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Azimuthal correlation between beauty particles produced in 350 GeV/c π^--Cu interactions

The BEATRICE Collaboration

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Abstract

Using a sample of 10^8 triggered events, produced in 350 GeV/c π^- interactions in a copper target, we have identified 26 $b\bar{b}$ events. These include 13 events where the decays of both B and $\overline{B}$ are well reconstructed. We measure the azimuthal correlation between beauty particles, and compare our result with predictions based on perturbative QCD.

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In this letter we report on a measurement of the azimuthal angle, $\Delta\phi$, between associated beauty particles produced in π^--Cu interactions at a centre-of-mass energy of $\sim$ 26 GeV. At the energy considered, the beauty production cross-section is of the order of nanobarns, and is a fraction $\sim 10^{-7}$ of the inelastic cross-section. In experiment WA92, performed at the CERN Super Proton Synchrotron, we have identified 26 $b\bar{b}$ events [1], the largest sample of beauty events so far obtained in a fixed-target environment. We compare our measurement of the azimuthal correlation with theoretical predictions and with the result from experiment E653 [2], where the decays of 9 beauty pairs were reconstructed in nuclear emulsion.

High-energy hadronic interactions can be treated in the framework of the QCD-improved parton model. In this model, a hadron is viewed as a beam of partons (quarks and gluons). These carry varying fractions of the parent-particle momentum, as prescribed by some parton density function. A hard scattering between hadrons is seen as resulting from elementary interactions between partons. Production of a quark having a mass, m_Q, much greater than the QCD parameter Λ_{QCD} can be calculated perturbatively via a power-series expansion in the strong coupling constant $\alpha_s(m_Q{}^2) \sim 1/\ln(m_Q{}^2/\Lambda_{QCD}{}^2)$. In the case of beauty production ($m_Q = m_b \sim 4.75\,\mathrm{GeV}/c^2$, $\Lambda_{QCD} \sim 140\,\mathrm{MeV}$), the perturbative calculations, currently evaluated to next-to-leading order (NLO) [3], are expected to be reliable. Nonetheless, the theoretical predictions have uncertainties arising from a dependence on the choices made for the scales of renormalization and factorization, the b-quark mass, the parameter Λ_{QCD}, and the parton density functions. For some quantities, such as the production cross-section, the uncertainties in the theoretical predictions are large. Smaller uncertainties affect the prediction of the $\Delta\phi$ distribution.

In leading-order production processes (quark-antiquark annihilation and gluon-gluon fusion), a heavy quark and its antiquark are emitted back-to-back in the parton-parton centre-of-mass system. This would suggest that B and $\overline{B}$ particles produced in a fixed-target interaction should have opposite directions in the plane perpendicular to the beam. The distribution of the azimuthal angle between B and $\overline{B}$ should then be sharply peaked at 180°. Inclusion of NLO processes results in a broadening of the distribution. Further broadening may result from perturbative corrections beyond NLO, and from non-perturbative effects. However, in the QCD model [3], the $\Delta\phi$ distribution is supposed not to be modified by the fragmentation of quarks into hadrons but it is altered significantly when allowance is made for the interacting partons' momentum, k_T, transverse to the beam direction. Indeed the effect of heavy quark fragmentation has been evaluated with Pythia 5.4 [4] and for the b-quark it is negligible, as shown in Fig. 1.

Data taking for the WA92 experiment was performed at the CERN Ω' spectrometer in 1992 and 1993, with a 350 GeV/c π^- beam incident on a 2 mm copper target. The number of events recorded was 10^8, corresponding to an integrated luminosity of 8.1 (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, occupying 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 2 T magnetic field and drift chambers (8 planes). A muon detector, based on resistive-plate chambers, was positioned downstream of the tracking planes.

