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ABSTRACT

Measurements of the energy and t-dependence of diffractive J/ψ photoproduction are presented. A significant rise in the cross section over the energy range 60-300 GeV is observed. We find that 30 ± 4% of the events are inelastic.

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The production of the J/ψ meson by photons[1] was observed almost immediately after its discovery in hadronic[2] and electron-positron[3] collisions. The early measurements [1-4] focussed on the extraction of the ψ-nucleon total cross section using the vector dominance model. More recently, there have been several attempts to describe ψ-photoproduction by means of constituent models such as photon-gluon fusion[5].

We have studied the production of ψ-mesons by photons up to the highest available energy, 300 GeV, incident on both liquid hydrogen and deuterium targets. In particular, we measure, in open geometry, the reactions

$$\gamma + (p \text{ or } d) \rightarrow \psi\ (\mu^+\mu^- \text{ or } e^+e^-) + X \qquad (1)$$

The Fermilab Broad Band Photon Beam struck a 41cm liquid target. Non-interacting photons traversed the detector, and deposited their energy in an integrating quantameter. Forward-going dilepton final states were detected in a multiparticle spectrometer, consisting of two analyzing magnets and a PWC tracking system, which is described elsewhere.[6] Recoil protons and target fragments were observed in a recoil detector added specifically for this experiment.

Tracks are called "inner" tracks if they pass through both analyzing magnets. "Outer" tracks passed through the first magnet only. The acceptance was ± 35 mr (± 85 mr) for inner (outer) tracks. The momentum resolution of an inner (outer) track was $\Delta p/p = 0.015\%\ p\ (0.045\%\ p)$.

A fly's-eye array of lead glass blocks, preceded by a layer of blocks placed transversely, identified inner electrons. A lead-scintillator shower counter tagged outer electrons. The lead glass, hadron calorimeter (7 absorption lengths), and an additional 72" of steel absorbed hadrons so that a crossed scintillator hodoscope at the back of the detector could identify inner muons. An array of scintillators behind the yoke of the second magnet flagged outer muons.

The recoil detector consisted of three concentric hexagonal counter arrays around the target. The inner and middle rings contained 6 and 18 scintillation counters, respectively. The outer ring contained 12 lucite Cherenkov counters. These rings provided azimuthal angle resolution of $\pm 10^{\circ}$ for protons with momenta greater than 280 MeV/c.

The trigger collected events with two muon candidates or two electron candidates, at least one of which was an "inner" track. A fast trigger processor, the M7[7], inspected each event to verify that there was at least one good track pointing at the target.

The dimuon analysis required each track to register hits in the appropriate muon counters after allowances were made for multiple scattering. Hadronic punch-throughs and pion decay in flight contributed negligible background under the ψ. Figure 1a shows the mass spectrum for $M_{\mu^+\mu^-} > 2.0$ GeV/c^2 for inner-inner (unshaded) and inner-outer (shaded) dimuons. The center of the ψ peak is 3.08 GeV/c^2 and the RMS width is 40 MeV/c^2 for inner-inner ψ's and 70 MeV/c^2 for inner-outer ψ's. Events range in energy from 50 GeV, where the spectrometer acceptance cuts off, to 300 GeV, where the photon spectrum runs out.

The dielectron analysis required the position of each track at the lead glass to be within a 3" radius of the position from the shower reconstruction program. Each track was required to have its ratio of shower energy divided by momentum be greater than 0.85. For 30% of the events, a photon, radiated by one of the electrons, was found and the energy and direction of the appropriate track corrected (bremsstrahlung correction).

The mass spectrum for $M_{e^+e^-} > 2.0$ GeV/c^2 is shown in Figure 1b. The mean value of the ψ mass peak is 3.09 with a width of 70 MeV/c^2. The shaded region in Fig. 1b is the ψ mass spectrum before bremsstrahlung correction.

The spectrometer acceptance was calculated using a Monte Carlo program with the following inputs: a) A $1 + \cos^2\theta$ decay angle distribution. This was found to be consistent with the data. b) An exponential dependence on four momentum transfer squared, t, with a slope b, of -4 GeV^{-2}. Varying b from 60 to 1 changed the acceptance by less than 20% and produced no appreciable energy dependence. The Monte Carlo program included effects of beam size, target length, chamber and trigger inefficiencies, and electron bremsstrahlung.

