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ABSTRACT

We report measurements of J/ψ(3100) and ψ'(3700) production by 200, 300 and 400 GeV protons striking Be and Cu targets. Both e^+e^- and $\mu^+\mu^-$ decay modes are studied. Cross-sections vs. p_t and y are presented, along with s and A dependences. Ratios of ψ'/ψ production are also measured at two energies.

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This letter reports on $J/\psi(3100)$ and $\psi'(3700)$ production in proton-nucleus collisions at Fermilab. Preliminary results on J/ψ and ψ' production in proton-beryllium collisions at 400 GeV have already appeared.[1,2,3] Here we present 200, 300 and 400 GeV p-Be electron pair data and 400 GeV p-Be and p-Cu muon pair data.

Electron pairs were detected with a magnetic and lead glass spectrometer system described in Ref. 1 and pictured in Fig. 1 of that reference. Modifications to this apparatus made to detect muon pairs are described in Ref. 3 which reports on higher mass dimuon data. These included the insertion of beryllium and polyethylene to absorb hadrons and the addition of several detector elements to identify muons and better define trajectories. The muon experiment was run at higher luminosity and yielded a final sample of 1138 $J/\psi \rightarrow \mu^+\mu^-$ events at 400 GeV in contrast to 347 $J/\psi \rightarrow e^+e^-$ events obtained with twice the running time. This yield was achieved at the expense of a factor of 3 in resolution and increased background.

Figure 1 presents the lower mass 400 GeV spectra for both the electron and muon pair experiments. Raw data from three magnet currents are shown. The low current settings (600A and 800A) have a flat mass acceptance near 3-4 GeV. Figures 1c and d show the low mass data from the high current, high mass setting of the spectrometer. These have a steeply rising mass acceptance in the 3-4 GeV region which results in a large increase in the yield of ψ' relative to J/ψ. The J/ψ peaks in these graphs (with

the production cross-section determined from the data in Fig. 1 a, b) provide checks on the acceptance calculation at a mass below the ψ'. Thus the ψ' yield may be transformed to a cross-section with some confidence.

The dominant problem in the Monte Carlo acceptance calculation for muon pair data is the multiple Coulomb scattering in and near the hadron absorber. The Monte Carlo calculation correctly described the widths and centroids of the J/ψ mass distributions for a variety of spectrometer settings as well as the apparent target width as reconstructed from the data.

The muon data taken with Cu (843 J/ψ events) and with Be (294 J/ψ events) determine that the A-dependence of J/ψ production is $A^{0.90 \pm .10}$. We use this result to convert cross-sections per nucleus to cross-sections per nucleon.

Figure 2 presents J/ψ and ψ' production dynamics. In Fig. 2a we plot the invariant cross-section for J/ψ production vs. p_t for electron and muon final states. The muon accidental background (amounting to 5% of the data) was subtracted bin by bin by combining single arm data normalized according to accidental monitors. An additional 5% was subtracted from each bin. This is our estimate (accurate to $\pm 100\%$) of all other backgrounds, including a possible continuum contribution, based on the data at masses lower and higher than the J/ψ. Muon and electron data are in very good agreement at 400 GeV, both sets being well described by the linear exponential fit:

$$B_{ee} \cdot E \left.\frac{d^3\sigma}{dp^3}\right|_{y=0} = B_{\mu\mu} \cdot E \left.\frac{d^3\sigma}{dp^3}\right|_{y=0} = (3.5\pm.9)\times10^{-33}\ e^{-(1.51\pm.12)p_t} \text{ cm}^2/\text{GeV}^2/\text{nucleon}.$$

Parameters from separate fits to dimuons at 400 GeV and to dielectrons at 300 GeV and 400 GeV are given in Table I. We note that although the electron data are equally well fit by a quadratic exponential form, the muon data prefer a linear exponential fit by 2.9σ.[4]

Figure 2b presents cross-sections $\frac{d\sigma}{dy} \cdot B$ vs. center of mass rapidity y. The data are all consistent with being flat over the range of acceptance (-0.2 to +0.3 for 400 GeV; -0.1 to +0.4 for 300 GeV).

The distribution in decay angles must also be known for accurate determination of the production cross-section. Due to limited acceptance we could not determine this dependence independently for all production configurations. Instead we assumed this distribution to be independent of y and p_t and to have the form $f(\cos\theta, \phi)|_{\phi=0,\pi} \propto 1 + \alpha \cos^2\theta$. We then found the best fit for α in both the helicity frame and the Gottfried-Jackson frame.[5] A good fit was found only for values of α near 1 in the helicity frame. Since this form was preferred to isotropic by more than three standard deviations it was used to calculate all the results in this paper. If we had assumed an isotropic decay angle distribution the cross section would have been proportional to $e^{-1.2\ p_T}$ and $d\sigma/dy$ would have been 60% larger.

