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Measurement of $\pi^- p \rightarrow \pi^- p\, \pi^0$ Reaction near Threshold and Breaking of Chiral Symmetry

OMICRON Collaboration

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Abstract

A full-kinematics measurement of the $\pi^- p \rightarrow \pi^- p\, \pi^0$ reaction in the incident π^- momentum region from 295 to 450 MeV/c is presented. The measurement was performed with the OMICRON spectrometer at the CERN synchrocyclotron.

An incident-momentum dependent number of $\pi^- p \rightarrow \pi^- p\, \pi^0$ events, ranging from 6 to 430 has been extracted from collected data. Differential cross-sections are found to be consistent with phase-space distributions. Integrated cross-sections are used to determine the value of the chiral symmetry breaking parameter ξ. The measured value of $\xi = 0.1^{+0.5}_{-0.7}$ is obtained in a model-independent way, strongly favouring Weinberg's choice of $\xi = 0$.

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There are no experimental data for the reaction $\pi^- p \rightarrow \pi^- p \pi^0$ in the vicinity of threshold. Measurements were performed only at incoming pion momenta higher than 390 MeV/c (1,2), far above the threshold laboratory momentum of 270 MeV/c. On the other hand there is considerable theoretical interest in threshold pion production. Using current algebra, PCAC and chiral symmetry, Weinberg gave a prediction on π-π scattering lengths (3) and suggested $\pi p \rightarrow \pi\pi N$ reactions as one of the best tools to study π-π scattering. Olsson and Turner (4) extended Weinberg's ideas to show that integrated cross sections for $\pi p \rightarrow \pi\pi N$ reactions depend on a single parameter ξ, which determines the way chiral symmetry is broken at the level of the phenomenological Lagrangian. Weinberg's prediction of $\xi = 0$ was found to be consistent with the quark model, but other values (ξ = 1, 2, -2) were also proposed (5).

Nearly all experimental information on $\pi p \rightarrow \pi\pi N$ reactions used for the determination of ξ consisted of data on the $\pi^- p \rightarrow \pi^+\pi^- n$ reaction. However it has been observed (6) that there is evidence for a $\pi^+\pi^-$ final state resonance, which extends into the threshold region making the determination of ξ largely extrapolation dependent. And finally, for resolving the sign ambiguity in the amplitude, data from an additional reaction channel are essential.

The main reason for absence of $\pi^- p \rightarrow \pi^- p \pi^0$ data in the threshold region is the difficulty to reject background (mainly elastic scattering) at the trigger level. As the elastic cross-section peaks at 300 MeV/c (Δ resonance) the signal to background ratio there amounts to approximately 10^{-5}, resulting in a huge amount of data and a difficult analysis.

Our measurement of $\pi^- p \rightarrow \pi^- p \pi^0$ was performed with OMICRON, a large volume magnetic spectrometer at the CERN SC. Here we give only a brief summary of the experiment. A detailed description of the experimental set-up and details of the analysis procedure are given in refs. (7,8).

Negative pion beams covering the momentum region from 295 to 450 MeV/c were used, the momentum spread being approximately 7 % (FWHM). A large volume cylindrical target (80 x ϕ15 cm) was filled with gaseous hydrogen at 1.2 MPa. The incoming pion as well as the two charged secondaries were detected in MWPC's and drift chambers enabling determination of their momenta and a fit of their tracks to a common vertex. The trigger was formed from scintillator signals in anticoincidence with a pulse from an electron threshold Čerenkov counter. The scintillator signals provided also time-of-flight and pulse-height information for the identification of particles. A Monte

Carlo simulation of the experiment was used to determine the acceptance of the apparatus.

