DESY LHC Physics Discussion

October 15, 2018

Extraction of top quark mass and strong coupling constant from inclusive $\mathrm{t\bar{t}}$ cross section

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on behalf of the CMS Collaboration

introduction and motivation

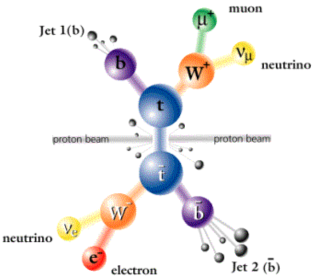
- why do we want to measure α_S and m_t
- how to extract them from the inclusive $t\bar{t}$ cross section

a little bit of history

- extraction of α_S and m_t^{pole} at 7 TeV
- extraction of m_t^{pole} at 7+8 TeV

preliminary CMS results at 13 TeV

- strategy of 13 TeV analysis
- details about measurement of $\sigma_{t\bar{t}}$
- extraction of α_S and m_t at 13 TeV



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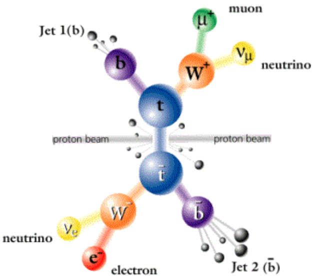
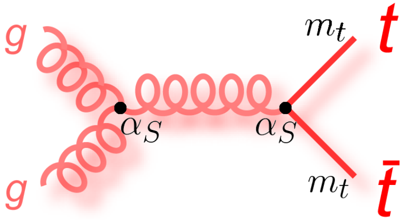


calculations of $\mathrm{t\bar{t}}$ production depend on:

1. strong coupling α_S
2. top quark mass m_t
3. gluon (quark) PDF in the proton

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



strong coupling

- α_S known with sub-percent precision
- significant contribution to uncertainty for several QCD predictions
- can be measured at NNLO from $\sigma_{\mathrm{t\bar{t}}}$ (NLO for hadronic jet production)

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

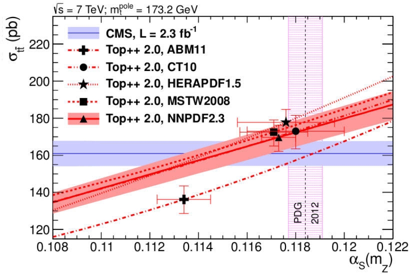
$\rightarrow$ **NB:** α_S and m_t cannot be determined simultaneously from inclusive $\sigma_{\mathrm{t\bar{t}}}$

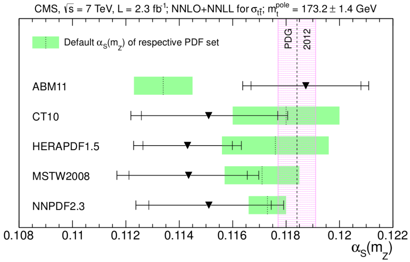
determination of $\alpha_S(M_Z)$ from $\sigma_{t\bar{t}}$ at 7 TeV

Phys. Lett. B 728 (2013) 496

- using CMS measurement at 7 TeV in dilepton channel with 2.3 fb^{-1}, 4.1% accuracy (JHEP 11 (2012) 067)
- theory prediction with Top++2.0, NNLO+NNLL precision
- several different PDF sets considered
- $\alpha_S(M_Z)$ varied consistently in calculation and PDF
- experimental dependence of $\sigma_{t\bar{t}}$ on $\alpha_S(M_Z)$ found to be negligible
- assumed $m_t^{\mathrm{pole}} = 173.2 \pm 1.4$ GeV (Tevatron average $\oplus$ 1 GeV to account for difference between m_t^{pole} and m_t^{MC})

