NNLO fits of top-quark mass using total, single-differential and double-differential $t\bar{t}+X$ cross-section data

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see [arXiv:2311.05509], in JHEP 05 (2024) 321

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Top-quark mass can be extracted by comparing experimental data on top-quark production to theory predictions.
We preform an extraction at NNLO QCD.

Input:

- cross-sections computed with MATRIX [Catani et al. JHEP 07 (2019) 100] + PineAPPL [Carrazza et al., JHEP 12 (2020) 108]
- modern PDF sets: ABMP16,CT18, MSHT20, NNPDF4.0, with their associated $a_s(M_Z)$ values.
- experimental data: total cross-sections, single differential and double-differential distributions for top-antitop production

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

Experiment	decay channel	dataset	luminosity	$\sqrt{s}$	observable(s)	n
CMS	semileptonic	2016–2018	137 fb^{-1}	13 TeV	$M(t\bar{t})$, $\lvert y(t\bar{t})\rvert$	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

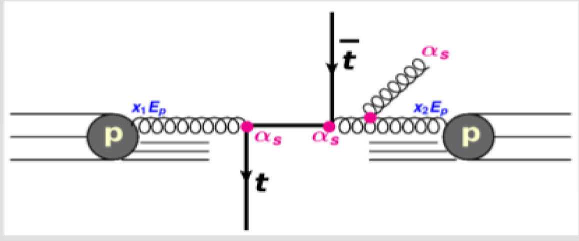
Total cross-section-data selection criteria

- Data considered in the LHC Top Working Group (June 2023, there is a 2024 update that however we expect to play only a minor role on our results).

Differential-data selection criteria

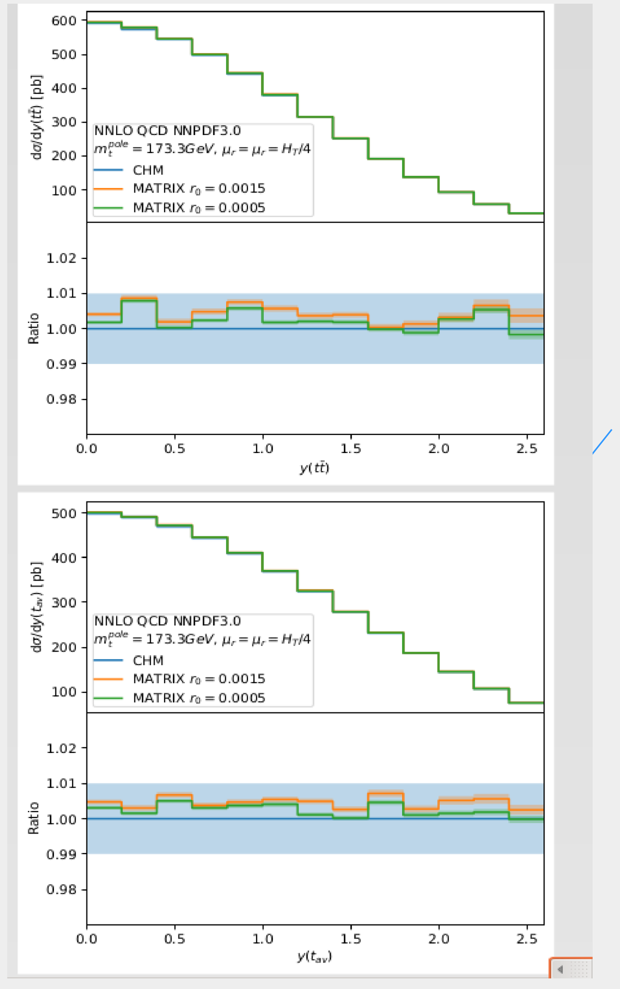
- we focus on $d\sigma/dM(t\bar{t})$ and $d^2\sigma/dM(t\bar{t})dy(t\bar{t})$ distributions.
- We use measurements where the experimental collaborations provide unfolding to the inclusive parton level ($t\bar{t}$) (MATRIX is being extended at decayed-top level only now, LHCb data so far only available at the particle level).
- We used measurements normalized, to reduce the effect of lack of information concerning correlations of uncertainties between different experimental analyses (source by source available only in CMS dilepton analyses!).
- we used measurements for which info on bin-by-bin correlated uncertainties are available.

