CHARGE ASYMMETRY OF HEAVY QUARKS AT HADRON COLLIDERS*

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A sizeable difference in the differential production cross section of top and antitop quarks, respectively, is predicted for hadronically produced heavy quarks. It is of order α_s and arises from the interference between charge odd and even amplitudes respectively. For the TEVATRON it amounts up to 15% for the differential distribution in suitable chosen kinematical regions. The resulting integrated forward-backward asymmetry of 4–5% could be measured in the next round of experiments. At the LHC the asymmetry can be studied by selecting appropriately chosen kinematical regions. Furthermore, a slight preference at LHC for centrally produced antitop is predicted, with top quarks more abundant at large positive and negative rapidities.

Heavy flavor production at hadron colliders is one of the most active fields of current theoretical and experimental studies. Large event rates, combined with improved experimental techniques, allow for detailed investigations of the properties of heavy quarks and their production mechanism at the same time. While charm production with a quark mass around 1.5 GeV is barely accessible to perturbative QCD calculations, bottom and *a forteriori* top production should be well described by this approach.

Theoretical and experimental results [1,2] for the cross section of hadronic top production are well consistent with this expectation. Obviously, in view of the large QCD coupling, the inclusion of higher order QCD corrections in these calculations is mandatory for a successful comparison. Recent studies have, to a large extent, concentrated on the predictions of the total cross section and a few selected one particle inclusive distributions. In this paper a different issue of heavy flavor production is investigated, namely the charge asymmetry, which is sensitive toward a specific subclass of virtual and real radiative corrections.

Evaluated in Born approximation the lowest order processes relevant for heavy flavor production

$$q + \bar{q} \to Q + \bar{Q} \ , \qquad (1)$$

$$g + g \to Q + \bar{Q} \ , \qquad (2)$$

do not discriminate between the final quark and antiquark, thus predicting identical differential distributions also for the hadronic production process. However, radiative corrections involving either virtual or real gluon emission lead to a sizeable difference between the differential quark and antiquark production process and hence to a charge asymmetry [3,4] which could be well accessible experimentally.

This asymmetry has its origin in two different reactions: radiative corrections to quark-antiquark fusion (Fig. 1) and heavy flavor production involving interference terms of different amplitudes contributing to gluon-quark scattering

$$g + q \to Q + \bar{Q} + q \ , \qquad (3)$$

a reaction intrinsically of order α_s^3. The contribution from quark gluon scattering to the asymmetry has been shown to be small [4] and will be ignored in this review. Gluon fusion remains of course charge symmetric. In both reactions (1) and (3) the asymmetry can be traced to the interference between amplitudes which are relatively odd under the exchange of Q and $\bar{Q}$. In fact, as shown below in detail, the asymmetry can be understood in analogy to the corresponding one in QED reactions and is proportional to the color factor d_{abc}^2. In contrast, the non-Abelian contributions, in particular those involving the triple gluon coupling, lead to symmetric pieces in the differential cross section.

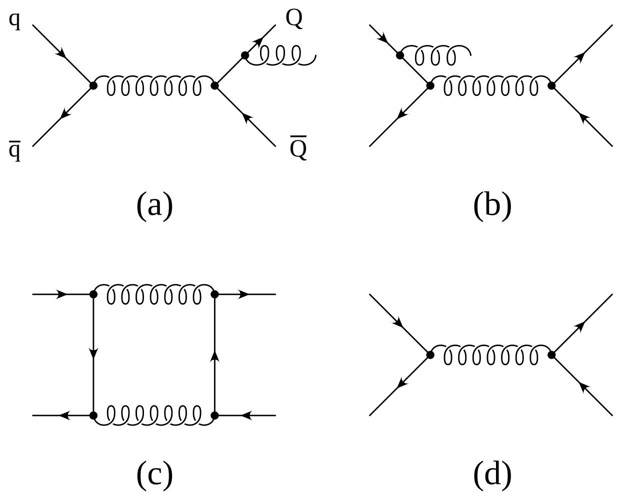

Figure 1: Origin of the QCD charge asymmetry in hadroproduction of heavy quarks: interference of final-state (a) with initial-state (b) gluon bremsstrahlung plus interference of the box (c) with the Born diagram (d). Only representative diagrams are shown.

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Let us briefly discuss a few important aspect of this calculation. The box amplitude for $q\bar{q} \to Q\bar{Q}$ is ultraviolet finite and the asymmetric contribution to the cross section of order α_s^3 is therefore not affected by renormalization, an obvious consequence of the symmetry of the lowest order reaction. The same line of reasoning explains the absence of initial state collinear singularities in the limit $m_q \to 0$ which would have to be absorbed into the (symmetric) lowest order cross section. Infrared singularities require a more careful treatment. They are absent in the asymmetric piece of the process in eq. (3). However, real and virtual radiation (Fig. 1), if considered separately, exhibit infrared divergences, which compensate in the sum, corresponding to the inclusive production cross section.

