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by


*PLUTO-Collaboration*

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Abstract:

Using the solenoidal magnetic detector PLUTO, we have measured the total cross section for $e^+e^-$ annihilation into hadrons. Results are presented for center of mass energies between 3.6 and 4.8 GeV, and in the regions of the $J/\psi(3.1)$ and $\psi(3.7)$ resonances. We also present results for the 2 prong cross section in the energy range 3.6 to 4.8 GeV.

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++ on leave from CERN, Geneva, Switzerland
+++ on leave at CERN, Geneva, Switzerland



## Introduction

We present measurements of the total cross section for $e^+e^-$ annihilation into hadrons at CMS energies between 3.6 and 4.8 GeV, and in the regions of the $J/\psi(3.1)$ and $\psi(3.7)$ resonances. We also present the cross section for the process $e^+e^- \rightarrow 2$ prongs + unseen neutrals at CMS energies between 3.6 and 4.8 GeV. Data were taken with the magnetic detector PLUTO at the $e^+e^-$ storage ring DORIS. We describe the criteria for event selection, the efficiency calculations and the luminosity monitor.

The total cross section for hadron production through one photon annihilation (or the ratio $R = \sigma_{had}/\sigma_{\mu\mu}$) provides fundamental information on the structure of hadrons. For example in the quark parton model the quantity R is directly related to the number of charged partons, provided that the CMS energy is large enough. In particular

$R = 2$ in the SU(3) model with colour
$R = 10/3$ in the SU(4) charm model with colour.

Recently data on R have been published for the CMS energy range 3.8-4.6 GeV.[1] The data show not only that R is large but also that there is at least one resonance and most probably more in this energy region. The strong threshold effect seen in the data above 4.0 GeV is widely assumed to be due to the onset of charmed particle production.[2]

With the present generation of $e^+e^-$ experiments the accuracy with which the absolute value of R can be measured is limited by systematic errors. The authors of Ref.(1) quote systematic errors of the order of 15% i.e. of the order of one unit in R at the energies in question. In view of the importance of R we consider it essential that the measurements be repeated by a detector with a different trigger system and high detection efficiency (hence a different systematic error). For the present experiment we estimate the systematic error to be of the order of 12%. We are making further studies of the systematic error by taking data with different trigger conditions and by changing the physical assumptions entering the Monte Carlo simulation.

The two prong cross section is interesting for the following reasons.
By studying prong cross sections in addition to the total cross section one

may hope to learn something about the decay mechanisms of the resonances produced in 4-4.5 GeV energy region. It has also been speculated that if a heavy lepton exists with mass near 2.0 GeV/$c^2$ [3] then its dominant decay modes are into channels with one charged particle.[4] The dominant decays of the pair of heavy leptons produced in $e^+e^-$ annihilation would then produce a sizeable effect in the 2 prong channel.

## Detector

Fig.1 shows a cross section of the detector which has been described in detail elsewhere.[5] We review briefly the features important for the total cross section measurements. The superconducting coil produces a 2T magnetic field parallel to the beam axis, with a usable magnetic volume of 1.4 m diameter × 1.05 m length. Inside the coil there are 14 cylindrical proportional wire chambers and two lead converters whose radii and thickness are 37.5 cm and 2 mm, 59.4 cm and 9 mm respectively. The detector is triggered by a logic combination of signals from the proportional wire chambers. Track elements are recognized in groups of chambers inside and outside the lead converters. Events are accepted by the trigger if they satisfy at least one of the following conditions

(i) at least two tracks inside the inner lead cylinder, with their azimuthal angles not belonging to two adjacent $45^o$ sectors
(ii) at least three track elements outside one of the lead converters, with at least two of them not belonging to adjacent $45^o$ sectors
(iii) two track elements outside the outer lead converter, if they are coplanar within $\pm 13.5^o$.

The trigger acceptance is 86% of $4\pi$ and the transverse momentum cut-off for tracks recognized by the trigger is 240 MeV/c. The luminosity is monitored by small angle (130 mrad) $e\bar{e}$ scattering, as explained in more detail below.

## Event Selection

Hadronic events were selected by the following criteria

i) at least two tracks coming from the interaction region
ii) for two prong events the coplanarity angle $\Delta\phi$ (difference between the azimuthal angles) must be less than $150^o$.
iii) for three prong events, at least two of the $\Delta\phi$'s between pairs of tracks must be less than $150^o$.



The cuts ii) and iii) are required to separate the hadronic events from the QED processes $e\bar{e} \to \mu\bar{\mu}$ and $e\bar{e} \to e\bar{e}$. The efficiency of the cut ii) can be seen from Fig.2 where we plot the scattering angle for two prongs. The characteristic forward peak from Bhabha events is not present.

The background from beam-gas interactions and cosmic ray events is subtracted using the distribution of reconstructed event vertices along the beam direction. To reduce the error introduced by the background subtraction we have divided the events into classes according to prong number and total charge (Q). The beam gas background is concentrated in the classes with an excess of positive charge. In calculating the number of events seen we have not used the classes with $Q > 0$ for $n \leq 4$ prongs, but rather used charged symmetry i.e. $n(Q > 0) = n(Q < 0)$. Of the remaining classes the background subtraction is most severe for the two prong $Q = 0$ class, where the background is of the order of 10-20% of the signal. In Fig.3 we show a vertex distribution summed over all classes using charge symmetry as described above.

We have checked on a high statistics point that the numbers of events obtained after subtraction in each class satisfy charge symmetry - Fig.4a shows the results.

The contamination due to events from the two photon process is expected to be small at the energies at which data was taken. At our energies the dominant $2\gamma$ process is $e\bar{e} \to e\bar{e}\,\ell\ell$ with only the $\ell\bar{\ell}$ being seen in the detector. Calculations[6] show that the number of events with the 2 tracks having a coplanarity angle less than $150^o$ is very small.

## Efficiency

In order to determine the true number of events from the observed number we must use a Monte Carlo simulation to correct for the unobserved particles. Monte Carlo events are generated according to isotropic phase space and then the produced tracks are followed through the detector including a simulation of the photon conversion process. This last point is important because certain two prong events can be triggered by the presence of a converted photon (e.g. those with an opening angle less than $45^o$ plus a photon shower). The Monte Carlo simulation is controlled by two parameters, the average charged multiplicity and the fraction of neutral to charged energy. The charged and neutral multiplicities are chosen from independent Poisson distributions. As initial value for the charged multiplicity we have taken the observed results of SLAC-LBL,[7] about 4 at the energies in question. The fraction of neutral particles included is chosen to make the ratio of neutral to total energy 0.5 on average.

We have checked that these parameters are reasonable by comparing the simulated and real multiplicity distributions (Fig.4) and the momentum spectrum for three or more charged particles (Fig.5). Further comparisons for the +- class between real and simulated data are shown in Fig.2 (angular distribution) Fig.6(a) (coplanarity distribution) and Fig.6(b) (seen energy). The agreement between the Monte Carlo data and the real data is acceptable.

Following standard procedure[8] we construct an efficiency matrix $\varepsilon_{ij}$ from the Monte Carlo simulation of the final states $a\cdot(\pi^+\pi^-)+\sum_{b=0}^{7} b(\pi^0)$ i.e. $\varepsilon_{ij}$ is the efficiency to see i prongs given $j = 2a$ prongs input. Then

$$n_i^{seen} = \Sigma_j \, \varepsilon_{ij} \, m_j^{true}$$

where $\{n_i\}$ is the seen prong distribution and $\{m_j\}$ is the true one. Since the physical prong distribution must satisfy the constraint $m_j \geq 0$, a simple matrix inversion cannot be used. Instead a fit procedure is employed, in which the constraint is included. This procedure has been used to determine the true multiplicity distribution for high statistics points at energies of the $J/\psi(3.1)$, $\psi(3.7)$ and at 3.6, 4.1, 4.4 and 4.6 GeV. If our efficiency calculation is to be selfconsistent the average multiplicity obtained by this procedure should agree with the input into the Monte Carlo at the corresponding energy. This is indeed the case. For the other data points in our energy scan we have used a simpler two by two inversion procedure, using only 2 classes, namely, (i) 2 prongs Q = 0, and ii) all other classes summed together.

For multiprongs our event detection efficiency is of the order of 95% and for two prongs we find an efficiency of the order of 45%. In Fig.7 we show a plot of the average efficiency $\langle\varepsilon\rangle$ versus energy where

$$\langle\varepsilon\rangle = \frac{\sum_i n_i^{seen}}{\sum_j m_j^{true}} \qquad i,j \geq 2$$

$\langle\varepsilon\rangle$ is a slowly rising function of energy, 70% at 3.1 GeV and 80% above 4 GeV.



