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Photoproduction of π^+-Mesons on Polarized Protons

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Abstract:

The asymmetry of the cross sections for the photoproduction of π^+-mesons on polarized protons $\gamma + p\uparrow \rightarrow \pi^+ + n$ has been studied in the four-momentum transfer range $0.1 \leq |t| \leq 1.25$ $(GeV/c)^2$ for photon energies of 2.5, 3.4 and 5.0 GeV. The measurements were carried out on a polarized butanol target. Both particles in the final state were detected: the pion by a magnetic spectrometer, the recoil nucleon in a scintillation counter matrix. The asymmetry was found to be negative with values around -0.4.

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High energy photoproduction of charged pions $\gamma + N \rightarrow \pi + N'$ has been investigated by many authors, both theoretically and experimentally +). It offers a number of valuable tests for theoretical models based either on the exchange of pure Regge poles or additional Regge cuts. Further interest in high energy pion photoproduction is given by the predictions of the vector meson dominance model and through the connection to the low energy region via finite energy sum rules.

In spite of the complicated spin structure - 4 complex helicity amplitudes are needed for a complete description of any isospin channel of the reaction $\gamma N \rightarrow \pi N'$ - quite detailed information has been obtained from just a few experimental quantities. The sharp forward peak of the differential cross sections $d\sigma/dt$, together with the polarized photon asymmetry Σ, can be considered as strong evidence for one pion exchange at small momentum transfers ($|t| \leq m_\pi^2$). Moreover, this forward peak implies that Regge poles alone are not sufficient since they predict a vanishing forward cross section; Regge cuts like absorption corrections or s-channel contributions have to be included. The differential cross sections for π^+ and π^- photoproduction are quite different outside the forward direction. This means that a large interference between isoscalar and isovector photons exists, or - in terms of t-channel exchange - between exchanges of different G parity.

The polarized photon measurements decide that outside the forward peak, i.e. for momentum transfers $|t| > m_\pi^2$, this interference occurs mainly between particles or systems of natural spin-parity, that is ρ and A_2 in a Regge pole picture.

+) For experimental data see ref. (16). A number of recent theoretical analyses are given in ref. (1-6).

The polarized target asymmetry T is not in a simple way related to certain t-channel exchanges like the polarized photon asymmetry Σ. However, T gives information on the s-channel helicity-flip and non-flip amplitudes for natural parity exchange. The target asymmetry vanishes for single particle contributions and for exchange degenerate systems; it depends critically on the relative phases of different contributions and is thus an experimental quantity which tests specific features of a model, after a general frame has been set by the cross sections and photon asymmetries.

A first measurement of the polarized target asymmetry was carried out at SLAC for energies of 5 and 16 GeV (7). The present experiment was planned to extend these measurements to the low energy part of the Regge region.

Experimental setup

The measurements on a polarized proton target were carried out at DESY. Both particles in the final state were detected in coincidence: the pion by a magnetic spectrometer and the recoil neutron in a scintillation counter matrix (fig. 1).

A bremsstrahlung beam of about 10^{12} equivalent quanta/min and with a maximum energy k_{max} of 2.6, 3.5 or 5.1 GeV was collimated on a target area of 15 x 15 mm^2 (fwhm). The beam intensity was measured with a Wilson type quantameter and monitored with a counter telescope.

The polarized target had a cross sectional area of 20 x 20 mm^2 and a length of 40 mm along the beamline. It consisted of small prefrozen spheres of 95% n-butanol and 5% H_2O, doped with porphyrexide. The target material was cooled to a temperature of 1 K in a He^4 evaporation cryostat of the CERN type (8). In a magnetic field of 2.5 T, an average degree of polarization for the free protons of about 33% was achieved using dynamic orientation with a microwave frequency of 70 GHz. During the measurements this value of the polarization dropped to about 30% due to radiation damage. The target magnet PT was similar to the CERN prototype PT6; it had a field inhomogeneity of about 10^{-4} over the whole target volume (9). The dynamic polarization was continuously monitored by a proton magnetic resonance at 106 MHz (10). Its magnitude was determined by comparison with the NMR signal under thermal equilibrium conditions. The temperature of the cryostat was defined by the He^4 vapour pressure. The multimode cavity containing the target was separated into two parts by a septum of 30μ copper foil perpendicular to the γ-beam as proposed by Morehouse (11) for an improved filling of the cavity with rf radiation. Measurements with a partly filled cavity showed that the NMR response was uniform over the whole target volume (12).

