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OBSERVATION OF REGGE POLE EFFECTS IN $\rho^o\Delta^{++}$ AND $\omega^o\Delta^{++}$ PRODUCTION AT 3.7 GeV/c*

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Evidence is presented for zeroes in the π exchange contribution to $\rho^o\Delta^{++}$, and in the ρ exchange contribution to $\omega^o\Delta^{++}$ production. The position of the π exchange zero is consistent with a π trajectory with $\alpha'_\pi(0) \approx 1.2$ $(\text{GeV/c})^{-2}$. Evidence is also presented suggesting that the A_2 chooses the Gell-Mann mechanism (nonsense choosing). A model of π exchange with exact π-B exchange degeneracy is found to describe the data quantitatively.

A study of the channels

$$\pi^+ p \rightarrow \rho^o\Delta^{++} \tag{1}$$

and

$$\pi^+ p \rightarrow \omega^o\Delta^{++} \tag{2}$$

yields information about π and A_2 exchanges, and about ρ and B exchanges, respectively. For small t values ($|t| \lesssim 0.3$ $(\text{GeV/c})^2$) channel (1) is reasonably well described by the absorptive peripheral model with elementary or Reggeized pion exchange, as well as by form factor and pure Regge pole models. Similar success has not been attained for channel (2), where neither the differential cross section nor the decay density matrix elements resemble the predictions of models based on the dominance of the leading t-channel singularity, the ρ trajectory. By extending the experimental data to larger t, we are able to see evidence for Regge behavior of the pion exchanged in channel (1). A comparison of channels (1) and (2) reveals a marked similarity in their decay density matrix elements, suggesting π-B exchange degeneracy. Evidence is also seen for the exchange of the ρ trajectory in channel (2), as a zero in the natural parity contribution to this channel is observed near $\alpha_\rho = 0$. The assumption of ρ-A_2 exchange degeneracy then leads to a possible determination of the ghost-killing mechanism of the A_2, and indicates that the A_2 trajectory is nonsense choosing.

This analysis is based on data from an exposure of the Lawrence Radiation Laboratory 72-inch hydrogen bubble chamber to a π^+ beam with central momentum 3.7 GeV/c and a momentum range of ±0.2 GeV/c. The data reduction system was described earlier.[1] The events for channel (1) are selected from the four-body final state

$$\pi^+ p \to p\pi^+\pi^+\pi^- \qquad (13{,}000 \text{ events}) \qquad (3)$$

and channel (2) from the five-body final state

$$\pi^+ p \to p\pi^+\pi^+\pi^-\pi^0 \qquad (13{,}600 \text{ events}) \quad . \qquad (4)$$

From the measured π^+ beam flux of 3 events/μb,[2] the cross sections for the observed final states are

$$\sigma(p\pi^+\pi^+\pi^-) = 3.52 \pm 0.10 \text{ mb}$$

$$\sigma(p\pi^+\pi^+\pi^-\pi^0) = 3.62 \pm 0.10 \text{ mb}$$

where the errors are statistical only.

To measure the differential cross sections and density matrix elements for ρΔ or ωΔ production we have defined the resonance mass bands:

$$\Delta^{++}: \quad 1160 \le M(p\pi^+) \le 1280 \text{ MeV}/c^2 \qquad (5a)$$

$$\rho^0: \quad 680 \le M(\pi^+\pi^-) \le 860 \text{ MeV}/c^2 \qquad (5b)$$

$$\omega^{o} : \qquad 763 \leq M(\pi^{+}\pi^{-}\pi^{o}) \leq 803 \text{ MeV}/c^{2} \quad . \tag{5c}$$

Background underneath the double resonance events was measured by selecting all events within a resonance mass band, and plotting the mass distribution of the particles recoiling against the (predominantly) resonant system. A hand-drawn curve was used to determine the background under the resonant signal in the recoiling system, as well as the fraction of the recoiling resonance included within the defining mass limits [Eq. (5)]. This procedure was followed for both the Δ^{++} and the vector meson mass bands, and for control mass bands both above and below the vector meson mass signal (so that no vector meson events are included in these control intervals); this latter selection provides a measure of the number of events in the double resonance region which are in neither resonance.

The cross sections for channels (1) and (2), using the background subtraction method outlined above and correcting for the fraction of events lost due to either the mass band selection criteria or to unseen decay modes, are[3]

$$\sigma(\pi^{+}p \rightarrow \rho^{o}\Delta^{++}) = 0.90\pm0.10 \text{ mb} \tag{6a}$$

$$\sigma(\pi^{+}p \rightarrow \omega^{o}\Delta^{++}) = 0.66\pm0.08 \text{ mb} \tag{6b}$$

where the errors include a possible systematic misestimation of background.

