, $y(t\bar{t})$; for each bin, grid of components of partonic cross-sections as a function of x_1, x_2, μ_F^2.
Different components correspond to different α_s powers, $\ln^k \mu_r$, $\ln^l \mu_f$, $\ln\mu_r \ln \mu_f$ terms.

Allows for reconstructing LO, NLO, NNLO distributions with whichever PDFs and $\alpha_s(M_Z)$ and scale variations around the central scale $H_T/4$.

Solution B) NNLO code output stored as ntuples



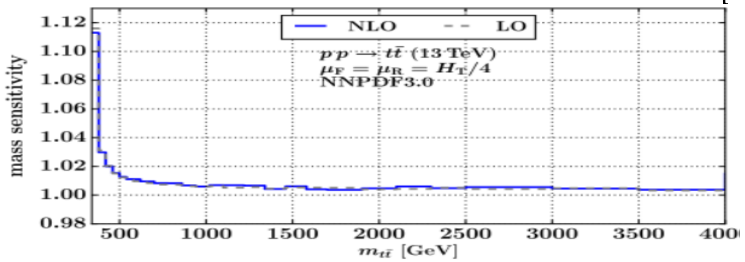
Enables use of multi-differential experimental data to do precision fits

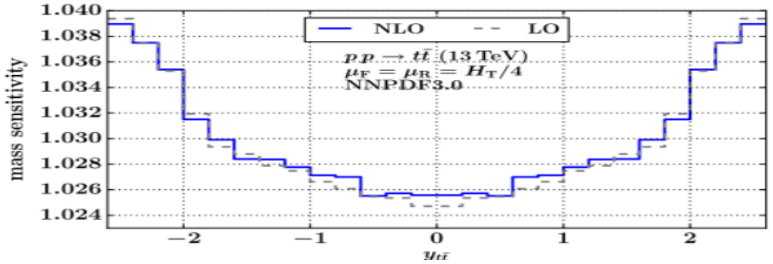
application: m_t fits

Absolute m(tt) data sensitive to m_t close to threshold,

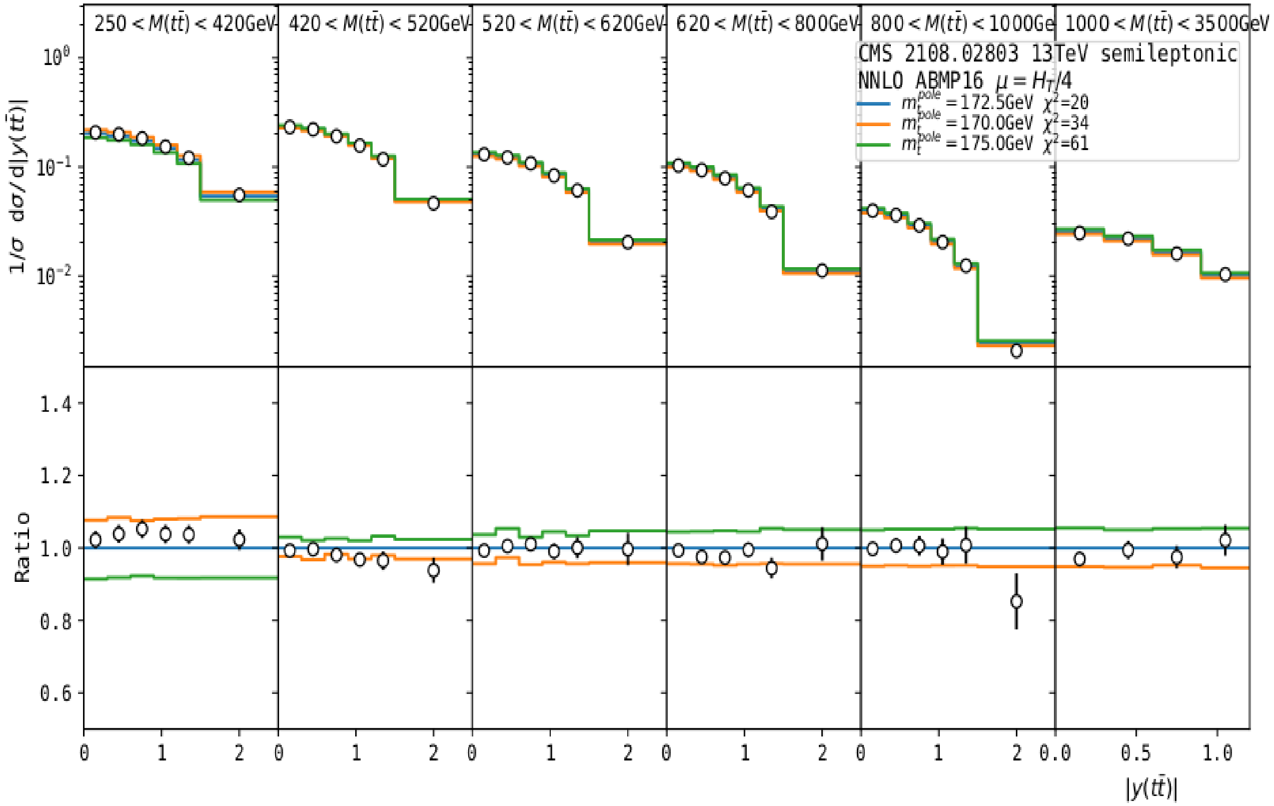
Absolute y(tt) data sensitive to m_t at large rapidity

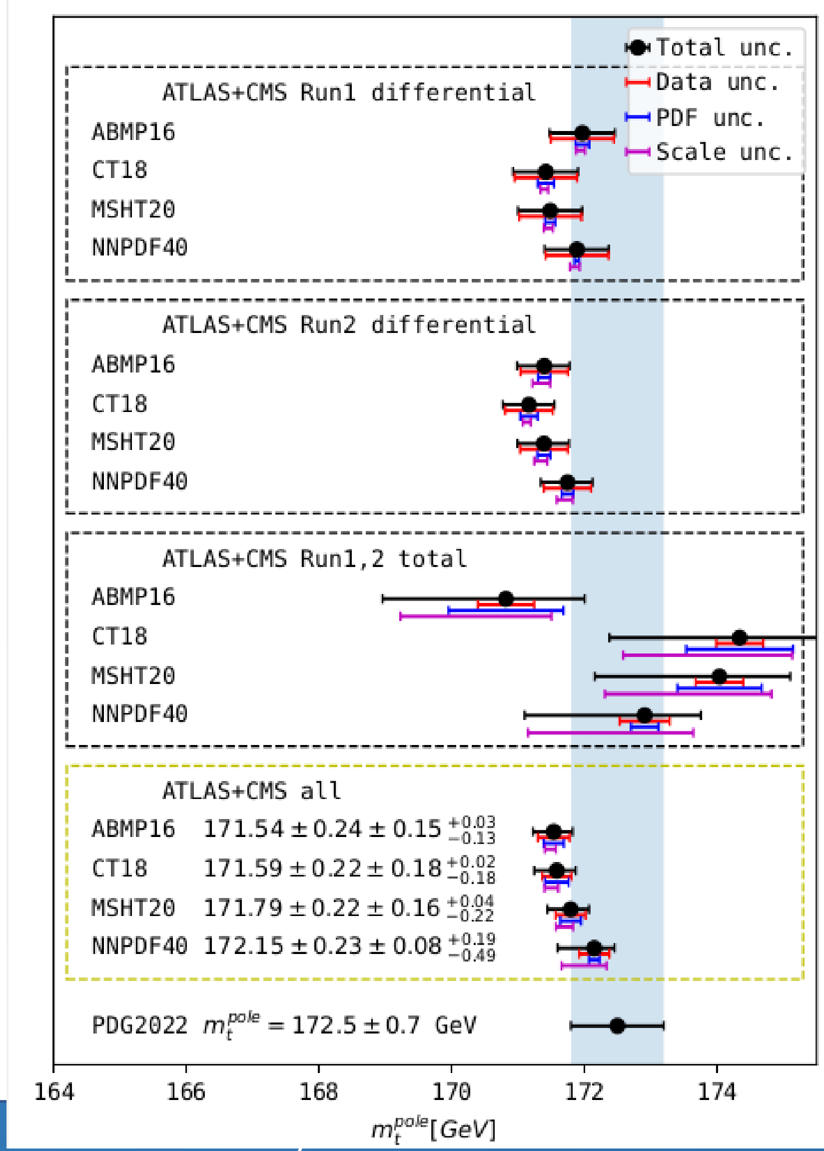
Czakon et al., 2016, MVG et al. 2023





Normalized (m(tt),y(tt)) 2diff-distribution sensitive to m_t in all bins

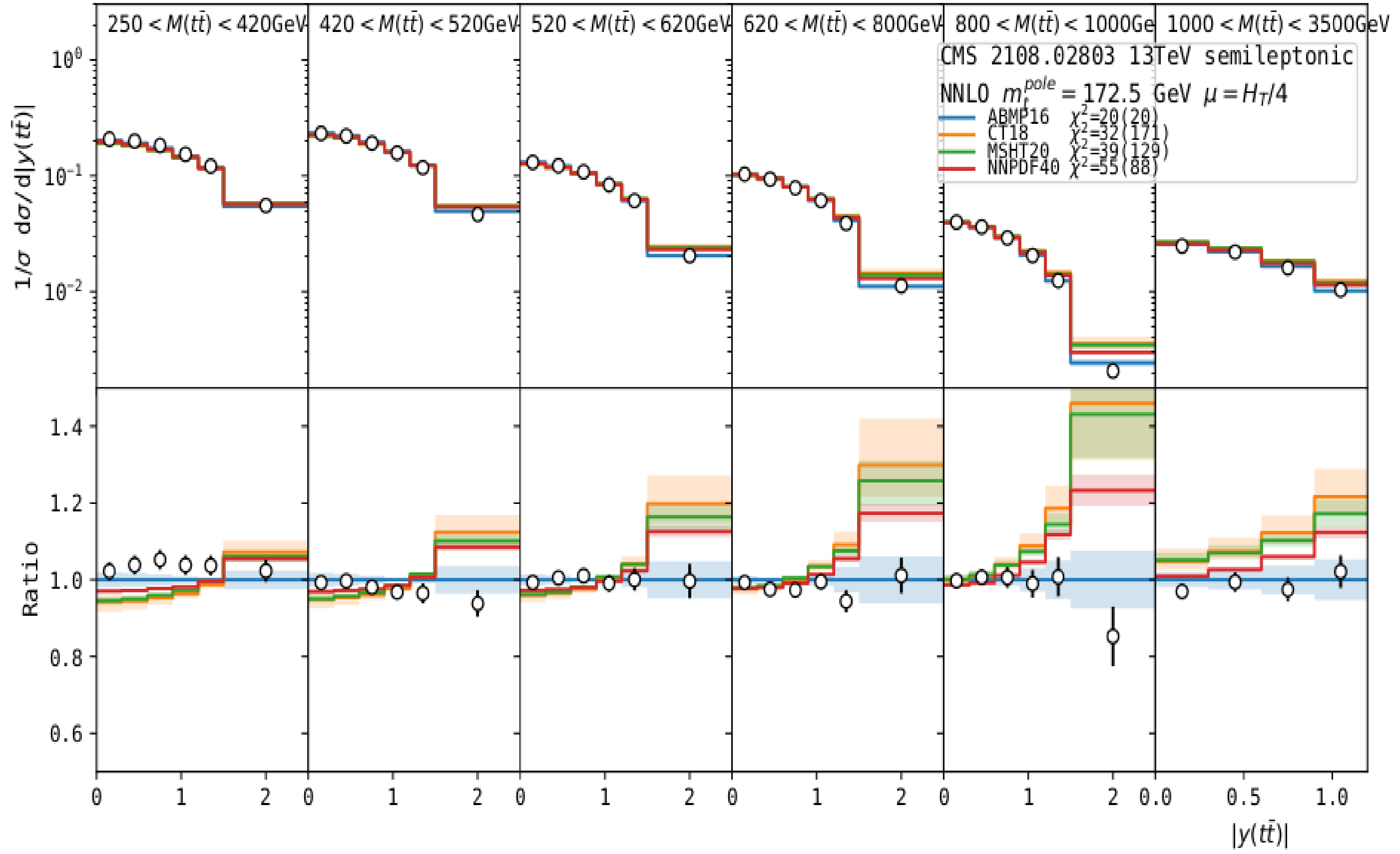




application: PDFs+(m_t+α_s (m_Z)) fits

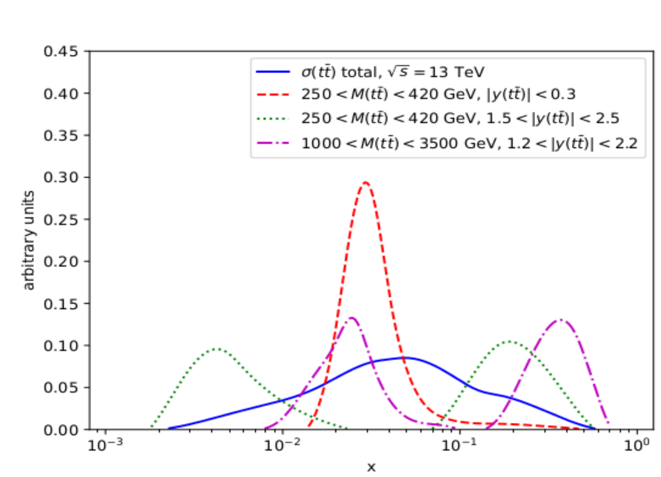
Alekhin et al. 2024

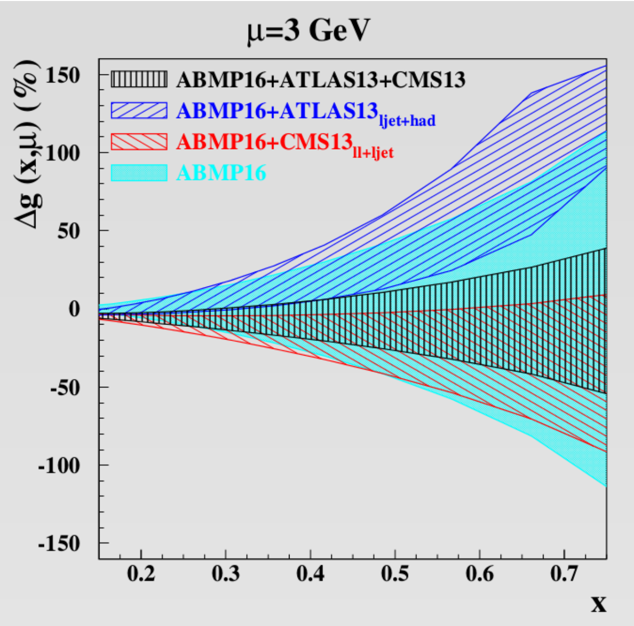
Using CMS and ATLAS data differential in M(tt) and y(tt)



