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CHARACTERISTICS OF J/ψ AND Υ PRODUCTION AT THE CERN INTERSECTING STORAGE RINGS

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ABSTRACT

We present the $B(d\sigma/dy)_{y=0}$ for J/ψ over the full range of ISR energies and for Υ at $\sqrt{s}$ = 53 and 63 GeV, using their dielectron decay mode. The average transverse momentum and the decay angles are presented. We found $\langle p_T \rangle = 1.75 \pm 0.19$ GeV for Υ, being higher than $\langle p_T \rangle$ of the continuum and rising with $\sqrt{s}$. We present a comparison of the cross-sections of J/ψ and Υ with those of the continuum, at the same masses, as a function of $\sqrt{s}$. An approximate scaling of the hadronic production of quark-antiquark narrow bound states involving ϕ, J/ψ, ψ', Υ, and Υ' is presented as a function of $m/\sqrt{s}$ at $y = 0$, and is compared with Drell-Yan scaling.

We have already published preliminary results on the cross-sections of J/ψ [1,2], Υ [2,3] and χ [4] states. The final data presented here represent a tenfold increase on the previous statistics of the J/ψ and Υ.

The J/ψ and Υ signals were extracted from the dielectron data described in the preceding paper in this issue, to which reference should be made for a description of the apparatus, luminosities, and analysis methods.

Observation of the J/ψ over a wide range of transverse momenta and decay angles requires the selection of events where one electron has a relatively low energy. This poses an experimental problem, because the number of background events from photons and charged hadrons rises very steeply as the electron energy threshold is reduced. This problem was overcome with the aid of a "correlation" trigger, which required that a localized electromagnetic shower in the liquid-argon detector be spatially correlated with a charged track satisfying conditions regarding the presence of transition radiation and compatibility with single-particle ionization in the scintillation counters. This technique allowed the electron threshold to be reduced to 750 MeV/c, while keeping the trigger rate to a few per second, for an event rate approaching 10^6 per second. Using the technique described in the previous paper, we found that the correlation trigger was 64% efficient. The track reconstruction efficiency was 87% and the shower reconstruction efficiency was 95% [5].

The typical background under the J/ψ ($2.8 < m < 3.4$ GeV) varied from 7% to 4% of the signal when the efficiency of the cuts applied to select the dielectron signal varied from 0.25 to 0.11. Similar values also characterize the Υ region defined as $8.7 < m_{ee} < 10.3$ GeV.

Our mass spectrum corrected for acceptances and inefficiencies is shown in fig. 1 of the previous paper; in that paper we had fitted a decay distribution of the form $dN/d\cos\theta \sim 1 + \alpha \cos^2\theta$, where $\alpha = 0.31 \pm 0.28$ for the Υ, and α is consistent with zero for the J/ψ. Figure 1a represents our acceptance as a function of transverse momentum for J/ψ and Υ regions assuming an isotropic decay and a flat rapidity distribution for $|y| < 1$.

Our invariant differential distributions as a function of transverse momentum are represented in fig. 1b for J/ψ for three c.m. energies. Our results for the fit to the form $E(d^3\sigma/dp^3) = A \exp(-bp_T)$ are: $\sqrt{s} = 30$: $\langle p_T \rangle = 1.14 \pm 0.12$; $\sqrt{s} = 53$: $\langle p_T \rangle = 1.39 \pm 0.05$; $\sqrt{s} = 63$ GeV: $\langle p_T \rangle = 1.29 \pm 0.05$ GeV, showing little dependence on $\sqrt{s}$. Also the $\langle p_T \rangle$ of the J/ψ is not different from the continuum in nearby mass regions (see also fig. 5 of previous paper).

