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Production of $\psi(3100)$ in 400-GeV/c proton interactions

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We present measurements of ψ production and subsequent dimuon decay from 400-GeV/c proton interactions in an iron target over a range of P_t from 0 to 4 GeV/c and x_F from -0.25 to 0.40. The best fits give $E d\sigma/dx_F \propto (1-|x_F|)^{2.96\pm0.27}$ and $d\sigma/dP_t^{\,2} \propto \exp(-2.23\pm0.05P_t)$ for $P_t > 1.2$ GeV/c. The observed values of $B d\sigma/dy|_{y=0}$ and $B\sigma$ are 14.0 ± 2.9 and 22.9 ± 4.7 nb/nucleon, respectively.

Production of the $\psi(3100)$ and subsequent dilepton decay have been observed[1] in hadron collisions by several experiments under varying conditions of transverse momentum (P_t), Feynman x (x_F), and center-of-mass energy squared (s). Comparison with measurements[2] in e^+e^- colliding beams has shown that production via intermediate photon states does not account for the bulk of the hadronic cross section.[3] Other production mechanisms are not well understood and testing of alternative models of hadronic ψ production[4] (e.g., gluon or quark fusion, cascading through intermediate χ states) will require measurements of production distributions over the widest possible kinematic range. In the experiment reported here we have measured ψ production and dimuon decay with good efficiency and statistics over a range of P_t from 0 to 4 GeV/c and x_F from -0.25 to 0.40 at a higher s than previously reported for a large acceptance apparatus.

The experiment was performed in the Fermilab N5 hadron beam[5] using 400-GeV/c diffracted protons. A system of four x-y proportional wire chambers and a 16-mr horizontal dipole magnet determined the incident beam momentum to 0.5% and the vertex transverse position to 0.3 mm. The apparatus (Fig. 1), located in laboratory E directly upstream of the 15-ft bubble chamber, consisted of a fine-grained iron target calorimeter,[6] a module of four x-y and one u-v wire spark chambers with capacitor diode readout,[7] a coarse-grained calorimeter/muon identifier,[8] a second similar spark-chamber module, and a toroidal muon spectrometer.

The spectrometer, which could be moved transversely to the beam axis to change triggering conditions or for use in laboratory E neutrino experiments, consisted of 24 iron disks of 3.5-m diameter and 20-cm thickness with magnetostrictive readout wire spark chambers after every four sections. Large-area acrylic scintillation counters[9] (ACR) were located after the first three disks; conventional 3-m-square counter arrays were placed after every eight sections.

The magnetic field was calculated using computer program TRIM,[10] and agreed to within 1.5% with a Hall probe measurement in an air gap formed by 1-cm Al shims inserted between the two semicircular halves of each disk. The total $\int B_\phi dz$ of the magnet was 80 kG m, corresponding to a radial momentum kick of 2.4 GeV/c and a momentum resolution of 10%.

Counters $B0$, $B1$, and $B2$ defined the incident beam while the H counter vetoed halo particles outside of a 6-cm-square central region. Good beam particles were required by the trigger to

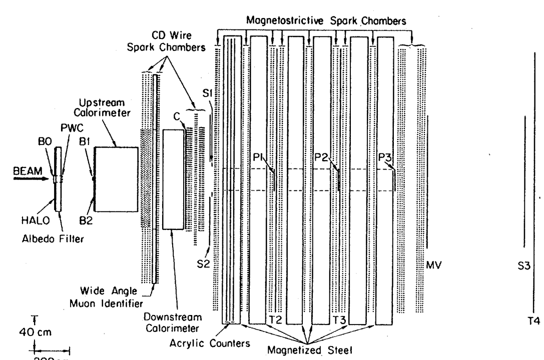

FIG. 1. Plan view of the experimental apparatus. A 400-GeV/c proton beam is incident from the left. $B0$–2, H (halo), C, $S1$–3, ACR1–3 (acrylic), $T2$–4, MV, and $P1$–3 are all counters used in trigger logic or event selection.

interact in the first 38 cm of the target, and to be unaccompanied by additional beam particles within 95 nsec.

The data sample reported on here was taken with the spectrometer centered on the beam axis and with a typical intensity of 8×10^5 good beam particles in a 1.8 second spill, and corresponded to a directly counted total flux during experiment live time of 1.4×10^{10} protons. The apparatus was triggered by single positive muons of high transverse momentum (p_t) by requiring that the focusing trajectories of the muons remain in the same azimuthal quadrant of the apparatus until reaching counter MV downstream of the magnet.

