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Bottom Production in π^--Be Collisions at 515 GeV/c

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We report on a sample of J/ψ mesons coming from secondary vertices, a characteristic of heavy-quark decay, detected in the Fermilab Meson West spectrometer. Based upon 8 signal events in which a J/ψ emerges from a secondary vertex occurring in an air-gap region, we obtain an inclusive $b\bar{b}$ cross section of $(75 \pm 31 \pm 26)$ nb/nucleon. This result is compared to recent QCD predictions. We have also observed several events in the exclusive decay modes $B^{\pm} \rightarrow J/\psi + K^{\pm}$ and $B^0 \rightarrow J/\psi + K^{0*}$ in which the B mass is fully reconstructed.

Next-to-leading-order (NLO) calculations for the production of heavy quarks have become available during the past few years [1,2,3]. Recent collider data have shown that these predictions underestimate bottom production [4]. The calculations require the convolution of hard-scattering cross sections with parton distribution functions, and uncertainties result from the choice of gluon distribution functions, scale factors, and b-quark mass. Calculations by Berger [2] and by Mangano, Nason, and Ridolfi (MNR) [3] also provide predictions at fixed-target energies. Consequently, our measurement of the $b\bar{b}$ cross section for 515 GeV/c incident pions provides an opportunity to test these NLO QCD calculations.

In this paper, we report on a measurement of the cross section for $\pi^- + \mathrm{Be} \rightarrow b + X$, with $b \rightarrow J/\psi + X$ and $J/\psi \rightarrow \mu^+\mu^-$. $b \rightarrow J/\psi + X$ decays are uniquely tagged by $J/\psi s$ emerging from secondary vertices. Although the branching ratio into J/ψ is small (1.3%) [5], this decay is advantageous since the resulting dimuons provide a clean trigger and signal. A significant background to secondary-vertex $J/\psi s$ from b decays is, however, produced by events in which a high-momentum particle from the primary collision interacts further downstream in the target and produces a J/ψ (secondary interactions).

The experiment was carried out in the Fermilab Meson West beamline using a large-aperture, open-geometry spectrometer with the capability of studying high-mass muon pairs. The muon detector, located 20 m downstream of the target, consisted of two muon PWC stations, a beam dump, a toroid magnet with an average p_T impulse of 1.3 GeV/c, four more muon PWC stations separated by iron and concrete shielding, and two muon hodoscopes [6]. The upstream part of the spectrometer consisted of 16-planes of silicon-strip detectors (SSDs), a dipole magnet with a p_T impulse of 0.45 GeV/c, 16 planes of PWCs and 16 planes of straw drift tubes, a liquid-argon calorimeter with electromagnetic and hadronic sections, and a forward calorimeter [7]. Dimuon pretriggers required coincidences between interaction counter and muon hodoscope signals. A fast (10 μs) processor was used to trigger on the effective mass of track combinations in the muon PWCs. Data were collected during the 1990 Fermilab fixed-target run with a 515 GeV/c π^- beam incident on beryllium and copper targets. Approximately 5×10^6 dimuon triggers were recorded (corresponding to a luminosity of 8 pb^{-1} per nucleon), yielding 7×10^5 events with a reconstructed dimuon combination originating from the target region.

A fit was performed to link muon tracks through the entire detector. This fit included multiple-scattering considerations and a consistency requirement for the track momentum as measured via the dipole magnet and by the toroid. Only events with at least two fully-linked muons were kept. The remaining segments in the SSDs and upstream PWCs were used to find the hadronic tracks and event vertices. Figure 1 shows the reconstructed opposite-sign dimuon invariant-mass distribution in the J/ψ region. A fit to this data yields $12{,}640\pm150$ $J/\psi s$ with a mass resolution of 68 MeV/c^2, and 387 ± 79 $\psi(2S)s$. The measured J/ψ mass is (3.097 ± 0.001) GeV/c^2, and that of the $\psi(2S)$ is (3.67 ± 0.01) GeV/c^2.

To increase the efficiency and precision for finding a secondary vertex, the origin of the J/ψ was found by a muon-oriented vertex refitting procedure. First, opposite-sign muon pairs were selected in the reconstructed mass range 2.85 GeV/c^2 $< M_{\mu\mu} <$ 3.35 GeV/c^2. Pairs with consistent intersections in the x-z and y-z planes were then fit with simultaneous vertex and J/ψ mass constraints. The resulting vertex served as a seed for an iterative vertex-fitting procedure which associated other tracks to this vertex. Only SSD-PWC linked tracks with transverse impact parameter within 1.5 standard deviations of the J/ψ vertex seed position were used in the fit. This procedure increased the secondary J/ψ vertex finding efficiency by 26% over the initial vertex finding. The average vertex resolution was 14 μm and 350 μm in the transverse and longitudinal directions, respectively [8]. The reconstructed J/ψ vertex z-position distribution for these events is shown in Fig. 2a.

