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Measurement of the kinematic variables of beauty particles produced in 350 GeV/c π^--Cu interactions

The BEATRICE Collaboration

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Abstract

Using a sample of 26 $b\bar{b}$ events, produced in 350 GeV/c π^- interactions in a copper target, which includes 13 events where the decays of both B and $\overline{B}$ are well reconstructed, we measure the differential distributions with respect to x_F and p_T^2 as well as some two-particle kinematic variables. We also compare our results with a previous experiment and with predictions based on perturbative QCD.

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Hadroproduction of heavy quarks is an important testing ground for Quantum Cromodynamics (QCD). In fact the production of a quark having a mass, m_{Q}, much larger than the QCD parameter Λ_{QCD} can be calculated perturbatively via a power-series expansion in the strong coupling constant $\alpha_{\mathrm{s}}({m_{\mathrm{Q}}}^2) \sim 1/\ln({m_{\mathrm{Q}}}^2/{\Lambda_{\mathrm{QCD}}}^2)$. In the case of beauty production ($m_{\mathrm{Q}} = m_{\mathrm{b}} \sim 4.75\,\mathrm{GeV}/c^2$, $\Lambda_{\mathrm{QCD}} \sim 140\,\mathrm{MeV}$), the perturbative calculations, currently evaluated to next-to-leading order (NLO) [1], are expected to be reliable. Nonetheless, the theoretical predictions have uncertainties arising from a dependence on the chosen renormalization and factorization scales, the b-quark mass, the parton density functions and Λ_{QCD}. Other uncertainties are due to the fragmentation of quarks into hadrons and to the interacting partons' momentum, k_{T}, transverse to the beam direction. For some quantities, such as the production cross-section, the uncertainties in the theoretical predictions are large. Smaller uncertainties affect the prediction of the kinematic distributions.

At fixed-target energies, the beauty production cross-section is of the order of few nanobarns and amounts to $\sim 10^{-7}$ of the inelastic cross-section. In experiment WA92, performed at the CERN Super Proton Synchrotron, we identified 26 beauty events [2], the largest sample so far obtained in a fixed-target environment. We previously reported results on the beauty production cross-section [2] and on the azimuthal angle $\Delta\phi$ between associated beauty particles [3]. In this letter we complete our studies of beauty hadroproduction by reporting on the measurement of kinematic variables. These measurements require knowledge of the beauty-particle momenta which must be either measured or estimated. The measured variables include the p_T^2 and x_F of the beauty particles (single-differential distributions) and some correlation variables such as the invariant mass $M(B\overline{B})$, the Feynman-x of the $B\overline{B}$ system and the Feynman-x difference $|\Delta x_F| = |x_F(B) - x_F(\overline{B})|$ (double-differential distributions). We compare the measurements with the results from experiment E653 [4], where the decays of 9 beauty pairs were reconstructed in nuclear emulsion.

Data taking for the WA92 experiment was performed at the CERN Ω' spectrometer in 1992 and 1993, with a $350\,\mathrm{GeV}/c$ π^- beam incident on a 2 mm copper target. The number of events recorded was $\sim 10^8$, corresponding to an integrated luminosity of $8.1\,(\mathrm{nb\ per\ Cu\ nucleus})^{-1}$.

Full details of the experimental apparatus and trigger are given elsewhere [5]. The present analysis exploits the imaging capabilities of the high-resolution tracking system. This was formed from silicon-microstrip planes, arranged as a decay detector (DkD) and a vertex detector (VxD). The DkD, covering the first 3.2 cm downstream of the target, consisted of 17 silicon planes with 10 μm pitch and analogue readout. The VxD consisted of 12 silicon planes of 25 μm pitch and 5 planes of 50 μm pitch. Tracking further from the target was performed using multiwire proportional chambers (58 planes in a 1.8 T magnetic field) and drift chambers (8 planes). A muon detector, based on resistive-plate chambers, was positioned downstream of the tracking detectors.

