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ABSTRACT

Dimuon production is studied in 217 GeV/c π^--hydrogen and π^--beryllium collisions in an open geometry with a lead glass array to detect photons associated with the ψ. The ψ-γ mass spectrum shows a 2.6 standard deviation peak above background at $\sim$ 3.5 GeV. This result implies that 0.70 ± 0.28 of the ψ's are produced via the radiative decay of one of the $\chi(\sim 3.5)$ states.

We have observed production of $\chi(\sim 3.5$ GeV) states in an experiment done at Fermilab using a 217 GeV/c π^- beam incident on beryllium and liquid hydrogen targets. It has been suggested[1,2] that hadronic production of the ψ occurs primarily through the production of an intermediate χ state, followed by the decay $\chi \to \psi + \gamma$ or $\chi \to \psi$ + hadrons. A recent result[3] from the CERN ISR has indicated that such intermediate χ states are important in proton-proton collisions. We report here on results obtained in a search for $\chi \to \psi + \gamma$ in $\pi^- N$ interactions.

The Chicago Cyclotron Magnet Spectrometer facility was used in an open geometry to detect and identify particles associated with dimuon production. A schematic drawing of the apparatus is shown in Figure 1. Negative pions of 217 GeV/c strike a 2.5 cm-long beryllium target followed by a 40 cm-long, 3.0 cm-diameter liquid hydrogen target. The trigger required two penetrating particles in diagonally-opposed quadrants of a scintillation counter hodoscope located downstream of a steel hadron absorber (2.5–3.5 m thick). This particular geometric constraint reduced the trigger rate due to prompt low-mass dimuons (ρ,ϕ) and due to low-mass dimuons originating from pions decaying in flight. During most of the runs, the π^- beam intensity was 8×10^5 π/pulse. The K^- and $\bar{p}$ contaminations of the beam were about 2.5% and 0.5% respectively. The typical trigger rate was 3 per pulse. This report is based on a total incident beam flux of 4×10^{10} pions.

Charged particle positions were measured upstream of the magnet by a 7500 wire system of multiwire proportional chambers and downstream of the magnet by 14 gaps (28 planes) of multiwire spark chambers. The magnet was run with a 14-kG central field. A 2 m-long 18 cell threshold Cherenkov counter allowed partial π-K separation in an 8-30 GeV/c momentum interval. A 76-element lead-glass Cherenkov array (each 6.35 cm x 6.35 cm x 61 cm, 20.5 radiation lengths) detected photons.

The lead-glass array calibration was monitored during this experiment with an LED system. Following the data run, the array was moved into an electron beam in the Proton area at Fermilab for calibration. To demonstrate the resolution of the lead-glass system, we show in Figure 2 the γ-γ mass spectrum for a sample of hadronic triggers from the data run. There is a clear π^0 peak with a full width at half maximum of $\sim$ 35 MeV. The η^0 is not seen due to the limited transverse acceptance of the array. The background curve in Figure 2 was calculated by pairing γ's from separate events. All photons are required to have an energy above 5 GeV. Hadronic showers have been removed by a cut on the lateral spread of the shower.

The dimuon mass spectrum above 2.7 GeV is shown in Figure 3. A clear ψ peak of about 160 events above background is evident. The full width at half maximum of the ψ peak is 100 MeV and is consistent with the expected resolution of the apparatus. Events with $\mu^+\mu^-$ effective mass between 2.9 and 3.3 GeV were fit to the one-constraint (1-C) hypothesis that the $\mu^+\mu^-$ are from the decay of the ψ(3098). Demanding a chi-squared less than 10 for the 1-C fits extracts 163 ψ events (referred to hereinafter as 1-C fit ψ's); we estimate the non-ψ contamination in these 163 events to be less than 10 events. Figure 4 shows the Feynman x (x_F) and transverse momentum (p_T) distributions for the 1-C fit ψ events. The raw x_F distribution peaks at 0.45, while the acceptance corrected distribution can be fit to the form $(1/E)(1-x_F)^A$ with A = 1.25 ± 0.23. The p_T dependence of the ψ fits the form $(p_T)\exp(-Bp_T)$ with B = 1.45 ± 0.13. We have also fit the x_F and p_T distributions separately for π^-p and π^-Be events. The results of these fits are given in Table I.

