

Top-quark pole mass extraction at NNLO accuracy, from total, single- and double-differential cross sections for $t\bar{t} + X$ production at the LHC

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arxiv:2309.XXXXX in preparation

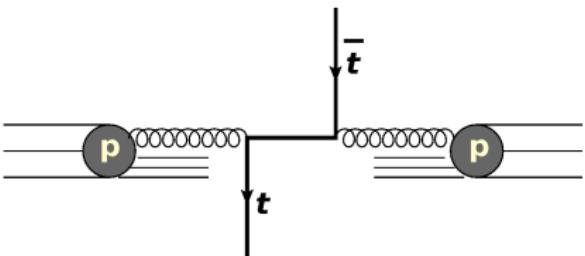
EPS 2023 talk by M.V. Garzelli



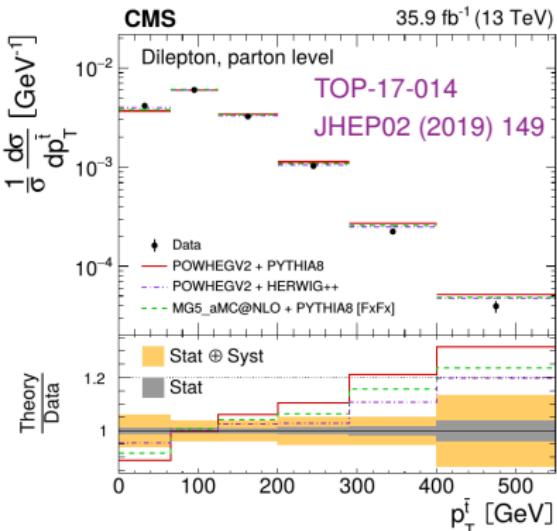
Matter To The Deepest 2023 (Ustron, Poland)
21 September 2023

Introduction

Why study $t\bar{t}$ production?



- m_t provides a hard scale
⇒ **ultimate probe of pQCD**
(NLO, aNNLO, NNLO, ...)
- Produced mainly via gg
⇒ **constrain gluon PDF at high x**
- Production sensitive to α_s and m_t
- May provide insight into possible new physics

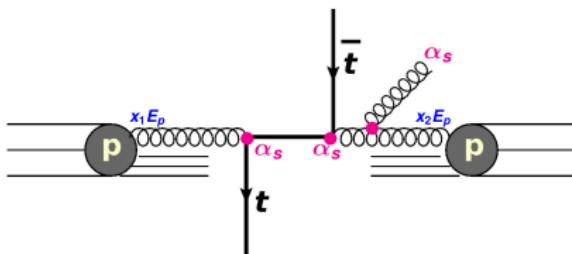


Why study 2D/3D?

- 1D measurements: overall good agreement, but reveal some trends
- 2D [EPJ C77 (2017) 459, PRD97 (2018) 112003]: study production dynamics in more detail
- 3D [EPJ C80 (2020) 658]: simultaneously constrain α_s (extra jets), m_t^{pole} , PDFs

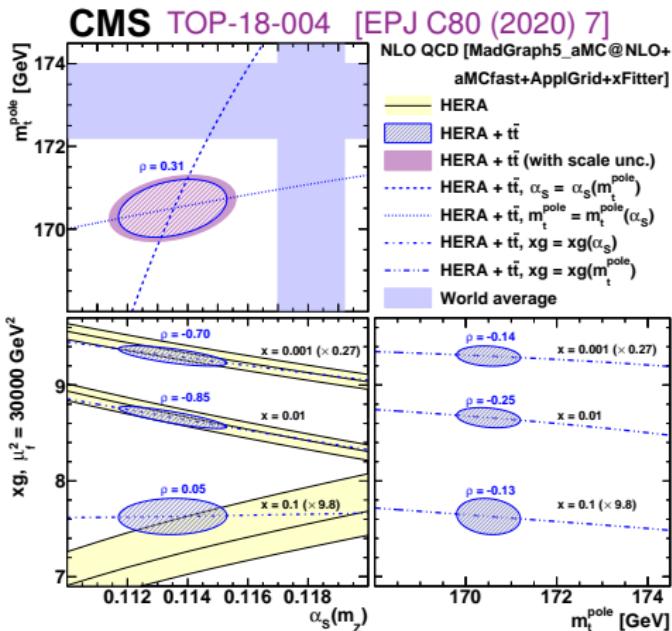
Introduction

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Example:



- Simultaneous extraction of PDFs, α_s , m_t^{pole} using normalised triple-differential cross sections at NLO
- Extended to $\overline{\text{MS}}$, MSR schemes in JHEP 04 (2021) 043 [Garzelli, Kemmler, Moch, Zenaiev]

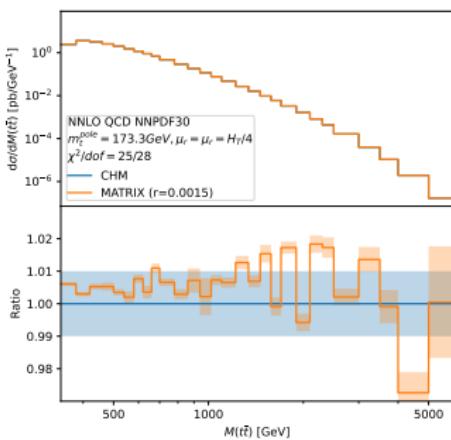
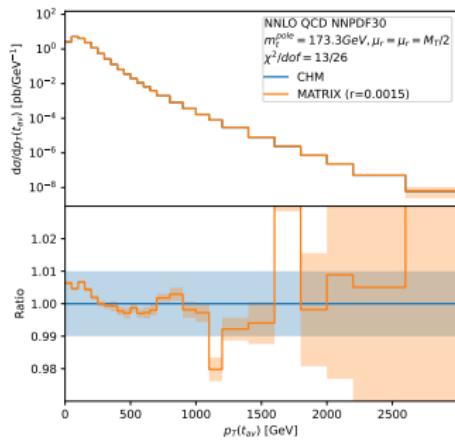
Scope of this work

- NNLO calculations for total and fully differential $t\bar{t}$ (q_T subtraction) are now publicly available with MATRIX framework [Catani, Devoto, Grazzini, Kallweit, Mazzitelli Phys.Rev.D 99 (2019) 5, 051501; JHEP 07 (2019) 100]
 - ▶ fully differential NNLO calculations were also published in JHEP 04 (2017) 071 [Czakon, Heymes, Mitov] (sector-improved residue subtraction scheme STRIPPER), but no public code available
 - ▶ these predictions can be accessed through the HighTEA project [2304.05993]
- Comparing double-(triple-)differential $t\bar{t}$ x-sections with NNLO calculations makes it possible to extract PDFs, α_s , m_t^{pole}
 - ▶ for 3D x-sections $M(t\bar{t})$, $y(t\bar{t})$, N_{jet} [CMS TOP-18-004] NNLO calculations are not available for $t\bar{t} + \text{jets}$
- For the time being, focused on PDF and m_t^{pole} sensitivity and looked at double-differential $M(t\bar{t})$, $y(t\bar{t})$ x-sections
 - ▶ $M(t\bar{t})$ provides sensitivity to m_t
 - ▶ $y(t\bar{t})$ provides sensitivity to PDFs via relation to partonic momentum fraction x :
at LO $x_{1,2} = (M(t\bar{t})/\sqrt{s}) \exp [\pm y(t\bar{t})]$

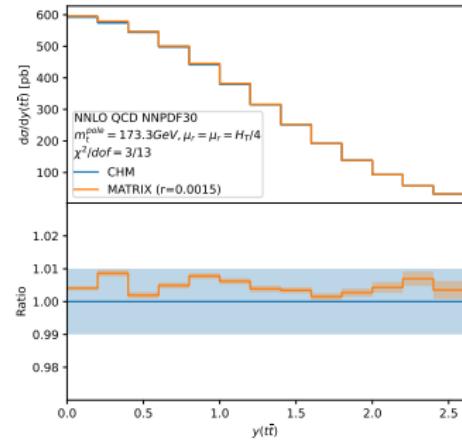
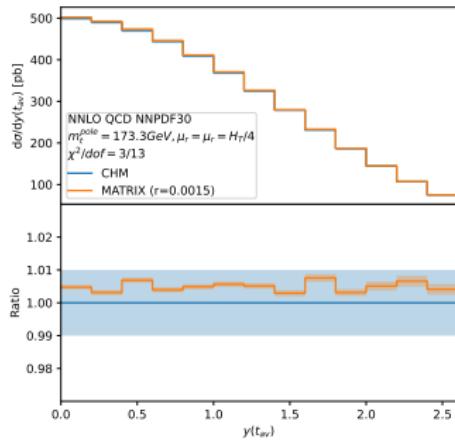
Theoretical calculations with MATRIX framework

- Using “private” (custom) version of MATRIX provided by Javier Mazzitelli
- Interfaced to PineAPPL [Carrazza et al., JHEP 12 (2020) 108] to produce PDF interpolation grids which are further used in xFitter <https://gitlab.com/fitters/xffitter>
 - ▶ reproduce NNLO calculations using any PDF set and/or varied μ_r, μ_f in \sim seconds
 - ▶ implemented privately and only for $t\bar{t}$ process
- Further modifications to MATRIX to make possible runs with $\Delta\sigma_{t\bar{t}} < 1\%$
 - ▶ skip calculation of identical things (tailored for $t\bar{t}$)
 - ▶ adapted to DESY Bird Condor cluster and local multicore machines of theory department
 - ▶ technical fixes related to memory and disk space usage etc.
- For the time being, did 6 runs with different m_t^{pole} values 165–177.5 GeV with step of 2.5 GeV and $\Delta\sigma_{t\bar{t}} = 0.2\%$
 - ▶ $\approx 350K \times 6 \approx 2M$ CPU hours (200 years on single CPU, 3 months of real time)
 - ▶ for differential distributions, integration uncertainties in bins are $\lesssim 0.5\%$
- Differential distributions obtained with fixed $r_{cut} = 0.0015$ (q_T subtraction)
 - ▶ checked $r_{cut} = 0.0005$ (more reliable, but slower convergence)
 - ▶ checked extrapolation to $r_{cut} = 0: < 1\%$ (see also JHEP 07 (2019) 100)
 - we assign extra 1% theoretical uncertainties to cover these effects. This is small enough, but not totally negligible compared to data precision
- $\mu_r = \mu_f = H_T/4, H_T = \sqrt{m_t^2 + p_T^2(t)} + \sqrt{m_{\bar{t}}^2 + p_{\bar{T}}^2(\bar{t})}$, varied up and down by factor 2 with $0.5 \leq \mu_r/\mu_f \leq 2$ (7-point method)

Validation vs JHEP 04 (2017) 071 by Czakon, Heymes, Mitov [CHM]

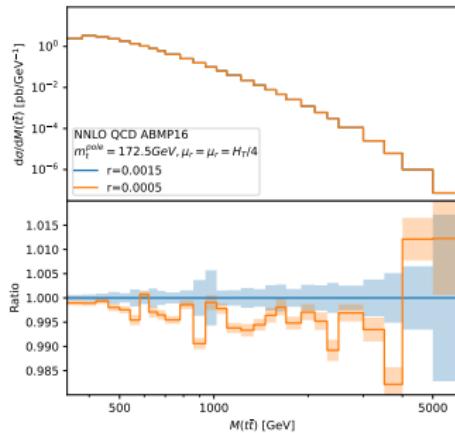
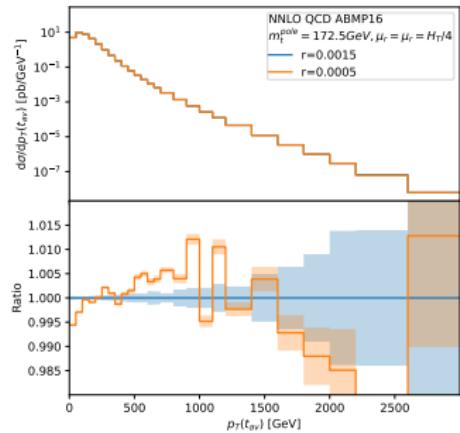


Good agreement < 1%

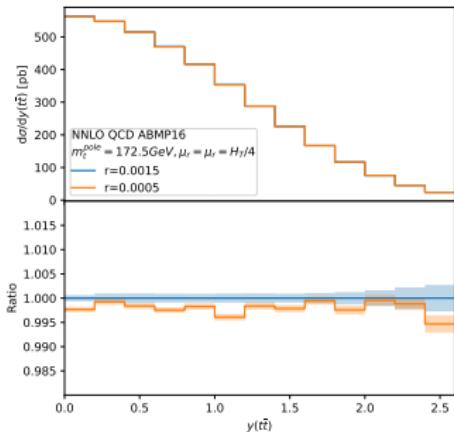
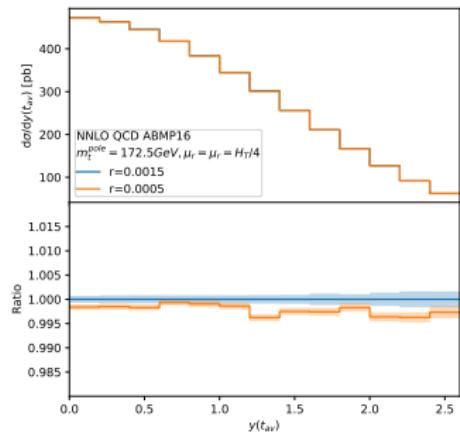


m_t^{pole} extraction at NNLO

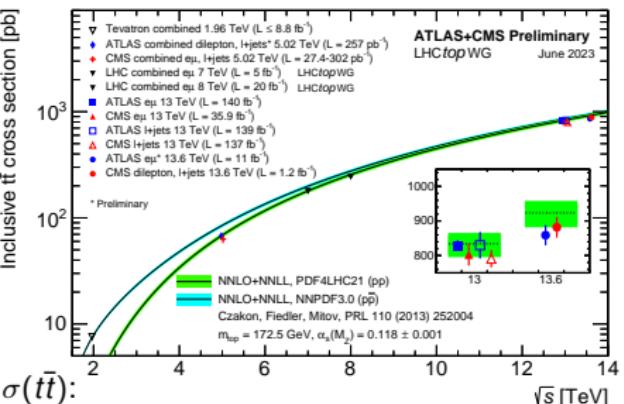
Variation of r cut



Good agreement $< 1\%$



Data for pheno analysis



Selection of data:

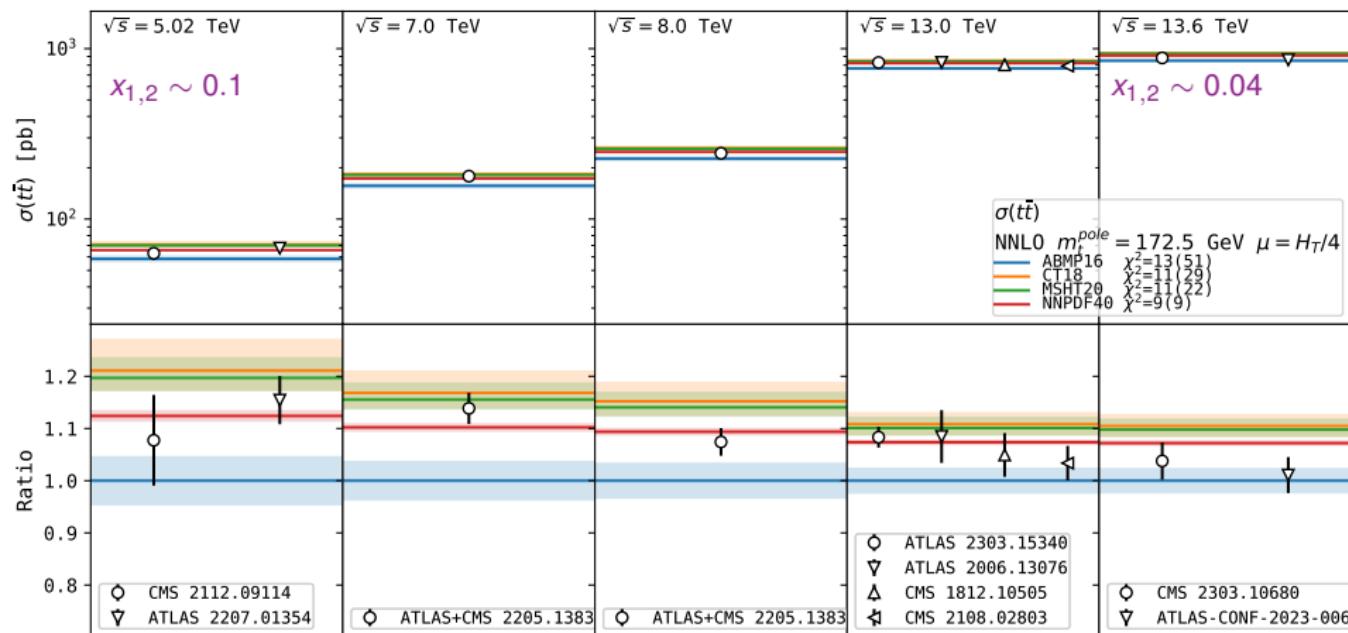
- all measurements of total $t\bar{t}$ cross sections $\sigma(t\bar{t})$:
 - 10 data points, including recently combined CMS+ATLAS cross section at 7 and 8 TeV
- differential measurements $\frac{1}{\sigma(t\bar{t})} \frac{d\sigma(t\bar{t})}{dO}$ which satisfy following criteria:
 - as function of $M(t\bar{t})$ (if available, 2D $M(t\bar{t})$ and $y(t\bar{t})$)
 - unfolded to parton level (no cuts on p_T , y of leptons or jets): no LHCb data
 - normalized cross sections (to avoid unknown correlation with total $\sigma(t\bar{t})$)
 - bin-by-bin correlations are available

$$\sigma(t\bar{t})$$

Experiment	decay channel	dataset	luminosity	\sqrt{s}
ATLAS & CMS	combined	2011	5 fb^{-1}	7 TeV
ATLAS & CMS	combined	2012	20 fb^{-1}	8 TeV
ATLAS	dileptonic, semileptonic	2011	257 pb^{-1}	5.02 TeV
CMS	dileptonic	2011	302 pb^{-1}	5.02 TeV
ATLAS	dileptonic	2015-2018	140 fb^{-1}	13 TeV
ATLAS	semileptonic	2015-2018	139 fb^{-1}	13 TeV
CMS	dileptonic	2016	35.9 fb^{-1}	13 TeV
CMS	semileptonic	2016-2018	137 fb^{-1}	13 TeV
ATLAS	dileptonic	2022	11.3 fb^{-1}	13.6 TeV
CMS	dileptonic, semileptonic	2022	1.21 fb^{-1}	13.6 TeV

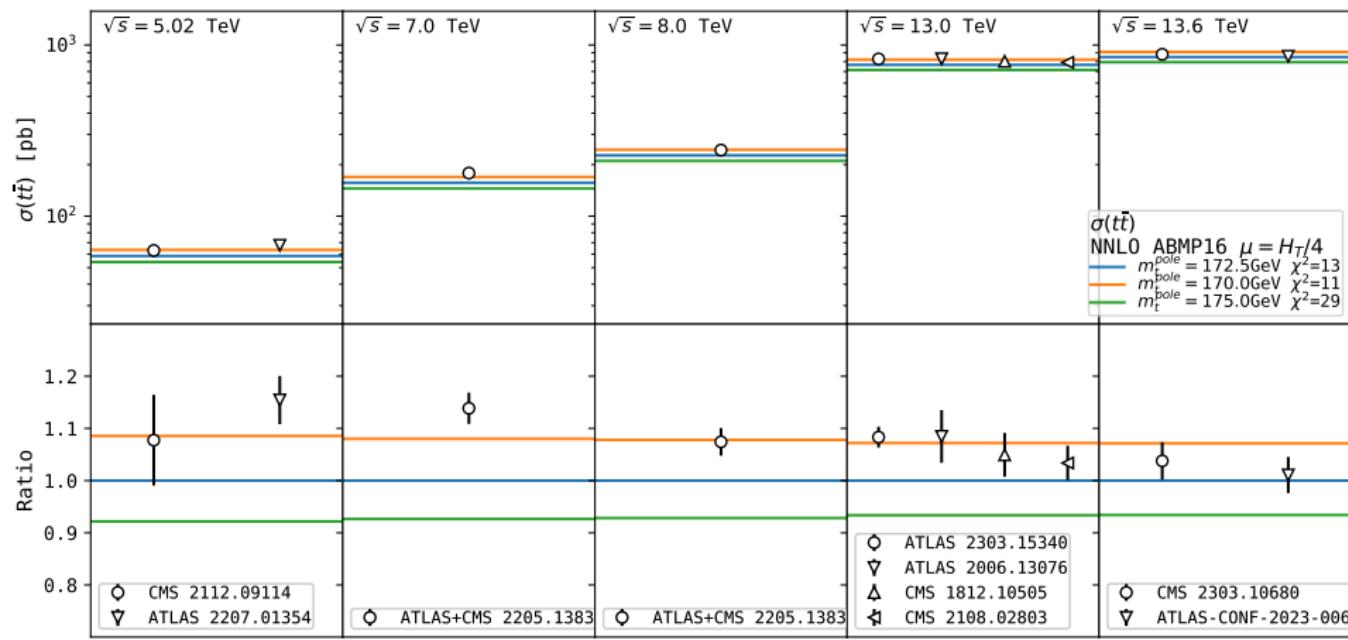
Experiment	decay channel	dataset	luminosity	\sqrt{s}	observable(s)	n
CMS	semileptonic	2016-2018	137 fb^{-1}	13 TeV	$M(t\bar{t}), y(t\bar{t}) $	34
CMS	dileptonic	2016	35.9 fb^{-1}	13 TeV	$M(t\bar{t}), y(t\bar{t}) $	15
ATLAS	semileptonic	2015-2016	36 fb^{-1}	13 TeV	$M(t\bar{t}), y(t\bar{t}) $	19
ATLAS	all-hadronic	2015-2016	36.1 fb^{-1}	13 TeV	$M(t\bar{t}), y(t\bar{t}) $	10
CMS	dileptonic	2012	19.7 fb^{-1}	8 TeV	$M(t\bar{t}), y(t\bar{t}) $	15
ATLAS	semileptonic	2012	20.3 fb^{-1}	8 TeV	$M(t\bar{t})$	6
ATLAS	dileptonic	2012	20.2 fb^{-1}	8 TeV	$M(t\bar{t})$	5
ATLAS	dileptonic	2011	4.6 fb^{-1}	7 TeV	$M(t\bar{t})$	4
ATLAS	semileptonic	2011	4.6 fb^{-1}	7 TeV	$M(t\bar{t})$	4

$\sigma(t\bar{t})$ vs NNLO predictions using different PDFs



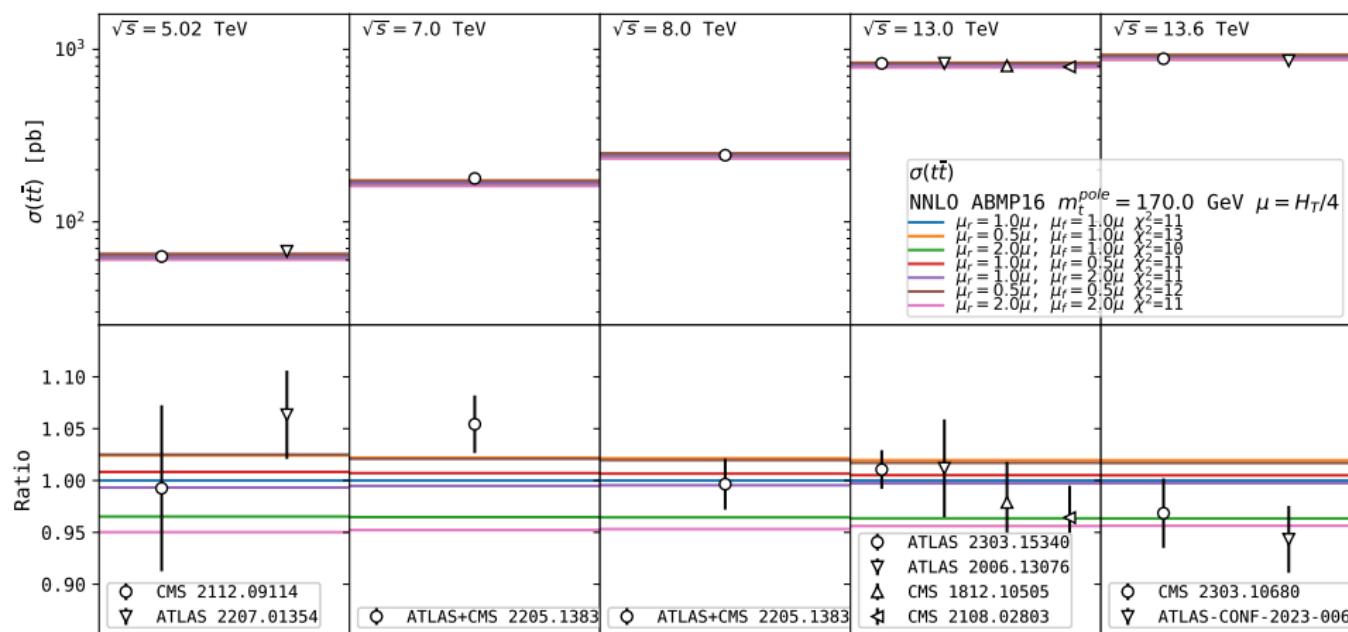
- Fixed $m_t^{\text{pole}} = 172.5$ GeV, $\mu_r = \mu_f = H_T/4$
- Reported χ^2 values with (and without) PDF uncertainties
- All PDF sets describe data reasonably well (depends on m_t^{pole} , α_S)
- Sensitivity to PDFs reduces with increasing \sqrt{s} (lower x probed)

$\sigma(t\bar{t})$ vs NNLO predictions using different m_t^{pole}



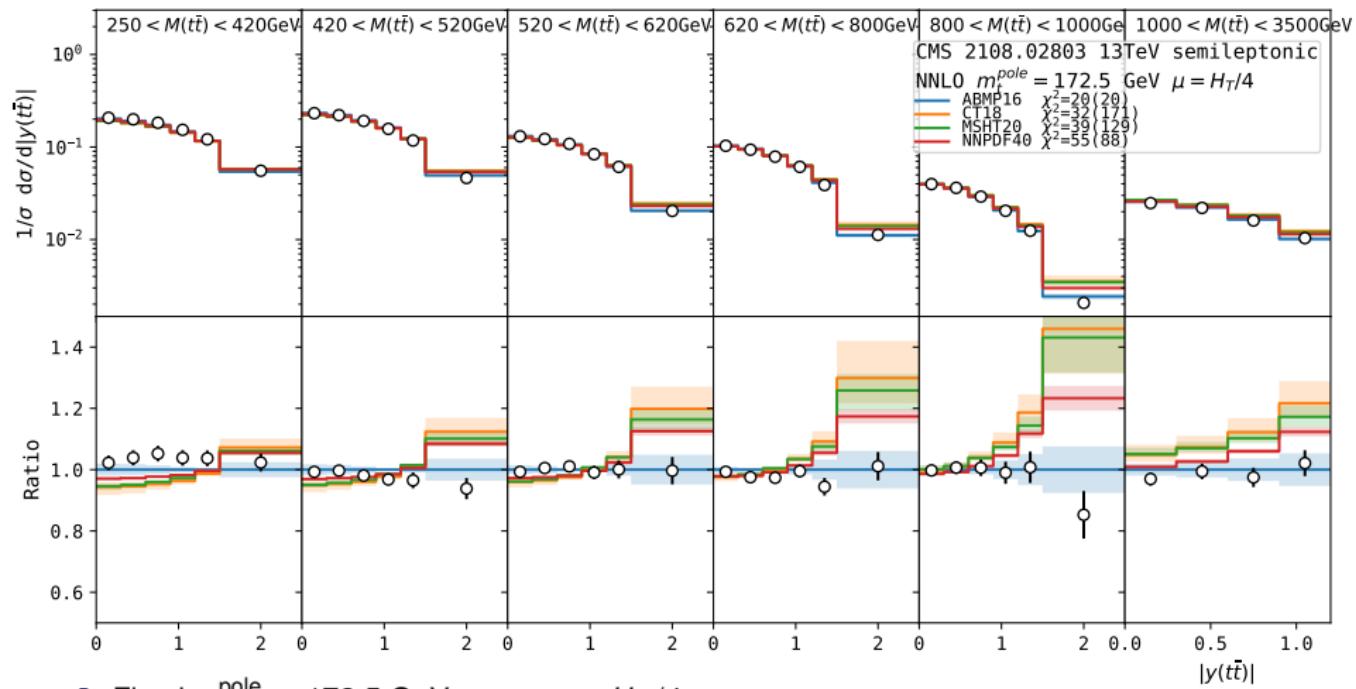
- ABMP16, fixed $\mu_r = \mu_f = H_T/4$
- Change of m_t^{pole} by 1 GeV \rightarrow change of $\sigma(t\bar{t})$ by $\approx 3\%$
- Preferable $m_t^{\text{pole}} \sim 170\text{--}172.5 \text{ GeV}$ (depends on PDF and α_S)