Normalisation

For the normalisation of the observed cross section, the beam luminosity is continuously monitored by small angle Bhabha scattering. An external monitor system was employed. Four identical telescopes, each equipped with three plastic scintillation counters and a lead-scintillator sandwhich shower counter, were arranged symmetrically around the beam pipe outside the magnetic field region of the solenoid (Fig.8). The average scattering angle is 130 mr, and about 2msr solid angle are covered by each telscope. This yields a counting rate of 30 times the QED $\mu\bar{\mu}$ production cross section. By virtue of the fourfold symmetry of the monitor, the summed counting rate in all telescope arms is in first order independent of the position of the interaction point, and the beam direction.[9] The effects due to the magnetic field of the solenoid and multiple scattering in the beam pipe were studied by Monte Carlo and found to be small.[10]

Bhabha scattering is defined by a collinear event observed simultaneously in two telescopes on opposite sides of the interaction point. For events of this type, the trigger pattern and timing, and the shower detectors' pulse-heights are recorded. In the final analysis hits are required in counter M in one arm, and in counters G , together with large pulse-heights in the shower detectors S of both arms (see Fig.8 for nomenclature). The counters K served to monitor the efficiency of the other trigger counters.

From known uncertainties in the geometry of the monitor, and from the tails observed in the pulse-height distributions of the shower detectors, we estimate an uncertainty of ±5% in the absolute determination of the luminosity.

We have checked the reliability of the monitor by measuring the QED processes $e\bar{e} \to \mu\bar{\mu}$ and wide angle Bhabha scattering $e\bar{e} \to e\bar{e}$ seen in the detector. The $\mu$ pair reaction has been used to check the absolute normalisation. We can identify muons over 51% of $4\pi$ solid angle with a $\mu$ momentum cut-off of about 1 GeV/c. From the data at 3.6 GeV CMS energy we have 604 ± 37 events classified as $e\bar{e} \to \mu\bar{\mu}$ (2 prong collinear events with at least one track identified as a muon). From QED we expect 603 ± 12 events in agreement with the data. We have allowed for a 5% radiative correction to the measured integrated luminosity, and an 11% radiative correction to $e\bar{e} \to \mu\bar{\mu}$.[11] To check the relative normalisation we have compared the rate for the wide angle

Bhabhas with the monitor rate. The ratio of the rates is a constant with respect to the CMS energy.

## Results

Having determined the corrected numbers of events and integrated luminosity we calculate the total cross section

$$\sigma_{tot} = \frac{\sum_j m_j^{true}}{Lt}$$

where Lt is the integrated luminosity (in $nb^{-1}$) as measured by the small angle Bhabha scattering monitor.

In Fig.9 we show the results for the total $e^+e^-$ hadronic cross section in the energy range 3.6 to 4.8 GeV. In Figs.10 and 11 we show the excitation curves for the $J/\psi(3.1)$ and $\psi(3.7)$ resonances. The data in Figs.9, 10 and 11 have not been corrected for radiative loss in the initial state.

To obtain the true cross section we applied radiative corrections following standard procedures.[12] For the two narrow resonances the observed excitation curves Figs.10 and 11 have been fitted with the mass, area, and machine energy resolution as free parameters, after allowing for radiative correction of the monitor.[13] The results for the integrated resonance cross section are

$$\int \sigma_t \, dE_{cm} = \begin{array}{l} 9700 \pm 1200 \text{ nb MeV at } J/\psi(3.1) \\ 3060 \pm 340 \text{ nb MeV at } \psi(3.7) \end{array}$$

The errors include estimates of the systematic uncertainties in the present analysis, 12% at the $J/\psi$ and 11% at the $\psi'$ .

For the nonresonant cross section the radiative correction consists of three terms, i) the monitor correction, ii) the $J/\psi(3.1)$ and $\psi(3.7)$ radiative tails and finally iii) the correction from the integral over the cross section for $E_{cm} < 2E_{beam}$. The results for $R = \sigma_{had}/\sigma_{\mu\mu}$ after allowing for radiative corrections, are shown in Fig.12. From a value of 2.5 at 3.6 GeV the ratio R rises steeply in the vicinity of 4.0 GeV to reach a value of the order of 5.



Between 4 and 4.4 GeV the ratio R shows further structure, ranging in value between 4 and 5. Above 4.4 GeV R drops again to a value of the order of 4. Our data seem to indicate a peak at 4.4 GeV and a more complicated structure in the 4-4.2 region.

In order to ensure that this structure is really due to the toal cross section, and not simulated by rapid changes in event characteristics, we have investigated the energy dependence of the average observed energy for events with $\geq$ 3 charged particles, and the average observed multiplicity. Neither one shows any striking change with energy. This can also be seen from Fig.7, which shows the energy dependence of the average detection efficiency and from Fig.13 showing that the ratio of the 2 prong to the total cross sections has only a weak energy dependence.

At present we estimate systematic errors in the overall normalisation of the order of 12%, mainly from the trigger and Monte Carlo unfold.

In Fig.14 we show the quantity $R_{2pr} = \sigma_{2prong}/\sigma_{\mu\mu}$ for the process $e^+e^- \rightarrow$ 2 prongs + neutrals. The 2 prong cross section follows the structure seen in the total cross section fairly well. The steep rise at 4.0 GeV and the bump at 4.4 GeV are common to both data. Another way of seeing this is from Fig.13 which shows that the ratio of 2 prong to total cross sections is almost structureless.

## Discussion

Our results for $R = \sigma_{had}/\sigma_{\mu\mu}$ agree with those of the SLAC-LBL group within systematic errors. We find our cross sections to be 10-15% lower than those of SLAC-LBL on the narrow $\psi$ resonances[14] and at higher energies.[15] In fact the agreement on the energy dependence of the total cross section between 3.6 and 4.8 GeV CMS energy is very good. We emphasize once more that the accuracy with which R can be measured is limited by systematic errors, which amount to almost one unit in R in the above energy range. This uncertainty must be borne in mind when any attempt is made to draw theoretical inferences from the measured value of R.

We now turn our attention to the results for the 2 prong cross section. As shown in the previous section the 2 prong cross section follows the structure seen in the total cross section. There is no apriori reason to expect such a result. That it does so is consistent with the fact, mentioned in the previous section, that the average multiplicity shows no striking energy dependence. This observation has also been made by the SLAC-LBL group.[1] Our data show that the new states responsible for the rise in R above 4 GeV also contribute strongly to two prong final states.

It has been argued that $p\bar{p}$ annihilation is very similar in many respects to $e^+e^-$ annihilation.[16] In so far as a comparison is possible the similarity does not seem to be so close for the ratio of 2 prongs to total cross sections. From the results on $p\bar{p}$ annihilation is Ref.(17) we find 2 prongs/total = 15% at a CMS energy of 3.5 GeV dropping to 6% at 4.5 GeV. Our data on $e^+e^-$ annihilation gives 40% for the ratio 2 prongs/total at 3.6 GeV, dropping to about 32% at 4.8 GeV. (Fig.13)

However at energies above 4 GeV the $e^+e^-$ 2 prong cross section could be complicated by the addition of a contribution from a heavy lepton. The anomalous $e\mu$ events seen by the SLAC-LBL group have been interpreted as being due to the existence of a heavy lepton with a mass in the range 1.8-2 GeV.[3] The standard models for the decays of such heavy leptons[4] indicate that their contribution to the cross section for $e^+e^-$ annihilation into hadrons (as presently defined) will be mostly in the 2 prong channel. To show how large this effect could be we have plotted in Fig.14 the expectation for a point like heavy lepton of mass 2 GeV/$c^2$ with the probability for a pair to decay into 2 prongs in the range 60-80%.[4] We can see from the figure that at the highest energies (4.8 GeV) the heavy lepton would account for almost half of the two prong cross section. From the data points at 3.6 GeV, below the threshold for charm production and for heavy lepton production, the level of $R_{2pr}$ is 1. If we assume that the old hadronic 2 prong cross section has a similar energy dependence to that of $p\bar{p}$ annihilation then at 4.8 GeV $R_{2pr}$ (old hadrons) is roughly 0.25. This would leave 1.35 units of R for the contribution from both charm and heavy lepton production. As the heavy lepton contribution is of the order of 0.5 units of R this leaves of the order of 0.8 units of R for the contribution from charm production to $R_{2pr}$ which is consistent with the observed rise in $R_{2pr}$ at 4.0 GeV. We emphasize that this conclusion depends on the old hadronic 2 prong contribution having a rapid decrease with energy.



