LHC differential top-quark pair production cross sections in the ABMP16 PDF fit

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Garzelli, Mazzitelli, Moch, Zenaiev JHEP 05 (2024) 321 [arXiv:2311.05509]

Alekhin, Garzelli, Moch, Zenaiev arXiv:2407.00545

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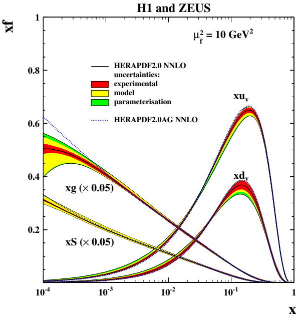
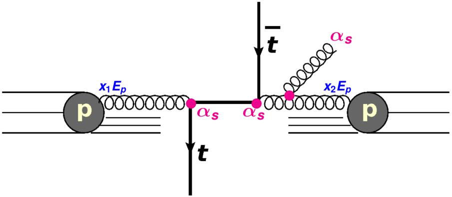
Challenge of gluon PDF, α_S and m_t

- Parton distribution functions (PDFs) cannot be computed perturbatively and must be extracted from data: *ep* DIS, DY etc.
- In this work we focus on gluon PDF g: it is a challenge because is not directly constrained by DIS data (backbone of PDF fits)
  - especially at large x (important for BSM searches at LHC)
  - in addition, g is strongly correlated with α_S
- Processes to constrain g:
  - heavy-quark production: NNLO, but depend on m_Q
  - jet production: larger NNLO scale choice
- We focused on double-differential $t\bar{t}$ LHC data $d^2\sigma/M(t\bar{t})y(t\bar{t})$:
  - $M(t\bar{t})$ provides sensitivity to m_t
  - $y(t\bar{t})$ provides sensitivity to PDFs via relation to partonic momentum fraction x: $x_{1,2} = (M(t\bar{t})/\sqrt{s})\exp[\pm y(t\bar{t})]$

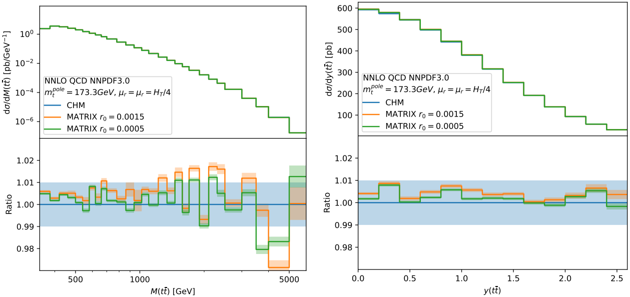
$\rightarrow$ *helps to de-correlate gluon PDF, α_S and m_t*





Theoretical calculations and scope of our work

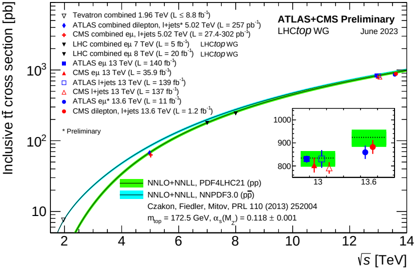
- NNLO calculations for total and fully differential $t\bar{t}$ (q_T subtraction) are publicly available with MATRIX framework Catani et al. PRD99 (2019) 5, 051501 Catani et al. JHEP 07 (2019) 100
  - fully differential NNLO calculations were also published in Czakon, Heymes, Mitvo JHEP 04 (2017) 071 [CHM], but no public code available



- We have interfaced MATRIX $t\bar{t}$ to PineAPPL interpolation library: **no NNLO/NLO K-factors**
- Garzelli, Mazzitelli, Moch, Zenaiev JHEP 05 (2024) 321: extraction of m_t^{pole} from the total and differential $t\bar{t}$ data using different PDF sets
- **Alekhin, Garzelli, Moch, Zenaiev arXiv:2407.00545: global PDF+α_S+m_t fit within the ABMP16 framework**
  - using collider and fixed-target DIS, DY (see BACKUP), updated single top and $t\bar{t}$ data

Data used in this analysis

All available measurements are used!



Selection of data:

- all LHC measurements of single t:
  - 6 data points from LHCTopWG
- all LHC measurements of total $\sigma(t\bar{t})$:
  - 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
  - bin-by-bin correlations are available (no Tevatron data)
  - normalized cross sections (to avoid unknown correlation with total $\sigma(t\bar{t})$ and to reduce unknown correlations between different data sets)
  - for the moment only Run-2 2D data included in the PDF fit (besides the total $t\bar{t}$ x-section data)

$$\frac{1}{\sigma(t\bar{t})}\frac{d\sigma(t\bar{t})}{dO}$$

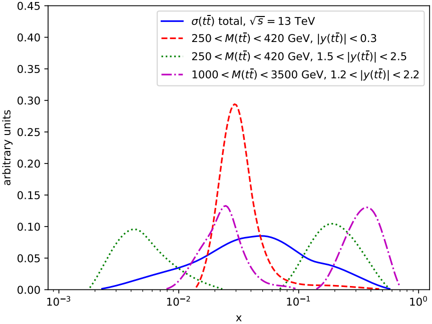
Experiment	decay channel	dataset	luminosity	$\sqrt{s}$	observable(s)	n
CMS	semileptonic	2016–2018	137 fb^{-1}	13 TeV	$M(t\bar{t})$, $\lvert y(t\bar{t})\rvert$	34
CMS	dileptonic	2016	35.9 fb^{-1}	13 TeV	$M(t\bar{t})$, $\lvert y(t\bar{t})\rvert$	15
ATLAS	semileptonic	2015–2016	36 fb^{-1}	13 TeV	$M(t\bar{t})$,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

Kinematic region probed by $t\bar{t}$, DY and Higgs production

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

- Double-differential $t\bar{t}$ @ 13 TeV probes $0.002 \lesssim x \lesssim 0.7$ (relatively high)
  - gg contributes $\approx 90\%$
- E.g. Higgs production at the LHC probes $x \sim m_H/\sqrt{s} \sim 0.01$ which is well covered by differential $t\bar{t}$ data
- Energy scales (masses of H, W, Z and t) are similar

→ *with new PDFs, we can expect improvement for predicting Higgs and DY processes at the LHC, as well as new physics probing high x*



Example: CMS 2108.02803 vs NNLO predictions using different PDFs

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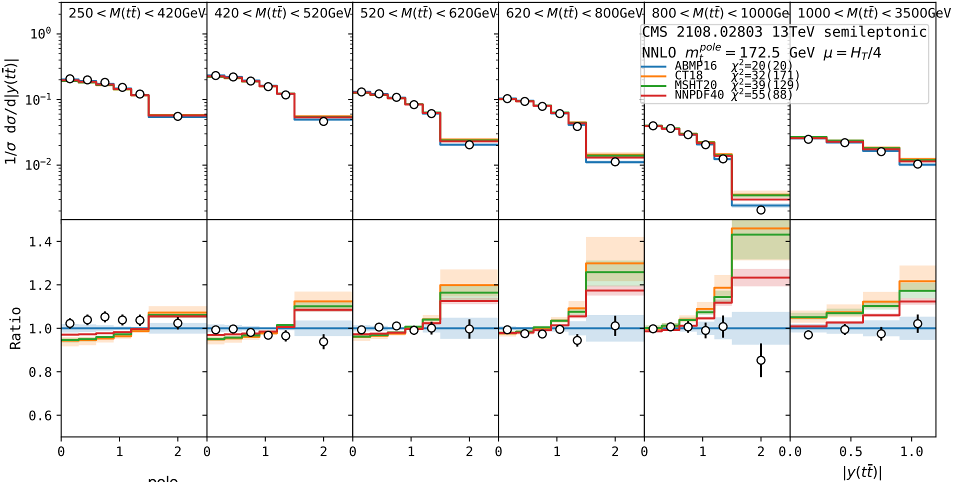

- Fixed $m_t^{\text{pole}} = 172.5$ GeV (not always consistent with PDF sets), $\mu_r = \mu_f = H_T/4$
- Reported χ^2 values with (and without) PDF uncertainties
- All PDF sets describe data reasonably well, with best description by ABMP16
  - CT18, MSHT20 and NNPDF40 show clear trend w.r.t data at high $y(t\bar{t})$ (large x)