$$\alpha_S(M_Z) = 0.1151\ ^{+0.0028}_{-0.0027} \quad \text{(NNPDF2.3)}$$





determination of m_t^{pole} from $\sigma_{t\bar{t}}$ at 7 TeV

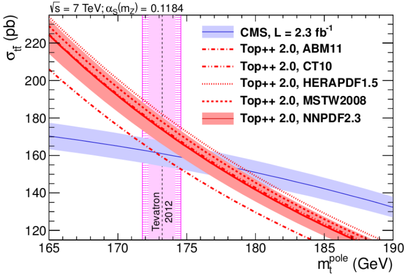
Phys. Lett. B 728 (2013) 496

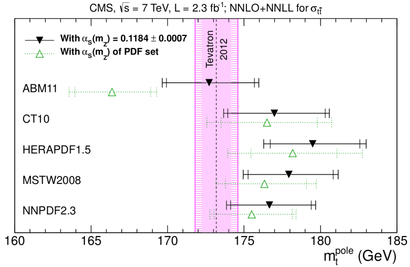
- same procedure used to extract m_t^{pole}
- assumed world average strong coupling: $\alpha_S(M_Z) = 0.1184 \pm 0.0007$
- measured $\sigma_{t\bar{t}}$ depends on m_t^{MC} through acceptance corrections
- effect has to be taken into account

assumption: $m_t^{pole} = m_t^{MC} \pm 1\,\text{GeV}$

- additional uncertainty corresponding to 1 GeV added to measured $\sigma_{t\bar{t}}$

$$m_t^{pole} = 176.7\ ^{+3.0}_{-2.8}\ \text{GeV} \quad (\text{NNPDF2.3})$$

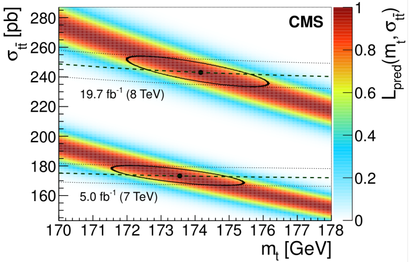




JHEP 08 (2016) 029

- simultaneous measurement of $\sigma_{t\bar{t}}$ at 7 and 8 TeV with template fit of final state distributions
- similar m_t^{pole} determination as in 7 TeV measurement
- m_t^{pole} determined separately from $\sigma_{t\bar{t}}$ at 7 and 8 TeV
- results combined taking correlations into account

	m_t [GeV]
NNPDF3.0	$173.8^{+1.7}_{-1.8}$
MMHT2014	$174.1^{+1.8}_{-2.0}$
CT14	$174.3^{+2.1}_{-2.2}$



	m_t [GeV]	
	7 TeV	8 TeV
NNPDF3.0	$173.5^{+1.9}_{-2.0}$	$174.2^{+2.0}_{-2.2}$
MMHT2014	$173.9^{+2.0}_{-2.1}$	$174.4^{+2.1}_{-2.3}$
CT14	$174.1^{+2.2}_{-2.4}$	$174.6^{+2.3}_{-2.5}$

outline of this presentation

introduction and motivation

- why do we want to measure α_S and m_t
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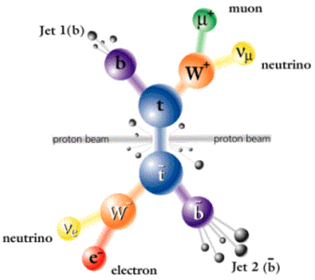


- simultaneous fit of $\sigma_{t\bar{t}}$ and m_t^{MC}
- $\sigma_{t\bar{t}}$ determined at **optimal mass point**

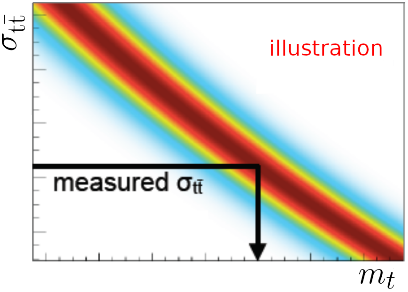
→ with this approach:

- dependence of $\sigma_{t\bar{t}}$ on m_t^{MC} mitigated
- uncertainty on $\sigma_{t\bar{t}}$ includes contribution from m_t^{MC}
- no assumption on relation between m_t^{MC} and m_t needs to be made