For the Υ region we obtain $\langle p_T \rangle = 1.65 \pm 0.12$ GeV, while for the mass interval $6 < m < 8.7$ GeV we have found $\langle p_T \rangle = 1.43 \pm 0.09$ GeV. After unfolding the effect of the continuum (using our estimate of 2:1 for the Υ:continuum ratio) we find $\langle p_T \rangle_\Upsilon$ = 1.75 ± 0.19 GeV. This distribution is shown in fig. 1b for a combination of $\sqrt{s}$ = 53 and 63 GeV *). Although the $\langle p_T \rangle$ of J/ψ and Υ are quite different, it is interesting to observe the similar slopes of their invariant cross-sections as a function of p_T. We conclude that the $\langle p_T \rangle$ of the Υ is substantially higher than that of the continuum at the same c.m. energies and rises with $\sqrt{s}$. These features were also observed by Yoh et al. at $\sqrt{s}$ = 27.4 GeV (see also fig. 5 of the previous paper).

The cross-sections for J/ψ and Υ were extracted from the dielectron production cross-sections of fig. 3 of our previous paper by subtracting the continuum fit to our data quoted there. They are shown in fig. 2 and table 1 together with the results of other experiments [6]. We note the factor of 30 for the Υ cross-sections from $\sqrt{s}$ = 27 GeV to $\sqrt{s}$ = 63 GeV. The J/ψ cross-sections have a tendency to level off in the same c.m. energy range.

Different models [7-9] have been suggested for the hadronic production of narrow vector mesons. Among them, Gaisser et al. [9] have suggested that all differences among the couplings of vector mesons to the hadronic systems from which they emerge, are contained in their hadronic widths Γ_h. Assuming a universal function $F(m_V/\sqrt{s})$ (where m_V is the mass of the meson) which describes all the kinematics and dynamics of the production, and using dimensional arguments, the following scaling rule was given:

$$\sigma\ (pp \to V + X) = \frac{\Gamma_h}{m_V^3}\, F\left(\frac{m_V}{\sqrt{s}}\right) .$$

We apply this scaling in the central region for the available data on φ, J/ψ, ψ′, Υ, and Υ′ produced in proton-nucleon interactions; this is shown in fig. 3a, which displays a compilation of these cross-sections at y = 0 [8,10]. One can note a spread over six orders of magnitude for the different cross-sections, although the $c\bar{c}$ and $b\bar{b}$ states manifest a similar $m/\sqrt{s}$ behaviour.

Figure 3b shows the function $F(m_V/\sqrt{s})$ as evaluated from the cross-sections, masses, and known widths. The error bars correspond to quoted errors in cross-sections. The errors in hadronic branching ratios are in general small and are ignored in this plot. The J/ψ cross-sections have been corrected for 47% non-direct production due to χ states [4]. The degree to which all values lie on a single line is remarkable, although in detail deviations are present.

A similar scaling law applies to the continuum of lepton pairs produced in hadronic interactions:

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*) If one uses $d^2N/dp_T^2 \sim \exp(-bp_T)$, one fits for the Υ $\langle p_T \rangle$ = 1.78 ± 0.13 GeV with b = 1.12 ± 0.08 GeV^{-1} and an unchanged value for the continuum $\langle p_T \rangle$ = 1.44 ± ± 0.08 GeV. After the subtraction of the continuum, one obtains $\langle p_T \rangle_\Upsilon$ = 1.95 ± ± 0.28 GeV.

$$\sigma\ (pp \to \ell^+\ell^- + X) = \frac{1}{m^3_{\ell\ell}}\ F'\left(\frac{m_{\ell\ell}}{\sqrt{s}}\right)\ .$$

Both vector dominance and quark fusion models would further suggest that $F'(\sqrt{\tau})$ and $F(\sqrt{\tau})$ (where $\sqrt{\tau} = m/\sqrt{s}$) should have the same form.

To make such a comparison, the fit to the function $F'(\sqrt{\tau})$ taken from the preceding paper has been scaled up by a factor of 4×10^6 and also plotted in fig. 3b. Again the agreement is remarkable despite small deviations. One could even assume that the scaling laws are exact and that the deviations observed are due to experimental systematic errors.

This hypothesis would predict that the ratio of any vector meson production to the lepton pair continuum at the same mass should be independent of $\sqrt{s}$. Such ratios are measured in our experiments and in others*) and are less affected by experimental systematics. Values of these ratios for J/ψ and Υ are shown in fig. 4 **). It can be observed that the J/ψ has the same $\sqrt{s}$ dependence as the continuum, while the Υ may manifest some rise as a function of $\sqrt{s}$.