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Figure Captions

1. Detector PLUTO viewed along the beam

2. Scattering angle (w.r.t. $e^+$ beam direction) of the positive particle for the two prong +- class. ⫵ real data —— Monte Carlo data

3. Vertex distribution along the beam axis for hadronic events in the 4 GeV region. Summed over all classes of events and using charge symmetry as explained in the text

4. Fractions of seen prongs at 4.0 GeV compared to Monte Carlo data
   (a) Individual class, separating total charge
   (b) no charge separation

5. Momentum spectrum at 4.4 GeV for $\geq$ 3 prongs. Comparison between real ( ⫵ ) and simulated data (——)

6. Comparison between real (⫵) and Monte Carlo data (——) for the +-class
   (a) coplanarity distribution
   (b) seen energy

7. Average detection efficiency per event (see text for definition) $\langle\varepsilon\rangle$ versus CMS energy

8. Schematic top view of the monitor system used to measure the luminosity at the interaction point. The four telescope arms (A,B,C,D) consist each of three plastic scintillation counters (G,M,K) and a lead-scientillator sandwich shower detector (S)

9. Total hadronic cross section for $e\bar{e} \to$ hadrons before radiative corrections versus CMS energy. The points o and $\Delta$ represent data taken in different run periods

10. Excitation curve for the $J/\psi(3.1)$ resonance

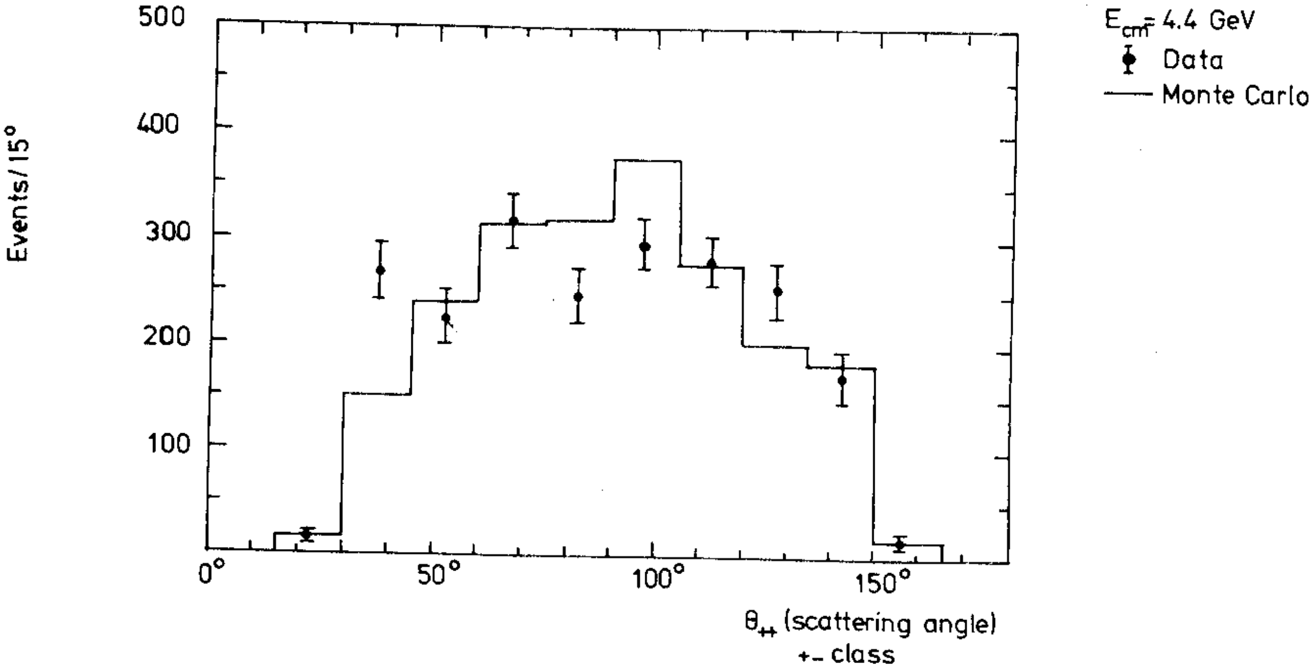
11. Excitation curve for the $\psi(3.7)$ resonance



12. The ratio $R = \sigma_{had}/\sigma_{\mu\mu}$ (allowing for radiative corrections) versus CMS energy

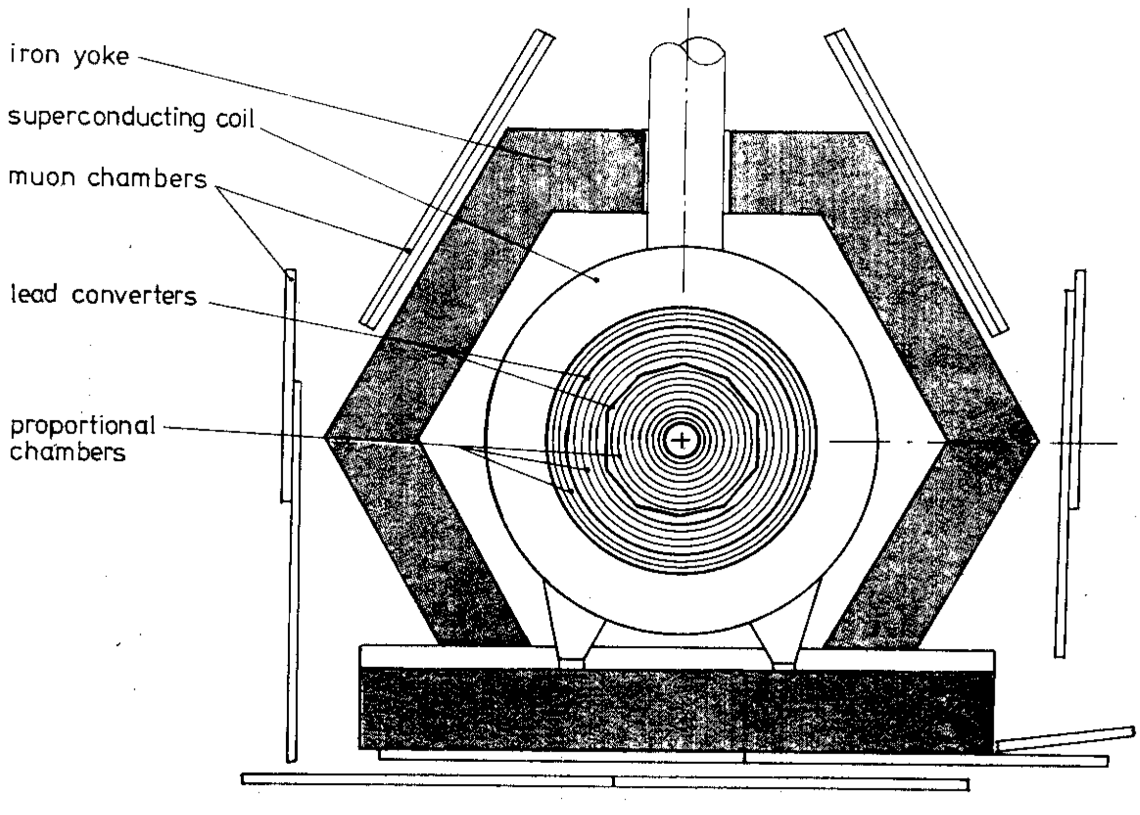
13. The fraction of two prong cross section with respect to the total cross section

14. The ratio $R_{2pr} = \sigma_{2pr}/\sigma_{\mu\mu}$ for $e\bar{e} \to 2$ prongs (with radiative corrections applied) versus CMS energy. The curve indicates the contribution to $R_{2pr}$ for a heavy lepton of 2.0 GeV mass.



500
400
300
200
100
Events/15°
0°
50°
100°
150°
θ₊₊ (scattering angle)
+- class
$E_{cm}$ = 4.4 GeV
Data
Monte Carlo


Fig. 2



iron yoke
superconducting coil
muon chambers
lead converters
proportional chambers


Fig. 1

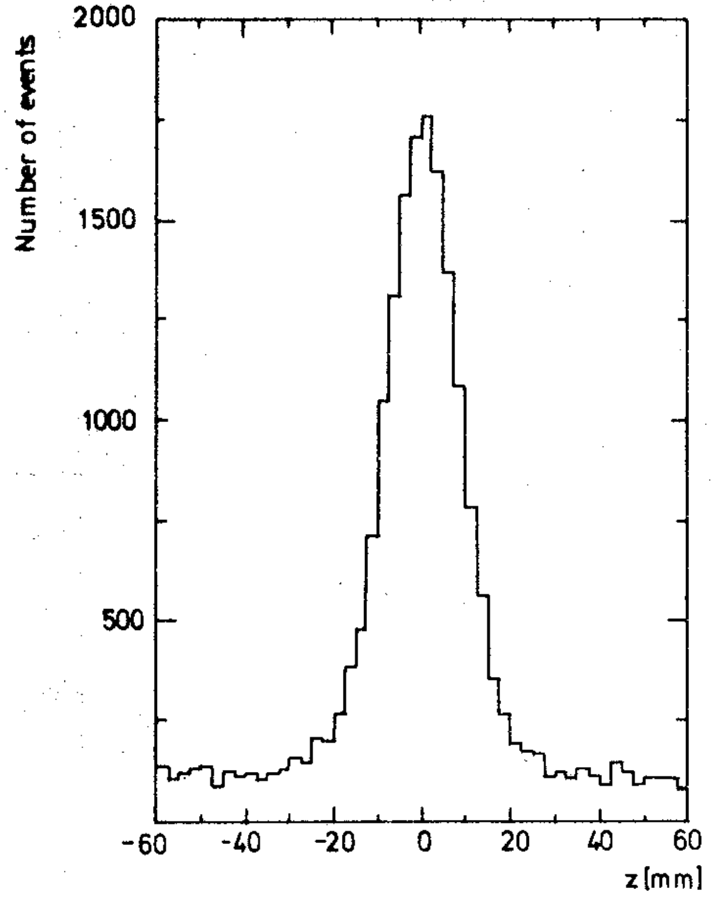

Number of events
2000
1500
1000
500
-60
-40
-20
0
20
40
60
z [mm]

