

ABMPtt: updated ABMP16 PDFs with differential $t\bar{t}$ data and impact on predicted Higgs cross section

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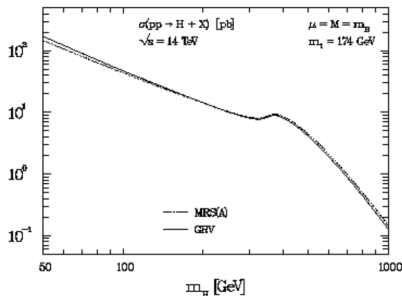
Garzelli, Mazzitelli, Moch, Zenaiev JHEP 05 (2024) 321 [arXiv:2311.05509]

Alekhin, Garzelli, Moch, Zenaiev 240X.XXXXX, to appear

ggF: aN3LO PDFs for Run3
26 Jun 2024

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 ~ 100 GeV.

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

Higgs cross section (2020)

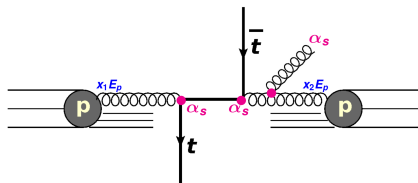
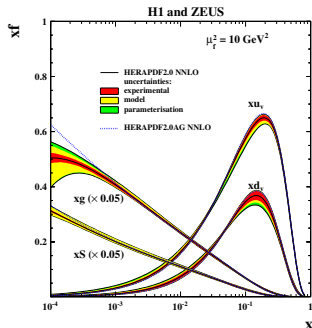
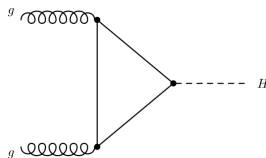
- Cross section $\sigma(H)$ at NNLO with uncertainties: $\sigma(H) + \Delta\sigma(\text{PDF} + \alpha_s)$ for $m_H = 125.0$ GeV at $\sqrt{s} = 13$ TeV with $\mu_R, \mu_F = m_H$ and nominal α_s

PDF sets	$\sigma(H)^{\text{NNLO}}$ [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 $\sigma(H) = 38.0 \dots 43.0$ pb
- PDF and α_s differences between sets amount to up to 12%
 - significantly larger than residual theory uncertainty due to N³LO QCD and NLO electroweak corrections

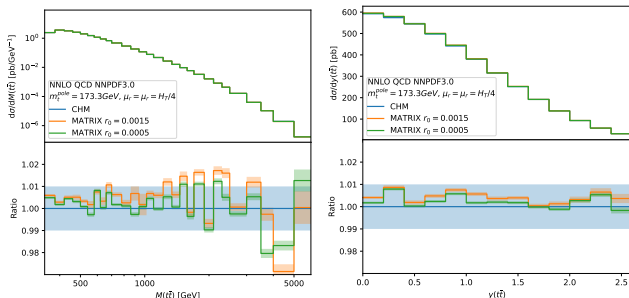
Importance of gluon PDF for predicting $pp \rightarrow H$

- $gg \rightarrow H$ is the largest Higgs production channel at LHC
- Parton distribution functions (PDFs) cannot be computed perturbatively and must be extracted from data: ep DIS, DY etc.
- Gluon PDF g is a challenge because it is not directly constrained by DIS data (backbone of PDF fits)
 - ▶ especially at large x
 - ▶ 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 : $x_{1,2} = (M(t\bar{t})/\sqrt{s}) \exp[\pm y(t\bar{t})]$



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

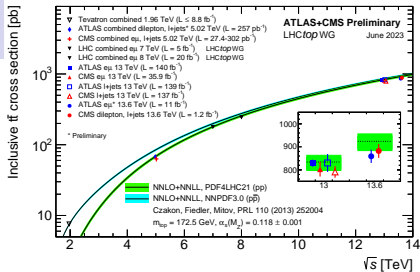


- We have interfaced MATRIX $t\bar{t}$ to PineAPPL interpolation library: **no NNLO/NLO K-factors**
- [\[Garzelli, Mazzitelli, Moch, Zenaiev JHEP 05 \(2024\) 321\]](#): extraction of m_t^{pole} from the total and differential $t\bar{t}$ data using different PDF sets
- [\[Alekhin, Garzelli, Moch, Zenaiev 240X.XXXXX, to appear\]](#): **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

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



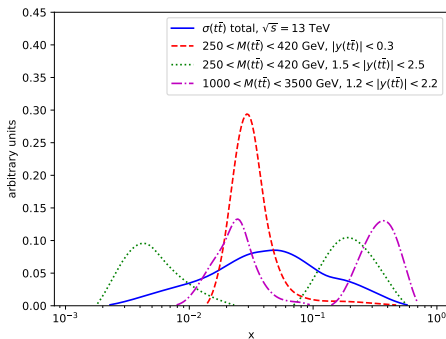
$$\frac{1}{\sigma(t\bar{t})} \frac{d\sigma(t\bar{t})}{d\mathcal{O}}$$

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

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

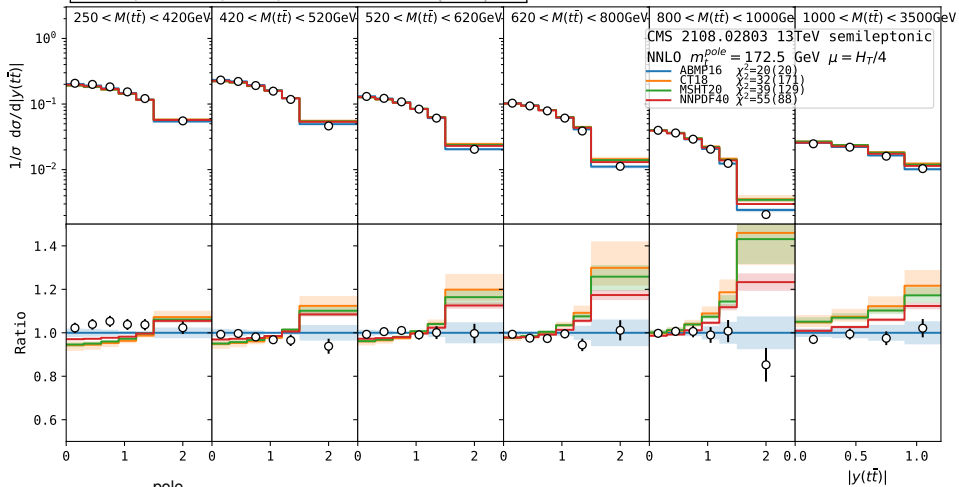
- Double-differential $t\bar{t}$ @ 13 TeV probes $0.002 \lesssim x \lesssim 0.7$
 - ▶ gg contributes $\approx 90\%$
- Higgs production probes $x \sim m_H/\sqrt{s} \sim 0.01$ which is well covered by $t\bar{t}$ data
- Energy scales m_H and m_t are also similar