The charge asymmetry in the partonic reactions (1) and (3) implies for example a forward-backward asymmetry of heavy flavor production in proton-antiproton collisions. In particular, it leads to a sizeable forward-backward asymmetry for top production which is dominated by reaction (1), and can, furthermore, be scrutinized by studying $t\bar{t}$ production at fixed longitudinal momenta and at various partonic energies $\hat{s}$. However, the charge asymmetry can also be observed in proton-proton collisions at high energies. In this case one has to reconstruct the $t\bar{t}$ restframe and select kinematic regions, which are dominated by $q\bar{q}$ annihilation or flavor excitation $gq \to t\bar{t}X$. Alternatively, one may also study the difference in the one-particle inclusive rapidity distribution of top versus antitop, which again integrates to zero.

The analysis of these effects allows to improve our understanding of the QCD production mechanism. At the same time it is important for the analysis of single top production through Wb fusion. This reaction is charge asymmetric as a consequence of weak interactions. Although the final states in single top production and hadronic $t\bar{t}$ production are different and should in principle be distinguishable, it is nevertheless mandatory to control the charge asymmetry from both sources.

As shown in [3], the dominant contribution to the charge asymmetry originates from $q\bar{q}$ annihilation, namely from the asymmetric piece in the interference between the Born amplitude for $q\bar{q} \to Q\bar{Q}$ (Fig. 1d) and the one loop corrections to this reaction (Fig. 1c), which must be combined with the interference term between initial state and final state radiation (Fig. 1a,1b).

However, only QED like terms are relevant for the charge asymmetric piece [4]. The QCD asymmetry is thus obtained from the QED results by the replacement

$$\alpha_{QED} Q_q Q_Q \to \frac{d_{abc}^2}{16 N_C T_F C_F} \alpha_s = \frac{5}{12} \alpha_s \ . \qquad (4)$$

Let us note in passing that diagrams involving the triple gluon coupling lead to charge symmetric terms.

The differential charge asymmetry in the inclusive cross section

$$q + \bar{q} \to Q + X \ , \qquad (5)$$

at the partonic level can then be defined through

$$\hat{A}(\cos\hat{\theta}) = \frac{N_t(\cos\hat{\theta}) - N_{\bar{t}}(\cos\hat{\theta})}{N_t(\cos\hat{\theta}) + N_{\bar{t}}(\cos\hat{\theta})} \ , \qquad (6)$$

where $\hat{\theta}$ denotes the top quark production angle in the $q\bar{q}$ restframe and $N(\cos\hat{\theta}) = d\sigma/d\Omega(\cos\hat{\theta})$. Since $N_{\bar{t}}(\cos\hat{\theta}) = N_t(-\cos\hat{\theta})$ as a consequence of charge conjugation symmetry, $\hat{A}(\cos\hat{\theta})$ can also be interpreted as a forward-backward asymmetry of top quarks (Fig. 2).

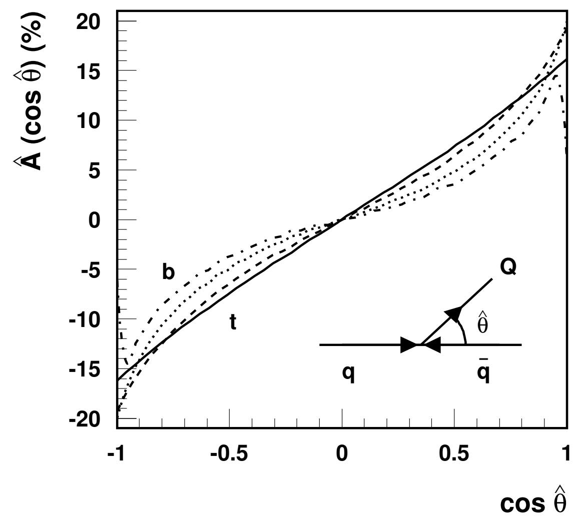

Figure 2: Differential charge asymmetry in top quark pair production for fixed partonic center of mass energies $\sqrt{\hat{s}} = 400$ GeV (solid), 600 GeV (dashed) and 1 TeV (dotted). We also plot the differential asymmetry for b-quarks with $\sqrt{\hat{s}} = 400$ GeV (dashed-dotted).