The production of ψ' is observed at both 400 GeV (Fig. 1c) and 300 GeV in the e^+e^- mode and the following production cross-section ratios are found:

$$\frac{\left.\frac{d\sigma}{dy}\right|_{y=0} \cdot B_{ee}(\psi')}{\left.\frac{d\sigma}{dy}\right|_{y=0} \cdot B_{ee}(J/\psi)} = \begin{array}{l} .018 \pm .006 \text{ at } 400 \text{ GeV} \\ .014 \pm .005 \text{ at } 300 \text{ GeV}. \end{array}$$

Using known values of B_{ee} and their errors[6,7] the production ratios at y=0 are 0.13 ± .06 and 0.09 ± .05. These results are for inclusive production after background subtraction. The muon data (Fig. 1b) exhibits a shoulder at the ψ' mass which is consistent with a resolution broadened ψ' peak of amplitude given above from electron pair data.

The invariant cross section vs. p_t for ψ' is given in Fig. 2c and is fit by:

$$E\left.\frac{d^3\sigma}{dp^3}\right|_{y=0} \cdot B_{ee}(\psi') = (9.6\pm3.5)\times10^{-35} e^{-(1.9 \pm .5)p_t} \text{ cm}^2/\text{GeV}^2/\text{nucleon}.$$

Table II presents the measurements of the quantity $B \cdot \left.\frac{d\sigma}{dy}\right|_{y=0}$ for J/ψ and ψ'. These are plotted in Fig. 3 vs. the center of mass energy $\sqrt{s}$ along with results of a number of other experiments.[9,10,11,12,13] There is a suggestion that the steep portion of the ψ' excitation curve may be at much higher s than that of the J/ψ. Both the excitation curve and the ratio of J/ψ to ψ' are relevant to models for psion production in hadron collisions. The large ratio observed here may indicate a significant cascade contribution to J/ψ production.[14,15,16] However we note that phenomenological models of all hadron production also predict this ratio without invoking any special dynamics.[17]

We reiterate our previous acknowledgements [1,2,3] but add special thanks to the Fermilab accelerator staff.

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TABLE I

PARAMETERS OF LINEAR EXPONENTIAL FITS

$$B_{\ell\ell} \cdot E \frac{d^3\sigma}{dp^3}\Big|_{y=0} = Ae^{-bp_t}$$

FOR J/ψ(3100)

	A (10^{-33} cm^2/GeV^2/nucleon)	B (GeV^{-1})	P(χ^2)
400 GeV			
$J/\psi \to e^+e^-$	3.32 ± 0.83	1.54 ± .14	.06
$J/\psi \to \mu^+\mu^-$	3.78 ± 0.95	1.50 ± .10	.08
300 GeV			
$J/\psi \to e^+e^-$	2.81 ± 0.79	1.65 ± .23	.15

TABLE II

$B_{\ell\ell} \cdot \frac{d\sigma}{dy}\Big|_{y=0}$ for $J/\psi(3100)$ and $\psi'(3700)$

$(10^{-33}\ cm^2/nucleon)$

	400 GeV	300 GeV	200 GeV [a]
$J/\psi \to e^+e^-$	8.8 ± 2.2	6.5 ± 1.6	7.6 ± 2.2
$J/\psi \to \mu^+\mu^-$	10.6 ± 2.7	----------	----------
$\psi' \to e^+e^-$	0.16 ± 0.06	0.09 ± 0.04	----------

a) The 200 GeV result is preliminary. The mean rapidity for this point is 0.4.

FIGURE CAPTIONS

Figure 1: Raw mass spectra for various spectrometer settings and targets. All spectra are for 400 GeV protons incident on the target.

Figure 2: J/ψ and ψ' production dynamics near y = 0:

a) Invariant cross section times branching ratio vs. transverse momentum for J/ψ.

b) Differential rapidity distributions for J/ψ.

c) Invariant cross-section vs. transverse momentum for ψ'.

