Nonphotonic electrons at BNL RHIC within the k_t-factorization approach and with experimental semileptonic decay functions

M. Łuszczak,[1,*] R. Maciuła,[1,2,†] and A. Szczurek[1,2,‡]

[1]*University of Rzeszów, PL-35-959 Rzeszów, Poland*
[2]*Institute of Nuclear Physics PAN, PL-31-342 Cracow, Poland*
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We discuss production of nonphotonic electrons in proton-proton scattering at the relativistic heavy ion collider. The distributions in rapidity and transverse momentum of charm and bottom quarks/antiquarks are calculated in the k_t-factorization approach. We use Kwieciński unintegrated parton distributions and Ivanov-Nikolaev unintegrated gluon distribution. The hadronization of heavy quarks is done by means of Peterson and Braaten *et al.* fragmentation functions. The semileptonic decay functions are found by fitting recent semileptonic data obtained by the CLEO and *BABAR* collaborations. We get good description of the data at large transverse momenta of electrons and find a missing strength concentrated at small transverse momenta of electrons. Plausible missing mechanisms are discussed.

I. INTRODUCTION

Recently the PHENIX and STAR collaborations have measured the transverse momentum distribution of so-called nonphotonic electrons [1,2]. It is believed that the dominant contribution to the nonphotonic electrons/positrons comes from the semileptonic decays of charm and beauty mesons. These processes have 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 are turned to heavy charmed mesons D, D^* or B, B^*. The vector D^* and B^* mesons decay strongly producing D and B mesons. Finally, the heavy pseudoscalar mesons decay semileptonically producing electrons/positrons.

The inclusive heavy quark/antiquark production can presently be calculated at Fixed-Order plus Next-to-Leading-Log (FONLL) level [3]. The predictions for electron spectra in proton-proton collisions at the relativistic heavy ion collider (RHIC) can be found in Ref. [4]. An alternative approach for inclusive heavy quark production is k_t-factorization [5–11]. In this approach emission of gluons (see left panel in Fig. 1) is encoded in so-called unintegrated gluon distributions (UGDFs). The latter approach is very efficient for description of $Q\bar{Q}$ correlations [12]. Here we generalize this approach including quark and antiquark unintegrated distributions (see right panel in Fig. 1).

The hadronization of heavy quarks is usually done with the help of fragmentation functions. The Peterson fragmentation functions are often used in this context [13]. The parameters of the Peterson fragmentation functions are adjusted to the production of heavy mesons in e^+e^- or

$p\bar{p}$ collisions. Another, perturbative, fragmentation model has been proposed in Ref. [14] (BCFY).

The last ingredient are semileptonic decays of heavy mesons. Until recently this component was treated by modeling the decay [15–17]. Only recently the CLEO [18] and *BABAR* [19] collaborations has measured very precisely the spectrum of electrons/positrons coming from the decays of D and B mesons, respectively. This is done by producing resonances: $\Psi(3770)$ which decays into D and $\bar{D}$ mesons (CLEO) and $\Upsilon(4S)$ which decays into B and $\bar{B}$ mesons (*BABAR*). In both cases the heavy mesons are almost at rest, so in practice one measures the meson rest frame distributions of electrons/positrons.

In the present analysis we shall apply the k_t-factorization approach. At relatively low RHIC energies rather intermediate x-values become relevant. The Kwiecinski unintegrated gluon (parton) distributions seem relevant in this case [20]. We shall use also Ivanov-Nikolaev distributions which were fitted to deep-inelastic HERA data including intermediate-x region [21]. We shall use both Peterson and BCFY fragmentation functions. The electron/positron de-
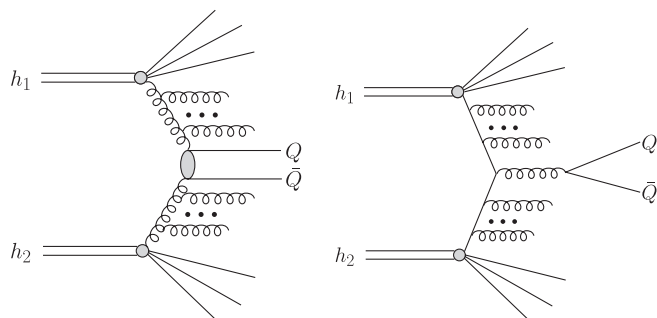

FIG. 1. A basic diagram relevant for gluon-gluon fusion (left panel) and quark-antiquark annihilation (right panel) in our k_t-factorization approach.

*luszczak@univ.rzeszow.pl
†rafal.maciula@ifj.edu.pl
‡Antoni.Szczurek@ifj.edu.pl

cay functions will be fitted to the recent CLEO and *BABAR* data.

II. FORMALISM

Let us consider the reaction $h_1 + h_2 \rightarrow Q + \bar{Q} + X$, where Q and $\bar{Q}$ are heavy quark and heavy antiquark, respectively. In the leading-order (LO) approximation within the collinear approach the quadruply differential cross section in the rapidity of Q (y_1), in the rapidity of $\bar{Q}$ (y_2) and the transverse momentum of one of them (p_t) can be written as

$$\frac{d\sigma}{dy_1 dy_2 d^2 p_t} = \frac{1}{16\pi^2 \hat{s}^2} \sum_{i,j} x_1 p_i(x_1, \mu^2) x_2 p_j(x_2, \mu^2) \overline{|\mathcal{M}_{ij}|^2}.$$

(2.1)

Above, $p_i(x_1, \mu^2)$ and $p_j(x_2, \mu^2)$ are the familiar (integrated) parton distributions in hadron h_1 and h_2, respectively. There are two types of the LO $2 \rightarrow 2$ subprocesses which enter Eq. (2.1): $gg \rightarrow Q\bar{Q}$ and $q\bar{q} \rightarrow Q\bar{Q}$. The first mechanism dominates at large energies and the second one near the threshold. The parton distributions are evaluated at: $x_1 = \frac{m_t}{\sqrt{s}}(\exp(y_1) + \exp(y_2))$, $x_2 = \frac{m_t}{\sqrt{s}} \times (\exp(-y_1) + \exp(-y_2))$, where $m_t = \sqrt{p_t^2 + m_Q^2}$. The formulas for matrix element squared averaged over the initial and summed over the final spin polarizations can be found e.g. in Ref. [22].