Example: CMS 2108.02803 vs NNLO predictions using different m_t^{pole}

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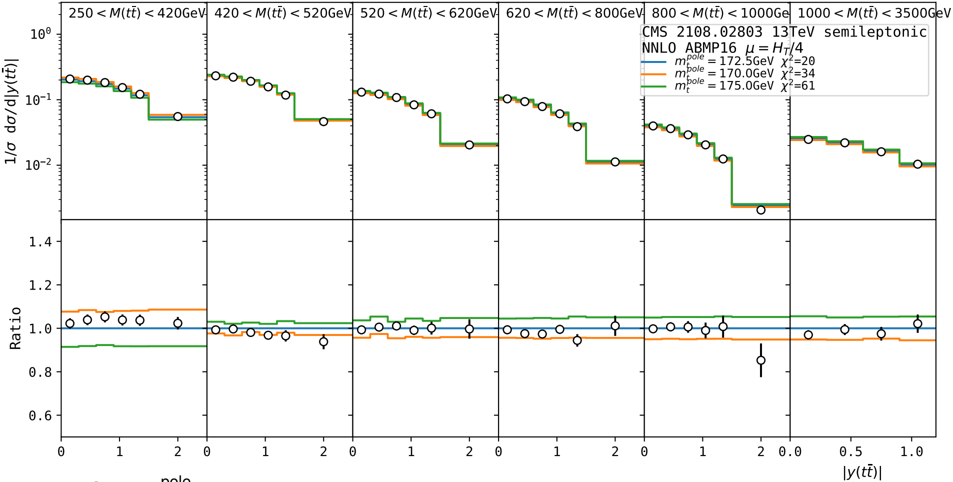

- NOTE: m_t^{pole} values on this plot are not the same as the ones obtained in ABMP16 fit ($m_t^{\text{pole}} = 170.4 \pm 1.2$ GeV)
- Low $M(t\bar{t})$: strong dependence on m_t^{pole} via threshold effects
- High $M(t\bar{t})$: opposite dependence due to cross section normalization

Example: CMS 2108.02803 vs NNLO predictions: scale variations

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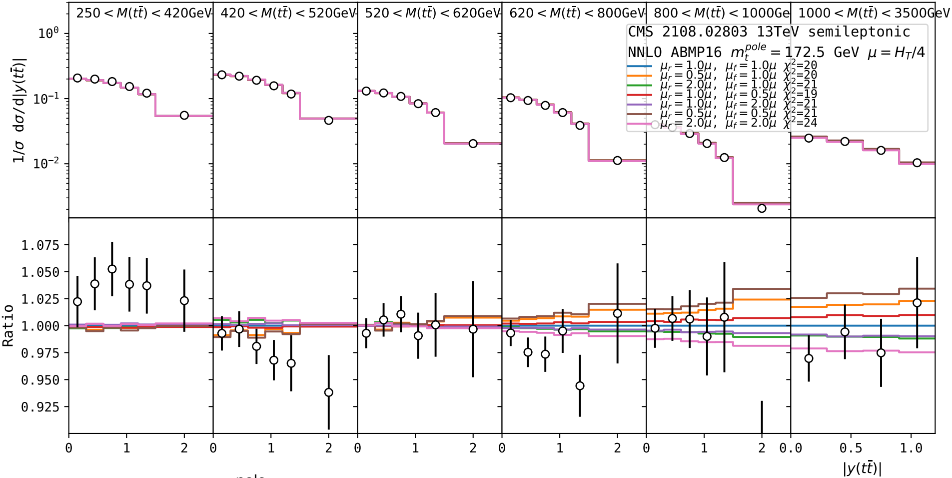
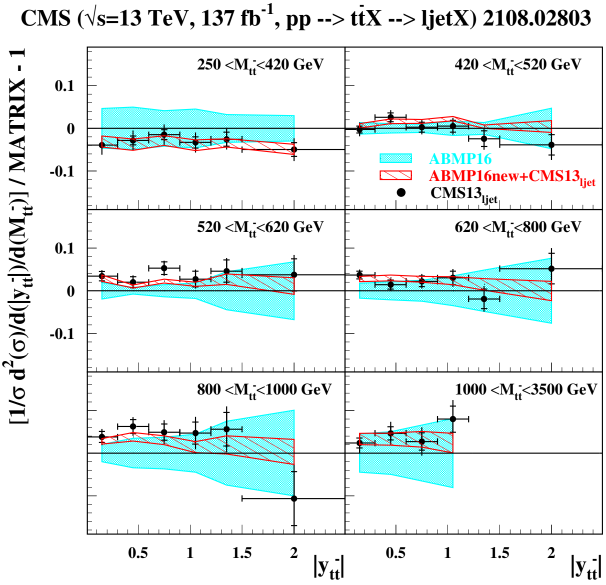


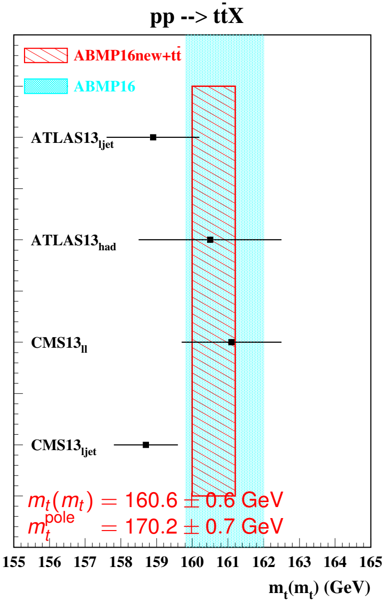
- ABMP16, fixed $m_t^{\text{pole}} = 172.5$ GeV
- Scale variations $< 1\%$ at low $M(t\bar{t})$ (largest cancellation), reach $\approx 4\%$ at high $M(t\bar{t})$
  - $\rightarrow$ *these data are useful to provide constraints on m_t and PDFs*



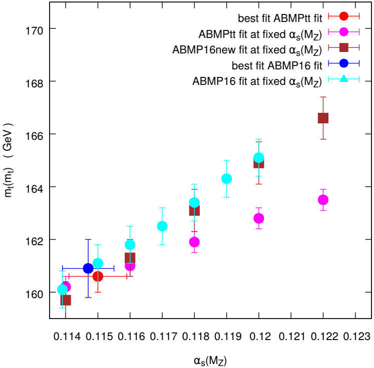
→ all data (including DY) are in good agreement with NNLO theoretical predictions and put significant constraints on the PDFs

(other $t\bar{t}$ data sets in BACKUP)

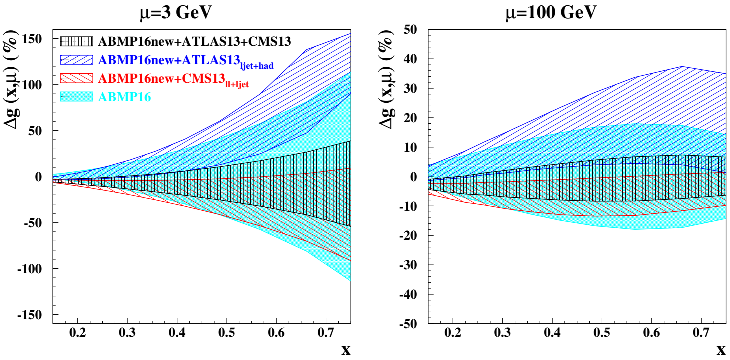
$m_t(m_t)$ and α_s in ABMP16 PDF fit



- Overall, good agreement between $m_t(m_t)$ extracted from different data sets
- Good agreement with ABMP16 fit and $\sim$ 50% reduced uncertainty on $m_t(m_t)$
- ABMP16new: consistent with ABMP16, but with extra iteration for DY data
- Positive correlation between α_s and $m_t(m_t)$ reduced with $t\bar{t}$ differential data

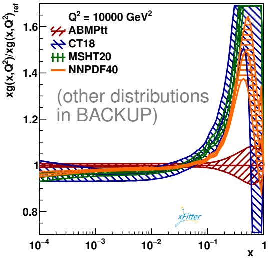


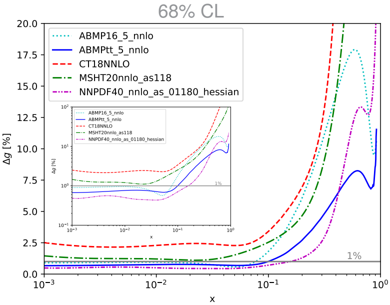
Fitted gluon PDF



- Significant reduction of the gluon PDF uncertainty once differential $t\bar{t}$ data are included
- The fitted gluon PDF is consistent with ABMP16 and differs w.r.t to other global fits at large x (some clues in BACKUP)
- Fitted $\alpha_S(M_Z) = 0.1150 \pm 0.0009$ in ABMPtt vs fixed $\alpha_S(M_Z) = 0.118$ in other fits

