FERMILAB-Pub-93/264-E

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August 1993

Accepted for publication in *Physics Letters B*

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Abstract

Measurements of elastic photoproduction cross sections for the J/ψ meson from 100 GeV to 375 GeV are presented. The results indicate that the cross section increases slowly in this range. The shape of the energy dependence agrees well with the photon-gluon fusion model prediction.

Photoproduction of the J/ψ meson has been studied extensively since its discovery and the cross section measured in the energy range 10 GeV to 250 GeV[1]. Here we present results from Fermilab experiment E687 which used the "Wide Band Photon" beam[2] to provide a useful spectrum of photons to nearly 400 GeV. This beam line and the E687 detector have been described in detail elsewhere[3]. Here we recall some features relevant to the present topic. The Wide Band Photon beam is a tertiary beam. Protons of 800 GeV incident on a beryllium target produce photons, primarily via the production and decay of π^0's. Charged particles are swept aside. The photons are then converted in lead to electron-positron pairs and the electrons are transported using conventional beam optics while the neutral hadrons and the positrons are absorbed in a dump. The transported electrons bremsstrahlung in a lead foil just upstream of the E687 spectrometer and their remaining energy determined as they are swept into the recoil electron shower hodoscope (RESH). The bremsstrahlung photons form the photon beam for this experiment. The neutral hadron contamination is approximately 10^{-5} per photon.

The E687 spectrometer is a multiparticle detector[3]. Only certain components of the spectrometer are of interest for identification and reconstruction of the J/ψ signal. A pair of large aperture analysis magnets are operated with opposite polarities. Silicon microstrip detectors (SSD) provide high resolution tracking upstream of the first magnet, and immediately after the Be target. Proportional wire chambers (PWC) complete the tracking system and momentum measurements. Between the magnets there are three stations of four views each, and after the second magnet, two stations of four and three views respectively. At the downstream end the "Beam Gamma Monitor" (BGM), a lead-lucite calorimeter covering 4 mr around the beam center, monitors the beam photons. The muon detectors used in the present measurement are located downstream of the PWCs and cover the polar angle of ± 30 mr. They consist of three planes of scintillation counters for triggering and four planes of proportional tubes for position measurement.

Approximately 6×10^7 events were written to tape from December 1987 to February 1988. The events used in the current analysis were from the "muon" trigger set, which required a signal consistent with at least two muons in the muon detectors. This sample is about 5% of the total data set. The muon triggered events were then further selected with the following criteria: 1.) Only two tracks coming from a single vertex were reconstructed in the event. 2.) The two tracks have opposite sign. 3.) At least one of the tracks is identified as a muon. [1] 4.) Dimuon invariant mass of the two particles is greater than 1.0 GeV/c^2. From this selection 2300 candidates were found. The dimuon mass spectrum is presented in Fig. 1 and clearly shows a J/ψ signal well above the background.

The error on the mass was calculated analytically event by event and the normalized variable $\Delta M/\sigma = (M - M_0)/\sigma_M$ was plotted, where M is the measured mass, M_0 is the nominal J/ψ mass, and σ_M is the calculated error on the measurement of M. A cut of three standard deviations was made and the resulting 310 events were defined as the "elastic" J/ψ's used in the present analysis. The effect of this cut is to enhance the J/ψ signal over the slowly varying distribution of the background events relative to a straight mass cut. A discussion of the validity of the "elastic" [2] definition will be presented in a subsequent section.

The square of the 4-momentum transfer or $|t|$-distribution of the "elastic" J/ψ sample is shown in Fig. 2. The coherent part of the cross section is expected to be small above a $|t|$ value of 0.15 $(\mathrm{GeV/c})^2$, both from diffractive models and from experimental results. A fit to the incoherent part was therefore made from 0.15 $(\mathrm{GeV/c})^2$ to 1.4 $(\mathrm{GeV/c})^2$ to the form $Ae^{(-a|t| + bt^2)}$. A second fit was then made to the range of $|t|$ from 0.0 $(\mathrm{GeV/c})^2$ to 1.4 $(\mathrm{GeV/c})^2$ using the form $Ae^{(-a|t| + bt^2)} + Be^{(-c|t|)}$. The parameters in the first term were fixed to the values obtained from the incoherent fit with the final result shown in Fig. 2. The χ^2 per degrees of freedom for this fit was 0.41.

The event background is almost exclusively from the Bethe-Heitler production of dimuons. The other possible background sources are ρ/ϕ mesons decaying to pions/kaons which either decay to muons or are misidentified as

[1]The details of muon identification are described elsewhere[4,5,6,7].

[2]The E687 spectrometer is not sensitive to diffractive target dissociation. The definition "elastic" used above corresponds to "forward elastic" (see [16]).

muons. The contribution to large dimuon masses (≥ 1 GeV/c^2) from these processes is negligible.