The criteria for the selection of events belonging to the reaction $\pi^- p \to \pi^- p \pi^0$ were based on geometrical and kinematical properties of this reaction. A cut on the fiducial volume of the target was applied to reject background originating from target walls. A constraint on the χ^2 of the vertex fit eliminated most of the random-type background as well as events with large reconstruction errors. Particle identification resulted in a good separation (over 95 %) of protons versus pions, muons and electrons was achieved, which largely suppressed background with a positron in the final state (single Dalitz pairs and external conversion) as well as background from the $\pi^- p \to \pi^+ \pi^- n$ channel. For elastic scattering events energy and momentum conservation yield four kinematical constraints. Because of the good angular resolution of the apparatus angular correlation criteria were used in addition to the cut on the χ^2 of the four constraint fit.

The distributions of remaining events as a function of the only kinematical constraint left for a three-body reaction - the missing mass squared of the neutral particle - are shown in figs. 1. Two peaks can be seen in the spectra, the one at the origin due to $\pi^- p$ bremsstrahlung events and the peak near 0.02 GeV^2 belonging to the $\pi^- p \to \pi^- p \pi^0$ reaction. At lower incoming pion momenta the two peaks are well separated and the number of $\pi^- p \to \pi^- p \pi^0$ events can be obtained directly from the distribution (Fig. 1a). At higher momenta the peaks broaden (Fig. 1b) and a subtraction of Monte Carlo generated bremsstrahlung events was needed to estimate the number of $\pi^- p \to \pi^- p \pi^0$ events (Fig. 1c). The difference between the shape of spectra of measured and Monte Carlo generated events was taken as an estimate of the systematic uncertanity in the subtraction procedure.

As the result of the whole selection procedure an incident momentum dependent number of $\pi^- p \to \pi^- p \pi^0$ events, ranging from 6 at 295 MeV/c up to 430 at highest momenta, was obtained.

Measured angular and invariant-mass distributions were compared with the corresponding Monte-Carlo distributions of the $\pi^- p \to \pi^- p \pi^0$ reaction generated according to phase space. The comparison showed no differences beyond experimental errors, which was confirmed by a χ^2 test. The significance of such a conclusion is limited by poor statistics allowing only for comparison of one-dimensional distributions, which could be disturbed by the fact, that the experiment did not cover the entire phase space.

For the calculation of the integrated cross-section an extrapolation into the phase-space region not covered by our apparatus is needed. Differential distributions show no considerable departure from a phase space distribution in agreement with available information from previous experiments in the region below 500 MeV/c (2). Therefore, a uniform distribution in phase space was taken to be adequate for the extrapolation. The resulting cross sections with statistical and systematic errors summed in quadrature are summarized in Table 1.

Statistical errors are dominated by the number of measured events. They range from 42 % at 295 MeV/c and 28% at 315 MeV/c to 5 % at highest momenta. The statistical error from the number of simulated events is marginal, its value ranging from 5 % at 295 MeV/c down to 2 % at higher momenta. For measurements at momenta higher than 350 MeV/c the bulk of systematic errors originates from the uncertanities in the subtraction of bremsstrahlung events. This error was estimated from the difference of measured and simulated missing-mass event distributions, and amounts to a value between 15 and 25 %. At lowest momenta the overlap between the two peaks in the missing mass spectrum was taken as a measure of the systematic error, amounting to 33 % at 295 MeV/c, 15 % at 315 MeV/c and 5 % at 334 MeV/c. Other sources of systematic errors considered were those on the number of simulated events (6 % at 295 MeV/c down to 1 % at momenta above 400 MeV/c), the number of incident pions (5 %), efficiencies of chambers and counters (4 %), the particle identification efficiency (5 %) and on the hydrogen density (1 %). Various contributions were considered uncorrelated and therefore summed in quadrature.

A comparison of our measurement with existing data is shown in Fig. 2. One can see that there is good agreement at higher momenta, where data exist, yet our data reveal a whole new region extending down to 25 MeV/c above threshold.

The $\pi p \rightarrow \pi\pi N$ amplitudes derived from the phenomenological Lagrangian are believed to be valid only through terms linear in pion momenta while higher order terms might be strongly model-dependent (9). So before drawing conclusions about the symmetry breaking parameter ξ one should first check where soft pion calculations can be applied in a model independent way.