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



Example: **CMS 2108.02803** vs NNLO predictions using different PDFs

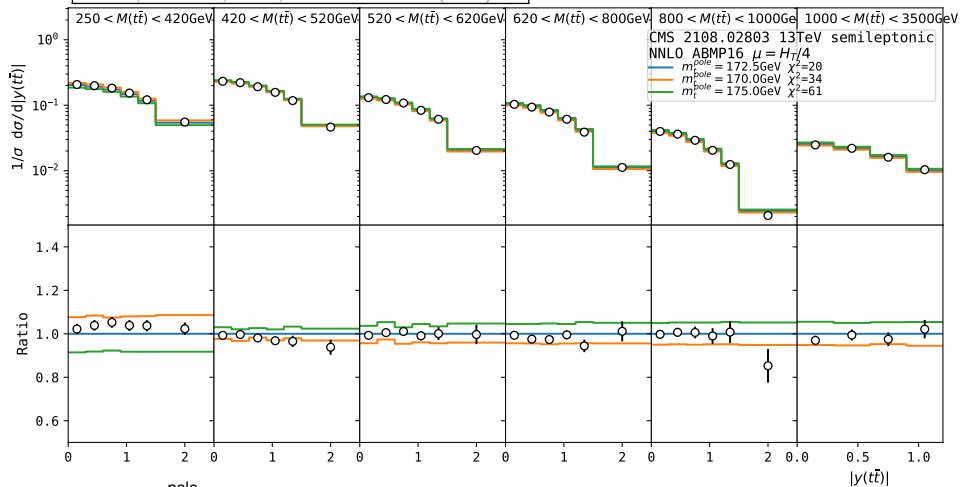
Garzelli, Mazzitelli, Moch, Zenaiev JHEP 05 (2024) 321



- Fixed $m_t^{\text{pole}} = 172.5 \text{ GeV}$ (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}

Garzelli, Mazzitelli, Moch, Zenaiev JHEP 05 (2024) 321



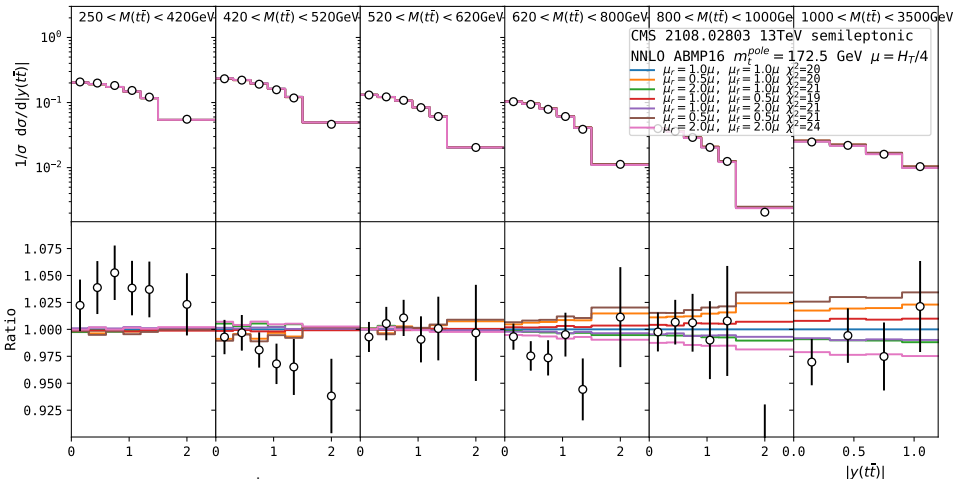
● NOTE: m_t^{pole} values on this plot are not the same as the ones obtained in ABMP16 fit ($m_t^{\text{pole}} = 170.4 \pm 1.2 \text{ GeV}$)

● 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

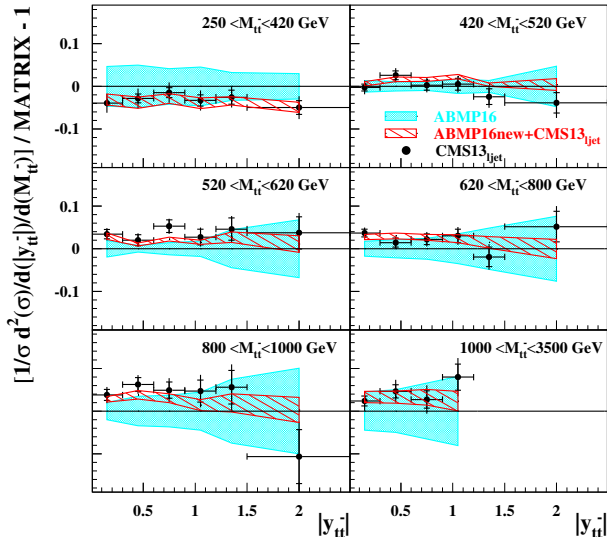
Example: **CMS 2108.02803** vs NNLO predictions: scale variations

Garzelli, Mazzitelli, Moch, Zenaiev JHEP 05 (2024) 321



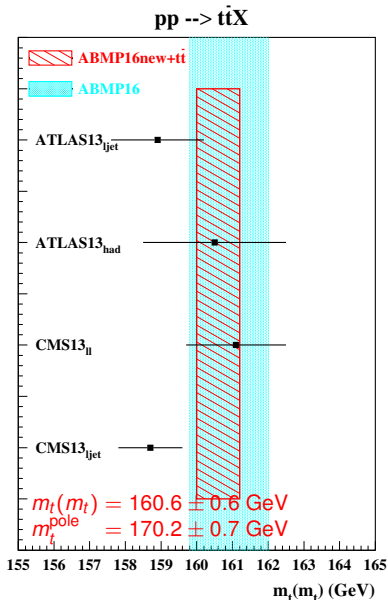
- ABMP16, fixed $m_t^{\text{pole}} = 172.5 \text{ GeV}$
 - Scale variations $< 1\%$ at low $M(t\bar{t})$ (largest cancellation), reach $\approx 4\%$ at high $M(t\bar{t})$
- these data are useful to provide constraints on m_t and PDFs

CMS ($\sqrt{s}=13$ TeV, 137 fb^{-1} , $pp \rightarrow ttX \rightarrow ljetX$) 2108.02803

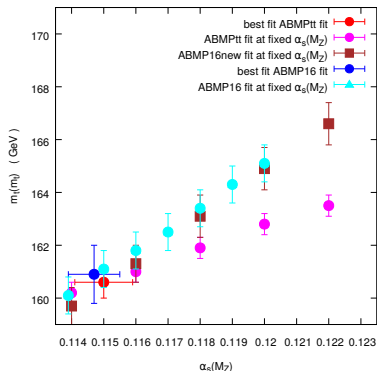


→ all data are in good agreement with NNLO theoretical predictions and put significant constraints on the PDFs
(other data sets in BACKUP)