The background from the Bethe-Heitler production of dimuons is expected to have low momentum transfer (below 0.02 (GeV/c)^2) both from theory and from the $|t|$ distribution of events outside the J/ψ mass peak in the present sample. Therefore, background events should populate the first bin of the $|t|$ distribution almost exclusively. The second term of the second fit is interpreted as arising from the coherent "elastic" events and the residual background. The number of events under the second term is found to be 89 ± 26 events, while the number of Bethe-Heitler events in the "elastic" sample is estimated, from the normalized mass distribution, to be 16^{+6}_{-4}. The effect of slope smearing from varying the bin size was found to be negligible in comparison to the uncertainty from the fit parameters.

Acceptance and reconstruction efficiencies for elastic vector meson photoproduction and Bethe-Heitler production of dimuons were measured by simulating the spectrometer using GEANT3[8], and an elastic vector meson photoproduction generator[9] with the cross section parameterized as:

$$\frac{d\sigma}{dt} = Ae^{-b|t-t_{min}|} \tag{1}$$

where t_{min} is the square of the minimum 4-momentum transfer. The slope parameter was taken to be 4 in the simulation but the acceptance was found to be insensitive to a change of b from 1 to 40 over the phase space of interest. The center of mass decay of the J/ψ meson was generated with a $1+\cos^2\theta$ distribution. Bethe-Heitler production of dimuons was simulated by a program described elsewhere[10]. This Monte Carlo program was also used to calculate cross sections for the Bethe-Heitler dimuon production which will be used later in this discussion.

Since the reconstruction and vertexing efficiencies for the J/ψ analysis were typically above 98%, most of the corrections came from acceptance. The total acceptance curves corrected for the detector and reconstruction efficiencies for the J/ψ events and the Bethe-Heitler dimuons are shown in Fig. 3.

The normalization for the cross section calculation was done using two methods[5,6]. One method consisted of using a scaler count from the BGM. Non-interacting photons went through the center of the detector, where there was little material, and struck the BGM. A scalar was incremented when the discriminated signal from the BGM was greater than 133 GeV. To measure the electron spectrum a special run was performed where the electrons were transported directly to the BGM. The photon spectrum was then obtained using the measured electron spectrum as an input to a Monte Carlo simulation of electron bremsstrahlung through the radiator. The number of photons as a function of energy was obtained by normalizing the electron energy loss spectrum to the photon count (or sum of coincident photon energies, in case of multiple bremsstrahlung). Having determined the number of photons per energy bin, the cross section per nucleus (Be target) for J/ψ production, can be written as:

$$\sigma_{J/\psi}(Be) = \frac{N_{J/\psi}}{A_{J/\psi} \cdot N_\gamma} \frac{1}{N_A \cdot \rho \cdot d \cdot e_t \cdot L \cdot Br(J/\psi \to \mu\mu)} \tag{2}$$

where $N_{J/\psi}$ is the number of J/ψ's, $A_{J/\psi}$ is the corrected acceptance for the J/ψ's, and N_γ is the number of photons. The target is described by its molar density ρ, its length d, its "efficiency" e_t, which is determined from the beam profile and the target geometry and calculated by Monte Carlo, and Avogadro's number, N_A. The additional factors are the live time of the detector L[5], and the branching ratio of J/ψ's into two muons, $Br(J/\psi \to \mu\mu)$ [11].

The second method used was to normalize to the Bethe-Heitler dimuons which appear as background to the J/ψ peak in Fig. 1. Given the fact that there is a substantial number of Bethe-Heitler dimuon pairs, [3] and also that the processes are calculable, it is possible to normalize the J/ψ cross section to the Bethe-Heitler cross section. In this method, the target and live-time factors cancel since the Bethe-Heitler dimuon events and J/ψ events are recorded simultaneously. Thus many of the systematic errors inherent in the first normalization method tend to cancel out. The J/ψ cross section per nucleus can be written as:

[3]There are typically a factor of 10 more Bethe-Heitler pairs than there are J/ψ dimuon pairs, except at the highest photon energies where both samples have similar statistics.

$$\sigma_{J/\psi}(Be) = \frac{N_{J/\psi}}{N_{BH}} \frac{A_{BH}}{A_{J/\psi}} \frac{\sigma_{BH}}{Br(J/\psi \to \mu\mu)} \tag{3}$$

where N_{BH}, A_{BH} and σ_{BH} are the number, acceptance and cross section of Bethe-Heitler dimuons respectively. The latter two quantities were obtained from a Monte Carlo simulation [10].

In addition, the number of photons per energy bin were calculated from the number of Bethe-Heitler dimuons. A comparison with the number of photons found from the BGM method is presented in Fig. 4 and shows excellent agreement.