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

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

PRL 116 (2016) 16 162001



CMS-PAS-TOP-17-001

measurement results

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

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

- simultaneous fit of $\sigma_{\mathrm{t\bar{t}}}$ and $m_{\mathrm{t}}^{\mathrm{MC}}$
- $\sigma_{\mathrm{t\bar{t}}}$ determined at **optimal mass point**

→ with this approach:

- dependence of $\sigma_{\mathrm{t\bar{t}}}$ on $m_{\mathrm{t}}^{\mathrm{MC}}$ mitigated
- uncertainty on $\sigma_{\mathrm{t\bar{t}}}$ includes contribution from $m_{\mathrm{t}}^{\mathrm{MC}}$
- no assumption on relation between $m_{\mathrm{t}}^{\mathrm{MC}}$ and m_{t} needs to be made

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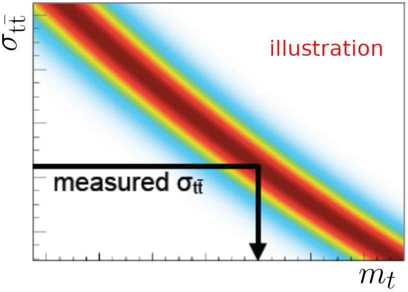

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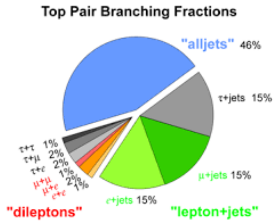
$$m_{\mathrm{t}}^{\mathrm{MC}} = 172.33 \pm 0.14\,(\mathrm{stat})\ \pm^{0.66}_{0.72}\,(\mathrm{syst})\ \mathrm{GeV}$$

- 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** $\sigma_{t\bar{t}}$ $\rightarrow$ 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

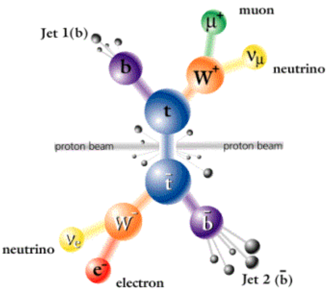
- di-leptonic channels, in particular $e\mu$
- l+jets channels ($l = e, \mu$)

$\rightarrow$ all-hadronic channel penalized by JES, modelling and b-tagging uncertainties

triggers: dilepton OR single lepton

offline selection

- at least two opposite-charge leptons:
  $p_{T1} > 25$ GeV, $p_{T2} > 20$ GeV
  $|\eta| < 2,4$, $m_{ll} > 20$ GeV
- jets: $p_T > 30$ GeV and $|\eta| < 2.4$
- b-tagging: CSVv2 Tight WP
  (0.1% mis-identification, 40% efficiency)

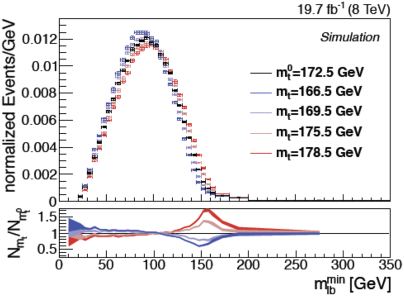


→ events classified in mutually-exclusive categories according to lepton flavour, b-tag and jet multiplicity method: **template fit** to distributions of final state observables

- systematic uncertainties treated as **nuisance parameters** and constrained in the visible phase space (with exception of luminosity)
- events categorized in **bins of jet and b-tag multiplicities** in order to constrain modelling uncertainties and b-tagging efficiencies
- result extrapolated to full phase space

1. jet p_T spectra are used to constrained JEC uncertainties
2. m_{lb}^{min} distribution used to constrain m_t^{MC}

m_{lb}^{min} = minimum invariant mass between reconstructed lepton and b-jet (sensitive to m_t^{MC} through end point of spectrum)