Use was made of a combination of several independent triggers [5], the aim being to keep the acceptance for beauty events high, with acceptable dead-time. An event was written to tape if an interaction trigger was satisfied in coincidence with any two of the following: a high p_{T} trigger, obtained using a pair of butterfly-shaped hodoscopes, crossed only by particles with transverse momentum greater than $0.6\,\mathrm{GeV}/c$; a muon trigger, requiring detection in the resistive-plate chambers of a muon consistent with an origin in the target; a secondary-vertex trigger, which used information from a silicon microstrip beam hodoscope and from the VxD.

The trigger acceptance was $\sim$ 2% for inelastic interactions and $\sim$ 30% for beauty events. Assuming a linear A-dependence, the total number of beauty events written on tape is of the order of 150 per nb of cross-section.

For the acceptance calculations, and for studies of backgrounds in the beauty search, we fully simulated $\mathrm{b\bar{b}}$, $\mathrm{c\bar{c}}$ and minimum-bias events. The last-mentioned were generated using Fluka [6]. Events with heavy quarks were generated using Pythia 5.4 [7] and Jetset 7.3 [8] to describe the hard process and quark fragmentation, and using Fluka to determine the characteristics of all other interaction products. Tracking of particles through the experimental apparatus was performed using Geant 3.21 [9].

Analysis of the data yielded a sample of 26 $\mathrm{b\bar{b}}$ events, with an estimated background of 0.6 $\pm$ 0.6 events; this sample includes 13 events where the decays of both B and $\overline{B}$ are well reconstructed. A complete account of the analysis strategy can be found elsewhere [2, 3]. Here we give only a brief outline of the procedure followed. Secondary vertices were searched for in the region between 0.3 cm and 6 cm from the primary vertex. Taking advantage of the analogue readout of the DkD, we disregarded secondary vertices close to large energy releases, which were usually due to hadronic interactions in the silicon planes. We then selected three categories of events, consistent with beauty-decay topologies:

i. events containing $\geq$ 1 secondary $\mu^{\pm}$ of $p_{\mathrm{T}} \geq 1\,\mathrm{GeV}/c$ and $\geq$ 2 secondary vertices with minimum mass $\geq 0.55\,\mathrm{GeV}/c^2$, at least one of which with minimum mass $\geq 2.3\,\mathrm{GeV}/c^2$;

ii. events containing a vertex consistent with the hadronic decay of a charmed meson not originating in the primary interaction (impact parameter relative to primary vertex $\geq 30\,\mu$m) and at least one other secondary vertex;

iii. events containing $\geq$ 3 secondary vertices and satisfying a high-p_{T}-track requirement (one track with $p_{\mathrm{T}} > 1.5\,\mathrm{GeV}/c$, or one track with $p_{\mathrm{T}} > 0.8\,\mathrm{GeV}/c$ and one track with $p_{\mathrm{T}} > 0.6\,\mathrm{GeV}/c$).

To calculate a vertex's minimum mass, we assumed that it corresponded to the decay of a particle from the primary vertex and that the energy-momentum conservation of the decay was ensured by an unobserved zero-mass particle. All detected decay products were assigned the pion mass.

Events from categories ii.) and iii.) above were filtered by a neural network [10], taking into account topology and kinematics through a set of 16 input variables. We next scanned events individually using a graphical display program, selecting 26 $\mathrm{b\bar{b}}$ events; each one contains at least one vertex interpreted as a beauty-particle decay.

The second step of the analysis consisted of the identification of the decay vertex of the associated beauty particle. First of all we used an interactive version of our reconstruction program [5, 11] to improve the vertex reconstruction accuracy. With the interactive program we were able to correct wrong assignments of hits to tracks, and of tracks to vertices, thus improving both the vertex position and our knowledge of the total momentum.

In our 26 $\mathrm{b\bar{b}}$ events, the majority of the secondary vertices are due to decays of charm and beauty. As a result, a candidate secondary vertex for the decay of the associated beauty was initially required to satisfy only minimal selection criteria:

i. to be outside the target, within 6 cm of the target edge, and with a distance from the primary vertex of at least six times the vertex separation uncertainty;

ii. not to be compatible with a hadronic interaction, and hence to be far from any large energy release in the DkD;

iii. not to be compatible with the decay of a Λ^0 or K^0, or with a photon conversion into an e^+e^- pair;

iv. not to be compatible with the decay of the charmed hadron from the beauty-particle decay already identified;

v. to have a transverse decay length of $> 50\,\mu$m.