We have examined the photons associated with the 1-C fit ψ events. Photons with (1) energy less than 5 GeV, (2) lateral shower distribution consistent with a hadronic shower, or (3) γ-γ invariant mass consistent with the π^o were removed. The cut (1) removes photons in an energy range where our shower finding algorithm is uncertain, but does not remove any χ signal (photons from χ's must have E_γ > 10 GeV in our apparatus). The cut (2) on lateral shower distributions removes $\sim$ 70% of hadronic showers and only $\sim$ 15% of real photon showers. Figure 5(a) shows the ψ-γ invariant mass spectrum. The estimated background (dashed line in Figure 5(a)) was obtained by taking photons from events with $\mu^+\mu^-$ invariant mass in the range 2.7-2.9 GeV and 3.3-4.0 GeV (Non-ψ events) and combining these photons with the complete sample of 1-C fit ψ's. This background was then normalized to the number of photons observed in the Non-ψ events, scaled by the ratio of 1-C fit ψ events to Non-ψ events. The result of subtracting this background is shown in Figure 5(b).

Figure 5 shows a clear peak in the ψ-γ mass spectrum at $\sim$ 3.5 GeV. We fit the distribution in Figure 5(a) with a Gaussian plus the normalized background and find an excess of 17.2 ± 6.6 events centered at 3.51 GeV with a σ of 75 MeV. The confidence level of this fit[4] is 99%. We expect a ψ-γ mass resolution with $\sigma \sim$ 60 MeV based on the observed width of our π^o peak (see Figure 2) since the error is primarily in the photon energy determination.

If we attribute the excess events at 3.5 GeV to the process $\chi \rightarrow \psi\gamma$, we obtain, with a Monte Carlo[5] determined acceptance of 0.15,

$$\left.\frac{(B_{\chi\rightarrow\psi\gamma})(\sigma_\chi)}{\sigma_\psi}\right|_{x_F\sim 0.5} = 0.70 \pm 0.28.$$

This result compares favorably with the value of 0.43 ± 0.21 obtained by Cobb et al.[3] at $x_F \sim 0$ in pp collisions at $\sqrt{s}$ = 55 GeV.

Our $\sigma \sim 60$ MeV ψ-γ mass resolution does not allow us to clearly separate the $\chi(3415)$: $\chi(3510)$: $\chi(3555)$ states, although our fit indicates the higher mass is preferred. We note that a current gluon fusion model[1] predicts production cross sections for these states in the ratio 3:4 for $\chi(3415)$: $\chi(3555)$. Production of the $\chi(3510)$ by fusion of two gluons is forbidden. Folding in the measured[6] branching ratios for $\chi \to \psi\gamma$, we would expect to see ψ-γ's in the ratio 1:6.5 for $\chi(3415)$: $\chi(3555)$. Our data is consistent with this ratio.

To recapitulate, our measurement of the ψ-γ mass spectrum in the region 3.4–3.6 reveals an excess of 17.2 ± 6.6 events above the expected background. Including acceptance corrections, this result implies that $\sim$ 70% of all ψ's in $\pi^- N$ interactions at 217 GeV/c near $x_F = 0.5$ come from the production of χ states followed by the decay $\chi \to \psi\gamma$.

We would like to thank the staff of the Fermilab Neutrino and Proton Areas for their help in this experiment and the members of the CHIO Muon Collaboration for the loan of equipment built by them. We also thank the University of Chicago for the loan of their Sigma-3 on-line computer and particularly S. C. Wright for his help with the Sigma-3. Mr. Stephen Hahn was instrumental in the data reduction at the University of Illinois. This work was supported by the U. S. Department of Energy under contracts EY-76-C-02-3000, EY-76-C-02-3064, EY-76-C-02-1195, EY-76-C-02-3023, and by the Science Research Council (United Kingdom).

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2. S. D. Ellis, M. B. Einhorn and C. Quigg, Phys. Rev. Lett. 36, 1263 (1976).

3. J. H. Cobb *et al.*, Phys. Lett. 72B, 497 (1978).

4. The confidence level of a fit to the data in Figure 5(a) by the background curve alone (no signal) is 12%.

5. The Monte Carlo calculation assumed $\chi(\sim 3.5)$ production according to $(d^2N/dx_F dp_T) \sim (1 - x)^2\, p_T \exp(-2\, p_T)$ and an isotropic decay of $\chi \to \psi\gamma$.