If one assumes that the continuum is of an electromagnetic nature (as in the Drell-Yan mechanism), one can investigate the character of the production of resonances in hadronic interactions by comparing the ratios of fig. 3 with the equivalent ratios of purely electromagnetic productions of resonances and lepton pairs in e^+e^- storage rings. The ratio $\int B\sigma_{\ell\ell}(V)dE \big/ \int \sigma(e^+e^- \to \mu^+\mu^-)dE$ at $E = \sqrt{s} = m_V$ was found to be ~ 0.092 for J/ψ and ≤ 0.022 for Υ. The discrepancy between these values and our equivalent ratios of the hadronically produced J/ψ and Υ with respect to the neighbouring continuum suggests that in pp interactions the production mechanism of these resonances is not electromagnetic.

In summary, the J/ψ cross-sections at $y = 0$ were found to rise by a factor of 1.5 from $\sqrt{s} = 27.4$ GeV to $\sqrt{s} = 63$ GeV, while Υ + Υ′ cross-sections manifest a factor of 30 increase. The average transverse momentum of the J/ψ was found to have little dependence on $\sqrt{s}$. At $\sqrt{s} = 63$ GeV we have measured $\langle p_T \rangle_{J/\psi} = 1.29 \pm 0.05$ GeV and $\langle p_T \rangle_{\Upsilon} = 1.75 \pm 0.19$ GeV. The $\sqrt{s}$ behaviour of the J/ψ is similar to that of the continuum, while the cross-section for Υ may be rising more quickly with $\sqrt{s}$ than the continuum.

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*) The values used for the continuum are integrated over a mass interval of 1 GeV.

**) The relative difference between the J/ψ:continuum and Υ + Υ′:continuum ratios may be reduced by correcting for differences in the leptonic branching ratios and additional non-direct sources for J/ψ (e.g. χ states [4]).

The scaling function

$$\frac{m_V^3}{\Gamma h} \left.\frac{d^2\sigma}{dmdy}\right|_{y=0} = F\left(\frac{m_V}{\sqrt{s}}\right) ,$$

which was suggested for the hadronic production of narrow quark-antiquark bound states, was found to hold approximately for ϕ, J/ψ, ψ', Υ, and Υ' up to the top ISR energy, $\sqrt{s}$ = 63 GeV.

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Table 1

Cross-sections times dilepton branching ratios at $y = 0$ for the J/ψ and Υ regions ($8.7 < m_{ee} < 10.3$ GeV); ratios of $B(d\sigma/dy)$/continuum at $y = 0$ for J/ψ and $\Upsilon + \Upsilon'$.

$\sqrt{s}$ (GeV)	30	53	63
J/ψ			
No. of events ($2.8 < m < 3.4$ GeV)	38	637	2966
Background (%)	4	4	4
$\varepsilon \cdot \mathcal{L}$ ($\times 10^{37}$ cm^2)	0.202×10^{-2}	0.0206	0.0830
ε for electron identification	0.134	0.134	0.134
σ (subtracted continuum) ($\times 10^{-33}$ cm^2)	0.15	0.24	0.27
$B(d\sigma/dy)_{y=0}$ ($\times 10^{-33}$ cm^2)	9.1 ± 2.5	13.6 ± 3.1	14.8 ± 3.3
σ (continuum) ($2.6 < m < 3.6$ GeV) ($\times 10^{-33}$ cm^2)	0.26 ± 0.05	0.43 ± 0.09	0.47 ± 0.09
$R = \left[B(d\sigma/dy)_{J/\psi}\right]$/continuum at $y = 0$	35.4 ± 12.0	32.0 ± 9.7	31.4 ± 9.4
$\Upsilon + \Upsilon'$			
No. of events ($8.7 < m < 10.3$ GeV)		10	87
Background (%)		12	12
$\varepsilon \cdot \mathcal{L}$ ($\times 10^{37}$ cm^2)		0.074	0.60
ε for electron identification		0.29	0.29
σ (subtracted continuum) ($\times 10^{-36}$ cm^2)		7.7	7.8
$B(d\sigma/dy)_{y=0}$ ($\times 10^{-36}$ cm^2)		13.5 ± 7.4	15.2 ± 5.5
σ (continuum) ($9 < m < 10$ GeV) ($\times 10^{-36}$ cm^2)		4.8 ± 1.0	4.7 ± 1.0
$R = \left[B(d\sigma/dy)_{\Upsilon+\Upsilon'}\right]$/continuum at $y = 0$		2.7 ± 1.4	3.2 ± 0.9