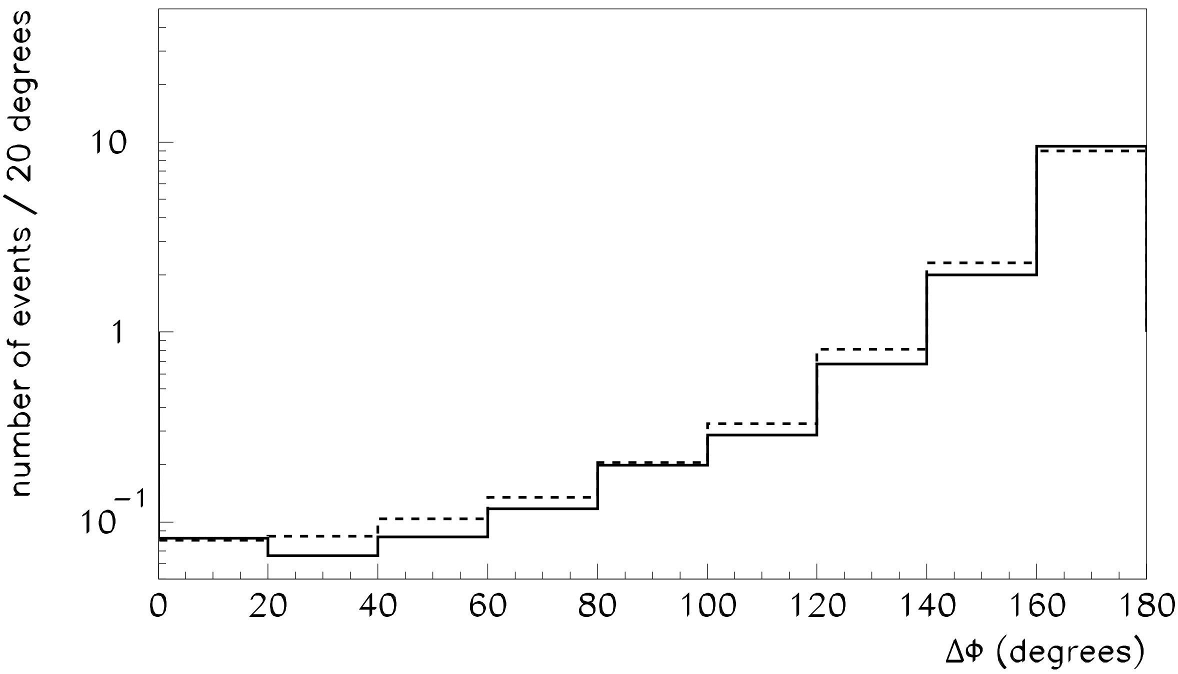

Figure 1: *Azimuthal correlation between beauty quarks (solid line) and between beauty hadrons (dotted line), as given by Pythia. Distributions are normalized to the number of beauty pairs (13) used in the WA92 analysis.*

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 our acceptance calculations, and for studies of backgrounds in our beauty search, we have 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 and Jetset 7.3 [7] 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 [8].

Analysis of our data has yielded a sample of 26 $\mathrm{b\bar{b}}$ events, with an estimated background of 0.6 $\pm$ 0.6 events. A complete account of the analysis strategy can be found elsewhere [1]. Here we give only a brief outline of the procedure followed. Secondary vertices were looked for in the region between 0.3 cm and 6 cm from the primary vertex. Taking advantage of the analogue readout of the DkD, secondary vertices close to large energy releases, usually due to hadronic interactions in the silicon planes, were disregarded.

We then selected three categories of events, consistent with beauty-decay topologies:

i. events containing $\geq$ 1 secondary $\mu^{\pm}$ of $p_T \geq 1\,\mathrm{GeV}/c$ and $\geq$ 2 secondary vertices with minimum mass $\geq 0.55\,\mathrm{GeV}/c^2$, including $\geq$ 1 secondary vertex 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 $p_T > 1.5\,\mathrm{GeV}/c$, or one track with $p_T > 0.8\,\mathrm{GeV}/c$ and one track with $p_T > 0.6\,\mathrm{GeV}/c$).