$\sigma(t\bar{t})$ vs NNLO predictions with scale variations



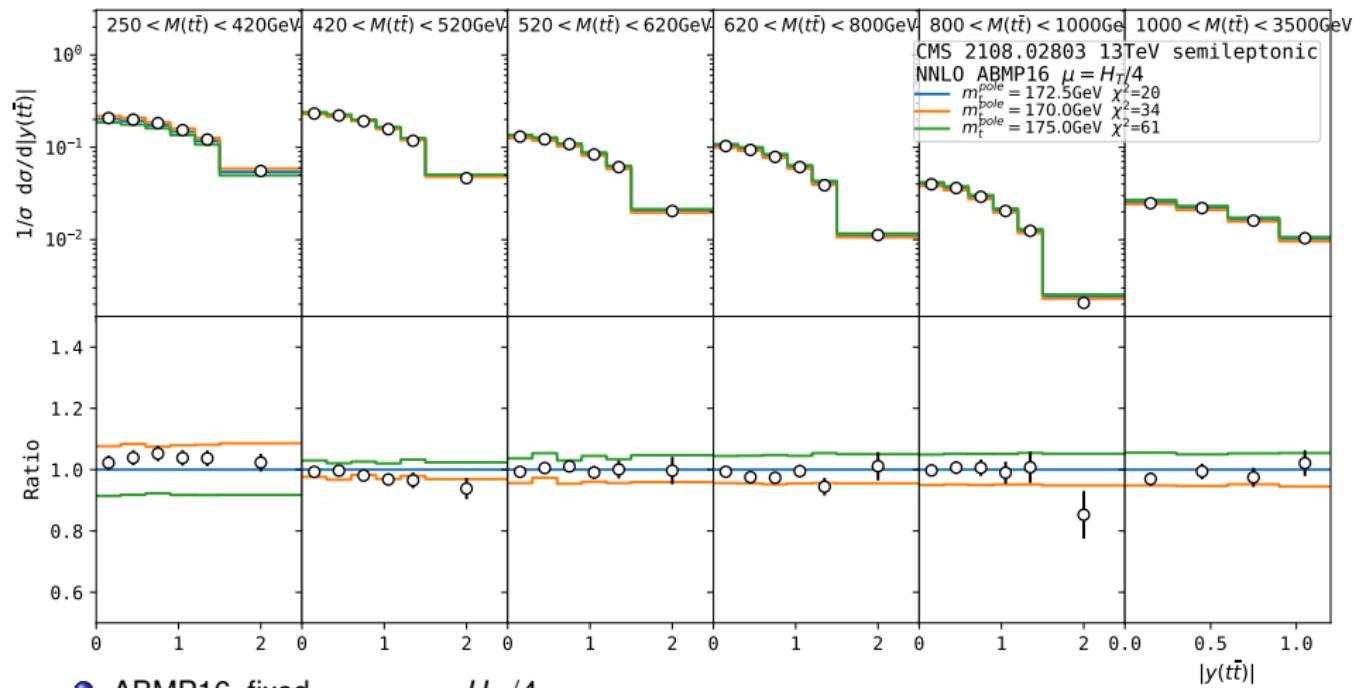
- ABMP16, fixed $m_t^{\text{pole}} = 172.5 \text{ GeV}$
- Scale variations $\pm 3\%$:
 - ▶ larger than data uncertainty (best data uncertainty $\pm 1.9\%$)
 - ▶ limit precision of m_t^{pole} extraction to 1 GeV
 - ▶ can be reduced by using e.g. $\overline{\text{MS}}$ mass $m_t(m_t)$ EPJ C74 (2014) 3167, JHEP04 (2021) 043

CMS 2108.02803 vs NNLO predictions using different PDFs



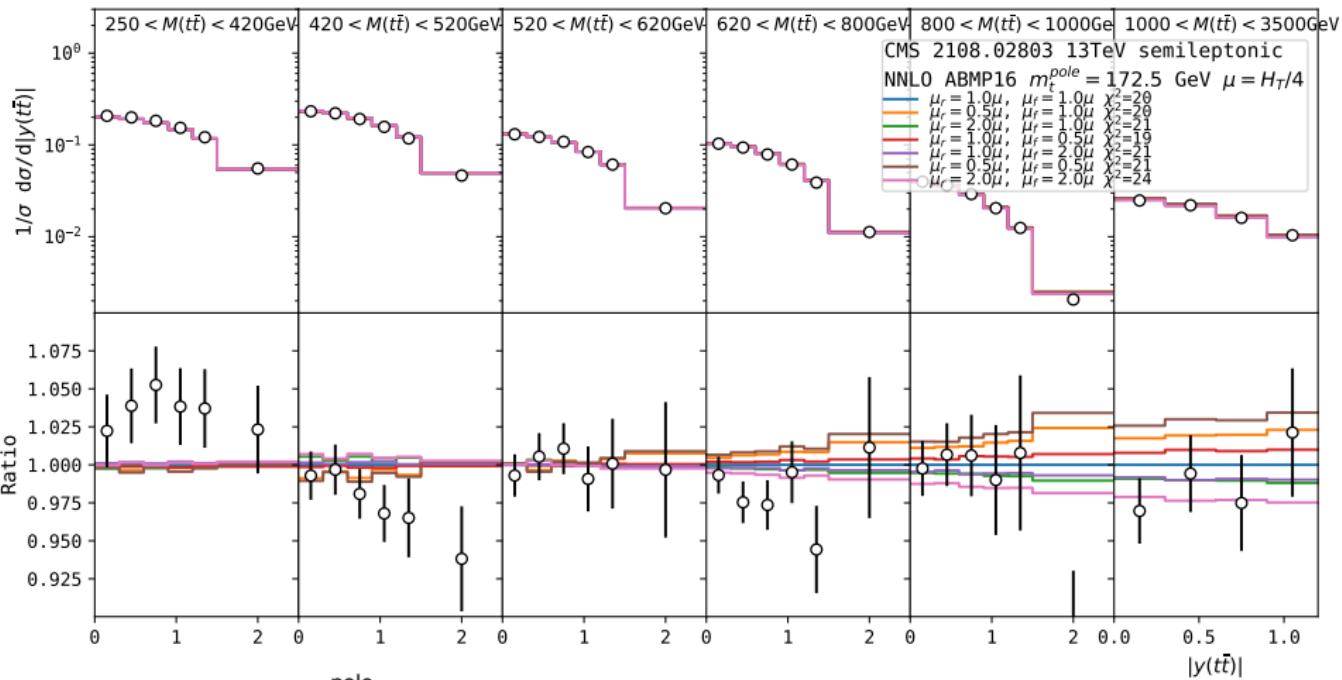
- Fixed $m_t^{\text{pole}} = 172.5 \text{ GeV}, \mu_r = \mu_f = H_T/4$
- Reported χ^2 values with (and without) PDF uncertainties
- All PDF sets describe data reasonably well, with best description by ABMP16
 - ▶ CT18, MSHT20 and NNPDF40 show clear trend w.r.t data at high $y(t\bar{t})$ (large x)
- This is most precise currently available data set with finest bins (other data in BACKUP)

CMS 2108.02803 vs NNLO predictions using different PDFs



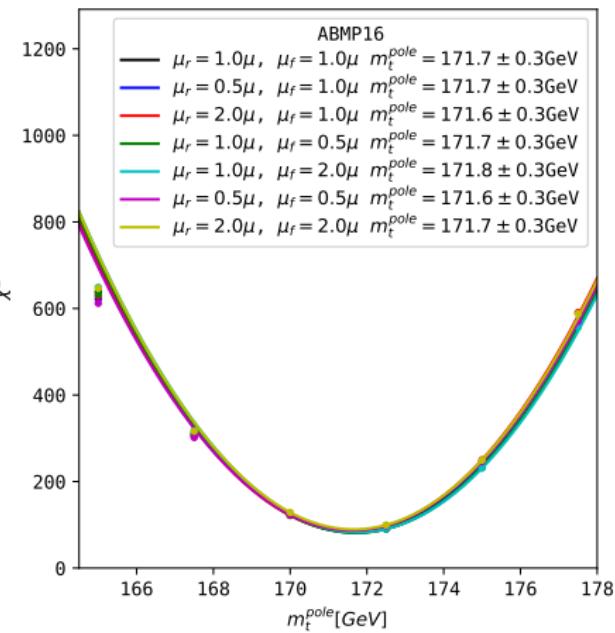
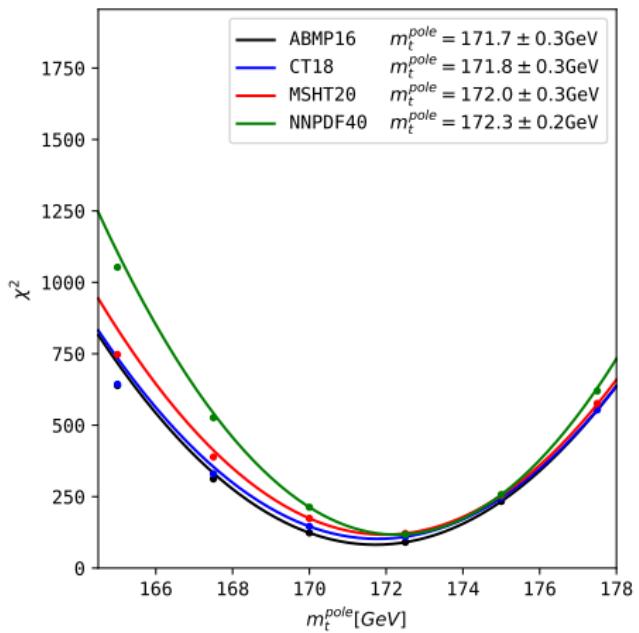
- ABMP16, fixed $\mu_r = \mu_f = H_T/4$
- Low $M(t\bar{t})$: strong dependence on m_t^{pole} via threshold effects
- High $M(t\bar{t})$: opposite dependence due to cross section normalization
- Preferable $m_t^{\text{pole}} \approx 172 \text{ GeV}$ (other data in BACKUP)

CMS 2108.02803 vs NNLO predictions using different PDFs



- ABMP16, fixed $m_t^{\text{pole}} = 172.5 \text{ GeV}$
- Scale variations $< 1\%$ at low $M(t\bar{t})$ (largest cancellation), reach $\approx 4\%$ at high $M(t\bar{t})$

Extraction of m_t^{pole} (work in progress)



- χ^2 minimization is carried out with xFitter (xfitter.org)
- Experimental, PDF and numerical theory uncertainties are included in χ^2
- Scale theory variations are not included in χ^2 but they are done explicitly (offset method) (typically amount to ± 0.2 GeV)

xFitter [https://xfitter.org] [https://gitlab.com/fitters/xfitter]

xFitter



Welcome to xFitter (former HERAFitter)

Proton parton distribution functions (PDFs) are essential for precision physics at the LHC and other hadron colliders. The determination of the PDFs is a complex endeavor involving several physics process. The main process is the lepton proton deep-inelastic scattering (DIS), with data collected by the HERA ep collider covering a large kinematic phase space needed to extract PDFs. Further processes (fixed target DIS, ppbar collisions etc.) provide additional constraining powers for flavour separation. In particular, the precise measurements obtained or to come from LHC will continue to improve the knowledge of the PDF.

The xFitter project is an open source QCD fit framework ready to extract PDFs and assess the impact of new data. The framework includes modules allowing for a various theoretical and methodological options, capable to fit a large number of relevant data sets from HERA, Tevatron and LHC. This framework is already used in many analyses at the LHC.

Downloads of xFitter software package

All the xFitter releases can be accessed [HERE](#) including 2.2.0 FutureFreeze release

All the former (HERAFitter) releases can be accessed [HERE](#).

Description: <http://arxiv.org/abs/1410.4412>

xFitter Meetings

xFitter Workshop at CERN 2-5 May 2023

- User's Meetings: meetings to enhance communication between users and developers (open access)
- Developer's Meeting: technical weekly meetings to ensure communication among developers (restricted access)
- Steering Group's Meeting (restricted access)



xFitter representation

- Snowmass contribution
- List of results
- List of collected talks

Developers Info (restricted to developers)

- Internal Developments

Organisation

- Release coordinator/Librarian (revision of the release candidates): Sasha Glazov, Oleksandr Zenaiev
- DESY IT Contact: Yves Kemp

Getting help

See our help forum <https://groups.google.com/forum/#!forum/xfitter-users>

In case of questions or problems, please post a message there (requires a google account) or send it via email xfitter-users@googlegroups.com (no account required)

- xFitter (HERAfitter before 2015) is a unique open-source QCD fit framework:

- ▶ extract PDFs and theory parameters
- ▶ assess impact of new data
- ▶ check consistency of experimental data
- ▶ test different theoretical assumptions
- ▶ ...any exercise which involves data vs. theory

- It is widely used by LHC experiments and theorists (> 100 publications)

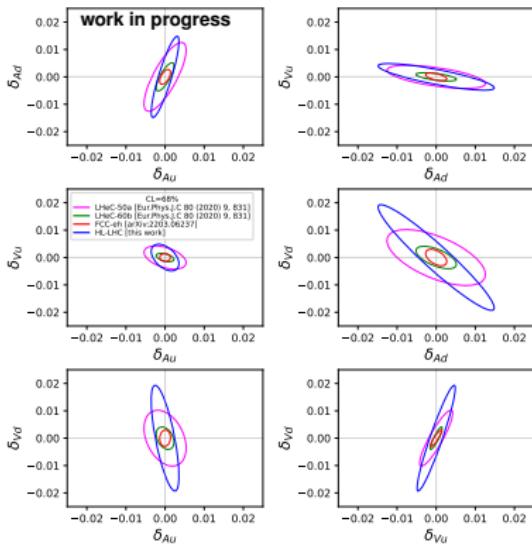
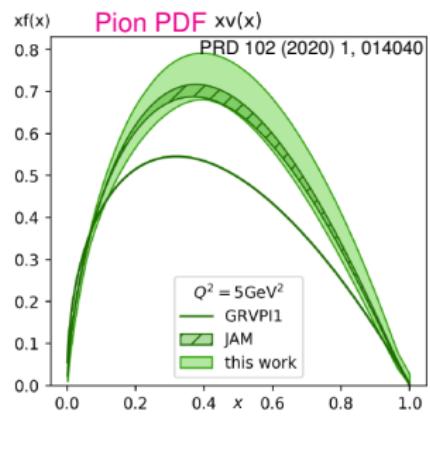
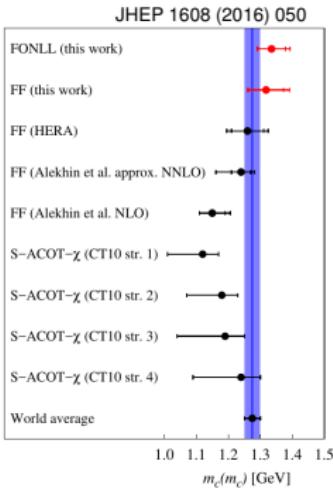
- Why is xFitter unique and so nice?