Pre-fit predictions: data not yet included in the fits

LO: $x_{1,2} = (M(t\bar{t})/\sqrt{s}) \exp[\pm y(t\bar{t})]$



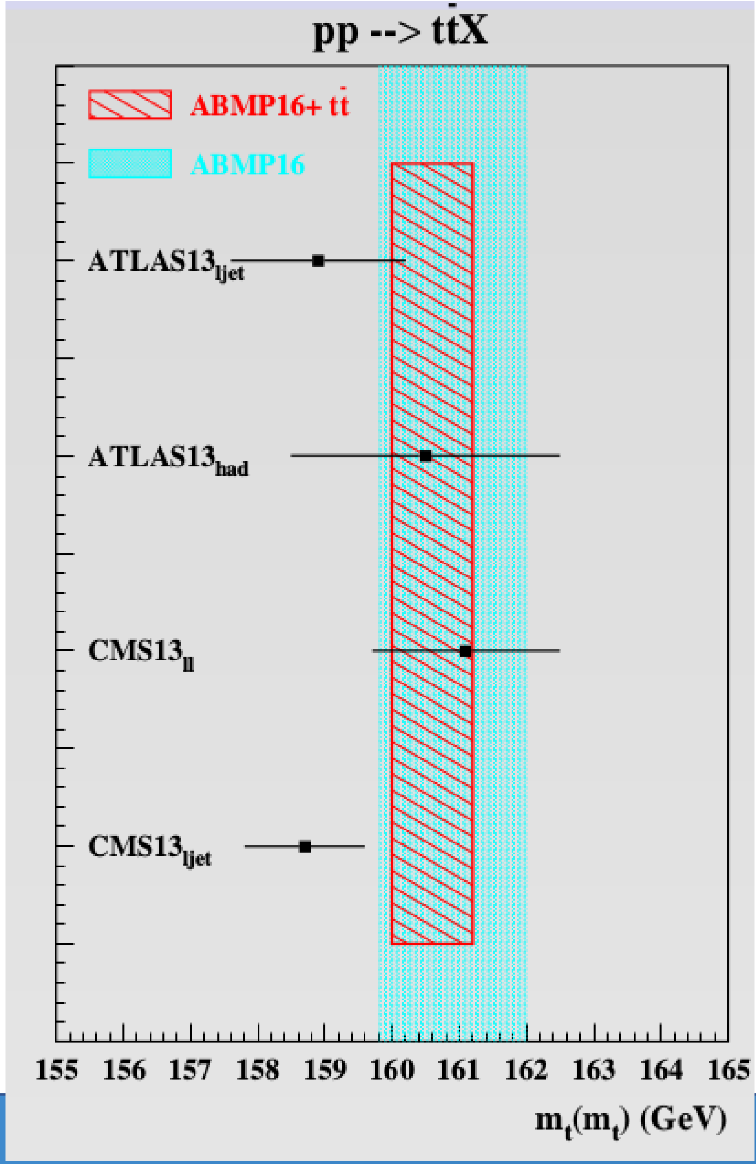


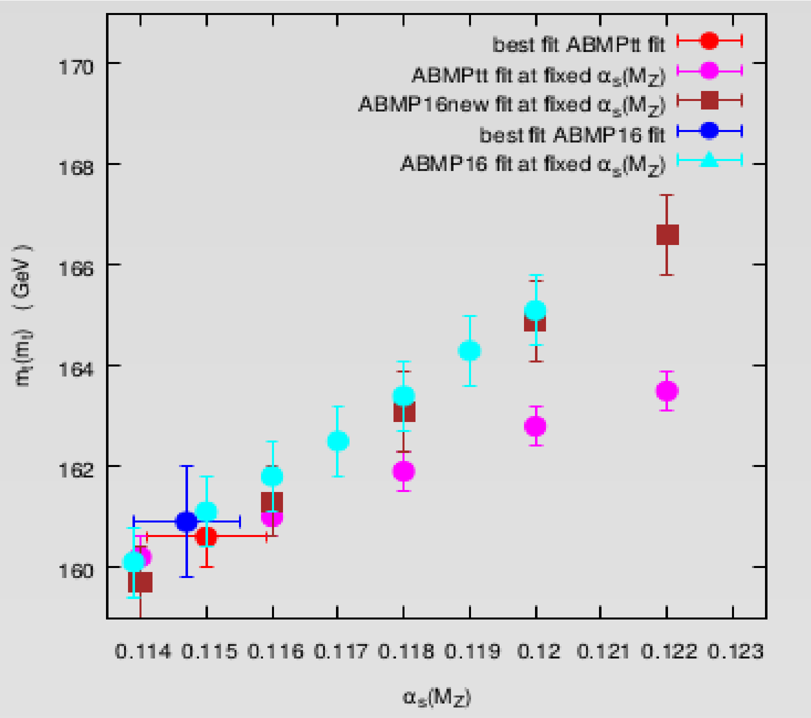
PDFs compatible with those extracted By using total cross-sections only

application:(PDFs)+m_t+$\alpha_s(m_Z)$ fits

CMS and ATLAS data lead to compatible $m_t(m_t)$

Alekhin et al. 2024





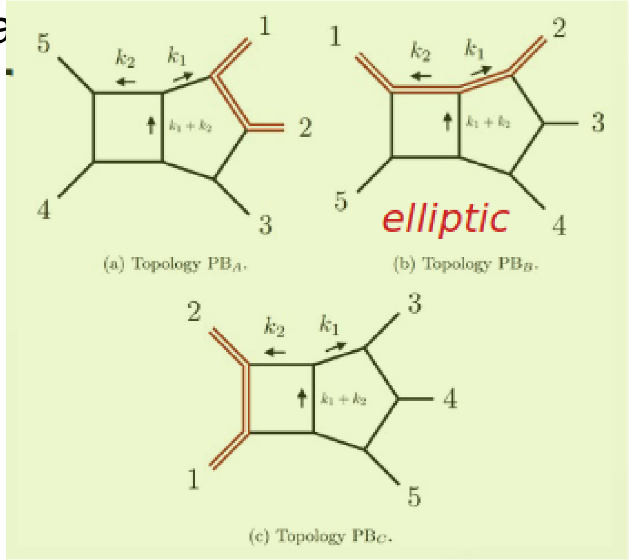
$\alpha_s(M_Z, N_f = 5)$		$m_t(m_t)$ (GeV)
Fitted	0.1150(9)	160.6(6)
$\alpha_s(M_z)$ fixed	0.114	160.2(4)
	0.116	161.0(4)
	0.118	161.9(4)
	0.120	162.8(4)
	0.122	163.5(4)

H. Hartanto et al., Top 2025
S. Badger et al. 2022, 2024; M. Becchettti et al. 2025

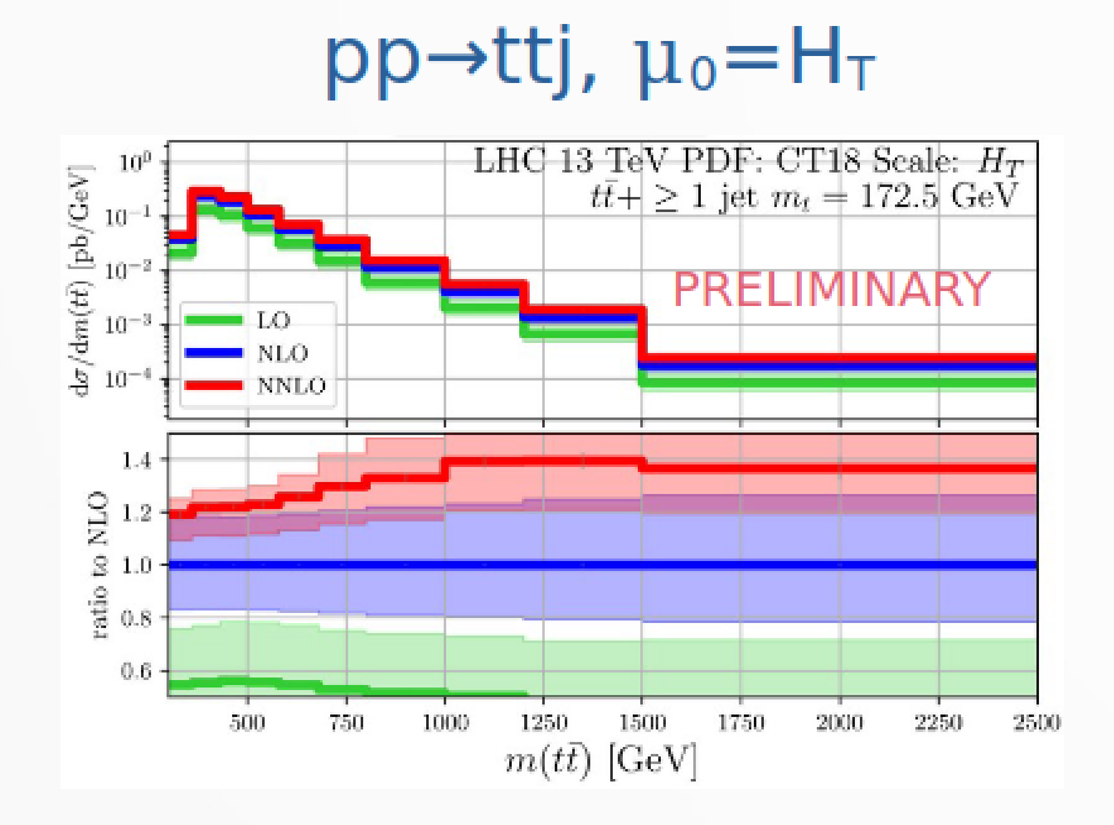
- NNLO QCD

RR: ttjjj, RV: ttjj, VV: ttj, STRIPPER subtraction scheme (M. Czakon et al.)

2-loop amplitudes in leading color:
- rewrite in terms of master integrals
(fa



- compute master integrals:
  numerically, through generalized power series exp.
- expand them in terms of special functions
- subtract UV/IR singularities, etc.…



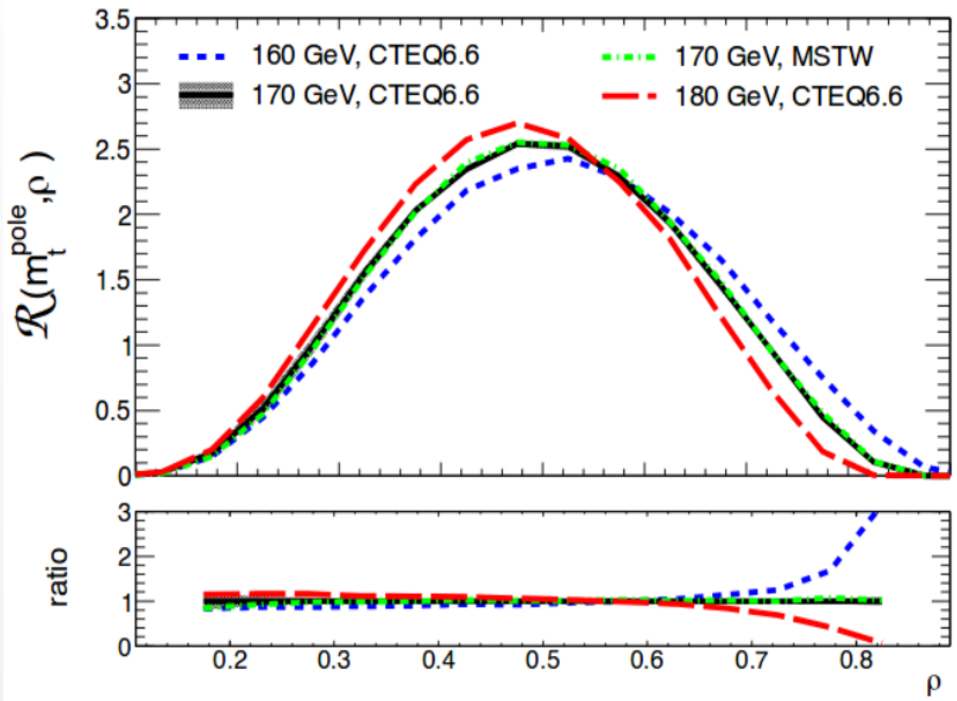
Observables sensitivite to mt+alphaS+PDFs: an example

