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Total Cross Section for Top Quark Production *

Edmond L. Berger and Harry Contopanagos

High Energy Physics Division, Argonne National Laboratory

Argonne, Illinois 60439, USA

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Abstract

We summarize our calculation of the total cross section for top quark production at hadron colliders within the context of perturbative quantum chromodynamics, including resummation of the effects of initial-state soft gluon radiation to all orders in the strong coupling strength.

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TOTAL CROSS SECTION FOR TOP QUARK PRODUCTION

EDMOND L. BERGER and HARRY CONTOPANAGOS
High Energy Physics Division, Argonne National Laboratory, Argonne, IL 60439, USA

We summarize our calculation of the total cross section for top quark production at hadron colliders within the context of perturbative quantum chromodynamics, including resummation of the effects of initial-state soft gluon radiation to all orders in the strong coupling strength.

1 Introduction and Motivation

In hadron interactions at collider energies, $t\bar{t}$ pair production proceeds through partonic hard-scattering processes involving initial-state light quarks q and gluons g. In lowest-order perturbative quantum chromodynamics (QCD), $\mathcal{O}(\alpha_s^2)$, the two partonic subprocesses are $q + \bar{q} \to t + \bar{t}$ and $g + g \to t + \bar{t}$. Calculations of the cross section through next-to-leading order, $\mathcal{O}(\alpha_s^3)$, involve gluonic radiative corrections to these lowest-order subprocesses as well as contributions from the $q + g$ initial state [1]. A complete fixed-order calculation at order $\mathcal{O}(\alpha_s^n), n \geq 4$ does not exist. The calculations described in this report [2,3,4] extend beyond fixed-order perturbation theory through the resummation of the effects of initial state soft gluon radiation to all orders in the strong coupling strength, α_s.

We use s to denote the square of the partonic center-of-mass energy, and m to denote the top mass. The variable $\eta = \frac{s}{4m^2} - 1$ measures the distance from the partonic threshold. A comparison of the partonic cross section at next-to-leading order with its lowest-order value reveals that the ratio becomes very large in the near-threshold region. This large ratio casts doubt on the reliability of simple fixed-order perturbation theory for physical processes for which the near-threshold region in the subenergy variable contributes significantly to the physical cross section. Top quark production at the Fermilab Tevatron is one such process. Other examples include the production of hadronic jets that carry large values of transverse momentum and the production of pairs of supersymmetric particles with large mass.

The origin of the large threshold enhancement may be traced to initial-state gluonic radiative corrections to the lowest-order channels. We define the variable z through the invariant $(1 - z) = \frac{2k \cdot p_1}{m^2}$, where k and p_t are the four-vector momenta of the gluon and top quark. In the limit that $z \to 1$, the radiated gluon carries zero momentum. After cancellation of soft singularities and

factorization of collinear singularities in $\mathcal{O}(\alpha_s^3)$, there are left-over integrable large logarithmic contributions to the cross section associated with initial-state gluon radiation. These contributions are proportional to $\alpha_s \ln^2(1-z)$. The goal of gluon resummation is to sum the series in $\alpha_s^n \ln^{2n}(1-z)$ to all orders in α_s in order to obtain a more defensible prediction. Different methods of resummation differ in theoretically and phenomenologically important respects. Formally, if not explicitly in some approaches, an integral over the radiated gluon momentum z must be done over regions in which $z \to 0$. Therefore, one significant distinction among methods has to do with how the inevitable "non-perturbative" region is handled in each case.

2 Perturbative Resummation

The method of resummation we employ[3] is based on a perturbative truncation of principal-value resummation[5]. Factorization and evolution lead directly to exponentiation of the set of large threshold logarithms in moment (n) space in terms of a finite exponent E^{PV} that includes both perturbative and non-perturbative content. The non-perturbative content is not a prediction of perturbative QCD. In our study of top quark production, we apply the exponent only in the interval in moment space in which the perturbative content dominates. After inversion of the Mellin transform from moment space to the physically relevant momentum space, the resummed partonic cross sections, including all large threshold corrections, can be written

$$\hat{\sigma}_{ij}^{R;pert}(\eta, m^2) = \int_{z_{min}}^{z_{max}} dz e^{E_{ij}(\ln(\frac{1}{1-z}),\alpha_s)} \hat{\sigma}'_{ij}(\eta, m^2, z). \qquad (1)$$

The leading large threshold corrections are contained in the exponent $E_{ij}(x, \alpha_s)$, a calculable polynomial in x. The derivative $\hat{\sigma}'_{ij}(\eta, m^2, z) = d(\hat{\sigma}_{ij}^{(0)}(\eta, m^2, z))/dz$, and $\hat{\sigma}_{ij}^{(0)}$ is the lowest-order $\mathcal{O}(\alpha_s^2)$ partonic cross section expressed in terms of inelastic kinematic variables. The two separate production channels are denoted by the subscript ij. The upper limit of integration in Eq. (1) is set by the boundary between the perturbative and non-perturbative regimes, well specified within the context of the calculation.

