Z. Phys. C – Particles and Fields 39, 7–11 (1988)

Zeitschrift für Physik C Particles and Fields
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Open beauty production in high energy π^--tungsten interactions

NA10 Collaboration

P. Bordalo[a], Ph. Busson, L. Kluberg, A. Romana, R. Salmeron, Cl. Vallée
Ecole Polytechnique and CNRS-IN2P3, F-91128 Palaiseau, France

J.J. Blaising[b], A. Degré[b], P. Juillot, R. Morand[b], M. Winter
CRN, CNRS-IN2P3 and Université Louis Pasteur, F-67037 Strasbourg, France

M. Guanziroli, P. Le Coultre, H. Suter, V.L. Telegdi
ETH, CH-8093 Zürich, Switzerland

K. Freudenreich[c]
CERN, CH-1211 Geneva 23, Switzerland

L. Carotenuto, A. Ereditato, E. Gorini, P. Strolin
Università di Napoli and INFN Sezione di Napoli, I-80125, Italy

Received 26 October 1987

Abstract. We present a study of $B\bar{B}$ meson pair production in π^--tungsten interactions at 140, 194 and 286 GeV incident pion energy. At 286 GeV, where we have the best statistics, we find a model-dependent $B\bar{B}$ production cross-section $\sigma_{B\bar{B}} = 14^{+7}_{-6}$ nb/nucleon.

Several experiment have already studied open beauty production in hadronic interactions. After its observation at the ISR [1], now confirmed by the same group [2], and several unsuccessful searches [3, 4], positive results have been reported: hadroproduction of a $B\bar{B}$ pair has been observed in a nuclear emulsion target [5] and, more recently, evidence for the production of $B\bar{B}$ pairs in π^--Uranium interactions at a beam energy of 320 GeV has been published [6]. In addition, the production of beauty particles has recently been observed at the SPS $p\bar{p}$ collider [7].

In this letter we present a search for $B\bar{B}$ meson pair production in π^--tungsten interactions based on the study of events with three muons in the final state. The result of an early study at a beam energy of 194 GeV has been already published [8]. Since then, a new analysis method allowed to increase, by a factor of $\simeq 6$, the overall acceptance due to the data reduction procedure and the background was evaluated by a different method which makes the results less sensitive to possible systematic effects. This new analysis has been applied to the data collected at beam energies of 140, 194 and 286 GeV. In addition the method of analysis used in [8] has been improved, leading to a complementary analysis of 286 GeV data.

The reaction considered in this study is

$$\pi^- W \to [\mu^+ \mu^- \mu^\pm] + X,$$

the trimuon event being assumed to result from an original $B\bar{B}$ production

$$\pi^- W \to B + \bar{B} + X$$

followed by semi-leptonic decays of the B mesons and, for at least one of them, by an additional semi-leptonic decay, according to

$$B \to \mu^- + D(\to \mu^+ + X) + X,$$
$$\bar{B} \to \mu^+ + \bar{D}(\to \mu^- + X) + X.$$

It should be noted that processes where a weak *hadronic* decay of the B (or $\bar{B}$) meson is followed by a semi-leptonic decay of the $D(\bar{D})$ meson are not relevant here since in these two of the three muons come from $D(\bar{D})$ decays and hence have too low transverse momenta ($p_T \sim 0.7$ GeV/c) to satisfy the trigger requirement.

The trimuon events used in this study are a subsample of the large number of events collected at the CERN SPS using the NA10 spectrometer, in which

[a] Now at LIP, Lisbon, Portugal
[b] Now at LAPP, Annecy-le-Vieux, France
[c] Now at ETH, Zürich, Switzerland

the trigger required at least two muons in the final state. The experimental setup has been described elsewhere [9].

The incident π^--beam interacted with a tungsten target separated from the spectrometer by a beam-dump hadron absorber. For the 140 and 286 GeV runs, a 120 cm long liquid deuterium target was added 2 m upstream of the tungsten target. Events produced in tungsten constitute the bulk of our data and are the only ones considered in the present study. They are not contaminated by events produced either in deuterium or in the beam dump, thanks to the spatial selectivity of the trigger and to the vertex reconstruction resolution ($\sigma_Z \simeq 25$ cm).

