UPPER LIMITS FOR $B\bar{B}$ PRODUCTION IN π^-–TUNGSTEN INTERACTIONS AT 194 GeV/c

NA 10 Collaboration

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We present a study of events with three muons in the final state, produced in π^-–tungsten interactions at 194 GeV/c. Trimuons can be attributed to B-meson pair production, and this allows us to set (model-dependent) upper limits for the corresponding cross section. Assuming a correlated central production model, we obtain the limit of 1.5 nb per nucleon at the 95% confidence level.

1. Introduction. Our information on hadronic beauty production is still meager. At the CERN Intersecting Storage Rings (ISR) one single experiment [1] observed a positive signal yielding (under the assumption of diffractive production) an estimate for open beauty cross section. A contrary result was found by Drijard et al. [2]. Fixed-target experiments [3–8] reported only upper limits going from a few nanobarns to tens of nanobarns. These limits are strongly model-dependent, in particular because of the small acceptances of the set-ups; in general, a central production model is assumed.

In this letter we report on the search for $B\bar{B}$-meson pair production by negative pions. The decay chain of b quarks [9], possibly involving intermediate J/ψ production, would produce trimuons which would be detected by the NA10 spectrometer.

2. Experimental set-up. The results presented here

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are based on data collected at the CERN Super Proton Synchrotron (SPS). A 194 GeV/c π^- beam interacted with either a 5.6 cm or a 12 cm long tungsten target, followed by a spectrometer (NA10 spectrometer) whose characteristics are described in detail elsewhere [10]. The total number of interacting pions was 1.21×10^{14} and the integrated luminosity 1.48×10^7 (nb per nucleon)$^{-1}$. The set-up comprises a beam-dump/hadron-absorber followed by two telescopes, one upstream and one downstream of an air-core toroidal magnet. Each telescope consists of four multiwire proportional chamber (MWPC) modules and two scintillation counter hodoscopes (designated as R1, R2 and R3, R4, respectively, for the two telescopes) which are used for the trigger. The four trigger hodoscopes are subdivided into radially segmented sextants; the total number of scintillation counters is about 700. This spectrometer has been designed to measure, with high luminosity and good mass resolution, the hadronic production of high-mass muon pairs. However, as described hereafter, it allows the detection, with the standard trigger, of multimuon events.

At the trigger level, the muon momenta are measured by means of a quadruple coincidence between two counters of hodoscopes R1 and R2 pointing to the target (V = R1 * R2), and two counters of hodoscopes R3 and R4 aligned with the intercept of the track (as measured by R1 * R2) with the median plane of the magnet. By virtue of the $1/r$ dependence of the toroidal field, the deflection by the magnet, as determined by the above coincidences, yields directly a rough measurement of the muon transverse momentum p_T. The whole p_T range is divided into four intervals (p_T superbin signals) defined as follows:

$$\mathrm{A} \leftrightarrow p_T \geqslant 4.0\ \mathrm{GeV}/c\ ,$$

$$\mathrm{B} \leftrightarrow 2.0 \leqslant p_T < 4.0\ \mathrm{GeV}/c\ ,$$

$$\mathrm{C} \leftrightarrow 1.4 \leqslant p_T < 2.0\ \mathrm{GeV}/c\ ,$$

$$\mathrm{D} \leftrightarrow 0.6 \leqslant p_T < 1.4\ \mathrm{GeV}/c\ .$$

The standard trigger requires two superbins in two different sextants, falling within a 16 ns gate opened by the earliest p_T signal. A further requirement is that at least one of the superbins be A, B, or C. There is no constraint, at the trigger level, on the number or the characteristics of any extra muons. Trimuons are selected off-line from among the events which satisfy the standard trigger, requiring the presence of a third superbin signal in a sextant that is different from the two "trigger sextants". This third signal is only required to fall within the 16 ns gate opened by the earliest p_T signal which was necessarily part of the trigger.