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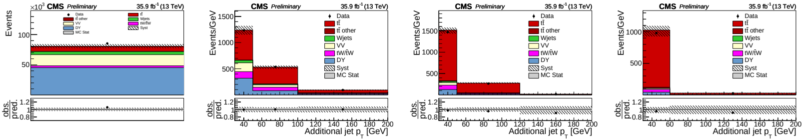
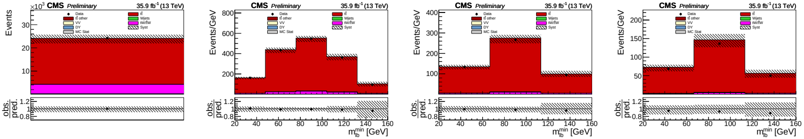
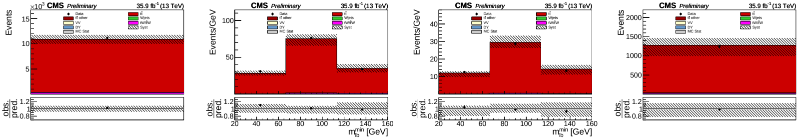
0 b-tags: 0,1,2,3 additional jets



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



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



binned Poisson Likelihood

$$L = \prod_i \exp[\mu_i]\mu_i^{n_i}/n_i! \cdot \prod_m \pi(\lambda_m)$$

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

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

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

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

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

results for $\sigma_{t\bar{t}}$ and m_t^{MC}

total $t\bar{t}$ cross section

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

top MC mass

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

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

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

main systematic uncertainties on m_t^{MC}

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

Name	Contribution [%]
Trigger	0.4
Lepton ID/isolation	2.2
Electron energy scale	0.2
Muon energy scale	0.2
Jet energy scale	0.7
Jet energy resolution	0.5
b tagging	0.3
Pileup	0.3
$t\bar{t}$ ME scale	0.5
tW ME scale	0.7
DY ME scale	0.2
NLO generator	1.2
PDF	1.1
m_t^{MC}	0.4
Top quark p_T	0.5
ME/PS matching	0.2
UE tune	0.3
$t\bar{t}$ ISR scale	0.4
tW ISR scale	0.4
$t\bar{t}$ FSR scale	1.1
tW FSR scale	0.2
B-Fragmentation	1.0
B-hadron BF	0.2
Colour reconnection	0.4
DY background	0.8
tW background	1.1
Diboson background	0.3
W+jets background	0.3
$t\bar{t}$ background	0.2
Statistical	0.2
Luminosity	2.5
MC Statistical	1.2
Total vis	4.2
$\sigma_{t\bar{t}}$(13 TeV) vis	12.86 pb
$t\bar{t}$ ME scale (extr)	$\mp^{0.4}_{<0.1}$
PDF (extr)	$\pm^{0.8}_{0.6}$
Top quark p_T (extr)	$\pm^{0.2}_{0.3}$
$t\bar{t}$ ISR scale (extr)	$\mp^{0.2}_{<0.1}$
$t\bar{t}$ FSR scale (extr)	$\pm^{0.1}_{0.1}$
UE tune (extr)	$\mp^{<0.1}_{<0.1}$
m_t^{MC} (extr)	$\mp^{0.2}_{0.3}$
Total	$\pm^{4.3}_{4.2}$
$\sigma_{t\bar{t}}$(13 TeV)	815 pb

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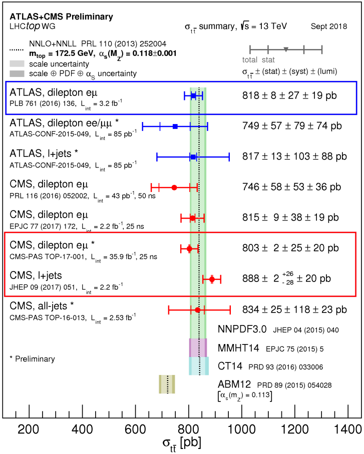

