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EXPERIMENTAL STUDY OF $B\bar{B}$ PRODUCTION IN π^-U INTERACTIONS AT 320 GeV ENERGY

WA78 Collaboration

M.G. Catanesi, M.T. Muciaccia, S. Natali, S. Nuzzo and F. Ruggieri
Università di Bari and INFN, Bari, Italy

H. Cobbaert and R. Roosen
Inter-University Institute for High Energies, ULB-VUB, Brussels, Belgium

G. Crosetti[1], M. Fidecaro, G. Poulard and H. Sletten
CERN, Geneva, Switzerland

M. Coupland, I.G. Roberts and P.T. Trent
Birkbeck College, London, United Kingdom

J.H. Bartley, J.E. Conboy, M.J. Esten, P. Fennel, P.F. Harrison[2],
F.F. Heymann and D.C. Imrie[3]
University College London, United Kingdom

M. De Vincenzi, S. Di Liberto, A. Frenkel, M. Iori, E. Lamanna, G. Marini,
G. Martellotti, A. Nigro, A. Parisi, G. Penso, S. Petrera, E. Petrolo,
P. Pistilli[4], G. Romano, G. Rosa and A. Sciubba
Università di Roma 'La Sapienza' and INFN, Rome, Italy

B. Alessandro, W. Alpe, V. Bisi, D. Gamba, L. Ramello and L. Riccati
Università di Torino and INFN, Turin, Italy

ABSTRACT

A sample of 29 $\mu^+\mu^+$ and 35 $\mu^-\mu^-$ coming from $B\bar{B}$ decay have been observed in π^-U interactions at 320 GeV energy. The experimental distributions and the total cross-section are found to be in good agreement with QCD predictions. The effect of $B^0\bar{B}^0$ mixing is discussed.

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1 Now at INFN, Genoa, Italy.
2 Now at University of Liverpool, United Kingdom.
3 Now at Brunel University, London, United Kingdom.
4 Now at Università di Lecce and INFN, Lecce, Italy.

The production of heavy quarks in hadronic interactions is considered to be an important test of QCD. While a comparison of theoretical and experimental results for charm [1] shows poor agreement, beauty hadroproduction is expected to be well described in terms of leading-order QCD perturbation theory [2], owing to the larger b-quark mass.

The first evidence of $B\bar{B}$ hadroproduction in a fixed-target experiment was the observation of a single event identified in a nuclear emulsion target exposed to a 350 GeV energy π^- beam at CERN [3]. At ISR energy a signal of beauty baryon production has been presented by the CERN–Bologna Collaboration [4]. More recently, evidence of beauty hadroproduction has been obtained at CERN by the UA1 Collaboration [5] at the $p\bar{p}$ Collider, by NA10 [6], and by the WA78 Collaboration in π^-U interactions at 320 GeV/c [7].

In a previous paper [7] we reported on a study of $B\bar{B}$ hadroproduction using a sample of 13 events of the type:

$$\pi^- N \rightarrow 3\mu + X .$$

In the present paper we discuss further results on $B\bar{B}$ hadroproduction obtained from the study of the channels

$$\pi^- N \rightarrow \mu^\pm \mu^\pm + X ,$$

resulting from the $B\bar{B}$ semileptonic decay chain:

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

These events are characterized by the large transverse momentum of the muons (p_t) produced by B decays as well as by the large 'missing energy' associated with escaping neutrinos.

The WA78 apparatus [8] comprised a dump calorimeter followed by a magnetic spectrometer to provide the muon energy (E_μ). The missing energy (E_{miss}) was obtained by comparing the beam energy (E_{beam}) with the total energy of outgoing muons (ΣE_μ) and the hadronic energy measured in the dump calorimeter (E_{cal}):

$$E_{miss} = E_{beam} - E_{cal} - \Sigma E_\mu .$$

The calorimeter, which consisted of a uranium/scintillator sandwich, was constructed so that it could be expanded easily in order to vary its mean density (ϱ). This facility was used to measure directly the non-prompt muon background by the $1/\varrho$ extrapolation method.