The yields are also corrected for electronic deadtime (17%), accidental muon halo vetoes (10%), and trigger counter inefficiency (3%). The branching ratio to dimuons and dielectrons are each taken to be 7%.(8)

The flux calculation is the major possible source of energy dependent systematic uncertainties. The number of photons at each energy is derived from the total beam power and the shape of the photon spectrum. The beam power is measured with a Wilson-type quantameter. The shape of the photon spectrum was measured by four methods: 1) A 20 radiation length lead glass block was placed in the beam and the energy of the individual photons was measured directly. The spectrum was corrected for energy leakage out of the block. 2) A sample of low mass Bethe-Heitler pairs were accumulated during normal data taking with a special, heavily pre-scaled, trigger. The e^+e^- energy spectrum is corrected for acceptance and bremsstrahlung. 3) Monte Carlo triplet

(e^-e^+ + recoiling atomic electron) events were generated according to the determined photon energy distribution and their energy dependence was compared to the observed spectrum of triplets. 4) The observed yield of dimuon pairs in the mass range 1.2 to 2.8 GeV/c^2 was divided by the Bethe-Heitler pair production cross section and acceptance factors calculated by a Monte Carlo program to get the absolute number of photons at each energy. Since the data for this last method were collected under the same trigger as the ψ data, it serves as a check for additional energy dependent effects arising from the triggering scheme or the data analysis procedures. Fig. 2 shows the spectrum shapes determined by all four methods. The agreement is excellent.

A correction to the cross section for background under the ψ mass peak was determined for each energy and t-bin by using the Bethe-Heitler production formula to extrapolate from the region between 2.0 and 2.8 GeV/c^2. This background subtraction is very small except in the lowest t-bin, where it is as large as 10%.

The estimated error in absolute normalization is 15%. Energy dependent systematic errors are less than 5% below 200 GeV and are less than 10% from 200 to 300 GeV.

The ratio $\sigma \cdot B_{ee}$ to $\sigma \cdot B_{\mu\mu}$, where σ is the cross section per nucleon, from the deuterium sample is 0.98 ± 0.06. Fig. 2 gives the average of these two partial cross sections as a function of energy. The cross section calculations are based on 1650 two-track events in the mass range 2.85 GeV/c^2 to 3.35 GeV/c^2. The forward spectrometer has a large acceptance for additional charged tracks, but such events are very rare (5%) and are excluded from this data sample. Less than 3% of the remaining events show any evidence for associated photons. The two-track events represent primarily the sum of "elastic " scattering, diffractive target dissociation, and other events in which at most the target has fragmented. The cross section rises significantly in the energy range from 60 to 300 GeV and is well fitted by a linear dependence with an energy slope of 0.007 ± 0.0014 nb/GeV.

About 20% of the data was taken with a liquid hydrogen target. The energy dependence, based on 175 two track events, also shown in Fig. 3, is consistent with the deuterium data. These events are studied further by using information available from the recoil detector. Elastic events are identified by (a) a track in the azimuthal location opposite to the transverse momentum of the ψ, to within multiple scattering and resolution tolerances, (coplanarity requirement), (b) the absence of hits in other elements, (c) a pulse height consistent with a recoil proton, (d) the absence of any hit in the detector when the proton would be expected to range out in the target ($t \lesssim 0.07$ GeV^2/c^2). With these definitions, 30% ± 4% of the events are inelastic.

Figure 4 shows the t-dependence of the elastic events on hydrogen. The curve superimposed on the data is a fit, over the t-range from 0.0 to 1.0 GeV^2/c^2 to the form $d\sigma/dt = A \exp(bt + ct^2)$ with $A = 80 \pm 13$ nb/GeV^2, $b = -5.6 \pm 1.2$, $c = 2.9 \pm 1.3$. The total elastic cross section at an average energy of 150 GeV is 18 ± 2 nb. The ψ-nucleon cross section may be extracted from the elastic cross section on hydrogen using the standard VMD prescription, neglecting the real part, and using the photon-ψ coupling from the leptonic width as measured at SPEAR.(8) We find $\sigma_{tot}^{\psi N} = 1.5 \pm 0.2$ mb at an average energy of 150 GeV in good agreement with other measurements(9) at these energies.

