NNLO PDFs driven by top-quark data

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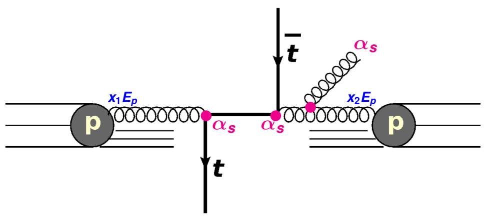
Mainly on the basis of [arXiv:2407.00545[hep-ph]]
and work in progress.

LHC Top WG meeting, November 11-13, 2024

Heavy-quark pair hadroproduction in QCD and fits of SM quantities



- m_t, $\alpha_s(M_Z)$, g, q and $\bar{q}$ PDFs are inputs for the computation of $pp \to t\bar{t} + X$ cross sections already at LO.
- m_t, q and $\bar{q}$ PDFs also appear in the computation of cross sections for single-top production at LO, whereas in the *s*- and *t*-channels the dependence on $\alpha_s(M_Z)$ and g PDFs appear only at higher orders.

$\Rightarrow$ If we want to use the cross-section data to extract PDFs, we have to take into account the correlations with m_t and $\alpha_s(M_Z)$ (unless one supposes to know already the values of m_t and $\alpha_s(M_Z)$, e.g. from independent measurements).

$\Rightarrow$ Simultaneous fits of PDFs, $m_t(m_t)$ and $\alpha_s(M_Z)$ have been performed:
- ABMP16, using total inclusive top data [S. Alekhin et al., PRD 96 (2017) 014011],
- ABMPtt, using multidifferential top data → this talk.

Main messages from the ABMPtt fit, including top-quark data

$*$ The precision of current top-quark LHC experimental data (full Run 2 + start of Run 3) has allowed to reduce our uncertainties on the g PDF at large x and on $m_t(m_t)$ w.r.t the baseline ABMP16 by a factor ~ 2, remaining consisting.

$*$ The use of $t\bar{t} + X$ multi-differential data is a key aspect in this respect.
It also allows to reduce the large correlations between $\alpha_s(M_Z)$ and $m_t(m_t)$.

$*$ To facilitate the fitting work, it is very important that the experimental collaborations provide normalized cross-section data and, as much as info as possible on correlations of the uncertainties within an analysis and between different analyses. We also encourage cross-calibrations and combinations of ATLAS and CMS results and of results of a same experiment into different decay channels.

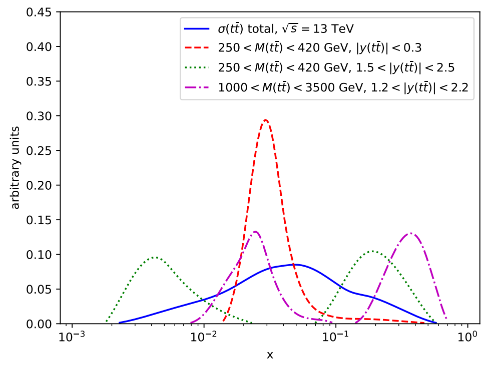
$*$ More studies, both at the experimental level and at the theory level, have to be done on single-top hadroproduction, to reduce the systematic uncertainties. This allows us to study flavour dependence of q PDFs and might be crucial, once the experimental uncertainties will be reduced, to further reduce the correlations between extracted values of $\alpha_s(M_Z)$ and $m_t(m_t)$.

$*$ PRELIMINARY: accomodating a photon in our PDFs (new fit in preparation: ABMPttγ) produces results consistent with those shown in the following.

x intervals probed by $t\bar{t} + X$ hadroproduction

- $pp \to t\bar{t} + X$ @ 13 TeV probes $0.002 \lesssim x \lesssim 0.7$
  - gg contributes $\approx 90\%$
- (double)-differential data probe different x subintervals
- in particular we consider distributions double-differential in $M(t\bar{t})$ and $y(t\bar{t})$.
- Scales m_H, M_W, M_Z and m_t are similar among each other
- Higgs production at the LHC probes $x \sim m_H/\sqrt{s} \sim 0.01$ which is well covered by differential $t\bar{t} + X$ data
- DY production at the LHC probes a similar region $x \sim m_{W,Z}/\sqrt{s}$
  - mostly sensitive to quark PDFs
  - helps with light flavor separation

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



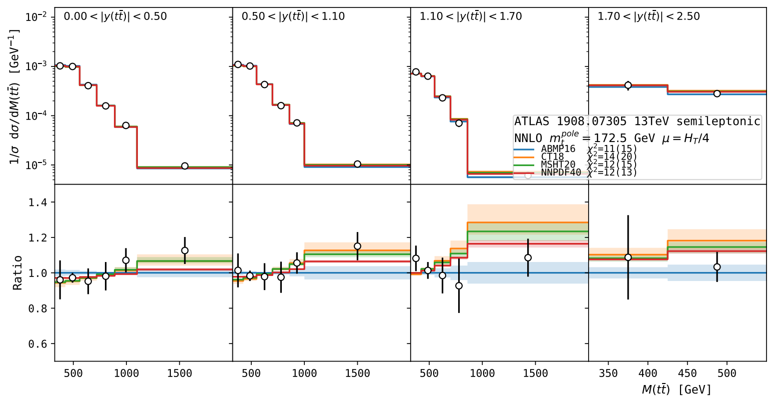
Our theory calculations with `MATRIX + PineAPPL` framework

