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## ABSTRACT

We study the production of slow protons from neutron targets in the reaction $p + n \rightarrow p + X$ at 100 and 400 GeV/c, and in the reaction $\pi^+ + n \rightarrow p + X$ at 100 GeV/c, in the kinematic region $|t| < 1.0$ GeV$^2$. The data are observed to scale as a function of $M^2/s$ and t. We extract an effective Regge trajectory from the pn data of $\alpha_{eff}(t) = (0.26 \pm 0.04) + (1.07 \pm 0.11)\,t$, and obtain a similar result with the $\pi^+n$ data. We conclude that Reggeized one-pion-exchange alone is not sufficient to describe these reactions.

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We present an analysis of slow proton production from neutron targets at Fermilab energies. This work doubles the statistics of our previous study[1] of the reactions

$$p + n \rightarrow p + X \quad (1)$$

and

$$\pi^+ + n \rightarrow p + X \quad (2)$$

at 100 GeV/c, and presents new results for Reaction (1) at 400 GeV/c. Previous studies of these reactions[1-4] have reported that various aspects of the data are consistent with expectations of a Reggeized one-pion-exchange model[5,6]. Our new data allow us to examine Reactions (1) and (2) in sufficient detail to extract an effective Regge-exchange trajectory. We present below evidence that pion-exchange alone does not describe Reactions (1) and (2) in the kinematic region accessible in our experiment.

The data were obtained from exposures of the Fermilab 30-inch deuterium-filled bubble chamber to beams of positive particles at 100 and 400 GeV/c. A tagging system[7] allowed the identification of individual beam particles from their position in the bubble chamber. The exposure at 100 GeV/c consisted of a total of 80,000 pictures, with an average beam composition of 48% proton, 48% $\pi^+$, 2% $K^+$, and 2% $\mu^+$. The 400 GeV/c exposure consisted of 100,000 pictures with a pure proton beam.

The film was scanned twice, with an efficiency of (99 ± 1)%, for interactions resulting in three or more charged particles. The tracks of outgoing particles with projected laboratory momentum less than 1.5 GeV/c were measured and reconstructed in space. We isolate neutron target interactions on an event-by-event basis by the presence of a spectator proton with momentum less than 300 MeV/c, and identify protons with momentum less than 1.4 GeV/c by their ionization in the bubble chamber. We assume the impulse approximation to be valid, and assign to each event a target momentum equal in magnitude but opposite in direction to that of the spectator proton. The majority of the events have an invisible spectator proton, and for these we assume the target to be at rest. The requirement that the event sample for Reactions (1) and (2) have, in addition to the spectator proton, an identified slow proton means that the contamination from other than neutron target interactions is negligible.

In Table I we present a summary of our data for Reactions (1) and (2). We limit our analysis to events with $|t| < 1.0$ GeV$^2$, where t is the square of the four-momentum transfer from the neutron target to the slow proton, in order to ensure unbiased identification of the slow proton for all values of target momentum. The contribution of one-prong events to Reactions (1) and (2) has been found to be negligible[1,4] and is ignored in the present work. The cross sections for these reactions were calculated from a sample of the data with spectator proton momentum less than 120 MeV/c. This choice minimizes the effect of any multiplicity-dependent spectator visibility bias. We assume that this event sample constitutes an unbiased selection of neutron target events, and calculate the cross section for Reactions (1) and (2) by normalizing the total number of events with a spectator proton with momentum less than 120 MeV/c to the inelastic hadron-neutron cross sections[8,9]. The fraction of these events which have, in addition to the spectator proton, a proton with $|t| < 1.0$ GeV$^2$ determines the cross sections listed in Table I. This method automatically compensates for the effects of Glauber screening and double scattering within the deuteron target, and no further corrections are applied.

The cross sections for Reactions (1) and (2) listed in Table I are consistent with the values (5.15 ± 0.25) mb and (3.4 ± 0.3) mb, respectively, reported[4] at 195 GeV/c for $|t| < 1.0$ GeV$^2$. A value of $(5.1^{+0.4}_{-0.1})$ mb is reported[2] for Reaction (1) for $|t| < 0.82$ GeV$^2$ at a beam momentum of 11.6 GeV/c. If we make the same t-cut, our cross sections are (5.34 ± 0.23) mb and (5.15 ± 0.23) mb at 100 and 400 GeV/c, respectively. Thus, we see that the inclusive cross sections for these reactions are consistent with being constant over a wide range of incident momenta.