→ *we have confirmed ABMP16 gluon and α_S with new data*





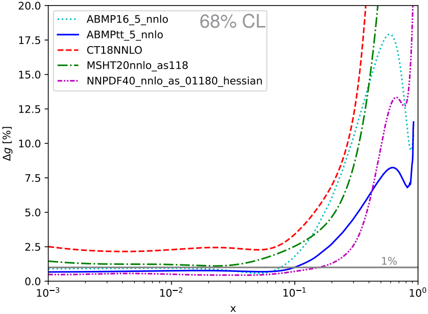
PDF Name	N2LO	N3LO	N4LOsv
ABMP16	$(45.4 \pm 4.6)^{+0.7}_{-0.7}$	$(49.6 \pm 2.6)^{+0.8}_{-0.8}$	$(50.8 \pm 1.9)^{+0.9}_{-0.9}$
ABMPtt	$(45.0 \pm 4.6)^{+0.6}_{-0.6}$	$(49.2 \pm 2.6)^{+0.7}_{-0.7}$	$(50.4 \pm 1.9)^{+0.8}_{-0.8}$
CT18NNLO	$(47.4 \pm 5.1)^{+1.3}_{-1.7}$	$(52.0 \pm 2.9)^{+1.4}_{-1.9}$	$(53.4 \pm 2.1)^{+1.5}_{-1.9}$
MMHT2014nnlo68cl	$(47.7 \pm 5.1)^{+0.6}_{-0.8}$	$(52.3 \pm 2.9)^{+0.7}_{-1.0}$	$(53.8 \pm 2.2)^{+0.7}_{-1.0}$
MSHT20nnlo_as118	$(47.4 \pm 5.1)^{+0.5}_{-0.6}$	$(52.0 \pm 2.9)^{+0.6}_{-0.6}$	$(53.4 \pm 2.1)^{+0.6}_{-0.6}$
NNPDF40_nnlo_as_01180	$(47.8 \pm 5.1)^{+0.3}_{-0.3}$	$(52.4 \pm 2.9)^{+0.3}_{-0.3}$	$(53.8 \pm 2.2)^{+0.3}_{-0.3}$
PDF4LHC21_40	$(47.6 \pm 5.1)^{+0.8}_{-0.8}$	$(52.3 \pm 2.9)^{+0.9}_{-0.9}$	$(53.7 \pm 2.2)^{+0.9}_{-0.9}$
MSHT20an3lo_as118	$(45.0 \pm 4.8)^{+0.8}_{-0.7}$	$(49.4 \pm 2.8)^{+0.9}_{-0.8}$	$(50.7 \pm 2.0)^{+0.9}_{-0.8}$

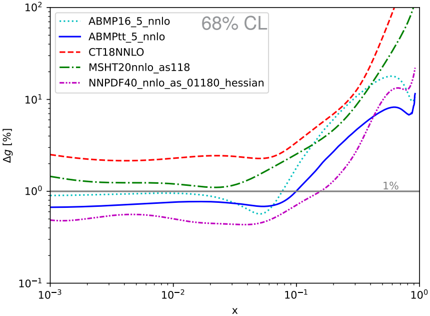
Table 1: Higgs cross-section along with the absolute error obtained from seven-point scale variation around $(\mu_R{}^c, \mu_F{}^c) = (1,1)m_H$ as well as intrinsic PDF uncertainty using LHAPDF. $\sqrt{S} = 14$ TeV, α_S from LHAPDF (NNLO value).

- *ABMPtt predictions are consistent with ABMP16 and have smaller PDF uncertainties*
- N4LOsv estimates missing higher-order corrections: 2%
- Larger differences originate from PDF and α_S sets:

  7% (1995) $\to$ 12% (2020) $\to$ **7% (2024)** (more in BACKUP)
- Expect smaller effect of NNLO→N3LO PDFs

Summary and outlook

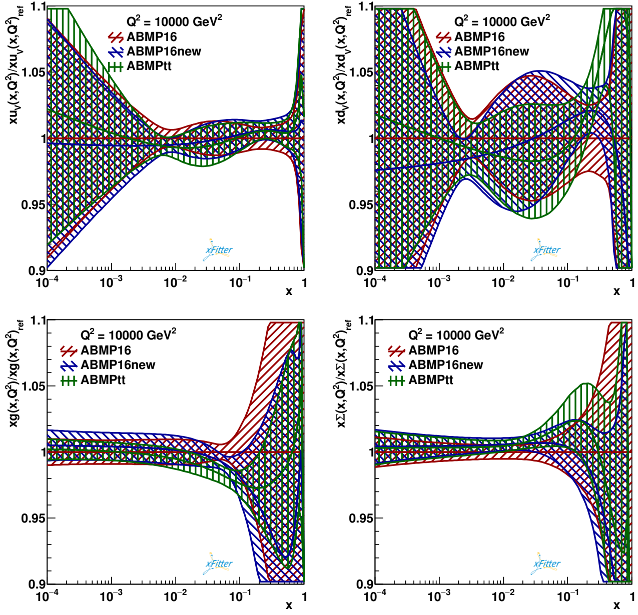




- ABMPtt NNLO fit includes new data on differential $t\bar{t}$, total $t\bar{t}$ and single t production
- PDFs, α_S and $m_t(m_t)$ are consistent with ABMP16 NNLO
- Uncertainty on gluon PDF reduced by up to a factor of 2 w.r.t ABMP16
- $\alpha_S(M_Z) = 0.1150 \pm 0.0009$ remains almost unchanged, but less correlated with $m_t(m_t)$
- ABMPtt done at exact NNLO for $t\bar{t}$ (no K factors etc.)
- ABMPtt gluon at large x is different vs. other global fits
  - important for LHC phenomenogy, e.g. Higgs x-sections
- More information in arXiv:2407.00545; LHAPDF tables will appear soon (ABMPtt_5_nnlo, ABMPtt_4_nnlo, ABMPtt_3_nnlo)

BACKUP

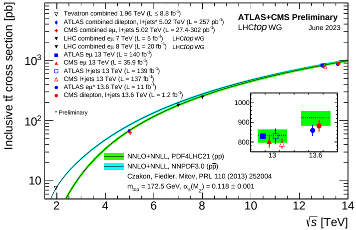
ABMPtt vs ABMP16

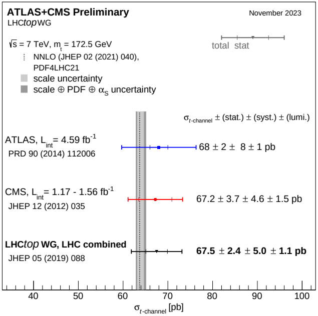


Data in ABMP16 fit [Alekhin et al., arXiv:1701:05838] (1)

Experiment	Process	Reference	NDP	χ^2
DIS				
HERA I+II	$e^{\pm}p \to e^{\pm}X$ $e^{\pm}p \to \overset{(-)}{\nu}X$	[4]	1168	1510
BCDMS	$\mu^{+}p \to \mu^{+}X$	[61]	351	411
NMC	$\mu^{+}p \to \mu^{+}X$	[60]	245	343
SLAC-49a	$e^{-}p \to e^{-}X$	[54, 62]	38	59
SLAC-49b	$e^{-}p \to e^{-}X$	[54, 62]	154	171
SLAC-87	$e^{-}p \to e^{-}X$	[54, 62]	109	103
SLAC-89b	$e^{-}p \to e^{-}X$	[56, 62]	90	79
DIS heavy-quark production				
HERA I+II	$e^{\pm}p \to e^{\pm}cX$	[63]	52	62
H1	$e^{\pm}p \to e^{\pm}bX$	[15]	12	5
ZEUS	$e^{\pm}p \to e^{\pm}bX$	[16]	17	16
CCFR	$\overset{(-)}{\nu}p \to \mu^{\pm}cX$	[64]	89	62
CHORUS	$\nu p \to \mu^{+}cX$	[18]	6	7.6
NOMAD	$\nu p \to \mu^{+}cX$	[17]	48	59
NuTeV	$\overset{(-)}{\nu} \to \mu^{\pm}cX$	[64]	89	49
DY				
FNAL-605	$pCu \to \mu^{+}\mu^{-}X$	[67]	119	165
FNAL-866	$pp \to \mu^{+}\mu^{-}X$ $pD \to \mu^{+}\mu^{-}X$	[68]	39	53
Top-quark production				
ATLAS, CMS	$pp \to tqX$	[27–32]	10	2.3
CDF&DØ	$\bar{p}p \to tbX$ $\bar{p}p \to tqX$	[53]	2	1.1
ATLAS, CMS	$pp \to t\bar{t}X$	[33–52]	23	13
CDF&DØ	$\bar{p}p \to t\bar{t}X$	[53]	1	0.2

$t\bar{t}$ and single top LHC data have been updated to latest LHCTOPWG:





Experiment		ATLAS		CMS		DØ		LHCb		
$\sqrt{s}$ (TeV)		7	13	7	8	1.96		7	8	
Final states		$W^+ \to l^+\nu$ $W^- \to l^-\nu$ $Z \to l^+l^-$	$W^+ \to l^+\nu$ $W^- \to l^-\nu$ $Z \to l^+l^-$	$W^+ \to \mu^+\nu$ $W^- \to \mu^-\nu$ (asym)	$W^+ \to \mu^+\nu$ $W^- \to \mu^-\nu$	$W^+ \to \mu^+\nu$ $W^- \to \mu^-\nu$ (asym)	$W^+ \to e^+\nu$ $W^- \to e^-\nu$ (asym)	$W^+ \to \mu^+\nu$ $W^- \to \mu^-\nu$ $Z \to \mu^+\mu^-$	$Z \to e^+e^-$	$W^+ \to \mu^+\nu$ $W^- \to \mu^-\nu$ $Z \to \mu^+\mu^-$
Cut on the lepton P_T		$P_T^l > 20$ GeV	$P_T^e > 25$ GeV	$P_T^\mu > 25$ GeV	$P_T^\mu > 25$ GeV	$P_T^\mu > 25$ GeV	$P_T^e > 25$ GeV	$P_T^\mu > 20$ GeV	$P_T^e > 20$ GeV	$P_T^\mu > 20$ GeV
Luminosity (1/fb)		0.035	0.081	4.7	18.8	7.3	9.7	1	2	2.9
Reference		[66]	[26]	[24]	[25]	[23]	[22]	[19]	[21]	[20]
NDP		30	6	11	22	10	13	31	17	32
χ^2	present analysis [a]	31.0	9.2	22.4	16.5	17.6	19.0	45.1	21.7	40.0
	CJ15 [6]	–	–	–	–	20	29	–	–	–
	CT14 [7]	42	–	– [b]	–	–	34.7	–	–	–
	JR14 [8]	–	–	–	–	–	–	–	–	–
	HERAFitter [197]	–	–	–	–	13	19	–	–	–
	MMHT14 [9]	39	–	–	–	21	–	–	–	–
	NNPDF3.0 [10]	35.4	–	18.9	–	–	–	–	–	–

[a] The ABM12 [1] analysis has used older data sets from CMS and LHCb.

[b] For the statistically less significant data with the cut of $P_T^\mu > 35$ GeV the value of $\chi^2 = 12.1$ was obtained.

TABLE VI: Compilation of precise data on W- and Z-boson production in pp and $p\bar{p}$ collisions and the χ^2 values obtained for these data sets in different PDF analyses using their individual definitions of χ^2. The NNLO fit results are quoted as a default, while the NLO values are given for the CJ15 [6] and HERAFitter [197] PDFs. Missing table entries indicate that the respective data sets have not been used in the analysis.

Experiment	Data set	$\sqrt{s}$ (TeV)	Reference	NDP	χ^2		
					I	II	III
ATLAS	$ATLAS\,13_{l\,jet}$	13	[25]	19	34.2	27.2	–
	$ATLAS\,13_{had}$	13	[26]	10	11.8	12.1	–
CMS	$CMS\,13_{ll}$	13	[24]	15	21.1	–	19.9
	$CMS\,13_{l\,jet}$	13	[22]	34	42.2	–	40.8

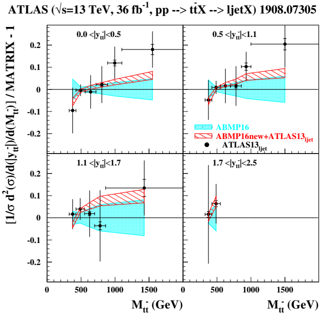
I: both ATLAS and CMS

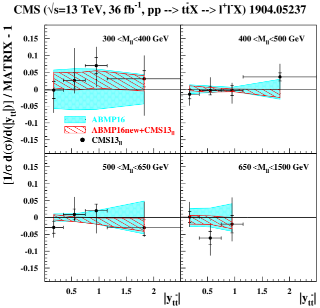
II: only ATLAS

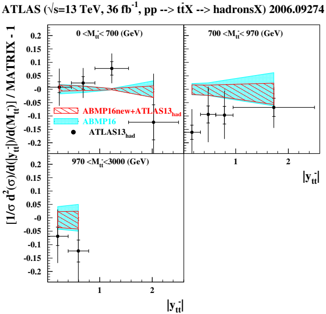
III: only CMS

$\rightarrow$ **Overall good description of data by NNLO theoretical predictions, but some tension between ATLAS and CMS differential $t\bar{t}$ data is noticeable**

Other $t\bar{t}$ differential data in ABMP16 PDF fit

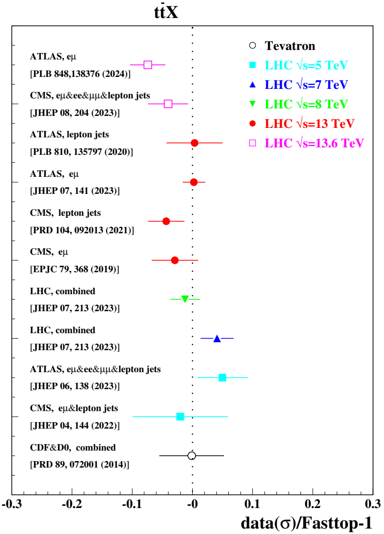


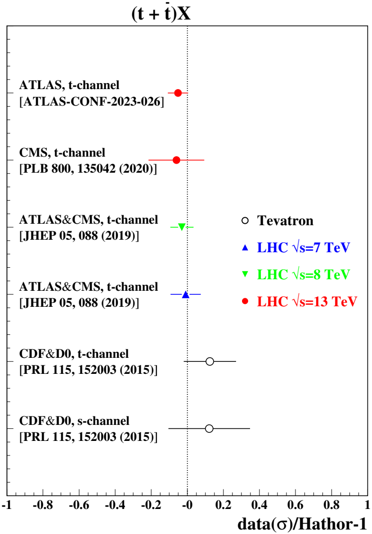




→ all data are in good agreement with NNLO theoretical predictions and put significant constraints on the PDFs

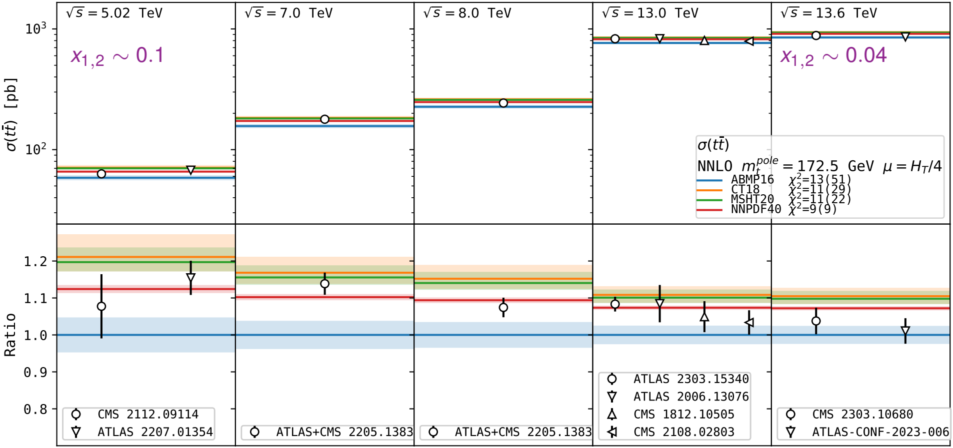
$\sigma(t\bar{t})$ and single t in ABMP16 PDF fit





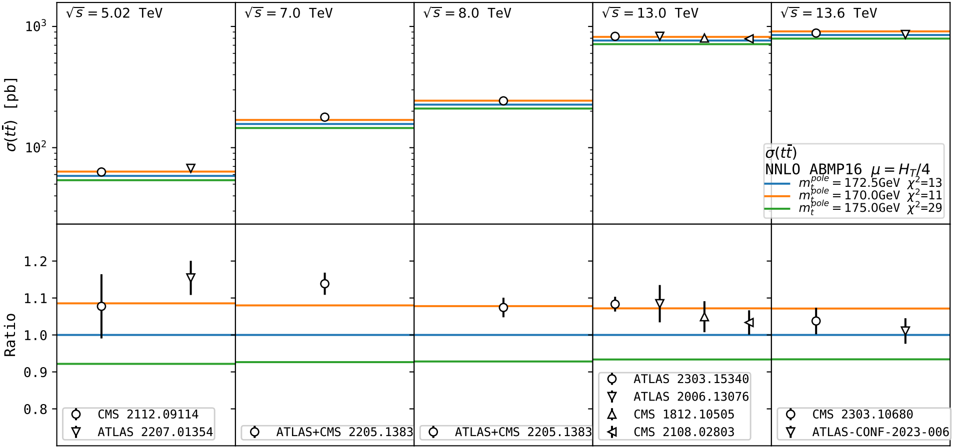
- good description of total $t\bar{t}$ and single t data
- single t data provide additional constraint on m_t (less correlated with g and α_S)