Fig. 3

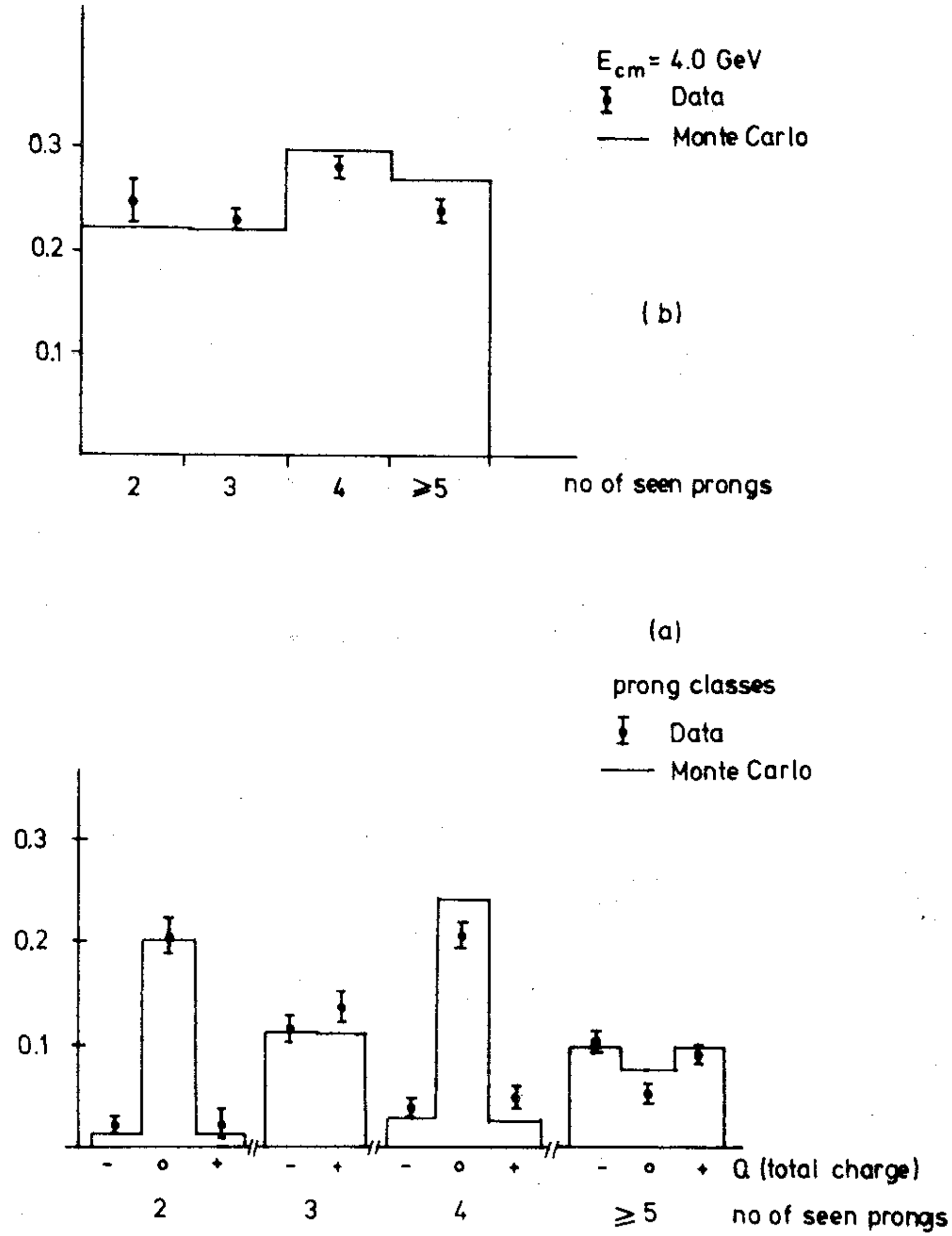

$E_{cm}$ = 4.0 GeV
Data
Monte Carlo
0.3
0.2
0.1
2
3
4
≥5
no of seen prongs
(b)
(a)
prong classes
Data
Monte Carlo
0.3
0.2
0.1
- o + Q (total charge)
2
3
4
≥ 5
no of seen prongs

