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Determination of the top-quark mass from hadro-production of single top-quarks

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ABSTRACT

We present a new determination of the top-quark mass m_t based on the experimental data from the Tevatron and the LHC for single-top hadro-production. We use the inclusive cross sections of s- and t-channel top-quark production to extract m_t and to minimize the dependence on the strong coupling constant and the gluon distribution in the proton compared to the hadro-production of top-quark pairs. As part of our analysis we compute the next-to-next-to-leading order approximation for the s-channel cross section in perturbative QCD based on the known soft-gluon corrections and implement it in the program HatHor for the numerical evaluation of the hadronic cross section. Results for the top-quark mass are reported in the $\overline{\mathrm{MS}}$ and in the on-shell renormalization scheme.

Since the discovery of the top-quark in 1995 [1,2], the precise value of its mass has always been of great interest as a fundamental parameter of the Standard Model (SM). In the course of time several approaches have been used to extract the top-quark mass m_t as summarized for instance in [3]. While kinematic fits to the top-quark decay products allow for a very precise determination of parameters in Monte Carlo (MC) programs that are used to describe the measured distributions, the relation of these MC parameters to the fundamental SM parameters needs to be calibrated and related uncertainties need to be taken into account [4]. The determination of the top-quark mass from inclusive cross sections measured at the hadron colliders Tevatron and the Large Hadron Collider (LHC) provides an alternative way. This allows to relate the experimental cross section measurements directly to theoretical calculations which use a top-quark mass parameter in a well-defined renormalization scheme.

In this regard, the pair production of top-quarks has been of primary interest. It is dominantly mediated by the strong interactions. In consequence, theoretical predictions for top-quark pair production are highly sensitive to the value of the strong coupling constant α_s as well as to the parton luminosity parameterized through the parton distribution functions (PDFs) of the colliding hadrons. In fact, the uncertainty in the value of α_s and the dependence on the gluon PDF are the dominant sources which limit the precision of current theory predictions at the LHC [5]. Future measurements in particular at the LHC in Run 2 can potentially provide improved determinations of α_s and the PDFs, yet it is worth to investigate other methods to access m_t that do not rely on these controversial quantities.

In this letter we determine the top-quark mass based on single-top production cross section measurements as a complementary way to arrive at a well-defined value for m_t that is largely independent of α_s and the gluon PDFs. Single-top production generates the top-quark in an electroweak interaction, predominantly in a vertex with a bottom-quark and a W-boson. The orientation of this vertex assigns single-top production diagrams to different channels as illustrated in Fig. 1. As our focus is on the minimization of the correlation between m_t, α_s and the gluon luminosity, we consider only the so-called s-channel and t-channel production of single top-quarks in the following. The cross sections for those processes are directly proportional to the light quark PDFs, which are nowadays well constrained by data on the measured charged lepton asymmetries from $W^\pm$ gauge-boson production at the LHC. We use the inclusive single-top cross section measurements for those channels to determine m_t and compare the results to the ones obtained from $t\bar{t}$ production. Our study is based on data from the Tevatron at center-of-mass energy $\sqrt{S} = 1.96$ TeV as well as from the LHC at $\sqrt{S} = 7, 8$ and the most recent one at 13 TeV.

The theoretical description of both top-quark pair production and single-top production has reached a very high level of accuracy. The total cross section of $t\bar{t}$ hadro-production has been calculated up to the next-to-next-to-leading order (NNLO) corrections

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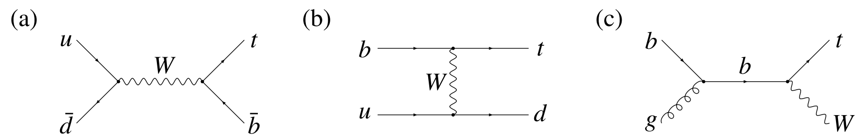

Fig. 1. Representative leading order Feynman diagrams for single top-quark production: (a) s-channel; (b) t-channel; (c) in association with a W boson.

in perturbative QCD [6–9]. The NNLO result shows good apparent convergence of the perturbative expansion and greatly reduced sensitivity with respect to a variation of the renormalization and factorization scales μ_R and μ_F, which is conventionally taken to estimate the uncertainty from the truncation of the perturbation series.

For the t-channel of single-top production, the NNLO QCD corrections have been determined in the structure function approximation [10] (see also Ref. [11]), by computing separately the QCD corrections to the light- and heavy-quark lines, see Fig. 1 (b). Any dynamical cross-talk between the two quark lines, e.g., double-box topologies, has been neglected in Ref. [10] and is expected to be small due to color suppression. The current theoretical status regarding those non-factorizing corrections is summarized in Ref. [12].

The inclusive cross section of s-channel single-top production is fully known up to the next-to-leading order (NLO) QCD corrections [13], see also [14] for fully differential results. Beyond NLO accuracy, fixed-order expansions of the resummed soft-gluon contributions up to the next-to-leading logarithms (NLL) have been provided as an approximation of the complete NNLO result, both for the Tevatron [15] and the LHC [16]. Subsequently, these results have been extended to next-to-next-to-leading logarithmic (NNLL) accuracy [17]. The threshold corrections in the s-channel are large and dominant and, therefore, they provide a good approximation to the full exact result, see Ref. [18] for a validation at NLO. In our study we use Refs. [15–17] to derive compact expressions for the approximate corrections at NLO and NNLO including soft-gluon effects almost complete to NNLL accuracy. To that end, we integrate the partonic double-differential cross section given in Refs. [15–17] over the phase space, i.e., the partonic Mandelstam variables t and u, and obtain the inclusive partonic cross section to logarithmic accuracy in the top-quark velocity $\beta = (1 - m_t^2/s)^{1/2}$.