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Trigger	0.02
Lepton ID/isolation	0.02
Electron energy scale	0.10
Muon energy scale	0.03
Jet energy scale	0.57
Jet energy resolution	0.09
b tagging	0.12
Pileup	0.09
$t\bar{t}$ ME scale	0.18
tW ME scale	0.02
DY ME scale	0.06
NLO generator	0.14
PDF	0.05
$\sigma_{t\bar{t}}$	0.09
Top quark p_T	0.04
ME/PS matching	0.16
UE tune	0.03
$t\bar{t}$ ISR scale	0.16
tW ISR scale	0.02
$t\bar{t}$ FSR scale	0.07
tW FSR scale	0.02
B-Fragmentation	0.11
B-hadron BF	0.07
Colour reconnection	0.17
DY background	0.24
tW background	0.13
Diboson background	0.02
W+jets background	0.04
$t\bar{t}$ background	0.02
Statistical	0.14
Total Stat+Syst	$\pm^{0.57}_{0.64}$
MC Statistical	0.36
Total	$\pm^{0.68}_{0.73}$
m_t^{MC}	172.33

results for $\sigma_{t\bar{t}}$ and m_t^{MC}

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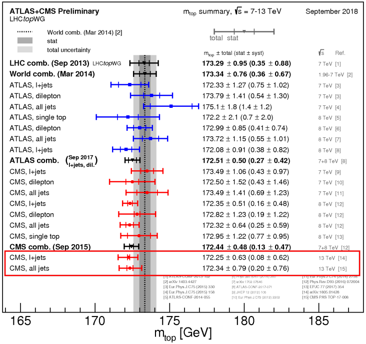


CMS-PAS-TOP-17-001

parameters determined from data-theory χ^2 using xFitter framework

α_S and m_t cannot be determined simultaneously
$\Rightarrow$ m_t fixed to native value of PDF

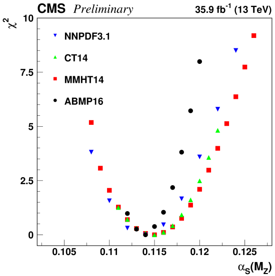
uncertainties

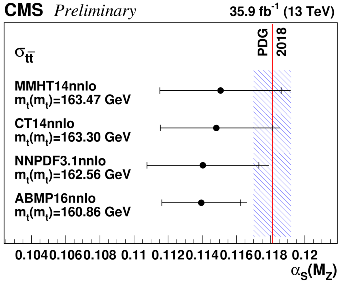
- experimental: from $\sigma_{t\bar{t}}$ measurement
- PDF: from eigenvectors
- independent μ_r, μ_f variations by factor 2

results

- challenging precision on $\alpha_S(M_Z)$, most precise from hadronic processes to date
- better precision with ABMP16

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





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α_S and m_t cannot be determined simultaneously
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uncertainties

- experimental: from $\sigma_{t\bar{t}}$ measurement
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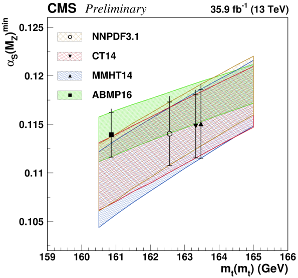
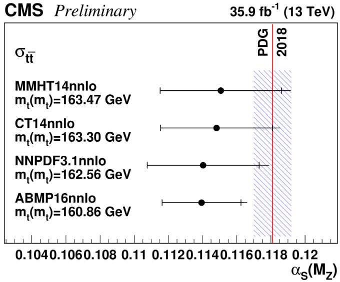
- independent μ_r, μ_f variations by factor 2

results

- dependence of extracted α_S vs m_t investigated $\rightarrow$ linear
- somehow flatter in case of ABMP16





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

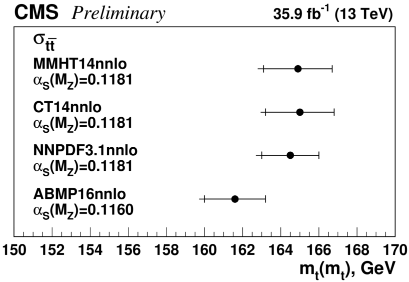
CMS-PAS-TOP-17-001

- same procedure used to extract top mass in $\overline{\mathrm{MS}}$ scheme, $m_t(m_t)$
- $\alpha_S(M_Z)$ fixed at native values of PDF

results

- first consistent determination of $m_t(m_t)$ (uncertainty $\simeq 1.2\%$)
- lower m_t result with ABMP16 due to lower $\alpha_S(M_Z)$ in PDF determination

