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QCD CORRECTIONS TO SINGLE TOP PRODUCTION AT THE FERMILAB TEVATRON

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Abstract

Recent results from analyses of electroweak and collider data and an expected sizeable increase in statistics of collider data for both CDF and D0 experiments at the Fermilab hadron accelerator, demand more precise cross-section calculations and evaluation of production mechanisms for the top quark.

We present results for the full $O\left(\alpha_s\alpha^2\right)$ computation of the total cross-section for single top quarks. We briefly summarize preceding studies of this production mechanism and outline the calculations. Details on the choice of regularisation and factorisation scheme are given.

Finally, a comparison between the total cross section as function of the top quark mass for semiweak and QCD pair production of top quarks at the Tevatron is presented.

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Electroweak precision data collected by experiments at the Cern Large Electron Positron (LEP) collider allow for, within the Standard Model, a rather stringent estimate of the top quark mass: $m_{top} = 174^{+11+17}_{-12-19} GeV/c^2$ [1]. The D0 collaboration at the Fermilab Tevatron reports a lower limit of $m_{top} = 131 GeV/c^2$ [2]. Recent analyses by the CDF collaboration at the same collider, give a first direct hint for the existence of the top quark with a mass estimate remarkably well in agreement with predictions from electroweak data [3]. The large value of the top mass has an interesting phenomenological consequence: beside pure QCD mechanisms, semiweak production of top has to be considered as well. Indeed, while suffering from a small value of the weak coupling constant, exchange of a W-boson in the t-channel leads to a flat cross-section dependence on the mass of the heavy final state.

Semiweak production of the heavier member of a doublet of quarks was already studied in the framework of electron-proton collisions [4]. It has been shown that the semiweak process dominates over pure QCD pair production at large top mass (~ 250 GeV/c^2) [5, 6, 7]. Since the mass of the top is in any case much larger than the mass of the bottom quark, semiweak production mechanisms tend to lead to rather distinct event topologies. These event signatures [5], quite different from the ones appearing in heavy flavour pair production, justify precise and detailed studies not only on discovery potential, mass and width of the top quark [6, 7], but also on the structure of the top quark coupling to the charged weak current. It has been argued that the process may trigger new physics [7], CP-violation studies and the measurement of the number of degrees of freedom of the W as well [8]. However, those claims should be taken with some caution since conclusions are based on rather optimistic assumptions for event rates, detector acceptance and capacity of isolating signal from background. A similar analysis leading to opposite conclusions has been published as well [9].

Considering both bottom and top quarks as massive partons, the Born interaction for single top production is described by the $O(\alpha_s \alpha^2)$ process $qg \to q' t\bar{b}$, where the amplitude is dominated by the singularity arising from the b-quark and gluon becoming collinear. Resummation and absorption of this singularity in the bottom quark density distribution in the proton provides an alternative description at $O(\alpha^2)$: $qb \to q' t$ (Born). Accurate determination of the absolute cross-section implies however, precise evaluation of higher order terms.

In references [7] and [10], we have attempted to approximate the size of these higher orders by summing the $qb \to q' t$ and $qg \to q' t\bar{b}$ processes. Double counting is avoided by subtracting the singularity from the q-g scattering contribution. $O(\alpha_s^2 \alpha^2)$ tree-level contributions are presented in ref. [10], enhancing the inclusive single top cross-section and giving rise to events in which the heavy flavours are accompanied by two additional jets.

We calculate the complete set of diagrams for single top production up to $O(\alpha_s)$ ($qb \to q' t(g)$, $qg \to q' t\bar{b}$) guided by similar analyses for QCD pair production [11] as well as single heavy flavour production in electron-proton scattering [12, 13]. The ensemble of virtual diagrams contains ultraviolet (U.V.) and infrared (I.R.) divergences, while the diagrams with gluon emission or gluon splitting have, besides I.R. divergences, collinear divergences due to vanishing quark masses. We adopt the massive regularisation scheme. In this formalism, divergences are mastered by introducing four parameters that will not appear in the final result: m_g (to regularise the I.R. divergence), m_q (to regularise the collinear divergence) and an energy cut-off, ΔE (to separate soft and hard Bremsstrahlung). The gluon and quark masses satisfy the relations $m_g << m_q$ and $m_q << \Delta E$. Finally, an U.V. cut-off is introduced: $\Lambda >> \sqrt{s}$,