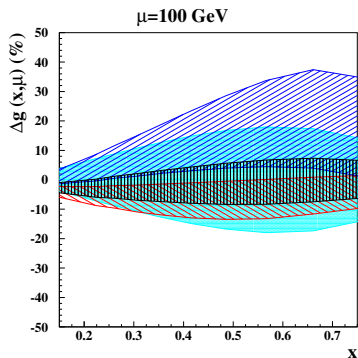
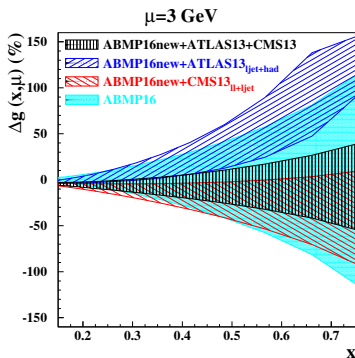
$m_t(m_t)$ and α_s in ABMP16 PDF fit



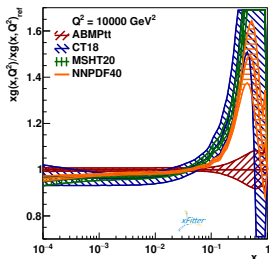
- Overall, good agreement between $m_t(m_t)$ extracted from different data sets
- Good agreement with ABMP16 fit and $\sim 50\%$ reduced uncertainty on $m_t(m_t)$
- ABMP16new: consistent with ABMP16, but with extra iteration for DY data
- Positive correlation between α_s and $m_t(m_t)$ reduced with $t\bar{t}$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



Higgs cross section with ABMPtt (contribution from Goutam Das)

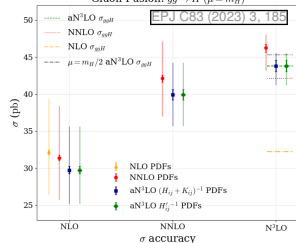
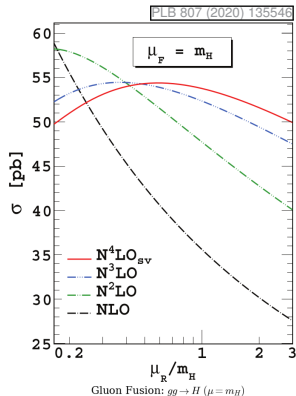
PDF Name	N2LO	N3LO	N4LOsv
ABMP16	$(45.4 \pm 4.6)^{+0.7}_{-0.7}$	$(49.6 \pm 2.6)^{+0.8}_{-0.8}$	$(50.8 \pm 1.9)^{+0.9}_{-0.9}$
ABMPtt	$(45.0 \pm 4.6)^{+0.6}_{-0.6}$	$(49.2 \pm 2.6)^{+0.7}_{-0.7}$	$(50.4 \pm 1.9)^{+0.8}_{-0.8}$
CT18NNLO	$(47.4 \pm 5.1)^{+1.3}_{-1.7}$	$(52.0 \pm 2.9)^{+1.4}_{-1.9}$	$(53.4 \pm 2.1)^{+1.5}_{-1.9}$
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)**
- Expect smaller effect of NNLO→N3LO PDFs (talk by Sven-Olaf Moch)
- Progress with other channels and EW corr. is also important: e.g. approximate NNLO for $t\bar{t}H$ [Catani et al., PRL 130 \(2023\) 11, 111902](#)



Some reasons for 7% difference

- 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

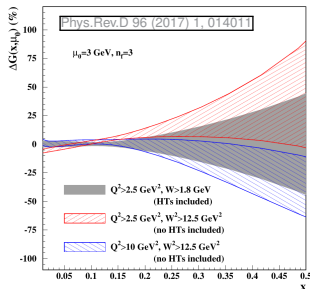
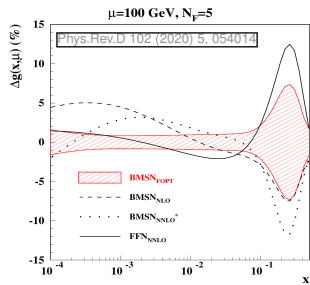
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- ▶ ABMPtt/ABMP16 fits HT terms
- ▶ other fits apply cuts to reduce HT: not sufficient

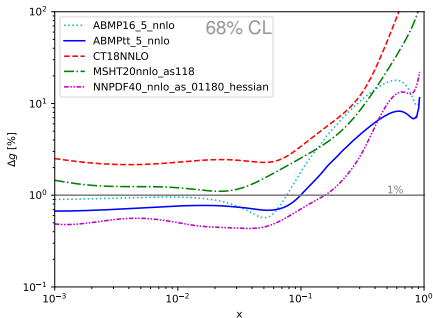
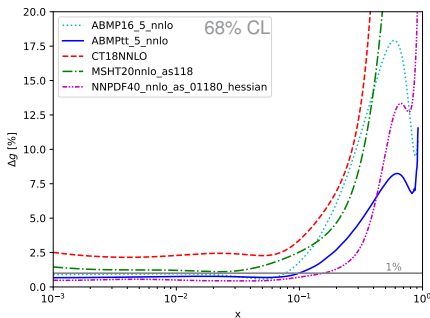
- Correlation between gluon PDF, α_S and m_t :

- ▶ 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**



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.)
- Predicted total Higgs x-section differs by 7% w.r.t most recent CT, MSHT, NNPDF (NNLO)
 - ▶ might be even larger difference for differential Higgs x-sections
- ABMPtt will appear soon [arXiv:240X.XXXXX] together with LHAPDF tables (ABMPtt_5_nnlo, ABMPtt_4_nnlo, ABMPtt_3_nnlo)

BACKUP

Higgs cross section with $\mu/2$

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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	$(49.3 \pm 4.8)^{+0.9}_{-0.8}$	$(51.1 \pm 1.8)^{+1.0}_{-0.8}$	$(51.2 \pm 2.0)^{+1.0}_{-0.9}$

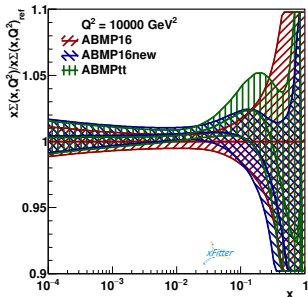
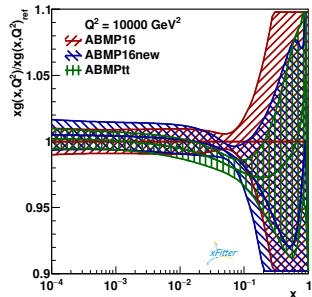
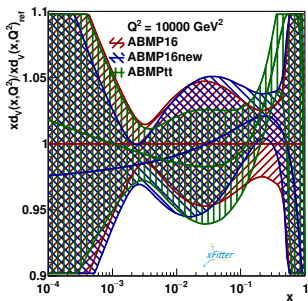
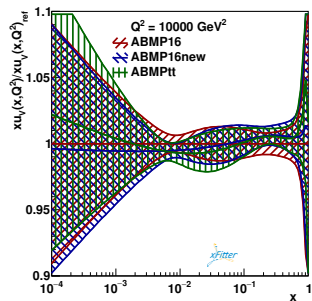
Table 2: Higgs cross-section along with the absolute error obtained from seven-point scale variation around $(\mu_R^c, \mu_F^c) = (1/2, 1)m_H$ as well as intrinsic PDF uncertainty using LHAPDF. $\sqrt{S} = 14$ TeV, α_S from LHAPDF (NNLO value).