The spectrometer has two telescopes, one upstream and one downstream of an air-core toroidal magnet. Each telescope consists of two scintillation counter hodoscopes used for the trigger and four multiwire proportional chambers (MWPC's), which allow a precise reconstruction of the muon trajectories. Each hodoscope is subdivided into 6 radially segmented sextants.

The muons of the data analysed in this paper have a typical momentum of 25 GeV/c and a transverse momentum $p_T \simeq 1.4$ GeV/c. The p_T resolution is dominated by multiple scattering and amounts to 0.14 GeV/c.

The apparatus had been designed to study the hadronic production of high-mass muon pairs, a low cross-section process. It could stand very high incident beam intensities ($\simeq 1.5 \times 10^9$ pions/burst), a feature which made the present search feasible. The total integrated luminosities and corresponding numbers of interacting pions are given in Table 1 for the three energies.

As a consequence of the very high beam intensity, the main contamination of our data results from a time-accidental coincidence of a dimuon with a single muon originating in a different interaction. The amount of this contamination is determined by comparing the data with a linear combination of Monte-Carlo generated $B\bar{B}$ events and time-accidental trimuons simulated as described in detail hereafter.

At the trigger level a muon is defined by the time coincidence of four counters, one in each hodoscope and all in the same sextant. These counters must satisfy the space constraints of a track originating in the target and deflected by the magnet. Due to the $1/r$ dependence of the toroidal magnetic field, the transverse momentum p_T of a muon is inversely proportional to the deflection angle of its trajectory and is therefore directly given by the fired counters of the hodoscopes.

The standard dimuon trigger, which was optimized for pairs with masses above 3 GeV/c^2, required at least two muons in different sextants of the hodoscopes, one of them having $p_T > 0.8$ GeV/c and the other $p_T > 1.4$ GeV/c.

The trigger timing was determined by the first arriving muon signal and had a jitter of ± 5 ns, mainly due to the distances of the photomultipliers from the impact points in the counters. We measured the maximum time interval between the signal of two muons produced in the same interaction as 10 ns. In order to be fully efficient, the trigger allowed for 16 ns maximum separation between the two muon signals. Following a trigger, the hodoscopes and the chambers were gated with 40 and 80 ns wide signals respectively centered on the trigger leading edge.

A study of like-sign pairs showed that reconstructed muon pairs satisfying the trigger conditions and originating from two different interactions are negligible ($<1\%$). The two muons can be accompanied by a third one produced in the same or in a different interaction. In this latter case, the third muon is recorded by both the hodoscopes and the chambers if it is separated from the first arriving muon signal by less than 20 ns. It is recorded only by the chambers if that separation is between 20 and 40 ns.

Trimuon events were selected from the large sam-

Table 1. Summary of the data and simulated background

π^--Energy (GeV)	Luminosity 10^7 (nb/nucleon)$^{-1}$	Interacting π^- (10^{14})	In-time data events	Simulated background events	Acceptance $\times (10^5)$
140	0.58	1.0	58	426	2.8
194	1.36	1.1	185	1289	2.6
286	0.75	0.8	92	476	4.6
286[a]	0.40	0.3	42	1133	9.2

[a] Complementary analysis

ple of events containing at least one reconstructed muon pair. The third muon, which is not necessarily part of the trigger, was reconstructed using the MWPC's only; it is required to have its trajectory contained in one sextant of the hodoscopes and its $p_T > 0.5$ GeV/c. It is called "in-time" if the four counters of the hodoscopes intercepted by the trajectory fired (which insures that that third muon is separated from the first one by less than 20 ns). It is called "out-of-time" if none of the four counters mentioned above fired (which proves that that third muon and the first one were produced in different interactions, being separated by more than 20 ns).

The trimuon events originating from $B\bar{B}$ production are to be looked for in the in-time trimuon sample with two muons of different sign. This sample is contaminated by events in which the three muons were produced in two different interactions and, to a considerably smaller extent, by events in which one of the muons had a physical origin other than $B\bar{B}$ production though belonging to the same pion interaction. In both cases these contaminating events are referred to as "background trimuons"; one of their three muons is expected to have the characteristics of the out-of-time muons.