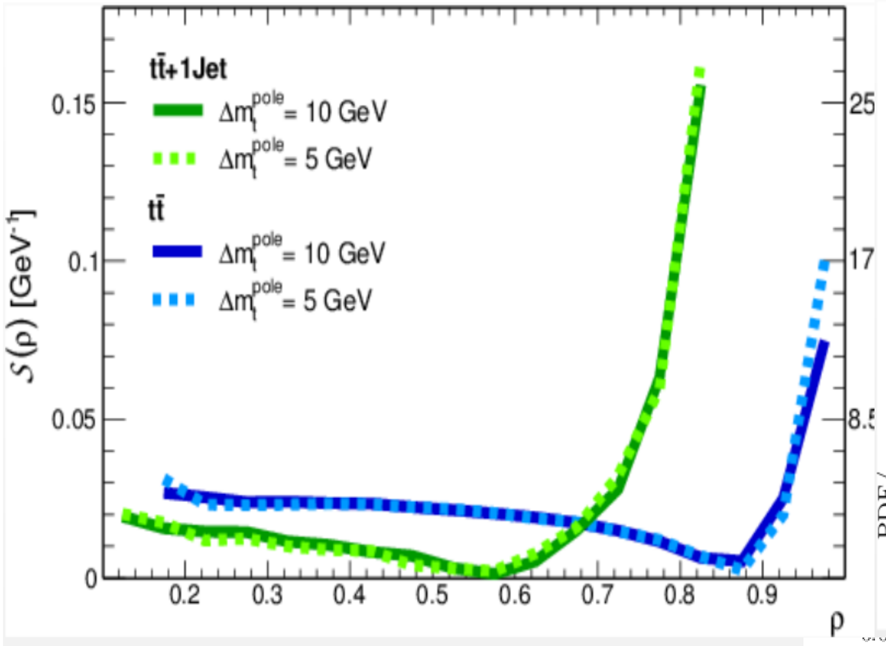
For ttj:

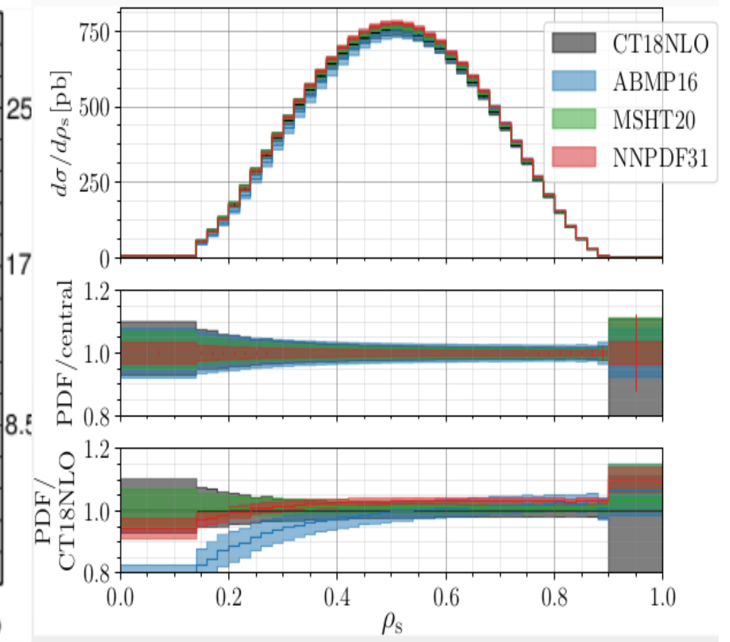
Alioli et al. 2013, 2022

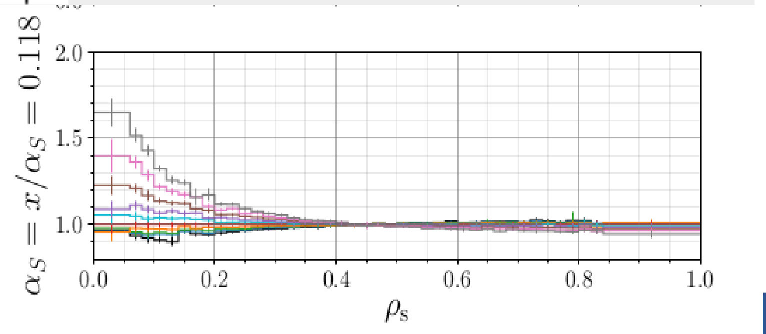
$$\mathcal{R}(m_t^R, \rho_s) = \frac{1}{\sigma_{t\bar{t}+1\text{-jet}}} \frac{d\sigma_{t\bar{t}+1\text{-jet}}}{d\rho_s}(m_t^R, \rho_s), \quad \text{with} \quad \rho_s = \frac{2m_0}{\sqrt{s_{t\bar{t}j}}}$$

Analogous definition for tt









$$\mathcal{S}(\rho_s) = \sum_{\Delta=\pm 5-10\ \text{GeV}} \frac{|\mathcal{R}(170, \rho_s) - \mathcal{R}(170 + \Delta, \rho_s)|}{2|\Delta|\mathcal{R}(170, \rho_s)}$$

Single top @ ATLAS and CMS

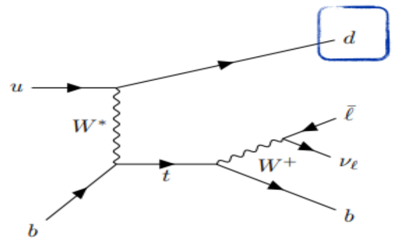
* t-channel (70%): NNLO in MCFM (J.Campbell et al., 2012.01574)

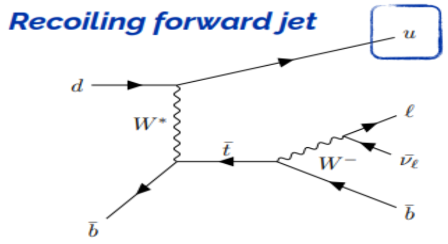
* tW-channel (26%): NLO+NNLL (N. Kidonakis, 2102.11300)

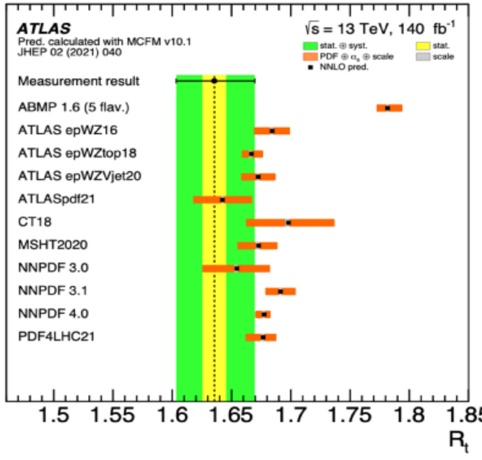
* s-channel (4%): NNLO prod/decay in NWA (Z. Liu et al. 1807.03835)
O(10%) corrections, NNLO not in NLO uncertainty bands

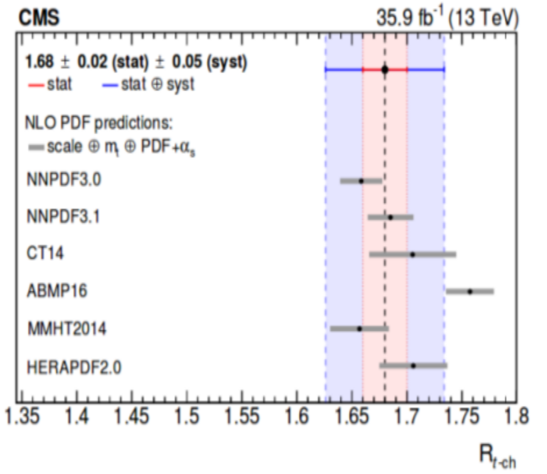
measurement of tWb coupling, m_t;

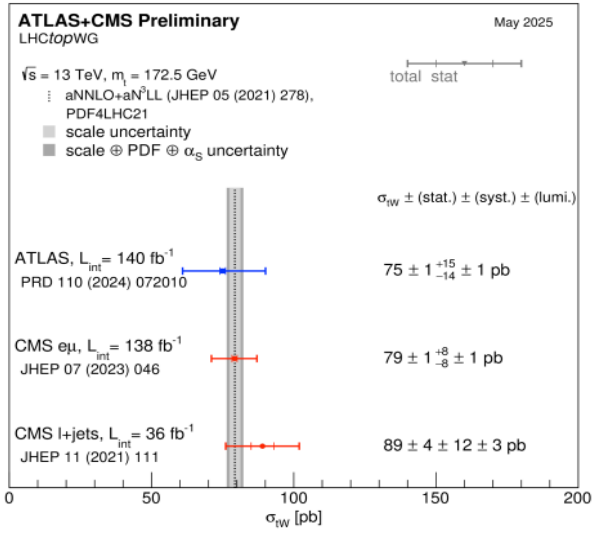
t-channel R_t (ratio of single-top/single-antitop) sensitivity to d/u

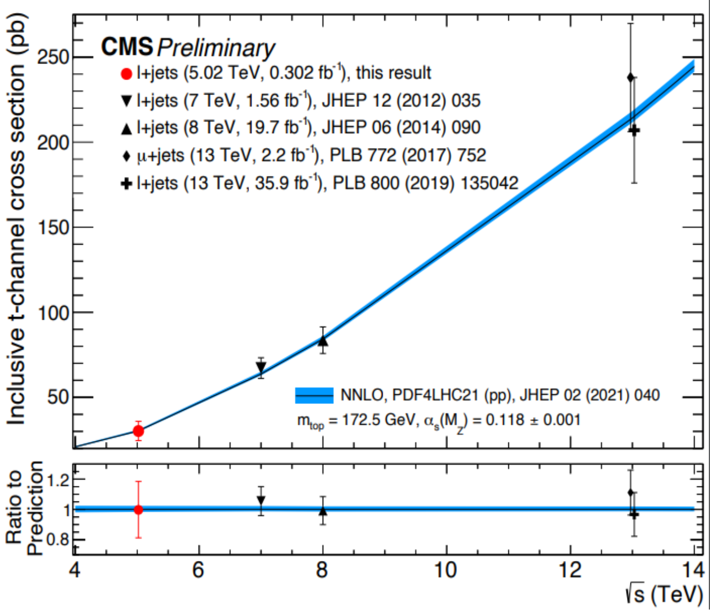


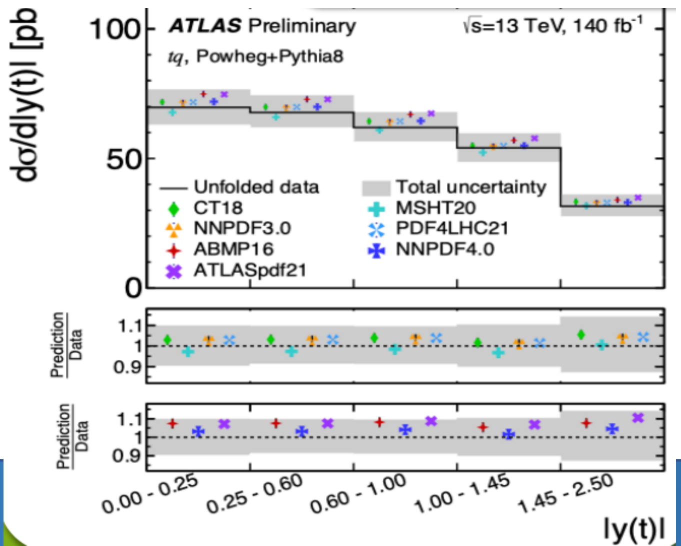










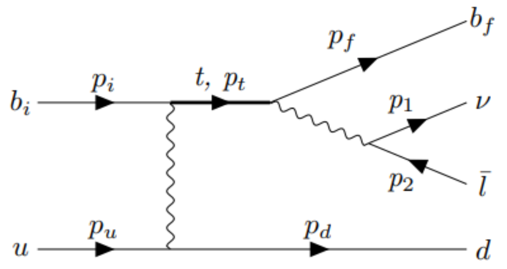


$|f_{LV} V_{tb}|$ = 0.97 ± 0.10

m_t measurement and single top at NNLO

m_t measurement:
control of non-perturbative uncertainties needed. These are power corrections.

S. Marakov et al.
2408.00632



Lepton observables are considered less prone to non-perturbative effects.

Study of linear power corrections to single-top production allows to check if this is true.

Single-top production and decay in NWA ($\Gamma_t << \Lambda_{QCD}$) are not independent due to momentum conservation and polarization effects: direction of e^+ and jet are correlated

Linear power corrections do not affect cross-sections for top stable,
but affect cross-sections if top-quarks is allowed to decay and kinematical distributions of leptons –-> attention in their use to reconstruct the top-quark mass!