The standard trigger was realized at two levels. The first-level trigger was obtained with a system of hodoscope counters requiring at least two muons in the spectrometer. The second-level trigger used a hardware processor to perform on-line selection of those events having a calorimeter energy below a threshold normally set at 280 GeV. With this trigger, 2.2×10^7 events were recorded on tape corresponding to 5.5×10^{11} effective interactions in the dump.

After the off-line muon reconstruction requiring at least two muons with $E_\mu > 15$ GeV and 80 GeV $< E_{cal} <$ 260 GeV, the following statistics of events were obtained:

$$N(\mu^+\mu^-) \approx 3.5 \times 10^6$$
$$N(\mu^+\mu^+) = 8193$$
$$N(\mu^-\mu^-) = 15539$$
$$N(\geqslant 3\mu) = 5589 .$$

The $\mu^\pm\mu^\pm$ sample has been analysed similarly to the trimuon sample [7]. The total of 8193 $\mu^+\mu^+$ (15539 $\mu^-\mu^-$) was reduced to 2685 (6847) events by applying appropriate cuts on the hit multiplicity in the counter hodoscopes to reject punch-through events and upstream interactions. All remaining events were displayed and examined, and badly reconstructed events were rejected. This reduced the sample to 2157 (3744) clean $\mu^+\mu^+$ ($\mu^-\mu^-$) events.

The background in the like-sign two-muon sample is mainly due to the coincidence of a 'non-prompt' muon with either a single muon from D decay or a Drell–Yan ($\mu^+\mu^-$) pair where one muon was not detected in the spectrometer.

A sample of background pseudoevents was generated by combining the experimental single-muon events taken in special runs with a second muon extracted from the 'non-prompt' muon distribution obtained by the $1/\varrho$ extrapolation method.

The mean momentum and mean transverse momentum of the like-sign muons from a $B\bar{B}$ decay are expected to be larger than those for background muons. The missing energy due to the escaping neutrinos is also expected to be higher for the $B\bar{B}$ events.

To enhance the signal-to-noise ratio in the sample combined cuts were applied to the sum of transverse momenta $p_{t_{tot}}(\Sigma p_{t_i})$, E_{miss}, and E_{lept} ($E_{lept} = E_{miss} + \Sigma E_\mu$). Requiring $p_{t_{tot}} > 2.7$ GeV/c, $E_{miss} > 20$ GeV, and $E_{lept} > 100$ GeV, 35 $\mu^+\mu^+$ and 49 $\mu^-\mu^-$ remained; the contribution estimated from the background pseudoevent sample is 6 $\mu^+\mu^+$ and 14 $\mu^-\mu^-$.

There is evidence from experiment WA75 [9] for processes with 4 charmed quarks in the final state $\psi\psi$, $\psi D\bar{D}$, and $D\bar{D}D\bar{D}$, which can also give rise to like-sign dimuons. A separate analysis of these processes is in progress; however, we consider that they do not form a significant background in the region selected by our kinematic cuts.

After background subtraction 29 $\mu^+\mu^+$ and 35 $\mu^-\mu^-$ events remain; the distributions of these like-sign events and of the 13 events of the selected 3-μ sample are compared with the QCD predictions [10] for $B\bar{B}$ production in πU interactions.

The x_F, p_t behaviour of the b quark given by QCD is represented by expression (1), where the shift of the x_F distribution towards positive values reflects the difference in quark and gluon x distributions for pions and nucleons:

$$d^2\sigma/dx_F\,dp_t^2 \propto \exp\,[-(x_F - 0.05)^2/A_\pi^2]\,\exp\,(-p_t^2/B) \qquad (1)$$

[$A_\pi \approx 0.30$, $B \approx 6.9\,(\mathrm{GeV/c})^2$].

Correlations between the two particles as predicted by QCD [11] have been taken into account. Smearing due to the b-quark fragmentation into physical particles and the semileptonic B and D decay have been folded with eq. (1). We have included a 20% probability of a B^0 ($\bar{B}^0$) decaying as $\bar{B}^0$ (B^0), as observed by the UA1 [12] and ARGUS [13] Collaborations, and assumed that charged and neutral B mesons are produced in equal numbers*). We then obtain a better agreement (fig. 1), in the like-sign sample, between Monte Carlo predictions and experimental data, particularly in the distribution of $p_{t_{min}}$ [$p_{t_{min}} = \min(p_{t_1}, p_{t_2})$], the variable most sensitive to the amount of mixing.

