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Determination of the top-quark pole mass and strong coupling constant from the $t\bar{t}$ production cross section in pp collisions at $\sqrt{s} = 7$ TeV

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ABSTRACT

The inclusive cross section for top-quark pair production measured by the CMS experiment in proton–proton collisions at a center-of-mass energy of 7 TeV is compared to the QCD prediction at next-to-next-to-leading order with various parton distribution functions to determine the top-quark pole mass, m_t^{pole}, or the strong coupling constant, α_S. With the parton distribution function set NNPDF2.3, a pole mass of $176.7^{+3.8}_{-3.4}$ GeV is obtained when constraining α_S at the scale of the Z boson mass, m_Z, to the current world average. Alternatively, by constraining m_t^{pole} to the latest average from direct mass measurements, a value of $\alpha_S(m_Z) = 0.1151^{+0.0033}_{-0.0032}$ is extracted. This is the first determination of α_S using events from top-quark production.

1. Introduction

The Large Hadron Collider (LHC) has provided a wealth of proton–proton collisions, which has enabled the Compact Muon Solenoid (CMS) experiment [1] to measure cross sections for the production of top-quark pairs ($t\bar{t}$) with high precision employing a variety of approaches [2–10]. Comparing the presently available results, obtained at a center-of-mass energy, $\sqrt{s}$, of 7 TeV, to theoretical predictions allows for stringent tests of the underlying models and for constraints on fundamental parameters. Top-quark pair production can be described in the framework of quantum chromodynamics (QCD) and calculations for the inclusive $t\bar{t}$ cross section, $\sigma_{t\bar{t}}$, have recently become available to complete next-to-next-to-leading order (NNLO) in perturbation theory [11]. Crucial inputs to these calculations are: the top-quark mass, m_t; the strong coupling constant, α_S; and the gluon distribution in the proton, since $t\bar{t}$ production at LHC energies is expected to occur predominantly via gluon–gluon fusion.

The top-quark mass is one of the fundamental parameters of the standard model (SM) of particle physics. Its value significantly affects predictions for many observables either directly or via radiative corrections. As a consequence, the measured m_t is one of the key inputs to electroweak precision fits, which enable comparisons between experimental results and predictions within and beyond the SM. Furthermore, together with the Higgs-boson mass and α_S, m_t has direct implications on the stability of the electroweak vacuum [12,13]. The most precise result for m_t, obtained by combining direct measurements performed at the Tevatron, is 173.18 ± 0.94 GeV [14]. Similar measurements performed by the CMS Collaboration [2,15–17] are in agreement with the Tevatron result and of comparable precision. However, except for a few cases [17], these direct measurements rely on the relation between m_t and the respective experimental observable, e.g., a reconstructed invariant mass, as expected from simulated events. In QCD beyond leading order, m_t depends on the renormalization scheme [18,19]. The available Monte Carlo generators contain matrix elements at leading order or next-to-leading order (NLO), while

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higher orders are simulated by applying parton showering. Studies suggest that m_t as implemented in Monte Carlo generators corresponds approximately to the pole ("on-shell") mass, m_t^{pole}, but that the value of the true pole mass could be of the order of 1 GeV higher compared to m_t in the current event generators [20]. In addition to direct m_t measurements, the mass dependence of the QCD prediction for $\sigma_{t\bar{t}}$ can be used to determine m_t by comparing the measured to the predicted cross section [13,19,21–24]. Although the sensitivity of $\sigma_{t\bar{t}}$ to m_t might not be strong enough to make this approach competitive in precision, it yields results affected by different sources of systematic uncertainties compared to the direct m_t measurements and allows for extractions of m_t in theoretically well-defined mass schemes. It has been advocated to directly extract the $\overline{\text{MS}}$ mass of the top quark using the $\sigma_{t\bar{t}}$ prediction in that scheme [21]. The relation between pole and $\overline{\text{MS}}$ mass is known to three-loop level in QCD but might receive large electroweak corrections [25]. In principle, the difference between the results obtained when extracting m_t in the pole and converting it to the $\overline{\text{MS}}$ scheme or extracting the $\overline{\text{MS}}$ mass directly should be small in view of the precision that the extraction of m_t from the inclusive $\sigma_{t\bar{t}}$ at a hadron collider provides. Therefore, only the pole mass scheme is employed in this Letter.

With the exception of the quark masses, α_S is the only free parameter of the QCD Lagrangian. While the renormalization group equation predicts the energy dependence of the strong coupling, i.e., gives a functional form for $\alpha_S(Q)$, where Q is the energy scale of the process, actual values of α_S can only be obtained based on experimental data. By convention and to facilitate comparisons, α_S values measured at different energy scales are typically evolved to $Q = m_Z$, the mass of the Z boson. The current world average for $\alpha_S(m_Z)$ is 0.1184 ± 0.0007 [26]. In spite of this relatively precise result, the uncertainty on α_S still contributes significantly to many QCD predictions, including expected cross sections for top-quark pairs or Higgs bosons. Furthermore, thus far very few measurements allow α_S to be tested at high Q and the precision on the average for $\alpha_S(m_Z)$ is driven by low-Q measurements. Energies up to 209 GeV were probed with hadronic final states in electron–positron collisions at LEP using NNLO predictions [27–30]. Jet measurements at the Tevatron and the LHC have recently extended the range up to 400 GeV [31], 600 GeV [32], and 1.4 TeV [33]. However, most predictions for jet production in hadron collisions are only available up to NLO QCD. Even when these predictions are available at approximate NNLO, as used in [34], they suffer from significant uncertainties related to the choice and variation of the renormalization and factorization scales, μ_R and μ_F, as well as from uncertainties related to non-perturbative corrections.