To define the differential cross section we use the variable $t' = t - t_{min}$, where $|t_{min}|$ is the smallest value of $|t|$ kinematically allowed for a given event. At the vector meson and Δ^{++} central mass values $t_{min} \approx -0.075\ (\text{GeV}/c)^2$ for 3.7 GeV/c incident π^{+}. Thus all t' values can be translated into effective t values by $t_{eff} = t' - 0.075\ (\text{GeV}/c)^2$. The background subtraction method outlined above was used with a coarse $|t'|$ selection to give adequate statistics to measure the double resonance purity within the intersection of the double resonance bands as a function of $|t'|$. Interpolating these data points for the purity for finer $|t'|$ bins, and normalizing to the total $\rho\Delta$ and $\omega\Delta$ cross sections yields the differential cross sections shown in Figs. 1a,b. The number of events in each channel within the mass bands is also shown. The overall normalization errors of Eqs. (6a,b) are not included in the errors shown in Fig. 1 (or in Fig. 4).

The $\rho\Delta$ distribution is seen to be more sharply peaked in the forward direction than the $\omega\Delta$ distribution. While the $\rho\Delta$ data can be fitted to the simple functional form of the sum of two exponentials, with slopes 13.0±0.5 $(\mathrm{GeV}/c)^{-2}$ in the most forward direction and 2.4±0.5 $(\mathrm{GeV}/c)^{-2}$ for $0.4 < |t'| < 1.0$ $(\mathrm{GeV}/c)^2$, the $\omega\Delta$ data appears more complicated. Significant dips are seen in $d\sigma/d|t'|$ for the $\omega\Delta$ near $|t'| = 0$ (0°) and $|t'| = 0.15$ $(\mathrm{GeV}/c)^2$. For $|t'| > 0.2$ $(\mathrm{GeV}/c)^2$, the $\omega\Delta$ data are consistent with an exponential fall-off with slope 4.02±0.20 $(\mathrm{GeV}/c)^{-2}$.

More detailed information about the production mechanisms for $\rho\Delta$ and $\omega\Delta$ is conveyed by the decay density matrix elements. Using the standard t-channel coordinate system[4] and the method of moments to evaluate the matrix elements and their errors, we present the $\rho\Delta$ and $\omega\Delta$ density matrix elements in Figs. 2 and 3, respectively. For these figures, all events lying within the crossing double resonance bands were used without a background subtraction. The $|t'|$ dependence of the matrix elements has also been measured for background events (not shown), and indicates no sharp features such as are discussed below for $\rho\Delta$ and $\omega\Delta$ selections.

Considering first the $\rho^o\Delta^{++}$ channel, we see that for $|t'| < 0.2$ $(\mathrm{GeV}/c)^2$, ρ_{00} is large (~ 0.8) while the other elements are much smaller ($\lesssim 0.1$) in magnitude. This is in qualitative agreement with the predictions of a model with elementary pion exchange, where $\rho_{00} = 1$ and all other terms are zero. A new feature of this data is the extension to large $|t'|$, and finer detail in the small $|t'|$ (< 0.2 (GeV/c)^2) data.

Evidence for a zero in ρ_{00} near $|t'| = 0.75$ (GeV/c)^2 is given in Fig. 2a; additional evidence for the vanishing of the amplitude to produce a ρ^o in the $m = 0$ state at this $|t'|$ value is provided by the zero in Re $\rho_{1,0}$ (Fig. 2b). The data unambiguously demonstrate that ρ_{00} approaches zero at $|t'| = 0.75$ (GeV/c)^2. However, it is difficult to ascertain the significance of the observed rise in ρ_{00} for larger $|t'|$ values, since a background subtraction is unreliable with the meager statistics available.

We note[4] that ρ_{00} measures the unnatural parity exchange when the vector meson is in the zero t-channel helicity state. Hence we present evidence that the unnatural parity exchange amplitude has a zero near $|t'| = 0.75$ (GeV/c)^2. Such a zero is predicted by simple Regge pole models[5,6] for nonsense wrong signature points; if the observed zero corresponds to the point $\alpha_\pi(t) = -1$, then we infer a slope for a linear π trajectory of ~ 1.2 (GeV/c)$^{-2}$. While the simple form factor model[7] does not predict this zero, models with interfering poles,[8] or pole plus cut contributions,[9] or optical models[10] also yield this type of structure.