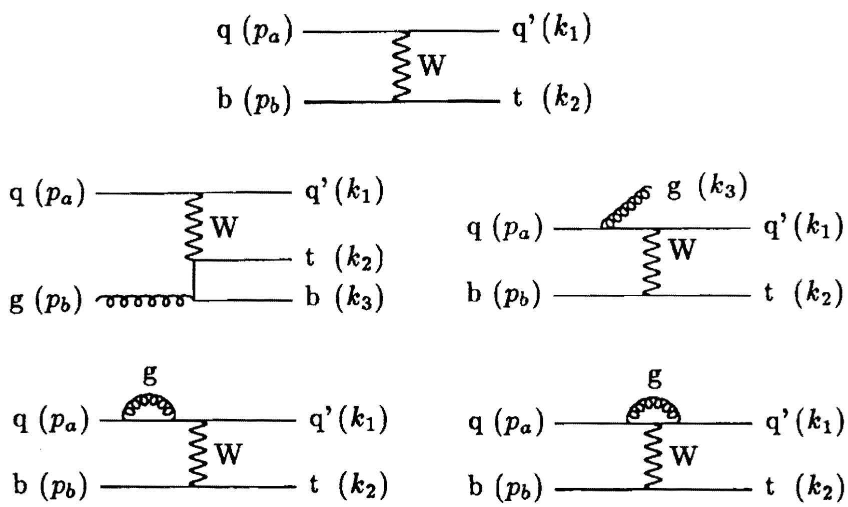

Fig. 1: *Order $\alpha^2\alpha_s$ contributions (below) to top production via W exchange in hadronic interactions.*

We recall the relatively simple expression for the differential Born cross-section (with $Q^2 = -q^2 = -(p_a - k_1)^2$):

$$\frac{d\sigma^{Born}(qb \to q't)}{dQ^2} = -\frac{\pi\alpha^2}{4s\sin^4\theta_W}\frac{s - m_t^2}{\left(Q^2 + M_W^2\right)^2 + M_W^2\Gamma_W^2}$$

The full set of Feynman graphs contributing to the process $qg \to q't\bar{b}$ has already been detailed in ref. [7]. Using a decomposition into form factors, and after integration over the outgoing b-quark momentum, the differential cross-section takes the form (with $s_3 = (k_2 + k_3)^2$):

$$\frac{d\sigma}{ds_3 dQ^2} = \frac{\alpha_s\alpha^2}{32\sin^4\theta_W}\frac{1}{\left(Q^2 + M_w^2\right)^2 + M_w^2\Gamma_w^2}\left[\frac{Q^2}{s^2}(F_1 - F_3) + \frac{2\left(s - Q^2 - s_3\right)F_2 + 2Q^2F_3}{s\left(Q^2 + s_3\right)}\right]$$

The momentum fraction (z_b) the intermediate b takes from the gluon reduces to $z_b = \frac{Q^2 + m_t^2}{Q^2 + s_3}$. We write s_3 in terms of z_b and after integration, we obtain (the expressions for F_2 and F_3 take a similar form and are given in ref. [14]):

$$F_1 = 2P_{qg}L_1 + \left(8x_0z_b^2 - 4z_b\right)(1 - x_0)L_2 + 8x_0z_b(1 - z_b) - 2\frac{1 - z_b}{1 - x_0z_b}$$

where the following shorthand notations were introduced:

$$x_0=\frac{Q^2}{Q^2+m_t^2} \qquad L_1=Log\frac{Q^2(1-z_b)^2}{m_b^2x_0z_b^2(1-x_0)} \qquad L_2=Log\frac{(1-x_0)z_b}{(1-x_0z_b)}$$

while the Dokshitzer-Gribov-Lipatov-Altarelli-Parisi splitting function (DGLAP)[15] appears in front of the singular logarithms L_1.