If one allows for transverse momenta of the initial partons, the sum of transverse momenta of the final Q and $\bar{Q}$ no longer cancels. Formula (2.1) can be easily generalized if one allows for the initial parton transverse momenta. Then

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

(2.2)

where now $\mathcal{F}_i(x_1, \kappa_{1,t}^2)$ and $\mathcal{F}_j(x_2, \kappa_{2,t}^2)$ are the so-called unintegrated gluon (parton) distributions.[1] Leading-order matrix elements for off-shell gluons [5–7] were used in the present analysis. The extra integration is over transverse momenta of the initial partons. The two extra factors $1/\pi$ are due to the integration over $d^2\kappa_{1,t}$ and $d^2\kappa_{2,t}$ instead over $d\kappa_{1,t}^2$ and $d\kappa_{2,t}^2$ as in the conventional relation between the unintegrated ($\mathcal{F}$) and the integrated (g) parton distributions. The two-dimensional Dirac delta function assures momentum conservation. Now the unintegrated parton distributions must be evaluated at: $x_1 = \frac{m_{1,t}}{\sqrt{s}} \times \exp(y_1) + \frac{m_{2,t}}{\sqrt{s}} \exp(y_2)$, $x_2 = \frac{m_{1,t}}{\sqrt{s}} \exp(-y_1) + \frac{m_{2,t}}{\sqrt{s}} \times \exp(-y_2)$, where $m_{i,t} = \sqrt{p_{i,t}^2 + m_Q^2}$. In general, the matrix element must be calculated for initial off-shell partons. The corresponding formulas for initial gluons were calculated in [5,6] (see also [7]). It is easy to check [12] that in the limit $\kappa_1^2 \rightarrow 0$, $\kappa_2^2 \rightarrow 0$ the off-shell matrix elements converge to the on-shell ones.

Introducing new variables:

$$\vec{Q}_t = \vec{\kappa}_{1,t} + \vec{\kappa}_{2,t}, \qquad \vec{q}_t = \vec{\kappa}_{1,t} - \vec{\kappa}_{2,t}, \qquad (2.3)$$

we can write:

$$\frac{d\sigma_{ij}}{dy_1 dy_2 d^2 p_{1,t} d^2 p_{2,t}} = \int d^2 q_t \frac{1}{4\pi^2} \frac{1}{16\pi^2(x_1 x_2 s)^2} \overline{|\mathcal{M}_{ij}|^2} \mathcal{F}_i(x_1, \kappa_{1,t}^2) \mathcal{F}_j(x_2, \kappa_{2,t}^2). \qquad (2.4)$$

This formula is very useful to study correlations between the produced heavy quark Q and heavy antiquark $\bar{Q}$ [12].

For example

$$\frac{d\sigma_{ij}}{dp_{1,t} dp_{2,t}} = \int d\phi_1 d\phi_2 p_{1,t} p_{2,t} \int dy_1 dy_2 \int d^2 q_t \frac{1}{4\pi^2} \frac{1}{16\pi^2(x_1 x_2 s)^2} \overline{|\mathcal{M}_{ij}|^2} \mathcal{F}_i(x_1, \kappa_{1,t}^2) \mathcal{F}_j(x_2, \kappa_{2,t}^2)$$

$$= 4\pi \frac{1}{2} \frac{1}{2} \int d\phi_- p_{1,t} p_{2,t} \int dy_1 dy_2 \int d^2 q_t \frac{1}{4\pi^2} \frac{1}{16\pi^2(x_1 x_2 s)^2} \overline{|\mathcal{M}_{ij}|^2} \mathcal{F}_i(x_1, \kappa_{1,t}^2) \mathcal{F}_j(x_2, \kappa_{2,t}^2). \qquad (2.5)$$

In the last equation we have introduced $\phi_- \equiv \phi_1 - \phi_2$, where $\phi_- \in (-2\pi, 2\pi)$. The factor 4π comes from the integration over $\phi_+ \equiv \phi_1 + \phi_2$. The first factor $1/2$ comes from the Jacobian transformation while the second

factor $1/2$ takes into account an extra extension of the domain when using ϕ_+ and ϕ_- instead of ϕ_1 and ϕ_2.

At the Tevatron and LHC energies the contribution of the $gg \rightarrow Q\bar{Q}$ subrocess is more than an order of magnitude larger than its counterpart for the $q\bar{q} \rightarrow Q\bar{Q}$ subprocess. At RHIC energy the relative contribution of the quark-antiquark annihilation is somewhat bigger. Therefore in the following we shall take into account not only
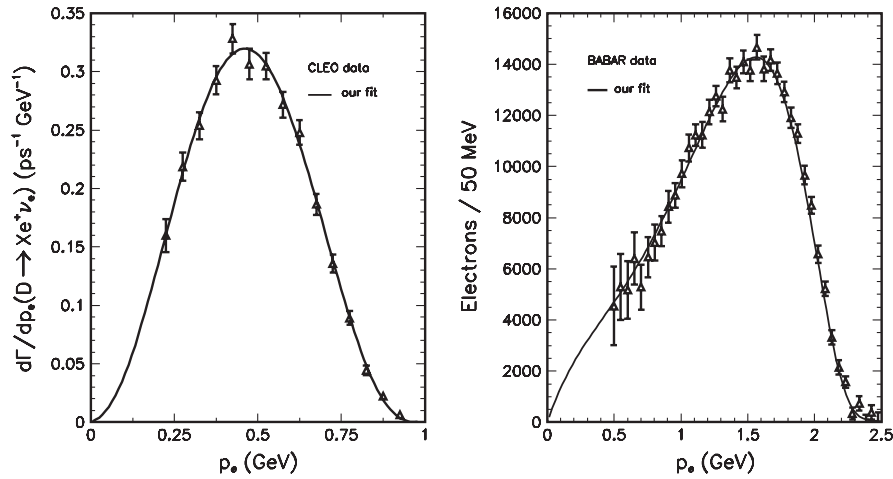
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[1]In this paper we shall use the following convention of unintegrated gluon distributions: $\int_0^{\mu^2} \mathcal{F}(x, \kappa^2) d\kappa^2 \sim xg(x, \mu^2)$

FIG. 2. Our fit to the CLEO [18] and *BABAR* [19] data.

gluon-gluon fusion process i.e. $i = 0$ and $j = 0$ but also the quark-antiquark annihilation mechanism.