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



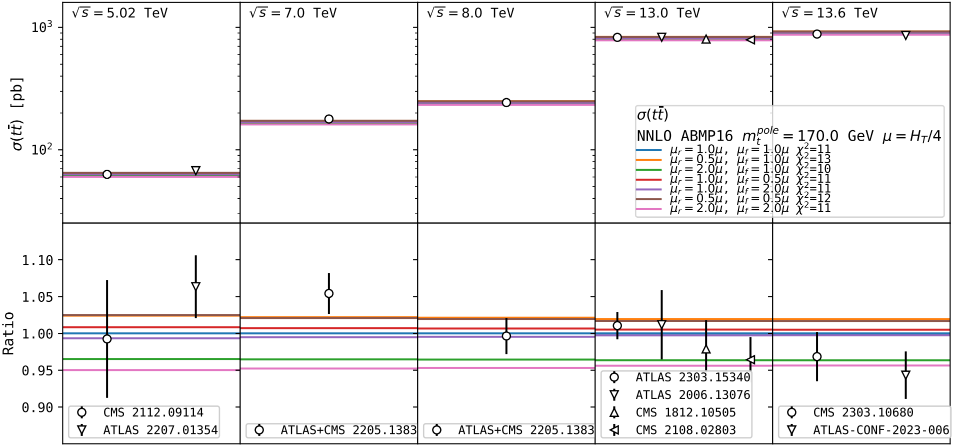
- Fixed $m_t^{\text{pole}} = 172.5$ GeV, $\mu_r = \mu_f = H_T/4$
- Reported χ^2 values with (and without) PDF uncertainties
- All PDF sets describe data reasonably well (depends on m_t^{pole}, α_S)
- Sensitivity to PDFs reduces with increasing $\sqrt{s}$ (lower x probed)

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



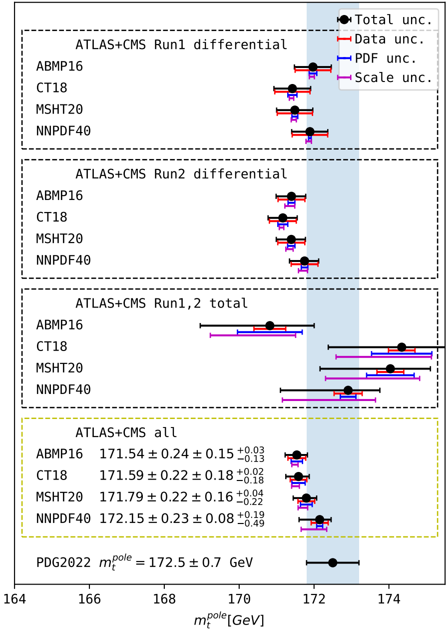
- ABMP16, fixed $\mu_r = \mu_f = H_T/4$
- Change of m_t^{pole} by 1 GeV $\rightarrow$ change of $\sigma(t\bar{t})$ by $\approx 3\%$
- Preferable $m_t^{\text{pole}} \sim 170$–$172.5$ GeV (depends on PDF and α_S)

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



- ABMP16, fixed $m_t^{\text{pole}} = 172.5$ GeV
- Scale variations $^{+3\%}_{-5\%}$:
  - 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

Extraction of m_t^{pole}: summary

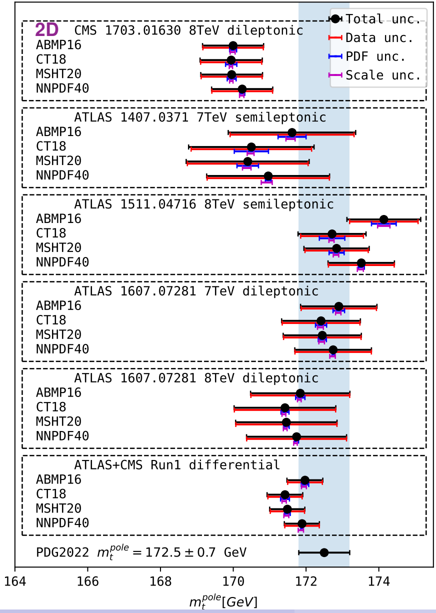


- Extracted m_t^{pole} values with precision ± 0.3 GeV are consistent with PDG value 172.5 ± 0.7 GeV
  - data uncertainty ~ 0.2 GeV
  - PDF uncertainty ~ 0.1 GeV
  - NNLO scale uncertainty ~ 0.2 GeV
- Significant dependence on PDFs (~ 0.5 GeV):
  - different m_t^{pole} used in different PDFs
  - PDFs, 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 $t\bar{t}$ +jets
- Possible effects from Coulomb and soft-gluon resummation near the $t\bar{t}$ production threshold are neglected: might be ~ 1 GeV?

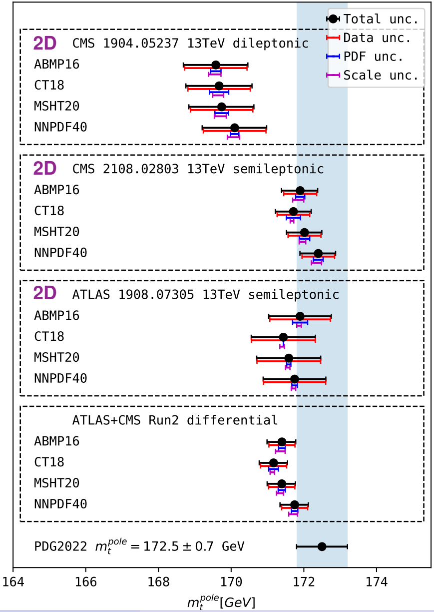
[CMS Coll. EPJ C80 (2020) 658; Kiyo, Kuhn, Moch, Steinhauser, Uwer EPJ C60 (2009) 375; Mäkelä, Hoang, Lipka, Moch 2301.03546]