The "elastic" sample, as defined above, was partitioned into energy bins of 50 GeV, assuming the energy of the dimuon system to be the energy of the incoming photon. As a test of our definition of the "elasticity" of the events used, the Z $(\equiv \frac{E_{J/\psi}}{E_\gamma})$ distributions for an "elastic" and "inelastic" sample are shown in Fig. 5. These data in Fig. 5 are from the 1990-1991 data set in which the beam tagging system was fully functional [4]. A small but equivalent subset to the 1987-1988 run is presented here. The definition used for the "elastic" sample was the same as that used for the 1987-1988 run. The "inelastic" events had the additional requirement of one or more charged tracks in association with the J/ψ in the primary. While the resolution of the beam tagging system does not allow the separation of an "elastic" from an "inelastic" event on an event by event basis, it does show that the amount of "inelastic feedthrough" [5] is small. One can estimate an upper limit for the "inelastic feedthrough" to be of the order of 8% from the small excess of events on the low tail of the "elastic" Z distribution and assuming that these events follow the same Z distribution as the "inelastic" events.

The Bethe-Heitler dimuon background was also partitioned. Bethe-Heitler events above a $|t|$ value of 0.05 $(\mathrm{GeV/c})^2$ were cut to eliminate inelastic production not simulated by the Monte Carlo. The numbers of events are shown in Table 1. The elastic J/ψ cross sections per nucleon are shown in Table 2. They were calculated from eq. 3, subtracting the coherent "elastic" component in each energy bin and assuming an A dependence of $A^{1.0}$. In addition

[4]For a full description of the tagging system see reference 3.

[5]A J/ψ event associated with no other charged track(s), but associated with neutral track(s).

Table 2 includes the results using the BGM normalization method (eq. 2), with a J/ψ signal defined with the additional constraint that both tracks be identified as muons. This requirement reduced the systematic uncertainties in the determination of the acceptance for this sample. The agreement between the two measurements of cross section is excellent. Quoted energy values are the averages of the events in each bin.

The systematic uncertainties in the cross sections in the Bethe-Heitler results are dominated by the fit to the |t| distribution in the subtraction of the coherent part from the total elastic sample and the amount of "inelastic" contamination. The systematic uncertainty is found by extending the fit $Ae^{(-a|t|+bt^2)}$ down to 0.1 (GeV/c)^2 and up to 0.2 (GeV/c)^2 from 0.15 (GeV/c)^2, and including the upper limit on the amount of "inelastic" feedthrough of 8%. The resulting variations in the cross sections are found to be +9% and -18%.

Fig. 6 shows the elastic cross section per nucleon from previous experiments along with the Bethe-Heitler normalization result from this analysis. The compilation includes results from SLAC[13], Cornell[14], E401[15], E516[16], and NA14[17]. All comparisons are for "forward elastic" cross sections assuming an $A^{1.0}$ dependence and corrected for the present value of $Br(J/\psi \rightarrow \mu\mu)$[11]. If one assumes a linear energy dependence for the Bethe-Heitler normalization result, a slope of 0.040 ± 0.015 nb/GeV is obtained. For comparison E401[15] [6] data is fit with a slope of 0.075 ± 0.017 nb/GeV.

A theoretical comparison is also included in Fig. 6, as the solid and dashed curves superimposed on the experimental results. The theoretical curves are the result of using different gluon distribution functions in the photon-gluon fusion model with the other parameters chosen as $m_c = 1.5\, GeV/c^2$, $f = 1/7$ [7], and $\alpha_s = 0.3$. One gluon distribution function, shown by the dashed curve, is based on the parameterized[18] form using measurements by the CDHS neutrino experiment[19] and extrapolated to a momentum transfer of

[6] We have compared to Fig. 3 of the E401[15] paper which represents the sum of elastic and inelastic "two track" events.

[7] The fraction of $c\bar{c}$ bound states, below open charm threshold, that actually become J/ψ.

10 $(\mathrm{GeV}/c)^2$ using the Altarelli-Parisi equations[20]. This gluon distribution function is in reasonable agreement with experimental measurements at momentum transfers of 10 $(\mathrm{GeV}/c)^2$ [21]. The solid curve assumes a second gluon distribution function of the form $xG(x) = 3(1-x)^5$. One must note that the theoretical curves are not uniquely constrained because of the multiple input parameters involved. They are shown only to demonstrate that theory and these data have similar energy dependence.

The present measurement of the cross section extends the upper energy range of elastic J/ψ photoproduction to 375 GeV. We have employed two normalization methods in this analysis which have resulted in consistent values of cross section. These results indicate that the cross section increases slowly in the energy range presented, in agreement with the photon-gluon fusion model prediction of the shape of the energy dependence.

This research was supported in part by the Istituto Nazionale di Fisica Nucleare (I.N.F.N.) of Italy, Ministero della Universita' e della Ricerca Scientifica, the National Science Foundation, and the U.S. Department of Energy.