- NNLO computations for total and multi-differential $pp \to t\bar{t} + X$ cross sections can now be performed thanks to the publicly available `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] , but no public code available. However, the `HighTEA` database [Czakon et al., arXiv:2304.05993] has recently appeared.
- We use private version of `MATRIX` [Grazzini, Kallweit, Wiesemann, EPJC 78 (2018) 537]
- Interfaced to `PineAPPL` [Carrazza at al., JHEP 12 (2020) 108] to produce interpolation grids which are further used in `xFitter` `https://gitlab.com/fitters/xfitter`
  - reproduce NNLO calculations using any PDF + $\alpha_s(M_Z)$ set and/or varied μ_r, μ_f in $\sim$ seconds
  - interface implemented privately and only for the $pp \to t\bar{t} + X$ process
- Further modifications to `MATRIX` to make possible runs with $\Delta\sigma_{t\bar{t}} < 0.1\%$
  - adapted to DESY Bird Condor cluster and local multicore machines
  - technical fixes related to memory and disk space usage, etc.
- We did runs with different m_t values with step of 2.5 GeV and $\Delta\sigma_{t\bar{t}} = 0.02\%$
  - $\approx$ 350000 CPU hours/run ($\sim$30 years on a single CPU)
  - for differential distributions, statistical uncertainties in bins are $\lesssim 0.5\%$
- $\mu_r = \mu_f = H_T/4$, $H_T = \sqrt{m_t^2 + p_T^2(t)} + \sqrt{m_t^2 + p_T^2(\bar{t})}$, varied up and down by factor 2 with $0.5 \leq \mu_r/\mu_f \leq 2$ (7-point variation)

ATLAS and CMS data used in this work

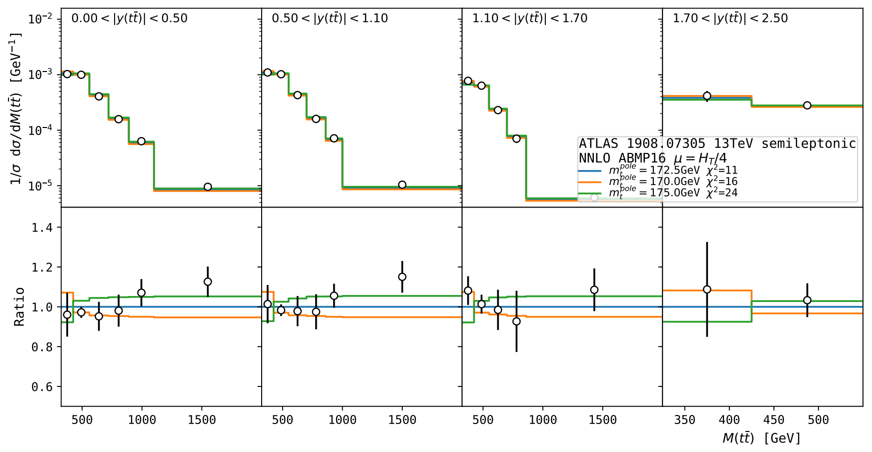
- We focus especially on measurements at 13 TeV where double-differential $M(t\bar{t})$, $y(t\bar{t})$ cross sections at parton level are available
  - **(1)** CMS EPJ C80 (2020) 658 [1904.05237, TOP-18-004]: 2D cross sections in dileptonic channel, $L = 35.9\ \mathrm{pb}^{-1}$
    - for 3D $M(t\bar{t})$, $y(t\bar{t})$, N_{jet} cross sections, NNLO is not available for $t\bar{t}$ + jets + X
  - **(2)** CMS Phys.Rev.D104 (2021) 9, 092013 [2108.02803, TOP-20-001]: 2D cross sections in l+jets channel, $L = 137\ \mathrm{pb}^{-1}$
  - **(3)** ATLAS EPJ C79 (2019) 1028 [1908.07305]: 2D cross sections in l+jets channel, $L = 36\ \mathrm{pb}^{-1}$
  - **(4)** ATLAS JHEP 01 (2021) 033 [2006.09274]: 2D cross sections in all-hadronic channel, $L = 36.1\ \mathrm{pb}^{-1}$
- For all measurements, we use normalised cross sections unfolded to the final-state parton level
- We use information on correlations of experimental uncertainties as provided in the paper (1) or in the HEPDATA database (2,3,4)
  - assumed no correlation between different measurements (reasonable assumption for normalised cross sections)
- it would be interesting to also add LHCb data (sensitivity to larger x and to m_t), but they are only available in the fiducial phase-space (cuts on leptons)
- Additionally, we use total inclusive $t\bar{t} + X$ and single-top cross-section data at all energies, according to summary plots by the LHC Top Working Group + Tevatron.

ATLAS 1908.07305 vs NNLO predictions using different PDFs



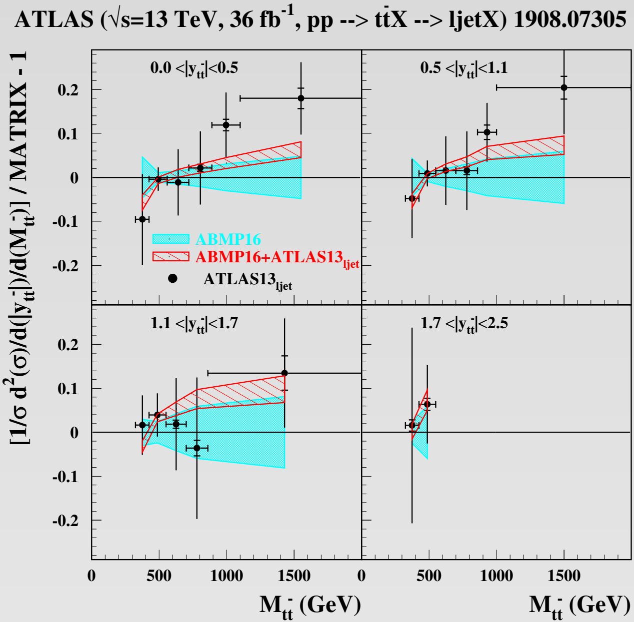
- Fixed $m_t^{\text{pole}} = 172.5$ GeV, $\mu_r = \mu_f = H_T/4$
- Reported χ^2 values with (and without) PDF uncertainties
- All PDF sets describe data equally well
- $\chi^2/\text{dof} < 1$ indicating possible overestimate of experimental uncertainties (additionally, the data covariance matrix is not singular, i.e. $\det(\text{cov}) \neq 0$: we suspect this is related to numerical inaccuracy of data stored in Hepdata. This affects estimates of correlated uncertainties. Same issue in the $\sqrt{s} = 8$TeV ATLAS analysis [arXiv:1607.07281].