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7. J. G. Branson *et al.*, Phys. Rev. Lett. 38, 1331 (1977).

TABLE I. Results of ϕ invariant cross section fits for acceptance-corrected distributions in x_F and p_T. $(E)(dN/dx_F)$ was fit to the form $(1 - x_F)^A$ in the x_F range 0.1–0.9. $(E/p_T)(dN/dp_T)$ was fit to the form $\exp(-Bp_T)$ in the p_T range 0.0–3.2 GeV/c.

Interaction	A	Confidence Level	$B(GeV/c^{-1})$	Confidence Level
$\pi^- p$ and $\pi^- Be$	1.25 ± 0.23	0.013	1.45 ± 0.13	0.19
$\pi^- p$	1.11 ± 0.28	0.24	1.16 ± 0.18	0.18
$\pi^- Be$	1.39 ± 0.33	0.41	1.66 ± 0.22	0.86
$\pi^- C$[a]	1.93 ± 0.20	---	1.98 ± 0.13	---
$\pi^+ C$[a]	1.33 ± 0.21	---	2.06 ± 0.10	---

[a] These results are from Reference 7.

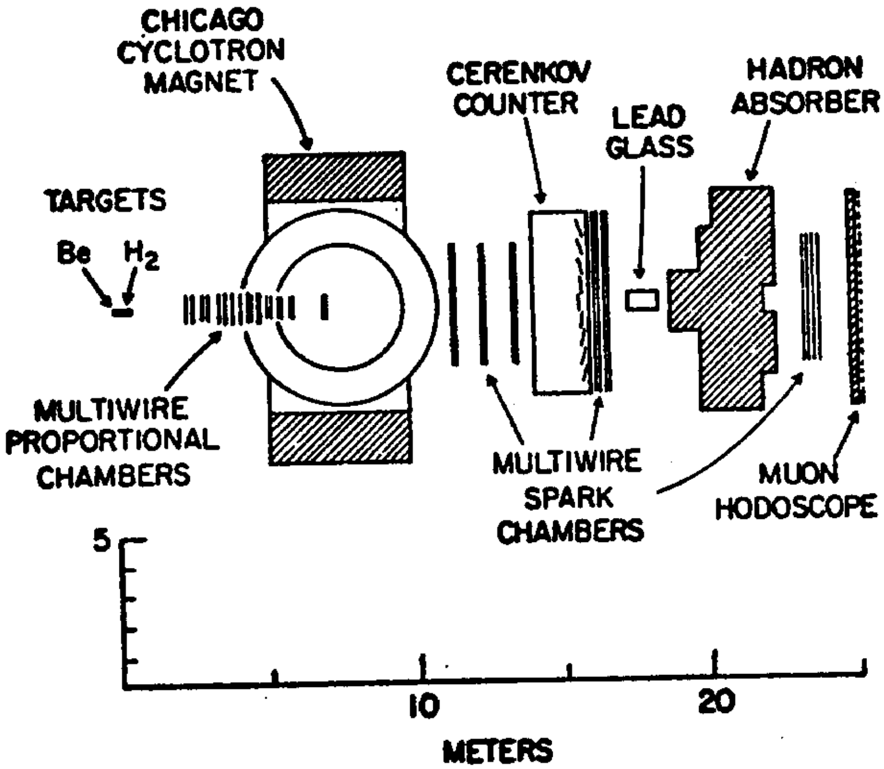


Fig. 1. The Chicago Cyclotron Magnet Spectrometer Facility as configured for this experiment.