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 `lhpdf` [?] 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 N³LO 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 N³LO.

ABMPtt vs ABMP16



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

Experiment	Process	Reference	NDP	χ^2
DIS				
HERA I+II	$e^+p \rightarrow e^+X$ $e^+p \rightarrow \bar{\nu}X$	[4]	1168	1510
BCDMS	$\mu^+p \rightarrow \mu^+X$	[61]	351	411
NMC	$\mu^+p \rightarrow \mu^+X$	[60]	245	343
SLAC-49a	$e^-p \rightarrow e^-X$	[54, 62]	38	59
SLAC-49b	$e^-p \rightarrow e^-X$	[54, 62]	154	171
SLAC-87	$e^-p \rightarrow e^-X$	[54, 62]	109	103
SLAC-89b	$e^-p \rightarrow e^-X$	[56, 62]	90	79

DIS heavy-quark production

HERA I+II	$e^+p \rightarrow e^+cX$	[63]	52	62
H1	$e^+p \rightarrow e^+bX$	[15]	12	5
ZEUS	$e^+p \rightarrow e^+bX$	[16]	17	16
CCFR	$\bar{\nu}p \rightarrow \mu^+cX$	[64]	89	62
CHORUS	$\nu p \rightarrow \mu^+cX$	[18]	6	7.6
NOMAD	$\nu p \rightarrow \mu^+cX$	[17]	48	59
NuTeV	$\bar{\nu}p \rightarrow \mu^+cX$	[64]	89	49

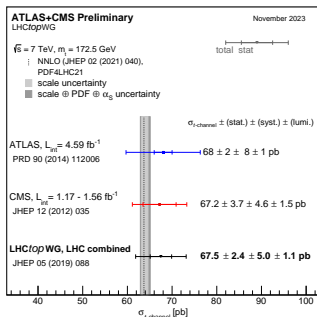
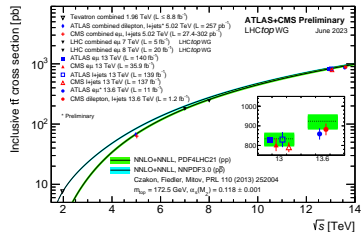
DY

FNAL-605	$pCu \rightarrow \mu^+\mu^-X$	[67]	119	165
FNAL-866	$pp \rightarrow \mu^+\mu^-X$ $pD \rightarrow \mu^+\mu^-X$	[68]	39	53

Top-quark production

ATLAS, CMS	$pp \rightarrow tqX$	[27, 32]	10	2.3
CDF&DØ	$\bar{p}p \rightarrow tbX$ $\bar{p}p \rightarrow tqX$	[53]	2	1.1
ATLAS, CMS	$pp \rightarrow t\bar{t}X$	[33, 52]	23	13
CDF&DØ	$\bar{p}p \rightarrow t\bar{t}X$	[53]	1	0.2

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



Data in ABMP16 fit [Alekhin et al., arXiv:1701:05838] (2)

Experiment	ATLAS		CMS		DØ		LHCb			
\sqrt{s} (TeV)	7	13	7	8	1.96		7	8		
Final states	$W^+ \rightarrow l^+ \nu$ $W^- \rightarrow l^- \nu$ $Z \rightarrow l^+ l^-$	$W^+ \rightarrow l^+ \nu$ $W^- \rightarrow l^- \nu$ $Z \rightarrow l^+ l^-$	$W^+ \rightarrow \mu^+ \nu$ $W^- \rightarrow \mu^- \nu$ (asym)	$W^+ \rightarrow \mu^+ \nu$ $W^- \rightarrow \mu^- \nu$	$W^+ \rightarrow \mu^+ \nu$ $W^- \rightarrow \mu^- \nu$ (asym)	$W^+ \rightarrow e^+ \nu$ $W^- \rightarrow e^- \nu$ (asym)	$W^+ \rightarrow \mu^+ \nu$ $W^- \rightarrow \mu^- \nu$ $Z \rightarrow \mu^+ \mu^-$	$Z \rightarrow e^+ e^-$	$W^+ \rightarrow \mu^+ \nu$ $W^- \rightarrow \mu^- \nu$ $Z \rightarrow \mu^+ \mu^-$	
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]	
<i>NDP</i>	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	<i>ATLAS</i> 13 _{ljet}	13	[25]	19	34.2	27.2	–
	<i>ATLAS</i> 13 _{had}	13	[26]	10	11.8	12.1	–
CMS	<i>CMS</i> 13 _{ll}	13	[24]	15	21.1	–	19.9
	<i>CMS</i> 13 _{ljet}	13	[22]	34	42.2	–	40.8

I: both ATLAS and CMS

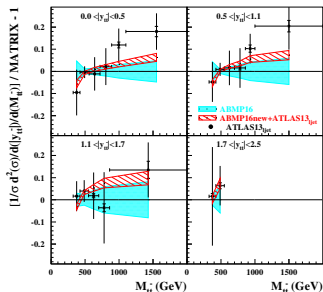
II: only ATLAS

III: only CMS

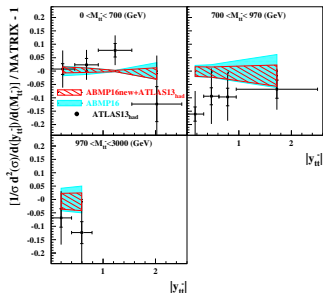
→ Overall good description of data by NNLO theoretical predictions, but some tension between ATLAS and CMS differential $t\bar{t}$ data is noticeable

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

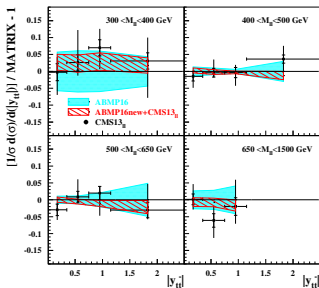
ATLAS ($\sqrt{s}=13$ TeV, 36 fb^{-1} , pp \rightarrow $t\bar{t}X$ \rightarrow $l\bar{t}X$) 1908.07305



ATLAS ($\sqrt{s}=13$ TeV, 36 fb^{-1} , pp \rightarrow $t\bar{t}X$ \rightarrow hadronsX) 2006.09274

