Physics at the Terascale meeting
26^{th} November 2019 - Hamburg

Running of the top quark mass from proton-proton collisions at $\sqrt{s} = 13\,\mathrm{TeV}$

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

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running of α_S is described by renormalization group equation (RGE)

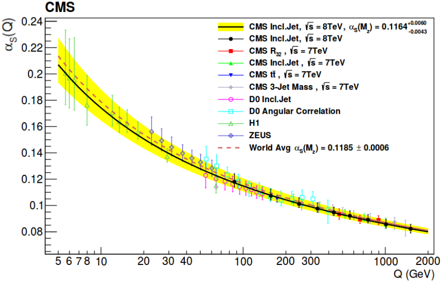
$$\alpha_S(\mu) = \frac{\alpha_S(\mu_0)}{1+\alpha_S(\mu_0)\frac{11n_c-2n_f}{12\pi}\ \ln\frac{\mu^2}{\mu_0^2}} \quad \text{(1 loop)}$$

typical procedure to measure α_S running:

- extract $\alpha_S(m_Z)$ from some final state observable in limited scale range (e.g. $\mu = \text{jet } p_T$)
- convert $\alpha_S(m_Z)$ to $\alpha_S(\mu)$ using RGE, w. appropriate choice of μ in each bin

N.B. this is equivalent to extracting $\alpha_S(\mu)$ directly (RGE implicitly assumed)

CMS summary plot



- **well-established procedure**
- experimentally verified on a very wide range of scales, at different experiments

running of quark masses

- similar procedure can be used to extract running of heavy quark masses

short distance $\overline{\mathrm{MS}}$ mass can be expressed in terms of pole mass

$$m_\mathrm{q}(m_\mathrm{q}) = m_\mathrm{q}^\mathrm{pole}\left[1 - \frac{4}{3\pi}\alpha_\mathrm{S}(m_\mathrm{q}) + \mathcal{O}(\alpha_\mathrm{S}^2)\right]$$

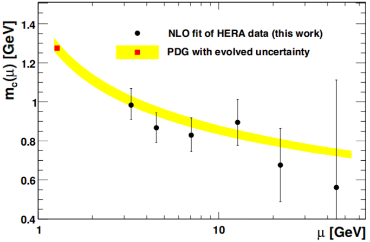
and evolved to an arbitrary scale μ

$$m_\mathrm{q}(\mu) = m_\mathrm{q}(m_\mathrm{q})\left[1 - \frac{\alpha_\mathrm{S}(\mu)}{\pi}\ln\frac{\mu^2}{m_\mathrm{q}^2} + \mathcal{O}(\alpha_\mathrm{S}^2)\right]$$

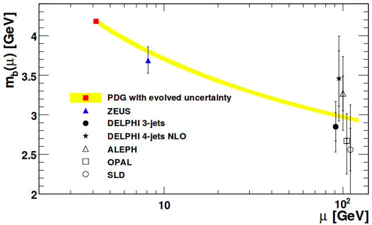
- running of m_c has been experimentally determined at HERA experiments
- running of m_b determined with data from different experiments

→ **running of m_t investigated for the first time**, using LHC data at $\sqrt{s} = 13\,\mathrm{TeV}$

Phys. Lett. B775 (2017)