Fig. 4

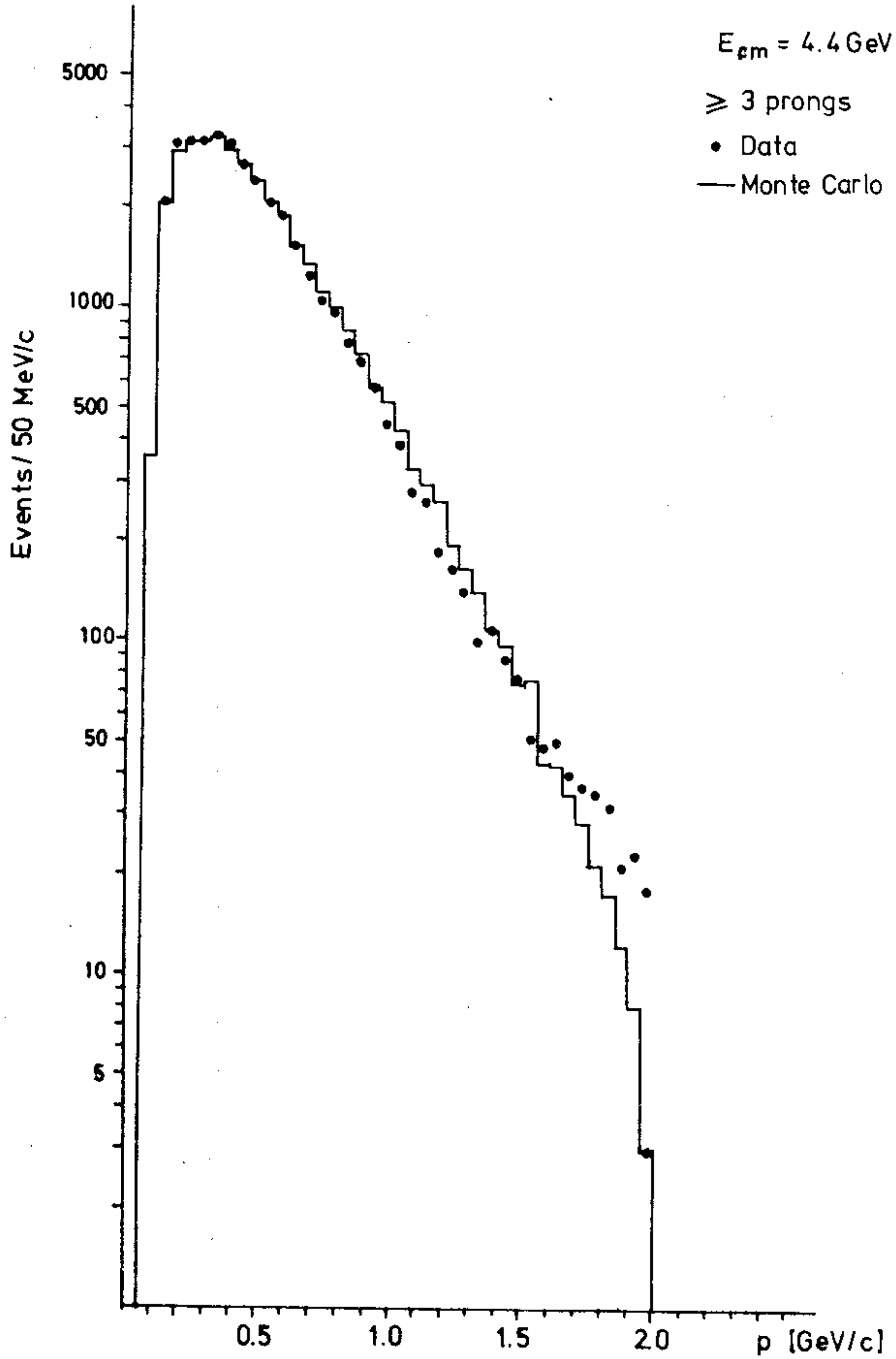



Fig. 5

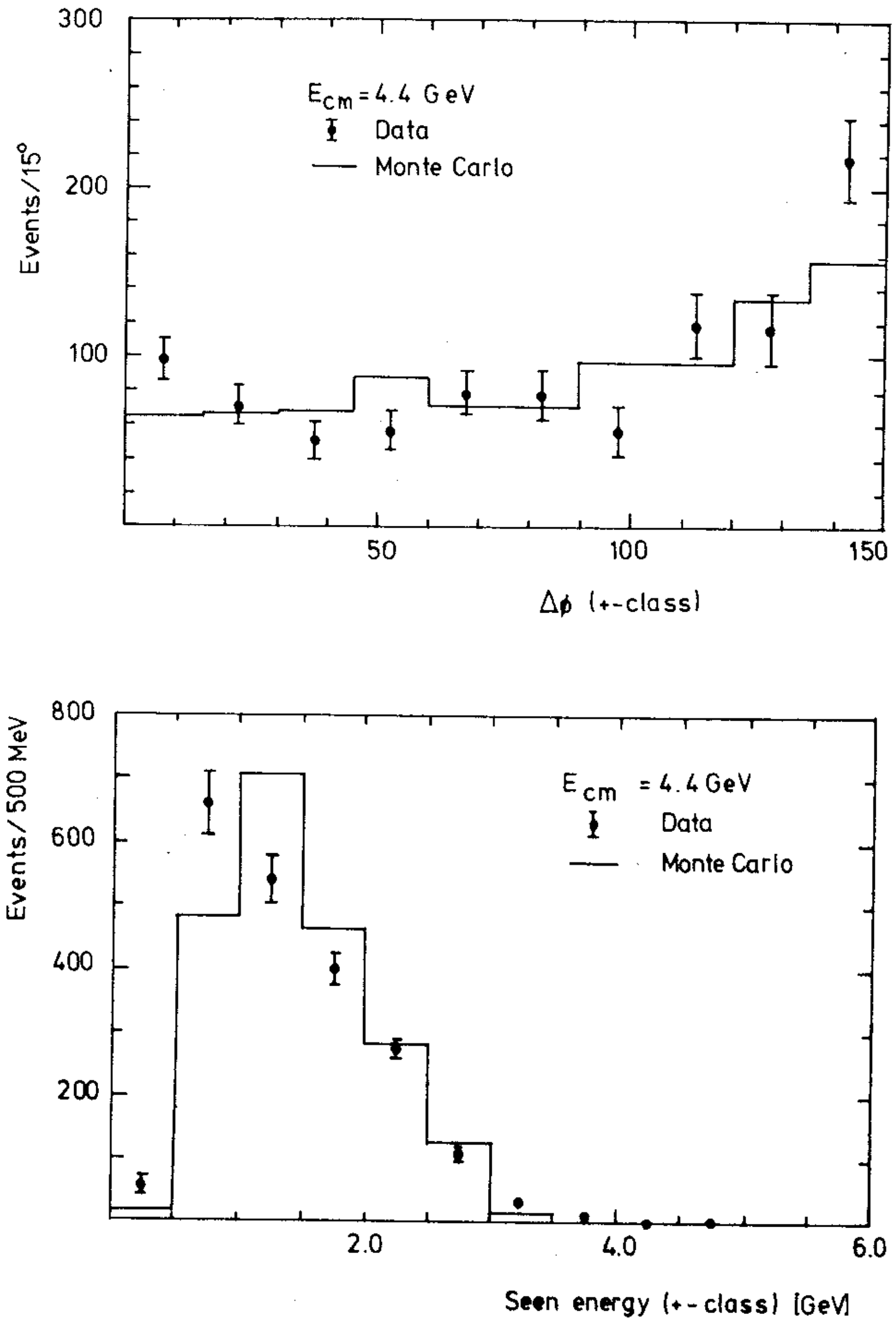



Fig. 6 a(top) b(bottom)