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TABLE I. Dimuon sample from J/ψ and Bethe-Heitler

Energy [GeV]	Bethe-Heitler [events]	J/ψ [events]
100-150	327	43
150-200	238	65
200-250	156	55
250-300	96	65
300-350	48	52
350-450	10	11

TABLE II. Elastic J/ψ cross section/nucleon

Energy [GeV]	Cross Section (B. H. Normalization) [nanobarns]	Cross Section (B.G.M Normalization) [nanobarns]
121	$12.3\pm3.0^{+1.1}_{-2.2}$	9.8 ± 2.9
177	$16.6\pm3.8^{+1.5}_{-3.0}$	17.9 ± 4.0
223	$14.0\pm3.4^{+1.3}_{-2.6}$	14.8 ± 3.6
272	$17.9\pm4.2^{+1.6}_{-3.2}$	17.0 ± 4.2
324	$26.7\pm7.3^{+2.4}_{-4.8}$	27.8 ± 7.5
374	$19.9\pm10.9^{+1.8}_{-3.6}$	23.0 ± 11.8

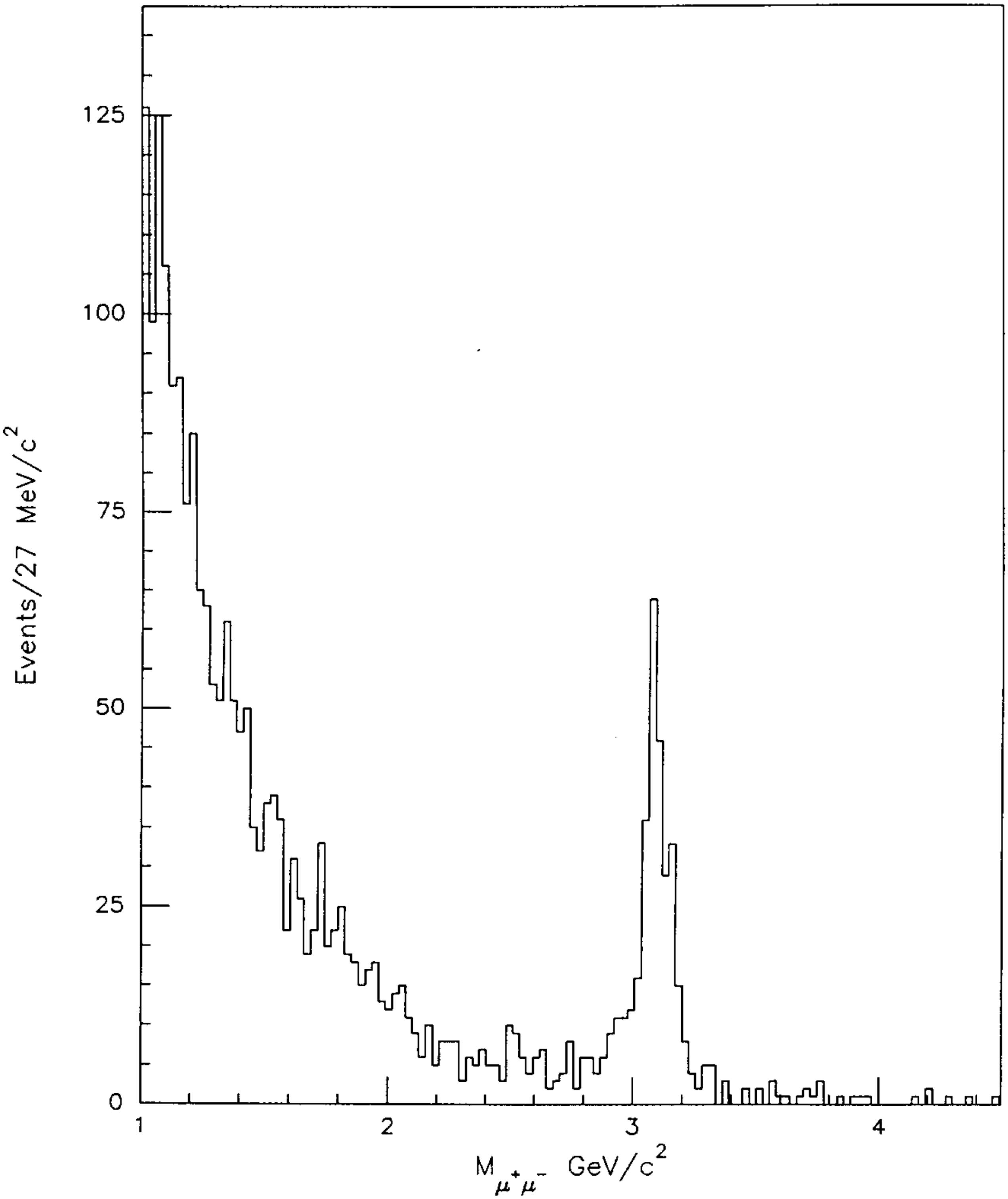

FIG. 1. Invariant Mass Distribution of Candidate Events.