In particular this last requirement, together with a similar cut of $> 20\,\mu$m on the transverse decay length for the other beauty particle, improved the resolution on the measured variables.

In order to avoid confusing the associated beauty vertex with its secondary charm decay, we introduced two further kinematic conditions:

i. at least one outgoing track with a momentum component $> 1\,\text{GeV}/c$ transverse to the line joining the vertex to the primary-interaction point;

ii. a minimum mass $> 2\,\text{GeV}/c^2$.

With these selection criteria, we identified the associated beauty-decay vertex in 13 events (double-differential sample); we have thus a total of 39 beauty decays (single-differential sample). The background, already low (0.6 ± 0.6) for the 26 $b\bar{b}$ events [2], becomes negligible for the double-differential sample; therefore in the present analysis we neglected the background for both samples. We identified the secondary charmed hadron in half of the single-differential sample. This fraction, as well as the charge distribution of the beauty particles, was well reproduced by a sample of simulated $b\bar{b}$ events passing the same selection criteria.

The study of the kinematics of our samples requires an estimator for the momentum of the partially reconstructed vertex, taking into account the unseen decay products. We used an estimator very similar to the one already used by this collaboration for the analysis of charm pair production [12]: a combination of two methods that are based on different physical considerations. The first method consists in closing the beauty decay by adding a neutral pion balancing the visible decay momentum on the beauty line of flight. Imposing the beauty mass on the decay vertex and requiring that its total momentum vector point to the primary vertex, leads to two possible choices for the beauty momentum. The second method was used by other experiments [4] and is based on the assumption that in the rest frame of the beauty particle the unseen momentum is emitted on average in a direction perpendicular to the beauty laboratory momentum. The Lorentz boost γ_B from the beauty rest frame to the laboratory frame is then given by $\gamma_B = E_{vis}/\sqrt{M_{vis}^2 + p_{T_{vis}}^2}$ where E_{vis} is the visible energy, $p_{T_{vis}}$ is the visible transverse momentum, and M_{vis} is the mass of the visible system, calculated assigning the pion mass to all the detected particles. A comparison between these two methods and the simulation indicates that both give useful and independent information; however the first method systematically underestimates the momentum while the second one systematically overestimates it. The best estimator for the beauty momentum is a weighted average of the results of the two methods. The possible presence of a charmed particle from the beauty decay was taken into account since the charmed hadron usually carries a large fraction of its parent's momentum (mean momentum fraction $\sim 50\%$). The same estimator was adopted also for the charm momentum when the charm decay was not completely reconstructed. If more than one secondary vertex could be identified as the charmed hadron, all the possibilities were taken into account and the solutions for the beauty momentum were equally weighted.

Using the charm momentum, the accuracy of the beauty momentum was

$$\sigma_p/p \,=\, 0.017 \,+\, 1.7 \cdot 10^{-4}\; p$$

while if the charm decay coming from the beauty was not reconstructed the accuracy of the beauty momentum was

$$\sigma_p/p \,=\, 0.057 \,+\, 4.3 \cdot 10^{-4}\; p$$

where p is in GeV/c.

Acceptance distributions for single- and double-differential variables are shown in Fig. 1. Acceptance corrections for these variables were determined from a simulation of 13500 $\mathrm{b\bar{b}}$ events, corresponding to about 4.5 times the $\mathrm{b\bar{b}}$ events produced in the data-taking period. These simulated events were processed with the same analysis and selection chain as the experimental data. After scanning, a sample of 116 events survived; we identified the decay vertex of the associated beauty particle in 72 events, obtaining a total of 188 beauty decays. Comparisons of the simulated and reconstructed values showed that the experimental precision in each variable is smaller than the bin sizes chosen, therefore we calculated the acceptance corrections by dividing each distribution of reconstructed events by the corresponding distribution of generated events. For the square of the transverse momentum of the $B\overline{B}$ pair, $p_T^2(B\overline{B})$, the comparison between simulated and reconstructed values would impose too large a bin size with respect to our statistics, therefore we do not have a significant measurement of this variable.

