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A STUDY OF THE pp → ppπ° REACTION AT 800 MeV BEAM ENERGY USING THE DIOGENE DETECTOR AT SATURNE.

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A study of the $pp \rightarrow pp\pi^0$ reaction at 800 MeV beam energy using the DIOGENE detector at Saturne

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The reaction $pp \rightarrow pp\pi^0$ has been investigated at the Saturne accelerator using a transversely polarized beam of 800 MeV incident kinetic energy and the DIOGENE detector. We have measured the total cross section, the differential cross section as a function of the pion energy and the anisotropy parameter b. We find a strongly dominant contribution, greater than 90%, of the Delta resonance to this process. We have determined the analyzing power A_y of the reaction and get negative values.

Nuclear Reaction ${}^1H(p,pp)\pi^0$, E=800 MeV;Δ contribution; measured total σ; differential $\sigma(E_\pi)$; Analysing power.

I. INTRODUCTION

Nucleon-nucleon interactions play a central role in nuclear physics, and the single pion production channel $NN \to NN\pi$ at intermediate energies is of particular interest because it is strongly related to the physics of the Delta resonance $\Delta(1232)$. In the beam energy range from pion production threshold up to 1 GeV, several experiments have been performed in the charged pion channel. They provided accurate data to understand the reaction mechanisms and to constrain the models of strong interactions at intermediate energies [1]. In the neutral pion channel $pp \to pp\pi^0$ the situation is not so clear; scarce data with less accuracy are available. Some experiments detected the π^0 directly by its decay in two photons but did not cover the full pion phase space [2, 3]. Bubble chamber experiments detected the two protons but had generally low statistics [4, 5]. Our experiment detected the two protons and covered the full phase space of the neutral pion. In this paper we present new data for the $\vec{p}(p,pp)\pi^0$ reaction at 800 MeV beam energy obtained in this experiment [6].

II. APPARATUS AND EVENT SELECTION

The experiment was carried out using the DIOGENE detector and a polarized proton beam of kinetic energy 800 MeV delivered by the Saturne accelerator at Saclay. DIOGENE consists essentially of a cylindrical proportional drift chamber (TPC) placed inside a solenoidal magnetic field of 1 Tesla, and in which the pressure is maintained at 4 atmospheres. The drift chamber is divided into ten identical sectors, each of them subtending 36° in azimuth and including a plane of 16 sensitive wires. This detector has been described in detail elsewhere [7]. It was originally built for experiments studying heavy ions collisions with large multiplicity.

Two modifications were made for this experiment. First we replaced the usual thin solid target by a liquid hydrogen target 200 mm long and 27 mm in radius, of cylindrical symmetry around the beam axis. The target walls were made of mylar of thickness 0.120 mm with windows made ot titanium of thickness 0.028 mm. To ensure a thermic isolation, the whole target was surrounded with 12 layers of aluminized mylar of thickness 0.005 mm each. Along the beam axis, the target center was moved 22 cm upstream of the detector's center to increase forward phase space coverage. The second modification consisted in adding a beam position detector. For this purpose two 4x4 cm^2 drift chambers were placed respectively at 2.25m and 3.80m before the entrance of DIOGENE and intercepting the beam. The measured X and Y coordinates in the chambers were used to determine the interaction point in the target for each event.

DIOGENE is a large solid angle detector (nearly 4π) which can detect all charged particles : $\pi^{\pm}, p, d$, etc; with a threshold of 60 MeV/c for pions and 300 MeV/c for protons. The azimuthal coverage is complete and with our target configuration the acceptance in polar angle was between 15° and 135°. For each detected particle, the reconstruction program RATRADI [8] provides particle identification using the energy loss measurement in the DIOGENE TPC, and determines the transverse momentum p_T , polar angle θ and azimuthal angle ϕ by tracking. We used a modified version of the code in order to account for an extended target [9]. Typical resolutions for protons in the momentum range 500-1500 MeV/c are the following in FWHM : $\Delta\theta \leq 2°$, $\Delta\phi \leq 1°$, and $\Delta P/P \sim 10 - 20$ % for $\theta > 30°$.