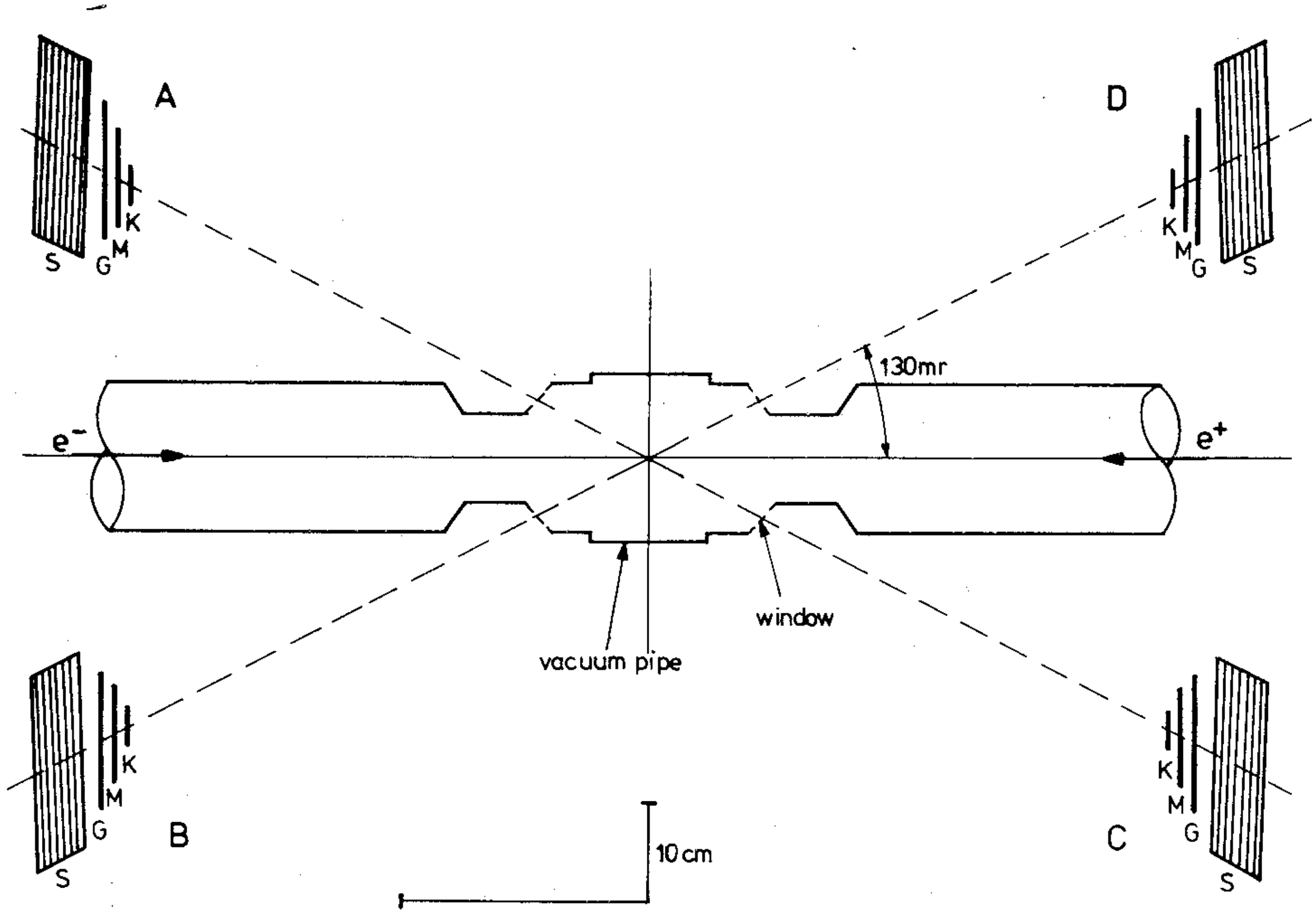

A
D
S
G
M
K
130mr
e⁻
e⁺
window
vacuum pipe
B
C
10 cm
1 m

Fig. 8

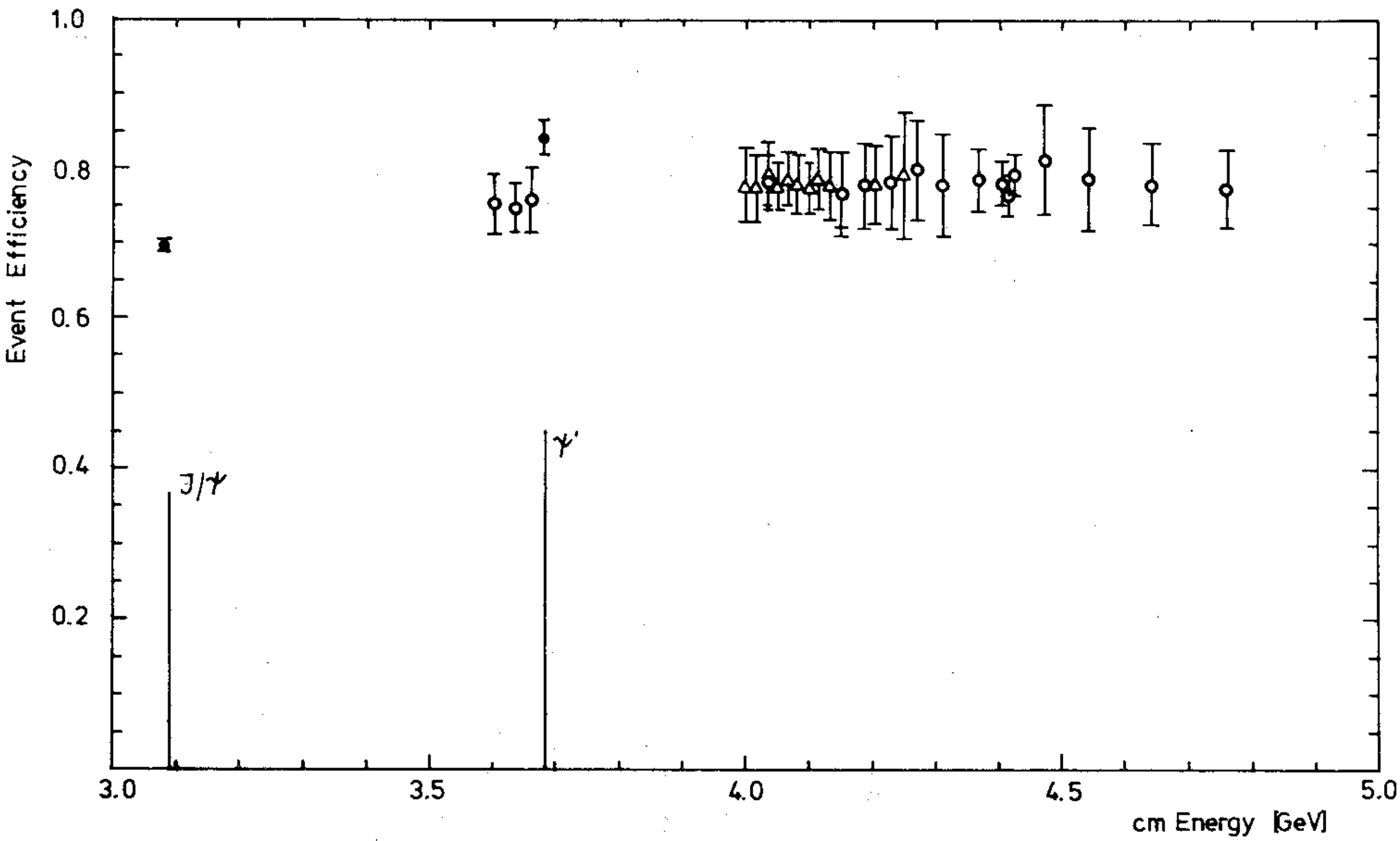
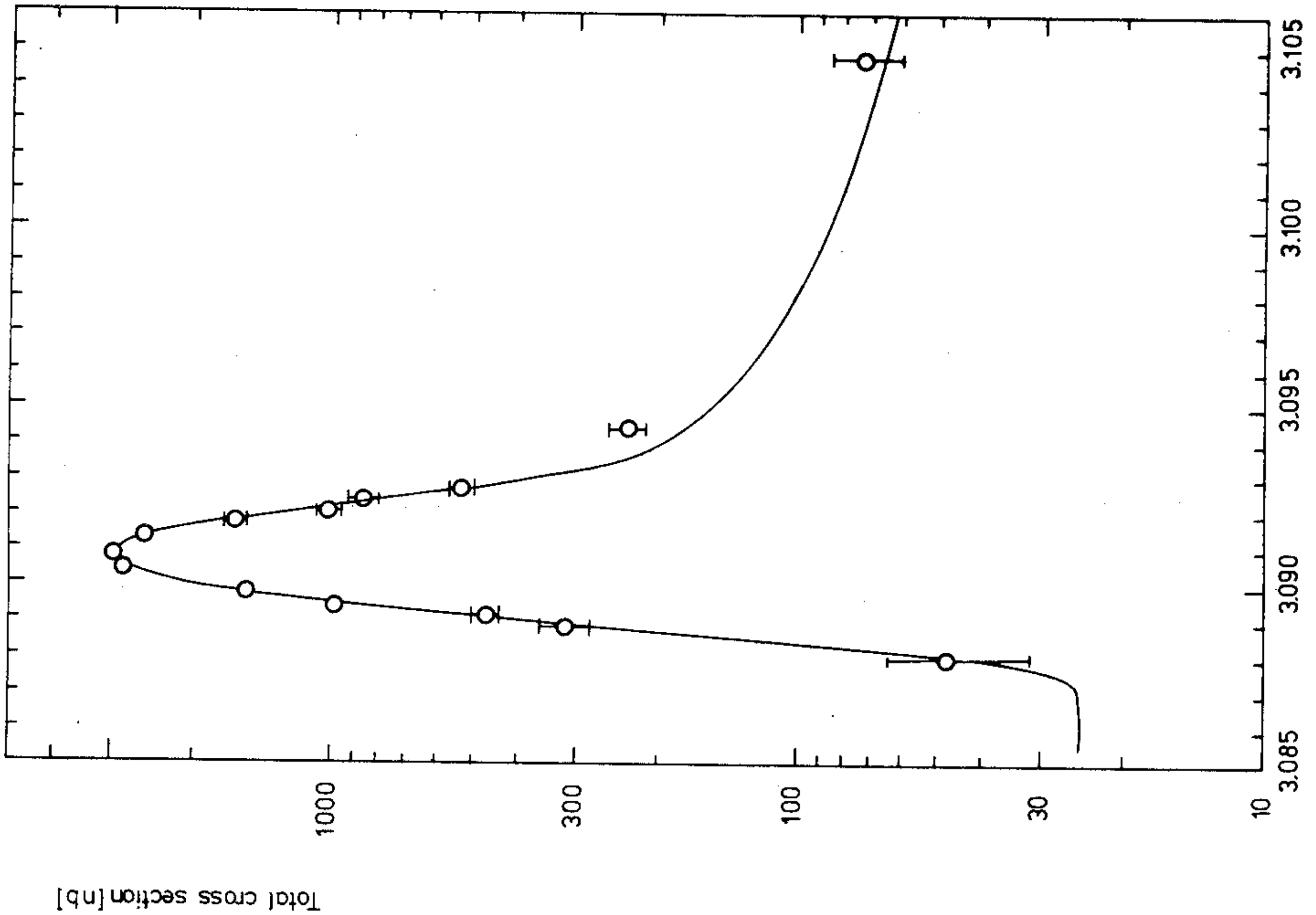
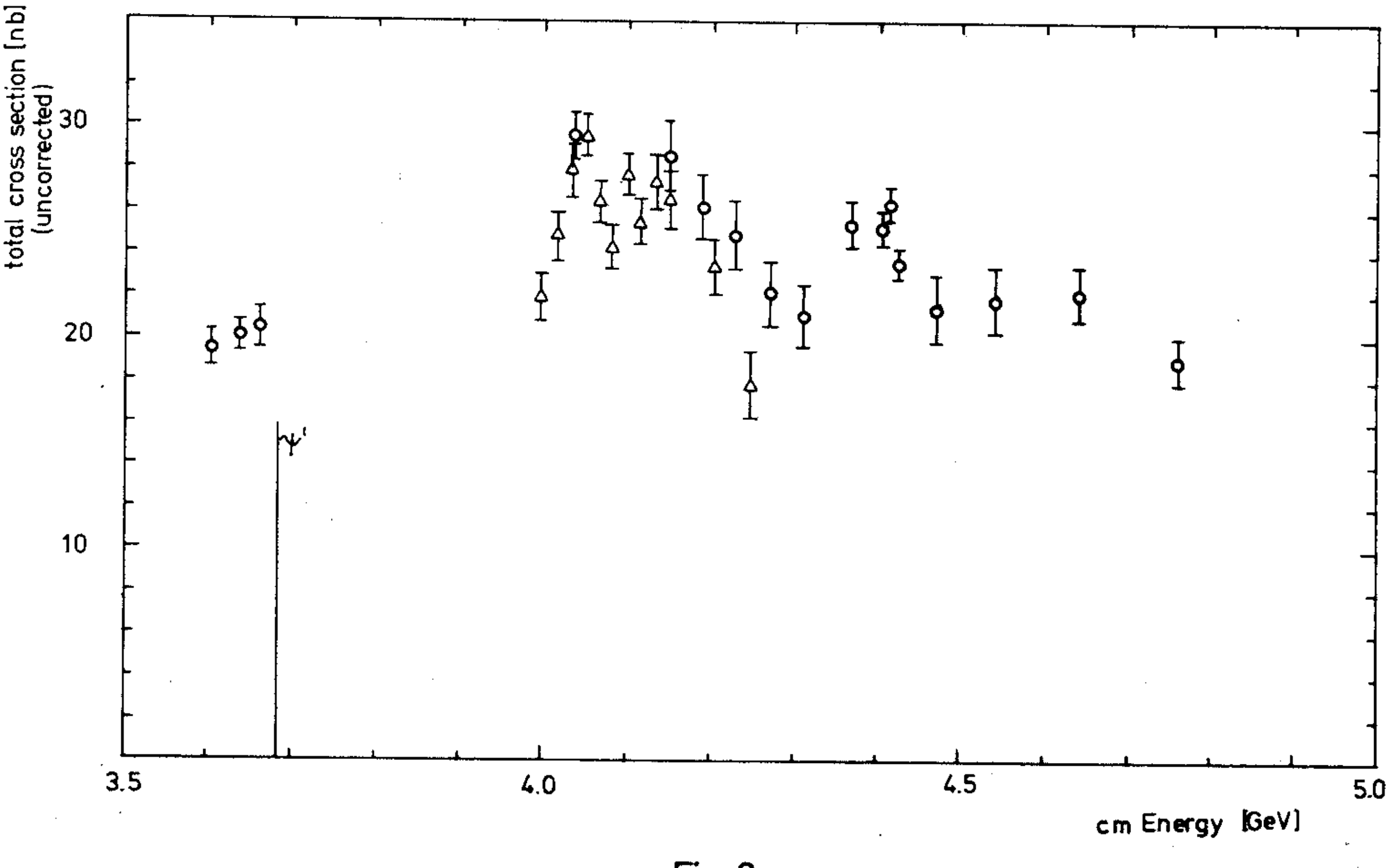