The p_T^2 and x_F distributions of the single-differential sample, corrected for acceptance, are plotted in Fig. 2a)-b) together with the results of experiment E653 and the predictions based on NLO QCD calculations. The theoretical distributions were obtained taking $m_{\mathrm{b}} \;=\; 4.75\,\mathrm{GeV}/c^2$; $\Lambda_{\mathrm{QCD}} \;=\; 140\,\mathrm{MeV}$; the factorization scale μ_F and the renormalization scale μ_R are equal to $\sqrt{{m_b}^2 + {p_{\mathrm{T}}}^2}$, where p_{T} is the transverse momentum of the b-quark. We used the SMRSπ2 [13] parton density set for the beam pion, and the MRSD- [14] parton density set for target nucleons. Within the large statistical uncertainties, our data are consistent both with the result of experiment E653 and with the theoretical predictions. The consistency with the theoretical predictions is not surprising since, thanks to the large b-quark mass, the NLO QCD calculations are expected to be reliable and the corrections due to fragmentation, intrinsic transverse momentum of the incoming partons or higher order contributions are small. The single-differential distributions were fitted with the usual parametric functions $exp(-bp_T^2)$ for the p_T^2 and $(1-|x_F|)^n$ for the x_F; fit parameters are $b \;=\; (0.14 \,\pm\, 0.03)\;(\mathrm{GeV}/c)^{-2}$ and $n \;=\; 3.1 \,\pm\, 0.9, x_F \;>\; 0$. The mean values of the distributions are reported in Table 1.

Using the double-differential sample, we measured the invariant mass $M(B\overline{B})$, the Feynman-x of the $B\overline{B}$ system and the Feynman-x difference $|\Delta x_F| \;=\; |x_F(B) \,-\, x_F(\overline{B})|$. Fig. 2c)-e) show these kinematic correlation variables, corrected for acceptance, along with results from experiment E653, when available, and the predictions based on NLO QCD calculations. The theoretical distributions were obtained taking the same parameter values used for the single-differential distributions, apart from fixing $\mu_{\mathrm{R}} \;=\; \mu_{\mathrm{F}} \;=\; \sqrt{{m_b}^2 + \frac{1}{2}({p_{\mathrm{T}}}^2 + {\bar{p}_{\mathrm{T}}}^2)}$, where p_{T} and $\bar{p}_{\mathrm{T}}$ are the transverse momenta of the b-quark and the $\mathrm{\bar{b}}$-antiquark respectively. In the calculation of the invariant mass of the $B\overline{B}$ system, the b-quark mass was taken to be $m_{\mathrm{b}} \;=\; 5.3\,\mathrm{GeV}/c^2$, in order to reproduce the physical threshold for B-mesons production. Again, within the large statistical uncertainties, our data are consistent both with the results of experiment E653 and with the theoretical predictions. Table 1 reports the mean values found by the present analysis for all measured correlation variables.

A study of beauty particle hadroproduction was performed in the WA92 experiment, in which a beam of 350 GeV/c π^- particles interacted in a 2-mm-thick copper target. The WA92 experiment recorded 26 events featuring production of beauty particles; in 13 of our 26 $\mathrm{b\bar{b}}$ events we identified the decay vertex of the second beauty particle, giving a total of 39 beauty decays. Using this sample of beauty decays and optimising an estimator for the momentum of the partially reconstructed vertices, we measured the distributions with respect to x_F and p_T^2 for the beauty particles as well as some kinematic correlation variables. Our results, which are consistent with the only previous measurements for 9 $\mathrm{b\bar{b}}$ events, were compared to NLO QCD predictions.