Neutral particles are not detected, so in the case of the $pp \rightarrow pp\pi^0$ reaction a kinematical reconstruction of the π^0 was necessary using the measured variables of the two protons. We first selected events for which two protons (and only two protons) were detected and identified with an overall acceptance of 50%. Each track was required to have at least five points (or hit wires) to ensure reliable tracking. The dominant reactions giving rise to these events are the elastic scattering and the $pp \to pp\pi^0$ channel, with total cross sections of the order of 24 and 4 mb respectively, at our beam energy. The other inelastic channels with two protons in the final state ($pp \to pp\pi^0\pi^0$ and $pp \to pp\pi^+\pi^-$) have cross sections smaller than 20 μb [10]. Besides, the probability for detecting only the two protons in DIOGENE is negligible for the reaction $pp \to pp\pi^+\pi^-$. The separation of $pp \to pp\pi^0$ and the elastic channel was the first difficulty of the analysis because events from these two reactions could not be separated using a missing mass test. Indeed, the resolution on the missing mass for the two protons system was of the order of the pion mass (see fig. 1, the negatives values are due to the experimental resolution on the different measured variables). We based the separation upon two other kinematical variables : $|\phi_1 - \phi_2|$ and $\Gamma^2 \tan\theta_1 \tan\theta_2$ which we shall call C_ϕ and C_θ respectively, for simplicity. Here 1 and 2 are labels for the measured variables of the outgoing protons number 1 and 2 and Γ is the Lorentz boost parameter from lab to center-of-mass system. For ideal elastic events one has : $C_\phi = 180°$ and $C_\theta = 1$. An experimental sample of elastic events was used in a preliminary analysis of the detector performances [9]. These events were selected requiring both $170° < C_\phi < 190°$ and $0.8 < C_\theta < 1.2$. To select the $pp \to pp\pi^0$ channel in our experimental data, we first removed these events. However some additional cuts were necessary to reduce the contamination level and they have been applied in the (C_ϕ, C_θ) plot. We kept only events lying inside the area limited by : $C_\theta < 0.72$ and $70° < C_\phi < 290°$ and the two parabolic curves defined in fig. 2. These cuts were established by comparison with a pure set of simulated $pp \to pp\pi^0$ events which we obtained with a Monte-Carlo program including acceptance effects and experimental resolutions. Events rejected by these cuts originated mostly from elastic scattering on hydrogen and $(p, 2p)$ reactions in the target walls, and this diagnostic was made observing reconstructed variables such as the missing mass or the vertex coordinate along the beam.

Most of the physics results in the $pp \to pp\pi^0$ channel require to know the pion variables, so we had to reconstruct this missing particle kinematically from the two detected protons. This is an unfavorable case since all experimental errors add up, and indeed the resolution of the DIOGENE detector was too limited to determine some variables directly with acceptable accuracy, essentially the missing energy. We used a constrained fit as the optimal method to get the pion variables with the best resolution. This procedure applied to simulated events yielded the following resolution in FWHM : $\Delta(\cos\theta^*_\pi) = 0.2$, $\Delta\phi_\pi = 13°$, $\Delta T^*_\pi = 13$ MeV; where θ^*_π and T^*_π are the pion polar angle and kinetic energy in the center-of-mass system. A further cut was introduced when the fit had bad convergence or when the χ^2 of the fit was too large. After all cuts, we obtained a sample of 21105 $pp \to pp\pi^0$ events with negligible contamination (less than 0.5 %) from which we extracted the physics results at 800 MeV beam energy.

