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OBSERVATION OF REGGE EFFECTS IN THE REACTION $\pi^+ p \rightarrow \pi^0 \Delta^{++}$

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July 1969

We report a measurement of the total and differential cross sections and Δ^{++} decay angular distributions for the reaction $\pi^+ p \rightarrow \pi^0 \Delta^{++}$ at incident momenta between 2.67 and 4.08 GeV/c. A dip near $t = -0.5$ and a backward peak are clearly observed. In a Regge pole exchange model we determine the parameters of the ρ trajectory.

The Regge pole model is most easily tested in reactions in which only a single trajectory can be exchanged in the t channel. The success of the ρ-trajectory model in describing the $\pi^- p$ charge-exchange reaction[1] makes it important to see if the same trajectory also describes other reactions dominated by ρ exchange. The reaction $\pi p \rightarrow \pi \Delta$ is the only other such example. The dip observed near $t = -0.5$ in the differential cross section for the $\pi^- p$ charge-exchange reaction has been interpreted as evidence that the ρ trajectory passes through zero at this point, and so we expect to observe the same dip in the $\pi \Delta$ final state if the same trajectory is exchanged.[2]

We report here a study of the $\pi^0\Delta^{++}$ final state[3] as observed in the reaction

$$\pi^+ p \rightarrow \pi^+ p \pi^0. \qquad (1)$$

An exposure of the 72-inch hydrogen bubble chamber to a separated π^+ beam at the Bevatron yielded 96 000 two-prong events distributed among the five incident momenta 2.95, 3.20, 3.53, 3.74, and 4.08 GeV/c. A similar exposure of the 25-inch bubble chamber has yielded to date 45 000 two-prong events at 2.67 GeV/c.[4] The events were measured on the Flying Spot Digitizer (FSD) and constrained to hypothesis (1). Extensive use was made of the automatic ionization measurements[5] available from the FSD in the form of HM = H/T, the ratio of the total number of times the spot was sufficiently obscured to produce a digitizing to the total number of times the track was traversed by the spot. An ionization chi square (χ^2_{ion}) was calculated and a cut was then made on χ^2_{ion} just as for the kinematic χ^2, avoiding the tedious and inconsistent procedure of checking each event on the scan table. A sample of film was, however, looked at to determine the appropriate χ^2_{ion} cut so that the fraction of events in which ionization and kinematics were in clear disagreement would be less than 1%.

A major problem in the 3–4-GeV/c experiment was the proton contamination in the beam, which varied from 3–10% for most of the film but was 22% for the 4.08-GeV/c exposure. This is a particularly severe problem in the small-momentum-transfer region, where the process $pp \rightarrow \Delta^{++}n$ is difficult to distinguish from the process $\pi^+ p \rightarrow \Delta^{++}\pi^0$ with the usual kinematic constraint and ionization method.[6] The former process has a cross section approximately 15 times the latter in our energy range, making even a small beam proton contamination manifest. However, the mass difference between the

π and p produces an upward shift in the missing mass when a real proton event is treated as a pion event. By measuring small samples of film with incident protons at 2.95, 3.65, and 4.0 GeV/c and treating $pp \rightarrow n\Delta^{++}$ events as $\pi^+p \rightarrow \pi^0\Delta^{++}$ events, we have determined the cuts on the missing mass squared required to remove incident proton events.[7] The 2.67-GeV/c film was taken with a beam proton contamination of less than 0.5%.