Figure 2 shows the experimental distributions of the total leptonic energy E_{lept} and fig. 3 the $p_{t_{max}}$ [$p_{t_{max}} = \max(p_{t_i})$] distribution for the 3-μ and $\mu^\pm\mu^\pm$ events compared with the QCD predictions. We obtain good agreement between the data and predictions for all variables of interest.

To compute the total cross-section the acceptance has been evaluated using the QCD prediction for $B\bar{B}$ production including the correlation between the two particles. The absolute normalization has been determined using a sample of reconstructed ψ events [7]. The following values for the branching ratio have been taken:

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*) In our case, the neutral B state is an unknown mixture of B_d^0 and B_s^0.

$$\mathrm{BR}(B \to \mu + X) = 11.0\%$$
$$\mathrm{BR}(D \to \mu + X) = 12.6\%$$
$$\mathrm{BR}(B \to D) = 100\% \,.$$

To derive a cross-section per nucleon from the observed values on uranium we have assumed a linear dependence on atomic number. With these assumptions the total cross-sections computed separately for the $\mu^-\mu^-$, $\mu^+\mu^+$, and 3-μ samples are

$$\sigma_{\mu^-\mu^-} = (2.55 \pm 0.6)\ \text{nb per nucleon}$$
$$\sigma_{\mu^+\mu^+} = (2.1 \pm 0.5)\ \text{nb per nucleon}$$
$$\sigma_{3\mu} = (1.6 \pm 0.5)\ \text{nb per nucleon}\,,$$

where the quoted errors are statistical ones only.

The present value of $\sigma_{3\mu}$ is smaller than that given in ref. [7] owing to the different production mechanism used to compute the acceptance. There it was assumed that each B was produced without any dynamical correlation, and according to the following form,

$$d^2\sigma/dx_F\,dp_t^2 \propto (1 - x_F)^\alpha\, e^{-\beta p_t{}^2}\,, \tag{2}$$

a total cross-section $\sigma_{B\bar{B}} = (4.5 \pm 1.4 \pm 1.4)$ nb per nucleon was obtained for $\alpha = 2.5$ and $\beta = 0.9\ (\mathrm{GeV}/c)^{-2}$. Expression (1) leads to a larger acceptance of the apparatus because of the asymmetric x_F distribution.

The systematic error is mainly due to uncertainty in the absolute normalization and in the acceptance of the apparatus. These effects factorize in the three channels and the other systematic errors for each channel have been estimated to be smaller than the corresponding statistical errors; therefore combining the three values we obtain

$$\sigma = (2.0 \pm 0.3 \pm 0.9)\ \text{nb per nucleon}\,,$$

the first error being statistical and the second one systematic. Uncertainties from B and D semileptonic branching ratios have not been taken into account.

We find that the cross-section calculated using like-sign dimuons is quite sensitive to the amount of $B\bar{B}$ mixing, because the acceptance for muons from semileptonic B decay is several times larger (after our kinematic cuts) than the acceptance for muons from D decay. In the three-muon channel most events include two muons from B-meson decay and so the cross-section is nearly independent of the amount of mixing. The variation of the like-sign cross-section with probability P, defined by

$$P = \Gamma(B^0 \to \bar{B}^0 \to X)/\Gamma(B^0 \to X) \tag{3}$$

is shown in fig. 4.

The experimental value of the total cross-section is in good agreement with QCD [10], which leads to a predicted value between ~ 1 and ~ 3 nb per nucleon. Similar conclusions have been arrived at by the UA1 Collaboration at $\sqrt{s} = 630$ GeV.

We conclude that within experimental and theoretical uncertainties the QCD predictions describe the main features of the $B\bar{B}$ hadroproduction over a very wide interval of c.m. energy.

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Figure captions

Fig. 1 The $p_{t_{min}}$ distributions, after background subtraction, for like-sign events, selected by the cuts discussed in the text. The lines represent the QCD predictions with (solid line) and without (dotted line) mixing effects.