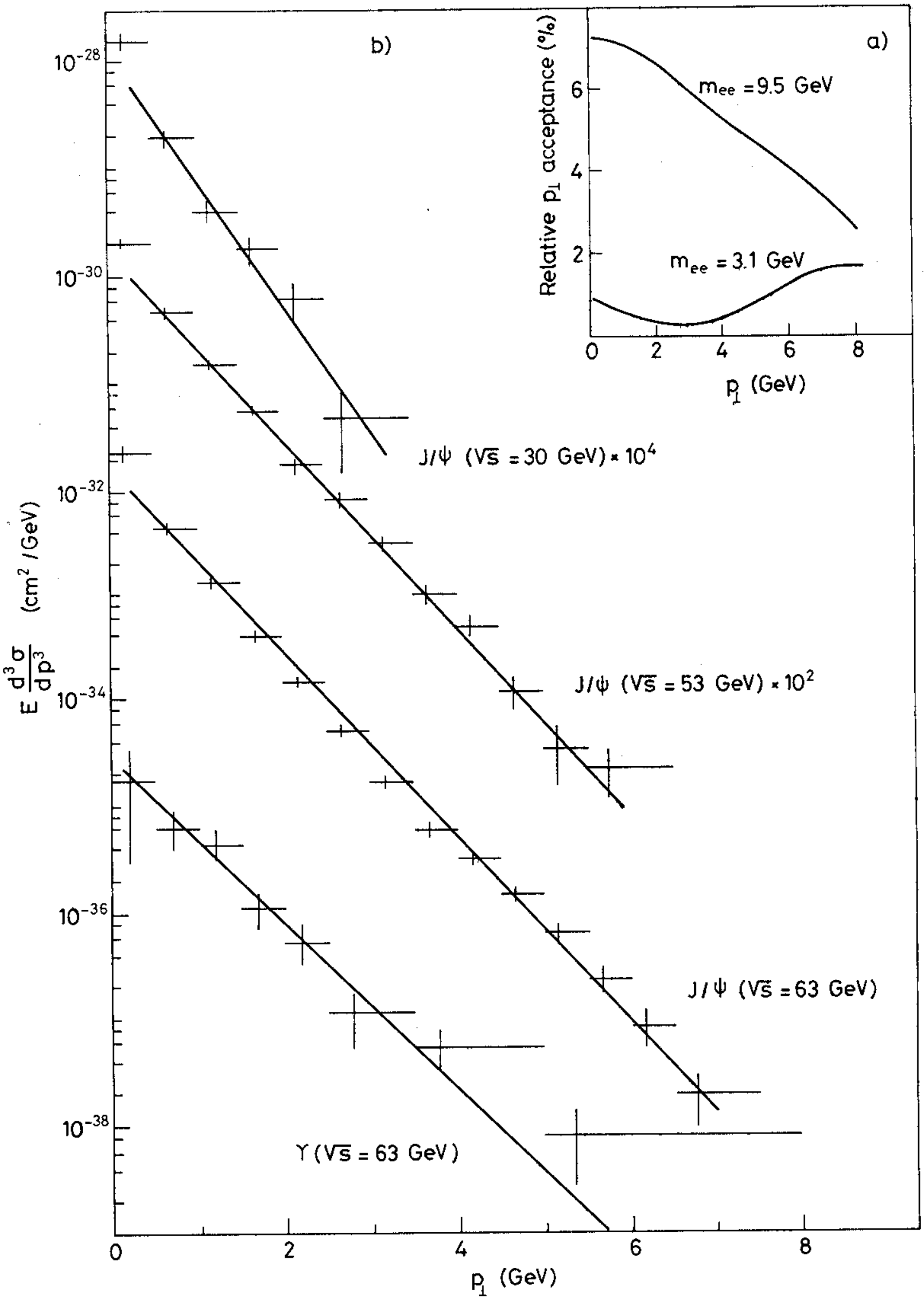
Figure captions

Fig. 1 : a) Plot of p_T acceptance for J/ψ and Υ, evaluated using isotropic decay and flat rapidity.
b) Plot of the $E(d^3\sigma/dp^3)$ versus p_T for J/ψ ($\sqrt{s}$ = 30, 53, and 63 GeV) and for Υ ($\sqrt{s}$ = 53 and 63 GeV combined). The lines represent the results of the fit $E(d^3\sigma/dp^3) \sim \exp(-bp_T)$.