Examination of the Dalitz plot for reaction (1) shows that this final state is dominated by the reactions

$$\pi^+p \rightarrow \pi^0\Delta^{++}, \tag{2}$$

$$\pi^+p \rightarrow \rho^+p, \tag{3}$$

and

$$\pi^+p \rightarrow \pi^+\Delta^+. \tag{4}$$

If one evaluates the $\pi^+\pi^0$ invariant mass from reaction (1) in the Δ^{++} rest frame, one finds that there is a linear relationship between the decay angle of the Δ and the dipion mass. The decay distribution of the Δ with respect to its direction of motion is such that reaction (3) overlaps reaction (2) in a region of decay angles lying entirely in the forward hemisphere. This allows us to use the method of Eberhard and Pripstein[8] to remove the overlap events and repopulate the sample with events from the corresponding part of the backward decay hemisphere. These repopulated events represent 15% of our sample (with a ρ band cut of $0.64 < M_{\pi\pi} < 0.90$) at 3—4 GeV/c, and 30% of our sample at 2.67 GeV/c.[9] The peripheral nature of the production process (3) reflects itself as very small momentum transfers to the Δ, so that the removal of these overlap events is essential for studying reaction (2). The Δ^{++} band is defined by the mass interval $1.12 < M(\pi^+p) < 1.32$.

We then present results for 385 events between 3 and 4 GeV/c and 420 events at 2.67 GeV/c. The Dalitz plot projections show less than 10% background for most production angles. This may be somewhat higher in the back-

ward hemisphere, where small signals make background estimates difficult. The cross section for reaction (2) is presented in Fig. 1 together with some previous measurements from the literature.[10] We note the power-law behavior with incident pion momentum; a fit to our data and the 8-GeV/c point gives a $p^{-1.6}$ behavior.

Figure 2a shows the differential cross section, $d\sigma/dt$, for the two energy regions. A fit of the forward peak to $d\sigma/dt = Ae^{Bt}$ yields $B = 8.8 \pm 1.0$ at 2.67 GeV/c and $B = 8.0 \pm 0.9$ at 3 to 4 GeV/c. The dip near $t = -0.5$ is clearly observed at both energies.[11] A second minimum near $t = -2.5$ is observed in the 2.67-GeV/c data. A backward peak is observed at both energies, and is shown as a function of u in Fig. 2b.[12]

(a) t-Channel Interpretation

In the ρ Regge pole description the helicity flip amplitudes for $\pi^+ p \to \pi^0 \Delta^{++}$ go as $g(\alpha)F(s-u,\alpha)\beta(t)[1-e^{-i\pi\alpha}]/\Gamma(\alpha+1) \sin \pi\alpha$ (where $g(\alpha) \to 0$ as $\alpha \to 0$), and for a canonical ρ trajectory of $0.5 + t$ have zeros at $t = -0.5$, -2.5, etc. Thus the minima at 0.5, and that at -2.5 in the 2.67-GeV/c data, may be taken as evidence for exchange of the ρ trajectory in this reaction. This second minimum could be confirmed by its observation at constant t, independent of incident momentum.

As a representation of the available $\pi^- p$ charge-exchange data, we show a best fit of Barger and Phillips[13] to those data (with a particular ansatz for the large-t region), normalized to this experiment. The similarity of the shapes is evident, and suggests that both processes are dominated by exchange of the same trajectory.

Krammer and Maor[14] have done a simultaneous fit to the reactions $\pi^+ p \to \pi^0 \Delta^{++}$, $\pi^+ p \to \eta^0 \Delta^{++}$, and $K^+ p \to K^0 \Delta^{++}$ with a $\rho + A_2$ Regge pole model; the fit included our 3–4-GeV/c data, so the dotted curve in Fig. 2a shows the

predictions of this model for 2.67 GeV/c only. We have extended the model past the t region considered valid by the authors, and in this region the model should be taken as indicating the dip expected near $t = -2.5$ rather than as a quantitative prediction. The spin density matrix elements in the Jackson frame for the decay are shown in Fig. 2c as a function of t, together with the predictions by Krammer and Maor. Within the limited statistics the two are consistent, with the possible exception of ρ_{33} near $t = -0.6$ for the 2.67-GeV/c data. We keep in mind that the predictions of the M1 dominance model[15] at the $\rho\Delta p$ vertex are $\rho_{33} = 0.373$, $\rho_{3-1} = 0.216$, and $\rho_{31} = 0$.