The pions were detected in a focusing magnetic spectrometer (13) consisting of 5 bending and 2 quadrupole magnets.

The deflection of the pions in the target magnet was compensated by adjusting the spectrometer angle properly. Since both directions of polarization were measured with the same polarity of the target magnet, no artificial asymmetry was introduced by this procedure. The pions were identified by two threshold Cerenkov counters. The spectrometer had a momentum acceptance $\Delta p/p = \pm 3\%$ and a solid angle $\Delta\Omega = 0.3$ msterad.

The resolution was improved by hodoscopes and proportional chambers.

The recoil neutrons were detected in a scintillation counter matrix of 5 x 7 elements each 100 x 100 x 500 mm^3 large.

A sweeping magnet and lead absorbers (25 - 100 mm thick) in front of the counters reduc ed the large electromagnetic background which was swept into the recoil neutron direction by the target magnet. The threshold for the neutron counters was set moderately high (about 10 MeV). The neutron detection efficiency was measured to (25 ± 3)% for energies between 50 and 700 MeV, in agreement with calculations based on the report by Kurz (14).

Data analysis and results

Coincident pion-neutron events were detected by measuring the time of flight of the neutron with respect to the pion. Fig. 2 shows that the accidental background underneath the time of flight peak is of the order of 10%. This background can be safely subtracted by a linear interpolation. As a check, the neutron time of flight was also measured with respect to a random trigger in the pion spectrometer. The resulting spectrum was completely flat.

The pion-neutron coincidence rates contain a 5 - 20 % fraction (depending on the t-value) of events which come from photon interactions with the bound nucleons in the target. Two different methods were employed to extract the number of π-n events coming from the free protons in the butanol:

a) measurements were made with a carbon target, again detecting pion and neutron in coincidence. Fig. 2 shows the time of flight spectra obtained from a butanol target (both directions of polarization) and the carbon target. The spectra are normalized to the same number of equivalent quanta and bound protons. From the ratio $\lambda = (\pi n)$ carbon / (πn) butanol one gets a correction factor $1/\kappa = 1/(1-\lambda)$ by which the raw target asymmetry (measured with the butanol target) has to be multiplied to get the asymmetry for the free protons.

This factor $1/\chi$ is slightly t-dependent and of the order 1.1 ÷ 1.2 (see fig. 3). Here a coincidence experiment demonstrates its great advantage over a single arm experiment where such a factor is about 3.5.

b) Because of the Fermi motion in the nuclei, pion-neutron events from carbon, oxygen and other nuclei can be distinguished from hydrogen events by coplanarity and collinearity requirements. The data were also analyzed this way. The results were compatible with those of method (a) but not as accurate because of the problem of the spatial resolution in a neutron counter.

The cross section asymmetry T for π^+ photoproduction on protons polarized parallel (↑) or antiparallel (↓) to the normal of the reaction plane $\vec{n} = (\vec{k} \times \vec{q}) / |\vec{k} \times \vec{q}|$ ($\vec{k}$, $\vec{q}$ being the momenta of the photon and meson) is defined as

$$T = \frac{\frac{d\sigma}{dt}(\uparrow) - \frac{d\sigma}{dt}(\downarrow)}{\frac{d\sigma}{dt}(\uparrow) + \frac{d\sigma}{dt}(\downarrow)} .$$

In terms of the pion-neutron yields $N\uparrow$ and $N\downarrow$ from butanol for both directions of proton spin orientation, the corresponding degrees of polarization $P\uparrow$ and $P\downarrow$ and the bound-nucleon correction factor $1/\chi$ this quantity is given by the expression

$$T = \frac{1}{\chi} \frac{N\uparrow - N\downarrow}{N\uparrow \cdot |P\downarrow| + N\uparrow \cdot |P\downarrow|}$$

(For the case $|P\uparrow| = |P\downarrow| = P$ this reduces to the more familiar expression

$$T = \frac{1}{\chi \cdot P} \cdot \frac{N\uparrow - N\downarrow}{N\uparrow + N\downarrow}$$