Counters C, ACR, $S2$, and $T4$ were segmented in four azimuthal quadrants, while $S1$, $T2$, $T3$, and MV were divided into half planes. The $P2$ counter and holes in $S1$ and ACR were used to reject rays passing through the magnet-coil return hole in the center of the toroid. A Monte Carlo simulation of the trigger geometry indicated that trigger efficiency for positive muons of momentum (p) between 20 and 50 GeV/c was independent of p and was 0.1 at p_t of 0.7 GeV/c, 0.5 at 1.0 GeV/c, and 0.9 at 1.3 GeV/c.

The dimuon invariant mass ($m_{\mu\mu}$) distribution of 35300 events with hits in at least two distinct quadrants of the ACR counter is shown in Fig. 2. The observed width of the ψ is mainly due to the finite momentum resolution of the spectrometer ($\Delta p/p \sim 0.10$) and measurement errors in the opening angle resulting from the fact that muons traverse 100 radiation lengths downstream of the vertex before track determination. The observed width is consistent with a Monte Carlo calculation.

The nonresonant background under the ψ has been assumed to have the shape $m_{\mu\mu}^{-3}e^{-14.9m_{\mu\mu}/\sqrt{s}}$, which is the observed distribution of the zero rapidity (y) continuum.[11] The amount of background was determined by requiring that the sum of the background plus the calculated ψ-tail contribution at 2.5 GeV/c^2 (using our observed ψ width of 0.4 GeV/c^2) agrees with the total number of events at that mass value. This procedure yields a total continuum contribution of 10.6 $\pm$ 1.1% of all the events in the mass band between 2.4 to 4.0 GeV/c^2. This nonresonant background curve is shown in Fig. 2.

Figure 3 presents the resolution-corrected P_t, x_F, and decay angular distributions for the 5440 events of $m_{\mu\mu}$ between 2.4 and 4.0 GeV/c^2, corrected by the trigger efficiences (with two-ACR-quadrant requirement) shown. The efficiencies were calculated via a Monte Carlo method, assuming x_F and P_t ψ-production distributions consistent with those observed and flat decay-angular

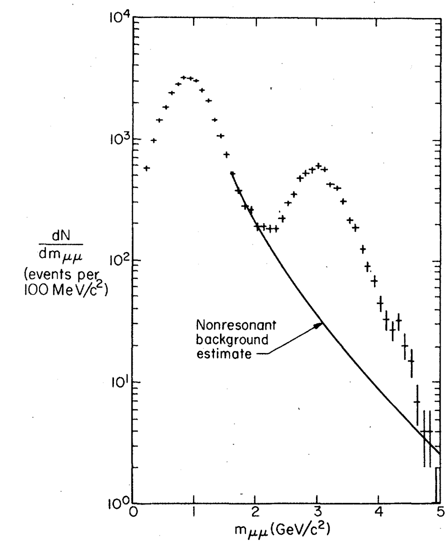

FIG. 2. Uncorrected mass distribution of 35300 $\mu^+\mu^-$ events with hits in two or more quadrants of the ACR hodoscope. The events with $m_{\mu\mu}$ between 2.4 and 4.0 GeV/c^2 have been used in the subsequent ψ analysis. The curve represents an estimate of the nonresonant background.

distribution in the ψ rest frame. They include effects of trigger acceptance, reconstruction efficiency, and distortion due to multiple scattering in the target-calorimeter.

The observed P_t distribution shows a departure from exponential behavior at $P_t \lesssim 1$ GeV/c which is qualitatively similar to that reported in ψ production at 225 GeV/c.[1] For our data, the best fit to the form $d\sigma/dP_t^{\,2} \propto e^{-bP_t}$ for $P_t > 1.2$ GeV/c yields $b = 2.23 \pm 0.05$. For comparison, a similar fit in the region $P_t < 1.2$ GeV/c yields $b = 1.52 \pm 0.08$.[12]

The invariant x_F distribution $Ed\sigma/dx_F$ is well fitted by a form $(1-|x_F|)^c$ with a fit value for c of 2.96 ± 0.27. A fit of the noninvariant distribution $d\sigma/dx_F$ to the identical form also describes the data well with an exponent of 4.41 $\pm$ 0.27.