Because it is fully modular. E.g., hadron interactions are realized as

- ▶ PDF parametrisation at starting scale: it is enough to type your favourite formulas
- ▶ PDF decomposition: construct valence, sea and gluon, apply sum rules (automatic integration)
- ▶ PDF evolution: interfaced various codes (QCDNUM, OPENQCDRAD, APFEL, LHAPDF); one can easily interface a new code
- ▶ hard scattering ("reaction"): again, supports various options:
 - ★ various HQ schemes for ep DIS
 - ★ some "simple" calculations, e.g. LO DY
 - ★ interfaced external packages, e.g. HATHOR (NNLO HQ total $t\bar{t}$ and single t hadroproduction) and HVQMNR (NLO HQ differential hadroproduction)
 - ★ but main emphasis is put on interfaces to fast interpolation tables, such as fastNLO, ApplGrid, PineAppl: allows us to get recent higher-order calculations (e.g. MCFM, MATRIX etc.) "for free"
- ▶ ...and one can mix all these ingredients freely

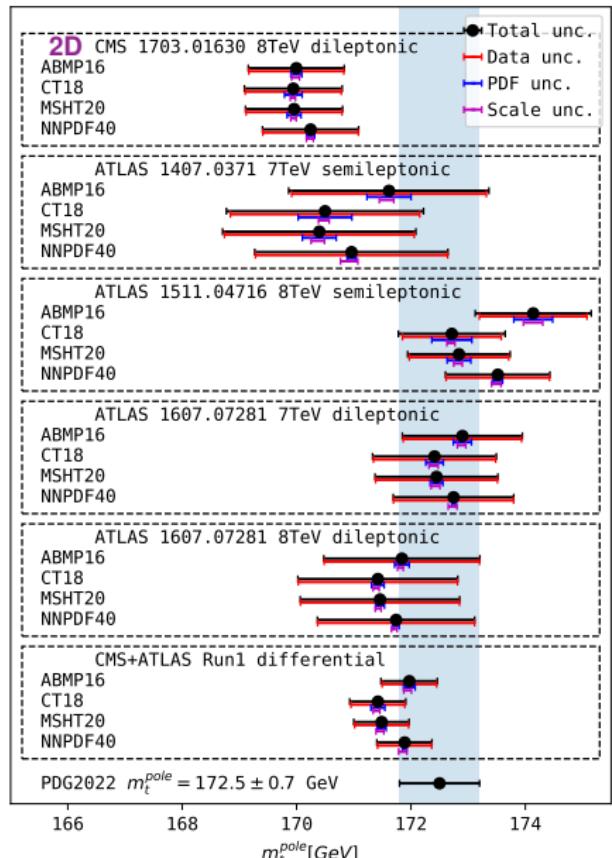
Selected studies by the xFitter team

- “A determination of $m_c(m_c)$ from HERA data using a matched heavy flavor scheme” [JHEP 1608 (2016) 050]
- “Probing the strange content of the proton with charm production in charged current at LHeC” [Eur. Phys. J. C 79, 864 (2019)]
- “PDF Profiling Using the Forward-Backward Asymmetry in Neutral Current Drell-Yan Production” [JHEP 2019, 176 (2019)]
- “Parton Distribution Functions of the Charged Pion Within The xFitter Framework” [Phys.Rev.D 102 (2020) 1, 014040]
- “Exploring SMEFT Couplings Using the Forward-Backward Asymmetry in Neutral Current Drell-Yan Production at the LHC” [work in progress, [EPS2023 talk](#)]

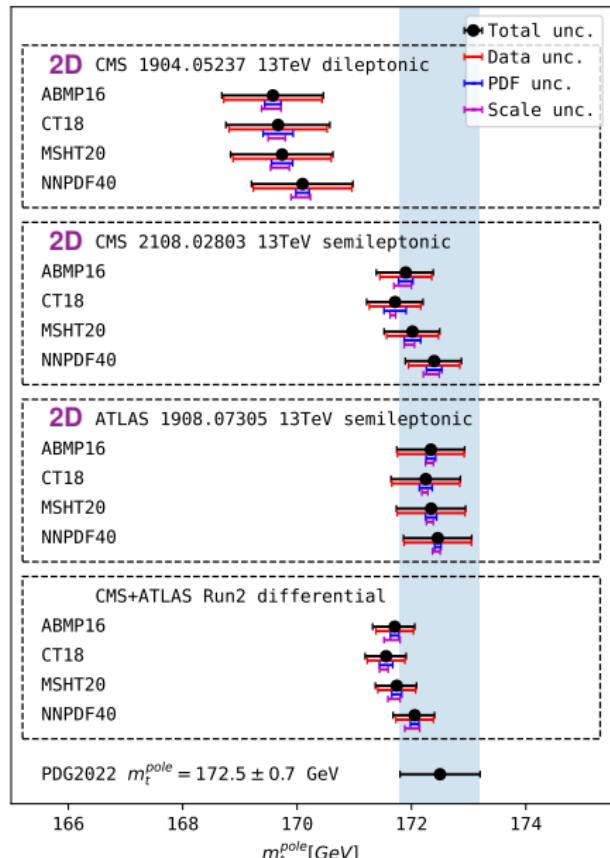


Extraction of m_t^{pole} : differential Run 1, Run 2

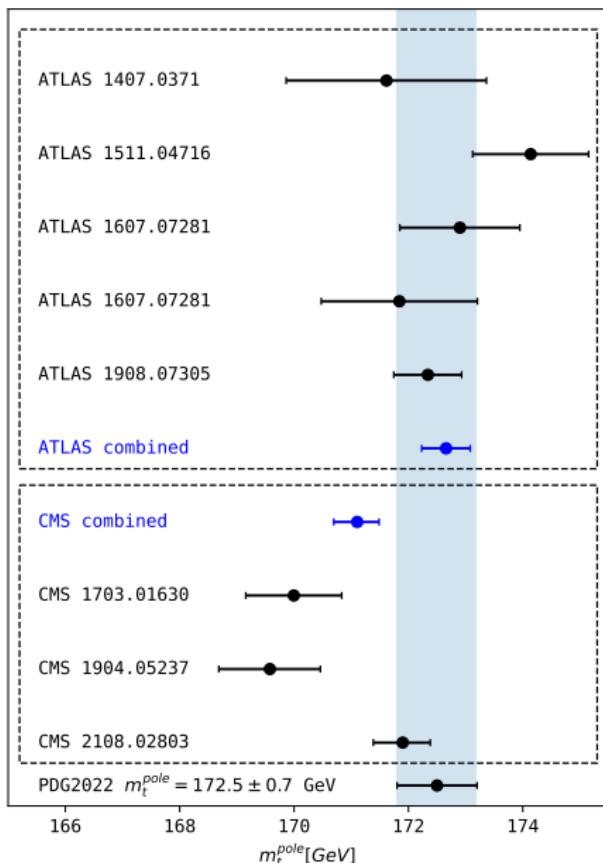
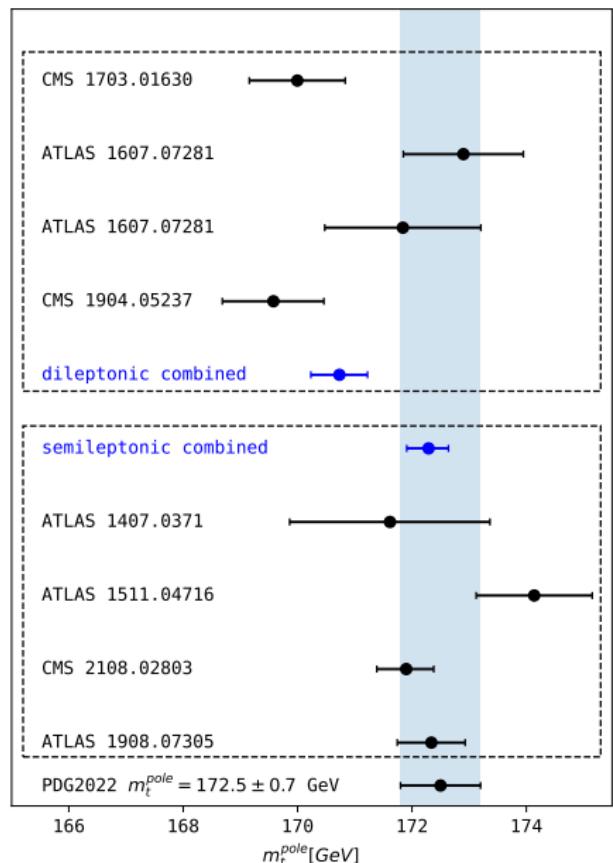
Run 1 differential



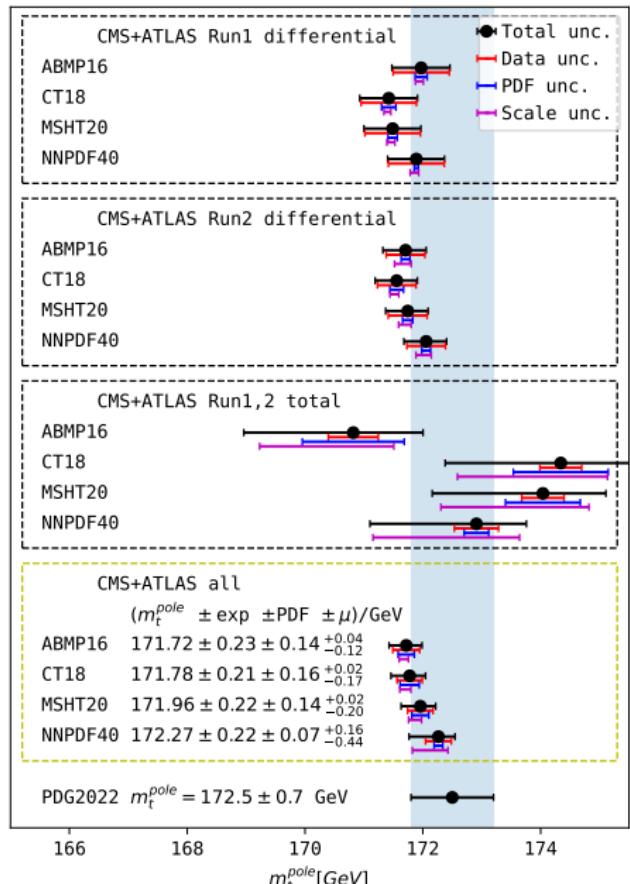
Run 2 differential



Extraction of m_t^{pole} : dilepton vs semileptonic, ATLAS vs CMS



Extraction of m_t^{pole} : summary (work in progress)



- Extracted m_t^{pole} values with precision $\pm 0.3 \text{ GeV}$ are consistent with PDG value $172.5 \pm 0.7 \text{ GeV}$
 - data uncertainty $\sim 0.2 \text{ GeV}$
 - PDF uncertainty $\sim 0.1 \text{ GeV}$
 - NNLO scale uncertainty $\sim 0.2 \text{ GeV}$
- Significant dependence on PDFs ($\sim 0.5 \text{ GeV}$):
 - different m_t^{pole} used in different PDFs
 - PDFs, m_t^{pole} , α_s should be determined simultaneously
- For CMS 1904.05237, NNLO results are consistent with published results obtained at NLO
 - good convergence of perturbative series
- Larger sensitivity comes from differential data
 - 2D differential x-sections in $M(t\bar{t})$, $y(t\bar{t})$ constrain m_t^{pole} , PDFs and (indirectly) α_s
 - ideally, 3D cross section in $M(t\bar{t})$, $y(t\bar{t})$ and number of extra jets constrain α_s directly, but NNLO not yet available for $t\bar{t} + \text{jets}$
- Possible effects from Coulomb and soft-gluon resummation near the $t\bar{t}$ production threshold are neglected: might be $\sim 1 \text{ GeV}$

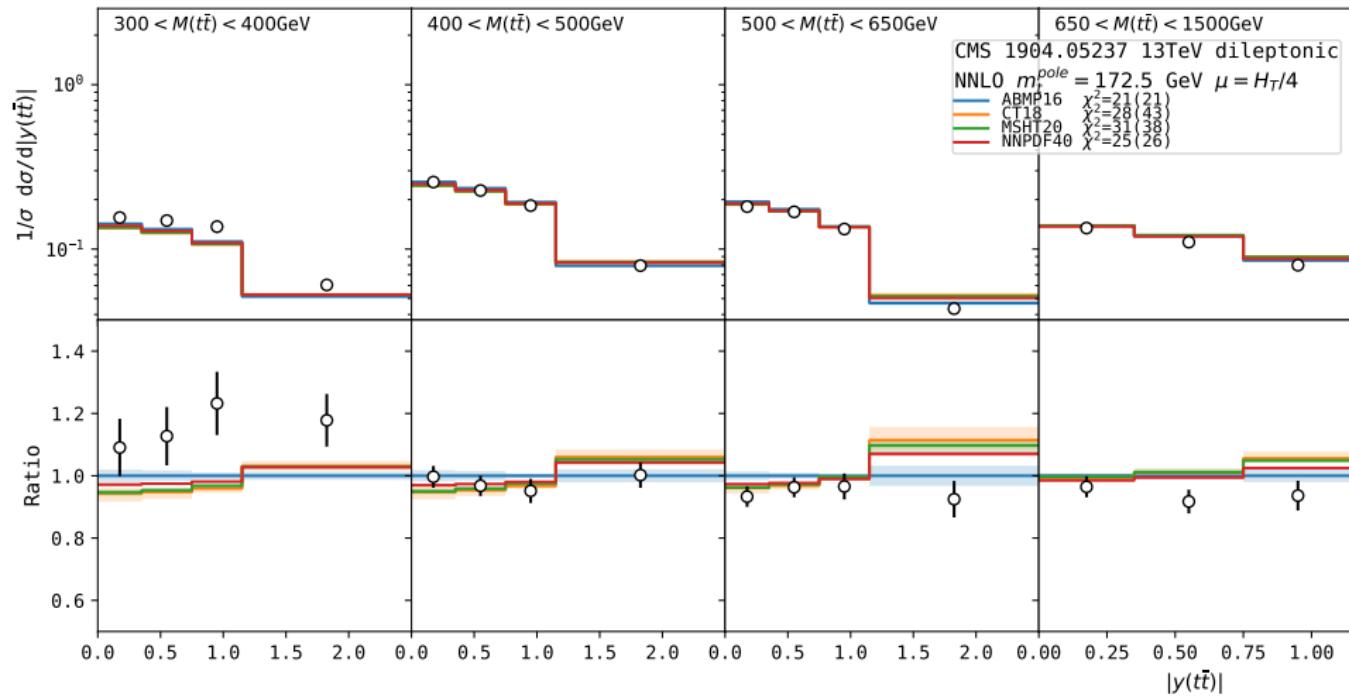
[CMS Coll. EPJ C80 (2020) 658; Kiyo, Kuhn, Moch, Steinhauser, Uwer
EPJ C60 (2009) 375; Mäkelä, Hoang, Lipka, Moch 2301.03546]

Summary & Discussion

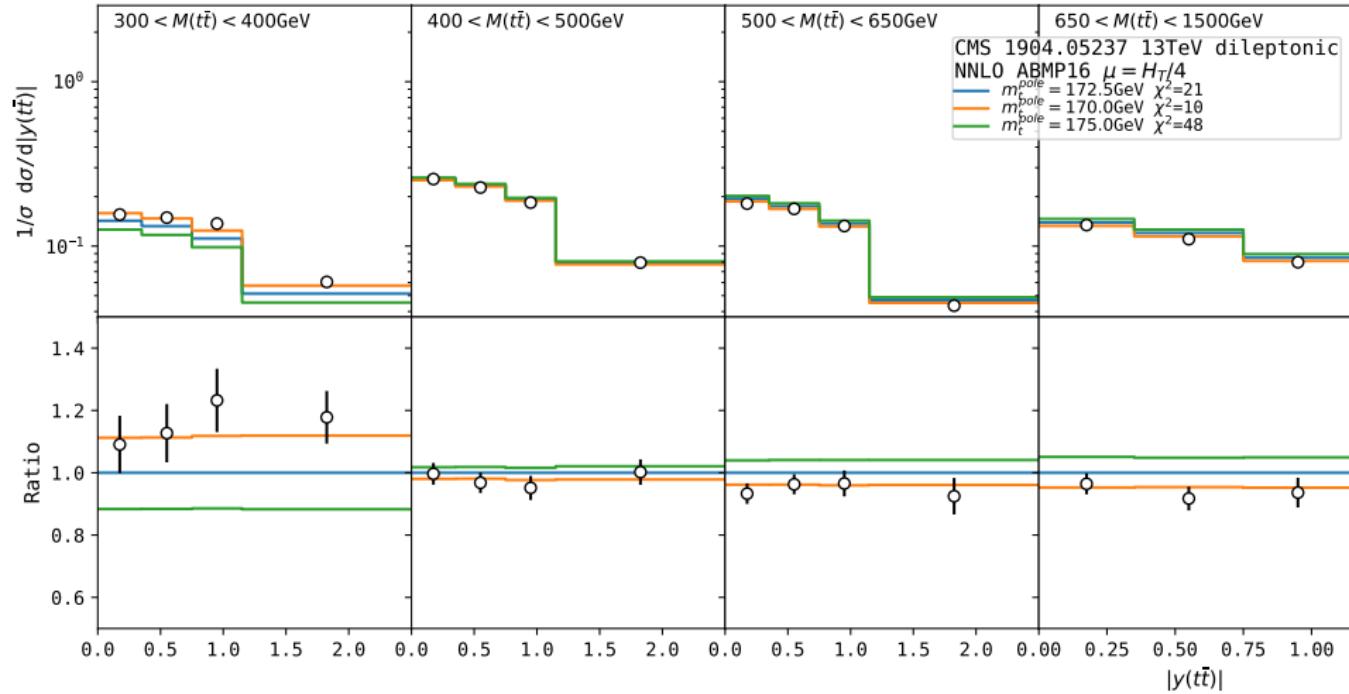
- Measurements of $t\bar{t}$ production at LHC have very rich potential for phenomenology
 - provide information on m_t^{pole} (0.2 GeV), α_S (2%) and gluon PDF (competitive to jets)
[CMS Coll., EPJ C80 (2020) 658, EPJ C77 (2017) 459]
 - **overall, good agreement of experimental data and NNLO predictions for $t\bar{t}$**
- Measurements of total $t\bar{t}$ production reached experimental precision $< 2\%$
 - cf. NNLO scale variations 3–5%
- Current experimental accuracy is already at % level for normalized $t\bar{t}$ cross sections
 - theory tools require a lot of resources to compute predictions. This will need to be improved in the future
- Differential measurements of $t\bar{t}$ production seem to show a small tension
 - ATLAS+CMS effort on combining differential $t\bar{t}$ data will be useful
- LHCb covers a complementary kinematic region sensitive to higher x , but no measurements unfolded to parton level (without cuts p_T , y of decay products) were done
 - would be useful to have such measurements from LHCb
- It would be very nice to have NNLO differential calculations for $t\bar{t}+\text{jets}$
 - would allow direct constraints on α_S
- It would be very nice to have NNLO differential calculations for $b\bar{b}$ and (especially) $c\bar{c}$
 - important to constrain gluon PDF at low x for astroparticle physics (see e.g. PROSA Coll., Eur. Phys. J. C75 (2015) 396)