Fig. 2 : Plot of $B(d\sigma/dy)_{y=0}$ versus $\sqrt{s}$ for the J/ψ and Υ regions ($8.7 < m_{ee} <$ < 10.3 GeV). For our data, see table 1.

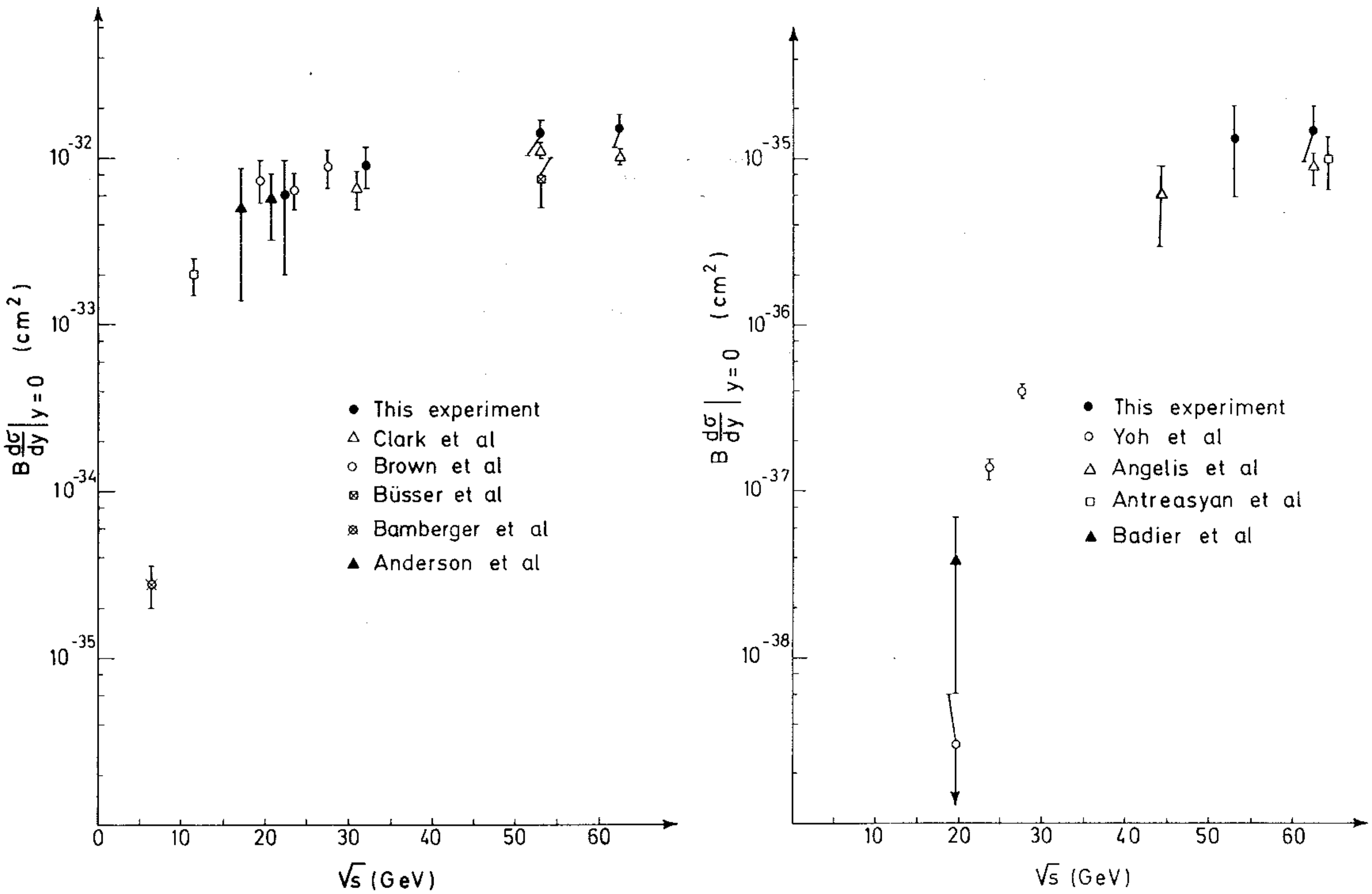
Fig. 3 : a) $d\sigma/dy|_{y=0}$ versus $m/\sqrt{s}$ for ϕ, J/ψ, ψ', Υ, and Υ'.
b) $(M^3/\Gamma_h)(d\sigma/dy)_{y=0}$ versus $m/\sqrt{s}$ for all the resonances in fig. 3a. The curve represents the function fitted to the continuum in fig. 2 in the preceding paper in this issue, upscaled by 4×10^6.