In cross section calculations, α_s appears not only in the expression for the parton–parton interaction but also in the QCD evolution of the parton distribution functions (PDFs). Varying the value of $\alpha_S(m_Z)$ in the $\sigma_{t\bar{t}}$ calculation therefore requires a consistent modification of the PDFs. Moreover, a strong correlation between α_S and the gluon PDF at large partonic momentum fractions is expected to significantly enhance the sensitivity of $\sigma_{t\bar{t}}$ to α_S [35].

In this Letter, the predicted $\sigma_{t\bar{t}}$ is compared to the most precise single measurement to date [6], and values of m_t^{pole} and $\alpha_S(m_Z)$ are determined. This extraction is performed under the assumption that the measured $\sigma_{t\bar{t}}$ is not affected by non-SM physics. The interplay of the values of m_t^{pole}, α_s and the proton PDFs in the prediction of $\sigma_{t\bar{t}}$ is studied. Five different PDF sets, available at NNLO, are employed and for each a series of different choices of $\alpha_S(m_Z)$ are considered. A simultaneous extraction of top-quark mass and strong coupling constant from the total $t\bar{t}$ cross section alone is not possible since both parameters alter the predicted $\sigma_{t\bar{t}}$ in such a way that any variation of one parameter can be compensated by a variation of the other. Values of m_t^{pole} and $\alpha_S(m_Z)$ are therefore determined at fixed values of $\alpha_S(m_Z)$ and m_t^{pole}, respectively. For the m_t^{pole} extraction, $\alpha_S(m_Z)$ is constrained to the latest world average value with its corresponding uncertainty (0.1184 ± 0.0007) [26]. Furthermore, it is assumed that the m_t parameter of the Monte Carlo generator that is employed in the $\sigma_{t\bar{t}}$ measurement is equal to m_t^{pole} within ± 1.00 GeV [20]. For the α_S extraction, m_t^{pole} is set to the Tevatron average of 173.18 ± 0.94 GeV [14]. To account for the possible difference between the pole mass and the Monte Carlo generator mass [20], an additional uncertainty, assumed to be 1.00 GeV, is added in quadrature to the experimental uncertainty, resulting in a total uncertainty on the top-quark mass constraint, δm_t^{pole}, of 1.4 GeV. Although the potential α_S dependence of the direct m_t measurements has not been explicitly evaluated, it is assumed to be covered by the quoted mass uncertainty.

2. Predicted cross section

The expected $\sigma_{t\bar{t}}$ has been calculated to NNLO for all production channels, namely the all-fermionic scattering modes ($q\bar{q}$, qq', $q\bar{q}'$, $qq \to t\bar{t} + X$) [36,37], the reaction $qg \to t\bar{t} + X$ [38], and the dominant process $gg \to t\bar{t} + X$ [11]. In the present analysis, these calculations are used as implemented in the program Top++ 2.0 [39]. Soft-gluon resummation is performed at next-to-next-leading-log (NNLL) accuracy [40,41]. The scales μ_R and μ_F are set to m_t^{pole}. In order to evaluate the theoretical uncertainty of the fixed-order calculation, the missing contributions from higher orders are estimated by varying μ_R and μ_F up and down by a factor of 2 independently, while using the restriction $0.5 \leqslant \mu_F/\mu_R \leqslant 2$. These choices for the central scale and the variation procedure were suggested by the authors of the NNLO calculations and used for earlier $\sigma_{t\bar{t}}$ predictions as well [42].

Five different NNLO PDF sets are employed: ABM11 [43], CT10 [44], HERAPDF1.5 [45], MSTW2008 [46,47], and NNPDF2.3 [48]. The corresponding uncertainties are calculated at the 68% confidence level for all PDF sets. This is done by recalculating the $\sigma_{t\bar{t}}$ at NNLO + NNLL for each of the provided eigenvectors or replicas of the respective PDF set and then performing error propagation according to the prescription of that PDF group. In the specific case of the CT10 PDF set, the uncertainties are provided for the 90% confidence level only. For this Letter, following the recommendation of the CTEQ group, these uncertainties are adjusted using the general relation between confidence intervals based on Gaussian distributions [26], i.e., scaled down by a factor of $\sqrt{2}\,\text{erf}^{-1}(0.90) = 1.64$, where erf denotes the error function.

The dependence of the predicted $\sigma_{t\bar{t}}$ on the choice of m_t^{pole} is studied by varying m_t^{pole} in the range from 130 to 220 GeV in steps of 1 GeV and found to be well described by a third-order polynomial in m_t^{pole} divided by $(m_t^{pole})^4$. The α_S dependence of $\sigma_{t\bar{t}}$ is studied by varying the value of $\alpha_S(m_Z)$ over the entire valid range for a particular PDF set, as listed in Table 1. The relative change of $\sigma_{t\bar{t}}$ as a function of $\alpha_S(m_Z)$ can be parametrized using a second-order polynomial in $\alpha_S(m_Z)$, where the three coefficients of that polynomial depend linearly on m_t^{pole}.

The resulting $\sigma_{t\bar{t}}$ predictions are compared in Fig. 1, both as a function of m_t^{pole} and of $\alpha_S(m_Z)$. For a given value of $\alpha_S(m_Z)$, the predictions based on NNPDF2.3 and CT10 are very similar. The cross sections obtained with MSTW2008 and HERAPDF1.5 are