In Fig. 4a we show ρ_{00} multiplied by $d\sigma/d|t'|$ for the $\rho^o\Delta^{++}$ channel (we define the quantity $\sigma_0^- \equiv \rho_{00}\, d\sigma/d|t'|$). Aside from the zero near $|t'| = 0.75$ (GeV/c)^2, evidence for a change in slope may be seen, with the forwardmost data appearing steeper than the data at larger $|t'|$. The curve in this figure is from a fit to the σ_0^- distribution for $0 < |t'| < 1.4$ (GeV/c)^2 using the Reggeized pion exchange model described in Reference 11. The slope of the pion trajectory is fitted to be 1.16 ± 0.03 (GeV/c)$^{-2}$, and is thus consistent with the position of the zero in ρ_{00}. The small error in the slope is due to the sensitivity of the model to the relatively precise measurements for $|t'| < 0.4$ $(\text{GeV/c})^2$. The Regge model fit may be seen to be in quantitative agreement with the data for all $|t'|$.

We next consider the helicity-flip contributions to $\rho^0\Delta^{++}$ production,[12]

$$2\sigma_1^+ = \rho_{1,1} + \rho_{1,-1} \tag{7a}$$

$$2\sigma_1^- = \rho_{1,1} - \rho_{1,-1} \tag{7b}$$

where, as $s \to \infty$, σ_1^+ (σ_1^-) measures the natural (unnatural) parity contribution to the vector meson in the (t-channel) helicity one state. The distribution of σ_1^- (see Fig. 2h) for $\rho\Delta$ production, which includes the π exchange contribution to the helicity one state, does not show a dip near $|t'| = 0.75$ $(\text{GeV/c})^2$, where the π contribution to the helicity zero state has been observed to vanish. Hence we conclude that, at least at large $|t'|$, the π exchange contribution to σ_1^- is unimportant. Whether the dominant contributions to σ_1^- are due to cuts or additional poles cannot be decided with the available data.

The distribution of σ_1^+ (see Fig. 2g) for $\rho\Delta$, which in a pole model would be dominated by A_2 exchange, shows evidence for a change of slope near $|t'| = 0.16$ $(\text{GeV/c})^2$, and appears smooth near $|t'| \sim 0.6$ $(\text{GeV/c})^2$. A zero near $|t'| = 0.2$ in the A_2 amplitude has been inferred from finite energy sum rules.[5] The lack of a dip in σ_1^+ near $|t'| = 0.6$ $(\text{GeV/c})^2$ may be used to extract information about the ghost-killing mechanism of the A_2, assuming that the A_2 dominates other contributions to σ_1^+. Noting that the Δ^{++} density matrix elements (Figs. 2d,e,f) near $|t'| = 0.6$ are consistent with those expected from a magnetic dipole (M1) coupling at the $\bar{p}A_2\Delta$ vertex ($\rho_{3,3} = 3/8$, Re $\rho_{3,-1} = \sqrt{3}/8$, Re $\rho_{3,1} = 0$), we surmise that there is a unit flip of helicity at the nucleon vertex. Since there exists good evidence of approximate ρ-A_2 exchange degeneracy,[6] $\alpha_\rho \approx \alpha_{A_2}$, and hence $|t'| \approx 0.6\ (\text{GeV}/c)^2$ is a sense point for the A_2. The absence of a dip in σ_1^+ near the point $\alpha_{A_2} = 0$ is then evidence that the A_2 chooses to couple to nonsense channels (Gell-Mann mechanism).

The $\omega\Delta$ channel is amenable to a similar analysis. If ρ exchange dominates the production of $\omega\Delta$, we expect $\rho_{0,0} = \rho_{1,0} = 0$ and $\rho_{1,1} = \rho_{1,-1} = 1/2$, as well as M1 coupling at the nucleon vertex (see the discussion of σ_1^+ above). As may be seen in Fig. 3, the data indicate a preference for a production mechanism that resembles that of $\rho^o\Delta^{++}$ (π exchange). In particular the large value of $\rho_{0,0}$ indicates a sizable contribution from unnatural parity exchange; generically we shall call such exchanges B exchange.

For the $\omega\Delta^{++}$ channel we isolate the B contribution to the helicity zero state as before by plotting σ_0^- (Fig. 4b). The distribution is seen to be much less sharply peaked than the corresponding distribution for $\rho\Delta$. A new feature of the data is the significant dip at $|t'| = 0.17\ (\text{GeV}/c)^2$, which is contributed to by dips in both $\rho_{0,0}$ and in $d\sigma/d|t'|$. It has been suggested[13] that such a dip could be due to the vanishing of the B amplitude at $\alpha_B = 0$ for $t \approx -0.25$, near the dip observed in this experiment. However, the sharpness of the dip argues against this interpretation. Since $d\sigma/d|t'|$ alone does not show as large a dip as σ_0^-, the dominant cause of the dip is a sudden change in the polarization of the ω^o over a small interval in $|t'|$. While the sharpness of the dip is reminiscent of interference effects, we cannot offer a specific explanation of this effect. For $|t'| > 0.2\ (\text{GeV}/c)^2$ the σ_0^- distribution is consistent with an exponential fall-off with slope $3.09 \pm 0.26\ (\text{GeV}/c)^{-2}$.

