HEAVY QUARK PRODUCTION AT COLLIDER ENERGIES: SOME SELECTED TOPICS*

Antoni Szczurek

The Henryk Niewodniczański Institute of Nuclear Physics
Polish Academy of Sciences
Radzikowskiego 152, 31-342 Kraków, Poland
and
Rzeszów University, Rejtana 16A, 35-959 Rzeszów, Poland

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We discuss production of charm quarks and mesons as well as nonphotonic electrons in pp scattering at RHIC. The distributions in rapidity and transverse momentum are calculated in the k_{t}-factorization approach. The hadronization of heavy quarks is done by means of phenomenological fragmentation functions. The semileptonic decay functions found by fitting semileptonic decay data are used. Good description of the inclusive data at large transverse momenta of electrons is obtained and a missing strength at small transverse momenta of electrons is found. We discuss kinematical correlations between charged leptons from semileptonic decays of open charm/bottom, leptons produced in the Drell–Yan mechanism as well as some other mechanisms not included so far in the literature. A good description of the dilepton invariant mass spectrum measured by the PHENIX Collaboration is achieved. Predictions for the dilepton pair transverse momentum distribution as well as distribution in azimuthal angle between electron and positron are presented.

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1. Introduction

Some time ago the PHENIX and STAR collaborations have measured transverse momentum distribution of so-called nonphotonic electrons [1, 2]. The nonphotonic electrons/positrons come from the semileptonic decays of charm and/or beauty mesons. Formally, such processes can be divided into three subsequent stages. First $c\bar{c}$ or $b\bar{b}$ quarks are produced. The dominant mechanisms being gluon–gluon fusion and quark–antiquark annihilation. Next, the heavy quarks/antiquarks fragment into heavy charmed

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mesons D, D^* or B, B^*. The vector D^* and B^* mesons decay strongly producing (pseudo)scalar D and B mesons. Finally, the heavy pseudoscalar mesons decay semileptonically producing electrons/positrons.

In this presentation, the results have been obtained within the $k_{\rm t}$-factorization approach. At rather low RHIC energies intermediate x-values become relevant. The Kwieciński unintegrated gluon (parton) distributions seem the best suited in this context [3]. We shall use both Peterson [4] and so-called perturbative [5] fragmentation functions. The electron/positron decay functions fitted recently [6] to the recent CLEO [7] and BABAR [8] data are used here.

Recently, the PHENIX Collaboration has measured dilepton invariant mass spectrum in pp collisions at $\sqrt{s} = 200$ GeV [9]. Up to now, production of open charm and bottom was studied only in inclusive measurements of charmed mesons [10] and electrons [11] and only inclusive observables were calculated in pQCD approach [6, 12]. Such predictions give rather good description of the experimental data, however, the theoretical uncertainties are quite large.

Some time ago we have studied kinematical correlations of $c\bar{c}$ quarks [13], which is, however, difficult to study experimentally. High luminosity and, in consequence, better statistics at present colliders gives a new possibility to study not only inclusive distributions but also correlations between outgoing particles. Kinematical correlations constitute an alternative method to pin down the cross section for charm and bottom production.

Below, I shall limit the presentation to the results obtained in [6,14]. The original presentation at the conference included also diffractive processes.

2. Formalism

Let us consider the reaction $h_1 + h_2 \to Q + \bar{Q} + X$, where Q and $\bar{Q}$ are heavy quark and heavy antiquark, respectively. In the $k_{\rm t}$-factorization approach the multiply differential cross section reads

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

where $\mathcal{F}_i(x_1, \kappa_{1,{\rm t}}^2)$ and $\mathcal{F}_j(x_2, \kappa_{2,{\rm t}}^2)$ are the so-called unintegrated gluon (parton) distributions. Leading-order matrix elements for off-shell gluons [15,16, 17] were used. The two-dimensional Dirac delta function assures momentum conservation.

