Heavy quark correlations
in hadronic collisions

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We discuss results of the k_t - factorization approach for heavy quark-heavy antiquark correlations in proton-proton and proton-antiproton collisions for RHIC, Tevatron and LHC. We consider correlations in the azimuthal angle as well as in the two-dimensional space of transverse momentum of heavy quark and heavy antiquark. We compare results obtained with the help of different unintegrated parton distributions (UPDF) from the literature.

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1. Introduction

The heavy quark-antiquark hadroproduction is known as a very important test of conventional gluon distributions within a standard factorization approach. The standard collinear approach does not include transverse momenta of initial gluons. The method to include transverse momenta is the k_t - factorization approach [1, 2, 3]. At the leading order of the collinear approach the heavy quark and heavy antiquark are produced back-to-back. In the unintegrated parton distributions (UPDF) approach [4, 5, 6], the azimuthal angle and p_t decorrelations (from the collinear leading-order configurations) are obtained already in the leading order of perturbative expansion [7]. In Ref.[7] we have explored in detail $c\bar{c}$ kinematical correlations at the Tevatron energies. Here we wish to discuss a more general case of (heavy quark)–(heavy antiquark) correlations for the RHIC, Tevatron and LHC energy range. We wish to empasize that this is a not yet well explored field of high-energy physics which could and should be studied in the future, in particular at LHC.

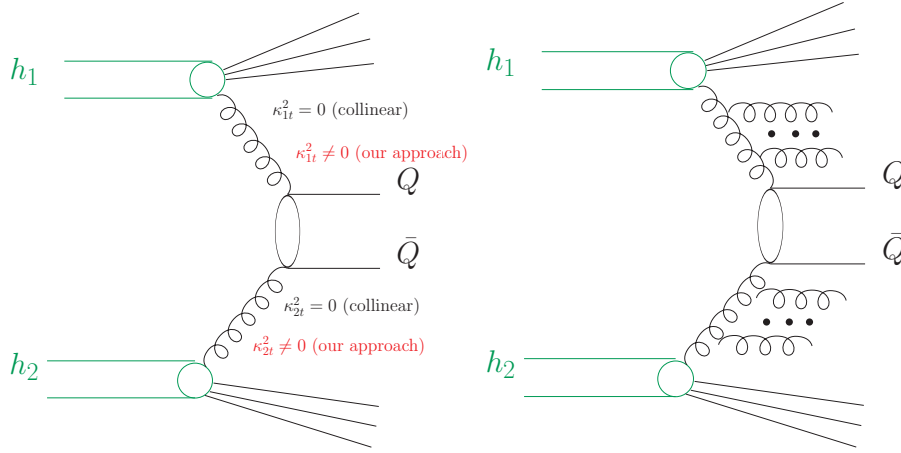## 2. (Heavy quark)-(heavy antiquark) correlations

Figure 1: Typical diagrams for heavy quark - antiquark production.

Let us consider the reaction $h_1 + h_2 \to Q + \bar{Q} + X$ (see Fig.1), where Q and $\bar{Q}$ are heavy quark and heavy antiquark, respectively. In the leading-order k_t- factorization approach the cross section in rapidity of Q (y_1), in rapidity of $\bar{Q}$ (y_2) and transverse momentum of heavy quark ($p_{1,t}$) and heavy antiquark ($p_{2,t}$) can be written as

$$\frac{d\sigma}{dy_1 dy_2 d^2 p_{1,t} d^2 p_{2,t}} = \sum_{i,j} \int \frac{d^2\kappa_{1,t}}{\pi} \frac{d^2\kappa_{2,t}}{\pi} \frac{1}{16\pi^2(x_1 x_2 s)^2} \overline{|\mathcal{M}_{ij}|^2}$$
$$\delta^2\left(\vec{\kappa}_{1,t} + \vec{\kappa}_{2,t} - \vec{p}_{1,t} - \vec{p}_{2,t}\right) f_i(x_1, \kappa_{1,t}^2) f_j(x_2, \kappa_{2,t}^2) , \tag{2.1}$$

where $f_i(x_1, \kappa_{1,t}^2)$ and $f_j(x_2, \kappa_{2,t}^2)$ are so-called unintegrated parton distributions. The two extra factors $1/\pi$ attached to the integration over $d^2\kappa_{1,t}$ and $d^2\kappa_{2,t}$ are due to the conventional relation between unintegrated and integrated parton distributions. The two-dimensional delta function assures momentum conservation.