B exchange is observed to contribute almost half of the $\omega\Delta$ cross section at 3.7 GeV/c, suggesting relatively strong couplings of the B to $\pi\omega$ and to $\bar{p}\Delta$. A model with π-B exchange degeneracy[11] supplies such strong couplings; the smooth curve in Fig. 4b shows that for $0.2 < |t'| < 1.0$ $(\text{GeV/c})^2$ such a model is in good agreement with the data. While the dip at $|t'| = 0.17$ $(\text{GeV/c})^2$ is not accounted for by the model, an interesting consequence is predicted for $|t'| < 0.14$ $(\text{GeV/c})^2$. It is seen that an enhancement of ~ 70 events over the π-B exchange degeneracy prediction occurs for small $|t'|$. This is precisely the region in which destructive $\omega\rho$ interference was observed[1] for the $M(\pi^+\pi^-)$ distribution of channel (1), where ~ 80 events are removed from the $\pi^+\pi^-$ mass distribution near the mass of the ω^o. If the off-diagonal element of the $\rho\omega$ mass mixing matrix is essentially real, for the observed ω-ρ production phase ~ 80 events should be added to the ω^o sample with $|t'| < 0.14$ $(\text{GeV/c})^2$, in agreement with the deduced excess number of events. We further note that the observed[1] ω-ρ production phase $\beta = 1.5 \pm 0.3$ rad has also been interpreted as a consequence of π-B exchange degeneracy.[14]

Finally we consider the distributions of $\sigma_1^{\pm}$ for the $\omega^o\Delta^{++}$ channel. It is seen (Fig. 3h) that σ_1^-, the unnatural parity contribution, shows no sharp structure as a function of $|t'|$, while σ_1^+ (see Fig. 3g), which measures the ρ contribution in pole models, has a zero near $|t'| = 0.65$ $(\text{GeV/c})^2$. The position of this zero is thus slightly displaced from the point where $\alpha_\rho = 0$, $|t'| \approx -0.5$ $(\text{GeV/c})^2$. A background subtraction in the region of the zero enhances the effect, but does not increase its significance (~ 2 standard deviations). Evidence for this zero has not been seen previously in two-body final states with an ω^o (and either a nucleon or nucleon isobar). A possible explanation for the apparent lack of a dip in other experiments is that ρ

exchange is <u>not</u> the dominant mechanism in ω^o production; as indicated above B exchange is dominant at the intermediate energies studied to date. Hence the ρ contribution σ_1^+ must be isolated with good statistics to see the appearance or lack of a dip near 0.6 $(GeV/c)^2$. It is worth noting that since the ρ chooses M1 coupling, for $\sigma_1^+(\omega\Delta)$ there is a unit helicity flip at both the meson and the nucleon vertices in both the s and t channel coordinate systems. Hence the net helicity flip is either 0 or 2, so that a zero (or dip) in σ_1^+ would be expected near $|t'| = 0.2$ or 1.2 $(GeV/c)^2$, respectively, for models[10] which attribute the observed dip in $\pi^- p \to \pi^o n$ to a zero in the Bessel function J_1. Our result thus contradicts such simple models, and favors the hypothesis that the ρ exchange amplitude vanishes at the nonsense wrong signature point $\alpha_\rho = 0$.

In conclusion, evidence is found for structure in t for both $\rho^o\Delta^{++}$ and $\omega^o\Delta^{++}$ production which is readily accounted for by simple Regge pole models. Evidence for nonsense wrong signature zeroes are seen for both the π and the ρ trajectories, and π-B exchange degeneracy appears to be consistent with the $\rho\Delta$, $\omega\Delta$ data. Data consistent with the hypothesis of $\rho\omega$ interference effects appearing in the $\pi^+\pi^-\pi^o$ events is also presented, although the unexplained dip in $\sigma_0^-(\omega\Delta)$ at $|t'| = 0.17$ $(GeV/c)^2$ clouds the complete theoretical interpretation of the data.

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†On leave from David Lipscomb College, Nashville, Tennessee.

