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A B S T R A C T

Inelastic and elastic J/ψ photoproduction on hydrogen are investigated at a mean energy of 105 GeV. The inelastic cross section with $E_\psi/E_\gamma < 0.9$ is significantly lower than the corresponding result for muoproduction on iron targets, but is consistent with a second order perturbative QCD calculation. The mean p_t of the inelastic events is larger than that of the elastic events, again in accord with the QCD calculation.

There has been considerable interest in the use of perturbative QCD to describe J/ψ production by real and virtual photons.[1-5] Success has been achieved in describing the energy dependence, and, to a lesser extent, the magnitude of the elastic cross section.[5,6] Recent measurements of inelastic muoproduction cross sections on iron targets[7,8] confirm the dependence upon $z = E_\psi/E_\gamma$ predicted[2] by QCD, but greatly exceed the predictions in magnitude. In what follows, we describe the inelastic and elastic production of J/ψ mesons on hydrogen by real photons. Further details of this analysis can be found in reference 9.

The experiment was performed with the Fermilab Tagged Photon Spectrometer, which is described elsewhere in detail.[9,10,11] Tagged photons with energies $60 \leq E_\gamma \leq 160$ GeV interacted in a 1.5 meter liquid hydrogen target. The forward spectrometer had nearly full acceptance for charged particles, whose momenta were determined by a system of 29 drift chamber planes and two magnets, and for photons, whose positions and energies were measured in two large electromagnetic calorimeters. Muons were identified by minimum ionizing signals in an iron-scintillator hadron calorimeter and hits in a set of scintillator hodoscopes downstream of an iron muon filter. A recoil detector,[12] consisting of a set of PWC's and scintillators of cylindrical geometry surrounding the hydrogen target, was used to determine the momenta and particle types of tracks emerging from the target at large angles.

A dimuon trigger was created by hits in two or more of the muon hodoscopes. Offline, events with dimuon triggers were required to have at least one pair of oppositely charged identified muons which verticized within the target. The resulting dimuon mass plot is shown in Figure 1b. The J/ψ mass region is taken to be 2.8 to 3.4 GeV/c^2. The J/ψ is also seen in the e^+e^- decay mode (Figure 1a). The ratio of dielectron to dimuon elastic cross sections is consistent with unity. Because the dielectron events were recorded on a recoil trigger which is biased toward elastic production,[10] they are excluded from the inelastic analysis that follows.

Events are classified as inelastic if they satisfy one or both of the following criteria: 1) Forward Inelastic - Additional forward tracks, photons, or hadronic neutrals accompany the J/ψ; 2) Recoil Inelastic - The data from the recoil detector is inconsistent with the parameters of the single recoil proton calculated from the incident photon and the reconstructed J/ψ, assuming elastic production. The systematic uncertainty in assigning the 147 dimuon events is ±4 events for the forward case and ±6 events for the recoil case.

The data were divided into seven categories based upon the above classifications (and upon a z cut, as discussed below). In Table I, column 1, the raw numbers of events in each category are displayed. Background was estimated by joining the mass regions above and below the J/ψ with a smooth curve. The hashed area in Figure 1b is the mass spectrum for the forward inelastic events.

The efficiencies for detection of elastic and inelastic events were calculated by separate Monte-Carlo programs. In both cases the results were relatively insensitive to the exact kinematical distributions used for the J/ψ and, for the inelastic case, the accompanying particles.

The z value for each event was determined by $z = E_\psi/E_\gamma$, for the case of low z events; for the higher z events, where tagging energy resolution can allow $z > 1$, the formula $z = E_\psi/(E_\psi+F\cdot E_x)$ was used, where E_x is the detected energy accompanying J/ψ and F is an efficiency correction factor.

Events that are inelastic only in the recoil system are assigned to the highest z bin. The resulting z spectrum, corrected for efficiency, is shown in Figure 2. A cut of $z < \sim .9$ (category 7 of Table I) is often used both experimentally[7,8] and in the theory[2] to isolate the truly inelastic process from elastic and quasi-elastic processes.

The cross sections in each category and fractions of the total are shown in Table I, columns 2 and 3. The cross sections have an additional 25% normalization uncertainty.

Four of the forward inelastic events were fully reconstructed as $\psi' \rightarrow \psi\pi^+\pi^-$. This implies, after efficiency corrections, a ψ' photoproduction cross section consistent with previously measured results.[8,13] For comparison with theory it is desirable to measure direct inelastic ψ production as opposed to cascade production from higher mass charmonium states. To this end, we present in Table I, columns 4 and 5, the cross sections and fractions in each category after subtracting out the contributions estimated from the known ψ' cross section and branching ratios to ψX. The z spectrum of this contribution, determined by Monte-Carlo, is indicated by the points in Figure 2.