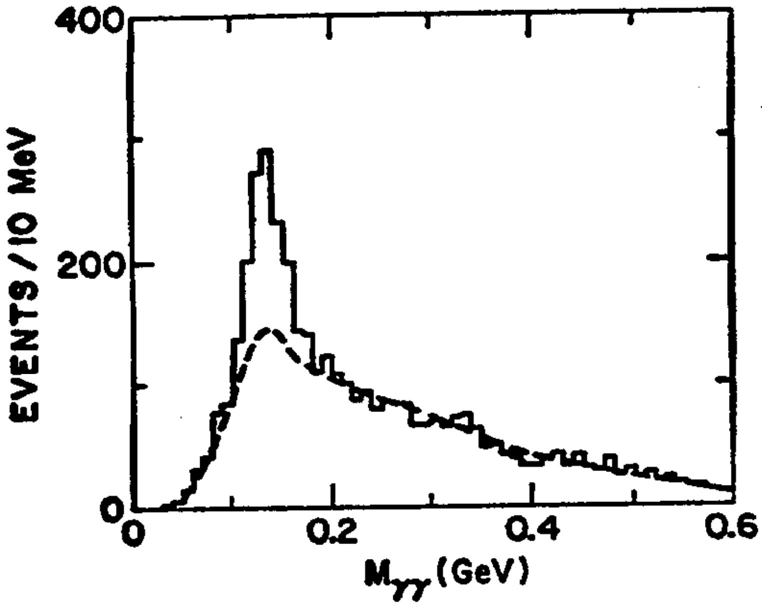


Fig. 2. The γ-γ mass spectrum for a sample of hadronic triggers. The curve is a background calculated using uncorrelated γ's and is normalised to the number of events in the mass range 0.25–0.50 GeV.

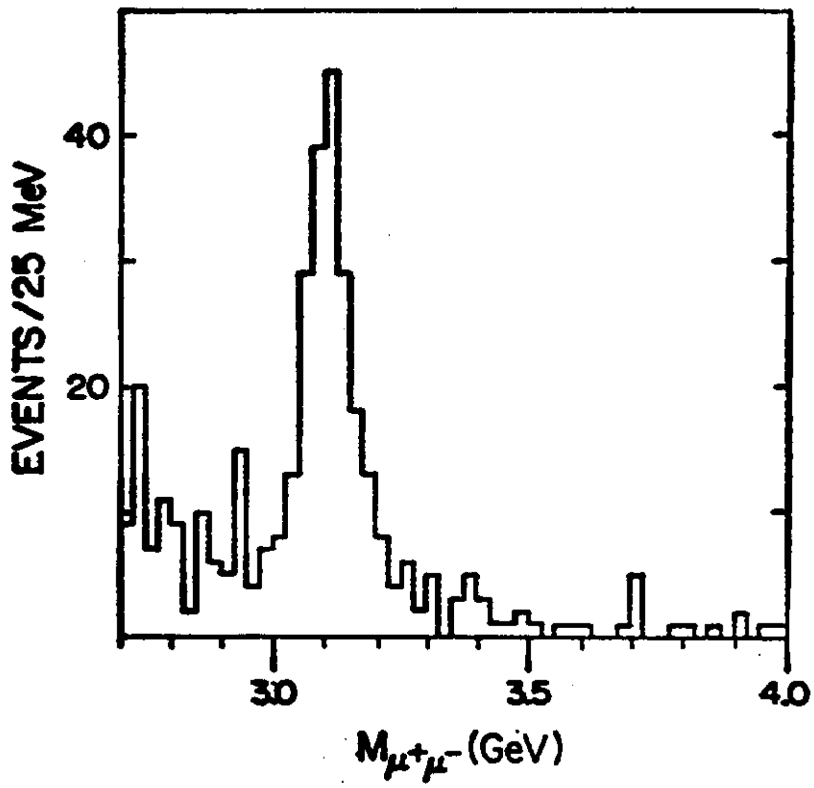
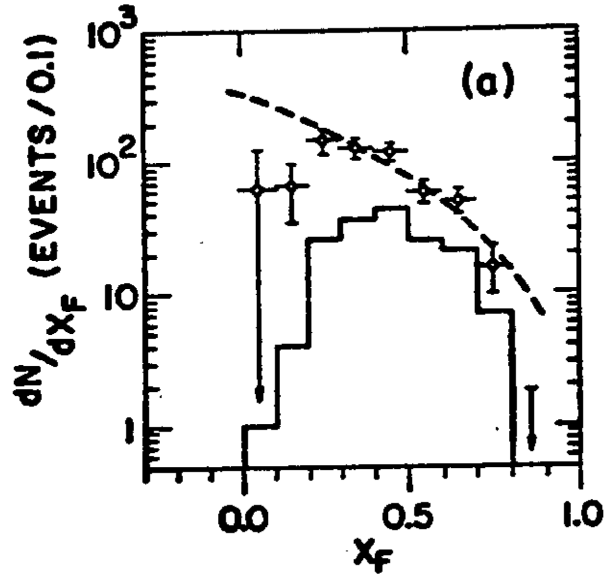


Fig. 3. The $\mu^+\mu^-$ invariant mass spectrum.