The largest systematic uncertainty of the experiment concerns the degree of polarization P of the target. The determination of P by means of the NMR is believed to be accurate to ± 5%. During data taking the target suffers radiation damage. P can be parametrized as $P = P_o \exp(-\phi/\phi_o)$, where ϕ is the integrated beam intensity and $\phi_o = (10 \pm 4) \cdot 10^{15}$ equivalent quanta, compared to $\phi_o = 3.4 \cdot 10^{15}$ equivalent quanta for the SLAC measurements (11) and $\phi_o = 0.85 \cdot 10^{15}$ equivalent quanta/cm^2 for measurements at Bonn (15). The radiation damage can be annealed by heating the butanol to a temperature of 120 K. A special target was irradiated with a total dose of 10^{16} equivalent quanta and was annealed 12 times without loss in polarization. The degree of polarization does not stay constant over the target volume during irradiation by the photon beam. The material outside the beam profile is depolarized with a depolarization constant of about $2 \cdot \phi_o$. Since it seemed very difficult to determine the actual polarization profile, the annealing procedure was already repeated when the polarization had dropped to about 80% at the most.

The results of the target asymmetry T are given in table 2 and plotted in fig. 4 for energies of 3.4 and 5 GeV. The error bars contain the statistical uncertainties including those from the accidentals' subtraction. Not included is a systematic uncertainty $\Delta T/T \approx \pm 0.1$ which is mainly due to the determination of the degree of polarization ($\Delta P/P \approx \pm 5\%$) and to the corrections for pion photoproduction on carbon nuclei ($\Delta\chi/\chi \approx \pm 5\%$).

The asymmetry is negative in the whole momentum transfer range $0.1 \leq |t| < 1.2$ (GeV/c)^2 covered by the experiment. Between 2.5 and 5 GeV, no significant energy dependence can be stated from the present data. At 5 GeV there is fair agreement with the data of Borghini et al. (7). Taking into account also the 16 GeV data of ref. (7) only a slight energy dependence can be seen, if it exists at all. The t dependence shows no significant structure near $t = -0.6\ (\mathrm{GeV}/c)^2$, the point of the ρ-trajectory, in particular no zero crossing.

Comparison with theoretical models

In terms of the parity-conserving s-channel helicity amplitudes the target asymmetry is given by (3)

$$T = \frac{\pi}{2k^2 \frac{d\sigma}{dt}} \mathrm{Im}(H_+\phi_+^* + H_-\phi_-^*)$$

$H_\pm$ are the amplitudes with helicity-non-flip at the nucleon vertex, $\phi_\pm$ the amplitudes with helicity-flip.

In the limit of large s they correspond to natural (+) or unnatural (-) parity exchange in the t-channel.

Since natural parity exchange dominates strongly at $|t| > m_\pi^2$ we have

$$T \sim \mathrm{Im}(H_+ \cdot \phi_+^*)$$

As mentioned in the introduction pion exchange modified by either absorption or direct channel contributions is necessary to explain the forward peak of the cross section. Also at larger $|t|$ values a cut contribution is required (e.g. ref. 4): if ρ and A_2 are assumed to be exchange degenerate their trajectories are $\pi/2$ out of phase and cannot interfere, so the π^+ and π^- cross sections would have to be equal. At larger $|t|$ values the interference of the ρ, A_2 contributions with the cut in ϕ_+ can explain the π^-/π^+ ratio. At the same time we may expect a sizeable target asymmetry. The near equality of the π^+ and π^- cross sections at small $|t|$ suggests that the ρ, A_2 and the cut contributions are about $\pi/2$ out of phase, thus giving rise to a large target asymmetry. The ρ, A_2 phase factor will rotate faster with increasing $|t|$ than the phase factor of the cut, so the asymmetry should decrease towards larger $|t|$-values (1). This seems to be qualitatively confirmed by the data, although the experimental $|t|$-dependence is not very conclusive.

A general difficulty for most Regge models is the lack of structure in the asymmetry near $t = -0.6\ (GeV/c)^2$, the NWS zero point of the ρ-trajectory, and the absence of a zero crossing.

Detailed fits to pion photoproduction have been performed by a number of authors. Some of the more recent papers will be discussed briefly.

In his fit to pion photoproduction Kellett (5) uses the gauge invariant electric Born term model to reproduce the forward cross sections. A phenomenological form factor for higher nucleon resonances is introduced to describe the decrease of $d\sigma/dt$ towards larger values of $|t|$. In addition not exchange degenerate ρ and A_2 are used, modified by double Regge exchanges (ρ-P, A_2-P). The ρ-trajectory is assumed to follow the fixed pole mechanism. Since the SLAC data (7) on the target asymmetry had not been included in Kellett's fit, his curve is a true prediction and in reasonable agreement with the data (see fig. 4).