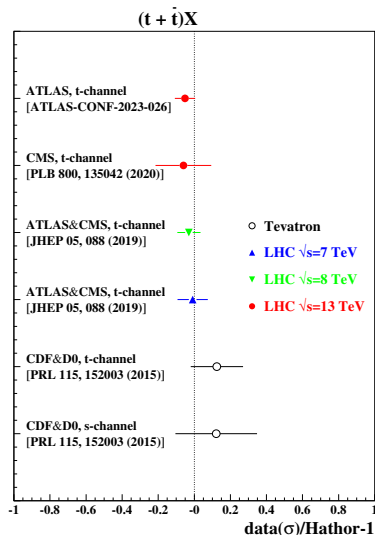
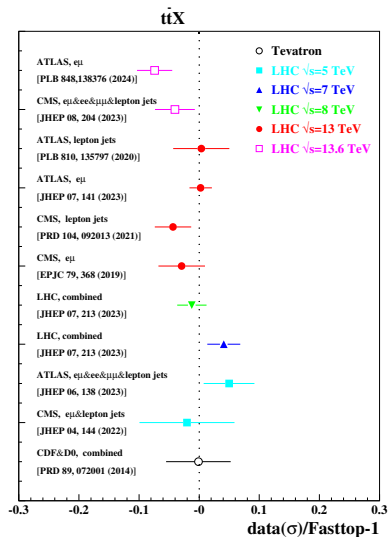


CMS ($\sqrt{s}=13$ TeV, 36 fb^{-1} , pp \rightarrow $t\bar{t}X$ \rightarrow $l^+\bar{l}X$) 1904.05237



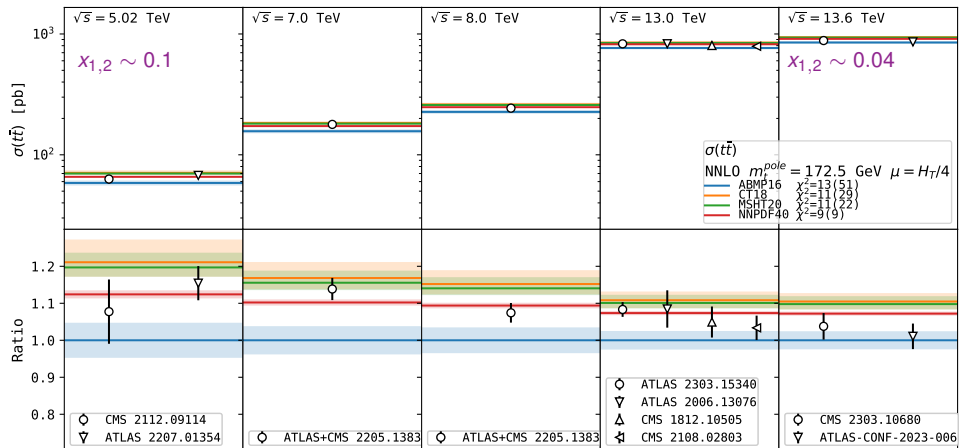
→ all data are in good agreement with NNLO theoretical predictions and put significant constraints on the PDFs

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



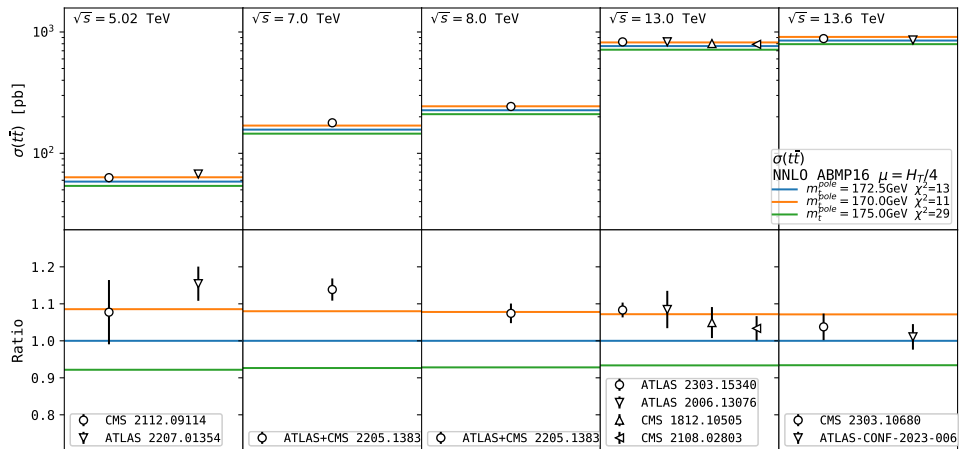
- good description of total $t\bar{t}$ and single t data
- single t data provide additional constraint on m_t (less correlated with g and α_S)

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



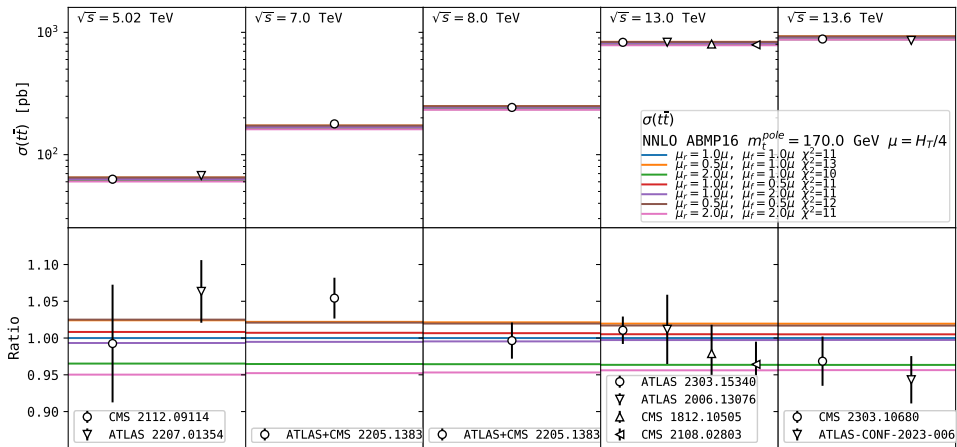
- Fixed $m_t^{\text{pole}} = 172.5$ GeV, $\mu_r = \mu_f = H_T/4$
- Reported χ^2 values with (and without) PDF uncertainties
- All PDF sets describe data reasonably well (depends on m_t^{pole} , α_S)
- Sensitivity to PDFs reduces with increasing \sqrt{s} (lower x probed)