We display in Fig. 1 values of $s d\sigma/dM^2$ as a function of $M^2/s$ for Reaction (1) at 100 and 400 GeV/c, and for Reaction (2) at 100 GeV/c, where $M^2$ is the square of the missing mass recoiling against the slow proton, and s is the square of the center-of-mass energy. In Fig. 2 we plot $d\sigma/dt$ as a function of t for the same data. The negative $M^2/s$ values shown in Fig. 1 result primarily from the assignment of zero target momentum to the invisible spectator events.

From Figs. 1 and 2 we observe that the 100 and 400 GeV/c cross sections for Reaction (1) are independent of incident energy as functions of both $M^2/s$ and t. The differential cross sections for Reaction (2) are seen to have the same shape as those for Reaction (1), and to scale in the ratio of the inclusive cross sections, for both the $M^2/s$ and t distributions. A more detailed comparison[10] reveals that the invariant cross section $s d^2\sigma/dt\, dM^2$ for these reactions scales simultaneously as functions of $M^2/s$ and t. This scaling suggests that the mechanism for production of slow protons from a neutron target is independent of both incident energy and beam type.

We parameterize the $M^2/s$ dependence of the invariant cross section at a fixed value of t by the equation

$$s \frac{d^2\sigma}{dt\, dM^2} \propto \left(\frac{M^2}{s}\right)^{1-2\alpha_{eff}}, \qquad (3)$$

where $\alpha_{eff}$, as a function of t, defines the effective Regge-exchange trajectory which mediates the reaction under study. Values of $\alpha_{eff}$ are extracted from our data by the following technique. Six non-overlapping t-bins are defined in the range $0.02 < -t < 1.00$ such that each t-bin has approximately the same number of events. We use a Monte-Carlo technique to generate events in the allowed $M^2/s$ and t region according to Eq. (3), with the neutron target described by the Hulthen wave function. For each of the six t-bins we generate distributions of $M^2/s$ for values of $\alpha_{eff}$ in the range $-1.0 < \alpha_{eff} < 1.0$ in steps of 0.01. The effect of the invisible spectator proton events, for which the target momentum is unknown, is reproduced in the generated distributions by computing s, $M^2$, and t assuming the target to be at rest for those Monte Carlo events with a target momentum less than 100 MeV/c. Each of the 1200 generated $M^2/s$ distributions is then fit to a polynomial over the region $0.02 < M^2/s < (M^2/s)_{max}$, where $(M^2/s)_{max}$ is determined for each t-bin such that $(M^2/s)_{max}$ is within the allowed physical region for all values of t in that particular t-bin. The polynomial is then normalized over the region of the fit to obtain a probability density distribution for each trial value of $\alpha_{eff}$ in each t-bin. The probability distributions are then used to obtain the values of $\alpha_{eff}$ which best fit the data by a maximum likelihood technique.

Values of $\alpha_{eff}$ resulting from the maximum likelihood fits are displayed in Fig. 3, for each of the three data sets used in this study, as functions of the average value of t for each t-bin. Our Monte Carlo studies reveal a negligible shift in $< t >$ due to the uncertainty in the target momentum in the invisible spectator events, which we ignore in this analysis.

The straight lines in Fig. 3 represent the results of least squares fits of the data to an effective Regge trajectory of the form

$$\alpha_{eff}(t) = \alpha_o + \alpha' < t >. \qquad (4)$$

The fitted parameters are tabulated in Table 1. As expected from the observed scaling of these three data sets, the effective Regge trajectories derived from these data are consistent with one another. The slopes $\alpha'$ are all consistent with 1.0 $GeV^{-2}$, while the intercepts $\alpha_o$ lie mid-way between the $\pi$ and $\rho/A_2$ intercepts of 0.0 and 0.5, respectively.