The production of electrons/positrons is a multi-step process. The whole procedure of electron/positron production can be written in the following schematic way

$$\frac{d\sigma^e}{dyd^2p} = \frac{d\sigma^Q}{dyd^2p} \otimes D_{Q\to D} \otimes f_{D\to e}\,, \tag{2}$$

where the symbol $\otimes$ denotes a generic convolution. The first term is responsible for production of heavy quarks/antiquarks. Next step is the process of formation of heavy mesons. We follow a phenomenological approach and take *e.g.* Peterson [4] and Braaten *et al.* [5] fragmentation functions with parameters from the literature [18]. The electron decay function accounts for the proper branching fractions. The inclusive distributions of hadrons can be obtained through a convolution of inclusive distributions of heavy quarks/antiquarks and $Q \to h$ fragmentation functions

$$\begin{aligned}\frac{d\sigma\left(y_1, p_{1\mathrm{t}}^H, y_2, p_{2\mathrm{t}}^H, \phi\right)}{dy_1 dp_{1\mathrm{t}}^H dy_2 dp_{2\mathrm{t}}^H d\phi} \approx & \int \frac{D_{Q\to H}(z_1)}{z_1} \cdot \frac{D_{\bar{Q}\to\bar{H}}(z_2)}{z_2} \\ & \times \frac{d\sigma\left(y_1, p_{1\mathrm{t}}^Q, y_2, p_{2\mathrm{t}}^Q, \phi\right)}{dy_1 dp_{1\mathrm{t}}^Q dy_2 dp_{2\mathrm{t}}^Q d\phi} dz_1 dz_2\,,\end{aligned} \tag{3}$$

where $p_{1\mathrm{t}}^Q = \frac{p_{1\mathrm{t}}^H}{z_1}$, $p_{2\mathrm{t}}^Q = \frac{p_{2\mathrm{t}}^H}{z_2}$ and $z_1, z_2 \in (0,1)$ are the meson longitudinal fractions. We use the decay functions fitted recently [6] to the CLEO and BABAR data. In our approach the electrons (positrons) are generated isotropically in the heavy meson rest frame.

3. Results

Before we start presenting our results for the spectra, let us focus for a moment on the decay functions discussed shortly above. In Ref. [6] we presented a fit to the CLEO and BABAR data. The good quality fit of the data allows us to obtain reliable predictions for electron/positron single particle spectra.

Now we shall concentrate on transverse momentum distribution of electrons/positrons measured recently by the STAR and PHENIX collaborations at RHIC [1, 2]. In Fig. 1 we show, as an example, the results obtained with the Kwieciński UPDFs [3]. In Ref. [6] we have discussed in addition other UGDFs. In these calculations we have included both gluon–gluon fusion as well as quark–antiquark annihilation. In the latter case we use matrix elements with on-shell formula but for off-shell kinematics (the discussion of this point can be found in our earlier paper [13]). In Ref. [6] we have discussed also uncertainties due to the choice of quark masses.

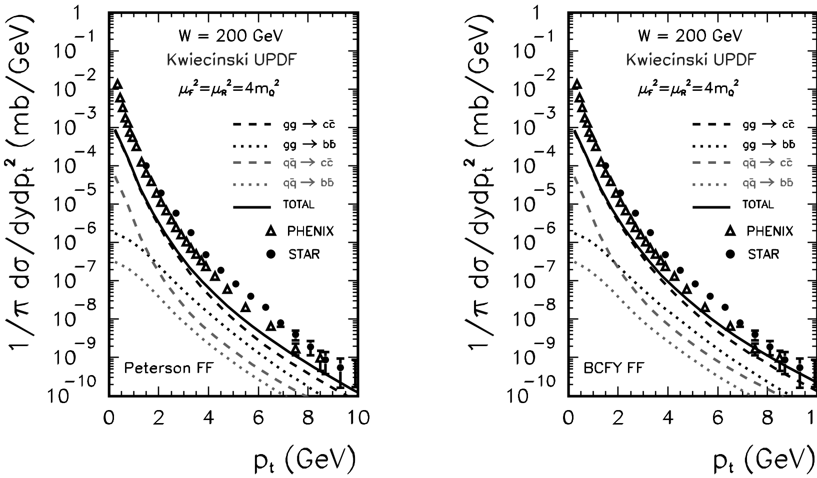

Fig. 1. Transverse momentum distribution of electrons/positrons obtained with the Kwieciński UPDFs. Different combinations of factorization and renormalization scales are used. We show separately contributions of the gluon–gluon fusion (black) and quark–antiquark annihilation (grey). On the left-hand side, results with the Peterson fragmentation functions and, on the right-hand side, with BCFY fragmentation functions.

Study of nonphotonic $e^{\pm}$ and hadron correlations allows one to "extract" a fractional contribution of the bottom mesons $B/(D+B)$ [19,20]. Recently, the STAR Collaboration has extended the measurement of the relative B contribution to electron/positron transverse momenta ~ 10 GeV [19,21].

When calculating correlation observables, we have included also several electromagnetic processes as well as exclusive diffractive process. The photon–photon induced processes were first included in Ref. [14]. The central exclusive diffractive process was first proposed in Ref. [22].