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

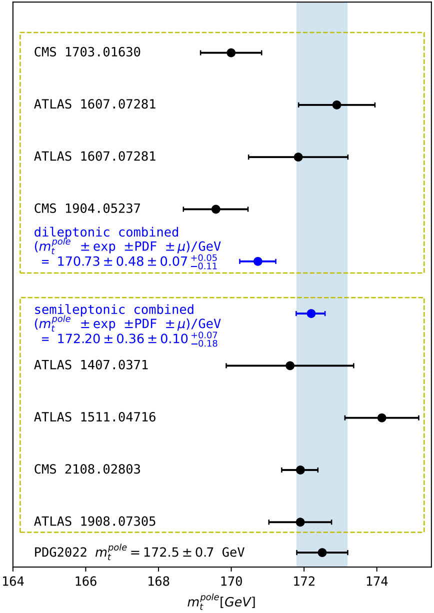
Run 1 differential

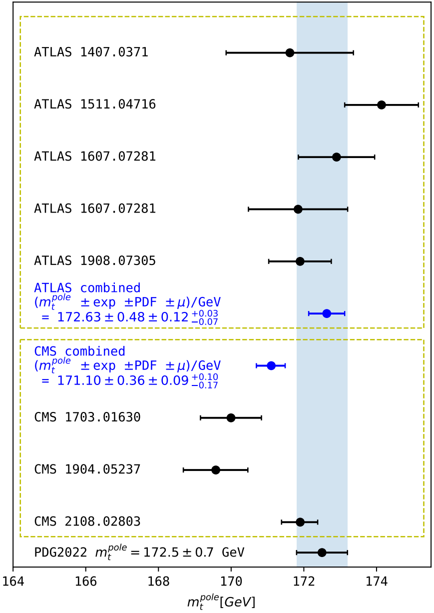


Run 2 differential

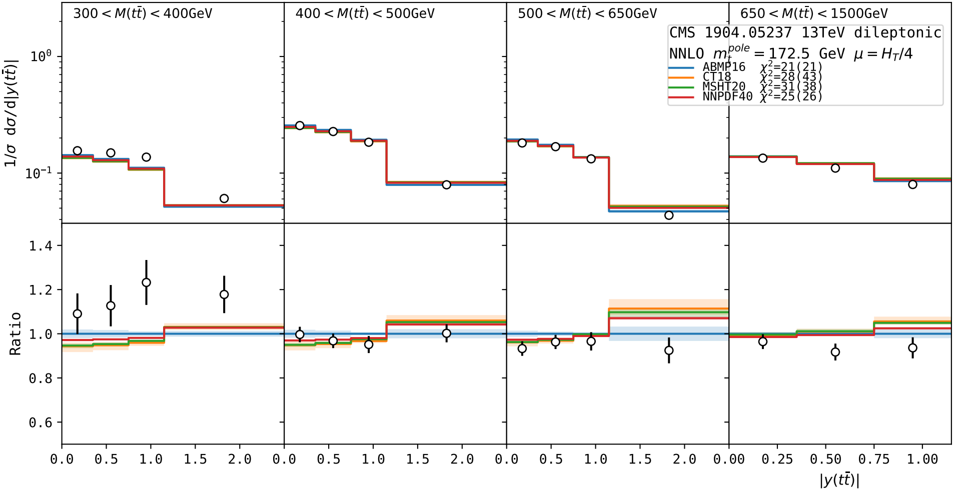


Extraction of m_t^{pole}: dilepton vs semileptonic, ATLAS vs CMS

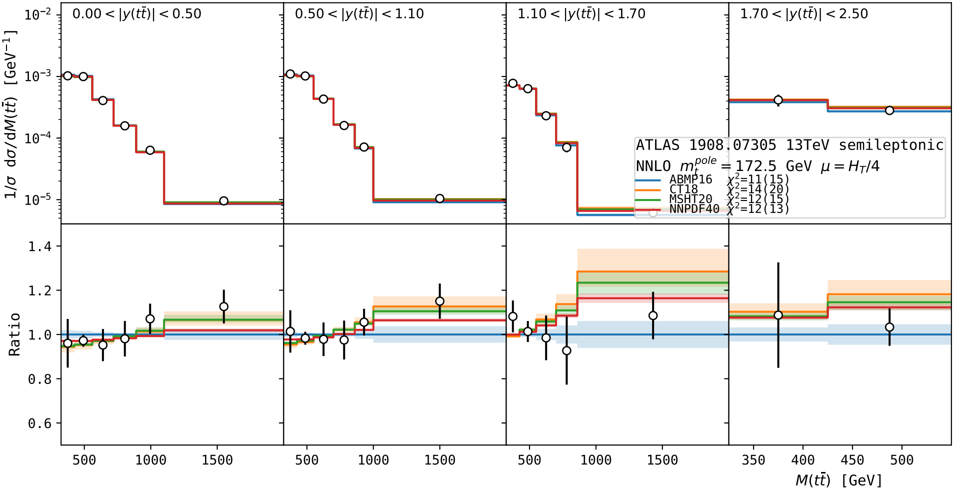




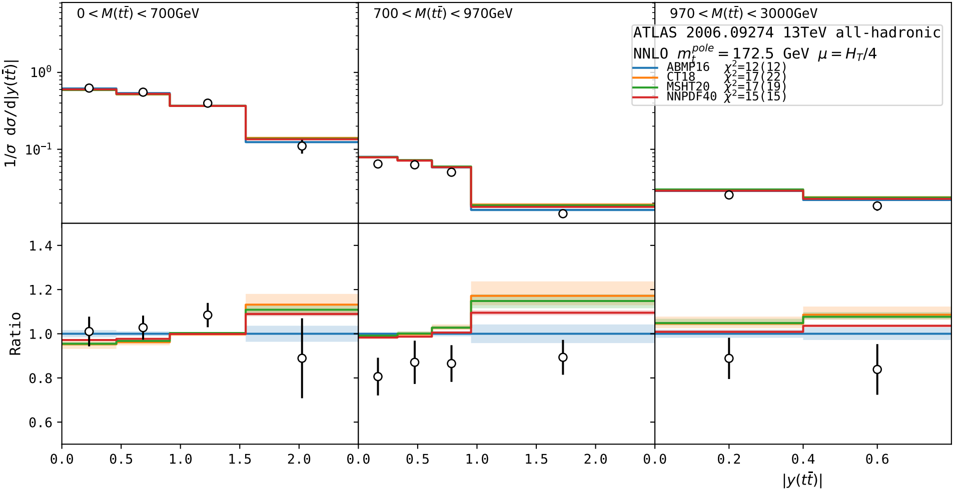
Data vs NNLO predictions using different PDFs

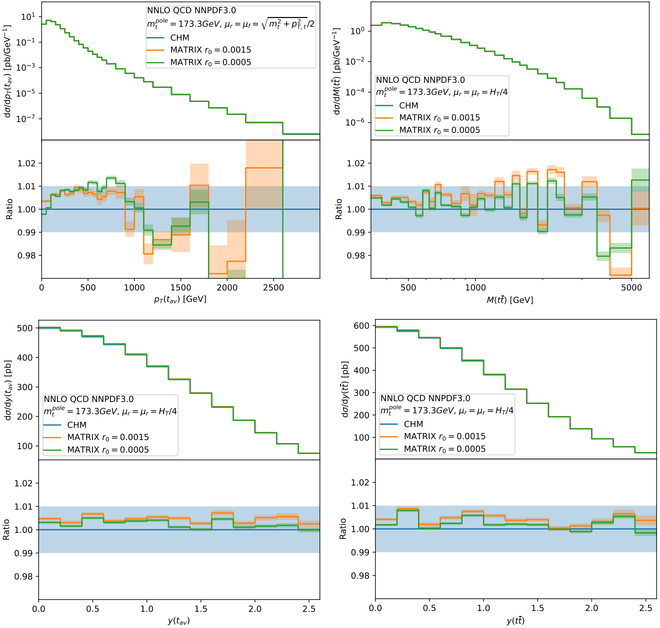


Data vs NNLO predictions using different PDFs



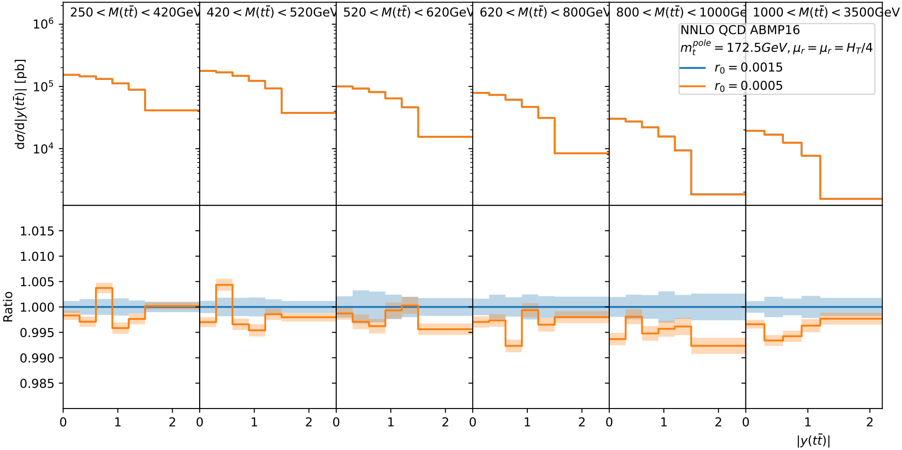
Data vs NNLO predictions using different PDFs



