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Beauty production in two-photon interactions at LEP2: k_T-factorization versus data

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Inclusive beauty quark production in photon-photon collisions at CERN LEP2 is considered in the framework of the k_T-factorization approach. Both direct and resolved photon contributions are taken into account. The unintegrated gluon distributions in a photon are either obtained from the full Catani–Ciafoloni–Fioyani–Marchesini (CCFM) evolution equation or from the Kimber-Martin-Ryskin prescription. The predicted beauty cross section reasonably agrees with the recent experimental data taken by the ALEPH collaboration. We argue that theoretical and experimental studies of the azimuthal correlations in heavy quark production at high energies can serve as a crucial probe of the unintegrated gluon densities.

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The problem of beauty quark production at high energies continues to be a subject of pointed discussions and intense theoretical studies up to now [1]. First results [2] on the b-quark cross section in ep-collisions at HERA were significantly higher than the QCD predictions calculated at next-to-leading order (NLO) approximation. Similar observations were made in hadron-hadron collisions at the Fermilab Tevatron [3] and also in photon-photon interactions at LEP2 [4]. In the latter case the theoretical NLO QCD predictions were below the experimental data by three standard deviations. Although the latest measurements [5] do not confirm the large excess of the first HERA data over the NLO QCD, the problem is not solved so far. The disagreement between the experimental data at the Tevatron and NLO QCD predictions was reduced by adopting a special non-perturbative fragmentation function of the b-quark into the B-meson [6][2].

From our point of view, a more adequate solution was found [8] in the framework of k_T-factorization approach [9]. The k_T-factorization approach has also been used for a detailed description of numerous experimental data on b-quark production at HERA [10]. However the problem of the b-quark production in $\gamma\gamma$ interactions is not solved so far in the k_T-factorization approach [11–14].

Recently the ALEPH collaboration at LEP2 has presented the result on open beauty production cross section in $\gamma\gamma$ collisions [15]. This is the first published measurement in which the lifetime information has been used to identify the heavy flavor in two-photon physics[3]. The cross section of the process $e^+e^- \to e^+e^- b\bar{b}\,X$ has been found to be 5.4 ± 0.8 (stat.) $\pm\, 0.8$ (syst.) pb which is fully inconsistent with the previous results quoted by the L3 and OPAL collaborations [4], namely 12.8 ± 1.7 (stat.) $\pm\, 2.3$ (syst.) pb and 14.2 ± 2.5 (stat.)$^{-4.8}_{+5.3}$ (syst.) pb, respectively. In the present note we would like to demonstrate that the ALEPH experimental data can be described in the k_T-factorization approach also and to propose an additional test to distinguish the different unintegrated gluon distribution functions, which are the main ungredient of the k_T-factorization (see, for example, [16]).

Theoretically, heavy quarks in $\gamma\gamma$ collisions can be produced via direct and resolved production mechanisms. In the direct events, two photons couple directly to a heavy quark pair. This contribution is governed by simple QED amplitudes (which are independent of the gluon density in the photon). In the resolved events, one photon ("single-resolved") or both photons ("double-resolved") fluctuate into a hadronic state and a gluon or a quark from of this hadronic fluctuation takes part in the hard interaction. At LEP2 conditions the heavy quark production via the double resolved processes is highly suppressed [17] and, therefore, it will not be taken into account in our analysis.

The single-resolved contribution to the $\gamma\gamma \to b\bar{b}$ process is dominated by the gluon component of the photon and has the following form in the k_T-factorization approach:

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[2] A more exotic solution to this problem was proposed in [7].

[3] The previous measurements by L3 and OPAL collaborations [4] were based on a fiting the transverse momentum of leptons with respect to jets.

$$\frac{d\sigma_{1-\mathrm{res}}(\gamma\gamma\to b\bar{b}X)}{dy d\mathbf{p}_T^2} = \int \frac{1}{16\pi(xs)^2(1-\alpha)} \times$$

$$\times \mathcal{A}_\gamma(x,\mathbf{k}_T^2,\mu^2)|\bar{\mathcal{M}}|^2(\gamma g^*\to b\bar{b})d\mathbf{k}_T^2\frac{d\phi_b}{2\pi}\frac{d\phi}{2\pi}, \qquad (1)$$