Mathews[16] has discussed a linear fit of the available data to

$$d\sigma/dt = [G(t)/P_{lab}^2] \left(\frac{s-u}{2}\right)^{2\alpha(t)} . \qquad (5)$$

A least-squares fit to our data and the 8-GeV/c data

gives $\alpha_\rho(t) = (0.56 \pm 0.04) + (1.34 \pm 0.12)t$, from $\pi^+ p \to \pi^0 \Delta^{++}$, using the 3–4- and 8-GeV/c data

and $\alpha_\rho(t) = (0.49 \pm 0.03) + (0.82 \pm 0.07)t$, from $\pi^+ p \to \pi^0 \Delta^{++}$, using the 2.7-GeV/c data as well,

compared with $\alpha_\rho(t) = (0.57 \pm 0.01) + (0.91 \pm 0.06)t$ from $\pi^- p \to \pi^0 n$.

The ρ_{ij} for reaction (2) are approximately independent of p_{lab}, showing the s independence of the relative contributions of the several helicity amplitudes. This enables us to use Eq. (5) to determine $\alpha_\rho(t)$ as in the spinless problem. These results are taken as evidence that the same trajectory is exchanged in both reactions. The flattening of the trajectory obtained by including the 2.67-GeV/c data is due to the steeper low-t behavior at this momentum, a possible consequence of an s-channel resonance contribution, as discussed below.

(b) <u>s-Channel Interpretation</u>

The 2.67-GeV/c incident momentum is at the peak of the $I = 3/2$, $J^P = 11/2^+$, $\Delta(2420)$. The locations in $\cos\theta$ of the minima and the backward

peak are consistent with H-wave decay of this resonance into $\Delta\pi$. We can estimate the branching ratio of this resonance into the $\Delta\pi$ channel by using the formula

$$\sigma(N^* \to \Delta^{++}\pi^0) = (3/5)(J + 1/2)\, 4\pi\, \lambda^2 X_{\pi N} X_{\pi\Delta}.$$

If we take twice the backward hemisphere as being resonance contribution and take[17] $X_{\pi N} = 0.10$, we obtain $X_{\pi\Delta} \approx 0.07$.

(c) u-Channel Interpretation

A backward peak is observed in both sets of data, and is shown as a function of u in Fig. 2b. The ratio of the cross sections in the backward interval $\Delta u = 0.2$ GeV/c^2 between 2.67 GeV/c and 3-4 GeV/c data is approximately 1.8, corresponding to a p^{-3} behavior, consistent with that observed for baryon exchange processes.[18] A fit to $d\sigma/du = Ae^{Bu}$ gives $B = 3 \pm 1$. Both the energy dependence and the shape of the backward cross section are in excellent agreement with recent results from $\pi^- p$ charge exchange.[19] The spin density matrix elements for the backward interval $-0.4 \leq u \leq 0.2$ are $\rho_{33} = 0.31 \pm 0.07$, $\rho_{3-1} = 0.04 \pm 0.07$, and $\rho_{31} = -0.10 \pm 0.08$.

Duality[20] prevents a clearer statement of the contribution from the various processes, and it may be that the above explanations are all equivalent.

In the $\pi^- p$ charge-exchange reaction a polarization has been observed[21]--something which is impossible if only a single trajectory is exchanged. Many theoretical models have been proposed to explain this polarization, and we can ask if a similar phenomenon is present in reaction (2). Ringland and Thews[22] have proposed a test for the exchange of a single trajectory which asks if the contributing amplitudes are relatively real. The test requires that the combination

$$\rho_{33}\rho_{11} - (\mathrm{Re}\rho_{31})^2 - (\mathrm{Re}\rho_{3-1})^2$$

be zero. A violation of this condition implies the exchange of more than one trajectory, but satisfaction gives no information. Figure 3 shows this sum as a function of momentum transfer for our data and the 8-GeV/c CERN data.[23] This highest energy shows a violation at small t which is no longer present at the other energies. As this violation depends on the differences in the rate of rise from zero of the ρ_{ij}'s, we cannot attach much significance to the observed violation at the present statistical level.[24]

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FOOTNOTES AND REFERENCES

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1. G. Hohler, J. Baacke, H. Schlaile, and P. Sonderegger, Phys. Letters 20, 79 (1966).