An improved value of the effective Regge-exchange trajectory for Reaction (1) is obtained from a simultaneous maximum likelihood fit to the combined 100 GeV/c and 400 GeV/c data. The values of $\alpha_{eff}$ thus obtained are shown in Fig. 4, together with the trajectory obtained from a least squares fit to Eq. (4). The fitted trajectory $\alpha_{eff}(t) = (0.26 \pm 0.04) + (1.07 \pm 0.11)t$ is compared in Fig. 4 with the $\pi$ and $\rho/A_2$ trajectories. The intercept is observed to be inconsistent with both.

In our previous study[1] of Reactions (1) and (2) at 100 GeV/c, we observed that the differential cross sections for these reactions were consistent with the predictions of a Reggeized one-pion-exchange model, but that the data did not discriminate against a model incorporating $\rho/A_2$ exchange in addition to $\pi$ exchange. Our present analysis differs from our previous study in that the increased statistics and the energy dependence of the present data allow us to perform a quantitative analysis of the data, and to extract directly an effective Regge exchange trajectory. The result is evidence that pion exchange alone is insufficient to describe the data.

Our result for reaction (1) may be compared with an analysis[2] of 11.6 GeV/c pn interactions, where it was found that $\alpha_{eff}(t) = (0.11 \pm 0.06) + (1.37 \pm 0.25)t$. The 11.6 GeV/c result is consistent with the pion exchange trajectory, although it is also compatible with our effective trajectory. We note that both analyses result in a positive value for the intercept $\alpha_o$.

Our conclusion is opposite to that reached in a study[4] of Reactions (1) and (2) at 195 GeV/c, where it was concluded that pion exchange yields a dominating contribution to these reactions, with little or no contribution from $\rho$ exchange. Our analysis, which is based on five times more data than the 195 GeV/c study, clearly indicates that $\pi$ or $\rho/A_2$ exchange alone cannot describe Reactions (1) and (2); at a minimum, a combination of $\pi$ and $\rho/A_2$ exchange is required.

In conclusion, we find little incident energy or beam type dependence in the production of slow protons from neutron targets at Fermilab energies, when studied as a function of $M^2/s$ and t. We extract from the data an effective Regge trajectory which is inconsistent with both the $\pi$ and $\rho/A_2$ trajectories, indicating that neither of these exchanges alone is sufficient to describe the data.

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Table I. Summary of data ($|t| < 1.0$ GeV$^2$).

| Reaction | Beam Momentum | Number of Events | Cross Section (mb) | Parameters of Effective Trajectory* $\alpha_o$ | $\alpha'$(GeV$^{-2}$) |
|---|---|---|---|---|---|
| $p + n \to p + X$ | 100 GeV/c | 870 | 5.70 ± 0.27 | 0.27 ± 0.07 | 1.18 ± 0.16 |
| $\pi^+ + n \to p + X$ | 100 GeV/c | 665 | 3.61 ± 0.18 | 0.29 ± 0.08 | 0.98 ± 0.18 |
| $p + n \to p + X$ | 400 GeV/c | 1583 | 5.52 ± 0.26 | 0.25 ± 0.06 | 1.03 ± 0.13 |