This sample was searched for events in which the dimuon vertex was downstream of the primary vertex, yielding 857 events. To clean the sample, several cuts were applied. Only events with at least three fully reconstructed tracks from the primary were kept, yielding 631 events. Fiducial-volume cuts for both primary and secondary vertices passed 577 events. A significance greater than 3 was required for both the longitudinal and transverse separation between the primary and secondary vertices, with significance defined as the separation divided by the combined vertex uncertainty. An absolute longitudinal separation of 2.5 mm was required, leaving 121 events. Secondary J/ψ vertices with more than four associated hadrons were discarded to reduce the background from secondary interactions; 73 events passed this cut. The primary- and secondary-vertex z-position distributions for these events are shown in Figs. 2b and 2c, respectively. In several events, the secondary J/ψ vertex occurs in an air gap region; the background from secondary interactions is negligible for such events. The positions in the y-z plane of the J/ψ vertices in these gaps are shown in Fig. 3 (with z error bars). In ten events, the J/ψ vertex is at least three standard deviations away from the Be target elements.

The background to this signal from false vertex reconstruction was estimated using Monte Carlo simulations, and by searching the data sample for reconstructed J/ψ vertices upstream of the primary vertex and for dimuons from secondary vertices with invariant mass in the J/ψ side bands. The resulting background to the secondary-vertex J/ψ sample was found to be 11 ± 2 events, with 2 ± 1 events occurring in the gap regions. From these considerations, we obtain a background subtracted signal (attributed to b-decays) of 8 ± 3.3 secondary-vertex J/ψ events in which the secondary vertex occurs in a region where only air is present.

The total number of J/ψs from b decays in the fiducial volume can be estimated from the number observed in the gaps. Monte Carlo studies indicate that $(37 \pm 5)\%$ of the reconstructed vertices from bs produced in Be occur in the gap regions. Thus, 22 ± 10 $b \rightarrow J/\psi + X$ events are expected from Be, with an additional 4 events expected from Cu. Although the requirement of low secondary multiplicity certainly improves the likelihood of the J/ψ coming from a b decay, secondary-interaction events remain in the non-gap sample. An analysis using Monte-Carlo generated events indicates that 80 secondary-interaction events pass the J/ψ vertex quality cuts, and 33 also pass the multiplicity cut. This number added to the estimate of b events (22 + 4) and false vertex reconstructions (11) gives a total of 70 events, consistent with the 73 events observed.

We searched this sample of secondary $J/\psi s$ for the exclusive channels $B^{\pm} \rightarrow J/\psi + K^{\pm}$ and $B^0 \rightarrow J/\psi + K^{0*}$. Events with three-prong secondaries (2 muons plus another track) were selected as candidate $B^{\pm} \rightarrow J/\psi + K^{\pm}$ decays. To reduce background, only combinations with a secondary hadron having $p_T > 0.5$ GeV/c were considered. This track was assumed to be a kaon, and its momentum was added to that of the J/ψ to form a candidate B momentum vector. The vector was projected back from the secondary to the primary vertex, and a transverse impact parameter, δ_v, was calculated; only events with $\delta_v < 80$ μm were kept [9]. Since tracks from the underlying event can be coincidentally associated with a secondary vertex, 4-prong secondary vertices were also included in the selection. None of the 4-prong vertex events in the sample had both secondary hadron tracks pass the $p_T > 0.5$ GeV/c cut. The secondary vertices for these events were refit omitting the low p_T track, and the events were analyzed under the hypothesis of 3-prong B decays. Four events survived the above cuts (three having 3-prong secondary vertices, and one with a 4-prong secondary). Two events fell in the B-mass region, one in each charged K mode.

The $K^{0*}s$ were observed by their decays into $K^{\pm}\pi^{\mp}$ pairs. A kinematic criterion was used to reduce combinations: kaon mass was assigned only to tracks with momentum greater than half that of the other track. In the secondary-vertex J/ψ sample, charged track pairs having mass consistent with the K^{0*} were combined with the J/ψ in the same manner as in the $B^{\pm}$ analysis. Momentum vectors of B^0 candidates were required to satisfy $\delta_v < 100$ μm. Five events passed these cuts (none had double $K\pi$ combinations), and three have reconstructed masses in the B-mass region. One of these 3 events occurred in an air gap region.