Out-of-collision plane component of three-momentum of e^+ is free of power corrections and sensitive to mt

More complicated analysis ($\Gamma_t > \Lambda_{QCD}$), involving non-factorizable corrections, still to be performed

Towards off-shell tt prod & decay at NNLO

L. Buonocore et al. 2507.11410

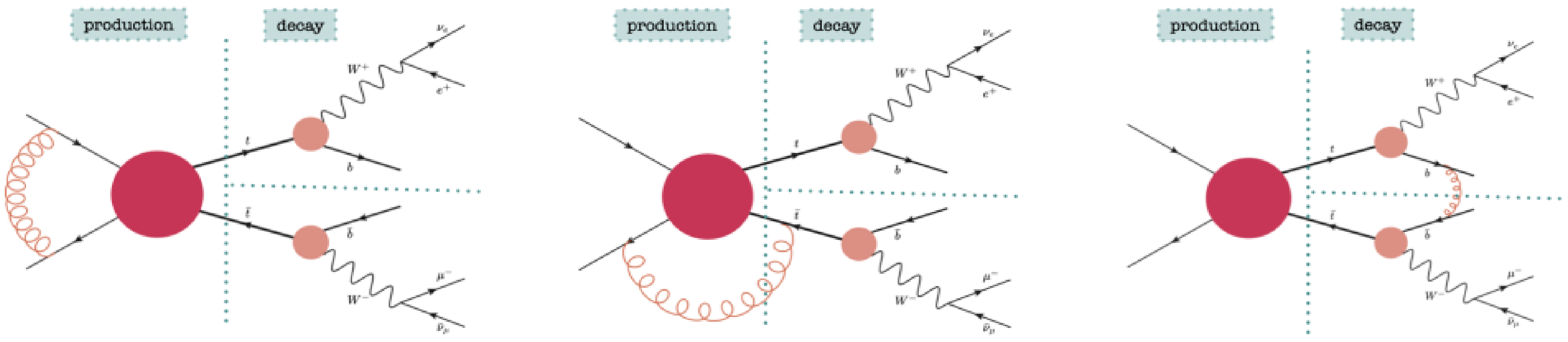
- NNLO QCD

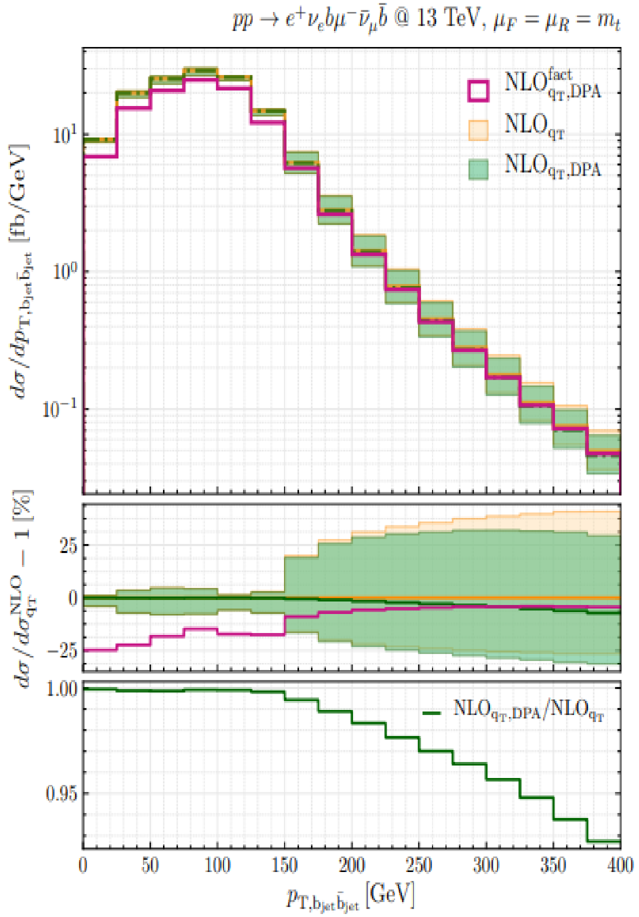
  RR: 2->8, RV: 2->7, VV: 2->6, q_T subtraction scheme

  Bottleneck: VV, use double-pole approximation (DPA)

  DPA expansion in $\delta = \Gamma_t/m_t$ around the double-resonant structure

  preserves IR structure of virtual contribution and log(δ) terms





- factorizable corrections
- non-factorizable corrections: interference between different hard subprocesses: smaller, but of the same order of magnitude of previous ones

DPA at NLO applied to virtual only.

Towards off-shell tt prod & decay at NNLO

L. Buonocore et al. 2507.11410

- NNLO QCD

  RR: 2->8, RV: 2->7, VV: 2->6, q_T subtraction scheme

  Bottleneck: VV, use double-pole approximation (DPA)

  Factorizable corrections at NNLO known

  Non factorizable ones can be obtained by observing that

$$\Delta\sigma_{\mathrm{NNLO,H}}|_{\mathrm{non-fact}} = A^{(2)}_{\mathrm{nf}} \log^2\left(\frac{\Gamma_t}{Q_h}\right) + B^{(2)}_{\mathrm{nf}} \log\left(\frac{\Gamma_t}{Q_h}\right) + C^{(2)}_{\mathrm{nf}} + \mathcal{O}\left(\frac{\Gamma_t}{Q_h}\right)$$

and that at the most inclusive level (no cuts)

$$\lim_{\Gamma_t\to 0}\int d\sigma_{\mathrm{off-shell}} = \int d\sigma_{\mathrm{prod\times dec}} = \sigma_{t\bar{t}} \underbrace{\frac{\Gamma_{t\to e^+\nu_e b}}{\Gamma_t}}_{\mathrm{BR}(t\to e^+\nu_e b)} \underbrace{\frac{\Gamma_{\bar{t}\to\mu^-\bar{\nu}_\mu\bar{b}}}{\Gamma_t}}_{\mathrm{BR}(\bar{t}\to\mu^-\bar{\nu}_\mu\bar{b})} \equiv \sigma_{\mathrm{on-shell}}$$

Extract non-fact corrections by numerical matching to on-shell calculation

$$\Delta\sigma_{\mathrm{NNLO,H}}|_{\mathrm{non-fact}}(\Gamma_t) = \Delta\sigma^{\mathrm{on-shell}}_{\mathrm{NNLO}} - \lim_{r_{\mathrm{cut}}\to 0}\Delta\sigma_{\mathrm{NNLO}^{\mathrm{fact}}_{q_T,\mathrm{DPA}}}(r_{\mathrm{cut}},\Gamma_t)$$

- double scan in Γ_t and r_{cut}, result for Γ_t and r_{cut} ---> 0 (fit)

Towards off-shell tt prod & decay at NNLO

σ [fb]	all	gg	$q\bar{q}$	gq	$qq+\bar{q}\bar{q}+q'\bar{q}$
σ_{LO}	$6482.21(6)\,^{+29.32\%}_{-21.24\%}$	5783.84(6)	698.36(2)	$--$	$--$
$\sigma_{\mathrm{NLO}_{\mathrm{CS}}}$	$9584(2)\,^{+8.18\%}_{-10.01\%}$	8631(2)	901.7(4)	50.4(1)	$--$
$\sigma_{\mathrm{NLO}_{q_T}}$	$9589(6)\,^{+8.21\%}_{-10.02\%}$	8637(6)	901.8(1.3)	50.5(1)	$--$
$\sigma_{\mathrm{NLO}_{q_T,\mathrm{DPA}}}$	$9498(6)\,^{+7.86\%}_{-9.84\%}$	8543(5)	903.9(1.3)	50.5(1)	$--$
$\sigma_{\mathrm{NLO}_{q_T,\mathrm{DPA}'}}$	$9614(2)\pm 2$	$8664(2)\pm 2$	$899.1(2)\pm 0.3$	50.5(1)	$--$
$\sigma_{\mathrm{NNLO}_{q_T,\mathrm{DPA}'}}$	$10623(55)\pm 152\,^{+3.2\%}_{-4.6\%}$	$9599(54)\pm 152$	$979(5)\pm 6$	67(10)	7.46(7)
$\sigma_{\mathrm{NNLO}^{\mathrm{fact}}_{q_T,\mathrm{DPA}}}$	9546(55)	8623(54)	849(5)	67(10)	7.46(7)
$\Delta\sigma_{\mathrm{NNLO,H}}\vert_{\mathrm{fact}}@m_t$	5323.4(7)	4726.7(7)	596.74(8)	$--$	$--$
$\Delta\sigma_{\mathrm{NNLO,H}}\vert_{\mathrm{non-fact}}@m_t$	1107 ± 152	976 ± 152	131 ± 6	$--$	$--$

Table 3: Inclusive LO, NLO and NNLO cross sections at $\sqrt{s}=13\,\mathrm{TeV}$, for the different contributing partonic channels. The quoted relative uncertainties are obtained through scale variations, while the errors in parentheses take into account the statistical errors from the Monte Carlo integration combined with the systematic errors from the $r_{\mathrm{cut}}\to 0$ extrapolation. The additional systematic error at NNLO originates from the $\Gamma_t\to 0$ extrapolation procedure for the determination of the non-factorisable corrections. In the last two rows, we report the factorisable two-loop corrections, computed at scale $\mu=m_t$, and the fitted non-factorisable corrections, respectively.

L. Buonocore et al.
2507.11410

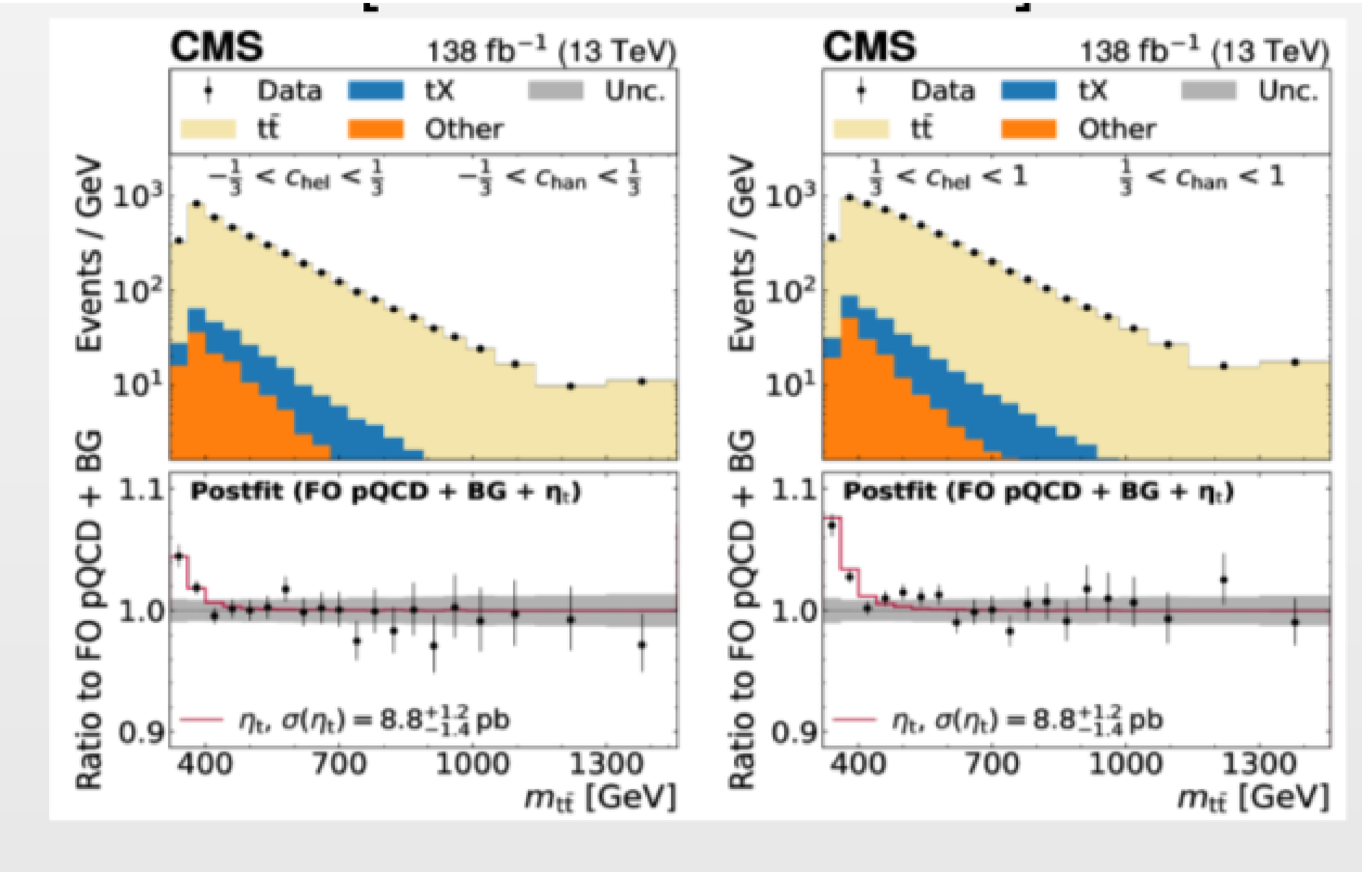
NNLO Non-factorizable corrections ~ O(20%) of factorizable ones

$$K_{\mathrm{NLO}}^{\mathrm{off-shell}}=1.479$$
$$K_{\mathrm{NNLO}}^{\mathrm{off-shell}}=1.1084$$

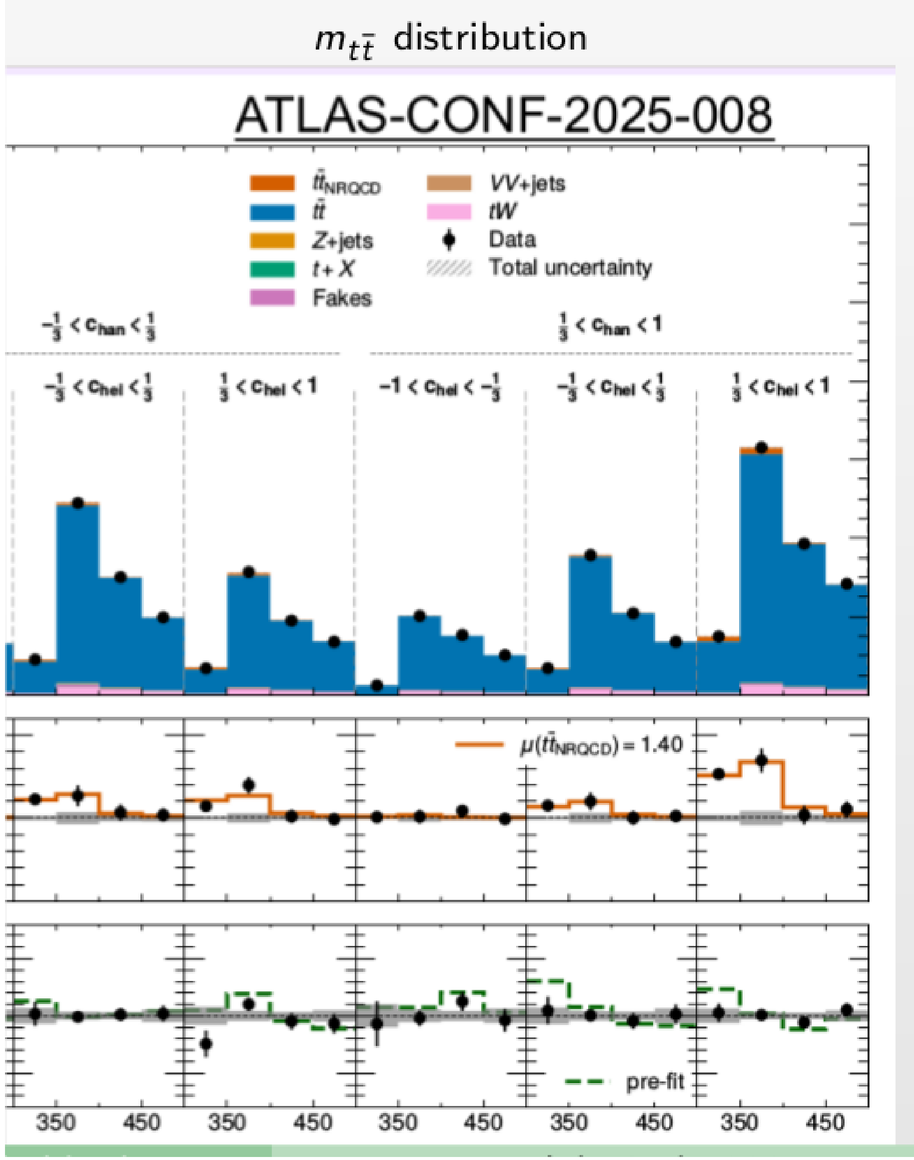
$$K_{\mathrm{NLO}}^{\mathrm{on-shell}}=1.470$$
$$K_{\mathrm{NNLO}}^{\mathrm{on-shell}}=1.1080$$

excess at the tt production threshold

CMS, [arXiv:2503.22382]



m_{tt} in c_{hel} and c_{han} bins, excesses for large c_{hel}



spin related observables, excess of several sigmas
Eplanations: BSM Higgs ? Toponium ? Both ?