Fig. 2 The E_{lept} distributions, after background subtraction, for (a) the $\mu^-\mu^-$, (b) the $\mu^+\mu^+$, and (c) the 3-μ samples, selected by the cuts discussed in the text. Continuous lines represent the QCD predictions.

Fig. 3 The $p_{t_{max}}$ distributions, after background subtraction, for (a) the $\mu^-\mu^-$, (b) the $\mu^+\mu^+$, and (c) the 3-μ samples, selected by the cuts discussed in the text. Continuous lines represent the QCD predictions.

Fig. 4 Variation of the like-sign dimuon $B\bar{B}$ cross-section with P, the probability of B^0–$\bar{B}^0$ mixing, defined in eq. (3). The shaded areas correspond to a one standard deviation interval about the three-muon (dotted line) and like-sign dimuon (solid line) values. The result quoted in the text is also shown. Only statistical errors are represented.

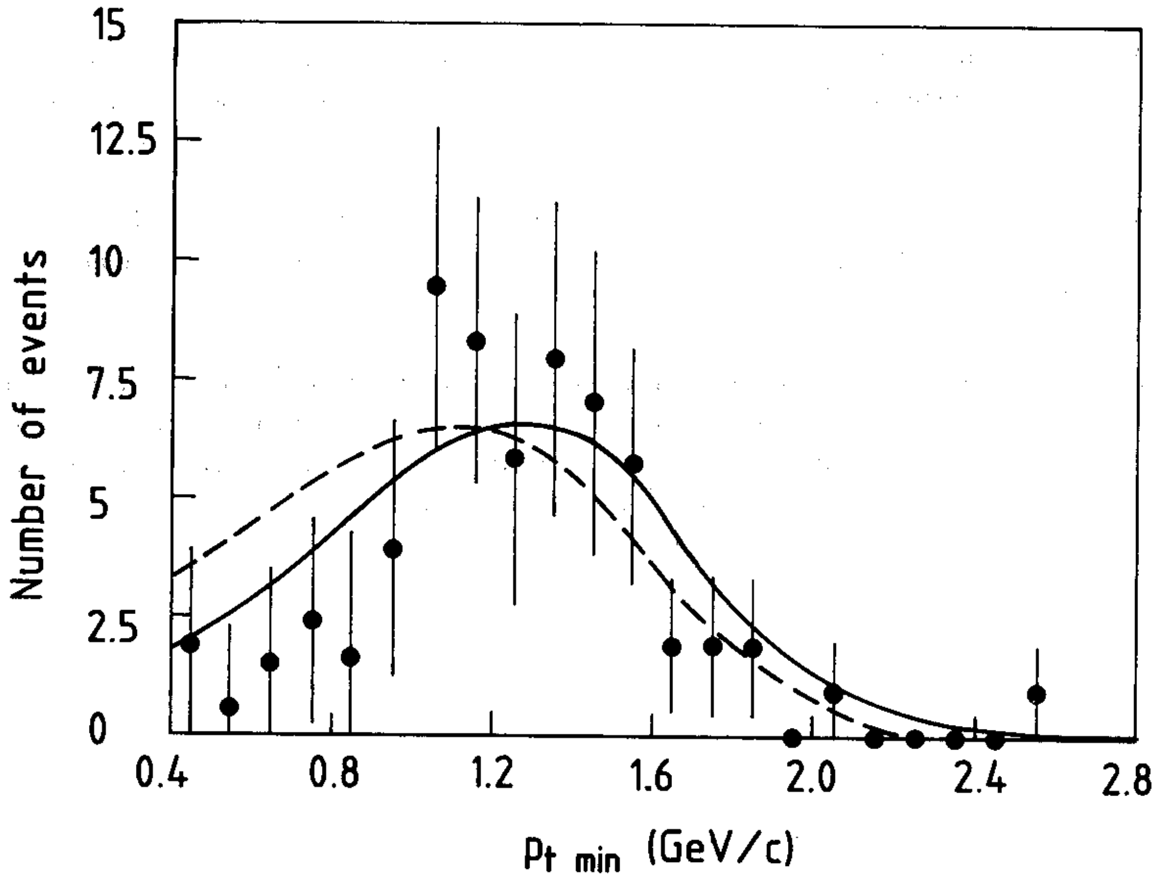
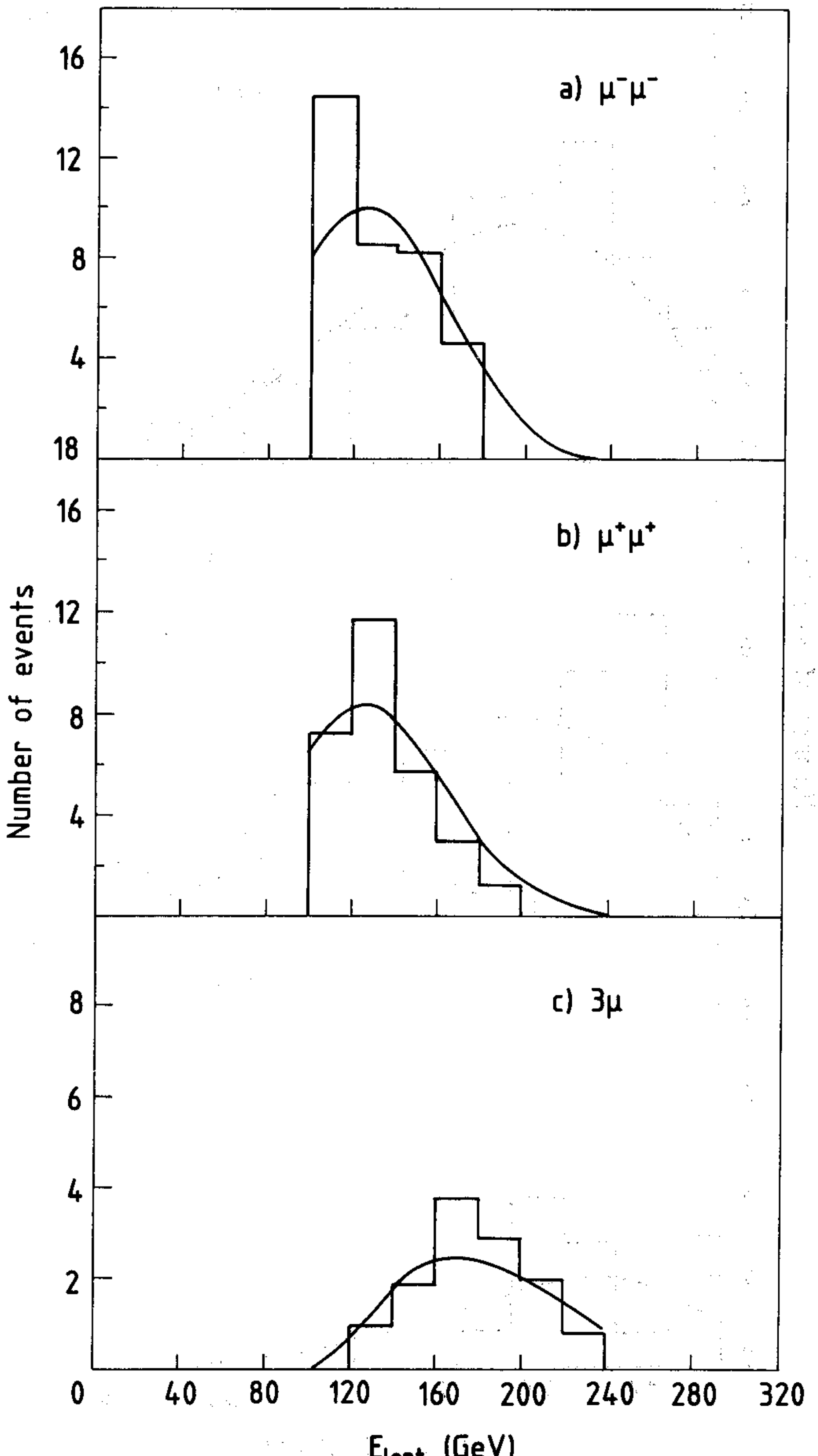
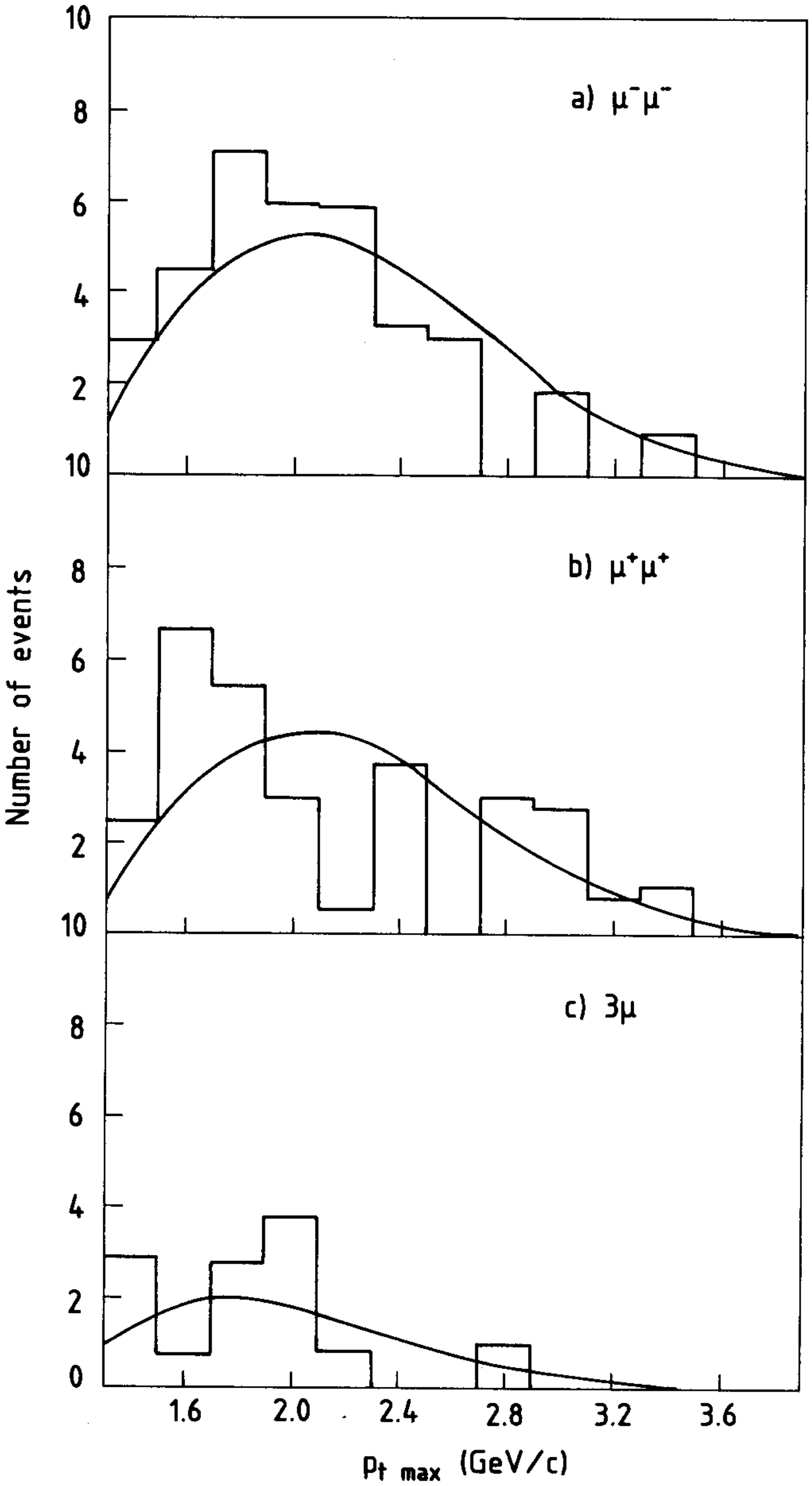