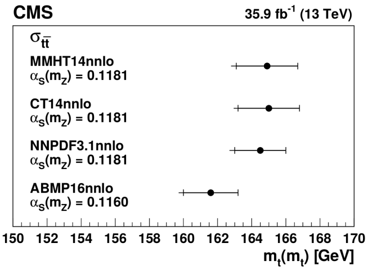


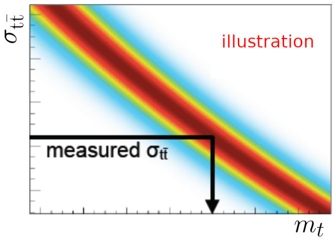
review, arXiv:1506.07519

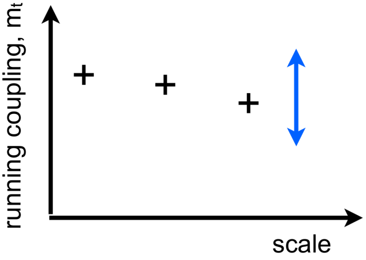


- simultaneous determination of $\sigma_{\mathrm{t\bar{t}}}$ and $m_{\mathrm{t}}^{\mathrm{MC}}$ from likelihood fit to multi-differential distributions
- mitigates experimental dependence of $\sigma_{\mathrm{t\bar{t}}}$ on $m_{\mathrm{t}}^{\mathrm{MC}}$
- measured $\sigma_{\mathrm{t\bar{t}}}$ used to extract $m_{\mathrm{t}}(m_{\mathrm{t}})$ @NNLO using Hathor predictions in $\overline{\mathrm{MS}}$ scheme

Eur. Phys. J. C79 (2019) 368







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

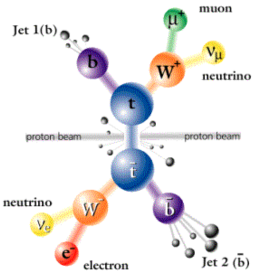
- perform precise measurement of $\mathrm{d}\sigma_{\mathrm{t\bar{t}}}/\mathrm{d}m_{\mathrm{t\bar{t}}}$ (likelihood fit)
- extract $m_{\mathrm{t}}(\mu)$ by comparing to differential theory predictions in $\overline{\mathrm{MS}}$ scheme

	TOP-17-001	TOP-19-007
experimental input	inclusive $\sigma_{\mathrm{t\bar{t}}}$	$\mathrm{d}\sigma_{\mathrm{t\bar{t}}}/\mathrm{d}m_{\mathrm{t\bar{t}}}$ at parton level
theory input	incl. $\sigma_{\mathrm{t\bar{t}}}$ @NNLO, $\overline{\mathrm{MS}}$	$\mathrm{d}\sigma_{\mathrm{t\bar{t}}}/\mathrm{d}m_{\mathrm{t\bar{t}}}$ @NLO, $\overline{\mathrm{MS}}$
output	$m_{\mathrm{t}}(m_{\mathrm{t}})$ @NNLO	$m_{\mathrm{t}}(\mu)$ @NLO, $\mu = m_{\mathrm{t\bar{t}}}$

dataset: 2016 data, 35.9 fb^{-1}
triggers: dilepton OR single lepton

offline selection

- one electron and one muon of OS $(\mathrm{e}^{\mp}\mu^{\pm})$
  $\mathrm{p_{T1}} > 25\,\mathrm{GeV}$, $\mathrm{p_{T2}} > 20\,\mathrm{GeV}$
- jets with $\mathrm{p_T} > 30\,\mathrm{GeV}$ considered
- b-tagging: CSVv2 Tight WP
  → only used to classify events



analytic kinematic reconstruction in events with at least two jets

the kin. reco. assumes:

1. MET solely originates from neutrinos
2. certain values for M_{W}, m_{t} $(=m_{\mathrm{t}}^{\mathrm{kin}})$

→ introduces dependence on assumed $m_{\mathrm{t}}^{\mathrm{kin}}$

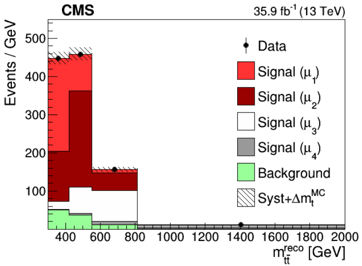
mitigation of the effect:

- kin reco repeated with different values of $m_{\mathrm{t}}^{\mathrm{kin}}$, and varying $m_{\mathrm{t}}^{\mathrm{MC}} = m_{\mathrm{t}}^{\mathrm{kin}}$
- **dependence propagated to the fit**, where $m_{\mathrm{t}}^{\mathrm{MC}}$ is a free parameter

signal definition

- $\mathrm{t\bar{t}}$ signal split into 4 subsamples in bins of parton-level $m_{\mathrm{t\bar{t}}}$ (before radiation)
- each bin treated as independent signal, and corresponds to a bin in $\mathrm{d}\sigma_{\mathrm{t\bar{t}}}/\mathrm{d}m_{\mathrm{t\bar{t}}}$
- binning reflects $m_{\mathrm{t\bar{t}}}$ resolution ($\simeq 13\%$)

Bin	$m_{\mathrm{t\bar{t}}}$ [GeV]	μ_k [GeV]
1	< 420	384
2	420-550	476
3	550-810	644
4	> 810	1024



- a representative scale μ_k is assigned to each signal
- μ_k = centre-of-gravity of bin k in $m_{\mathrm{t\bar{t}}}$ (table)

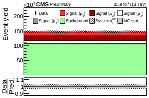
- cross section of signal μ_k:

$$\sigma_{\mathrm{t\bar{t}}}^{(\mu_k)} = \int_{m_{\mathrm{t\bar{t}}}^{\mathrm{low},k}}^{m_{\mathrm{t\bar{t}}}^{\mathrm{high},k}} \frac{\mathrm{d}\sigma_{\mathrm{t\bar{t}}}}{\mathrm{d}m_{\mathrm{t\bar{t}}}} \mathrm{d}m_{\mathrm{t\bar{t}}}$$

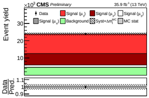
post-fit distributions of fit inputs

CMS-PAS-TOP-19-007

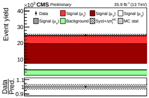
0 b-tags, no $m_{t\bar{t}}^{reco}$



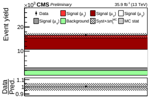
0 b-tags, $m_{t\bar{t}}^{reco}$ 1



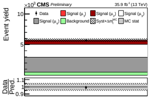
0 b-tags, $m_{t\bar{t}}^{reco}$ 2



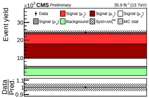
0 b-tags, $m_{t\bar{t}}^{reco}$ 3



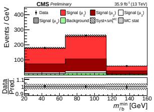
0 b-tags, $m_{t\bar{t}}^{reco}$ 4



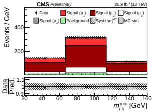
1 b-tag, no $m_{t\bar{t}}^{reco}$



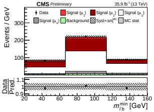
1 b-tag, $m_{t\bar{t}}^{reco}$ 1



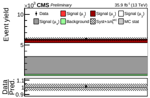
1 b-tag, $m_{t\bar{t}}^{reco}$ 2



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

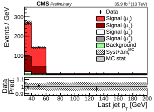


1 b-tag, $m_{t\bar{t}}^{reco}$ 4

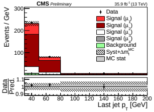


"no $m_{t\bar{t}}^{reco}$" = events with less than 2 jets

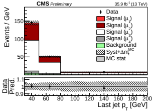
2 b-tags, $m_{t\bar{t}}^{reco}$ 1



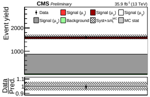
2 b-tags, $m_{t\bar{t}}^{reco}$ 2



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



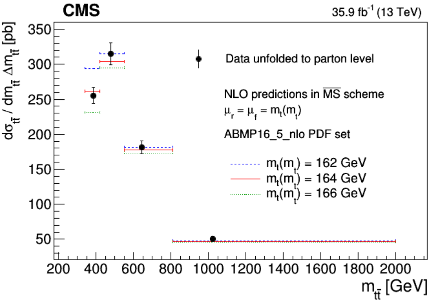
2 b-tags, $m_{t\bar{t}}^{reco}$ 4



- 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 ($n_f = 5$)