The purely perturbative[2] k_t-factorization formalism to $h_1 h_2 \to Q\bar{Q}$ applies if $\kappa_{1,t}^2, \kappa_{2,t}^2 > \kappa_0^2$. The choice of κ_0^2 is to a large extent arbitrary. In Refs. [8] a rather large κ_0^2 was chosen and the space $\kappa_{1,t}^2 \times \kappa_{2,t}^2$ was subdivided into four disjoint regions. For example the contribution when both $\kappa_{1,t}^2$ and $\kappa_{2,t}^2$ are small was replaced by the leading-order collinear cross section. Such an approach assures that $\sigma_{Q\bar{Q}}^{tot} > \sigma_{Q\bar{Q}}^{tot}$ (collinear LO) by construction. It is rather obvious that the resulting cross section strongly depends on the choice of κ_0^2 which makes the procedure a bit arbitrary. Our philosophy here is different. Many models of UGDF in the literature treat the soft region explicitly. Therefore we use the k_t-factorization formula everywhere on the $\kappa_{1,t}^2 \times \kappa_{2,t}^2$ plane.

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

$$\frac{d\sigma^e}{dy d^2 p} = \frac{d\sigma^Q}{dy d^2 p} \otimes D_{Q \to D} \otimes f_{D \to e}, \qquad (2.6)$$

where the symbol $\otimes$ denotes a generic convolution. The first term responsible for production of heavy quarks/antiquarks is calculated in the k_t-factorization approach. Some details were already discussed above. Next step is the process of formation of heavy mesons. We follow a phenomenological approach and take Peterson and Braaten *et al*. fragmentation functions with parameters from the literature (see e.g. [23]). The electron decay function should account for the proper branching fractions. The latter are known experimentally (see e.g. [18,19,23]). These functions can in principle be calculated [15,17]. This introduces, however, some model uncertainties and requires inclusion of all final state channels explicitly. An alternative is to use experimental input. The decay functions have been measured only recently [18,19]. How to use the recent experimental information will be discussed in the next section.

III. RESULTS

In principle, the semileptonic decays can be modeled (see e.g. [15–17]). Since there are many decay channels with different number of particles this is not an easy task. In our approach we take less ambitious but more pragmatic approach. In Fig. 2 we show our purely mathematical fit to not absolutely normalized data of the CLEO [18] and *BABAR* [19] collaborations. We find a good fit with:

$$f_{CLEO}(p) = 12.55(p + 0.02)^{2.55}(0.98 - p)^{2.75} \qquad (3.1)$$

for the CLEO data [18] and

$$f_{BABAR}(p) = (126.16 + 14293.09 \exp(-2.24 \ln(2.51 - 0.97p)^2))(-41.79 + 42.78 \exp(-0.5(|p - 1.27|)/1.8)^{8.78}) \qquad (3.2)$$

for the *BABAR* data [19]. In these purely numerical parametrizations p must be taken in GeV.

After renormalizing to experimental branching fractions for $D \to e$ (about 10%[3] and $B \to e$ (10.36 ± 0.06(stat.) ± 0.23(syst.)% [19]) we shall use them to generate electrons/positrons in the rest frame of the decaying D and B mesons in a

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[2]when both UGDFs are generated perturbatively

[3]The branching fraction for different species of D mesons is different: $BR(D^+ \to e^+ \nu_e X) = 16.13 \pm 0.20$(stat.) ± 0.33(syst.)%, $BR(D^0 \to e^+ \nu_e X) = 6.46 \pm 0.17$(stat.) ± 0.13(syst.)%) [18]. Because the shapes of positron spectra for both decays are identical within error bars we can take the average value and simplify the calculation.
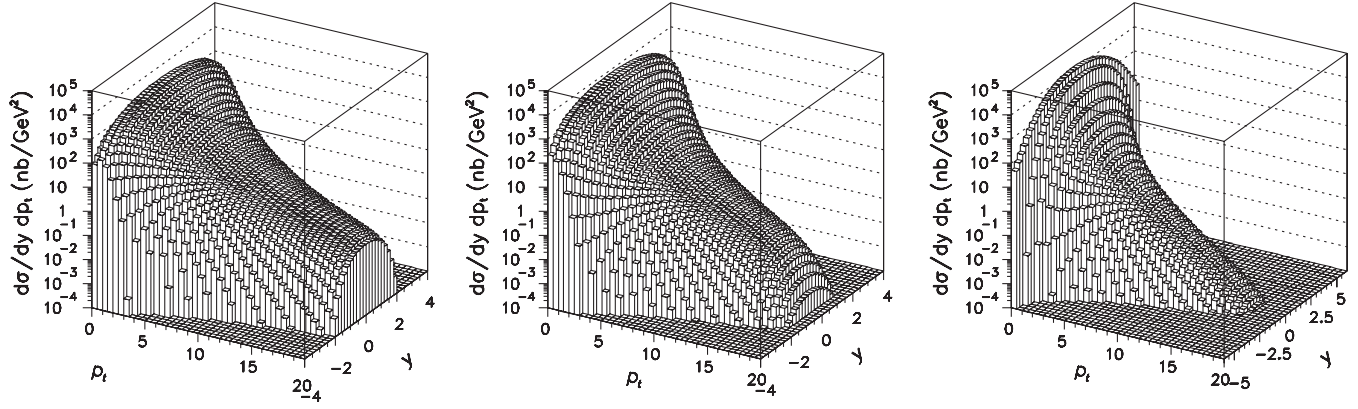
FIG. 3.   Two-dimensional distributions in rapidity and transverse momentum for charm quark/antiquark, *D* mesons and electrons/positrons.
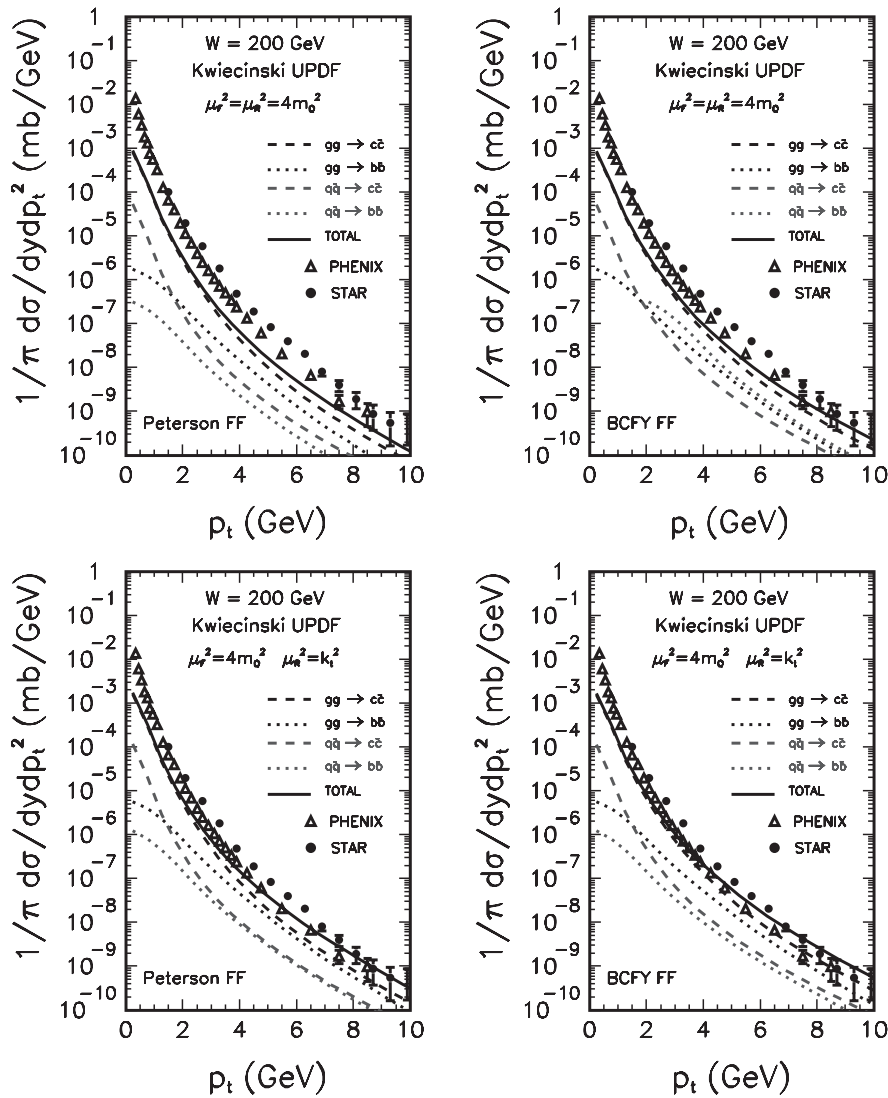