In calculating a vertex's minimum mass, we assume that the vertex corresponds to the decay of a particle from the primary vertex and that the energy-momentum conservation of the decay is ensured by an unobserved zero-mass particle. All detected decay products are taken to be pions.

Events from categories ii.) and iii.) above were filtered using a neural network [9], which took into consideration topological and kinematical information supplied through a set of 16 input variables. We next performed a scanning analysis, in which events were examined individually using a graphical display program. This scanning gave us our 26 $b\bar{b}$ events.

In evaluating the background in our beauty sample we investigated three possible background sources: charm events; events containing secondary interactions without nuclear breakup; events with in-flight decays of pions and kaons.

Each of our $b\bar{b}$ events contains one vertex interpreted as a beauty-particle decay. We now aim to identify the decay vertex of an event's second beauty particle. Before proceeding, we use an interactive version of our reconstruction program [5, 10] to improve the vertex measurement accuracy, fundamental to the determination of $\Delta\phi$. The interactive program allows us to correct errors in the assignments of hits to tracks, and in the assignments of tracks to vertices.

In our 26 $b\bar{b}$ events, nearly all of the secondary vertices are due to decays of charm and beauty. As a result, a secondary vertex to be considered as a candidate for an event's second beauty-particle decay is initially required to satisfy only minimal selection criteria:

i. it must be outside the target, but within 6 cm of the target edge, and its distance from the primary vertex must be at least six times the vertex separation uncertainty;

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

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

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

At this point we have to distinguish between vertices from the decay of an event's second beauty particle and vertices from the decay of a charmed hadron that is a daughter of the second B partner. Misidentification of the charmed-hadron daughter as the second beauty particle should, in general, have little effect on the $\Delta\phi$ distribution, since the charmed hadron usually carries a large fraction of its parent's momentum (mean momentum fraction $\sim$ 50%) and, in the laboratory frame, tends to be emitted at a small angle relative to the parent's line-of-flight (mean emission angle 1.5°). Quantitative information on the effect of misidentification has been obtained in a study of simulated $b\bar{b}$ events. We consider the azimuthal angle, $\Delta\phi_{bb}$, between pairs of beauty particles, and the azimuthal