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



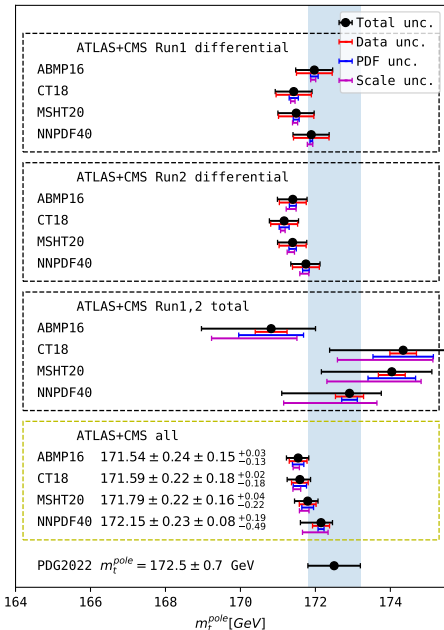
- ABMP16, fixed $\mu_r = \mu_f = H_T/4$
- Change of m_t^{pole} by 1 GeV \rightarrow change of $\sigma(t\bar{t})$ by $\approx 3\%$
- Preferable $m_t^{\text{pole}} \sim 170\text{--}172.5$ GeV (depends on PDF and α_S)

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

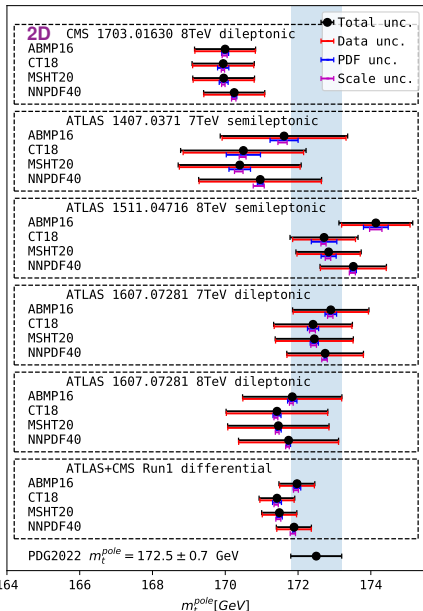
- ▶ 2D differential x-sections in $M(t\bar{t})$, $y(t\bar{t})$ constrain m_t^{pole} , PDFs and (indirectly) α_S
- ▶ ideally, 3D cross section in $M(t\bar{t})$, $y(t\bar{t})$ and number of extra jets constrain α_S directly, but NNLO not yet available for $t\bar{t}$ +jets

- Possible effects from Coulomb and soft-gluon resummation near the $t\bar{t}$ production threshold are neglected: might be ~ 1 GeV?

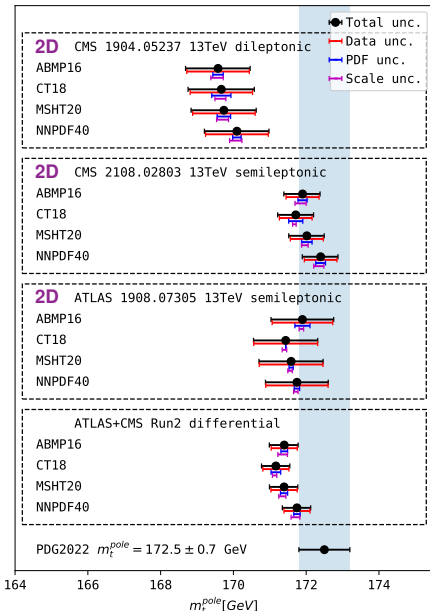
[CMS Coll. EPJ C80 (2020) 658; Kiyo, Kuhn, Moch, Steinhauser, Uwer EPJ C60 (2009) 375; Mäkelä, Hoang, Lipka, Moch 2301.03546]

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

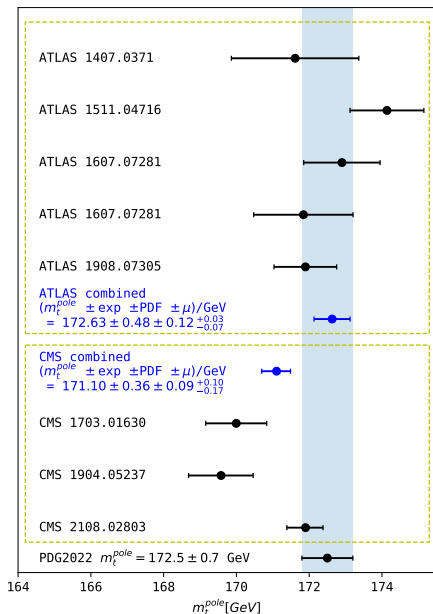
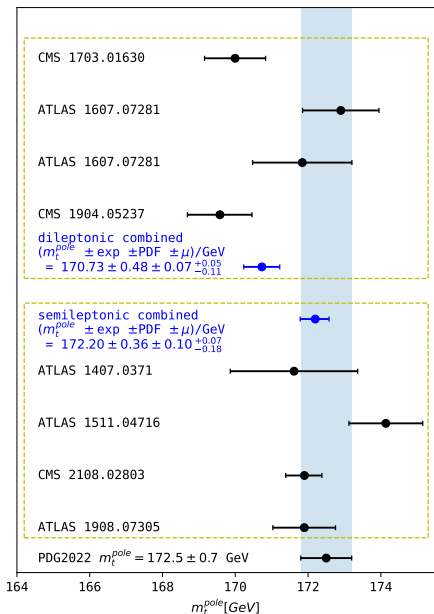
Run 1 differential