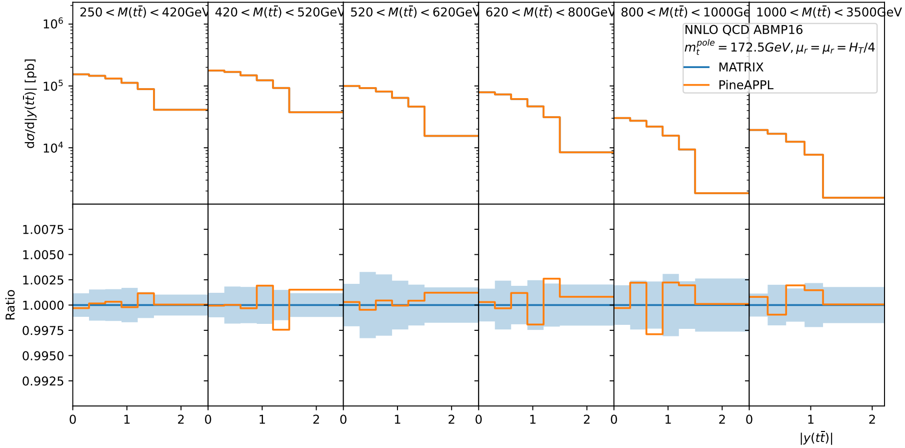


Good agreement $< 1\%$

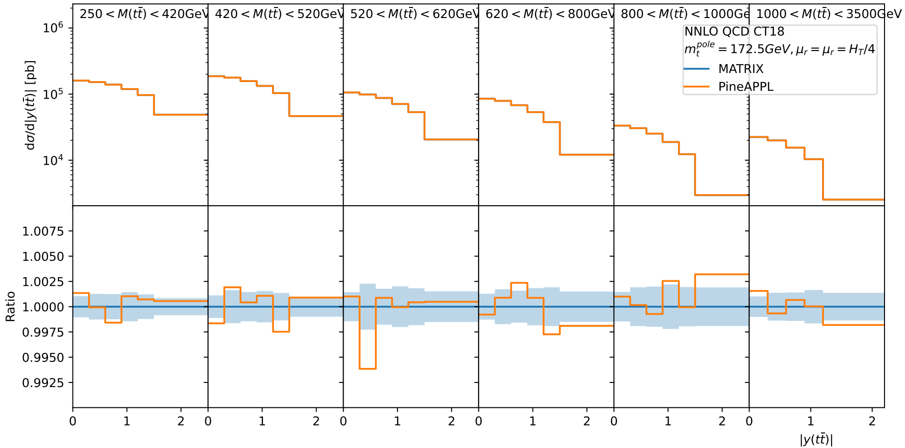
r cut variation in bins of TOP-20-001



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

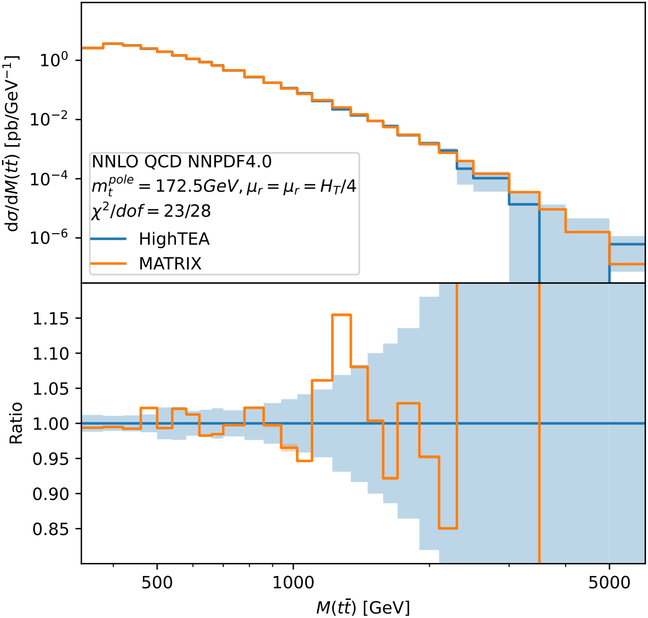


PineAppl vs MATRIX in bins of TOP-20-001 [CT18]

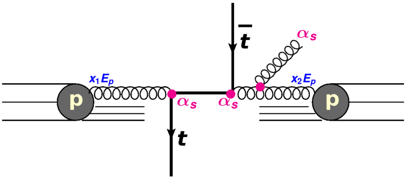


- grids were produced with ABMP16

MATRIX vs HighTEA

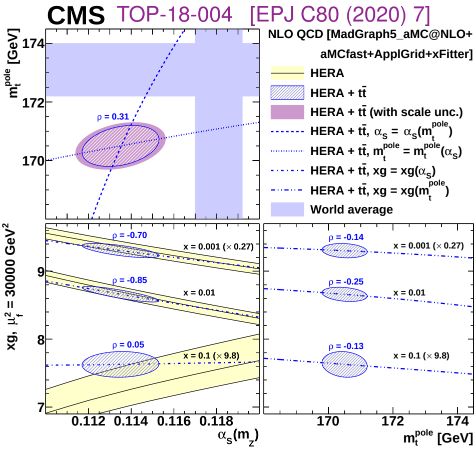


Why study $t\bar{t}$ production?



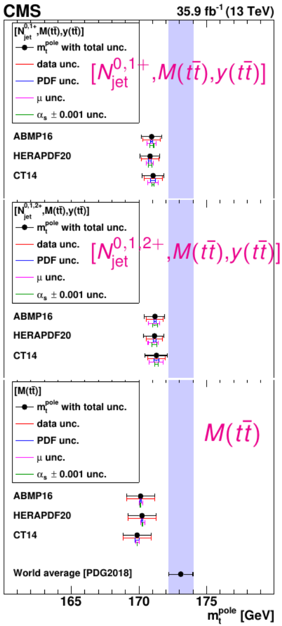
- m_t provides a hard scale
  $\Rightarrow$ ultimate probe of pQCD
  (NLO, aNNLO, NNLO, ...)
- Produced mainly via gg
  $\Rightarrow$ constrain gluon PDF at high x
- Production sensitive to α_s and m_t^{pole}
- May provide insight into possible new physics

Example:

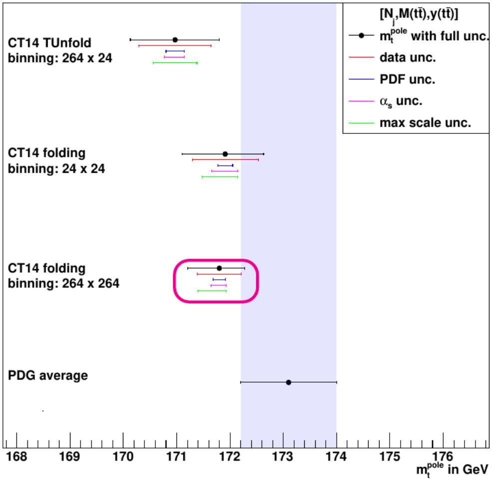


- Simultaneous extraction of PDFs, α_s, m_t^{pole} using normalised triple-differential cross sections at NLO
- Extended to $\overline{\text{MS}}$, MSR schemes in JHEP 04 (2021) 043 [Garzelli, Kemmler, Moch, Zenaiev]

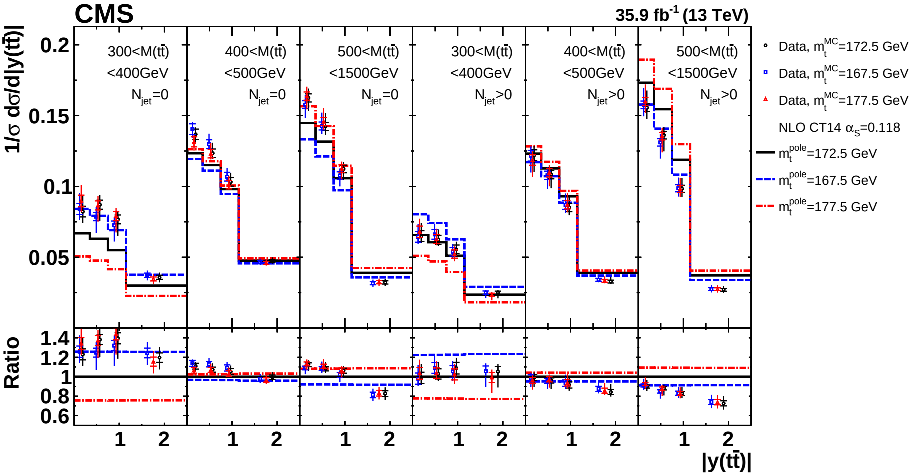
CMS TOP-18-004 checks



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]



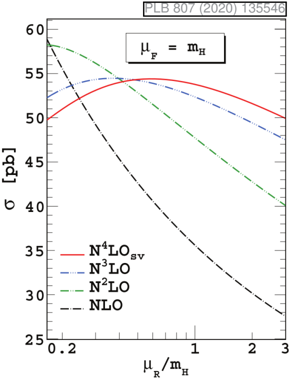
m_t dependence of measured cross sections [CMS TOP-18-004]



Higgs cross section with ABMPtt (contribution from Goutam Das)

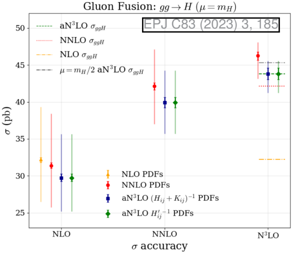
PDF Name	N2LO	N3LO	N4LOsv
ABMP16	$(45.4 \pm 4.6)^{+0.7}_{-0.7}$	$(49.6 \pm 2.6)^{+0.8}_{-0.8}$	$(50.8 \pm 1.9)^{+0.9}_{-0.9}$
ABMPtt	$(45.0 \pm 4.6)^{+0.6}_{-0.6}$	$(49.2 \pm 2.6)^{+0.7}_{-0.7}$	$(50.4 \pm 1.9)^{+0.8}_{-0.8}$
CT18NNLO	$(47.4 \pm 5.1)^{+1.3}_{-1.7}$	$(52.0 \pm 2.9)^{+1.4}_{-1.9}$	$(53.4 \pm 2.1)^{+1.5}_{-1.9}$
MMHT2014nnlo68cl	$(47.7 \pm 5.1)^{+0.6}_{-0.8}$	$(52.3 \pm 2.9)^{+0.7}_{-1.0}$	$(53.8 \pm 2.2)^{+0.7}_{-1.0}$
MSHT20nnlo_as118	$(47.4 \pm 5.1)^{+0.5}_{-0.6}$	$(52.0 \pm 2.9)^{+0.6}_{-0.6}$	$(53.4 \pm 2.1)^{+0.6}_{-0.6}$
NNPDF40_nnlo_as_01180	$(47.8 \pm 5.1)^{+0.3}_{-0.3}$	$(52.4 \pm 2.9)^{+0.3}_{-0.3}$	$(53.8 \pm 2.2)^{+0.3}_{-0.3}$
PDF4LHC21_40	$(47.6 \pm 5.1)^{+0.8}_{-0.8}$	$(52.3 \pm 2.9)^{+0.9}_{-0.9}$	$(53.7 \pm 2.2)^{+0.9}_{-0.9}$
MSHT20an3lo_as118	$(45.0 \pm 4.8)^{+0.8}_{-0.7}$	$(49.4 \pm 2.8)^{+0.9}_{-0.8}$	$(50.7 \pm 2.0)^{+0.9}_{-0.8}$

Table 1: Higgs cross-section along with the absolute error obtained from seven-point scale variation around $({\mu_R}^c, {\mu_F}^c) = (1,1)m_H$ as well as intrinsic PDF uncertainty using LHAPDF. $\sqrt{S} = 14$ TeV, α_S from LHAPDF (NNLO value).