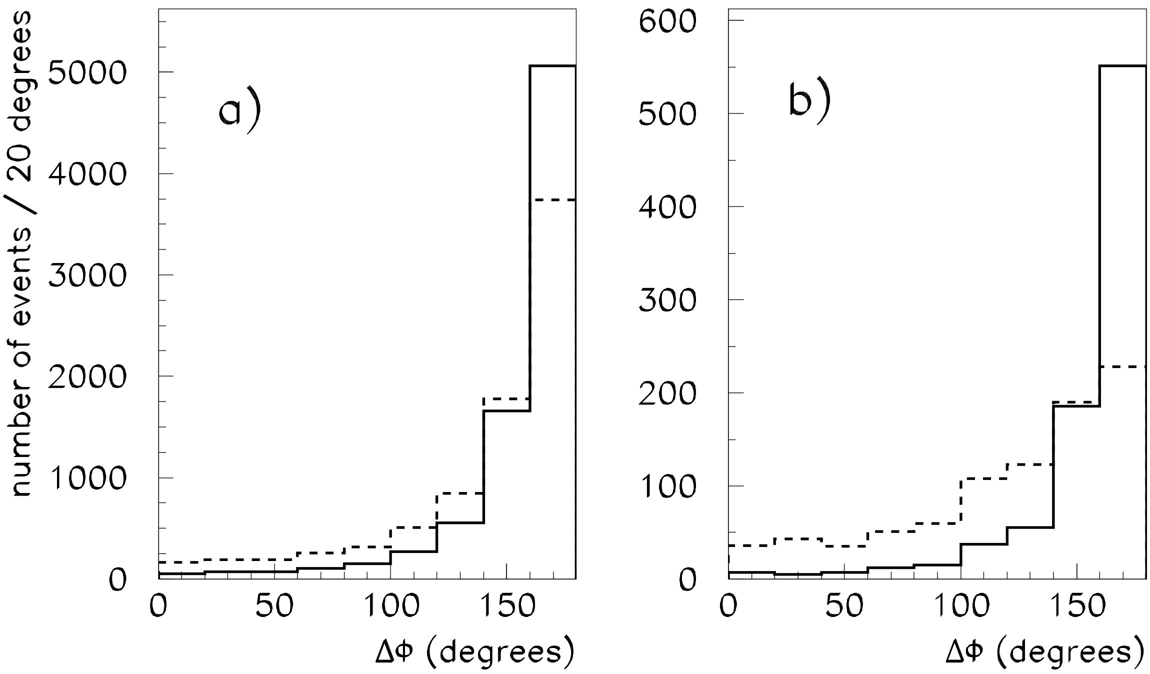

Figure 2: *Distribution from simulated beauty events of the azimuthal angle, $\Delta\phi$, between B and $\overline{B}$ (solid line), and between B and the charmed meson from $\overline{B}$ or charge-conjugate combination (dashed line): a) for all events; b) for events where B or $\overline{B}$ decays less than 1 mm from the primary vertex.*

angle, $\Delta\phi_{bc}$, between one of an event's beauty particles and a charmed hadron from the other beauty particle. Globally, as we expect, $\Delta\phi_{bb}$ and $\Delta\phi_{bc}$ have distributions that are similar (Fig. 2a). However, for the 11% of events where the second beauty particle decays less than 1 mm from the primary vertex, the distribution of $\Delta\phi_{bc}$ is significantly broader than the distribution of $\Delta\phi_{bb}$ (Fig. 2b). We must therefore ask for an explicit identification of the second beauty-decay vertex.

We accept as a beauty decay a vertex that, in addition to the criteria specified above, satisfies one, or both, of two conditions usually not met by the vertex of a charm decay:

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

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

A vertex is wrongly identified as a beauty decay with a probability of only 3.6%, and the effect on our measurement is negligible.

Having applied all selection criteria, we identify the decay vertex of the second beauty particle in 15 of our 26 $b\bar{b}$ events, giving us a total of 41 beauty decays. The background, already low (0.6 ± 0.6) for the 26 $b\bar{b}$ events, is expected to be negligible for the 15 events with two identified beauty-decay vertices.

Among the 41 beauty particles for which we identify the decay vertex, 10 are charged and 16 are neutral. In the remaining 15 cases the charge is poorly measured: the possible presence of low-momentum tracks, or of tracks that are collinear, gives an uncertainty in the vertex's charged-particle multiplicity; and the number of silicon planes between the vertex and the primary-interaction point is too small to allow unambiguous determination of whether hits are present along the decay path. The charmed-hadron daughter is identified for 20 of our 41 beauty particles. As shown in Table 1, the basic composition of our beauty sample is well reproduced by a sample of simulated $b\bar{b}$ events passing the same selection criteria.

Table 1: *Comparison between the sample of beauty events obtained experimentally and a sample of simulated beauty events identified using the same selection criteria. Data for the simulation (13500 $b\bar{b}$ events generated) are normalized such that the number of selected beauty events is the same as is found experimentally. The statistical fluctuations associated with each number are indicated.*

	Experiment	Simulation
Selected beauty events	26 ± 5.1	26.0 ± 2.4
Beauty pairs	15 ± 3.9	18.4 ± 2.0
Identified beauty particles	41 ± 6.4	44.4 ± 3.2
Beauty with identified charm	20 ± 4.5	25.1 ± 2.4
Beauty without identified charm	21 ± 4.6	19.3 ± 2.1
Charged beauty particles	10 ± 3.2	15.2 ± 1.8
Neutral beauty particles	16 ± 4.0	14.6 ± 1.8
Beauty particles of undetermined charge	15 ± 3.9	14.6 ± 1.8
Beauty pairs after imposing minimum transverse decay length	13 ± 3.6	16.1 ± 0.9