2. That we did not observe such a dip in the reaction $\pi^+ p \rightarrow \omega^0 \Delta^{++}$ has been interpreted as evidence that the B trajectory plays an important role in that reaction. D. Brown et al., Phys. Rev. Letters 19, 664 (1967).

3. Preliminary reports on this reaction were presented at the XIVth International Conference on High Energy Physics, Vienna, 1968; and Bull. Am. Phys. Soc. 14, 484 (1969), invited Paper AB2.

4. This represents 40% of the exposure at this momentum.

5. G. Borreani, D. Hall, L. Shalz, and P. Hanson, Argonne Conference Proceedings, Oct. 1968, also UCRL-18545, Oct. 1968.

6. Some experiments on pp interactions in our energy range are, S. Coletti et al., Nuovo Cimento 49, 479 (1967); G. Alexander et al., Phys. Rev. 154, 1284 (1967); W. J. Fickinger et al., Phys. Rev. 125, 2082 (1962); G. A. Smith et al., Phys. Rev. 123, 2160 (1961).

7. This asymmetric cut certainly distorts the mass spectra, but this distortion is minimal when we restrict ourselves to the Δ^{++} band. The cut is very wide in the backward hemisphere where kinematics alone separates the reactions.

8. P. Eberhard and M. Pripstein, Phys. Rev. Letters 10, 351 (1963).

9. The statistical errors are accordingly adjusted.

10. M. Abolins et al., Phys. Rev. 136B, 195 (1964); Aachen et al., Phys. Rev. Letters 10, 229 (1964) and Phys. Rev. 138B, 897 (1965); Saclay-Orsay-Bari-Bologna Collaboration, Phys. Letters 13, 341 (1964);

M. Deutschmann et al., Phys. Rev. Letters 18, 351 (1965).

11. A compilation of the works cited in Ref. (9) gives an indication of this dip. A Carnegie-Mellon-Brookhaven group has also seen evidence for this dip in the reaction $\pi^- p \rightarrow \pi^- \Delta^+$ at 8 GeV/c incident momentum. N. C. Hien, Bull. Am. Phys. Soc. 13, 713 (1968), invited Paper KA3.

12. In this backward peak region, where ionization is no longer a useful criterion, there is no kinematic ambiguity with the $\pi^+\pi^+n$ final state. We cannot rule out some residual contamination from $2\pi^0$ production in this region, and so designate our measurement as an upper limit.

13. V. Barger and R. J. N. Phillips, Phys. Rev. Letters 22, 116 (1969), and private communication from V. Barger.

14. M. Krammer and U. Maor, Nuovo Cimento 50A, 963 (1967); Tel Aviv University preprint (TAUP-78-69). We use solution 1 with a ρ trajectory of 0.57 +0.96 t. G. H. Renninger and K. V. L. Sarma have done a similar fit, Phys. Rev. 178, 2201 (1969); G. Renninger, private communication.

15. L. Stodolsky and J. J. Sakurai, Phys. Rev. Letters 11, 90 (1963).

16. Robert D. Mathews, Nuclear Phys. B11, 339 (1969).

17. Review of Particle Properties, UCRL-8030, 1969.

18. D. R. O. Morrison, in Proceedings of the Stony Brook Conference on High Energy Two Body Reactions, April 1966 (unpublished).