In the analysis of Kramer (3) the π-B and the ρ-A_2 trajectories are similar but not exchange degenerate. The target polarization is given by the interference of these amplitudes, modified by absorption with the s-channel nucleon pole. There is no α-factor for the NWS zero of the ρ-trajectory. The results of Kramer's Regge model are also displayed in fig. 4. The agreement with the experimental data at 3.4 and 5 GeV is good for $|t| < 0.8\ (GeV/c)^2$.

The change of sign predicted near 1 $(GeV/c)^2$ is not confirmed by the data.

Worden (4) has presented a Regge model which fits all pion and η production data. He uses echange degenerate ρ-A_2 and π-B poles with NWS zeroes and a "square cut" form of absorption by which the low partial waves are completely absorbed. The predictions of his model are in good agreement with most of the high energy data and with finite energy sum rules. The target asymmetry T is given by the interference of the ρ-A_2 non-flip amplitude with the pion-cut helicity flip amplitude. The agreement with the data of the present experiment is fair but a predicted structure near $t = 0.45\ (\mathrm{GeV}/c)^2$ is not confirmed experimentally (see fig. 4).

The approach of Goldstein and Owens (6) is similar to that of Worden but in addition Regge-Regge cuts are included. Concerning the polarized target asymmetry T the situation is not very conclusive since the 5 GeV data of this experiment would allow for a dip structure in T near $|t| \geq 0.6\ (\mathrm{GeV}/c)^2$ whereas the SLAC 5 GeV data (7) suggest a smooth t dependence. It should be noted, however, that the SLAC point at this t-value differs by only two standard deviations from our one. The results of the present experiment therefore do not specifically favour the inclusion of Regge-Regge cuts. Goldstein and Owens predict a rather striking influence of an isoscalar Regge-Regge cut on the target asymmetry in π^--photoproduction off neutrons. Also for other models this quantity would be of interest since it would provide information on the relative importance of ρ and A_2 exchange.

Barbour and Moorhouse (2) make a Regge ansatz for the high energy imaginary parts of the photoproduction amplitudes using exchange degenerate ρ-A_2 and π-B trajectories. The residues are supposed to have Bessel function like behaviour as suggested by the dual absorption model. Taking the low energy imaginary parts from partial wave analyses they evaluate the high energy real parts from fixed-t dispersion relations. The authors state that their results should be reliable for momentum transfers $|t| < 0.7\ (\mathrm{GeV}/c)^2$. Here the agreement with the measured cross sections and polarized photon and target asymmetries is indeed reasonable. At larger momentum transfers the real parts of the amplitudes are not considered as being reliable. In fact, a predicted large positive bump in the target asymmetry near $|t| = 0.9\ (\text{GeV/c})^2$ is ruled out by the data.

Acknowledgement

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Table captions

Table 1 : Possible exchange contributions to the amplitudes $H_\pm$ and $\phi_\pm$ at large s.

Table 2 : Target asymmetry T for $\gamma p \to \pi^+ n$

Figure captions

Fig. 1: Setup of the experiment. PT target and target magnet; PM,M... bending magnets; Q...quadrupoles; S...scintillation counters; C_e,C_π electron and pion Cerenkov counters; Φ, Θ, p, S2-Hod... scintillation counter hodoscopes and multi-wire proportional chambers; QM quantameter; ZT scintillation counter telescope

Fig. 2: Time-of-flight distribution of the recoil neutrons for both polarization directions off the butanol target and off a carbon target

Fig. 3: The correction factor $x_{\pi n}$ which reduces the $< \pi n >$ yields from the butanol target to the free proton contribution. Plotted are the results obtained from a carbon target (C) and a helium target (He).