where $\mathcal{A}_\gamma(x,\mathbf{k}_T^2,\mu^2)$ is the unintegrated gluon distribution in the photon, $|\bar{\mathcal{M}}|^2(\gamma g^*\to b\bar{b})$ is the off-shell (i.e. depending on the initial gluon virtuality) matrix element squared, s is the total c.m. frame energy and $\alpha = \sqrt{m_b^2+\mathbf{p}_T^2}\exp(y)/\sqrt{s}$. The produced beauty quark has the transverse momentum $\mathbf{p}_T$, rapidity y and azimuthal angle ϕ_b. The initial off-shell gluon has a fraction x of the parent photon's longitudinal momentum, the non-zero transverse momentum $\mathbf{k}_T$ ($\mathbf{k}_T^2 = -k_T^2 \neq 0$) and azimuthal angle ϕ. In accord with the k_T-factorization prescription [9], the off-shell gluon spin density matrix is taken in the form

$$\epsilon^\mu(k)\epsilon^{*\,\nu}(k) = k_T^\mu k_T^\nu/\mathbf{k}_T^2. \qquad (2)$$

In all other respects our calculations follow the standard Feynman rules. The analytic expression for the $|\bar{\mathcal{M}}|^2(\gamma g^*\to b\bar{b})$ is given in our previous paper [13]. Note that if we average Eq. (1) over the azimuthal angle ϕ and take the limit $\mathbf{k}_T^2\to 0$, we recover the well-known formulas corresponding to the leading-order (LO) QCD calculations.

The recent experimental data [15] refer to beauty quark production in the e^+e^- collisions. In order to obtain the corresponding cross sections, the $\gamma\gamma$ cross sections need to be weighted with the photon flux in the electron:

$$d\sigma(e^+e^-\to e^+e^-b\bar{b}X) =$$

$$= \int f_{\gamma/e}(x_1)dx_1 \int f_{\gamma/e}(x_2)dx_2\, d\sigma(\gamma\gamma\to b\bar{b}X), \qquad (3)$$

where we use the Weizacker-Williams approximation for the photon distribution in the electron:

$$f_{\gamma/e}(x) = \frac{\alpha_{em}}{2\pi}\left(\frac{1+(1-x)^2}{x}\ln\frac{Q^2_{\max}}{Q^2_{\min}} + \right.$$

$$\left. + 2m_e^2 x\left(\frac{1}{Q^2_{\max}} - \frac{1}{Q^2_{\min}}\right)\right). \qquad (4)$$

Here α_{em} is the fine structure constant, m_e is the electron mass, $Q^2_{\min} = m_e^2x^2/(1-x)^2$ and $Q^2_{\max} = 6\,\mathrm{GeV}^2$ [15].

The unintegrated gluon distribution in the photon $\mathcal{A}_\gamma(x,\mathbf{k}_T^2,\mu^2)$ can be obtained from the analytical or numerical solution of the BFKL or CCFM evolution equations. In order to estimate the degree of theoretical uncertainty connected with the choice of unintegrated gluon densities, in the numerical calculations we tested two different sets, namely the CCFM [12] and Kimber-Martin-Ryskin (KMR) [18] ones. First of them was obtained in [12] from the full CCFM equation formulated for the photon, and the second one was obtained from the usual (collinear) parton densities[4)] using the KMR prescription [18]. These distributions are widely discussed in the literature (see, for example, [16]). Other essential parameters were taken as follows: the b-quark mass $m_b = 4.5 \pm 0.1$ GeV and the renormalization and factorization scale $\mu = \xi\sqrt{m_b^2+\langle\mathbf{p}_T^2\rangle}$, where $\langle\mathbf{p}_T^2\rangle$ is set to the average $\mathbf{p}_T^2$ of the beauty quark and antiquark. In order to investigate the scale dependence of our results we vary the scale parameter ξ between 1/2 and 2 about the default value $\xi = 1$. For completeness, we use the LO formula for the coupling constant $\alpha_s(\mu^2)$ with $n_f = 4$ active quark flavours and $\Lambda_{\mathrm{QCD}} = 200$ MeV, such that $\alpha_s(M_Z^2) = 0.1232$. The multidimensional integration has been performed by means of the Monte-Carlo technique, using the routine VEGAS [20]. The full $C++$ code is available from the authors on request. This code is identical to that used in [13, 14].