19. R. C. Chase et al., Phys. Rev. Letters 22, 1137 (1969); V. Kistiakowsky et al., Phys. Rev. Letters 22, 618 (1969).

20. C. Schmid, Phys. Rev. Letters 20, 689 (1968).

21. P. Bonamy et al., Phys. Rev. Letters 23, 501 (1966).

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24. This test is not expected to be sensitive to the presence of a conspiring ρ' trajectory as its effect is maximal near the dip, where we have few events. We thank Dr. G. Fox for a discussion of this point.

FIGURE CAPTIONS

Fig. 1. Total cross section as a function of incident momenta for $\pi^+ p \rightarrow \pi^0 \Delta^{++}$. The solid curve is $P_{inc}^{-1.6}$ from a fit to this experiment and the 8.0-GeV/c data.

Fig. 2. (a) $d\sigma/dt$ vs t at 2.67 GeV/c and 3 to 4 GeV/c. The curves are discussed in the text. (b) $d\sigma/du$ vs u in the small $|u|$ region. (c) Density matrix elements as a function of t. The curves are discussed in the text.

Fig. 3. Test of the Ringland-Thews condition; $[\rho_{33}\rho_{11} - (\mathrm{Re}\rho_{31})^2 - (\mathrm{Re}\rho_{3-1})^2]$ vs t for 2.67 GeV/c, 3 to 4 GeV/c, and 8 GeV/c.