BACKUP

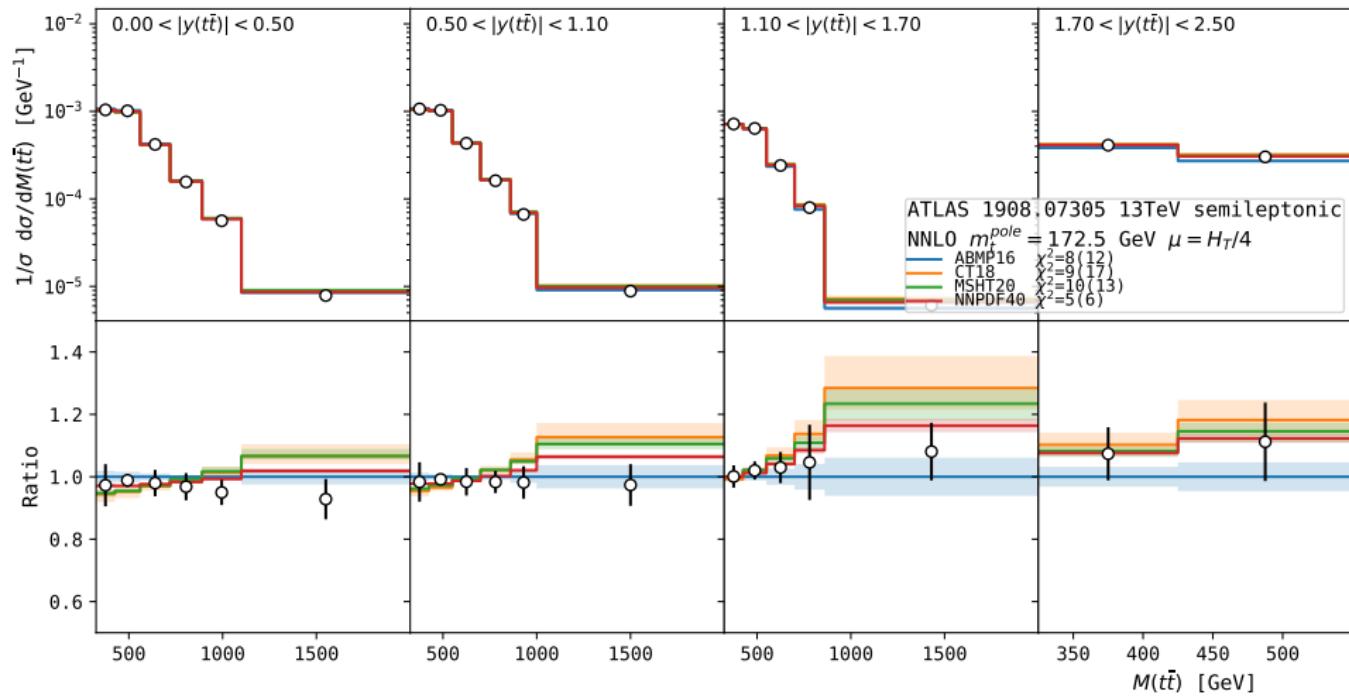
Data vs NNLO predictions using different PDFs



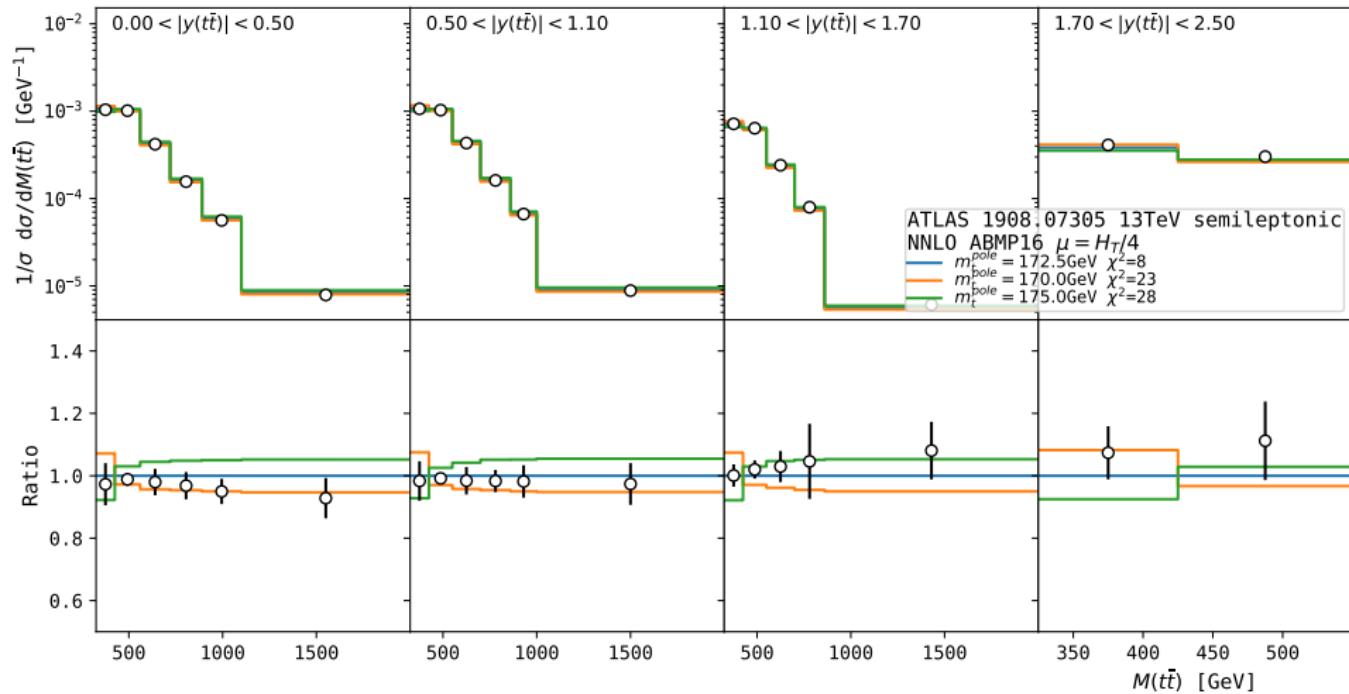
Data vs NNLO predictions using different m_t^{pole}



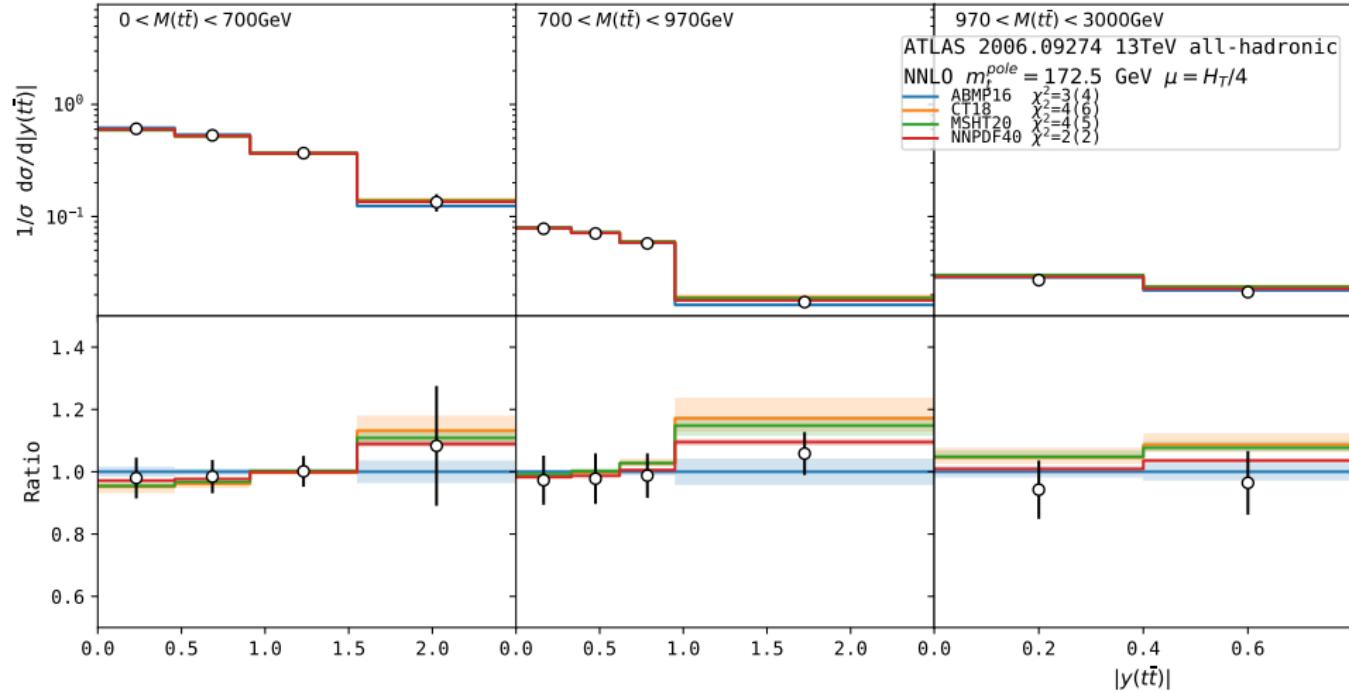
Data vs NNLO predictions using different PDFs



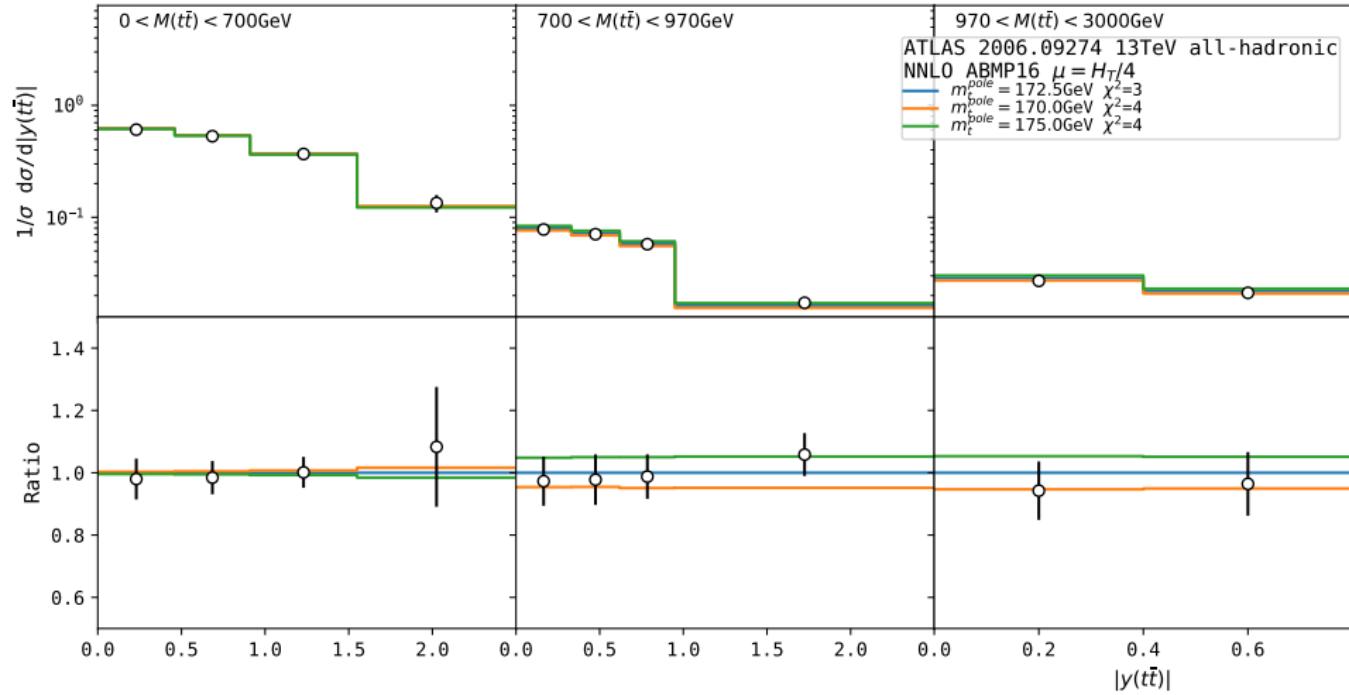
Data vs NNLO predictions using different m_t^{pole}