$t\bar{t}+X$ production



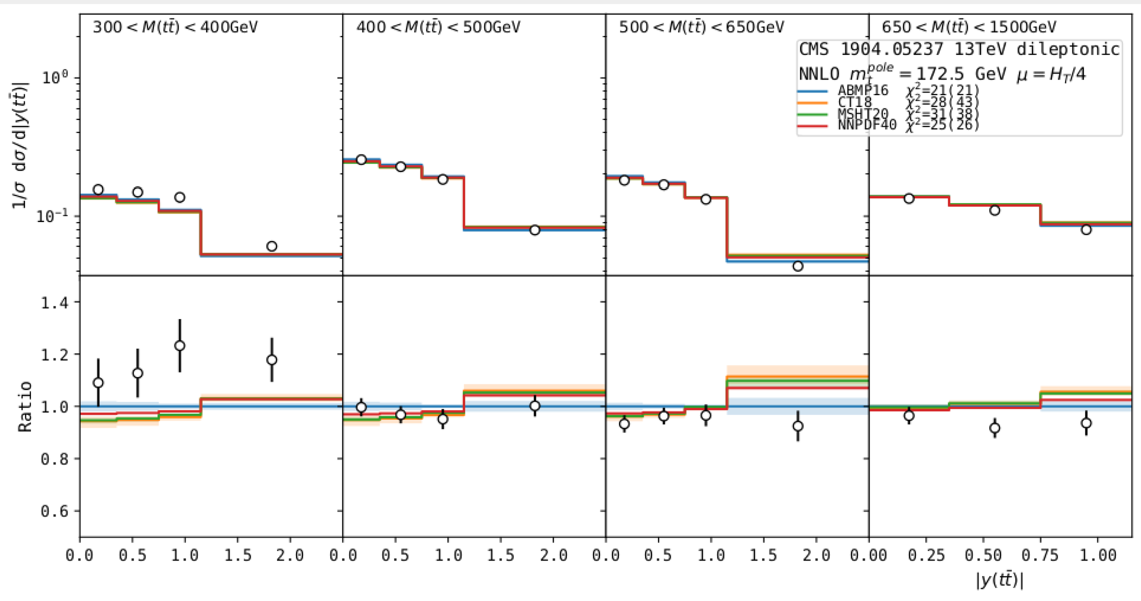
- m_t provides a hard scale
  ⇒ ultimate probe of pQCD
  (NLO, aNNLO, NNLO, ...)
- Produced mainly via gg
  ⇒ constrain gluon PDF at high x
- Production sensitive to α_s and m_t
- May provide insight into possible new physics

Validation differential calculation with MATRIX at NNLO vs CHM one

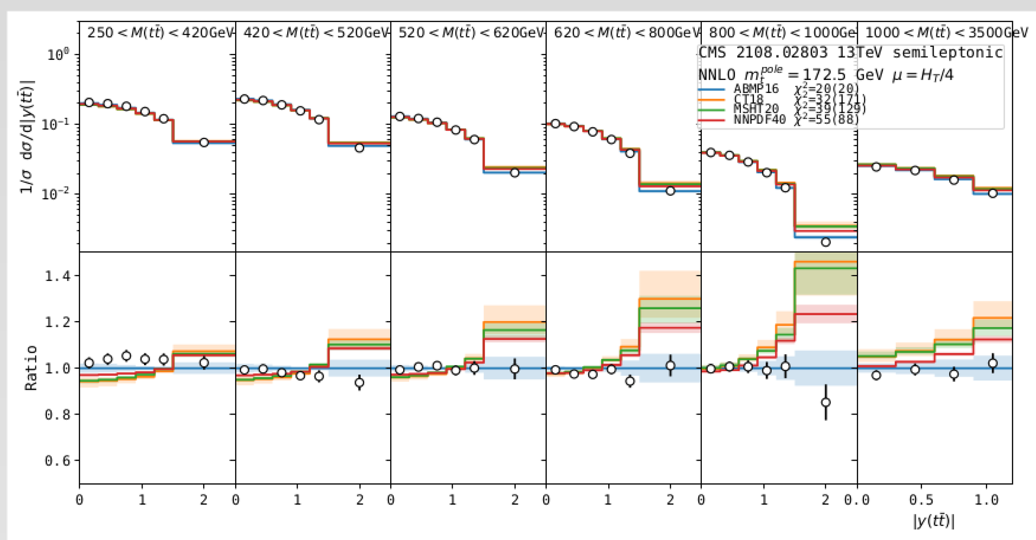


Results of the non-local subtraction method q_T-subtraction implemented in MATRIX) are in agreement within ~1% with those of the local subtraction method STRIPPER implemented in CHM (Czakon et al., JHEP 04 (2017) 071).