Toponium

Quasi-bound state of a top-antitop quark pair
Main difference to “properly-bound” states charmonia and bottomonia:
top quark decays before hadronizing, while charm and bottom do not

Spectroscopic notation $^{2S+1}L_J^{[1,8]}$ for classifying “toponium” states:

- S=0, L=0 ⇒ J=0
- S=1, L=0 ⇒ J=0, 1 (gg contribution suppressed)

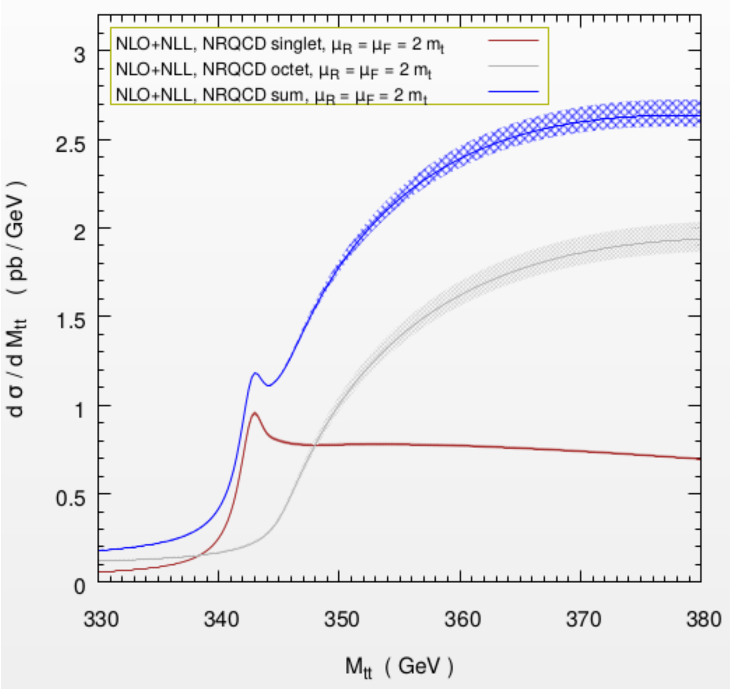
Close to threshold gluon exchange between top and antitop quarks becomes important:
not included in standard tools used by the LHC experimentalists for their simulations

Several approaches:
* NRQCD factorization or NRQCD-inspired approaches
* fixed-order expansion in α_s/v, up to N^{3}LO.
* simplified models: BSM pseudoscalar coupled to tt,
  whose mass and width are fitted to reproduce NRQCD

NRQCD factorization for invariant mass:

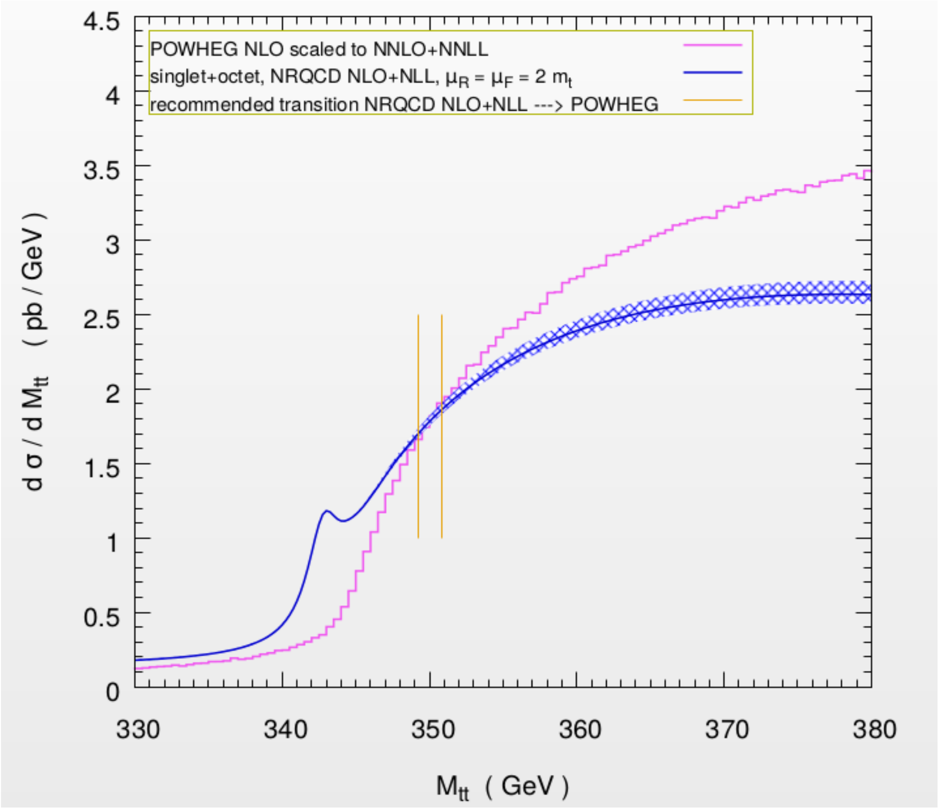
$$M_{t\bar{t}}\frac{d\hat{\sigma}_{ij\to T}}{dM_{t\bar{t}}}(\hat{s},M_{t\bar{t}}^2,\mu_f^2) = F_{ij\to T}(\hat{s},M_{t\bar{t}}^2,\mu_f^2)\,\frac{1}{m_t^2}\,\mathrm{Im}\,G^{[1,8]}(M_{t\bar{t}}+i\Gamma_t)$$

$$\left\{2m_t + \left[\frac{(-i\nabla)^2}{m_t} + V_C^{[1,8]}(\vec{r})\right] - (M_{t\bar{t}} + i\Gamma_t)\right\} G^{[1,8]}(\vec{r};\, M_{t\bar{t}}+i\Gamma_t,\, m_t) = \delta^{(3)}(\vec{r})$$



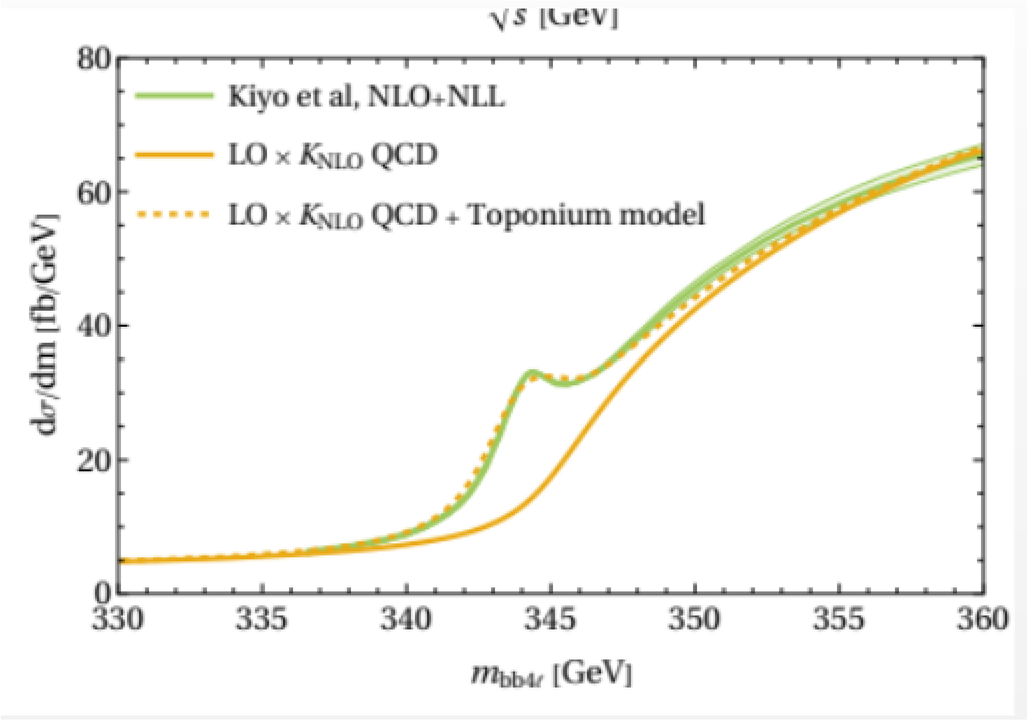
Predictions for toponium at the LHC

Kyio et al. 2008, MVG et al. 2025



NRQCD validity limited to a restricted range around threshold.
Matching to QCD necessary outside

Fuks et al., 2021
Maltoni et al., 2024



Simplified models allow for fully-exclusive events

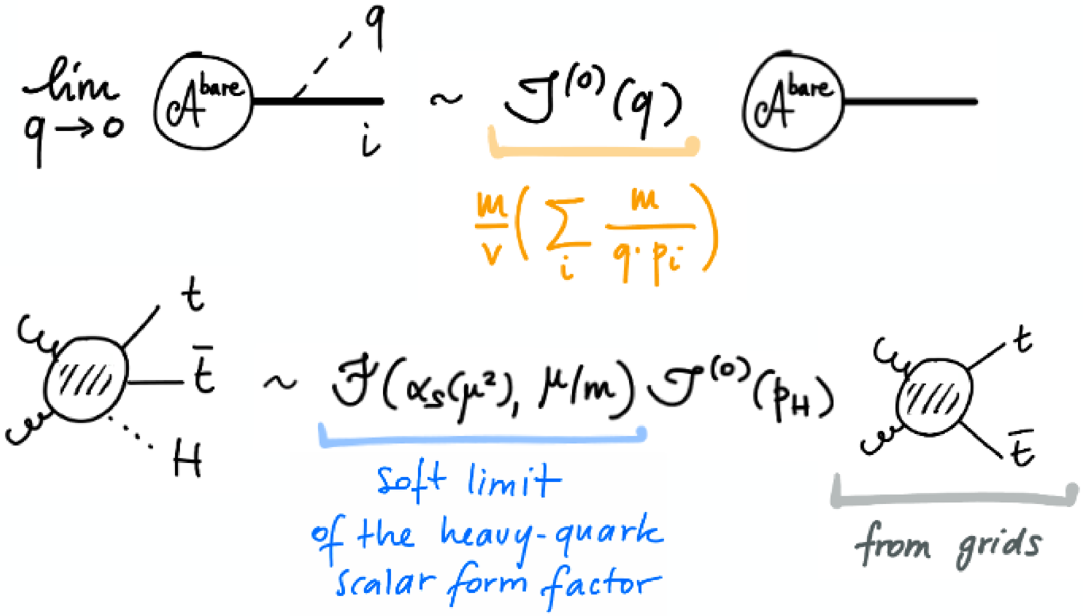
Open issues:
how to implement octet contribution ?