ATLAS 1908.07305 vs NNLO predictions with ABMP16 and different m_t^{pole}



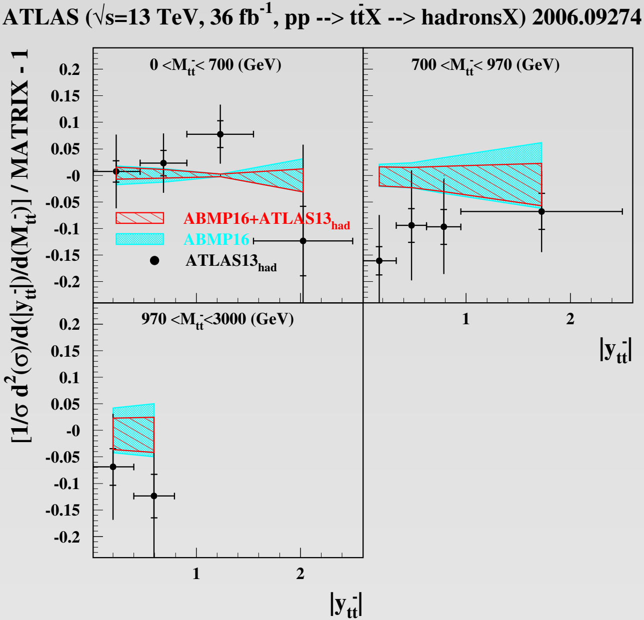
- Using ABMP16, $\mu_r = \mu_f = H_T/4$
- Reported χ^2 values with PDF uncertainties
- Large sensitivity to m_t^{pole} in the first $M(t\bar{t})$ bin (and even in other $M(t\bar{t})$ bins, thanks to cross section normalisation). The sensitivity does not increase with rapidity due to cross-section normalization.

Pulls of ATLAS 1908.07305 data with respect to ABMP predictions



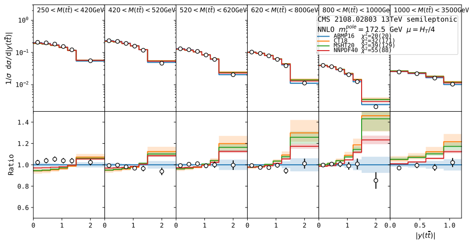
- ABMP PDF fit variant incorporating this specific dataset, w.r.t. already available ABMP16 PDF fit without it.
- ATLAS $\ell + j$ data tend to be larger than central theory predictions at large $M(t\bar{t}) \sim 1500$ GeV. But the data uncertainties are still large.
- ATLAS $\ell + j$ analysis with better statistics wanted.

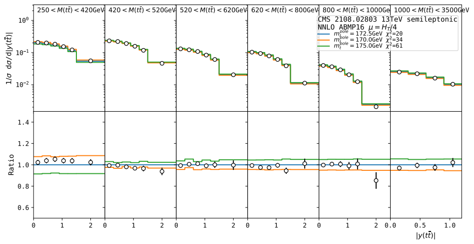
Pulls of ATLAS 2006.09274 data with respect to ABMP predictions



- ABMP PDF fit variant incorporating this specific dataset, w.r.t. already available ABMP16 PDF fit without it
- ATLAS hadronic data smaller than central theory predictions at large $M(t\bar{t})$.
- ATLAS $(\ell + j)$ data larger than central theory predictions at large $M(t\bar{t})$.

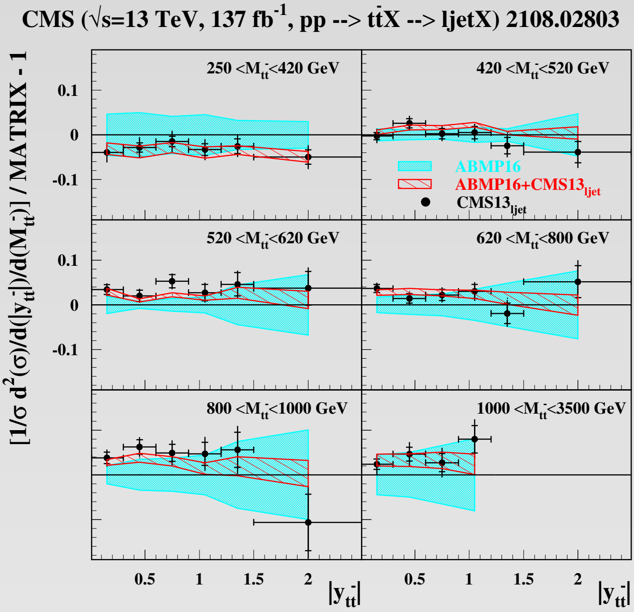
CMS TOP-20-001 vs NNLO predictions





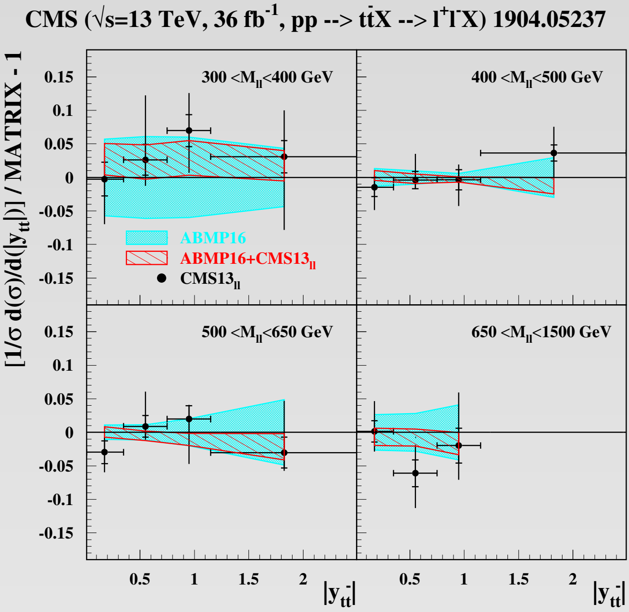
- $\mu_r = \mu_f = H_T/4$
- Reported χ^2 values with (and without) PDF uncertainties
- All PDF sets describe data reasonably well, with best description by ABMP16
  - CT18, MSHT20 and NNPDF40 show clear trend w.r.t data at high $y(t\bar{t})$ (large x)
- This is most precise currently available dataset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

Pulls of CMS TOP-20-001 data with respect to ABMP predictions



- ABMP PDF fit variant incorporating this specific dataset, w.r.t. already available ABMP16 PDF fit without it