The hydrogen data is too weak statistically to study the energy dependence of $d\sigma/dt$ $(t = 0.0)$ but the deuterium data can be used for this purpose. At t-values above 0.1 the deuterium differential cross section agrees with the hydrogen cross section and therefore represents single nucleon scattering. In the t-interval below 0.1, there is a small, but obvious, coherent peak in the deuterium data. The rise in the cross section for deuterium occurs uniformly across the whole t-distribution. Moreover, the coherent peak also rises. These results show that the elastic scattering participates in the cross section increase and strongly suggests that inelastic processes, which are more important at large t, also contribute. To determine the energy dependence of $d\sigma/dt$ $(t=0)$, the deuterium data is first fit for the values of $d\sigma/dt$ $|t|>0.1$ GeV^2. These values were then corrected for inelastic contamination (11 ± 3% at $|t| = 0.1$ GeV^2 as determined from the hydrogen data) and extrapolated from $|t| = 0.1$ GeV^2 to $t = 0$ using the shape of the elastic t-distribution as measured from hydrogen. Fig. 5 shows the results for $d\sigma/dt$ ($t = 0.0$) per nucleon in four energy bins and compares it to other experiments. The rise from 53 nb/GeV^2 to 106 nb/GeV^2, interpreted from the viewpoint of VMD, implies an increase in $\sigma_{tot}^{\psi N}$ of 40% from 60 to 300 GeV.

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FIGURE CAPTIONS

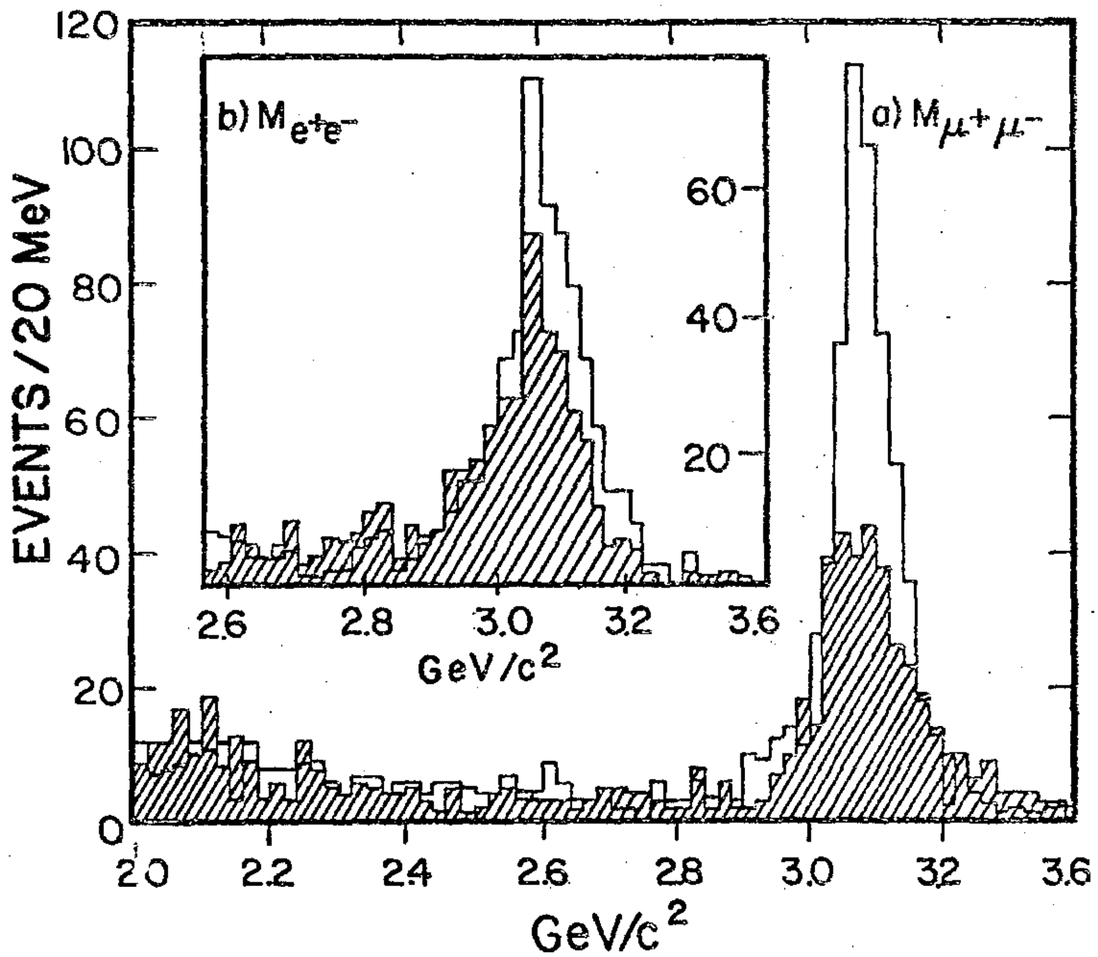
1. Dilepton mass spectra (two track events only).
   a) dimuon spectrum, b) dielectron spectrum

