12^{th} International Workshop on Top Quark Physics
24 September 2019 - Beijing

Running of the top quark mass from pp collisions at $\sqrt{s} = 13$ TeV

results from arXiv:1909.09193
(submitted to Phys. Lett. B)

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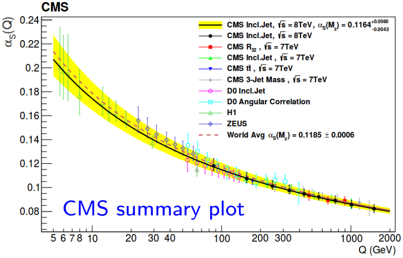
in $\overline{\mathrm{MS}}$ scheme, running of QCD parameters (α_S, m_q) described by a set of RGEs

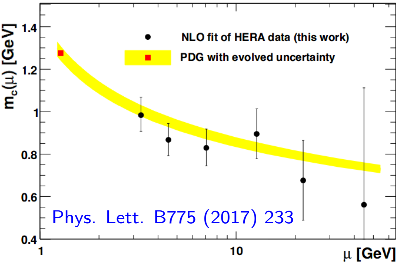
$$\text{For } m_\mathrm{q}: \quad \mu^2 \frac{\mathrm{d}m_\mathrm{q}}{\mathrm{d}\mu^2} = -\gamma(\alpha_\mathrm{S})m_\mathrm{q}$$

anomalous dimension γ calculated pQCD, and can be modified by BSM physics

- running of α_S experimentally verified on a wide range of scales
- running of m_c and m_b investigated at HERA and LEP experiments

→ **running of m_t experimentally investigated for the first time**

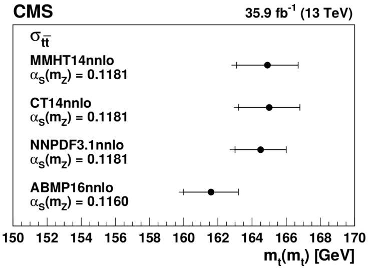




Eur. Phys. J. C79 (2019) 368

inclusive analysis (presented last year)

- simultaneous measurement of inclusive $\sigma_{\mathrm{t\bar{t}}}$ and $m_{\mathrm{t}}^{\mathrm{MC}}$ from likelihood template fit
- $m_{\mathrm{t}}(m_{\mathrm{t}})$ extracted in $\overline{\mathrm{MS}}$ scheme @NNLO from measured $\sigma_{\mathrm{t\bar{t}}}$



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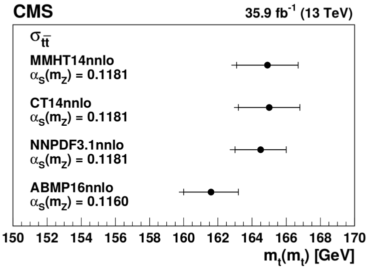

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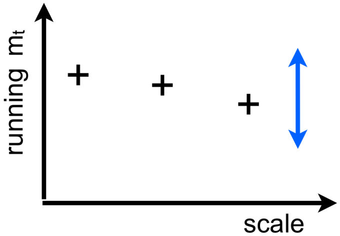


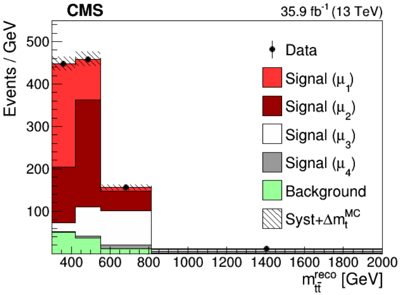
running: measure $m_{\mathrm{t}}(\mu)$ as a function of the scale $\mu = m_{\mathrm{t\bar{t}}}$

- perform precise measurement of $\mathrm{d}\sigma_{\mathrm{t\bar{t}}}/\mathrm{d}m_{\mathrm{t\bar{t}}}$
- extract running by comparing to differential theory predictions in $\overline{\mathrm{MS}}$ scheme

