Standard Model at the LHC 2019

April 25, 2019 - Zürich

Measurements of the $t\bar{t}$ production cross section, the top quark mass and the strong coupling constant with the CMS detector at $\sqrt{s} = 13\ \mathrm{TeV}$

selection of results from arXiv:1812.10505

(submitted to EPJC)

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on behalf of the CMS Collaboration

introduction and motivation

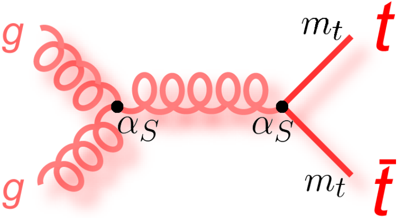
calculations of $\mathrm{t\bar{t}}$ production cross sections in perturbative QCD depend on

① strong coupling constant α_S

② top quark mass m_t

③ gluon (quark) PDF in the proton

→ measurements of $\sigma_{\mathrm{t\bar{t}}}$ can be used to constrain these parameters



strong coupling constant

- α_S known with sub-percent precision
- **significant contribution** to uncertainty for several QCD predictions
- can be determined at NNLO from $\sigma_{\mathrm{t\bar{t}}}$

top quark mass

- consistency test of Standard Model
- can be determined in **well defined scheme** ($\overline{\mathrm{MS}}$, on-shell) from $\sigma_{\mathrm{t\bar{t}}}$
- avoid interpretation problems of m_t^MC

→ **NB:** α_S and m_t cannot be determined simultaneously from inclusive $\sigma_{\mathrm{t\bar{t}}}$

experimental dependence of $\sigma_{t\bar{t}}$ on m_t^{MC}

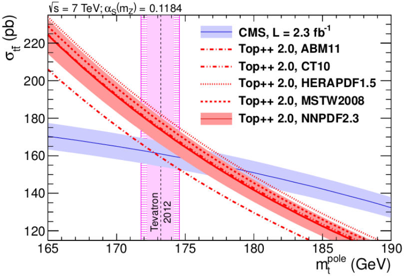
measured $\sigma_{t\bar{t}}$ has a **residual dependence** on assumed m_t^{MC} (affects acceptance)

→ has to be taken into account

in 7 TeV analysis

- **assumption** $m_t^{\mathrm{MC}} = m_t^{\mathrm{pole}} \pm 1\ \mathrm{GeV}$

Phys. Lett. B 728 (2013) 496



experimental dependence of $\sigma_{t\bar{t}}$ on m_t^{MC}

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in 7 TeV analysis

- **assumption** $m_t^{\mathrm{MC}} = m_t^{\mathrm{pole}} \pm 1\ \mathrm{GeV}$

in this analysis

- **simultaneous fit** of $\sigma_{t\bar{t}}$ and m_t^{MC}
- $\sigma_{t\bar{t}}$ measured at optimal mass point
- **no prior assumption** on relation between m_t^{MC} and m_t (pole, $\overline{\mathrm{MS}}$)

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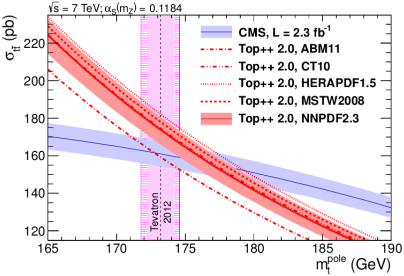
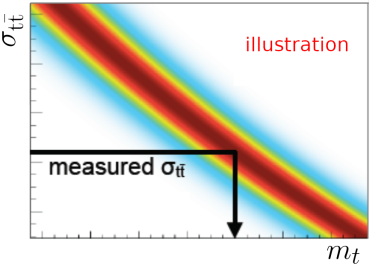


PRL 116 (2016) 16 162001



simultaneous measurement of $\sigma_{t\bar{t}}$ and m_t^{MC}: strategy

arXiv:1812.10505

method: **template fit** to multi-differential distributions of final state observables

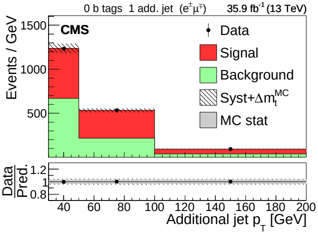
- measurement performed in $e^{\mp}\mu^{\pm}$ channel
- events split in **bins of jet and b-tagged jet multiplicities** to constrain modelling uncertainties and b-tagging efficiencies
- systematic uncertainties constrained in the visible phase space (except lumi)