The results of our calculations are displayed in Figs.1–4. Fig.1 confronts the total cross section $\sigma(e^+e^-\to e^+e^-b\bar{b}X)$ calculated as a function of the total c.m. energy $\sqrt{s}$ with recent experimental data [15] taken by the ALEPH collaboration. The solid and dash-dotted lines correspond to the results obtained with the CCFM and KMR unintegrated gluon densities, respectively. The upper and lower dashed lines correspond to the CCFM gluon density with b-quark mass and scale variations as it was described above. Separately shown (as a dotted line) is the contribution from the direct production mechanism $\gamma\gamma\to b\bar{b}$. It is clear that at $\sqrt{s}\sim 200\,\mathrm{GeV}$ the cross section is mostly controlled by the single-resolved contribution, i.e. $\gamma g^*\to b\bar{b}$ subprocess. Despite the fact that the central predictions are slightly lower than the measured cross section, we observe a reasonable agreement between our calculations and the ALEPH experimental data [15] within the theoretical and experimental uncertainties. The CCFM-evolved gluon density gives slightly larger cross section compared to the KMR one, where the small-x logarithms are not taken into account [18]. A similar effect (but much more clear) has been demonstrated in [10] where, in particular, the beauty photo- and lepto-production at HERA has been studied. Note that the sensitivity of our results to the variations in the scale μ and beauty mass m_b is rather large. However, this sensitivity is of the

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[4)] In the numerical calculations we have used the standard GRV (LO) parametrizations [19] of the collinear quark and gluon distributions.

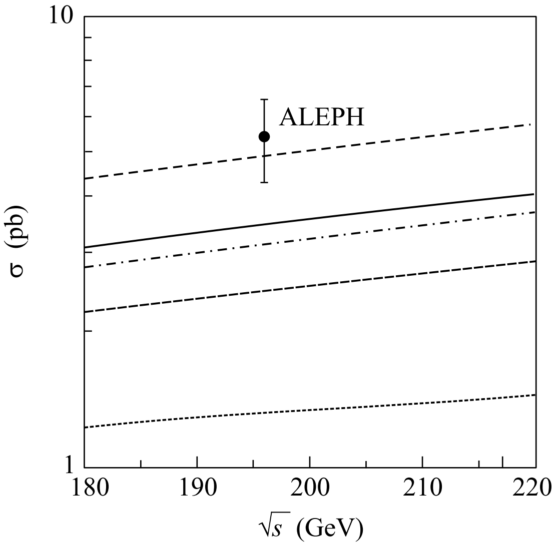

Fig.1. The beauty total cross section $\sigma(e^+e^- \to e^+e^- b\bar{b}\,X)$ as a function of the e^+e^- center-of-mass energy $\sqrt{s}$. The solid and dash-dotted lines correspond to the results obtained with the CCFM and KMR unintegrated gluon densities, respectively. The upper and lower dashed lines correspond to the CCFM gluon density with variation in b-quark mass and scale as it was described in text. Separately shown is the contribution from the direct production mechanism (dotted line). The experimental data are from ALEPH [15]

same order approximately as in the massive NLO QCD calculations [21].

The transverse momentum and pseudo-rapidity distributions calculated at the averaged total e^+e^- energy $\sqrt{s} = 196$ GeV ($130 < \sqrt{s} < 209$ GeV) are shown in Figs.2 and 3. As a representative example, we have used the following cuts: $p_T < 20$ GeV and $|\eta| < 2$. In our calculations we took into account for both the beauty quarks and anti-quarks. One can see again that the difference between the CCFM and KMR predictions is not significant, except at large p_T (namely $p_T \sim 10$ GeV) only. A similar observation was also made [14] in the case of charm production at LEP2. It was shown that the shape and the absolute normalization of D^* transverse momentum and pseudo-rapidity distributions practically do not depend on the unintegrated gluon density.

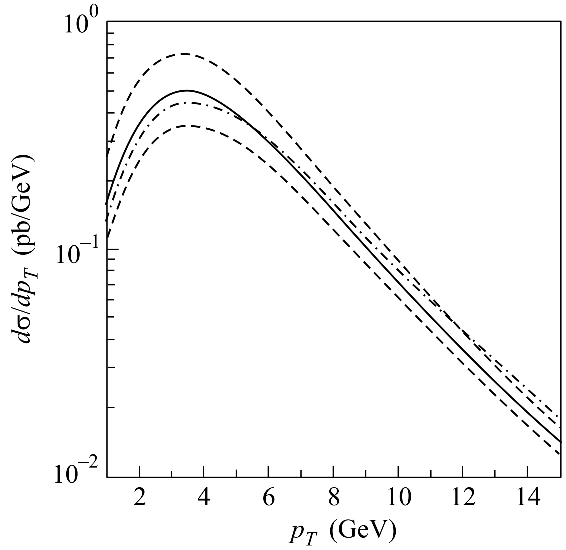

Fig.2. The differential beauty cross section $d\sigma/dp_T$ for the process $e^+e^- \to e^+e^- b\bar{b}\,X$ at $|\eta| < 2$ and $\sqrt{s} = 196$ GeV. Notation of curves is the same as in Fig.1