FIG. 4.   Transverse momentum distribution of electrons/positrons with the Kwieciński UPDFs. Different combinations of factorization and renormalization scales are used. We show separately contributions of the gluon-gluon fusion (black) and quark-antiquark annihilation (grey). On the left side we show results with Peterson fragmentation functions and on the right side with BCFY fragmentation functions.

Monte Carlo approach. We shall neglect a small effect of the nonzero motion of the D mesons in the case of the CLEO experiment and of the B mesons in the case of the BABAR experiment. This effect is completely negligible.

The first stage of our calculation, the production of $c\bar{c}$ and $b\bar{b}$ pairs, depends on the nonperturbative parameters—heavy quark masses. In the following we shall use $m_c = 1.5$ GeV and $m_b = 4.75$ GeV. This will be considered as our "standard values". The uncertainties on this parameters will be discussed separately by varying the quark masses within a reasonable ranges. A similar procedure is often done for the standard collinear approach (see e.g. [4]).

It is interesting to compare the leading-order k_t-factorization approach with the standard collinear approach. Some comparison was already done for the Tevatron energy [12]. At RHIC energy the general trends are similar. In general, the main differences occur at low

transverse momenta. One observes some enhancement with respect to the collinear approach at very small transverse momenta. This enhancement depends on both factorization and renormalization scale and is therefore difficult to quantify in a simple plot. At higher transverse momenta the differences between both approaches are rather small.

The second stage of our calculation, the fragmentation process, depends on the phenomenological fragmentation functions used and on parameters of such model fragmentation functions. In the following we shall consider $\epsilon = 0.05$ (D mesons) and $\epsilon = 0.006$ (B mesons) as a standard values for the Peterson fragmentation functions [24]. Similarly $r = 0.1$ (D mesons) and $r = 0.03$ (B mesons) are used as standard values for the BCFY fragmentation functions [14]. At the end of the result section we shall discuss uncertainties related to the choice of these parameters.
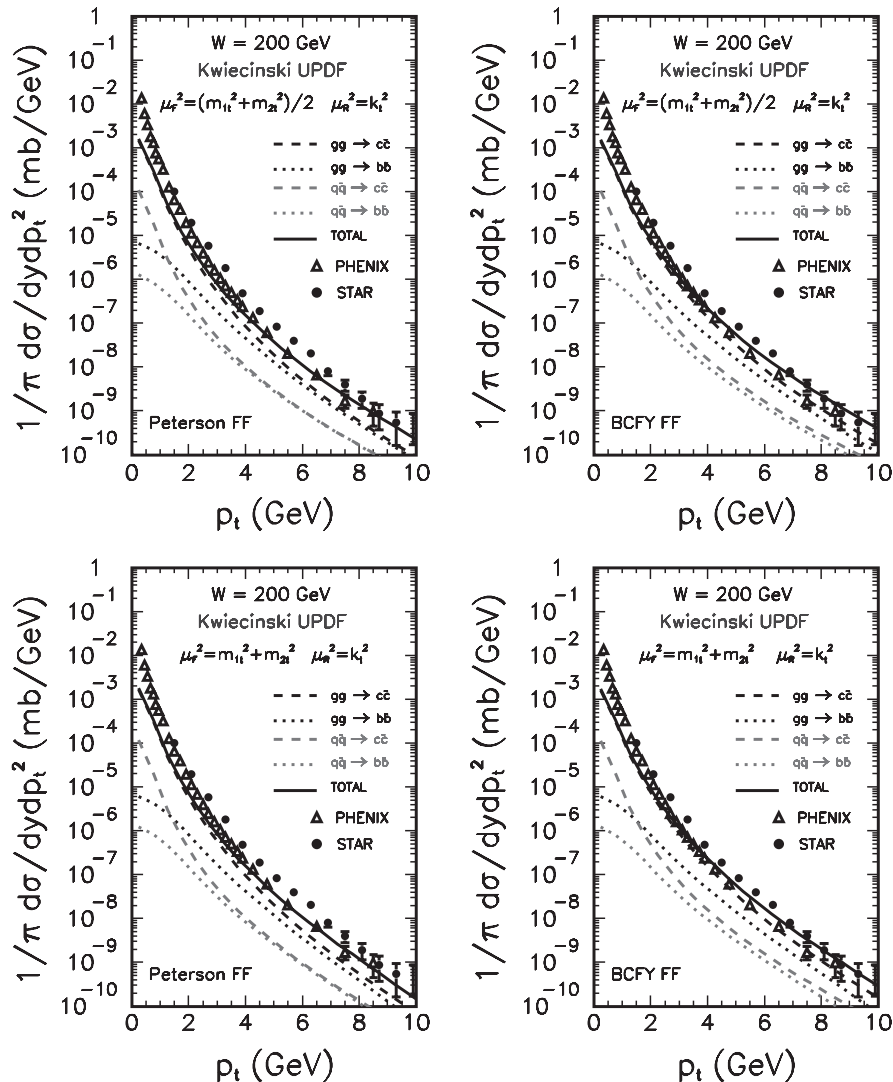