Arndt et al. (10) calculated amplitudes for $\pi p \rightarrow \pi\pi N$ reactions by evaluating graphs derived from the phenomenological Lagrangian up to the tree level. They suggested the difference between these amplitudes and their threshold approximations as being a measure of the model dependence of their calculations. Their study of the $\pi^- p \rightarrow \pi^- p \pi^0$ reaction shows that this difference is negligible only in the region from threshold up to 320 MeV/c, covering two of our data points (295 and 315 MeV/c), while at our third datum point (334 MeV/c) the same comparison already yields a difference of 25 %. So we consider our first two data points as being suitable for a comparison with theoretical calculations in a model-independent way.

Close to threshold the cross section for $\pi^- p \to \pi^- p \pi^0$ is a sum of the s ymmetric and antisymmetric cross sections

$$\sigma = \sigma^+ + \sigma^- \quad (I)$$

In the threshold limit these are given by

$$\sigma^+ = |a_+|^2 \cdot Q^2 \cdot PHS \qquad (IIa)$$

$$\sigma^- = |a_-|^2 \cdot \overline{(\mathbf{q}_1 - \mathbf{q}_2)^2} \cdot PHS \qquad (IIb)$$

Here a_+ and a_- are the symmetric ($I_{\pi\pi} = 2$) and antisymmetric ($I_{\pi\pi} = 1$) reduced amplitudes, Q is the CMS initial momentum and $\mathbf{q}_1$ and $\mathbf{q}_2$ denote the CMS pion momentum vectors in the final state. In the threshold limit the symmetric reduced amplitude is given by (4,10)

$$|a_+| = 0.47 + 0.19\,\xi \qquad (III)$$

while the antisymmetric reduced apmlitude is ξ-independent (10) and has the value of $|a_-| = 0.92$. In evaluating $|a_+|$ and $|a_-|$ the pion decay constant was taken at its Goldberger-Treimann value of 87 MeV. In (II) PHS is the phase space factor, in a nonrelativistic approximation amounting to

$$PHS = 2.56 \times 10^4 \cdot T^2/Q \quad \mu b \cdot c/GeV^3 \qquad (IV)$$

where T is the CMS kinetic energy in the final state.

Applying these formulae to our experimental data we extract for the symmetric reduced amplitude

$$|a_+ (295\ \text{MeV/c})| = 0.54\ ^{+\ 0.17}_{-\ 0.26} \qquad \text{(Va)}$$

$$|a_+ (315\ \text{MeV/c})| = 0.45\ ^{+\ 0.12}_{-\ 0.15} \qquad \text{(Vb)}$$

The combined average used in equation (III) yields, in principle, two values for ξ

$$\xi_1 = 0.1\ ^{+\ 0.5}_{-\ 0.7} \qquad \xi_2 = -5.0\ ^{+\ 0.5}_{-\ 0.7} \qquad \text{(VI)}$$

This sign ambiguity in the amplitude can be resolved by taking into account complementary data on the reaction $\pi^- p \rightarrow \pi^-\pi^+ n$. In our recent analysis (6) we find the two possible values $\xi_1 = -0.5 \pm 0.8$ and $\xi_2 = 5.1 \pm 0.8$, which clearly rejects ξ_2 in both measurements.

To conclude we have performed a full-kinematics measurement of the $\pi^- p \rightarrow \pi^- p \pi^0$ reaction covering the incident momentum region from 295 to 450 MeV/c. This represents the first measurement in the region below 390 MeV/c. From the two measurements closest to the threshold we extract the chiral symmetry breaking parameter ξ in a model independent way. Combining with our data on the $\pi^- p \rightarrow \pi^-\pi^+ n$ reaction we also resolve sign ambiguity. The measured value of $\xi = 0.1\ ^{+\ 0.5}_{-\ 0.7}$ represents the most accurate model-independent result on ξ, largely favouring Weinberg's choice of $\xi = 0$.