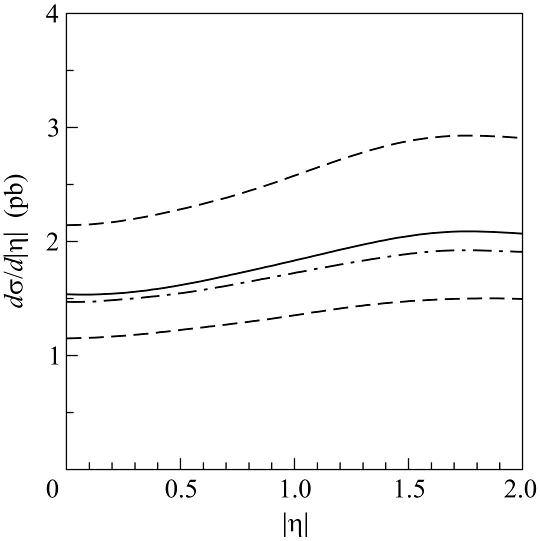

Fig.3. The differential beauty cross section $d\sigma/d|\eta|$ for the process $e^+e^- \to e^+e^- b\bar{b}\,X$ at $p_T < 20$ GeV and $\sqrt{s} = 196$ GeV. Notation of curves is the same as in Fig.1

We would like to stress that further understanding of the process dynamics may be obtained from the angular correlation between the transverse momenta of the produced quarks. These quantities are particularly sensitive to high-order corrections. So, in the naive LO collinear approximation of QCD, the distribution over $\Delta\phi = \phi_b - \phi_{\bar{b}}$ must be simply a delta function $\delta(\Delta\phi - \pi)$ since the produced quarks are back-to-back in the transverse plane. Large deviations from these values may come from higher-order QCD effects. In the k_T-factorization approach, taking into account the non-vanishing initial gluon transverse momentum $\mathbf{k}_T$ leads to the violation of this back-to-back kinematics even at leading order. It is an illustration to the fact that the LO k_T-factorization formalism incorporates a large part of standard (collinear) high-order corrections (see also [9, 16] for more information). The differential cross section $d\sigma/d\Delta\phi$ calculated at $\sqrt{s} = 196$ GeV is shown in Fig.4. One can see that the shape of this distribution predicted by the CCFM and KMR gluon densities are strongly differ from each other. At large $\Delta\phi \sim \pi$ both gluon densities under consideration give similar results, whereas at low $\Delta\phi \sim 0$ the difference is about a factor of 2 in the absolute normalization. This fact is directly connected with the properties of non-collinear evolution model. Therefore these correlations can be used to constraint the unintegrated gluon distributions. A similar effect was also pointed out in the case of beauty production at the Tevatron [8].

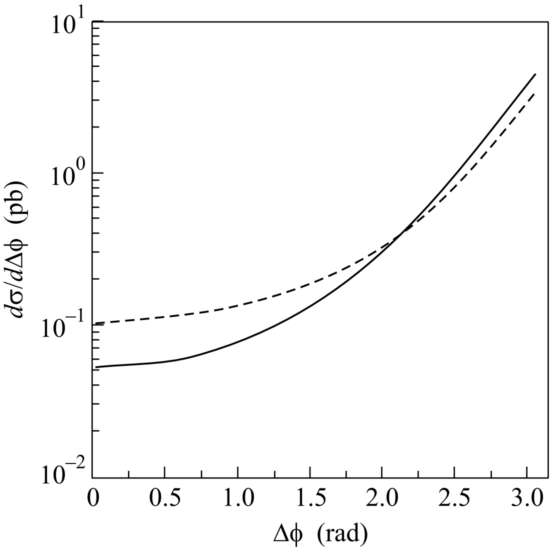

Fig.4. The differential beauty cross section $d\sigma/\Delta\phi$ for the process $e^+e^- \to e^+e^- b\bar{b}\, X$ at $\sqrt{s} = 196$ GeV. Notation of curves is the same as in Fig.1

In conclusion, we would like to emphasize additionally that the k_T-factorization approach supplemented with the CCFM-evolved gluon density agrees well with the numerous data on the b-quark production at HERA and Tevatron (without any special assumption on the b-quark to B-meson fragmentation function), as it was demonstrated earlier in [10, 8]. So we can conclude that at present there is no contradiction between the CCFM-based theoretical predictions and available data on the beauty production at high energies, and we believe that the k_T-factorization holds a possible key to understanding the production dynamics at high energies.

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