FIG. 5.   The same as in the previous section but with different choices of factorization/renormalization scales.
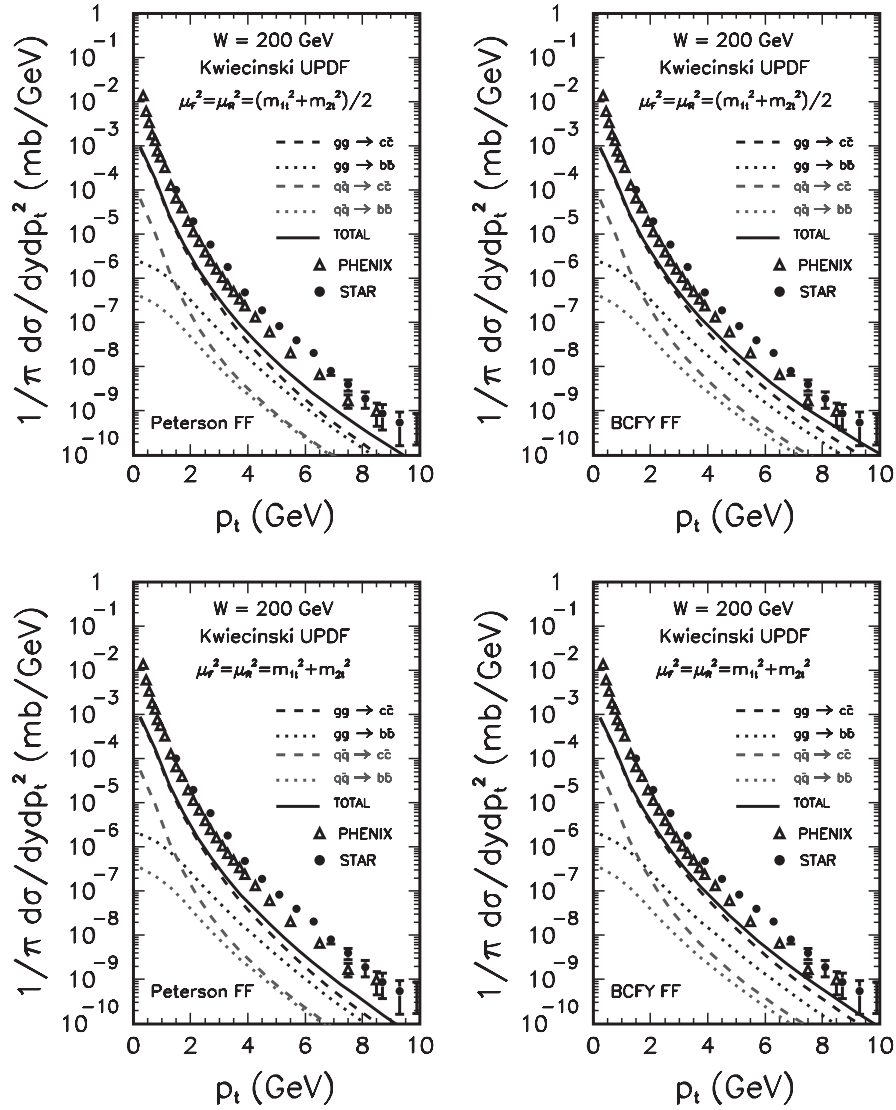
FIG. 6. The same as in the previous section but with different choices of factorization/renormalization scales.

For illustration of the whole procedure in Fig. 3 we show as an example two-dimensional distributions in rapidity and transverse momentum for charm quarks, D mesons and electrons from the decay of D mesons. Both fragmentation and semileptonic decays cause degradation of transverse momentum. On average $p_{t,e} < p_{t,D} < p_{t,c}$. The spectra of electrons are much softer than initial spectra of charm quarks. On the other hand the distributions in rapidity of electrons are much broader than the corresponding distributions of quarks/antiquarks.

The standard k_t-factorization approach includes only gluon-gluon fusion which is known to be dominant contribution at large center-of-mass energies (Tevatron, LHC). At RHIC energies the typical longitudinal momentum fractions of gluons are still not too small x_1, $x_2 \sim 0.01$ and the contribution of the quark-antiquark annihilation may be not negligible. Therefore in the following we shall

include also quark-antiquark annihilation process. Those processes can be included in a similar way in the formalism of unintegrated parton distributions. The Kwieciński formalism [20] allows to calculate unintegrated quark/antiquark distribution in the same framework as unintegrated gluon distributions.

Now we shall concentrate on invariant cross section as a function of electron/positron transverse momentum. Such distributions have been measured recently by the STAR and PHENIX collaborations at RHIC [1,2]. In Fig. 4–6, we show results obtained with Kwieciński UPDFs [20] and different combinations of factorization and renormalization scales as well as for different fragmentation functions (Peterson and BCFY). In this calculation we have included both gluon-gluon fusion as well as quark-antiquark annihilation. In the last case we use matrix elements with on-shell formula but for off-shell kinematics (the discussion of
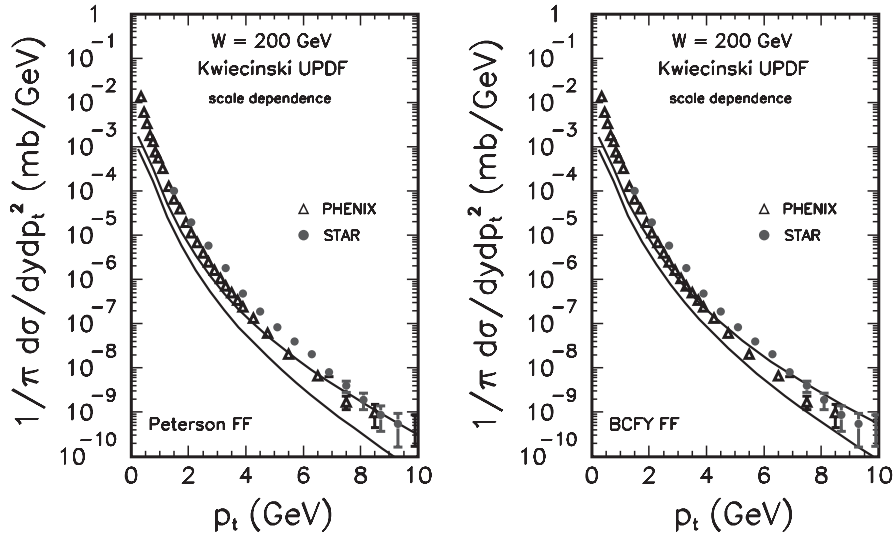
FIG. 7.   Factorization and renormalization uncertainty band of our k_t-factorization calculation (both D and B decays) with unintegrated Kwieciński gluon, quark and antiquark distributions for Peterson fragmentation function (left panel) and BCFY fragmentation function (right panel). The open triangles represent the PHENIX collaboration data and the solid circles the STAR collaboration data.

this point can be found in our earlier paper [12]). Our calculation is compared to recent experimental data of the PHENIX [2] and STAR [1] collaborations.