Approximations for ttH two-loop amplitudes

From C. Biello et al., TOP2025

Soft Higgs-boson approximation

based on Kniehl, Spira [hep-ph/9505225] and refs. therein

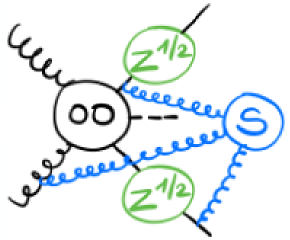


First application in $t\bar{t}H$:
Catani, Devoto, Grazzini, Kallweit, Mazzitelli, Savoini [2210.07846]

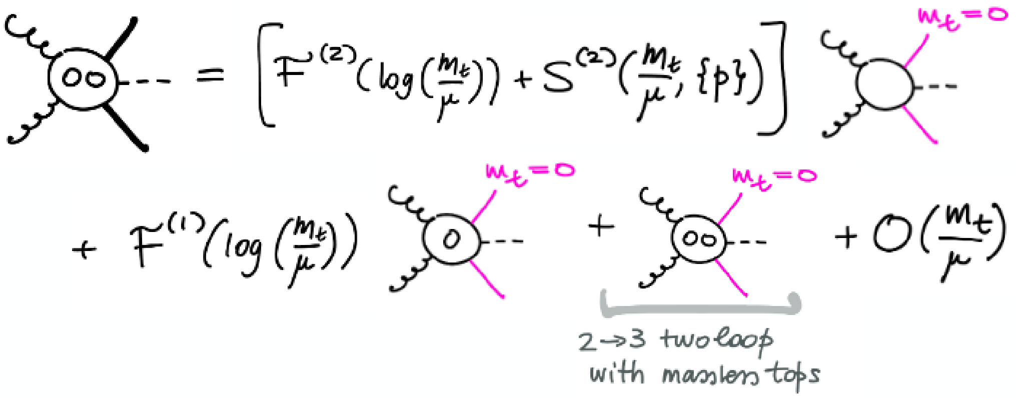
Two-loop $t\bar{t}$ grids:
Bärnreuther, Czakon, Fiedler [1312.6279]

Mapping preserves m_{ttH}

Massification of top-quarks



based on Mitov, Moch [hep-ph/0612149]
and Wang, Xia, Yang, Ye [2312.12242]



perturbative functions known

Mapping preserves p_{tt}

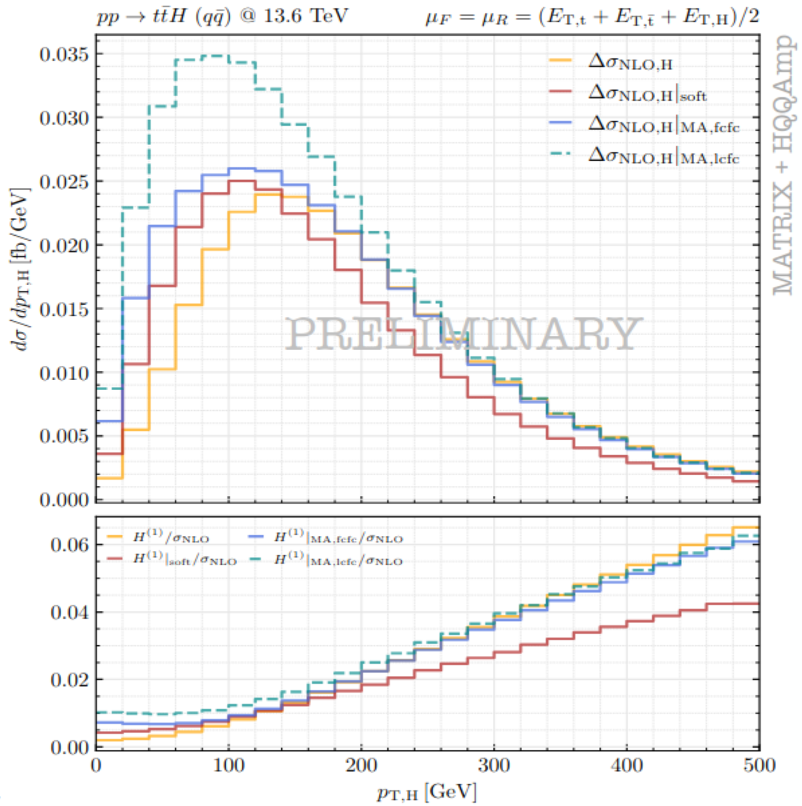
ttH

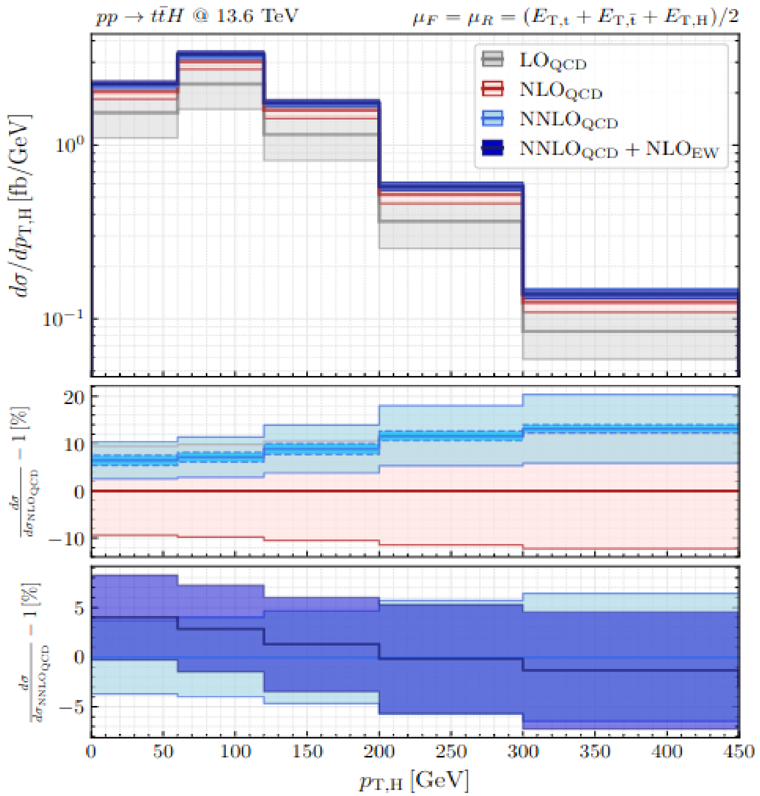
S. Devoto et al., [arXiv:2411.15340]

- complete NNLO predictions with approximated 2-loop amplitudes
  * Soft Higgs approximation (tt) (see Kniehl and Spira, hep-ph/9505225)
  * Massification approximation: HE expansion in the small m_t limit (H+4 light partons)

Consistent results within their respective uncertainties

More solid estimate of 2-loop amplitudes by using both approximations





+EW corrections

	σ [fb]
LO_{QCD}	$423.9\ ^{+30.7\%}_{-21.9\%}$ (scale)
NLO_{QCD}	$528.9\ ^{+5.7\%}_{-9.0\%}$ (scale)
$NNLO_{QCD}$	$550.7(5)\ ^{+0.9\%}_{-3.1\%}$ (scale) $\pm 0.9\%$ (approx)
$NNLO_{QCD} + NLO_{EW}$	$562.3(5)\ ^{+1.1\%}_{-3.2\%}$ (scale) $\pm 0.9\%$ (approx)

Expected accuracy at HL-LHC:
O(2%)

ttH

R. Balsach et al., [arXiv:2503.1504]

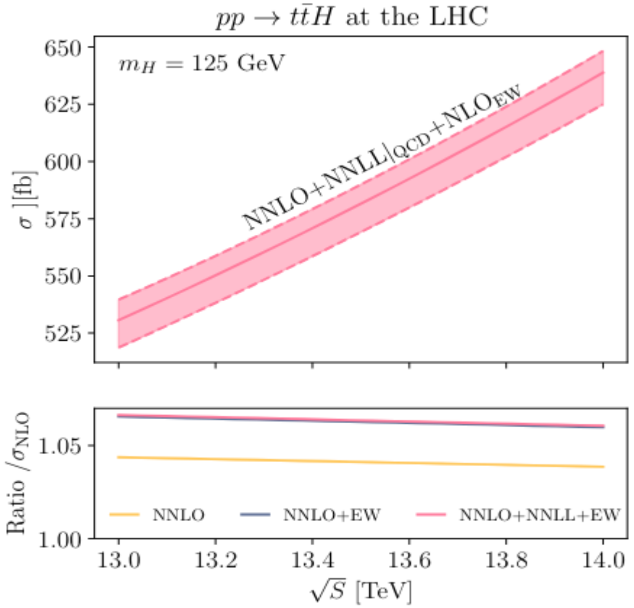
- NNLO + NNLL predictions with approximated 2-loop amplitudes
  * Soft Higgs approximation (tt)
  * Massification approximation: HE expansion in the small mt limit (H+4 light partons)

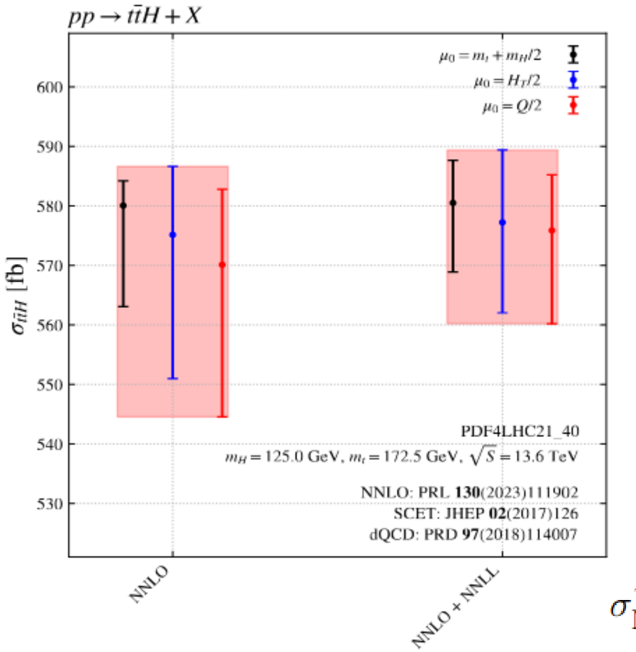
NNLL resummation of threshold logs

$$\sigma\left(S, m_t, m_H\right) = \frac{1}{2S}\int_{\tau_{min}}^{1} d\tau \int_{\tau}^{1} \frac{dz}{\sqrt{z}} \sum_{ij} ff_{ij}\left(\frac{\tau}{z}, \mu\right) \times \int d\mathrm{PS}_{t\bar{t}H} \mathrm{Tr}\left[\mathbf{H}_{ij}\left(\{p\}, \mu\right) \mathbf{S}_{ij}\left(\frac{Q(1-z)}{\sqrt{z}}, \mu\right)\right]$$

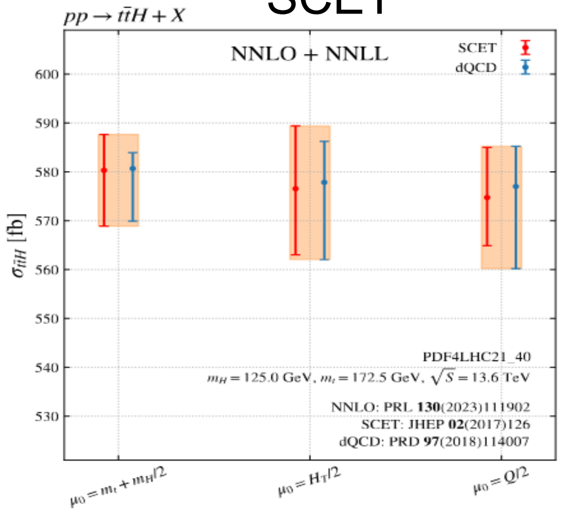
In SCET

$$z = Q^2/\hat{s}, \qquad \tau_{\min} = \frac{(2m_t + m_H)^2}{S}, \qquad \tau = \frac{Q^2}{S}$$





dQCD vs SCET



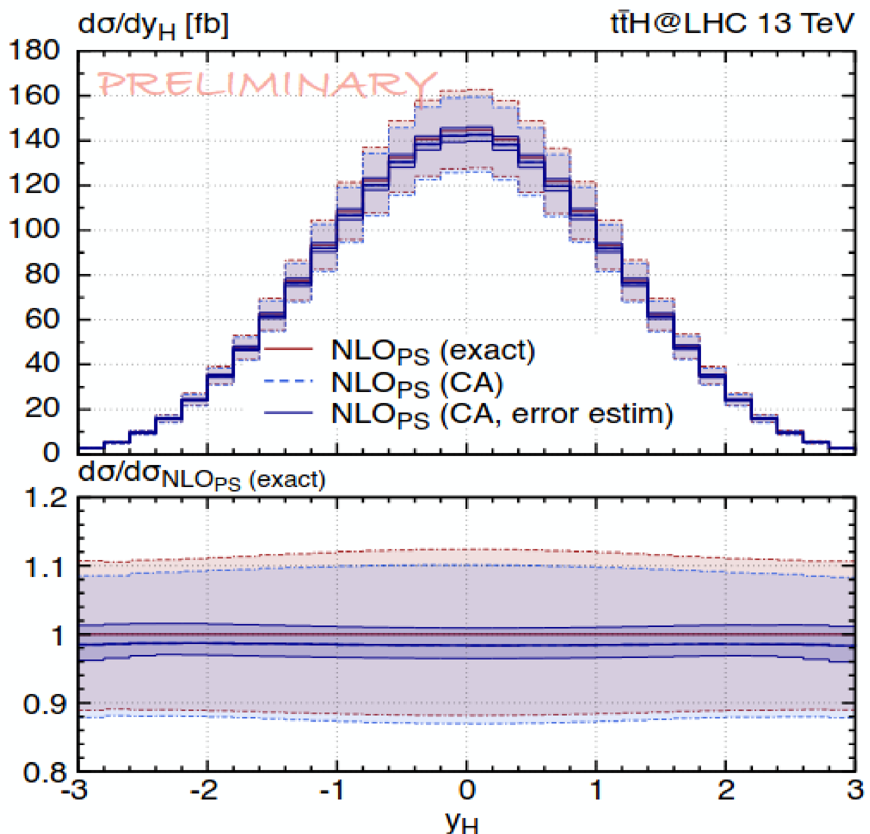
$$\sigma_{\rm NNLO+NNLL+EW}^{\sqrt{S}=13.6\,\rm TeV,\, m_H=125.09\,\rm GeV} = 592.1\ \mathrm{fb}\ \underbrace{^{+1.5\%}_{-2.2\%}}_{\Delta_\mu}\ \underbrace{\pm 2.2\%}_{\Delta_{\rm PDF}}\ \underbrace{\pm 1.7\%}_{\Delta_{\alpha_s}}\ \underbrace{\pm 0.9\%}_{\Delta_{\rm virt}}$$