$m_t(m_t) = 161.6\ ^{+1.6}_{-1.9}$ GeV (ABMP16)



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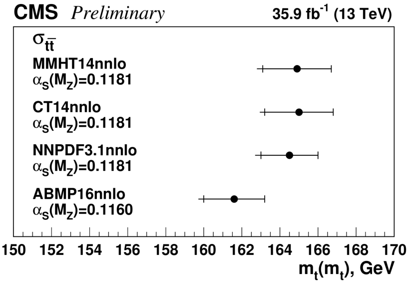
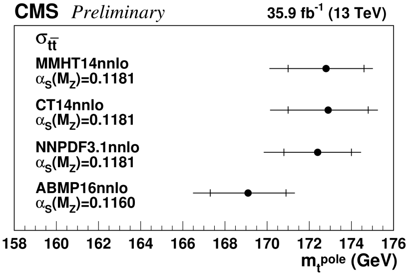
$$m_t(m_t) = 161.6\ ^{+1.6}_{-1.9}\ \text{GeV (ABMP16)}$$

pole mass m_t^{pole}

- missing soft gluon resummation $\Rightarrow$ for illustration purposes only
- results consistent with previous measurements





CMS results at 7 and 8 TeV

- $\sigma_{t\bar{t}}$ measured at fixed mass $\Rightarrow$ dependence on m_t^{MC} has to be considered
- assumption: $m_t^{MC} = m_t^{pole} \pm 1\,\text{GeV}$

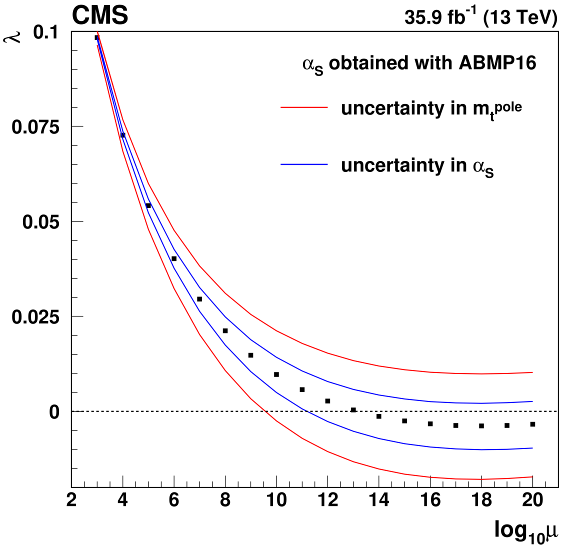
CMS preliminary results at 13 TeV (CMS-PAS-TOP-17-001)

- $\sigma_{t\bar{t}}$ determined at optimal mass point through simultaneous fit with m_t^{MC}
- uncertainty on $\sigma_{t\bar{t}}$ contains contribution from m_t^{MC}
- top quark mass treated in $\overline{\text{MS}}$ scheme $\rightarrow$ faster perturbative convergence
- first consistent determination of $m_t(m_t)$ with $\simeq 1.2\%$ precision

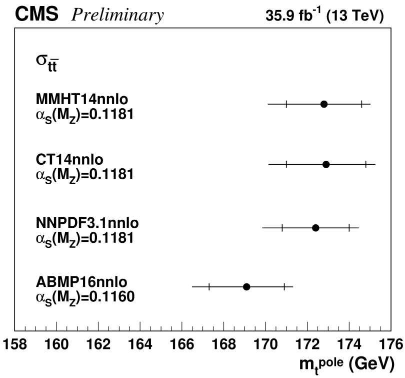
extracted α_S and m_t used to predict stbaility of EW vacuum at higher scales