Pulls of CMS TOP-18-004 data with respect to ABMP predictions



- ABMP PDF fit variant incorporating this specific dataset, w.r.t. already available ABMP16 PDF fit without it

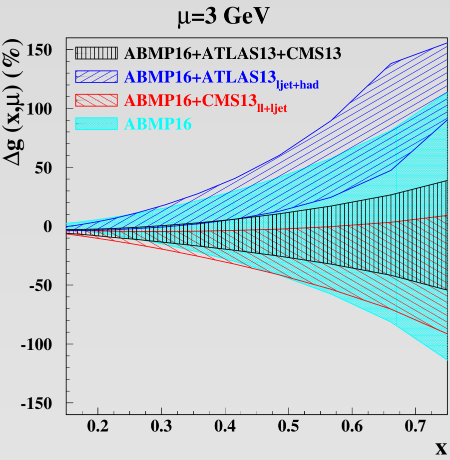
Partial χ^2 for variants of the new ABMP analysis including double-differential $t\bar{t} + X$ data at 13 TeV

Experiment	Dataset	$\sqrt{s}$ (TeV)	*NDP*	χ^2		
				I	II	III
ATLAS	ATLAS13_{ljet}	13	19	34.0	28.2	–
	ATLAS13_{had}	13	10	11.9	11.6	–
CMS	CMS13_{ll}	13	15	20.7	–	19.6
	CMS13_{ljet}	13	34	44.3	–	42.4

Table: The values of χ^2 obtained for various $t\bar{t} + X$ datasets included in the present analysis (column I: both ATLAS and CMS datasets; column II: only ATLAS ones; column III: only CMS ones).

- In comparison to the fit including both CMS datasets (III), the χ^2 slightly deteriorates when including also the datasets of the ATLAS analyses (I), but is still compatible within statistical uncertainties.
- In comparison to the fit including both ATLAS datasets (II), the χ^2 for the all-hadronic dataset remains compatible within statistical uncertainties when including also the datasets of the CMS analysis (I). Viceversa the χ^2 for the ATLAS $\ell + j$ dataset worsens. ⇒ Tension of the ATLAS $\ell + j$ dataset with all other datasets

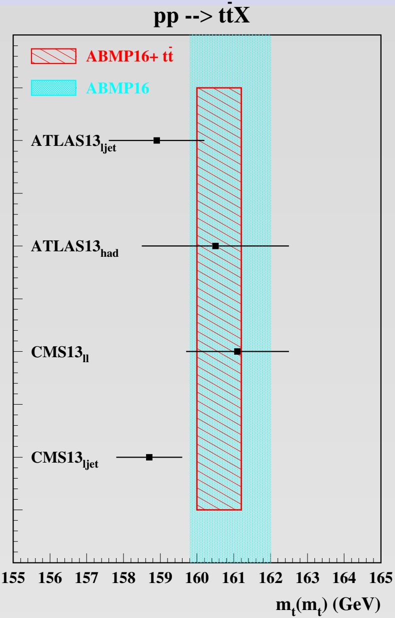
Extracted $g(x)$ in variants of the ABMP fit



- $g(x)$ at the starting scale $\mu = 3$ GeV.

- $g(x)$ in the new ABMP fit variants compatible with ABMP16 previous fit.
- uncertainties on $g(x)$ decreased by a factor ~ 2 w.r.t. ABMP16 previous fit.
- ATLAS and CMS data points towards opposite trends of $g(x)$ at large x. ATLAS prefers a larger $g(x)$, related to the fact that ATLAS $(\ell + j)$ data tend to be larger than theory predictions at large $M(t\bar{t}) \sim 1500$ GeV. Note that this trend is not visible for ATLAS hadronic data.
- fit including both ATLAS and CMS data dominated by the CMS $\ell + j$ differential data.
- Observe that new $m_t(m_t)$ and $\alpha_s(M_Z)$ values are extracted simultaneously. In particular, the smaller $g(x)$ of the “global” fit is accompanied by a smaller $m_t(m_t)$ value (see next slides).

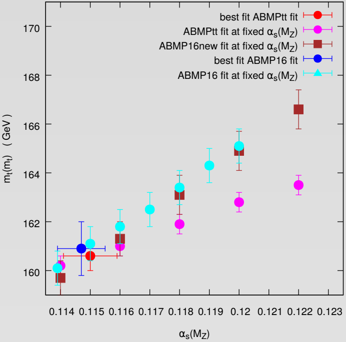
Extracted values of $m_t(m_t)$ in variants of the ABMP fit



- Legenda:
  Black: ABMP PDF fit variant incorporating a single specific dataset,
  light-blue: previous ABMP16 PDF fit,
  red: new ABMP PDF fit, incorporating all $t\bar{t} + X$ double-differential data at 13 TeV.

- Good compatibility of $m_t(m_t)$ extracted in the different variants of the fit.
- ATLAS hadronic data are too uncertain to play a constraining role on $m_t(m_t)$.
- New central value of $m_t(m_t)$ = 160.6 GeV slightly smaller than 160.9 GeV obtained in the previous ABMP16 fit, due to effect of the ATLAS and CMS $\ell + j$ differential data.
- Including all 13 TeV $t\bar{t} + X$ double-differential data allow to decrease by a factor 2 the uncertainty band on $m_t(m_t)$, varying from 1.1 GeV to 0.6 GeV.
- Observe that new PDFs and $\alpha_s(M_Z)$ values are extracted simultaneously.