2. Shape of photon spectrum determined by four different methods.

3. Cross section vs. energy for ψ photoproduction

4. Elastic cross section on hydrogen averaged over energies from 60 to 300 GeV.

5. Cross section, $d\sigma/dt$ ($t = 0.0$) vs. energy. Error bars reflect statistical uncertainties only. An additional 20% systematic uncertainty is due to the uncertainties in the parameters used for extrapolation to $t = 0$.



120
100
80
60
40
20
0
EVENTS/20 MeV
2.0
2.2
2.4
2.6
2.8
3.0
3.2
3.6
GeV/c²
a) $M_{\mu^+\mu^-}$
b) $M_{e^+e^-}$
60
40
20
2.6
2.8
3.0
3.2
3.6
GeV/c²

Fig. 1

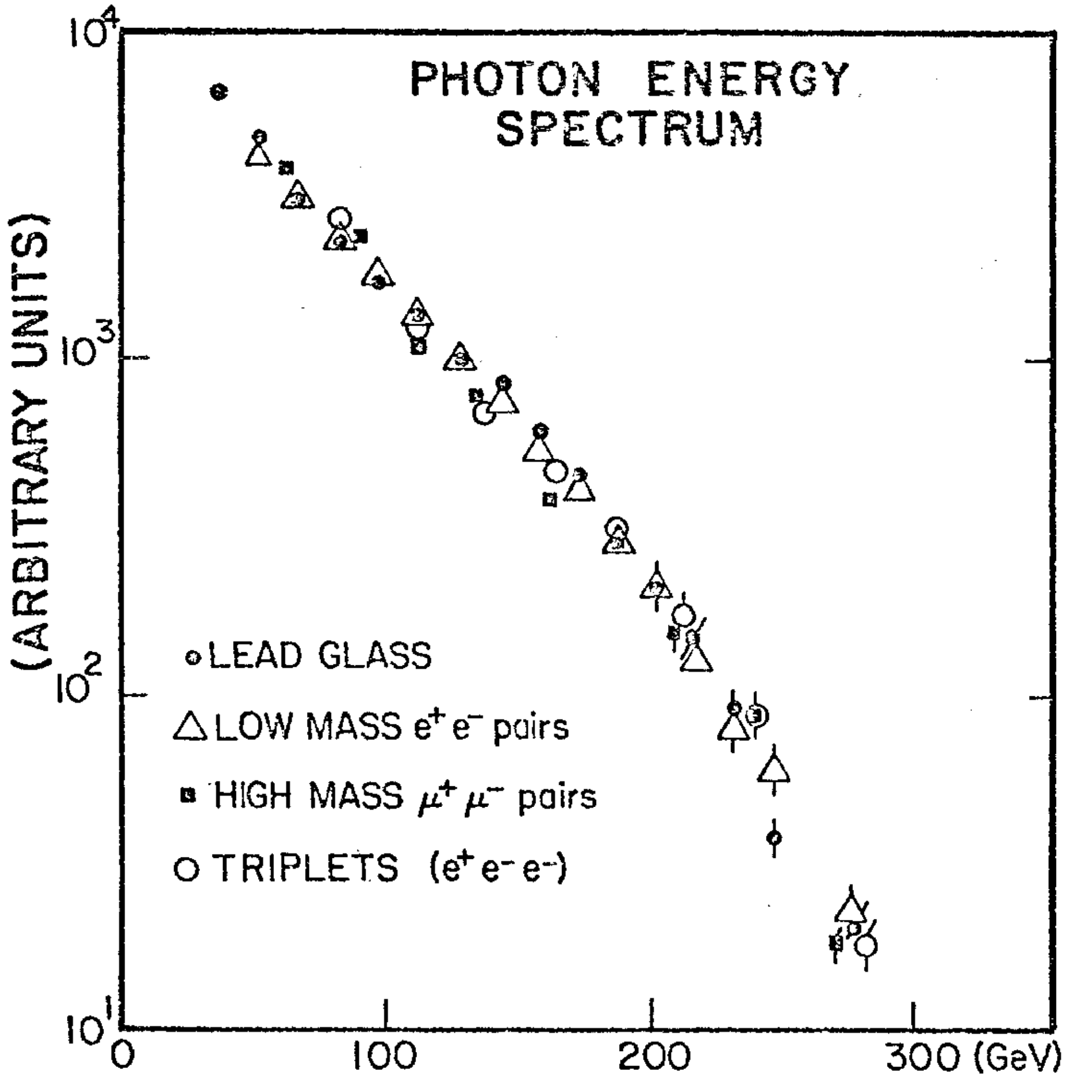
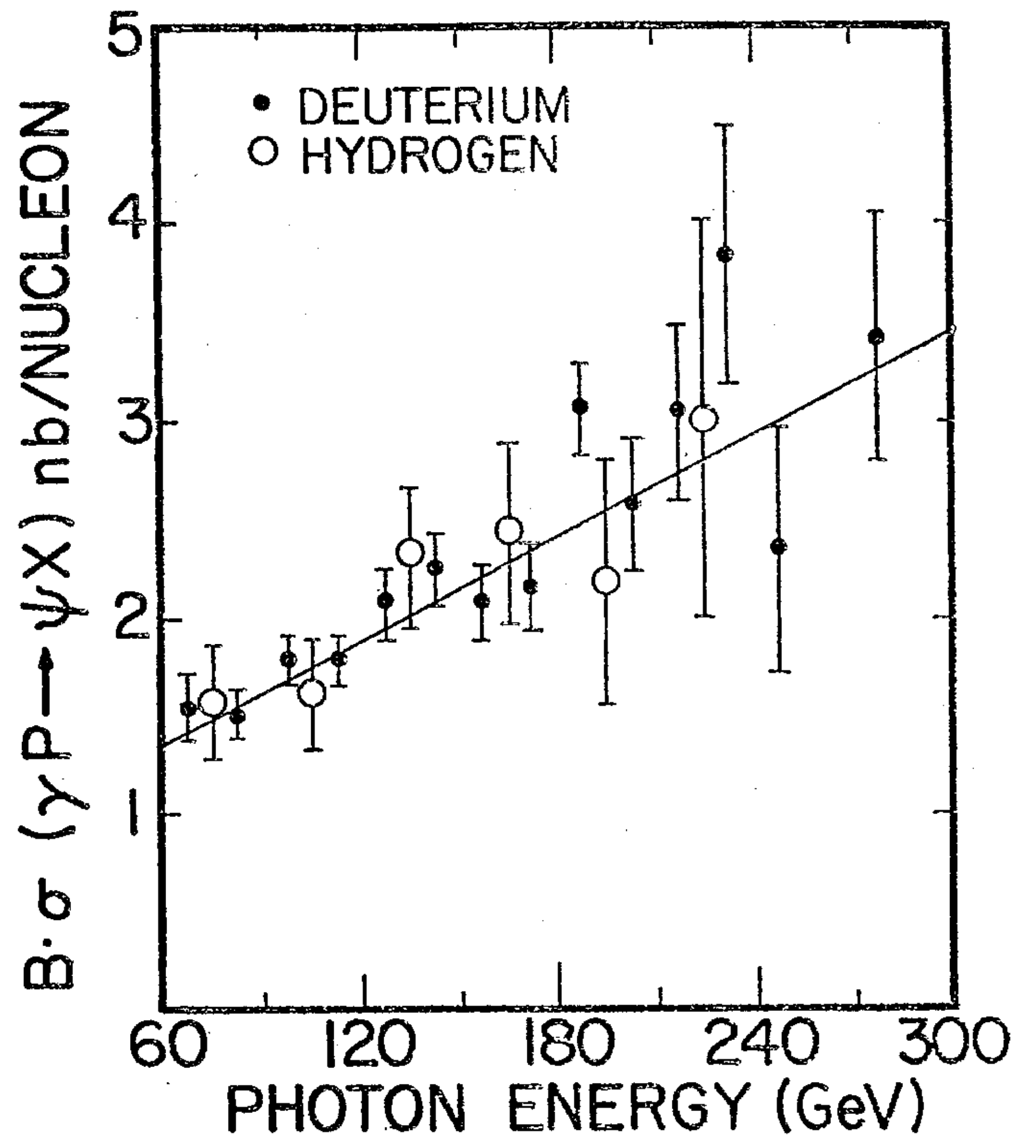