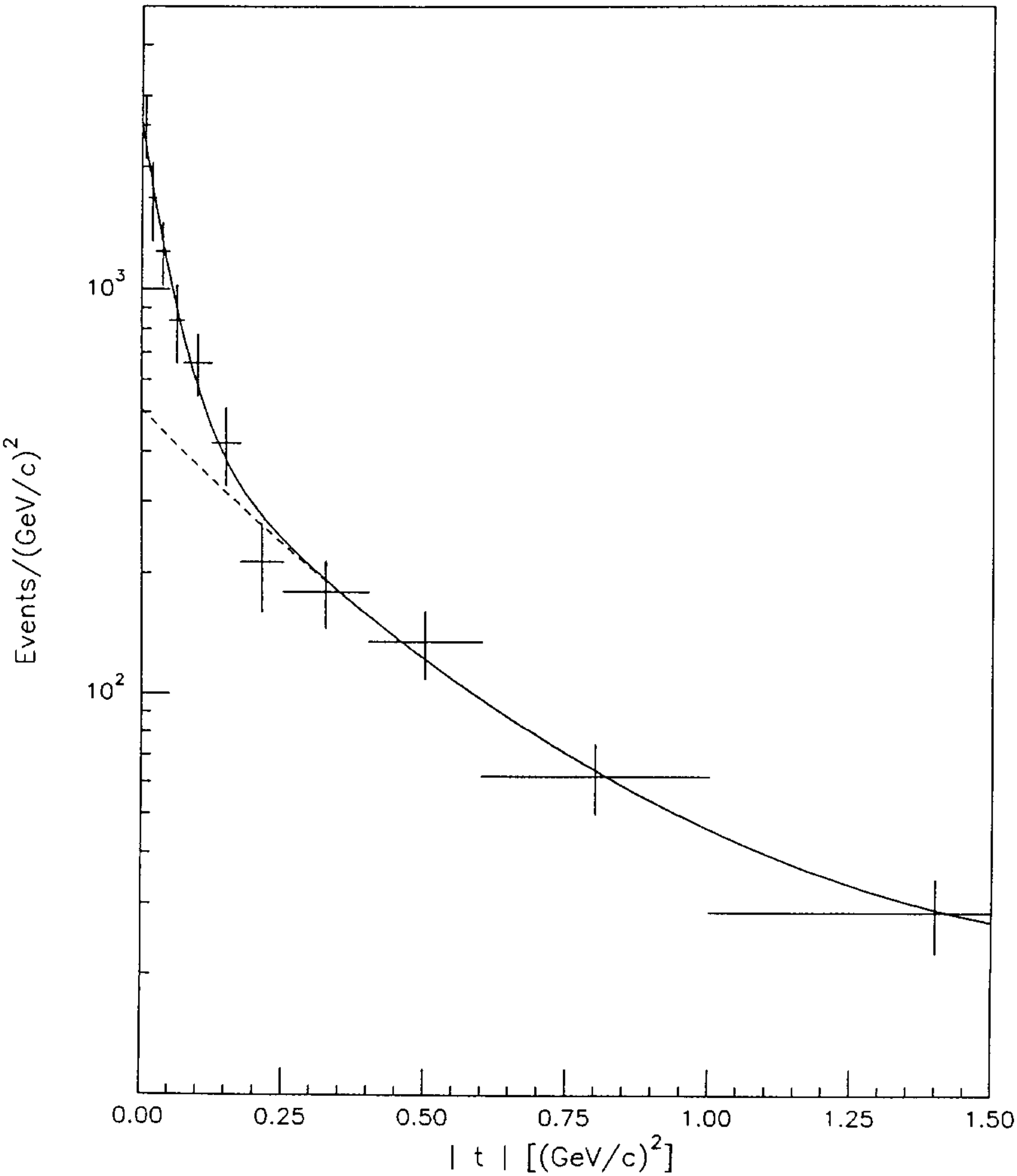

FIG. 2. t-distribution of the "Elastic" Sample.