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Table caption

Table1: Integrated cross-section for the $\pi^- p \rightarrow \pi^- p\ \pi^o$ reaction as a function of the incident pion momentum p_o. Δp_o indicates the r.m.s. beam momentum spread. The statistical and systematic errors are quoted separately.

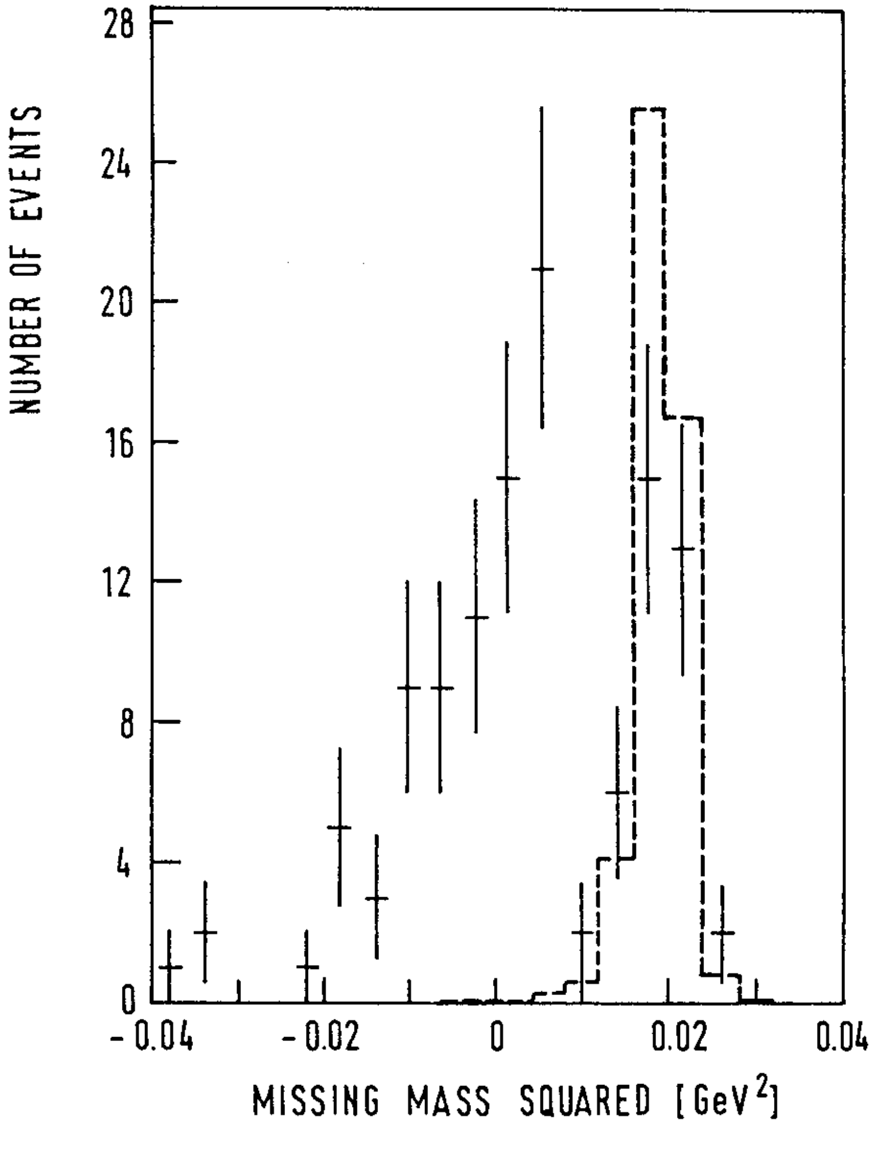
Figure captions

Figure 1: Missing mass squared distributions of events selected by geometrical and kinematical properties of the $\pi^- p \rightarrow \pi^- p\ \pi^o$ reaction: 1a) Distribution at 334 MeV/c, 1b) Distribution at 450 MeV/c, 1c) Same as 1b after the subtraction of simulated $\pi^- p$ bremsstrahlung events. The dashed histogram drawn in each figure represents the missing mass squared distributions of simulated $\pi^- p \rightarrow \pi^- p\ \pi^o$ events.