III. RESULTS

In our energy range, the formation of a Delta resonance ($\Delta(1232)$ or P_{33}) is a dominant mechanism in the reaction $NN \to NN\pi$. The $pp \to pp\pi^0$ cross section can be described as the incoherent sum of a non resonant cross section (or "phase space") and a resonant cross section associated to an $N\Delta$ intermediate state : $pp \to p\Delta^+$, $\Delta^+ \to p\pi^0$ [1, 11]. We first determined the proportion λ_Δ of events going through a Δ resonance. The method required two different sets of simulated events corresponding to the two partial cross sections. Then the experimental data was adjusted by a combination of the two simulated sets. The first simulated sample was generated according to the three body phase space (FOWL program of CERN library). The second one was generated according to the isobar model using a procedure identical to the one of ref. [4]. For the first step of the reaction : $pp \to p\Delta^+$, the center-of-mass polar angle θ_Δ of the Delta resonance was chosen randomly in a $(1 + 2cos^2\theta)$ law [12] and the mass of the resonance followed a relativistic Breit-Wigner distribution [13]. For the second step : $\Delta^+ \to p\pi^0$ the decay angular distribution $W(\theta, \phi)$ is usually given in terms of density matrix elements in the Gottfried-Jackson t-channel frame , i.e. the Δ^+ center-of-mass frame with the z-axis along the incident proton momentum and the y-axis normal to the $p\Delta^+$ production plane [13]. Measurements both in the $pp \to n\Delta^{++}$ and $pp \to p\Delta^+$ channels [12, 4] have shown that in our energy range this decay angular distribution is almost flat in azimuth and follows a $(1 + \frac{1}{3}cos^2\theta)$ law to a good approximation. We used this distribution in the simulation; it corresponds to all density matrix elements ρ_{ij} being negligible except $\rho_{33} \sim 0.2$.

For a proper choice of variable, i.e. a variable sensitive to the differences between pure phase space and isobar model, we adjusted the experimental spectrum by a combination of the two simulated spectra with relative contributions $1 - \lambda_\Delta$ and λ_Δ. We used a χ^2 minimization with λ_Δ as a free parameter. As an example fig. 3 shows the experimental and simulated distributions of the pion kinetic energy in the center-of-mass which is one of the most sensitive variables. The fit was performed for five different choices of variables and the results are listed in table 1. They show good consistency and we took their average as the final value $\lambda_\Delta = 94 \pm 2$ $(stat.) \pm 5$ $(syst.)$ %. The statistical error is given by the fit and the systematic error is estimated by the maximal spread among the five values. Our result disagrees with the only other measurement of the Delta contribution in the $pp\pi^0$ channel, given by Shimizu et al [4]. These authors found $\lambda_\Delta = 66 \pm 10$ % and 56 ± 11 % at 767 MeV and 857 MeV beam energies respectively, using a fitting procedure similar to ours based on the

$(p\pi^0)$ invariant mass spectrum. We did not find any explanation to this discrepancy.

To discuss these results one can consider the basic isospin decomposition of the total cross sections in the $pp \to pp\pi^0$ and $pp \to pn\pi^+$ channels [1]:

$\sigma(pp \to pp\pi^0) = \frac{1}{6}\sigma_1(\frac{3}{2}) + \frac{1}{3}\sigma_1(\frac{1}{2})$.

$\sigma(pp \to pn\pi^+) = \frac{5}{6}\sigma_1(\frac{3}{2}) + \frac{2}{3}\sigma_1(\frac{1}{2})$.

where the index 1 is the total isospin and $\frac{3}{2}$ (or $\frac{1}{2}$) stands for the isospin of the (πN) state. From this, one can deduce the percentage of events $\lambda_{\frac{3}{2}}$ going through a $(I_{\pi N} = \frac{3}{2})$ state in the $pp \to pp\pi^0$ channel; it can be written as:

$$\lambda_{\frac{3}{2}} = \frac{\frac{1}{6}\sigma(\frac{3}{2})}{\sigma(pp \to pp\pi^0)} = \frac{1}{3}\left[\frac{\sigma(pp \to pn\pi^+)}{\sigma(pp \to pp\pi^0)} - 2\right] \quad (3.1)$$

Using the cross section measurements of Shimizu et al. at 767 MeV beam energy: $\sigma(pp \to pn\pi^+) = 16.44 \pm 0.44$ mb and $\sigma(pp \to pp\pi^0) = 3.61 \pm 0.21$ mb, one finds: $\lambda_{\frac{3}{2}} = 85 \pm 8$ %. The result of Shimizu et al. for λ_Δ (66 %) suggests that there might exist contributions to the $(I_{\pi N} = \frac{3}{2})$ state other than (πN) in a Δ state, whereas our result for λ_Δ could be interpreted as indicating that almost all isospin $\frac{3}{2}$ contribution comes from (πN) in a Delta state.