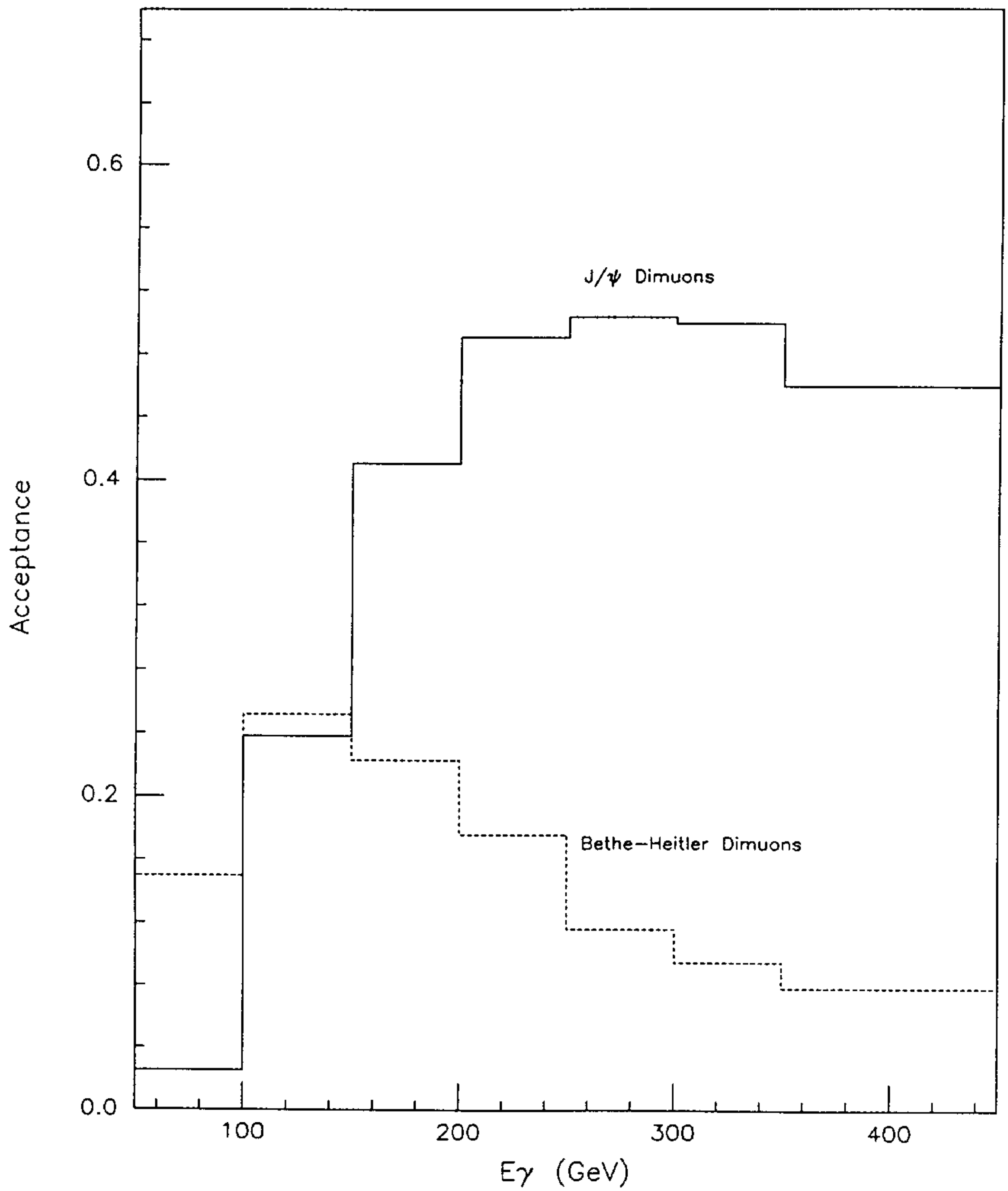

FIG. 3. Acceptance for J/ψ and Bethe-Heitler Dimuons.