For the splitting of gluons into light quarks we write (with $s_4=(k_1+k_3)^2$):

$$\frac{d\sigma}{ds_4dQ^2}=\frac{\alpha_s\alpha^2}{32\sin^4\theta_W}\frac{1}{(Q^2+M_w^2)^2+M_w^2\Gamma_w^2}\times$$

$$\left[\frac{Q^2+m_t^2}{s^2}(F_1-F_3)+\frac{2\left(s-Q^2-s_4\right)F_2+2Q^2F_3}{s\left(Q^2+s_4\right)}+\frac{4m_t^2\left(Q^2+m_t^2\right)}{s^2\left(Q^2+s_4\right)}F_4+\frac{2m_t^2}{s\left(Q^2+s_4\right)}F_5\right]$$

The expressions for F_i have the same structure as before and can be found in ref. [14].

Bremsstrahlung corrections to the Born process $qb\to q't$ give similar singular logarithms. Next, we isolate an I.R. divergences free part, where formulae with the same structure as above are obtained [14]. Now the form factors present I.R. divergences at $z_a, z_b=1$, which implies that derived expressions are only valid provided $z_a, z_b<1-\varepsilon$. The I.R. singularities in the soft Bremsstrahlung contribution can be controlled by introducing a (small) mass for the gluon. In the gluon energy interval $m_g<<E_g<<\omega_0=\frac{\varepsilon Q^2}{2m_tx_0}$, the contribution is computed in the eikonal approximation. For emission off the heavy quark lines, after integration, one obtains (with $L_i=\log\frac{m_i^2x_0(1-x_0)}{Q^2}$):

$$d\sigma=\frac{2\alpha_s}{3\pi}d\sigma^{Born}\left[-2\log\frac{4\omega_0^2}{m_g^2}-L_b+2-\log\frac{4\omega_0^2}{m_g^2}L_b-\frac{1}{2}L_b^2-\frac{\pi^2}{3}\right]$$

Replacing the heavy flavour mass by a light quark mass leads to a similar expression.

The virtual contributions contain both U.V. and I.R. divergences. We regularise these divergences by replacing the gluon propagator by $D_{\mu\nu}(k)=ig_{\mu\nu}\int_{m_g^2}^{\Lambda}dl\left(k^2-l\right)^{-2}$. In the on-shell renormalisation scheme, the self-energy correction reads:

$$d\sigma^{Self}=-\frac{2\alpha_s}{3\pi}d\sigma^{Born}\left(\log\frac{\Lambda^2}{m^2}+2\log\frac{m_g^2}{m^2}+\frac{9}{2}\right)$$

After adding the vertex correction, the complete contribution from the virtual diagrams for the light quark lines becomes:

$$d\sigma^{Virtual}=\frac{2\alpha_s}{3\pi}d\sigma^{Born}\left(-3\log\frac{m_q^2}{Q^2}-2\log\frac{m_q^2}{Q^2}\log\frac{m_g^2}{m_q^2}-\log^2\frac{m_q^2}{Q^2}-2\log\frac{m_g^2}{m_q^2}-4+\frac{\pi^2}{3}\right)$$

in agreement with for example the result quoted in ref. [16] for the on-shell regularisation scheme.

While the self-energy corrections are universal for light and heavy quarks, the vertex correction for the heavy quark lines turns out to be slightly more complicated. As expected however, both expressions contain singular logarithms in the limit $m_g\to 0$. Soft Bremsstrahlung and virtual corrections may now be combined. For heavy quarks we obtain:

$$d\sigma = \frac{2\alpha_s}{3\pi} d\sigma^{Born} \times \left[-4\log\varepsilon - 2 - L_b\left(2\log\varepsilon + \frac{3}{2}\right) - 2Li_2(1-x_0) - \log^2(1-x_0) + 2\log(1-x_0) \right]$$
$$- \frac{2\alpha_s\alpha^2}{12\pi\sin^4\theta_w} \frac{1}{\left(Q^2+M_w^2\right)^2 + M_w^2\Gamma_W^2} \left(4\frac{m_t^2}{s}\log(1-x_0)\right)$$

For light quarks we derive:

$$d\sigma = \frac{2\alpha_s}{3\pi} d\sigma^{Born} \left(-\frac{3}{2}\log\frac{m_q^2}{Q^2} - 2\log\frac{m_q^2}{Q^2}\log\varepsilon - \log^2\varepsilon - \frac{7}{2}\log\varepsilon - \frac{5}{2} - \frac{\pi^2}{3} \right)$$

Both heavy quark and light quark contributions are free of I.R. divergences. However, they still contain mass (M) singularities and depend on the value of the cut-off parameter ε.