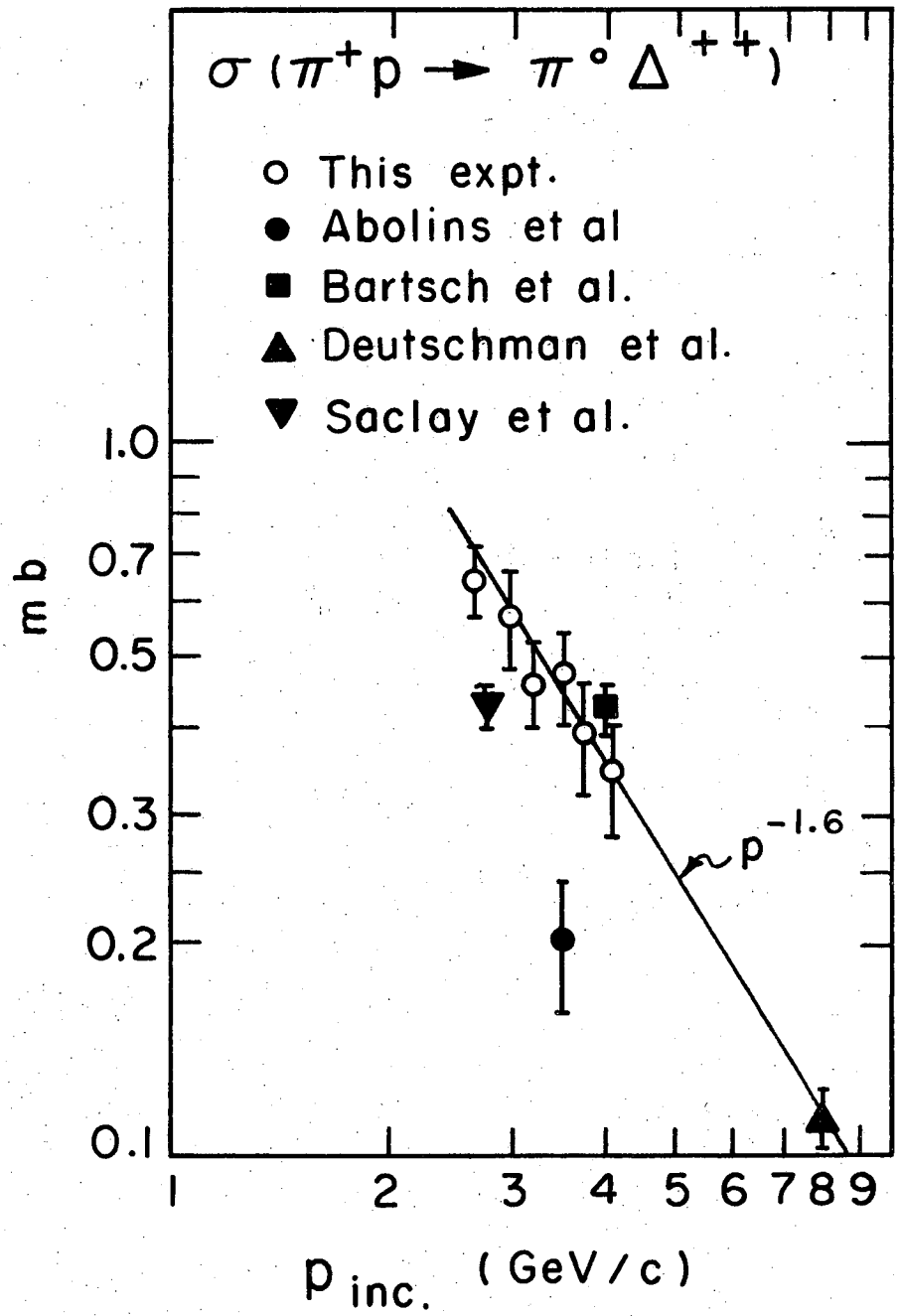

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Fig. 1

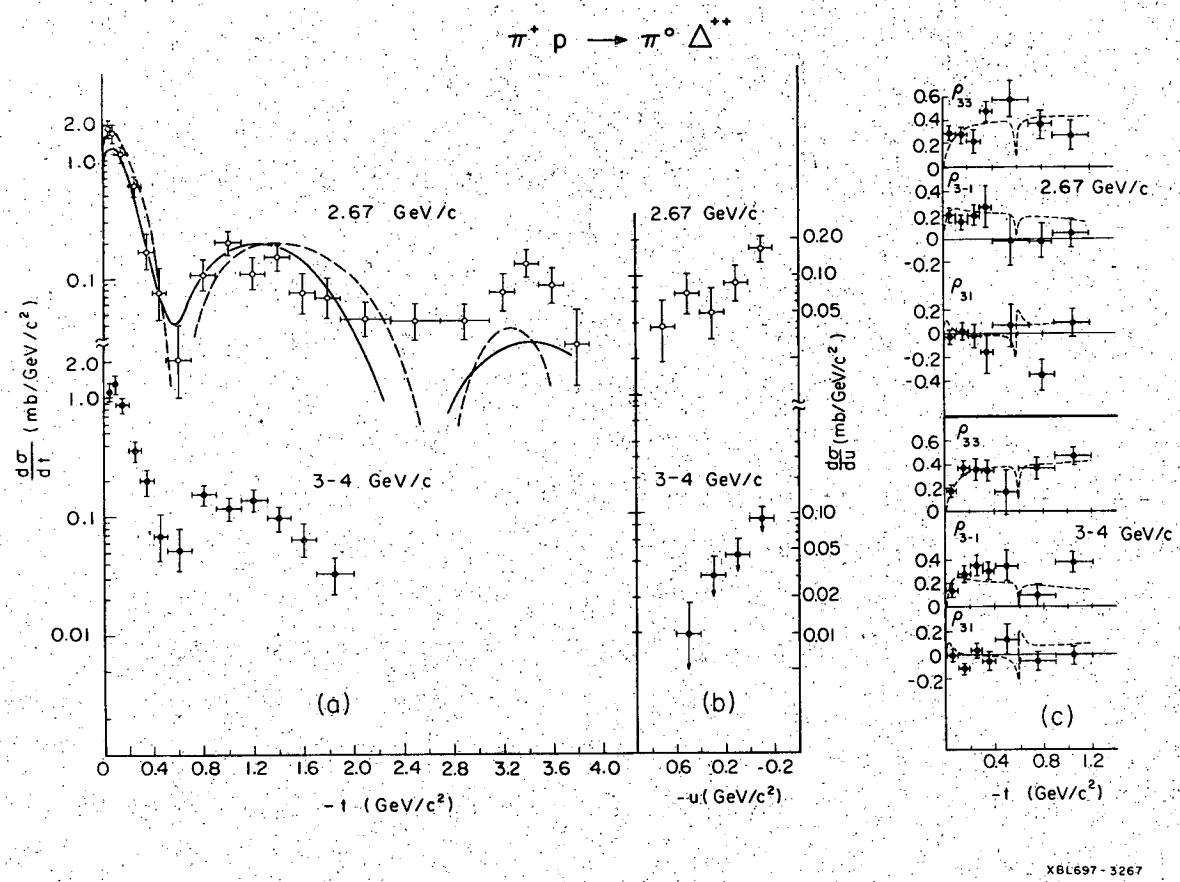
$\pi^+ p \rightarrow \pi^\circ \Delta^{++}$
2.67 GeV/c
3-4 GeV/c
(a)
(b)
(c)
$\frac{d\sigma}{dt}$ (mb/GeV/c²)
$\frac{d\sigma}{du}$ (mb/GeV/c²)
-t (GeV/c²)
-u (GeV/c²)
ρ_{33}
ρ_{3-1}
ρ_{31}
XBL697-3267