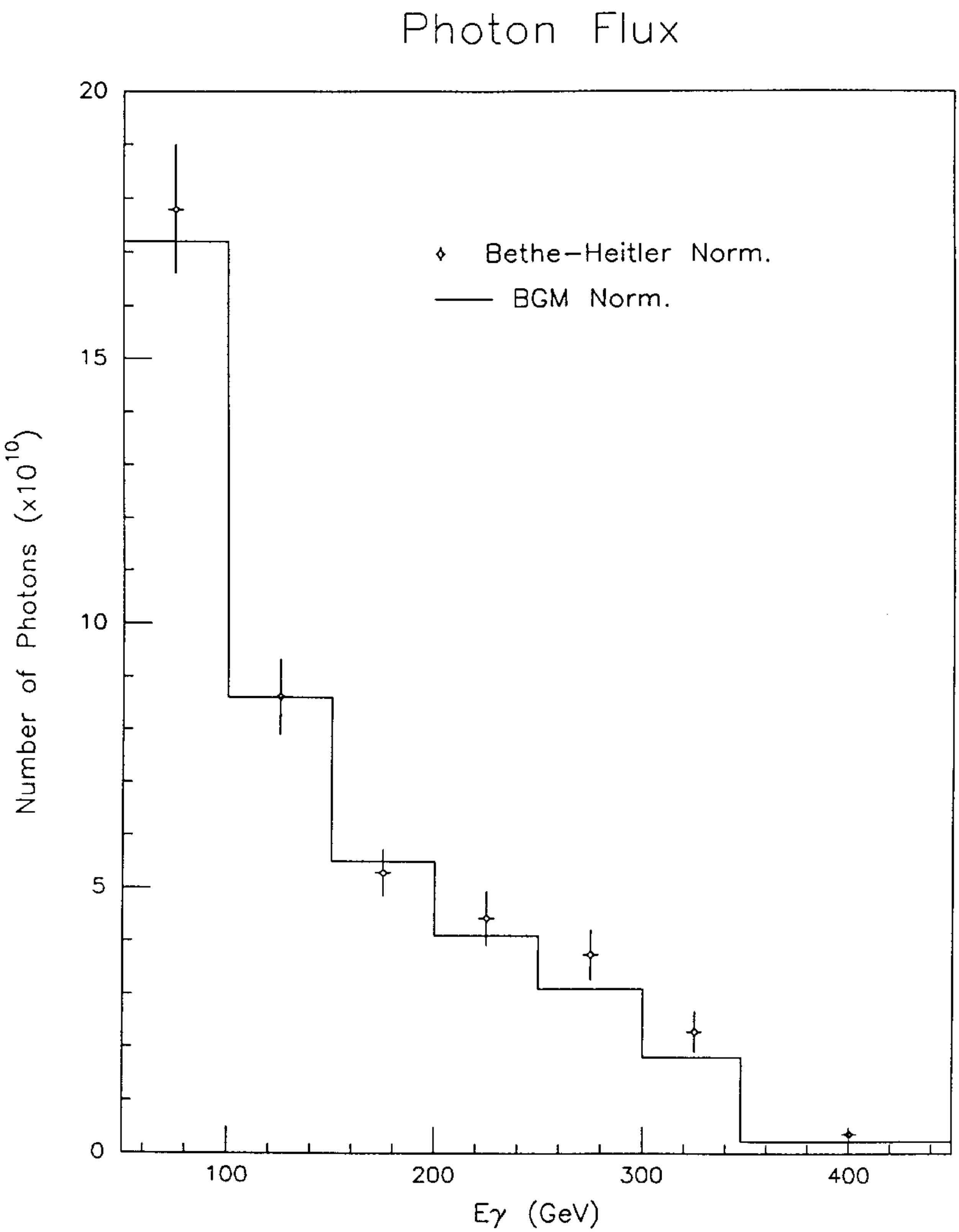

FIG. 4. Photon Flux of the "Wide Band Photon" beam.

