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

selection of results from arXiv:1812.10505
(submitted to EPJC)

Matteo Defranchis, Deutsches Elektronen-Synchrotron (DESY)
on behalf of the CMS Collaboration
calculations of $t\bar{t}$ production cross sections in perturbative QCD depend on

1. strong coupling constant $\alpha_S$
2. top quark mass $m_t$
3. gluon (quark) PDF in the proton

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

strong coupling constant

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

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

top quark mass

- consistency test of Standard Model
- can be determined in well defined scheme ($\overline{\text{MS}}$, on-shell) from $\sigma_{t\bar{t}}$
- avoid interpretation problems of $m_t^{\text{MC}}$
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 $m_t^{MC} = m_t^{pole} \pm 1$ GeV

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** $m_t^{MC} = m_t^{pole} \pm 1$ 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, $\overline{MS}$)
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 $e^{\pm}\mu^{\pm}$ 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. $m_{\ell b}^{\text{min}}$ 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
simultaneous measurement of $\sigma_{t\bar{t}}$ and $m_{t}^{\text{MC}}$: results

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total $t\bar{t}$ cross section

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

top MC mass

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

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

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

main uncertainties on $m_{t}^{\text{MC}}$

- 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 $\chi^2$

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

- Hathor2.0 at NNLO+NLL precision
- several NNLO PDF sets considered
- $\overline{MS}$ 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 $\overline{\text{MS}}$ scheme
- precision of order 2-3%

$\alpha_S(M_Z) = 0.1139^{+0.0027}_{-0.0023}$ (ABMP16)
extraction of $\alpha_S(M_Z)$ from $\sigma_{t\bar{t}}$ at 13 TeV

parameters determined from data/theory $\chi^2$

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results for $\alpha_S(m_Z)$
- dependence of extracted $\alpha_S$ vs $m_t$  
  investigated $\rightarrow$ linear
- milder dependence in case of ABMP16 due to simultaneous fit of $\alpha_S$ and $m_t(m_t)$ in PDF determination
extraction of $m_t$ from $\sigma_{tt}$ at 13 TeV

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

results for $m_t(m_t)$

- first direct 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)
extraction of $m_t$ from $\sigma_{t\bar{t}}$ at 13 TeV

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

top mass extraction
- calculations with Top++2.0 (NNLO+NNLL)
- results consistent with previous measurements of $m_t^{\text{pole}}$

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<thead>
<tr>
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Matteo M. Defranchis
Thank you for your attention
measurement is performed in the visible phase space where a **fiducial cross section** $\sigma_{\text{vis}}^{t\bar{t}}$ is measured (systematic uncertainties can be constrained)

observed $\sigma_{\text{vis}}^{t\bar{t}}$ is extrapolated to full phase space to get **total cross section** $\sigma_{t\bar{t}}$ → introduces model dependence

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

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

"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
**triggers**: dilepton OR single lepton

**offline selection**

- at least two opposite-charge leptons:
  \[ p_T^1 > 25 \text{ GeV}, \quad p_T^2 > 20 \text{ GeV} \]
  \[ |\eta| < 2, 4, \quad m_{ll} > 20 \text{ GeV} \]
- jets: \( p_T > 30 \text{ GeV} \) 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)

arXiv:1812.10505
b-tagging efficiencies in arXiv:1812.10505

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

\begin{align}
    s_{1b} &= \mathcal{L}\sigma_{tt}^{\text{vis}}\epsilon_{ll} \cdot 2\epsilon_{b}(1 - C_{b}\epsilon_{b}) \quad (1) \\
    s_{2b} &= \mathcal{L}\sigma_{tt}^{\text{vis}}\epsilon_{ll} \cdot \epsilon_{b}^{2} C_{b} \quad (2) \\
    s_{\text{other}} &= \mathcal{L}\sigma_{tt}^{\text{vis}}\epsilon_{ll} \cdot (1 - 2\epsilon_{b}(1 - C_{b}\epsilon_{b}) - C_{b}\epsilon_{b}^{2}) \quad (3)
\end{align}

- $\epsilon_{ll}$ is the efficiency of the full selection
- $\epsilon_{b}$ 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
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 $p_T$ spectra are used to constrained JEC uncertainties

binned Poisson Likelihood

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

$$ \mu_i = s_i(\sigma^{\text{vis}}_t, \vec{\lambda}^i) + \sum_k b^{MC}_{k,i}(\vec{\lambda}) $$

- $\vec{\lambda}$ 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: post-fit distributions ($e^{\pm}\mu^{\pm}$)

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

CDF

35.9 fb$^{-1}$ (13 TeV)

CMS

Normalized pull

Fit constraint

MC statistical

Pre-fit uncertainty

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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 $\lambda_k = 0, +1$ and $-1$ respectively
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
numerical values for $\alpha_S(m_Z)$

<table>
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<tr>
<th>PDF set</th>
<th>$\alpha_S(m_Z)$</th>
<th>(fit + PDF) $\pm$</th>
<th>(scale) $\pm$</th>
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<tr>
<td>ABMP16</td>
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<td>$-0.0002$</td>
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<tr>
<td>CT14</td>
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<td>$+0.0018$</td>
<td>$-0.0002$</td>
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<tr>
<td>MMHT14</td>
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numerical values for $m_t(m_t)$

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### QCD parameters in PDF

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<td>174.2</td>
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<td>2</td>
<td>3</td>
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<tr>
<td>$m_t(m_t)$ [GeV]</td>
<td>160.86</td>
<td>162.56</td>
<td>163.30</td>
<td>163.47</td>
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<tr>
<td>$\alpha_S(m_Z)$</td>
<td>0.116</td>
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<td>$\alpha_S$ range</td>
<td>0.112–0.120</td>
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