Because DIOGENE could detect all protons with polar angles greater than 15 degrees, the experimental acceptance was large enough to cover the entire phase space of the outgoing pion. This allowed us to measure total and differential cross sections without any model assumption. We determined the total $pp \to pp\pi^0$ cross section and found $\sigma_{tot} = 3.78 \pm 0.03\ (stat.) \pm 0.13\ (syst.)$ mb, in good agreement with previous measurements at this energy (see [1] and [2,5].) The systematic error comes mainly from the uncertainty on the global detection plus reconstruction efficiency, represented by a number $\epsilon < 1$. We determined this number from a renormalization of our experimental $(pp \to pp)$ events to the measured elastic cross section $d\sigma/dt$ of ref. [14] and found : $\epsilon = (85 \pm 3)$ %.

We measured the differential cross sections $d\sigma/dT^*_\pi$, $d\sigma/dp_\pi$, and $d\sigma/dp^*_\pi$. Our results are presented in tables 2,3 and 4 respectively, with the systematic error determined as for the total cross section. Fig. 4 illustrates our values of $d\sigma/dp^*_\pi$. They are in excellent agreement with the measurement of Andreev et al [15] at 820 MeV beam energy but our error bars are a factor of three smaller.

In fig. 5, we report the results of a calculation by Laget [16] performed using a meson (π and ρ) exchange model [17] which includes also final state interactions via Paris potential. The comparison between theory and experiment shows a qualitative agreement. For more quantitative comparison, σ_{tot} obtained from ref [16] is 4.1 mb overestimating our measured value by $\simeq$ 10 %. An improvement to this model requires the inclusion of the intermediate state nucleon-delta interactions [18]. The need for such a treatement has also become clear in recent results [19] of the pion photoproduction on the deuteron obtained at Mainz. A calculation according to these lines is in progress [16]. Another, more comprehensive, approach based on relativistic and unitary three-body isobar formalism [20] is also being applied [21] to the process investigated in this paper.

The pion angular cross section is usually described [1] by : $d\sigma/d\Omega \propto (1/3) + b\cos^2\theta^*_\pi$ where θ^*_π is the pion polar angle in the center-of-mass and b is the anisotropy parameter expressing how many partial waves contribute to the πN system. Although our bad resolution on the reconstructed angle θ^*_π did not allow to extract the differential cross section $d\sigma/d\Omega$, we were able to determine the anisotropy parameter b by a direct comparison of the experimental and simulated spectra of $\cos\theta^*_\pi$, owing to the large acceptance for this variable. We used a χ^2 minimization with b as a free parameter and obtained : $b = 0.41 \pm 0.03$ $(stat.) \pm 0.11$ $(syst.)$ with the statistical error given by the minimization. As the fit was of bad quality (χ^2 around 90) we adjusted b separately in the two regions $\cos\theta^*_\pi < 0$ and > 0 and took the obtained values as the limits of the systematic error bar. Our result tends to indicate a high anisotropy contrary to the most recent measurement indicating a value of b around 0.2 at 800 MeV [2]. It should be noted that this parameter is intrinsically difficult to measure; for example the experimental b values of ref. [15] are spread between 0.2 and 0.4 in the vicinity of 800 MeV.