In Table II elastic and $z < \sim .9$ inelastic cross sections from this experiment, and their ratio, are compared to those (where available) of the Berkeley Fermilab Princeton (BFP),[7] European Muon Collaboration (EMC),[8] and Illinois Fermilab (IF),[14] groups. The EMC, BFP and IF data have been averaged over the photon energy range of this experiment, for comparison. The elastic numbers agree within the rather large errors, but it is clear that the inelastic cross section and the ratio from this experiment are substantially smaller than those from EMC and BFP. After ψ' subtraction, the numbers from this experiment become even smaller (Table I), and are consistent with the second order perturbative QCD inelastic cross section calculated by Berger and Jones;[2] the muoproduction cross sections are roughly a factor of 5 larger than the QCD predictions.[7,8] The $z < .9$ inelastic to elastic ratio for this experiment becomes .36 ± .06 (stat.) ± .06 (syst.) after ψ' subtraction.

Table I can be used to show that (31±6)% of the forward elastic events are recoil inelastic, in excellent agreement with the 30% reported by the IF group[14] for this number.

Figure 3 shows that the forward inelastic J/ψ p_t distribution is much flatter than that of the forward elastic, recoil elastic events. This phenomenon is predicted by perturbative QCD,[2] and is reported also by the BFP[7] and EMC[8] groups.

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TABLE CAPTIONS

1. The J/ψ data are divided into seven categories as indicated. The figure in parentheses is statistical error; the systematic error follows. Cross sections (only) have an additional 25% normalization uncertainty.

2. Comparison of inelastic and elastic J/ψ data with other experiments. The number in parentheses is the statistical error if followed by a systematic error; otherwise it is the overall error. The systematic errors for this experiment here also contain the normalization uncertainty. Cross sections are in nanobarns.

TABLE I

CATEGORY	EVENTS RAW	EVENTS BKD	σ(nb)	FRACTION	
All	147	23	21.5(2.1)1.4	1.0	
Forward Elastic	110	18	14.2(1.6)1.3	.66(.03).07	
Forward Inelastic	37	4	7.3(1.3)1.0	.34(.05).06	
Fwd. El. & Rec. In.	33	5	4.4(0.9)1.1	.20(.03).05	
Fwd. El. & Rec. El.	77	13	9.8(1.4)1.5	.46(.04).08	
Fwd. In. or Rec. In.	70	9	11.7(1.6)1.3	.54(.05).07	9
Inelastic z < .9	30	3	6.6(1.3)0.7	.31(.05).04	5.

TABLE II

THIS EXPT.	BFP	EMC
$\sigma_{\text{Fwd. Elas.}}$	σ_{Elastic}	$\sigma_{z \geq .95}$
14.2(1.6)3.8	19.5(0.7)2.9	12.9(1.)
$\sigma_{z < .9}$	$\sigma_{z < .9}$	$\sigma_{z < .95}$
6.6(1.3)1.8	15.5(0.7)3.1	20.6(1.8)
$\dfrac{\sigma_{z < .9}}{\sigma_{\text{Fwd. Elas.}}}$	$\dfrac{\sigma_{z < .9}}{\sigma_{\text{Elastic}}}$	$\dfrac{\sigma_{z < .95}}{\sigma_{z \geq .95}}$
.46(.07).08	.79(.08)	1.6(.2)

FIGURE CAPTIONS

1. a) Dielectron mass spectrum. There are 63 events in the J/ψ mass region, $2.8 \leq 3.4$ GeV/c^2. b) Dimuon mass spectrum. There are 147 events in the J/ψ region. The hashed region represents the forward inelastic events (category 3 of Table I).

2. Z distribution for inelastic J/ψ photoproduction. Dashed line indicates the contribution of the forward elastic, recoil inelastic events (category 4 of Table I). Points are an estimate of the contamination of the inelastic sample by ψ' production.

3. p_t distributions for totally elastic and forward inelastic J/ψ events. The mean p_t for the totally elastic is $.39 \pm .11$ GeV/c; for the forward inelastic, $.96 \pm .11$ GeV/c.