The combined $J/\psi + K^{\pm}$ and $J/\psi + K^{0*}$ invariant-mass distribution is shown in Fig. 4. The expected B mass resolution is 35 MeV/c^2. There are 5 events near the nominal B-meson mass. A background analysis using primary-vertex events subject to the same cuts as the B-candidate sample shows no evidence for arbitrary enhancement in the B-mass region due to the imposed cuts.

Based upon the background subtracted signal of 8 $b \rightarrow J/\psi + X$ air gap events (and using J/ψ production as normalization), the $b\bar{b}$ cross section is given by

$$\sigma_{b\bar{b}} = \frac{N_{b\rightarrow\psi}}{\varepsilon_{b\rightarrow\psi}\, a_{b\rightarrow\psi}\, 2Br(b\rightarrow\psi\rightarrow\mu^+\mu^-)} \left[\frac{\sigma_\psi\, Br(\psi\rightarrow\mu^+\mu^-)}{A}\, \frac{\varepsilon_\psi a_\psi}{N_\psi} \right], \tag{1}$$

where $\varepsilon_{b\rightarrow\psi}$ and ε_ψ are reconstruction efficiencies, $a_{b\rightarrow\psi}$ and a_ψ are detector acceptances, and A is the target atomic weight. The factor of 2 arises since either the b or the $\bar{b}$ in an event can result in a J/ψ. The branching ratio $Br(b \rightarrow J/\psi + X) = 1.3\%$ [5], and $Br(J/\psi \rightarrow \mu^+\mu^-) = 5.9\%$ [10] give a combined branching ratio of $Br(b \rightarrow J/\psi \rightarrow \mu^+\mu^-) = 7.7\times10^{-4}$, averaged over all b-hadron species, including baryons.

There are $N_\psi = 9800 \pm 130$ reconstructed $J/\psi s$ from the Be target having $x_F(\psi) > 0.1$ in the data sample. The reconstruction efficiency and acceptance for these $J/\psi s$ are $\varepsilon_\psi = 64\%$ and $a_\psi = 43\%$, respectively. A J/ψ cross section (on Be) of $\sigma_\psi \cdot Br(\psi \rightarrow \mu^+\mu^-)/A = (9.2 \pm 1.2)$ nb/nucleon for $x_F(\psi) > 0.1$ was measured by this experiment.

The acceptance and reconstruction efficiency for $b \rightarrow J/\psi + X$ events were calculated using Monte Carlo simulations. Bottom hadron pairs were generated according to the NLO calculations of MNR [3], with hadron momentum taken to be equal to that of the parent quark [11]. One of the b-hadrons in each event was randomly chosen to decay into $J/\psi + X$ with $J/\psi \rightarrow \mu^+\mu^-$. Our apparatus was found to accept only events in which the parent b-quark had $x_F > 0$. We, therefore, measure only the forward part of the $b\bar{b}$ cross section; the overall acceptance in this region is $a_{b\rightarrow\psi} = 19\%$. The reconstruction efficiency for $b \rightarrow J/\psi + X$ events is 39%, combined with a 27% probability of a decay occurring in an air gap region, yields an effective efficiency $\varepsilon_{b\rightarrow\psi} = 15\%$.

Using these values, and $N_{b\to\psi} = 8\pm3.3$, we obtain a bottom hadroproduction cross-section in the forward direction ($x_F > 0$) of $\sigma_{b\bar{b}} = (47\pm19\pm14)$ nb/nucleon (assuming A^1-dependence) for, π^--N collisions at 515 GeV/c, where the first uncertainty is statistical and the second is systematic. The main sources of systematic uncertainty are in the normalization (13%), branching ratios (13%), b production, hadronization, and decay properties (16%), and reconstruction efficiencies (18%). For comparison with theory and other experiments, this measurement is extrapolated from $x_F > 0$ to all values of x_F. Based on x_F distribution predictions by MNR [3], a multiplicative factor of 1.58 is required. Thus, we obtain a total cross section of $\sigma_{b\bar{b}} = (75\pm31\pm26)$ nb/nucleon, where the first uncertainty is statistical and the second is systematic. Extrapolations based on x_F distributions from Berger's predictions [2], and a measurement by Fermilab experiment E653 [12] are reflected in the quoted systematic uncertainty.