The differences between results obtained with different combinations quantify theoretical uncertainties. Similarly as for the standard collinear approach [4] one gets uncertainties of the order of a factor 2. We show individual contributions of electrons/positrons initiated by $c/\bar{c}$ or $b/\bar{b}$. The contribution of the $c/\bar{c}$ (dashed) dominates at low transverse momenta of electrons/positrons. At trans-

verse momenta of the order of 4–5 GeV both the contributions become comparable. We obtain rough agreement for large transverse momenta. Similarly as for the higher-order collinear approach [4] there is a missing strength at lower transverse momenta. A better agreement is obtained with renormalization scale taken as transverse momentum of the initial gluon(s). There are two strong coupling constants in the considered order. In practice we take $\alpha_s(k_{1t}^2)\alpha_s(k_{2t}^2)$, i.e. different arguments for each running coupling constant. This is rather a standard prescription used in
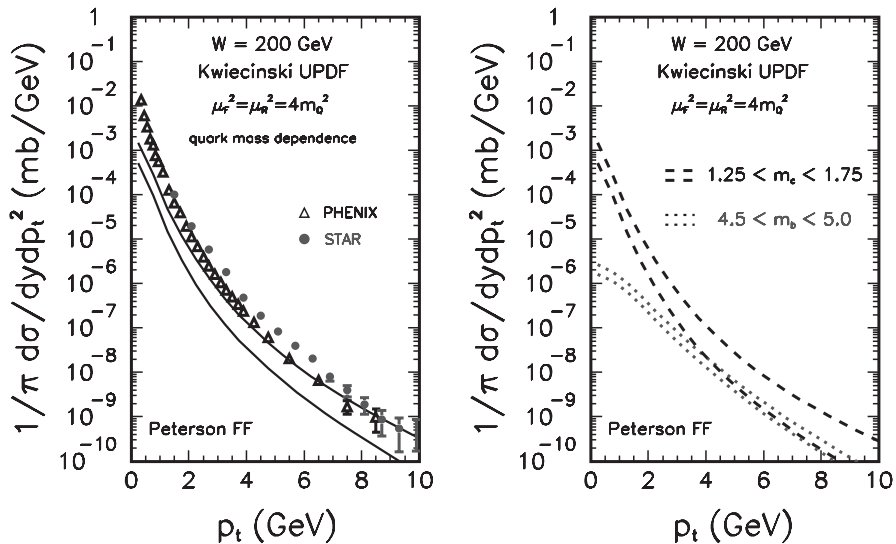

FIG. 8.   An example of quark mass uncertainty band of our k_t-factorization calculation (both D and B decays) with unintegrated Kwieciński gluon, quark and antiquark distributions for Peterson fragmentation function (left panel). The open triangles represent the PHENIX collaboration data and the solid circles the STAR collaboration data. In the right panel we show the uncertainties separately for charm and bottom mesons.
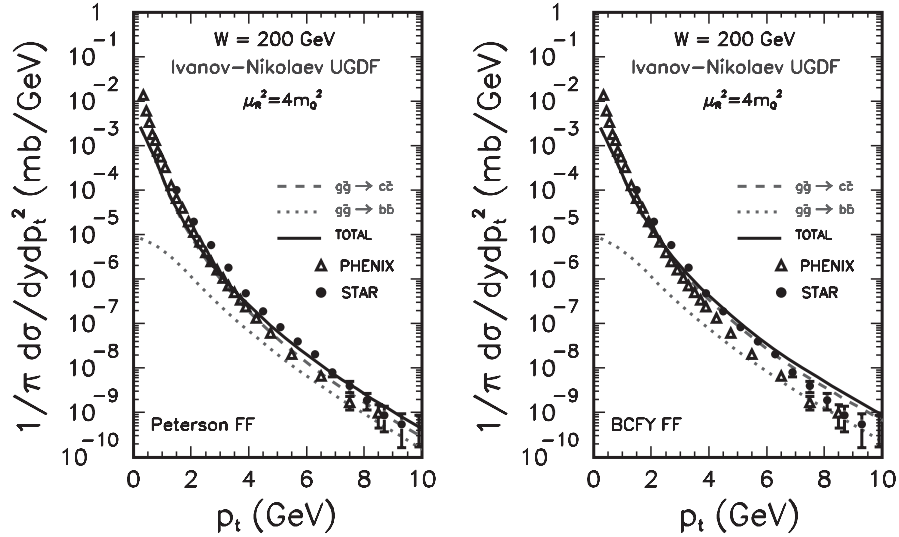
FIG. 9. Transverse momentum distributions of electrons/positrons obtained with Ivanov-Nikolaev UGDF and Peterson (left panel) and BCFY (right panel) fragmentation functions.

k_t-factorization approach (see e.g. [9,10]) although it does not have a deep theoretical foundation. In the latter case to avoid Landau pole we use analytic prescription of Shirkov and Solovtsov [25].

The situation for the Kwieciński UPDFs is summarized in Fig. 7 where we have shown an uncertainty band of our theoretical calculation related to the choice of factorization and renormalization scale. The upper curves are for $\mu_R^2 = k_t^2$ and $\mu_F^2 = 4m_Q^2$ and the lower curves are for $\mu_R^2 = \mu_F^2 = m_{1t}^2 + m_{2t}^2$. The experimental results of both groups are not completely consistent. In the interval 3 GeV $< p_t(\text{lepton}) < 6$ GeV, the STAR data points are somewhat

higher than the PHENIX data points. This disagreement needs further explanation. Our results are roughly consistent with both experimental sets at large $p_t(\text{lepton})$. There is a missing strenght at small transverse momenta where only the PHENIX collaboration data exist. This will be discussed further in the following.