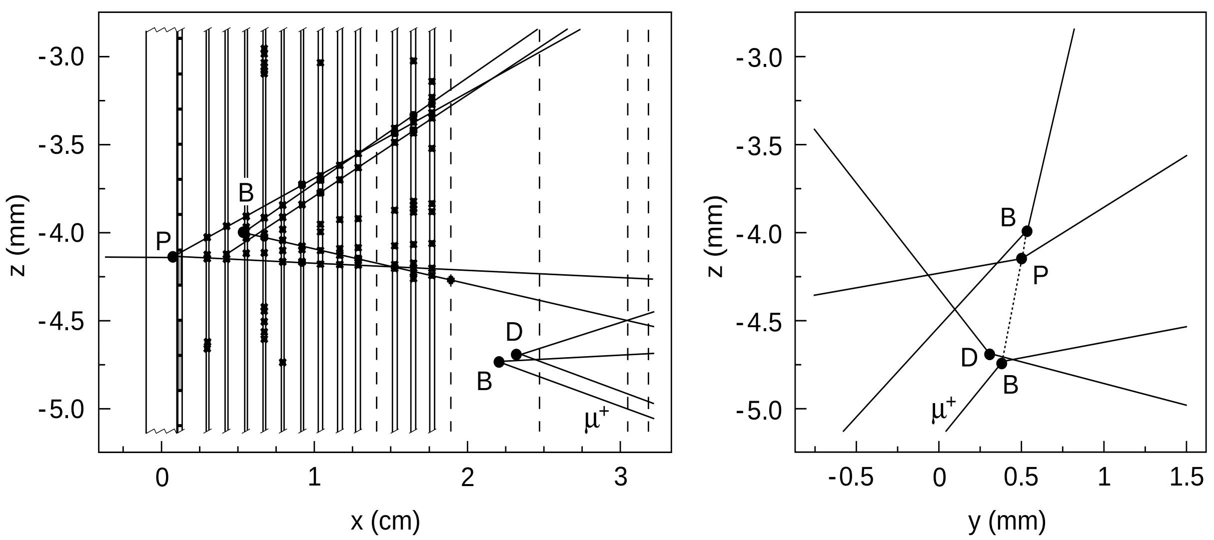

Figure 3: *Two views of a $b\bar{b}$ event in which both beauty decays (marked B) are visible. The primary interaction occurs at point P. A vertex (D) consistent with the decay of a charmed hadron from the more downstream beauty particle is also reconstructed. The beam is along the x axis (left view). In the transverse view (right), the azimuthal angle between the beauty particles is seen to be about 180°.*

Two views of an event where we reconstruct the decay vertices of associated beauty particles, and of one of the charmed-hadron daughters, are shown in Fig. 3. The absence