The use of a transversely polarized beam and the full azimuthal coverage of DIOGENE allowed us to measure the analyzing power A_y of the $\vec{p}p \rightarrow pp\pi^0$ reaction as a function of $\cos\theta^*_\pi$. A first method consisted in integrating the pion counting rates in the two halves of the detector in ϕ for the two beam polarization states "up" and "down" and computing the asymmetry from these numbers. A second method consisted in fitting the pion azimuthal distribution by the function $1 + P_b A_y \cos(\phi_\pi + \phi_0)$ for each beam polarization state. A_y is a free parameter, ϕ_0 is adjusted from our data in the $(pp \rightarrow pp)$ channel, and the beam polarization P_b was equal to 92 %. Results obtained by the two methods were in excellent agreement. Our final values for the analyzing power A_y are presented in table 5 and depicted in fig. 6. They indicate a negative analyzing power, in agreement with a recent measurement of this observable at Saturne by G.Rappenecker et al [2]. Our measurements can be compared with those obtained in the $np \rightarrow pp\pi^-$ with the Arcole detector at Saturne [22]. Indeed, using the standard notation σ_{if} where i and f stand for the isospin of the two-nucleons in the initial and final states, we know [1] that $\sigma(pp \rightarrow pp\pi^0)$ is a pure σ_{11}, while $\sigma(np \rightarrow pp\pi^-) = \frac{1}{2}(\sigma_{11} - \sigma_{01})$. The difference in the measured analyzing power A_y in the π^0 and π^- channels could indicate that the σ_{01} cross section might not be negligible at 800 MeV beam energy.

IV. CONCLUSION

In this paper we have presented differential and total cross sections as well as the analyzing power for the neutral pion production in proton-proton collisions at 800 MeV, with improved accuracies over the previous data and for the full pion phase space. The most striking feature of our results concerns a quite large contribution ($> 90\%$) of the Delta resonance to the reaction mechanism. Comparing the only available theoretical prediction with our differential cross section results, the need for more realistic calculations is clear. As expected, both this observable and the analyzing power bring in strong constraints on the theoretical approaches in progress [16, 21].

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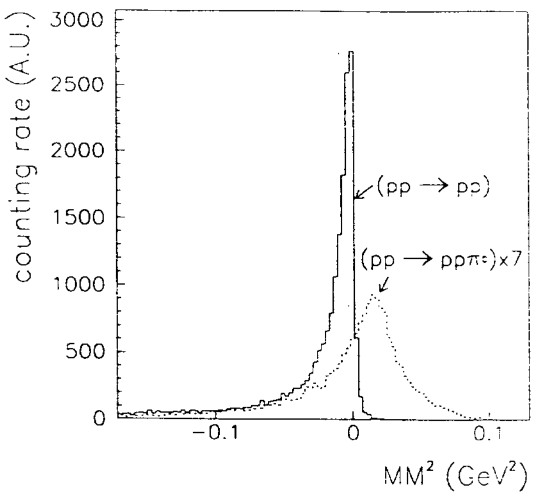

Figure 1: missing mass squared for experimental data in the $pp \rightarrow pp$ and $pp \rightarrow pp\pi^0$ channels. The (π^0) peak has been multiplied by a factor 7 .

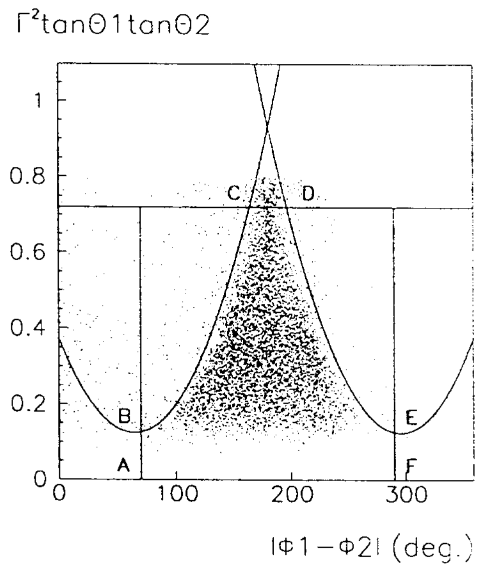

Figure 2: kinematical cuts in the $(|\phi_1 - \phi_2|, \Gamma^2 tan\theta_1 tan\theta_2)$ plane to separate experimental $pp \rightarrow pp\pi^0$ events from background. Events lying outside the area ABCDEF are rejected.

