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Parton Shower Effects in Heavy Flavour Production at Tevatron

Mira Krämer*
DESY, Hamburg, Germany
E-mail: `mira.kraemer@desy.de`

Hannes Jung
DESY, Hamburg, Germany
E-mail: `hannes.jung@desy.de`

Artem V. Lipatov
SINP - MSU, Moscow, Russia
E-mail: `lipatov@theory.sinp.msu.ru`

Nikolai P. Zotov
SINP - MSU, Moscow, Russia
E-mail: `zotov@theory.sinp.msu.ru`

In general, heavy flavour production at hadron colliders is reasonably well understood using the collinear approach. But especially angular correlations between the produced heavy quarks reveal the necessity of further investigations, since the data are not fully described in this region. Here, non-collinear gluon evolution dynamics are expected to dominate the scenario. Therefore, we studied heavy flavour production at the Tevatron in the non-collinear approach by comparing the data to numerical calculations and to predictions of the hadron-level Monte Carlo generator CASCADE. We focus on parton shower effects and the influences of different unintegrated parton density functions. Studies of systematic uncertainties are also presented. We observe, that the non-collinear approach is able to describe heavy flavour production at Tevatron within the systematic uncertainties.

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*Speaker.

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1. Introduction

We compare beauty and charm measurements at Tevatron to predictions of the hadron-level Monte Carlo generator CASCADE [1] and to numerical calculations within the non-collinear approach [2]. We focus on angular correlations, since these quantities are sensitive to non-collinear gluon evolution dynamics and therefore provide the opportunity to test unintegrated parton density functions (uPDFs) and parton shower effects. The numerical calculations and the CASCADE predictions use unintegrated PDFs convoluted with off-mass shell matrix elements for the hard scattering. In contrast to the collinear approach, the use of unintegrated PDFs provides the feature of correct event kinematics from the beginning, while in the collinear approach a mapping of the $n+1$ to the n-partonic configuration has to be performed with the associated rearrangement of kinematics. The b quark mass in our predictions is $m_b = 4.75$ GeV and the c mass is set to $m_c = 1.4$ GeV. We use $\mu_r = m_q + (p_{1T}^2 + p_{2T}^2)/2$ as renormalization scale, where p_{nT}, with $n = 1,2$, is the transverse momentum of the produced heavy quarks. The factorization scale is $\mu_f = \hat{s} + Q_T^2$, where Q_T^2 is the sum of the transverse momenta of the initial gluons, and the QCD scale is set to $\Lambda_{QCD} = 200$ MeV. We chose the Peterson fragmentation function [3] with the usual shape parameters $\varepsilon_b = 0.006$ and $\varepsilon_c = 0.06$.

1.1 $b\bar{b}$ Dijet Production

Recently, $b\bar{b}$ dijet production at Tevatron was investigated in the kinematical region $|y_1| < 1.2$, $|y_2| < 1.2$, $E_{1T} > 35$ GeV and $E_{2T} > 32$ GeV by the CDF collaboration [4]. The measured cross section as a function of the angular separation of the two jets are compared to Pythia, Herwig and MC@NLO predictions. The leading order Monte Carlos using the collinear approach, which is based on the DGLAP evolution equations, are neither able to describe the peak, nor the tail of the distribution, while MC@NLO gives a reasonable description. This gives the hint, that higher order processes play a crucial role here.

2. Unintegrated PDFs

We used the uPDF sets A0 and B0 [5], which can be obtained from the solution of the CCFM

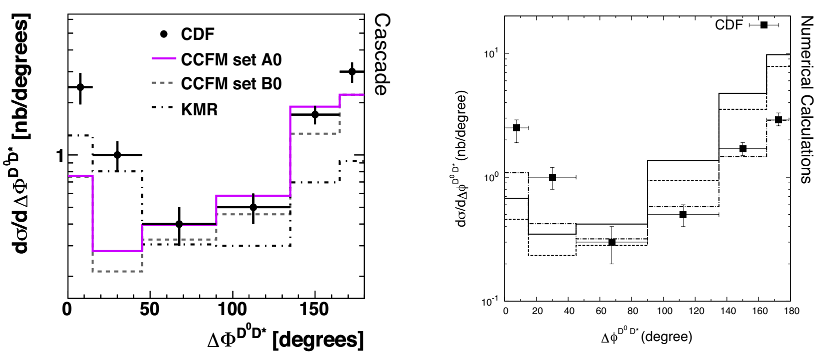

Figure 1: CASCADE predictions and numerical calculations using the unintegrated PDFs CCFM set A0, B0 and KMR for the charm measurement in [7].