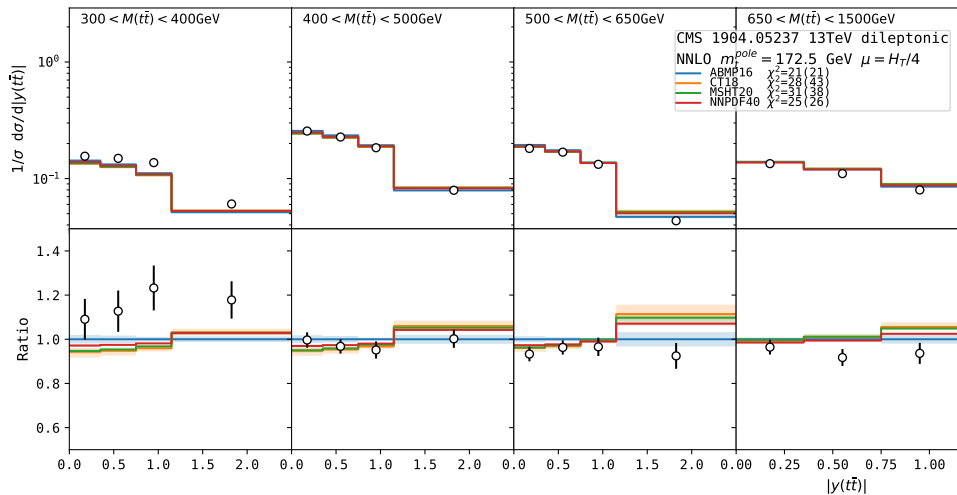
Run 2 differential



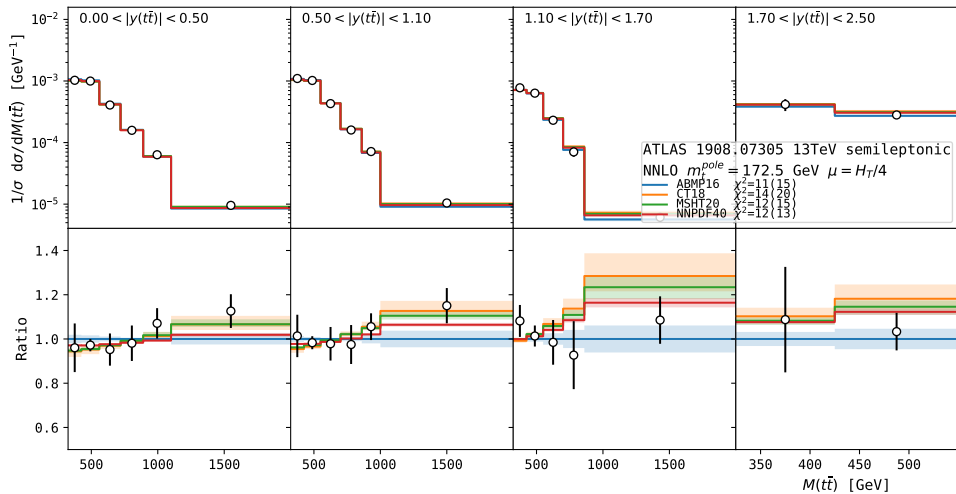
Extraction of m_t^{pole} : dilepton vs semileptonic, ATLAS vs CMS



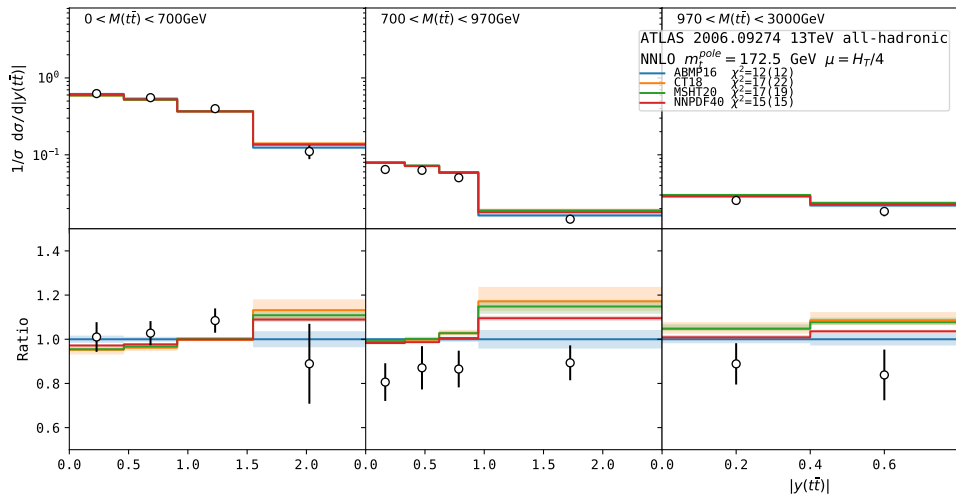
Data vs NNLO predictions using different PDFs



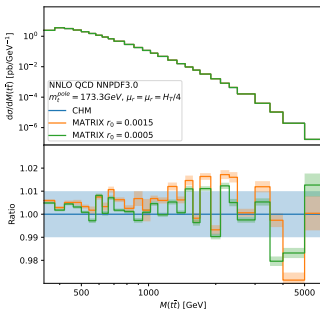
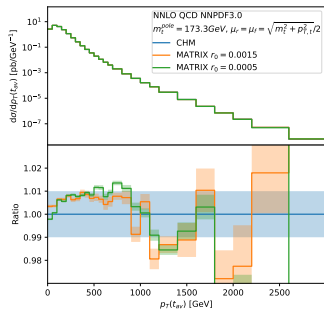
Data vs NNLO predictions using different PDFs



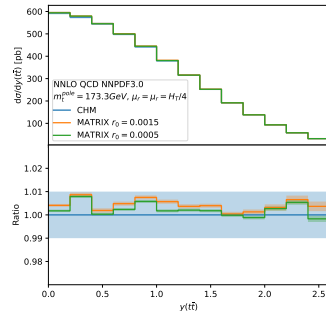
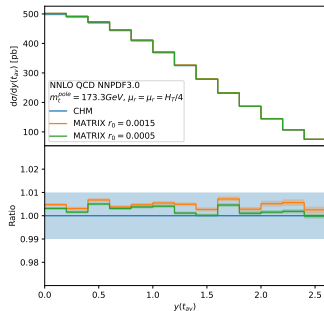
Data vs NNLO predictions using different PDFs



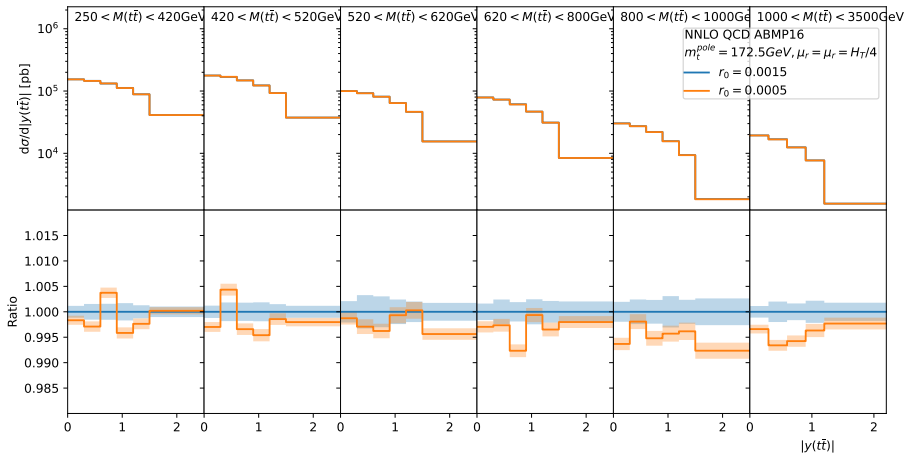
Variation of r cut, validation vs JHEP 04 (2017) 071 by Czakon et al. [CHM]