We expand the partonic cross section for s-channel single-top production as a power series

$$\sigma = \sigma^{(0)} + \alpha_s \sigma^{(1)} + \alpha_s^2 \sigma^{(2)} \,, \tag{1}$$

with $\alpha_s = \alpha_s(\mu_R)$ taken at the renormalization scale μ_R and the leading-order partonic cross section for the process $u\bar{d} \to t\bar{b}$ given by

$$\sigma^{(0)} = \frac{\pi \alpha^2 V_{tb}^2 V_{ud}^2 (m_t^2 - s)^2 (m_t^2 + 2s)}{24 s^2 \sin^4\theta_W (m_W^2 - s)^2} \,. \tag{2}$$

Here, $\sqrt{s}$ is the partonic center-of-mass energy, m_W the W-boson mass and α, $\sin\theta_W$, V_{tb} and V_{ud} are the electroweak and CKM parameters [19].

The NLO result in Eq. (1) is denoted $\sigma^{(1)}$ and the exact result is known [13] and has been implemented in the program HATHOR [20,19] for a fast and efficient evaluation of the total cross section. Based on the threshold enhanced soft-gluon contributions we can provide an approximate NLO (aNLO) result for $\sigma^{(1)}$ as

$$\sigma^{(1)} \simeq \sigma^{(0)} \left(1 - \beta^2\right) \frac{C_F}{8\pi} \left(112 \log^2(\beta) - 148 \log(\beta) + 63 - 4 \log\left(\frac{\mu_F^2}{m_t^2}\right) (8 \log(\beta) - 3)\right) + \mathcal{O}(\beta) \,, \tag{3}$$

where the coefficients of $\log^2(\beta)$ and $\log(\beta)$ are exact while we are lacking terms independent of β, i.e., $\mathcal{O}(\beta^0)$ from the virtual contributions at one loop. In addition we multiply the result by a kinematical suppression factor $(1 - \beta^2) = m_t^2/s$ to restrict the soft-gluon logarithms to the threshold region.

The NNLO result $\sigma^{(2)}$ in Eq. (1) is currently unknown, but we can compute an approximate NNLO (aNNLO) expression for $\sigma^{(2)}$ valid near threshold $\beta \simeq 0$ as

$$\begin{aligned}
\sigma^{(2)} \simeq \sigma^{(0)} & \left(1 - \beta^2\right) \frac{C_F}{24\pi^2} \Bigg(2352 C_F \log^4(\beta) \\
& - 8 \log^3(\beta)(17\beta_0 + 777 C_F) \\
& + \frac{1}{3} \log^2(\beta) \Bigg(801\beta_0 - 28 \left(3\pi^2 - 67\right) C_A + 24759 C_F \\
& - 504\pi^2 C_F - 280 n_f + \frac{144}{N_c} \Bigg) \\
& + \frac{1}{18} \log(\beta) \Bigg(-4293\beta_0 + C_A \left(3240\zeta_3 - 18007 + 1008\pi^2\right) \\
& + 6480 C_F \zeta_3 - 111348 C_F + 4104\pi^2 C_F + 2758 n_f \\
& - 72\pi^2 n_f + \frac{3456}{N_c}\zeta_3 + \frac{288}{N_c}\pi^2 - \frac{7344}{N_c} \Bigg) \\
& - \frac{1}{120} \Bigg(-10215\beta_0 + 25 C_A \left(648\zeta_3 - 2315 + 144\pi^2\right) \\
& + 32400 C_F \zeta_3 - 251550 C_F + 11880\pi^2 C_F + 8990 n_f \\
& - 360\pi^2 n_f + \frac{23040}{N_c}\zeta_3 + \frac{32}{N_c}\pi^4 + \frac{3840}{N_c}\pi^2 - \frac{69120}{N_c} \Bigg) \\
& + \log\left(\frac{\mu_F^2}{m_t^2}\right) \Bigg(-1344 C_F \log^3(\beta) \\
& + 12 \log^2(\beta)(7\beta_0 + 190 C_F) - \frac{1}{3} \log(\beta) \Big(333\beta_0 \\
& - 8 \left(3\pi^2 - 67\right) C_A + 6066 C_F - 144\pi^2 C_F - 80 n_f \Big) \\
& + \frac{1}{4} \Big(189\beta_0 - 8 \left(3\pi^2 - 67\right) C_A + 3282 C_F - 144\pi^2 C_F \\
& - 80 n_f \Big) + \log\left(\frac{\mu_R^2}{\mu_F^2}\right) (-24\beta_0 \log(\beta) + 18\beta_0) \Bigg) \\
& + \log^2\left(\frac{\mu_F^2}{m_t^2}\right) \Big(192 C_F \log^2(\beta) - 12 \log(\beta)(\beta_0 + 12 C_F) \\
& + 3(3\beta_0 + 20 C_F) \Big) + \log\left(\frac{\mu_R^2}{\mu_F^2}\right) \Bigg(84\beta_0 \log^2(\beta) \\
& - 111\beta_0 \log(\beta) + \frac{189}{4}\beta_0 \Bigg) \Bigg) + \mathcal{O}(\beta)
\end{aligned} \tag{4}$$