Fig. 4 : The ratio of $B(d\sigma/dy)$/continuum at $y = 0$ versus $\sqrt{s}$ for J/ψ and $\Upsilon + \Upsilon'$. For our data, see table 1.



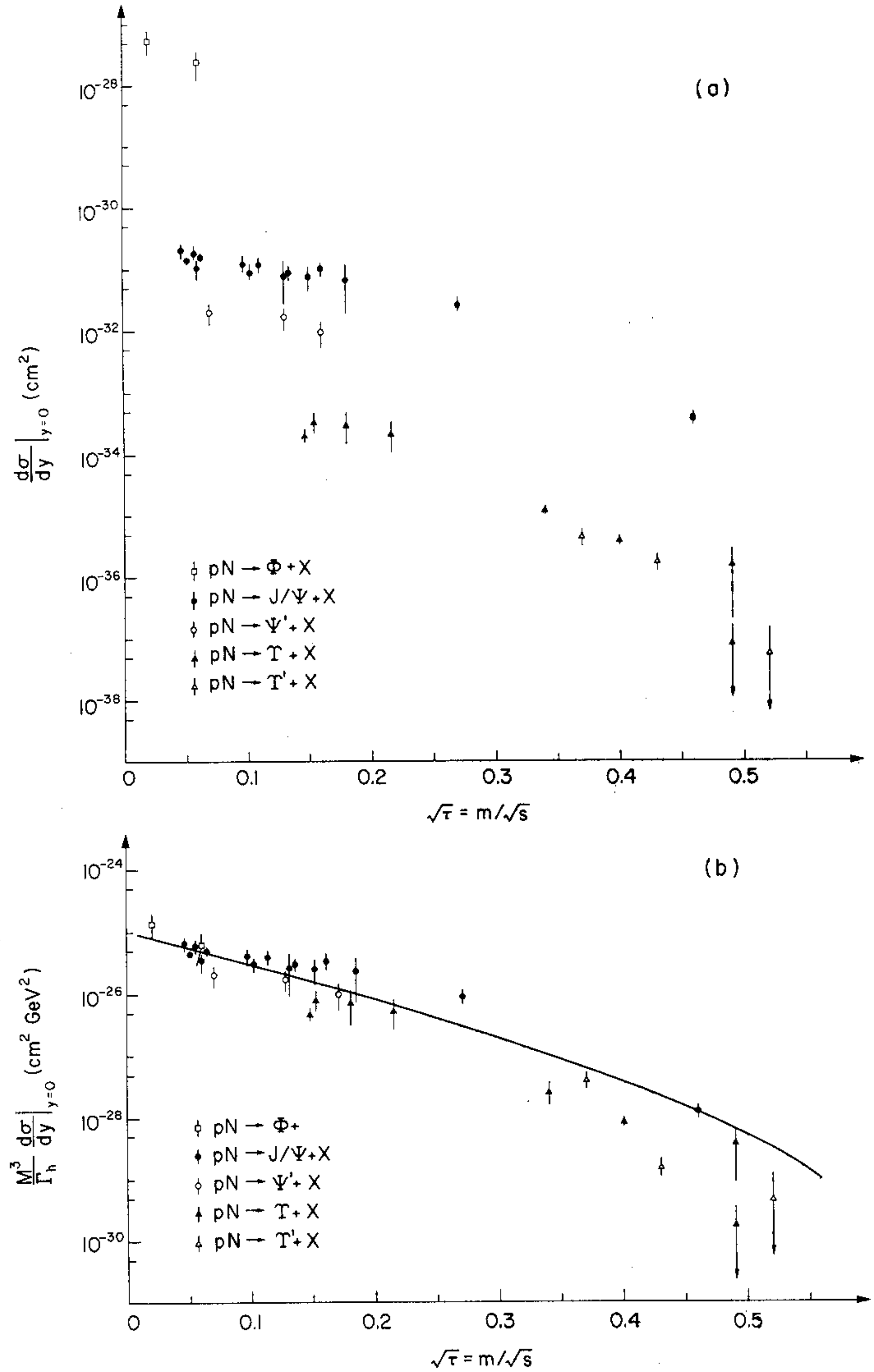
b)
a)
Relative $p_\perp$ acceptance (%)
m_{ee} = 9.5 GeV
m_{ee} = 3.1 GeV
$p_\perp$ (GeV)
$E\frac{d^3\sigma}{dp^3}$ (cm^2/GeV)
J/ψ (√s = 30 GeV) × 10^4
J/ψ (√s = 53 GeV) × 10^2
J/ψ (√s = 63 GeV)
Υ (√s = 63 GeV)
$p_\perp$ (GeV)