1. jet p_T spectra used to constrain JES
2. $m_{\ell b}^{min}$ distribution used to constrain m_t^{MC}

extrapolation

- result is extrapolated to the full phase space
- **constraints** obtained in visible phase space **not considered in extrapolation**

0 b-tags, 1 add. jet



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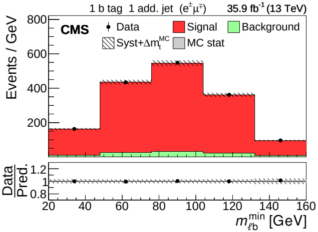


simultaneous measurement of $\sigma_{t\bar{t}}$ and m_t^{MC}: results

arXiv:1812.10505

total $t\bar{t}$ cross section

$$\sigma_{t\bar{t}} = 815 \pm 2\,(\mathrm{stat}) \pm 29\,(\mathrm{syst}) \pm 20\,(\mathrm{lum})\ \mathrm{pb}$$

top MC mass

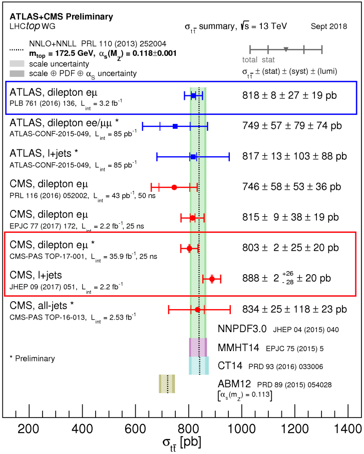
$$m_t^{\mathrm{MC}} = 172.33 \pm 0.14\,(\mathrm{stat})\ {}^{+0.66}_{-0.72}\,(\mathrm{syst})\ \mathrm{GeV}$$

main uncertainties on $\sigma_{t\bar{t}}$

- integrated luminosity (2.5%)
- lepton identification (2.2%)

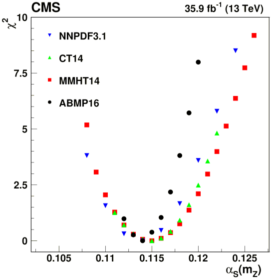
main uncertainties on m_t^{MC}

- jet energy scale (570 MeV)
- statistics of simulation (360 MeV)



extraction of $\alpha_S(M_Z)$ from $\sigma_{t\bar{t}}$ at 13 TeV

arXiv:1812.10505



parameters determined from **data/theory χ^2**

calculations of $\sigma_{t\bar{t}}$

- Hathor2.0 at NNLO+NLL precision
- several NNLO PDF sets considered
- $\overline{\mathrm{MS}}$ scheme adopted for m_t
  $\rightarrow$ faster perturbative convergence
  (see EPJC 74 (2014) 11 3167)
- soft gluon resummation not included

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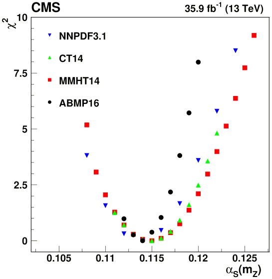
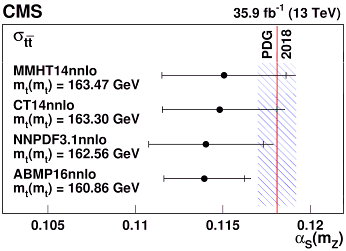
results for $\alpha_S(m_Z)$

- first time with treatment of quark masses in $\overline{\mathrm{MS}}$ scheme
- precision of order 2-3%

$$\alpha_S(M_Z) = 0.1139 \; {}^{+0.0027}_{-0.0023} \quad \text{(ABMP16)}$$





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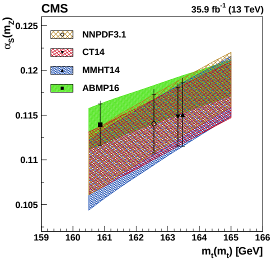
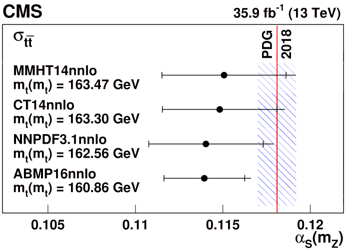
results for $\alpha_S(m_Z)$