15
12.5
10
7.5
5
2.5
0
Number of events
0.4
0.8
1.2
1.6
2.0
2.4
2.8
$p_{t\ min}$ (GeV/c)

Fig. 1



a) μ⁻μ⁻
b) μ⁺μ⁺
c) 3μ
Number of events
16
12
8
4
18
16
12
8
4
8
6
4
2
0
40
80
120
160
200
240
280
320
E_lept (GeV)

Fig. 2



a) μ⁻μ⁻
b) μ⁺μ⁺
c) 3μ
Number of events
10
8
6
4
2
0
1.6
2.0
2.4
2.8
3.2
3.6
pt max (GeV/c)

Fig. 3

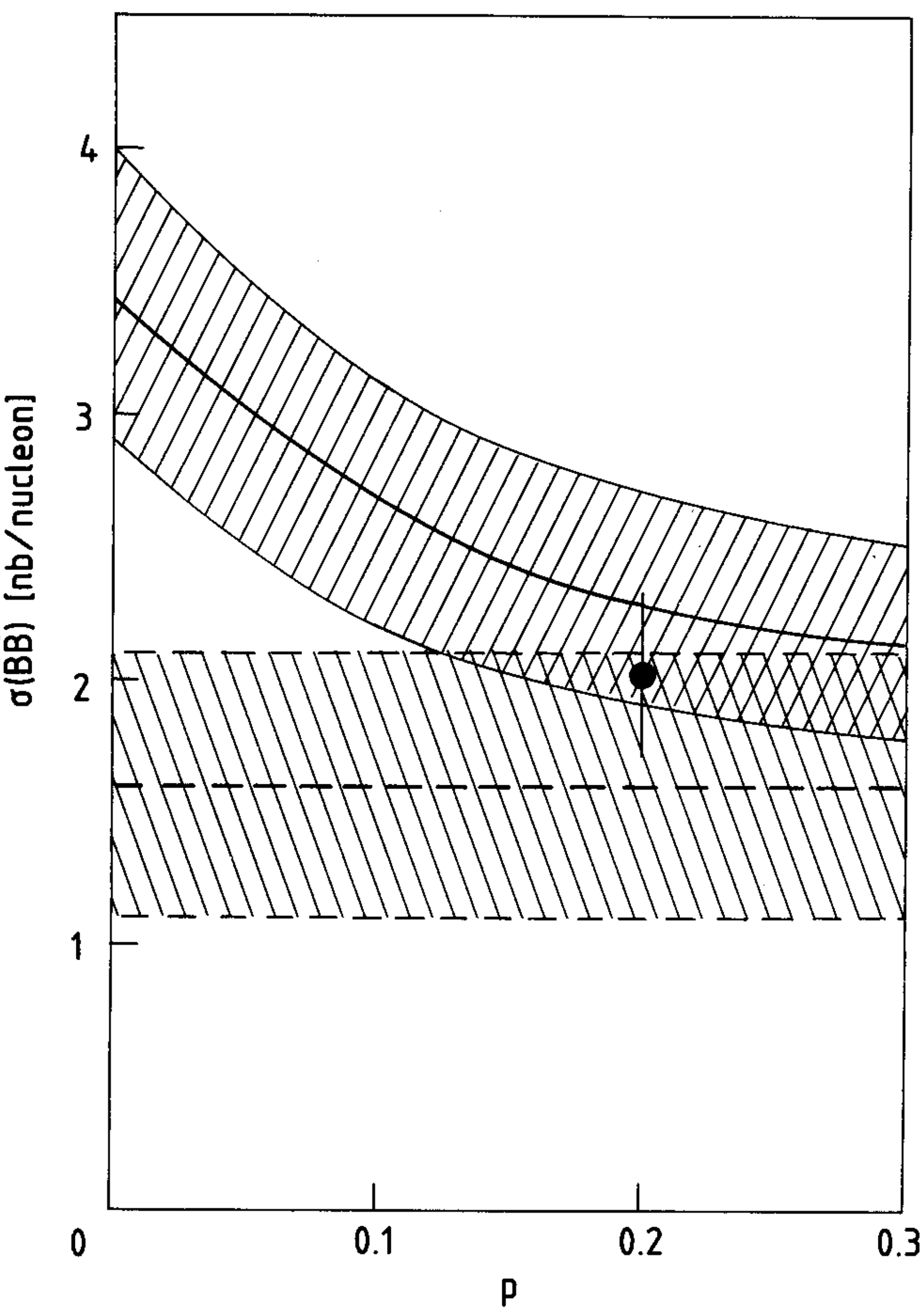


Fig. 4