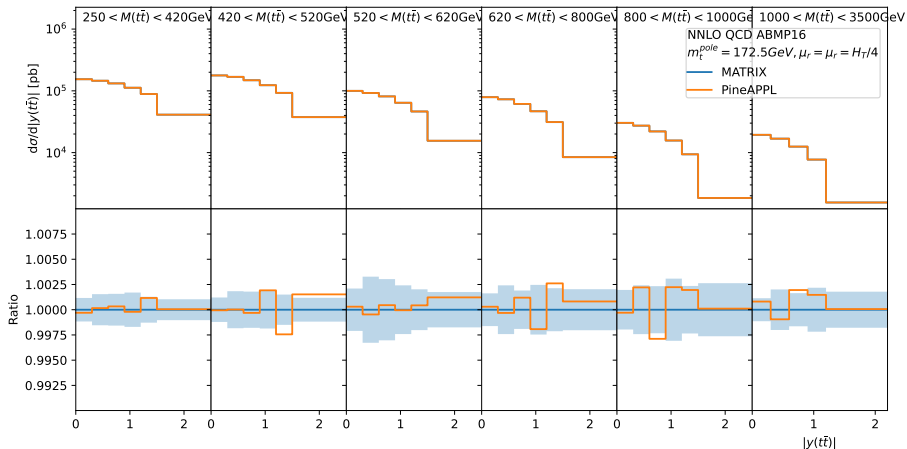
Good agreement < 1%



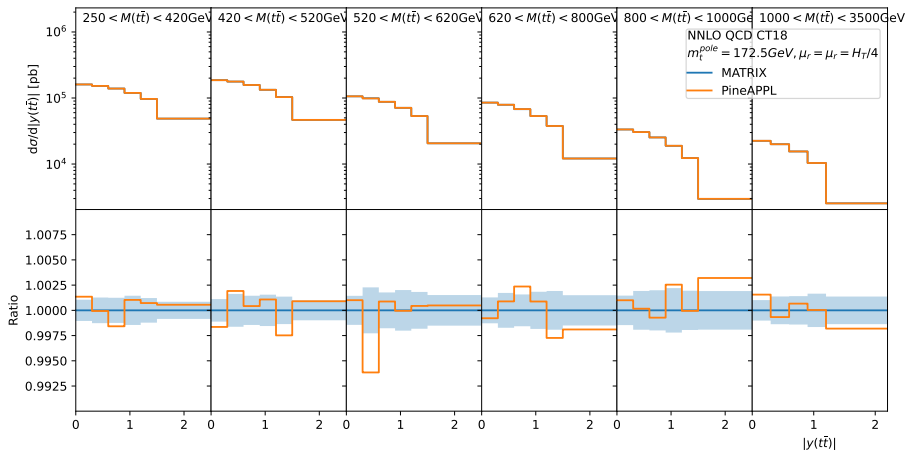
r cut variation in bins of TOP-20-001



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

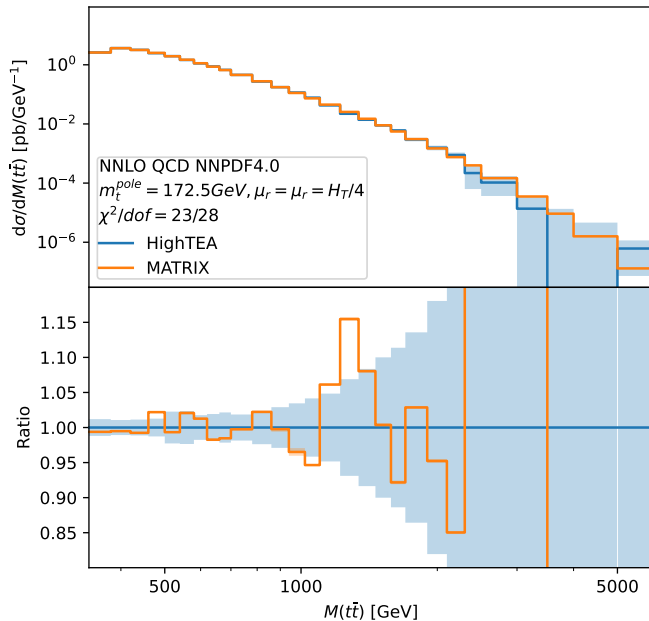


PineAPpl vs MATRIX in bins of TOP-20-001 [CT18]



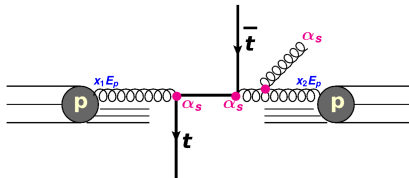
● grids were produced with ABMP16

MATRIX vs HighTEA

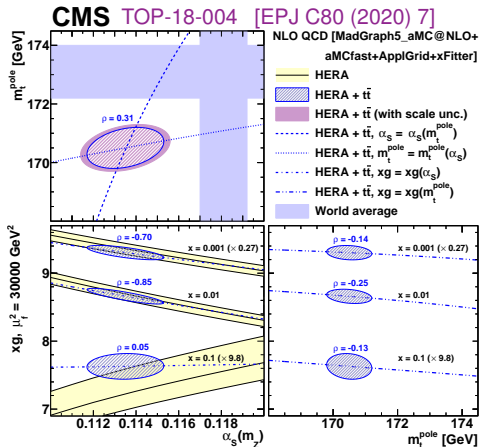


Example:

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

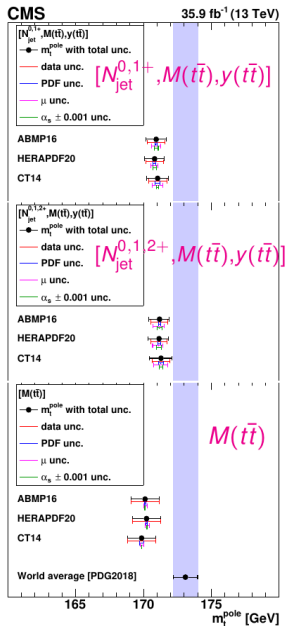


- m_t provides a hard scale
 \Rightarrow ultimate probe of pQCD
 (NLO, aNNLO, NNLO, ...)
- Produced mainly via gg
 \Rightarrow constrain gluon PDF at high x
- Production sensitive to α_s and m_t^{pole}
- May provide insight into possible new physics

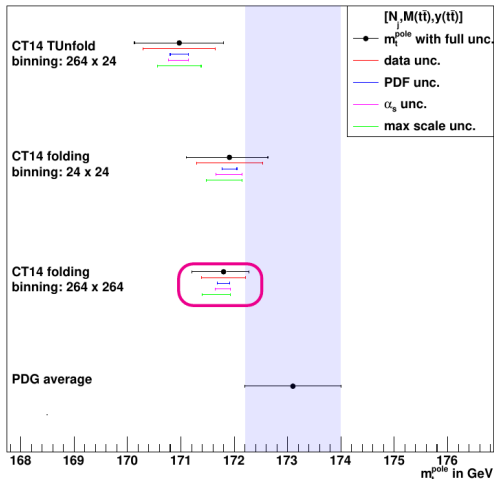


- Simultaneous extraction of PDFs, α_s , m_t^{pole} using normalised triple-differential cross sections at NLO
- Extended to $\overline{\text{MS}}$, MSR schemes in JHEP 04 (2021) 043 [Garzelli, Kemmler, Moch, Zenaiev]

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]