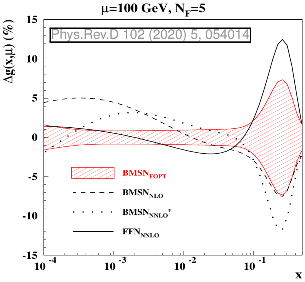


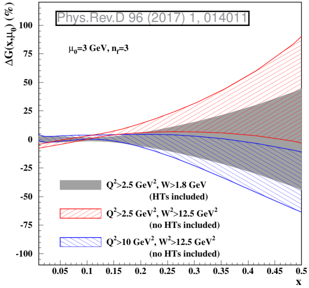
- Das, Moch, Vogt, Phys.Lett.B 807 (2020) 135546:
  - N4LOsv: soft virtual ggF corrections at 4 loops
  - N3LO: effective theory for $m_t \gg m_H$
  - N2LO: full theory for $m_H \lesssim m_t$
  - → apparent convergence of perturbative series (further details and predictions with $\mu/2$ in BACKUP)
- N4LOsv estimates missing higher-order corrections: 2%
- Larger differences originate from PDF and α_S sets:

  7% (1995) → 12% (2020) → **7% (2024)** (more in BACKUP)
- Expect smaller effect of NNLO→N3LO PDFs



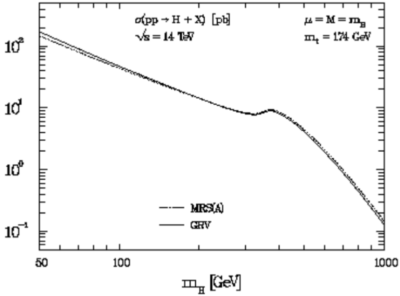
- Heavy-flavor PDF evolution and heavy flavour scheme for DIS
  Phys.Rev.D 102 (2020) 5, 054014
  - fixed-flavour number scheme in ABMP fits is accurate to NNLO for light and heavy quark production (exact or to the best available approximation) and works very well for HERA kinematics
  - CT, MSHT and NNPDF fits use different variable-flavour number schemes which miss some NNLO corrections for heavy quark production and have further theoretical uncertainties $\Rightarrow$ very relevant for LHC phenomenology
- Higher-twist (HT) corrections for DIS
  Phys.Rev.D 96 (2017) 1, 014011
  - ABMPtt/ABMP16 fits HT terms
  - other fits apply cuts to reduce HT: not sufficient
- Correlation between gluon PDF, α_S and m_t:
  - fully accounted for in ABMPtt/ABMP16
  - α_S and m_t are fixed in other fits
- **These issues need to be solved independently of switching to N^{3}LO evolution**





Higgs cross section (1995)

NLO QCD corrections



MRS(A): Martin, Roberts and Stirling, Phys. Rev. D50 (1994) 6734

GRV: Glück, Reya and Vogt, Z. Phys. C53 (1992) 127

One of the main uncertainties *in the prediction of the Higgs production cross section is due to the* **gluon density**. *[...] Adopting a set of representative parton distributions [...], we find a* **variation of about 7%** *between the maximum and minimum values of the cross section for Higgs masses above* $\sim$ *100 GeV.*

Spira, Djouadi, Graudenz, Zerwas (1995)
hep-ph/9504378

Higgs cross section (2020)

- Cross section $\sigma(H)$ at NNLO with uncertainties: $\sigma(H) + \Delta\sigma(\mathrm{PDF} + \alpha_s)$ for $m_H = 125.0$ GeV at $\sqrt{s} = 13$ TeV with $\mu_R, \mu_F = m_H$ and nominal α_s

PDF sets	$\sigma(H)^{\mathrm{NNLO}}$ [pb] nominal $\alpha_s(M_Z)$
ABMP16 Alekhin, Blümlein, S.M., Placakyte ‘17	40.20 ± 0.63
CJ15 Accardi, Brady, Melnitchouk et al. ‘16	$42.45\,^{+\,1.73}_{-\,1.12}$
CT18 Hou et al. ‘19	$42.06\,^{+\,1.16}_{-\,1.48}$
HERAPDF2.0 H1+Zeus Coll.	$42.62\,^{+\,0.35}_{-\,0.43}$
JR14 (dyn) Jimenez-Delgado, Reya ‘14	38.01 ± 0.34
MMHT14 Martin, Motylinski, Harland-Lang, Thorne ‘14	$42.36\,^{+\,0.56}_{-\,0.78}$
NNPDF3.1 Ball et al. ‘17	42.98 ± 0.40
PDF4LHC15 Butterworth et al. ‘15	42.42 ± 0.78

- Large spread for predictions from different PDFs $\sigma(H) = 38.0 \ldots 43.0$ pb
- PDF and α_s differences between sets amount to up to 12%
  - significantly larger than residual theory uncertainty due to $\mathrm{N^3LO}$ QCD and NLO electroweak corrections

Higgs cross section with $\mu/2$

PDF Name	N2LO	N3LO	N4LOsv
ABMP16	$(49.9 \pm 4.6)^{+0.8}_{-0.8}$	$(51.2 \pm 1.6)^{+0.9}_{-0.9}$	$(51.3 \pm 1.7)^{+0.9}_{-0.9}$
ABMPtt	$(49.6 \pm 4.6)^{+0.7}_{-0.7}$	$(50.8 \pm 1.6)^{+0.8}_{-0.8}$	$(50.9 \pm 1.7)^{+0.8}_{-0.8}$
CT18NNLO	$(52.3 \pm 5.1)^{+1.4}_{-1.9}$	$(53.8 \pm 1.9)^{+1.5}_{-2.0}$	$(53.9 \pm 2.0)^{+1.5}_{-2.0}$
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PDF4LHC21_40	$(52.7 \pm 5.1)^{+0.9}_{-0.9}$	$(54.1 \pm 1.9)^{+0.9}_{-0.9}$	$(54.2 \pm 2.1)^{+0.9}_{-0.9}$
MSHT20an3lo_as118	$(49.3 \pm 4.8)^{+0.9}_{-0.8}$	$(51.1 \pm 1.8)^{+1.0}_{-0.8}$	$(51.2 \pm 2.0)^{+1.0}_{-0.9}$

Table 2: Higgs cross-section along with the absolute error obtained from seven-point scale variation around $({\mu_R}^c, {\mu_F}^c) = (1/2, 1)m_H$ as well as intrinsic PDF uncertainty using LHAPDF. $\sqrt{S} = 14$ TeV, α_S from LHAPDF (NNLO value).

We keep the setting same as the Higgs paper: $\kappa_4 = 1/25000 \simeq 1/(4\pi)^4$, $\kappa_4\, g_{0,4} = 65 \pm 65$.

The predictions for the ggF cross sections at the collision energy of 14 TeV use a Higgs mass $m_H = 125$ GeV, an on-shell top quark mass $m_t = 172.5$ GeV, $n_f = 5$ active quark flavors and the PDF sets ABMP16 [**?**] and MMHT2014 [**?**] using the `lhapdf` [**?**] interface. The PDF sets and as well as the value of the strong coupling constant α_s corresponding to the respective PDF set are taken order-independent at NNLO throughout. The prefactor $C(\mu_R^2)$ in Eq. (**??**) is improved with the full top-mass dependence of the Born cross section. The results up to N^3LO are computed with the program *iHixs* [**?**] which directly provides the cross sections in this rescaled effective field theory.

The central scale choices ${\mu_R}^c = {\mu_F}^c = m_H$ and ${\mu_R}^c = m_H/2, {\mu_F}^c = m_H$. For $\sqrt{S} = 14$ TeV, ${m_H}^c = 125$ GeV, the central scale $\mu_R = m_H$, and including the PDF uncertainties at N^3LO.