In Fig. 2, we show e^+e^- invariant mass distributions calculated with the Kwieciński (left) and KMR (right) UGDFs. One can clearly see that both the Kwieciński and KMR [23] UGDFs give fairly good description of the data for $M_{e^+e^-} > 3$ GeV. At small invariant masses the Kwieciński UGDF underestimates the PHENIX data and the KMR UGDF starts to overestimate the data points below $M_{e^+e^-} = 2$ GeV.

If the detector can measure both transverse momenta of electron/positron and their directions, one can construct a distribution in transverse momentum of the dielectron pair: $\vec{p}_{\rm t,sum} = \vec{p}_{\rm 1t} + \vec{p}_{\rm 2t}$. Our predictions including the semileptonic decays and Drell–Yan processes are shown in the left panel of Fig. 3. Both processes give rather similar distributions. To our knowledge the distributions of this type have never been measured experimentally. The distribution in $p_{\rm t,sum}$ is not only a consequence of gluon transverse momenta but involves also fragmentation process and semileptonic decays.

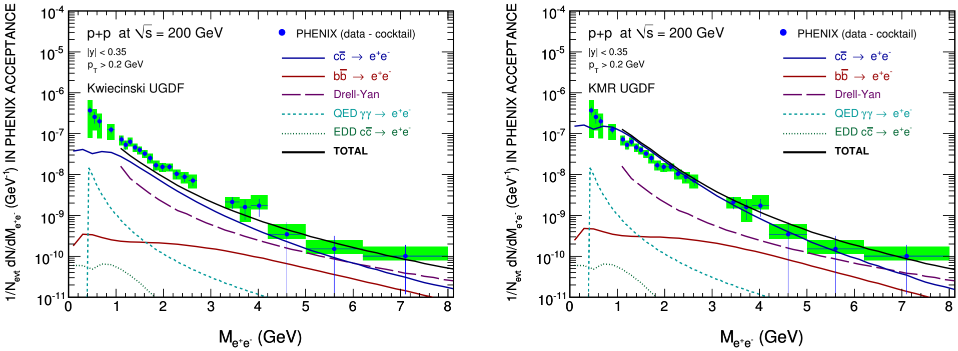

Fig. 2. Dielectron invariant mass distribution for pp collisions at $\sqrt{s} = 200$ GeV for the Kwieciński (left) and KMR (right) UGDFs. Different contributions are shown separately: semileptonic decay of charm by the (blue) solid line, semileptonic decay of bottom by the (red) solid line, Drell–Yan mechanism by the long dashed line, gamma–gamma processes by the dashed (blue) line and the central diffractive contribution by the dotted (green) line. In this calculation, we have included azimuthal angle acceptance of the PHENIX detector [9].

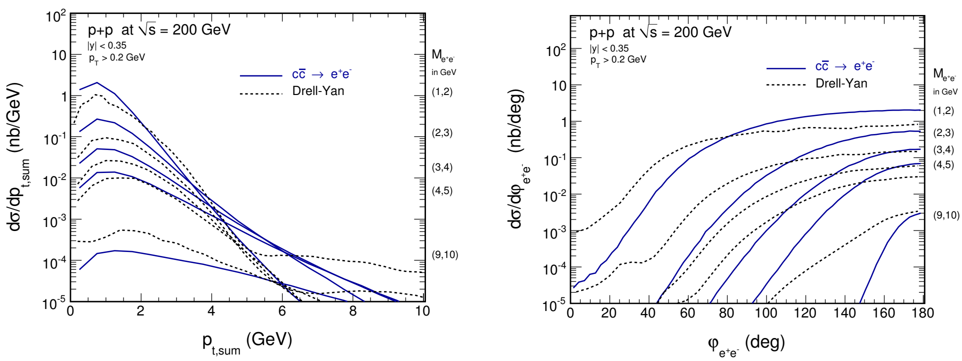

Fig. 3. Distribution in transverse momentum of the dielectron pair (left) and in azimuthal angle between electron and positron (right) for semileptonic decays (solid line) and Drell–Yan processes (dashed line). Here Kwieciński UGDF and Peterson fragmentation function were used.

With good azimuthal granulation of detectors, one could also construct distribution in azimuthal angle between electron and positron. Corresponding predictions are shown in the right panel of Fig. 3. One can see an interesting dependence on the invariant mass of the dielectron pair — the smaller the invariant mass the large the decorrelation in azimuthal angle.

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