Fig. 4: The target asymmetry T at 3.4 and 5.0 GeV. The curves are taken from theoretical models:

____________ G.Kramer (3)

------------ R.Worden (4)

-.-.-.-.-.-. B.H.Kellett (5)

.... G. Goldstein, J. F. Owens III (6)

Table 1

Amplitude	Exchange	
H_+	ρ , A_2	natural
$\emptyset_+$	ρ , A_2, πP-cut s-channel N-pole	parity
H_-	A_1	unnatural
$\emptyset_-$	π , B , πP-cut, s-channel N-pole	parity

Table 2

k = 5.0 GeV

$\|t\|$ $(GeV/c)^2$	T
0.1	-0.27 ± 0.07
0.19	-0.26 ± 0.06
0.29	-0.43 ± 0.09
0.39	-0.40 ± 0.07
0.48	-0.39 ± 0.10
0.6	-0.39 ± 0.09
0.67	-0.18 ± 0.12
0.8	-0.18 ± 0.12
0.98	-0.27 ± 0.15
1.25	-0.38 ± 0.19

k = 3.4 GeV

$\|t\|$ $(GeV/c)^2$	T
0.1	-0.18 ± 0.10
0.2	-0.35 ± 0.09
0.3	-0.33 ± 0.09
0.4	-0.40 ± 0.11
0.48	-0.24 ± 0.10
0.6	-0.53 ± 0.11
0.68	-0.29 ± 0.08
0.8	-0.57 ± 0.15
1.0	-0.31 ± 0.13
1.14	-0.10 ± 0.16

k = 2.5 GeV

$\|t\|$ $(GeV/c)^2$	T
0.1	-0.17 ± 0.09
0.2	-0.30 ± 0.09
0.3	-0.46 ± 0.08
0.4	-0.61 ± 0.15
0.5	-0.38 ± 0.11
0.7	-0.30 ± 0.12
0.87	-0.14 ± 0.14

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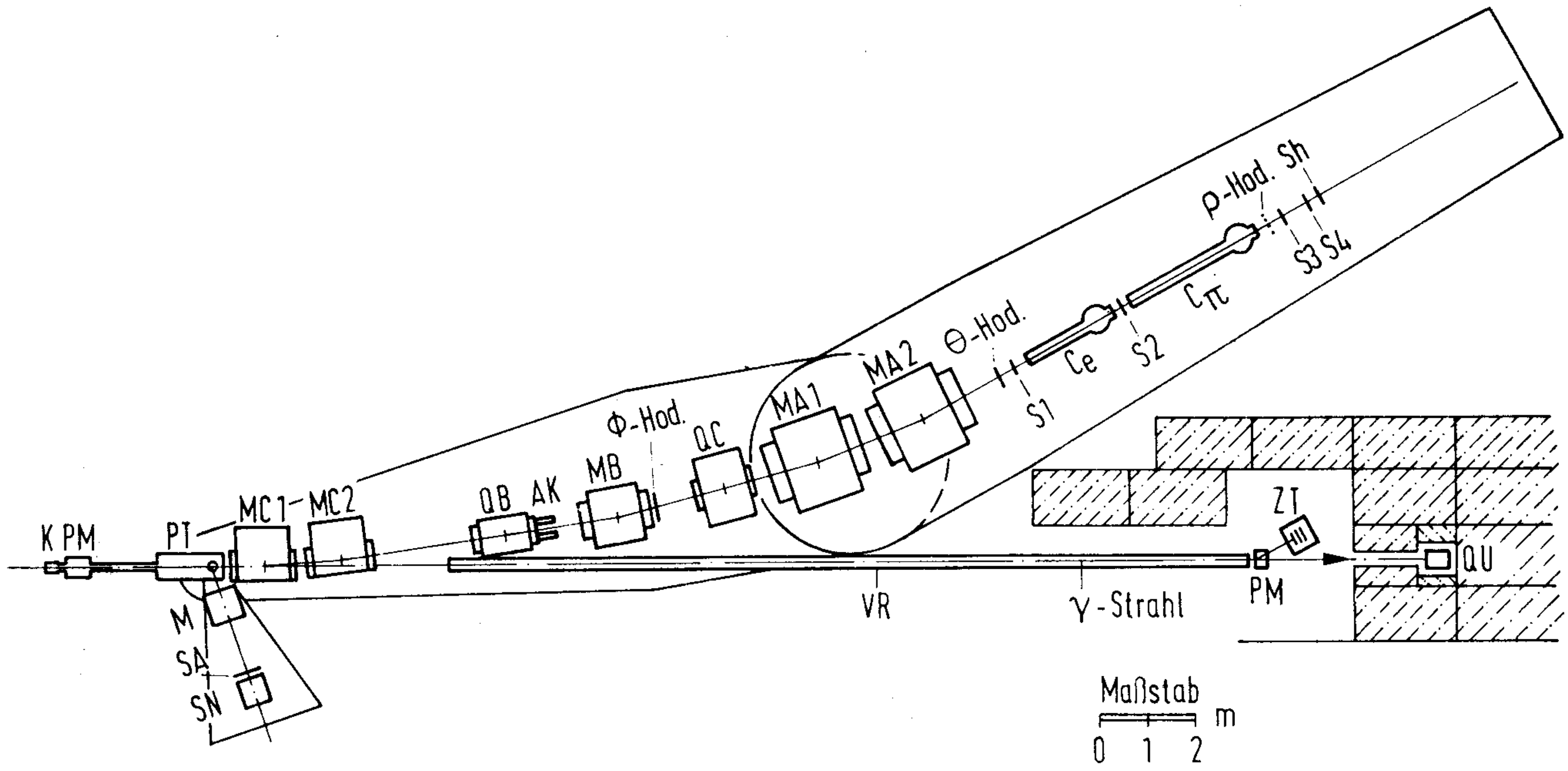
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Fig. 1