Fig. 1



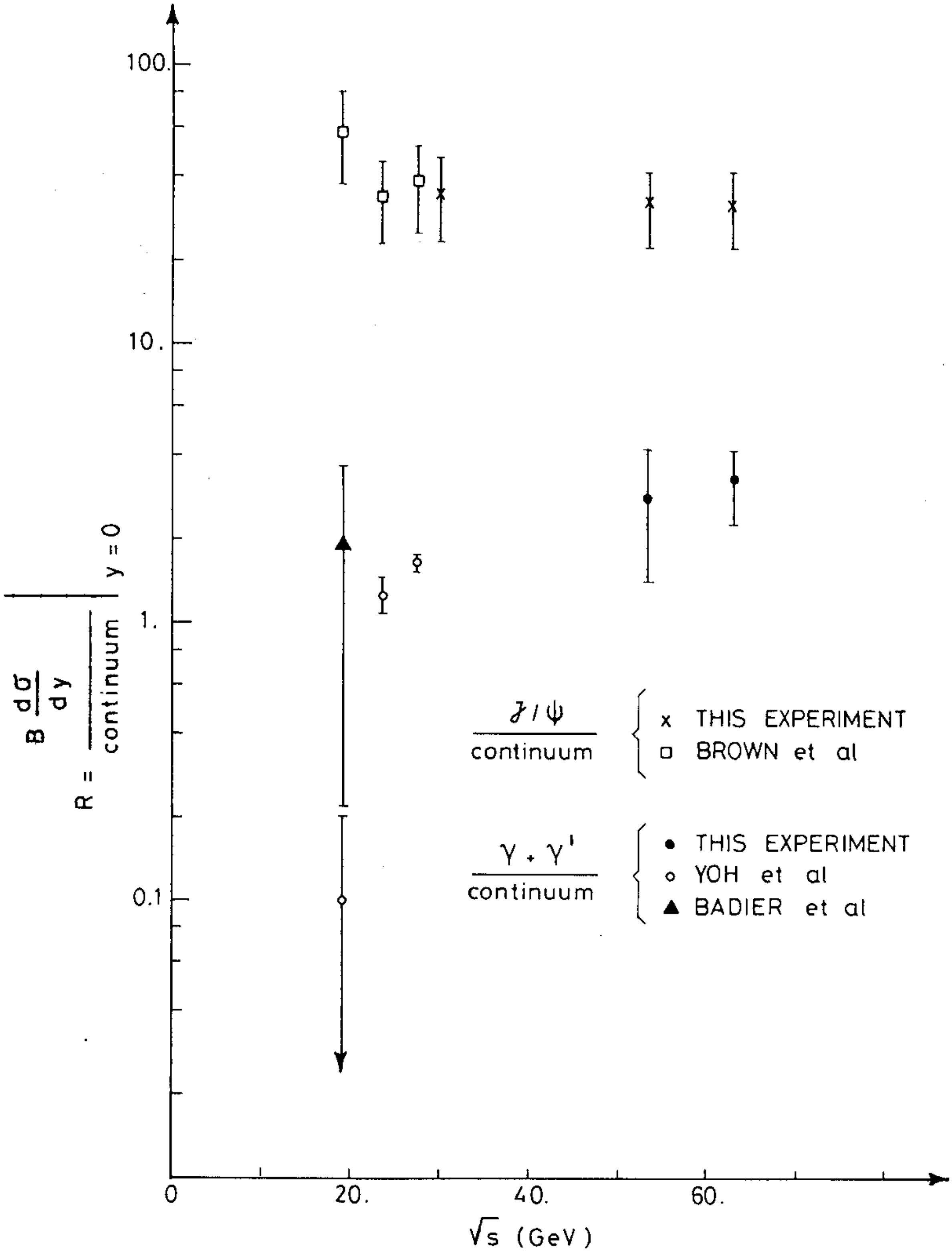
10^{-32}
10^{-33}
10^{-34}
10^{-35}
$B\frac{d\sigma}{dy}\Big|_{y=0}$ (cm^2)
● This experiment
△ Clark et al
○ Brown et al
⊠ Büsser et al
⊗ Bamberger et al
▲ Anderson et al
0 10 20 30 40 50 60
$\sqrt{s}$ (GeV)
10^{-35}
10^{-36}
10^{-37}
10^{-38}
$B\frac{d\sigma}{dy}\Big|_{y=0}$ (cm^2)
● This experiment
○ Yoh et al
△ Angelis et al
□ Antreasyan et al
▲ Badier et al
10 20 30 40 50 60
$\sqrt{s}$ (GeV)

Fig. 2



(a)
10^{-28}
10^{-30}
10^{-32}
10^{-34}
10^{-36}
10^{-38}
$\frac{d\sigma}{dy}\big|_{y=0}$ (cm^2)
pN → Φ + X
pN → J/Ψ + X
pN → Ψ' + X
pN → Υ + X
pN → Υ' + X
0
0.1
0.2
0.3
0.4
0.5
$\sqrt{\tau} = m/\sqrt{s}$
(b)
10^{-24}
10^{-26}
10^{-28}
10^{-30}
$\frac{M^3}{\Gamma_h}\frac{d\sigma}{dy}\big|_{y=0}$ (cm^2 GeV^2)
pN → Φ+
pN → J/Ψ+X
pN → Ψ'+ X
pN → Υ+ X
pN → Υ'+ X
0
0.1
0.2
0.3
0.4
0.5
$\sqrt{\tau} = m/\sqrt{s}$

Fig. 3



100.
10.
1.
0.1
R = B dσ/dy / continuum |y=0
0
20.
40.
60.
√s (GeV)
J/ψ / continuum
x THIS EXPERIMENT
□ BROWN et al
Υ + Υ' / continuum
• THIS EXPERIMENT
○ YOH et al
▲ BADIER et al

Fig. 4