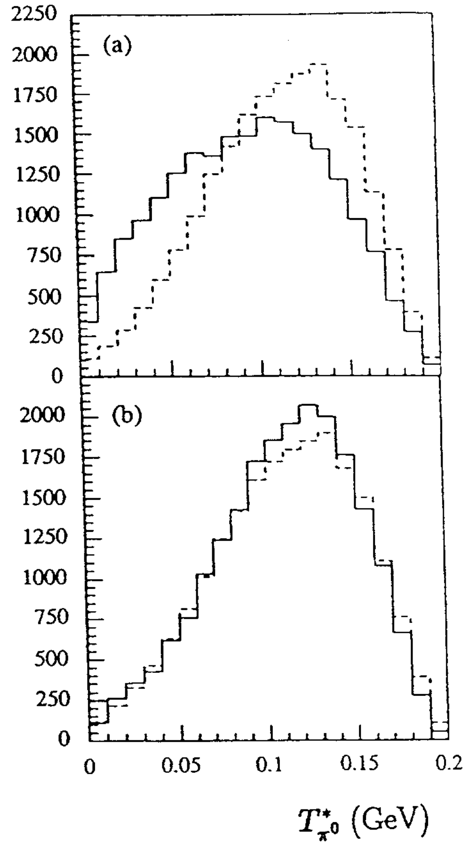

Figure 3: spectrum of π^0 kinetic energy in the center of mass. (a) the two simulated distributions: "phase space" (solid line) and "Delta" (dashed line); (b) experimental distribution (solid line) and the result of the fit (dashed line) which combines the two above simulated distributions.

Table 1: our results for the contribution of the Delta resonance (see text) using five different variables. M(ab) is the invariant mass formed with particles a and b. The indices 1 and 2 are for protons emitted with the largest and the smallest polar angle respectively.

choice of variable for the fit	fitted value for λ_Δ (%)
$M(p\pi)$ closest to M_Δ	89 ± 2
$M(p_1\pi)$ versus $M(p_2\pi)$	96 ± 2
$M(p_1\pi)$ and $M(p_2\pi)$ cumulated	99 ± 2
$M(p_1p_2)$	94 ± 2
c.m. kinetic energy $T^*_{\pi^0}$	94 ± 2

Table 2: Our measurement of the pion kinetic energy differential cross section in the center of mass. The bins are 20 MeV wide and we have reported the central value of the bin.

$T^*_{\pi^0}$(GeV)	0.01	0.03	0.05	0.07	0.09	0.11	0.13	0.15	0.17	0.19
$\frac{d\sigma}{dT^*_{\pi^0}}$(mb/GeV)	2.13	6.53	11.8	19.0	25.0	29.3	31.4	27.9	24.3	13.6
$\pm\Delta stat.$	0.11	0.23	0.31	0.40	0.45	0.47	0.49	0.49	0.58	0.75
$\pm\Delta syst.$	0.07	0.23	0.41	0.67	0.88	1.03	1.11	0.98	0.86	0.48

Table 3: Our measurement of the pion momentum differential cross section in the laboratory. The bins are 62 MeV/c wide and we have reported the central value of the bin.

p_{π^0}(GeV/c)	0.031	0.093	0.155	0.217	0.279	0.341	0.403	0.465	0.527	0.589
$\frac{d\sigma}{dp^{Lab}_{\pi^0}}$ (mb/(GeV/c))	0.49	4.70	8.04	9.17	10.3	11.2	9.5	6.2	2.8	0.36
$\pm\Delta stat.$	0.037	0.12	0.17	0.18	0.19	0.18	0.16	0.12	0.082	0.043
$\pm\Delta syst.$	0.017	0.16	0.28	0.32	0.36	0.39	0.33	0.22	0.099	0.013

Table 4: Our measurement of the pion momentum differential cross section in the center of mass. The bins are 32 MeV/c wide and we have reported the central value of the bin.(see figure 5).