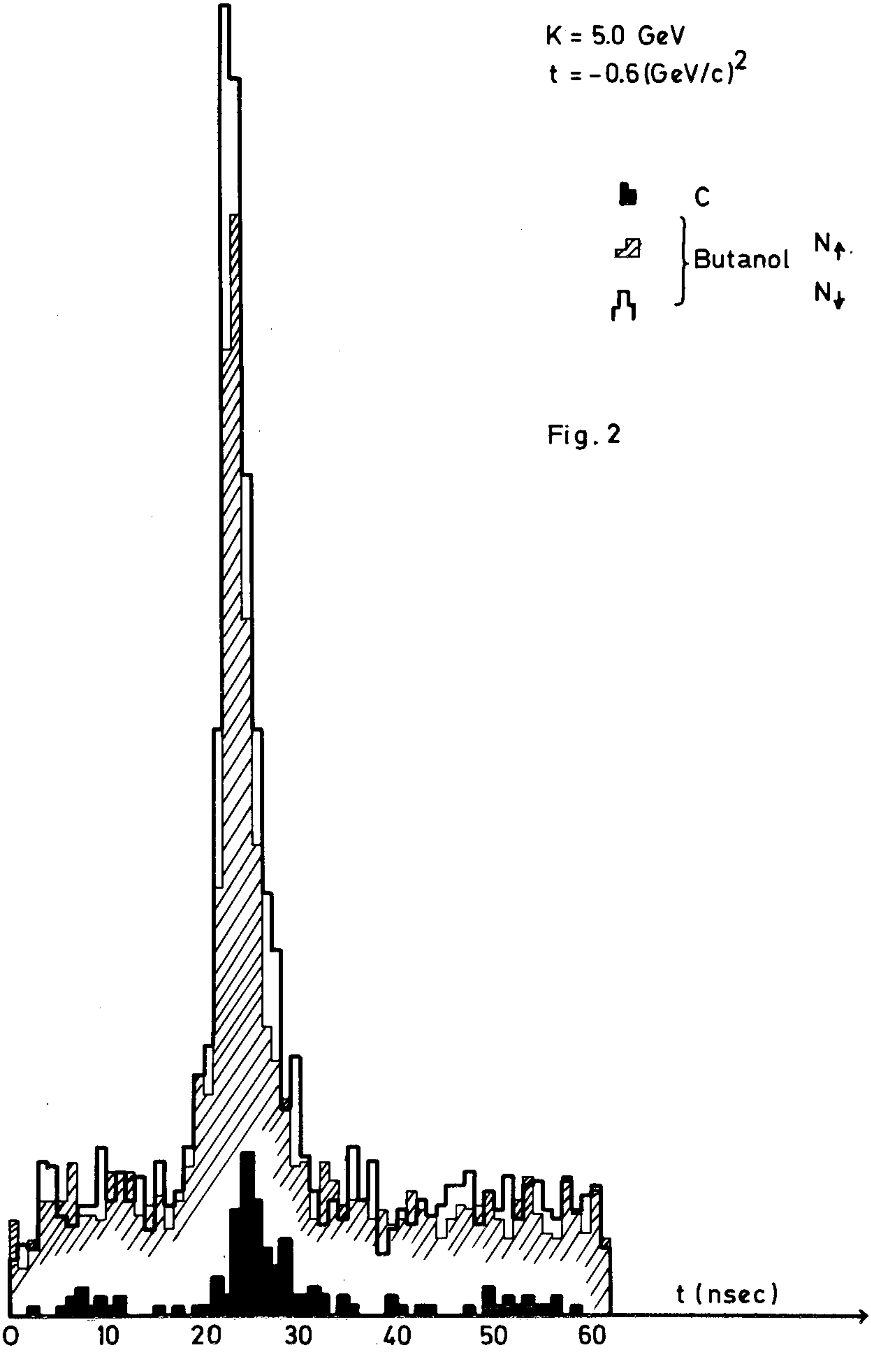
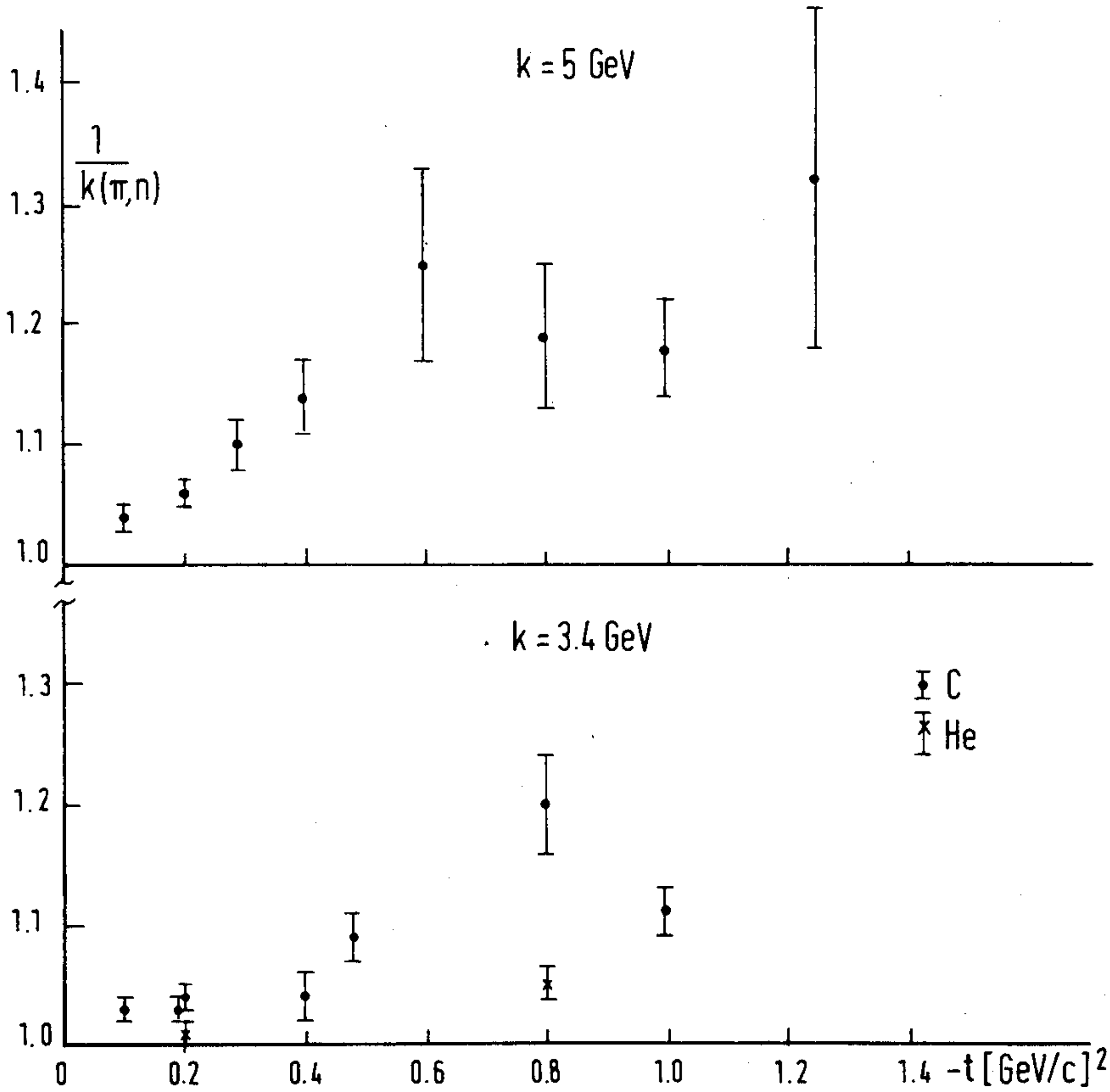
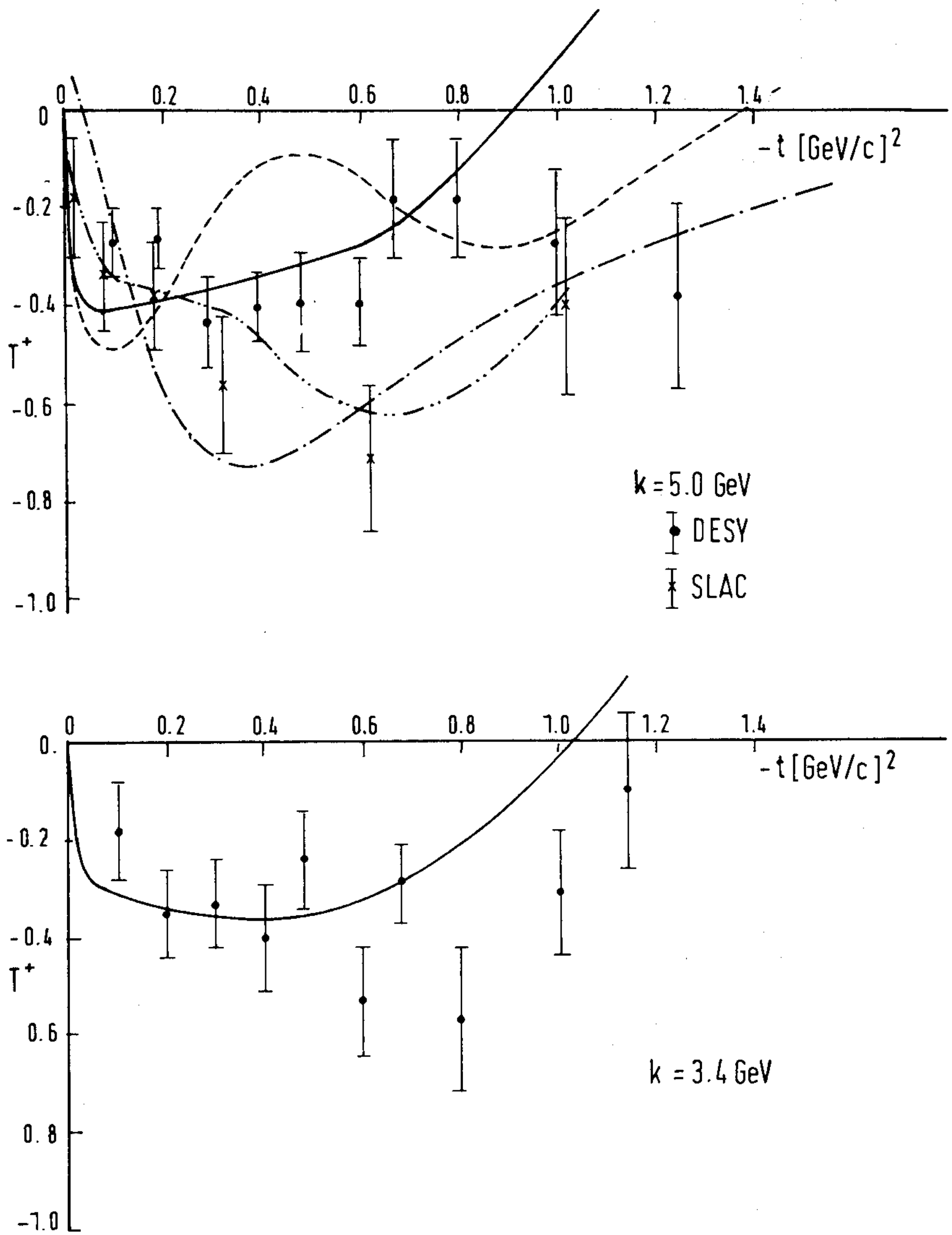


Fig. 2



k = 5 GeV
$\frac{1}{k(\pi,n)}$
1.4
1.3
1.2
1.1
1.0
k = 3.4 GeV
C
He
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
$-t\,[GeV/c]^2$

Fig. 3



0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
-t [GeV/c]^2
-0.2
-0.4
-0.6
-0.8
-1.0
T^+
k = 5.0 GeV
DESY
SLAC
0.
-t [GeV/c]^2
k = 3.4 GeV

Fig. 4