A comparison of our measurement to predictions for bottom cross sections in πN collisions made by MNR [3] and Berger [2], and to those of previous experiments [12,13], is shown in Fig. 5. Our measurement favors predictions with smaller b-quark mass values, and renormalization scales that are a smaller fraction of the mass scale. This is consistent with recent analysis of collider bottom-quark data [14].

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Figure Captions

FIG. 1. The invariant mass distribution of $\mu^+\mu^-$ pairs. The solid curve is a fit to the data; the dashed curve shows the background contribution.

FIG. 2. Vertex z coordinate distributions: (a) all refit $J/\psi s$; (b) primary vertex for the 73 events passing the cuts described in the text; (c) secondary J/ψ vertex for these events.

FIG. 3. J/ψ secondary vertex positions in the y-z plane showing events in the gap between target elements.

FIG. 4. Combined $J/\psi + K^{\pm}$ and $J/\psi + K^{0*}$ invariant-mass distribution; the hatched entries are $J/\psi\ K^{\pm}$ combinations.

FIG. 5. Total bottom cross sections in πN collisions, compared with several theoretical predictions. Uncertainties on measurements represent statistical and systematic contributions added in quadrature.

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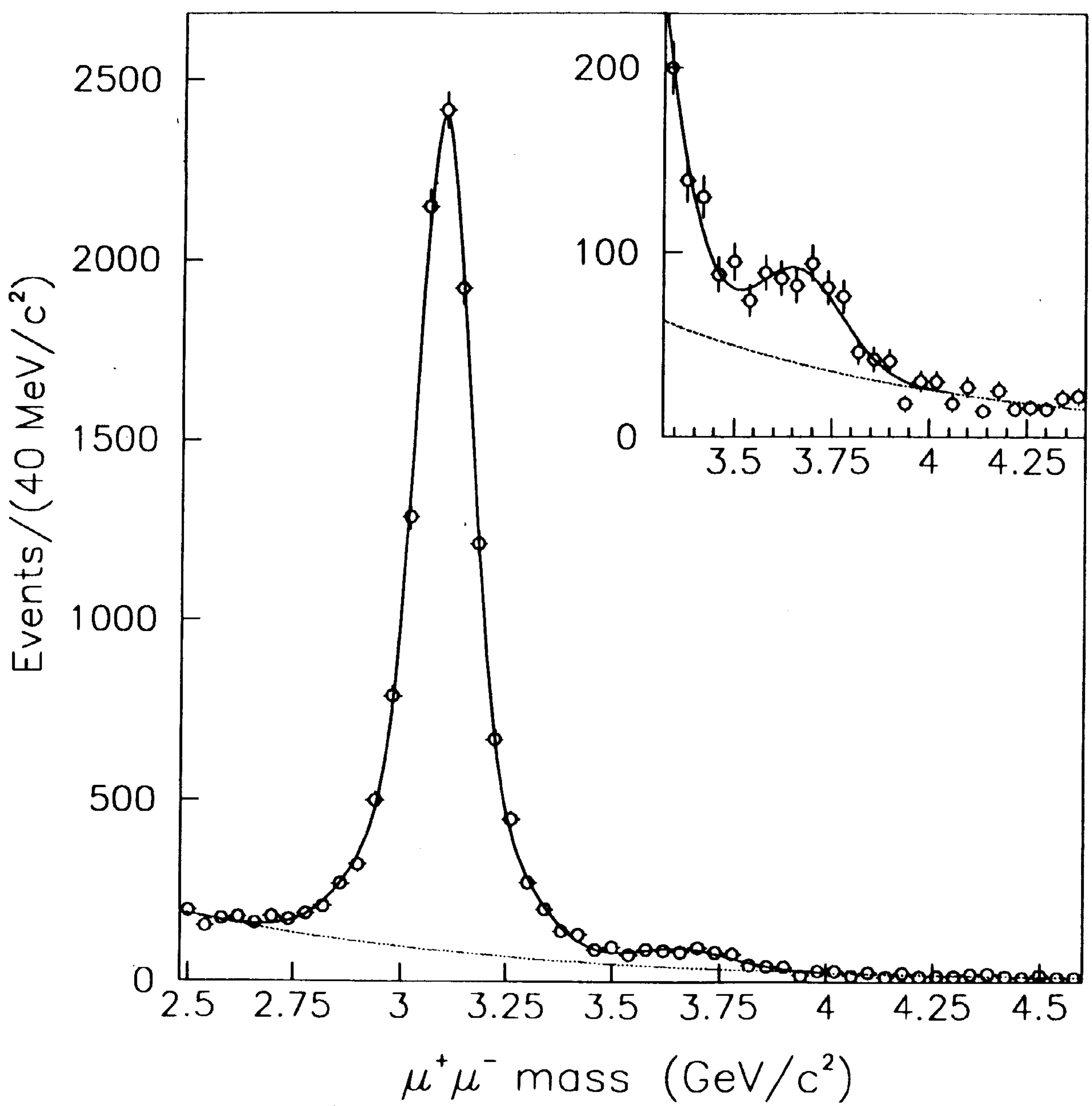
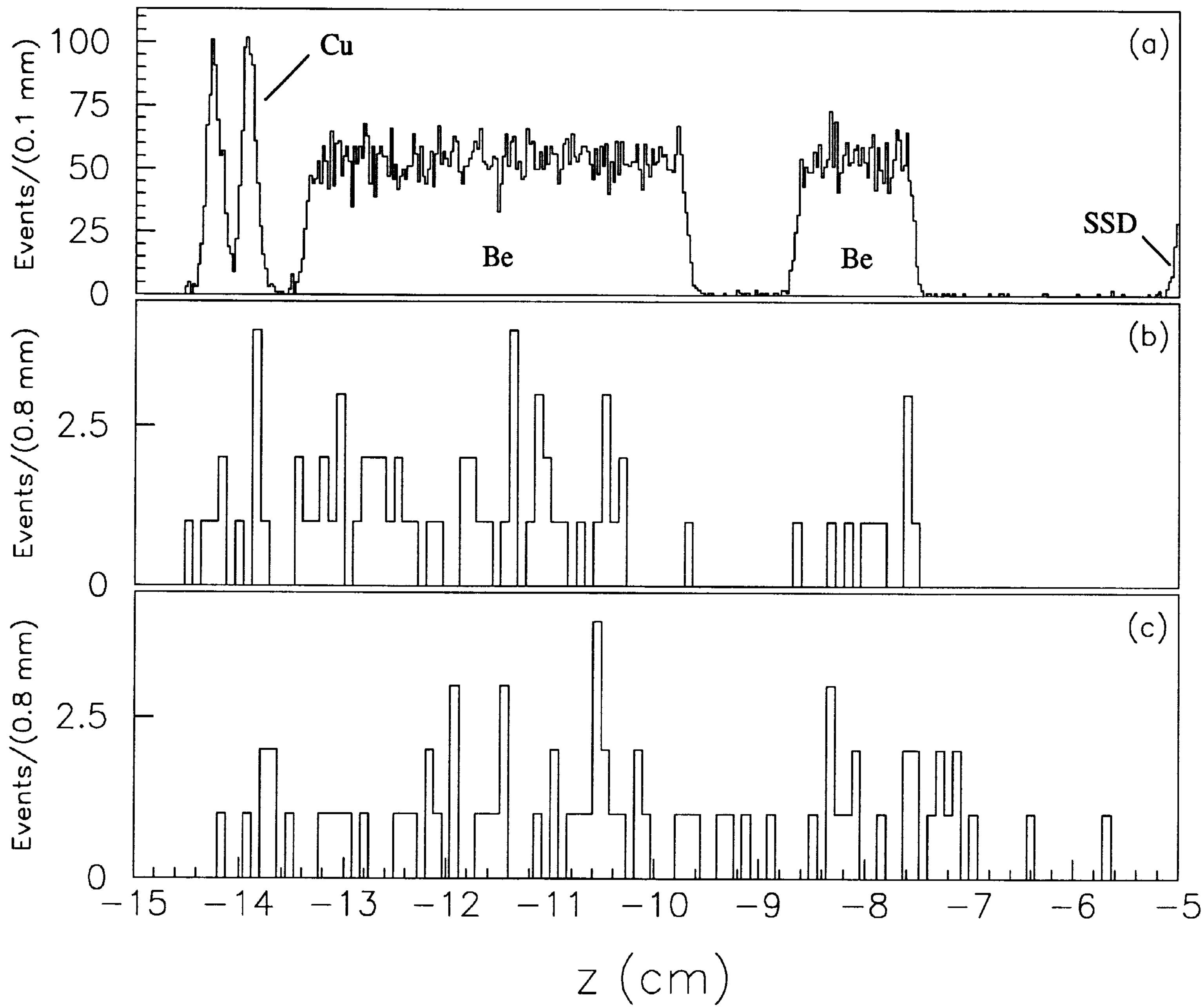
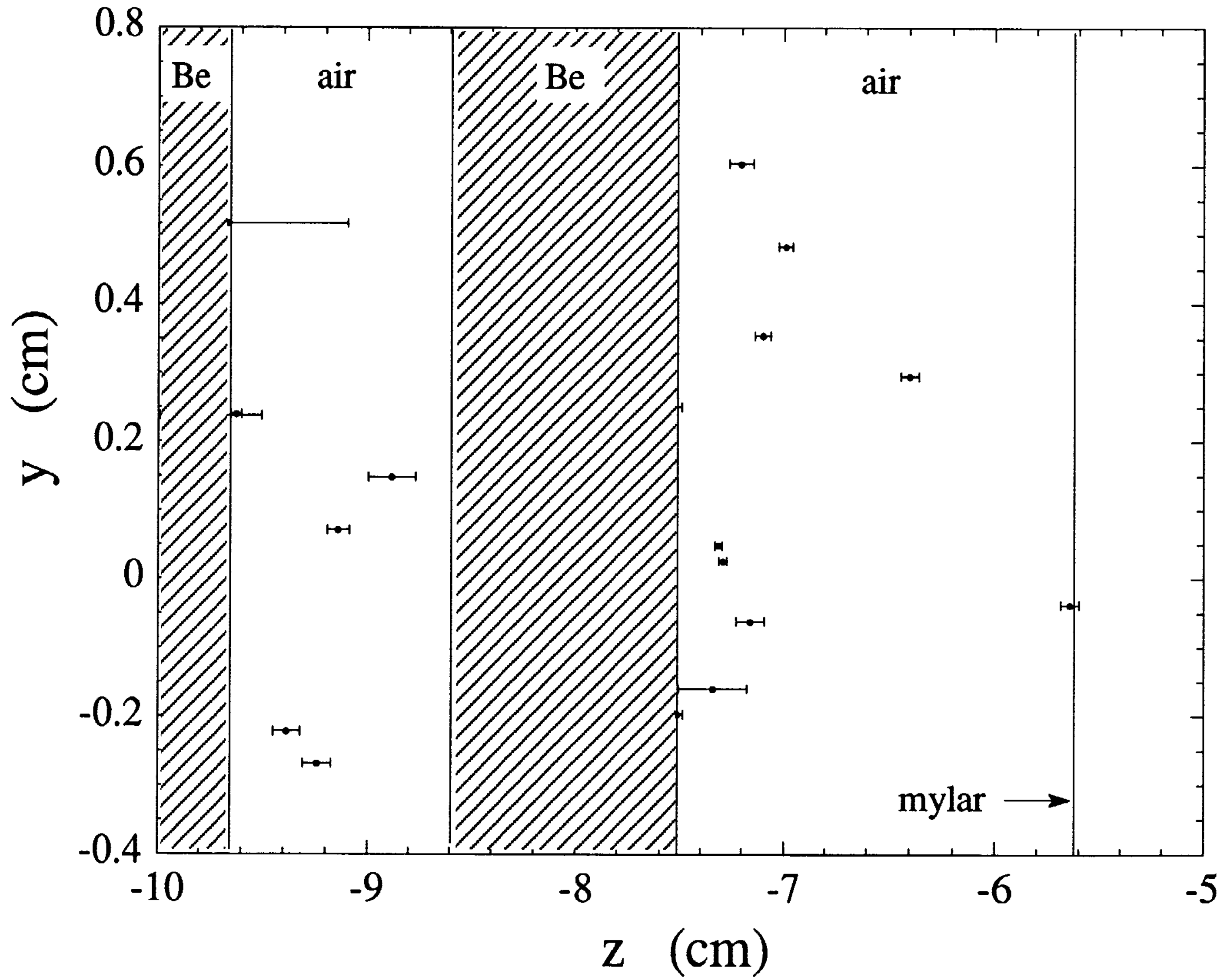
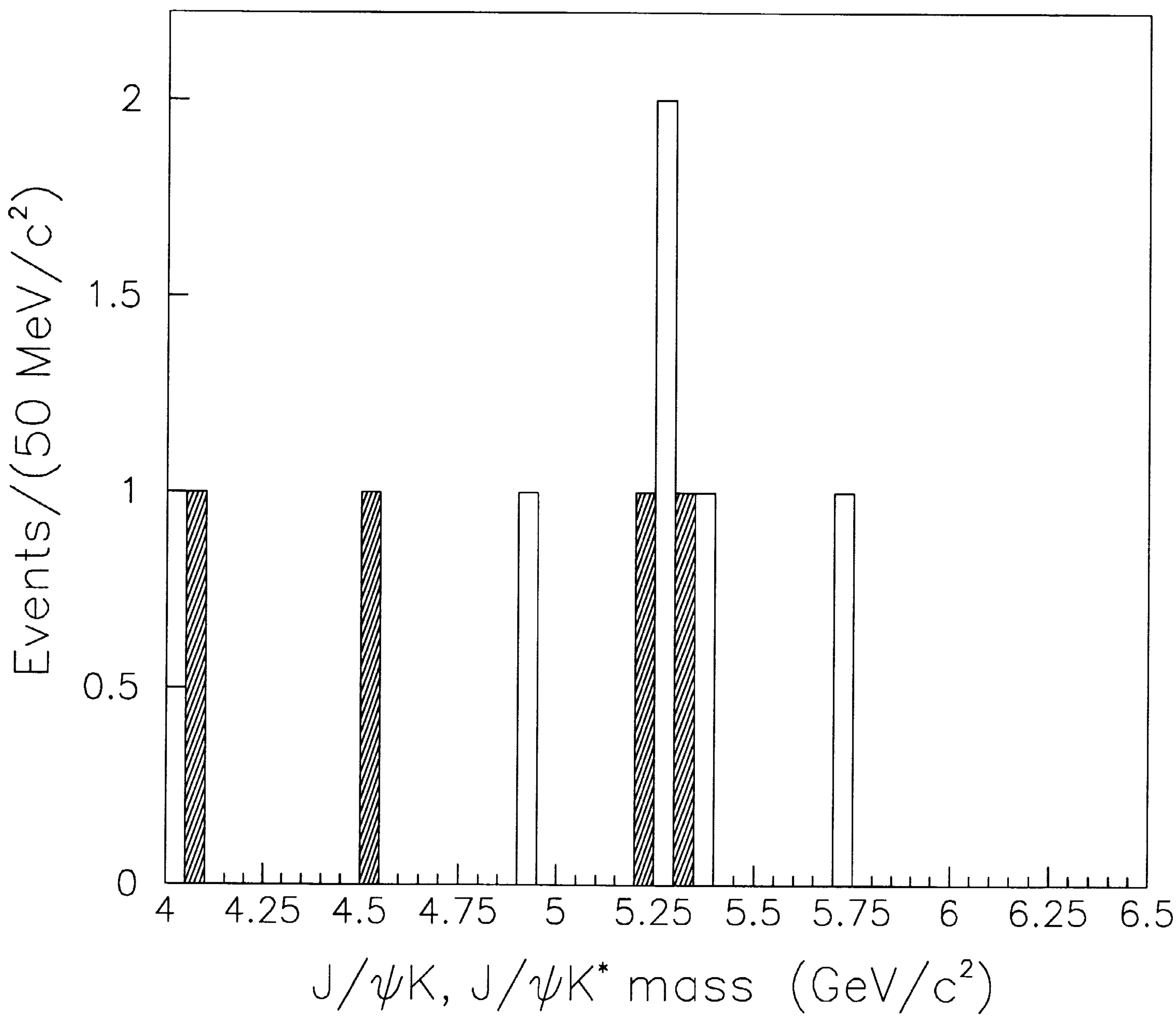
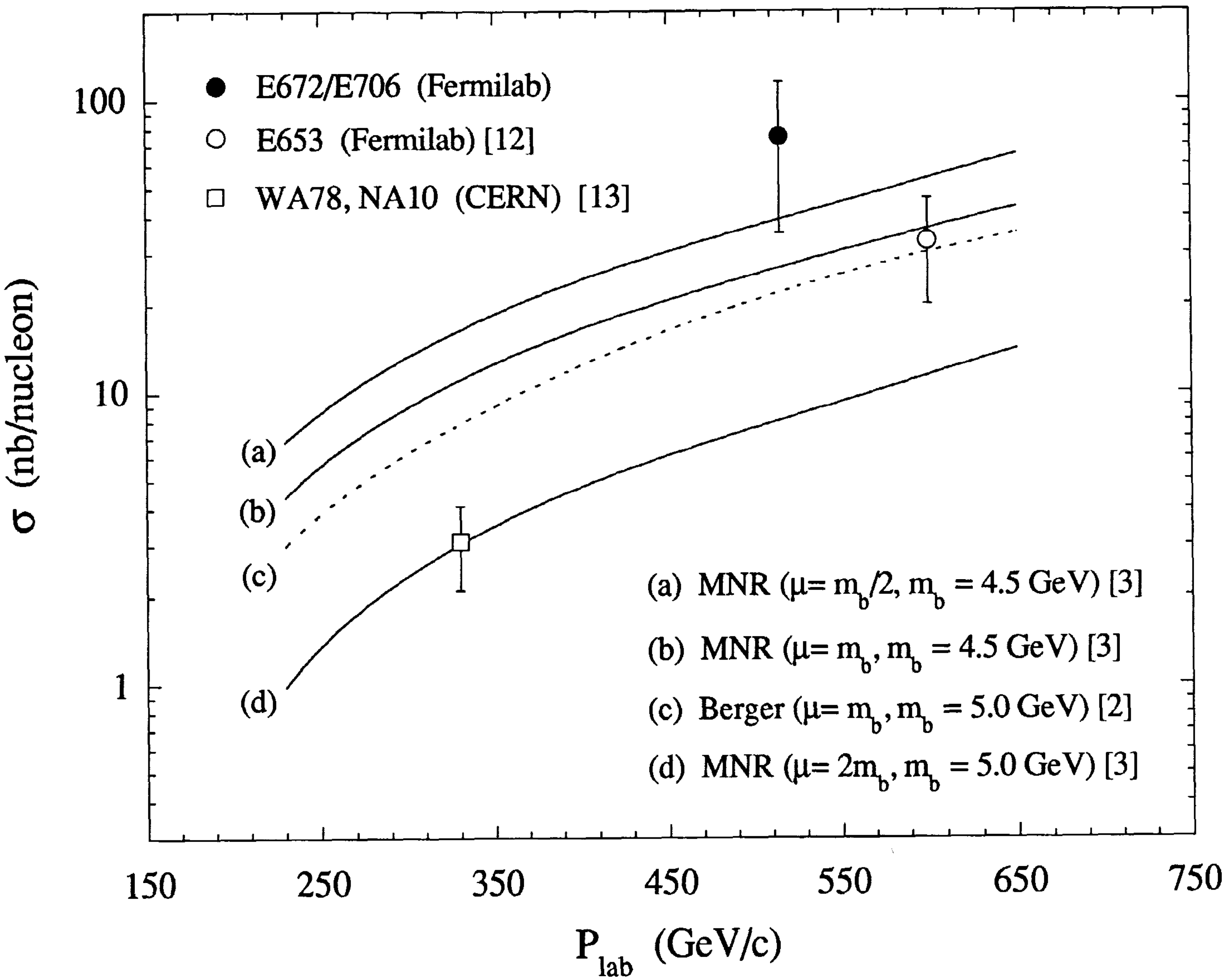