PHOTON ENERGY
SPECTRUM
(ARBITRARY UNITS)
10^4
10^3
10^2
10^1
LEAD GLASS
LOW MASS e+ e- pairs
HIGH MASS μ+ μ- pairs
TRIPLETS (e+ e- e-)
0
100
200
300 (GeV)

Fig. 2



5
4
3
2
1
• DEUTERIUM
○ HYDROGEN
B·σ (γP → ψX) nb/NUCLEON
60
120
180
240
300
PHOTON ENERGY (GeV)

Fig. 3

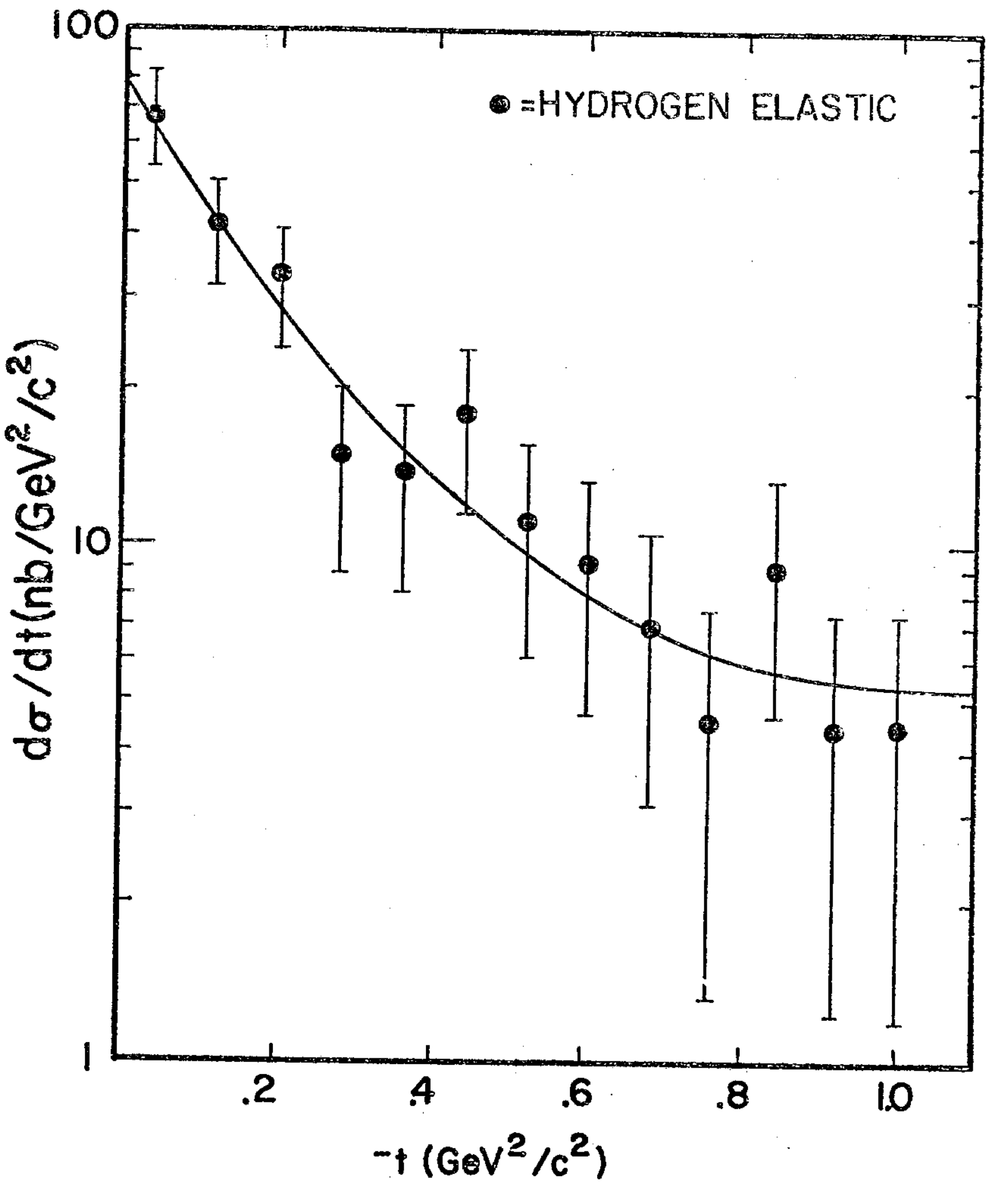


Fig. 4

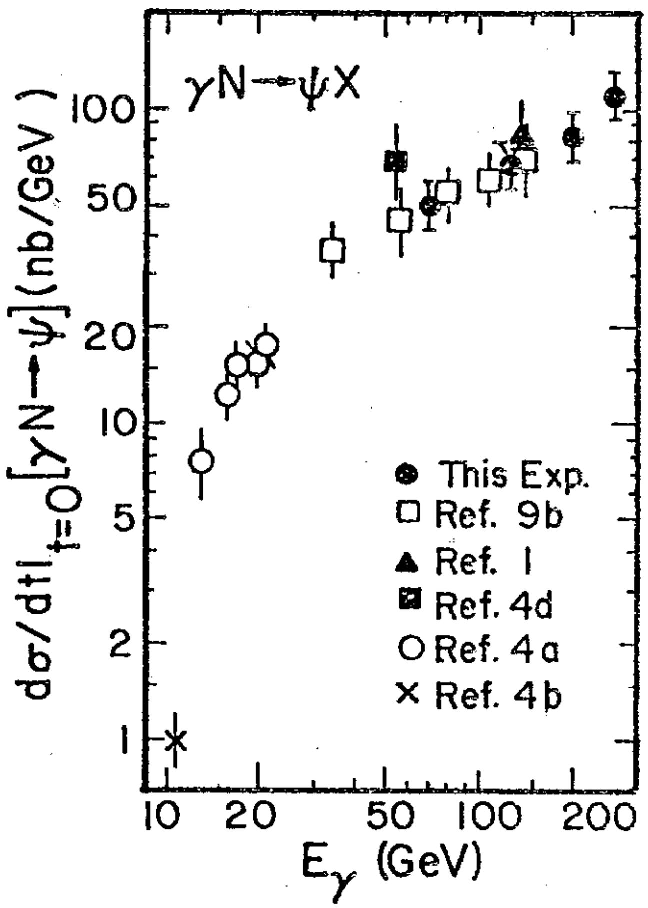

γN→ψX
dσ/dt|_{t=0}[γN→ψ] (nb/GeV)
E_γ (GeV)
100
50
20
10
5
2
1
10
20
50
100
200
This Exp.
Ref. 9b
Ref. 1
Ref. 4d
Ref. 4a
Ref. 4b

Fig. 5