- dependence of extracted α_S vs m_t investigated → **linear**
- milder dependence in case of ABMP16 due to simultaneous fit of α_S and $m_t(m_t)$ in PDF determination





extraction of m_{t} from $\sigma_{\mathrm{t\bar{t}}}$ at 13 TeV

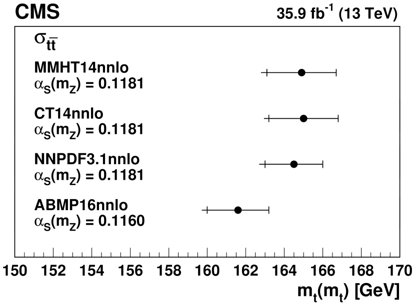
arXiv:1812.10505

- same procedure used to extract top mass in $\overline{\mathrm{MS}}$ scheme, $m_{\mathrm{t}}(m_{\mathrm{t}})$

results for $m_{\mathrm{t}}(m_{\mathrm{t}})$

- first direct determination of $m_{\mathrm{t}}(m_{\mathrm{t}})$ (uncertainty $\simeq$ 1.2%)
- lower m_{t} result with ABMP16 due to lower $\alpha_{\mathrm{S}}(\mathrm{M_Z})$ in PDF determination

$$m_{\mathrm{t}}(m_{\mathrm{t}}) = 161.6\,^{+1.6}_{-1.9}\ \mathrm{GeV}\ (\mathrm{ABMP16})$$



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results for $m_\mathrm{t}(m_\mathrm{t})$

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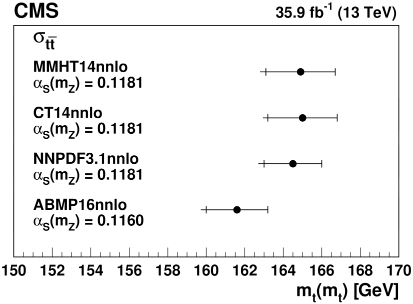


pole mass extraction

- calculations with Top++2.0 (NNLO+NNLL)
- results consistent with previous measurements of $m_\mathrm{t}^\mathrm{pole}$

PDF set	$m_\mathrm{t}^\mathrm{pole}$ [GeV]
ABMP16	$169.9 \pm 1.8\ (\text{fit + PDF} + \alpha_S)\ ^{+0.8}_{-1.2}$ (scale)
NNPDF3.1	$173.2 \pm 1.9\ (\text{fit + PDF} + \alpha_S)\ ^{+0.9}_{-1.3}$ (scale)
CT14	$173.7 \pm 2.0\ (\text{fit + PDF} + \alpha_S)\ ^{+0.9}_{-1.4}$ (scale)
MMHT14	$173.6 \pm 1.9\ (\text{fit + PDF} + \alpha_S)\ ^{+0.9}_{-1.4}$ (scale)

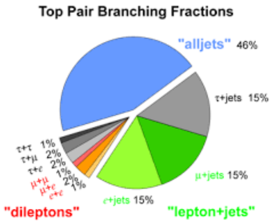
Thank you for your attention

top pair production cross section: general procedure

- measurement is performed in the visible phase space where a **fiducial cross section** $\sigma_{t\bar{t}}^{\mathrm{vis}}$ is measured (systematic uncertainties can be constrained)
- observed $\sigma_{t\bar{t}}^{\mathrm{vis}}$ is extrapolated to full phase space to get **total cross section** $\sigma_{t\bar{t}}$ → introduces model dependence

$$\sigma_{t\bar{t}}^{\mathrm{vis}} = \frac{N_{\mathrm{data}} - N_{\mathrm{bkg}}}{\epsilon_{\mathrm{sel}} \cdot L_{\mathrm{int}}}$$

$$\sigma_{t\bar{t}} = \frac{\sigma_{t\bar{t}}^{\mathrm{vis}}}{A_{\mathrm{sel}} \cdot \mathrm{BR}}$$



"golden" decay channels for $\sigma_{t\bar{t}}$ measurement

- di-leptonic channels, in particular $e\mu$
- l+jets channels ($l = e, \mu$)

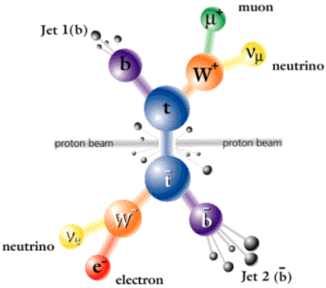
→ all-hadronic channel penalized by JES, modelling and b-tagging uncertainties

event selection in arXiv:1812.10505

triggers: dilepton OR single lepton

offline selection

- at least two opposite-charge leptons:
  $\mathrm{p_{T1}} > 25\,\mathrm{GeV}$, $\mathrm{p_{T2}} > 20\,\mathrm{GeV}$
  $|\eta| < 2,4$, $m_{\mathrm{ll}} > 20\,\mathrm{GeV}$
- jets: $\mathrm{p_T} > 30\,\mathrm{GeV}$ and $|\eta| < 2.4$
- b-tagging: CSVv2 Tight WP