Figure 3: $d\sigma/dy$ at y=0 vs. $\sqrt{s}$ for J/ψ and ψ' production. The solid lines are from the cascade model calculation of Carlson and Suaya.[16] The dashed line is from the quark fusion model calculation of Donnachi and Landshoff.[14]

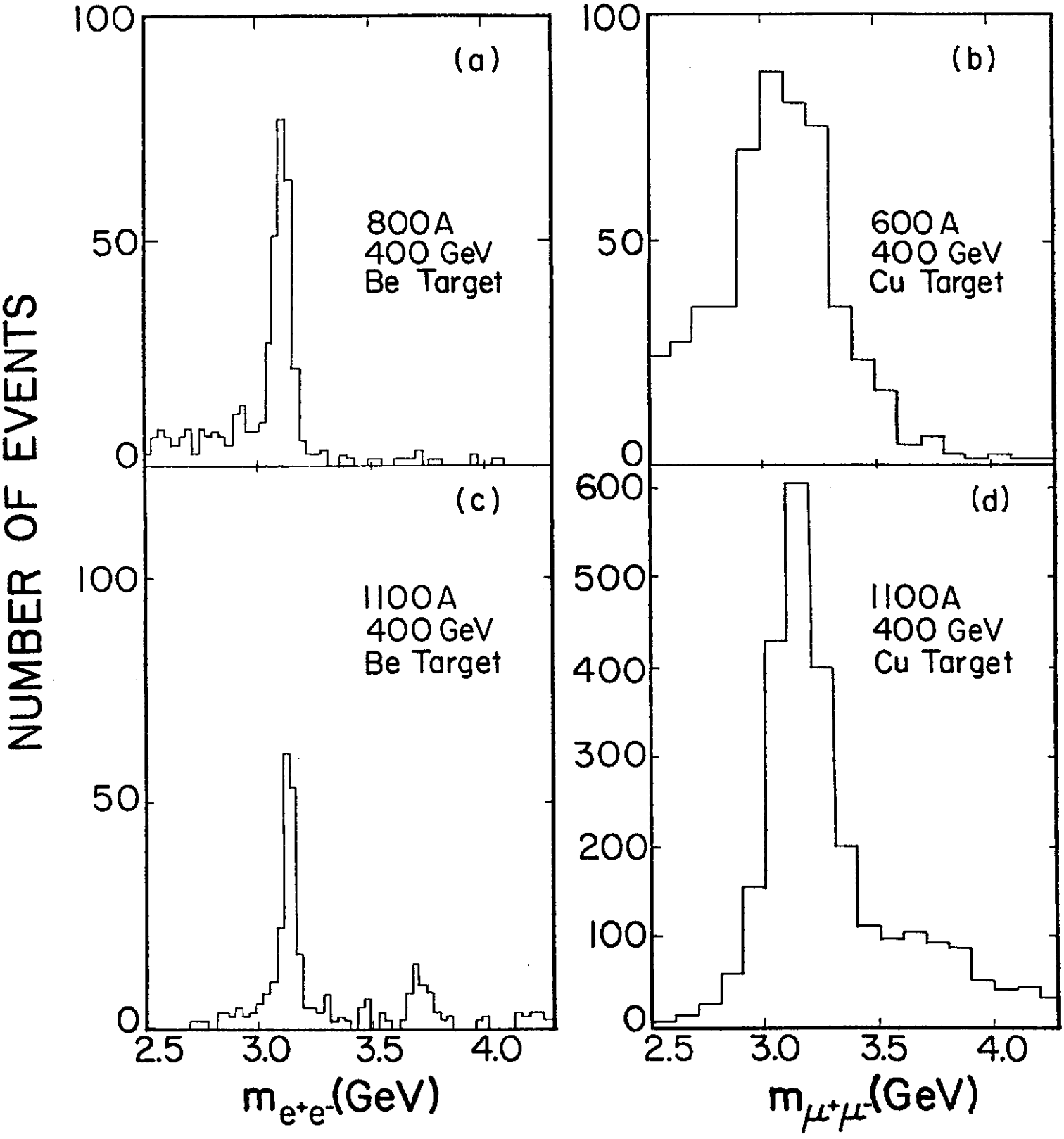
NUMBER OF EVENTS
(a)
800A
400 GeV
Be Target
(b)
600A
400 GeV
Cu Target
(c)
1100A
400 GeV
Be Target
(d)
1100A
400 GeV
Cu Target
100
50
0
600
500
400
300
200
100
2.5
3.0
3.5
4.0
$m_{e^+e^-}$(GeV)
$m_{\mu^+\mu^-}$(GeV)