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2. On a sample of ~ 1/3 of the film all events were measured. Correcting for scanning and measuring losses, a bias against finding small angle elastic scatters, and proton contamination in the beam (via comparison with film exposed to a proton beam), we use the π^+p total cross section at 3.7 GeV/c [28.1 mb interpolated value, A. Citron et al., Phys. Rev. 144, 1101 (1966)] and the corrected number of events (39,500) to yield 0.712 μb/event. Scaling by the ratio of events from reaction (3) in the ~ 1/3 sample to the number in the total sample gives the flux of 3 events/μb.

3. For the mass bands considered the double resonance background is ~ 10-20% in the forward direction, and increases as the scattering angle increases; about 75% of each resonance is included within the defining resonance band, and does not appear to vary as a function of scattering angle. The branching fraction of $\rho^0 \to \pi^+\pi^-$ was taken to be 1.0, and of $\omega^0 \to \pi^+\pi^-\pi^0$ to be 0.87±0.04 [Particle Properties Tables, Rev. Mod. Phys. 42, 87 (1970)].

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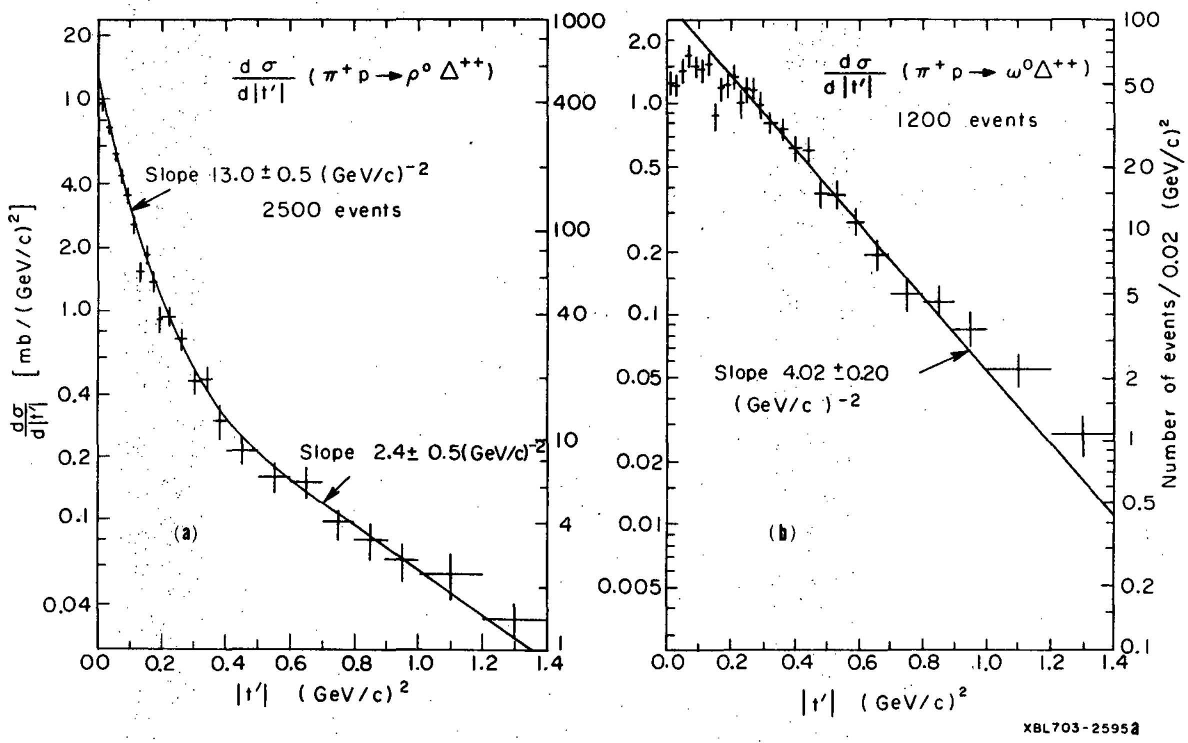
FIGURE LEGENDS

Fig. 1. Differential cross sections for vector meson and Δ^{++} production, corrected for nonresonant background. (a) $\pi^{+}p \rightarrow \rho^{o}\Delta^{++}$, (b) $\pi^{+}p \rightarrow \omega^{o}\Delta^{++}$.

Fig. 2. Density matrix elements for $\rho^{o}\Delta^{++}$ production as a function of $|t'|$. (a) $\rho_{0,0}$; (b) Re $\rho_{1,0}$; (c) $\rho_{1,-1}$; (d) $\rho_{3,3}$; (e) Re $\rho_{3,1}$; (f) Re $\rho_{3,-1}$; (g) $\rho_{1,1} + \rho_{1,-1}$; and (h) $\rho_{1,1} - \rho_{1,-1}$.