2016 data: 35.9 fb^{-1} (13 TeV)

offline selection

- $\mathrm{e}^{\mp}\mu^{\pm}$ with $\mathrm{p}_{\mathrm{T}\,1\,(2)} > 25\,(20)$ GeV
- jets with $\mathrm{p}_{\mathrm{T}} > 30$ GeV considered
- b-tagging used to classify events
- kinematic reconstruction of $\mathrm{t\bar{t}}$ system in events with ≥ 2 jets $\rightarrow m_{\mathrm{t\bar{t}}}^{\mathrm{reco}}$



signal definition and scale choice

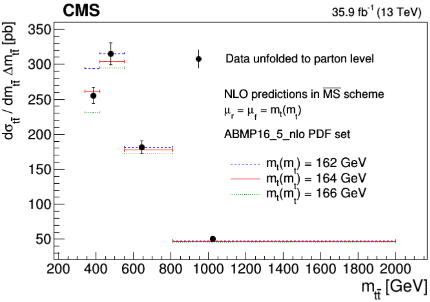
- $\mathrm{t\bar{t}}$ signal split into 4 subsamples in bins of parton-level $m_{\mathrm{t\bar{t}}}$
- each subsample treated as independent signal, and corresponds to a bin in $\mathrm{d}\sigma_{\mathrm{t\bar{t}}}/\mathrm{d}m_{\mathrm{t\bar{t}}}$
- representative scale μ_k assigned to each signal: μ_k = centre-of-gravity of parton-level $m_{\mathrm{t\bar{t}}}$

bin	range [GeV]	μ_k [GeV]
1	< 420	384
2	420-550	476
3	550-810	644
4	> 810	1024

- fit performed in categories of b-jet multiplicity and bins of $m_{t\bar{t}}^{reco}$
- systematic uncert. constrained within visible phase space
- dependence on m_t^{MC} fully incorporated in the fit

response matrix embedded in the likelihood $\Rightarrow$ maximum likelihood unfolding to parton-level

- $m_t(m_t)$ extracted in each bin of $m_{t\bar{t}}$ independently via χ^2 fit of theory predictions to data
- $m_t(m_t)$ converted to $m_t(\mu_k)$ using one-loop RGE solutions ($n_f = 5$)

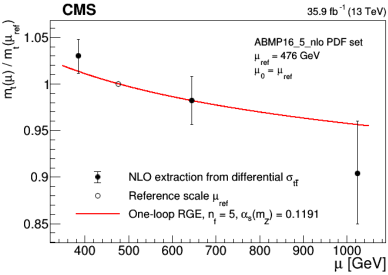


NLO differential calculations obtained with version of MCFM where m_t is treated in $\overline{\text{MS}}$ scheme (EPJ C74 (2014) 3167) running $r(\mu)$ is defined as ratio of $m_\mathrm{t}(\mu)$ to reference mass $m_\mathrm{t}(\mu_\mathrm{ref})$

$$\text{th:}\quad r(\mu) = m_\mathrm{t}(\mu)/m_\mathrm{t}(\mu_\mathrm{ref})$$
$$\text{exp:}\quad r_k = m_\mathrm{t}(\mu_k)/m_\mathrm{t}(\mu_\mathrm{ref})$$

- $r(\mu)$ depends solely on RGE
- r_k benefits from cancellation of correlated uncertainties

$\rightarrow$ choice: $\mu_\mathrm{ref} = \mu_2 = 476\,\mathrm{GeV}$



extraction of the running

running $r(\mu)$ is defined as ratio of $m_{\mathrm{t}}(\mu)$ to reference mass $m_{\mathrm{t}}(\mu_{\mathrm{ref}})$