Theory predictions using different PDFs vs. CMS exp. data from arXiv;1904.05237 (dileptocnic top-quark decays) and arXiv:2108.02803 (semileptonic top-quark decays)

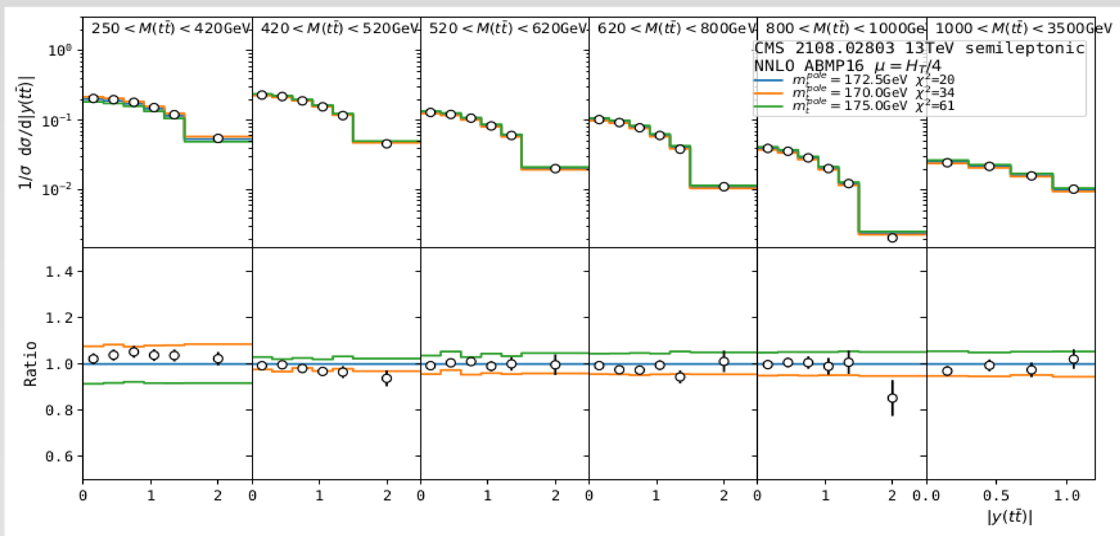


- Fixed $m_t^{pole} = 172.5$ GeV, $\mu_r = \mu_f = H_T/4$
- Reported χ^2 values with (and without) PDF uncertainties
- All PDF sets describe data reasonably well, with best description by ABMP16