Fig. 3. Density matrix elements for $\omega^{o}\Delta^{++}$ production as a function of $|t'|$. (a) $\rho_{0,0}$; (b) Re $\rho_{1,0}$; (c) $\rho_{1,-1}$; (d) $\rho_{3,3}$; (e) Re $\rho_{3,1}$; (f) Re $\rho_{3,-1}$; (g) $\rho_{1,1} + \rho_{1,-1}$; and (h) $\rho_{1,1} - \rho_{1,-1}$.

Fig. 4. $\rho_{0,0}\, d\sigma/d|t'|$ for vector meson and Δ^{++} production. (a) $\pi^{+}p \rightarrow \rho^{o}\Delta^{++}$, (b) $\pi^{+}p \rightarrow \omega^{o}\Delta^{++}$.



$\frac{d\sigma}{d|t'|}$ ($\pi^+ p \rightarrow \rho^0 \Delta^{++}$)
Slope 13.0 ± 0.5 (GeV/c)$^{-2}$
2500 events
Slope 2.4 ± 0.5 (GeV/c)$^{-2}$
(a)
$\frac{d\sigma}{d|t'|}$ [mb/(GeV/c)^2]
|t'| (GeV/c)^2
$\frac{d\sigma}{d|t'|}$ ($\pi^+ p \rightarrow \omega^0 \Delta^{++}$)
1200 events
Slope 4.02 ± 0.20 (GeV/c)$^{-2}$
(b)
Number of events/0.02 (GeV/c)^2
|t'| (GeV/c)^2
XBL703-2595A