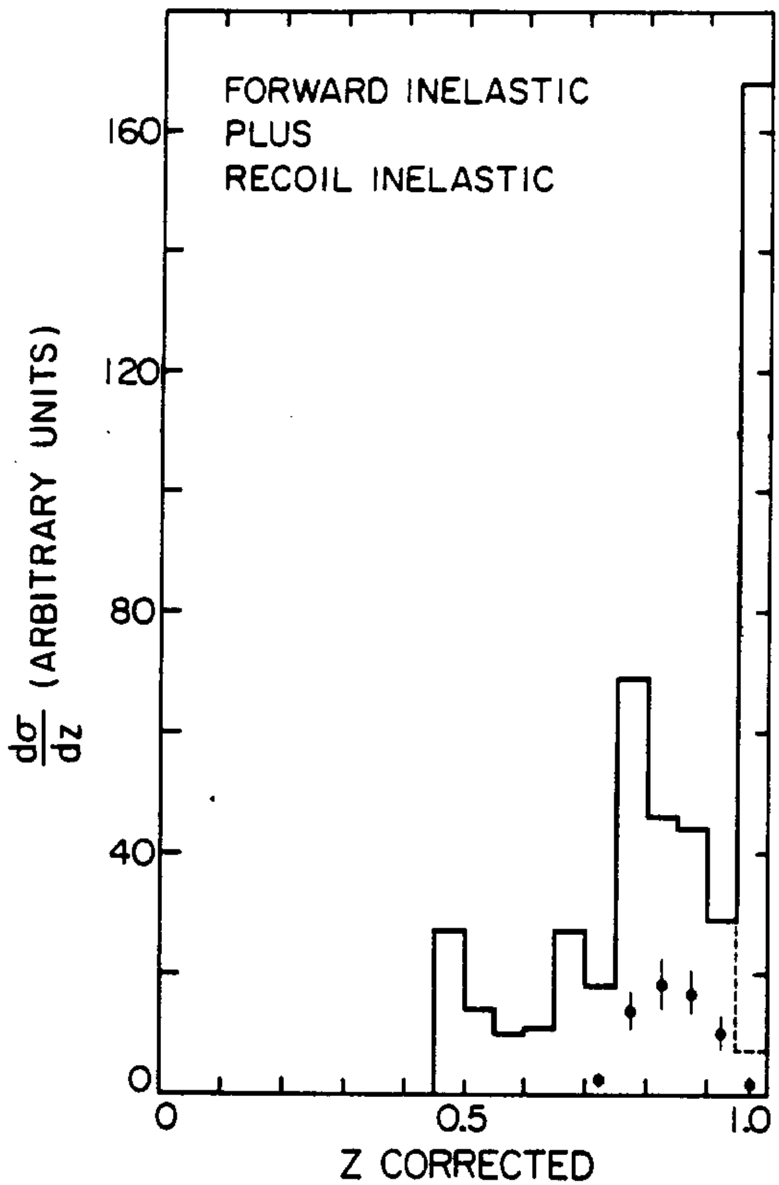
FORWARD INELASTIC
PLUS
RECOIL INELASTIC
160
120
80
40
0
$\frac{d\sigma}{dz}$ (ARBITRARY UNITS)
0
0.5
1.0
Z CORRECTED

Figure 2

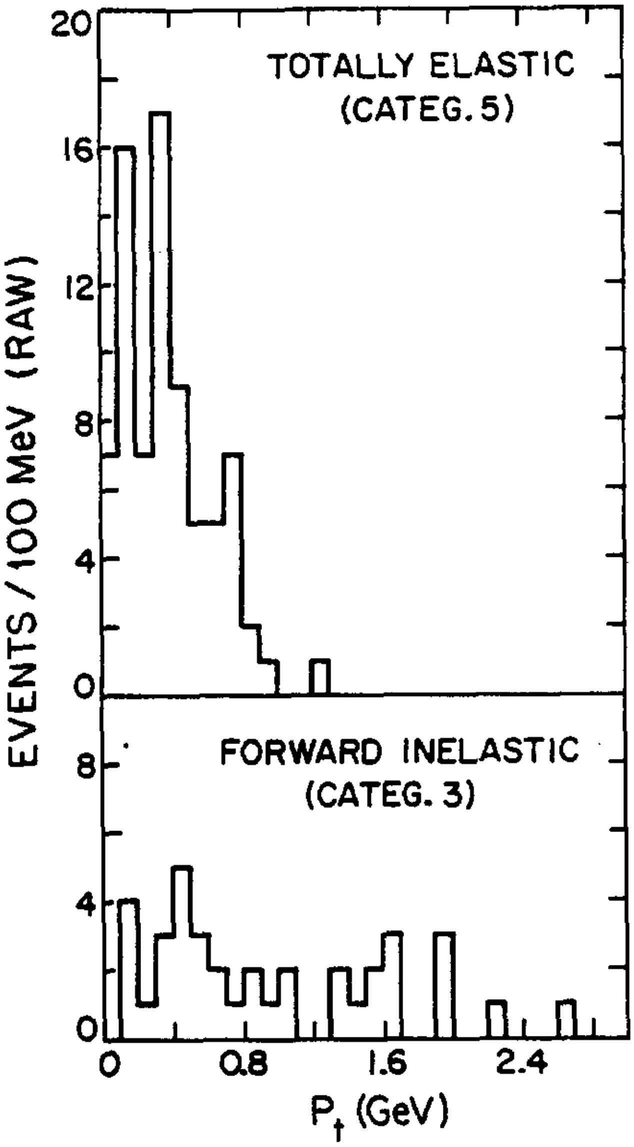
TOTALLY ELASTIC
(CATEG. 5)
FORWARD INELASTIC
(CATEG. 3)
EVENTS / 100 MeV (RAW)
20
16
12
8
4
0
8
4
0
0
0.8
1.6
2.4
P_t (GeV)