3. Data and background simulation. The tightness of the off-line event selection criteria is particularly important for multimuon studies, in view of the low cross section and the fact that events with a shower originating in the beam dump tend to fake multimuons because of the high multiplicity of the counter and chamber hits. In order to select clean trimuons, we applied geometrical cuts which had been investigated and checked by scanning multimuon candidates. We restricted ourselves to trimuons with only two like-sign muons such as would correspond to $\mathrm{B\bar{B}}$ decay. The small rejection by this cut (≈0.5%) shows that multimuon events are associated with the production of opposite-sign muon pairs, independently of their source (background, or $\mathrm{B\bar{B}}$ production and decay).

Because of the high intensity of the beam (on the average 1.3×10^9 π^- per 2 s burst) and the fact that the dimuon sample is dominated by true opposite-sign dimuons, the main source of background is the accidental (time) coincidence of the latter with a muon from a different interaction. We have simulated this background, using real data, by randomly associating a dimuon trigger, as described above, with a single muon (pointing to the target) as obtained from the analysis of events taken with a trigger requiring at least one muon in any one of the four superbins.

In order to obtain, without trigger biases, samples of data and of simulated background events that are comparable with one another, we have however to restrict ourselves to trimuons having

(i) at most one D muon ("1D trimuon") – in fact, trimuon events with two D muons cannot be correctly simulated, owing to the non-existence of DD dimuon triggers;

(ii) all muons in different sextants – such a requirement is built into the 2μ trigger.

Applying these cuts, the data sample is reduced by a factor of 6, and we are left with 158 trimuon candidates.

The expected number of time accidentals can be estimated from the trigger gate width and the dimuon and single-muon average rates. The estimated ratio 3μ data events/accidentals is 1.23 ± 0.37. This value, even with its large uncertainty, leads one to anticipate that if no cuts are applied on phase space (a comparison of spectra for data and simulated background is made in section 5 and leads to cross section estimates), the observed "trimuon" events will essentially be due to accidental background. An indication in this sense is also given by the observed intensity dependence of the trimuon rate, as well as by a comparison of the invariant (opposite sign) dimuon mass-distributions of the trimuon candidates ("data") and of the simulated (properly normalized) background. These distributions are shown in fig. 1, and it is evident that they are very close to each other. One could therefore tend to conclude that the entire data sample can be attributed to accidentals. Such a conclusion would, however, be imprudent, since it is *a priori* not clear whether the real trimuons have a dimuon mass spectrum closely resembling that of the accidentals or not. To answer this question, a Monte Carlo simulation of the presumed trimuon events, based on specific models, is needed.

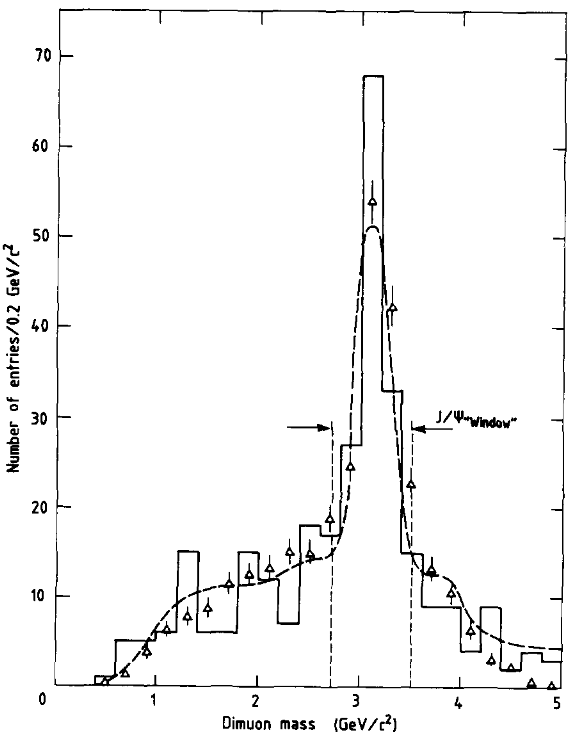

Fig. 1. Mass spectrum of opposite-sign muon pairs ($m < 5$ GeV/c^2) for data (histogram), simulated background (dashed line) and Monte Carlo $B\bar{B}$ decays (open triangles) from a correlated production model. The simulated distributions are normalized to the data entries. Note that for each trimuon event there are two entries to the histogram.