Fig. 1

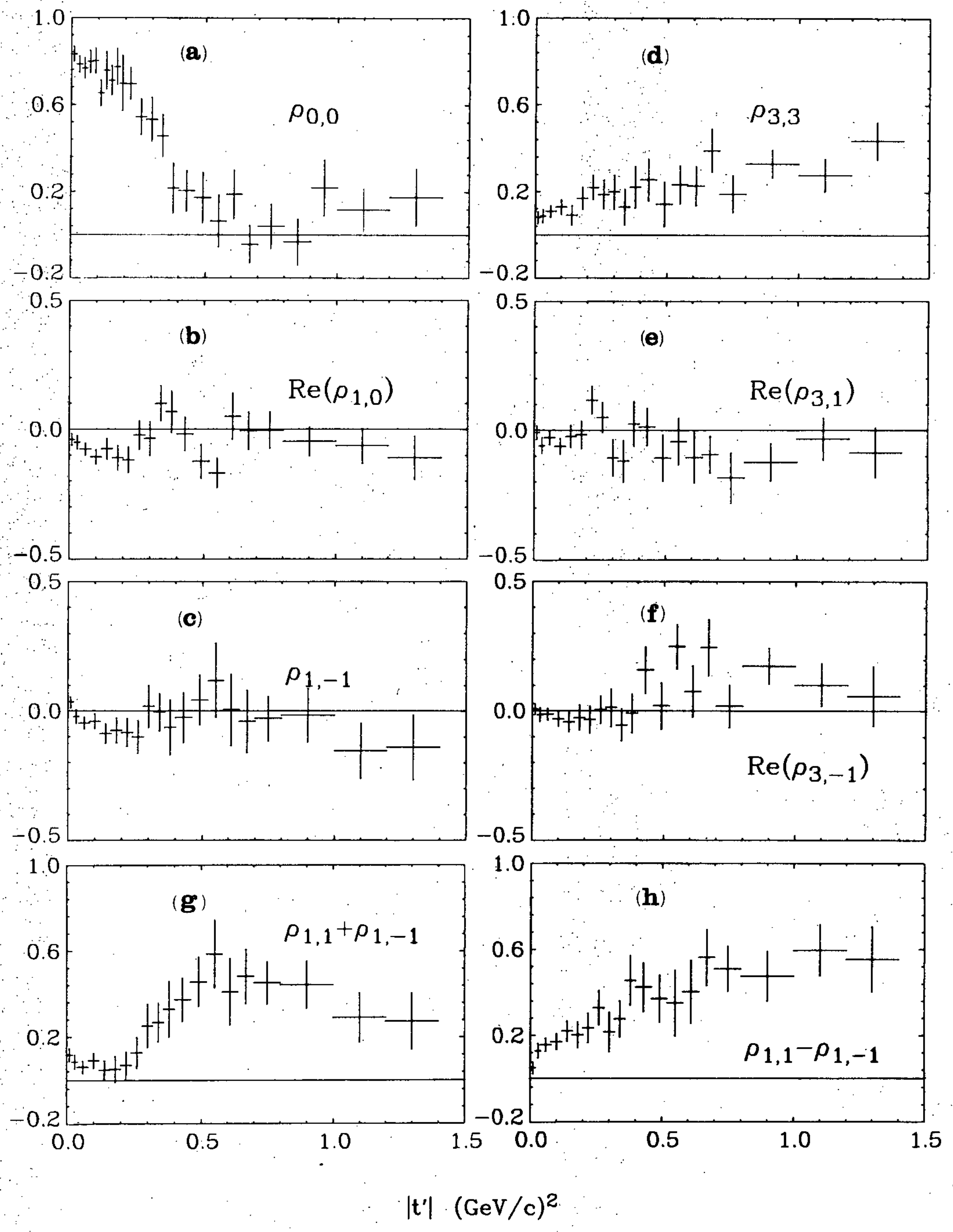

(a)
$\rho_{0,0}$
(b)
Re($\rho_{1,0}$)
(c)
$\rho_{1,-1}$
(d)
$\rho_{3,3}$
(e)
Re($\rho_{3,1}$)
(f)
Re($\rho_{3,-1}$)
(g)
$\rho_{1,1}+\rho_{1,-1}$
(h)
$\rho_{1,1}-\rho_{1,-1}$
|t'| (GeV/c)^2
XBL 705-939