Correlation between $m_t(m_t)$ and $\alpha_s(M_Z)$ in the new ABMP fit (vs. old ABMP16)

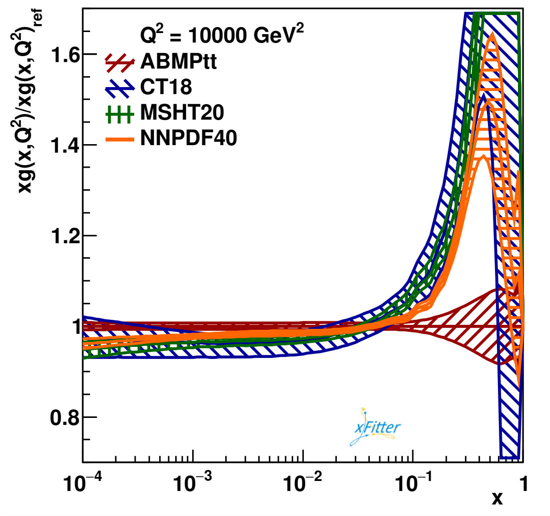


	$\alpha_s(M_Z, N_f = 5)$	$m_t(m_t)$ (GeV)
Fitted	0.1150(9)	160.6(6)
$\alpha_s(M_z)$ fixed	0.114	160.2(4)
	0.116	161.0(4)
	0.118	161.9(4)
	0.120	162.8(4)
	0.122	163.5(4)

Table: The values of $m_t(m_t)$ obtained with different values of α_s in the new ABMP fit.

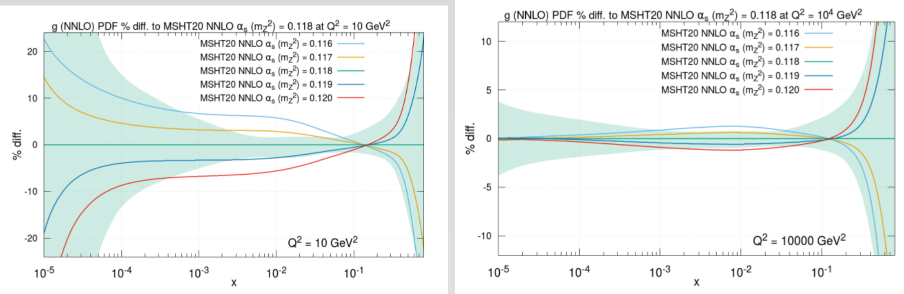
- Correlations between PDF $g(x)$, $\alpha_s(M_Z)$ and $m_t(m_t)$ follows from the factorization theorem.
- Fit of $m_t(m_t)$ at fixed $\alpha_s(M_Z)$ shows positive correlation between $\alpha_s(M_Z)$ value and $m_t(m_t)$.
- When including the $t\bar{t} + X$ differential data, the correlation coefficient decreases w.r.t. to the ABMP16 analysis, whereas the best-fit $\alpha_s(M_z)$ value remains approximately the same.
- With improved precision of data on single-top production in the t-channel, the impact of $\alpha_s(M_Z)$ on the m_t determination could be further leveled.

Extracted $g(x)$ in comparison with global PDF fits



$*$ Large differences at large x: Besides the effect of the $t\bar{t} + X$ data, these are due to different $\alpha_s(M_Z)$ treatment, heavy-flavour DIS scheme, etc.

PDF fits using as input different $\alpha_s(M_Z)$ values

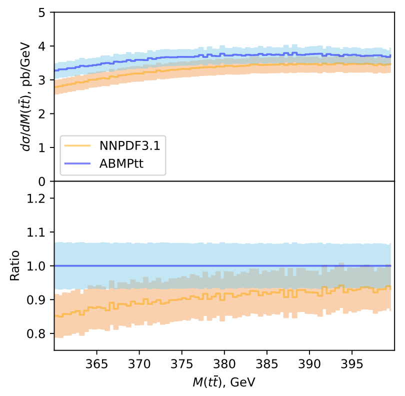


from T. Cridge et al., MSHT20, arXiv:2106.10289

$*$ Different $\alpha_s(M_Z)$ values as input play a large impact on the gluon at all x values, especially at small Q^2

$\Rightarrow$ If $\alpha_s(M_Z)$ in MSHT20 would be similar to the one in ABMP16, the $g(x)$ would also look more similar to the latter (at least in the region covered by $t\bar{t}$ data).

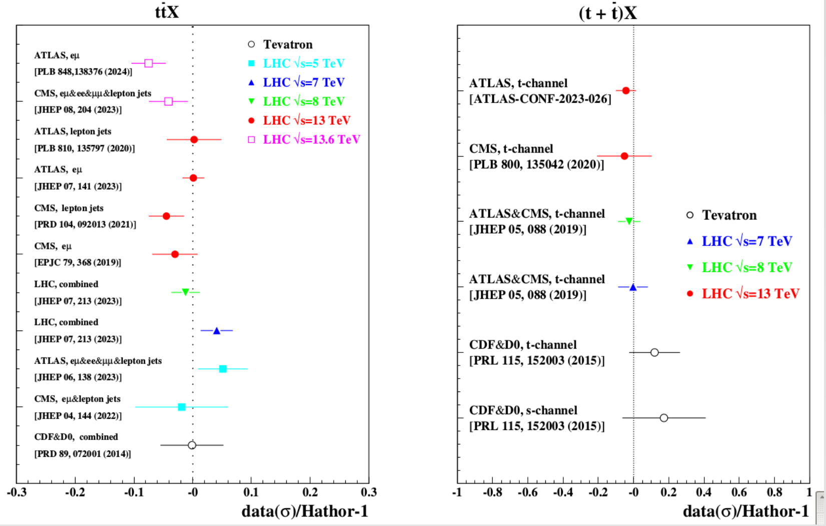
Application: NNLO inclusive M_{tt} distribution above threshold



$*$ NNLO predictions using ABMPtt PDFs + $\alpha_s(M_Z)$+ $m_t(m_t)$ vs. typical setup considered by experimental collaborations at $\sqrt{S} = 13$ TeV: NNPDF3.1 NNLO PDFs + $\alpha_s(M_Z)$, $m_t = 172.5$ GeV

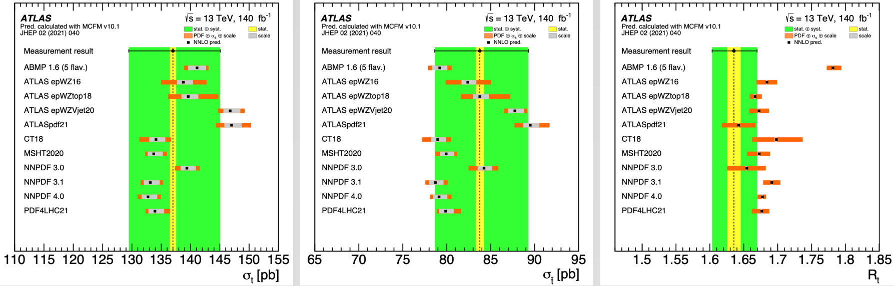
$*$ difference of 10-15% in the region of 360 GeV $< M_{t\bar{t}} <$ 400 GeV mostly probing $10^{-2} < x < 10^{-1}$, where scale uncertainties (shown in the plot) dominate with respect to PDF ones.