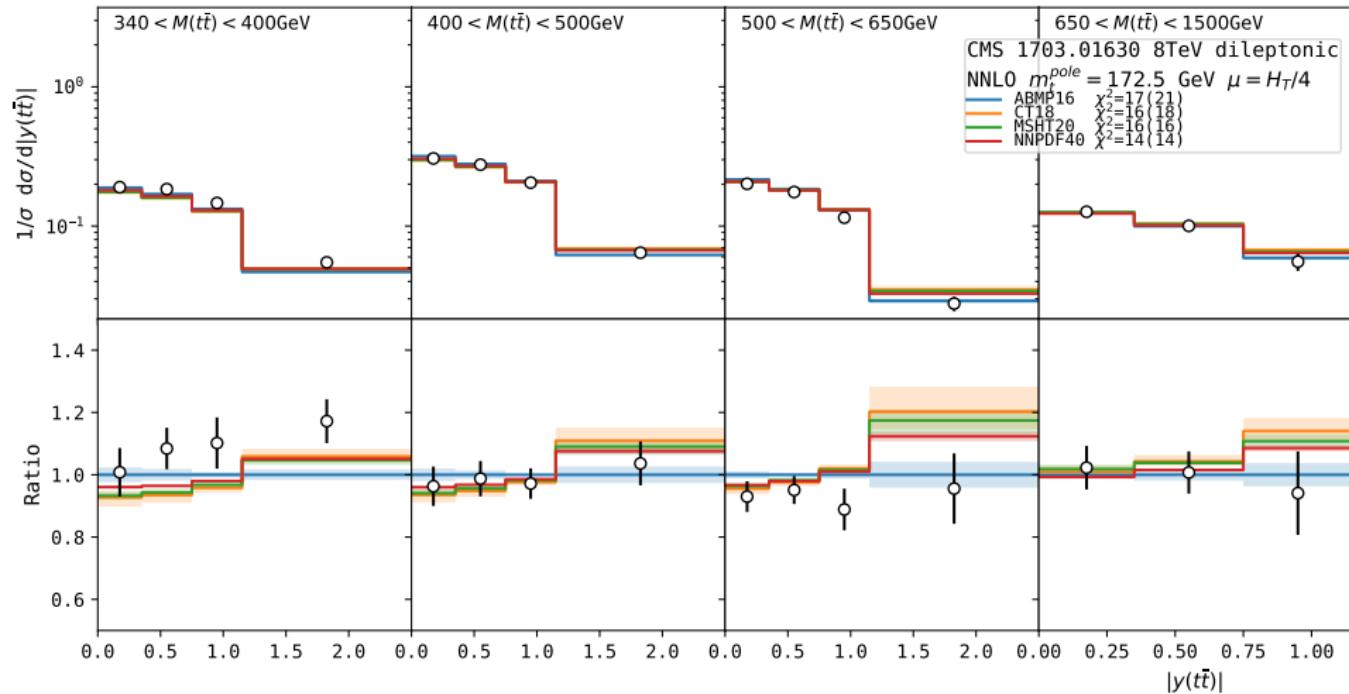
Data vs NNLO predictions using different PDFs



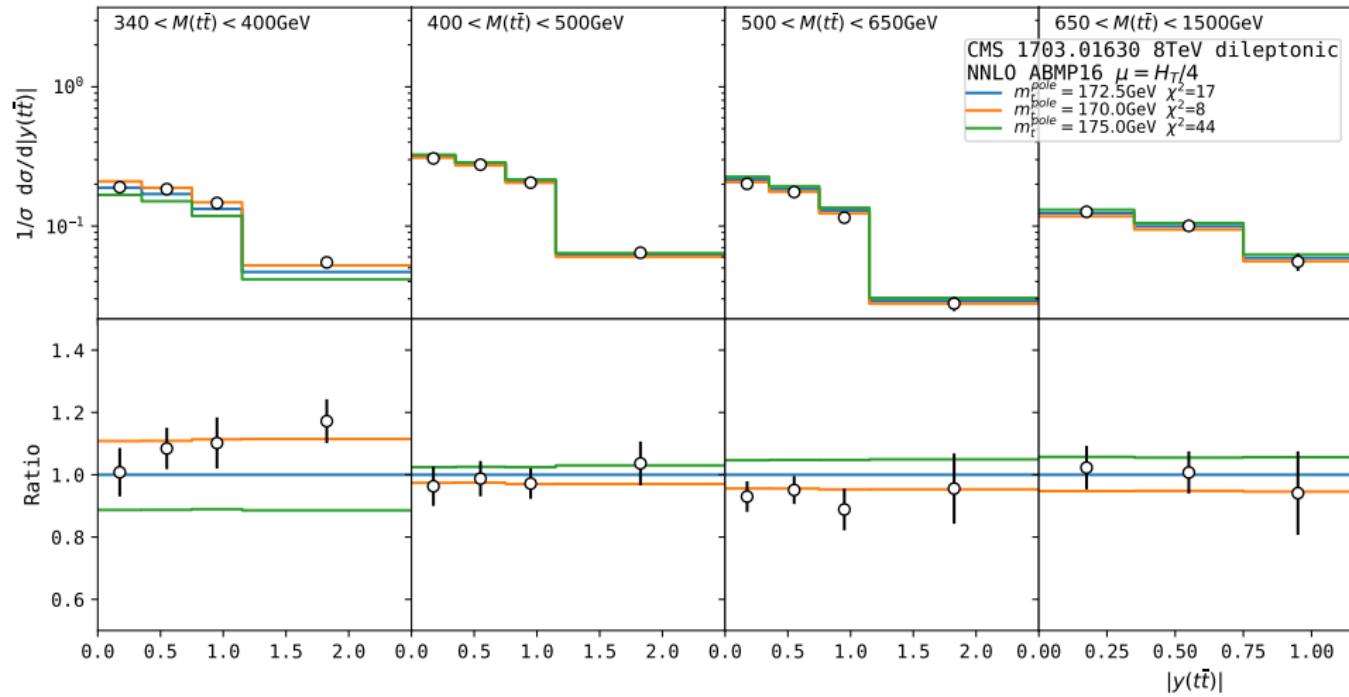
Data vs NNLO predictions using different m_t^{pole}



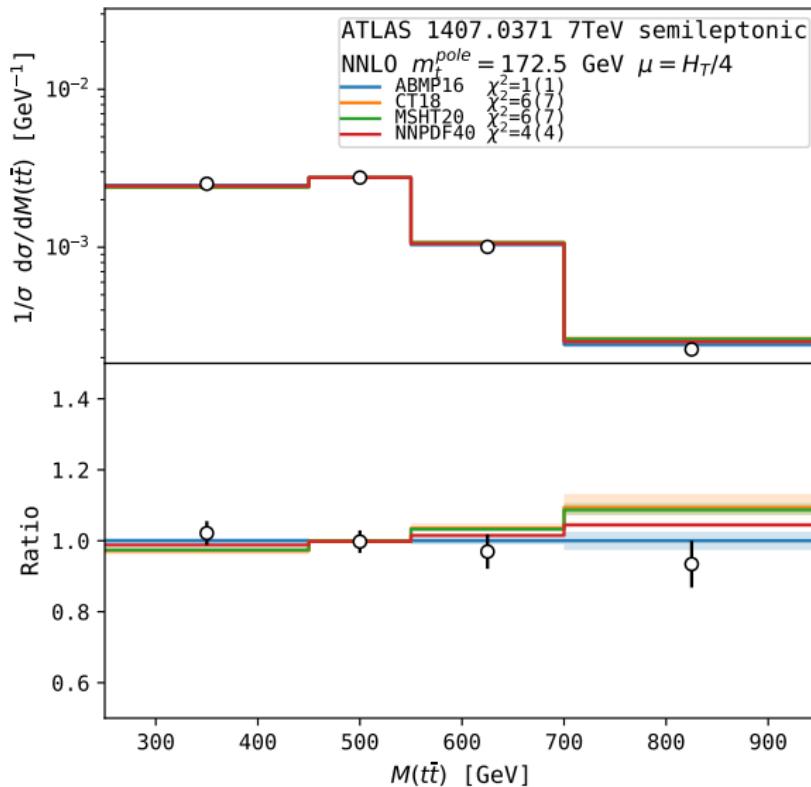
Data vs NNLO predictions using different PDFs



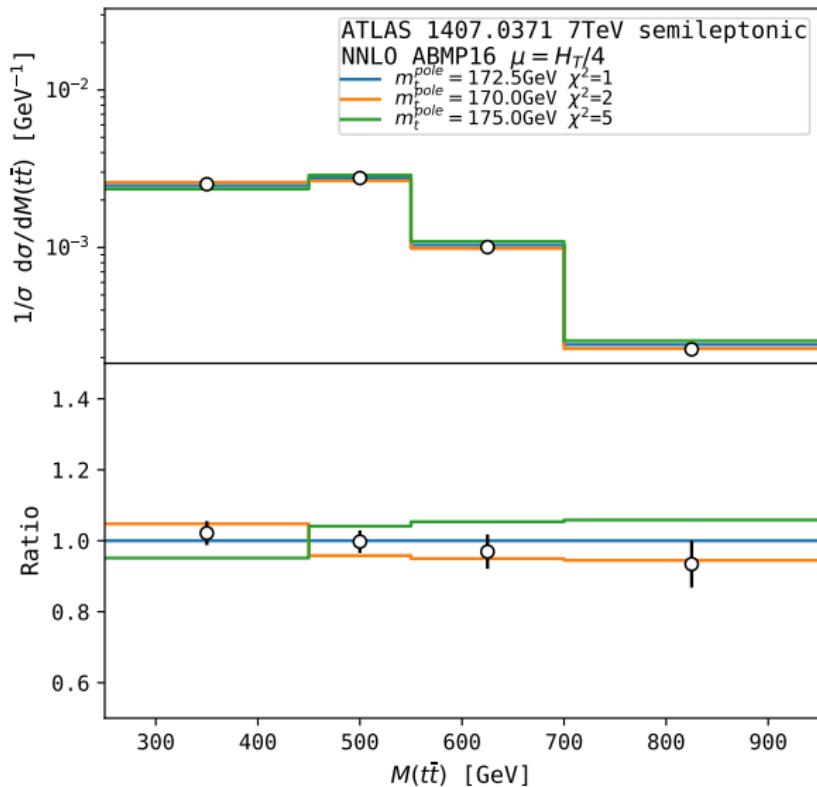
Data vs NNLO predictions using different m_t^{pole}



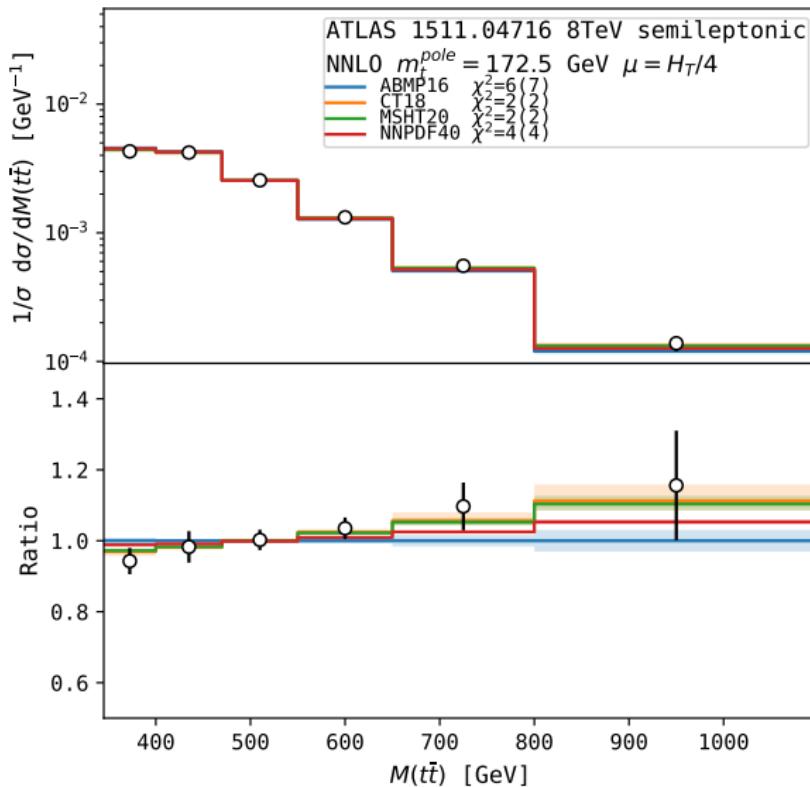
Data vs NNLO predictions using different PDFs



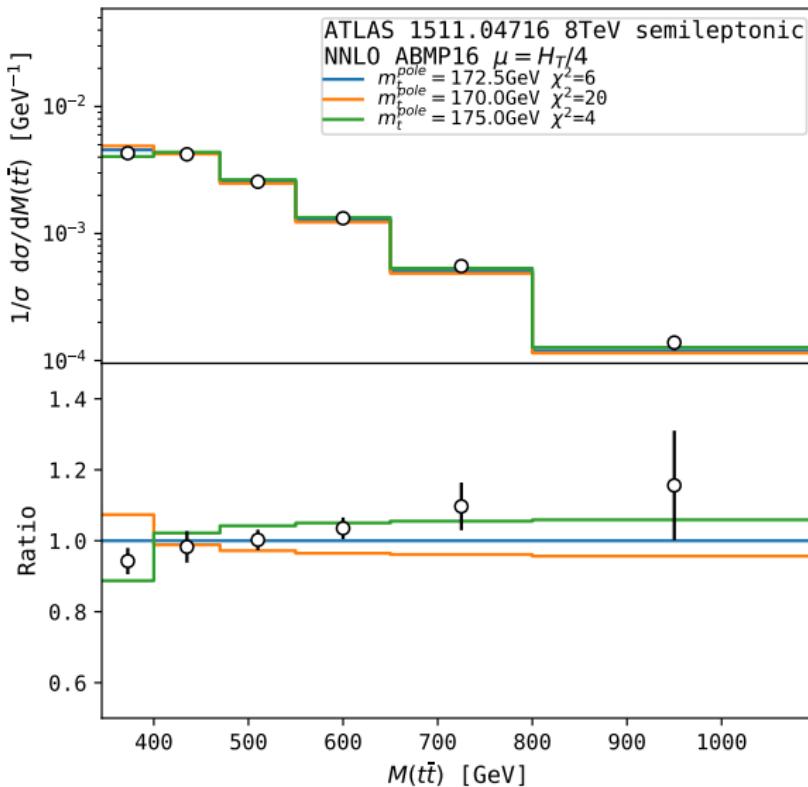
Data vs NNLO predictions using different m_t^{pole}



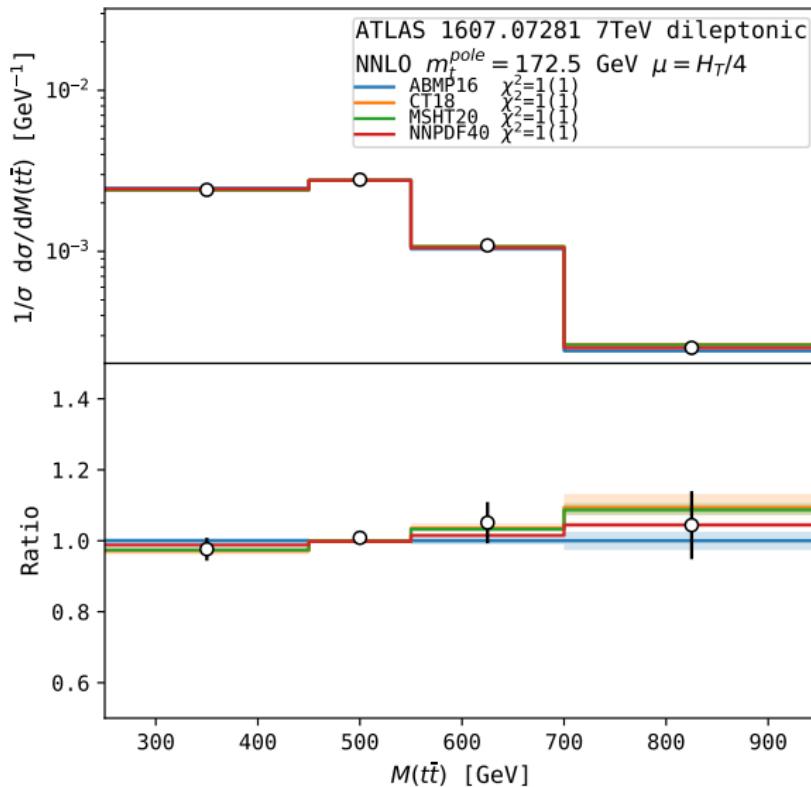
Data vs NNLO predictions using different PDFs