Events/(40 MeV/c²)
2500
2000
1500
1000
500
0
2.5
2.75
3
3.25
3.5
3.75
4
4.25
4.5
μ⁺μ⁻ mass (GeV/c²)
200
100
0
3.5
3.75
4
4.25


(a)
(b)
(c)
Cu
Be
Be
SSD
Events/(0.1 mm)
Events/(0.8 mm)
Events/(0.8 mm)
100
75
50
25
0
2.5
0
2.5
0
−15
−14
−13
−12
−11
−10
−9
−8
−7
−6
−5
z (cm)


Be
air
Be
air
mylar
0.8
0.6
0.4
0.2
0
-0.2
-0.4
y (cm)
-10
-9
-8
-7
-6
-5
z (cm)


Events/(50 MeV/c²)
0
0.5
1
1.5
2
4
4.25
4.5
4.75
5
5.25
5.5
5.75
6
6.25
6.5
J/ψK, J/ψK* mass (GeV/c²)


E672/E706 (Fermilab)
E653 (Fermilab) [12]
WA78, NA10 (CERN) [13]
(a) MNR ($\mu = m_b/2$, m_b = 4.5 GeV) [3]
(b) MNR ($\mu = m_b$, m_b = 4.5 GeV) [3]
(c) Berger ($\mu = m_b$, m_b = 5.0 GeV) [2]
(d) MNR ($\mu = 2m_b$, m_b = 5.0 GeV) [3]
(a)
(b)
(c)
(d)
100
10
1
150
250
350
450
550
650
750
σ (nb/nucleon)
P_{lab} (GeV/c)