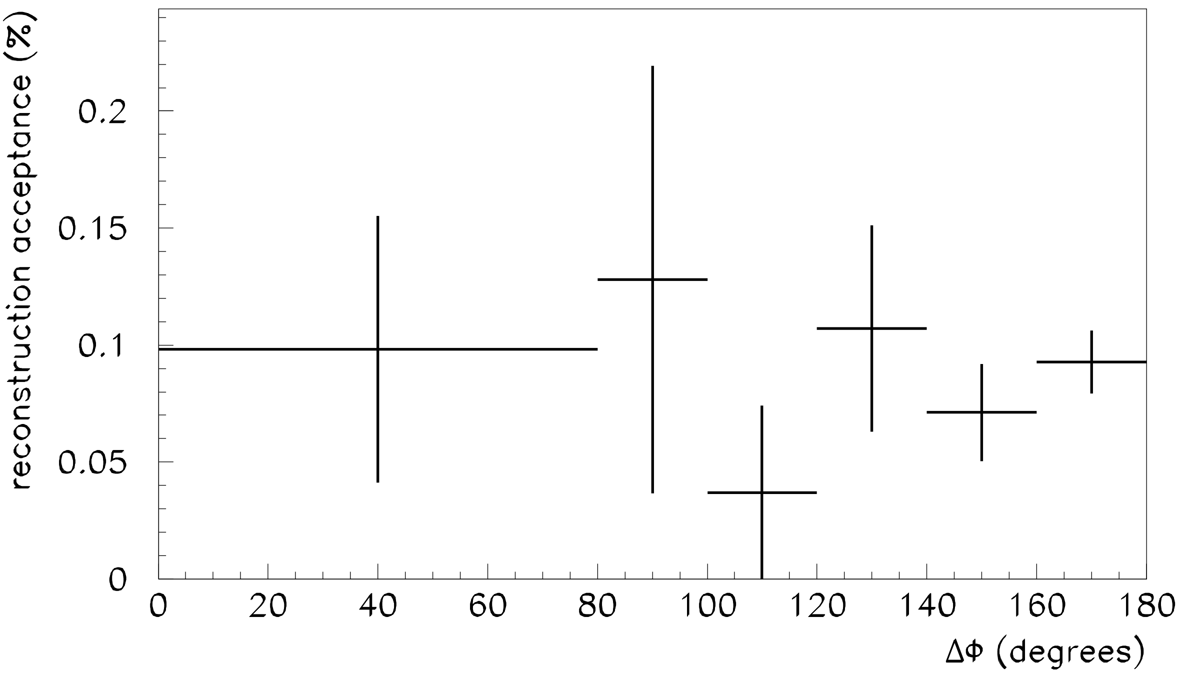

Figure 4: *Reconstruction acceptance of beauty pairs as a function of $\Delta\phi$.*

of hits along the decay paths suggests that both beauty particles are neutral. The more downstream beauty particle has a μ^+ among its decay products, and so can be identified as a B^0. In the projection transverse to the beam line the beauty particles are emitted back-to-back.

As a final condition to be satisfied by a $b\bar{b}$ event to be used in our $\Delta\phi$ measurement, we require a transverse decay length of $> 20\,\mu$m for one of the beauty particles and of $> 50\,\mu$m for the associated beauty particle. This requirement, which reduces our data sample to 13 events, improves the experimental resolution on $\Delta\phi$ to better than 5°. We choose to plot the $\Delta\phi$ distribution with a bin width of 20°. Among the simulated $b\bar{b}$ events with two identified beauty-decay vertices, from a simulation of 13500 $b\bar{b}$ events, the number in which the $\Delta\phi$ value measured after reconstruction differs from the generated (true) value by less than the chosen bin width is $68/82 = 83\%$ before imposing the requirement on transverse decay length and $66/72 = 92\%$ afterwards. We then calculate our acceptance by dividing the $\Delta\phi$ distribution of the 72 simulated $b\bar{b}$ events satisfying all selection criteria by the $\Delta\phi$ distribution of the generated events. The acceptance distribution, shown in Fig. 4, has large statistical uncertainties, but is consistent with a flat behaviour similar to the one found in our analysis of charmed-particle correlations [11].

In Fig. 5a) we compare our data, corrected for acceptance, with predictions based on NLO QCD. The theoretical distributions have been obtained taking $m_b = 4.75\,\mathrm{GeV}/c^2$; $\Lambda_{QCD} = 140\,\mathrm{MeV}$; $\mu_R = \mu_F = \sqrt{\mu_0{}^2 + \frac{1}{2}(p_T{}^2 + \bar{p}_T{}^2)}$, with p_T and $\bar{p}_T$ the transverse momenta of b-quark and $\bar{b}$-antiquark respectively, and $\mu_0 = m_b$. We used the SMRSπ2 [12] parton density set for the beam pion, and the MRSD- [13] parton density set for target nucleons. The effect of corrections beyond NLO on the perturbative calculations has been estimated by varying μ_0 between $\frac{1}{2}m_b$ and $2m_b$. Fig. 5a) shows that the consequent variation in the $\Delta\phi$ distribution is small.