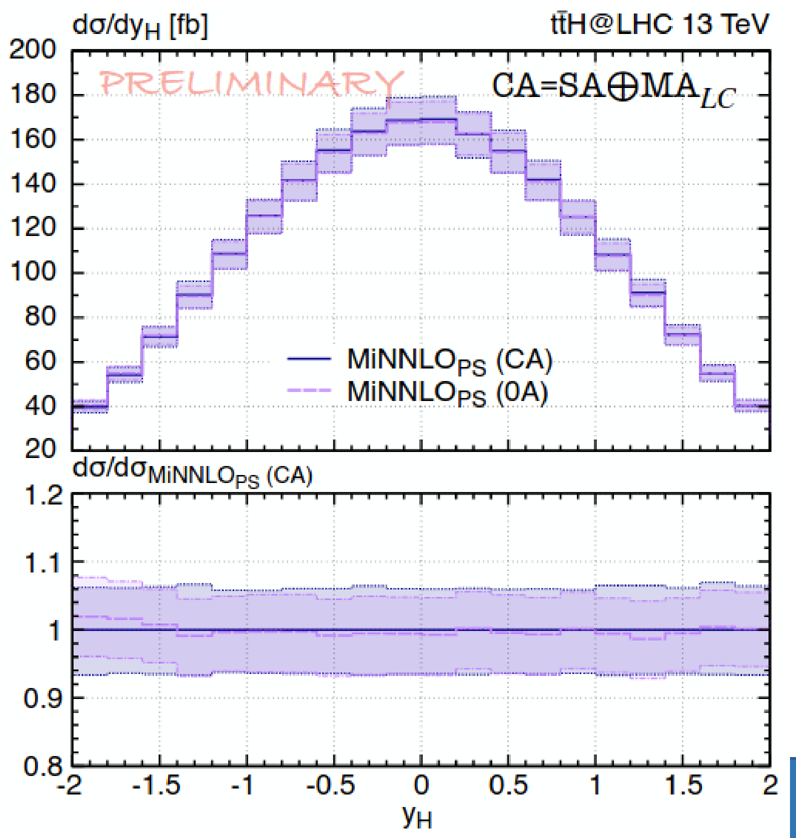
ttH

C. Biello et al., TOP2025

- NNLO + PS framework MINNLOPS already applied to tt [arXiv:2012.14267, 2112.12135], bb [2302.01645], bbZ [2404.08598], bbH [2412.09510], now extended to ttH

Soft Higgs-boson approximation and massification of top quarks implemented in POWHEG
Combined point-wise with a weight depending on the two scales of the problem: $p_{T,H}$ and m_t





ttW

L. Buonocore et al. [arXiv:2306.16311], C. Savoini, Moriond 2024

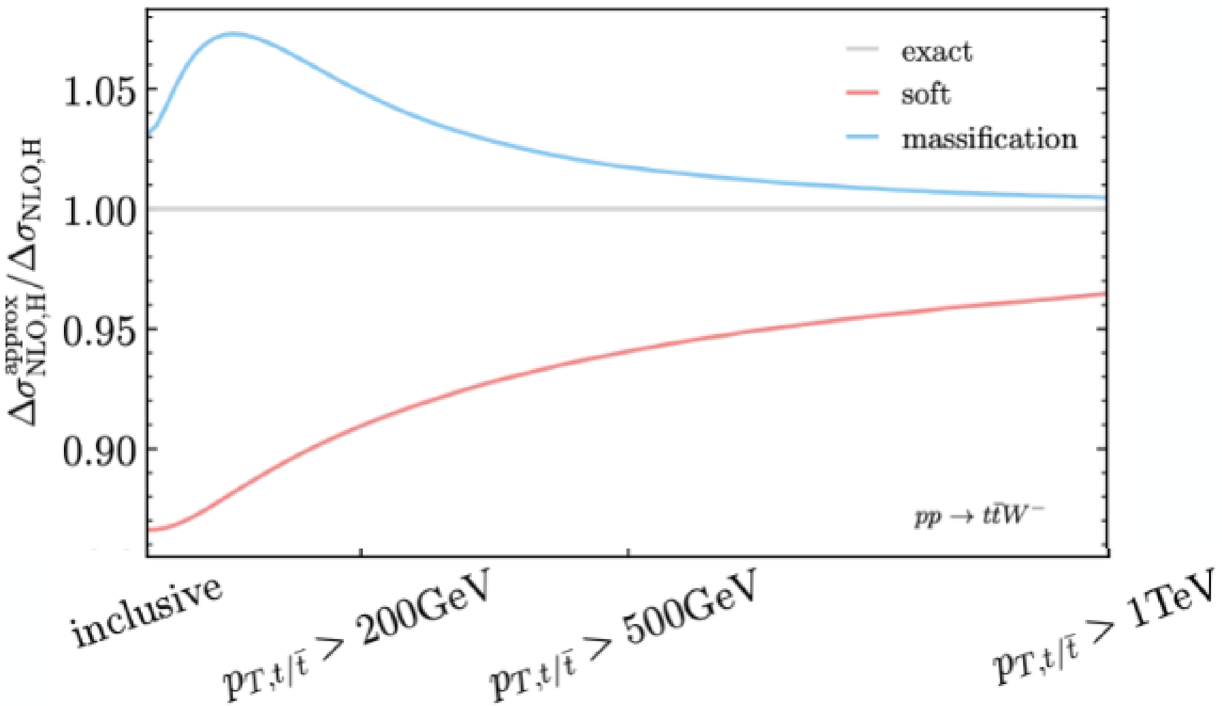
- complete NNLO predictions with approximated 2-loop amplitudes:

  Soft Higgs boson approximation: valid for $E_w \to 0$, $m_w << m_t$

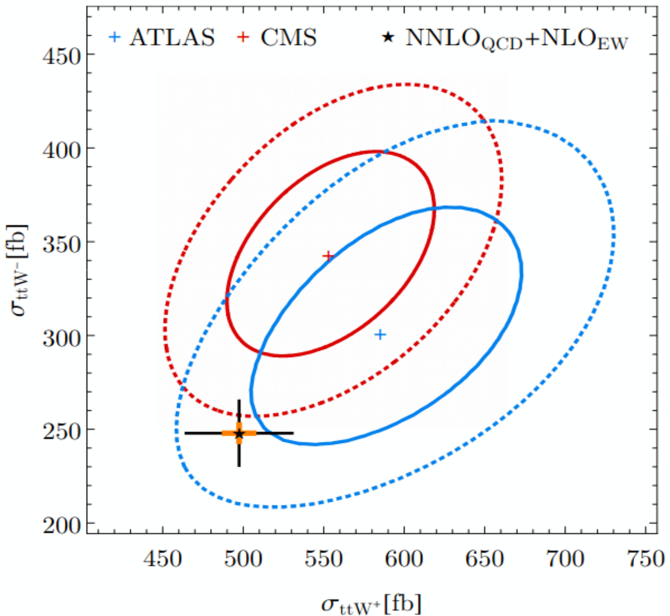
  Massification: valid for $m_t << Q(ttW)$

  None of the two approximations is valid for the bulk of the events

Validation at NLO
within 15%, asymptotically good at large p_T



"Best" prediction: average of the two, with uncertainty that is linear combination of the uncertainties accompanying each approximation



depending on variation seen at NLO and μ_{IR} variation

2-loop virtual ~ 7% sigma(NNLO)

NNLO corrections ~ 15%

Comparison with ATLAS-CONF-2023-019]
[CMS: arXiv 2208.06485]

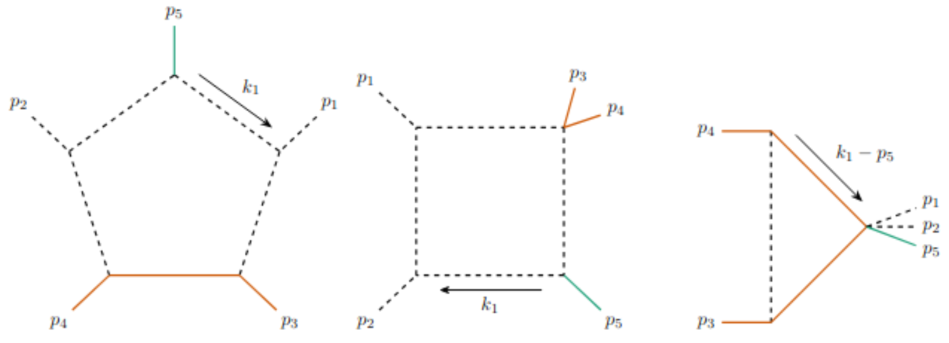
Recent ingredients for leading color ttW

NLO corrections ~ 50%, NNLO corrections ~ 15%, 2-loop virtual ~ 7% sigma(NNLO)

M. Becchetti et al. [arXiv:2502.14952]

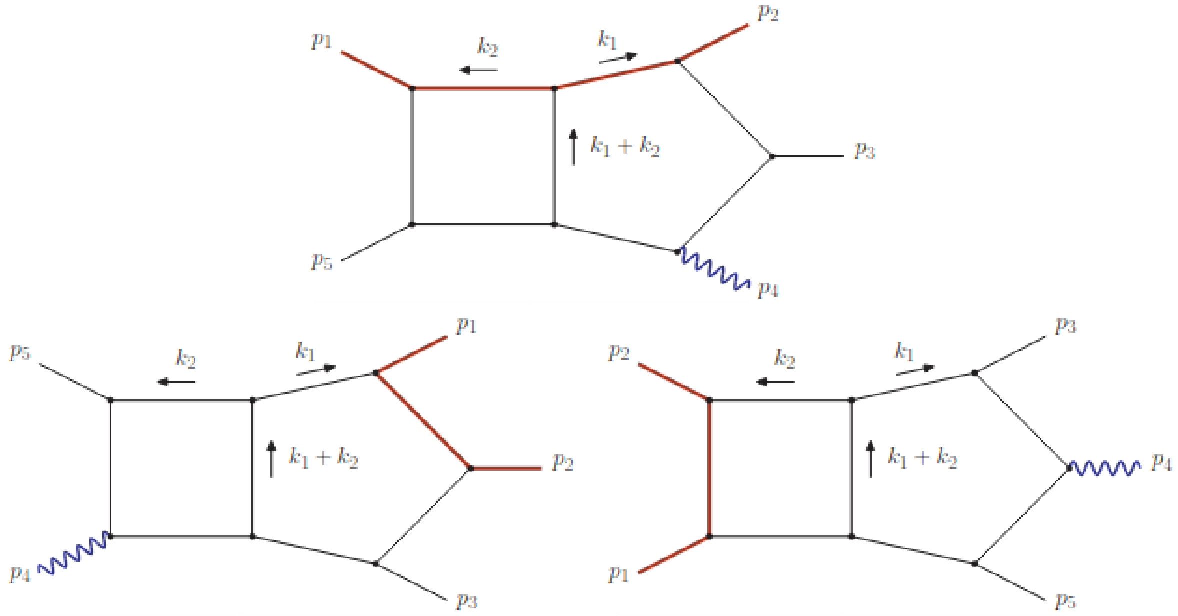
Seminumerical work: computation of the one-loop form factors from the decomposition of one-loop scattering amplitudes up to order ε^2 in dim reg.

Available in Mathematica package TTW



(a) Topology A. (b) Topology B. (c) Topology C.

M. Becchetti, et al. [arXiv: 2504.13011]; D. Canko, Top 2025



Using IBP, 141, 122 and 131 Master Integrals for the three families above.

Due to appearance of special functions, numerical evaluation with generalized power series expansion in DiffExp

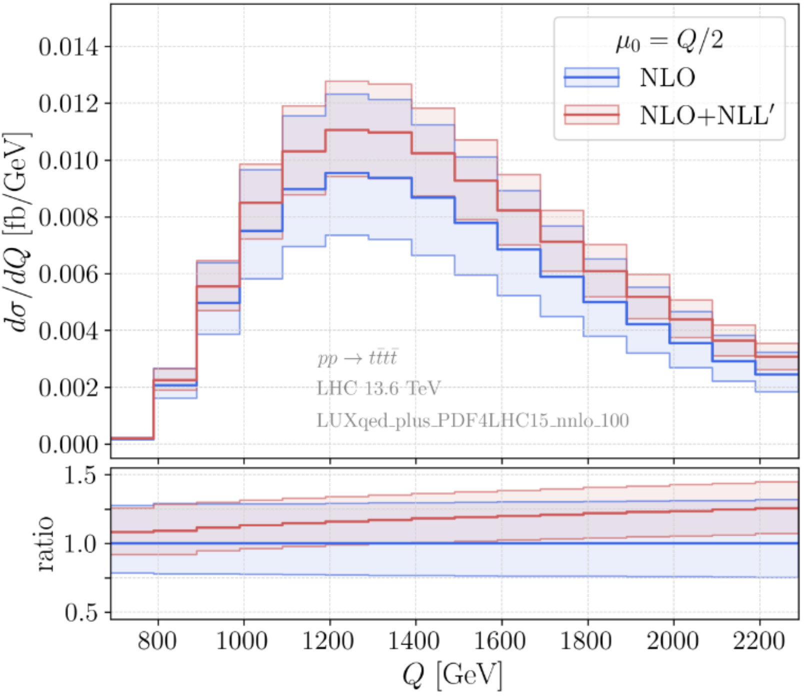
tttt

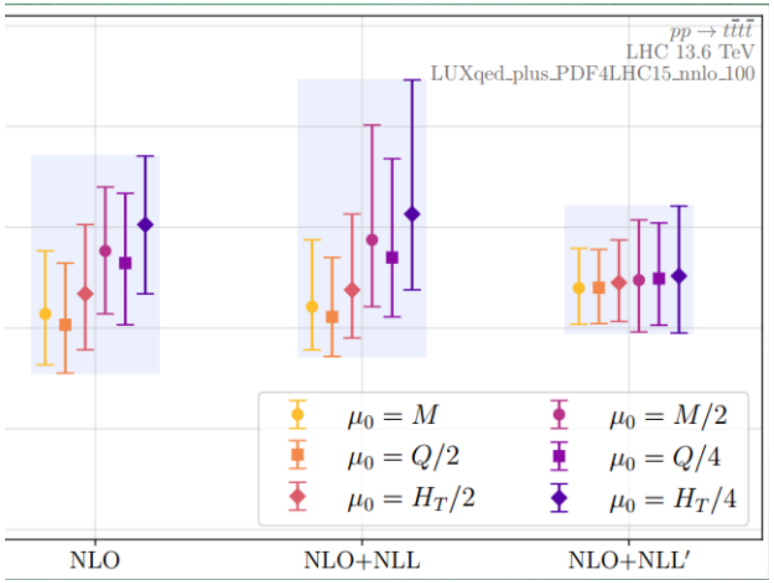
Van Beekveld et al. [arXiv:2505.10381]
See parallel-session talk by M. Lupatelli