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The unintegrated parton distributions must be evaluated at: $x_1 = \frac{m_{1,t}}{\sqrt{s}} (\exp(y_1) + \exp(y_2))$, $x_2 = \frac{m_{2,t}}{\sqrt{s}} (\exp(-y_1) + \exp(-y_2))$. The matrix element must be calculated for initial off-shell partons. The corresponding formulae for initial gluons were calculated in [1, 2] (see also [3]). In our paper we compare results obtained for both on-shell and off-shell matrix elements for charm-anticharm correlations.
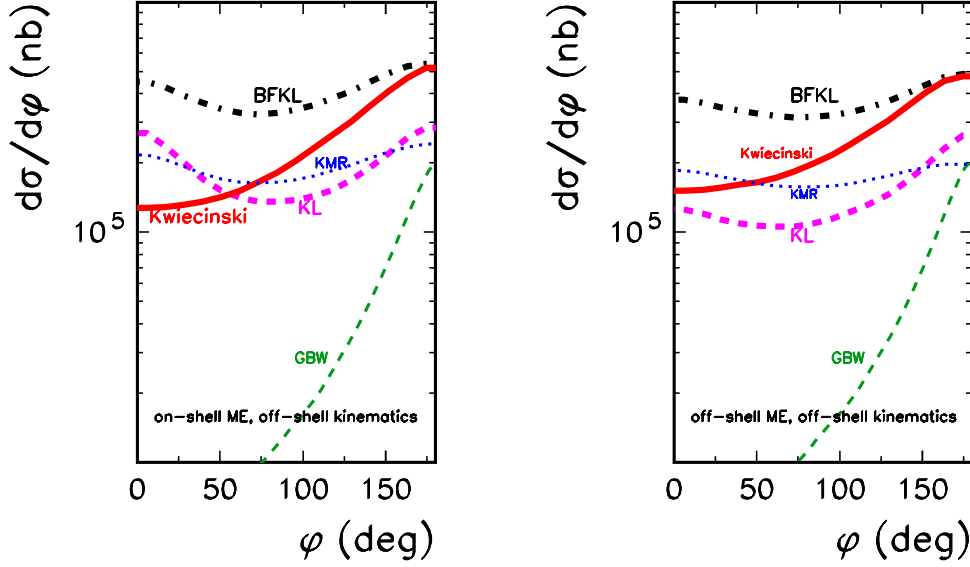
3. Results

Figure 2: $d\sigma/d\phi$ for charm - anticharm production at W = 1960 GeV for different UGDFs. The results with on-shell kinematics are shown in the left panel and results with off-shell kinematics in the right panel. In this calculation both factorization and renormalization scales were fixed for 4 m_c^2.

In Fig.2 we compare results for different unintegrated gluon distributions from the literature. Here there is no place to discuss different models of UGDFs and we refer the reader to the original paper [7] and references therein. Different results are obtained for different UGDF. BFKL dynamics leads to strong decorrelations in azimuthal angle between charm and anticharm quarks. In contrast, the nonperturbative GBW glue leads to strong azimuthal correlations between c and $\bar{c}$. The saturation idea inspired KL distribution leads to an local enhancement for $\phi_{c\bar{c}} \approx 0$ which is probably due to simplifications made in parametrizing the KL UGDF. In the last case there is sizeable difference between the result obtained with on-shell (left panel) and off-shell (right panel) matrix elements. All this is due to an interplay of the matrix element and the unintegrated gluon distributions.