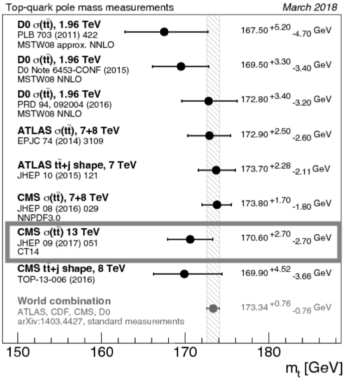
prediction obtained with **mr** (Matching and Running) program (link)

stability up to $\mu \simeq 10^{13}$ GeV



Thank you for your attention





$$m_t^{pole} = 172.9\ ^{+2.4}_{-2.8}\ \text{GeV} \quad \text{(CT14)}$$

- results consistent with previous measurements at Tevatron and LHC

numerical values for $\alpha_S(M_Z)$ with Hathor2.0

CMS-PAS-TOP-17-001

top quark mass in $\overline{\mathrm{MS}}$ scheme

PDF set (NNLO)	$\alpha_S^{min}(M_Z)$
ABMP16	0.1139 ± 0.0023 (fit + PDF) $^{+0.0014}_{-0.0001}$ (scale)
NNPDF3.1	0.1140 ± 0.0033 (fit + PDF) $^{+0.0021}_{-0.0002}$ (scale)
CT14	0.1148 ± 0.0032 (fit + PDF) $^{+0.0018}_{-0.0002}$ (scale)
MMHT14	0.1151 ± 0.0035 (fit + PDF) $^{+0.0020}_{-0.0002}$ (scale)

top quark mass in on-shell scheme

PDF set (NNLO)	$\alpha_S^{min}(M_Z)$
ABMP16	0.1164 ± 0.0021 (fit + PDF) $^{+0.0024}_{-0.0014}$ (scale)
NNPDF3.1	0.1184 ± 0.0027 (fit + PDF) $^{+0.0037}_{-0.0021}$ (scale)
CT14	0.1186 ± 0.0028 (fit + PDF) $^{+0.0034}_{-0.0019}$ (scale)
MMHT14	0.1205 ± 0.0029 (fit + PDF) $^{+0.0037}_{-0.0021}$ (scale)

numerical values for m_t with Hathor2.0

CMS-PAS-TOP-17-001

top quark $\overline{\mathrm{MS}}$ mass

PDF set (NNLO)	$m_\mathrm{t}(m_\mathrm{t})$ [GeV]
ABMP16	$161.6 \pm 1.6\ (\mathrm{fit} + \mathrm{PDF} + \alpha_\mathrm{S})\ ^{+0.1}_{-1.0}\ (\mathrm{scale})$
NNPDF3.1	$164.5 \pm 1.5\ (\mathrm{fit} + \mathrm{PDF} + \alpha_\mathrm{S})\ ^{+0.1}_{-1.0}\ (\mathrm{scale})$
CT14	$165.0 \pm 1.7\ (\mathrm{fit} + \mathrm{PDF}) \pm 0.6\ (\alpha_\mathrm{S})\ ^{+0.1}_{-1.0}\ (\mathrm{scale})$
MMHT14	$164.9 \pm 1.7\ (\mathrm{fit} + \mathrm{PDF}) \pm 0.5\ (\alpha_\mathrm{S})\ ^{+0.1}_{-1.1}\ (\mathrm{scale})$

top quark pole mass

PDF set (NNLO)	$m_\mathrm{t}^\mathrm{pole}$ [GeV]
ABMP16	$169.1 \pm 1.8\ (\mathrm{fit} + \mathrm{PDF} + \alpha_\mathrm{S})\ ^{+1.3}_{-1.9}\ (\mathrm{scale})$
NNPDF3.1	$172.4 \pm 1.6\ (\mathrm{fit} + \mathrm{PDF} + \alpha_\mathrm{S})\ ^{+1.3}_{-2.0}\ (\mathrm{scale})$
CT14	$172.9 \pm 1.8\ (\mathrm{fit} + \mathrm{PDF}) \pm 0.7\ (\alpha_\mathrm{S})\ ^{+1.4}_{-2.0}\ (\mathrm{scale})$
MMHT14	$172.8 \pm 1.7\ (\mathrm{fit} + \mathrm{PDF}) \pm 0.6\ (\alpha_\mathrm{S})\ ^{+1.3}_{-2.0}\ (\mathrm{scale})$