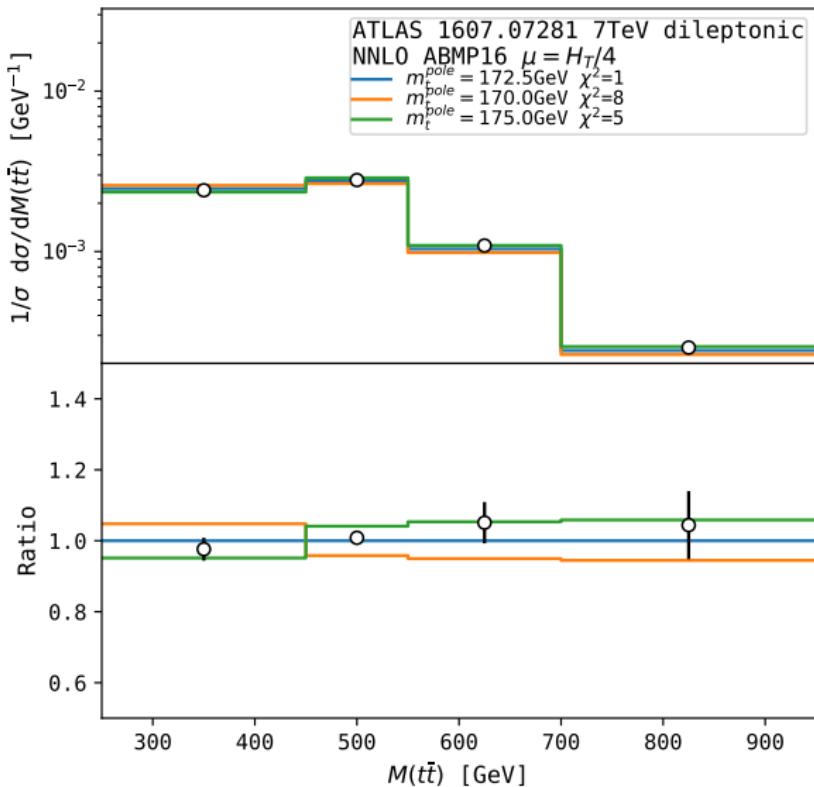
Data vs NNLO predictions using different m_t^{pole}



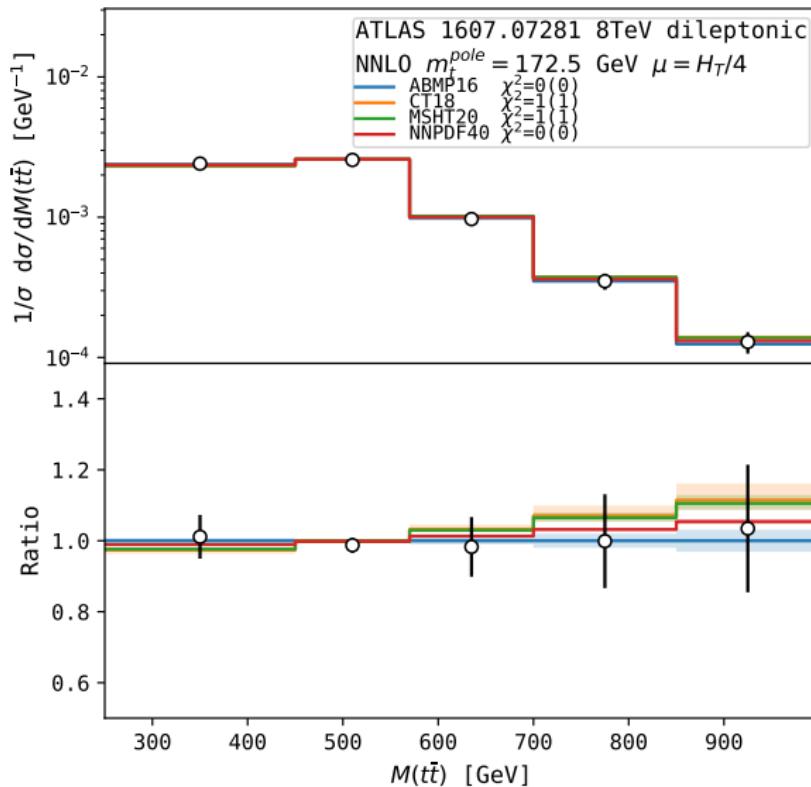
Data vs NNLO predictions using different PDFs



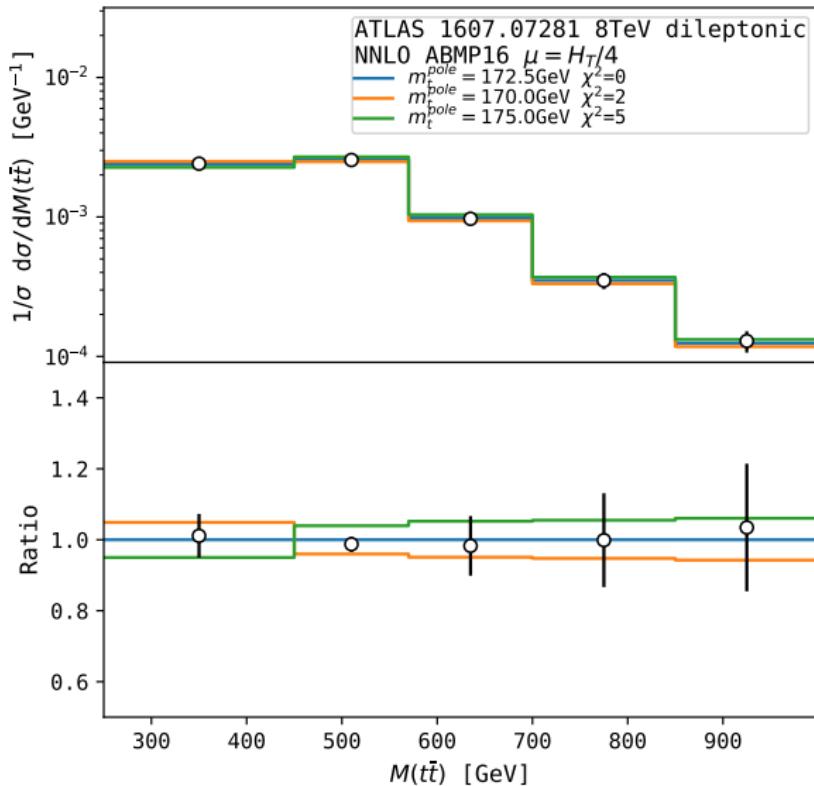
Data vs NNLO predictions using different m_t^{pole}



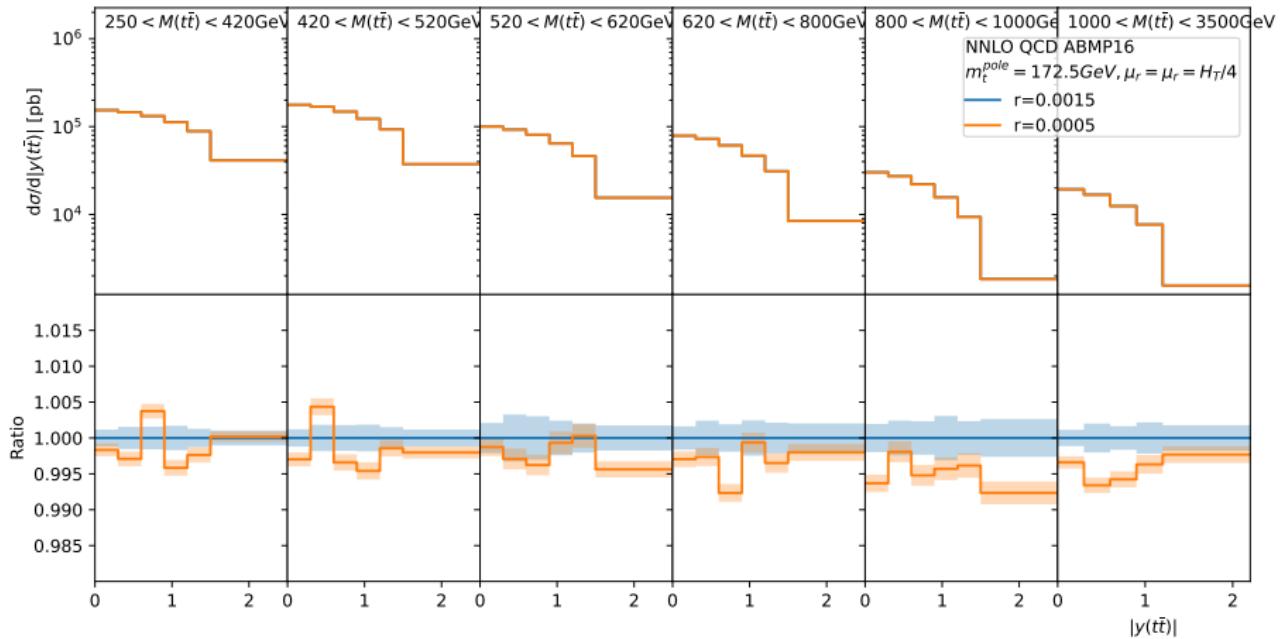
Data vs NNLO predictions using different PDFs



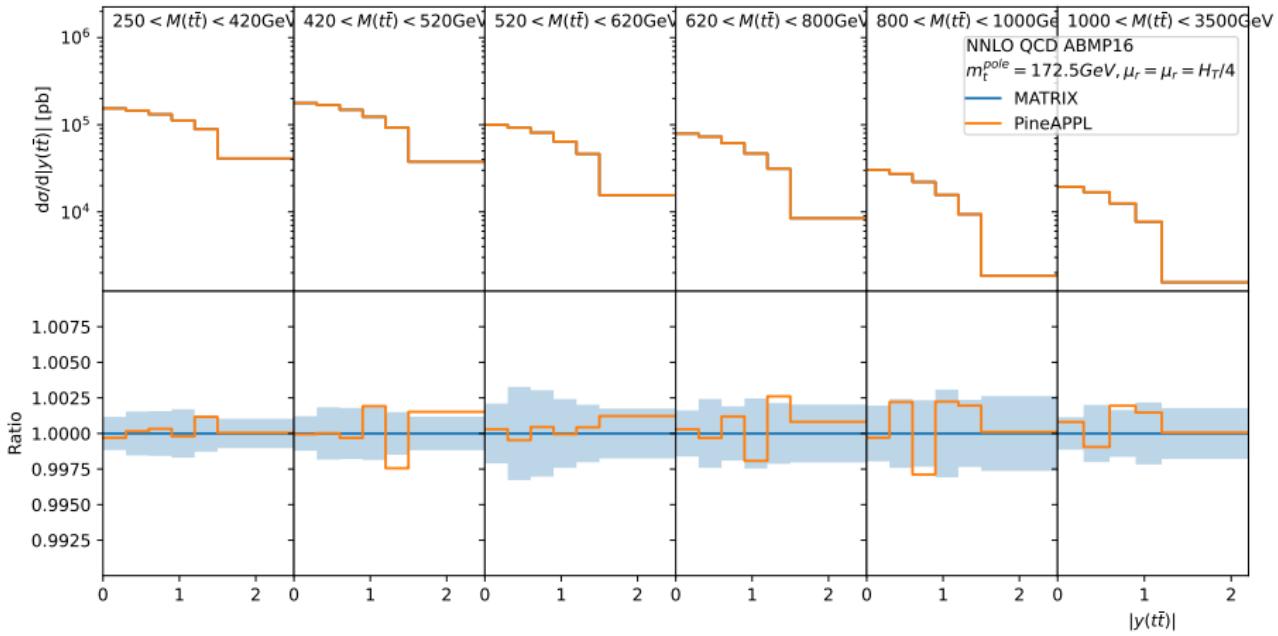
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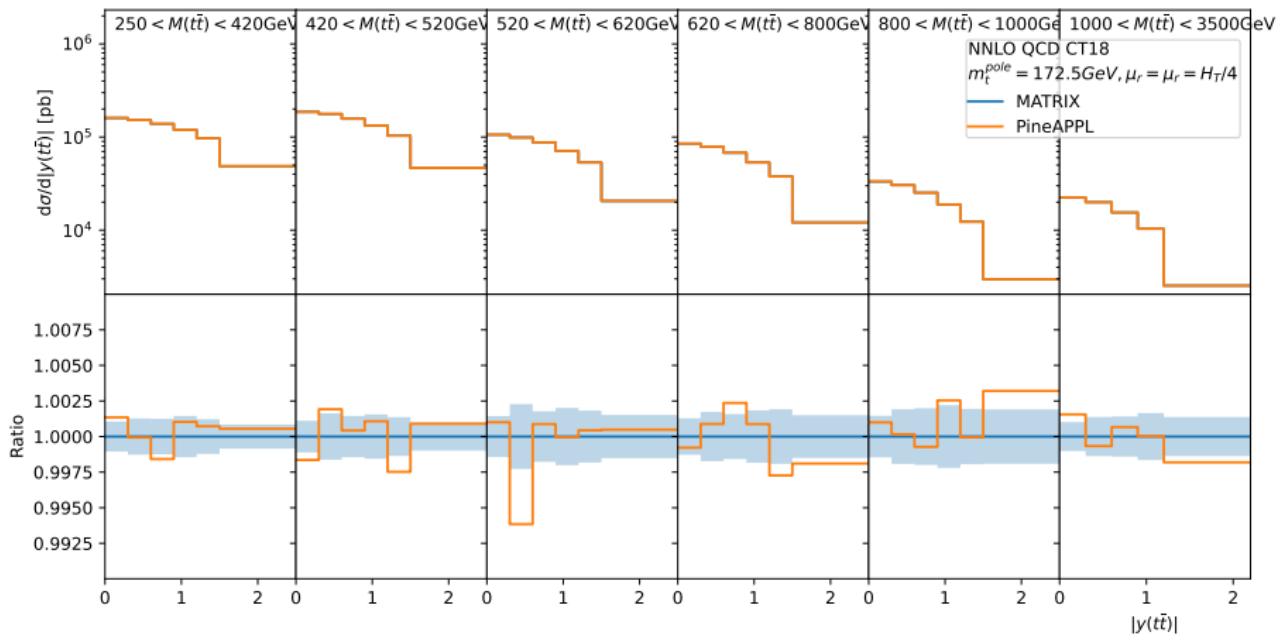
r cut variation in bins of TOP-20-001



PineAppl vs MATRIX in bins of TOP-20-001 [ABMP16]