→ events classified in mutually-exclusive categories according to lepton flavour, b-tag and jet multiplicity

control distributions ($e^{\mp}\mu^{\pm}$ channel)

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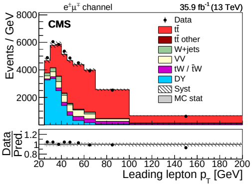
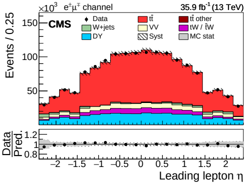
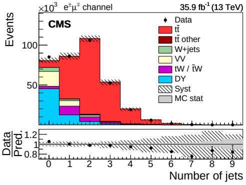
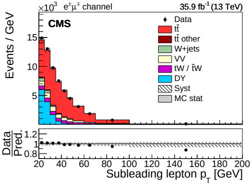
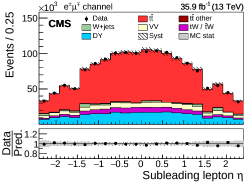
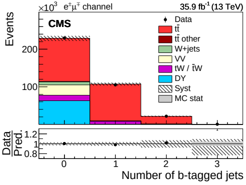












b-tagging efficiencies in arXiv:1812.10505

b-tagging efficiencies are determined *in situ* by exploiting the $\mathrm{t\bar{t}}$ topology:

$$
\begin{aligned}
s_{1\mathrm{b}} &= \mathcal{L}\sigma^{\mathrm{vis}}_{\mathrm{t\bar{t}}}\epsilon_{\ell\ell} \cdot 2\epsilon_{\mathrm{b}}(1 - C_{\mathrm{b}}\epsilon_{\mathrm{b}}) && (1)\\
s_{2\mathrm{b}} &= \mathcal{L}\sigma^{\mathrm{vis}}_{\mathrm{t\bar{t}}}\epsilon_{\ell\ell} \cdot \epsilon^{2}_{\mathrm{b}} C_{\mathrm{b}} && (2)\\
s_{\mathrm{other}} &= \mathcal{L}\sigma^{\mathrm{vis}}_{\mathrm{t\bar{t}}}\epsilon_{\ell\ell} \cdot (1 - 2\epsilon_{\mathrm{b}}(1 - C_{\mathrm{b}}\epsilon_{\mathrm{b}}) - C_{\mathrm{b}}\epsilon^{2}_{\mathrm{b}}) && (3)
\end{aligned}
$$

- $\epsilon_{\ell\ell}$ is the efficiency of the full selection
- ϵ_{b} is the b-tagging efficiency
- C_{b} represents the residual correlation of tagging the two b-jets

→ all parameters are derived by the simulation and depend on the systematic uncertainties

fit strategy of arXiv:1812.10505

template fit to distributions of final state observables

- systematic uncertainties treated as nuisance parameters and constrained *in situ* (with exception of luminosity)
- events categorized in bins of jet and b-tag multiplicity in order to constrain modelling systematics and b-tagging efficiency
- jet $\mathrm{p_T}$ spectra are used to constrained JEC uncertainties

binned Poisson Likelihood

$$L = \prod_i \frac{e^{-\mu_i}\mu_i^{n_i}}{n_i!} \cdot \prod_m \pi(\lambda_m)$$

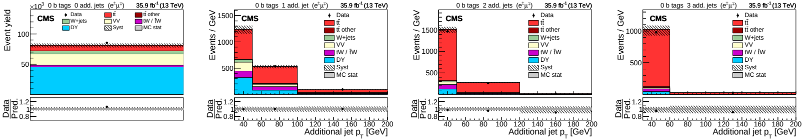
$$\mu_i = s_i(\sigma_{\mathrm{t\bar{t}}}^{\mathrm{vis}}, \vec{\lambda}) + \sum_k b_{k,i}^{\mathrm{MC}}(\vec{\lambda})$$

- $\vec{\lambda}$ is a set of nuisance parameters
- $\pi(\lambda_m)$ parametrizes the prior knowledge of m^{th} parameter