According to the factorisation theorem [17], the total partonic cross-section can be expressed as a convolution of splitting functions and a M-singularity free term. All M-singularities are then removed from the expression for the matrix element squared for the partonic interaction and absorbed into the parton density distributions.

At $O(\alpha_s)$, the process we are considering only receives contributions from gluon splitting into quarks and gluon emission off quarks. The relevant splitting functions can be derived from our results replacing the top mass by a vanishing one. Thus we obtain a reduced cross-section which is free of M-singularities, but still contains logarithmic dependencies on the cut-off parameter ε. Compensation among and explicit dependence on ε in the soft plus virtual contribution and the hard Bremsstrahlung part is verified numerically. In order to obtain the total cross-section, we perform a numerical integration over the remaining four parameters using the Eurojet package [18]. Because the factorisation of the collinear singularities are carried out in the deep inelastic scheme (DIS), we adopted the Morfin et al. structure function parametrisations (Cteq2D, [19]). These functions have been derived in the DIS-scheme as well. Uncertainties in the total cross-section due to even higher order contributions can be estimated by varying the factorisation scale. Here we chose three different values: M_{top}, $\frac{1}{2}M_{top}$ and $2M_{top}$, conform the choice made by Laenen et al. [20] in their calculation of the total QCD pair cross-section.

In figure 2 we present our results for the semiweak process and compare with the estimates for pair production presented in table 1 of ref. [20].

The calculations show that after the first glance of the top quark reported by the CDF collaboration at the Fermilab collider and the rather precise hints and mass predictions from electroweak data, both semiweak and QCD pair production mechanisms should be considered as potential discovery channels. However, their relative importance largely depend on detector acceptance and integrated luminosity on one hand and precise determination of the variety of background channels on the other. We recall that the event topology in either case is very distinct, one or more charged leptons, b-jet(s) and energetic jet(s). The jet multiplicity in $t\bar{t}$ however, is larger due to a second top quark in the event.

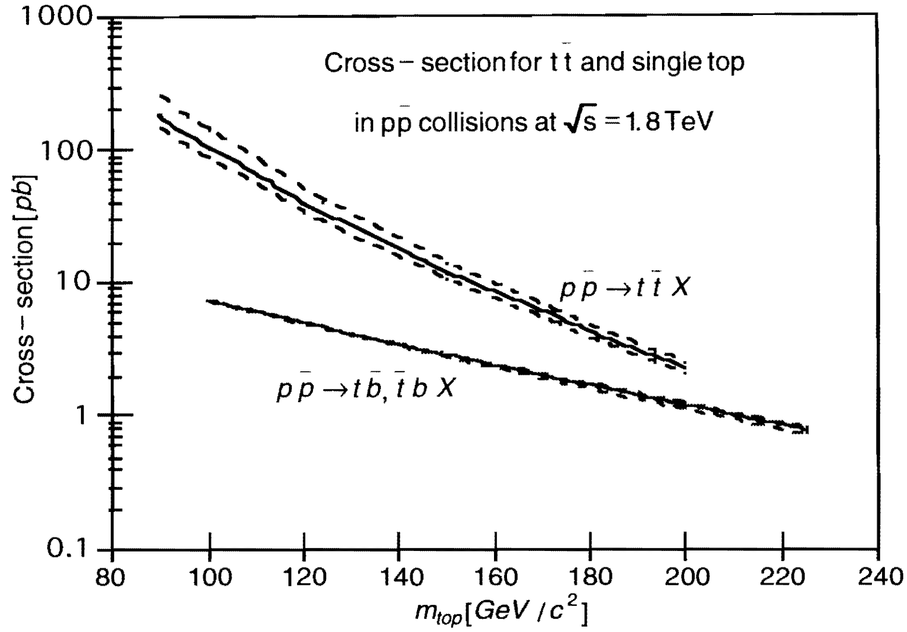

Fig. 2. Comparison between the total cross-section [pb] for QCD top-pair production and single top production .

We have already included the process $qg \to q' t\bar{b}g$ in the Eurojet event generator [18]. Appropriate choice of factorisation scale and rescaling the process $qg \to q' t\bar{b}$ with the cross-section presented here, should provide a complete set of accurate tools for future comparisons between experimental data and theoretical calculations.

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