*$\alpha_{eff}(t) = \alpha_o + \alpha' \langle t \rangle$

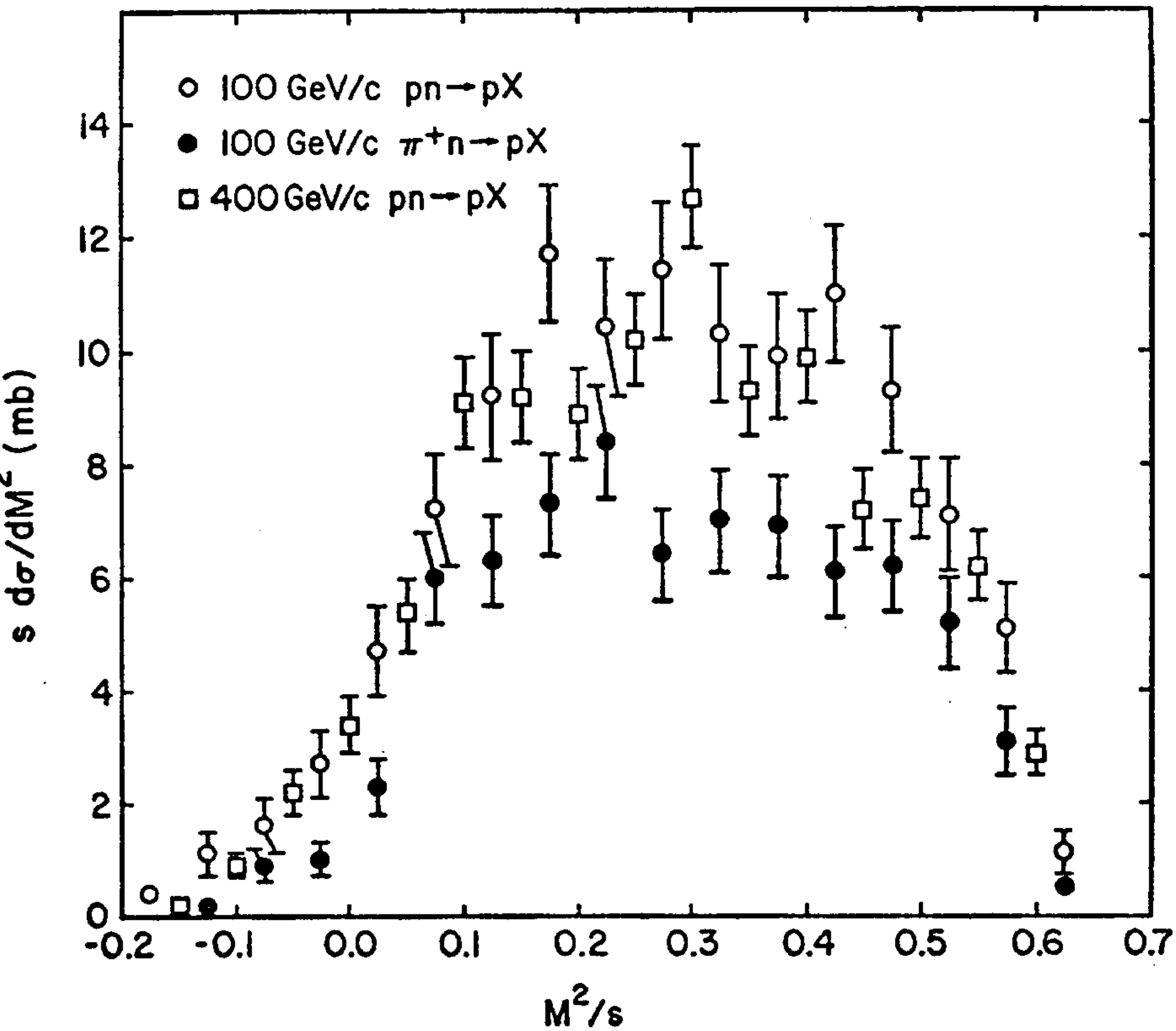


Fig. 1. $s\, d\sigma/dM^2$ as a function of $M^2/s$ for the reactions $p + n \rightarrow p + X$ and $\pi^+ + n \rightarrow p + X$ at 100 GeV/c, and for the reaction $p + n \rightarrow p + X$ at 400 GeV/c, for $|t| < 1.0$ GeV$^2$.