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

Sensitivity to top-quark mass

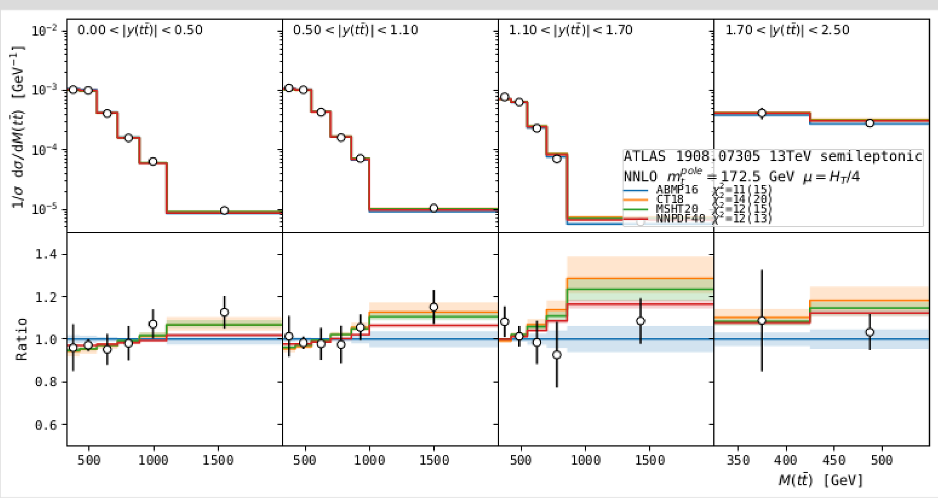


- Using ABMP16, $\mu_r = \mu_f = H_T/4$
- Reported χ^2 values with PDF uncertainties
- Large sensitivity to m_t^{pole} in the first $M(t\bar{t})$ bin (and due to x-section normalisation, also in other $M(t\bar{t})$ bins)

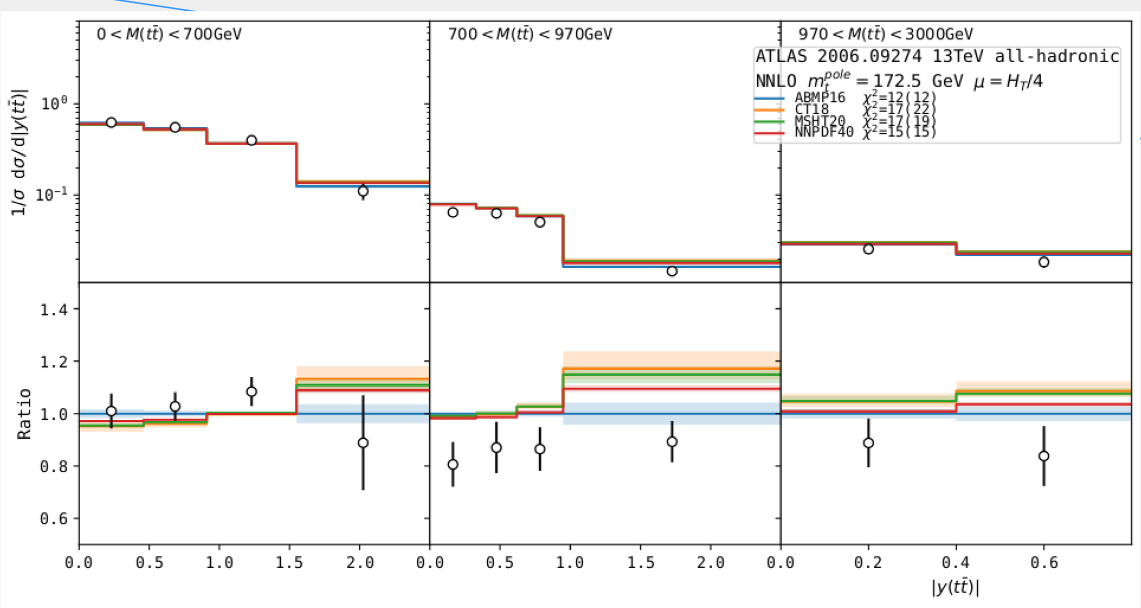
Theory predictions vs. 2-diff data at 13 TeV: summary

PDF	$t\bar{t}$ data in PDF fit	χ^2/NDP (all data)	
		w/ PDF unc.	w/o PDF unc.
ABMP16	only total $\sigma(t\bar{t}+X)$	56/78	61/78
CT18	total and diff. $\sigma(t\bar{t}+X)$	80/78	250/78
MSHT20	total and diff. $\sigma(t\bar{t}+X)$	92/78	196/78
NNPDF4.0	total and diff. $\sigma(t\bar{t}+X)$	104/78	139/78

Theory predictions using different PDFs vs. ATLAS exp. data from arXiv:1908.07305 (semileptonic top-quark decays) and arXiv:2006.09274 (all-hadronic top-quark decays)