In Fig.3 we show results for correlations in ($p_{1,t}$) of c and ($p_{2,t}$) of $\bar{c}$ for different unintegrated gluon distributions. Our results depend strongly on different UGDF. This is very interesting, because it can be verified in future experimental studies.
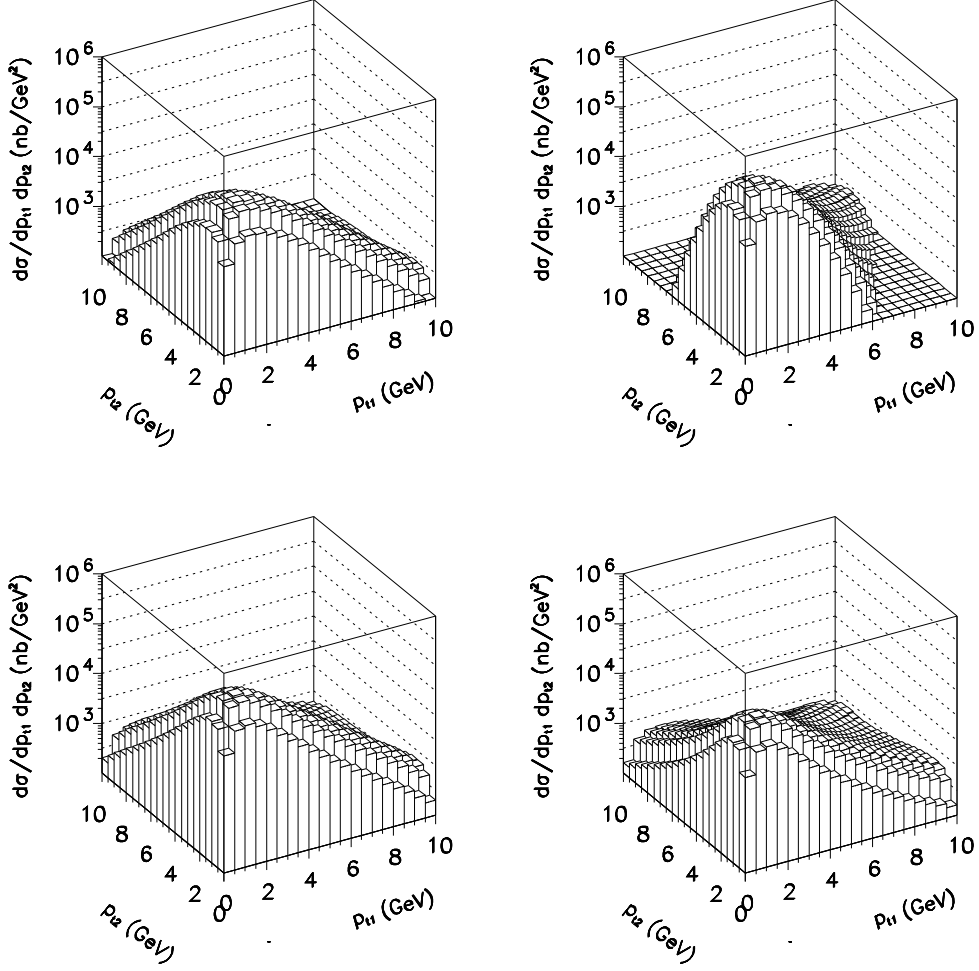
Figure 3: Two dimensional distributions in ($p_{1,t}$) of charm quark and ($p_{2,t}$) of charm antiquark for KMR (left top), Kwieciński ($b_0 = 1$ GeV^{-1}, $\mu^2 = 10$ GeV^2) (right top), BFKL (left bottom), KL (right bottom) UGDFs for W= 1960 GeV.

In Fig.4 we show another type of two-dimensional distribution. Generally, the bigger the transverse momentum of the produced quark (or antiquark) the stronger back-to-back correlation in azimuth. Similarly as in the previous case, the results depend on UGDFs used in the calculation. The somewhat stronger the back-to-back correlation in the case of the Kwieciński UGDF requires a separate discussion. As an example in Fig.5 we show the dependence of the azimuthal correlations for $p_{1,t}, p_{2,t} \in (5,15)$ GeV. We show the result for different values of the parameter b_0 describing initial (for QCD evolution) nonperturbative distribution of gluons in nucleons as well as for different values of the scale parameter μ^2. The results can be characterized as follows. The smaller b_0, the bigger the decorrelation between c and $\bar{c}$. On the other hand, the decorrelation increases with raising μ^2. Physically one would expect $\mu^2 = \mu^2(p_{1,t}, p_{2,t})$. A reasonable choice would be