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References

[1] S. Frixione *et al.*, Heavy Flavours II (Advanced Series on Directions in High Energy Physics - Vol. 15), eds. A.J. Buras and M. Lindner (World Scientific, Singapore, 1998), p. 609 and references therein [preprint CERN-TH/97-16 (1997)].
[2] M. Adamovich *et al.*, Nucl. Phys. B495 (1997) 3.
[3] Y. Alexandrov *et al.*, Phys. Lett. B433 (1998) 217.
[4] K. Kodama *et al.*, Phys. Lett. B303 (1993) 359.
[5] M. Adamovich *et al.*, Nucl. Instr. and Meth. A379 (1996) 252.
[6] A. Fassò *et al.*, Proc. IV International Conference on Calorimetry and their Applications, La Biodola, Italy (World Scientific, 1994) 493.
[7] H.-U. Bengtsson and T. Sjöstrand, Comput. Phys. Commun. 46 (1987) 43.
[8] M. Bengtsson and T. Sjöstrand, Comput. Phys. Commun. 43 (1987) 367.
[9] GEANT Detector Description and Simulation Tool, CERN Program Library Long Writeup W5013 (1994).
[10] L. Malferrari, Nucl. Instr. and Meth. A368 (1995) 185.
[11] J.C. Lassalle *et al.*, Nucl. Instr. and Meth. 176 (1980) 371.
[12] M. Adamovich *et al.*, Phys. Lett. B385 (1996) 487.
[13] A.D. Martin *et al.*, Phys. Rev. D45 (1992) 2349.
[14] A.D. Martin *et al.*, Phys. Rev. D43 (1991) 3648.

Table 1: *Mean values of the single and double-differential variables. Theoretical expections are shown for comparison.*

	WA92	NLO QCD
$< p_T^2 >$ (GeV/c)^2	7.9 ± 1.0	6.2
$< x_F >$	0.06 ± 0.04	0.096
$< M(B\overline{B}) >$ (GeV/c)	12.4 ± 0.3	12.3
$< x_F(B\overline{B}) >$	0.16 ± 0.08	0.21
$< \lvert x_F(B) - x_F(\overline{B}) \rvert >$	0.28 ± 0.04	0.27