Up to now we used our "standard values" of the charm and bottom masses. In Fig. 8 we show as an example what happens if we vary the quark masses as: $m_c = 1.5 \pm 0.25$ GeV, $m_b = 4.75 \pm 0.25$ GeV (a typical variation used in other calculations in the literature) for one selected value of the factorization and renormalization
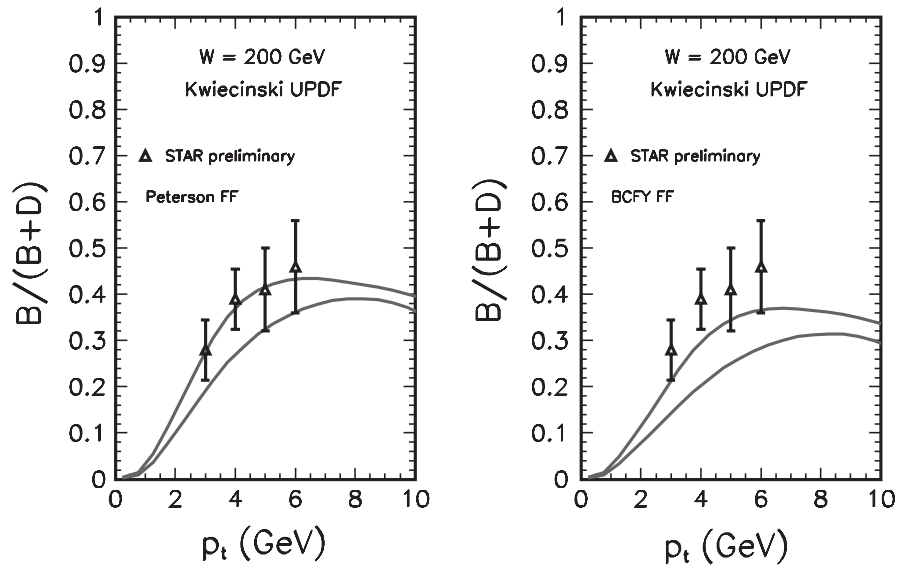

FIG. 10. The fraction of the B decays for the Kwieciński UPDFs. The uncertainty band due to the choice of the scales is shown for Peterson (left) and Braaten *et al.* (right) fragmentation functions. Both gluon-gluon fusion as well as quark-antiquark annihilation are included in this calculation.

scale. The uncertainty band related to quark masses is similar as the one related to the choice of factorization and renormalization scale. We do not intend to show a combined uncertainty band which includes both effects. Such a procedure is not justified statistically and the result-ing broad band makes a false impression of agreement with experimental data. In the right panel of Fig. 8 we show the mass uncertainties of the charm and bottom contributions separately. As seen from the figure the charm mass uncer-tainties are more important than the uncertainties of the bottom quark mass.

In Fig. 9 we show results obtained with Ivanov-Nikolaev UGDF. Compared to the Kwieciński distributions there is some improvement at low transverse momenta. The cross section for larger transverse momenta exceeds the PHENIX experimental data and is almost consistent with the STAR experimental data. The Ivanov-Nikolaev UGDF was obtained in a phenomenological approach by adjusting mainly to DIS data. Its application to large p_t, i.e. large x, is therefore not so sure. There seems to be a missing strength for small transverse momenta. It is not clear at the moment what is the missing strength. We shall discuss this a bit in the conclusion section.

Study of nonphotonic $e^{\pm}$ and hadron correlations allows to "extract" a fractional contribution of the bottom mesons $B/(D + B)$ as a function of electron/positron transverse momentum [26]. Recently the STAR collaboration has extended the measurement of the relative B contribution to electron/positron transverse momenta ~ 10 GeV [27]. In Fig. 10 and 11 (Kwieciński UPDFs) we present our results for different scales and different fragmentation functions. There is a strong dependence on the factorization and renormalization scale in the case of the Kwieciński unin-tegrated gluon/parton distributions. A better agreement is obtained with the Peterson fragmentation functions. For Ivanov-Nikolaev gluon distribution we show only depen-dence on fragmentation functions.

The separation into charm and bottom contributions is very important in the context of identifying the missing strength. A new correlation method was proposed recently to identify and separate charm and bottom production on a statistical basis [27]. The method was tested using known event generators. An alternative method of extracting the relative B contribution from azimuthal angular correlations of nonphotonic electrons and D_0 mesons was proposed [28]. One can hope that application of the new methods will help in disentangling the contributions better.

In Fig. 12 we show uncertainties of the ratio discussed above related to the variation of quark masses. This ob-servable is surprisingly sensitive to the choice of quark masses.

Finally we wish to discuss uncertainties related with pure knowledge of the fragmentation process. In Fig. 13 we show transverse momentum distributions for Kwieciński UPDFs for a broad range of the parameters
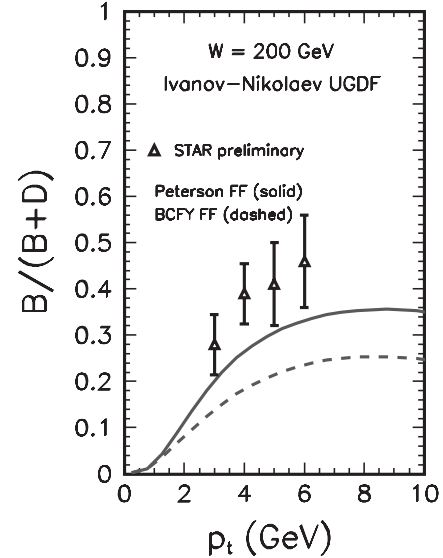

FIG. 11.   The fraction of the B decays for the Ivanov-Nikolaev UGDF for Peterson (solid) and BCFY (dashed). Here only gluon-gluon fusion is included as explained in the text.

of the Peterson (left panel) and BCFY (right panel) frag-mentation functions. The values of the parameters are given in the figure. While the variation of parameters in the broad range does not change significantly the cross section, there is a sizeable difference between results ob-tained with the Peterson and BCFY fragmentation func-tions. The uncertainties related to the fragmentation seem smaller than the uncertainties related to the choice of the factorization and renormalization scales and/or those re-
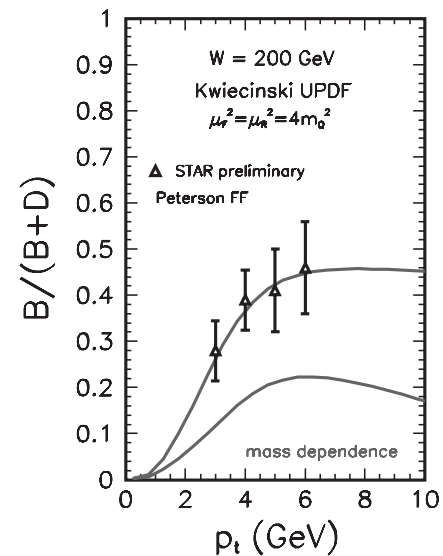