evolution equations. Here, the resummation of small x logarithms is taken into account. All input parameters of the two sets have been fitted to describe the proton structure function $F_2(x,Q^2)$. Additionally, we also use the KMR [6] scheme. In this approach, the unintegrated gluon distribution is based on the usual unregulated leading order DGLAP splitting functions. Here, the resummation of small x logarithms is not taken into account in contrast to the two CCFM sets A0 and B0. As depicted exemplarily in figure 1, the CCFM set A0 gives the best description of the charm measurement [7] as a function of the azimuthal separation of the D^0 and D^* at high values of $\Delta\Phi^{D^0D^*}$. The same holds for the $b\bar{b}$ dijet measurement, which is not shown. The high $\Delta\Phi$ region represents the leading order picture, where the jets are back-to-back. But also set A0 underestimates the peak. At small values, all uPDFs fail to describe the data. In this region, gluon radiation is expected to contribute significantly. We are able to describe the data in both regions by including parton shower effects and additional gluon processes, as described in the following.

3. Parton Shower

In CASCADE, the initial state parton shower is angular ordered and based on the CCFM evolution equations. The final state parton shower is also angular ordered, but based on the DGLAP evolution equations. To investigate the dependence on the parton shower (not shown), we produced the $b\bar{b}$ dijet cross sections without, only initial state, only final state and both initial and final state parton shower using CCFM set A0. We observe a very small contribution of the initial state parton shower, the prediction is here very similar to the case without parton shower. Since the two b jets are initiated by the hard scattering, the azimuthal dependence is essentially driven by the k_T of the gluons, which is determined by the uPDF. Therefore, the cross section is sensitive to the k_T of the gluons, but not to the parton shower itself. The main contribution comes from the final state parton shower. The underestimation of the peak leads to the conclusion, that the final state parton showering includes too much gluon radiation, which causes less correlated jets. To solve this problem, we changed the amount of final state gluon radiation by decreasing the final state parton shower scale from $Q_{max} = 4m_T$ to $Q_{max} = m^2$, where m ist the quark mass. As shown in figure 2, this leads to a higher correlation of the b jets and the CASCADE prediction is now able to describe the peak of the azimuthal separation of the jets.

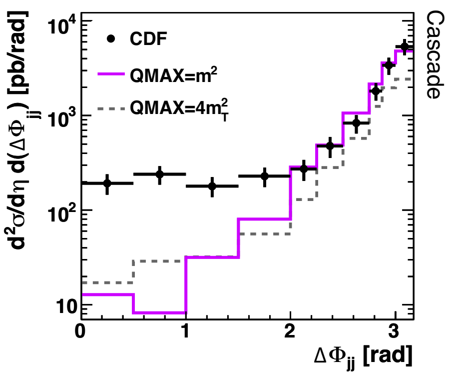

Figure 2: CASCADE predictions with two different scales for the final state parton shower for $b\bar{b}$ dijet production at Tevatron [4].

4. Additional Gluon Processes

At lower values of the azimuthal separation of the dijet system, higher order processes are expected to contribute significantly. Therefore, we repeated the beauty and charm analyses for the process $gg \to gg$, which represents a NNLO effect. In the matrix element calculation, which was performed in [8], one gluon in the initial state is on-shell while the other one is off-shell. The heavy