Fig. 1

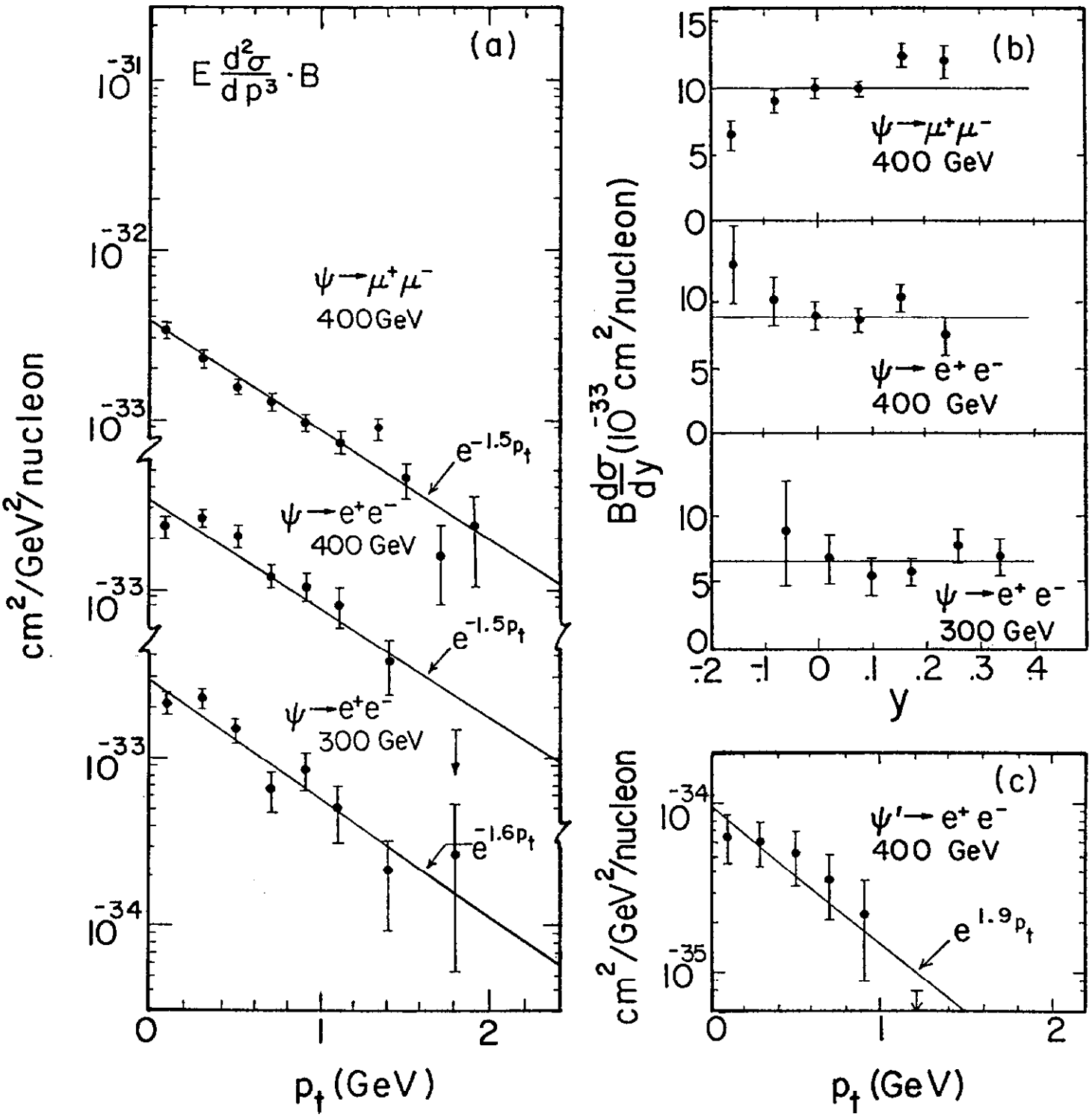
(a)
$E\frac{d^2\sigma}{dp^3}\cdot B$
$\psi\to\mu^+\mu^-$
400GeV
$e^{-1.5p_t}$
$\psi\to e^+e^-$
400 GeV
$e^{-1.5p_t}$
$\psi\to e^+e^-$
300 GeV
$e^{-1.6p_t}$
$cm^2/GeV^2/nucleon$
p_t (GeV)
(b)
$\psi\to\mu^+\mu^-$
400 GeV
$\psi\to e^+e^-$
400 GeV
$\psi\to e^+e^-$
300 GeV
$B\frac{d\sigma}{dy}(10^{-33}cm^2/nucleon)$
y
(c)
$\psi'\to e^+e^-$
400 GeV
$e^{1.9p_t}$
$cm^2/GeV^2/nucleon$
p_t (GeV)