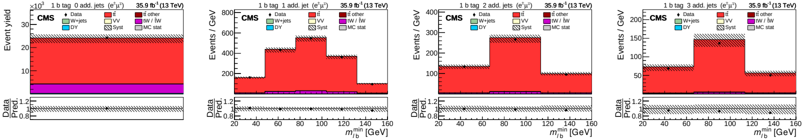
combined $\sigma_{t\bar{t}}$ and m_{t}^{MC} results: pre-fit distributions ($e^{\mp}\mu^{\pm}$)

arXiv:1812.10505

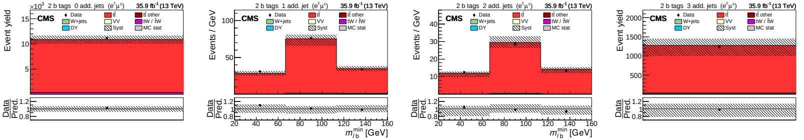
0 b-tags: 0,1,2,3 additional jets



1 b-tag: 0,1,2,3 additional jets



2 b-tags: 0,1,2,3 additional jets



combined $\sigma_{\mathrm{t\bar{t}}}$ and $m_{\mathrm{t}}^{\mathrm{MC}}$ results: post-fit distributions ($\mathrm{e}^{\mp}\mu^{\pm}$)

arXiv:1812.10505

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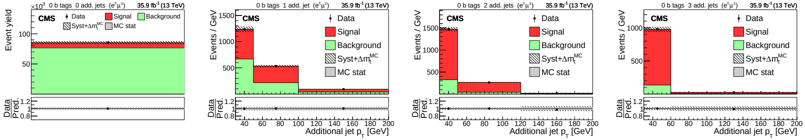

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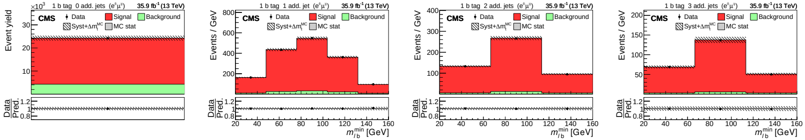

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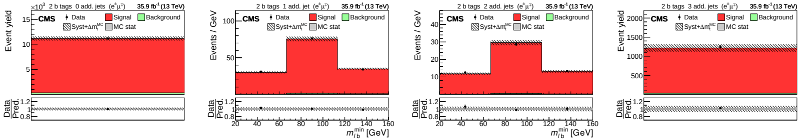
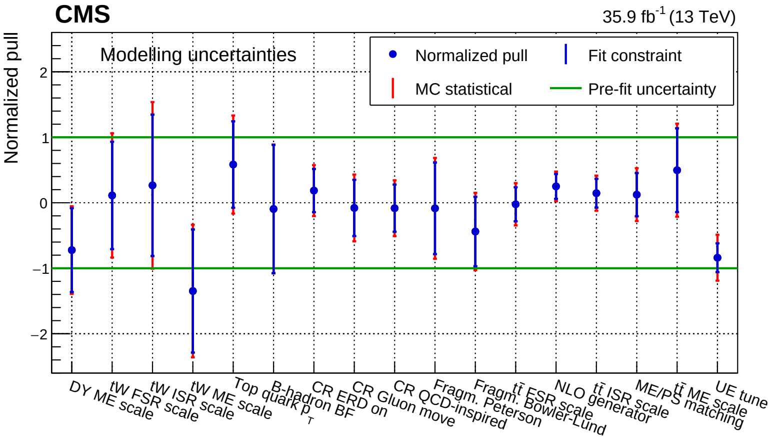


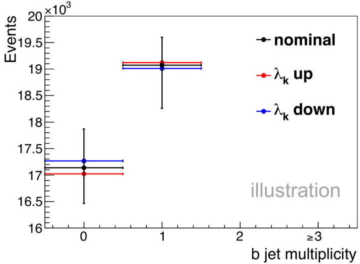
pulls and constraints of modelling uncertainties: $\sigma_{t\bar{t}} + m_t^{MC}$