As already stated, the trigger requires at least one muon with $p_T > 1.4$ GeV/c. It follows that in the sample of out-of-time events, *one of the two triggering muons* must have $p_T > 1.4$ GeV/c. In the sample of in-time events, where any muon can contribute to the trigger, it is sufficient that *any out of the three muons* satisfies $p_T > 1.4$ GeV/c. In order to have comparable samples, we requested off-line that two out of three muons have $p_T > 1.4$ GeV/c.

Since the background is dominated by events in which a J/Ψ is associated with an extra muon, we restricted our analysis to trimuon events in which neither of the two possible opposite sign combinations had an invariant mass in the J/Ψ mass region [2.7 GeV/c$^2 < M_{\mu\mu} < 3.5$ GeV/c^2].

The small number of out-of-time events in the data surviving all the cuts mentioned above has led us to an artificial extension of this sample as follows: we constructed a "simulated background" by randomly associating each original out-of-time muon with a dimuon. This association was made for events taken under the same relevant experimental conditions, in particular the same magnet polarity, in order not to introduce any bias due to the charge asymmetry of the trimuon. If the resulting trimuon configuration did not satisfy the cuts, a new trial was made associating the same out-of-time muon, which is uncorrelated with the dimuon, with another pair until the new configuration satisfied the cuts.

Table 1 shows the number of in-time events surviving after the cuts as well as the number of simulated background events used in the analysis.

A Monte-Carlo simulation was used in order to obtain the features of $B\bar{B}$ produced trimuons and the acceptance of the apparatus. For the $B\bar{B}$ production we considered a correlated model where the $B\bar{B}$ pair is assumed to be the sole decay product of an intermediate state with mass larger than $m_{\Upsilon'''}$, the Υ''' mass. This state is centrally produced with a cross-section

$$\frac{d\sigma}{dm} \propto e^{-(m-m_{\Upsilon'''})^2/2\delta^2}$$

where the value of δ depends on the c.m. energy of the reaction $\sqrt{s}$ and is given in [10]. The distributions in the Feynman variable x_F and in p_T are assumed to be [11]

$$\frac{d^2\sigma}{dx_F\,dp_T} \propto (1-|x_F|)^3\, p_T\, e^{-2p_T}.$$

The general features concerning the B and D decays were assumed to follow the model of Ali [12]. The experimental acceptances including the effects of the data reduction procedure are given in Table 1.

In order to separate the signal from the background we study the respective two dimensional distributions in the variables:

$$g_{\pm} = \min\left\{\frac{|\mathbf{p}_+ \times \mathbf{p}_-|}{|\mathbf{p}_+ + \mathbf{p}_-|}, \frac{|\mathbf{p}_+ \times \mathbf{p}_-|}{|\mathbf{p}_+ - \mathbf{p}_-|}\right\} \quad \text{and} \quad p_T,$$

where $g_{\pm}$ [13] refers to one of the two opposite sign muon combinations and p_T is the transverse momentum of the third muon; thus each trimuon enters twice the distribution. Figure 1 shows the distributions for the Monte-Carlo generated signal and for the simulated background. Their different behaviour suggests that the above variables are suitable to discriminate signal from background.

The $B\bar{B}$ production cross-section was determined by fitting the data with a linear combination of fractional amounts f of $B\bar{B}$ Monte-Carlo events and $(1-f)$ of simulated background events, where f is the free parameter of the fit. A maximum likelihood technique applied to the two dimensional diagram ($g_{\pm}$, p_T), leads to the values of f given in Table 2.

In order to compute the cross-sections, the following branching ratios were adopted for the B meson [14]:

$$\mathrm{BR}(B \to \mu^- + X) = 11.3\%,$$

$$\mathrm{BR}(B \to D) = 100\%.$$

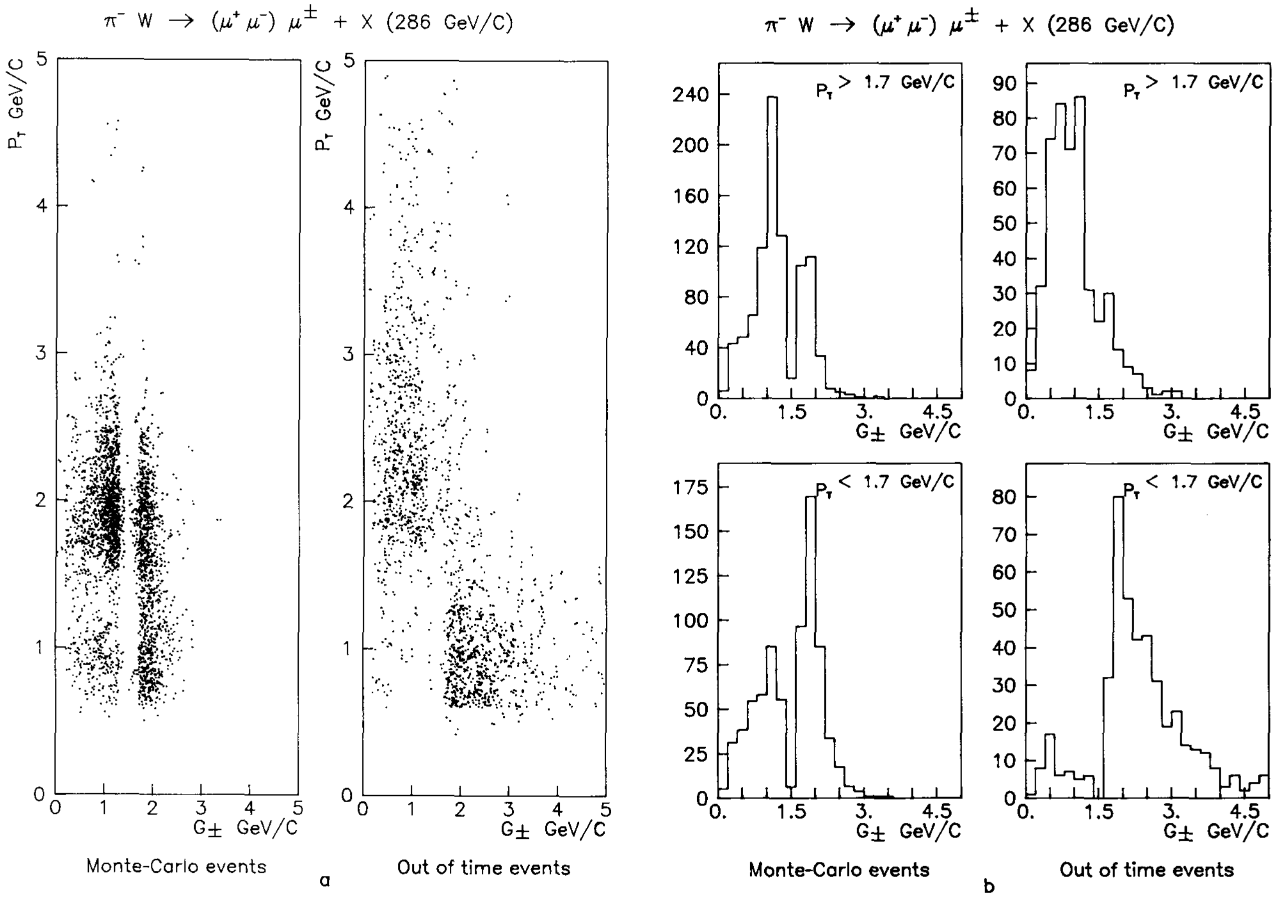

Fig. 1a, b. Scatter plot of $g_\pm$ and p_T showing the different behavior of Monte-Carlo (left) and simulated background events (right); **a** two dimensional distribution; **b** $g_\pm$ distributions for events with $p_T > 1.7$ GeV/c (top) and $p_T < 1.7$ GeV/c (bottom)

The value taken for the branching ratio of $D \rightarrow \mu^+ + X$ was 11.0% deduced* from results given in [15]. The resulting overvall branching ratio was 2.81×10^{-3}. Assuming a linear dependence of the cross-section on the atomic mass number, the fitted values of f together with the acceptances, luminosities and branching ratios give the cross-section listed in Table 2.

The sensitivity of our results to the $B\bar{B}$ production model was tested taking, for the intermediate hidden beauty state, the x_F and p_T distributions of the Υ given in [16]. The test, performed on the 286 GeV data, yields a value $f = 0.14 \pm 0.07$ and a cross-section $\sigma_{B\bar{B}} = 10 \pm 5$ nb/nucleon. The comparison between this value and the 14^{+7}_{-6} nb/nucleon given in Table 2 provides a qualitative estimate of the sytematics induced by the production model.