1.0
0.8
0.6
0.4
0.2
Event Efficiency
J/ψ
ψ'
3.0
3.5
4.0
4.5
5.0
cm Energy [GeV]

Fig.7



Total cross section [nb]
1000
300
100
30
10
cm Energy [GeV]
3.085
3.090
3.095
3.100
3.105


Fig.10



total cross section [nb]
(uncorrected)
30
20
10
ψ'
3.5
4.0
4.5
5.0
cm Energy [GeV]


Fig.9

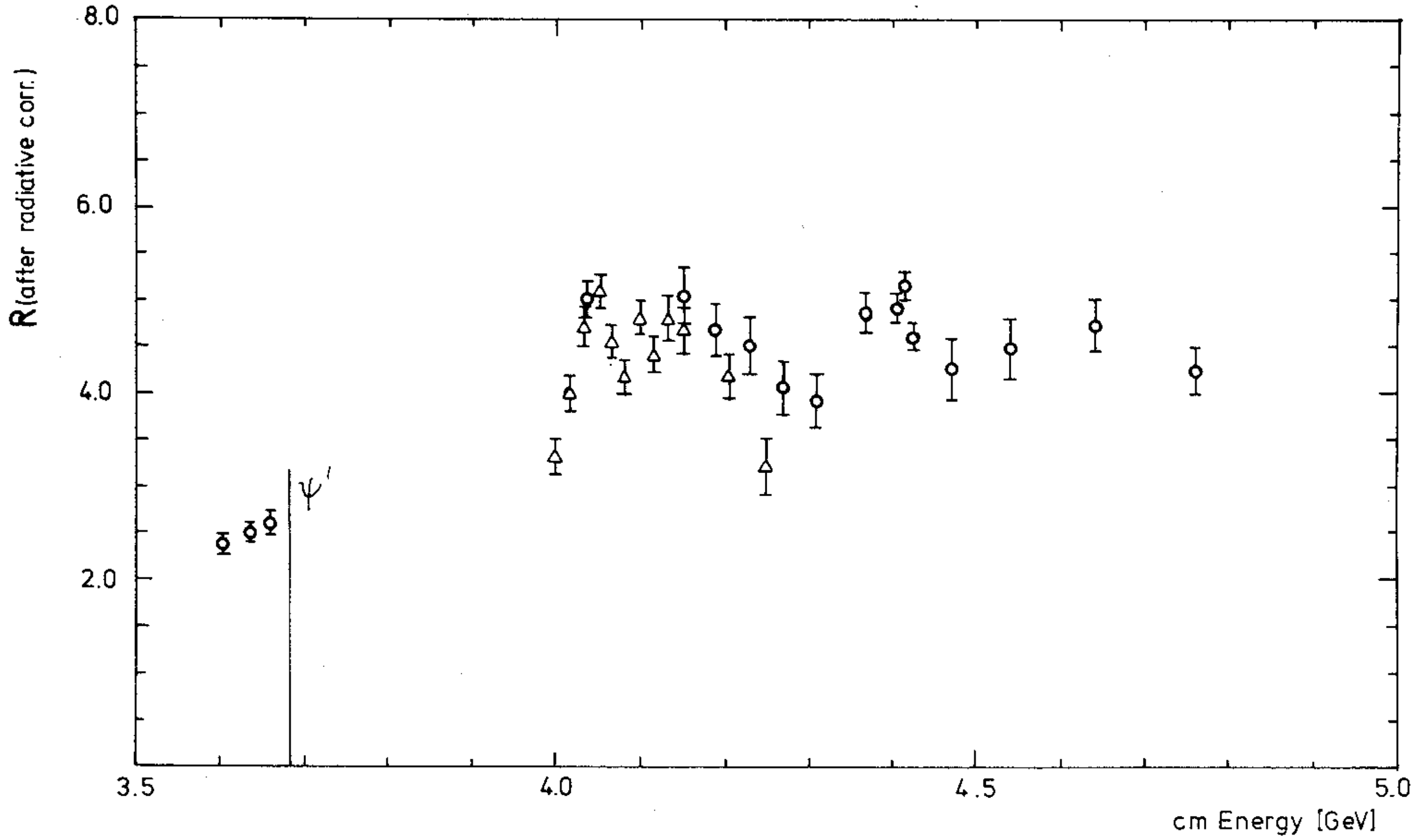

8.0
6.0
4.0
2.0
R(after radiative corr.)
ψ'
3.5
4.0
4.5
5.0
cm Energy [GeV]