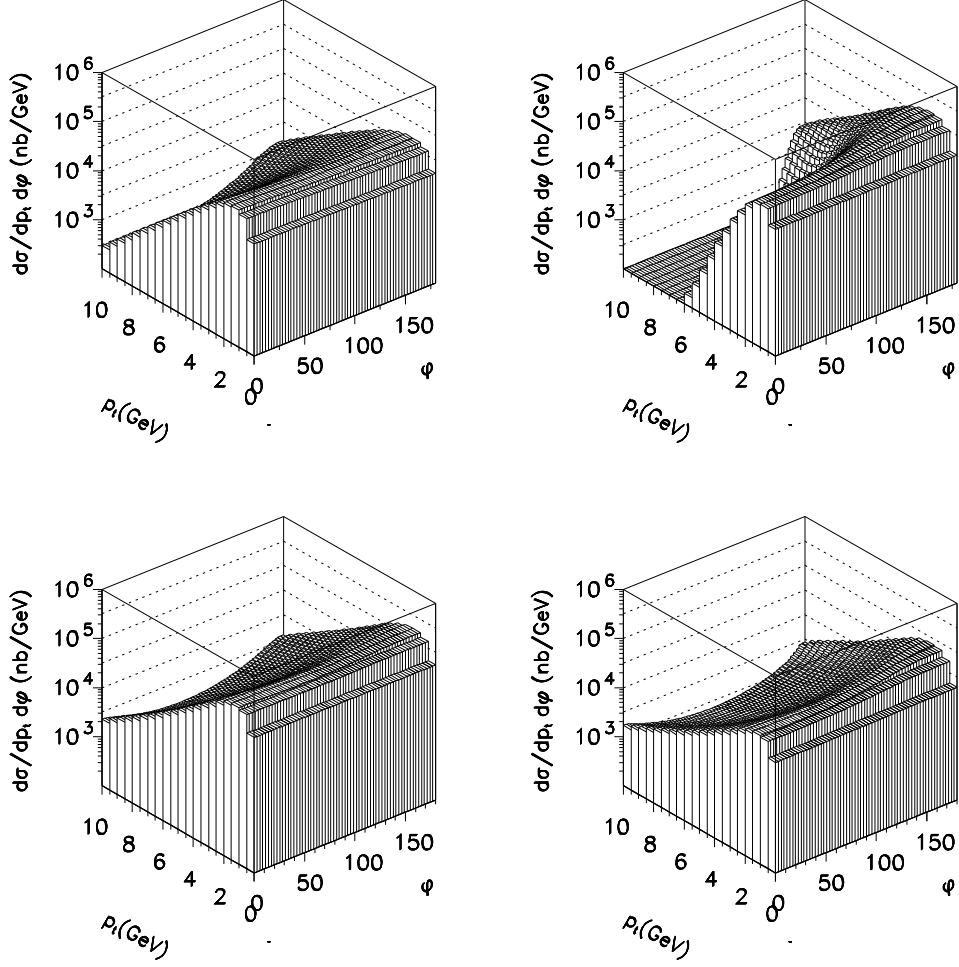$$\mu^2(p_{1,t}, p_{2,t}) = C_1 m_c^2 + C_2(p_{1,t}^2 + p_{2,t}^2) \,, \tag{3.1}$$

Figure 4: Two dimensional distributions in p_t and ϕ for KMR (left top), Kwieciński ($b_0 = 1$ GeV^{-1}, $\mu^2 = 10$ GeV^2) (right top), BFKL (left bottom), KL (right bottom) for W = 1960 GeV.

where $C_1, C_2 \sim 1$ may be expected. This would require the use of a running scale instead of a fixed one as at present. At the moment this was not possible technically and therefore only typical values of the scales were taken (see Fig.5). The scale $\mu^2 = 100$ GeV^2 is justified by the averaged values of the momenta in our calculation $\langle p_{1,t}^2 \rangle, \langle p_{2,t}^2 \rangle \approx 100$ GeV^2. The figure shows that QCD evolution embedded in the Kwieciński equations leads to a strong extra decorrelation of c and $\bar{c}$ in addition to that of the nonperturbative origin as encoded in the parameter b_0.