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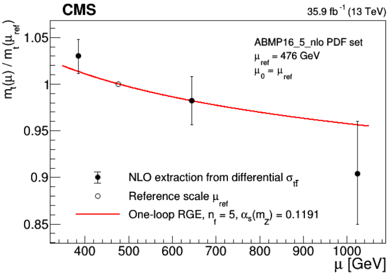
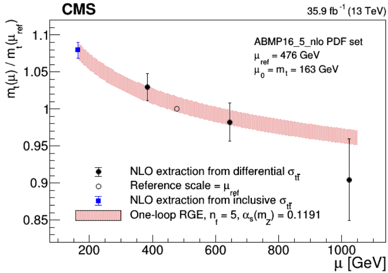
$\rightarrow$ choice: $\mu_{\mathrm{ref}} = \mu_2 = 476\,\mathrm{GeV}$

- result compared to value of $m_{\mathrm{t}}(m_{\mathrm{t}})$ extracted at NLO from inclusive $\sigma_{\mathrm{t\bar{t}}}$
- good agreement with RGE on a wide range of scales, up to $\mu > 1\,\mathrm{TeV}$





summary and outlook in a nutshell

- first experimental investigation of running of the top quark mass
- good agreement with RGE, up to $\mu > 1\ \mathrm{TeV}$
- looking forward to NNLO calculations in the $\overline{\mathrm{MS}}$ scheme to probe the running at two-loops precision

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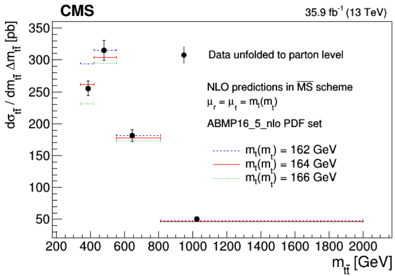
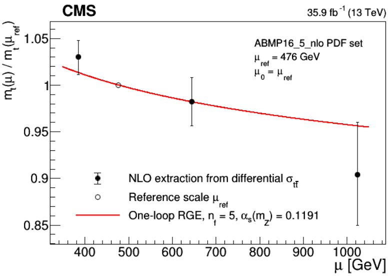
Thank you for your attention!





BACKUP

b-tagging efficiencies are determined *in situ* by exploiting the $\mathrm{t\bar{t}}$ topology, separately in each bin of $m_{\mathrm{t\bar{t}}}$

$$
\begin{aligned}
S^k_{\mathrm{1b}} &= \mathcal{L}\sigma^{(\mu_k)}_{\mathrm{t\bar{t}}} A^k_{\mathrm{sel}} \epsilon^k_{\mathrm{sel}} 2\epsilon^k_{\mathrm{b}} (1 - C^k_{\mathrm{b}} \epsilon^k_{\mathrm{b}}) \\
S^k_{\mathrm{2b}} &= \mathcal{L}\sigma^{(\mu_k)}_{\mathrm{t\bar{t}}} A^k_{\mathrm{sel}} \epsilon^k_{\mathrm{sel}} C^k_{\mathrm{b}} (\epsilon^k_{\mathrm{b}})^2 \\
S^k_{\mathrm{other}} &= \mathcal{L}\sigma^{(\mu_k)}_{\mathrm{t\bar{t}}} A^k_{\mathrm{sel}} \epsilon^k_{\mathrm{sel}} \left[1 - 2\epsilon^k_{\mathrm{b}} (1 - C^k_{\mathrm{b}} \epsilon^k_{\mathrm{b}}) - C^k_{\mathrm{b}} (\epsilon^k_{\mathrm{b}})^2\right]
\end{aligned}
$$

- $\epsilon^k_{\mathrm{sel}}$ is the efficiency of the full selection in $m_{\mathrm{t\bar{t}}}$ bin k
- ϵ^k_{b} is the b-tagging efficiency in $m_{\mathrm{t\bar{t}}}$ bin k
- C^k_{b} represents the residual correlation of tagging the two b-jets