4. Monte Carlo simulation. In choosing a model for $B\bar{B}$ production yielding trimuons, it is evident that either the B or the $\bar{B}$ meson must decay via a two-step semileptonic cascade. However, the marked peak near the J/ψ (2.7–3.5 GeV/c^2) in the observed dimuon mass distribution (fig. 1) clearly implies that such cascades could never explain the totality of observed events; a mechanism directly involving the J/ψ, such as $B \to J/\psi \to \mu^+\mu^-$ discussed by Fritzsch [11], has to be invoked for some of the B ($\bar{B}$) decays [12]. On the other hand, the analysis may well be carried out separately for the events within/without the J/ψ "window" in fig. 1.

For the trimuon signal, the dominant decay mechanism without J/ψ's is that in which one of the B's undergoes two successive muonic decays while the other B ($\bar{B}$) decays with muon emission in only the first step. As concerns the general features of these decays, we followed Ali [13], and adopted a branching ratio (BR) of 11.8% for the first step and 8% for the second [14–17], yielding an overall BR of 2.2×10^{-3}. For decays with the J/ψ as an intermediate step, we assumed a BR of 1% for $B \to J/\psi$ [18] and 7.4% for $J/\psi \to \mu^+\mu^-$, i.e. an overall BR of 1.75×10^{-4}.

For the production process, two models were used:

(i) *Uncorrelated model.* On the basis of results [19] on hadronic production of charmed mesons, it is assumed that B mesons are produced individually with the invariant cross section

$$d^2\sigma/dx_F d(p_T^2) \propto (1 - |x_F|)^a \exp(-bp_T) ,$$

where x_F is the Feynman variable, with $a = 3$ and $b = 1.6$ [5]. The acceptance (excluding BRs) for trimuons from purely semileptonic decays) is $(6.1 \pm 0.5) \times 10^{-5}$, and 46% of the accepted events have no opposite-sign dimuons within the J/ψ "window" indicated in fig. 1.

(ii) *Correlated model.* In this approach – probably more realistic than the preceding one – the $B\bar{B}$ pair is assumed to be the sole decay product of a hypothetical intermediate particle, centrally produced, with a m^2 distribution exponentially decreasing above Υ''' [20]. The acceptance (excluding BRs) for purely semileptonic decays is $(4.6 \pm 0.2) \times 10^{-5}$, and 43% of the accepted dimuons do not fall within the J/ψ mass "window", while for the decay mechanism involving $J/\psi \to \mu^+\mu^-$ the acceptance is $(76 \pm 3) \times 10^{-5}$. This considerably larger acceptance is due to the relatively high p_T of the muons from J/ψ decay.

For comparison with the data, both decay mechanisms are of course superimposed in the appropriate ratio (see fig. 1, open triangles).

5. Cross section evaluation. The J/ψ peak in the simulated background in fig. 1 is due to the fact that in our experiment the dimuon spectrum is dominated by the J/ψ. For this reason, we consider two subsamples of events:

(i) events in which neither of the two possible opposite-sign combinations has an invariant mass in the J/ψ mass "window" (37 events);

(ii) events where the mass of at least one of the opposite-sign dimuons lies in the J/ψ window (121 events).

We first consider subsample (i), for which only models without intermediate J/ψ's are relevant, apart from a small correction due to the tails of the J/ψ.