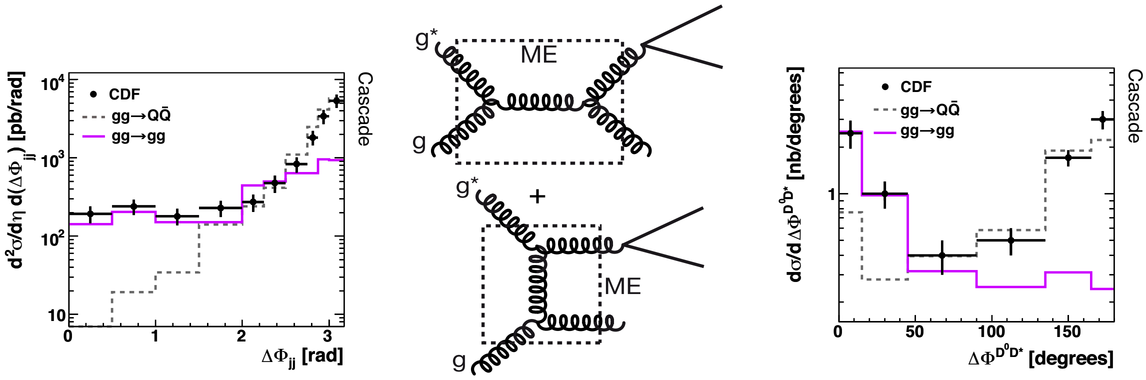

Figure 3: Feynman diagrams for additional gluon processes as calculated in [8]. The heavy quark pair is produced via parton shower.

quark pair is then produced via parton showers in the final state. In figure 3, two Feynman diagrams for the process $gg \to gg$ are shown exemplarily. For further details see [8]. As depicted in figure 3, this process is able to describe the tail of the azimuthal separation of the two $b\bar{b}$ jets and the D^0D^* nicely. To fully describe heavy quarks at Tevatron, these two processes have to be added.

5. Systematic Uncertainties

Source / Cross Section	$\sigma(B^+)[\mu b]$	$\sigma(D^+)[\mu b]$
CDF Data	2.78 ± 0.24	$4.31 \pm 0.1 \pm 0.7$
CCFM set A0	$2.62\pm^{0.39}_{0.37}$	$3.17\pm^{0.41}_{0.86}$
CCFM set A0+	$+11\%$	$+10\%$
CCFM set A0-	$+1\%$	$+8\%$
Quark Mass up	-9%	-5%
Quark Mass down	$+10\%$	$+4\%$
Flavour def. parameter	-10%	-27%
Total	$\pm^{15\%}_{14\%}$	$\pm^{13\%}_{27\%}$

Table 1: Summary of systematic uncertainties obtained with CASCADE for the B^+ and D^+ measurements from [9], [10].

To determine systematic uncertainties for heavy quarks at Tevatron, we repeated a beauty [9] and charm [10] analyses using different parameters in CASCADE. The summary of these studies is shown in table 1. As default, we used the CCFM set A0 and the parameters as described in section 1. The uPDF sets A0+ and A0- reflect a variation of the scale by a factor of 2 up and down. Both variations lead to a higher cross section for the beauty and the charm analyses. The quark masses are changed by $m_b \pm 0.25$ GeV and $m_c \pm 0.1$ GeV. If the quark mass is higher, the resulting cross section is lower and vice versa. Additionally, we investigated the influence of the tuned flavour parameters obtained with PROFESSOR [11] in comparison to the default parameters. For the charm measurement, this is observed to be the dominant contribution of the total uncertainty. In total, we obtain $\pm^{15\%}_{14\%}$ systematic uncertainty for the beauty and $\pm^{13\%}_{27\%}$ for the charm measurement by adding up the positive and negative contributions separately in quadrature. This result shows, that the k_T factorization approach is able to describe heavy flavour production at Tevatron within the systematic uncertainties.

6. Conclusion

We investigated heavy flavour production at Tevatron using the k_T factorization approach and focussed especially on angular separations of the produced quark-antiquark pair. The investigation of systematic uncertainties revealed, that the non-collinear approach is able to describe both the beauty and charm analyses within the errors. We describe the back-to-back region of the azimuthal separation of the $b\bar{b}$ dijets by adjusting the final state parton shower scale. This leads to less gluon radiation and to more correlated jets in the final state. The data at low values of the angular separation are well described now by taking into account additional gluon processes $gg \rightarrow gg$.

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