Fig.12

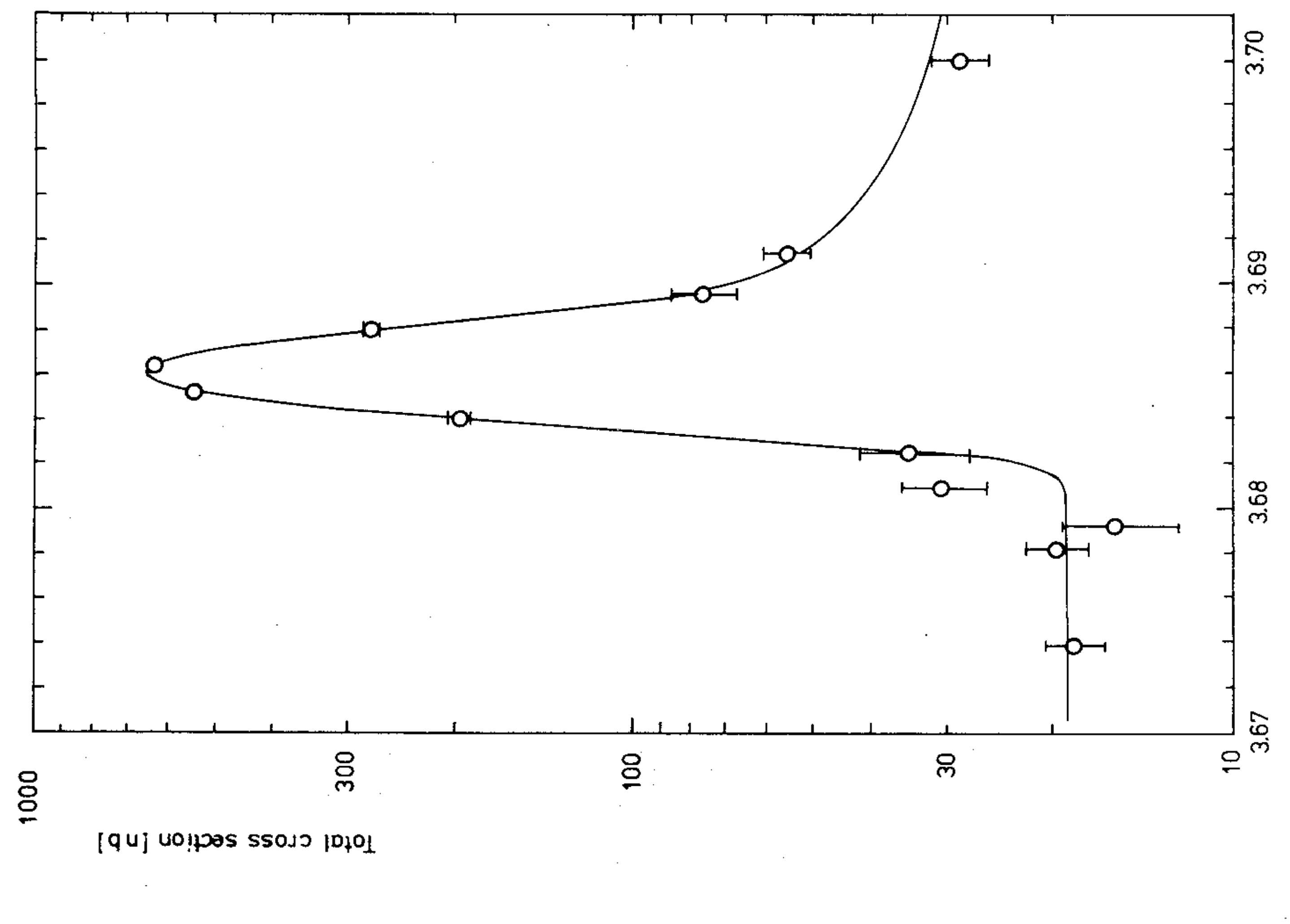
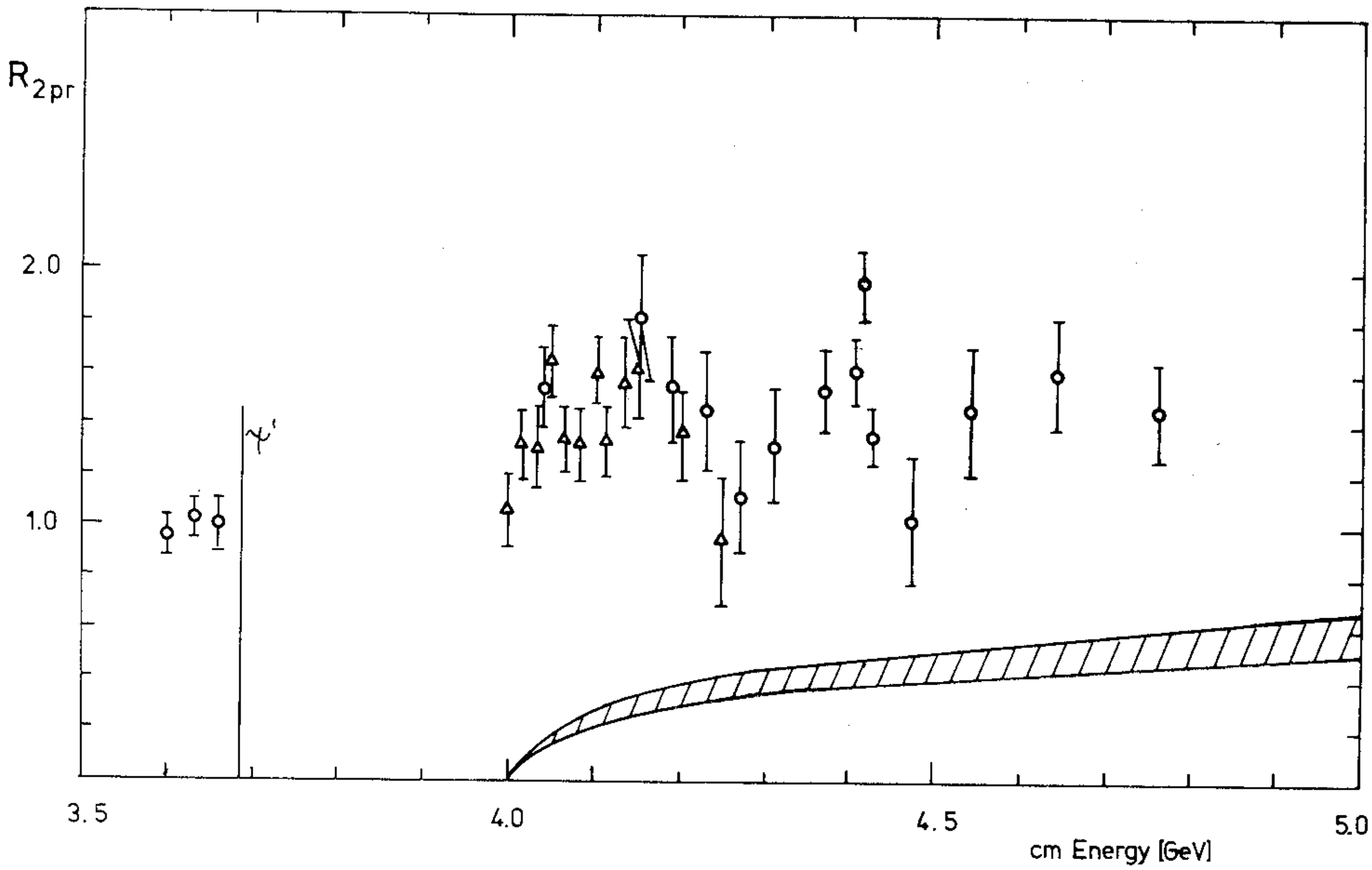
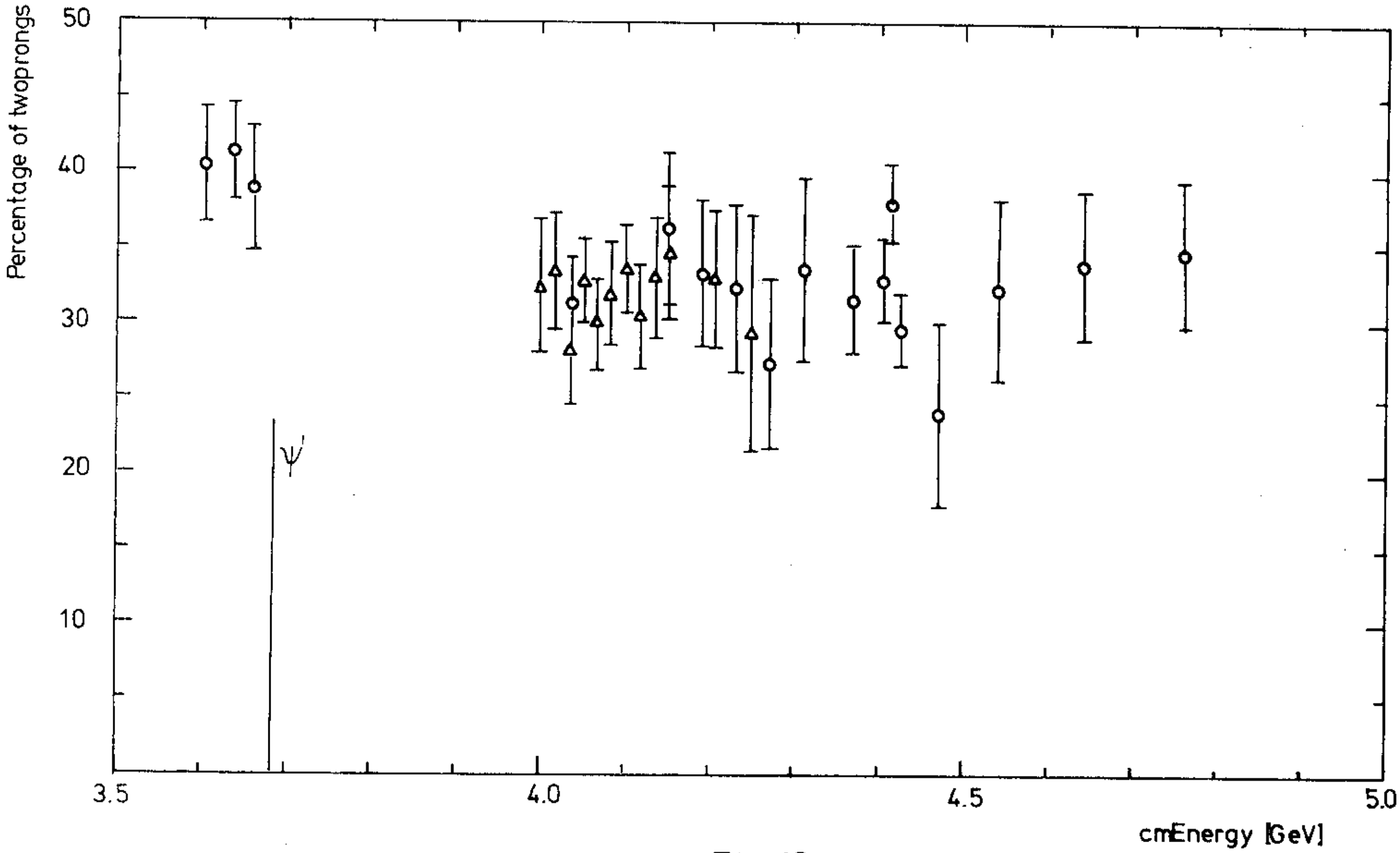

1000
300
100
30
10
Total cross section [nb]
3.67
3.68
3.69
3.70
cm Energy [GeV]

Fig.11



R2pr
2.0
1.0
ψ'
3.5
4.0
4.5
5.0
cm Energy [GeV]


Fig.14



Percentage of twoprongs
50
40
30
20
10
ψ'
3.5
4.0
4.5
5.0
cmEnergy [GeV]


Fig. 13