It was predicted for jet-jet correlations some time ago that a large rapidity gap between jets leads to increased decorrelation in azimuth. Can one expect a similar interesting effect for $c\bar{c}$ correlations? In Fig.6 we show our result for $c\bar{c}$ correlations as a function of the rapidity gap between c and $\bar{c}$. Of course, the bigger the rapidity distance between c and $\bar{c}$ the smaller the cross section. However the shape of the distribution in azimuth stays practically the same, except at $\Delta y \approx 0$, where a singularity for collinear quark and antiquark emissions shows up.
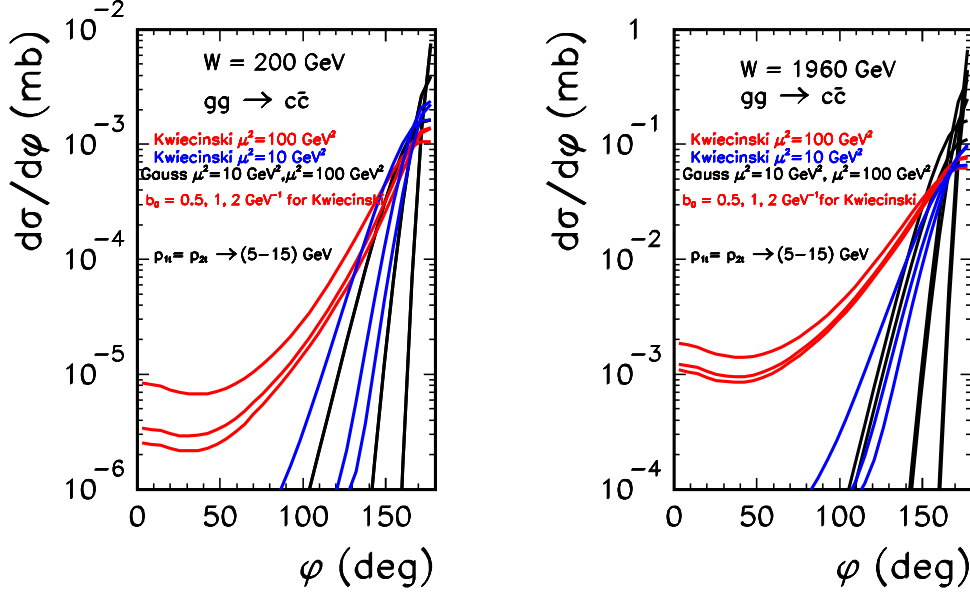
Figure 5: (Color on-line) The azimuthal correlations for the $gg \to c\bar{c}$ for RHIC and Tevatron energy with the Kwieciński UGDFs for different values of the nonperturbative parameter b_0 ($0, 5 \text{ GeV}^{-1}$, 1 GeV^{-1}, 2 GeV^{-1}) and for different evolution scales $\mu^2 = 10 \text{ GeV}^2$ (blue line) and $\mu^2 = 100 \text{ GeV}^2$ (red line). The initial distributions (without evolution) are shown for reference by black lines.

Finally we wish to come to azimuthal correlations of t and $\bar{t}$. Such an analysis seems possible even at present at the Tevatron. In Fig.7 we show the azimuthal correlation function for two energies: W = 1960 GeV (Tevatron) and W = 14 000 GeV (LHC). We show separately two contributions: $gg \to t\bar{t}$ (red) and $q\bar{q} \to t\bar{t}$ (black). While at the Tevatron energy the $q\bar{q} \to t\bar{t}$ contribution dominates over the $gg \to t\bar{t}$ contribution, the situation reverses at the LHC energy where the $gg \to t\bar{t}$ is the dominant contribution. The shape of both components is, however, very similar.

It would be very interesting to compare the result obtained with the k_t-factorization approach here with the result of the NLO collinear-factorization approach. The work in this direction is in progress.

4. Summary and outlook

Summarizing, we have discussed the (heavy quark) – (heavy antiquark) correlations in proton-proton and proton-antiproton collisions within the k_t-factorization approach. Different unintegrated gluon distributions have been used in the calculation. The results for azimuthal angle as well as in $p_{1,t} \times p_{2,t}$ correlations have been presented.