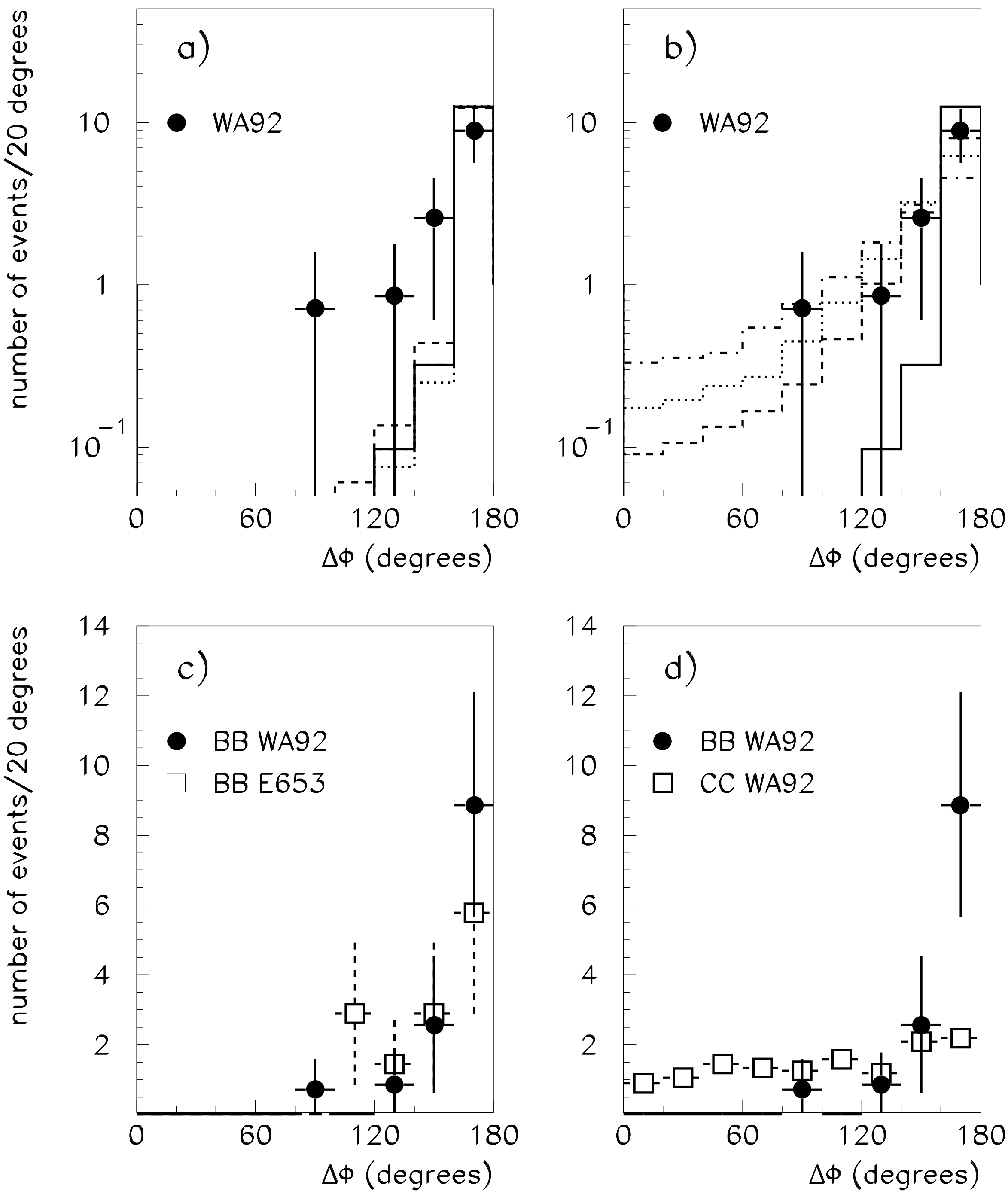

Figure 5: *WA92 measurement of the* $\Delta\phi$ *distribution compared with: a) distributions given by NLO QCD for* $\mu_0 = m_b$ *(solid line),* $\mu_0 = \frac{1}{2}m_b$ *(dashed line),* $\mu_0 = 2m_b$ *(dotted line); b) distributions given by NLO QCD for* $\mu_0 = m_b$ *and* $\langle {k_T}^2 \rangle = 0\,GeV^2/c^2$ *(solid line),* $\langle {k_T}^2 \rangle = 0.5\,GeV^2/c^2$ *(dashed line),* $\langle {k_T}^2 \rangle = 1\,GeV^2/c^2$ *(dotted line) and* $\langle {k_T}^2 \rangle = 2\,GeV^2/c^2$ *(dashed-dotted line); c) E653 measurement [2] for beauty particles; d) WA92 measurement [11] for charmed particles. All distributions are normalized to the number of beauty pairs (13) used in the WA92 analysis.*

We have also investigated the effect on the QCD results of the initial-state partons having a momentum component, k_T, transverse to the direction of the beam particle. We take k_T to be distributed as $dN/dk_T{}^2 \propto \exp(-k_T{}^2/\langle k_T{}^2\rangle)$. A comparison between the measured $\Delta\phi$ distribution and the theoretical distributions for $\langle k_T{}^2\rangle = 0\,\mathrm{GeV}^2/c^2$ (corresponding to bare NLO QCD), $\langle k_T{}^2\rangle = 0.5\,\mathrm{GeV}^2/c^2$, $\langle k_T{}^2\rangle = 1\,\mathrm{GeV}^2/c^2$ and $\langle k_T{}^2\rangle = 2\,\mathrm{GeV}^2/c^2$ is shown in Fig. 5b). Our data favour a $\langle k_T{}^2\rangle$ value of between $0.5\,\mathrm{GeV}^2/c^2$ and $1\,\mathrm{GeV}^2/c^2$. This is consistent with measurements of charmed-particle production [3, 11, 14] where, for both hadroproduction and photoproduction, the experimental data are best reproduced using a $\langle