Figure 2: Integrated cross-sections for the $\pi^- p \rightarrow \pi^- p\ \pi^o$ reaction as measured in this experiment (full circles) compared to previous experimental studies (1,2). Errors shown are a combination of statistical and systematic errors summed in quadrature.

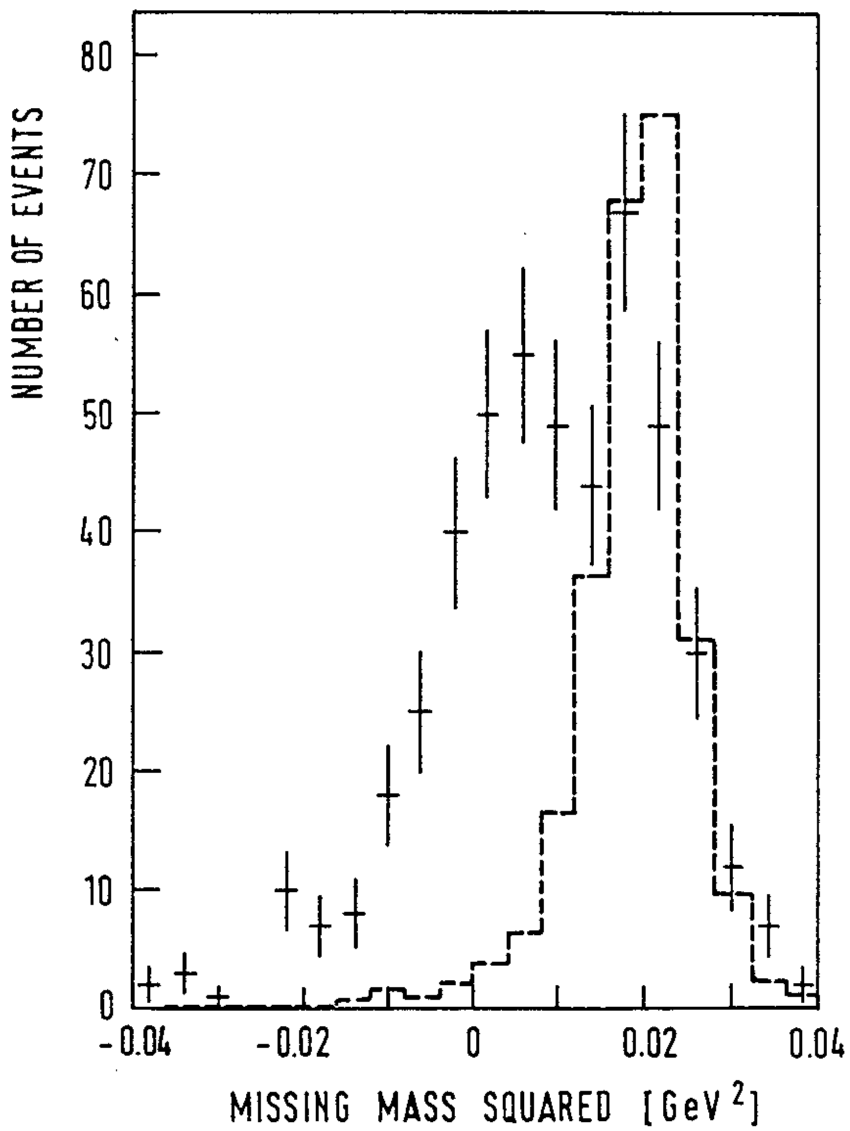
$p_o \pm \Delta p_o$ [MeV/c]	$\sigma \pm \Delta\sigma_{stat} \pm \Delta\sigma_{syst}$ [μb]
295 ± 9	0.75 ± 0.3 ± 0.3
315 ± 10	2.2 ± 0.6 ± 0.4
334 ± 10	8.5 ± 1.4 ± 0.8
354 ± 10	20 ± 3 ± 4
375 ± 11	27 ± 4 ± 4
394 ± 10	50 ± 4 ± 12
413 ± 10	73 ± 4 ± 14
432 ± 11	119 ± 8 ± 18
450 ± 12	157 ± 9 ± 36