In principle, corresponding experimental results would provide new information and could test the unintegrated gluon distributions from the literature. In practice, this could be more difficult as one measures rather heavy mesons or charged leptons from the decays and only correlations of
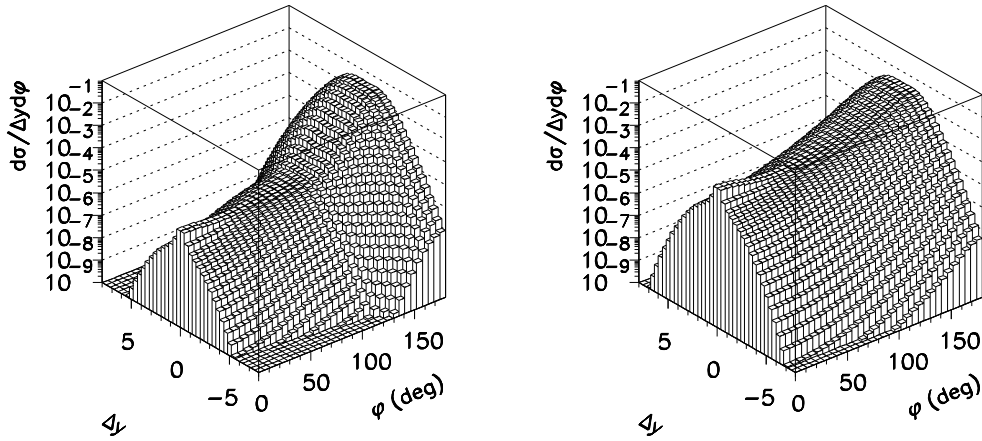
Figure 6: $d\sigma/d\phi$ versus rapidity gap between c and $\bar{c}$ for W = 1960 GeV^2. ($p_{1,t} = p_{2,t} \rightarrow (5,15)$ GeV, $\Delta y = y_1 - y_2$, $\mu^2 = 10$ GeV^2 (left panel), $\mu^2 = 100$ GeV^2 (right panel).
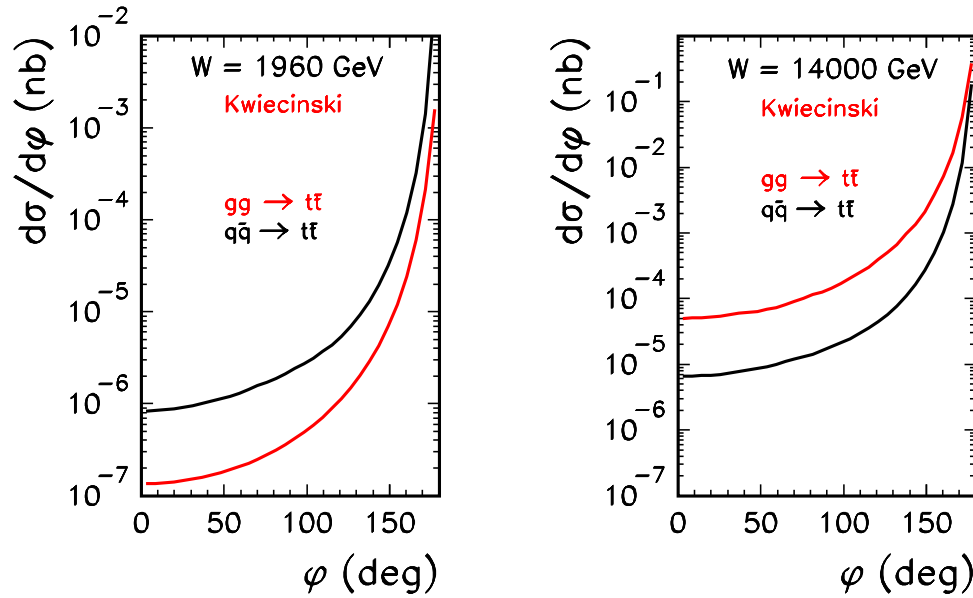

Figure 7: (Color on-line) $d\sigma/d\phi$ for $t\bar{t}$ production at W = 1960 GeV (left panel) and W = 14000 GeV (right panel) for two process: gg $\rightarrow t\bar{t}$ and $q\bar{q} \rightarrow t\bar{t}$ for Kwieciński distributions. In this calculation $\mu^2 = 10000$ GeV^2.

such objects can be studied. However, both heavy mesons and charged leptons from the decays "remember" to a large extend the direction of the initial heavy quark/antiquark.

On the theoretical side, a relation between k_t-factorization and standard NLO approaches

should be better understood and clarified.

We expect exciting future studies of $Q\bar{Q}$ correlations at the LHC, especially for $t\bar{t}$ where detailed studies will be possible for the first time in history.

References

[1] S. Catani, M. Ciafaloni and F. Hautmann, Nucl. Phys. **366** (1991) 135.

[2] J.C. Collins and R.K. Ellis, Nucl. Phys. **B360** (1991) 3.

[3] R.D. Ball and R.K. Ellis, J.H.E.P. **0105** (2001) 053.

[4] D. Kharzeev and E. Levin, Phys. Lett. **B523** (2001) 79.

[5] K. Golec-Biernat and M. Wüsthoff, Phys. Rev. **D60** (1999) 114023-1.

[6] M.A. Kimber, A.D. Martin and M.G. Ryskin, Eur. Phys. J. **C12** (2000) 655;
M.A. Kimber, A.D. Martin and M.G. Ryskin, Phys. Rev. **D63** (2001) 114027-1.

[7] M. Łuszczak and A. Szczurek, Phys. Rev. **D73** (2006) 054028.

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