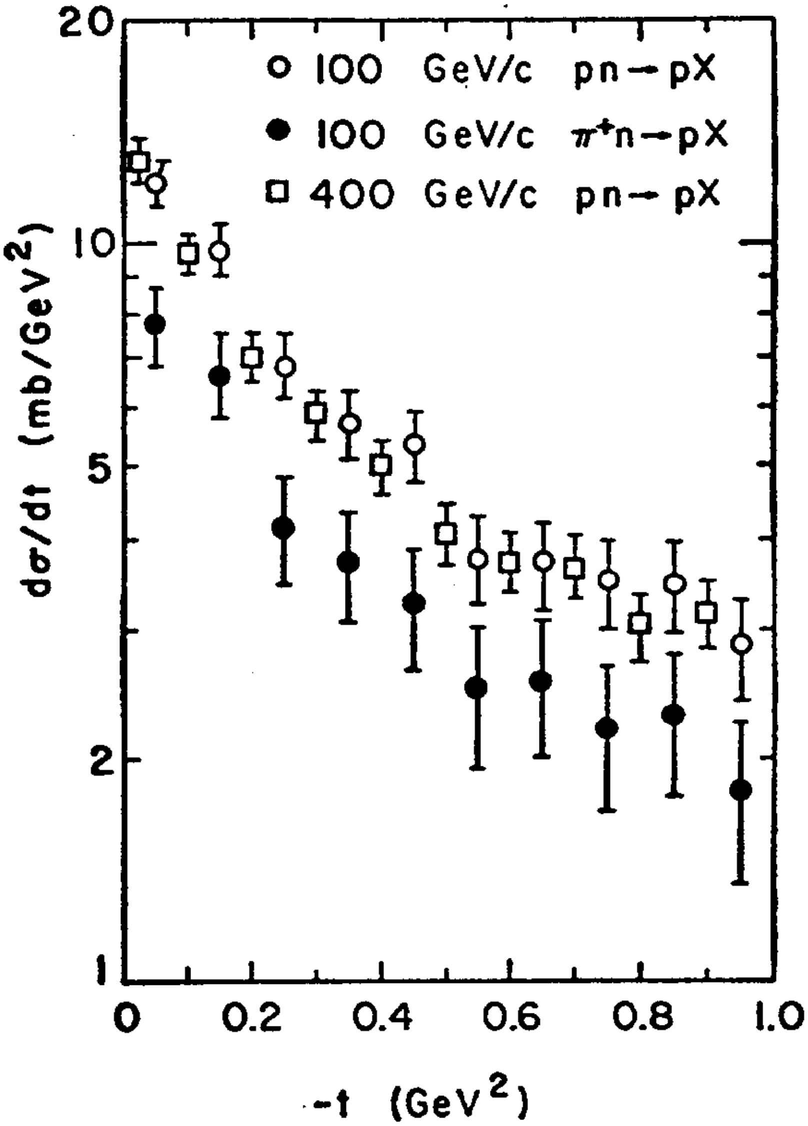


Fig. 2. $d\sigma/dt$ as a function of t for the reactions $p + n \rightarrow p + X$ and $\pi^+ + n \rightarrow p + X$ at 100 GeV/c, and for the reaction $p + n \rightarrow p + X$ at 400 GeV/c.