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



- Fixed $m_t^{pole} = 172.5$ GeV, $\mu_r = \mu_f = H_T/4$
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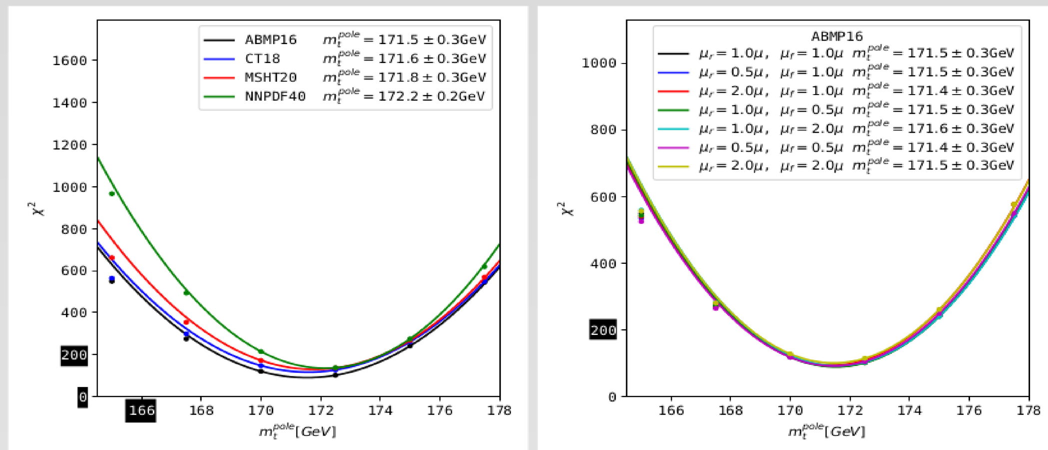
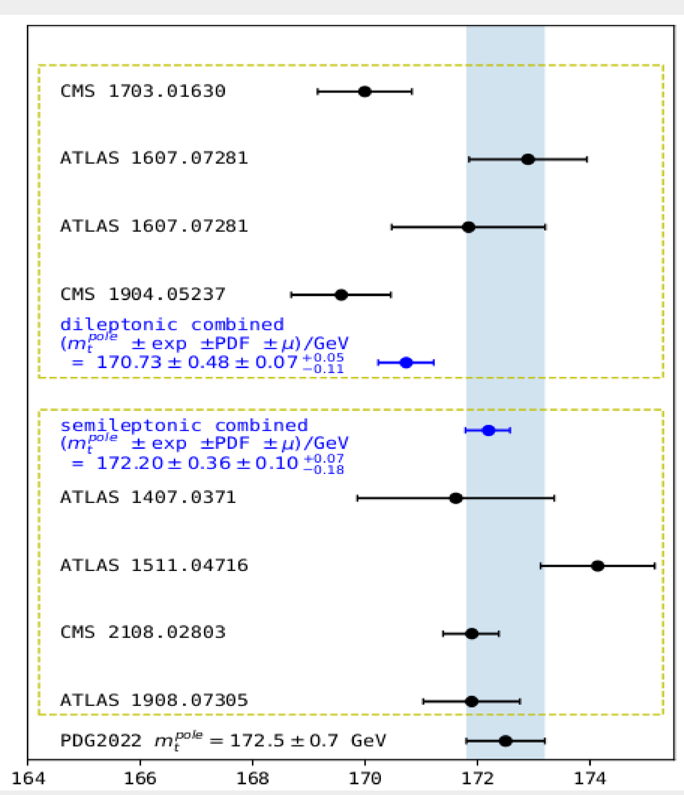
Extraction of the top-quark pole mass: global analysis