FIG. 12.   The fraction of the B decays for the Kwieciński UPDFs. The uncertainty band due to the choice of the quark masses is shown for Peterson fragmentation function. Both gluon-gluon fusion as well as quark-antiquark annihilation are included in this calculation.
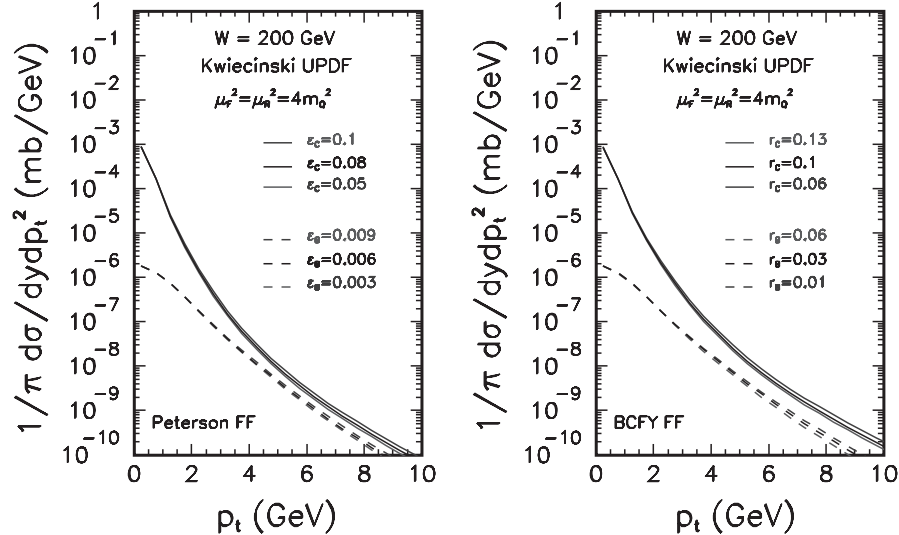
FIG. 13.   Uncertainty bands for parameters for Peterson (left panel) and BCFY (right panel) fragmentation functions.

lated to the choice of quark masses. Fitting fragmentation parameters to the nonphotonic-electron spectra would not be reasonable as in our opinion not all sources of the electrons were identified (see e.g. discussion in the following section).

IV. DISCUSSION OF THE RESULTS

We have calculated inclusive spectra of nonphotonic electrons/positrons for RHIC energy in the framework of the k_t-factorization. We have concentrated on the dominant gluon-gluon fusion mechanism and used two recent unintegrated gluon distribution functions from the literature. Special emphasis was devoted to the Kwieciński unintegrated gluon (parton) distributions. In this formalism, using unintegrated quark and antiquark distributions, one can calculate in addition the quark-antiquark annihilation process including transverse momenta of initial partons (quarks/antiquarks). In addition, we have used unintegrated gluon distributions constructed by Ivanov and Nikolaev to describe deep-inelastic data measured at HERA.

When calculating spectra of charmed (D, D^*) and bottom (B, B^*) mesons we have used Peterson and Braaten *et al* fragmentation functions with model parameters from the literature. There are small differences between results obtained with both fragmentation functions.

A very important ingredient, which influences the final spectra, is the distribution of electrons/positrons from the decay of D and B mesons. Here we have used recent results of the CLEO and *BABAR* collaborations. The momentum spectra of electrons/positrons from the decays of D and B mesons produced in the e^+e^- collisions were used in the present calculation to generate distribution of electrons/positrons coming from the decays of D and B mesons produced in the hadronic reactions. This way we have avoided all uncertainties associated with modeling semileptonic decays of mesons.

We have compared results obtained in our approach with experimental data measured recently by the PHENIX and STAR collaborations at RHIC. We get a reasonable description of the data at large transverse momenta of electrons/positrons. We have carefully studied uncertainties related to the choice of the factorization and renormalization scales, heavy quark masses, and those related to the fragmentation process.

Although the uncertainty bands are rather large, similarly as for the higher-order collinear approach, there is a missing strength at lower transverse momenta.

Up to now there is no clear explanation of the enhanced production of electrons/positrons at low transverse momenta. There can be several reasons of the unexplained strength at low transverse momenta.

The k_t-factorization approach includes many higher-order contributions which are embodied in unintegrated gluon (parton) distributions. Some higher-order contributions are definitely not included. A simple and transparent example are emissions of gluons of the heavy quarks/antiquarks. This contribution can be estimated in the standard collinear approach. This effect is, however, not limited to low transverse momenta.

It is commonly assumed that $D/\bar{D}$ mesons are produced via fragmentation of $c/\bar{c}$ quarks. However, at lower energies (fixed target experiments) an asymmetry between different species of D mesons have been observed [29]. This asymmetry can be due to fragmentation of light (u,d,s) quarks/antiquarks [30] ($q \to D(q\bar{c})c$ or $\bar{q} \to D(\bar{q}c)\bar{c}$)[4] or meson cloud effects [31]. The asymmetry increases with

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[4]There is a substantial fragmentation of light quarks ($q \neq s$) in the case of kaon production. Such a contribution for D mesons is therefore also not excluded.

rapidity (or Feynman x_F). This makes questionable the common assumption that D mesons are produced exclusively via fragmentation of c quarks. In this context, it would be very useful to analyze electronic spectra at larger rapidities. If these mechanisms are responsible for the missing strength then the discrepancy there would be even larger. In the moment only muons were measured at forward rapidities [32] and there seems to be some enhancement, although systematic error bars are rather large.

The results of the PHENIX collaboration were obtained by subtraction of several components, including decays of vector mesons, so-called Dalitz decays, K_{e3} decays and other mechanisms. All of them ''are concentrated'' at low transverse momenta [2]. Only a sketch of the subtraction procedure was presented [33]. The details of the subtraction are not presented *in extenso*. It is therefore not clear to us how reliable such subtraction is. In addition, there are several mechanisms which were not included. These are

Drell-Yan processes, processes initiated by photon and gluon, by two photons (they are expected to be concentrated at low transverse momenta) and several other exclusive processes never calculated in the literature. To draw definite conclusions one would have to evaluate the cross sections for all these processes. We leave such calculations for separate detailed studies. In principle, also analysis of coincidence spectra, e.g. in invariant mass of the dilepton pair M_{ee}, could help to pin down the missing mechanisms.

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