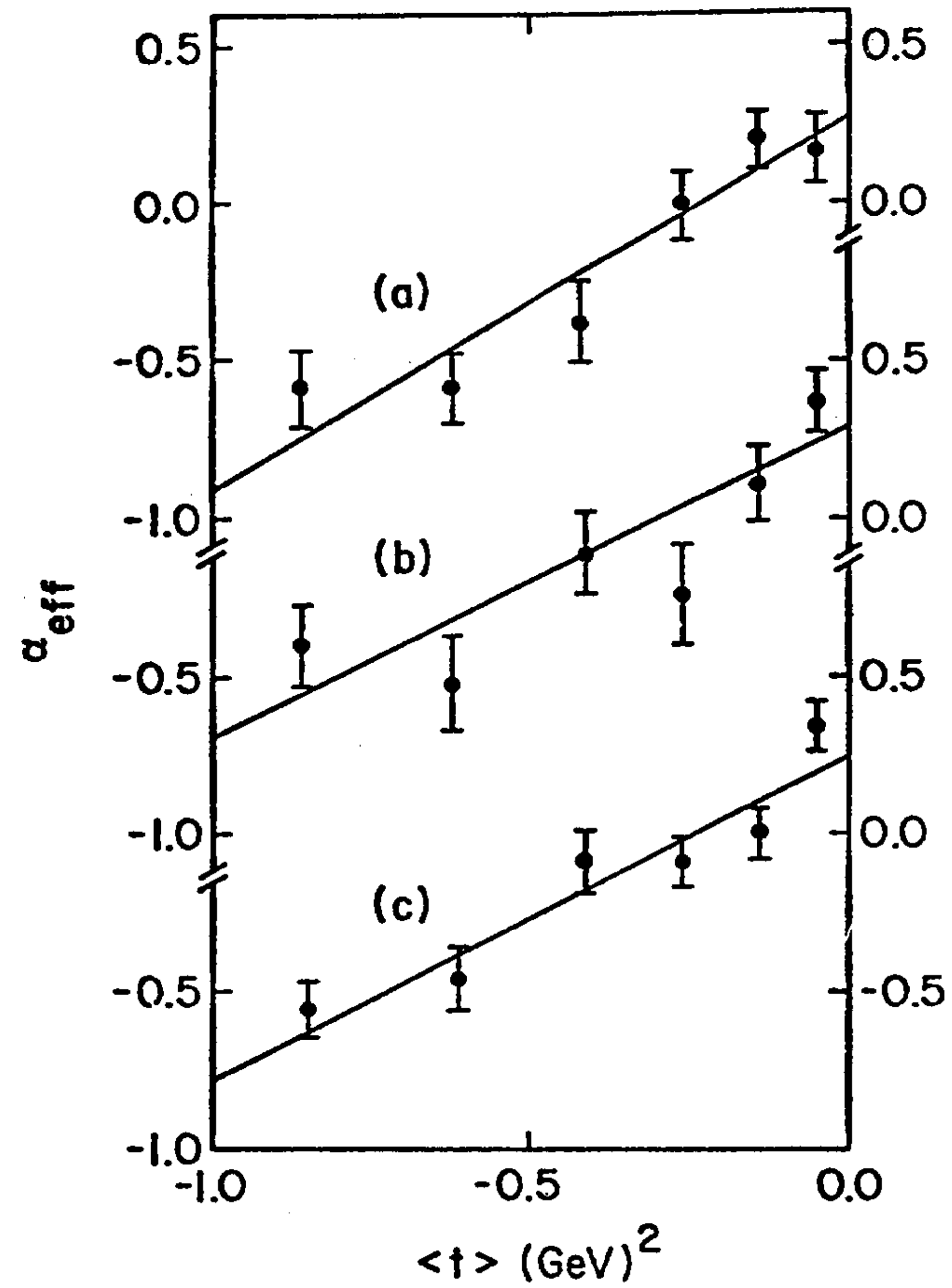


Fig. 3. The effective trajectory $\alpha$ (t) as a function of t as determined from the reaction (a) p + n → p + X at 100 GeV/c, (b) $\pi^+$ + n → p + X at 100 GeV/c, and (c) p + n → p + X at 400 GeV/c.

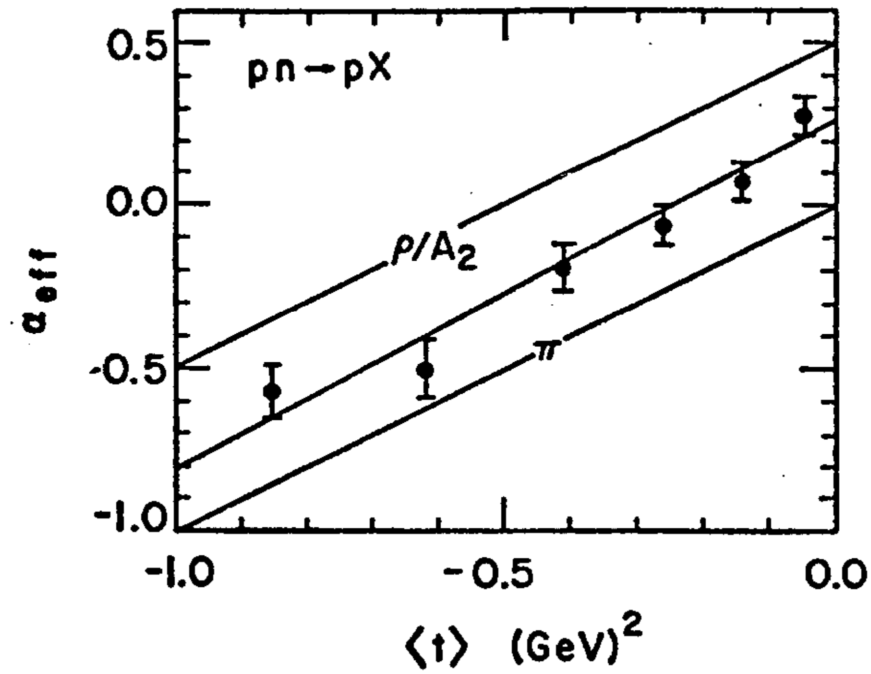


Fig. 4. The effective trajectory $\alpha$ (t) as a function of t as determined from the combined data from the reaction $p + n \rightarrow p + X$ at 100 and 400 GeV/c. The effective trajectory is compared with the $\pi$ and $\rho/A_2$ trajectories.