ABMPtt fit: agreement with total inclusive cross-section data



Good agreement with both $t\bar{t} + X$ and $(t + X)$ + $(\bar{t} + X)$ data (included in fit)

ATLAS $t+X$, $\bar{t}+X$ data and their ratio vs NNLO theory predictions



from ATLAS collaboration

$(t+X)$ mainly probes u distribution, $(\bar{t}+X)$ mainly probes d distribution.

Still under investigation:

- Why is ABMP16 performing quite badly w.r.t. the ATLAS ratio ?
  - Are the input PDFs, $\alpha_s(M_Z)$, m_t used in the ATLAS computations fully consistently ?
  - Are central R_t value and uncertainties on it computed correctly ? Why are they asymmetric ? Our predictions smaller by $0.02-0.03$.
  - Are systematic uncertainties well under control ?
  - Are there issues with the u and d-quark distributions from ABMP16 fit (related to e.g. target mass corrections) ?
- What is happening when using as input ABMPtt ?

CMS $\sigma(t+X)/\sigma(\bar{t}+X)$ data vs. NNLO theory predictions

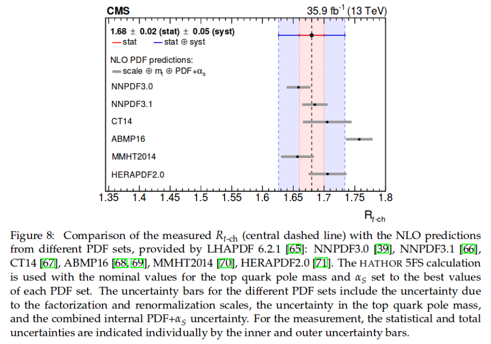


Figure 8: Comparison of the measured $R_{t\text{-ch}}$ (central dashed line) with the NLO predictions from different PDF sets, provided by LHAPDF 6.2.1 [65]: NNPDF3.0 [39], NNPDF3.1 [66], CT14 [67], ABMP16 [68, 69], MMHT2014 [70], HERAPDF2.0 [71]. The HATHOR 5FS calculation is used with the nominal values for the top quark pole mass and α_S set to the best values of each PDF set. The uncertainty bars for the different PDF sets include the uncertainty due to the factorization and renormalization scales, the uncertainty in the top quark pole mass, and the combined internal PDF+α_S uncertainty. For the measurement, the statistical and total uncertainties are indicated individually by the inner and outer uncertainty bars.

from CMS collaboration, [arXiv:1812.10514] PLB 800 (2020) 135042

- CMS ratio R_t shifted towards higher values (1.68 ± 0.05) with respect to the ATLAS case (1.635 ± 0.035).
  $\Rightarrow$ The disagreement with ABMP16 is less important, but still present.
- Smaller integrated luminosity.
- Our predictions: $R_t(\mathrm{ABMP16}) = 1.747 \pm 0.017$, $R_t(\mathrm{AMBPtt}) = 1.738 \pm 0.016$, almost insensitive to m_t value (uncertainty from PDF only).

Photon in fits

Knowing γ content of p is increasingly important at increasing higher orders.
Two approaches have been considered so far:

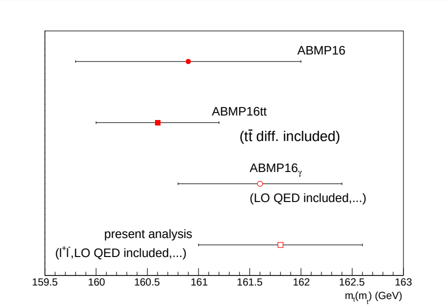
- γ according to the LUXQed approach
    - implemented in most modern PDF fits (MSHT, NNPDF),
      basically following the guidelines in the LUXQed papers, with some variations. Photon distributions are computed by first principles, however relying on assumptions on the proton structure functions down to low scales Q^2 and/or low hadronic invariant mass W^2 and on elastic contributions

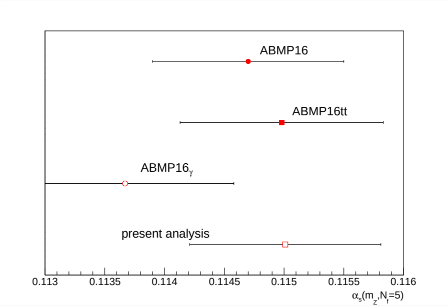
- γ treated similarly to partons
    - photon distribution parameterized at a low scale and then evolved
    - initial condition fixed at such a scale (difficult to establish, because the available experimental data are hardly constraining photons at low scales).
    - photon evolves with standard evolution equations (resummation effects included)
    - approach used in “old” PDFs (i.e. PDF fits before the LUXQed approach was introduced)

We are considering both of them in the ABMP framework.
Selected preliminary results:

- $m_t(m_t)$, $\alpha_s(M_Z)$ in variants of ABMP16 including γ distribution (and various datasets, but not yet single-top and $t\bar{t}$ double-differential data).
- Performances of the ABMPttγ fit, incorporating also all top data as ABMPtt, in comparison to the ABMPtt case.

$m_t(m_t)$ and $\alpha_s(M_Z)$ in variants of ABMP fits (partly preliminary)





$*$ ABMPγ include same data as ABMP16 (except single-top), but adds photon generated perturbatively.

$*$ “present analysis”, besides photon, adds non-resonant DY data. It also adds 2018 combined HERA b, c DIS data.

$*$ $m_t(m_t)$ values from the four variants all compatible among each other within uncertainties: also true for $m_b(m_b)$ and $m_c(m_c)$

$*$ the $t\bar{t}+X$ differential data play a crucial role in reducing the uncertainties on $m_t(m_t)$, while playing no role on $\alpha_s(M_Z)$.