An analysis of the simulated background reveals that the (known) dimuon can be identified with 94% probability by selecting, from the two like-sign muons, that with higher p_T. Fig. 2a shows the dimuon transverse momentum ($p_T^{\mu\mu}$) spectra, selected on the basis of this criterion, for the simulated background, the

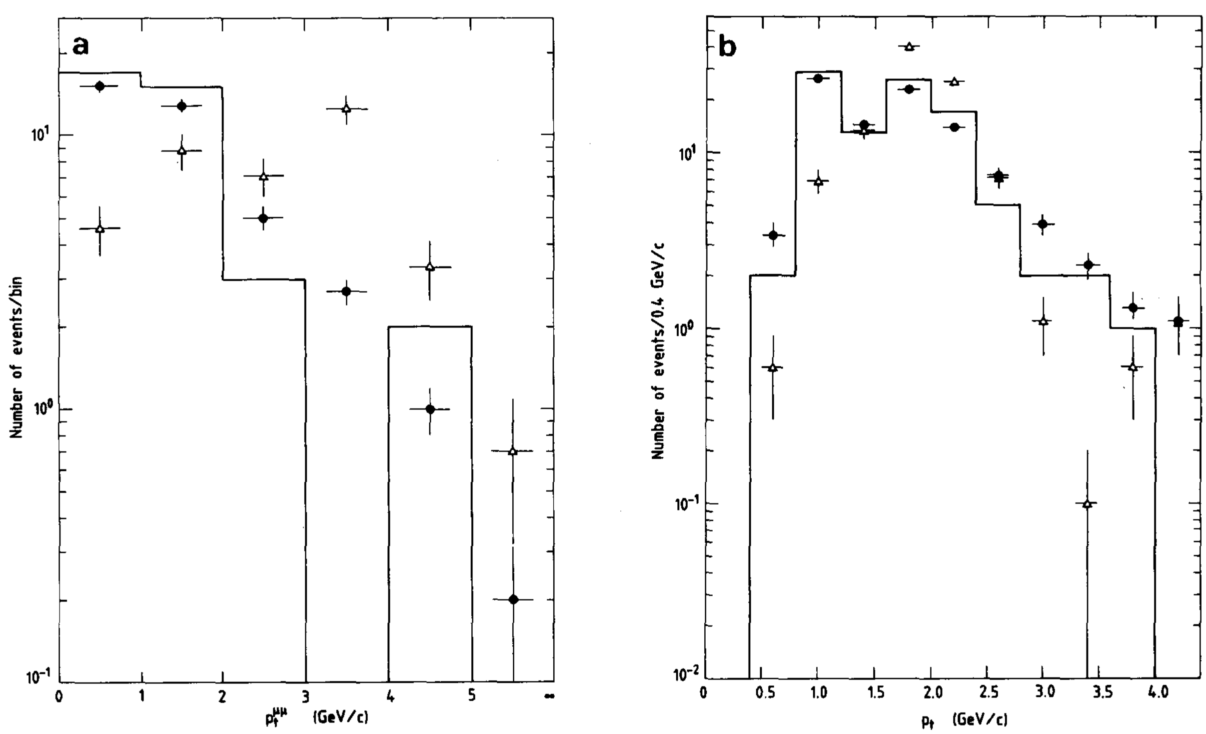

Fig. 2. (a) Transverse momentum distribution of dimuons outside the J/ψ "window" [data (continuous line), background (circles) and Monte Carlo (open triangles)]. The dimuons were selected by taking, from the two like-sign muons, that with higher p_T. The simulated distributions are normalized to the data events. (b) Transverse momentum distribution (normalized to data) of the "lone" muons for events within the J/ψ "window", for data (continuous line), background (circles), and Monte Carlo (open triangles). The "lone" muon is the one not belonging to the J/ψ dimuon.

data, and the Monte Carlo events (correlated model); the latter are normalized to the real data. A clear difference can be seen between the simulated background, which essentially reproduces the p_T spectrum of true dimuons, and the Monte Carlo events, where a muon from a B decay is associated either with the muon from the subsequent D decay or with the muon from the associated $\bar{B}$ decay. Hence the variable $p_T^{\mu\mu}$ is used to estimate the cross section as described below.