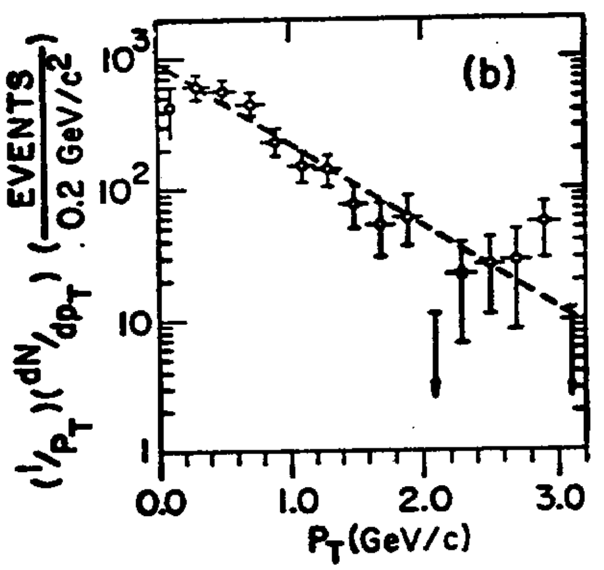


Fig. 4. (a) The x_F distribution for the one-constraint ψ event fits. The solid histogram indicates the raw data distribution and the open circles are the acceptance-corrected points. The dashed curve is a fit to the form $dN/dx_F \sim (1/E)(1-x_F)^{1.25}$ (see text).

(b) The acceptance-corrected distribution $(1/p_T)\ dN/dp_T$ for the one-constraint ψ event fits. The curve is a fit to the form $\exp(-1.45\ p_T)$ (see text).

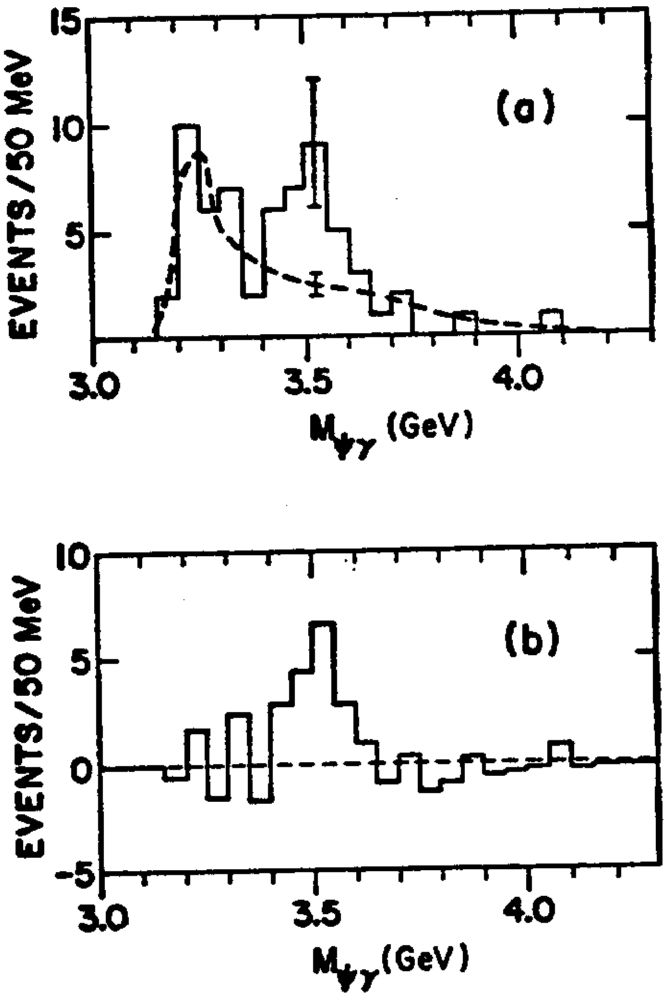


Fig. 5. (a) The ψ-γ invariant mass spectrum. The dashed curve is the estimated background (see text). The error bar on the background curve reflects the uncertainty in our normalization.

(b) The ψ-γ invariant mass spectrum after subtraction of the background shown in (a).