The integrated charge asymmetry

$$\bar{\hat{A}} = \frac{N_t(\cos\hat{\theta} \geq 0) - N_{\bar{t}}(\cos\hat{\theta} \geq 0)}{N_t(\cos\hat{\theta} \geq 0) + N_{\bar{t}}(\cos\hat{\theta} \geq 0)} \ , \qquad (7)$$

is shown in Fig. 3 as a function of $\sqrt{\hat{s}}$. With a typical value around $6 - 8.5\%$ it should be well accessible in the next run of the TEVATRON.

In addition to the pure QCD amplitudes also a mixed QCD-electroweak interference term will lead to an asymmetric contribution to the $q\bar{q}$ process [3,4]. This leads to an increase of the asymmetry as given by pure QCD by a factor 1.09.

The asymmetry can in principle be studied experimentally in the partonic restframe, as a function of $\hat{s}$, by

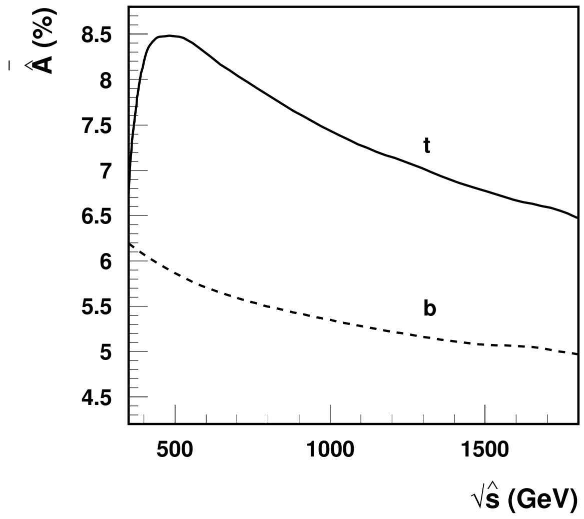

Figure 3: Integrated charge asymmetry as a function of the partonic center of mass energy for top and bottom quark pair production.

measuring the invariant mass of the $t\bar{t}$ system plus an eventually radiated gluon. It is, however, also instructive to study the asymmetry in the laboratory frame by folding the angular distribution with the structure functions[5,6]. For proton-antiproton collisions it is convenient to consider the forward-backward asymmetry as function of the production angle in the center of mass system. The differential asymmetry for $\sqrt{s} = 2$ TeV is shown in Fig. 4 which displays separately the contribution from $q\bar{q}$ and qg (plus $\bar{q}g$) initiated reactions. The denominator includes both $q\bar{q}$ and gg initiated processes in lowest order. The numerator is evidently dominated by quark-antiquark annihilation.

At this point we have to emphasize that both numerator and denominator are evaluated in leading order (LO). The next-to-leading (NLO) corrections to the $t\bar{t}$ production cross section are known to be large[7], around 30% or even more. In the absence of NLO corrections for the numerator we nevertheless stay with the LO approximation in both numerator and denominator, expecting the dominant corrections from collinear emission to cancel. However, from a more conservative point of view an uncertainty of around 30% has to be assigned to the prediction for the asymmetry.

For the total charge asymmetry at $\sqrt{s} = 1.8$ TeV we predict

$$\bar{A} = \frac{N_t(\cos\theta \geq 0) - N_{\bar{t}}(\cos\theta \geq 0)}{N_t(\cos\theta \geq 0) + N_{\bar{t}}(\cos\theta \geq 0)} = 4.8 - 5.8\% \ , \quad (8)$$

where different choices of the structure function and different choices of the factorization and renormalization scale, $\mu = m_t/2$ and $\mu = 2m_t$, have been considered and the factor 1.09 is included. An increase in the center of mass energy to 2 TeV leads to a slight decrease of our prediction to $4.6 - 5.5\%$.

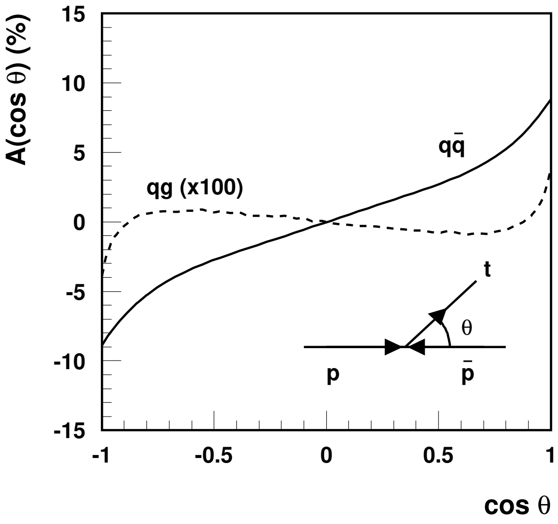

Figure 4: Differential charge asymmetry in the proton-antiproton restframe, $\sqrt{s} = 2$ TeV, using the CTEQ-1 structure function, $\mu = m_t$. The contributions from $q\bar{q}$ and qg (plus $\bar{q}g$) initiated processes are shown separately.