The angular (θ^*) distribution of the μ^+ with respect to the direction opposite the final-state recoil system (s-channel helicity angle) was fitted to the form $(1+P\cos^2\theta^*)$, yielding a value for P of 0.16 ± 0.08. This implies 20 ± 10% of the events are distributed as $(1+\cos^2\theta^*)$ while the remainder follows a flat spectrum. This apportionment would give less than 20% of the *observed* events from the $(1+\cos^2\theta^*)$ component since the acceptance falls near $|\cos\theta^*|$ of 1, thus yielding a higher total acceptance for the component with a flat decay distribution. We conclude that the total angular distribution is consistent with a flat decay distribution for ψ's, and the

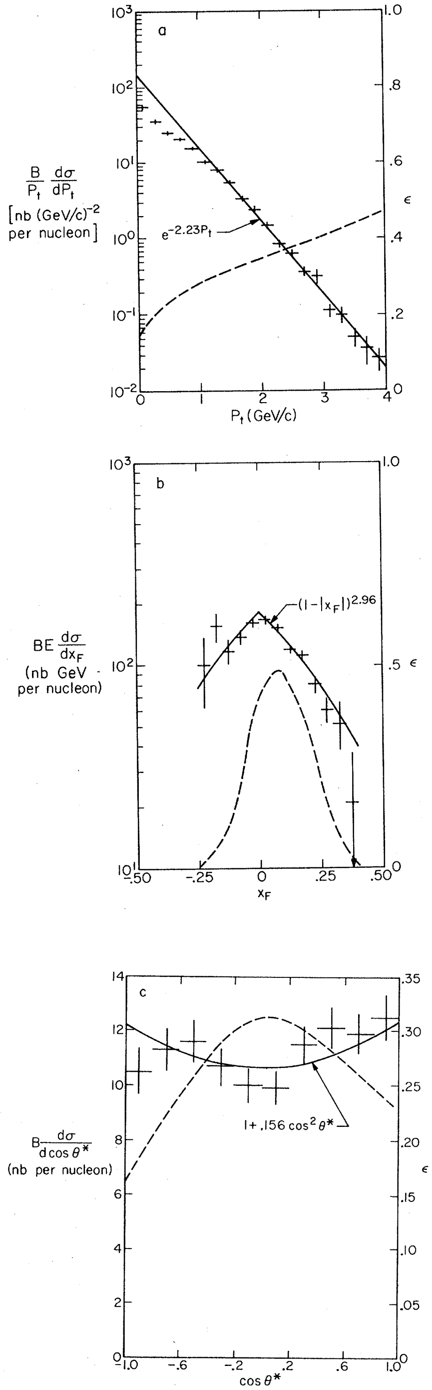

FIG. 3. Efficiency-corrected distributions for 5440 ψ events. Errors shown are statistical only. Solid lines represent best fits to the data, while dashed lines indicate the apparatus efficiency (ϵ). (a) $(B/P_t)(d\sigma/dP_t)$, (b) $BE\,d\sigma/dx_F$, (c) $B\,d\sigma/d\cos\theta^*$. Note that although the data are plotted on a logarithmic scale in (a) and (b), the efficiency scale is linear.

previously calculated (from the mass spectrum) 11% continuum contribution following a $1+\cos^2\theta^*$ distribution.

The x_F and $\cos\theta^*$ distributions have been corrected for a background from production by secondary hadrons reinteracting in the thick target. The x spectrum of the secondaries used was taken from the parametrization of Taylor *et al.*[13] and was corrected for heavy nucleus effects by using an additional factor of $A^{-0.25x}$ (where A is the target atomic weight).[14] These secondary events are estimated to account for $15.1\pm1.7\%$ of the observed data.

The total ψ production cross section per nucleon has been determined using the inelastic p-Fe cross section of 690 mb[15] and assuming a ψ-production A dependence[16] of $A^{0.90\pm0.05}$. This results in a single-event sensitivity of 1.29 ± 0.26 picobarns per nucleon. The observed values of $B\,d\sigma/dy|_{y=0}$ and $B\sigma$ are 14.0 ± 2.9 nb and 22.9 $\pm$ 4.7 nb, respectively. We note that $(86.3\pm1.3)\%$ of all ψ events fall into the acceptance region -0.25 to $0.40x_F$, and that the overall efficiency for the detection of $\psi\to\mu\mu$ events was 28%.

Direct comparison of the magnitude of the ψ production cross section with the results of other experiments[1] is difficult due to different assumptions for the A and $\cos\theta^*$ dependence of the signal. However, we do note the general similarity of our distributions to those measured by the large-acceptance Chicago-Princeton experiments at 225 GeV/c[1] which obtained values for the parameters b and c of 2.05 ± 0.09 and 3.44 $\pm$ 0.14, respectively.

In conclusion, we have measured ψ production in its dimuon decay with large acceptance at 400 GeV/c, extending both previous measurements at 400 GeV/c which were confined to x_F near 0 and at 225 GeV/c which were limited to $x_F>0$. Also, we measured for the first time proton-induced ψ production in the backward hemisphere in the center of mass.

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