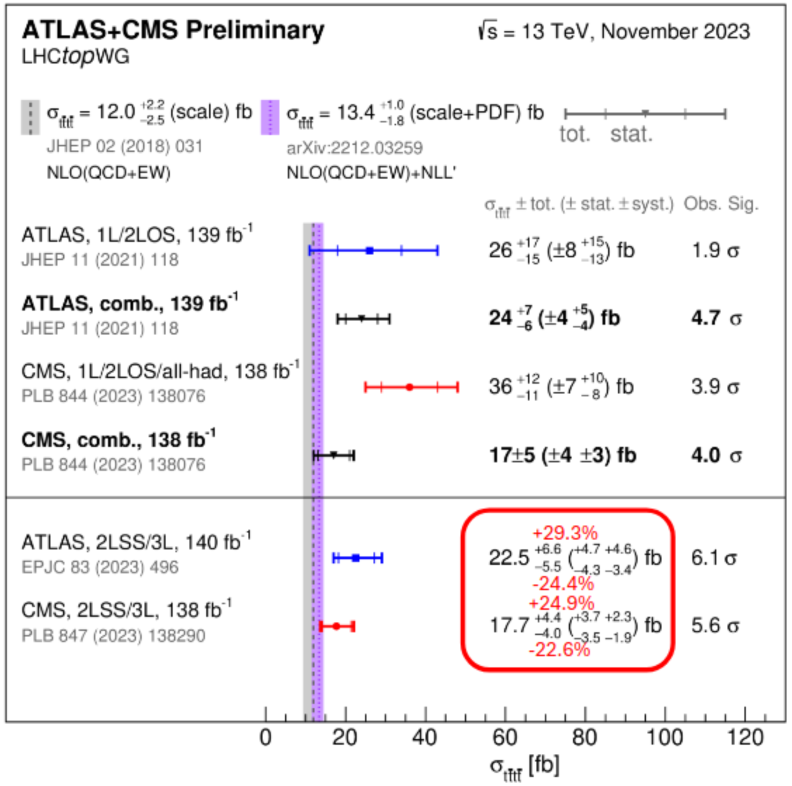
- Differential m(tt) at NLO+NLL'
  (resummation of logs due to real soft-gluon emission close to threshold)

$$\alpha_s^n \left[\frac{\log^m(1-\hat{\rho})}{1-\hat{\rho}} \right]_+ , \quad m \leq 2n-1$$

$$\hat{\rho} \to 1$$



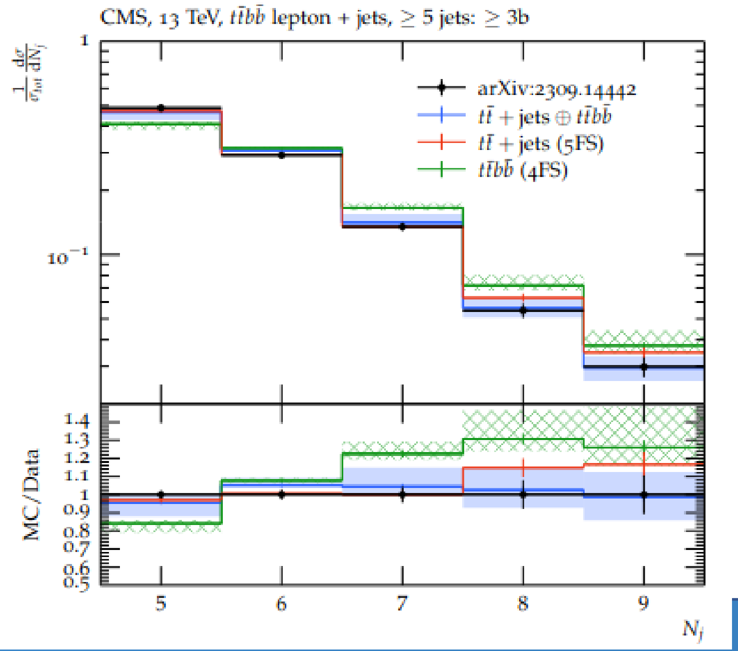


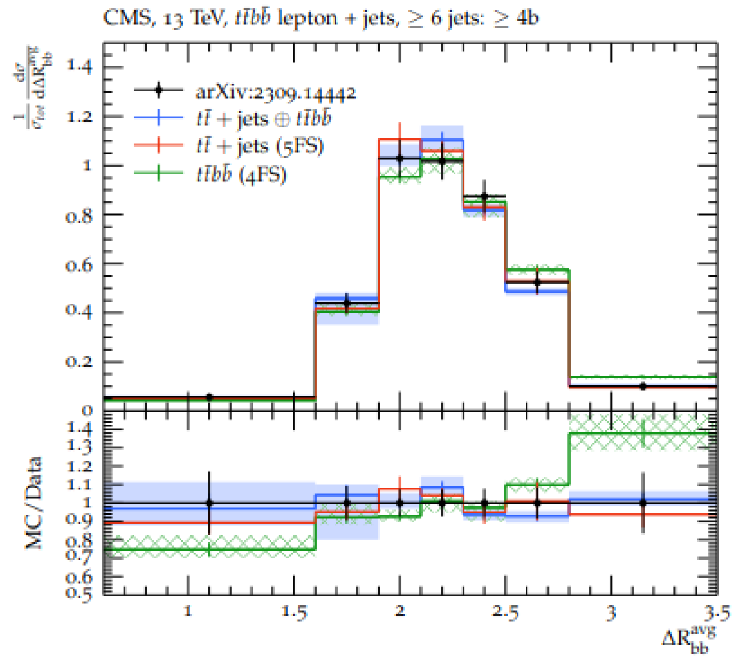


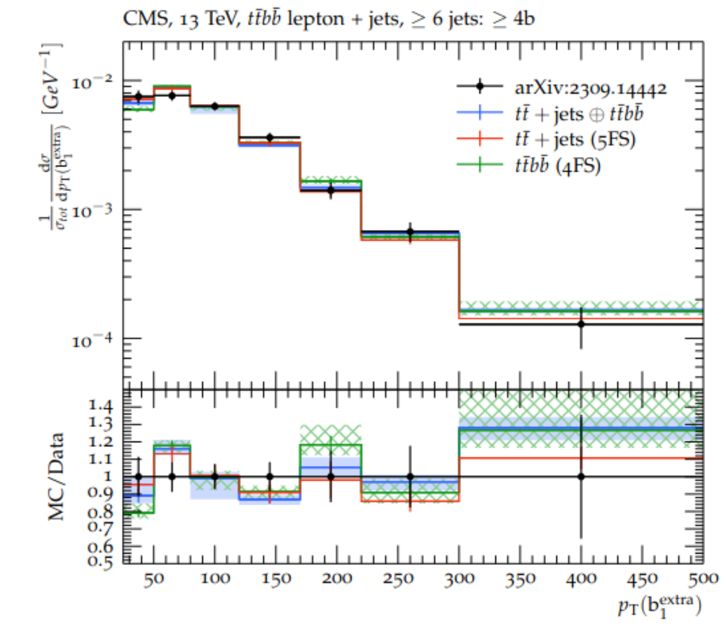
ttbb

L. Ferencz et al. [arXiv:2402.15497]
J. Katzy, top 2025

- Traditionally:
  5FS computations (ttbb+ttbbj+ttbbjj….with massless b): limited phase-space
  4FS computations (NLO+PS ttbb with massive b): hierarchy between different scales generates logs that are not resummed
- New: “fusing” 4FS and 5FS (VFNS approach in a multi-jet merging context)
Algorithm matches an inclusive MEPS@NLO merged simulation of tt+jet, with ttbb







Conclusions

- Impressive progress in the computation of radiative corrections to production processes involving top quarks:

*the focus of NNLO computations has shifted from 2 → 2 to 2 → 3 processes and processes involving top-quark decays beyond NWA

* 2 → 4 processes still at NLO

* resummation of real soft-gluon emission close to threshold applied to all processes

* top at threshold also requires Coulomb corrections: study of toponium, driven by new experimental results.

- Applications: fit of top-quark mass, PDFs, $\alpha_s(m_Z)$ still based on the simplest processes (single-top and tt):

* uncertainties have decreased by a factor of ~ 2 thanks to new differential data, that, however, still require unfolding of the experimental collaborations to the top-quark level.

* Open problems: how to directly use data of top-quark decay products.

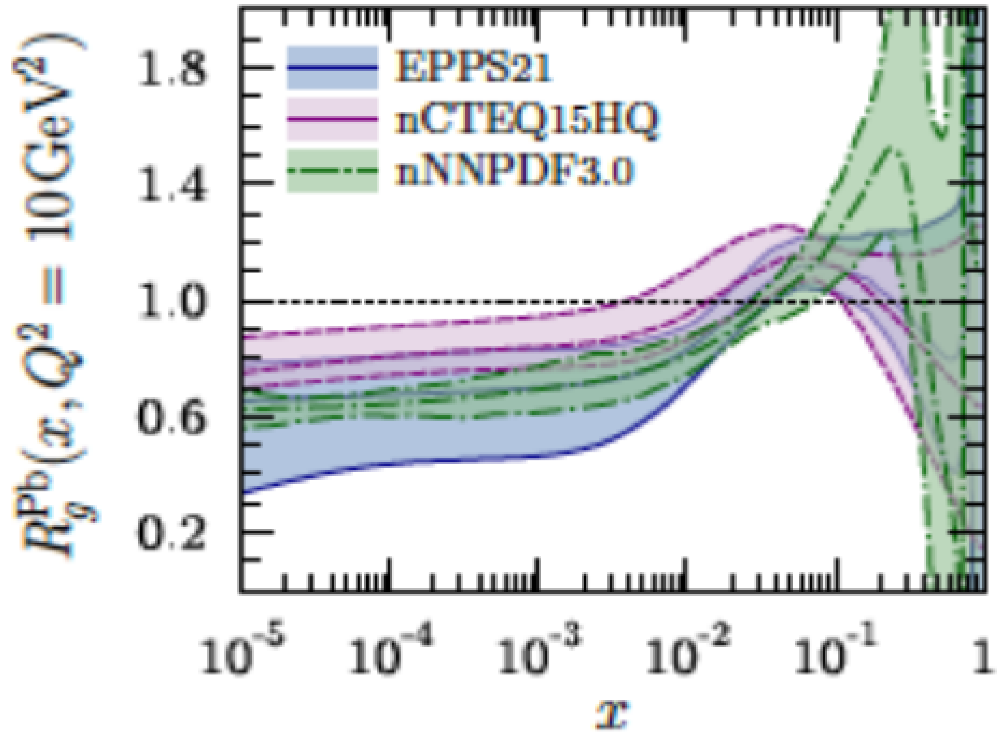
- Run-3 data still under analysis. HL-LHC eagerly waited.

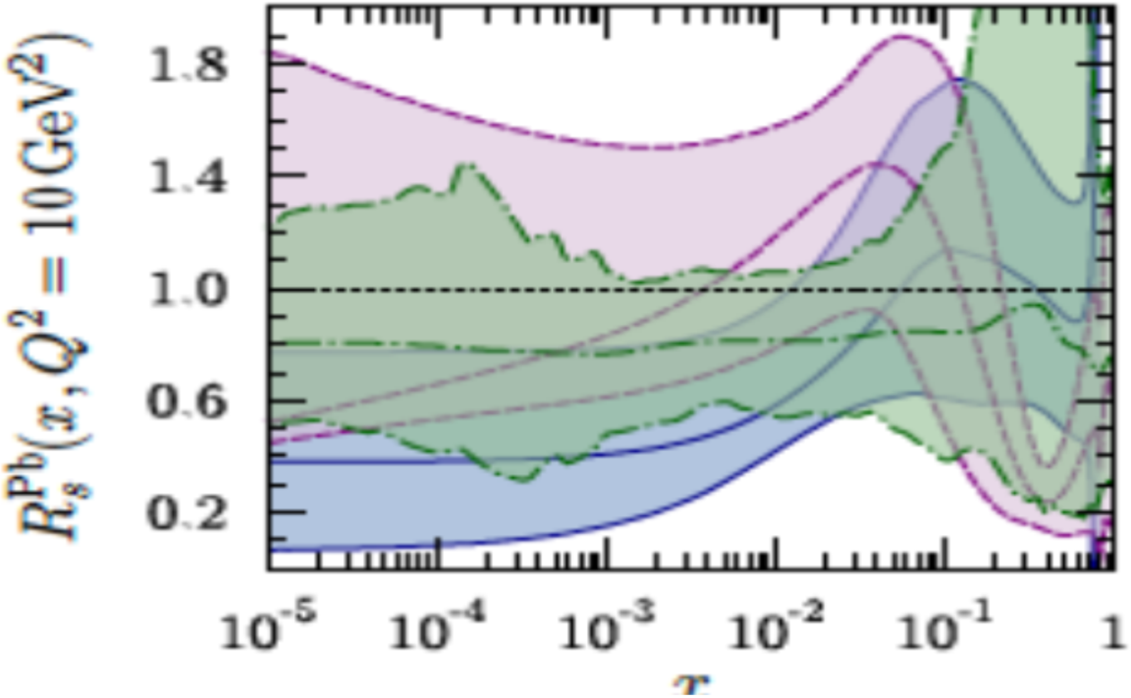
- Many other topics (BSM, future colliders, etc....) not discussed in this talk

Thank you very much for your attention

Backup

NLO nuclear PDFs





tt in PbPb can constrain nuclear PDFs (like tt constrains pPDF), especially as for gluons