k_T{}^2\rangle$ value of about $1\,\mathrm{GeV}^2/c^2$. It is noted that the theoretical predictions [3] of the $\Delta\phi$ distribution for beauty particles are strongly influenced only by the $\langle k_T{}^2\rangle$ value, whereas predictions for charmed particles are sensitive to several factors (choice of input parameters for perturbative calculations, corrections beyond NLO, hadronization, $\langle k_T{}^2\rangle$ value).

Within the large statistical uncertainties, our data are consistent with the result of experiment E653 [2], as shown in Fig. 5c). In Fig. 5d) we compare the $\Delta\phi$ distribution that we measure for beauty particles with our previous measurement [11] for charmed particles. The stronger peaking at 180° in the case of the beauty particles is consistent with a lower sensitivity to hadronization and NLO effects.

In conclusion we have measured the azimuthal correlation between beauty particles produced in $350\,\mathrm{GeV}/c$ π^- interactions in a copper target. The measurement performed relates to a sample of 13 events in which the decay vertices of a B and a $\overline{B}$ are identified, and where the resolution on the azimuthal separation is better than 5°. The background contamination of our event sample and the probability that a vertex has been wrongly identified as a beauty decay are both negligible. Our result, which is consistent with the only previous measurement, for 9 $b\bar{b}$ events, is well described by NLO QCD if the interacting partons are assumed to have a mean transverse momentum squared of between $0.5\,\mathrm{GeV}^2/c^2$ and $1\,\mathrm{GeV}^2/c^2$.

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