$\rightarrow$ all parameters are derived by the simulation and depend on the systematic uncertainties

binned Poisson Likelihood

$$L = \prod_i \frac{\mathrm{e}^{-\nu_i} \nu_i^{n_i}}{n_i!} \prod_j \pi(\omega_j) \prod_m \pi(\lambda_m)$$

$$\nu_i = \sum_{k=1}^{4} s_i^k(\sigma_{\mathrm{t\bar{t}}}^{(\mu_k)}, \vec{\lambda}, m_{\mathrm{t}}^{\mathrm{MC}}) + \sum_j b_i^j(\omega_j, \vec{\lambda})$$

- $\vec{\lambda}$ is the set of nuisance parameters
- ω_j is the normalization of background source j
- $\pi(\lambda_m)$ and $\pi(\omega_j)$ parametrize the prior knowledge of m^{th} nuisance parameter and j^{th} background normalization

fit performed in categories of b-tagged jet multiplicity and bins of $m_{t\bar{t}}^{reco}$

- b-tag categories constrain b-tagging efficiencies
- $m_{t\bar{t}}$ categories sensitive to different signals $\rightarrow$ constrain $\sigma_{t\bar{t}}^{(\mu_k)}$
- categories with < 2 jets, where kin reco cannot be performed, included in fit
  - increases visible phase space $\Rightarrow$ **reduces extrapolation uncertainties**

for each category and sub-category, suitable differential distribution fitted

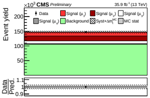
- $m_{\ell b}^{min}$ distribution used to constrain m_t^{MC}
- p_T of softest jet in event used to constrain JES

- systematic uncertainties profiled in Poisson likelihood and constrained in the visible phase space
- additional uncertainties assigned to extrapolation to full phase space
  (constraints in modelling uncertainties NOT considered in extrapolation)

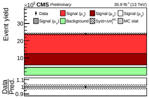
$\rightarrow$ this procedure yields results that are **unfolded to the parton level with maximum likelihood method**

CMS-PAS-TOP-19-007

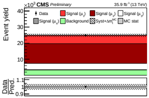
0 b-tags, no $m_{t\bar{t}}^{\text{reco}}$



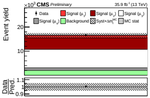
0 b-tags, $m_{t\bar{t}}^{\text{reco}}$ 1



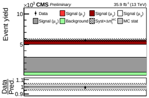
0 b-tags, $m_{t\bar{t}}^{\text{reco}}$ 2



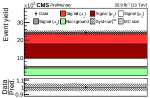
0 b-tags, $m_{t\bar{t}}^{\text{reco}}$ 3



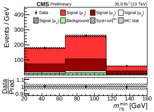
0 b-tags, $m_{t\bar{t}}^{\text{reco}}$ 4



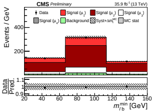
1 b-tag, no $m_{t\bar{t}}^{\text{reco}}$



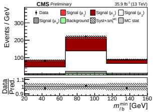
1 b-tag, $m_{t\bar{t}}^{\text{reco}}$ 1



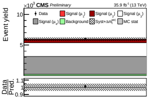
1 b-tag, $m_{t\bar{t}}^{\text{reco}}$ 2



1 b-tag, $m_{t\bar{t}}^{\text{reco}}$ 3

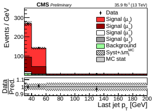


1 b-tag, $m_{t\bar{t}}^{\text{reco}}$ 4

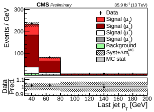


"no $m_{t\bar{t}}^{\text{reco}}$" = events with less than 2 jets

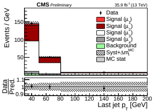
2 b-tags, $m_{t\bar{t}}^{\text{reco}}$ 1



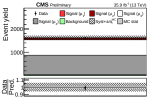
2 b-tags, $m_{t\bar{t}}^{\text{reco}}$ 2