Fig. 2

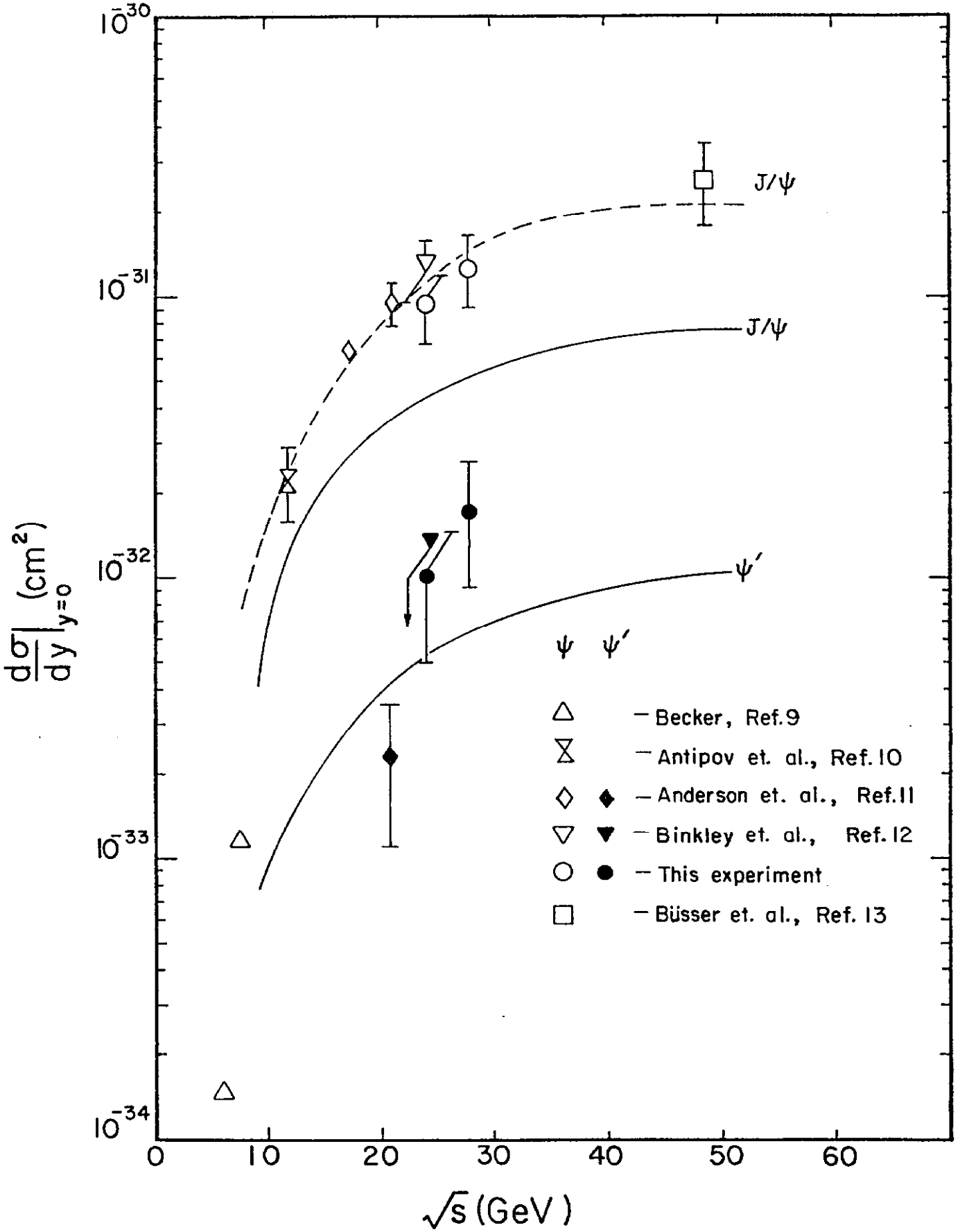
10^{-30}
10^{-31}
10^{-32}
10^{-33}
10^{-34}
$\frac{d\sigma}{dy}\Big|_{y=0}$ (cm^2)
0
10
20
30
40
50
60
$\sqrt{s}$ (GeV)
J/ψ
J/ψ
ψ′
ψ ψ′
— Becker, Ref.9
— Antipov et. al., Ref.10
— Anderson et. al., Ref.11
— Binkley et. al., Ref.12
— This experiment
— Büsser et. al., Ref. 13

Fig. 3