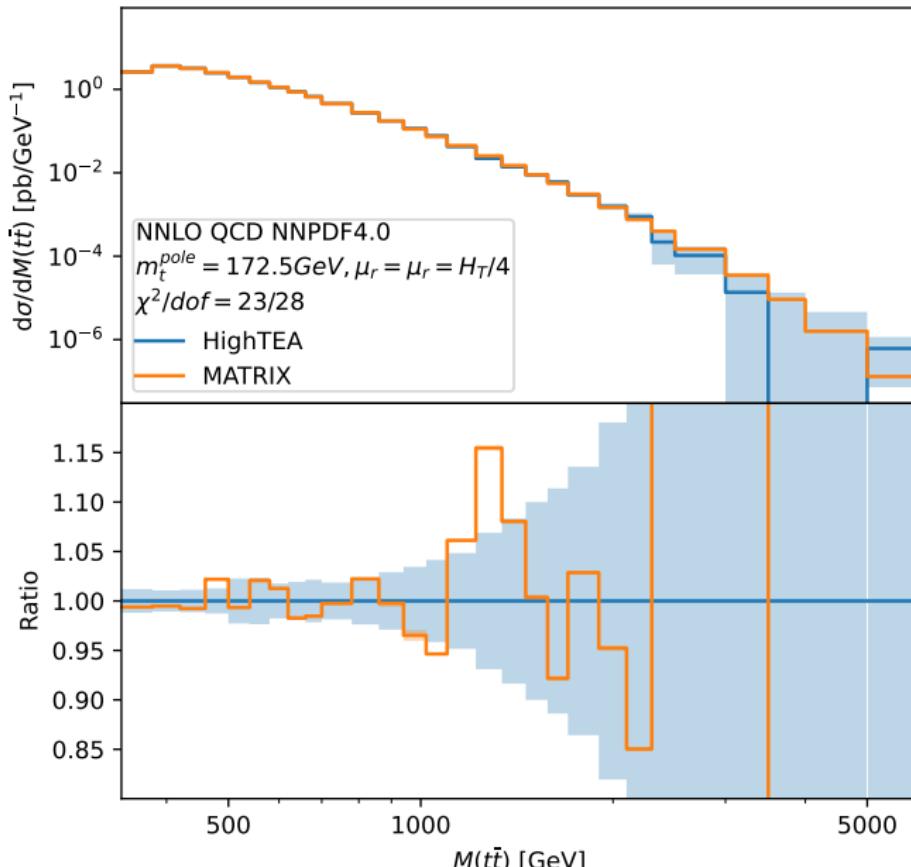


PineAppl vs MATRIX in bins of TOP-20-001 [CT18]

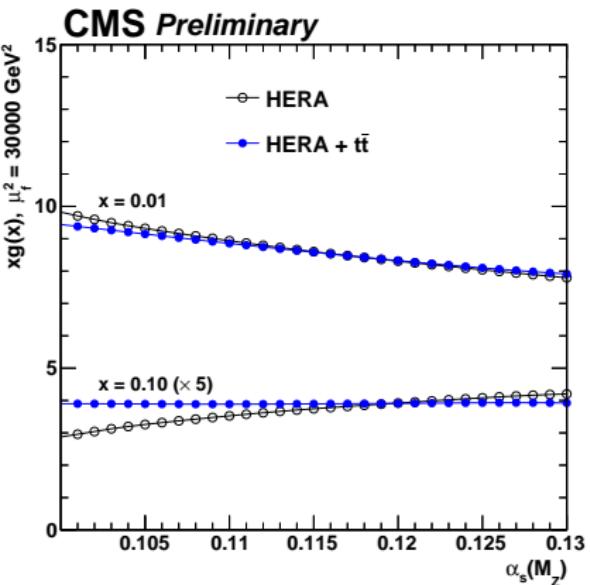
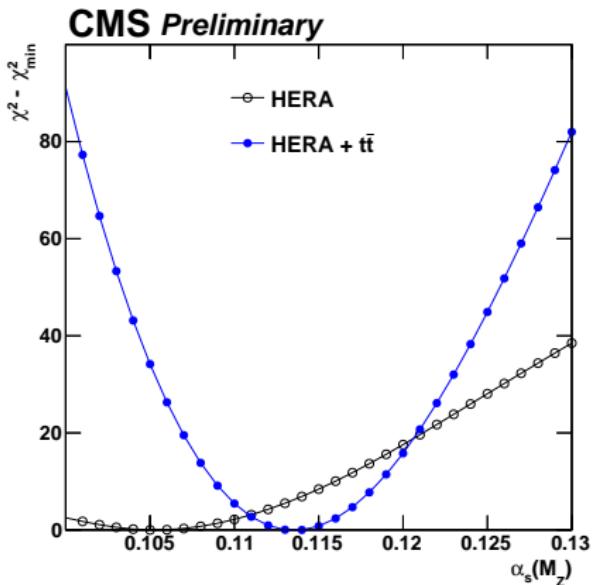


- grids were produced with ABMP16

MATRIX vs HighTEA



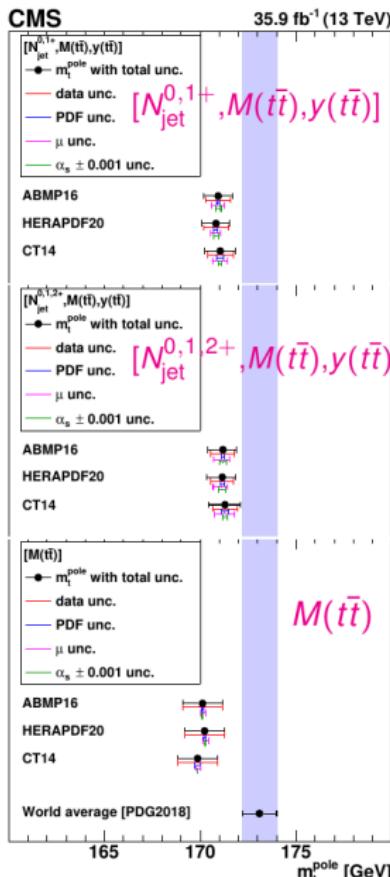
Simultaneous PDF + α_s + m_t^{pole} fit: correlation between α_s and gluon [CMS TOP-18-004]



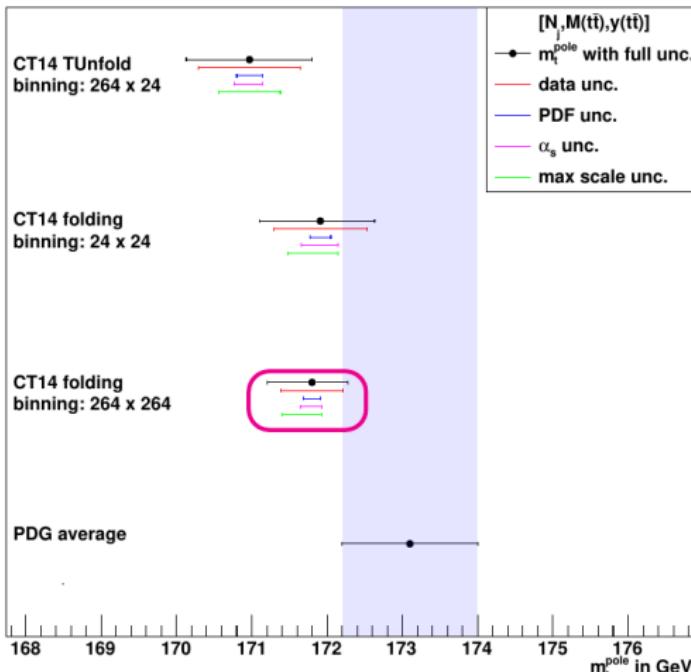
Adding $t\bar{t}$ data:

- constrain α_s (left)
- reduce correlation between α_s and gluon (g) (right)
 - weak correlation (α_s, m_t) \rightarrow weak correlation (g, m_t)

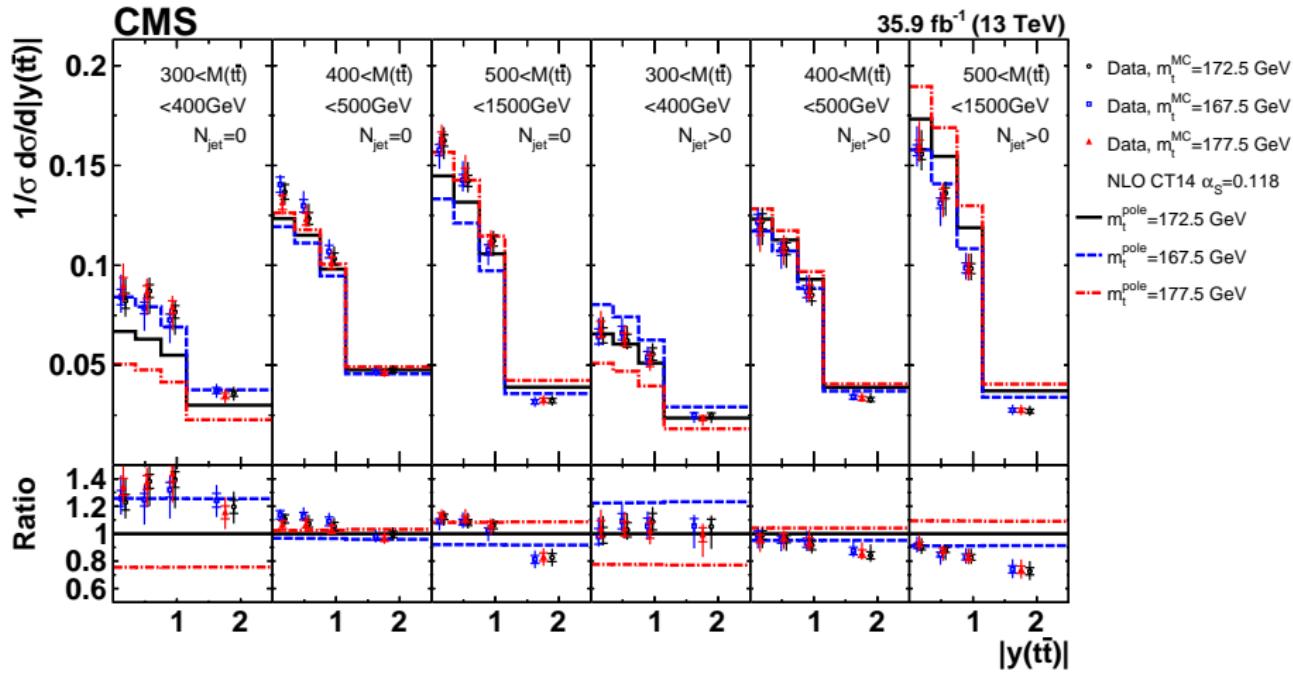
CMS TOP-18-004 checks



DESY 2018 summer school, L. Materne, bachelor thesis
 "Differential Top-Pair Production Cross Section with the CMS Detector - Optimization of Measurement Information",
 Karlsruher Institut für Technologie (KIT), Bachelorarbeit,
 2018 [ETP-Bachelor-KA/2018-11]



m_t dependence of measured cross sections [CMS TOP-18-004]



Charm production at LHC → gluon at low x → atmosphere ν fluxes

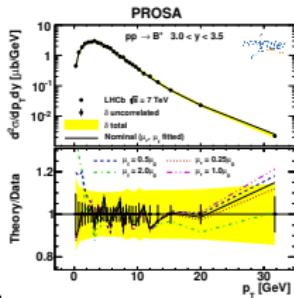
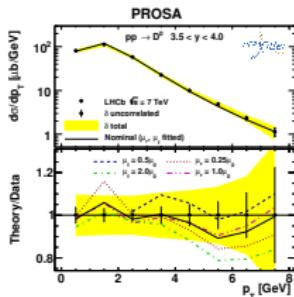
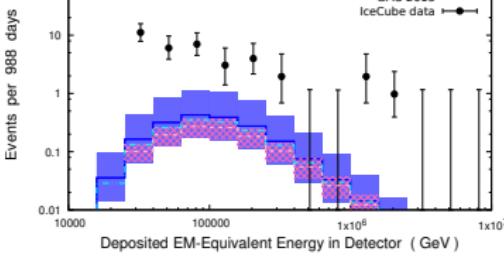
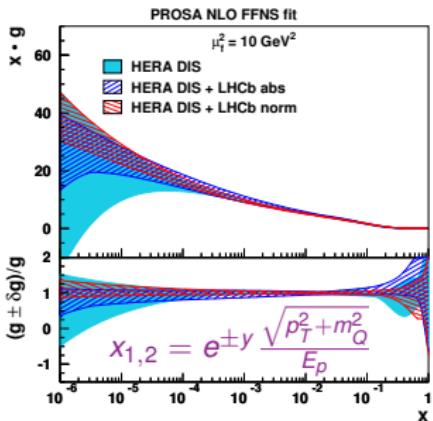
- LHCb measured:

- charm $0 < p_T < 8 \text{ GeV}$, $2 < y < 2.5$ [NPB871 (2013) 1]
- beauty $0 < p_T < 40 \text{ GeV}$, $2 < y < 2.5$ [JHEP 1308 (2013) 117]

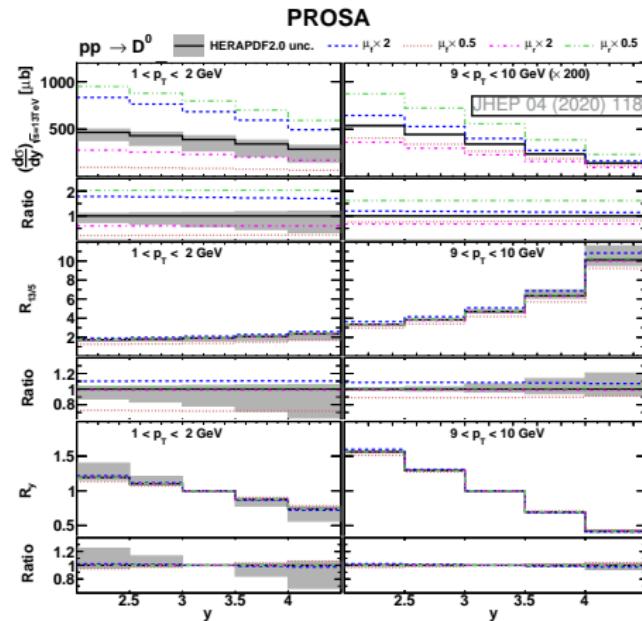
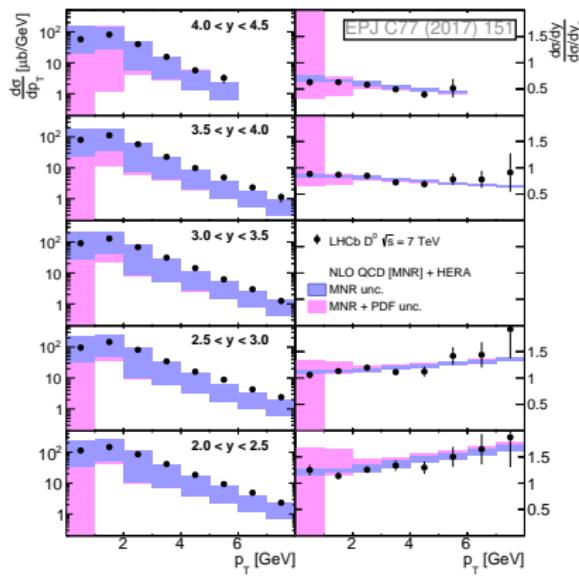
- First QCD analysis of these data: Eur. Phys. J. C75 (2015) 396

- Improved gluon and sea-quark distributions up to $x \gtrsim 5 \times 10^{-6}$
(not covered by other experimental data)

- used in next paper to predict IceCube background for very high energy cosmic ν [JHEP05 (2017) 004]
- further update with ALICE and new LHCb data [JHEP04 (2020) 118]



Charm production at LHC: dealing with large NLO scale variation uncertainties



- Taking **ratios** of data → reducing scale uncertainties by one order of magnitude
- Ratio to another kinematic region might be better than (traditional) ratio to another c.m.e.
- This relies on assumption that scale unc. are correlated across different kinematic regions:
 - ▶ can be tested e.g. by using another (dynamical) scale choice