2 b-tags, $m_{t\bar{t}}^{\text{reco}}$ 3



2 b-tags, $m_{t\bar{t}}^{\text{reco}}$ 4



- differential predictions @NLO obtained with version of MCFM where m_{t} treated in $\overline{\mathrm{MS}}$ scheme (Eur. Phys. J. C74 (2014) 3167)
- only theory calculation available with top mass in $\overline{\mathrm{MS}}$ scheme
- evolution of QCD couplings at 1-loop, 5 flavours
- scale choice: $\mu_{\mathrm{r}} = \mu_{\mathrm{f}} = m_{\mathrm{t}}(m_{\mathrm{t}})$
- interfaced with ABMP16_5_nlo PDF set: only available PDF set with m_{t} in $\overline{\mathrm{MS}}$ scheme, consistently with calculation

essence of this measurement: extract slope of NLO running, taking $m_t(\mu_2) = m_t(\mu_{ref})$ as reference

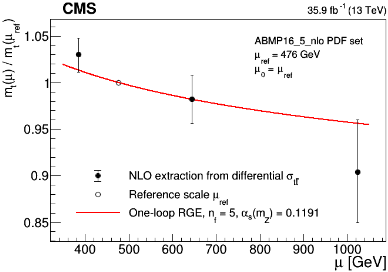
- $r(\mu) = m_t(\mu)/m_t(\mu_2)$
- $r_{k2} = m_t(\mu_k)/m_t(\mu_2),\ k = 1, 3, 4$

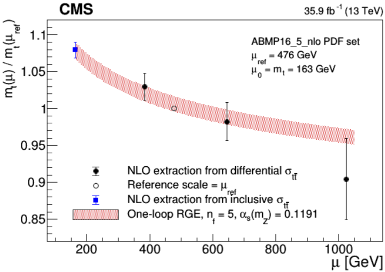
advantages

- slope $r(\mu)$ directly related to RGE prediction
- ratios r_{k2} benefit from partial cancellation of correlated uncertainties
- $\mu_{ref} = \mu_2$ to minimize correlations between extracted ratios

uncertainties in the ratios

- fit and extrapolation
- PDF and α_S from ABMP eigenvectors
- scale variations in MCFM not meaningful here, as scale dependence is being investigated
- all correlations properly taken into account





$\rightarrow$ observed running consistent with RGE

$$r_{12} = m_\mathrm{t}(\mu_1)/m_\mathrm{t}(\mu_2) = 1.030 \pm 0.018\ (\mathrm{fit})\ ^{+0.003}_{-0.006}\ (\mathrm{PDF} + \alpha_\mathrm{S})\ ^{+0.003}_{-0.002}\ (\mathrm{extr})$$

$$r_{32} = m_\mathrm{t}(\mu_3)/m_\mathrm{t}(\mu_2) = 0.982 \pm 0.025\ (\mathrm{fit})\ ^{+0.006}_{-0.005}\ (\mathrm{PDF} + \alpha_\mathrm{S})\ ^{+0.004}_{-0.004}\ (\mathrm{extr})$$

$$r_{42} = m_\mathrm{t}(\mu_4)/m_\mathrm{t}(\mu_2) = 0.904 \pm 0.050\ (\mathrm{fit})\ ^{+0.019}_{-0.017}\ (\mathrm{PDF} + \alpha_\mathrm{S})\ ^{+0.017}_{-0.013}\ (\mathrm{extr})$$

observed running parametrized as

$$f(x,\mu) = x\,[r(\mu) - 1] + 1$$

such that

- $f(1,\mu) = r(\mu) \to$ RGE running
- $f(0,\mu) = 1 \to$ no running

x_{min} extracted from χ^2 fit to r_{k2}:

- correlations in extracted ratios studied with toy experiment procedure
- correlations fully taken into account in estimate of x_{min}

$$x_{\min} = 2.05 \pm 0.61\ (\text{fit})\ ^{+0.31}_{-0.55}\ (\text{PDF} + \alpha_{\mathrm{S}})\ ^{+0.24}_{-0.49}\ (\text{extr})$$

$\to$ compatible with RGE within 1.1σ