Our perturbative resummation probes the threshold down to $\eta \geq \eta_0 = (1 - z_{max})/2$. Below this value, perturbation theory, resummed or otherwise, is not to be trusted. For $m = 175$ GeV, we determine that the perturbative regime is restricted to values of the subenergy greater than 1.22 GeV above the threshold ($2m$) in the $q\bar{q}$ channel and 8.64 GeV above threshold in the gg channel. The difference reflects the larger color factor in the gg case. The value 1.22 GeV is comparable to the decay width of the top quark.

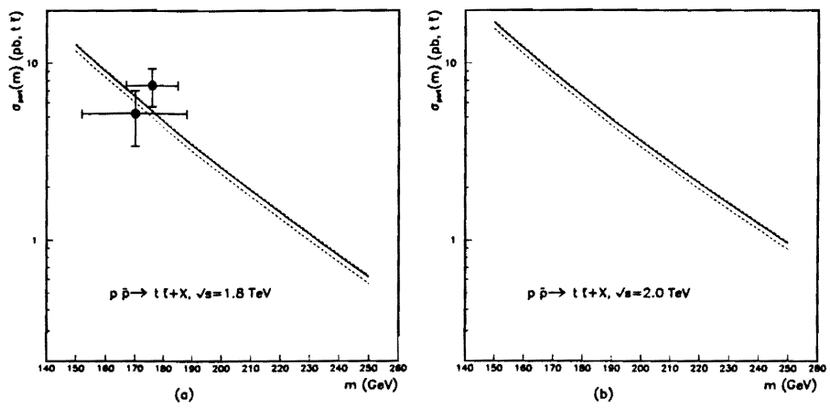

Figure 1: Inclusive total cross section for top quark production. The dashed curves show the upper and lower limits while the solid curve is our central prediction.

3 Physical cross section

Other than the top mass, the only undetermined scale in our approach is the usual QCD factorization/renormalization scale μ. We show our total $t\bar{t}$-production cross section as a function of top mass in Fig. 1. The central value is obtained with the choice $\mu/m = 1$, and the lower and upper limits are the maximum and minimum of the cross section in the range of the hard scale $\mu/m \in \{0.5, 2\}$. At $m = 175$ GeV, the full width of the uncertainty band is about 10% . Our calculation is in agreement with the data [6]. We find $\sigma^{t\bar{t}}(m = 175 \text{ GeV}, \sqrt{S} = 1.8 \text{ TeV}) = 5.52^{+0.07}_{-0.42}\ pb$. Our cross section is larger than the next-to-leading order value by about 9%.

Two other groups have published calculations of the total cross section at $m = 175$ GeV and $\sqrt{s} = 1.8$ TeV: $\sigma^{t\bar{t}}(\text{LSvN}\ ^2) = 4.95^{+0.70}_{-0.40}$ pb; and $\sigma^{t\bar{t}}(\text{CMNT}\ ^4) = 4.75^{+0.63}_{-0.68}$ pb. From the purely numerical point of view, all three agree within their estimates of theoretical uncertainty. However, the resummation methods differ and the methods for estimating the uncertainties differ. Both the central value and the band of uncertainty of the Laenen *et al* (LSvN) predictions are sensitive to their arbitrary infrared cutoffs. To estimate theoretical uncertainty, we use the standard μ-variation, whereas LSvN obtain theirs primarily from variations of their cutoffs. Catani *et al* (CMNT) calculate a central value of the resummed cross section (also with $\mu/m = 1$) that is less than 1% above the exact next-to-leading order value. The suppression of the effects of resummation arises from the retention by CMNT of numerically

significant non-universal subleading logarithmic terms in momentum space. Advantages of our perturbative resummation method [3] are that there are no arbitrary infrared cutoffs, and there is a well-defined perturbative region of applicability where subleading logarithmic terms are numerically suppressed.

For an upgraded Tevatron operating at $\sqrt{S} = 2$ TeV, we predict $\sigma^{t\bar{t}}(m = 175 \text{ GeV}, \sqrt{S} = 2 \text{ TeV}) = 7.56^{+0.10}_{-0.55}\ pb$. Extending our calculation to much larger values of m at $\sqrt{S} = 1.8$ TeV, we find that resummation in the principal $q\bar{q}$ channel produces enhancements over the next-to-leading order cross section of 21%, 26%, and 34%, respectively, for $m = 500$, 600, and 700 GeV. The reason for the increase of the enhancements with mass at fixed energy is that the threshold region becomes increasingly dominant. Since the $q\bar{q}$ channel also dominates in the production of hadronic jets at very large values of transverse momenta, we suggest that on the order of 25% of the excess cross section reported by the CDF collaboration [7] may well be accounted for by resummation.

Our theoretical analysis and the stability of our cross sections under μ variation provide confidence that our perturbative resummation procedure yields an accurate calculation of the inclusive top quark cross section at Tevatron energies and exhausts present understanding of the perturbative content of the theory.

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