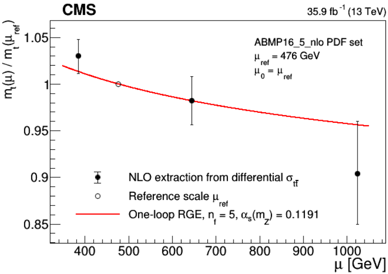
NLO differential calculations obtained with version of MCFM where m_t is treated in $\overline{\mathrm{MS}}$ scheme (EPJ C74 (2014) 3167) running $r(\mu)$ is defined as ratio of $m_{\mathrm{t}}(\mu)$ to reference mass $m_{\mathrm{t}}(\mu_{\mathrm{ref}})$

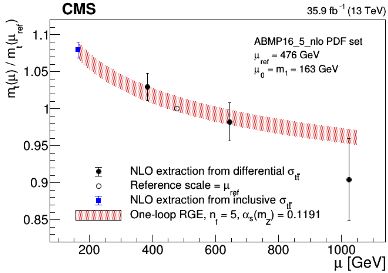
$$\text{th:} \quad r(\mu) = m_{\mathrm{t}}(\mu)/m_{\mathrm{t}}(\mu_{\mathrm{ref}})$$
$$\text{exp:} \quad r_k = m_{\mathrm{t}}(\mu_k)/m_{\mathrm{t}}(\mu_{\mathrm{ref}})$$

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

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

- 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 $\mu > 1\,\mathrm{TeV}$





observed running parametrized as

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

such that

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

$x_{\rm min}$ 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 $x_{\rm min}$

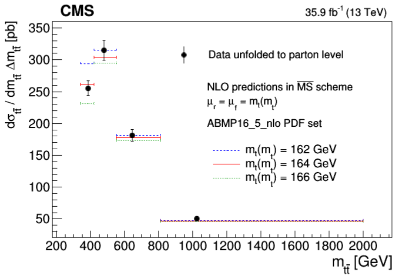
$$x_{\rm min} = 2.05 \pm 0.61\ (\text{fit})\ {}^{+0.31}_{-0.55}\ (\text{PDF} + \alpha_{\rm S})\ {}^{+0.24}_{-0.49}\ (\text{extr})$$

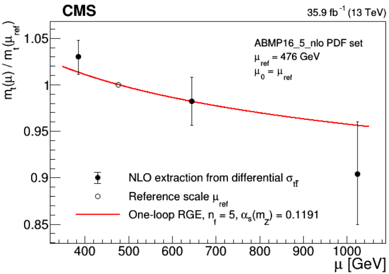
$\rightarrow$ compatible with RGE within 1.1σ

$\rightarrow$ no-running hp excluded above 95% CL

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

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

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

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

- $\vec{\lambda}$ 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

- 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
- 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 $m_{\mathrm{t}}(\mu_2) = m_{\mathrm{t}}(\mu_{\mathrm{ref}})$ as reference

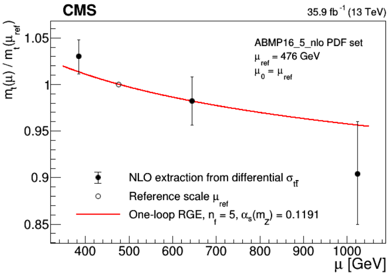
- $r(\mu) = m_{\mathrm{t}}(\mu)/m_{\mathrm{t}}(\mu_2)$
- $r_{k2} = m_{\mathrm{t}}(\mu_k)/m_{\mathrm{t}}(\mu_2),\ k = 1, 3, 4$

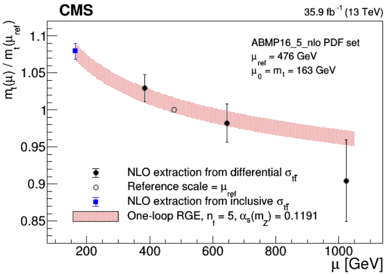
advantages

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

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

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

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