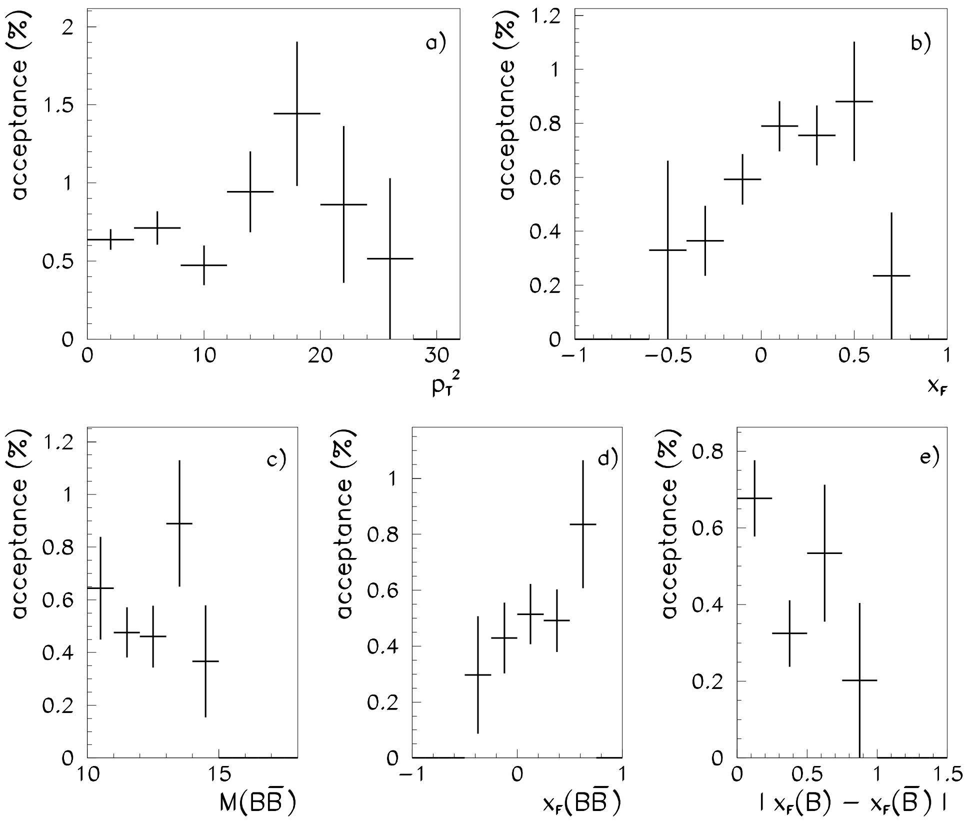

Figure 1: *Acceptances of beauty particles as a function of a) p_T^2 and b) x_F; acceptances of beauty pairs as a function of c) $B\overline{B}$ invariant mass, d) Feynman-x of the $B\overline{B}$ system and e) $|x_F(B) - x_F(\overline{B})|$.*

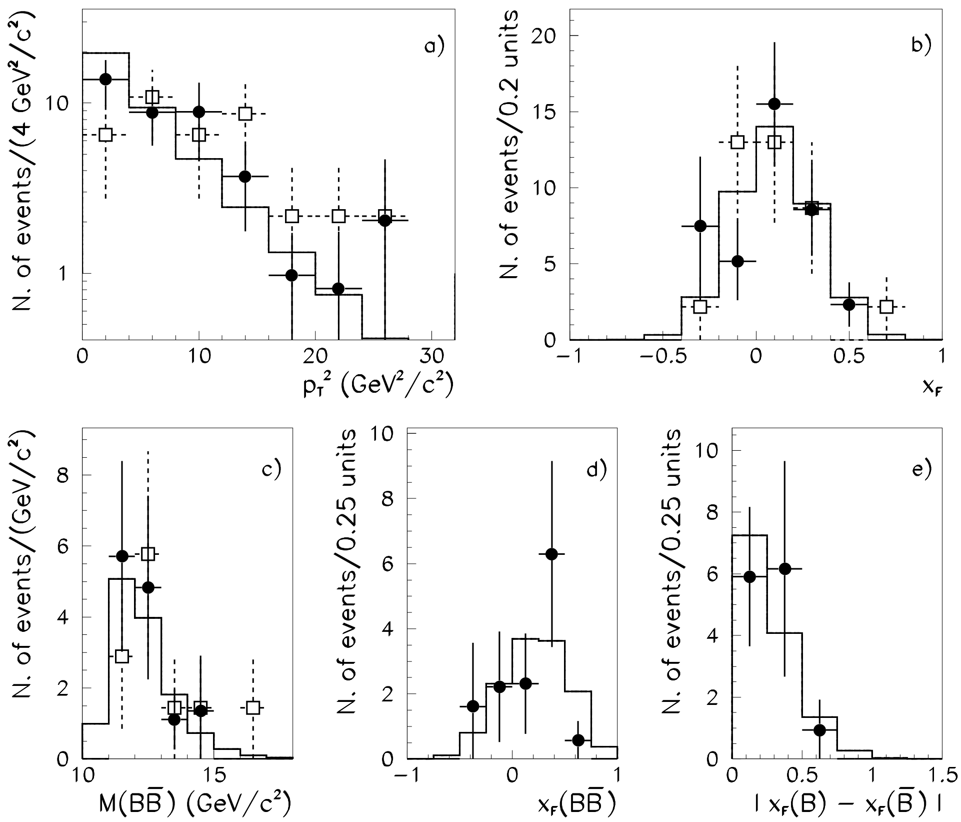

Figure 2: *Distributions of a) p_T^2 and b) x_F for the beauty particles; distributions of c) $B\overline{B}$ invariant mass, d) Feynman-x of the $B\overline{B}$ system and e) $|x_F(B) - x_F(\overline{B})|$. All the distributions are corrected for the experimental acceptances. Present results (solid circles) are compared with NLO QCD predictions (solid line) and E653 measurements (open squares).*