Preliminary: the ABMPttγ fit

Experiment	Dataset	$\sqrt{s}$ (TeV)	*NDP*	χ^2	
				ABMPtt	ABMPttγ
ATLAS	$ATLAS13_{ljet}$	13	19	34.0	32.9
	$ATLAS13_{had}$	13	10	11.9	12.4
CMS	$CMS13_{ll}$	13	15	20.7	22.7
	$CMS13_{ljet}$	13	34	44.3	36.3

Table: The values of χ^2 obtained for various $t\bar{t} + X$ datasets included in the present ABMPtt and ABMPttγ analyses

$*$ The fit including photons (ABMPttγ) allows to accomodate the $t\bar{t} + X$ normalized double-differential ATLAS data with χ^2 values within statistical uncertainties of the case of the fit without photons (ABMPtt).

$*$ For the CMS $\ell + j$ analysis the χ^2 turns out to improve in the fit including photons.

Conclusions from the ABMPtt/ABMPttγ studies

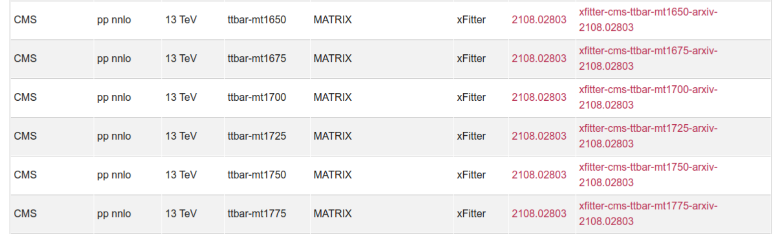
- Double-differential $M(t\bar{t})$, $y(t\bar{t})$ cross sections included in the ABMPtt PDF + $\alpha_s(M_Z)$ + $m_t(m_t)$ fit make it possible to reduce gluon PDF uncertainties at large x and $m_t(m_t)$ uncertainties by a factor ~ 2 with respect to ABMP16 fit, retaining consistency, with no impact on the $\alpha_s(M_Z)$ value and uncertainty.
- $m_t(m_t)$ fitted value from different variants of the fit agree among each other within uncertainties.
- correlations between $m_t(m_t)$ and $\alpha_s(M_Z)$ reduced by the inclusion of double-differential data in the fit w.r.t. to the case of total cross sections, where the effects of correlations are much larger.
- ATLAS $(\ell + \mathrm{j})$ data characterized by the worst theory description, in tension with all other data. A new ATLAS $(\ell + \mathrm{j})$ analysis producing normalized double-differential distributions with larger statistics (full Run 2 statistics) is needed.
- We encourage combinations of ATLAS and CMS data and unfolding to parton-level by LHCb.
- Single top production is still an open problem: discrepancy with ATLAS data on ratio of $(t + X)$ and $(\bar{t} + X)$ cross sections is due to issues in our d and u quark distributions, to issues in theory predictions, or to experimental systematics ?
- Accomodating a photon in the ABMP16/ABMPtt fits and LHC non-resonant dilepton data does not create tensions with the top-quark data.

Publicly available: grids for NNLO predictions of $t\bar{t} + X$ at the LHC

- We have made public the grids of NNLO QCD predictions we obtained from the `MATRIX + PineAPPL` framework, to facilitate their public use.

  We use the `Ploughshare` web-based utility for the automated distribution of fast interpolation grids for HEP:
  https://ploughshare.web.cern.ch/ploughshare/

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



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

Each .tgz file, using as input a different m_t value, includes:
– grid for double-differential distributions (Run 2) ($\sim$ 1000 MB)
– grid for single-differential distributions (Run 1) ($\sim$ 250 MB)
– grid for total cross sections ($\sim$ 5 MB)
– json file with information on the input used to generate the grids and citations.

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

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

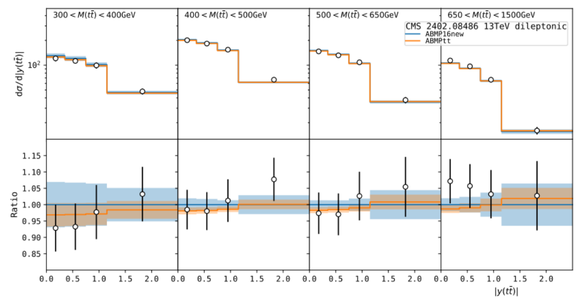
Publicly available

- ABMPtt PDFs in LHAPDF format are available on the web under:
  - `https://lhapdf.hepforge.org/pdfsets.html`

  ABMPtt_3_nnlo: 43500, ABMPtt_4_nnlo: 43530, ABMPtt_5_nnlo: 43560

  Thanks to the support of the LHAPDF team

- Example of predictions one can build from publicly available PDFs and grids:



Comparison of ABMPtt predictions with most recent CMS recent $t\bar{t} + X$ data [arXiv:2402.08486], not yet in the fit. How will the fit perform w.r.t. new ATLAS data ?

Thank you for your attention!

BACKUP

Theory framework for $t\bar{t} + X$ hadroproduction

- NNLO computations for total inclusive $pp \to t\bar{t} + X$ cross sections can be obtained with theory tools already publicly available since long (`HATHOR`, `Fasttop`, `Top++`).

- NNLO computations for total and multi-differential $pp \to t\bar{t} + X$ cross sections can now be performed thanks to the publicly available `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] , but no public code available. However, the `HighTEA` database [Czakon et al., arXiv:2304.05993] has recently appeared.