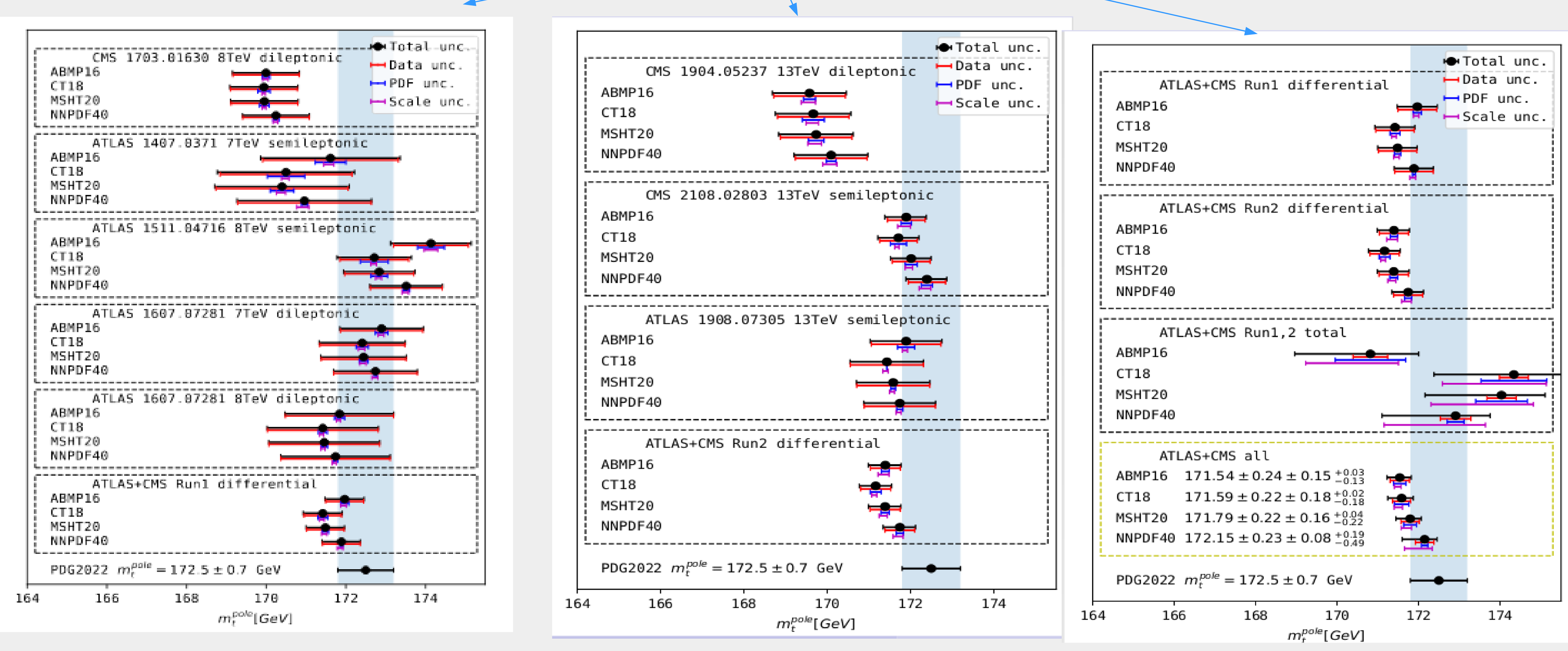
- χ^2 minimum is determined using parabolic interpolation of 3 points with lowest χ^2 values
- Both experimental, theory numerical, and PDF uncertainties included in χ^2
- Δm_t^{pole} uncertainty $\sim \pm 0.3$ GeV quoted in the plots takes into account all uncertainties included in the covariance matrix ($\Delta\chi^2 = 1$).
- Scale variations are not included in χ^2 (the uncertainties do not follow a gaussian distribution) but they are done explicitly (offset method) (span an interval of ~ 0.2 GeV)

Top-quark pole mass fit: tensions among datasets ?



Experimental analyses with full Run 2 luminosity and further Run 3 studies are needed to resolve the ~2σ tensions observed

Top-quark pole mass fit: summary from Run 1, Run 2 and global



- Global Run-1 + Run-2 fit:
  extracted m_t^{pole} values with precision ± 0.3 GeV are consistent with PDG value 172.5 ± 0.3 GeV
  - data uncertainty $\sim 0.2 - 0.3$ GeV
  - PDF uncertainty $\sim 0.1 - 0.2$ GeV
  - NNLO scale uncertainty $\sim 0.1 - 0.2$ GeV
- in case of total cross-sections only, m_t^{pole} uncertainties dominated by scale variation effects
- for each PDF set, compatibility within uncertainties between m_t^{pole} extracted using Run-1 or Run-2 differential data
- compatibility within uncertainties among m_t^{pole} extracted using as input different (PDF+$\alpha_s(M_Z)$) sets
- Significant dependence of the central m_t^{pole} value on PDFs (~ 0.6 GeV):
  - different m_t^{pole} used in different PDFs
  - PDFs, m_t^{pole} (and $\alpha_s(M_Z)$) should be determined simultaneously

Conclusions:
This work paves the way towards simultaneous NNLO fits of the gluon PDFs, the top-quak mass and the strong coupling constant. We have performed such a fit in [arXiv:2407.00545].

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