$\alpha_S(M_Z)$ and m_t in different PDF sets

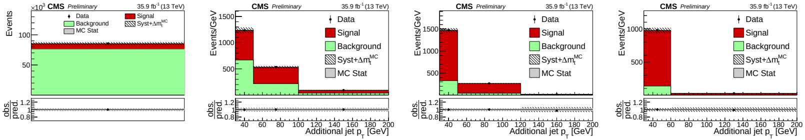
CMS-PAS-TOP-17-001

PDF set (NNLO)	ABMP16	NNPDF3.1	CT14	MMHT14
m_t^{pole}	170.37 GeV	172.5 GeV	173.3 GeV	174.2 GeV
RunDec conversion	3 loops	2 loops	2 loops	3 loops
$m_t(m_t)$	160.86 GeV	162.56 GeV	163.30 GeV	163.47 GeV
$\alpha_S(m_Z)$	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

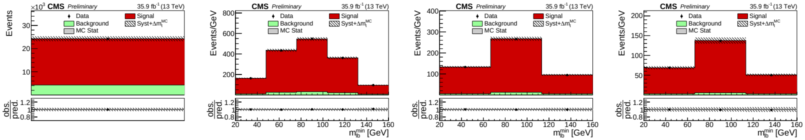
combined $\sigma_{t\bar{t}}$ and m_t^{MC} results: post-fit distributions

CMS-PAS-TOP-17-001

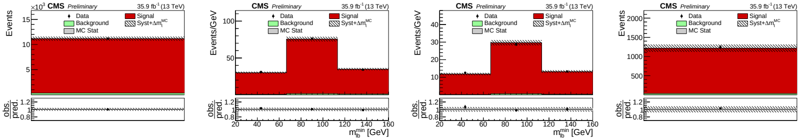
0 b-tags: 0,1,2,3 additional jets



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



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



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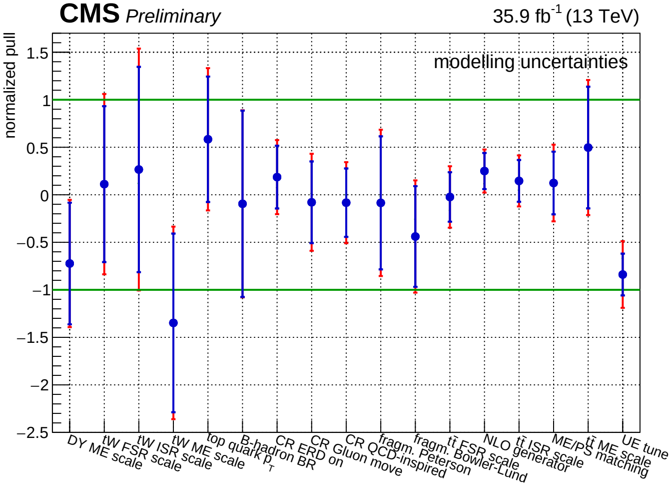
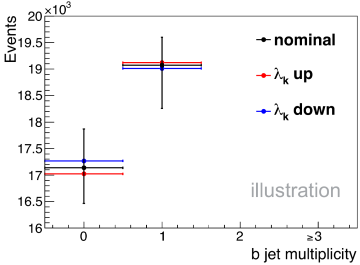
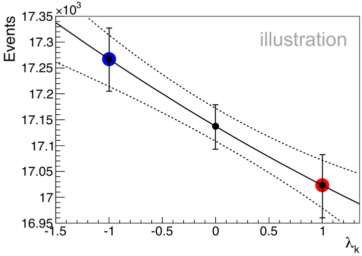


- templates corresponding to systematic variations are derived by varying parameters in analysis within their prior uncertainty or by using alternative samples
- in each bin, the dependency on the nuisance parameters is modelled with a second order polynomial
- if the variation is one-sided (comparison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





procedure to assess impact of MC statistics

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

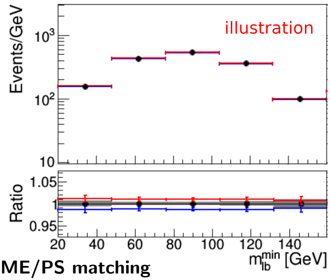
- by re-weighting events (e.g. ME scale)
- with alternative MC samples (e.g. ME/PS matching)

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