- Master formula for $t\bar{t} + X$ hadroproduction in `MATRIX`:

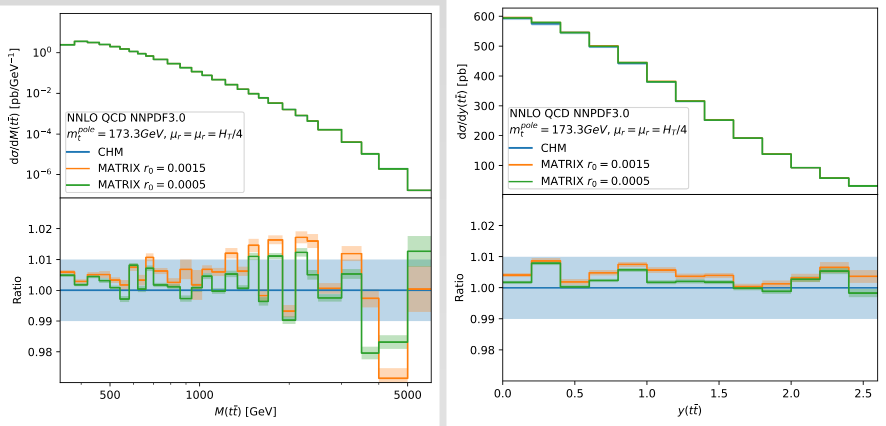
$$d\sigma^{t\bar{t}}_{(N)NLO} = \mathcal{H}^{t\bar{t}}_{(N)NLO} \otimes d\sigma^{t\bar{t}}_{LO} + \left[d\sigma^{t\bar{t}+jet}_{(N)LO} - d\sigma^{t\bar{t},CT}_{(N)NLO} \right]$$

$*$ based on q_T-subtraction for cancelling IR divergences, where $\vec{q}_T = \vec{p}_{t,T} + \vec{p}_{\bar{t},T}$, $\vec{q}_T = 0$ at LO.

$*$ $d\sigma^{t\bar{t}+jet}_{(N)LO}$ is IR divergent for $q_T \to 0$ The counterterm $d\sigma^{t\bar{t},CT}_{(N)NLO}$ compensating for the divergence is known from the fixed-order expansion of the resummation formula of the logarithmic contributions of the form $\alpha_s^{n+2}(1/q_T^2) ln^k(M^2_{t\bar{t}}/q_T^2)$ affecting the q_T distribution, which are large in the limit $q_T \to 0$. $\Rightarrow$ The square bracket is finite for $q_T \to 0$.

$*$ in practice the calculation is performed by introducing cuts in $r = q_T/M$, with $r_{cut} \in [0.01\%, r_{max}]$ with r_{max} varying between 0.5% and 1%.

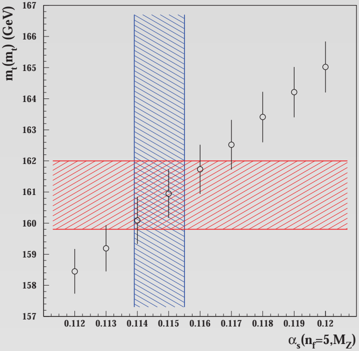
Predictions for differential distributions with different r_{cut} values



- ∗ In principle, the q_T-subtraction-based computation of (differential) cross-sections for finite r_{cut} introduces power corrections, which vanish in the limit $r_{cut} \to 0$.
- ∗ In practice, good agreement with the exact calculation (local) by Czakon, Heymes, Mitov (CHM) (at least considering their quoted 1% uncertainty).

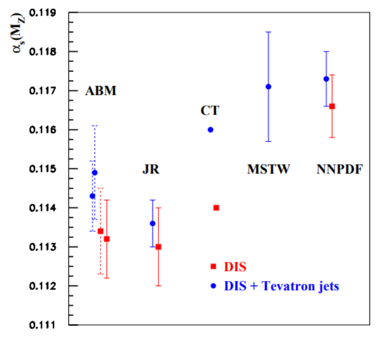
Correlation between $m_t(m_t)$ and $\alpha_s(M_Z)$ in the old ABMP16 fit

from ABMP16 fit



- Correlations between PDF $g(x)$, $\alpha_s(M_Z)$ and $m_t(m_t)$ follows from the factorization theorem.
- Fit of $m_t(m_t)$ at fixed $\alpha_s(M_Z)$ shows positive correlation between $\alpha_s(M_Z)$ value and $m_t(m_t)$.

$\alpha_s(M_z)$



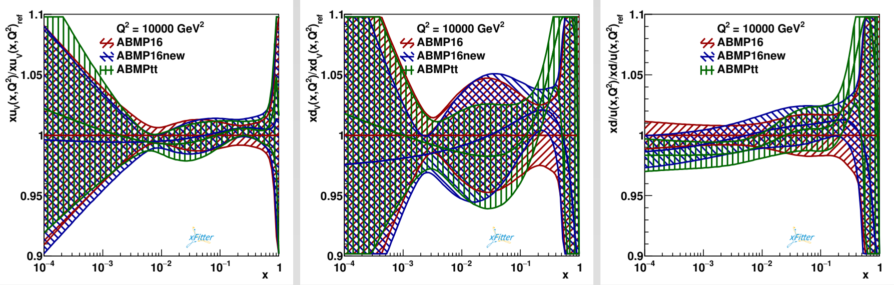
from S. Alekhin et al., PRD 89 (2014) 054028

$\ast$ Differences in $\alpha_s(M_Z)$ between ABM and other PDF+$\alpha_s(M_Z)$ sets date back to 15 years...., in relation to:

- F_L treatment
- Effects of including/not including jet data from hadronic collisions (Tevatron and LHC)
- Effects of including/not including higher-twist corrections: an analysis without the latter brings back $\alpha_s(M_Z)$ at large values an analysis without the latter but with cuts on $Q^2 > 10$ GeV^2, $W^2 > 12.5$ GeV^2 lead to low $\alpha_s(M_Z)$ values.
- Other power corections to DIS: target mass corrections, due to finite nucleon mass

$\ast$ Almost no impact of $t\bar{t} + X$ data on $\alpha_s(M_z)$: we would need to analyze $t\bar{t}j$ data.

The ABMP16 and ABMPtt u_v, d_v-quark distributions and the d/u ratio



- The u_v distribution of ABMPtt fully compatible with the one from ABMP16
- The d_v distribution of ABMPtt larger than ABMP16 at large x.
- This difference has some implication for the d/u ratio:
  - in the “right” direction, but not enough to solve the discrepancy with ATLAS $\sigma(t+X)/\sigma(\bar{t}+X)$ data.
  - useful to compare to old data at smaller $\sqrt{S}$:
    past work by [S. Alekhin et al. Phys.Rev.D 94 (2016) 11, 114038] shows that ABM12 R_t was well compatible with ATLAS data at $\sqrt{S}$= 7 TeV and CMS data at $\sqrt{S}$= 8 TeV