Fig. 2

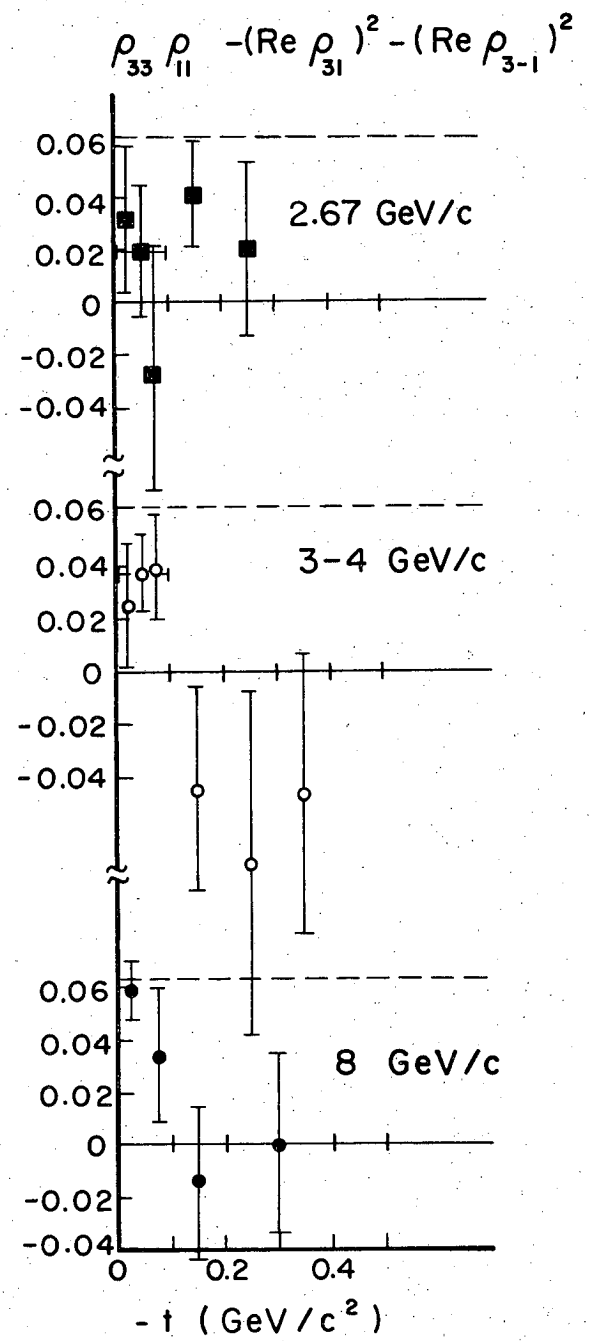

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Fig. 3

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