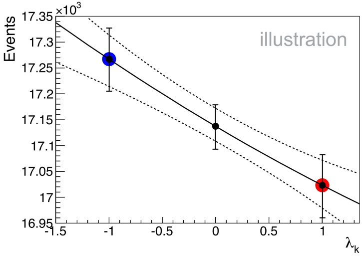
arXiv:1812.10505



parametrization of systematic uncertainties in arXiv:1812.10505

- templates corresponding to systematic variations are derived by varying parameters in analysis within their prior uncertainty or by using alternative samples
- in each bin, the dependency on the nuisance parameters is modelled with a second order polynomial
- if the variation is one-sided (comparison between two alternative models) a linear dependence is assumed
- nominal, up and down variations correspond to $\lambda_\mathrm{k} = 0$, $+1$ and -1 respectively





procedure to assess impact of MC stats in arXiv:1812.10505

general idea: effect of systematics on fit distributions is modelled with templates obtained either

- by re-weighting events (e.g. ME scale)
- with alternative MC samples (e.g. ME/PS matching)

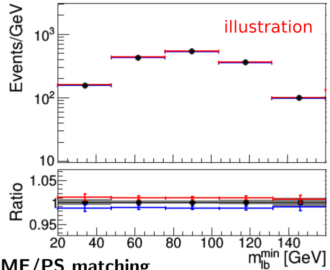
① **re-weighting**: stats of nominal templates and varied templates are fully correlated

② **alternative samples:** fully uncorrelated

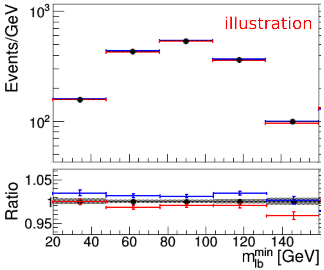
procedure

- produce **toy templates** where each bin is Poisson-smeared according to its MC stats
- fully consistent treatment of correlations between statistical uncertainties in the MC
  - throw individual toys for nominal and alternative samples and re-derive template dependencies
- **simultaneously for all the nuisance parameters**
- repeat fit to data points and assess effect on results (mass, cross section) and nuisances
- **estimates the impact of any possible MC fluctuation**

ME scale



ME/PS matching



numerical values for $\alpha_\mathrm{S}(m_\mathrm{Z})$

arXiv:1812.10505

PDF set	$\alpha_S(m_\mathrm{Z})$
ABMP16	$0.1139 \pm 0.0023\,(\text{fit + PDF})\,^{+0.0014}_{-0.0001}\,(\text{scale})$
NNPDF3.1	$0.1140 \pm 0.0033\,(\text{fit + PDF})\,^{+0.0021}_{-0.0002}\,(\text{scale})$
CT14	$0.1148 \pm 0.0032\,(\text{fit + PDF})\,^{+0.0018}_{-0.0002}\,(\text{scale})$
MMHT14	$0.1151 \pm 0.0035\,(\text{fit + PDF})\,^{+0.0020}_{-0.0002}\,(\text{scale})$

numerical values for $m_{\mathrm{t}}(m_{\mathrm{t}})$

arXiv:1812.10505

PDF set	$m_{\mathrm{t}}(m_{\mathrm{t}})$ [GeV]
ABMP16	161.6 ± 1.6 (fit + PDF + α_S) $^{+0.1}_{-1.0}$ (scale)
NNPDF3.1	164.5 ± 1.6 (fit + PDF + α_S) $^{+0.1}_{-1.0}$ (scale)
CT14	165.0 ± 1.8 (fit + PDF + α_S) $^{+0.1}_{-1.0}$ (scale)
MMHT14	164.9 ± 1.8 (fit + PDF + α_S) $^{+0.1}_{-1.1}$ (scale)

numerical values for m_t^{pole}

arXiv:1812.10505

PDF set	m_t^{pole} [GeV]
ABMP16	$169.9 \pm 1.8\ (\mathrm{fit} + \mathrm{PDF} + \alpha_S)\ ^{+0.8}_{-1.2}\ (\mathrm{scale})$
NNPDF3.1	$173.2 \pm 1.9\ (\mathrm{fit} + \mathrm{PDF} + \alpha_S)\ ^{+0.9}_{-1.3}\ (\mathrm{scale})$
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QCD parameters in PDF

arXiv:1812.10505

	ABMP16	NNPDF3.1	CT14	MMHT14
$m_\mathrm{t}^\mathrm{pole}$ [GeV]	170.37	172.5	173.3	174.2
RunDec loops	3	2	2	3
$m_\mathrm{t}(m_\mathrm{t})$ [GeV]	160.86	162.56	163.30	163.47
$\alpha_S(m_\mathrm{Z})$	0.116	0.118	0.118	0.118
α_S range	0.112−0.120	0.108−0.124	0.111−0.123	0.108−0.128