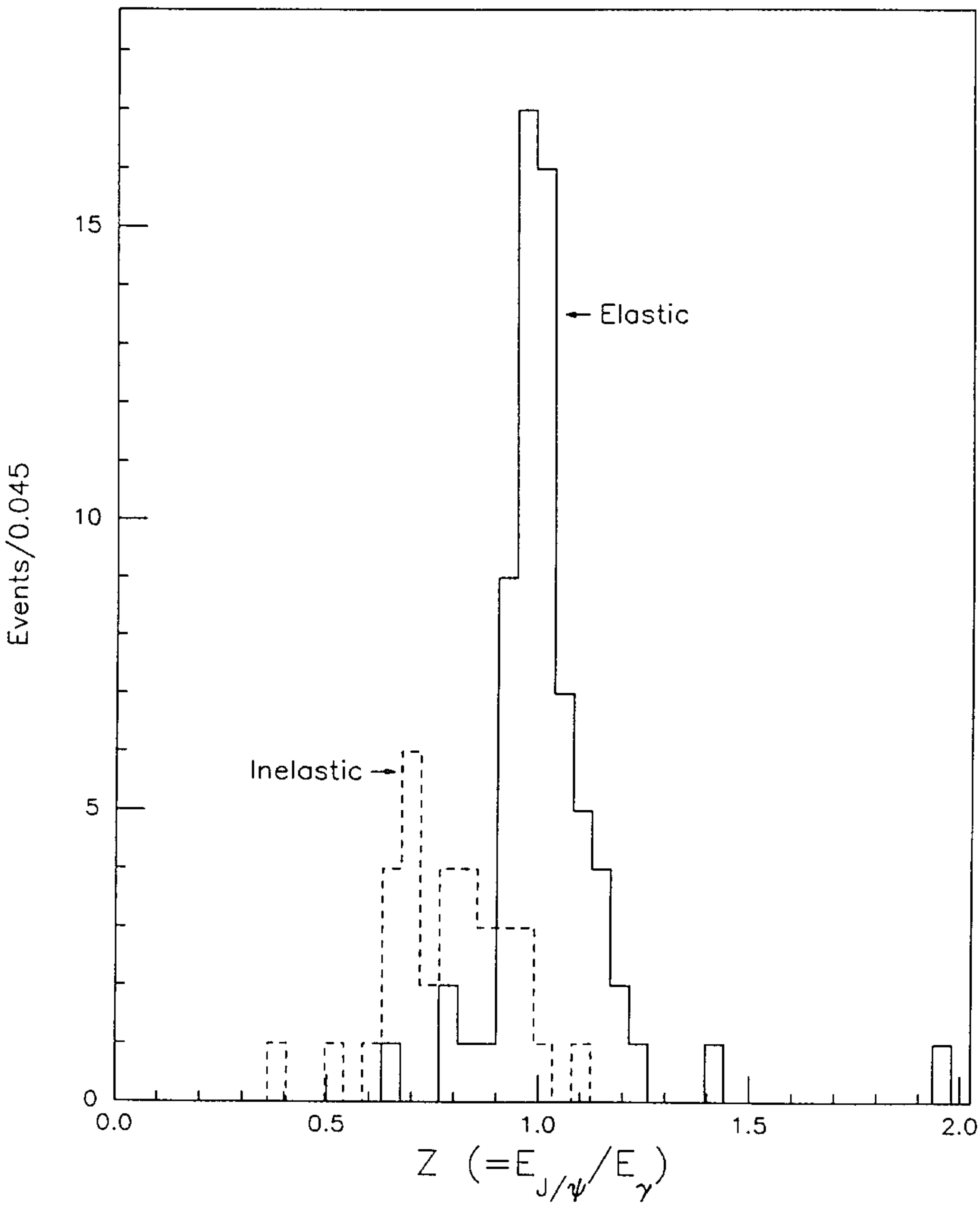

FIG. 5. $\frac{E_{J/\psi}}{E_\gamma} \equiv Z$ Distributions for "Elastic" and "Inelastic" events.

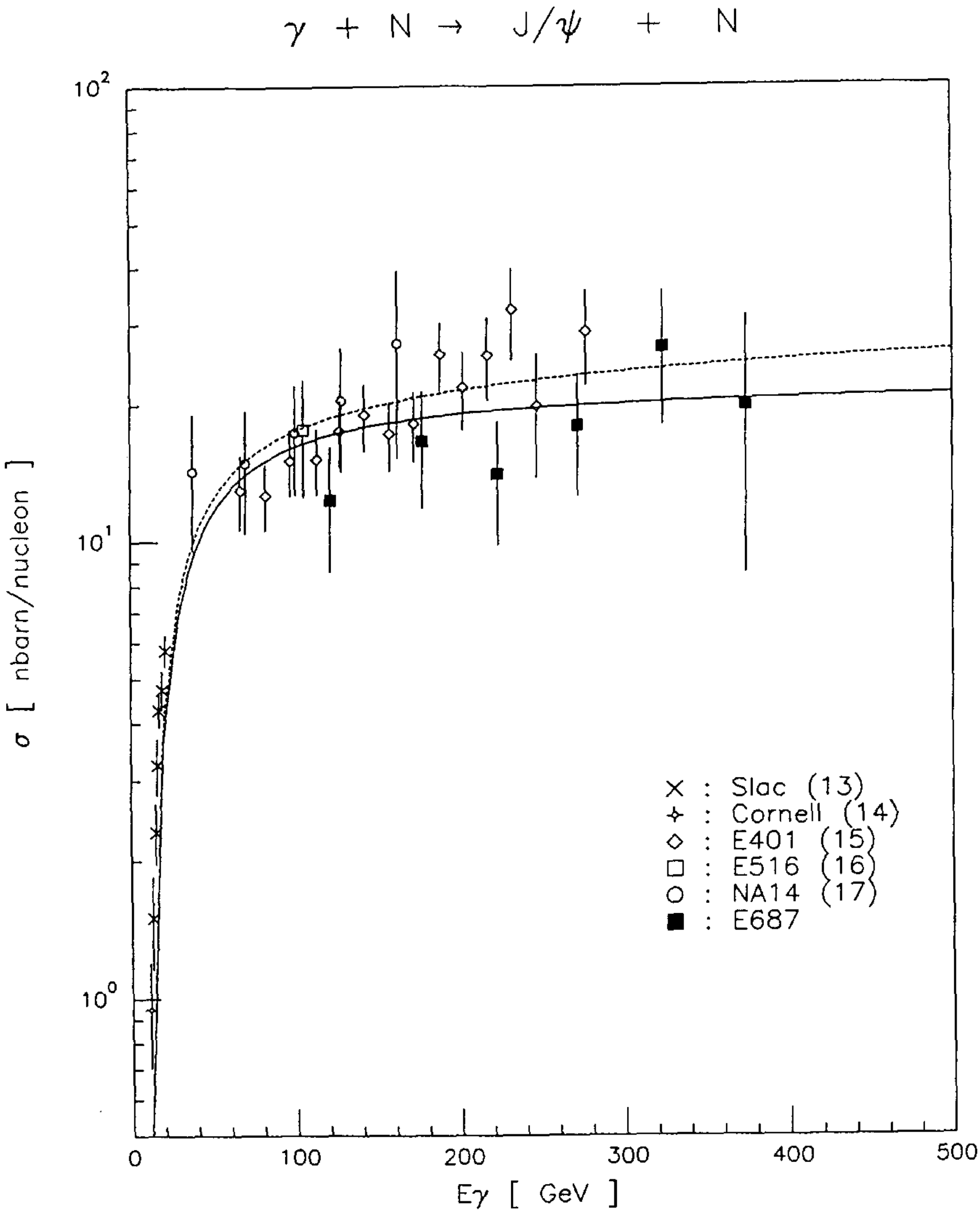

FIG. 6. Compilation of Elastic J/ψ Cross Section Data.