$p^*_{\pi^0}$ (GeV/c)	0.016	0.048	0.080	0.112	0.144	0.176	0.208	0.240	0.272	0.304
$\frac{d\sigma}{dp^*_{\pi^0}}$mb/(GeV/c)	0.056	0.91	2.90	5.61	11.8	19.2	24.6	26.3	21.9	8.1
$\pm\Delta stat.$	0.013	0.065	0.12	0.17	0.25	0.31	0.34	0.36	0.42	0.56
$\pm\Delta syst.$	0.002	0.032	0.10	0.20	0.42	0.68	0.87	0.93	0.77	0.29

Table 5: our result for the analyzing power of the reaction $\vec{p}p \to pp\pi^0$ (see fig.6).

bin width in $\cos\theta^*_{\pi^0}$	$A_y \pm \Delta A_y$
[+0.6, +1.0]	(−2.8 ± 1.9) %
[+0.2, +0.6]	(−3.0 ± 2.4) %
[−0.2, +0.2]	(−16.2 ± 3.6) %
[−0.6, −0.2]	(−25.0 ± 3.9) %
[−1.0, −0.6]	(−9.0 ± 3.4) %

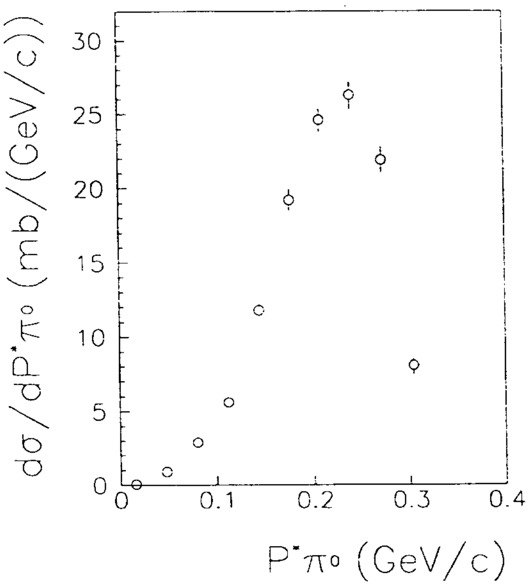

Figure 4: Our measurement of the pion's momentum differential cross section in the center of mass.

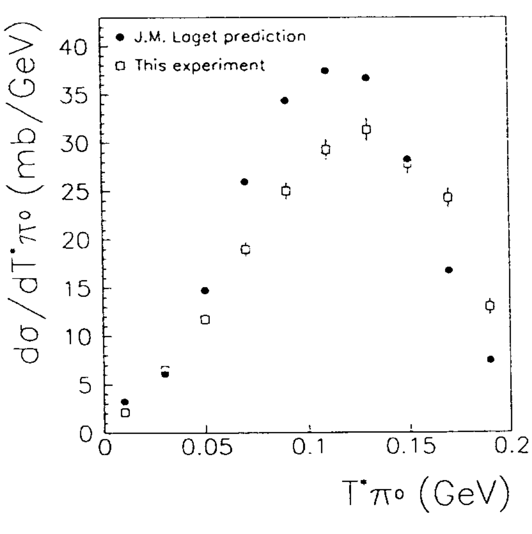

Figure 5: Pion kinetic energy differential cross section in the center of mass. Our measurement and theoretical prediction of J.M. Laget [16].

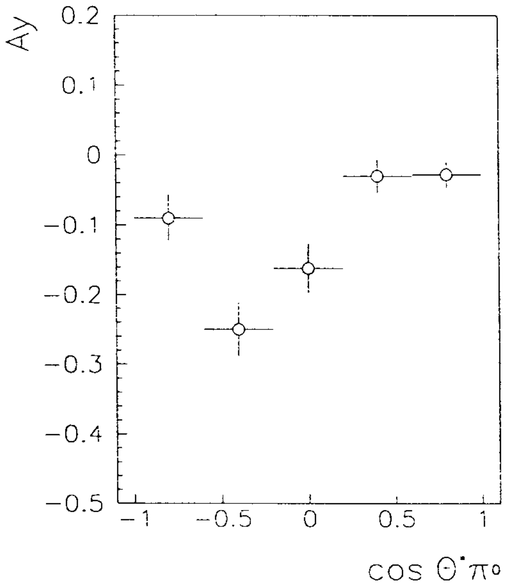

Figure 6: Our measurement of the analyzing power for the reaction $\vec{p}p \rightarrow pp\pi^0$.