Table 1



NUMBER OF EVENTS
28
24
20
16
12
8
4
0
- 0.04
- 0.02
0
0.02
0.04
MISSING MASS SQUARED [GeV^2]

Fig. 1a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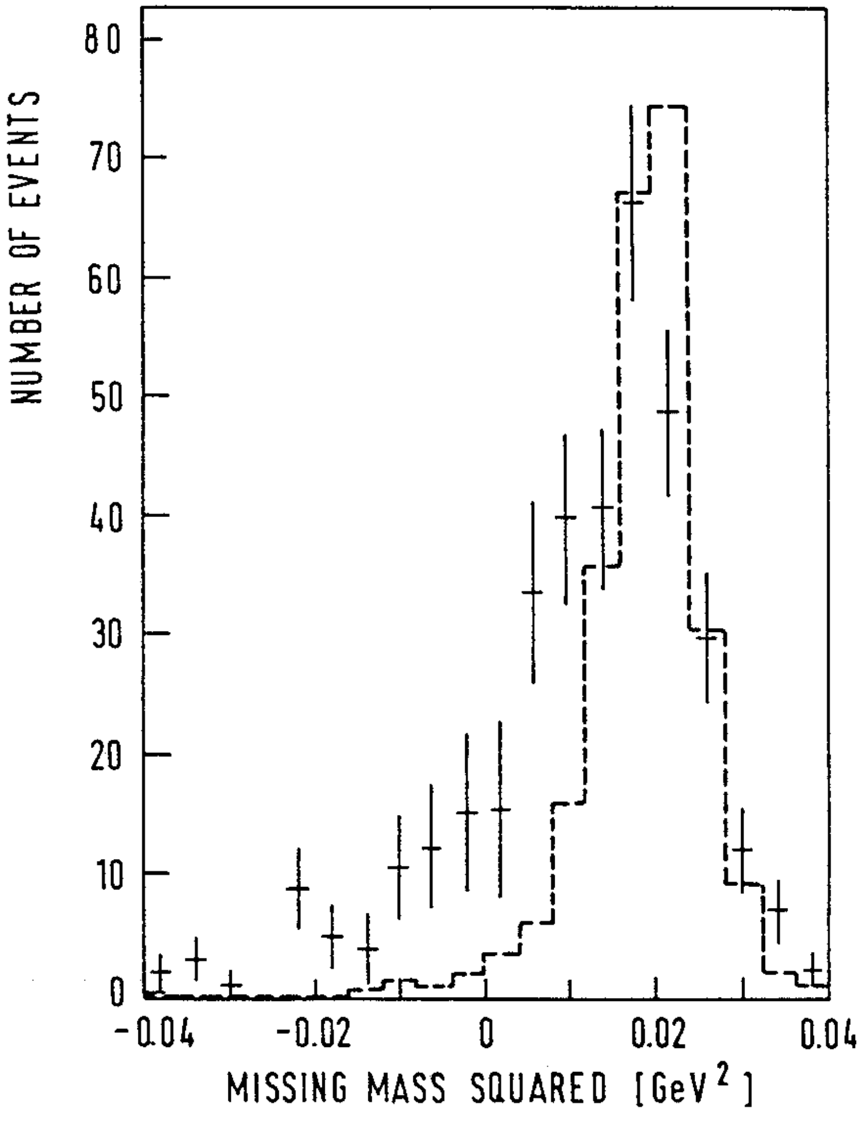
60
50
40
30
20
10
0
-0.04
-0.02
0
0.02
0.04
MISSING MASS SQUARED [GeV 2]