Figure 3

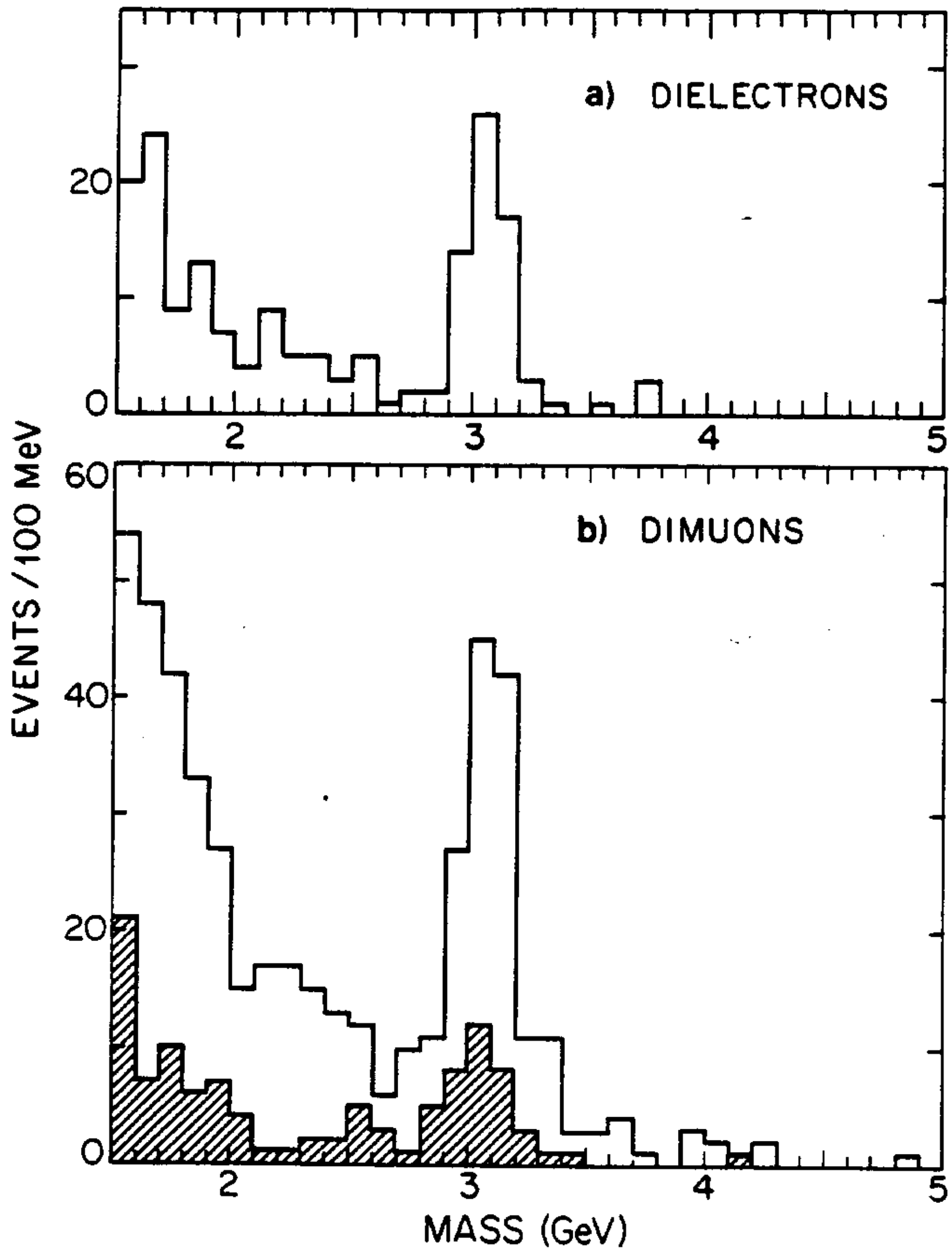
a) DIELECTRONS
b) DIMUONS
EVENTS /100 MeV
MASS (GeV)
0
20
40
60
2
3
4
5

Figure 1