Fig. 2

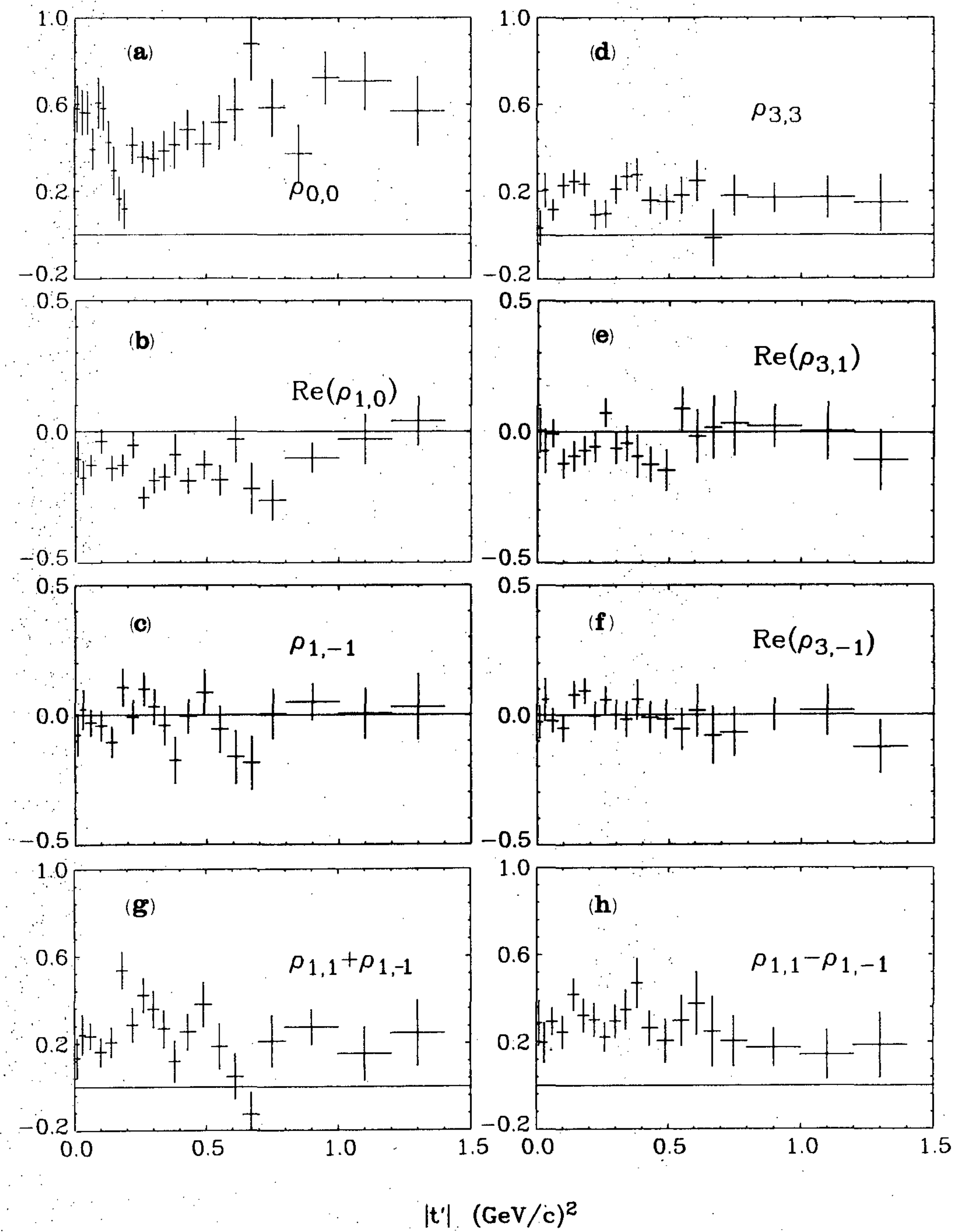

(a)
$\rho_{0,0}$
(b)
Re($\rho_{1,0}$)
(c)
$\rho_{1,-1}$
(d)
$\rho_{3,3}$
(e)
Re($\rho_{3,1}$)
(f)
Re($\rho_{3,-1}$)
(g)
$\rho_{1,1}+\rho_{1,-1}$
(h)
$\rho_{1,1}-\rho_{1,-1}$
|t'| (GeV/c)^2
XBL 705-940

Fig. 3

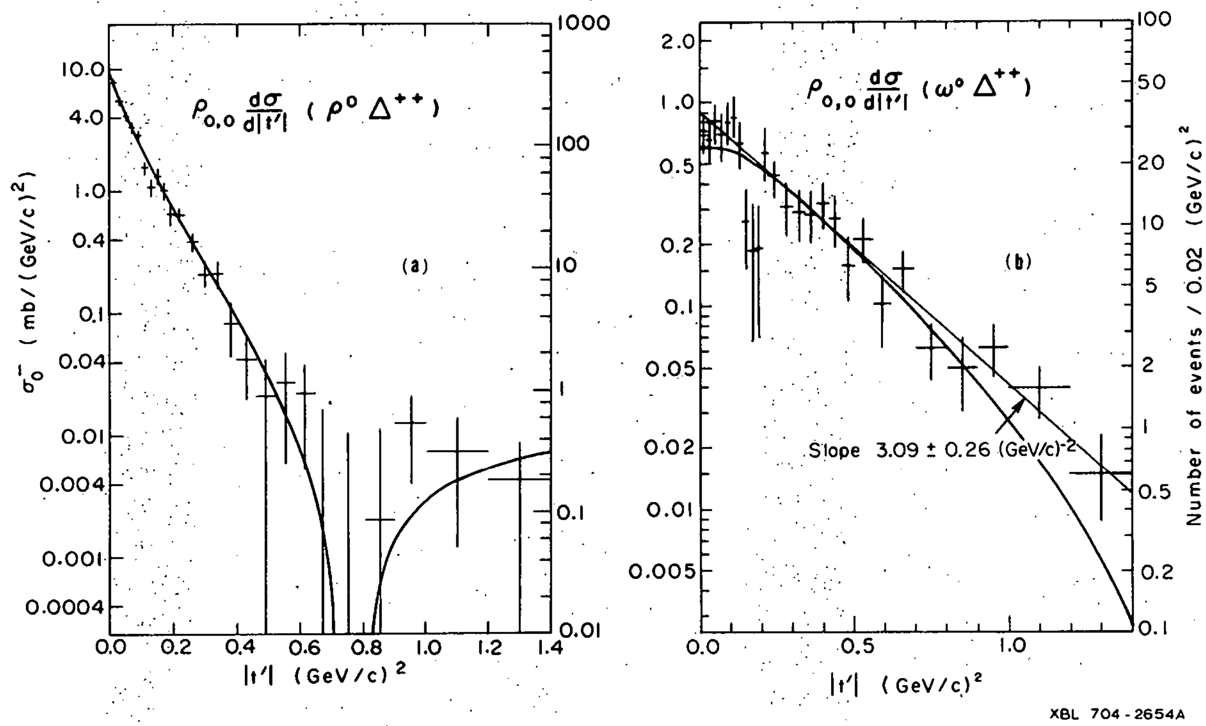

$\rho_{0,0}\frac{d\sigma}{d|t'|}$ ($\rho^0\Delta^{++}$)
(a)
σ_0^- (mb/(GeV/c)^2)
|t'| (GeV/c)^2
$\rho_{0,0}\frac{d\sigma}{d|t'|}$ ($\omega^0\Delta^{++}$)
(b)
Slope 3.09 ± 0.26 (GeV/c)$^{-2}$
Number of events / 0.02 (GeV/c)^2
|t'| (GeV/c)^2
XBL 704-2654A

Fig. 4

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