Fig. 1b



80
70
60
50
40
30
20
10
0
NUMBER OF EVENTS
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0
0.02
0.04
MISSING MASS SQUARED [GeV²]

Fig. 1c

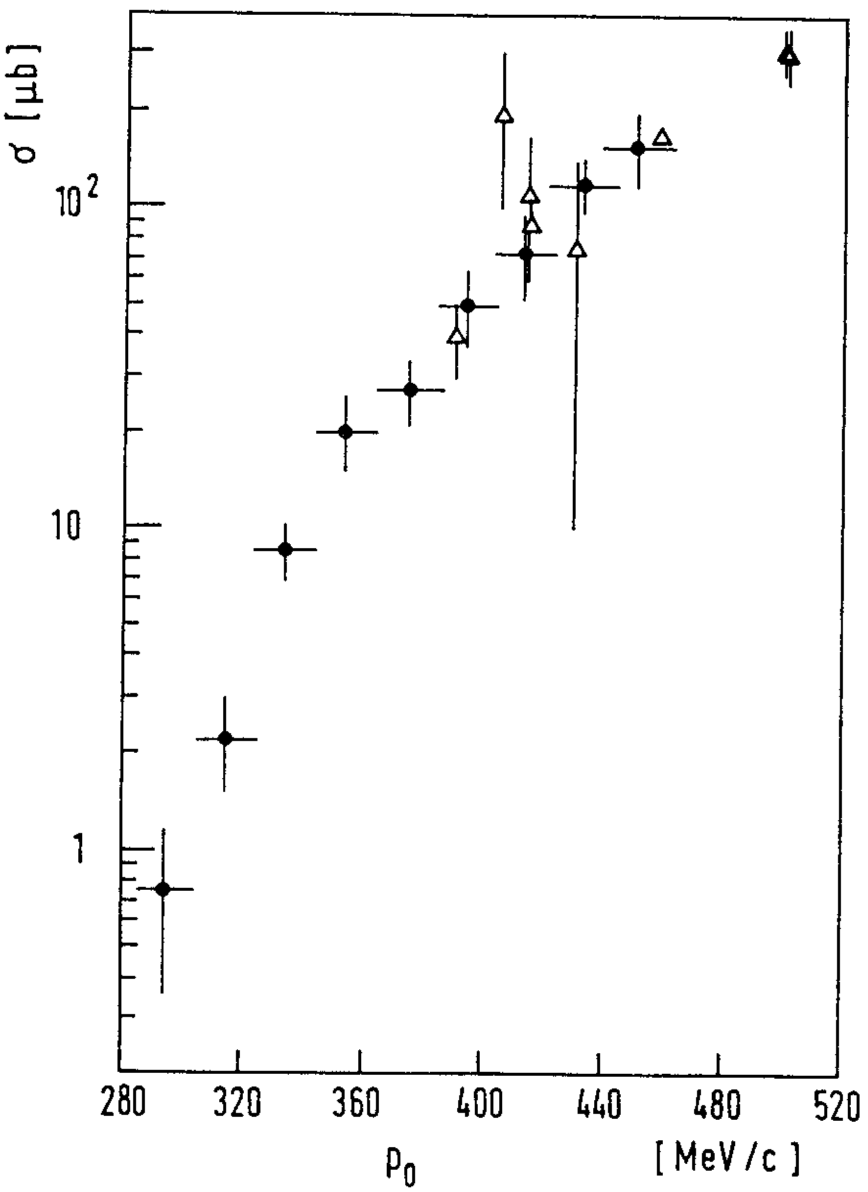

Fig. 2