Table 2. Estimated fraction f of $B\bar{B}$ events and corresponding cross-section

π^- Energy (GeV)	$\sqrt{s}$ (GeV)	f	$\sigma_{B\bar{B}}$ (nb/nucleon)
140	16.2	$0.11^{+0.09}_{-0.06}$	14^{+11}_{-8}
194	19.1	$0.08^{+0.05}_{-0.04}$	15^{+9}_{-7}
286	23.2	$0.15^{+0.07}_{-0.06}$	14^{+7}_{-6}
286[a]	23.2	$0.27^{+0.19}_{-0.19}$	11^{+8}_{-8}

[a] Complementary analysis

Note: errors are statistical only

A complementary analysis [17] was performed on a partial sample of the data. In this study the "background trimuons" were simulated in a complete dif-

* Values of 0.17 ± 0.02 and 0.20 ± 0.07 have been found for the D^+ branching ratio, 0.075 ± 0.011 and 0.15 ± 0.05 for the D^0. Weighting these results with 75% of D^0, 25% of D^+ (to take account of D^* production in B decay) leads to $\simeq 11\%$ for the global muonic branching ratio

ferent way based on data taken with special triggers. The "background trimuons" were in fact constructed by randomly associating a dimuon event with a single muon event, both taken in special trigger runs. The special dimuon trigger required two muons with $p_T > 0.8$ GeV/c and the special single muon trigger required one muon with $p_T > 0.8$ GeV/c. The resulting trimuons can thus be compared with the data and the Monte-Carlo generated events provided that the events with two muons in the same sextant are discarded, since they cannot be correctly simulated from the trigger point of view. The fact that both muons in the special dimuon trigger are allowed to have $p_T > 0.8$ GeV/c enabled us to retain also those trimuons where only one muon has $p_T > 1.4$ GeV/c.

In order to compare the simulated background with the data without trigger biases, cuts different from those used in the previous analysis were applied here. Moreover, a tighter cut was applied to the data, thus reducing the time-accidental background: the signal coming from a special coincidence, derived from the trigger system, was used to flag on-line, and to accept off-line, only the events with the signals of the three muons falling within a 10 ns interval.

The fact that the special triggers were available for only some of the 286 GeV data taking periods reduced the data sample on which this complementary analysis could be performed. This and the different cuts used lead to a sample of events different from the one used in the previous analysis (see Table 1).

Apart from these features, this analysis is analogous to the one previously discussed. Table 2 shows the resulting value of f. Under the assumption of a linear A-dependence, the cross-section for $B\bar{B}$ production is 11 ± 8 nb/nucleon, confirming the result obtained above.

Comparing with our previously published results [8], we should point out the following main differences. The overall acceptance has been significantly increased. The new method of analysis has made use of a powerful discriminator between signal and background, the $(g_\pm, p_T)$ two dimensional distribution. The reprocessing of all our data (and the use of more adapted special trigger runs for the complementary analysis) has allowed to build a sample of identified background events with characteristics identical to those of the background contaminating our signal. The above features lead to more precise results, free from systematic effects that could affect the results of [8].

The results reported here can be compared to a recent investigation of $B\bar{B}$ production in π^--Uranium interactions at a beam energy of 320 GeV [6]. A cross-section of $4.5 \pm 1.4 \pm 1.4$ nb/nucleon is reported, assuming a branching ratio for $D \to \mu^+ + X$ of 13%. Rescaling this result with the value of 11% adopted in our analysis leads to a cross-section of $5.0 \pm 1.6 \pm 1.6$ nb/nucleon in good agreement with the value obtained in our experiment.

In conclusion, we have studied the production of trimuon events by 140, 194 and 286 GeV π^- incident on tungsten. We determined a model-dependent cross-section for the associated production of beauty-flavoured mesons. Assuming a correlated central production mechanism, we obtain cross-sections $\sigma_{B\bar{B}}$ of 14^{+11}_{-8} (140 GeV), 15^{+9}_{-7} (194 GeV) and 14^{+7}_{-6} nb/nucleon (286 GeV), the quoted errors being statistical only. The statistical uncertainties of our results and the small $\sqrt{s}$ interval do not allow any statement on the increase of the cross-section $\sigma_{B\bar{B}}$ with energy.

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