We make the hypothesis that the data sample in fig. 2a is described by a combination of a fraction f of $B\bar{B}$-originated events and $(1-f)$ time-accidental background. To estimate f, the logarithm of the likelihood function

$$\ln(\mathcal{L}) = \sum_i \ln\,[\exp(-D_i) D_i^{\mathrm{DA}_i}/\mathrm{DA}_i!]\ ,$$

was used. Here $D_i = f\mathrm{MC}_i + (1-f)\mathrm{BG}_i$; MC_i, BG_i, DA_i are the contents of the ith bins of the Monte Carlo, background, and data $p_T^{\mu\mu}$ distribution, respectively.

By using a standard maximum likelihood procedure, we obtained for f the upper limit of 0.02 at 95% CL. The uncertainty from the statistics of the Monte Carlo simulated $B\bar{B}$ events and background events was taken into account by introducing the corresponding fluctuations into the above procedure. Combined with the acceptance and the branching ratio for the (correlated) model, as well as with the integrated luminosity, this yields an upper limit of 1.5 nb per nucleon for $B\bar{B}$ production at 95% CL, assuming a detection efficiency of 90% and a 10% overall normalization error. A linear dependence of the cross section on the atomic number has also been assumed. With the uncorrelated production model, the less sensitive upper limit of 7.5 nb per nucleon at 95% CL is obtained (corresponding to $f < 0.17$).

For subsample (ii), i.e. the events in the J/ψ "window" (see fig. 1), it is more efficient to extract the cross section limit by considering the p_T distribution of the "lone" muons, i.e. those not belonging to J/ψ pairs. Fig. 2b shows such a distribution for those events (97) for which a single combination yields a mass within the "window", i.e. that class of events for which the acceptance given in section 4 is pertinent. The distribution for simulated (Monte Carlo) events, also given in fig. 2b, was computed on the basis of the correlated model. By means of a statistical analysis analogous to the one used for subsample (i), one obtains for f an upper limit of 0.38 at 95% CL, which corresponds to a cross section for $B\bar{B}$ production of $\leqslant 19$ nb per nucleon.

We next compare our results with those obtained by Badier et al. [5] at a different energy. In deducing their limits, these authors evaluated the acceptances assuming a decay of the B meson into a muon and an object of mass $M_X = 2.2\ \mathrm{GeV}/c^2$, i.e. a two-body decay [21]. If we also adopt this decay scheme in the simulation program, we obtain, for the events which do not fall within the J/ψ "window", an acceptance of $(3.5 \pm 0.1) \times 10^{-3}$. This implies that, even in the limit where the entire sample of 37 events would be attributed to signal, we would obtain for $B\bar{B}$ production an upper limit of 0.4 nb/nucleon at 90% CL, which is about 6 times lower than the one quoted in ref. [5]. However, the two-body model cannot be considered as realistic, not even as an approximation to $b \to c\mu\nu$. The latter decay, computed for the V – A current [13], is found [22] to be in good agreement with experimental data; also, when introduced in our Monte Carlo, it reproduces the measured physical distributions [17].

6. Conclusions. We have studied the production of trimuon events by 194 GeV/c π^- on tungsten, obtaining model-dependent upper limits on the production cross section of a pair of beauty-flavoured mesons. From that subsample of events for which no opposite-sign dimuon combination yields a mass corresponding to the J/ψ, we obtain, assuming a correlated central production mechanism, $\sigma(B\bar{B}) < 1.5$ nb per nucleon at 95% CL. From the subsample of events involving unambiguous J/ψ signals we obtain a weaker limit, namely 19 nb per nucleon at 95% CL.

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