Top-antitop production in proton-proton collisions at the LHC is, as a consequence of charge conjugation symmetry, forward-backward symmetric if the laboratory frame is chosen as the reference system. However, by selecting the invariant mass of the $t\bar{t}(+g)$ system and its longitudinal momentum appropriately, one can easily constrain the parton momenta such that a preferred direction is generated for quark-antiquark reactions.

For some of the more extreme kinematic regions, namely large x and/or large $\hat{s}$, a sizeable difference between top and antitop production can be observed at the LHC[4]. From this it may seem that the reconstruction of both t, $\bar{t}$ and even the gluon is required for the study of the charge asymmetry in pp collisions. However, also the difference between the single particle inclusive distribution of t and $\bar{t}$ respectively may provide evidence for the charge asymmetry. Production of $t\bar{t}(g)$ with negative x is dominated by initial $\bar{q}$ with small x_1 and q with large x_2. The charge asymmetry implies that $Q(\bar{Q})$ is preferentially emitted into the direction of $q(\bar{q})$. The same line of reasoning is applicable for positive x, with $Q(\bar{Q})$ again preferentially emitted in the direction of $q(\bar{q})$, and the role of x_1 and x_2 reversed. In total this leads to a slight preference for centrally produced antiquarks and quarks slightly dominant in the forward and backward direction, i.e., at large positive and negative rapidities.

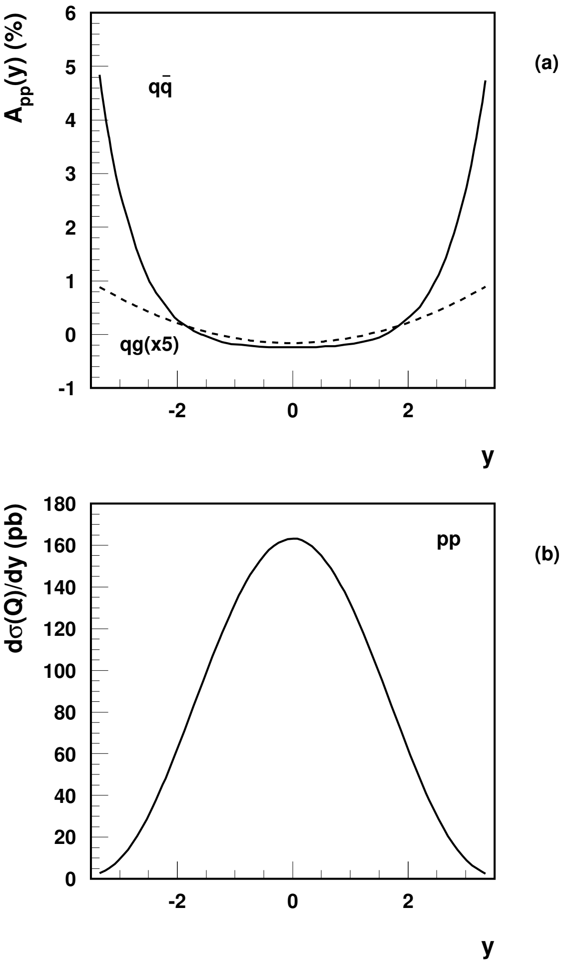

Figure 5: Rapidity distribution of charge asymmetry (a) and total cross section at Born order (b) of top quark production in proton-proton collisions, $\sqrt{s} = 14$ TeV and $\mu = m_t$. Contributions from $q\bar{q}$ fusion and flavor excitation, $qg(\bar{q}g)$, are shown separately. Laboratory frame (CTEQ-1).

The differential charge asymmetry

$$A_{pp}(y) = \frac{\dfrac{dN(Q)}{dy} - \dfrac{dN(\bar{Q})}{dy}}{\dfrac{dN(Q)}{dy} + \dfrac{dN(\bar{Q})}{dy}} \,, \tag{9}$$

is shown in Fig. 5a for top quark production at the LHC ($\sqrt{s} = 14$ TeV). As expected, a sizeable charge asymmetry is predicted in the region of large rapidity. It remains to be seen, if the low event rates in these extreme regions will permit the observation of this effect. The quark-gluon process is again negligible.

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